

НАЦІОНАЛЬНИЙ ТЕХНІЧНИЙ УНІВЕРСИТЕТ УКРАЇНИ
«КИЇВСЬКИЙ ПОЛІТЕХНІЧНИЙ ІНСТИТУТ
імені ІГОРЯ СІКОРСЬКОГО»
НАВЧАЛЬНО-НАУКОВИЙ ФІЗИКО-ТЕХНІЧНИЙ ІНСТИТУТ
КАФЕДРА ПРИКЛАДНОЇ ФІЗИКИ

«До захисту допущено»

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Дипломна робота
на здобуття ступеня бакалавра

зі спеціальності 105 «Прикладна фізика та наноматеріали»

(код і назва)

на тему: Підготовка прискорювача типу радіочастотного квадруполя
для медичних застосувань

Виконала: студентка 4 курсу, групи ФФ-11

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Рівень вищої освіти — перший (бакалаврський)
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2. Термін подання студентом роботи « 18 » червня 2025 р.

3. Об'єкт дослідження: процес інжекції пучка з джерела в RFQ-прискорювач

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5. Перелік завдань, які потрібно розробити: змоделювати геометрію джерела та дослідити вплив напруг на електродах на сформований пучок; ідентифікувати конфігурацію, яка максимізує передачу пучка; дослідити вплив струму пучка на якість узгодження; експериментально оптимізувати інші параметри джерела та валідувати результати моделювання; побудувати модель джерела гелію, та провести симуляції динаміки частинок в лінії транспорту; дослідити залежність коефіцієнта передачі пучка через RFQ від поданої потужності.

6. Орієнтовний перелік ілюстративного матеріалу: презентація — 20 аркушів
A4

7 Орієнтовний перелік публікацій: XXIII Всеукраїнська науково-практична конференція студентів, аспірантів та молодих вчених

8 Консультанти розділів роботи

Розділ	Прізвище, ініціали та посада консультанта	Підпис, дата	
		завдання видав	завдання прийняв
1	доцент, д.ф.-м.н. Монастирський Г. Є.	01.10.2024	13.06.2025
2	sen. accel. physicist, Alessandra Lombardi	01.10.2024	13.06.2025
3	sen. accel. physicist, Alessandra Lombardi	01.10.2024	13.06.2025
4	sen. accel. physicist, Alessandra Lombardi	01.10.2024	13.06.2025
5	sen. accel. physicist, Alessandra Lombardi	10.02.2025	13.06.2025

9 Дата видачі завдання « 14 » квітня 2025 р.

Календарний план

№ з/п	Назва етапів виконання бакалаврської роботи	Термін виконання етапів проекту	Примітка
1.	Опрацювання літератури за темою	01.10.2024 — 31.10.2024	виконано
2.	Написання літературного огляду	01.11.2024 — 14.11.2024	виконано
3.	Проведення моделювання для протонів	15.10.2024 — 14.01.2025	виконано
4.	Написання другого розділу дипломної роботи	20.11.2024 — 25.12.2024	виконано
5.	Отримання експериментальних даних	23.02.2025 — 07.03.2025	виконано
6.	Написання третього розділу дипломної роботи	01.04.2025 — 29.04.2025	виконано
7.	Проведення моделювання для гелію	01.04.2025 — 29.04.2025	виконано
8.	Підготовка тез до конференції дипломної роботи	01.04.2025 — 29.04.2025	виконано
9.	Написання четвертого розділу дипломної роботи	30.04.2025 — 20.05.2025	виконано
10.	Виступ на конференції	14.05.2025	виконано
11.	Написання п'ятого розділу дипломної роботи	20.05.2025 — 09.06.2025	
12.	Подання роботи на рецензування	12.06.2025	виконано
13.	Підготовка доповіді та презентації	10.06.2025 — 18.06.2025	виконано
14.	Подання роботи до захисту	18.06.2025	виконано

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РЕФЕРАТ

Темою даної дипломної роботи є введення в експлуатацію прискорювача типу радіочастотного квадрупольного (RFQ) для медичних застосувань.

Основною метою є узгодження параметрів пучка, згенерованого джерелом іонів, з RFQ та перевірка роботи системи.

Робота складається з п'яти основних розділів та висновків. У першому розділі розглядається контекст, у якому виконана робота, та дається огляд попереднім роботам за темою.

Другий розділ містить теоретичні відомості з динаміки пучків та основних понять фізики прискорювачів. Розділ починається з опису поперечної та повздовжньої динаміки пучка, далі розглядається принцип роботи джерел іонів, з акцентом на джерелах, що працюють на принципі циклотронного резонансу. Крім того, пояснюється принцип роботи RFQ, резонансні моди, його геометрія та дається визначення аксептансу.

У третьому розділі описується експериментальна установка, що складається з двох джерел іонів, RFQ та діагностичного блоку, оглядається програмне забезпечення та дається загальна методика моделювання.

Четвертий розділ присвячений результатам моделювання динаміки пучка. Особливу увагу приділено узгодженню вихідного пучка з аксептансом RFQ. Окрім того, наведене моделювання поведінки пучка всередині RFQ, а також аналіз ефективності прискорення частинок при різних рівнях потужності.

У п'ятому розділі наведено експериментальні результати з введення в експлуатацію протонного джерела. Це включає вимірювання

струму пучка, профілів, а також виміри струму на високоенергетичному виході RFQ.

Ключові слова: *динаміка частинок, джерела іонів, RFQ, адронна терапія*

SUMMARY

The subject of this thesis is the commissioning of a radio-frequency quadrupole (RFQ) for medical applications.

The main objective is to match the output beam from the ion source to the RFQ and to validate the system's performance.

This thesis consists of three main chapters and a conclusion. Chapter 1 discusses the context of this bachelor's thesis and reviews previous work on the topic.

Chapter 2 provides the theoretical background on beam dynamics and other key accelerator concepts. It begins with a discussion of transverse and longitudinal beam dynamics, followed by an overview of ion source technologies, with a particular focus on Electron Cyclotron Resonance (ECR) ion sources. The working principles of the RFQ are then explained, including resonant modes, geometry, and the definition of RFQ acceptance.

Chapter 3 describes the experimental setup, consisting of two ion sources, RFQ and a diagnostic box, reviews the software and presents the general modelling methodology.

Chapter 4 is dedicated to beam dynamics simulations. It includes simulations for two ECR sources: the Monogan 1000 proton source and the Supernanogan helium source. Special attention is given to matching the source output beam to the RFQ. The chapter concludes with simulations of beam dynamics inside the RFQ, including a study of particle transmission.

Chapter 5 presents the experimental results of the proton source commissioning. This chapter covers beam current measurements, beam

profiles and beam current measurement at the high-energy side of the RFQ.

Keywords: *beam dynamics, ion sources, RFQ, hadron therapy,*

CONTENTS

ABBREVIATIONS AND ACRONYMS.	6
INTRODUCTION.	7
CHAPTER 1. Literature review	9
CHAPTER 2. Theoretical background	14
2.1. Beam dynamics	14
2.1.1. Transverse beam dynamics	14
2.1.2. Longitudinal beam dynamics	17
2.2. Ion sources	19
2.2.1. Extraction system	19
2.2.2. ECR ion sources	21
2.3. RFQ	22
2.3.1. Resonant modes	23
2.3.2. RFQ geometry	24
2.3.3. Definition of RFQ acceptance	26
CHAPTER 3. Materials and methods	27
3.1. Experimental setup	27
3.1.1. Monogan proton source	28
3.1.2. Supernanogan source for helium beam	30
3.1.3. 750 MHz Carbon RFQ.	31
3.1.4. Diagnostic box	32
3.2. Simulation tools	36
3.2.1. Poisson Superfish	36
3.2.2. Travel	37
3.2.3. General simulation process	38
CHAPTER 4. Beam dynamics simulations	39
4.1. Monogan proton source	39
4.2. Supernanogan source for helium beam	45

4.3. 750 MHz Carbon RFQ	50
CHAPTER 5. Experimental results	53
5.1. Beam current measurements	54
5.2. Beam profiles	56
5.3. Beam current on the high-energy side	57
CONCLUSIONS AND OUTLOOK	59
Bibliography	61

ABBREVIATIONS AND ACRONYMS

DB — diagnostic box

ECR — electron cyclotron resonance

FC — Faraday cup

LEBT — low-energy beam transport

MP — matching plane

RF — radio frequency

RFQ — radio frequency quadrupole

INTRODUCTION

Accelerators are playing an increasingly important role in modern medicine, particularly in the field of hadron therapy. Unlike conventional X-ray radiation therapy, hadron therapy allows precise targeting of tumours by delivering a concentrated dose of energy at a specific depth. This makes it especially effective for treating deep-seated or radiation-resistant cancer while minimising damage to surrounding healthy tissue. However, due to the large size and complexity of existing synchrotron-based systems, such facilities remain relatively rare. To improve accessibility, linear accelerators have been proposed as a more compact, modular, and potentially more cost-effective alternative. A key component in such systems is the radio-frequency quadrupole (RFQ), a low-energy linear accelerator used for the initial acceleration, focusing, and bunching of particles.

As part of research into medical applications, a compact 750 MHz Carbon-RFQ was developed at CERN. This bachelor's thesis focuses on the initial steps in commissioning this RFQ, with particular emphasis on the low-energy side of the system.

The objective of this work is to study beam dynamics within the ion source and find the configuration that produces a beam with the maximum transmission through the RFQ.

The object of the study is the matching of the ion beam between the source and the RFQ to ensure efficient injection.

The work involves numerical simulations of proton and helium ion sources used during commissioning. For each source, the extraction geometry is modelled, followed by beam dynamics simulations to investigate the beam's behaviour under different electrode voltages. Based on the simulation results, either direct matching or a low-energy beam

transport (LEBT) line is used to match the beam into the RFQ. In addition, simulation results for the proton source are experimentally validated through measurements of beam current and transverse beam profiles.

The methods used include electrostatic field modelling, multiparticle beam tracking, and experimental diagnostics.

The author was responsible for modelling sources' geometry, performing beam dynamics simulations, setting up and running the experimental test stand, acquiring measurement data, and analysing the results. The results were frequently presented at internal meetings at CERN.

Scientific and practical significance. The identified matching configuration is used as reference parameters for RFQ operation in proton mode at the test facility. The simulations for the helium source are used for the design and production of a LEBT for a helium beam. Furthermore, they contribute to a joint effort in designing a future Sarajevo linear ion accelerator, aimed at applied physics research.

CHAPTER 1.

LITERATURE REVIEW

In the hundred years since the invention of particle accelerators, they have become an important tool in modern science, contributing to over one-third of Nobel Prizes in Physics. Although large-scale particle accelerators often dominate public attention, they represent less than 1% of all accelerator systems. In contrast, about 50% are used for industrial applications such as ion implantation, and 48% for medical purposes, including radiotherapy and biomedical research. Over the past few decades, accelerator technology has visibly shifted from serving purely scientific purposes to broader societal applications. Many key breakthroughs in the biological sciences over the last 50 years would not have been possible without accelerators [1]

In particular, *hadron therapy* is a type of particle beam therapy that uses protons or heavier ions for cancer treatment. It is considered an alternative to conventional radiotherapy, which uses X-rays. The possibility of using not only electrons, but also protons and heavier ions to treat cancer dates back to the early days of particle accelerators, especially after the first cyclotron was built by Lawrence and Livingstone in 1929 [2]. Effective cancer treatment relies on destroying as many cancer cells as possible while minimising damage to healthy tissue. The effectiveness of this process depends on the energy deposited by the particle as it interacts with the tissue. The idea of using hadrons to target tumours was proposed by Robert Wilson in 1946 after his discovery of the Bragg peak. Unlike X-ray photons, which release their energy along the entire path in the tissue, hadrons release most of their energy at the end of their path, presenting a sharp Bragg peak. This allows the treatment dose

to be concentrated precisely within the tumour, minimising exposure to surrounding healthy tissue. [3].

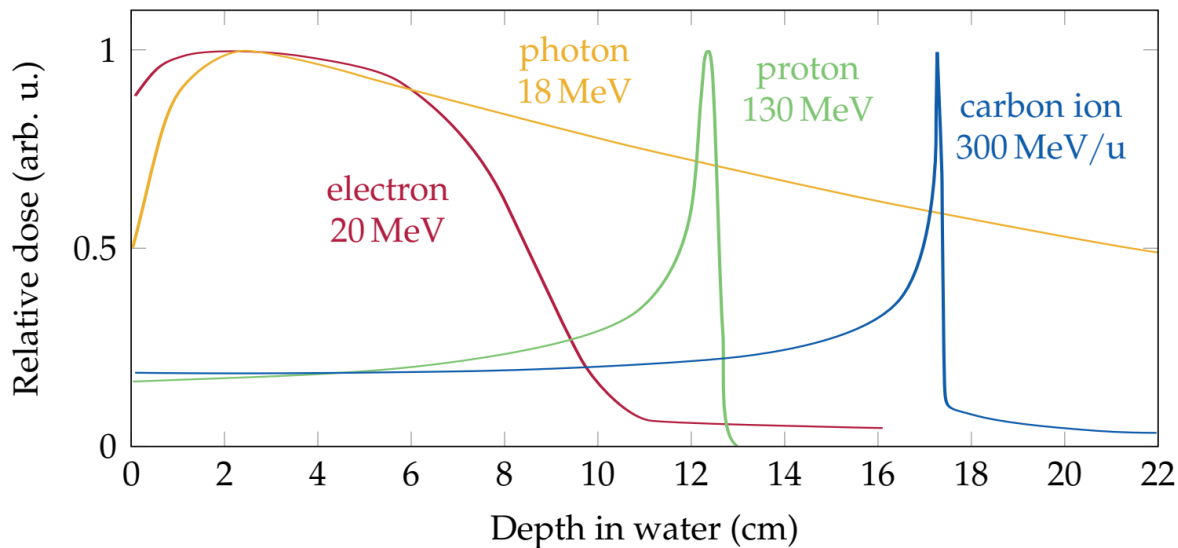


Figure 1.1. Energy deposition by different types of particles. [3]

Since the first introduction of proton therapy in the 1950s, the field of hadron therapy has grown rapidly. Clinical studies were carried out to evaluate the effectiveness of heavy ions such as helium, carbon, neon and argon. These studies showed that heavier ions can deliver precise doses of radiation to tumours while minimising damage to normal tissues [4]. After years of research, carbon ions were found to be especially effective for treating resistant tumours. To distinguish between treatment types, therapy with protons is known as *proton therapy*, while treatment with carbon ions is referred to as *carbon therapy*.

Currently, there are 140 hadron therapy centres in operation worldwide, with 122 used for proton therapy and 18 for carbon therapy. However, the high cost of the accelerators required for hadron therapy is still a major obstacle to its widespread use. Proton therapy typically costs two to three times more than conventional radiotherapy, and carbon ion therapy is even more expensive. The primary reason is the difference in the types of accelerators required. X-rays are produced by accelerat-

ing electrons to 10 MeV using a compact linear accelerator. In contrast, protons are 2000 times heavier, and need to be accelerated up to 230 MeV.

Since the 1990s, researchers have been working on developing more compact and affordable machines. Currently, three main types of accelerators are used for hadron therapy: cyclotrons, synchrotrons and linacs.

- *Cyclotrons* are the most established technology. They deliver continuous beams with high intensities but have fixed output energy. This leads to radio-protection concerns and limits beam modulation time.
- *Synchrotrons* are currently the only technology used for carbon ion therapy. They accelerate particles already pre-accelerated to 3.5-10 MeV/u particles. The beam energy can be controlled by adjusting magnets. The machines, however, are quite big (400 m²) and power-consuming.
- *Linear accelerators (Linacs)* are the newest proposed technology. They can produce high-quality pulsed beams at very high repetition rates compared to cyclotrons and synchrotrons. The beam energy can be adjusted by switching different sections of the accelerating modules.

CERN bent linac

In 2020, Bencini proposed a design of 3 GHz «bent linac» for carbon ions in [5] a sketch of which is shown in figure 1.2. It is designed to better fit into a hospital facility and includes either commercially available elements or the ones at an advanced development stage. In this system, fully stripped carbon $^{12}\text{C}^{6+}$ ions are produced by an ion

source, transported through a low-energy beam transport (LEBT) line, and matched into a radio-frequency quadrupole (RFQ), which is the first accelerating structure [6].

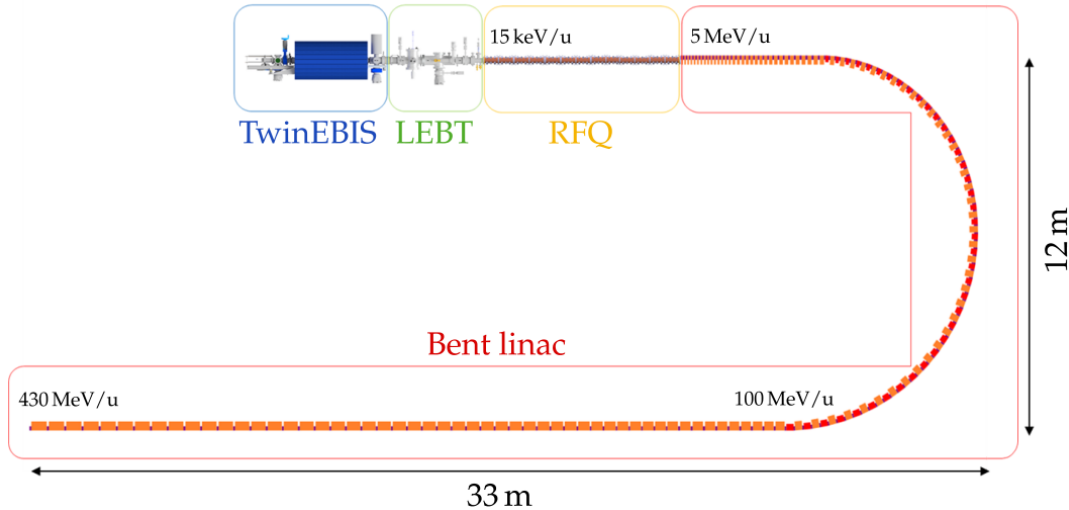


Figure 1.2. Concept of the bent linac with ion source, LEBT, and Carbon-RFQ as the first accelerating structure. [3]

As a part of the bent linac project, a compact 750 MHz Carbon RFQ has been designed at CERN as a joint effort between Bencini [5] and Pommerenke [3]. The RFQ is a low-energy linear accelerator used for the initial acceleration, focusing, and bunching of particles. It shapes the beam longitudinally and transversely for efficient injection into downstream accelerators. The RFQ is highly efficient and can accelerate a wide variety of ions. The design of Carbon-RFQ is based on the earlier HF-RFQ, developed and commissioned at CERN for proton therapy applications in 2018 [7]. The first cavity has already been constructed by CIEMAT and is now ready to be commissioned at CERN.

In this context, we focus on the commissioning of the Carbon-RFQ, with particular emphasis on the low-energy side. We consider initial commissioning in proton mode and aim to optimise the parameters of the ion source and the low-energy beam transport (LEBT) line for efficient injection into the RFQ. It involves modelling the electric field in the

extraction region of the ion source, determining the optimal electrode voltages required to form a proton beam suitable for RFQ injection, and investigating how different beam currents affect the resulting beam dynamics. The simulations are then experimentally verified by measuring the beam profiles and beam current. As the next step in commissioning, a similar approach is applied to a helium ion source.

CHAPTER 2.

THEORETICAL BACKGROUND

2.1. Beam dynamics

Accelerator physics is the field that deals with the design and operation of particle accelerators. It studies the motion of particle beams as they travel through accelerator components. Beam dynamics can be divided into two main branches closely related to each other: longitudinal dynamics and transverse dynamics. Longitudinal dynamics refers to the behaviour along the z axis – the direction of beam propagation. It is primarily concerned with beam acceleration, deceleration and bunching. Meanwhile, transverse dynamics describes the behaviour in the plane perpendicular to the beam motion, usually defined by the x and y . It deals with beam focusing and defocusing, beam size and emittance, and transverse matching.

2.1.1. Transverse beam dynamics

A particle beam represents an ensemble of trajectories displaced relative to the ideal orbit. At any moment, a particle can be displaced horizontally by x and vertically by y from the ideal trajectory, and can also have deflection angles $x' \approx p_x/p_z$ in a horizontal plane and $y' \approx p_y/p_z$ in a vertical plane.

The collective motion of particles can be described by transitioning to phase space, where each particle is described by a point in six-dimensional space with coordinates x, x', y, y', E, φ . The projections $x - x'$ and $y - y'$ of full 6D phase space are called the transverse *trace spaces*.

During particle motion along the accelerator, the particle's coordinate x and angle x' describe an ellipse in the $x - x'$ phase space. The phase ellipse is described by the equation:

$$\gamma x^2 + 2\alpha x x' + \beta x'^2 = \varepsilon, \quad (2.1)$$

where α , β , γ are the parameters that determine the shape and orientation of the ellipse and are called Twiss parameters.

This allows us to introduce an important parameter in beam dynamics — *emittance*. It is proportional to the area enclosed by the ellipse in phase space and has dimensions of length multiplied by angle.

$$\varepsilon = \frac{\text{Area}}{\pi} \quad (2.2)$$

Emittance ε characterises the spread of particles in coordinate-momentum space and is a measure of how coherent the beam is. The smaller the emittance, the better the beam quality is.

Since the beam distribution in phase space generally does not have a well defined boundary, several conventions exist for defining transverse emittance. One way is to define emittance as an ellipse that encompasses certain percentage of a beam. For example, 100% emittance ellipse includes all the particles of the beam. Often, it tends to be very big, since very distant particles are also considered, so it's often useful to consider instead 95% emittance that ignores them. The other way, and the most common one, is statistical definition of the *root-mean-square (RMS) emittance*:

$$\varepsilon_{\text{rms}} = \sqrt{\langle x^2 \rangle \langle x'^2 \rangle - \langle x x' \rangle^2} \quad (2.3)$$

In the presence of only linear forces, the beam distribution generally has an elliptical shape in phase space. However, if non-linear fields affect the beam, it can lose its laminar structure, leading to distortions in the particle distribution and significant deviations from an elliptical phase space shape. The RMS emittance gives important information about the phase space distribution under the effect of linear and non-linear forces acting on the beam. [8]

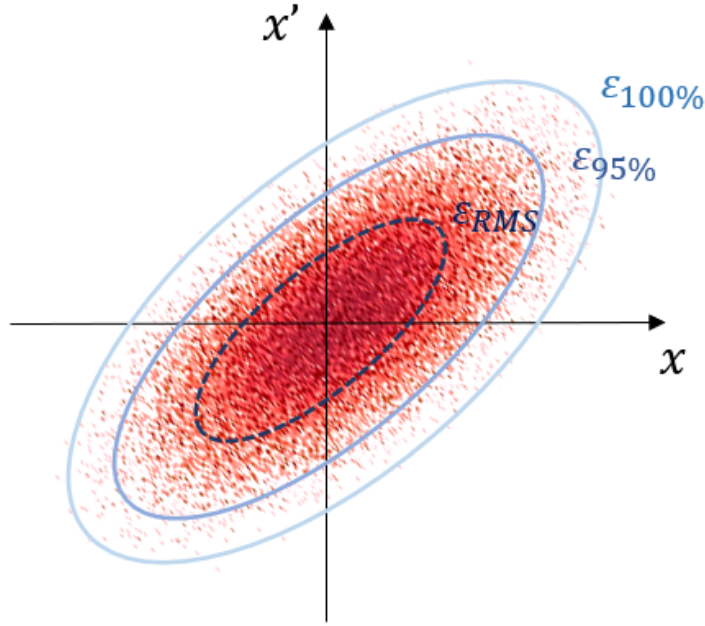


Figure 2.1. Illustration of different emittance definitions

One of the most important properties of emittance is its conservation during focusing and defocusing of the beam. This principle is a direct consequence of Liouville's theorem, which states that the phase space volume remains constant over time. In the context of beam dynamics, this implies that although the beam size or the orientation of the beam ellipse may change due to focusing or defocusing elements, the total area the beam occupies in phase space, the emittance, remains invariant as long as there are no non-conservative forces such as space charge effects.

For accelerators, it is more convenient to introduce the *normalised emittance*

$$\varepsilon_n = \beta\gamma\varepsilon \quad (2.4)$$

Since during acceleration the longitudinal momentum increases while the transverse momentum remains unchanged, this leads to an effective decrease of beam divergence $x' = p_x/p_z$, and consequently a decrease of emittance. Normalised emittance however remains constant even when the particle energy is changing due to external electric fields.

The concept of emittance is useful for characterising collective properties of a particle beam. Since all particles enclosed by the phase ellipse remain within this ellipse, describing the beam motion as a whole requires only knowing how the ellipse parameters change along the accelerator.

2.1.2. Longitudinal beam dynamics

While transverse fields allow to focus a beam and guide it through the beam line, they do not contribute to increasing the energy of the particles. To accelerate particles, we require fields with non-zero longitudinal component.

Accelerators are designed to accelerate an ideal particle, which always stays in phase with the accelerating field and follows an ideal trajectory. Let an electromagnetic wave propagate in the accelerating cavity:

$$E_z(z, t) = E(z) \cos(\omega t + \varphi)$$

For effective acceleration, the wave's phase velocity must be close to the particle velocity. A particle whose velocity at each moment equals the wave's phase velocity experiences a force $F_z = qE(z) \cos \varphi$ and is called a *synchronous particle*, with the phase $\varphi = \varphi_s$ called the *synchronous phase*.

Such a particle always arrives at the next cavity when the electromagnetic phase equals φ_s .

Longitudinal bunching and acceleration are stable if the synchronous particle arrives during the rising electric field, that is, when the synchronous phase satisfies $-\pi < \varphi_s < 0$. Particles that arrive earlier (with smaller phase) experience a smaller force and thus have smaller energy gain, while slower particles that arrive later (with larger phase) receive more energy and catch up with the synchronous one. Like this, a *bunch* of particles is formed around a synchronous particle.

If we consider instead a synchronous particle that arrives on the falling slope of the electric field, a particle that arrives early will gain more energy, accelerating even more. In this case, particles with a small deviation in phase from the synchronous will deviate even more and eventually will be lost.

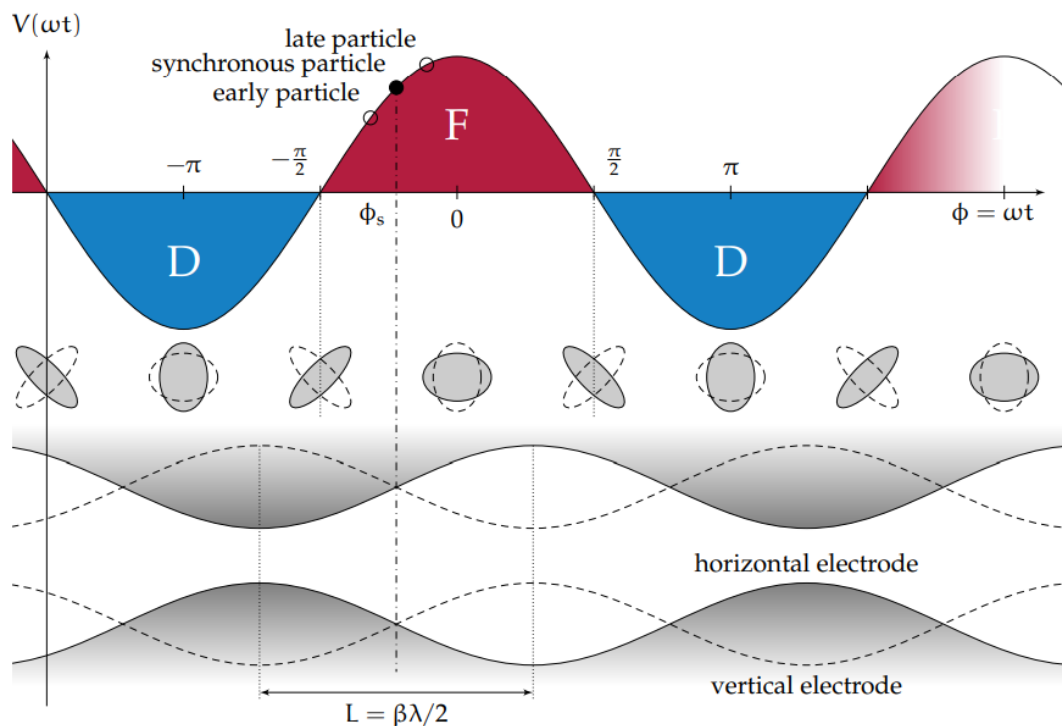


Figure 2.2. Illustration of the phase stability principle. Particles that arrive at the accelerating cavity earlier or later than the synchronous particle are collected into one group—a bunch. Phase ellipses show transverse focusing-defocusing when passing through an RFQ cavity. [3]

Similarly to transverse emittance, *longitudinal emittance* is also defined. For linear accelerators, it is most convenient to define it in terms of phase and energy:

$$\varepsilon_l = \Delta\varphi\Delta E$$

2.2. Ion sources

A particle source is an essential component of any particle accelerator, as it generates the initial beam that is accelerated by the rest of the system. A typical ion source consists of two main parts: a *particle generator* and an *extraction system*. A particle generator needs to provide a sufficient number of the desired particles for the extraction system. The extraction system, on the other hand, must be able to produce a beam with the desired shape and emittance for further transport and acceleration. [9]

The most common way of generating particles is by creating plasma with an electric discharge.

2.2.1. Extraction system

The extraction system has two main functions. First, it separates the desired ions from electrons and other particles coming from the plasma. Second, it shapes the initial beam parameters, especially its emittance. The basic principle of extraction consists of applying a high voltage between a particle-emitting surface and an extraction electrode with a hole in it. [9]

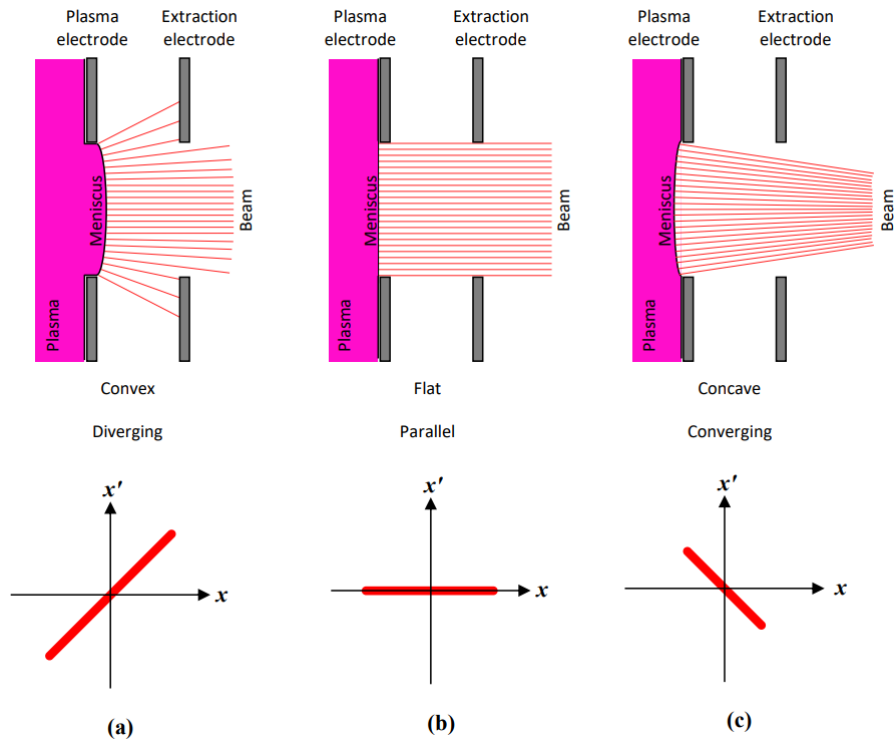


Figure 2.3. Relation between plasma meniscus shape and initial divergence of a beam.

At the extraction region, the plasma is bounded by an electrode with a hole in it, called the *plasma electrode*. The edge of the plasma limited by the plasma electrode is called the plasma meniscus and serves as the transition between the plasma and the particle beam. The shape of the plasma meniscus determines the initial divergence of the beam.

The shape of the plasma meniscus is influenced by the plasma density and the electric field in the region, which mainly depends on the geometry of the plasma electrode and the voltage applied to the puller electrode. When the distance between the plasma electrode and the puller is fixed, the beam divergence and emittance are primarily determined by the puller voltage. The voltage applied to the plasma electrode determines the energy gained by the particles during extraction. Due to the nature of the ion source, there is always a spread in the kinetic energy of the initial beam.

2.2.2. ECR ion sources

An Electron Cyclotron Resonance Ion Source (ECRIS) is a type of ion source commonly used to generate beams of singly and multiply charged ions. The main principle of ECRIS operation is electron impact ionisation, where electrons collide with neutral gas atoms to produce ions.

In an ECR ion source, ionisation is achieved by heating free electrons through electron cyclotron resonance (ECR). A few free electrons are heated by injecting an electromagnetic wave that matches the electron cyclotron frequency in a magnetic field

$$\omega_f = \omega_{ce} = \frac{eB}{m_e} \quad (2.5)$$

These resonantly heated electrons gain enough kinetic energy (on the order of a few keV) to ionise neutral gas atoms through successive collisions.

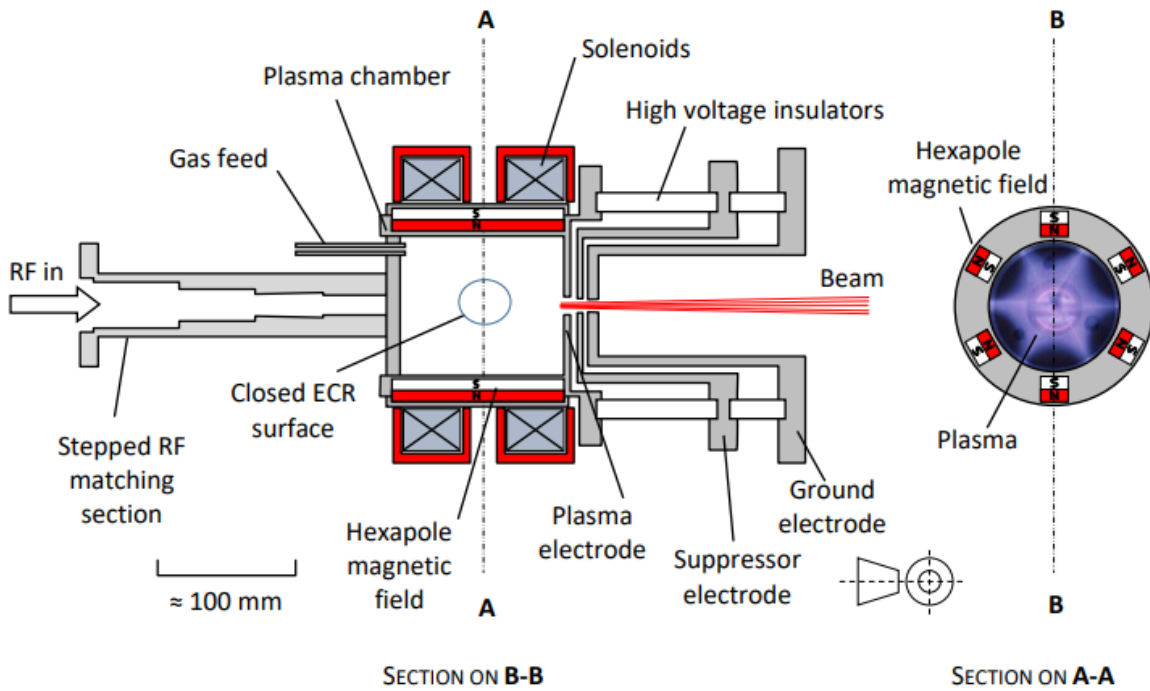


Figure 2.4. Schematics of ECR ion source [9]

To maintain the ionisation process, plasma needs to be confined through a combination of magnetic fields. The axial confinement is achieved using two solenoids that form a magnetic mirror. The solenoids generate stronger magnetic fields at the ends of the plasma chamber and a weaker field in the middle, trapping electrons along the axis. Radial confinement is achieved using a hexapole magnet, which surrounds the chamber and contains the plasma radially. The combination of hexapole and solenoidal fields creates a «closed ECR surface» where the Larmour frequency of the electrons is equal to the frequency of the injected microwaves. As electrons cross this surface multiple times, they are repeatedly accelerated. Due to complex magnetic fields, plasma electrons undergo gyromotion even outside the resonance surface. As a result, they can receive additional heating if their motion matches the frequencies of the excited modes within the plasma chamber. This ECR heating process can raise electron energies to a few kiloelectron volts, which are sufficient to ionise injected gas.[9; 10]

The performance of the ion source, especially the extracted beam current, is primarily determined by the plasma parameters. Although the extraction system and beam optics influence the beam quality, they cannot fundamentally change its properties.[11]

2.3. RFQ

The Radio Frequency Quadrupole (RFQ) is a crucial component of linear accelerators. RFQ is used to accelerate low-energy hadrons in the range of 2 keV to 3 MeV. It provides simultaneously acceleration, focusing and bunching using electric field. [1]

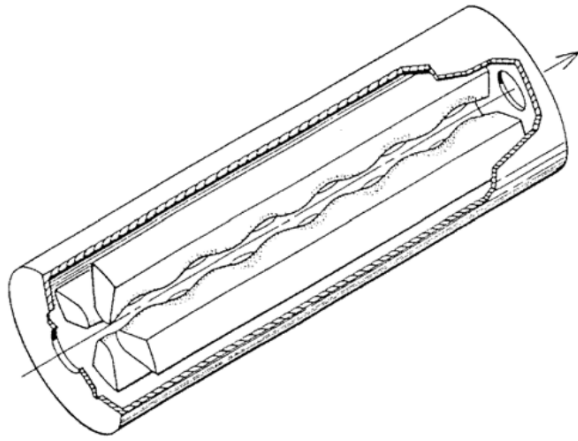


Figure 2.5. Schematic view of a four-vane RFQ [12]

2.3.1. Resonant modes

In free space, the solution to the wave equation

$$\nabla^2 \vec{E} - \frac{1}{c^2} \frac{\partial^2 \vec{E}}{\partial t^2} = 0 \quad (2.6)$$

is an electromagnetic wave of the transverse electromagnetic (TEM) type, where the electric and magnetic field vectors are perpendicular to the direction of propagation.

Inside a resonant cavity bounded by conducting walls, the solution must also satisfy boundary conditions:

$$\vec{n} \times \vec{E} = 0, \quad \vec{n} \cdot \vec{H} = 0 \quad (2.7)$$

Applying these boundary conditions leads to an eigenvalue problem, and the electromagnetic fields that satisfy it are the eigenmodes of the cavity. As a result, only TE or TM modes can exist inside the cavity, with transverse electric or magnetic components, respectively. Figure 2.6 shows the first two TE modes in a cylindrical cavity.

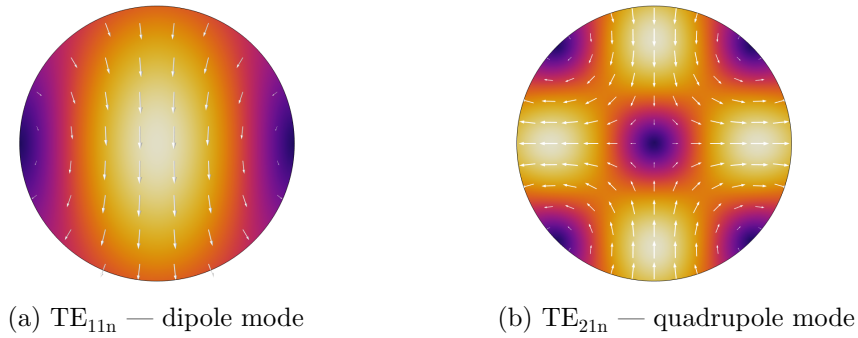


Figure 2.6. First two TE modes of a cylindrical cavity

2.3.2. RFQ geometry

The RFQ consists of a resonant cavity and four electrodes, as illustrated in Figure 2.5. This configuration creates a quadrupole electric field that supports the TE_{210} mode. An alternating voltage of the form $\pm V_0 \cos \frac{\omega t}{2}$ is applied to the electrodes so that adjacent electrodes have opposite polarity. This produces a field gradient that focuses the beam in one transverse direction while defocusing it in the other, without accelerating it. As the polarity alternates over time, the system creates a focusing-defocusing structure with a period of $\beta\lambda$, where β is the particle velocity and λ is the RF wavelength. The strength of the focusing remains constant along the RFQ and does not depend on the particle velocity.

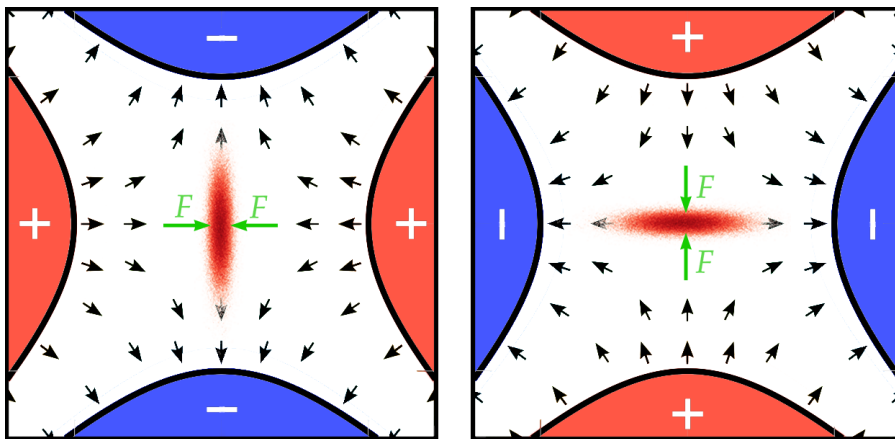


Figure 2.7. Focusing-defocusing mechanism of an RFQ

If the electrode profile is constant along the axis, the electric field remains purely transverse. To generate a longitudinal field component for

acceleration, the electrode profile must be modulated. This modulation distorts the pure TE mode and introduces a longitudinal field component whose strength is proportional to the modulation depth. The modulation of the top and bottom electrodes is phase-shifted by 180° relative to the left and right ones.

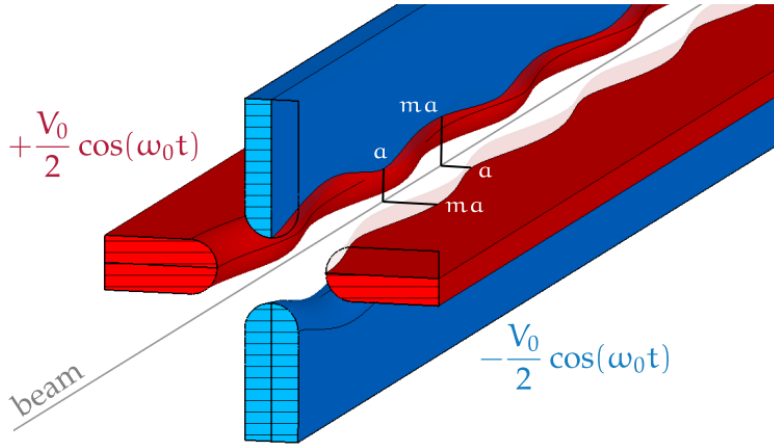


Figure 2.8. Principle of RFQ acceleration. Modulation of opposite electrodes is mirrored, while the modulation of adjacent electrodes is shifted by half a period. [3]

Another key feature of the RFQ is its ability to bunch the beam, which is crucial for efficient acceleration. Unlike conventional accelerators, where bunching and acceleration are performed in separate stages (often degrading beam quality), the RFQ combines both processes. Because acceleration is determined by the electrode geometry along the beam path, a smooth increase in modulation depth enables adiabatic bunching.

The beam dynamics in an RFQ are entirely defined by the electrode geometry. The aperture sets the focusing strength and allowable beam size, the modulation depth controls the accelerating field, and the spacing between modulation peaks and troughs determines the phase synchronism between the field and the particles. [13]

2.3.3. Definition of RFQ acceptance

The *acceptance* refers to the maximum beam ellipse that is able to pass through an RFQ and be effectively accelerated. Acceptance is expressed in the same units as emittance and similarly to emittance we distinguish between transverse and longitudinal acceptance.

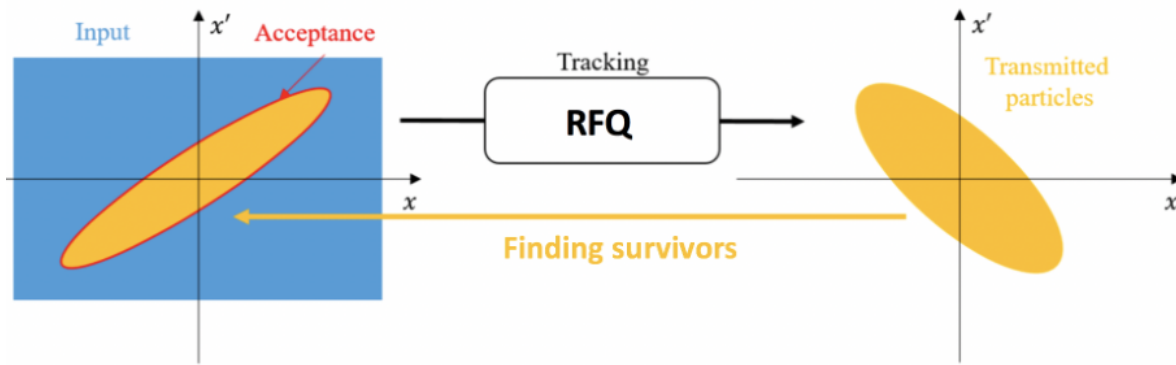


Figure 2.9. Illustration of how the acceptance is determined [2]

Acceptance is determined by identifying the surviving particles that were successfully accelerated by the RFQ. The distribution of the initial particles that correspond to acceptance forms an ellipse in transverse phase space. A beam is considered *matched* when it has the same Twiss parameters as the acceptance.

CHAPTER 3.

MATERIALS AND METHODS

3.1. Experimental setup

As a part of medical applications research, a compact 750 MHz RFQ was designed at CERN. It is designed to accelerate carbon $^{12}\text{C}^{6+}$ ions with a charge-to-mass ratio q/m of $1/2$, but is also capable of accelerating particles with a charge-to-mass ratio of 1, such as protons [14]. The RFQ has a total length of 4.75 m and is split into two cavities. The first cavity consists of four modules with a total length of 2.35 m, accelerating particles from 15 keV/u to 2.5 MeV/u, its main parameters are given in table 3.1.

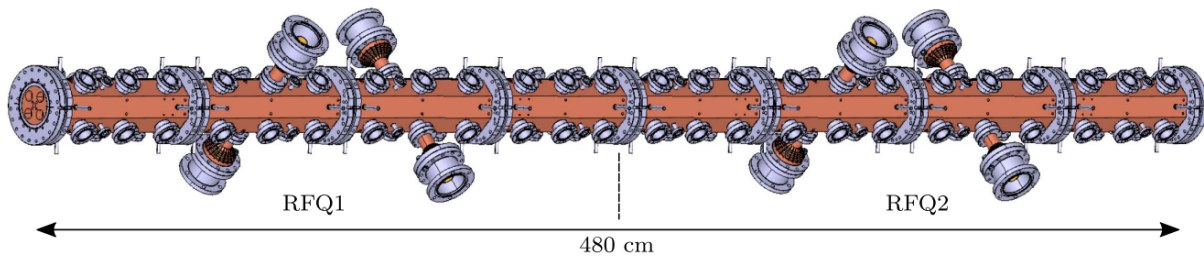


Figure 3.1. CAD model of two RFQ cavities [3]

Table 3.1

Main parameters of the first RFQ cavity [3]

Length	2.35 m
Input energy	15 keV/u
Output energy	2.5 MeV/u
RF frequency	750.00 MHz
Transmission	55 %
Transverse acceptance (RMS norm.)	0.02 $\pi\text{mm}\cdot\text{mrad}$
Input beam current	0.19 mA
Inter-vane voltage	50 kV

In the scope of commissioning the Carbon RFQ, several ion sources are considered. The initial commissioning will be done with proton beam, with subsequent transition to ${}^4\text{He}^{2+}$ which has the same charge-to-mass ratio of $1/2$ as ${}^{12}\text{C}^{6+}$, and, eventually, to ${}^{12}\text{C}^{6+}$ itself.

3.1.1. Monogan proton source

The proton source used for initial commissioning of the RFQ is the Monogan 1000 electron cyclotron resonance (ECR) ion source by Pantechnik. Two magnetic rings are placed around the plasma chamber to radially and axially confine the plasma. Monogan runs on 2.45 GHz RF and is capable of producing beam intensities up to 40 mA.

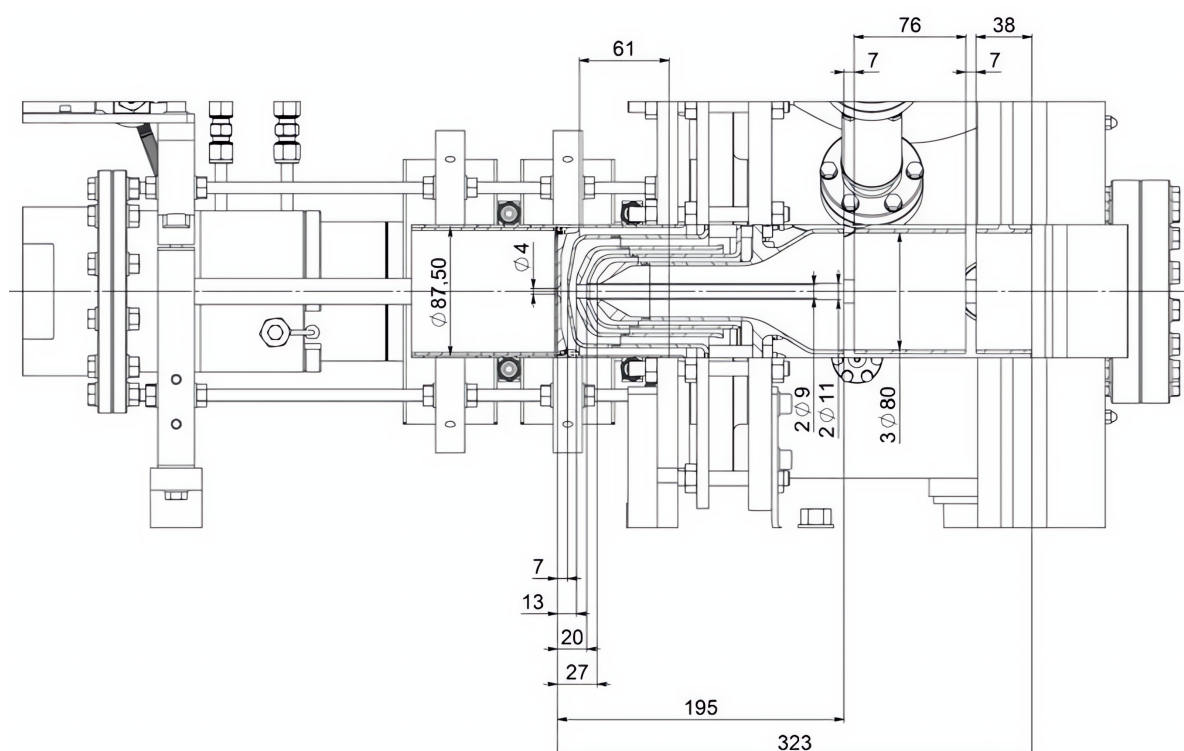


Figure 3.2. CAD drawing of Monogan 1000 ion source

The beam is extracted from the plasma using a five-electrode extraction system:

- 1) the *plasma electrode* determines the beam energy and is biased at 15 kV to match the RFQ input energy;
- 2) the *puller*
- 3) the first grounded electrode;
- 4) the *electron repeller* prevents electrons from escaping the plasma chamber. It is typically biased with a small negative voltage, but it is kept at ground potential in our case.
- 5) the second grounded electrode.

The source is additionally equipped with an einzel lens to focus the beam at the exit of the source. The einzel lens consists of three electrodes: the first grounded, an extension of the second grounded electrode of the pentode extraction system, a central electrode that can be biased positively or negatively up to 25 kV, and a third grounded electrode. Depending on the bias sign of the central electrode, we can have either a decelerating-accelerating configuration or an accelerating-decelerating one.

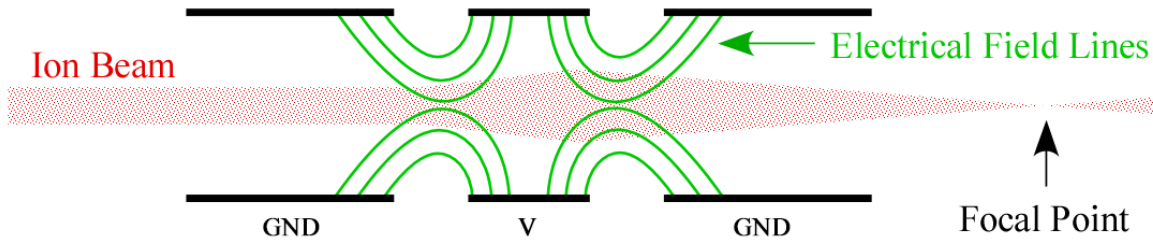


Figure 3.3. Einzel lens focusing mechanism

Electrostatic focusing elements, however, do not allow separation of different ion types or charge states.

Since compact design is important for hadron therapy, we aim to minimise the length of a beamline. Ideally, the beam should be matched to the RFQ acceptance right after the source with a small drift distance for connections and diagnostics.

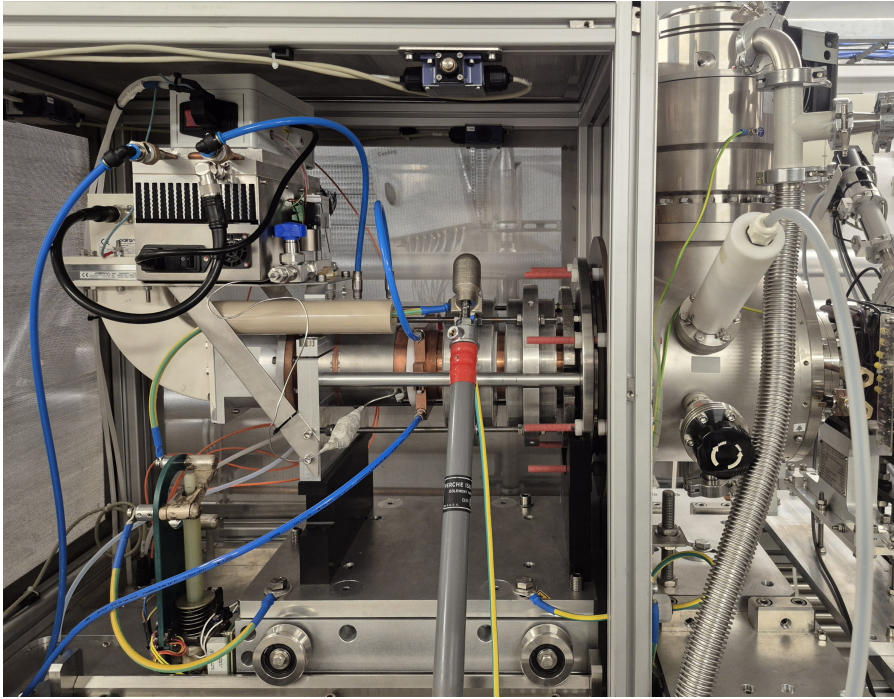


Figure 3.4. Picture of Monogan ion source

3.1.2. Supernanogan source for helium beam

The Supernanogan is a commercial 14.5 GHz ECR ion source by Pantechnik. It is capable of producing a wide range of multiply charged ions (Table 3.5) with energies of up to 30 keV.

ion / Q	1	2	4	6	8	9	20	27
H	2000							
He	2000	1000						
C			200	2,5				
Ar	1000		250	200	200	90		
Xe	500				220		15	1
Au							20	6
Pb							10	1

Figure 3.5. Beam intensity for various charge states in μA . (c) Pantechnik

The plasma chamber is surrounded by permanent magnets, which provide both radial and axial magnetic confinement of the plasma. A two-electrode system consisting of a *puller* and a *focus* electrode is used to extract a beam. The source body is placed at a positive potential of 30 kV,

while the puller is biased negatively to improve the beam extraction and achieve the required emittance. The focus electrode is biased positively and is used to focus and match the beam into the following optics.

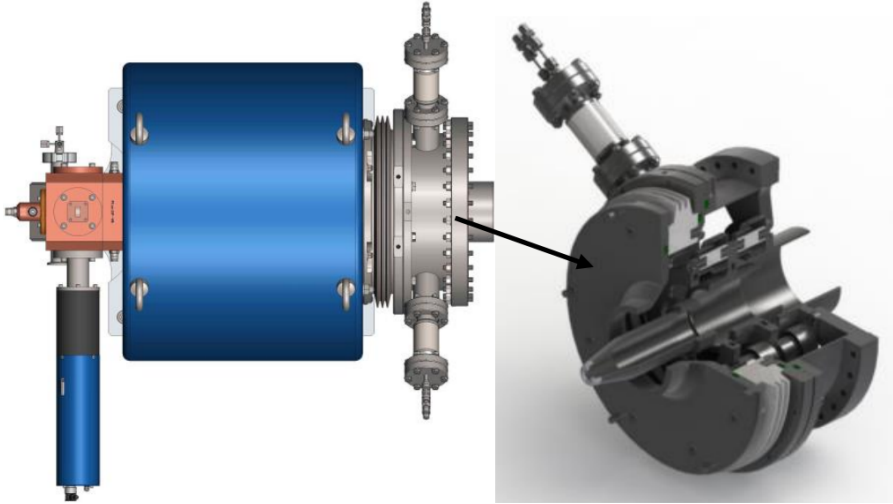


Figure 3.6. Supernanogan source body and extraction system

RF injection is done using a copper system that includes a waveguide-to-coaxial converter and a tuner to minimise reflected power. An RF window connects the high-vacuum side to the waveguide at atmospheric pressure. The injection flange also includes a DC bias system that adds electrons to the plasma. [15]

3.1.3. 750 MHz Carbon RFQ

As mentioned earlier, the 750 MHz Carbon RFQ was designed as a compact solution for medical applications. In this context, transmission efficiency was intentionally sacrificed to reduce the RFQ length. With a transmission of about 50%, the number of ions per pulse is $5 \cdot 10^8$, which is three orders of magnitude higher than the required dose for hadron therapy. The operating frequency of 750 MHz was chosen as a subharmonic of the 3 GHz linac to allow injection into subsequent accelerating structures.

A distinctive feature of this RFQ is its use of trapezoidal vane electrodes. This geometry was selected to increase acceleration efficiency, resulting in a 20% shorter RFQ and reduced power consumption compared to standard vane shapes. [6]

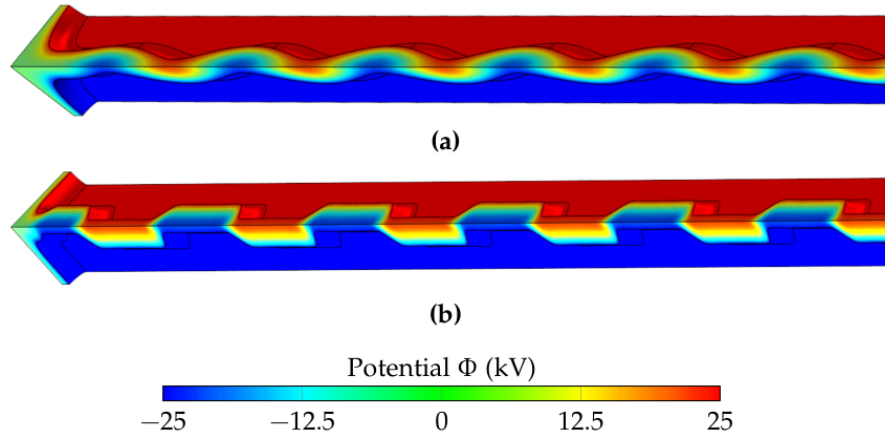


Figure 3.7. Electric potential of the Carbon RFQ vanes with standard design (a) and trapezoidal design (b) [6].

By design, the Carbon RFQ has an overall length of 4.75 m. To maintain RF-field stability, it is split into two nearly identical cavities that can be individually tuned and commissioned. The first cavity (RFQ1) is 2.35 m in length and accelerates ions from 15 keV/u to 2.5 MeV/u. The second cavity (RFQ2), with a length of 2.33 m, accelerates them further to 5 MeV/u

Each cavity consists of four 60 cm modules and is powered via four power couplers[14].

3.1.4. Diagnostic box

To characterise the source and validate the simulations, a diagnostic box (DB) was installed 56 cm downstream the source bore, 14 cm before the RFQ MP. It consists of two slits to measure horizontal and vertical

profile, and a Faraday cup for current measurements. Both tools are driven by stepper motors that allow precise positioning.

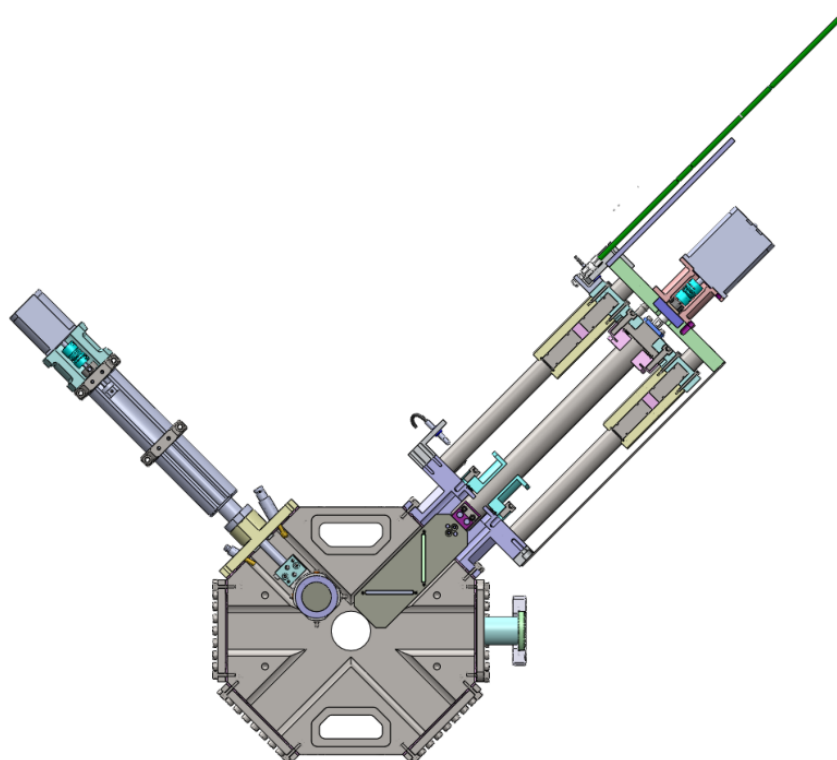


Figure 3.8. Section view of the DB

Faraday cup

A Faraday cup is a diagnostic device used to measure beam current and is capable of detecting currents as low as a few picoamperes. The Faraday cup is a destructive diagnostic tool, stopping the beam entirely. It is used for DC current measurements and is typically employed for low-current beams, as higher beam currents can generate significant heat.[\[16\]](#)

The Faraday cup operates on the principle of electrostatic induction. It consists of an outer shell made of conductive material. When the cup is inserted into the beam path, incoming particles induce a charge

on its walls proportional to their number. This results in a net charge accumulation, which is then discharged through a current-to-voltage converter, allowing the beam current to be measured. Inside the outer shell, there is often an insulating material to prevent the induced charge from dissipating into the surrounding environment.

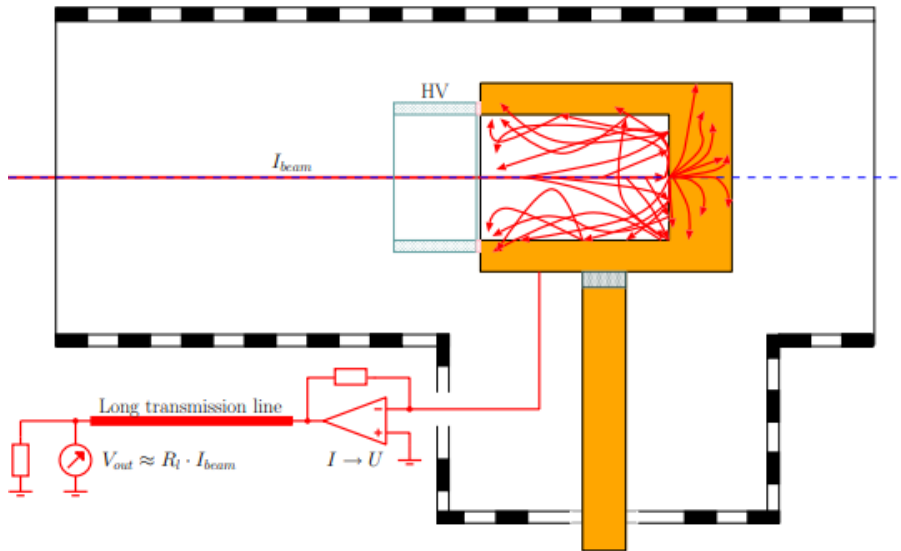


Figure 3.9. Principle of operation of a Faraday cup [16]

When the beam interacts with the cup material, it generates secondary electrons, which can distort current measurements. In the case of a proton beam, this leads to an apparent increase in the measured charge. To minimise this effect, the cup is negatively biased to recapture the low-energy secondary electrons. [2]

Slits

The diagnostic box is equipped with a blade that holds two slits, one horizontal and one vertical, for measuring the transverse beam profiles. The transverse beam profile is a histogram that shows the number of particles in a beam as a function of the position. The horizontal

slit provides the vertical beam profile, while the vertical slit gives the horizontal profile.

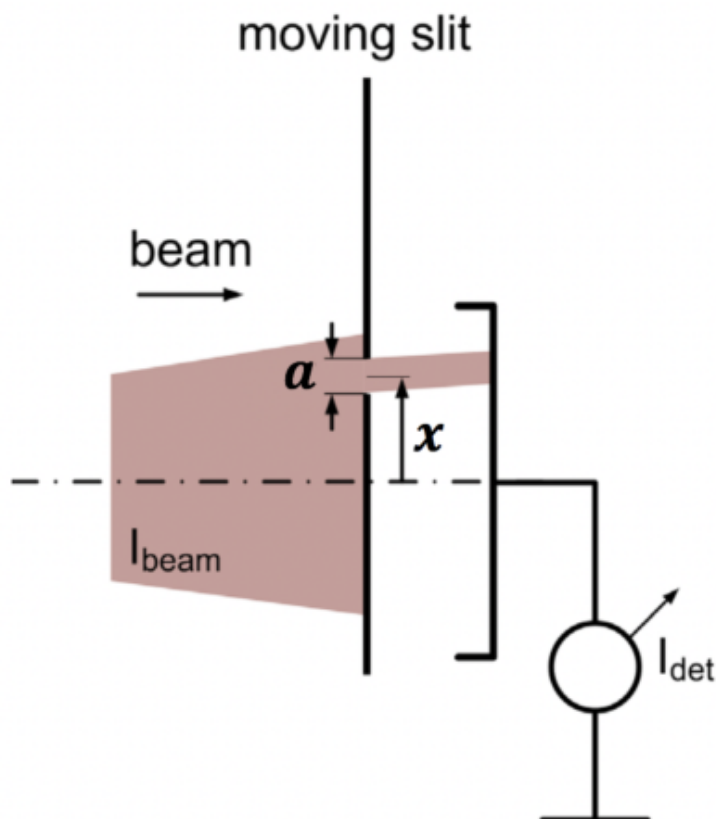


Figure 3.10. Principle of profile measurements

To perform the measurement, a stepping motor incrementally moves the blade so that the slit scans across the beam, sampling narrow slices. As the slit moves, a Faraday cup positioned downstream along the beam axis measures the current passing through the slit at each position. This is illustrated in figure 3.10. By recording the current as a function of slit position, it is possible to reconstruct the beam profile.

One of important parameters is the slit aperture. Narrower slits give better resolution but reduce signal strength. Moreover, a large fraction of particles is scattered on slit edges. Meanwhile wider slits increase the signal but have lower spatial accuracy. [2]

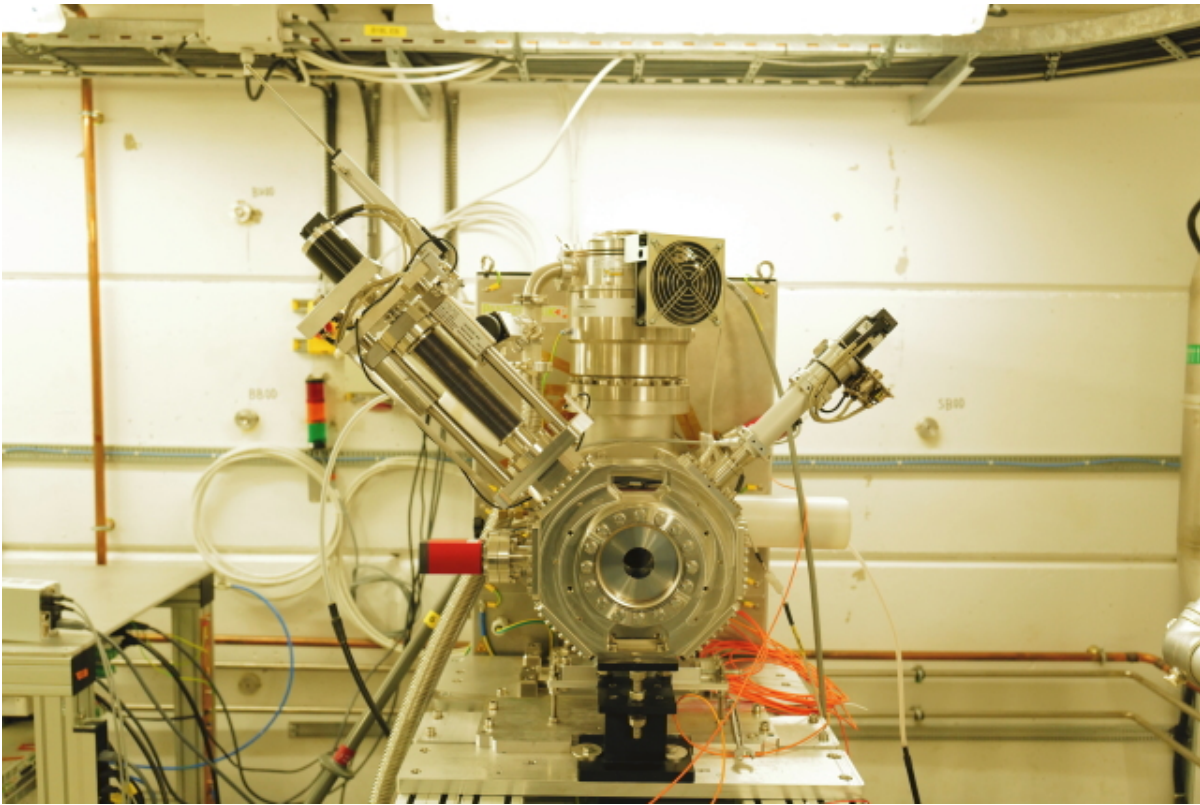


Figure 3.11. Diagnostic box installed after Monogan source

3.2. Simulation tools

Accurately predicting beam behaviour is essential for both the design and operation of particle accelerators. Multiparticle beam tracking is a fundamental tool to simulate particle dynamics as they traverse various accelerator components. Particle tracking codes are based on numerical integration and can account for interaction between particles and non-linear effects. The electromagnetic fields of accelerating components are represented by field maps generated beforehand in specialised software such as ANSYS or COMSOL.

3.2.1. Poisson Superfish

Poisson Superfish (SF) is an electromagnetic solver by LANL [17]. It is used to solve electrostatic problems in two and three dimensions

and is widely used in the design and optimisation of particle accelerators. It applies the finite element method to numerically solve the Poisson equation for the electric potential within the specified region. First, a triangular mesh is generated. Once the mesh and boundary conditions for the elements are defined, the Poisson solver based on the Successive Point Over-Relaxation (SPOR) method is used to solve the discretised problem. Once the Poisson equation has been solved in every point of the region of interest, the resulting field map is extracted and used for subsequent particle tracking simulations.

3.2.2. Travel

Generated field maps are then used to perform beam dynamics simulations using the particle tracking code TRAVEL [18], developed at CERN. TRAVEL is a program for numerical simulation of the motion of many-particle beams through electromagnetic fields in the presence of space charge. It allows tracking the evolution of the RMS and average parameters of the beam, particle losses, and selecting particles by imposing certain conditions.

In order to run a simulation in TRAVEL, we need to define an input beam and beamline structure. The input beam is a text file that contains information about initial coordinates, divergences, energy, phase etc of every particle in a beam. Beamline file allows to define step size, space charge and what accelerator components we have and where.

3.2.3. General simulation process

The general simulation process begins with analysing how different electric field distributions influence the beam coming from the source. First, electric fields inside the source are simulated using Superfish for a given voltage configuration, then an approximate output beam from the plasma is defined as the input beam used for particle tracking in TRAVEL. This process is repeated for a different fieldmap with different voltages applied to the electrodes.

Since the Poisson equation is linear, this process can be automated by generating individual field maps for each electrode and using a Python script to vary the voltages and combine them into a single field map. Based on the results of these voltage scans, we can see whether the beam can be matched directly to the RFQ or if we need to introduce a dedicated low-energy beam transport line (LEBT).

Finding matching condition corresponds to finding the set of parameters (electrode voltages, drift spaces etc.) that maximise the number of particles inside the RFQ acceptance.

CHAPTER 4.

BEAM DYNAMICS SIMULATIONS

4.1. Monogan proton source

Electric field simulations

To obtain the electric field distribution inside the source for different electrode voltages, the source geometry was reproduced (fig. 4.1) in Poisson Superfish (SF) under the assumption of cylindrical symmetry.

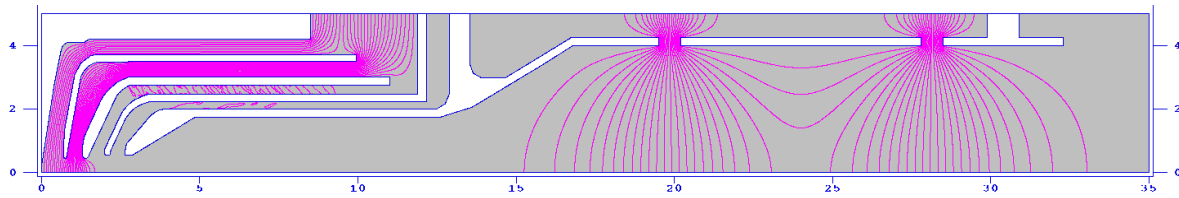


Figure 4.1. Monogan geometry reproduced in SF with electric field distribution

Figure 4.2 shows longitudinal electric field on axis E_z along the beamline for $V_{\text{plasma}} = 15$ kV, $V_{\text{puller}} = 10$ kV, and $V_{\text{lens}} = 12.5$ kV.

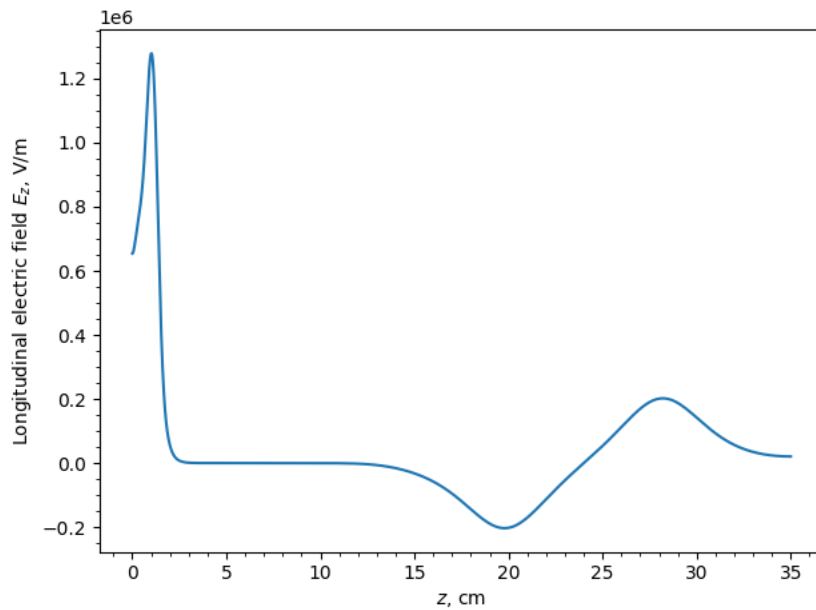


Figure 4.2. Electric field on axis along the beamline

We can observe a very high field on axis in the extraction region reaching up to $1.3 \cdot 10^6$ V/m. This field shapes the initial parameters of the beam. High field in this region can lead to an immediately over-focused beam that can be difficult to focus back with the einzel lens.

Beam particle tracking

Generated field maps are then used to perform beam dynamics simulations using the particle tracking code TRAVEL [18]

The input beam was taken to be a uniform proton beam with an energy of 100 eV, which spans from -2.5 mm to 2.5 mm, matching the plasma electrode aperture, and has a divergence of 10 mrad. A total of 50,000 particles were tracked.

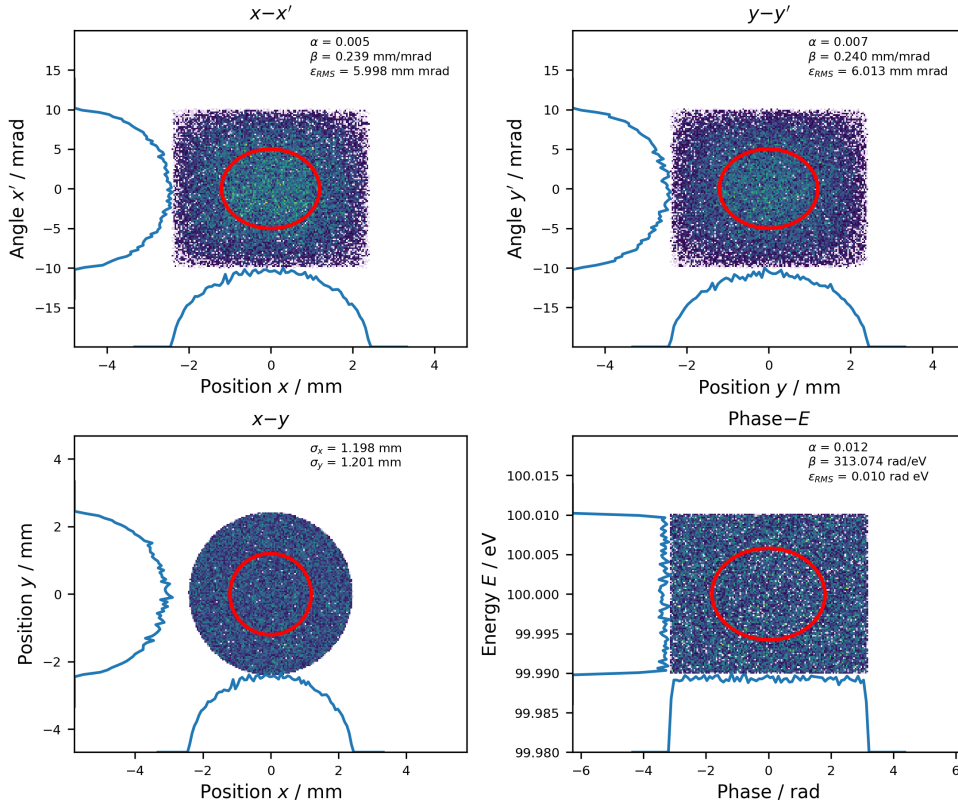


Figure 4.3. Input beam used for particle tracking simulations in TRAVEL

Figure 4.4 shows the evolution of beam parameters such as beam size and emittance along the beamline for different einzel lens voltages.

Increasing the Einzel lens voltage results in a more focused beam with a reduced size, however, it also causes higher emittance.

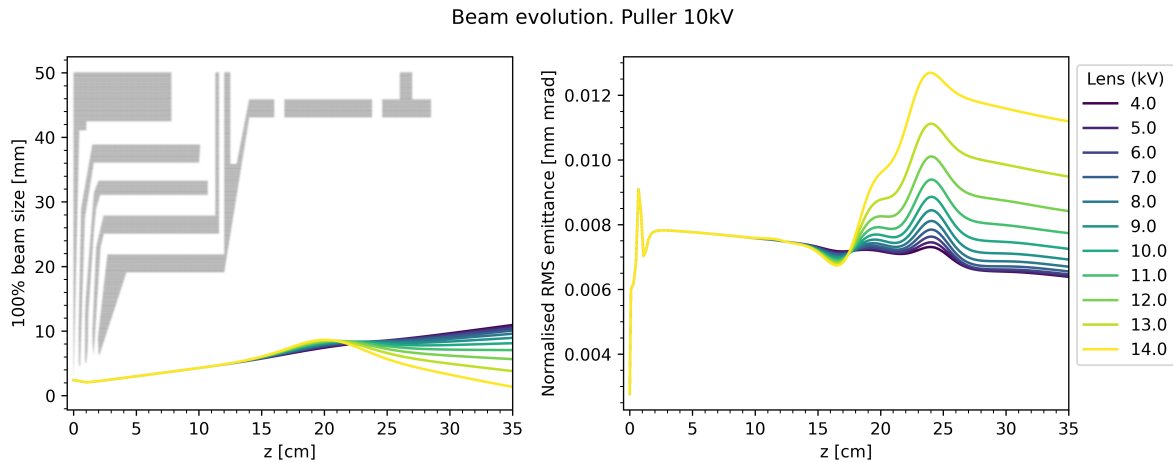


Figure 4.4. Full beam size and RMS emittance along the beamline for different einzel lens voltages

Figure 4.5 shows the evolution of beam parameters such as beam size and emittance along the beamline for different puller voltages. Higher puller voltages result in a more focused beam with reduced divergence and lower emittance. Lower puller voltages lead to significant beam expansion and higher emittance, with a beam more susceptible to focusing with an einzel lens. Nevertheless, high puller voltage may lead to overfocusing, resulting in an increased emittance and rapid beam size growth.

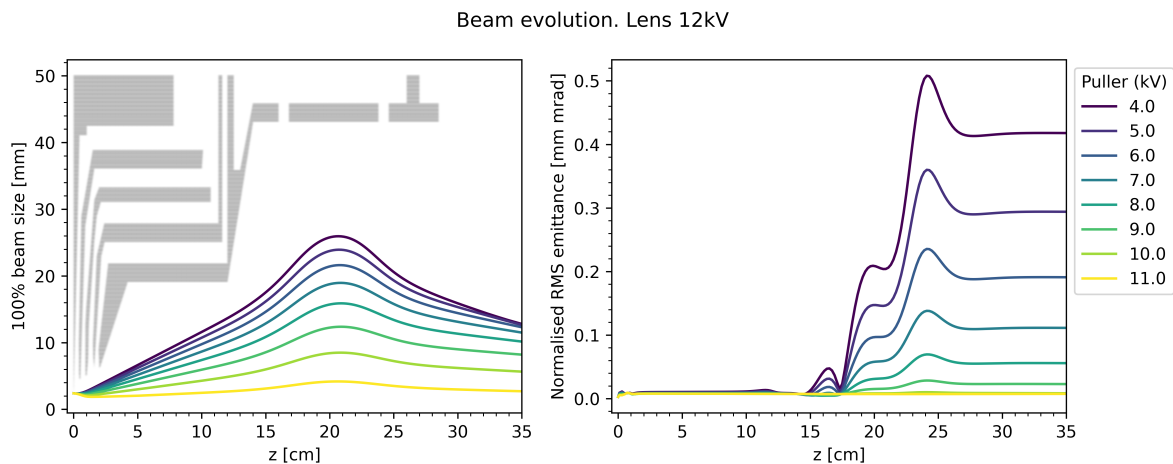


Figure 4.5. Full beam size and RMS emittance along the beamline for different puller voltages

Matching

To ensure optimal transmission and acceleration, the beam parameters must be matched to the RFQ acceptance at the RFQ matching plane (MP), located at the RFQ entrance. The RFQ acceptance is given in table 4.1.

Beam matching involves adjusting the puller and lens voltages, as well as the drift distance from the source to RFQ MP, to produce a beam that lies within RFQ acceptance and has maximal transmission.

Table 4.1

Transverse acceptance of the first RFQ cavity.		
Twiss α	Twiss β , mm/mrad	$\varepsilon_{100\%}$, mm·mrad
0.319	0.01	21.1

In the matching process, voltage configurations producing a divergent beam at the source exit were immediately discarded. Further selection excluded configurations where the matching plane is located less than 20 cm from the source to the RFQ due to technical constraints, as well as those where the distance between the source and RFQ MP is more than 70 cm in order to keep the setup compact. Potential voltage configurations and RFQ position are summarised in table 4.2.

Table 4.2

Potential matching configurations			
V_{puller} , kV	V_{lens} , kV	D , cm	Transmission
9	12.5	40	25%
9	13	18	40%
10	12.5	35	46%
10	13	18	52%
11	12.5	30	25%
11	13	18	40%

While the highest transmission coefficient ($T = 52\%$), close to the nominal value, was achieved with 10 kV puller and 13 kV einzel lens voltage and RFQ MP located 18 cm from the source, due to technical constraints we chose to go with another configuration, with RFQ MP located 35 cm from the source and voltages $V_{\text{pull}} = 10$ kV, $V_{\text{lens}} = 12.5$ kV.

Figure 4.6 shows the beam phase space at the RFQ MP, with the RFQ acceptance in red, indicating that the beam lies mostly within the acceptance.

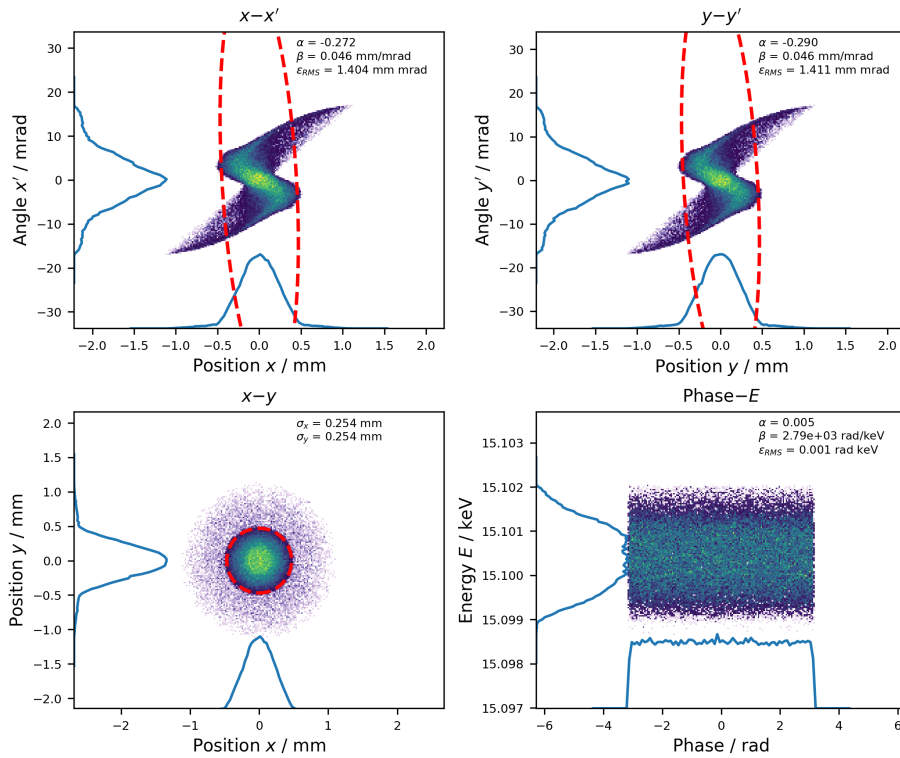


Figure 4.6. Comparison between the RFQ acceptance (in red) and the beam phase space at the RFQ MP

Figure 4.7 shows the beam parameter evolution from the source bore to the end of the RFQ. Particle losses occur within the 1-2 m section inside the RFQ due to collision with vanes, which are expected given the RFQ design.

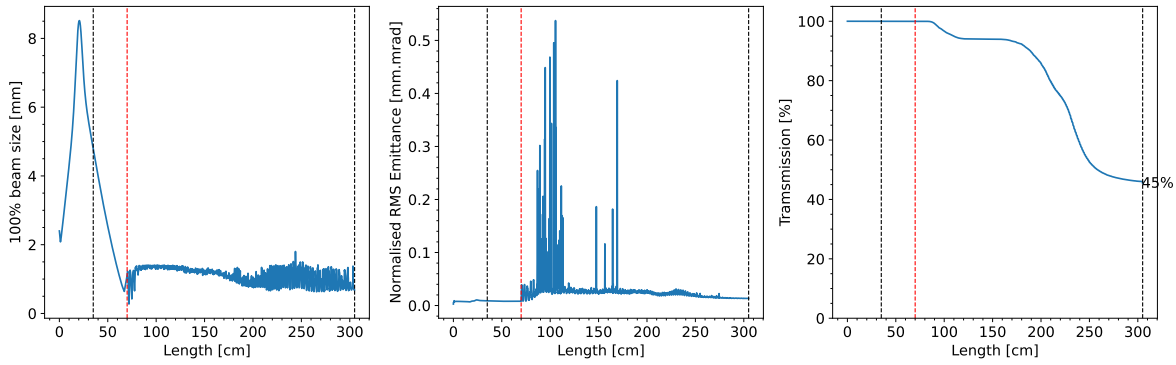


Figure 4.7. Evolution of beam parameters inside the RFQ

Space charge effects

Beam dynamics for different beam currents were simulated. The voltages were fixed at $V_{\text{puller}} = 10$ kV, $V_{\text{lens}} = 12.5$ kV, corresponding to a matched beam at 0.1 mA. Figure 4.8 shows the evolution of beam size and normalised RMS emittance for different currents.

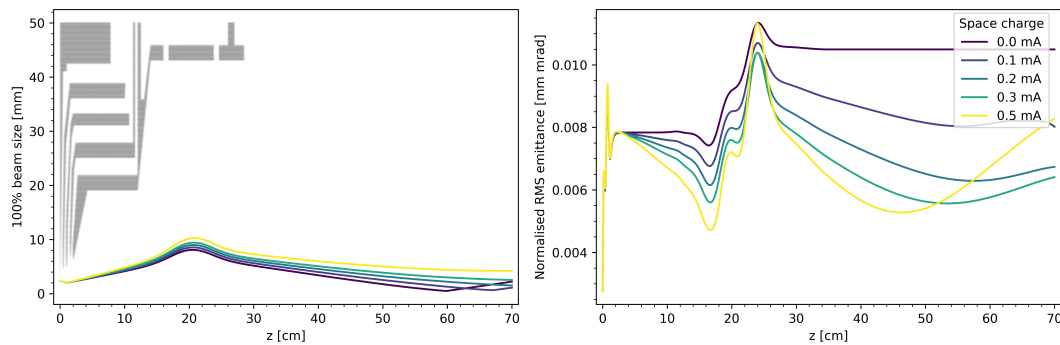


Figure 4.8. Beam parameters evolution for different space charge values

At higher beam currents, the beam size increases, requiring a higher lens voltage to compensate. However, there is a limit to how small the beam waist can become.

Space charge also has a significant effect on beam distribution. A beam matched for a specific space charge will not necessarily be matched for another. Figure 4.9 shows a comparison of the phase space for beams with currents 0.1 mA and 0.2 mA for the same voltage configuration.

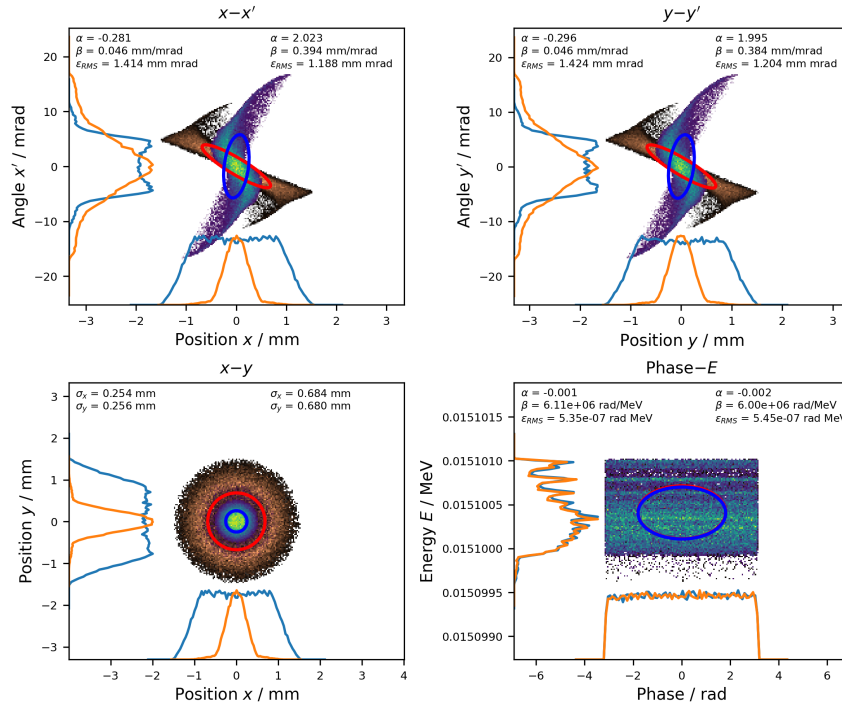


Figure 4.9. Comparison of beams with 0.1 mA current (blue) and 0.2 mA (orange) at the source output

While it is easy to compensate this for small differences in space charge, for other cases, re-matching might be complicated.

4.2. Supernanogan source for helium beam

Beam dynamics inside the source

Similarly to Monogan, the extraction geometry was reproduced in Poisson Superfish (Figure 4.10).

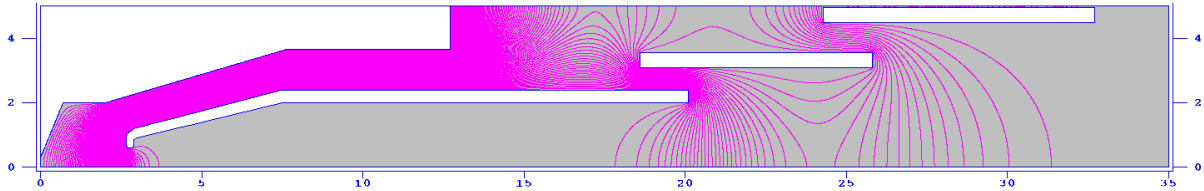


Figure 4.10. Supernanogan extraction geometry reproduced in Superfish

To investigate how different electrode voltages affect the output beam, a voltage scan was done. The input beam is He^{2+} uniform beam of energy 100 eV, initial divergence 100 mrad and beam size equal to the

source electrode aperture. In all simulations, the source electrode was kept of 30 kV, while the puller voltage was varied between 0 and -5 kV, and the focus electrode between 0 and 10 kV.

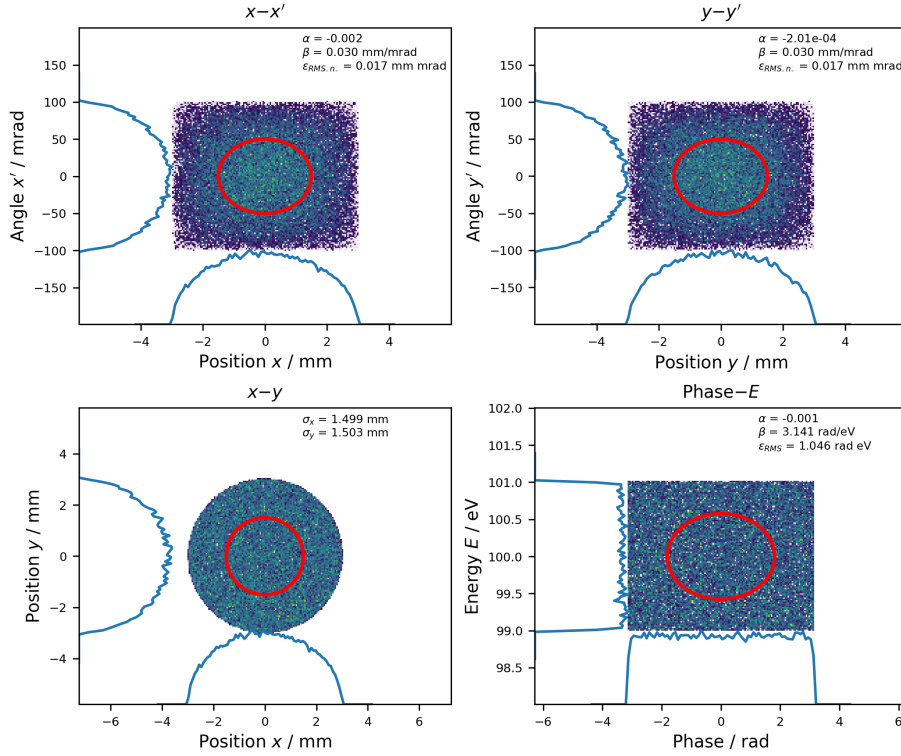


Figure 4.11. Input He^{2+} beam used for particle tracking simulations in TRAVEL.

From figures 4.12 and 4.13 we can see that beam dynamics is nearly identical in all the cases, except for a slight increase in emittance for higher focusing voltages. Output beam phase space is shown in figure 4.14 and is also quite similar for different voltages.

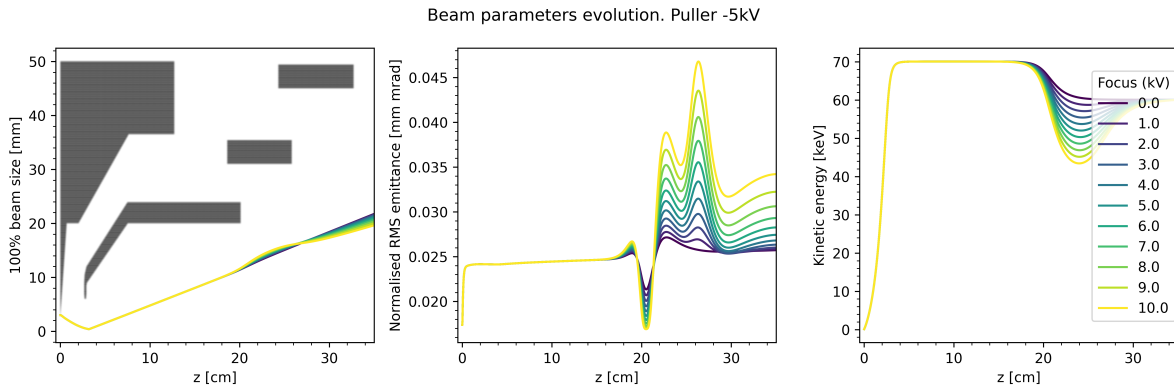


Figure 4.12. Full beam size (left), RMS emittance (center) and average energy (right) along the beamline for different focus electrode voltages. Puller is fixed at -5 kV

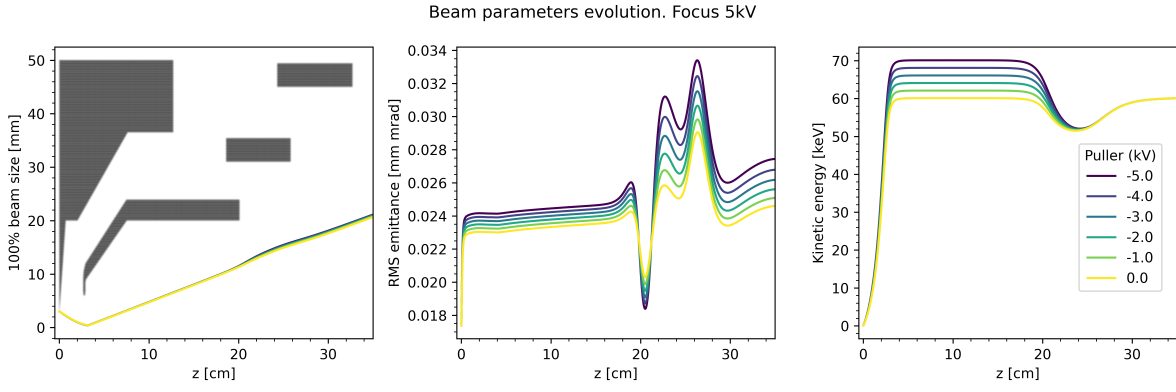


Figure 4.13. Full beam size (left), RMS emittance (center) and average energy (right) along the beamline for different puller voltages. Focus electrode is fixed at 5 kV

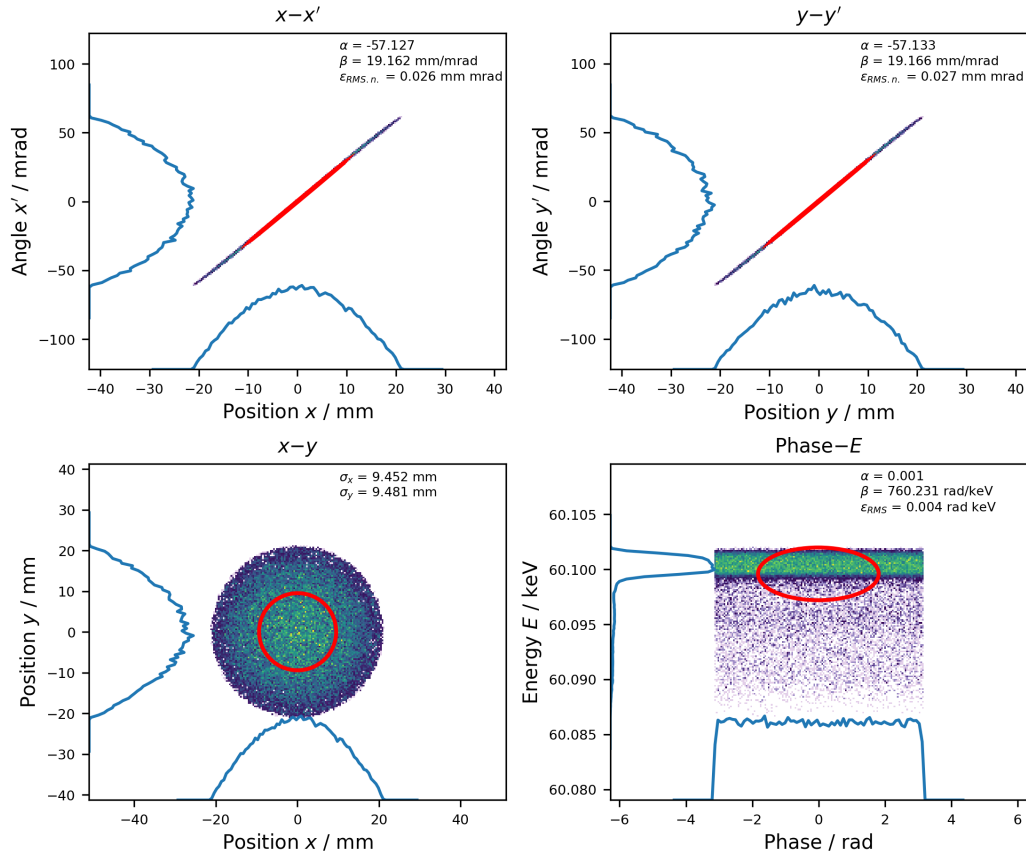


Figure 4.14. He^{2+} beam phase space at the source output

Unlike the Monogan source, where beam parameters could be matched to the RFQ acceptance by simply adjusting the focusing voltage on the einzel lens, Supernanogan geometry does not allow this. As a result, it becomes necessary to introduce a LEBT to transport and match the beam before injecting it into the RFQ.

LEBT dynamics

To match the helium beam into the RFQ, we use a LEBT that consists of two gridded lenses shown in figure 4.15.



Figure 4.15. Sketch of 2 gridded lenses LEBT [19]

The electrostatic gridded lens is an alternative to the more commonly used einzel lens or solenoid. The main advantage of the gridded lenses is smaller non-linear distortions that cause a typical for einzel lens «butterfly»-like beam in transverse plane [20]. This effect can be seen in figure 4.6 for Monogan that uses an einzel lens.

A gridded lens consists of a thin wire mesh mounted on a supporting ring that forms an equipotential surface. The mesh is made from a perpendicularly arranged grid of thin metal wires, such as tungsten. The wires are about $100\text{ }\mu\text{m}$ in thickness and spaced by a few millimetres, with smaller spacing producing smaller emittance increase. The emittance increase depends on factors such as the applied voltage, beam energy, and initial beam emittance. The gridded lens can sustain currents up to 80 mA, with beam losses at each gridded lens up to 20%. [20]

Figure 4.16 shows the evolution of beam parameters through the LEBT. We can see a rapid increase in emittance upon entering the first gridded lens, with the emittance doubling from $0.029\text{ mm}\cdot\text{mrad}$ to $0.056\text{ mm}\cdot\text{mrad}$ in the LEBT.

Figure 4.17 shows the beam phase space at the RFQ MP compared with the RFQ acceptance. We can see that most of the beam lies within acceptance, resulting in a transmission of 26% through the RFQ.

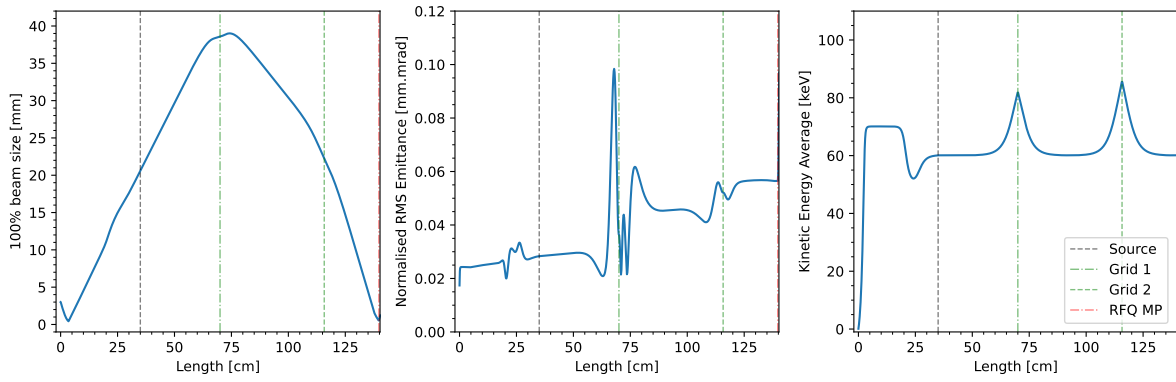


Figure 4.16. Evolution of full beam size, RMS emittance, and beam energy in the LEBT

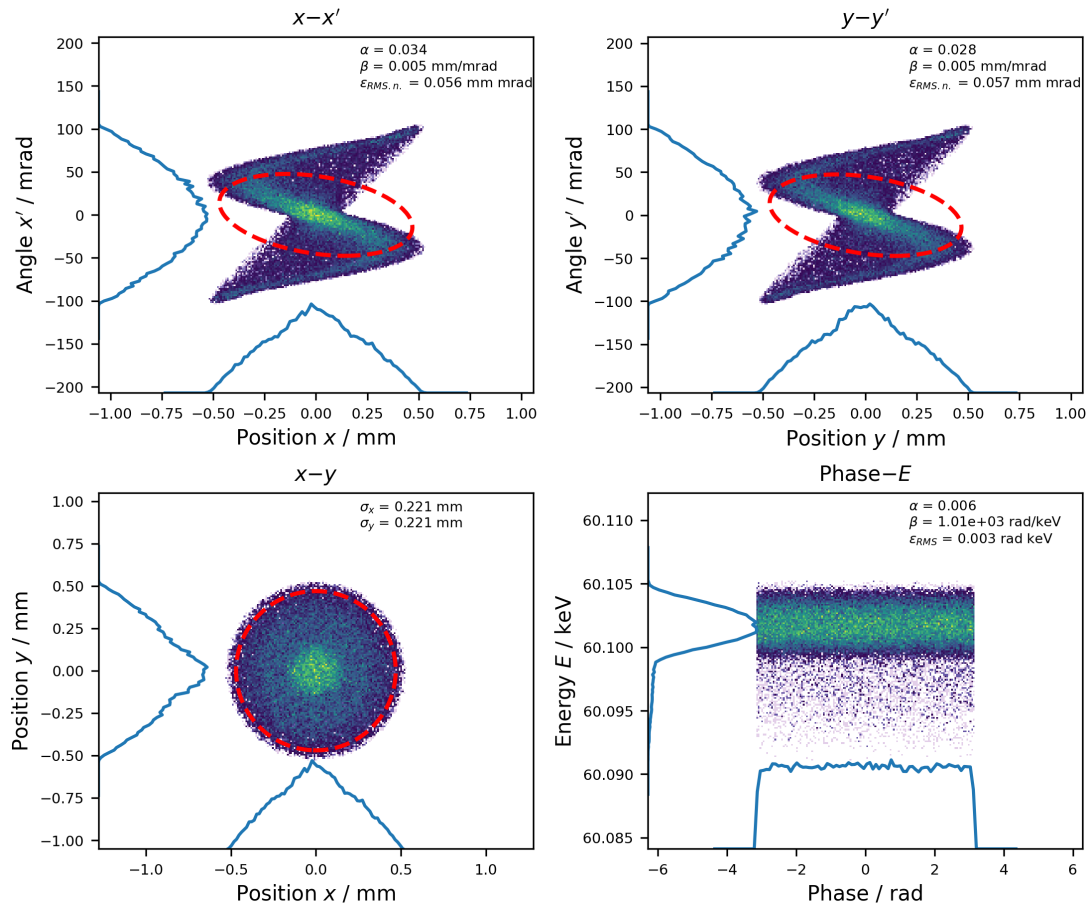


Figure 4.17. Beam phase space at the RFQ MP compared to the RFQ acceptance (red)

4.3. 750 MHz Carbon RFQ

After matching the beam to the RFQ acceptance (Fig. 4.6), we track particles through the RFQ fieldmap obtained in COMSOL. Figure 4.18 shows the evolution of horizontal and vertical RMS beam size along the RFQ together with the longitudinal electric field on axis. The beam enters the RFQ with RMS beam size of 0.25 mm, which rapidly oscillates along the RFQ due to alternating focusing in the RFQ cells. These oscillations are modulated by slower betatron beating. In the last section of the RFQ, we can clearly see the quadrupole focusing effect with the beam alternately focused in one direction and defocused in the other.

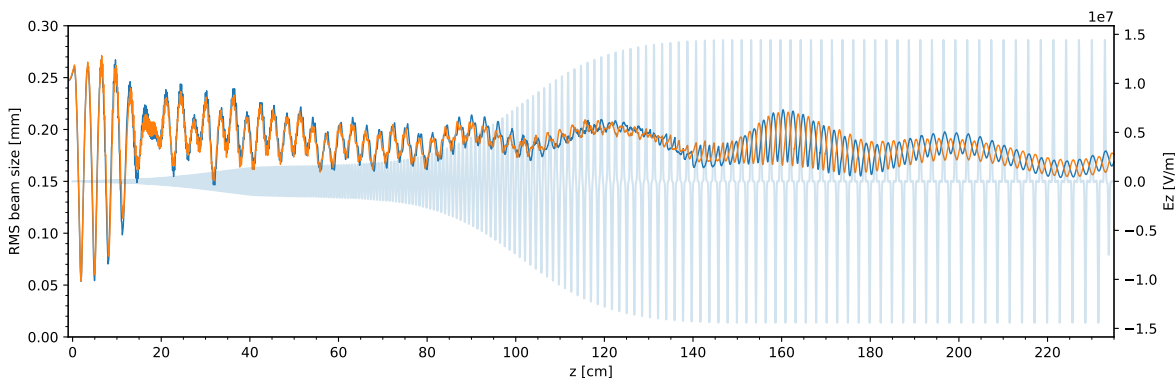


Figure 4.18. Evolution of horizontal and vertical RMS beam size along the RFQ.

A small fraction of particles exit the RFQ without being accelerated. Figure 4.19 shows a phase space of the output beam, after filtering out unaccelerated particles.

To better understand the RFQ performance, we monitor the transmission of both accelerated and unaccelerated particles as a function of the input power (Figure 4.20). Since protons have a charge-to-mass ratio of 1, compared to carbon or helium with $q/m = 1/2$, they require only half the power for acceleration. For proton beam, acceleration begins when the power reaches approximately 90% of the nominal level for protons, corresponding to an intervane voltage of 22.5 kV. At the nominal

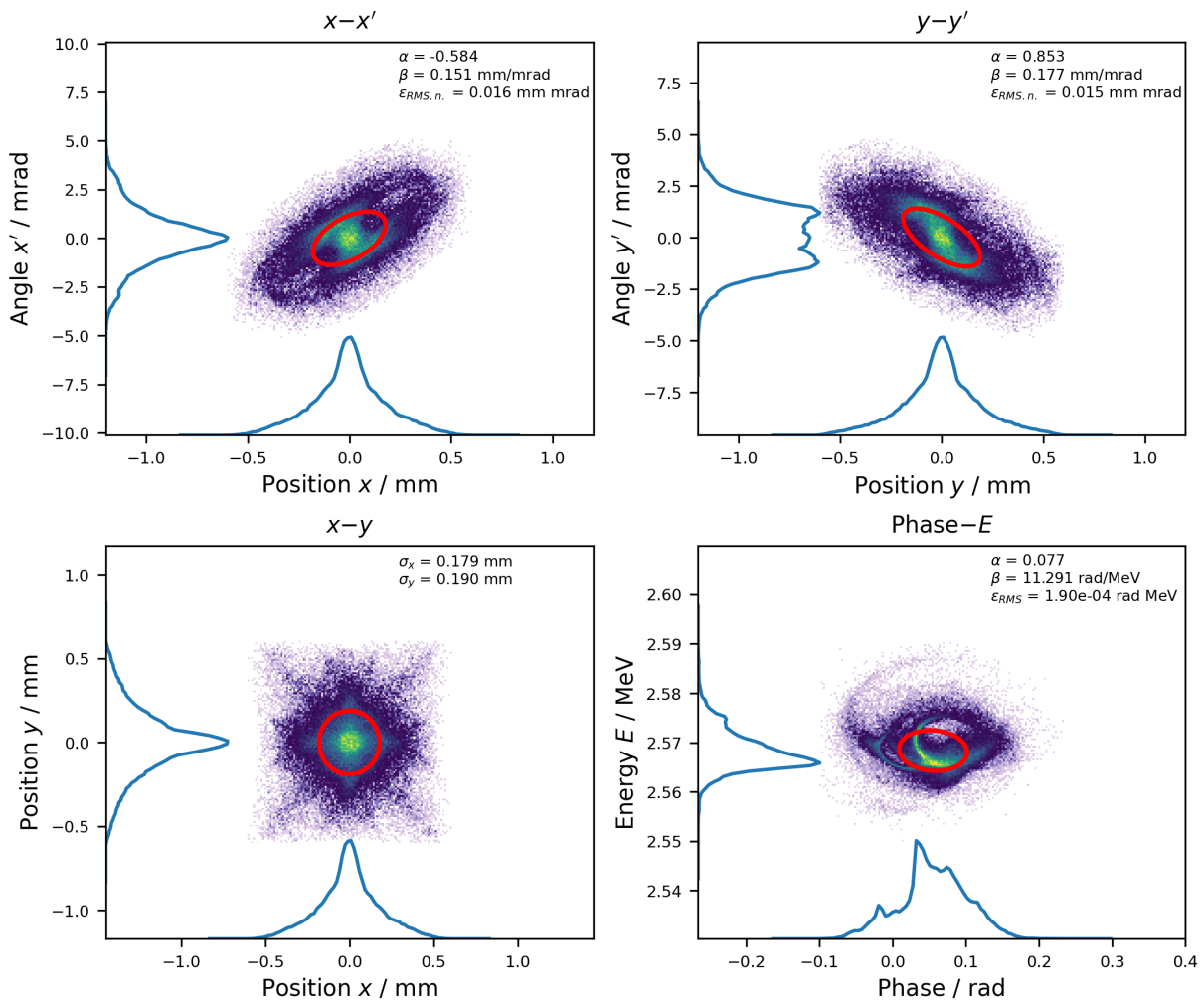


Figure 4.19. Beam phase space at the exit of the RFQ

level for protons (half of the one for carbon), about 45% of the particles are successfully accelerated. As the power increases, the transmission of accelerated particles continues to grow.

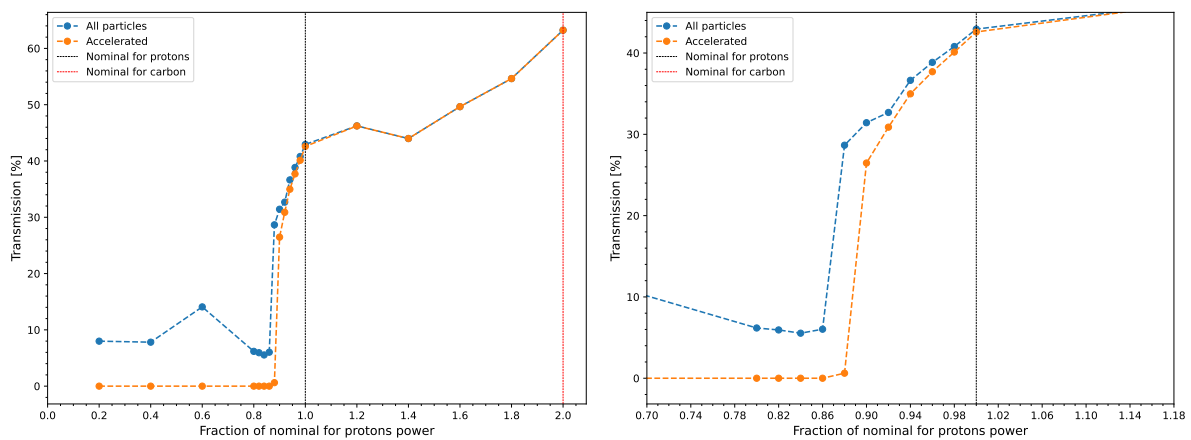


Figure 4.20. Transmission through the RFQ as a function of supplied power, with 1 being nominal power for carbon.

The fraction of accelerated particles compared to all transmitted also becomes almost 100% when we reach 90% of the nominal for protons power as shown in figure 4.21.

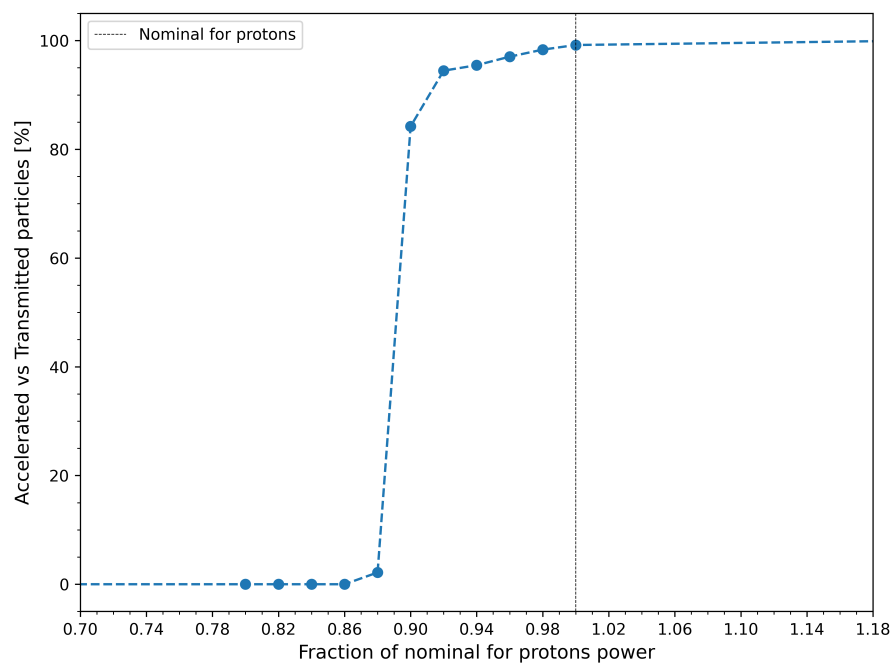


Figure 4.21. Percentage of accelerated particles in the output beam

CHAPTER 5.

EXPERIMENTAL RESULTS

System optimisation

Before starting the measurements, we made an effort to optimise other parameters of the source. The first step was to adjust the gas flow rate in order to maximise the extracted current, with the optimal value found to be 0.5 sccm, corresponding to a vacuum level of $1.0 \cdot 10^{-5}$ mbar. After this, we performed several scans of RF frequency. The first two preliminary scans were done with the beam extraction turned off and covered full allowed frequency range from 2400 MHz to 2500 MHz. In the first scan shown in figure 5.1, we measured the emitted and reflected RF power to find the frequency with lower reflected power. In the second scan shown in figure 5.2, we measured the current as a function of frequency with the beam extraction turned off at first.

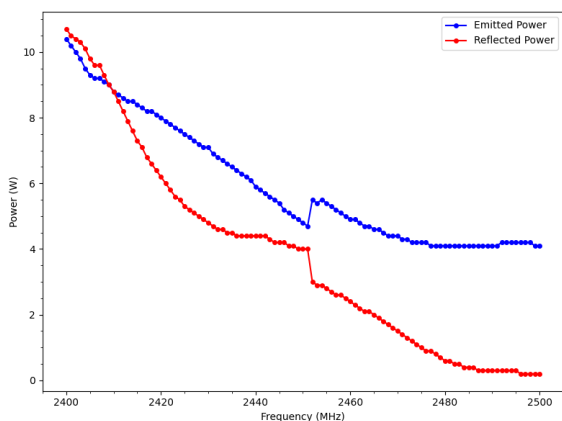


Figure 5.1. Emitted and reflected power as a function of frequency

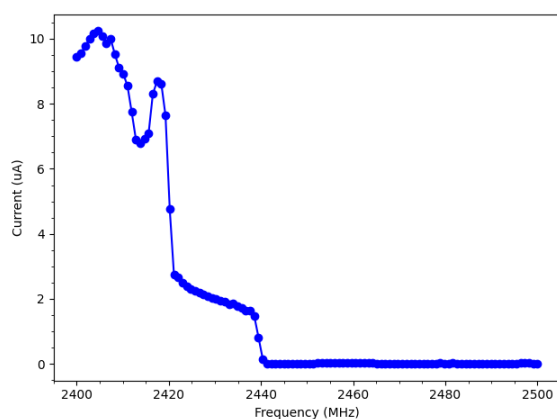


Figure 5.2. Current without beam extraction as a function of frequency

Both scans showed higher emitted power and higher current from plasma on the lower side of the range, however, it's important to note that although these scans covered the full frequency range of the RF

generator, the RF window is designed for operation at a specific frequency of 2450 MHz. For this reason, in the final step, we turned on the beam extraction and performed a scan only in a small range near 2450 MHz to understand how the RF frequency affects the beam current.

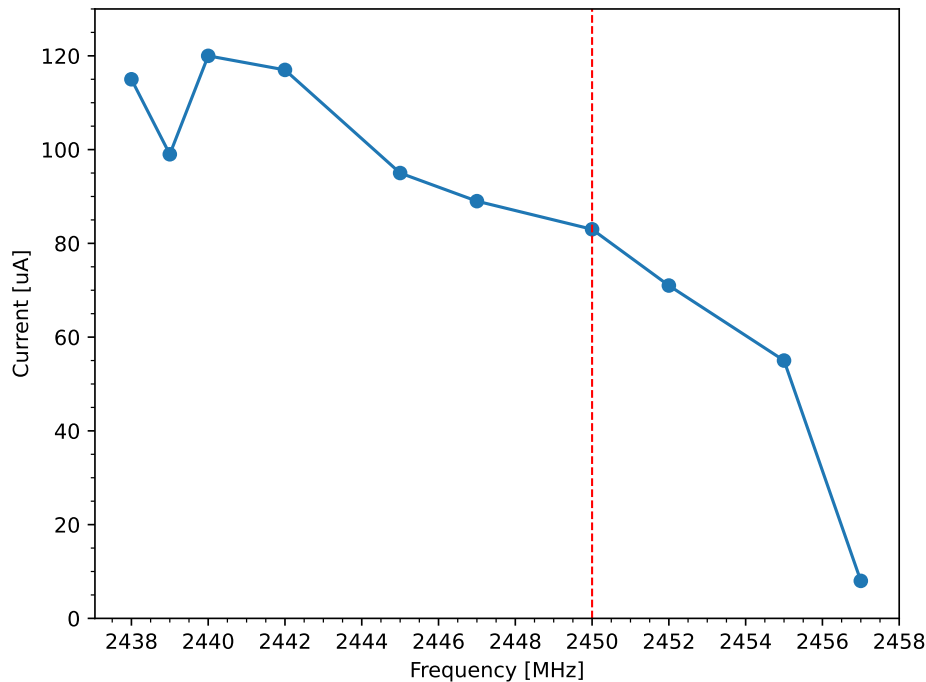


Figure 5.3. Beam current as a function of frequency near the designed frequency of 2450 MHz

5.1. Beam current measurements

After completing the RF frequency sweeps, we proceeded to measure the extracted beam current under different conditions. Figure 5.4 shows the process of tuning source parameters such as gas or RF frequency, as well as adjusting voltages to maximise the current. The extraction voltage is fixed at 15 kV

Measured current ranges from around 100 μA with an einzel lens at 11 kV to 180 μA with the lens at 10 kV. Sharp jumps at $t = 1250$ s and $t = 1800$ s correspond to tripping of the lens power supply.

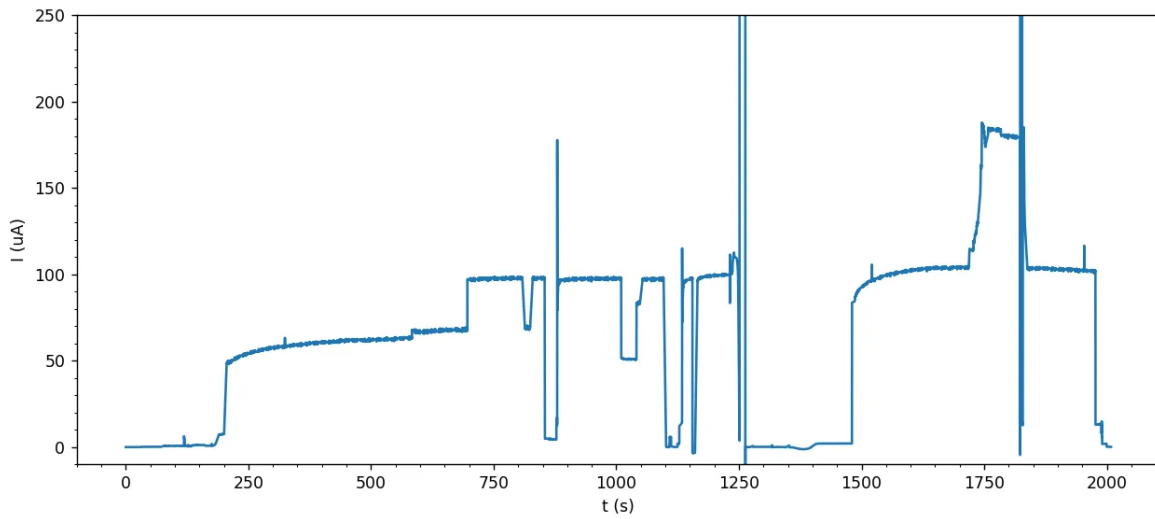


Figure 5.4. Current measured in the FC in the process of adjusting RF frequency, gas and the Einzel lens voltage.

As the second step, we carried out the scan of the einzel lens voltage for several fixed puller voltages. In this measurement, the RF power was set to 20 W at 2450 MHz, and the gas flow to 0.5 sccm, resulting in a vacuum of $1.0 \cdot 10^{-5}$ mbar.

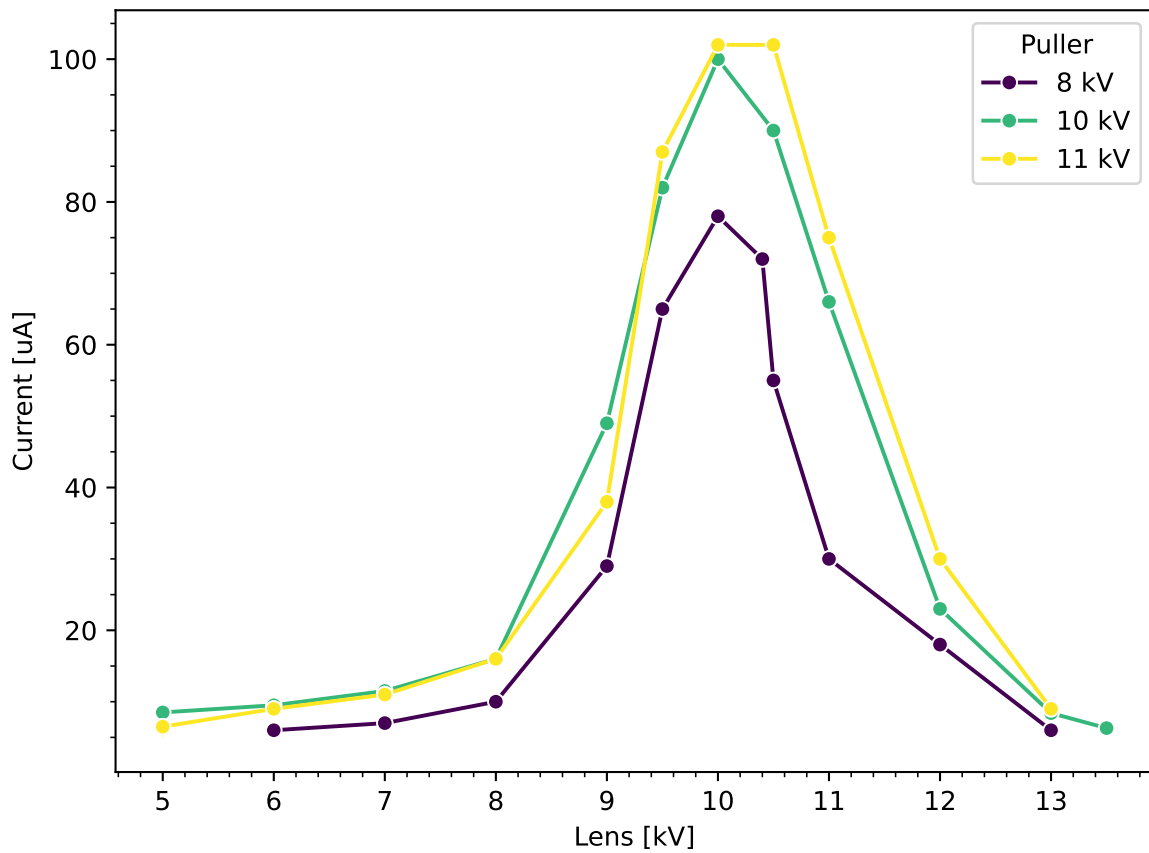


Figure 5.5. Current in the FC as a function of einzel lens voltage

For each puller voltage, there is a clear peak in current at approximately 10.5 kV on the einzel lens.

5.2. Beam profiles

After optimising the beam current, we proceeded to measure beam profiles and compare them with simulations. The puller voltage was held constant at 10 kV while the lens voltage was varied to get a focused beam.

The overall behaviour was consistent with simulations from figure 5.6, however, the voltages required to achieve similar focusing were shifted. For voltages between 8 and 10 kV we observe a «hollow beam», which is rapidly focused into a small spot when the voltage reaches 11 kV, and quickly expands for higher voltages, as can be seen from figure 5.7.

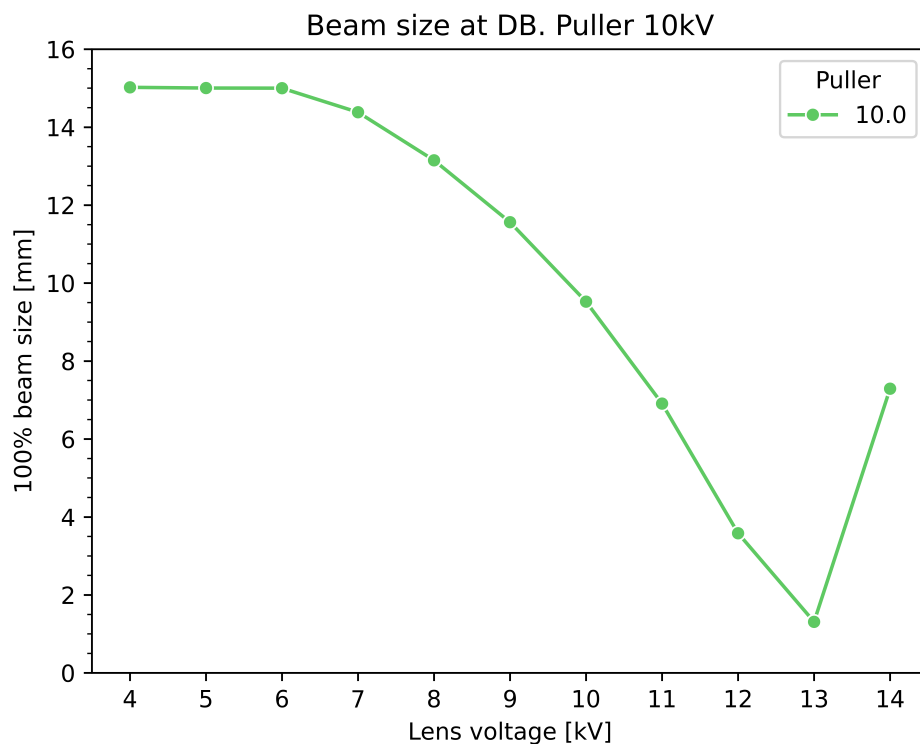


Figure 5.6. 100% beam size at DB for different einzel lens voltages. Puller is fixed at 10 kV

Unfortunately, quantitative profile measurements could not be obtained since secondary electrons produced by the beam interacting with the slit caused frequent trips in the power supplies. While the beam size estimates from the viewport are not very accurate, they suggest a beam diameter five times larger than predicted. This may indicate a higher initial emittance than originally assumed.

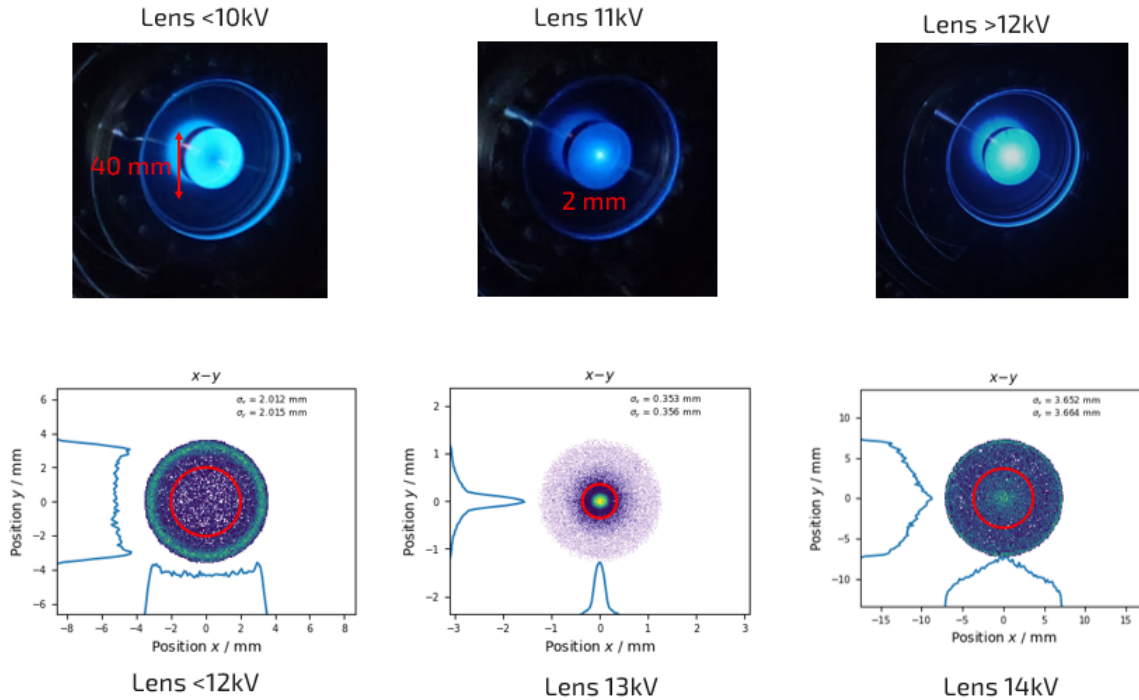


Figure 5.7. Comparison between observed beam and simulations for different lens voltages

5.3. Beam current on the high-energy side

As the next step, we performed a test run with the RFQ unpowered, meaning no acceleration is taking place. The goal was to verify that some portion of the beam reaches the high-energy side of the RFQ before actual acceleration.

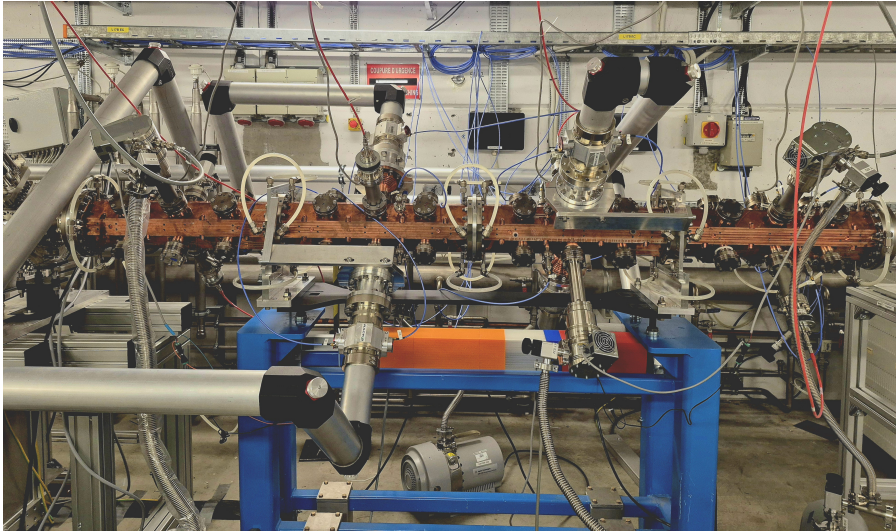


Figure 5.8. Installed RFQ with tuners, couplers, cooling pipes and vacuum pumps

Figure 5.9 shows the measured beam current on the high-energy side in the process of steering. As the beam alignment improved, the current increased, reaching a maximum of approximately 90 nA.

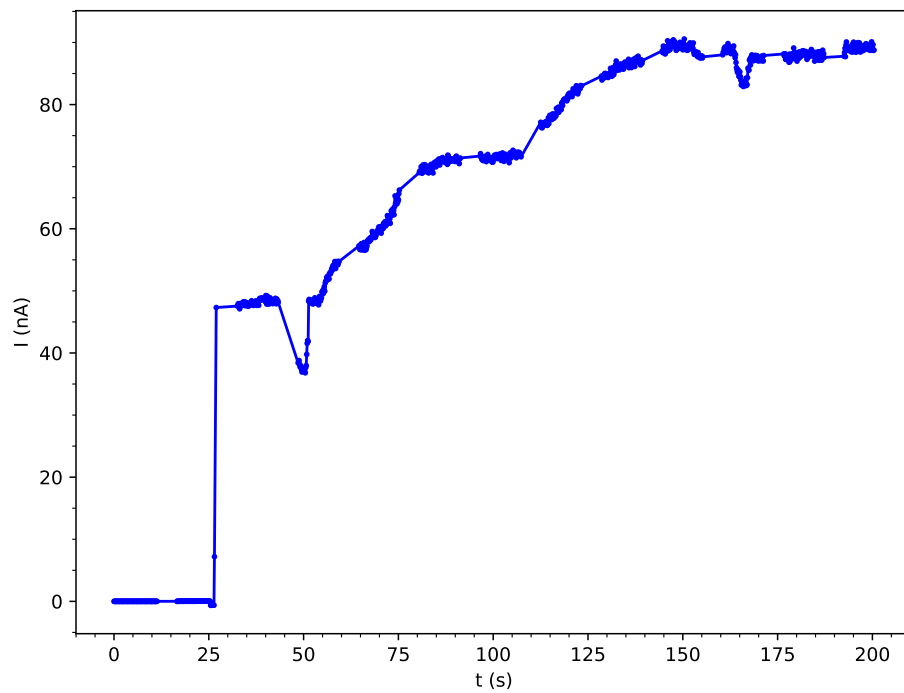


Figure 5.9. Current on the high-energy side

CONCLUSIONS AND OUTLOOK

As part of the commissioning of the 750 MHz RFQ for medical applications, beam dynamics and matching conditions were studied for two ion sources.

1. Based on computer simulations, the following was established:

a) The geometry of the Monogan ion source allows direct matching of the proton beam into the RFQ without the need for additional elements.

b) Increasing the puller voltage produces a more focused beam with lower divergence and reduced emittance. However, excessive voltage causes overfocusing, significantly increasing the beam size.

c) Small deviations in beam current result in minor losses in transmission, while significant current difference complicates the matching process.

d) The Supernanogan source geometry provides limited control over beam parameters due to the much greater distance between the puller and the plasma bore.

e) For the Supernanogan source, a low-energy beam transport (LEBT) line must be introduced to match the beam into the RFQ, increasing the overall size of the setup.

2. Simulation results for RFQ transmission as a function of input RF power show that acceptable transmission is achieved at approximately 90% of the nominal power for protons, with most of the transmitted particles being fully accelerated.

3. Experimental measurements for the proton beam confirmed the simulation results:

a) The measured beam current agrees well with expected values, despite some discrepancies in the beam profiles, likely due to an unknown initial beam used in simulations.

b) It was found that lower RF frequencies result in higher beam currents, although technical constraints limit the usable range to 2440–2450 MHz.

4. The beam matching parameters were applied during injection into the RFQ. With no power in the RFQ, a beam current of $70\ \mu\text{A}$ was measured at the RFQ entrance and 90 nA at the exit, corresponding to approximately 0.1% of particles transmitted.

In future work, it is planned to: a) increase the RF power to the level required for acceleration; b) further verify the beam dynamics simulations; c) design and install a diagnostic line at the high-energy end of the RFQ.

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