Monte Carlo simulation and experimental tests of a Faraday Cup for absolute dosimetry with high pulsed ion beams

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Introduction

During the last decades, the interest towards the medical physics research, issues of the whole scientific community, has notably increased. Many medical physics fields (radiotherapy, imaging, dosimetry, etc.), indeed, need a continuous research and development effort, in order to increase the quality of the developed devices and techniques and, hence, the impact on the quality of applications on patients. In this contest, the Radiotherapy based on the use of both external and internal ionizing radiation to kill the tumor cells is one of the most demanding and growing field. In the last decades, the radiotherapy has become an effective alternative with respect to the more invasive techniques, as for instance the surgery or the chemo-therapy which often do not allow the complete curing. The main purpose of the radiotherapy is to maximize the damage in the tumor tissues minimizing the irradiation on the surrounding normal tissue. The conventional radiotherapy is today the most largely widespread technique applied in the tumor treatments. It is based on the clinical use of gamma rays or electron beams[1].

Nevertheless, the conventional radiotherapy can cause non-desiderata effects, due to not negligible irradiation of the healthy tissues. On the other hand, the pioneering hadrontherapy approach, which is based on the use of hadron beams, particularly protons and ions, allows a more precise tumor irradiation minimizing the effect on the healthy surrounding tissues. Hadrontherapy allows to, indeed, target the tumor in a more precise way, reducing the damage and the dose delivered to the healthy tissue near the tumor and allowing to deliver an higher, more effective dose to the ill cells [5]. Hadrontherapy can also be used in combination with chemotherapy, as a follow-up treatment to surgery, and in combination with standard X-ray radiation treatment.
The main benefits of Hadrontherapy can be summarized in the following points:

- Reduced risk of damage to healthy tissue and organs
- Shown to be effective in adults and children
- Can be used to treat recurrent tumors even in patients who have already received traditional forms of radiation
- Fewer short- and long-term side effects
- Lower incidence of secondary tumors

The physicist who firstly proposed the use of protons and later also of the heavy ions, for cancer treatments was Robert R. Wilson [2] and the first experiments which proved the clinical favorable properties of proton beams was carried out in 1945. Up to now, according to the June 2014 statistics published by the Particle Therapy Co-Operative Group [3], a total of 122449 patients have been treated with hadrontherapy, 105747 with protons, 13119 with carbon ions and 433 with other heavy ions. Nowadays in the world about 40 hadrotherapy centers are active and in the next years about 20 centers will be realized.

Despite the clinical advantages of the hadrontherapy approach for the cancer treatment, its worldwide proliferation is, nowadays, very limited. The difficulty of the hadrontherapy centers spread around the world, is due to the high technical complexity and, consequently, to the high overall cost. Typically proton/ion acceleration facility requires the use of huge and expensive machines, like cyclotrons or synchrotrones, which need a careful and expensive upkeep. The ion beams accelerated from these machines are transported up to the irradiation point (i.e. the
patient) using huge and complex magnetic systems. Therefore, the construction of an hadrontherapy facility results extremely complex and expensive (about 150 M€).

In order to increase spread and diffusion of hadrontherapy, several advanced and/or innovative technological solutions are currently under investigation by both researchers and companies involved in this field. In this framework, during the last decades, the research in the field of the laser-matter interaction has led to the development of an innovative proton and ion acceleration technique, which might represent a valid alternative to the conventional ones.

This technique is based on the interaction of an ultra-intense ($>10^{18}$ W cm$^{-2}$) and ultra-short (between 30 fs and 10 ps) pulse laser with a solid target [29]. The laser pulse transfers the energy to the solid target, leading to the ionization of the target surface and the consecutive formation of the state of plasma. The fast and free electrons in the plasma are accelerated in the backward or forward direction, according to the thickness of the target, generating a strong electric field that produces the consequent acceleration of the positive charges up to energies of the order of MeV. The accelerated ions from the target surface show a decreasing exponential energy distribution characterized by a maximum energy cut-off which depends on the laser intensity and target characteristics. Moreover, the angular distribution is also very broad and depends on the particle energy [23]. Currently the laser intensities available limit the maximum energy of the ions and protons emitted, nevertheless in the next years a new generation of laser, will allow to reach laser power of the order of PW ($10^{15}$ W), and ion energy of the order of hundred’s of MeV [28] The use of laser-target interaction as ion and proton source, may lead to the the realization of more compact and economic acceleration and transport
system respect to the traditional systems.

The scientific community has shown a growing interest in the demonstration that laser-driven ion beams can be suitable for multidisciplinary and particularly medical applications (as for instance the hadrontherapy case). The international project ELIMED (MEDical applications at ELI-beamlines), born from a collaboration between the INFN-LNS (Istituto Nazionale di Fisica Nucleare- Laboratori Nazionali del Sud) and FZU (Fyzikální ústav, Prague (CZ)) researchers, has the objective to demonstrate the potential applicability of these particular optically accelerated ion beams in hadrontherapy [27]. In order to reach this goal, because of the peculiarities of such ion beams, a dedicated transport system which allows to focus and select in energy the beams is required. Moreover, since no dosimetry protocol has been already established for laser-driven ion beams the development and characterization of innovative detectors for absolute and relative dosimetry, beam diagnostics together with the investigation of the biological effects are critical key points that have to be accurately addressed [6]. This thesis, developed in the framework of the ELIMED project, is dedicated to the development of an absolute ion beam dosimeter, based on the Faraday Cup principle, designed and realized at LNS. In order to allow the dose measurements of the extremely intense and unstable laser-driven ion beams maximizing the accuracy in the charge collection, the FC prototype we developed, has very peculiar characteristics. This prototype is characterized by a peculiar geometrical configuration of the electric field, allowing to maximize the secondary electrons suppression. This will allow to reach an high as well level of accuracy in the charge collection and in the dose calculation. In the first chapter, the description of the charged particle interaction with the matter is reported. The advantages of using ion beams in tumor
treatment as well as the benefits of hadrontherapy with respect to the traditional radiotherapy in terms of greater biological effectiveness and survival probability are also discussed. In the second chapter, a description of the acceleration processes occurring when an high power laser interacts with a solid target, together with an overview of the ELIMED project are reported.

In the third chapter, the Monte Carlo simulation of the entire transport beam line along with the Faraday Cup prototype performed using the Geant4 toolkit is described. In particular, a simulation of a typical ion laser-driven transport beam line with all the designed transport elements and diagnostic devices is reported. Moreover, a simulation of the FC dose delivered by conventional monoenergetic proton beam have been also performed.

The Faraday Cup has been also experimentally tested for the first time in June 2014 at the Prague Asterix Laser System (PALS) laboratory in Prague, where an high intense laser is available. In the fourth chapter the study of the electromagnetic pulse (EMP) noise effecting the Faraday Cup signal due to the laser pulse propagation inside the interaction chamber performed during the experimental run is reported in order to highlight the noise characterization when no accelerated particles are detected. The characteristic frequencies of the noise signals have been investigated, performing the fast Fourier transforms and comparing them with the resonant frequencies of a spherical cavity. Moreover the noise signal amplitude as function of the bias applied to Faraday Cup electrode has been studied, in order to obtain some functional relation. The measurement and quantification of the EMP, in the particular environment of a laser-matter interaction chamber, is a fundamental step, for the use of this device as an accurate absolute dosimeter.
Chapter 1

Charged particles interaction mechanisms and biological effects

One of the aim of medical physics is the cancer treatment by means of Radiotherapy, that makes use of external beams of ionizing radiations with the purpose to locally destroy the neoplastic tissues. Radiotherapy takes advantage of physical features of ionizing radiations to gain medical and biological benefits.

Among radiotherapy techniques it’s possible to discern the conventional Radiotherapy with photons (X-rays, $\gamma$) and electrons beams and the Hadrontherapy that uses, instead, protons and heavy ions. The significant difference between conventional radiotherapy and hadrontherapy is related to the different photons and electrons (in the first case) and ions (in the second case) interaction mechanisms with matter.

In the case of hadrontherapy, the most important benefit is the possibility to damage a tumor placed at a some depth without causing excessive damages to outward healthy tissues. This is possible thanks to the peculiar stopping power curve (Bragg Peak) of heavy ions, that entails the maximum of the energy released, when the ions are stopping. On the other hand, photons that are not charged
particles, are absorbed by crossed material and their intensity decreases following an exponential law. For this reason photons cause a not negligible irradiation at the surface healthy tissues.

In the current chapter the features of charged particles interaction with matter will be briefly described, in order to highlight the hadrontherapy advantages as respect to the conventional radiotherapy in cancers treatment.

1.1 Charged particles interaction with matter

Hadrontherapy is based on the use of ions, like protons or carbon ions that crossing a material, interact with the electrons of atoms, through Columbian forces. Passing through the matter, charged particles transfer energy to surrounding atoms, mainly producing two effects [4]:

- **Excitation**: released energy is not enough to allow the emission of the electron from its own atom (ionizing potential). The atomic electron is just excited to an upper energy level but remaining inside atomic orbits. This process causes an electromagnetic radiation when the atom de-excites.

- **Ionization**: the energy lost from incident particle is enough to extract an atomic electron. The effect produces the creation of a positive ion-free electron couple.

Proton and ion beams can also directly interact with the atomic nuclei of the crossed material, through *Strong interaction* that produces elastic and non-elastic hadronic reactions. The contribute of the hadronic interactions is certainly negligible as respect the electromagnetic ones and should be taken into consideration only for energies of the incident ions greater than 100 AMeV. [4]
The energy transfer to the atoms is a continuous process, considering only Coulomb interaction. Indeed the incident particle does not lose all energy in a single collision with the atom, but it releases only a fraction of its total energy collision by collision. The incident particle, hence, loses its total energy after a lot of collisions with atomic electrons, continuously reducing its velocity till it stops. In order to evaluate the loss energy per collision an useful physical quantity is the *Stopping Power* \( -\frac{dE}{dx} \) which expresses the average value of the energy lost inside an infinitesimal element \( dx \).

Generally the *Stopping Power* is defined as the product between the *linear attenuation coefficient* \( \mu \), which express the probability of ions-electrons collisions, and the mean energy \( Q_m \) released by the beam during the collision. The physicist Bethe deduced its expression, using the quantum mechanics and the microscopic interaction laws. Later the physicist Bloch modified the expression, taking in account of the relativistic corrections indispensable when the beam velocity is close to light velocity.

The complete expression of *Stopping Power* which depends on the momentum is given by [4]:

\[
-\frac{dE}{dx} = \frac{4\pi e^4 z^2 Z N}{m_e v^2} \left( \ln \frac{2m_e v^2}{I(1 - \beta^2)} - \beta^2 - \frac{C}{Z} - \frac{\delta}{2} \right)
\]  

(1.1)

Where \( z \) and \( Z \) are respectively the nuclear charge of the beam and target particles; \( v \) is the beam velocity, \( \beta = \frac{v}{c} \), \( N \) is the atomic density of the medium, \( I \) is the mean ionization potential and the terms \( C/Z \) and \( \delta/2 \) are the shell and density corrections.

As is shown in 1.1 equation, the stopping power depends on the natural logarithm of the ratio between the kinetic energy and the ionization potential: this fact causes the presence of the *Minimum ionizing particle* (M.I.P) which represents
the momentum that corresponds to the minimum loss energy. The relativistic
terms introduce a rise in the stopping power curve at high momentum. In figure
1.1 is shown the typical variation of the Stopping power in respect to the beam
energy, for different incident particles.

![Stopping power curve](image)

Figure 1.1: Variation of the specific energy loss in air versus energy of the charged
particle. [4]

Dividing the stopping power for target density, it is possible to obtain the energy
loss per surface density unit, that is the energy loss by the particle per g/cm².

### 1.2 Interaction of fast electrons with matter

The electrons which cross a material, due to their lower mass as respect to hadrons,
make a greater number of collisions provoking an energy loss per collision more
chaotic and faster, above all if the incident electrons are very fast.

The Bethe-Bloch formula, in the fast electrons case, can be modified [4]:
Moreover, electrons can lose energy also through processes, which involve radiative transfer, like the Bremsstrahlung effect which provokes electromagnetic radiation emission in any point along the electron track. The probability of this process increases with the electron energy and the radiative energy loss can be written as [4]:

\[-\left(\frac{dE}{dx}\right)_r = \frac{NEZ(Z + 1)e^4}{137m_e^2c^4}\left(4\ln\frac{2E}{m_ec^2} - \frac{4}{3}\right)\]  

Then the total stopping power for fast electrons is given by the sum between collisional and radiative term:

\[\left(\frac{dE}{dx}\right) = \left(\frac{dE}{dx}\right)_c + \left(\frac{dE}{dx}\right)_r\]  

### 1.3 Bragg Peak and Range

Due to the strong dependence of charge particles stopping power on \(\beta\) and energy, the most of particle energy is lost at the end of their path in crossed material, when they are stopping.

The energy loss as a function of the depth reached by particles in the medium, is called Bragg Peak and its maximum position strongly depends on the material, on the \(z\) of particles and on the beam energy.

Indeed, thanks to the peculiar Bragg peak shape, charged particle beams are very interesting in radiation therapy because they allow the possibility to damage directly tumors placed at a certain depth. Comparing the charged particle energy
loss curve with that one characteristic of photons, like X-rays, usually used in traditional Radiotherapy it is immediately shown the advantage of Hadrontherapy (Figure 1.2): in hadrontherapy the superficial sane tissues are slightly damaged, thanks to the good ratio peak-plateau [5]. Instead, photons which are absorbed by crossed material through the three electromagnetic processes (photoelectric effect, Compton effect, pair production), follow the exponential absorption law for their intensity $I(x) = I_0 e^{-\mu x}$ which depends on the linear attenuation coefficient $\mu$.

Figure 1.2: Dose released as function of depth for protons, carbon ions, X-rays, $\gamma$ and neutrons

Due to the great number of collisions between the beam and the atoms of the target, the energy loss process is a statistic and random process and the Bethe-Bloch
expression gives only its mean value. Indeed, this randomness produces a dispersion of the beam energy after material crossing, called energy straggling (Figure 1.3).

Figure 1.3: Plots of energy distribution of a beam of initially monoenergetic charged particles at various penetration distances. E is the particle energy and X is the distance along the track [4].

The energy straggling introduces an error in the loss energy calculation, but also in the range determination, defined as the traveled distance by incident particle in the medium until it stops:

$$ R(T) = \int_0^T \left( -\frac{dE}{dx} \right)^{-1} dE $$  \hspace{1cm} (1.5)

where T is the incident particle kinetic energy. The integral range expression cannot be exactly calculated because of the straggling phenomenon but like so for energy loss, it is possible to define a mean range as the absorber thickness
that reduces the particle count to exactly one-half of its value without absorber. In figure 1.4, indeed, is shown the transmission coefficient, defined as the ratio between incident and transmitted particles, as function of the absorber material thickness. Moreover it is possible to define also the *extrapolated range*, which is obtained by extrapolating the linear portion of the end of the transmission curve to zero.

![Diagram](image)

**Figure 1.4:** Transmission coefficient as a function of the material depth

In order to use the peculiar energy loss of charged particles in medical field, it is fundamental the range calculation for specific crossed materials. For this reason, the *energy straggling* is one of the main problems in hadrontherapy, which can be solved predicting and simulating the involved physical processes during the collisions.

From radiotherapeutic point of view, as the cancer volume has a longitudinal dimen-
sion ranging few millimeter to centimeters, the dimension of a typical Bragg Peak is not sufficient to uniformly cover it. For this reason it has to be modified: the beam energy is progressively varied to fulfill an overlapping of different stopping power curves, each one correspondent to different beam energy. The Bragg Peak modified is called **Spread Out Bragg Peak (SOBP)** and its longitudinal length depends on cancer dimension along the beam axis (Figure 1.5) [6]. The resultant curve has a lower peak- plateau dose ratio as respect the monoenergetic curve, but comparing it to conventional radiotherapy, it shows an evident advantage.

![Figure 1.5: Overlapping of different Bragg peak curves in water and total effect in cumulative dose distribution (SOBP)](image)

**1.4 Dosimetry**

Apart from physical and chemical effects already described, the interaction of ionizing radiation with biological tissues also causes biological effects to irradiated cells.
In order to relate all these effects, it is possible to define two different physical quantities: the quantities connected to the field which describe the region in which the radiation field acts and the dosimetric quantities which consider the medium features [4].

1.4.1 Field physical quantities

A radiation field is created in the region where is located the cancer when it is irradiated by particles beams. The physical quantities which explicit the generated field are stochastic:

- **Particle fluence**, that is the particles number dN which go through a sphere characterized of a maximum section of dA, centered on the interest point:
  \[
  \Phi = \frac{dN}{dA} \quad [m^{-2}]
  \]  
  (1.6)

- **Particle fluence intensity**, which describes the particle fluence time evolution:
  \[
  \phi = \frac{d\Phi}{dt} \quad [m^{-2}s^{-1}]
  \]  
  (1.7)

- **Energy fluence**, that is the product between the particle fluence and energy:
  \[
  \Psi = \Phi E
  \]  
  (1.8)

1.4.2 Dosimetric physical quantities

In conventional radiotherapy and hadron therapy applications, the dosimetric quantities which have a fundamental role in energy deposition measurement are the exposure, the absorbed dose and the Kinetic Energy Released in Matter (K.E.R.M.A).
**Exposure**: the *exposure* concept, hails from the origin of Radiotherapy and hence it is defined only for X-rays and γ rays source. It refers to created charge (secondary electrons), due to the air ionization during the radiation crossing inside an infinitesimal air volume with mass $dm$, considering that all secondary electrons are stopped in air:

$$X = \frac{dQ}{dm} \quad (1.9)$$

The historical *exposure* unit of measure is the *Roentgen* (R) which in the International System (SI) corresponds to [4]

$$1R = 2.58 \times 10^{-4} C/Kg \quad (1.10)$$

The exposure depends only on the radiation intensity, source-air volume geometry and its experimental determination needs a direct or indirect measurement of generated charge by air ionization. But, because of the great number of secondary electrons interactions with the air this measurement is very difficult.

**Absorbed dose and dose rate** In order to consider the features of crossed medium by radiation and the absorbed energy variation according to target material, instead, it is useful to define the *absorbed dose* [7]:

$$D = \frac{dE}{dm} \quad [Gy = J/Kg] \quad (1.11)$$

where $D$ represent the deposited energy inside an infinitesimal volume with mass $dm$, its unit of measure is *Gray* (Gy) and depends on particle beams and on crossed tissue. In tumor treatment planning the water is employed as equivalent biological tissue due to the high water percentage presence ($\sim 70\%$) in human body. The delivered dose by monoenergetic protons in water can be expressed by

19
\[ D_W(Gy) = \frac{1}{A} (S(E))_W \frac{Q}{1.602 \cdot 10^{-10}} \]  

where \( A \) is the effective beam area \((cm^2)\), \((S(E))_W(MeVcm^2/g)\) is the mass stopping power for a specific proton energy and \( Q(C) \) is the collected charge.

In order to evaluate the variation rapidity of absorbed dose is useful to also define the absorbed dose rate as:

\[ \dot{D} = \frac{dD}{dt} \quad [Gys^{-1}] \]  

**K.E.R.M.A.** The *Kinetic Energy Released in Matter* describes the mass kinetic energy gained by secondary electrons during the radiation crossing:

\[ K = \frac{dE_{tr}}{dm} \quad [Gy] \]  

Due to the high number of secondary electrons produced, \( dE_{tr} \) is the sum of the initial kinetic energies of all generated secondary charges (before they deliver energy by collision).

### 1.5 Biological effects in Hadron-therapy

In order to quantify the ionizing radiation effects in biological tissues and evaluate, hence, the efficiency in terms of tumoral tissue damage it is useful to consider several parameters strictly connected to the damage. Among these parameters the most important ones are the *Linear Energy Transfer* (or LET) and the Relative Biological Effectiveness (RBE).

#### 1.5.1 L.E.T.

The *Linear Energy Transfer* is strictly connected to the charged particles mean stopping power, already described in the previous paragraph and it is defined as
the energy $dE$ lost inside an infinitesimal transverse volume $dl$ of crossed medium

$$L_\Delta = \left(\frac{dE}{dl}\right)_\Delta$$ \hspace{1cm} (1.15)

When charged particles delivers energy, they create secondary electrons ($\delta$ rays), which in turn, due to consecutive collisions, deposit energy in medium. Indeed, $dE$ represents the mean energy transferred to the medium per collision considering collisions with transferred energy less then threshold energy $\Delta$. This physical quantity, quantifies the ionization generated inside crossed medium along the incident particle flight direction and assumes a particular importance in hadron-therapy.

The heavy charged particles a part from the benefit of local dose deposition (Bragg Peak), show an high biological effectiveness due to high LET, in particular in the final part of their range.

### 1.5.2 Relative biological effectiveness (R.B.E.)

In medical tumor treatment, the absorbed dose determination has to be corrected with *quality factors* that have to take account of the different crossed tissues and organs. The product between the absorbed dose and the quality factor is called *equivalent dose* but it gives an overestimation of the dose which has to be deposited because the corrective factors impose upper limits to the dose.

In order to univocally establish the radiation effect on the crossed matter in radiotherapy it is necessary to define the **RBE (Relative biological effectiveness)** as the ratio between the dose delivered by a referential radiation, typically X-rays or $\gamma$ and the released dose by ions which generate the same biological effect:

$$R.B.E = \frac{D_{\text{ref}}}{D_{\text{ion}}}$$ \hspace{1cm} (1.16)
The R.B.E factor depends on different parameters: the effective dose delivered in the tissue, the type incident particles, energy loss mechanism (LET). All these physical quantities have to be experimentally measured in order to have a correct estimation of the radiation biological effectiveness. The purpose is to obtain an high R.B.E to optimize the radiation effect for tumor destruction.

1.5.3 Cell Survival

In order to accurately interpret the ionizing radiation effect on matter, it is necessary to consider the energy and spatial distribution and the dose delivered around the primary particle track. Indeed, the radiation crossing provokes the secondary electrons production (excitation or ionization) that through collisions transfer energy to the surrounding area. The best physical quantity that describes the energy loss is the L.E.T from which hence depends the radiation capacity to provoke an effective damage on cancer tissues.

Maximize the biological beam effectiveness means provoke the maximum damage to the cancer cells DNA: the DNA destroy causes the cells death.

Two different kind of DNA radiation damage exist [8]

- **Direct damage**: provoked by primary and secondary electrons which release energy directly to bombarded cells DNA

- **Indirect damage**: the energy transfer to DNA occurs through some different reactions with molecules and atoms of the cell and strongly depends on the medium composition

In both cases, the target which must to be bombarded and destroyed is the genetic patrimony, the DNA. The DNA lesions can have different effectiveness and most observed effects are [5]
Figure 1.6: Radiation effect on cells DNA

- **Single Strand Break (SSB)**

- **Double Strand Break (DSB)**

In the first case, the single DNA strand break does not provoke an irreparable damage because the cells, producing special protheins, are able to repair themselves and the cell inactivation is not caused.

The double strand break, instead, determining the breakage of the two strands of DNA helix, causes the cell death (the cell is not able to reproduce its self).

Indeed, one of the main way to quantitatively evaluate the produced damage to the cells, both by electromagnetic and ions beams, is the *cells survival* observation as a function of the absorbed dose. It needs to study the *survival curve* conducting some experiments in which the number of surviving cells, after two irradiation weeks, is counted.

The *surviving* cells are the cells that, during the two analysis weeks, have gener-
ated at least 50 daughter cells and did not lose the reproduction capacity. The surviving fraction cells will depend on the released dose \( D \) and follow a linear-square curve \([9]\)

\[
S(D) = e^{\alpha D - \beta D^2}
\]  
(1.17)

where \( \alpha \) and \( \beta \) are two experimental parameters, deduced from cell survival observation. The term \( e^{\alpha D} \) is due to the irreparable damages provoked to cell (DSB), instead the term \( e^{-\beta D^2} \) is referred to less serious damages (decreasing exponential).

Figure 1.7: Cell survival for different absorbed dose \([5]\)

The objective is minimize the cancer cell survival, calculating the necessary dose which has to be transfer to target in order to provoke the cells inactivation. In order to obtain this important value, it is useful to evaluate the RBE, already defined, which strongly depends on the L.E.T. According to different incident
particles it is possible to classify:

- **Low LET particles**: electrons and photons with any energy

- **high LET particles**: protons, $\alpha$, heavy ions and neutrons which densely ionize the crossed medium

Due to the high LET, protons and heavy ions represent an efficient alternative to traditional radiotherapy with X-rays which, having low LET, cause greater cells survival and smaller damage.

Indeed, the relative biological effectiveness increase with the LET until a maximum value and after decrease. The LET value for which the RBE is maximum depends on the particle beam type. For proton beams the maximum of RBE corresponds to a lower value of LET then that one of carbon ion beams. The RBE decreasing after this value depends on the fact that for very high LET value the deposited energy is so high to provoke low RBE value. This effect is called *overkill effect* and it happens because the ionizing density inside the single cell is higher then that one necessary to provoke the cell inactivation. Hence the dose in excess is dissipated inside the single cell and it does not contribute to cell death and so the RBE decreases.
Figure 1.8: RBE curve as function of LET for proton, helium and Neon incident beam [10]

1.6 The Monte Carlo method in medical physics

The Monte Carlo simulations are currently used in different field and in particular in the medical applications. Indeed, MC codes are strongly adopted for physical particles transport in matter thanks to the high accuracy level of simulations which assure precise predictions. The RBE, the LET calculation and the required physical and biological dose which has to be released to the cancer, request the a-priori knowledge of radiation effects [11]. In order to have a local treatment control, one of the most used complex but important Monte Carlo code is the Geant4 toolkit. GEANT4 is acronym of Geometry ANd Tracking. A more detailed Geant4 description wil be reported in the next chapter together with the
simulations conducted in the thesis.
Chapter 2

Laser-driven ions beams: production mechanisms and ELIMED project

In the present chapter, an interesting innovative and alternative method to accelerate ion and proton beams as respect the conventional ones will be described. Indeed, during the last years the research in the field of plasma produced by high power laser interaction with matter increased in number and reached good results.

In particular, the interest has been focused on the possibility of replacing conventional accelerating machines with laser-based accelerators in order to develop a new concept of hadrontherapy facilities, which could result more compact and less expensive. With this purpose the INFN PLASMAMED project, in close connection with the ELIMED (Extreme Light Infrastructure) European network, ELI-Beamlines for MEDical application, has been launched by LNS-INFN (Laboratori Nazionali del Sud- Istituto Nazionale di Fisica Nucleare) in collaboration with the Academy of Sciences of the Czech Republic-Fyzika Instar, Prague, Cz
This project has the objective to demonstrate the applicability of laser-driven proton and ions beams in Hadrontherapy and the realization of a laser-accelerated ion transport beamline for multidisciplinary applications.[12]

The project is based on the control and study of the high pulsed and intense laser interaction with solid target which provokes the formation of a plasma of electrons and ions. As it will be described in details, a strong electric field will be created, inside the plasma and the particles, like protons and ions, will be emitted in the normal direction as respect the target surface.

In the present chapter the plasma features and production mechanisms will be described to highlight the physical process which happens when an high intense laser pulse interacts with matter. Indeed, it is important to understand how atoms of solid target feel the high pulsed laser presence, and how they change their organization inside solid matter. The high temperature and the great quantity of energy released by laser pulse to the solid, allow a state change which provokes the plasma formation.

Then, the different acceleration mechanisms based on laser-target interaction will be explained in details and a description of the transport beam line designed in range of PLASMAMED project at LNS will be showed.

## 2.1 Introduction to Plasma Physics

The electromagnetic force usually produces a stable atomic structure, organized in crystalline solid lattices. If thermal conditions of the system are altered, as respect the equilibrium state, i.e. increasing temperature and so exceeding atom and molecules binding energy, the regular solid structure decomposes: molecules
and atoms splits into their constituents. In particular, if the temperature is so high to reach and exceed the ionization energy of atoms, a state of quasi-free positive charges (ions +) and negative charges (electrons) will be created.[13]

The totality of positive and negative charges is called *plasma* and it can be interpreted like a fourth state of matter which shows different interaction mechanisms between the charges.

In nature the plasma is spontaneously created inside the stars (in the nucleus) because the temperatures reach such great values to not permit the aggregation of electrons and nucleus to form atoms. Inside Sun nucleus, a temperature of $T \sim 15 \cdot 10^6 K$ is reached thanks to nuclear reactions caused by fusion mechanisms of four protons in helium nucleus. Indeed, the fusion physical process inside the stars generates the particular plasma state.

In terrestrial conditions, take advantage of the fusion to plasma creation is quite problematic, because the terrestrial temperatures are not so high, and because it is necessary to have a controlled fusion process.

Nowadays the most used plasma creation techniques are:

- **magnetic confinement**: a strong magnetic field is used in order to border on charged particles in a small space region.

- **inertial confinement**: ultra-intense and ultra-short laser pulses or similar high intensity sources are used to bombard termoatomic combustible. The intense incident pulse causes the surface ablation of target and an adiabatic compression which provokes the formation of an ultra-dense and ultra-hot region (plasma).

In order to describe the plasma matter state, it is necessary define three fundamental physical parameters:
• particle density $n$ (particles/cm$^3$)
• temperature, expressed in eV
• magnetic field intensity (Tesla)

Starting from these basic parameters, other important physical quantities can be derivated: Debye length, plasma frequency, interaction cross section.

2.2 The Debye length

Considering an ideal plasma, that is a plasma composed by an equal number of negative and positive charges in thermal equilibrium (finite temperature), the total particle density is [14]:

$$n \sim n_i \sim n_e$$ (2.1)

where $n_i$ and $n_e$ are respectively the ion and electron density (/m$^3$). This condition is called quasi-neutrality condition of the plasma and in first approximation an equal temperature for ions and electrons can be assumed, too.

Let’s suppose to insert, inside the plasma in equilibrium ($n_i=n_e$), a test charged particle $q_T$. The presence of charge disturbs the plasma, provoking a reorganization of spatial charge distribution. Indeed, particles with opposite sign as respect to the test particle, will be attracted going near it and on the contrary particles with opposite sign will be repelled. Obviously, the spatial charge reorganization provokes a spatial variation of electrostatic potential $\Phi$ which can be expressed by the convolution between the potential generated by test charged particle and the potential due to charges relocation. Indeed, if the test particle has positive charge, the electrons will be attracted by it and form a negative charge cloud around $q_T$ which provokes the screening of the charge $q_T$. This effect is called electronic
screening and causes a variation of electrostatic interaction potential. The screening effect can be calculated by Poisson equation:

\[ \nabla^2 \Phi = -\frac{1}{\varepsilon_0} [q_T \delta(r) + \sum_{\sigma} n_\sigma(r) q_\sigma] \]  

(2.2)

where \( q_T \delta(r) \) is the test particle charge density, the term \( \sum_{\sigma} n_\sigma(r) q_\sigma \) is the charge density of plasma particles which generate the screening.

One can assume:

- \( |q_\sigma \Phi| << K_B T_\sigma \), because the test particle has an infinitesimal charge density

- The initial condition of quasi-neutrality of the plasma imposes:

\[ \sum_{\sigma=i,e} n_{\sigma 0}(r) q_\sigma = 0 \]  

(2.3)

where \( K_B = 1.38 \times 10^{-23} \text{JK}^{-1} \) is the Boltzmann constant and \( T_\sigma \) is the ion temperature. With this assumption, the equation 1.2 can be written [13]:

\[ \nabla^2 \Phi - \frac{1}{\Lambda_D^2} \Phi = -\frac{q_T}{\varepsilon_0} \delta(r) \]  

(2.4)

where \( \Lambda_D \) is defined as the total Debye length:

\[ \frac{1}{\Lambda_D^2} = \sum_{\sigma} \frac{1}{\lambda_\sigma^2} \quad \lambda_\sigma^2 = \frac{\varepsilon K_B T_\sigma}{n_{\sigma 0} q_\sigma^2} \]  

(2.5)

Solving equation 1.3, it is possible to obtain the expression of the electrostatic potential modified by screening effect:

\[ \Phi(r) = \frac{q_T}{4\pi \varepsilon r} e^{-r/\lambda_D} \]  

(2.6)

For \( r << \lambda_D \), the potential becomes the typical electrostatic potential of a point test particle, instead for \( r >> \lambda_D \) the test particle is totally screened by surrounding charges and the potential goes to zero very quickly.
Then the Debye length $\lambda_D$ represents the radius of negative charged cloud around $q_T$ and then the electrostatic potential $\Phi$ effective range. In order to have an effective screening and fulfill the condition $r >> \lambda_D$, the Debye length must be small as respect to the typical plasma dimension.

### 2.3 Plasma frequency

An ion and electron plasma, can be sketched like a coupling of positive and negative charges which tend to neutralize each others because of the Coulombian force. In this context, the interaction between negative and positive charges can be conceived as an oscillation around equilibrium point, as result of a spatial separation. If one consider a repositioning in X-axis $\delta x$, the Newton motion equation referred to single charge is described by [14]:

$$m \frac{d^2 \delta x}{dt^2} = eE_x = -m\omega_p^2 \delta x \quad \delta x = \delta x_0 \cos(\omega_p t) \quad (2.7)$$

where the electric field is $E_x = -\frac{en}{\epsilon_0}$ with $n$ density and $\epsilon_0$ dielectric vacuum constant.

The plasma, and hence the charges, oscillates with a typical frequency $\omega_p$:

$$\omega_p = \frac{ne^2}{\epsilon_0 m} \quad (2.8)$$

The oscillation frequency is connected to the plasma period $\tau_p$ $(\tau_p = 1/\omega_p)$, which stands for the minimum elapsed time in order to observe plasma oscillations. Indeed, if the plasma is observed in a spatial scale $L$ smaller then the space $v_p \tau_p$ travelled by particle during the period $\tau_p$, it cannot find any change in the plasma behaviour. This limit length connected to the plasma period coincides with plasma Debye length, already explained, which can be written in a $\tau_p$-dependent
expression:
\[ \lambda_D^2 = \frac{K_B T}{m \omega_p^2} = \frac{K_B T}{m} \tau_p^2 \]  
(2.9)

The conditions which have to be verified in order to observe a plasma behaviour, concerns the observation time \( \tau \) and spatial \( L \) scale:

\[ \frac{\tau_p}{\tau} >> 1 \quad \frac{\lambda_D}{L} >> 1 \]  
(2.10)

### 2.4 Interaction cross section

The test particle, with mass \( m_T \), entering inside the plasma, interacts with charged particles by means of random collisions. These collisions modify test particle momentum and energy. The scattering angle \( \theta \) between the initial direction of test particle and its direction after collision, can be expressed using the Rutherford scattering theory, which depends on [13]:

- the impact parameter \( b \)
- Reduced mass \( \mu = \frac{m_T m_f}{m_T + m_f} \)
- Test incident particle charge \( q_T \) and target particle charge \( q_f \)
- Test particle initial velocity \( v_0 \)

The expression can be written as:

\[ \tan(\theta/2) = \frac{q_T q_f}{4 \pi \varepsilon_0 b \mu \nu_0^2} \]  
(2.11)

Usually the collisions can be classified according to the scattering angle: large scattering angles \( \frac{\pi}{2} < \theta < \pi \) which provoke the particle deflection in the opposite direction to incident direction and small scattering angles, \( \theta < < \frac{\pi}{2} \), typically called grazing collisions (forward emission).
The impact parameter $b$ for $\theta = \frac{\pi}{2}$ can be derived from (2.10):

$$b_{\frac{\pi}{2}} = \frac{qrq_f}{4\pi\epsilon_0\mu\nu_0^2}$$

Looking at Figure 2.1 $b_{\pi/2}$ is the radius of the inner small shaded circle. Large angle scatterings occur if the test particle is incident anywhere within this circle. The total cross section for all large collisions is:

$$\sigma_{\text{large}} \sim \pi b_{\pi/2}^2$$

Regarding the grazing collisions, they occur when the test particle impinges outside the shaded circle in Fig. 2.1 and so occur much more frequently than large angle collisions. These kind of collisions, called direct collisions, do not modify very much the test particle energy and momentum and strongly depend on impact parameter b. For this reason it is important to compare the cumulative effect of grazing collisions with the cumulative effect of large angle collisions.

The expression of the cross section for cumulative effect $\sigma^*$ can be derived, considering that in the scattering theory, a connection between the particle flux
the time $t$ and cross section $\sigma$ exists: $\Gamma \sigma = t^{-1}$

$$\sigma^* = \int 2\pi b[\theta(b)]^2 db$$ (2.14)

Regarding the integration extremes, inside a plasma the impact parameter $b$ for grazing collisions has to verify the condition: $b_{\pi/2} < b < \lambda_D$. Indeed, for $b > b_{\pi/2}$ it obtains large scatterings, instead $\lambda_D$ is the Debye radius, which borders the efficiency of interaction field. For very small scattering angles, one can approximate $tg(\theta/2) \sim \theta/2$ and the expression of scattering angle $\theta$ and of cumulative cross section are given by [13]:

$$\theta(b) = \frac{q_T q_f}{2\pi \epsilon_0 \mu v_0^2 b}$$ (2.15)

$$\sigma^* = \int_{b_{\pi/2}}^{\lambda_D} 2\pi db(\frac{q_T q_f}{2\pi \epsilon_0 \mu v_0^2 b}) = 8ln(\frac{\lambda_D}{b_{\pi/2}})\sigma_{large} = \frac{1}{2\pi}(\frac{q_T q_f}{\epsilon_0 \mu v_0^2})^2 ln(\frac{\lambda_D}{b_{\pi/2}})$$ (2.16)

In the equation is shown that the ratio between $\sigma^*$ and $\sigma_{large}$ depends on the natural logarithm of $\lambda_D/b_{\pi/2}$. Indeed, if $\lambda_D >> b_{\pi/2}$, the cumulative cross section $\sigma^*$ prevails on large cross section. Moreover, it is possible to note the dependence of $\sigma^*$ on the fourth power of the velocity $v_0$ which in a hot plasma is very great and this fact causes a reduction of the cumulative cross section principally at small angles.

### 2.5 Laser-target interaction

Laser-driven beams represent an attractive alternative to conventional beams production and offer very interesting applications also in the medical field. In order to understand the benefit of this new acceleration technique, it is useful to describe how laser is created and how it interacts with solid target’s matter. This
peculiar interaction produces the charged particle beams, like proton beams, with specific features in energy, direction and angular distribution.

2.6 Laser

A laser (*Light Amplification by Stimolated Emission of Radiation*) is a device, based on the principles of quantum mechanics, which creates a beam of light where all of the photons are in a coherent state, with the same frequency and phase. In this way the light beam is strongly focused and polarized and its divergence is small. This fact permits to focus a great quantity of energy in a very small area and create intense light beams.

It is necessary to describe the quantum features of atoms to better understand the laser production mechanism. As is known, in a stationary state the atomic electrons go around the nucleus, remaining bound inside their energy level without losing energy. If the atom is excited it means that an atomic electron is able to move itself towards an upper energy level. When the atom naturally comes back to its ground state, it emits a photon with an energy \( \Delta E \) equal to energy difference between ground state and excited state (Figure 2.2). This emission mechanism is called *Spontaneous emission* and it occurs when an electrons decays without external influence and it produces photons with random phases.
Physical process that happens when a laser light is produced is, instead, called *Stimulated emission* and it accours when the atoms is excited from an external electromagnetic field, for example a photon with energy $h\nu = E_2 - E_1$, where $E_1$ and $E_2$ are the energy levels of the system. This photon goes near atom and stimulates the emission of a second photon when the atom comes back to its ground state. The process, shown in the figure 2.3, produces in the final state two identical photons with the same energy, direction, polarization and phase. So the consequent effect is an amplification of the initial incident light that provokes a coherent emission.

In order to amplify the incident radiation and to obtain a coherent light emission, it is necessary that the number of atoms of the system with an energy $E_2$, so in the excited state, is greater then the number in the ground state with energy $E_1$. 

![Figure 2.2: Sketch of spontaneous emission](image)

![Figure 2.3: Scheme of stimulated emission](image)
This condition is called *population inversion*, and it’s illustrated in the Figure 2.4 [16].

![Population inversion](image)

**Figure 2.4: Scheme of population inversion**

To obtain a great number of coherent and monochromatic photons in the final state, an optically active medium is used together with two mirrors, which create a resonant cavity causing the natural line-width to be narrowed by many order of magnitude.

The *spatial coherence* that characterizes a laser is defined as the phase change of electromagnetic field of two separated points. If the phase difference of two points that are separated by a distance L is constant in time, then these two points are coherent and the maximum value of L is called coherent length.

In the other hand, the *temporal coherence* is defined as the phase change of the electromagnetic field in time in a fixed point. If the phase in this point is equal at time t and t+τ, for all times t, the point is coherent during the time τ. The maximum value of τ is called *temporal coherence of the laser*.

The maximum power of lasers reaches today intensities over $10^{21} W/cm^2$ in a
femtosecond pulse. The maximum electromagnetic field is about $10^{12} \text{V/m}$ and it is greater than the electric field binding the electrons to nucleus. The key to obtain an high pulse is the *chirped pulse amplification* (CPA) technique, developed for radar devices more than 40 years ago. In the CPA scheme a pulse made by a low power laser (Figure 2.5) which is able to create a really short packet, $\sim 50\text{fs}$, is first stretched in time (chirped in frequency) by a factor $\sim 10^4$, then amplified and finally recompressed. The stretching and compression steps are released using a pair of gratings that can be arranged to separate the output pulse spectrum from the oscillator in such a way that different wavelengths follow different path through the optical system. In CPA process not only an ultra-short high-intensity main pulse is produced, but also a weaker pedestal, or pre-pulse, due to the amplified part of the pulse that is not compressed again. [17] [18]
2.7 Laser Interaction with matter

The high intensity laser pulse provokes the ionization of the matter when the radiation passes through target and produces an ultra dense plasma from which the particles are accelerated. This effect causes, indeed, the electrons and ions acceleration from the target with particular energy and angular distribution which depends on the material and the thickness of the target. It’s useful to describe how laser releases energy in the matter to understand the physical mechanism which determines ion acceleration.

The most important steps of the interaction are:

• Creation of the plasma from laser-target interaction because of the target ionization and sputtering effect

• Interaction between plasma and the last part of the laser pulse by resonance absorption, which occurs when the beam energy is exactly equal to the excitation energy of the absorbing system and inverse bremsstrahlung effect

• Expansion of the plasma and particles emission through ponderomotive force

The physical mechanisms will be described in details in the next sections.

2.7.1 Ponderomotive force

A central role in the ions acceleration from target after the interaction of the laser with the matter is played by the ponderomotive force. This peculiar force is non-linear and concerns the electric field created by the electromagnetic waves
propagation inside the plasma. Indeed, the high intense and short laser pulse creates radial and longitudinal field gradients which are the cause of the electrons ejection from the regions where the field is higher.

In a non-relativistic case, a charged particle \( q \) inside the electromagnetic field of the laser pulse, feels the \textit{Lorentz force} which can be expressed by:

\[
F = q[E(r,t) + v \times B(r,r)]
\] (2.17)

where \( E(r,t) \) is the electric field and \( B(r,t) \), the magnetic field. The electric and magnetic field can be also written using the Maxwell equation, which connect them each others:

\[
\nabla \times E = -\frac{\partial B}{\partial t}
\] (2.18)

In this way, if electric field is expressed by \( E(r,t) = \hat{E}(r,t)e^{i\omega t} \), the magnetic field is:

\[
B(r,t) = \frac{i}{\omega} \nabla \times E(r,t)
\] (2.19)

where \( \omega \) is the electromagnetic waves frequency. The derivation of the ponderomotive force relies on the possibility to separate the relevant time scales: the fast motion on the time scale of the laser period \( 2\pi/\omega \) and a secular one due to the ponderomotive force.

The electric field, indeed, causes an oscillation of the particle around its current position \( r_0 \) and the motion equation, in lowest order, can be expressed by \[20\]

\[
m\ddot{r}_1 = q\hat{E}(r_0)e^{i\omega t}
\] (2.20)

In the next higher order one has:

\[
m\ddot{r}_2 = q[(r_1 \cdot \nabla)E(r_0,t) + \dot{r}_1 \times B(r_0,t)]
\] (2.21)
where the electric field has been expanded around $r_0$. Integrating the motion equation in x-axis, twice with respect to the time and with the initial condition $\dot{r}_0=0$ one obtains:

$$x = x_0 - \frac{qE_0}{m\omega^2} \cos(\omega t)$$

(2.22)

which describes the oscillating motion of the particle around its initial position $x_0$. Considering the higher order of approximation of motion equation, the calculation becomes non linear and the trick is not applicable anymore above all if one considers complex fields.

Taking into account these considerations the ponderomotive force can be written as:

$$F_p = m\ddot{r}_2 = -\frac{q^2}{4m\omega^2} \nabla |\vec{E}(r, t)|^2$$

(2.23)

It is important to remember that the time dependence of the envelop must be slow in respect to the laser period because otherwise the separation time-scales used in the derivation lose sense. Moreover, because of the dependence of ponderomotive force from the square of the charge and the mass of particles, the force is the same for positive and negative particles but it is higher for electrons then for protons. When ultra-short laser pulse begins to propagate in a underdense plasma, the ponderomotive force, pushing electrons while ions remains nearly unperturbed because of their bigger mass, creates a longitudinal charge separation that results in a longitudinal electric field which pulls back the electrons again. This perturbation induces a plasma wave that travels in the field at the group velocity of the pulse itself. In particular if the pulse wavelength is of the order of half plasma wavelength, the quasi-resonant condition $L_p \sim \lambda/2$, the formation is very efficient.
2.8 Particle acceleration mechanism

2.8.1 The TNSA regime

When an high pulsed laser bumps on the surface of a solid target, a very intense current of hot electrons are emitted from the plasma. In particular the electrons escaping from the nuclei because of the target ionization, gain a kinetic energy greater than their rest mass and become relativistic.

In this contest is useful to define a parameter called laser strenght as:

\[ a_0 = \frac{eA}{m_ec^2} \] \hspace{1cm} (2.24)

which describes the peak value of the laser potential vector normalized as respect the electron rest mass. The parameter \( a_0 \) can be connected to the laser peak intensity, \( I \), and to the laser wavelength \( \lambda \):

\[ a_0 = \frac{e}{m_ec^2} \sqrt{\frac{I\lambda^2}{2}} \] \hspace{1cm} (2.25)

Indeed, since the laser pulse cannot penetrate into solid density regions, the absorbed energy is transported mostly by energetic hot electrons created during the interaction from several mechanisms. Hot electrons are defined as relativistic electrons with a typical energy of the order of oscillation energy in the electric field of the laser in vacuum. The energy of hot electrons is the Ponderomotive Energy that can be written \[19\]:

\[ \epsilon_p = m_ec^2(\gamma - 1) = m_ec^2\sqrt{1 + \frac{a_0^2}{2} - 1} \] \hspace{1cm} (2.26)

where \( \gamma \) is connected to the laser strenght \( a_0 \).

The electrons which acquire energy from laser-target interaction, move toward the rear surface of the target and sometimes toward the front surface. In both
cases this type of particle acceleration mechanism is called \textit{Target Normal Sheath Acceleration} (TNSA), and it is confirmed by several experimental observations which show the ions emission in a normal direction in respect to the target surface with a typical energy of the order of $\sim$ MeV (Figure 2.6).

The hot electrons move to the rear side and attempt to escape from the target in vacuum, producing a charge unbalance inside the target. This charge unbalance provokes a sheath field $E_s$, normal to the rear surface. The sheath electric field $E_s$ holds back hot electrons with a typical temperature $T_h$ and spatial extension $L_s$:

\[ eE_s \sim \frac{T_h}{L_s} \quad (2.27) \]

From dimensional arguments, assuming a steep interface and $n_h$ and $T_h$ as the only parameters, $L_s$ may be estimated as the Debye length of hot electrons, $L_s \sim \lambda_D = (T_h/4\pi e^2 n_h)^{1/2}$. This strong field is able to backhold most of the escaping electrons, to ionize atoms in the rear surface and to accelerate ions.
As it is expected, the acceleration due to the electric field $E_s$ is more effective on protons, which usually are the most part of the constituents of target. Indeed, heavier ions have a greater inertia and they will be accelerated on a longer time scale. Direct experimental evidence of the generation of the sheat initial electric field at the rear surface was already performed by Romagnani et al. [22], using proton imaging technique. Moreover, the properties of laser-driven ion beams in the TNSA regime has been investigated in several experiments, with the purpose to have the possibility to control the generated beam. [23]

It is clear that the energy of accelerated particles from laser-target interaction strongly depends on the characteristics of the solid target, and on the plasma scalelenght at the rear surface.

Particles accelerated from target in laser interaction with the surface, show a very broad energy spectrum that can be assimilated to an exponential spectrum up to a cut-off energy. [?] A typical energy spectrum of laser-driven proton beams is
shown in figure 2.7.

![Proton Energy Spectrum]

Figure 2.7: Typical energy spectrum of laser-driven proton beams. [27]

The maximum energy of emitted particles depends on the energy of the laser pulse and on its duration, that is the power that characterizes the laser itself. Charged particle beams produced with this new acceleration technique, have also a very high peak current ($\sim 10^{12} - 10^{13}$ particles per shot) and rather small transverse and longitudinal emittance because of very small spatial dimension of laser spot and of its very short temporal amplitude, respectively. Despite this, the emitted particles show a very large angular divergence (up to 30 deg) when they leave the target surface. [24] [26] Moreover, the angular distribution also depends on the energy spectrum as it is shown in figure 2.8. This fact makes necessary the control of the beam since the particles are emitted from target to their detection.
2.8.2 Radiation Pressure Acceleration

The TNSA acceleration mechanism prevails when the energy of emitted particles is around $\sim$ MeV, and so in a non-relativistic regime. An other possible acceleration mechanism, that is called Radiation Pressure Acceleration, allows the acceleration of ions up to relativistic energies. Several simulations and theoretical models have shown that the RPA starts to dominate in respect to the TNSA regime at higher intensity of laser pulse. Indeed simulations have also shown that if a thin target is irradiated with an intense laser $\sim 10^23\text{W/cm}^2$ the produced ions reach energies in the GeV/nucleon range. The radiation pressure is a good mechanism of acceleration also when the laser is circularly polarized and the laser has low intensity.
If one consider the electromagnetic incident waves (laser), it carries momentum which can be delivered to the medium. This fact originates a Pressure due to the incident radiation and its expression for a plane monochromatic electromagnetic wave of intensity $I$ and frequency $\omega$ normally incident on the target surface is given by [23]:

$$P_{\text{rad}} = (1 + R - T) \frac{I}{c} = (2R + A) \frac{I}{c}$$  \hspace{1cm} (2.28)

where $R$, $T$ and $A$ are respectively the reflection, transmission and absorption coefficients. Indeed, the electromagnetic wave can release momentum to the target through three different mechanism: reflection, transmission and absorption. \(^1\) Clearly the radiation pressure is connected to the ponderomotive force which, as already described, provokes hot electrons emission at the surface of the overdense plasma, producing the back-holding electrostatic field that allows the ion acceleration. The effect of radiation pressure on particle acceleration depends on the thickness of the target.

Indeed, it is possible to distinguish two different regimes: Hole Boring regime and Light Sale regime.

### 2.9 The ELIMED project: description of a transport beam line developed at LNS

Over the last years, charged particle acceleration using ultra-intense and ultra-short laser pulses has been one of the most attractive topics in the relativistic laser-plasma interaction research. High current multi-MeV proton beams can be

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\(^1\)The reflection transmission and absorption coefficients here are defined in the Fresnel formulation which provides the dependence i.e. of the reflection coefficient $R$ from the frequency $\omega$: $R = R(\omega)$
produced and accelerated from the interaction of ultra-intense (higher than $10^{18}$ $W/cm^2$) short pulse (from 30 fs to 10 ps) laser with thin solid foils.[28] [29] [30] The ELIMED idea was born in 2012, from a collaboration between INFN-LNS (I) and ELI-Beamlines (CZ), with the aim to demonstrate the potential medical applicability of laser-driven ion beams in hadrontherapy. With this purpose the collaboration has also the objective to realize the first facility dedicated to the multidisciplinary and radiobiological studies of high energy laser-accelerated beams.[12] The interest about this new ion acceleration technique in medical physics field is growing above all because more compact laser-based accelerators could significantly increase the availability of high-energy ion beams and provide particle therapy to a broader range of patients.[1] The eventual applicability of this kind of proton beams in tumors therapy, will depend on the capability of control different parameters:

- Laser-driven technique that is connected to the stability of laser-target interaction
- Minimize the angular divergence of proton and ion beams. This is necessary to obtain a focused and collimated beam for the tumor treatment and to have the maximum transmittance of emitted particles to the tumor zone
- Select the energy beam taking into account of the typical broad energy spectrum of particles produced in laser-target interaction
- Control the dose and the fluence delivered by laser-driven beams considering the high electromagnetic noise of the laser

All these points have to be investigate to obtain a suitable beam for medical applications. With this purpose a dedicated transport beam line, which was
designed to optimize the transportation of beam from the target, located inside the interaction chamber, to the irradiation point, has been studied at INFN-LNS during the last years. (figure 2.9)

Figure 2.9: Scheme view of the transport beamline project. It includes the capturing system, the focusing system, the energy selector system and the beam diagnostic devices [31].

In the next paragraph, the entire transport beam line prototype will be described in details.
2.9.1 Collecting, focusing and selection system

The laser-driven beams are usually characterized by a large angular emission which makes necessary the realization of a system dedicated to the collection, focusing rather then the beam particle selection. The scheme to collect, focus and select the beams can be divided in two steps:

- **Capturing and collecting**: The system has to be able to deviate charged particles in order to reduce angular divergence, realize a collimated beam and maximize the number of particles collected. To fulfill such requirements the device must be quite compact in order to be placed directly inside the interaction chamber and as close as possible to the target. A strong magnetic field must be used (i.e. in solenoid configuration) in order to procure a large acceptance and ensure focusing on both transverse planes. The solenoid should have 3-4 cm of diameter, a reduced length and a magnetic field of the order of tens of Tesla. [35] Moreover, considering that the focal point of the solenoid depends on the particles energy, the system will provide already a preliminary energy selection if it is coupled with a collimator. An interesting alternative to this scheme, is the use of a couple of solenoid which permits the usage of lower magnetic fields. The energy selection, with this latter solution, can be improved placing a collimator between the two solenoids.

- **Beam Focusing and transport** After the collecting step, the beam will show a small angular divergence and the selected particles will be focused in a smaller spot size. At this point the beam has to be transported, without losing focusing, at the exit of the interaction chamber. A dedicated study has
been performed at LNS-INFN in collaboration with ELI-Beamlines team, on the design and construction of a focusing system based on a triplet of permanent magnet quadrupoles. With the support of several simulations, it has been shown that the three quadrupoles assure a better control on the beam shape and a beam focusing up to 30 MeV in the transverse planes. Particles with different energy will be focused at different point and this fact allows the optimization of particles transport with a certain energy.

The system is composed of three cylindrical quadrupoles of NdFeB permanent magnets in Hallbach configuration [27]. Each quadrupole is divided in 16 sectors as it is shown in figure 2.10, at the center there is a bore (35 mm) where the beam passes. The size of the bore was chosen to ensure a good geometric acceptance. This particular configuration, based on a spatial rotating pattern of the magnetisation, allows the increase of magnetic field in one side while cancels the field on the other side. The gradient field is about 70 T/m.

![Figure 2.10: Drawing of the triplet quadrupoles in 16 sector Halbach configuration.][27]
Several simulations have been done, using the FEM code, to predict the effect of this device on the beam selection.

2.9.2 Energy selector system

In order to obtain a more efficient selection in the energy beam, a dedicated Energy Selection System (ESS) has been developed, and preliminary characterization with conventional proton beams and laser-driven proton beams has already been done with the aim to obtain a real knowledge of the device. [32] [33] [11] The ESS consists of a sequence of four magnetic dipoles with alternating polarity and due to the magnetic field inside and between the dipoles it is possible to select particles in according to their energy. In particular the first and the last dipole have the same direction of magnetic field but opposite in respect to the field in the second and in the third one. As is shown in figure 2.11, between the second and the third dipoles the system is provided by an internal slit which can be transversely moved. Indeed the slit position in the middle of magnetic system determine the selected particles energy. Moreover the energy spread and the number of transported particles depends on:

- Collimation slit position
- Aperture size of the slit

Indeed, using a small slit aperture it is possible to select a narrow energy range of the beam and obtain at the exit of ESS a quasi-monochromatic beam[34]. On the other hands, the small aperture provokes a reduction of the number of transmitted particles. Moreover, as already explained, the energy spectrum and the angular distribution of laser-driven beams are not indipendent and in order to
perform an angular selection avoiding the spatial mixing of particles with different energies, a collimator has to be placed at the selection system entrance. A second collimator can be also placed after the last dipole to refine the energy selection.

Figure 2.11: Protons trajectories in the ESS system. C1 and C2 are the collimators, B1, B2,B3 and B4 are the dipoles and the slit is placed between B2 and B3

The dipoles are made of an hybrid combination of soft iron yoke and permanent magnet (NdFeB) which allows the possibility to use a maximum magnetic field of 8 KGauss on a gap of 10 mm. The $2^{nd}$ and the $3^{rd}$ dipole are placed on a roller guide system that permits to move them transversely of 50 mm in order to select the lower energy particles. In such a way, energies between 1 MeV and 60 MeV can be selected using this device. [36] The fourth dipole can be also shift of 50 mm back along the longitudinal direction in order to compensate the asymmetry of magnetic field.
2.9.3 Diagnostic systems

In order to obtain immediate information about proton and ion beams produced, a lot of detectors can be adopted.

The purpose of these detectors must be particles identification and energy measurement of beams in order to understand the physical process which is happened inside the target. The emitted particles nature, energy and direction depends also on the composition and the thickness of the target which can be investigated using accurate diagnostic system. With this aim, different technique of particle detection will be explained in the following paragraphes.

**Thomson Parabola** The Thomson spectrometer is a typical device used for laser-driven beams diagnostic and it is based on the application of an electric and a magnetic field on the particles beam. The fields are parallel each other and both of them is perpendicular to particle direction trajectory. The charged particle which goes throught an uniform electrostatic field and magnetic field perpendicular to its direction, feels the presence of the fields and it is deviated. The motion equation of particle can be written as:

\[
\frac{dp}{dt} - qE - qu \times B = 0
\]

This is the expression of the Lorentz Force.

Since the fields are parallel, the deflections are orthogonal each other and the deflections are proportional to deflection angle by means of the drift lenght between the electromagnetic device and the detector plane \(D\):

\[
y = \frac{qELD}{2K} \quad x = \frac{qBLD}{\sqrt{2}mv} \quad y = \frac{mE}{qLDB^2}x^2
\]
where the last expression, is the resolution of motion equation of a particle inside electric and magnetic field. Looking at this expression, many information can be acquired:

- the particle trajectory is parabolic
- particles with different energy are deflected in a different direction, according to equation
- the equation depends on the ratio \( \frac{q}{m} \) which means that the TP provides a separation in trajectory of all ion species and charge state.

For these reasons the TP spectrometer offers the possibility to identify the emitted ions, distinguishing also the different charge state, looking at the different radius of parabolic trajectory (figure 2.12).[37]

![Figure 2.12: Thomson parabolas of C\(^{12}\) ions and their intersections with constant velocity, energy and momentum](image)

A Thompson Parabola Spectrometer has been developed recently at LNS-INFN. It is able to analyze proton beams with energy up to 20 MeV. The fact that
this TP is able to measure high energy beams is very suitable for hadrontherapy, where the typical proton beam energy is about $\sim 60$-$70$ MeV (figure 2.13).[38]

![Magnet of the Thomson Parabola spectrometer developed at LNS](image)

Figure 2.13: Magnet of the Thomson Parabola spectrometer developed at LNS

**SiC and Diamants detectors** An other experimental technique which can be used for the diagnostic of the beams, is the measurement of particle *Time of Flight* (TOF) from target to the detector. Indeed, knowing the particles path length and measuring the TOF, it is possible to obtain information about particles energy and type. To reach this knowledge it is necessary to use detectors with a very high time resolution, and a very low dead time in order to avoid errors in time measurement. Between different kind of detectors, the new semi-conductor detectors based on junction between Silicon and Carbon, the Silicon Carbide detector or SiC) and the diamond detectors, have been tested [39] [40] and will be used in the immediate future in order to control the TOF spectrum of emitted particles, but also to monitor the X-rays coming from the laser interaction with the target. Indeed both SiC and diamond detector are also sensitive to electromagnetic
radiation and allow the acquisition of photo-electric peak, generated during the interaction of light with the matter, too.

### 2.9.4 Absolute and relative dosimetry

The high laser pulse intensity provokes an high dose delivered per pulse. In order to use laser-driven beams in hadrontherapy, it is fundamental the dose control of deposition. The high dose released per pulse makes necessary the development of dose-indipendent system for absolute and relative dose measurement with a level of accuracy required by absolute dosimetry. [41] Different detectors are in developing and tests are performing around the world to achieve this task.

Regarding the relative dose measures, nuclear-bored detector (ELIMon) or more classic scintillators as well as gafchromic films are studied.

For absolute dose estimation Faraday Cup detectors, CR39 nuclear track and RCF (Radiochromic films) can be used as well.

The following is a brief description of the ELIMon, RCF and CR39 detectors. The use of Faraday Cup for absolute dose will be extensively treated in the next chapter.

**ELImon**  ELImon is an innovative device for the online monitoring of the pulsed beam fluence. The detection system is shown in figure 2.15 The pulsed beam going through a thin Au target, is elastically scattered and the diffused protons are detected at a tunable angle by a battery-powered detection system consisting of a plastic scintillator coupled to a Photomultiplier.[27]
Radiochromic film In radiation dosimetry, it is important to measure the absorbed dose and the dose-profile of the radiation, in order to understand how radiation loses energy in the matter. Indeed, the purpose of dosimetry in medical application is also the calculation of the Bragg peak depth, connected to particle energy and spread. Some of these features have been achieved with the introduction of radiochromic dosimeters. These dosimeters have a very high spatial resolution, a low spectral sensitivity variation and being insensitive to visible light, they permit an easy handling of experiment preparation. When a radiation passes through a radiochromic film (RCF), the dosimeter changes color directly without any additional chemical processes. On the radiochromic film surface an image is created because of a polymerization process, in which energy is transferred from an energetic photon or particle to the receptive surface.[42]

Different model of RCF are available according to different dose sensitivity and dimension: GafChromic HD-V2, GafChromic MD-V3, GafChromic EBT3.

[27] In particular, GafChromic EBT3 has been developed specifically for ap-
plications in conventional radiotherapy and protontherapy.

**CR-39** The CR-39 is a Solid State Nuclear Track Detector, made of polycarbonate plastic and it is usually used to detect protons and heavy ions. Indeed, this kind of detector is immune to electromagnetic pulse and to X-rays which can be commonly produced in such environments. When a particle incides into the CR-39 detector, it provokes a molecule damage in the crossed region. This region extends for few tens of nano-meters along the particle trajectory. The track is called *latent Track* (LT) and the energy loss by particle to form that track is called *Restricted Energy Loss* (REL). To makes readable the CR-39 detectors, it is necessary to do a chemical etching, fixing some parameters like temperature, duration and chemical element for eaching process. The chemical treatment transform the material damages into permanent structures called ion track which can be analyzed using opposite sofware.

The CR-39 can be coupled with RCF or Ion collectors, to detect energetic proton beams produced by ultra-intense laser interaction with matter.
Chapter 3

Faraday Cup for absolute dosimetry and MonteCarlo Simulation

In order to evaluate the biological effectiveness of ionizing radiations in tissues, for tumor treatments, the absorbed dose measurement with an absolute error lower than 3% is essential. Indeed the minimization of the error in the dose measurement is a crucial point for the accuracy of the delivered dose in the tumor cells and hence allows to minimize the damage provoked in the healthy tissues. To do this, it is necessary to use devices which measure directly or indirectly the dose of the incident ion beams. Absolute dosimeters allow the measurement of the absorbed dose and they can be used to non-calibrate relative dosimeter. For high-pulsed and intense ion beams, like that ones accelerated in the interaction of an high power laser with the solid matter, it is not possible to perform absolute dose measurements with the dosimeters typically used for conventional accelerated beams. This is due to the peculiarities of the laser-accelerated ion beams, which are characterized by large energy spread, high dose rate and a not negligible electromagnetic noise. Indeed, considering the extremely high dose rate of laser-driven ion beams (up to $10^9$Gy/sec) [44], the detector signal must not be
effected by saturation effects therefore having a linear response with the number of particles. With this aim alternative solutions and several detectors have to be considered. During the last year, within the ELIMED project, an innovative Faraday Cup prototype has been designed and developed at INFN-LNS, in order to measure the absolute dose delivered by laser-driven ion beams and to investigate the applicability of these alternative beams in medical physics.

Monte Carlo simulations has been performed, using the toolkit Geant4, in order to study the most suitable geometrical configurations and material and to obtain a very accurate detection of all charged particles.

In the following chapter the description of the FC developed at INFN-LNS and some preliminary simulation results of the extracted dose will be presented for both the case of a mono-energetic conventional proton beams (with an energy of 62 MeV and 10 MeV) and in the case of typical laser-driven proton beam.

3.1 Faraday Cup description

A Faraday Cup is a device that counts the charged particles entering inside it and, when the energy spectrum is known, gives information on the absorbed dose. The relation between the absorbed dose, the fluence and the stopping power can be expressed as [6]:

\[
D_W = \frac{\Phi}{\rho_W} S_W \Pi K_i
\]

where \( \Phi \) is the particle fluence, \( S_W/\rho_W \) the mass stopping power of the proton beam in water and \( \Pi K_i \) is product of the correction factors due to the beam divergence, scattering, field nonuniformity, beam contamination and secondary particle build-up. The absorbed dose in water due to monoenergetic proton beam
irradiation can be written as [45]:

\[
D_W = \frac{1}{A}(S(E)W \frac{Q}{e} 1.60210^{-10} \quad (Gy)
\]

(3.2)

where \( A(cm^2) \) is the effective beam area, \( S(E)W \) the mass stopping power at energy \( E \ (MeV cm^2/g) \) and \( Q \) is the collected charge by Faraday Cup. The extraction of the equivalent dose delivered by a proton beam in water depends on the knowledge of:

- The beam area that has to be precisely measured
- The proton mass stopping power in water at the specific energy and, hence, the proton energy spectrum, particularly in case non mono-energetic beams
- The collected charges

Assuming that the charge collection efficiency is close to 100%, the main uncertainty in the dose calculation is, beyond the energy spectrum, in the knowledge of the beam area. Indeed, the effective area of the beam depends on the dose distribution inside and can be expressed as [46]:

\[
A_{eff} = \int_0^{2\pi} \int_0^R rP(r)drd\theta
\]

(3.3)

which can be approximated as:

\[
A_{eff} \sim 2\pi \sum_{i=0}^{i=R} r_i P(r_i)dr_i
\]

(3.4)

where \( r_i \) is the scan step, \( P(r_i) \) is the normalized dose or fluence distribution associated to the beam profile and \( R \) is the radius for \( P(R)=0 \).

The main purpose of a detector based on Faraday Cup principle, must be the collection of all incident charges (protons or positive ions) entering inside the device and of all the secondary electrons produced during the interaction with the
cup and with the Faraday Cup walls, in order to obtain a correct measurements and hence a precise dose calculation. One of the uncertainty source in FC measurements is due to the production of secondary electrons in the interaction of the incident ion beam with the entrance window and with the metallic surface of the cup. Indeed, the secondary electrons ejected from the interior surface of the cup, when the positive charged particles strike, may escape from the FC aperture, causing a wrong charge collection. Such effect may results on the overestimation of the positive charge and a current underestimation of the electrons from the true values of current. Based on a literature survey of existing Faraday Cups (Cambria et al.) [46] [47] [48]. an accurated study has been performed at INFN-LNS within the ELIMED activity. In the FC design, several parameters have been considered:

- **Cup size**: cup and wall thickness has to be sufficient in order to stop both the primary beam (protons) and the secondary particles produced in the interaction with the window and the cup itself

- **Material**: a material with an high interaction cross section is required in order to increase the collection efficiency

- **Entrance Window**: a *thin* entrance window has to be used (typically kapton or mylar) in order to not influence the secondary particle detection and maintain the vacuum

- **Vacuum**: the charged particle beam has to move in a high vacuum ($\sim 10^{-5}$) region before reaching in the cup in order to avoid the possible ionization of the gas generating a residual charge which can give an incorrect charge collection measurements
• guard ring or suppressor: an electric field can be applied in order to attract the secondary electrons generated in the cup toward the cup itself and stop the ones produced in the thin entrance window.

Typically the Faraday Cup is a metallic cylinder provided with a guard ring or suppressor on which a negative voltage is applied. The negative voltage generates a coaxial and symmetric electric field. The guard ring voltage needed for secondary electron suppression can be estimated considering the maximum energy $E_{\text{max}}$ transferred to secondary electrons during the collision with the cup. Assuming that the proton energy is higher than the orbital electron energy ($E_p \gg E_e$), the maximum energy transferred to electrons depends on the incident proton energy but also on the emission direction ([46]):

$$E_{\text{SEmax}} = 4\frac{m_e}{m_p}E\cos^2\theta$$

(3.5)

where $m_e$ and $m_p$ are respectively electron and proton masses, $E$ is the incident proton energy and $\theta$ is the angle between the direction of the incident beam and the trajectory of the outgoing electron.

A typical Faraday Cup characterized of a cylindrical electrode allows the secondary electrons ejected coaxially to the cylindrical guard ring and with energy greater than the suppressor voltage multiplied for electric charge to escape.

In order to maximize the number of collected secondary electrons and minimizing the collection of the secondary electrons produced in the entrance window, a careful research on the particular geometrical configuration of the guard ring and hence of the electric field has been performed, using both F.E.M (Finite Element Method) codes like Simion and Comsol, and Monte Carlo simulation code Geant4.

As suggested in J.D. Thomas et al. [49], the Faraday Cup developed at INFN-LNS is provided of two concentric electrodes. The external one is a metallic hollow
cylinder to which a positive voltage, up to +600 Volt, can be applied and the inner one, to which a maximum negative voltage of -600 Volt can be applied, has a peculiar beveled shape.

An high voltage can be then applied between the electrodes and the beveled inner cylinder, breaks the electric field cylindrical symmetry and generating a predominant transverse component of the electric field. The negative electric field of a traditional cylindrical guard ring has the major component along the beam direction and operates like a repeller for the secondary electrons emitted from the entrance window (fig. 3.1). The purpose of the electric field characterized by a cylindrical symmetry break due to the beveled cylinder, is twofold:

- Deflect the secondary electrons produced in the entrance of window by electric field towards the walls of the Guard Ring thanks to the big transverse component of the electric field.
- Accelerate and collect the secondary electrons produced in the cup and in the walls toward the cup.
Figure 3.1: Electric field components $E_x$ (green), $E_y$ (red), $E_z$ (blue) and the module $E$ (sky blue). The electric field is expressed in V/mm and the X axis in mm.

Several studies have been made in order to obtain the most suitable geometrical configuration taking into account the size of the cup, the guard ring and the material used for each components, using the Monte Carlo simulation toolkit Geant4 and the F.E.M code COMSOL and SIMION. In particular, these last codes allowed to study of the guard ring suppressor configuration, showing that the particular beveled cylinder electrode allows the 100 % suppression efficiency of secondary electrons with energy up to 520 eV and the 91 % for secondary electrons with energy higher up to 18 KeV.(fig. 3.2)
Figure 3.2: Simulation of the secondary electrons with an angular divergence of 10 ° and with an energy of 520 eV, emitted from the kapton entrance window (A) and from the cup bottom (B).

The final geometrical configuration for the Faraday Cup is shown in figure 3.3 together with a picture of the device. The size and the materials chosen are given in the table 3.1.
Figure 3.3: Scheme and picture of the Faraday Cup developed at LNS
Table 3.1: Materials and geometrical sizes of the Faraday Cup developed at LNS-INFN

<table>
<thead>
<tr>
<th>Material</th>
<th>Thickness</th>
<th>Outer Radius</th>
<th>Inner Radius</th>
</tr>
</thead>
<tbody>
<tr>
<td>Entrance Window</td>
<td>Kapton</td>
<td>25 μm</td>
<td>20 mm</td>
</tr>
<tr>
<td>Mass Ring</td>
<td>Steel</td>
<td>5 mm</td>
<td>45 mm</td>
</tr>
<tr>
<td>Guard Ring</td>
<td>Steel</td>
<td>180 mm</td>
<td>45 mm</td>
</tr>
<tr>
<td>Beveled Cylinder</td>
<td>Aluminium</td>
<td>180 mm</td>
<td>22.5 mm</td>
</tr>
<tr>
<td>Faraday Cup Bottom</td>
<td>Aluminium</td>
<td>120 mm</td>
<td>45 mm</td>
</tr>
<tr>
<td>Cup</td>
<td>Aluminium</td>
<td>10 mm</td>
<td>45 mm</td>
</tr>
</tbody>
</table>

In the following sections, the Monte Carlo simulation of this device and the dose delivered by mono-energetic conventional proton beams in it, will be reported in order to underline the greater collecting efficiency respect to the traditional cylindrical Faraday Cup.

3.2 Monte Carlo method

In order to verify the real applicability of laser-driven ion beams in medical physics, several tasks have to be accomplished like the possibility to predict the biological effects of these high pulsed beams on human body such as the dose absorbed during the irradiation. Hence a complete simulation of the transport beam line that have to be realized from the source to the irradiation point and of the dosimetric systems are required.

One of the most accurate simulation method is the Monte Carlo code, which is based on random numbers generation and belongs to the family of statistic and not parametric method. A complete definition of this method is very difficult. The name Monte Carlo has been initially given by J.Von Newmann e S. Ulam
during the II world war and derives from the famous Casinò, placed at Monaco. Indeed, the two scientists, arising from the randomness which characterizes the games at the casino, used a sequence of random numbers in order to generate the parameters needed for the equations describing the nuclear explosion dynamic. The random numbers generation avoided the need to perform a lot of experiments for parameter determination.

The Monte Carlo method consists of three main steps:

- Generation of a random number sequence and determination of the input variable (arising from the generated random numbers) which depends on the chosen probability distribution

- Determination of the output variable, using the input variables, and the mathematical relations which exists among them

- Repetition of the previous points and comparison of the results in order to establish which combination reproduces better the process

In order to perform these points, the randomness of the numbers generated is fundamental to obtain a method completely based on statistics. Indeed, if you imagine to launch a die, the probability to obtain a number between 1 and 6 is exactly the same to obtain a different number. Then if you realize a sequence with the extracted numbers, randomness condition has been satisfied because any relation exists among the extracted numbers. The use of a calculator as random numbers generator does not allow to obtain a perfect random sequence because it needs a deterministic algorithm to perform the calculation. Hence, the number sequence generated by a calculator will be a pseudo-random number sequence because a pre-established relation between an extracted number and the
previous one exists. The entire succession depends on the first number of the sequence which it is called *seed*. The sequence has also a *period*, that is the number of different events before it begins again. Obviously a *good* algorithm generates a sequence with a big period. The Monte Carlo method results more efficient then the analytic and deterministic methods above all when the complexity of the problem to solve is very high. The time needed to solve a problem is strictly connected to the problem complexity and as it is shown in figure 3.4. the resolution time increases more slowly with the complexity of the problem using Monte Carlo method as respect deterministic computations.

Several types of simulation codes based on the Monte Carlo method have been developed and used in different fields of application. In particular, many codes for particle tracing have been distributed in recent years in order to reproduce

Figure 3.4: Plot from Alex F. Bielajew, 2001
the correct physical processes and predict important physical results. One of the most used simulation codes in the high energy physics field as well as for their applications is the toolkit Geant4 and it will be explained in details in the following section.

3.3 The Geant4 simulation code

The simulation software Geant4, which means GEometry ANd Tracking is a toolkit based on Monte Carlo statistical method [50]. The first version of the code has been released, in 1974 at CERN (Geneve CH) in order to simulate, using calculators, the interaction of high energy elementary particles with the detectors really built and used in physical experiments. This first version was limited to a few number of transported particles and detector geometry. In 1982 the initial code evolves through Geant3, written in Fortran language and enhanced to simulate very big experimental devices (geometry) and the transport of very intense and high energetic beams. The limit of this language relies the huge number of lines strictly linked each other, difficult to understand and modify for external users. An important year that sign a big change in the code evolution is 1998. Indeed, during this year Geant4, the fourth version of the original code, has been developed. Geant4 is written in C++ language and it takes advantage from the object oriented software technology which allows to write a clearer and more partitioned code. The code is certainly has been created, and it is currently developed by an international collaboration constituted approximately by 100 members from Europe, US and Japan. It is important to say that the Geant4 code is open source and the user can directly download the source code from the official web site (www.geant4.cern.ch).
3.4 Geant4 structure

As already said, Geant4 is a collection of libraries which can be used in order to create a specific application. Indeed, the user must write his own application, establishing all the parameters, from the geometry to the physical processes.

The simulation covers all the aspects of real experiment:

- The user has to set the geometry and the material of the detectors, reproducing with high precision the real shape, sizes and the position in the space.

- The particles source must be chosen by user, setting the energy and angular spectrum, the intensity and all the features of the beam.

- The physical interaction processes and they have to be explicitly included in the user application, together to the model simulating the final state.

- The trajectory of the beam particles inside the matter can be calculated step by step including also the tracking in electromagnetic fields. The information related to the particles, like the energy and the position, can be obtained step by step along the particles track for each step.

- It is also possible to simulate sensitive detectors and to define their physical response.

- Geant4 gives several efficient visualization tools which allow to have a 3D visualization of the devices and the tracks.

One of the most important advantage of the Geant4 code is that it has a very modular structure, composed of several independent categories. Each class describes a particular aspect of the simulation, for example the geometry or the
particle source. Indeed, the developer who wants to construct his own application, uses the virtual classes provided in the Geant4 kernel, and creates the User (concrete) classes in accordance to specific requirements. The virtual classes (and also the user classes) can be divided in two categories: the initialization classes, which are invoked at the simulation initialization and the action classes, called during the execution.

Among the initialization classes there are [51]

- \texttt{G4VUserDetectorConstruction} class in which the detector is described, from the geometry and the materials used
- \texttt{G4VPhysicsList} class in which the physical processes and models are contained
- \texttt{G4VUserActionInitialization} class in which the simulation is initialized

The action classes, instead, define the dynamic of the simulation and among them there are:

- \texttt{G4VUserPrimaryGeneratorAction} class in which the primary beam is described and generated
- \texttt{G4VUserRunAction}
- \texttt{G4VUserEventAction}
- \texttt{G4VUserSteppingAction}
- \texttt{G4VUserStackingAction}
- \texttt{G4VUserTrackingAction}
In particular, the initialization classes and the \textit{G4VUserPrimaryGeneratorAction} are all mandatory classes which the user must create in order to start the simulation. The other ones are optional. In the following paragraphes the feature of the principal classes of Geant4 will be briefly described.

3.4.1 Geometry and material definition

The size, the shape, the position and the material of the detectors have to be described inside the \texttt{G4UserDetectorConstruction} category, using the classes 
\texttt{G4Geometry} and \texttt{G4Material}.

Regarding the geometry definition, before defining the detector volumes, it is necessary to create the virtual space in which the other volumes can be simulated. This volume is tipically called \textit{world volume} and nothing can be defined out of it. Inside Geant4 the concept of geometrical hierarchy is important. Indeed, each volume (with the exception of world volume) has always to be located inside a bigger one which entirely contains the first one. The volume which contains the smaller one, is usually called \textit{Mother} volume and can correspond to the world volume.

In order to create a volume, it is necessary to define it in three different levels:

- The \textit{Solid Volume} that sets the shape and the size of the volume
- The \textit{Logic Volume} that defines the material and other optical parameters
- The \textit{Physical Volume} that establishes the position and the orientation of the volume in respect to the center of its mother volume

It is important to remember that it is not possible to construct volumes out of the \textit{World} or overlapped volumes. Hence, the geometry construction has to be
done with extreme accuracy in order to avoid mistakes.

The materials have to be specified in the logic volume definition. and its definition can be done in two different ways:

- Creating directly the material, specifying the atomic number, the density, and the number of elements

- Using a database of materials already provided inside the Geant4 kernel

### 3.4.2 Primary Beam definition

The primary beam is defined inside the G4PrimaryGeneratorAction category and the user can establish all the characteristics of the primary beam, like the size of the source, the position, the energy and angular distribution and the type of particles. The G4PrimaryGeneratorAction is called each time that an event ends and another one is starting and it menages the primary particles together to the class G4Event which menages each single event.

### 3.4.3 Physics processes and cuts in Geant4

In order to obtain a simulation which reproduces with the highest accuracy the real experimental conditions, it is extremely necessary to define the physical processes characterizing the particle interaction. According to the particle type the user has to establish the interaction mechanism. In order to do this, inside the category G4PhysicList it is possible to set the suitable physical model and process (in according also to the particle energy) for each kind of particle. The following processes can be implemented in Geant4 [52]:

- electromagnetic
• *adronic*
• *transportation*
• *decay*
• *optical*
• *photelepton-hadron*
• *parametrization*

**Cut in range**  One of the difference of Geant4 in respect to the previous version Geant3, is the possibility to set the cut in range (not in energy) of the secondary particles that can be produced during the interaction of primary beam with the matter (in according to the different physical processes). To avoid infrared divergence, some electromagnetic processes require a threshold below which no secondary will be generated. Because of this requirement, gammas, electrons and positrons require production threshold. This threshold should be defined as a distance, or range cut-off, which is internally converted to an energy for individual materials. The range threshold should be defined in the initialization phase using the SetCuts() method of G4VUserPhysicsList.

**3.4.4 Particle Tracking**

In Geant4 both primary and secondary particles are tracked down to zero energy. The trajectory of each particle is divided in *steps* and for each step it is possible to retrieve all information about the particle, like the position, the momentum and the energy. A maximum step length can be set, depending on the simulated setup. The *step* has a variable length and obviously the length choice conditions
the simulation results. There is a specific category, called \textit{G4SteppingAction}, in which the \textit{G4Step} class is registered and the user can decide how to take the information from the simulation in according to his requirement.

### 3.5 Transport Beam Line Simulation in Geant4

In order to simulate the Faraday Cup, already described in the previous chapter, and to calculate the released dose by a conventional and a laser-driven proton beam, the application \textit{Hadrontherapy}, has been modified. \textit{Hadrontherapy} which is one of the Geant4 advanced exemples, reproduces the CATANA (Centro di AdroTerapia e Applicazioni Nucleari Avanzate) facility at Laboratori Nazionali del Sud-(LNS) (Catania, I). The facility uses the 62 MeV proton beam accelerated by the superconductivity Cyclotron of LNS in order to perform the proton-therapy treatment of the uveal melanoma [53] [54] [55]. The application \textit{Hadrontherapy}, which already includes the simulation of the Catana beam line has been modified in order to simulate a typical beam line for laser-driven beams. The structure of the application will be described in the following section in order to show the functionalities of the implemented classes necessary to reproduce the entire beam line and the Faraday Cup for absolute dosimetry measurements.

### 3.6 Structure of the application

A typical \textit{Geant4} application must contain a \textit{main} program that has the role to menage the different classes (the source files) that compose the entire application. The main classes implemented for the simulation of the entire beam line are:

- \textit{LaserDrivenBeamLine} in which the geometry of the energy selector system
and of the Faraday Cup are present.

- **HadrontherapyElectricTabulatedField3D** dedicated to read the electric field map inserted by the user.

- **HadrontherapyPhysicsList** in which the physical models that can be used are implemented. In particular, the physics models used in the simulation involve the electromagnetic processes \((\text{emstandard-option4})\), the Decay and Radioactive Decay processes \((\text{G4DecayPhysics G4RadioactiveDecayPhysics})\), and the Hadronic ones \((\text{G4HadronElasticPhysicsHP, G4StoppingPhysic, G4HadronPhysicsQGSP-BIC-HP})\).

- **LaserDrivenBeamLineMessanger**

- **HadrontherapySteppingAction** in which the code for the output files is implemented starting from the physical information of the particles for each steps.

In figure 3.5 the screen shot of the entire beam line simulated through the toolkit Geant4 is shown:
3.7 Implementation of the Electric Field

In order to create the Electric Field inside Geant4, the `HadrontherapyElectricTabulatedField3D` class has been added to the application hadrontherapy. Because of the non-uniform electric field which is applied to the Guard Ring of the Faraday Cup in the new configuration, an external map of the electric field has to be implemented in the code. In particular in the map the values of the three components of the electric field $E_x, E_y, E_z$ are tabulated with a resolution of 1 mm. The map has been simulated using the FEM code `COMSOL` and, in order to implement it inside Geant4, it must be associated to a specific volume.

A realistic simulation must reproduce the real trajectories of the charged particles deflected from the electric field. Indeed, as known, physically charged particle that moves inside an electromagnetic field is deflected and the trajectory satisfies
the Maxwell equations. In order to solve the differential motion equations Geant4 uses the *Range Kutta* approximation method that allows the integration of motion equations according to the different cases.

Moreover, in Geant4 the tracks inside the field must be calculated taking into account the particle crossing between two different materials. In order to do this, the curved tracks of charged particles are divided in linear chord segments whose the length can be chosen to better approximate the real track. How closely the set of chords approximates a curved trajectory is given by a parameter called the *miss distance* which can be setted by user and represents the upper bound for the value of the distance between the real trajectory and the approximate one (*sagitta*). With this parameter the user can control the precision of the charged particle track calculation.

In order to read the external electric field map the code has to be developed inside the class *HadrontherapyElectricTabulatedField3D* which is recalled in the class *LaserDrivenBeamLine* (where the Faraday Cup geometry is implemented), through the *G4FieldManager* class and the *G4EqMagElectricField*.

Using the G4MagIntegratorStepper the most suitable interpolation method in order to calculate the field value in the other points of interest.[51]

The code used for the Electric Field implementation is shown below:

```cpp
G4double exOffset = 0*cm;
G4double ezOffset = -42*mm;

G4FieldManager *pEFIELDmanager = new G4FieldManager();
```

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G4ElectricField *ElectricField =
new HadrontherapyElectricTabulatedField3D
("field/ElectricField-600V.TABLE",
exOffset, eyOffset, ezOffset);

G4EqMagElectricField *fLocalEquation =
new G4EqMagElectricField(ElectricField);

G4int nvar = 8;

G4MagIntegratorStepper* fLocalStepper =
new G4ClassicalRK4(fLocalEquation, nvar);
G4MagInt_Driver *pIntgrDriver_E =
new G4MagInt_Driver(0.02*mm, fLocalStepper,
fLocalStepper -> GetNumberOfVariables() );
G4ChordFinder *fLocalChordFinder =
new G4ChordFinder(pIntgrDriver_E);
pEFieldmanager -> SetDetectorField(ElectricField);
pEFieldmanager -> SetChordFinder(fLocalChordFinder);
G4double minEpsEF= 1.0e-5;
G4double maxEpsEF= 1.0e-4;
G4bool allLocal = true;
logicVirtualMag -> SetFieldManager(pEFieldmanager, allLocal);

In order to verify the correct tracking of the electrons inside the implemented
electric field, the tracks obtained in the Monte Carlo simulation have been compared with the tracks generated by the code *SIMION*, which has been used as reference. In figures 3.7, 3.8, 3.9 the electron track projections in three different planes (x-y,x-z,y-z) are shown in the case of an electron with energy of 200 eV and starting point x=5 mm, y=9 mm, z=0 mm. The electric field component along the beam direction (x) is shown in figure 3.6.

Figure 3.6: Electric Field profile along the beam axis (x)
Figure 3.7: Projection in the x-y plane of the electron’s trajectory with energy of 200 eV inside the electric field

Figure 3.8: Projection in the x-z plane of the electron’s trajectory with energy of 200 eV inside the electric field
Figure 3.9: Projection in the z-x plane of the electron’s trajectory with energy of 200 eV inside the electric field

As evidence the comparison shows a good agreement between the tracks of the secondary electrons simulated with the code \textit{SIMION} and with the Monte Carlo toolkit Geant4.

3.8 Faraday Cup simulation

The Faraday Cup described, has been simulated and its geometry has been added in the class \textit{LaserDrivenBeamLine}, together with the Energy Selection System realized at LNS. Final aim is to use it as a detector for the dosimetry of high pulsed ion beams transported through the ESS and the quadrupoles of the Laser-Driven beam line but also as an absolute dosimeter just for the conventional proton beams transported in the CATANA beam line.

In order to correct the uncertainties in the collected charge, five different \textit{virtual} planes made of vacuum have been simulated in order to count the secondary
electrons created in the interaction of the proton beam with the entrance kapton window and with the cup. More in details:

- **Virtual Window**, located just after the kapton entrance window to control the secondary electrons emitted from the window and that enter in the Faraday Cup

- **Virtual Middle**, located in the vacuum space between the Guard Ring suppressor and the walls of the cup itself. It is implemented in order to count the secondary electrons created in the kapton window that enter in the Cup ($N_{middleIn}$) producing an underestimation of the positive collected charge, and the ones created in the bottom of the cup that are scattered in the back direction and lost ($N_{middleBack}$).

- **Virtual Bottom**, placed ahead of the cup

- **Virtual OverBottom**, placed at the end of the cup and used in order to count the energetic electrons (and the protons too) that are not stopped in the cup ($N_{overBottom}$).

- **Virtual Lateral** placed around the cup walls it counting the electrons that escape from the Faraday Cup walls ($N_{lateral}$).

A scheme of the Faraday Cup with the mentioned virtual volumes is shown in figure 3.10.
In order to obtain the correct charge collection and hence the correct dose calculation, it is necessary to correct for charge underestimation due to the electrons collected in the cup, but originated in the kapton window, and the overestimation of the positive charge due to the secondary electrons (negative charge) which escape from the cup causing a loss of the negative charge. According to these considerations, the total charge that has to be considered in the dose calculation is:

\[ Q/e = N_p - N_{middle\text{In}} + N_{middle\text{Back}} + N_{Lateral} + N_{over\text{Bottom}} \]  

(3.6)

where \( N_p \) is the number of collected protons. The uncertainty associated to the collected charge depends on the uncertainty made in the count of the secondary electrons:

\[ \Delta Q/e = \sqrt{N_{middle\text{In}}} + \sqrt{N_{middle\text{Back}}} + \sqrt{N_{Lateral}} + \sqrt{N_{over\text{Bottom}}} \]  

(3.7)

An ideal Faraday Cup collects all the charges which go inside it, without losing
them. The uncertainty related to the counts of the charges, due to the loss of the primary and secondary particles, in respect to the incident charge \( Q_{\text{ideal}} \), is the charge accuracy and can be expressed as:

\[
\left( \frac{\Delta Q}{e} \right)_a = \frac{(Q/e)_{\text{calculated}} - (Q/e)_{\text{ideal}}}{(Q/e)_{\text{ideal}}} \tag{3.8}
\]

3.9 Simulation with mono-energetic conventional proton beams

In this section, the simulation of a monoenergetic proton beam with an energy of 62 MeV and 10 MeV using a Faraday Cup with traditional electric field configuration (one electrode with a voltage of -600 V (figure 3.6)) and with the already described beveled electrode have been performed. The study of the dose accuracy obtained in the two different electric field configurations, will allow to demonstrate the higher secondary electrons suppression capacity of the Faraday Cup in the case of the additional electric field.

3.9.1 Simulation of proton beam at 62 MeV

The 62 proton beams have been simulated because they are typically used for the uveal melanoma treatments at the CATANA facility.

In the simulation, an input beam with an energy of 62 MeV, no angular dispersion, with a radius of 10 mm has been simulated using the \textit{General Particle Source} class and writing the necessary commands in a specific \textit{script}. A cut range of 0.0001 mm which corresponds to 990 eV energy has been chosen.

In the following tables the charge calculation, using the formula (3.4) in the case of 100000 launched protons, has been reported both for the Faraday Cup with
the particular beveled electrode and for the traditional Faraday Cup composed by a single cylindrical electrode.

<table>
<thead>
<tr>
<th></th>
<th>(N_{\text{middleIn}})</th>
<th>(N_{\text{middleBack}})</th>
<th>(N_{\text{lateral}})</th>
<th>(N_{\text{overBottom}})</th>
</tr>
</thead>
<tbody>
<tr>
<td>FC with beveled electrode</td>
<td>110 ± 10</td>
<td>63 ± 8</td>
<td>139 ± 18</td>
<td>23 ± 5</td>
</tr>
<tr>
<td>Traditional FC</td>
<td>314 ± 18</td>
<td>105 ± 10</td>
<td>140 ± 12</td>
<td>35 ± 16</td>
</tr>
</tbody>
</table>

Table 3.2: Number of secondary electrons recoiled in the virtual volumes with a number of input proton \(N_p=100000\)

<table>
<thead>
<tr>
<th></th>
<th>(Q/e)</th>
<th>(\Delta Q/e)_a)</th>
<th>(\Delta Q/e)_s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>FC with beveled electrode</td>
<td>100315 ± 41</td>
<td>0.1 %</td>
<td>0.04 %</td>
</tr>
<tr>
<td>Traditional FC</td>
<td>99931 ± 60</td>
<td>0.1 %</td>
<td>0.06 %</td>
</tr>
</tbody>
</table>

Table 3.3: Total calculated charge with the correspondent charge accuracy and statistic error

Where \((\Delta Q/e)_s\) is the statistical uncertainty associated to the charge calculation. Considering that the beam area is \(A=3.14cm^2\) (the starting point of the beam coincides with the kapton entrance window position) and the stopping power in water in the case of a 62 MeV proton beam is equal to 10.51 MeVcm\(^2\)/g (ICRU Report 49 (ICRU, 1993)), the calculated dose in both case is:

<table>
<thead>
<tr>
<th></th>
<th>Dose [Gy]</th>
</tr>
</thead>
<tbody>
<tr>
<td>FC with beveled electrode</td>
<td>5.36 (\cdot) (10^{-5}) ± 5.37 (\cdot) (10^{-7})</td>
</tr>
<tr>
<td>Traditional FC</td>
<td>5.4 (\cdot) (10^{-5}) ± 5.41 (\cdot) (10^{-7})</td>
</tr>
</tbody>
</table>

Table 3.4: Dose calculation

where the dose uncertainty has been calculated using the error propagation theory
and considering that the stopping power has an uncertainty of 1% according to ICRU Report 49 (ICRU, 1993) [7]. From the tables 3.2 3.3 and 3.4 it is possible to see that with the new electric field configuration, the number of secondary electrons that crosses the Middle Virtual Volume, in both direction, is suppressed in respect to the secondary electrons collected in the simulation with traditional electrode. This fact results in the smaller statistic error in the recoiled charge. Instead, the charge accuracy is at 0.1% in both cases, because in the positive charge count the secondary electrons lost in the walls (Virtual Lateral) and out of the cup (Virtual Over Bottom) have to be considered. In any case, the secondary electron suppression efficiency of the beveled electrode is certainly upper then that one obtained in the simulation with traditional Faraday Cup.

In the following figures are reported the energy spectrum of the secondary electrons emitted in the kapton entrance window and the ones which go toward the cup in the case of the innovative Faraday Cup. Only the ~ 2% of secondary electrons emitted from the window can enter inside the cup. This demonstrates the effect of the big transverse electric field component that is able to deviate the most of the electrons created in the interaction with the window. Moreover, the number of secondary electrons $N_{\text{middleBack}}$ is also less the one obtained with the traditional electric field configuration.
Figure 3.11: Energy spectrum of the secondary electrons produced by the kapton entrance window (above) and energy spectrum of secondary electrons accrossing the virtual middle volume($N_{middleIn}$)(below)
3.9.2 10 MeV proton beam simulation

For the simulation of the the proton beam with energy of 10 MeV a different cut in range (0.00005 mm which corresponds to 110 eV electrons) has been chosen in order to take into account of the low energetic secondary electrons produced. The beam has a radius of 10 mm and it has no angular divergence. As in the case of 62 MeV, the results related to the charge collection and the dose calculation have been compared with the same simulation performed using the typical electric field applied to the Guard Ring (figure 3.6). In the following tables the number of secondary electrons counted in the virtual planes and the dose calculation with the error associated to the charge collection and to the dose calculation in the case of 30000 launched input protons, are reported:

<table>
<thead>
<tr>
<th></th>
<th>( N_{\text{middleIn}} )</th>
<th>( N_{\text{middleBack}} )</th>
<th>( N_{\text{lateral}} )</th>
<th>( N_{\text{overBottom}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>FC with beveled electrode</td>
<td>139 ±11</td>
<td>7± 3</td>
<td>3 ± 1</td>
<td>2 ± 1</td>
</tr>
<tr>
<td>Traditional FC</td>
<td>260 ± 16</td>
<td>94 ± 10</td>
<td>1 ± 1</td>
<td>2 ± 1</td>
</tr>
</tbody>
</table>

Table 3.5: Number of secondary electrons recoiled in the virtual volumes with a number of input proton \( N_p=30000 \)

<table>
<thead>
<tr>
<th></th>
<th>( Q/e )</th>
<th>( (\Delta Q/e)_a )</th>
<th>( (\Delta Q/e)_s )</th>
</tr>
</thead>
<tbody>
<tr>
<td>FC with beveled electrode</td>
<td>29873 ± 17</td>
<td>0.4 %</td>
<td>0.05 %</td>
</tr>
<tr>
<td>Traditional FC</td>
<td>29824 ± 40</td>
<td>0.6%</td>
<td>0.1 %</td>
</tr>
</tbody>
</table>

Table 3.6: Total calculated charge with the correspondent charge accuracy and statistic error
Looking at the comparison between the two performed simulations, the secondary electrons suppression capacity is certainly better in the case of beveled cylinder configuration with respect to the traditional one. The charge accuracy for the innovative Faraday Cup is of 0.4% in respect to the 0.6% obtained from the other simulation. The lower error in the charge collection with respect to the ideal case (all charges rcollected) allows to determine the dose with an high precision that is one of the aim of the project.

The energy spectrum of the secondary electrons emitted in the entrance kapton window and of the one entering in the cup, crossing the virtual middle volume, are reported in the following figures.
Figure 3.12: Energy spectrum of the secondary electrons produced by the kapton entrance window
Figure 3.13: Energy spectrum of secondary electrons crossing the virtual middle volume ($N_{\text{middle}}$).

In the figure 3.12, where is shown the energy spectrum of the secondary electrons which go inside the cup, it is evident that the low energy secondary electrons are stopped and deflected by suppressor electric field and only the more energetic ones are able to reach the cup in according to the figure 3.2.

3.10 Simulation of the dose delivered by a typical laser-driven proton beam

The Faraday Cup simulation has been tested also in the case of charge collection for a typical proton beam emitted from the interaction of an high intense laser with a solid target. Indeed, as already explained, the energy and angular spectrum of the output beam are very particular and make very difficult the experimental
dose measurements.

The ELIMED group has established a collaboration with Queens University researchers (Belfast UK) and an experimental campaign, started at the end of 2013, has been approved at Centre for Plasma Physics, where the TARANIS laser system is installed. Many studies have been already performed in order to characterize the proton beam and calibrate the energy selection system with the help of Monte Carlo simulation (Geant4).

Taking into account of the results obtained from the experimental run, a simulation of the dose delivered in the Faraday Cup in the case of 4 MeV and 7 MeV energy selection has been realized.

The experimental and simulation set-up is shown in figure 3.12. The TARANIS laser is a hybrid Ti:Sapphire-Nd:glass system operating in the chirped pulse amplification mode, characterized by \( \sim 5 \) J (delivered on target) in energy and \( \sim 560 \) fs in duration, and a focal spot diameter (measured in the low power, non amplified mode) of \( \sim 10 \) \( \mu m \), leading to an intensity on target of about \( 2 \times 10^{19} W cm^2 \).\[57\]

During the experimental campaign, a 12 \( \mu m \) gold target has been used and placed inside the interaction chamber. The energy selector system was placed inside the interaction chamber, where an high vacuum was realized, at a distance from the target of 8.2 cm. In the simulation, the Faraday Cup has been placed just after the exit pipe of the ESS box at a distance from the last collimator of 175 mm. The last collimator has a diameter of 3 mm both in the 4 MeV selected energy and 7 MeV.

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The energy spectrum of the proton beam emitted from the target and the relation with the angular spectrum has been experimentally evaluated using the Radio-chromic films HD810 layers wrapped in 12um Al foil at a distance from the target of 2.66 cm [57]. The experimental energy spectrum is reported in the figure 3.14 together with the spectrum simulated with Geant4 and used as input of the simulation itself.
The experimental energy spectrum has a range with a cut-off of 8 MeV shows a number of protons per bunch of $10^{10}$.

In order to decrease the computation time, the simulation has been divided into two steps. The first one gives the energy selection of the proton beam after the last collimator and after the crossing of the fourth dipoles, and the second one calculates the collected charge in the Faraday Cup due to the incident proton beam. The Faraday Cup was placed just after the exit pipe of the ESS and for this reason the entrance kapton window has not been adopted.

The selected proton beam, after the last collimator, has some characteristics that are the same both selecting an energy of 4 MeV and an energy of 7 MeV. In particular, the proton beam after the last collimator shows an angular dispersion...
characterized by a maximum half angle of 0.7 °. Moreover the proton beam axis create an angle of 1.5 ° in respect to the x direction (figure 3.16).

![Diagram](image)

Figure 3.16: Simply scheme of the proton beam after the last collimator

### 3.10.1 Selected energy: 4 MeV

The output file of the first step of the simulation, which gives the energy spectrum, and the fluence distribution of the proton beam after the last collimator has been used as input for the second step of the simulation which provides the calculation of the delivered dose in the Faraday Cup. In particular, in figure 3.17 the fluence \( (p/cm^2) \) in the transverse plane normalized for the total number of protons per bunch \( (10^{10}) \) just after the last collimator is shown together with the proton beam spot at the entrance of the Faraday Cup (at a distance of 175 mm from the last collimator).
Figure 3.17: In the left the fluence distribution in the z-y plane is shown. The mean fluence is $1.2 \cdot 10^6 \pm 0.2 \cdot 10^6$. In the right side the beam spot (in z-y plane) at the entrance of the Faraday Cup is reported in order to find the radius of the beam which can be assumed as $r=3.56 \text{ mm}$.

Because of the good uniformity of the fluence distribution in the beam area it has been chosen to simulate an extended proton source with a radius equal to the radius of the last collimator (1.5 mm) and with an angular spectrum uniformly distributed in the angular range $[-0.7^\circ, 0.7^\circ]$.

The energy spectrum, used as input in the simulation, is shown in figure 3.18 and performing a gaussian fit of the spectrum the centroid has been obtained: $4.5 \pm 0.2 \text{ MeV}$. 
Figure 3.18: Proton energy spectrum just after the last collimator of the ESS

Because of the absence of the kapton entrance window, the number of secondary electrons created inside the Faraday Cup is very low. Indeed, the proton beam crosses the Faraday Cup in vacuum before arriving to the cup. For this reason, an higher statistics has been chosen, and a number of $10^6$ input proton has been simulated. The calculated dose at the end has been normalized to the real number of proton per bunch of the initial proton beam. In the following tables the count of the secondary electrons obtained in the virtual planes and the consequent dose calculation are reported.
Table 3.8: Number of secondary electrons recoiled in the virtual volumes with a number of input proton $N_p=10^6$

<table>
<thead>
<tr>
<th>$N_{middle,In}$</th>
<th>$N_{middle,Back}$</th>
<th>$N_{lateral}$</th>
<th>$N_{over,Bottom}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 ± 1</td>
<td>17 ± 4</td>
<td>3 ± 3</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 3.9: The total charged collected, the charge accuracy and the static error of the total charge are reported

<table>
<thead>
<tr>
<th>$Q/e$</th>
<th>$(\Delta Q/e)_a$</th>
<th>$(\Delta Q/e)_s$</th>
<th>Dose [Gy]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$10^6$ ± 7</td>
<td>0.002 %</td>
<td>0.0006 %</td>
<td>$3 \cdot 10^{-3}$ ± $3.07 \cdot 10^{-6}$</td>
</tr>
</tbody>
</table>

From the table, it is possible to note that the charge accuracy is very low and this fact is due to the small number of secondary electrons created which are the biggest source of uncertainties.

### 3.10.2 Selected energy: 7 MeV

The same considerations have been done in the case of a selected energy of 6.7 ±0.5 MeV shown in figure 3.20. In this case the approximation of the uniform fluence distribution in the beam area, is worse in respect to the previous case, as it is possible to see in the figure 3.19. But at first approximation a uniform spatial and angular distribution can be adopted.
Figure 3.19: In the left the fluence distribution in the z-y plane is shown. The mean fluence is $1.8 \cdot 10^6 \pm 0.4 \cdot 10^6$. In the right side the beam spot (in z-y plane) at the entrance of the Faraday Cup is reported in order to find the radius of the beam which can be assumed as $r=3.35$ mm.

The energy spectrum of the proton just after the last collimator is shown in figure 3.19. The centroid of the spectrum has been obtained performing a gaussian fit and it is: $6.7 \pm 0.4$ MeV.
Figure 3.20: Energy spectrum

Also in this case a simulation with an high statistic has been performed, in order to evaluate the real charge accuracy of the Faraday Cup in this particular case.

<table>
<thead>
<tr>
<th>(N_{\text{middleIn}})</th>
<th>(N_{\text{middleBack}})</th>
<th>(N_{\text{lateral}})</th>
<th>(N_{\text{overBottom}})</th>
</tr>
</thead>
<tbody>
<tr>
<td>4 ± 2</td>
<td>39 ± 6</td>
<td>15 ± 4</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 3.10: Number of secondary electrons recoiled in the virtual volumes with a number of input proton \(N_p=10^6\)
Table 3.11: The total charged collected, the charge accuracy and the static error of the total charge are reported

<table>
<thead>
<tr>
<th>$Q/e$</th>
<th>$(\Delta Q/e)_a$</th>
<th>$(\Delta Q/e)_s$</th>
<th>Dose [Gy]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$10^6 \pm 12$</td>
<td>0.005 %</td>
<td>0.001 %</td>
<td>$5 \cdot 10^{-3} \pm 5.23 \cdot 10^{-6}$</td>
</tr>
</tbody>
</table>

The energy selected $\sim 4MeV$ and $\sim 7MeV$ are too low energies to use them in hadrontherapy treatments, but the study of laser-driven proton beams (at low and high energy), both for the transport from the target to the irradiation point and for the dosimetric measurements are required in order to demonstrate the applicability of the laser-driven ion beam in hadrontherapy.
Chapter 4

Preliminary experimental tests

In the period from 09-06-2014 to 20-06-2014, an experimental run was performed at the Prague Asterix Laser System (PALS) laboratory in Prague. The Prague Asterix Laser System facility is conceived as a laboratory providing the basis for experimental research in the field of high-power lasers and their applications, notably in the physics of laser plasmas. The laboratory is provided by an intense laser which can reach a power of 3 TW.

During the run we had the possibility to test for the first time with a laser driven ion beam the innovative Faraday Cup developed at INFN-LNS. The electromagnetic pulse (EMP) generated by the laser pulse outside and inside the interaction chamber has been measured in order to investigate the frequencies of the signal due to oscillation modes of the electromagnetic pulse inside the interaction chamber. Indeed, such kind of study is particularly useful since the high-pulsed laser interaction with the target produces an high electromagnetic noise, which can strongly affect the real signal. For example, the direct study of the measured noise signal of the device generated only by electromagnetic pulse propagation, can be useful to subtract the background from the real signal coming from the
ions in order to be able to distinguish the ion signal. During the experiment, Silicon Carbide (SiC) detectors and Diamond detectors have also been tested. They were mounted inside the interaction chamber in order to detect the ions emitted from the target surface.

In the present chapter the description of the PALS laboratory, where the experiment was performed, is provided followed by the experimental set-up description and the analysis results.

4.1 PALS: Prague Asterix Laser System

The PALS facility is constituted by an high-power iodine laser system Asterix IV. The system is able to reach a maximum energy delivered per pulse of 1 kJ, representing the nominal energy of the system. The fundamental wavelength is 1315 nm and in correspondence of this wavelength the usual maximum energy delivered per pulse is about 600 J. The time duration of the pulse is about $\sim 350$ ps and the power peak, corresponding to 600 J delivered energy, is about 2 TW [58].

The system consists of an oscillator which generates the initial pulse and a succession of five amplifiers which increase the energy of the pulse. The main oscillator, called master oscillator power amplifier (MOPA), creates a sequence of several identical light pulses from which one of them is selected to be amplified using Pockels cells (PC1-3). (Figure 4.1)
Figure 4.1: The kJ iodine laser system and its components installed at PALS [59].

The created pulse reaches the pre-amplifier, where it undergoes a first energy amplification, and leaving it with an energy of 10 mJ. Then the pulse is used to activate laser-triggered spark gap which admits the voltage signal to the Pockels cells PC1 and PC2. The next step is the laser amplification through five amplifiers in order to increase the energy of the pulse created from the oscillator section up to 1 kJ energy. The amplifiers are made of cuvettes filled by C3F7I gas. This gas laser uses neutral iodine atoms for the generation of a narrow infrared line at 1315 nm. The iodine atoms dissociate from the parent iodide molecule C3F7 through a photochemical process called photodissociation (or photolysis). The process is caused by an external UV radiation, provided from a fresh lamp, which
releases the iodine atom from the chemical bonding. The iodine atoms which emerge from photolysis process will be in a excited state and the laser pulse can be produced. During the amplification also the beam size is modified. Indeed, it starts from the original diameter of 8 mm up to the size of 290 mm after the fifth amplifier. The laser beam size amplification is made by optical telescopes, constituted by two convex lenses. The size increment is required in order to have a power density of the laser beam always below the threshold value at which the optics, in particular the lenses, can be damaged. In the following table are reported the output parameters of the Asterix IV at PALS [58] [60]:

<table>
<thead>
<tr>
<th>General</th>
<th>Fundamentale wavelength</th>
<th>Pulse duration</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>1315 nm</td>
</tr>
<tr>
<td></td>
<td></td>
<td>200 to 350 ps</td>
</tr>
<tr>
<td></td>
<td>Pulse contrast (prepulses)</td>
<td>~ 10^{-7}</td>
</tr>
<tr>
<td>Repetition shot rate</td>
<td></td>
<td>25 min</td>
</tr>
<tr>
<td>Output energy stability (over 10 shot)</td>
<td>1 &lt;± 1.5 %</td>
<td></td>
</tr>
</tbody>
</table>

| Main beam        | Pulse energy at 350 ps | 1 kJ |
| Auxiliary beam   | Pulse power at 350 ps  | 3 TW |
|                  | Diameter                | 290 mm|
|                  | Conversion efficiency to 3\omega | 55 % |

| Auxiliary beam   | Pulse energy at 350 ps | 100 J |
| Auxiliary beam   | Diameter                | 148 mm|
| Auxiliary beam   | Conversion efficiency to 3\omega | 30 % |

Table 4.1: The output parameters from the Asterix IV laser at PALS

4.2 Target chamber

The laser beam produced by the amplification system, has to be transported to the interaction chamber where the target is placed in order to generate the ion beams
through the laser-matter interaction. The target is placed inside an interaction chamber in which an high vacuum is done. The target chamber consists of a sphere with a diameter of 1 m equipped with a 80 cm diameter hinged end cap that serves as the main entrance port (Figure 4.2).

![Figure 4.2: Picture and scheme of the master interaction chamber at PALS](image)

The system is sealed by a pneumatic clamping system which allows a quick and easy access to the chamber. Fifteen circular ports of diameter ranging from 64 to 500 mm are available in order to connect the interaction chamber to diagnostic devices for the detection.
4.3 Experimental set-up

The experiment performed at PALS in June 2014, has been performed using a $5\mu m \, CD_2$ target. The vacuum inside the interaction chamber was fixed at about $5-6 \times 10^{-6}$ mbar for each shot. After every shot the chamber was opened in order to allow the re-placing of the target which is destroyed in every laser-target interaction.

The laser reaching the interaction chamber after all the amplification steps has a diameter of 129 mm and an energy of about 600 J.

![Interaction chamber at PALS](image)

Figure 4.3: Interaction chamber at PALS

The signal of the Faraday Cup(FC) was measured by a 2 GHz LeCroy Digital oscilloscope. The EMP noise signals were detected with the FC directly connected to the digital oscilloscope with 50 ohm impedance. As one can see in figure 4.4 the vacuum inside the FC was provided by a rotary pump. The vacuum control was performed using a pressure reader. The vacuum value inside the FC was about
$10^{-2}$ mbar. At first set of measurements were performed with the FC placed 5m away from the interaction chamber. The pump reached a value of vacuum of $2 - 3 \cdot 10^{-2}$ mbar. In this geometrical configuration, the electromagnetic noise of the laser pulse, which arrived inside the interaction chamber and spread in the entire experimental room, was evaluated.

Figure 4.4: Picture of the oscilloscope and the Faraday Cup connected to the pump at PALS.

Two different detectors, for TOF (Time Of Flight) have been mounted inside the interaction chamber, in order to detect the ions emitted from the target. In particular, a Silicon Carbide detector (SiC) and a Diamond detector placed at 45 in the backward direction with respect to the laser incident direction. Accord-
ing to the target thickness, and the acceleration regime involved, different signal amplitudes were expected. In particular, considering the backward position of the detectors, an higher signal amplitude was expected in the case of thick target with in respect to the thin case. Both spectra shown in fig. 4.5 were taken with a 6 μm CD2 target.

Figure 4.5: On the left the SiC TOF spectra is shown. The flight path, i.e. distance from the target, was 150 mm. A 6 dB attenuator was used and a bias of -200 Volt has been applied. On the right the Diamond TOF signal (BIAS=350 Volt, 6 dB attenuation and flight path= 180 mm) is shown.

4.4 ElectroMagnetic Pulse (EMP) noise analysis

An accurate study of the EMP noise e caused by the laser pulse inside the interaction chamber as well as in the entire experimental room has been performed. Indeed, the EMP propagation can produce an high signal amplitude in the detectors which might strongly affect the signal generated by charged particles. [61] [62] In order to subtract the EMP noise contribution from the detector signal and distinguish the ion signal, the identification and characterization of the noise itself is crucial.
In particular, the Faraday Cup collects the charges, giving typically a current signal. The EMP noise, especially in laser-driven ion beam presence, can strongly affect the real charged particle signal when its amplitude is comparable with the real signal amplitude. The EMP signal can disguise the smaller signal amplitude, causing a not correct signal evaluation. This fact introduces some errors in the consecutive dose calculation, determining a worsening in the accuracy of the device, fundamental in order to obtain the correct dose. The Faraday Cup described in the previous chapter, has been tested for the first time at PALS in Prague and in order to have a complete knowledge of the response of this device in high pulsed laser presence, an accurate study of the EMP generated in the detector has been performed. Following the study on the EMP characterization presented in [61], all the shots have been analyzed in order to compare the characteristics of the signals in terms of amplitude, time duration and principal frequencies. A set of measurements have been performed with the FC signal directly connected to the oscilloscope without any amplifier and attenuation. Two typical EMP signals registered by the oscilloscope

The ElectroMagnetic Pulse (EMP) referring to these different shots are shown in figures 4.6 and 4.7. As one can see, the signals are bipolar and the maximum signal amplitude registered in both shots is about 4 Volt (peak to peak) and the time duration is about 300 ns. In particular, a fast oscillation starts when the plasma is created and it is dampened in about 100 ns. After about 100 ns a slower oscillation starts characterized by a maximum amplitude of about 1 Volt (peak to peak), which rapidly falls to zero.
Figure 4.6: The EMP signal registered by the oscilloscope is shown for a shot when the energy of the laser pulse on the target chamber was 611,092 J.

Figure 4.7: The EMP signal registered by the oscilloscope is shown for a shot when the energy of the laser pulse on the target chamber was 599,518 J.
A study of the Fourier Transforms of the signals has been performed in order to characterize the signals in terms of frequencies and associate them to the EMP propagation.

### 4.4.1 Fast Fourier Transform

The FC signals registered by the scope show the time evolution of EMP noise signal. The time sampling of the scope, which represents the time difference between two consecutive counts, was set to 0.1 ns. The signal that must be analyzed is hence a discrete signal and for this reason some considerations have to be done to perform the Fourier Transform. In general the *Fourier Transform* is defined for *continuous* functions which in physics can describe some physical characteristics.

A physical process can be described in the time domain by a quantity as a function of the *time* \( h(t) \), which expresses the time evolution of the process, or in the frequency domain by another quantity \( H(f) \) depending on the *frequency* \( f \). The function \( h(t) \) and \( H(f) \) can be thought as two different *representations* of the same function. The *Fourier Transform* is the mathematical method which allows to go back and forth between these two representations [63]

\[
H(f) = \int_{-\infty}^{+\infty} h(t) e^{2\pi i f t} dt \quad h(t) = \int_{-\infty}^{+\infty} H(f) e^{-2\pi i f t} df \quad (4.1)
\]

The first one is called *Fourier Transform* and the second one is the *inverse Fourier Transform*. The time \( t \) is expressed in seconds (\( s \)) and the frequency \( f \) in *Hertz*. In general the results of the Fourier transform of a time depending real function is a complex function \( (H(f)) \) composed by a real and an imaginary part. An important quantity that can be defined is the *Total Power* which is the same
in both domains:

\[
\text{Power} = \int_{-\infty}^{+\infty} |h(t)|^2 dt = \int_{-\infty}^{+\infty} |H(f)|^2 df
\]  

(4.2)

In the case of a discrete function, as a physical signal, it is not possible to talk about \textit{function} but it is more correct to refer to a sequence of sampled values characterized by a time difference equal to \(\Delta t=0.1 \text{ ns}\) and a critical frequency given by: \(f_c = \frac{1}{2\Delta t}\). If \(N\) is the number of the sampled values \(k\) and \(n\) are respectively the index to distinguish consecutive points in time and frequency domain, the expression 4.1 for discrete functions can be approximated by 4.4 [63]:

\[
h_k = h(t_k) \quad t_k = k\Delta t, \quad k = 0, ..., N - 1
\]  

(4.3)

\[
H(f_n) \sim \sum_{k=0}^{N-1} h_k e^{2\pi i f_n t_k} \Delta t = \Delta t \sum_{k=0}^{N-1} h_k e^{2\pi i kn/N}
\]  

(4.4)

\(H(f_n)\) is the frequency distribution obtained by the Fourier transform of the input time distribution. The disadvantage of the calculation expressed in the formula 4.4 is the extremely long time of computation needed to the great number of processes that have to be effectuated (of the order of \(N^2\)).

On the other hands the discrete Fourier transform can be computed in \(N\log_2 N\) operations with an algorithm called \textit{Fast Fourier Transform} (FFT) [63]. Indeed, by using of this algorithm the time needed to process \(N\) data is drastically decreased. The FFT algorithm became known only in the 1960s from the work of J.W. Cooley and J.W. Tukey and reformulated in 1945 by Danielson and Lanczos. The algorithm is build on the fact that a Fourier Transform of length \(N\) can be rewritten as the sum of two discrete Fourier Transforms, each of length \(N/2\). The extended demonstration is provided in \textit{Numerical recip in C++, The Art of scientific computing}, W. Press, S. Teukolsky, W. Vetterling, B. Flennery. Using this algorithm, the Fourier Transform of a physical signal can be easily calculate.
In particular, the Fourier Transform analysis performed in this thesis in order to study the frequency components of the noise signal, has been curried on using the software MATLAB. The FFT algorithm gives a complex number with a real and an imaginary part. It is possible, therefore, to obtain the distribution of the real part or the imaginary part of the Fourier Transform as function of the frequency. A quantity that can be also defined is the Power Spectral Density that is the modulus-squared of the discrete Fourier Transform normalized with respect to the total number of samples. The power corresponds to the sum of the modulus-squared of the Fourier coefficients. Figures 1.8 and 1.9 represent the power spectrum obtained using the Fast Fourier Transform as discussed above. The code used to perform the Fourier Transform analysis is reported in the appendix A.

4.4.2 Experimental Results

The figures 4.8 and 4.9 show the Fourier Transforms of the two signals corresponding to the figures 4.6 and 4.7. A smoothing of the signal has been performed by using the mooving average function. In order to isolate the frequencies due to the initial fast oscillations generated by the plasma creation and producing an high-frequency component in the frequency distribution.
In order to discriminate the common frequencies in the two independent measurements in fig. 4.10 a comparison of the Fourier transform obtained in the two cases is shown. In figure 4.10 the overlapping of the Fourier transforms in the two cases is reported in order to highlight the common frequencies in two independent
measurements.

Figure 4.10: The comparison of the fast Fourier transform reported in figure 4.8 (in black) and 4.9 (in blue) is shown.

The laser pulse propagating inside the spherical interaction chamber can be considered as an electromagnetic wave inside a resonant cavity. Therefore as suggested in the study carried out in [64] a comparison between the frequencies extracted from the signals (figure 4.10) and the characteristic resonant frequencies of an electromagnetic wave in a spherical cavity has been performed.

From the theoretical point of view, for a spherical cavity enclosed by a conducting surface at \( r=R_0 \) (as for instance is the spherical PALS interaction chamber with \( R_0=0.5 \text{ m} \)), the \textit{Borgnis} function \( U(r) \) (connected to the electric field of the electromagnetic wave) or \( V(r) \) (connected to the magnetic field) satisfies the Helmholtz equation which describes the time evolution of the wave function only if \( U \) and \( V \) are expressed as [65]:
The Helmholtz equation can be written as:

\[ \nabla^2 F(r) + k^2 F(r) = 0 \]  \hspace{1cm} (4.6)

where \( k \) is the wavenumber. The oscillation modes for the electromagnetic waves can be separated in TE (Transverse Electric mode) depending on the Electric field and TM (Transverse magnetic mode) depending on the Magnetic field.

Regarding the TE modes the boundary condition through has to be satisfied to determine the correspondent \( k \) value is [66]:

\[ r F \bigg|_{r=R_0} = 0, \quad F \bigg|_{r=R_0} = 0 \]  \hspace{1cm} (4.7)

And for TM modes:

\[ \frac{\partial (rF)}{\partial r} \bigg|_{r=R_0} = \left[ F + r \frac{\partial F}{\partial r} \right] \bigg|_{r=R_0} = 0 \]  \hspace{1cm} (4.8)

The TE and TM modes depend on three quantic numbers \( n,m,p \) representing respectively \( r, \alpha \) and \( \theta \) as shown in figure 4.11. The three quantities determine the position of the point with respect to the center of the sphere.
The calculated values of the wave number for a spherical cavity with \( R_0 = 0.5 \) m are provided in tables 4.2 and 4.3 as a function of \( n,m,p \) [64] :

\[
\begin{array}{ccccccc}
TM_{nmp} & TM_{101} & TM_{201} & TM_{301} & TM_{401} & TM_{102} \\
\hline
k \: [m^{-1}] & 5.4874 & 7.7404 & 9.9468 & 12.12 & 12.233 \\
\hline
TM_{nmp} & TM_{501} & TM_{302} & TM_{601} & TM_{302} & TM_{701} \\
\hline
k \: [m^{-1}] & 14.279 & 14.886 & 16.42 & 17.44 & 18.5508 \\
\end{array}
\]

Table 4.2: TM oscillation modes.
The wave number is connected to the frequency by the dispersion relation:

\[ k = \frac{\omega}{c} = \frac{2\pi \nu}{c} \quad \nu = \frac{kc}{2\pi} \]  

(4.9)

Using this relation, giving the values in tables 4.2 and 4.3 the correspondent frequencies have been calculated and compared with the measured ones performing the Fourier Transform of the noise signal. In particular, five frequencies have been identified as resonant frequencies themselves are listed in table 4.4 and are shown in the figure 4.12.

<table>
<thead>
<tr>
<th>Exp. frequencies [MHz]</th>
<th>Theor. frequencies [MHz]</th>
<th>Modes</th>
<th>Variance [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>263</td>
<td>262</td>
<td>TM\textsubscript{101}</td>
<td>0.38</td>
</tr>
<tr>
<td>366</td>
<td>369</td>
<td>TM\textsubscript{202}</td>
<td>0.81</td>
</tr>
<tr>
<td>541</td>
<td>550</td>
<td>TM\textsubscript{401}</td>
<td>1.61</td>
</tr>
<tr>
<td>582</td>
<td>579</td>
<td>TM\textsubscript{401}</td>
<td>0.51</td>
</tr>
<tr>
<td>662</td>
<td>667</td>
<td>TE\textsubscript{301}</td>
<td>0.74</td>
</tr>
</tbody>
</table>

Table 4.4: Experimental and theoretical frequencies with the correspondent TE and TM modes and the variance are reported.
4.4.3 Signal amplitude as function of the bias applied voltage to the Faraday Cup electrodes

In order to perform a complete characterization of the FC noise signal the dependence of the noise signal amplitude from the applied voltage on the electrodes, has been investigated.

The voltage was applied to one of the electrodes using an electronic modular power supply (model: Quad BIAS supply ORTEC 710) with an accuracy of 1
Volt. The FC voltage signal was registered by the oscilloscope (2GHz) with an accuracy of $10^{-6}$ Volt. The values of the noise signal amplitudes along with the corresponding applied voltages are listed in table 4.5.

<table>
<thead>
<tr>
<th>Noise Signal Amplitude [Volt]</th>
<th>Voltage [Volt]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$0.616512 \pm 10^{-6}$</td>
<td>$50 \pm 1$</td>
</tr>
<tr>
<td>$1.233345 \pm 10^{-6}$</td>
<td>$100 \pm 1$</td>
</tr>
<tr>
<td>$1.606628 \pm 10^{-6}$</td>
<td>$200 \pm 1$</td>
</tr>
</tbody>
</table>

Table 4.5: Noise signal amplitudes and the voltage applied to the FC electrode are shown.

An exponential fit, having the functional expression $y = e^{p_0 + p_1 x}$, was used to analyze the data, using the Root analysis tool[67], and taking as independent variable ($x$) the signal amplitude (since the absolute error on the amplitude is negligible with respect to the error on the applied voltage) and as dependent variable ($y$) the BIAS [68]. Figure 4.13 shows the measured data along with the fit. The absolute error in the BIAS is within the data symbols.
In the table 4.6 the values of the parameters $p_0$ and $p_1$ are reported together with the mistakes calculated through the software Root:

\[
\begin{array}{cc}
p_0 \pm \Delta p_0 & p_1 \pm \Delta p_1 \\
2.74 \pm 0.41 & 1.58 \pm 0.27
\end{array}
\]

Table 4.6: Fit parameters

As one can see from the figure 4.13 the data are quite well reproduced by the exponential fit. The data analysis is still ongoing, and further characterization increasing the applied voltage to the electrode up to the maximum of about 600 V in order to obtain a dependence in the whole available voltage range.
Conclusions and future prospectives

The main purpose of this thesis is the design, Monte Carlo simulation and characterization of an innovative Faraday Cup, developed at LNS-INFN and optimized to perform absolute dosimetry measurements for high pulsed ion beams.

The Monte Carlo simulation, carried out by mean of the Geant4 toolkit, allowed to demonstrate the extremely accuracy in charge collection and hence in the dose calculation of the device either, in the case of mono-energetic conventional proton beams as well as of the laser-driven ones.

In particular, regarding the conventional proton beams, we obtained the following results:

- for 62 MeV proton beams a charge accuracy of 0.1% has been calculated and a consequent error in the dose of about 1% has been found
- for 10 MeV monoenergetic proton beam, a charge accuracy of 0.4% and a consequent dose error of about 1% have been calculated

In both cases the obtained results from the simulations, have shown optimal performances in terms of the collected charge and overall dose errors. The Faraday Cup response has been also investigated with Geant4 and a typical laser driven proton beam select in energy with a magnetic device developed at LNS. In particular, the setup of the experimental run performed in December 2013 at the Centre for Plasma Physics, Belfast (UK), has been simulated with all the characteristics, in terms of energy and angular spread, of the emitted protons from the target. Two different selected energy have been taken into account for the delivered dose calculation inside the Faraday Cup: \( \sim 4 \) MeV and \( \sim 7 \) MeV. In both case the charge accuracy is very high, respectively 0.002% and 0.005% with an
error in dose of about 0.1%. This good result is due to the fact that the Faraday Cup was placed directly after the exit window of the energy selector system, without kapton window in order to reproduce the real experimental conditions. Indeed, the most of the secondary electrons that cause the error in the charge recoil (like in the conventional proton beams) are created in the kapton window.

Experimentally the characterization of the electromagnetic pulse produced inside the Faraday Cup at the PALS laser center has been performed. Two independent shots have been analyzed and some common resonant frequencies have been found. These frequencies have been also similar to the ones resonant in a spherical cavity. In particular, performing the fast Fourier transforms of the signals, five frequencies can be identified like resonant frequencies and they are in the order of MHz. The highest frequencies (GHz) are connected to the fast and initial oscillations due to the impact of the laser with the target. An exponential relation between the noise amplitude and the bias applied to the Faraday Cup electrode has been found, but this result has to be considered very preliminary. A study varying the BIAS applied to the electrodes is required in order to have a total knowledge of noise behavior.

Regarding the future plans, the Faraday Cup will be finally tested with conventional mono-energetic proton and ion beams at Laboratori Nazionali del Sud in order to study the signal of collected charge, and measuring the released dose. It will be also tested using proton and ion beams accelerated from laser-target interaction in order to study the signal and optimize the measurements. It will be used coupled also with other dosimeter like the CR39 and the Radiochromic films, in order to retrieve all the necessary information for the dose calculation, like the beam area and the energy spectrum. The complete characterization of the FC
prototype, will allow to obtain a greater control of the dosimetry of laser-driven ion beams that is very difficult due to the high dose-rate of ion beams optically accelerated.
Appendix A

clear all;

a=load ('/Users/milluzzo/Desktop/PALS_SHOT/#46563/C2Trace00000.dat');
b=load ('/Users/milluzzo/Desktop/PALS_SHOT/#46564/C2Trace00000.dat');

%%%%%% Data from the file %%%%%%

t=a(:,1);
i=a(:,2);
T=b(:,1);
I=b(:,2);

%%%   Smoothing--> Mooving Avarage

y=smooth(i,10);
h=smooth(I,10);
figure;
plot(t,y);

%%%%%  -----------Fast Fourier Transform----------%%%%%

m = length(y);
k=length(h);
n = pow2(nextpow2(m))
p=pow2(nextpow2(k))

%%%% Calcolo della FFT %%%

Y = fft(y,n);
H=fft(h,p);

%%%%% Sampling frequency=10^{-10} Hz %%%

f = (0:n-1)*(10000000000000/n);
F= (0:p-1)*(10000000000000/p);
power = Y.*conj(Y)/n;
Power= H.*conj(H)/p;
plot(f,power,F,Power,'r');

%%%%%--------> Plot <-------- %%%%%

figure
subplot(2,2,1);
plot(t,i);
subplot(2,2,2);
plot(T,I,'g');
subplot(2,2,3);
plot(f,power);

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subplot(2,2,4);
plot(F,Power,'r');

Appendix B

G4double phi = 90*deg;
G4RotationMatrix rm;
rm.rotateY(phi);

virtualMag= new G4Box("virtualMag", 6.*cm, 6.*cm, 30.*cm );

logicVirtualMag= new G4LogicalVolume (virtualMag,
   internalChamberMaterialA,
   "LVirtualMag",
   0,0,0);

physicVirtualMag = new G4PVPlacement(
G4Transform3D(rm,G4ThreeVector(virtualMagPosX,0,-42*mm)),
   "PVirtualMag",
   logicVirtualMag,
   physicTreatmentRoom,
   true, 0);

logicVirtualMag -> SetVisAttributes(blue);
/// BeveledCylinder ///

G4RotationMatrix *Rot= new G4RotationMatrix;
Rot->rotateX(14*deg);
G4ThreeVector trans(0.,22.5*mm,-15*mm);
Cylinder= new G4Tubs("cylinder",20*mm,22.5*mm,90*mm,0.,2*pi);
Box= new G4Box("Box",22.5*mm,22.5*mm,90*mm);

G4SubtractionSolid* BeveledCylinder=new G4SubtractionSolid
("Cylinder-Box",
   Cylinder,
   Box,
   Rot,
   trans);

logicBeveledCylinder= new G4LogicalVolume
   (BeveledCylinder,
    GuardRingMaterial,
    "LBeveledCylinder",
    0,0,0);

physicBeveledCylinder = new G4PVPlacement
   (0,G4ThreeVector(0,0,GuardRingPosX),
    "physicBeveledCylinder",
    logicBeveledCylinder,
logicBeveledCylinder->SetVisAttributes(green);

///// KaptonEntranceWindow /////

KaptonEntranceWindow = new G4Tubs
   ("KaptonEntranceWindow",
    0,
    OuterRadiusFC,
    KaptonEntranceWindowThickness/2,
    0*deg,360*deg);

logicKaptonEntranceWindow = new G4LogicalVolume
   (KaptonEntranceWindow,
    KaptonEntranceWindowMaterial,
    "LKaptonEntranceWindow",
    0,0,0);

physicKaptonEntranceWindow = new G4PVPlacement
   (0,
    G4ThreeVector
    (0,0,KaptonEntranceWindowPosX),
    "PhysicEntranceWindow",
    136)
logicKaptonEntranceWindow, physicVirtualMag,true,0);
logicKaptonEntranceWindow -> SetVisAttributes(gray);

/////// MassRing ///////

MassRing=new G4Tubs("MassRing",
    InnerRadiusFC, OuterRadiusFC,
    MassRingThickness/2, 0*deg,360*deg);

logicMassRing=new G4LogicalVolume(MassRing,
    MassRingMaterial,
    "logicMassRing",
    0,0,0);

logicMassRing -> SetVisAttributes(green);

physicMassRing=new G4PVPlacement(0,
    G4ThreeVector(0,0,MassRingPosX),
    "PhysicMassRing",
    logicMassRing, physicVirtualMag, true,0);

logicMassRing -> SetVisAttributes(green);
VirtualWindow=new G4Tubs("VirtualWindow",
    0,
    OuterRadiusFC,
    VirtualWindowThickness/2,
    0*deg,360*deg);

logicVirtualWindow=new G4LogicalVolume
    (VirtualWindow,
     internalChamberMaterialA,
     "logicVirtualWindow",
     0,0,0);

physicVirtualWindow=new G4PVPlacement
    (0, G4ThreeVector(0,0,VirtualWindowPosX),
     "PhysicVirtualWindow",
     logicVirtualWindow,
     physicVirtualMag,
     true,0);

logicVirtualWindow->SetVisAttributes (G4VisAttributes::Invisible);

GuardRing=new G4Tubs ("GuardRing",

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InnerRadiusFC,
OuterRadiusFC,
GuardRingThickness/2,
0*deg,360*deg);

logicGuardRing=new G4LogicalVolume(GuardRing,
   GuardRingMaterial,
   "logicGuardRing",
   0,0,0);

physicGuardRing=new G4PVPlacement
   (0,G4ThreeVector(0,0,GuardRingPosX),
   "PhysicGuardRing",
   logicGuardRing,
   physicVirtualMag,
   true,0);

logicGuardRing -> SetVisAttributes(red);

/////VirtualMiddle ////

VirtualMiddle=new G4Tubs ("VirtualMiddle",
   0,
   OuterRadiusFC,
   VirtualMiddleThickness/2,
logicVirtualMiddle=new G4LogicalVolume
(VirtualMiddle,
    internalChamberMaterialA,
    "logicVirtualMiddle",
    0,0,0);

physicVirtualMiddle=new G4PVPlacement
(0,G4ThreeVector(0,0,VirtualMiddlePosX),
    "PhysicVirtualMiddle",
    logicVirtualMiddle,
    physicVirtualMag,
    true,0);

logicVirtualMiddle->SetVisAttributes (G4VisAttributes::Invisible);

///// FaradayCupBottom /////

FaradayCupBottom=new G4Tubs ("FaradayCupBottom",
    InnerRadiusFC,
    OuterRadiusFC,
    FaradayCupBottomThickness/2,
    0*deg,360*deg);
logicFaradayCupBottom = new G4LogicalVolume
    (FaradayCupBottom,
     FaradayCupBottomMaterial,
     "logicFaradayCupBottom",
     0, 0, 0);

physicFaradayCupBottom = new G4PVPlacement
    (0, G4ThreeVector(0, 0, FaradayCupBottomPosX),
     "PhysicFaradayCupBottom",
     logicFaradayCupBottom,
     physicVirtualMag,
     true, 0);

logicFaradayCupBottom -> SetVisAttributes(yellow);

///// Virtual Bottom /////

VirtualBottom = new G4Tubs ("VirtualBottom",
    0,
    OuterRadiusFC,
    VirtualBottomThickness/2,
    0*deg, 360*deg);

logicVirtualBottom = new G4LogicalVolume(VirtualBottom,
    internalChamberMaterial,
"logicVirtualBottom",
0,0,0);}

physicVirtualBottom=new G4PVPlacement
(0, G4ThreeVector
(0,0,VirtualBottomPosX),
"PhysicVirtualBottom",
logicVirtualBottom,
physicVirtualMag,
true,0);

logicVirtualBottom->SetVisAttributes (G4VisAttributes::Invisible);

/// Cup /////

Cup=new G4Tubs ("Cup",
0,
OuterRadiusFC,
CupThickness/2,
0*deg,360*deg);

logicCup=new G4LogicalVolume(Cup,
CupMaterial,
"logicCup",
0,0,0);
physicCup=new G4PVPlacement
                    (0,G4ThreeVector(0,0,CupPosX),
                     "PhysicCup", logicCup,
                     physicVirtualMag,
                     true,0);
logicCup -> SetVisAttributes(darkGreen);

 ///// Virtual OverBottom ////

VirtualOverBottom=new G4Tubs ("VirtualOverBottom",
                               0,
                               OuterRadiusFC,
                               VirtualOverBottomThickness/2,
                               0*deg,360*deg);

logicVirtualOverBottom=new G4LogicalVolume
                        (VirtualOverBottom,
                         internalChamberMaterialA,
                         "logicVirtualOverBottom",
                         0,0,0);

physicVirtualOverBottom=new G4PVPlacement
                        (0,G4ThreeVector
(0,0,VirtualOverBottomPosX),
"PhysicVirtualOverBottom",1
LogicVirtualOverBottom
physicVirtualMag,
    true,0);
logicVirtualOverBottom->SetVisAttributes (G4VisAttributes::Invisible);

///// Virtual Lateral /////

VirtualLateral=new G4Tubs ("VirtualLateral",
    OuterRadiusFC,
    OuterRadiusFC+1*um,
    VirtualLateralLength/2,
    0*deg,360*deg);

logicVirtualLateral=new G4LogicalVolume(VirtualLateral,
    internalChamberMaterialA,
    "logicVirtualLateral",
    0,0,0);

physicVirtualLateral=new G4PVPlacement
    (0,
     G4ThreeVector(0,0,VirtualLateralPosX),
"VirtualLateral",
logicVirtualLateral,
physicVirtualMag,

true, 0);
logicVirtualLateral->SetVisAttributes (G4VisAttributes::Invisible);
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Dedica

..Dedico questa tesi a chi mi ha sempre sostenuto, la mia famiglia, fin da quando ho deciso di scegliere la strada difficile della fisica e fin da quando da piccola amavo fare esercizi di matematica e non riuscivo a dormire se non li avevo risolti....ed è questa caparbietà che mi ha permesso di raggiungere questo traguardo...

.....la dedico a chi, nonostante ci conoscessimo da poco, mi ha dato fiducia in questo lungo percorso e mi ha aiutata a crescere sia professionalmente che umanamente dandomi l'opportunità di superare i miei stessi limiti...

...la dedico a chi invece, mi è stato vicino ogni giorno ed è stato capace di restare al mio fianco anche in momenti non facili...capendo il mio "esaurimento" e supportandomi senza mai chiedere nulla...

.....e la dedico a te...zio "Pippo" che non ci sei più... ma che mi hai insegnato che camminare non è una fatica...ma un'occasione per conoscersi, per parlare e per crescere.... continuerò a camminare facendo tesoro di questo tuo grande insegnamento...