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Advanced in Performance of PIG Ion Source for PETtrace Medical Cyclotron

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ملخص

على مدى السنوات القليلة الماضية، كان هناك تقدم ملحوظ في التقنيات والأساليب المستخدمة لعلاج وتشخيص السرطان. يشمل ذلك السيكلوترون الطبي، الذي يعتبر مهمًا في توليد النظائر المشعة. تهدف هذه الأطروحة إلى دراسة كيفية تأثير العوامل المختلفة مثل المجالات الكهربائية والمغناطيسية وضغط الغاز على أداء مصدر الأيونات penning (PIG) المستخدم في السيكلوترون الطبي PET . ومن خلال المحاكاة باستخدام CST Studio suite، تضع الدراسة نفسها في اتجاه تحديد الظروف الأكثر كفاءة لتشغيل مصدر الأيونات.

Abstract

Over the last few years, there has been remarkable progress in the techniques and methods used to treat and diagnose cancer. These include the medical cyclotron, which is important in generating radioactive isotopes. This thesis aims at examining how different parameters such as electric and magnetic fields, and gas pressure affect the performance of the Penning Ionization Gauge (PIG) ion source used in PET medical cyclotron. Using CST Studio Suite for simulations, this study aims to identify the optimal conditions under which the ion source operates most efficiently.
keywords:

Résumé

Au cours des dernières années, des progrès remarquables ont été réalisés dans les techniques et méthodes utilisées pour traiter et diagnostiquer le cancer. Ceux-ci incluent le cyclotron médical, qui est important pour générer des isotopes radioactifs. Cette thèse vise à examiner comment différents paramètres tels que les champs électriques et magnétiques, et la pression du gaz affectent la performance de la source d'ions à jauge d'ionisation Penning (PIG) utilisée dans le cyclotron médical PET. En utilisant CST Studio Suite pour les simulations, cette étude vise à identifier les conditions optimales dans lesquelles la source d'ions fonctionne le plus efficacement.

Contents

General Introduction

The different types of cancer diseases in the world have risen to first place in the ranking of the main causes of death in recent years. Algeria is no exception, with 64,713 new cases reported in 2022 [7]. This is why in hospitals and the pharmaceutical industry, compact medical cyclotron technology has made a significant step forward in nuclear medicine for the production of PET radioisotopes needed for medical imaging and treatments [5].
Compact medical cyclotrons produce accelerated ion beams. The ion source, a critical component of these cyclotrons, produces particles and is characterized by several key elements [20] an ionization chamber (where ionization occurs), a material (gas, heated liquid, or solid for obtaining gas), an ionization energy source (to power the source), and an extraction system (to release the produced ion beam into the central region for acceleration). Various types of ion sources are in use, with the Penning Ionization Gauge (PIG) being widely employed in PETtrace cyclotrons. The PIG ion source uses a cold cathode and an internal source with DC plasma discharge. The setup includes a cylindrical anode, with cathodes biased at each end of the cylinder. Due to the presence of a magnetic field (approximately 0.1T), electrons emitted by the cathode face difficulty reaching the anode, with a significant portion avoiding contact with the anticathode.
In this context, this thesis presents a numerical study using the CST Studio Suite to examine the effects of electric and magnetic fields, as well as gas pressure, on the performance of the ion source.
This work is divided into two parts:
The first part contains two chapters:

1. Chapter one explores the physical functioning of the different components constituting the cyclotron, the steps of isotope production by the cyclotron, and radiation safety.

2. Chapter two focuses on the PIG ion source, examining each component in detail to master its functionality.

The Second Part will be on one and only chapter about simulation of PIG ion source using the CST Studio Suite to examine the effects of electric and magnetic fields, as well as gas pressure, on the performance of the ion source.

Then well discuss the results and finally well achieved this work by a conclusion.

Chapter 1

Cyclotron for Medical Application

1.1 Introduction

The cyclotron is a circular charged particles accelerator. It works by using two perpendicular fields: an electric field and a magnetic field. Charged particles injected into the central region are accelerated by an electric field and guided in a spiral path by a uniform magnetic field. This allows the cyclotron to significantly increase the energy of the particles, reaching millions of electron volts (MeV). Advances in cyclotrons technology have led to the creation of compact medical cyclotrons [21], which are smaller and more efficient. These cyclotrons are essential not only in nuclear medicine for producing radioisotopes used in cancer treatment, medical imaging, and targeted therapies but also in nuclear research.

1.2 Nuclear medicine

Nuclear medicine is a medical specialty that uses artificial radioactive substances called radioisotopes to diagnose and treat various diseases of the body [17]. Radioisotopes are detected in combination of image devices and computers when inhaled or injected in the body, radioisotopes as tracers emit gamma rays which will be detected by PET or SPECT camera and will give the precision of these rays origin. The area where radioisotopes are well absorbed is the hot spot and where less collected is the cold spot.

1.3 Radio-isotopes Production

Medical isotopes are produced by accelerators and reactors. Accelerators are better used than reactors because of less radioactive waste and harmful debris [22]. Among accelerators cyclotrons, which are circular particle accelerators capable of generat-ing high-energy beams of charged particles, such as protons or deuterons. These particle beams are used to bombard stable target materials, resulting in nuclear reactions that pro-duce radio-nuclides, also known as radioisotopes. One of the primary applications of these radioisotopes is the production of radiopharma-ceuticals commonly utilized in various Medical imaging techniques, such as PET and SPECT scan, to visualize organs, tissues, and detect diseases within the human body. In Table 1.1 [16], we see the most common radioisotopes used in PET Imaging.

This process is known as nuclear transmutation, a phenomenon first introduced by Lord Rutherford [12] when he bombarded nitrogen gas with alpha particles from radium, resulting in the formation of oxygen, as illustrated by the following nuclear reaction:

$$^{14}\text{N} + \alpha \rightarrow ^{17}\text{O} + p \tag{1.1}$$

Table 1.1: Common PET radioisotopes

Isotope	Half-Life (min)	Nuclear Reaction	Type of Emission	Energy (MeV)
Fluorine-18	110	^{18}O(p, n)^{18}F	β^+	0.64
Carbon-11	20	^{14}N(p, α)^{11}C	β^+	0.97
Nitrogen-13	10	^{16}O(p, α)^{13}N	β^+	1.20
Oxygen-15	2	^{14}N(d, n)^{15}O	β^+	1.74

1.4 Principle of cyclotron operation

Cyclotrons have a unique way of working and can be divided into several subsystems [18]:

- RF System
- Magnet system
- Ion sources
- Vacuum system
- Extractions system

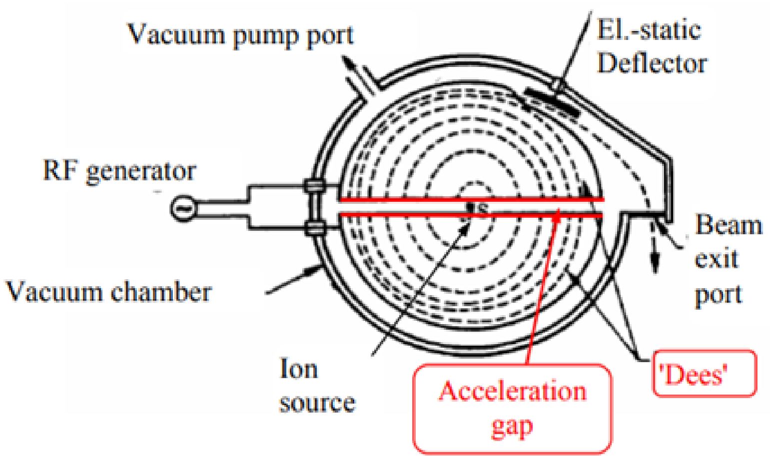

Figure 1.1: cross-sectional Schematic Diagram view of a cyclotron

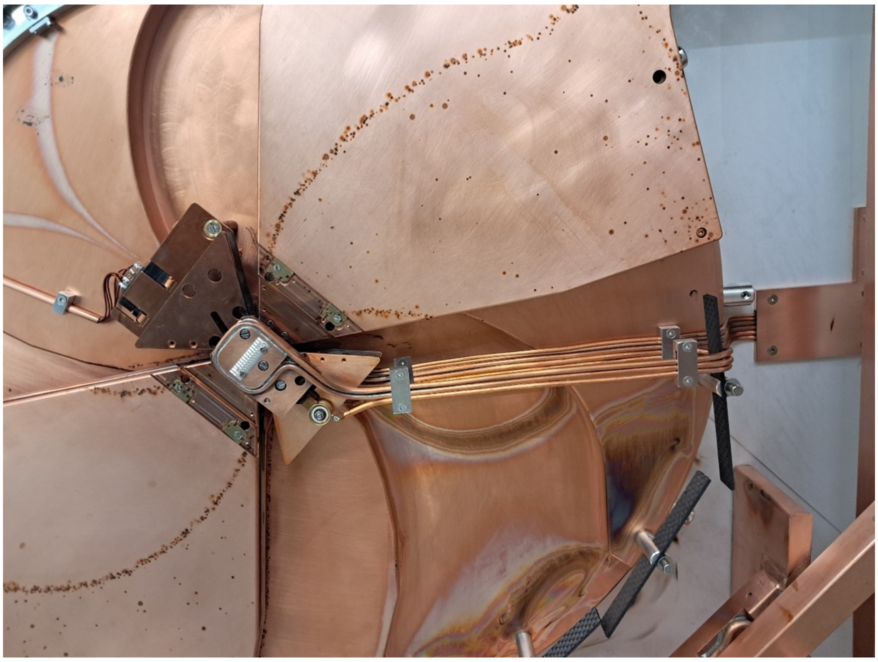

Figure 1.2: Interior View of Cyclotron Components [Biopharm].

1.4.1 RF System

A radiofrequency (RF) system is a crucial component in particle accelerators. It utilizes hollow electrodes called Dees. These Dees are designed to generate an alternating voltage within the radio frequency range. The result of this applied voltage is the cre-ation of an oscillating electric field between the Dees. This oscillating electric field acts like a powerful engine, accelerating charged particles as they travel through the gaps between the Dees.

The following equations describe the fundamental principles governing the RF system in a cyclotron:

Cyclotron Frequency (Resonance Frequency)

The cyclotron frequency is given by:

$$f_c = \frac{qB}{2\pi m} \tag{1.2}$$

where:

- f_c is the cyclotron frequency,
- q is the charge of the particle,
- B is the magnetic field strength,
- m is the mass of the particle.

Kinetic Energy of the Particle

The kinetic energy of the particle is given by:

$$E_k = \frac{1}{2}mv^2 = \frac{q^2B^2r^2}{2m} \tag{1.3}$$

where:

- E_k is the kinetic energy,
- v is the velocity of the particle,
- r is the radius of the particle's path.

Energy Gain per Acceleration Gap

The energy gain per acceleration gap is given by:

$$\Delta E = qV \sin(t) \tag{1.4}$$

where:

- ΔE is the energy gain,
- V is the peak voltage of the RF field,
- t is the time at which the particle crosses the gap.

1.4.2 Magnet System

The magnetic field is made of coils (uniform) and permanent magnet (strong non uniform). The latter made of Samarium-Cobalt (SmCo) and shaped of hill (strong field) and valley (weak field) as we see in fig1.3 The permanent magnetic field has a small size easy to use and it is more used than the coils [13]. The magnetic field is designed with hills (regions of strong field) and valleys (regions of weak field), covering the area of the Dees (hollow electrodes). When a charged particle enters one of the Dees, the Lorentz force is perpendicular to the particle?s velocity and the magnetic field, forces the particle to follow a circular trajectory. The Lorentz force and the centripetal force keeps the particles in the circular trajectory.

The following equations describe the fundamental principles governing the magnet system in a cyclotron:

Lorentz Force

The force exerted on a charged particle moving in a magnetic field is given by the Lorentz force:

$$\mathbf{F} = q(\mathbf{vB}) \tag{1.5}$$

where:

- $\mathbf{F}$ is the Lorentz force,
- q is the charge of the particle,

- $\mathbf{v}$ is the velocity of the particle,
- $\mathbf{B}$ is the magnetic field.

Centripetal Force

For a particle to move in a circular path, the centripetal force must be provided by the Lorentz force:

$$\frac{mv^2}{r} = qvB \tag{1.6}$$

where:

- m is the mass of the particle,
- v is the velocity of the particle,
- r is the radius of the particle's path,
- q is the charge of the particle,
- B is the magnetic field.

Radius of the Particle's Path

Solving for the radius of the particle's path, we get:

$$r = \frac{mv}{qB} \tag{1.7}$$

where:

- r is the radius of the particle's path,
- m is the mass of the particle,
- v is the velocity of the particle,
- q is the charge of the particle,
- B is the magnetic field.

Magnetic Rigidity

The magnetic rigidity, which is a measure of the particle's resistance to bending in a magnetic field, is given by:

$$B\rho = \frac{p}{q} \tag{1.8}$$

where:

- $B\rho$ is the magnetic rigidity,
- p is the momentum of the particle,
- q is the charge of the particle.

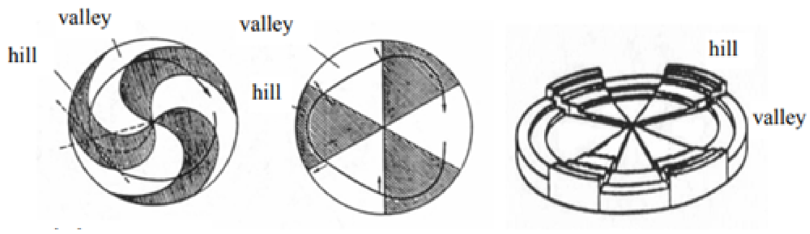

Figure 1.3: Magnetic Field Configuration in Cyclotrons: Hill and Valley Structures.

1.4.3 Ion Source

The ion source is a main component of a cyclotron responsible for particles (H, D) produc-ing. It contains a gas like hydrogen which is bombarded by emitted (by cathode) electrons then it undergoes a discharge arc leading a plasma. Plasma is the origin of the particles birth or production. There are many types of ions sources such as [19]:

- Electron bombardment
- Direct current (DC) / pulsed plasma discharge
- Radio-frequency (RF) discharge
- Microwave and electron cyclotron resonance (ECR)
- Laser-driven
- Charge exchange sources, etc.

The most used ion source (we can use double Ion sources) in cyclotrons is a cold cathode type the Penning Ionization Gauge (PIG) source using dc (typical operation: DC is 5 to 10 mA and voltage 4-5V) plasma discharge .

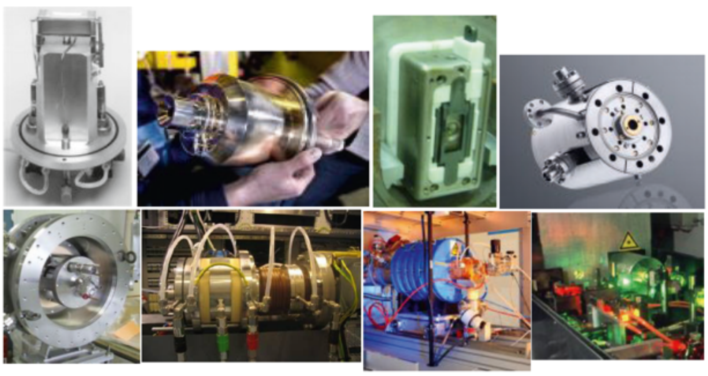

Figure 1.4: different types of ions sources .

As we see on The PIG ion has an aperture or an orifice. The orifice size, anode design, permanent magnet location are main parameters impacting the extracted ion beam (10-100 mA) which impact the efficiency of the source [17].

Utilizing a twin Penning ion source in cyclotrons helps optimize ion production, enhance reliability, and provide flexibility in ion species and beam characteristics, making them valuable tools for various scientific and industrial applications.

In the ion source, Pressure must be maintained between 10^{-3} mbar till 1mbar. If the pressure exceed (more than 1mbar) there will be a loss of energy and the ionization of the gas will not be possible. When the pressure is inferior to 10^{-3} mbar , the collison between electrons and gas will not occur. The beam current at extraction from ion source is 50 µA to 1000µA/1 mA. We can utilize a twin Penning ion source in cyclotrons helps optimize ion production, enhance reliability, and provide flexibility in ion species and beam characteristics, making them valuable tools for various scientific and industrial applications.

1.4.4 Vacuum system

The cyclotrons content a vacuum chamber covering pole magnets. This vacuum's pressure must be maintained into the interval from 10^{-5} mbar to 10^{-7} mbar. This high pressure and clean vacuum is an essential aspect for particles acceleration. To keep this high pressure, vacuum pumps like in the (turbo molecular, cryopump and diffusion) are used and must be controlled and surveyed from time to time [3]. These pumps require regular control and monitoring [19]. The turbo molecular pump is the most commonly used vacuum pump in cyclotron vacuum chambers. Proper vacuum conditions are essential for minimizing particle interactions with residual gas molecules, ensuring stable and efficient particle acceleration within the cyclotron The most used vacuum chamber pump is the turbo molecular chamber.

1.4.5 Extractions system

After being accelerated, particles are extracted from the cyclotron to collide with a target. The extraction of the particle beam is achieved using either deflectors for positive ions, which are commonly used for analysis purposes in nuclear physics, or a stripper foil for negative ions. Cyclotrons accelerating negative ions (H-) are widely used in the medical field for the production of the desired radio-isotope . PET trace cyclotrons typically have two or more carbon foils and can operate in either single mode (one target) or dual mode (two targets) for beam extraction.

1.4.6 Target

Cyclotron targets are specialized materials strategically placed in the path of the accelerated particle beam within the cyclotron. The high-energy particle beam interacts with the target material, initiating nuclear reactions that produce the desired radioisotopes for various applications in medicine and research. In the field of nuclear medicine, common cyclotron targets include enriched stable isotopes. For instance, an oxygen-18 (18O) target is used for the production of fluorine-18 (18F), a widely employed positron-emitting radioisotope for positron emission tomography (PET) imaging. Similarly, a nitrogen-14 (14N) target is utilized for the generation of carbon-11 (11C), another important radioisotope for PET applications.Appropriate target selection, design, and positioning are essential for enabling the successful production of radioisotopes through nuclear reactions induced by the accelerated particle beam within the cyclotron.

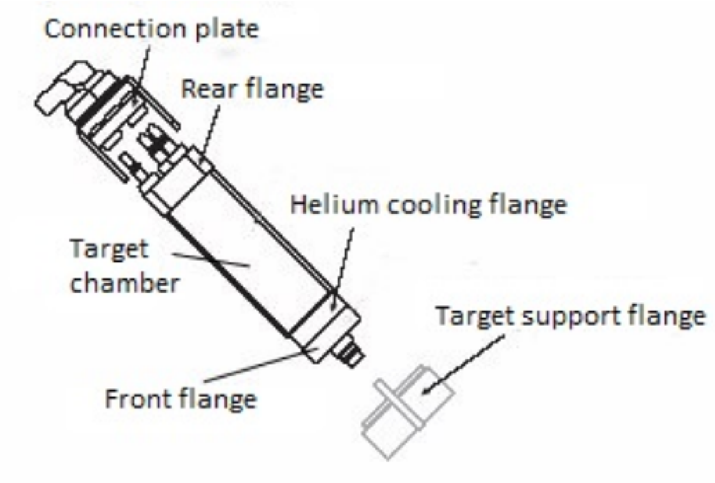

Figure 1.5: Structure of a generic target.

1.5 PETtrace Cyclotrons

There are several types of medical cyclotrons, such as the IBA Kubie, GE MiniTrace, or GE PETtrace 800. In this thesis, we focus on the GE PETtrace cyclotron.

The PETtrace cyclotron is an upright, commonly used model for producing radiopharmaceuticals, particularly in PET imaging. Here are some typical characteristics (as provided by GE manufacturer) of the PETtrace cyclotron:

- The typical proton energy for the PETtrace 800 cyclotron is around 16 to 18 MeV (mega-electron volts) and 8.4 MeV for deuterons [3]. This energy range is suitable for the production of a variety of radioisotopes used in PET imaging.
- The PETtrace cyclotron is capable of producing a range of radioisotopes, including fluorine-18 ($^{18}F^-$), carbon-11 (^{11}C), oxygen-15 (^{15}O), nitrogen-13 (^{13}N), zirconium-89 (^{89}Zr), gallium-68 (^{68}Ga), and technetium-99m (^{99m}Tc).
- The PETtrace cyclotron can typically achieve target currents in the range of tens to hundreds of microamperes (µA) depending on the specific radioisotope being produced and the target material used. The cyclotron uses solid targets made of materials such as enriched oxygen-18 water (^{18}O-H_2O) or nitrogen gas ($^{14}N_2$) for specific radioisotope production. The choice of target material depends on the desired radioisotope and production method.
- Modern PETtrace cyclotrons are equipped with advanced automation and control systems to manage the accelerator operation, target irradiation,

radioisotope production, and quality assurance processes efficiently and safely (self-shielding option).

Figure 1.6: PETtrace cyclotron with internal ion source

1.6 Conclusion

Cyclotrons are circular particle accelerators using both of the magnetic field and the electric field. The electric field produced by a radiofrequency coupled to Dees allows to accelerate particles. Particles are produced by an ion source. The ion, source is the producer of ion. It characteristics are necessary for a good function of cyclotron. When particles enter Dee where exists a magnetic field, their trajectory will be orbital. Whenever particles enter in electric gap they will be accelerated. The radius increases with velocity increases till a high energy (certain MEV) then after crossing the stripper foil (negative ions) or a deflector (for positive ions), particles will be extracted to collide with a target. Radioisotopes are produced after a nuclear reaction due to collision. Nevertheless, Radiation safety is needed to be re-spected by personal working in a cyclotron center.

Chapter 2

Ion Sources

2.1 Introduction

Ion sources are essential devices that generate beams of charged atoms (ions) from neutral gases or molecules. These devices play a crucial role in particle accelerators, such as cyclotrons, by providing the ion beams necessary for various applications. Ion sources work by ionizing a gas or vapor through processes like electron bombardment, creating a plasma from which ions are extracted. The efficiency and reliability of ion sources directly impact the performance of particle accelerators, making them indispensable in scientific research, medical diagnostics, and industrial applications.

2.2 Overview of Ion Sources

Ion sources consist of several critical elements and systems that work together to produce and extract ion beams. Understanding these components is essential for optimizing their performance in various applications. Key Elements and Systems Include:

The Ionization Chambers

This chamber serves as the heart of an ion source, where ionization occurs and plasma is contained. Within it, ions are generated and directed towards an extraction point. Although it usually acts as an anode, some sources, like the Penning source, use a cathodic chamber with an internal anode for practical considerations.

Ionization Energy Source

In the process of ionization within an ion source, energy is essential for converting neutral atoms into ions. The cathode plays a pivotal role by providing the required electrons. Hot cathodes, akin to light-bulb filaments, emit electrons upon heating, which subsequently collide with gas particles, leading to ion formation. In contrast, cold cathodes operate differently by utilizing plasma energy to liberate electrons without heating. This dual mechanism underscores the diverse approaches employed to facilitate ionization in ion sources.

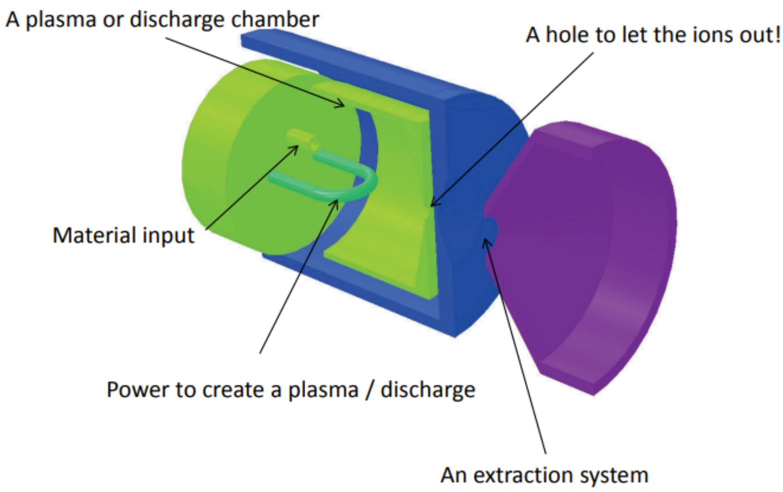

Figure 2.1: The scheme of a typical ion source(cathode-type)

Extraction system

Once ions are generated within the ion source, they require extraction to form a beam. This is achieved through a meticulously crafted aperture known as the extraction aperture. An electric field is applied across this hole, attracting positively charged ions out of the plasma and initiating their movement. The shape of the aperture, whether round or elongated, influences the initial shape of the ion beam. Placement of the hole, either at the end or on the side of the plasma, varies depending on the ion source type and the desired beam configuration.

2.3 Plasma

Ion sources fundamentally rely on producing plasma, often called the fourth state of matter, following solids, liquids, and gases. In this energized state, atoms in a gas become ionized through a process called electron impact ionization, where electrons are stripped away. This ionization creates a dynamic mixture of positively charged ions, freely moving electrons, and occasionally neutral atoms that remain un-ionized.

The desired ion species for forming an ion beam are extracted directly from this plasma environment. The properties of the plasma, such as its density (number of particles per unit volume) and temperature (a measure of particle energy), significantly influence the characteristics of the extracted ion beam. Thus, controlling and optimizing these plasma parameters is crucial for achieving the desired ion beam qualities [4].

2.4 Fundamental Plasma Characteristics

2.4.1 Density of Charged Particles

The density parameter represents the number of particles (ions, electrons, and neutral atoms/molecules) present within a given volume of the plasma, typically measured in cubic meters or cubic centimeters. Specific densities are denoted as n_i for ions, n_e for electrons, and n_n for neutral particles.

In most ion source plasmas, a state of quasi-neutrality exists, where the total positive charge from ions is approximately balanced by the total negative charge from electrons [11]. This equilibrium is often symbolized by the formula:

$$\sum(q_i \cdot n_i) = e \cdot n_e \tag{2.1}$$

where:

- q_i is the charge of the ions,
- n_i is the density of the ions,
- e is the elementary charge,
- n_e is the density of the electrons.

2.4.2 Particle Energies

The term "temperature" in plasma physics refers to the average kinetic energy of the particles within the plasma[28]. Due to their significantly lower mass compared to ions, electrons typically possess much higher kinetic energies, resulting in a higher electron temperature (Te) than the ion temperature (Ti). This temperature differential plays a crucial role in determining the energy distribution of the extracted ion beam and the rates of ionization processes within the plasma. Plasma temperatures are commonly expressed in electron-volts (eV), with ion sources typically operating in the range of several eV (1 eV = 11,600 K) [9].

2.4.3 Particle Interactions

Within an ion source plasma, charged particles like electrons and ions do not undergo simple, short-range collisions as in a neutral gas. Instead, they experience continuous, long-range Coulomb interactions [11]. Consequently, the traditional concept of "mean free path" (the average distance between collisions) is less appropriate for describing their behavior. Instead, scientists employ the idea of "relaxation time," which measures the average time it takes for a particle to significantly change its direction by 90° due to these interactions[4].

2.5 Plasma production

In plasma-based ion sources, creating charged particles from neutral species is achieved through various ionization techniques. Among these, electron impact ionization stands out as a widely employed method Fig2.2. This process begins with the generation of a plasma containing free electrons within the ion source chamber via an electrical discharge [1]. These energetic electrons are then accelerated, typically to around 70 electron volts (eV), by applying a potential difference.

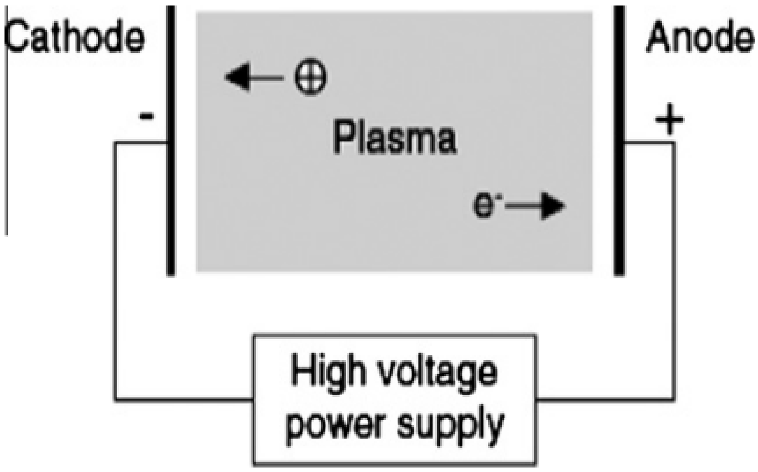

Figure 2.2: Electrical discharge between two parallel plane and electrodes.

The accelerated electron beam is directed to intersect a stream of neutral gas molecules (A) injected into the chamber. Upon collision, the high-energy electrons can strip off one or more outer electrons from the gas molecules, transforming them into positively charged ions (A+) Fig2.3, as depicted by the following equation: $e - +A \mapsto A^{+} + 2e-$

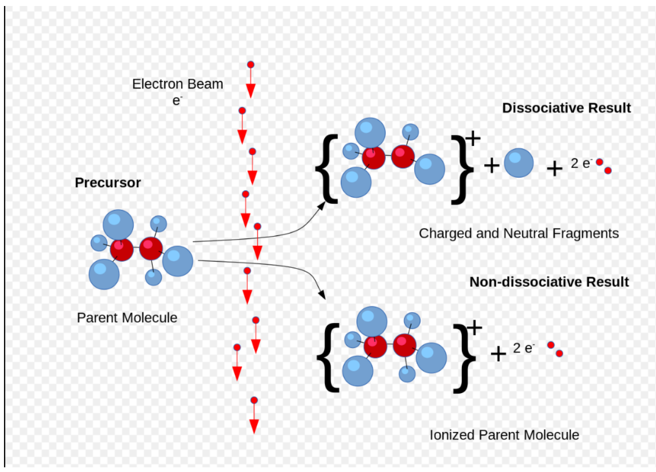

Figure 2.3: Electron ionization.

To maximize the ionizing collisions, the neutral gas inlet is positioned perpendicular to the electron beam trajectory, increasing the interaction path length. This strategic alignment enhances the ionization efficiency within the confined plasma region. Other ionization processes like surface ionization, photo-ionization, etc. can also occur depending on the ion source design and conditions.

2.6 Ion Beam Formation and Characterization

The formation of an ion beam from a plasma ion source involves the extraction of ions through an appropriately designed electrode system Figure 2.4 , commonly referred to as the extractor.This process the extraction beam is governed by various factors, including the shape of the plasma meniscus (the boundary between the plasma and the extracted beam), the available ion current from the plasma surface, and the space-charge limitations on the extractable current density.

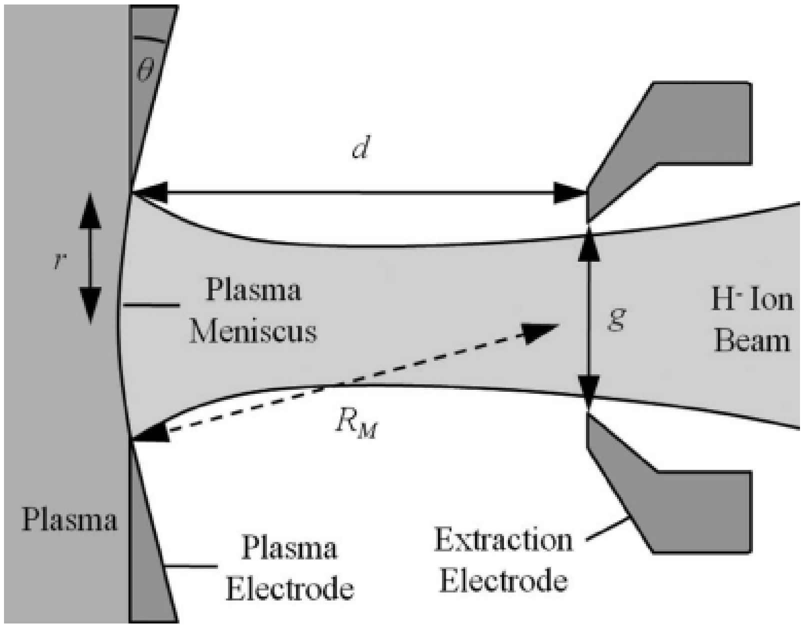

Figure 2.4: Optical elements of an ion extraction system.

The plasma meniscus shape plays a crucial role in determining the optical quality and geometric parameters of the extracted beam. Figure 2.5 illustrates the effect of the extraction field on the plasma meniscus geometry [2]. . An ideal scenario involves a flat plasma meniscus Figure 2.5d, which can be achieved by carefully adjusting the extraction field strength, typically using voltages in the range of 30-50 kV and an extraction gap of 1-2 cm.

The maximum ion current density (j) that can be extracted from the plasma surface is limited by space-charge forces, as described by the Child-Langmuir law:

$$j = \frac{4\epsilon}{9}\sqrt{\frac{2e}{M}}\frac{V^{3/2}}{d^2} \tag{2.2}$$

where:

- j is the maximum current density (mA/cm^2),
- ϵ is the vacuum permittivity,
- e is the elementary charge (charge of an electron),
- M is the mass of the ion,

- V is the accelerating voltage,
- d is the extraction gap.

The quality of the extracted ion beam is characterized by its emittance and brightness. Emittance represents the phase-space volume occupied by the beam, reflecting the spread in position and momentum (or angle). Brightness, on the other hand, is defined as the current density divided by the emittance and represents the ability to focus the beam to a small spot size.

By carefully designing and optimizing the extraction system, taking into account factors such as the plasma properties, electrode geometries, and space-charge effects, it is possible to achieve high-quality ion beams with desirable characteristics for various applications, including cyclotrons.

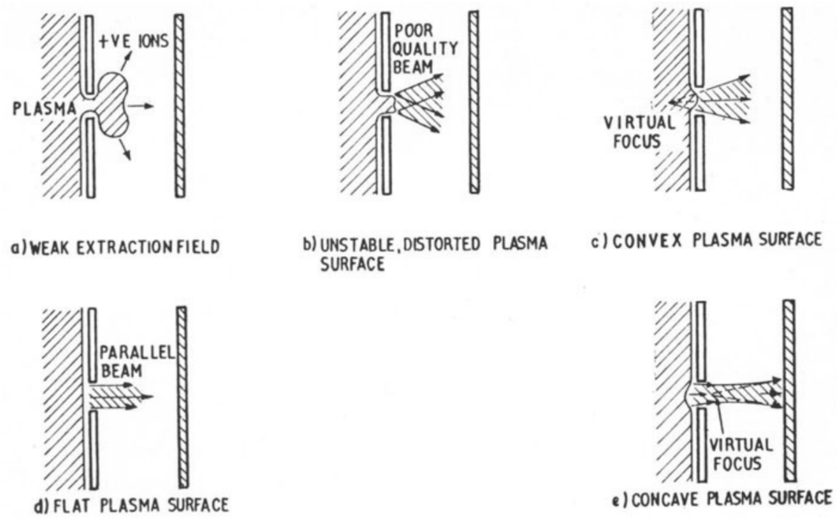

Figure 2.5: the effect of the extraction field on the plasma meniscus geometry.

2.7 Negative ions

Over the past few decades, the negative hydrogen ion (H-) has become the preferred choice for injection into high-power proton accelerator facilities. The use of H- ions offers several advantages, including the reduction of beam losses and the ability to extract efficient beams and multiple beams simultaneously [12]. To protect the fragile H- ions, a magnetic filter field is commonly employed to separate the hotter plasma production region from the cooler extraction region [11]. One of the most widely used negative ion sources for cyclotrons is the Penning Ion Gauge (PIG) source. Some characteristics of negative ions include:

Beam Circulation and Extraction The negative ion beam circulates in progressively greater radii as it accelerates until it comes into contact with the stripping foil. At this point, the Lorentz force operating on the beam reverses direction due to the charge transfer from negative to positive ions, a process known as "charge exchange." This reversal facilitates the clean extraction of the positive ion beam, enabling unique applications in various accelerator systems [10].

Fragility of Negative Ions Negative ions are inherently fragile due to their low electron binding affinity. Hydrogen, with an electron affinity of only 0.7542 eV, is the most commonly used negative ion species, forming H- ions [11].

Production Mechanisms Negative ion sources primarily employ a surface production mechanism where positive ions or energetic neutral atoms interact with a low work function surface, often coated with cesium (Cs), to facilitate electron transfer and negative ion formation [10]. Additionally, there is a volume production mechanism where hydrogen molecules are generated through vibration and form H- ions and neutral hydrogen atoms, as described by the equation: $H2*$ + e-($\leq 1eV$) ? H- + H $H2+e- \mapsto H^{+}+H$

2.8 The Penning Ion Gauge (PIG) source

In the field of compact cyclotrons for medical isotope production, there is a growing demand for efficient sources of negative hydrogen ions (H-). The Penning Ion Gauge (PIG) type ion source has emerged as a popular choice for this application due to its unique ability to generate intense beams of negative ions.

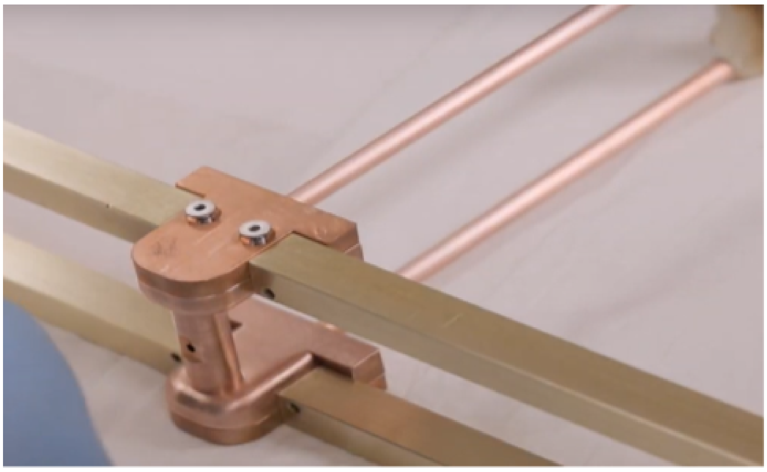

Figure 2.6: PIG ion source of PETtrace cyclotron

The PIG ion source operates on the principle of the Penning discharge, a phenomenon first observed by L. R. Maxwell in 1931 and later applied by Philips Penning in 1937 to develop the Penning or Philips ionization vacuum gauge, giving the discharge its name [14]. The source consists of a cylindrical anode with cathodes at each end. A strong magnetic field, typically above 0.1 Tesla, is applied parallel to the cylinder axis.
During operation, electrons emitted from the cathode are accelerated into the gaseous medium, where they ionize the gas atoms and molecules, forming plasma. The magnetic field prevents the electrons from easily reaching the anode, causing a significant fraction to be reflected by the anticathode. These reflected electrons oscillate between the two cathodes, leading to further ionization events.

The ions generated in the plasma diffuse to the anode wall, where a slit or aperture allows their extraction, forming an ion beam. This extraction aperture can be located either radially (on the anode wall) or axially (on the anticathode)as shown in Fig2.7. Radial extraction is mainly applied in cyclotrons due to its efficiency in directing the ion beam into the acceleration chamber. By optimizing the design and operation of PIG ion sources, it is possible to produce high-quality negative ion beams that meet the demands of medical isotope production in compact cyclotrons.

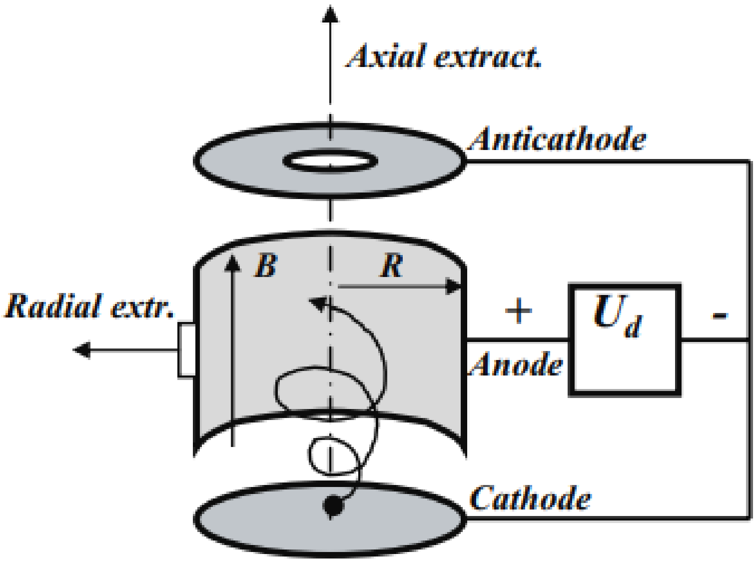

Figure 2.7: Operation principle of the Penning ion source.

There are two main variations of the PIG ion source:

a. Hot Cathode PIG In the hot cathode variation, one cathode is heated to serve as the electron emitter, while the other serves as an anticathode or reflector. A heated filament, typically composed of tungsten or tantalum, is utilized as the source of electrons through thermionic emission, as depicted in Fig2.8. This filament, heated to high temperatures, has a restricted lifespan due to sputtering and necessitates periodic replacement.

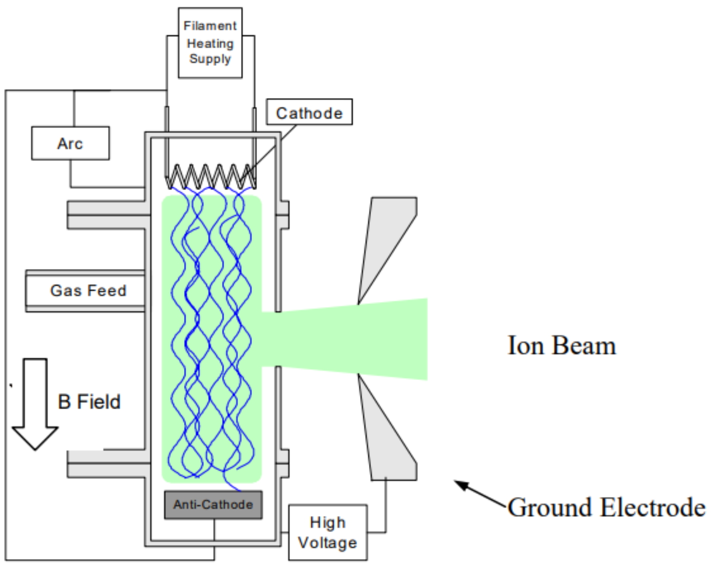

Figure 2.8: Hot cathode PIG ion source with a heated filament.

b. Cold Cathode PIG In this version, a high voltage is employed between the cathode and anode to instigate the discharge and generate electrons via field emission or secondary electron emission mechanisms. This obviates the necessity for a filament but may necessitate higher operating voltages. The distinctive design of the Penning ion source, integrating electric and magnetic fields, facilitated the generation of powerful ion beams suitable for cyclotron applications.

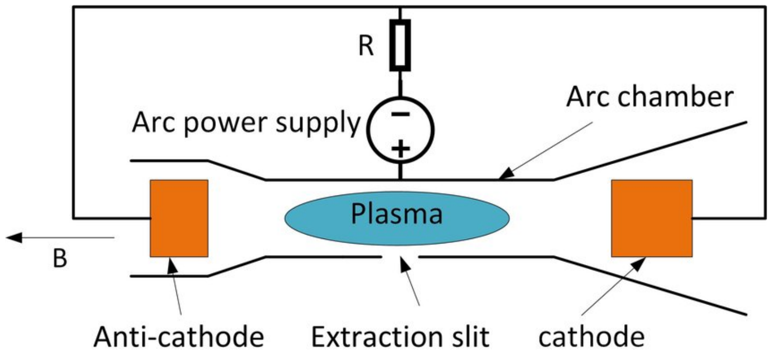

Figure 2.9: Cold cathode PIG ion source without a heated filament.

2.9 Conclusion

The Penning ion source plays a vital role as an ion producer, boasting a distinctive design that integrates electric and magnetic fields. This unique configuration facilitates the generation of robust ion beams, particularly well-suited for cyclotron applications, thereby making significant contributions to the advancement of particle accelerators.

This ion source can operate in both hot and cold configurations, offering versatility in various settings. Widely regarded as the premier ion source for compact cyclotrons, the Penning Ion Gauge (PIG) source is employed both internally within cyclotron facilities and externally. PIG operates as electronegative plasma, ensuring efficient ion production and enabling enhanced performance in compact cyclotrons.

Chapter 3

Simulation of the Penning Ion Source Using CST Studio

3.1 Introduction

Penning ion sources are essential tools for generating high-intensity ion beams, finding applications in diverse fields like particle accelerators. To understand and optimize their performance, simulation software plays a critical role. In this chapter, we will use CST Particle Studio to investigate the behavior of a Penning ion source under various conditions.Initially, an attempt was made to use Geant4 for the simulation, but it was not successful.
By adjusting parameters such as electric and magnetic fields, we aim to gain insights into how these factors affect the ion source's performance, including secondary electron emission and energy distribution. The simulations will also help identify optimal configurations for improved operation and efficiency

3.2 Initial Attempt with Geant4

The PIG ion source simulation was initially set up in Geant4, which is a software for simulating the passage of particles through matter. The decision was based on its its strong capabilities in dealing with complex geometries and electromagnetic fields. But the complexity of the PIG ion source and the special needs of the simulation posed significant challenges.

3.2.1 Geometry and Model Creation

In the first step, we created the geometry of the PIG ion source in Geant4. This part of the modeling includes defining the cylindrical anode, cathodes, and the magnetic field configuration.

3.2.2 Physics Setup

Setting up the physical processes in Geant4 to accurately simulate ionization and particle reactions within the PIG ion source was another difficult task. One of the main reasons for stopping the use of Geant4 is that it does not currently support plasma simulation. This limitation significantly affected the ability to accurately model the source of ions. It is hoped that future versions of Geant4 will include models for plasma simulation.

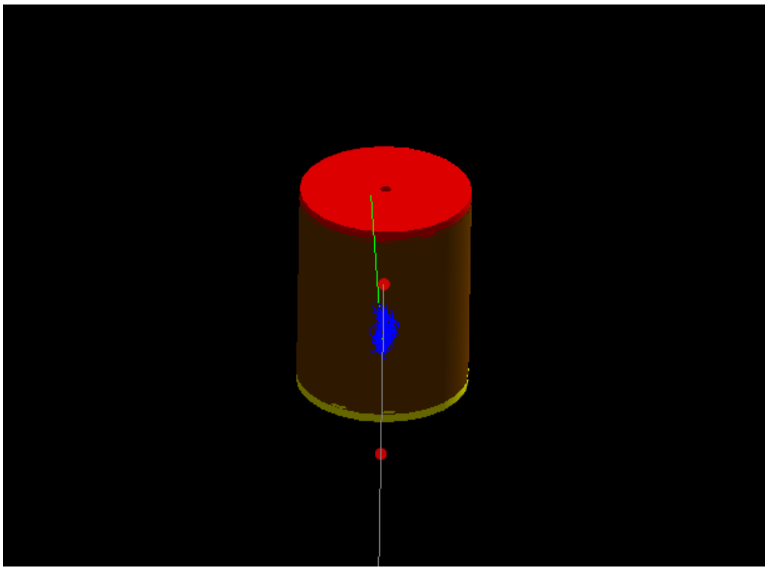

Figure 3.1: Geant4 Simulation of PIG Ion Source .

3.3 CST Studio Suite

CST Studio Suite, developed by Dassault Systems[8], is a powerful and versatile electromagnetic simulation software package. It finds wide applications in various fields, including charged particle dynamics, microwave and RF device design. Here's a brief comparison with another simulation tool, Geant4:

Geant4 Relies heavily on the Monte Carlo method, simulating individual particle interactions with matter using random numbers. This statistical approach is well-suited for simulating particle physics processes and radiation transport.

CST Studio Suite Focuses on solving electromagnetic field distributions using deterministic numerical methods, directly solving Maxwell's equations. This provides deterministic solutions for electromagnetic fields. While CST can incorporate Monte Carlo methods (e.g., in CST Particle Studio), its primary strength lies in its deterministic solver engine.

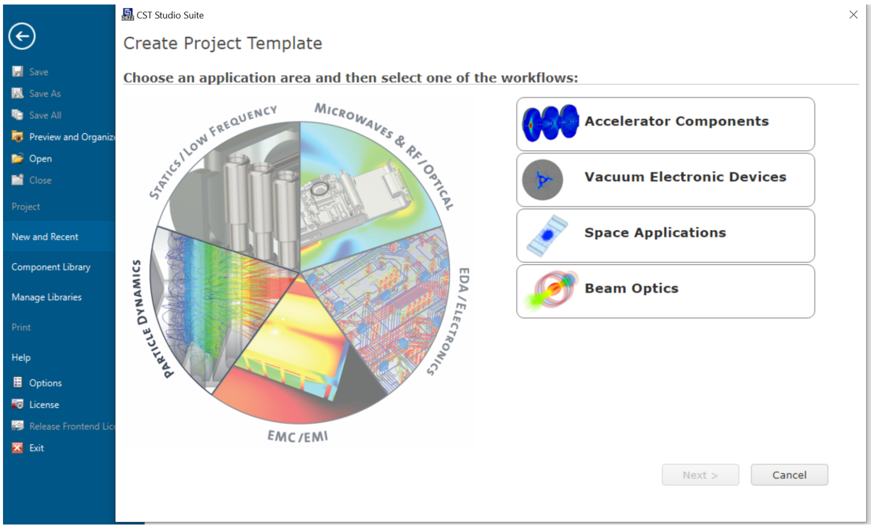

Figure 3.2: CST Studio Suite: Create Project Template Interface

3.4 Simulation with CST Particle Studio

CST Particle Studio is a specialized environment within CST Studio Suite designed for simulating charged particle interactions with electromagnetic fields, plasma sources, discharges, and other applications. It offers a range of solvers tailored to address specific challenges.

3.4.1 Geometry and Model Creation

Creating the Geometry

To initiate the simulation, we construct the geometry of the Penning ion source using CST Studio Suite. This process involves defining the shapes and materials of critical components, including the cathode, anode, and extraction electrode. CST Studio Suite offers the flexibility to import pre-defined shapes and materials, streamlining the geometry construction process. Additionally, it provides tools to create custom shapes and define new materials.

Magnetic Field Configuration

The magnetic field plays a critical role in confining electrons and enhancing ionization. In our simulation, we use a permanent magnet placed externally around the anode to generate the axial magnetic field. To configure the magnetic field in CST:

1. Open the permanent magnet dialog box.

2. Select the face of a non-PEC solid.

3. Specify the magnet parameters.

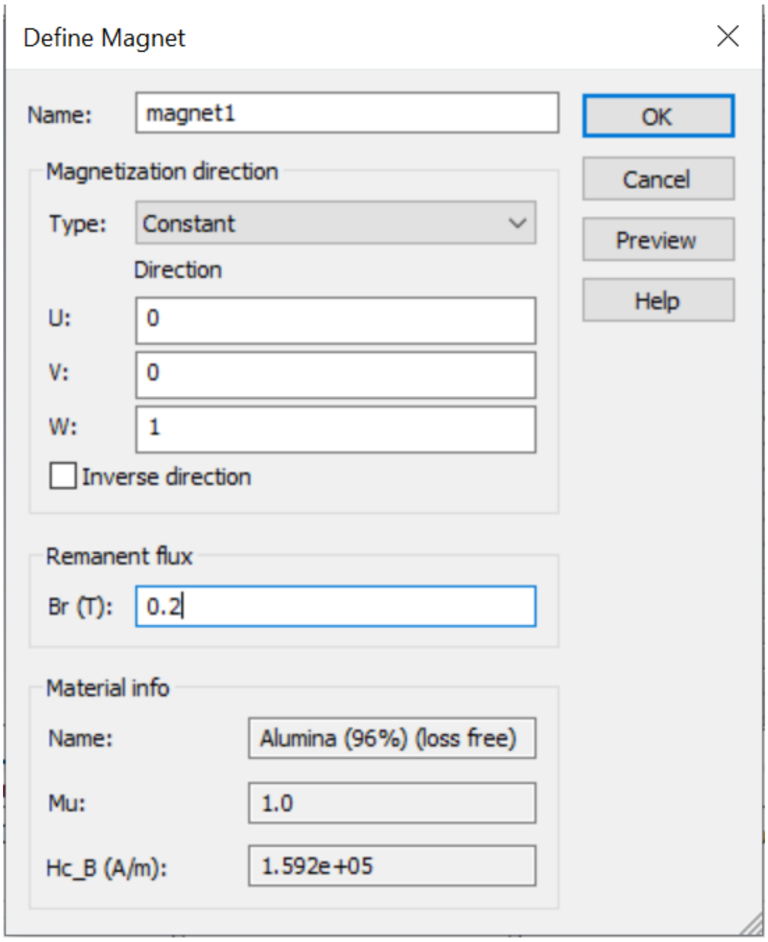

Figure 3.3: Dialog box for setting parameters of the magnet.

Electric Field Configuration

The electric field is responsible for accelerating electrons and extracting ions from the plasma. We establish this field by applying specific voltages to the anode, cathode, and extraction electrode. To configure the electric field in CST:

1. Define the electric potential on any PEC surface.

2. Activate the tool to visualize non-PEC solids as transparent.

3. Select multiple surfaces for potential definition.

4. Press ENTER to open the dialog box and set parameters such as name, potential value, and type.

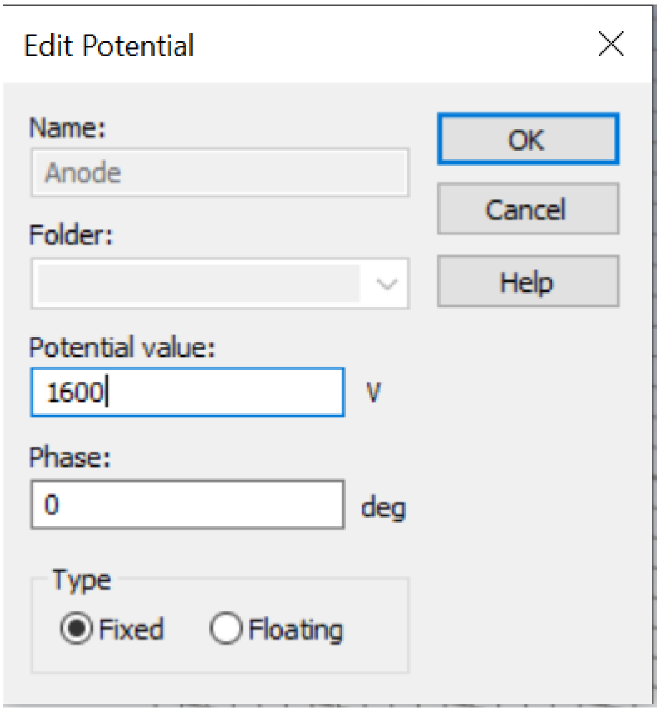

Figure 3.4: Dialog box for setting parameters of the Electric Field.

3.4.2 Physics Setup

Defining the Particle Source

The particle source and associated emission models are crucial for PIC simulations in CST Particle Studio. Each particle source consists of a geometrical definition, a particle type definition, and an emission model. For our Penning ion source:

1. Select the cathode as the emitting face.

2. Define it as a particle area source.

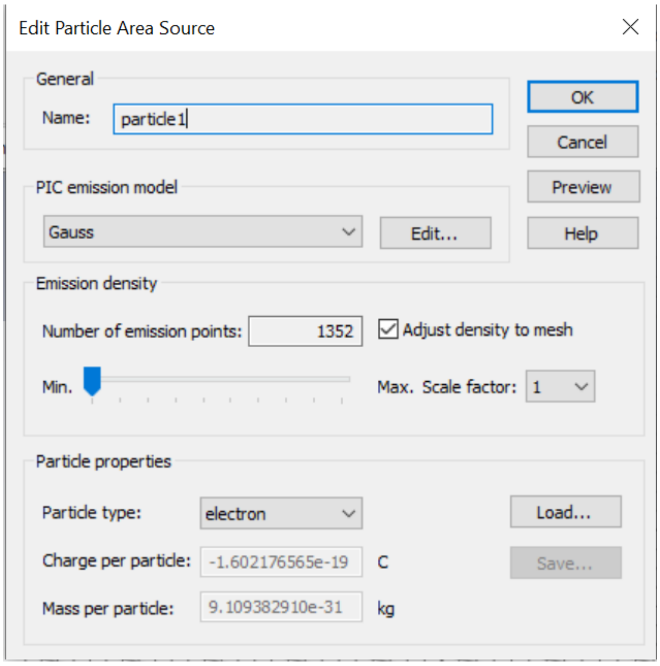

Figure 3.5: Dialog box for setting parameters of the Particle Source.

Defining the Background Gas

Collisions between simulated charged particles and neutral background gas particles are modeled using the Monte Carlo Collision (MCC) model. The following collision processes are included:

- Electron impact ionization

$$\mathrm{M} + e^- \rightarrow \mathrm{M}^+ + 2e^- \tag{3.1}$$

- Electron elastic

$$\mathrm{M} + e^- \rightarrow \mathrm{M} + e^- \tag{3.2}$$

- Electron excitation

$$\mathrm{M} + e^- \rightarrow \mathrm{M}^* + e'^- \tag{3.3}$$

- Ion elastic

$$\mathrm{M} + \mathrm{A}^+ \rightarrow \mathrm{A}'^+ + \mathrm{M} \tag{3.4}$$

These collisions occur randomly and alter the physical state of the simulated charged particles.

Simulation Parameters

Solver Configuration The Electrostatic Particle-in-Cell (ES-PIC) solver was employed to simulate the ion source. This solver is well-suited for modeling plasmas and charged particle dynamics. Key configurations included:

Monte Carlo Collisions Background gas pressure, ionization, and excitation cross-sections were specified.

Particle Merging : Used to manage the large number of particles generated, merging them after a specified number of time steps.

Time Step and Mesh Size Set to 0.07 ns to ensure efficient simulation on a typical workstation.

Particle Monte Carlo Collision Examples

```
' Particle Monte Carlo Collision definition of one background gas and one collision
With ParticleMCC
     .Reset
     .EnableAcceleration "False"
     .SetGasName "He"
     .SetGasMass "4"
     .SetGasPressure "0.01"
     .SetGasTemperature "300"
     .AddGas
     .IsActive "True"
     .SetIncidentSpecies "electron"
     .SetTargetedSpecies "He"
     .SetCollisionType "excitation"
     .SetParameter ""
     .SetCoulombScattering "True"
     .SetCrossSectionFileName "crosssection.txt"
     .CrossSectionImportDataPair "2.000e+01", "2.00e-20"
     .CrossSectionImportDataPair "2.200e+01", "2.00e-20"
     .AddCollision
End With
```

Figure 3.6: Particle MCC collision example definition of gas background .

3.5 General Description

In this model of a Penning Ion Gauge (PIG) ion source, the design is based on the standard geometry of PIG ion sources Fig3.7. First, the geometry of the model and the intensity of the electric and magnetic fields were defined, along with other necessary components, including the cathode and anode. The cathode is designed to be 25 mm in diameter and 2 mm in thickness, featuring an aperture. The anode, cylindrical in shape, is made of copper, with a diameter of 25 mm and a height of 24 mm. Tantalum (Ta) is used for the cathode material due to its low sputter rates and potentially long lifespan, which is advantageous for such sources. The anode is held at a positive voltage relative to the cathode, and the ion source is positioned within an axial magnetic field. Additionally, all conducting materials in the model are defined as perfect electrical conductors (PEC), while the background material is set to vacuum to simulate an experimental environment accurately. For the simulation, the electric potential was varied from 1000V to 2000V, and the magnetic field strength was considered at 0.2T, 0.4T, and 0.6T. These specific values were selected based on previous research in the literature [15].

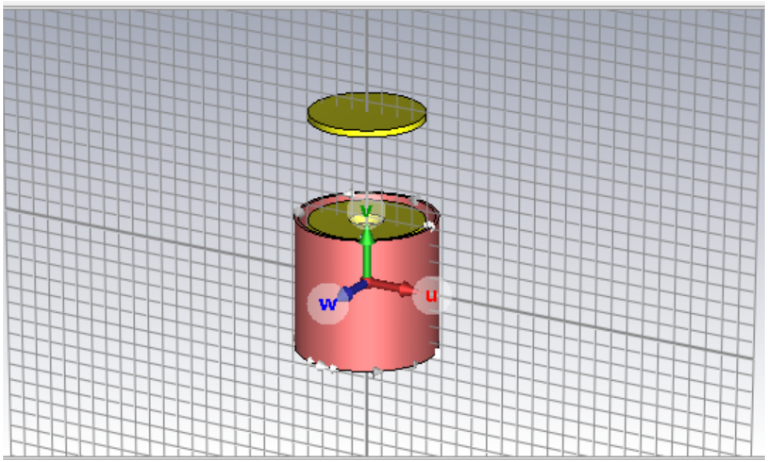

Figure 3.7: The of geometry of PIG ion sources with CST .

3.6 Results and discussion

Secondary electron emission, where electrons are ejected from surfaces due to ion impact, play a crucial role in maintaining the plasma density and enhancing the production of ions. And a higher rate of secondary electron emission can lead to a more stable and efficient ion source, the hydrogen plasma contains mainly H+ and H2+ ions, which have only low secondary electron emission yields at the typically used potentials in the range of 1 to 1.8 kV. [6].
Figure 3.8 show the relation ship between the secondary electron emission generated within the plasma chamber at different magnetic field strengths. As the voltage increases, the number of secondary electrons also increases. This is due to the higher energy imparted to the ions and primary electrons, which then hitting the cathodes , producing more secondary electrons.

Figure 3.9 and Figure 3.10 illustrates how the total number of electron and ions increase with the anode voltage, The total electron count includes both primary and secondary electrons. Higher electric field cause in create more electrons and accelerate them while that enhance the ionization rate of the gas molecules .The convergence between the number of electrons and ions is due to the quasi-neutrality condition of the plasma, which requires that the number of positive and negative charges be nearly equal. This balance is crucial for maintaining a stable plasma. Figure 3.11 show the influence of the electric field on the extracted current for different magnetic field strengths. The extracted current increases with the anode voltage, and this is a result of the increased production of charged particles (ions and electrons).The extracted current is a critical parameter for the performance of ion sources, as it directly relates to the efficiency and intensity of the ion beam produced.

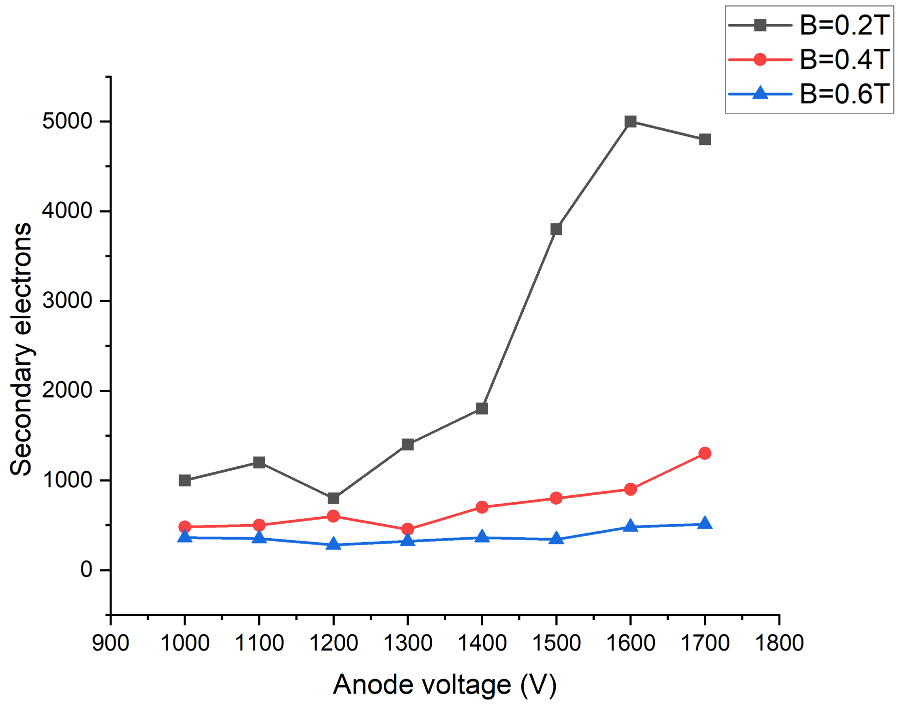

Figure 3.8: Effect of Anode Voltage on Secondary Electron Generation under Various Magnetic Fields

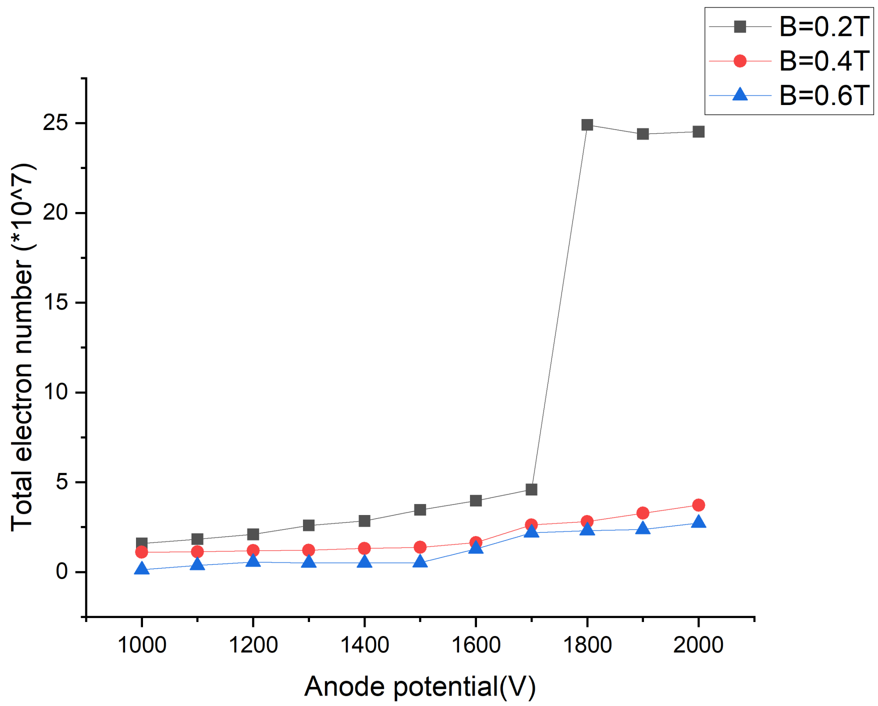

Figure 3.9: Variation of Total Electron Count with Anode Voltage under Various Magnetic Fields

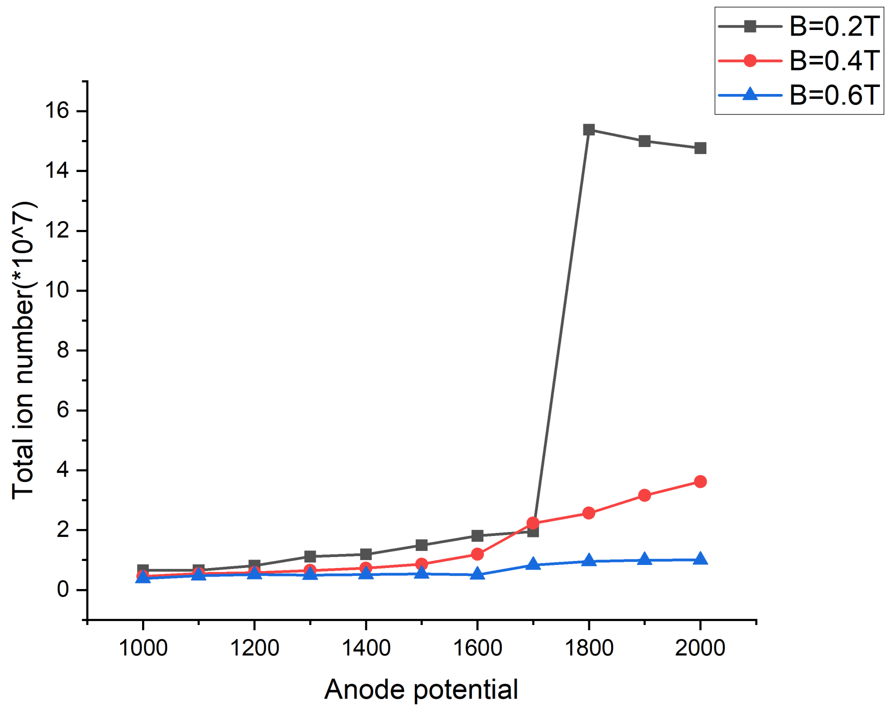

Figure 3.10: Influence of Anode Voltage on Ion Production under Different Magnetic Fields

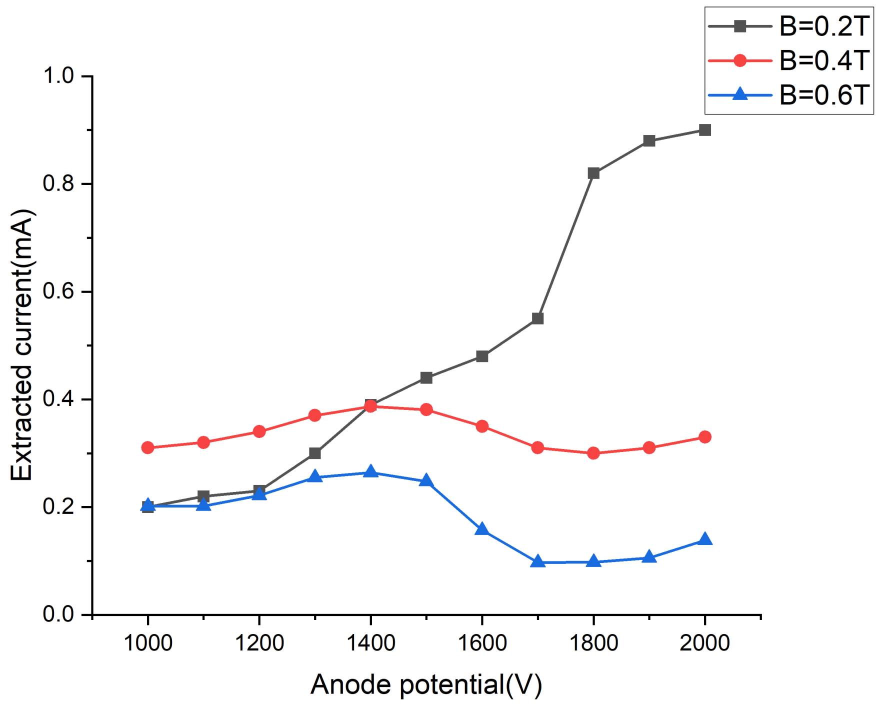

Figure 3.11: Dependence of Extracted Ion Current on Anode Voltage under Different Magnetic Fields

This Figure 3.12 demonstrates the visualization of charged particles in an 1800V electric field and a 0.2T magnetic field for the ion source. This visualization helps in understanding the behavior and trajectories of particles under these conditions.and the graph in Figure 3.13 compares the energy distribution of particle in the extracted beams under different magnetic field strength the difference in energy distribution can be attributed to various physical phenomena. Understanding these distributions is crucial for optimizing the beam extraction process and improving the efficiency and quality of the beam.

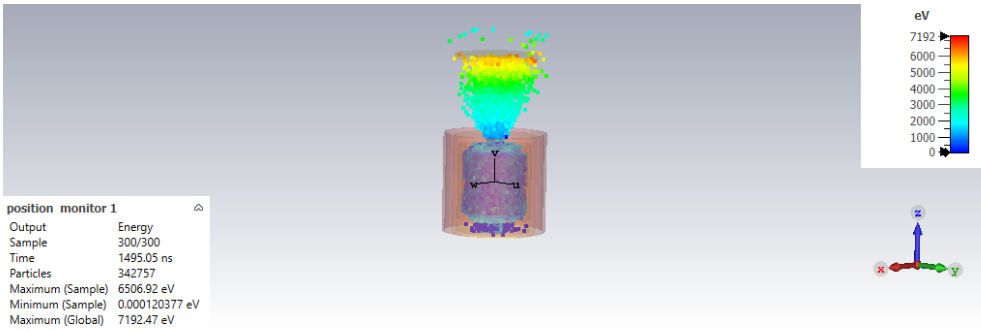

Figure 3.12: The ion trajectories plotted in 0.2T magnetic field and 1800V electric field

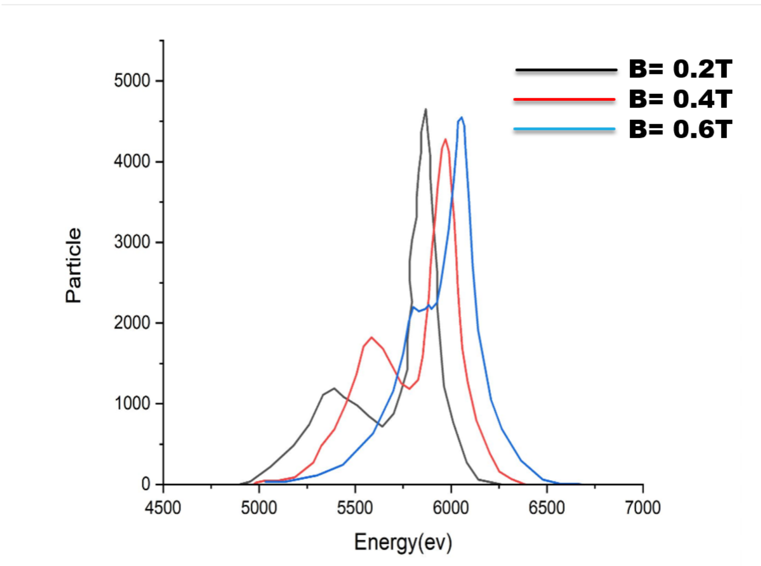

Figure 3.13: Energy distribution of particles in the extracted beams under different magnetic field strengths.

Another parameter that has an impact on the performance of the ion source is pressure.The graph in Figure 3.14 suggests that there is an optimal pressure range for maximizing ion production in the ion source. Too low or too high pressures can reduce ion efficiency due to insufficient ionization, the pressure within the ion source significantly affects ion production.

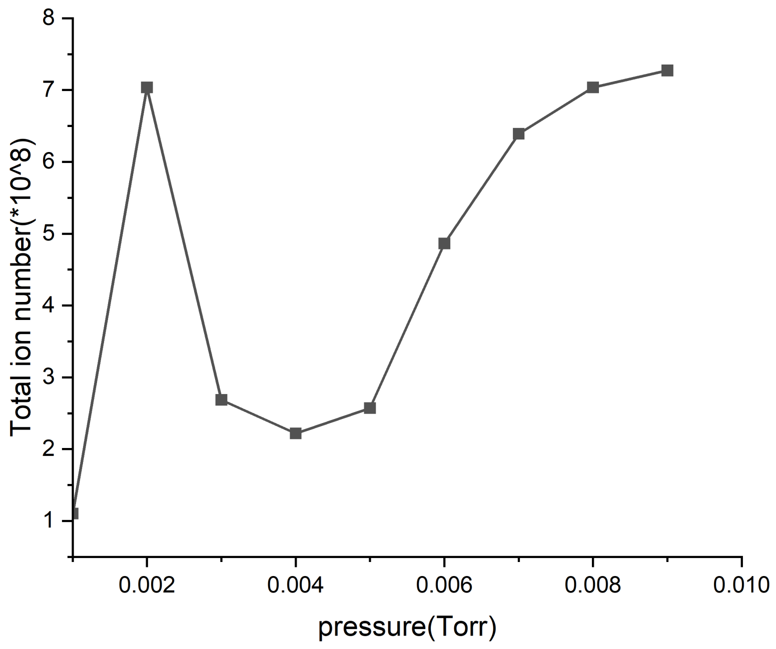

Figure 3.14: Influence of Pressure on ions production .

conclusion

In summary, the results highlight the importance of secondary electron emission, electric and magnetic field strengths, and pressure in optimizing the performance of the Penning ion source. Understanding these factors is crucial for improving ion production, stability, and extraction efficiency, which are essential for various applications such as particle accelerators.

General Conclusion

The research on the Penning Ionization Gauge (PIG) ion source for PETtrace medical cyclotrons, tried to meet the growth of efficient production of PET radioisotopes in nuclear medicine.The comprehensive study included a detailed examination of the cyclotron's components, particularly focusing on the PIG ion source, and the use of CST Studio Suite for numerical simulations. The key results from this inquiry show that electric and magnetic fields as well as gas pressure have significant influence on how well PIG ion source works. The simulation allowed to identify more optimal values of these parameters, which is important for high quality radioisotope production used in PET scans.

The study is divided into two major sections: first section gave basic understanding about how cyclotrons work and thorough examination of PIG ion sources while the second part dealt with its simulation and optimization processes. The results indicate that with suitable adjustments, it would be possible to significantly enhance the efficiency of an ion source and therefore make any PETtrace cyclotrons perform better. Future work could further explore the optimization of other cyclotron components and the integration of advanced technologies to continue improving the efficacy and efficiency of medical cyclotrons.

The results of our study are summarized as follows: For PIG Ion Source, a magnetic field of 0.2T, an electric field of about 1,800V and gas pressure value of almost 2 mTorr are the optimal conditions we found. Under these conditions, the simulation indicated that it is possible to generate a high density of plasma, which leads to the extraction of a high beam current for acceleration in the cyclotron. This is essential for producing radioisotopes required for medical imaging and treatment. To sum up our study has given important information regarding optimization of the PIG Ion Source used in medical cyclotrons. The identified parameters could be used as recommendations for more experimental efforts and practical development. Further research is still needed to validate these simulation results through experiments and investigate other factors influencing ion source performance.

List of Figures

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