Simulations of injection optics for an RFQ cooler and buncher

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2002

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Introduction

This report is about injection of ions to a new RFQ (which stands for a Radio Frequency Quadrupole) cooler & trap which will be built at ISOLDE, CERN.

This device brings very good advantages to existing beamline — for instance, lower emittance in transversal plane and lower energy spread in longitudinal direction. It will be possible to bunch the beam.

Lower emittance means that ions can be focused to smaller spot thus improving precision of measurements. For laser experiments bunched beam is much more useful compared to continuous beam. Bunch can be adjusted such that lasers are synchronized with the ion bunch thus increasing signal-to-background ratio. Using buffer gas cooling is also very cost effective and easy to operate – there is only a few tunable parameters in the RFQ. Buffer gas cooling is effective only if ions are much heavier than the buffer gas. Usually this is the case at ISOLDE.

One of the most crucial part in the whole RFQ project is the injection. Because of the presence of buffer gas, RF rods must be enclosed in a vessel that holds the buffer gas. To prevent buffer gas from reaching high vacuum areas, there is only narrow hole through which ions must pass. Because of this and deceleration of ions injection is not a straight forward procedure.

At present, there exists several working RFQ coolers in the world many of which are in EXOTRAP collaboration. For instance, in Jyväskylä, Finland RFQ cooler is used as an injector to laser experiments and for injector to a Penning trap which requires very high quality beam.

Simulations related to this report have been conducted at CERN during the summer 2002.

Chapter 1

Background information

1.1 Basic concepts

There are some terms that appear in this text that might need some explanation.

1.1.1 Emittance

One reason that RFQ is built is to reduce the emittance of the beam. Emittance is a beam quality that describes how good or bad the beam is. Bigger the emittance worse the beam. If beam has a big emittance, handling it will be more difficult.

Emittance is the phase space area which the ions enclose. There are two independent directions, say x and y, perpendicular to ions average flying direction z, all in cartesian coordinates. An ideal particle follows a *reference track* or *optical axis* with analogy to light optics, but of course there is no such thing as ideal particle. All ions have some deviations from this reference track. Transversal deviations are usually described as displacement from reference track and as velocity in coordinate's direction thus forming a phase space. For continuous beam longitudinal deviations from reference track are usually described as energy spread. For bunched beam phase space can be described in energy and time deviations.

There are two different unit systems which can describe the value of transversal emittance. One is in units of transversal length x and transversal momenta p_x. This choice is canonical — so to say emittance is conserved even if beam is accelerated or decelerated and the unit of emittance is usually mm·mm/μs for practical reasons.

The other possibility to describe emittance is in units of transversal length x and angle between ion path and z-axis. For this choice the unit of emittance is mm·mrad, depending on the longitudinal beam energy.

Both of these units can be converted, of course, to each other. Value of emittance can be determined from a beam bunch by plotting ion's x versus p_x for every ion and then the area which ions enclose is the emittance. In our case the emittance is formed like an ellipse. Two typical situations are shown in figure 1.1. This kind of plot is called a phase space diagram.

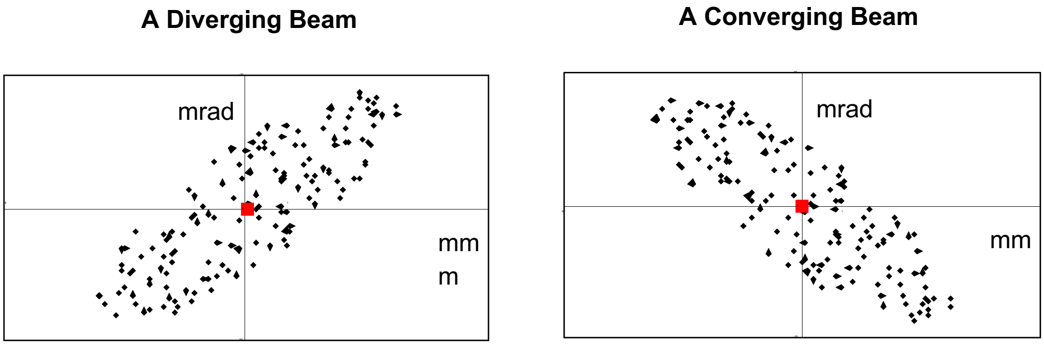

Figure 1.1: Typical phases of ion beam. When ions are converging they are moving towards optical axis and when diverging, away from it. The area which ions enclose is *emittance*.

It seems that ISOLDE's ion source emits beams with constant emittance regardless of ion mass in units of mm mrad. Emittance in ISOLDE is mainly determined by the extraction geometry of the ion source. Space charge effects also increase the emittance but is not a problem here because beam has not very high intensity and the time that ions travel in beam line is short.

It is impossible to reduce the emittance with conservative forces such as electric or magnetic forces; only the shape of the phase space diagram can be changed. *Liouville's theorem* says that the phase space area is conserved. One way to break this is to use some non-conservative method like buffer gas cooling.

1.1.2 Cooling of ions

Cooling means reducing emittance and energy spread of ions. There exists a variety of cooling techniques of which buffer gas cooling is a one. In buffer gas some of the ions energy will be transferred to buffer gas atoms due to elastic collisions between ions and buffer gas atoms. With this method the ions can be cooled to energies as low as thermal energies. Buffer gas cooling is effective only if buffer gas atoms are much lighter than the ions that are cooled; therefore helium gas suits in very well because its light, but also because it is chemically insensitive.

Cooling depends on ion-atom interactions which is described with concept of ion *mobility* K_0, which is a function of ion velocity, buffer gas pressure and temperature.

For lower velocity values of K_0 can be taken from literature(see for instance [6]) and at higher velocities ions behave like hard balls when colliding with buffer gas atoms. To different pressure P and temperature T mobility K can be scaled from reference conditions (P_0 and T_0) as

$$K = K_0 \frac{T}{T_0} \frac{P_0}{P}. \tag{1.1}$$

This model, which is based on ion mobility, changes only ions kinetic energy (not direction) when colliding with buffer gas atoms. Thus ions only slow down. In actual situation ions would also change its direction but in good approximation ion's average path is quite straight.

Another method to implement cooling is to use a Monte-Carlo method. In this model, in addition to kinetic energy decrease, ion do change its direction when colliding with buffer gas atoms. This type of cooling model is described very well in [2] and applied succesfully by its author.

1.2 About ISOLDE

ISOLDE is located at CERN and its research concentrates on atomic and nuclear research. It uses major fraction of protons accelerated by proton synchrotron booster, PSB, which accelerates protons up to 1.4 GeV in energy. At ISOLDE protons will be collided to a thick target which is about 20 cm long. Target chamber is at 60 kV potential and is isolated from the PSB beamline; in fact, the protons travel some time in normal air pressure.

Because protons come in short bunches and instantaneous ion beam current can be as high as 2 A, target chambers 60 kV voltage must be disconnected for a short time period when the beam hits the chamber thus avoiding current overflow.

Because incident protons are very energetic, radioactive nucleai are produced in spallation, fragmentation and fission. Reaction products leave the target chamber by means of diffusion and head for the ion source where the atoms become ions again and mostly only singly charged. After leaving the 60 kilovolt platform singly charged particles have 60 keV of energy. For an ion with mass 100 u the velocity will be around 340 km/s. At next stage the ions are transferred to a *mass separator* and in this case to a *high resolution separator, HRS*, which mainly consists of two separator magnets. The new RFQ cooler will be just after HR separator. HR separator can separate ions (at least) to a certain mass number.

At present there is approximately 3.5 meters of beamline after HRS separator with ordinary quadrupole triplet for beam focusing. This is the place, where the new RFQ cooler & buncher will be. After this location there are quadrupoles for beam focusing and a beam gate through which beam is transferred to experiments.

1.3 The new RFQ in a nutshell

The 3.5 meter space reserved for the RFQ will be spent like following:

- ~1.5 meter will be used to a new quadrupole triplet (or doublet), which shapes the beam such that it can be injected to the RFQ.
- ~1 meter for the RFQ itself and
- ~1 meter to the extraction.

The emittance of the beam after HRS is so awkward that it needs electrostatic quadrupole triplet (or at least a doublet) to modify the beam such that it can be injected to RFQ. Injection electrodes will be cylindrically symmetric so the best shape for the incoming would be that the beam is symmetric having both vertical and horizontal phases in same way. Injection electrodes are used to decelerate the beam from 60 keV to a few hundreds of volts which is called *injection energy.* For ions with mass 100 u the deceleration is from velocity of 340 km/s to 20 km/s. Deceleration does not affect to transversal velocity which is typically few km/s; in fact, this is the reason, why beam becomes rapidly diverging in short distances.

In the RFQ the ions feel the radiofrequency electric field, which confines the ions in transversal plane. On top of the RF field, a longitudinal electric field gradient is applied to speed up the ions' longitudinal movement. Ions also feel the presence of buffer gas, which cools ions down nearly to thermal energies. If there is no longitudinal electric field gradient, ions would move forward after cooling only by means of diffusion. After cooling, the ions are collected to a potential well for bunching and then extracted and accelerated back to 60 keV. If bunching is not needed, RFQ can run in continuous mode too. In any event, both emittance and energy spread of the beam will be smaller than before.

Chapter 2

Injection

The goal was to find a deceleration schema for an efficient injection of ions. That is to use as little space as possible and that there is no ion splatting on surfaces like electrodes and insulators. One electrode should have as small aperture as possible to keep buffer gas from reaching ultra high vacuum areas. Amount of electrodes should be minimized (= cost effective) and voltages that must be applied have to be reasonable avoiding voltage breakdowns (= high voltage safe).

2.1 Initial Conditions

2.1.1 Geometry

To start the simulations, we need a some sort of frame: Where the ions start, where is the high voltage platform and attributes of RFQ rod structure. What will be between ions starting point and rod structure is injection and deceleration electrodes. In figure 2.1 there is a schematic initial situation. Ground electrode is on the left where the ions start and on the right there is quadrupole rods with an endcap electrode which has a narrow channel of 8 mm in diameter.

The electric field near the optical axis is shadowed by high voltage platform of 60 keV. Potential rapidly increases and in some point transversal velocities come dominant and beam diverges and most of the ions are lost. This is the case if there is no injection and deceleration electrodes at all. Shooted ions simply push uphill and divergence is inavoidable. Some sort of ion optical structure is definitely needed.

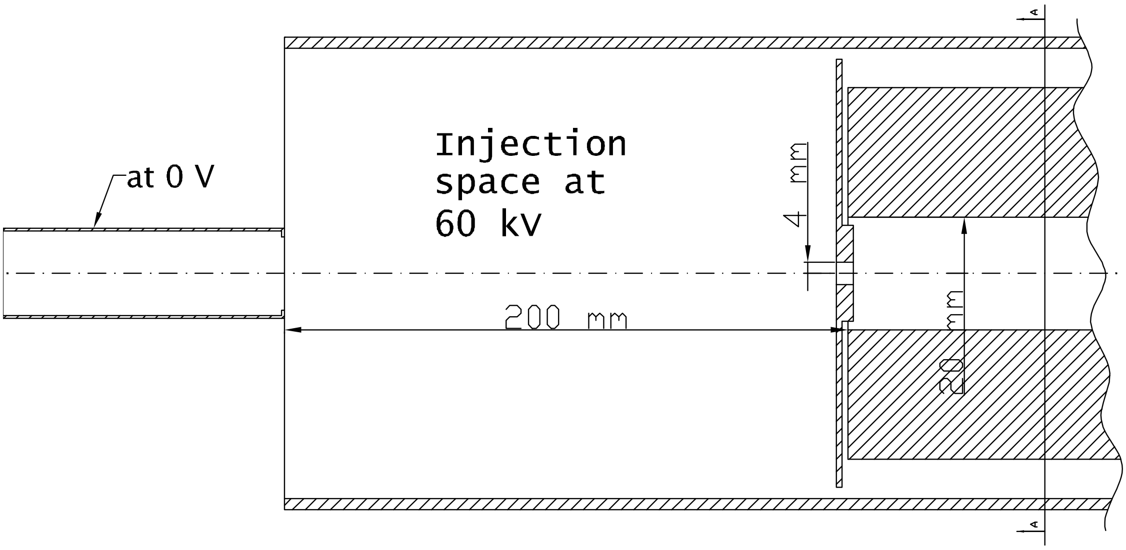

Figure 2.1: Missing injection electrodes. Leftmost electrode is at ground potential. RFQ rods are at right with an endcap electrode. Injection volume and RFQ are enclosed in a vacuum tank which is in high voltage of 60 kV. Injection electrodes will be somewhere in 200 mm area. Ground electrode forces the ions to start at 0 V.

2.1.2 Ions

In this scenario, ions start their travel at the back of ground electrode (at far left in figure 2.1). Ions are assumed to have

- charge of $+1e$
- some mass
- emittance of 40π mm mrad and
- kinetic energy of 60 keV.

To allow the ions to enter the RFQ, we need to lower the voltage of rods and endcap electrode by some amount; 60 keV beam has difficulties of entering to potential of 60 kV. In this case this *injection energy* is defined to be 200 volts. Because of this choice, longitudinal energy spread of the beam (few eVs or percents) becomes irrelevant. Transversal emittance is still a problem because transversal velocity is much higher compared to longitudinal velocity.

2.1.3 RF field

To confine the ions in the RF field, a proper voltage and frequency must be applied to rods. Although rods are only circular — ideal shape would be hyperbolic — the electric field is quite ideal even near the rod surface. So ions should be only be prevented from splatting into rods.

Ion motion in an RF field is described by *Mathieu parameters* a and q [1]. And in this case where we do not apply longitudinal DC voltage (which makes the ions to move forward) inside RFQ rods, a equals to zero. Now only q describes confinement and a good confinement is achieved if $q \in [0.5, 0.6]$. If q is less than this, then confinement might be too low and for bigger q values motion in RF field becomes macromotion and is not very effective in sense of cooling. Although in real situation longitudinal DC component is used, it has negligible effect to the injection.

To determine the RF voltage, we need some background information in addition to q-value such as ion mass m, RF frequency ω and characteristic radius of rods r_0 which is the closest distance from optical axis to rod surface. With this information it is possible to calculate RF voltage with formula

$$V_{RF} = \frac{qmr_0^2\omega^2}{4e}, \tag{2.1}$$

where $[\omega]=$ rad/s. This is the amplitude of voltage. While one pair of rods has some voltage V, then the other pair has a voltage of $-V$.

2.1.4 Emittance

It is assumed that emittance of the beam is 40 π mm mrad in both vertical and horizontal plane. In actual situation emittance is much lower than this (about 2.5 times lower). This is to give some safe margin to simulations because Simion might not be too accurate.

In literature, 95% of the ions are enclosed in the emittance ellipse and the distribution of ion displacement and ion velocity are gaussian-shaped. In these smulations ion distributions are just random and all ions born inside the defined ellipse. Thus 100% injection efficiency is possible and desired.

Emittance in mm·mrad can be converted to mm mm/μs. To do this, we need to know longitudinal ion energy (or momenta), ion mass and the angle between optical axis and velocity vector of ion. This is illustrated in figure 2.2. Emittance in units mm mm/μs can be called as *canonical emittance* because emittance in these units is not affected by acceleration and deceleration and is thus conserved satisfying Liouville's theorem. Usually emittance is given in mm mrads because this value is (often) the same regardless of ion mass; this unit is also favored in ion optic calculations. If beam has divergence of 1 mrad, then beam is moves one millimeter further away from reference track in one meter distance. Ion displacement from

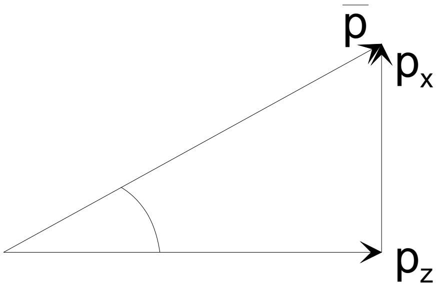

Figure 2.2: *Relation between deviation angle α and transversal velocity (momenta).* If we know the longitudinal momenta p_z, we can determine transversal momenta p_x with angle α. Furthermore, transversal velocity v_x can be calculated if we know the ion mass.

optical axis is the same in both units and is measured usually in millimeters [mm]. Angle can be converted to transversal momenta

$$\tan\alpha \approx \alpha = \frac{p_x}{p_z} \tag{2.2}$$

or vice versa

$$p_x = \alpha p_z. \tag{2.3}$$

Furthermore, longitudinal momenta for a classical ion ($E_k \ll mc^2$) is

$$p_z = \sqrt{2Em} = mv_z, \tag{2.4}$$

so that transversal velocity is

$$v_x = \alpha\sqrt{\frac{2E}{m}}. \tag{2.5}$$

Usually the unit of velocity is mm/μs or km/s. Because v_x is proportional to α the transformation is linear.

For example, if ion has a mass of 100 u, longitudinal energy of 60 keV and angle α of 5 mrad, then ion has transversal velocity of

$$v_x = 5\text{mrad}\sqrt{\frac{2 \cdot 60 \text{ keV}}{100 \text{ u}}} = 1.70 \text{ mm}/\mu\text{s}.$$

2.1.5 Defining an Emittance ellipse

One way to define an emittance ellipse is to use *Twiss parameters*[1]. There are three adjustables, A, B and C, which defines an ellipse

$$Cx^2 + 2Axp_x + Bp_x^2 = \text{emittance (area of ellipse)}. \tag{2.6}$$

Since we want that emittance is constant, we can solve C while A and B are still adjustable; thus

$$C = \frac{1 + A^2}{B}. \tag{2.7}$$

Other way to describe an ellipse is to use rotation of coordinates. Ellipse is defined by lengths of its semimajor axises a and b in addition to angle of rotation φ. The area of the ellipse is

$$\text{emittance} = E = \pi ab = \pi\epsilon. \tag{2.8}$$

To make a rotation, it is convenient to use *rotation matrix*

$$R(\theta) = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix}, \tag{2.9}$$

where θ is the rotation angle. So, the emittance can be described with phase-space area, angle of rotation and axis scaling factor r. Rotation is shown in figure 2.3.

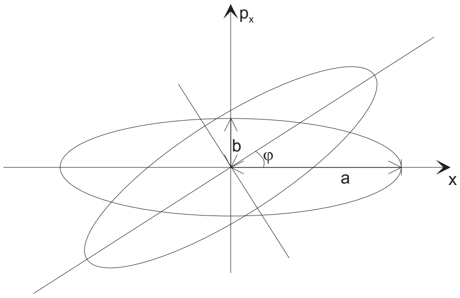

Figure 2.3: Rotation of coordinates. Ellipse is rotated by an angle of φ. If the axis ratio is r and ellipse area ϵ is known, it is easy to rotate ellipse by only changing φ.

If the scaling factor of axis is r, then semimajor axises a and b are

$$a = \sqrt{\text{emittance}} \cdot r \tag{2.10}$$

$$b = \frac{\sqrt{\text{emittance}}}{r}. \tag{2.11}$$

2.2 Adjustable Variables

There are only few variables in our system that can be changed. Those what are fixed at the moment are ion mass and charge, injection energy, space for injection electrodes and emittance — although emittance shape can be modified.

What can be adjusted is the injection electrodes and, in particular, what amount, shape and voltages those should have. Electrodes will be situated between ground electrode and endcap electrode (see figure 2.1). Obvious shape for these electrodes will be cylindrical; they are usually tubes with certain inner diameter or thin plates with circular hole in the center. Electrodes will have some voltage but in such a way that there is no danger of voltage breakdown. If we only want to decelarate ions, the appropriate electrode shape should be just plate with some hole in the middle.

Amount of electrodes and their shape will be fixed so that eventually user only plays with voltages of electrodes.

Chapter 3

Implementation to Simion and Results

Simion is a computer program, which simulates ion movement in electrode configuration. Simion needs to *refine* the potential field for certain geometry (this can take a lot of time) but after refining electrodes' voltages can be still changed. Only the geometry is fixed. Geometry is defined on special *geometry files* and if the geometry needs to be changed, all changes are done in geometry file. Implementing new geometry means new refining process.

Geometry, of course, changes in the process of achieving best injection conditions. Old geometry files are kept safe so that it can seen in which way one is going.

Simion calculates the potential array by solving Laplace's equation

$$\nabla^2 \phi = 0 \tag{3.1}$$

with an approximate Runge-Kutta[3] method. Simion can handle up to 30 different electrodes (conducting surfaces) of different shapes. It can use different symmetries — like cylindrical symmetry — to speed up calculations.

By default Simion simulates ions in vacuum and with static voltage on electrodes. By using *user program* one can implement methods which affects the ions. Those are, for instance, buffer gas cooling (changing ion's movement direction and kinetic energy) and radio-frequency electric field (changing electrodes' voltages on run). Also, ions initial conditions can be adjusted in user program. In simulations conducted here, the user program is made such that the emittance (area of the phase-space) must be set in units of mm mm/μs and the form of the ellipse by axis ratio and rotation angle of emittance.

If geometry file is changed, user program must be also changed to correspond to actual situations.

Although RFQ contains buffer gas, it is not used in injection simulations. Injection should not depend much on it because ions feel buffer gas atoms only inside RFQ and only for a short time period.

There exists very efficient buffer gas cooling program based on Monte Carlo method[2]. Ion movement inside this RFQ was simulated by Mikael Petersson.

3.1 Different electrode configurations

Several electrode configurations were evaluated. Elisabet Molin had a working solution which consisted of five injection electrodes. It looked clumsy and one electrode even needed ~40 kV voltage supply.

Starting point was to use four electrodes — one less than before. One working solution is shown in figure 3.1. This configuration can handle only beams with transversal displacement x of less than 5 mm. This is because ground electrode's opening is only that large. Typical electrode voltages for this configuration are in table 3.1.

Table 3.1: Typical operating values for geometry shown in figure 3.1. Emittance is defined as parallelogram with 40 π mm mrad.

Electrode	voltage
0 and 1	0 V
2	45.5 kV
3	36.6 kV
4	57.5 kV

Next move was to enlarge ground electrode. And, of course, ground electode is more wider than 5 mm in radius. This configuration takes in little more divergent beam but the geometry can furthermore be enhanced. Electrode number four in figure 3.1 must be displaced a little bit to the left because it is too close to endcap electrode. Another thing which was discovered was that injection was possible without applying *any* voltage to electrodes one and two (see figure 3.1). This means, that these electrodes are at ground potential. Concluding this, electrodes zero and one (both at ground voltage) form a focusing ion optical element with surrounding HV platform. This is kind of an einzel lens. Electrostatic potential in the middle between electrodes zero and one is about 30 kilovolts and this is caused by enclosing high voltage cylinder.

There is a drawback to use vacuum vessel's walls to act as an electrode to einzel lens. Vacuum vessel might not be cylindrical; it might well be box-shaped. And

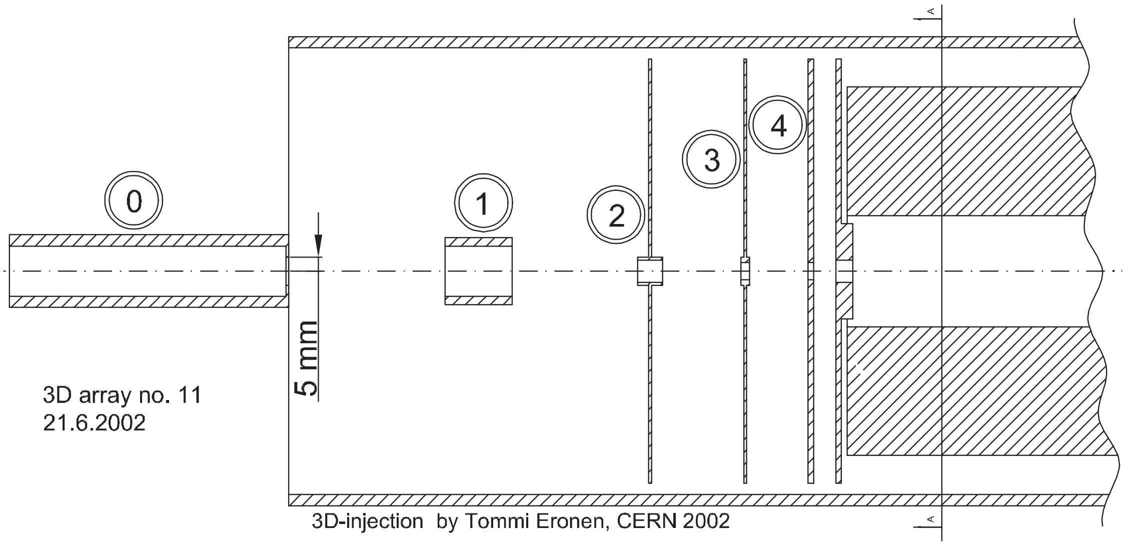

Figure 3.1: Somewhat working solution. There is four electrodes in this geometry. The most limiting factor here is the diameter of the ground electrode.

if there goes wire that has some voltage in it, it might cause serious distortions in the electric field.

After some intermediate steps the final version with focusing einzel lens is shown in figure 3.1. In here, the electrodes 0. and 2. are at zero voltage and electrode 1. has ∼30 kV voltage. Electrodes 3. and 4. are decelerating electrodes with voltages between 52 and 56 kV. Strongest electric field is between electrodes 2. and 3. It can be seen that the beam is quite divergent in this area. Between einzel lens electrodes there is only 5 mm gap compared to voltage difference of ∼30 kV. However, 5 mm should be enough because vacuum in this area is $\sim 10^{-7}$ mbar and thus propability to voltage breakdown should be negligible. Typical operating values for this geometry are in table 3.1. Electrodes 3 and 4 need ∼ 10 kV voltages supplies and electrode 1 ∼ 40 kV voltage supply. Electrodes are operable at these voltages: There is at least 12 mm between electrodes which have voltage diffrence less than 10 kV. Thus there is negligible propability of voltage breakdown. Other critical region is between electrodes 2 and 3. There is ∼ 50 kV potential difference and 33 mm between them. In this case electrode 2 must be shaped so that it has no sharp edges and and only smooth surfaces minimizing propability of voltage breakdown. Potential shape at $y = 0$–plane is drawn on figure 3.3. The general shape of the potential field is like this — only little voltage adjustments is needed if ions have different initial emittance conditions.

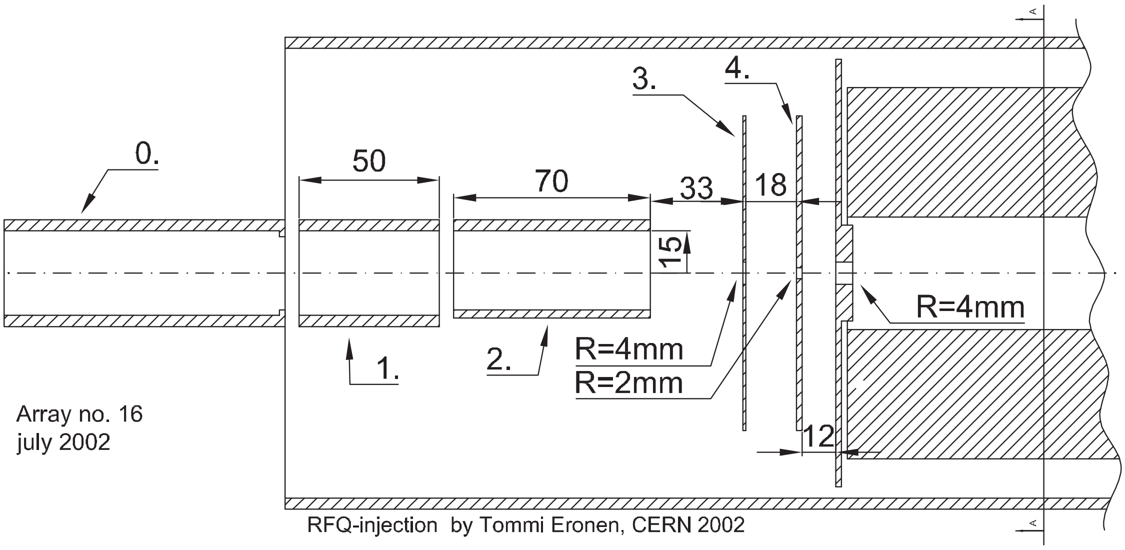

Figure 3.2: Geometry of injection electrodes. The beam is first focused (electrodes 0-2) and then decelerated (electrodes 3 and 4). This kind of geometry can take in even somewhat diverging beam.

Table 3.2: Operating parameters for the injection geometry shown in figure 3.1. Ions have mass 100 u and charge +1 e. Emittances corresponds to 40 π mm/mrad. Depending on phase of action diagram (see figure 2.3) the optimum injection is gained with certain voltage values.

quantity	value
mathieu q	0.5
frequency f	0.9 MHz
RF-voltage amlitude	1657 V
injection energy	200 eV
x-emittance	13.6 π mm^2/μs
y-emittance	13.6 π mm^2/μs
electrodes 0, 2	0 V
electrode 1	27 – 34 kV
electrode 3	51 – 55 kV
electrode 4	53 – 56 kV

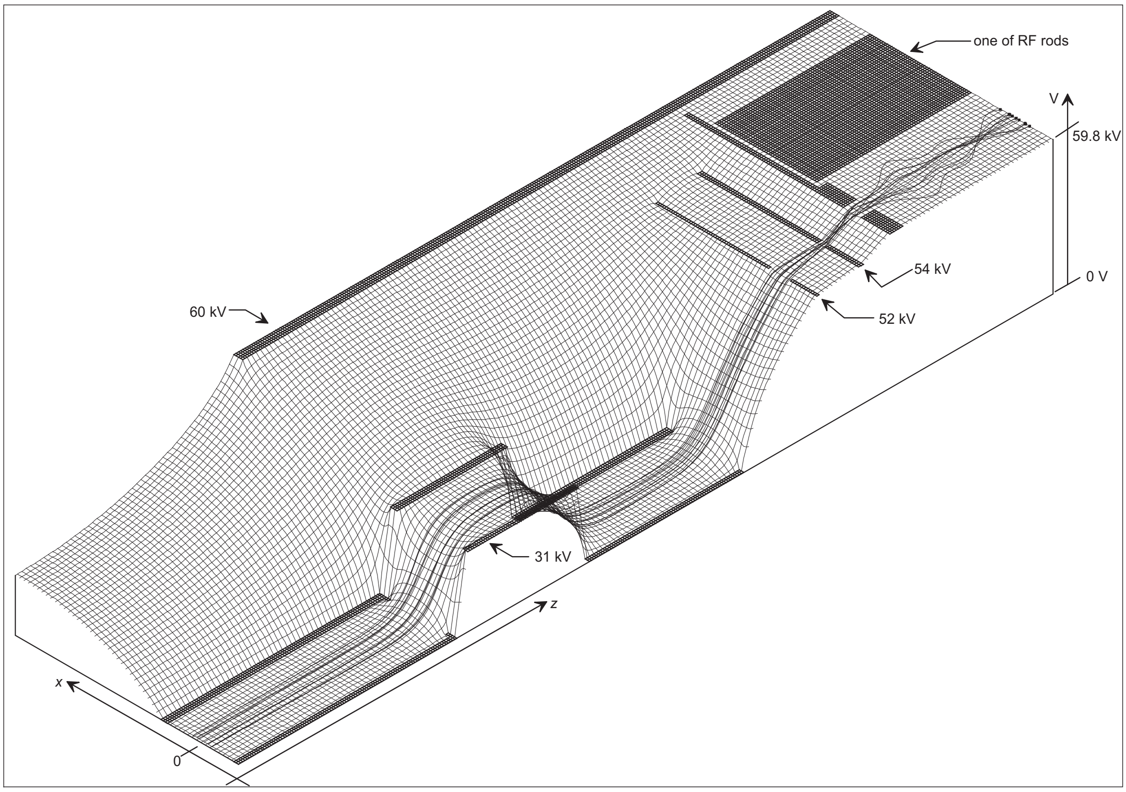

Figure 3.3: Potential field of geometry shown in figure 3.1. At start ($z = 0$) the phase space is at angle of 45 so that ions are diverging at this point. Ions are then focused with electrode at 31 kV and then decelerated with electrodes at 52 and 54 kV. Analogy to classical mechanics is to throw bowling balls so that they can reach the hilltop without hitting the obstacles (electrodes). The initial phase-space diagram of ions is shown in figure 3.4.

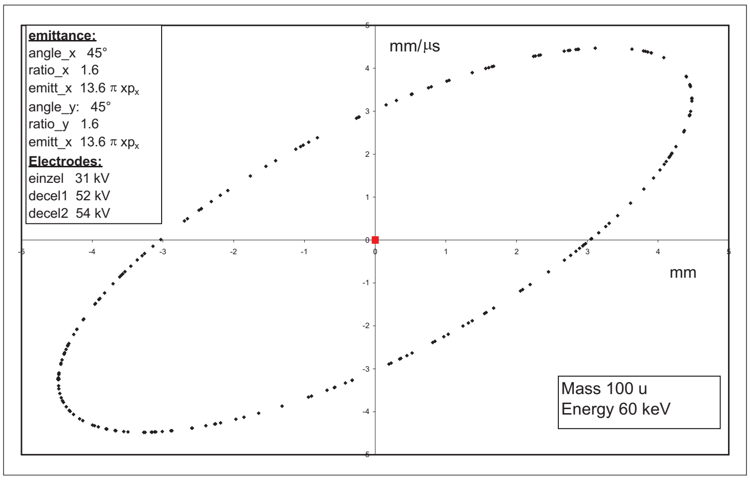

Figure 3.4: Initial phase space for ions flown in geometry 3.1. Ions path in potential field is shown in figure 3.3. Beam is initially diverging in both x and y directions like in this figure.

Ultimate geometry

The last and final geometry was like previous but in here the einzel was taken off. This means that we must assume converging beam so that it is possible to get beam through the first hole of only 8 mm in diameter. Second hole is only 4 mm in diameter. Another motivation for this geometry was the possibility to shorten the geometry; this gives a little bit of movement space for the static electrostatic quadrupole triplet, which will be used to modify the beam so that it can be injected. In this case beam must be shaped so that beam is converging in both x and y directions. Drawing of this geometry is in figure 3.5. This geometry has been tested for several masses. For a mediocre mass (that is 100 u) the potential field is shown in figure 3.6. With voltages depicted(?) in the figure, the injection is 100 % efficient. The initial phase space of the ions must then be assumed to be like in figure 3.7. This electrode configuration has been tested furher for different masses — 10 u and 200 u. Emittances for these masses are the same in units π mm mrad; converting this to π mm mm/μs is a straight forward procedure. Angle is converted to transversal velocity (to units mm/μs) with equation (2.5). Velocity dependence for different masses are shown in table 3.1. Initial phase spaces of ions which can be injected to RFQ are plotted in figures 5.1 and 5.2 for masses 10 u and 200 u. Voltages are little different than for reference mass 100 u. Emittances for these different masses are 40 π mm mrad.

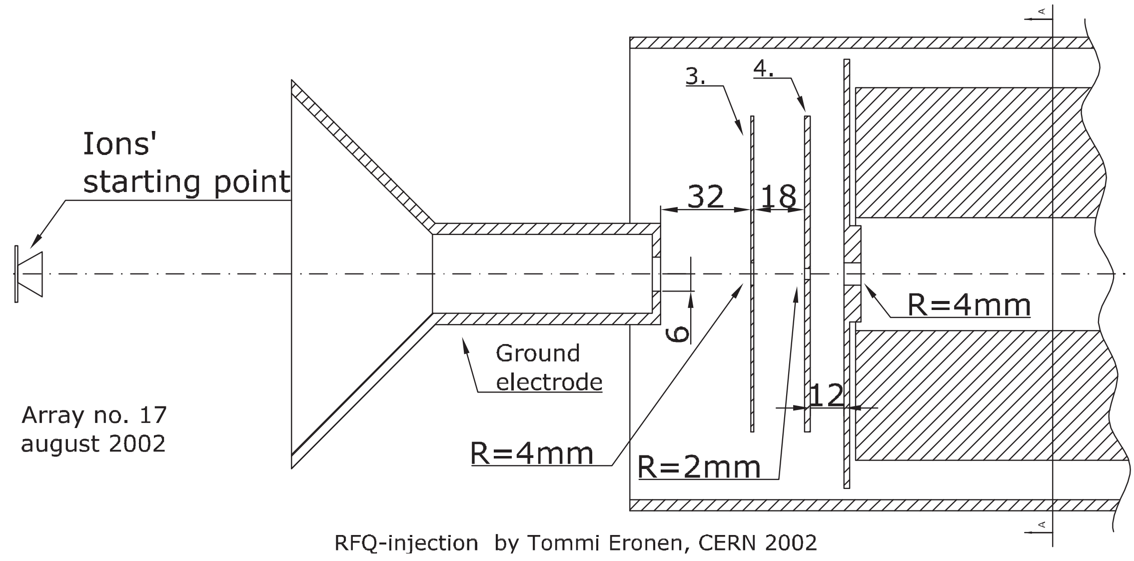

Figure 3.5: Geometry for converging beam only. The Ground electrode is cone-shaped because ions must be transferred at zero potential close to the deceleration electrodes (see potential field at figure 3.6). Deceleration section is like in figure 3.1.

Table 3.3: Coefficients for converting angle to transversal velocity when the longitudinal beam energy is 60 keV. Scaling factor is proportional to $\frac{1}{\sqrt{m}}$. It must be noted, that these values are valid only for low energy particles where we can use classical kinetic energy.

mass [u]	scaling factor $[\frac{\mathrm{mm}/\mu\mathrm{s}}{\mathrm{mrad}}]$	inverse $[\frac{\mathrm{mrad}}{\mathrm{mm}/\mu\mathrm{s}}]$
10	1.076	0.929
100	0.340	2.939
200	0.241	4.156

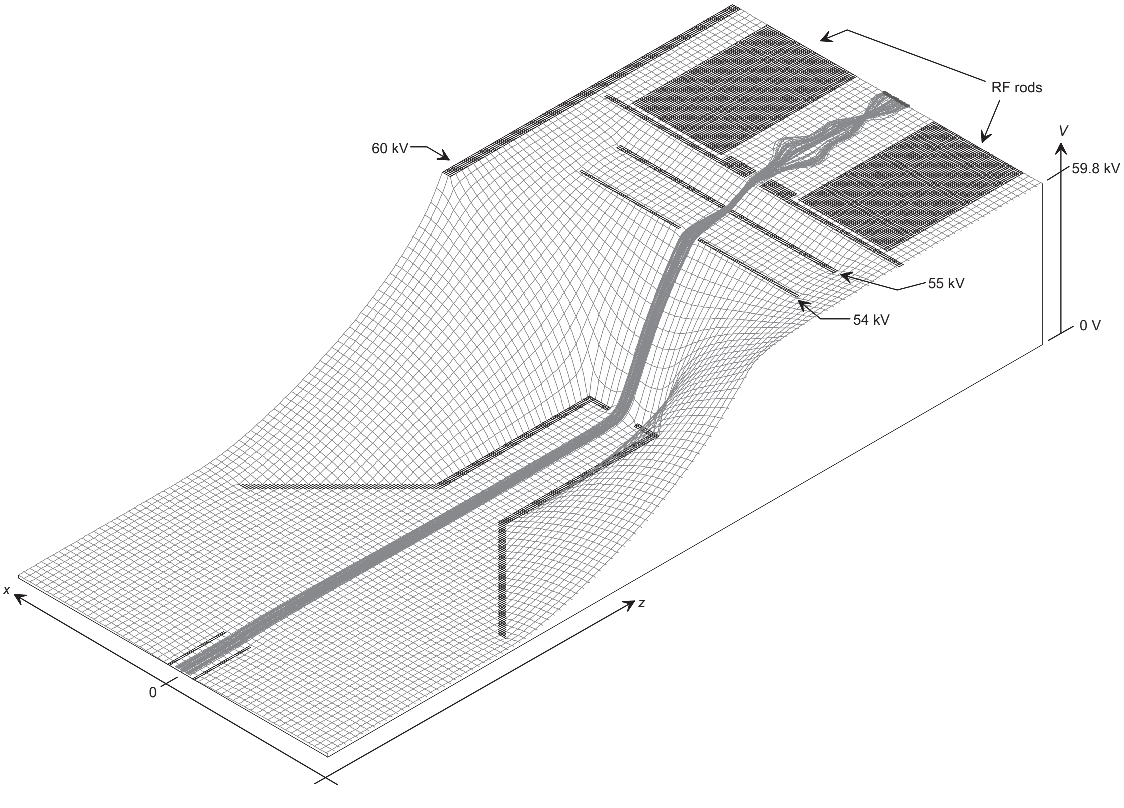

Figure 3.6: Potential field at $y = 0$ plane for geometry drawn in figure 3.5. Cone-electrode forces the potential to be zero inside and before the cone-electrode. Beam is assumed to be diverging and has an initial phase space shown in figure 3.7.

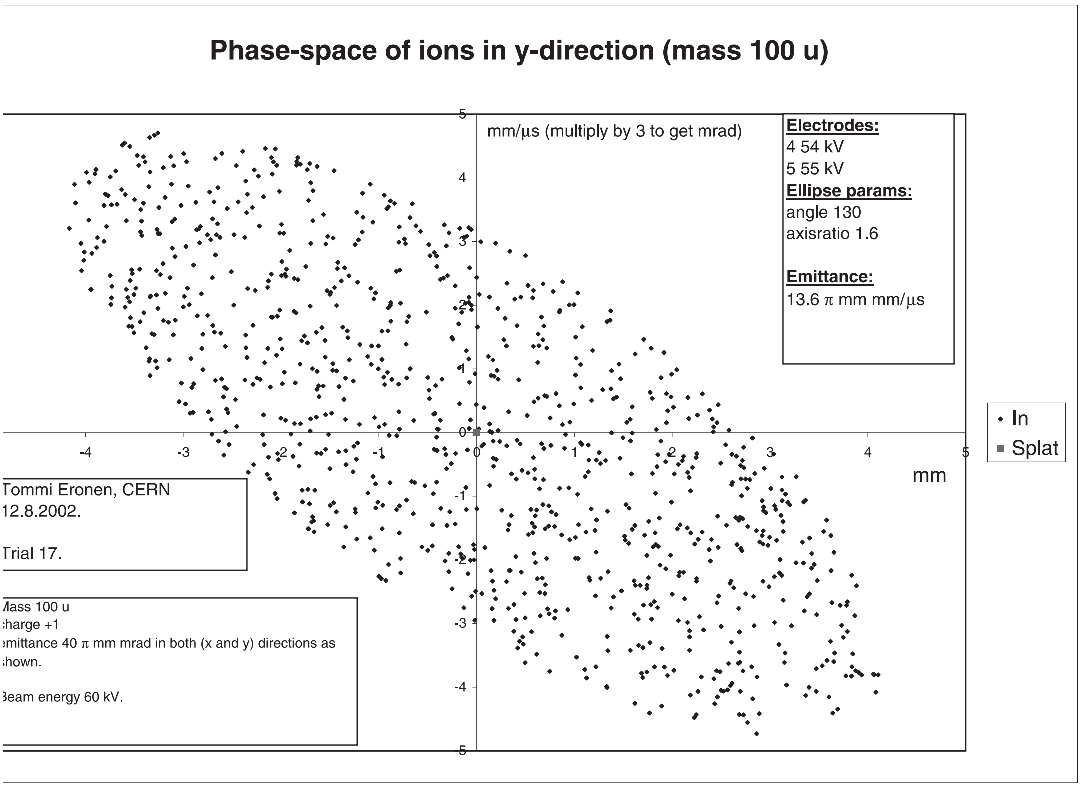

Figure 3.7: Typical phase space for diverging beam. In here the mass of ions is 100 u.

3.2 Simion user program in detail

Simion user program is listed in appendix A. It is divided into segments with #### -symbols. At first (# 1) section all adjustable and non-adjustable variables are defined. Most of the variables are self explanatory so only a few is explained.

There is a routine to count the ions that have safely injected inside the RFQ. This uses up three variables. *Safe_zone* is the coordinate that ion have to reach. *start_zone* defines a boundary that ions have to born on coordinate greater than this. Otherwise counting program gives false output. *insiders* is just the number of ions that have passed in.

Static variables are used in calculating the proper RF voltage.

Second section (# 2) is used in initialisation process. Some variables are copied so that original values can be used over and over again for each ion. Emittance circle is formed here. For instance for X-emittance, it is possible to use only maximum radius instead of randomizing it. Thus emittance ellipse is covered only by its outer boundary. If 100 % efficiency is gained then one can be sure that all ions *within* ellipse are also safely injected.

In third section (# 3) emittance circle is stretched to ellipse and rotated with help of rotation matrix. It must be noticed, that all things are done twice — separately for horizontal and vertical planes.

Fourth section (# 4) is fast adjust section where radio frequency electric field is implemented. RF rods are electrodes number 1 and 2. Average voltage for RF rods is high voltage – injection energy. Other static electrode voltages are set here also. There is no need to adjust voltages in Simion's fast adjust tab unless potential figure is needed. Comments on the section should be self explanatory.

Section # 5 is run only once and it determines the amplitude of RF voltage.

Section # 6 counts passed ions. Counter is on if variable is set as 1, and off when variable is set as zero. It is advised to turn counting off when data is recorded to disk. Otherwise ion number is also recorded on multiple lines.

Chapter 4

Electrostatic quadrupole triplet

Next thing to do was to plan quadrupole triplet, which will shape the beam from HRS such that beam emittance will be converging when injecting it to RFQ. Beam shape after HRS separator is very inconvenient: horizontally focused (very narrow but extremely diverging) beam and vertically parallel (very wide and only little angular spread). This is the situation in HR separator's final focuspoint. Emittance in this point is shown in appendix C.

Three electrostatic quadrupoles will be used to shape the beam to be cylindrical. While quadrupole focuses in one plane, it defocuses in the other plane. If first quadruple focuses in horizontal plane, it defocuses in vertical plane. Next quadrupole must do focusing in vertical plane and defocusingin horizontal plane. As a net effect, focusing happens in both planes because focusing + defocusing will be focusing. Third quadrupole is only for minor adjustments and it can simultaneously act as a xy steerer.

It is convenient to use some ion transport program instead of Simion, because beam is on ground potential after quadrupoles. One transport program is *GIOS*, which is used in these simulations. If ion's initial emittance and transfer matrix for the system is known, it is possible to calculate ion's phase space after system. In these simulations 3rd order calculations are used. In first order calculations ion phase (x, x') is

$$\begin{bmatrix} x \\ x' \end{bmatrix} = M \begin{bmatrix} x \\ x' \end{bmatrix}_0 , \tag{4.1}$$

where M represents system's transfer matrix, which have $\det M = 1$ to keep emittance as a constant. x is ion displacement from reference track and x' angle between ion's velocity vector and reference track; usually in units of mrad.

One important feature that GIOS takes into account, is *fringing fields*. That is, transfer line's potential does not jump to some other value in zero length like step function. Instead, some smoother gradient is used. In this way, GIOS represents real situation more accurately. Fringing fields are applied before and after every single ion optic element except drift length.

4.1 Geometry

Starting point for ions is the ion source. Beam is delivered to HR separator's final focus point and the phase space of ions in this point is shown in appendix C. This part was done by Tim Giles, and only things after this point are discussed here.

Right after focus point there is 20 cm of drift length, where ions are just diverging. After drift length there is 10 cm long electrostatic quadrupole with fringing fields in both ends. Shortest distance from optical axis to electrodes is defined to be 4 cm. Voltage is set as a negative valued variable. After first quadrupole there is 5.2 cm of drift length and another 10 cm long quadrupole with 4 cm aperture. This quadrupole's voltage is set as positive valued variable.

Third quadrupole comes after this with 5.2 cm of drift length. This quadrupole's voltage is set as zero because this quadrupole is (possible) needed for beam steering.

This triplet with RFQ injection geometry is shown in figure 4.1.

4.2 GIOS at work

After defining of geometry and initial conditions one must put GIOS to work. Goal is to get converging beam after quadrupole triplet so that it is possible to inject the beam to RFQ. Two parameters are left open for GIOS: voltages of first two quadrupoles.

Primary fitting objectives are given to GIOS in form of matrix elements. When GIOS is run, it tries to fit to matrix elements by altering voltage values.

4.3 Solution

Emittance after HRS is shown in appendix C. After quadrupoles emittance is shaped to be like in appendix D. Fitting was done with GIOS and voltage for first quadrupole is -3.714 kV and for middle quadrupole 5.698 kV. Voltage for third quadrupole was set as zero.

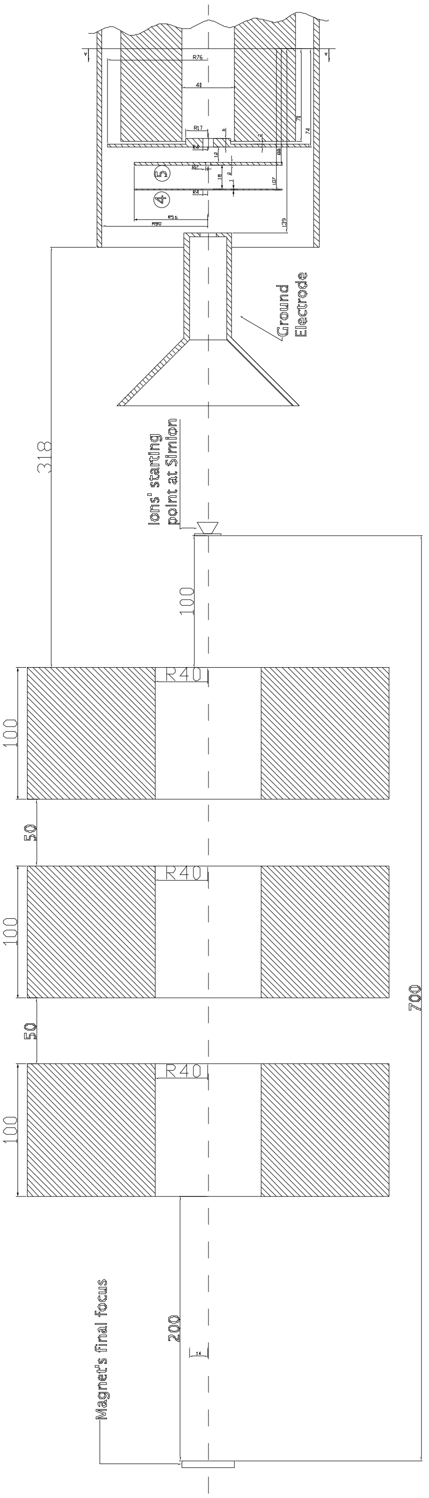

Figure 4.1: Electrostatic quadrupole triplet with RFQ injection geometry.

Chapter 5

Conclusions

The simplest and yet best geometry is shown in figure 3.5. There is only two electrodes which need voltage supplies of 10 kilovolts. The cone-shaped ground electrode is there just to assure that potential is at ground level very close to deceleration electrodes. In real situation there will be an insulator after 60 kV beam tube and then beam tube which is at ground potential thus limiting electric field's tail. Good thing is that this geometry takes only about 10 cm of space giving more space for electrostatic quadrupole triplet which right before injection geometry.

Phase space for ions must be converging in ions starting location (see figure 3.5). This gives the benefit that there is no need for beam focusing with einzel lens before deceleration electrodes.

In real system there must be some sort of cone-electrode, which is at ground potential and shields the ions when crossing insulator ring. Two deceleration electrodes are just plates with circular holes in them. They will have their voltages through high voltage platform. The inner electrode acts as vacuum barrier and so there must be a channel between RFQ and this electrode to a vacuum pump.

Geometry with einzel lens might be hard to do. First of all, there is two more electrodes and another needs a voltage supply of 40 kV, which is rather expensive. Another difficulty is to bring power cord to latter ground electrode, because there is 40 kV electrode in the middle. Another problem is to insulate these from each other and from the high voltage. Support to these electrodes must come from ground and because struture is so long it might cause some distortion.

Pumping should be easily arranged. Because inner electrode acts as good pumping barrier, there is no need for heavy pumping from beam line side.

The emittance of the beam is the same for all ion masses in units of 40 π mm mrad and the beam width is around 8 mm. A slightly different voltages must be applied depending on ion masses and 100 % injection efficiency is gained for a mass range from 10 u to 200 u.

5.1 Quadrupole triplet

Another task was to design a quadrupole triplet, which shapes the beam from HRS so that beam can be injected to RFQ. This was done with GIOS ion transfer program. There is only about 1.5 meters of space reserved for whole injection part so triplet had to designed to be as short as possible. This was possible by bringing quadrupole rods closer together (here 4 cm was shortest distance from optical axis to electrode) and increasing voltage of rods. Length of each quadrupole was set to 10 cm which is very short compared to existing ISOLDE quadrupoles.

Beam shape after HRS was very awkward — focused in other plane and diverging in the other plane. This is why triplet should be placed as close as possible to HRS focus point so that beam has only little time to diverge.

First quadrupole starts 20 cm after HRS focus point. If this is reduced to 10 or at least to 15 cm, this would improve emittance shown in appendix D quite a bit. But still with 20 cm length beam is injectable to RFQ.

GIOS fitting resulted the voltages of quadrupoles to be −3.714 kV and 5.698 kV while third quadrupole was set to zero.

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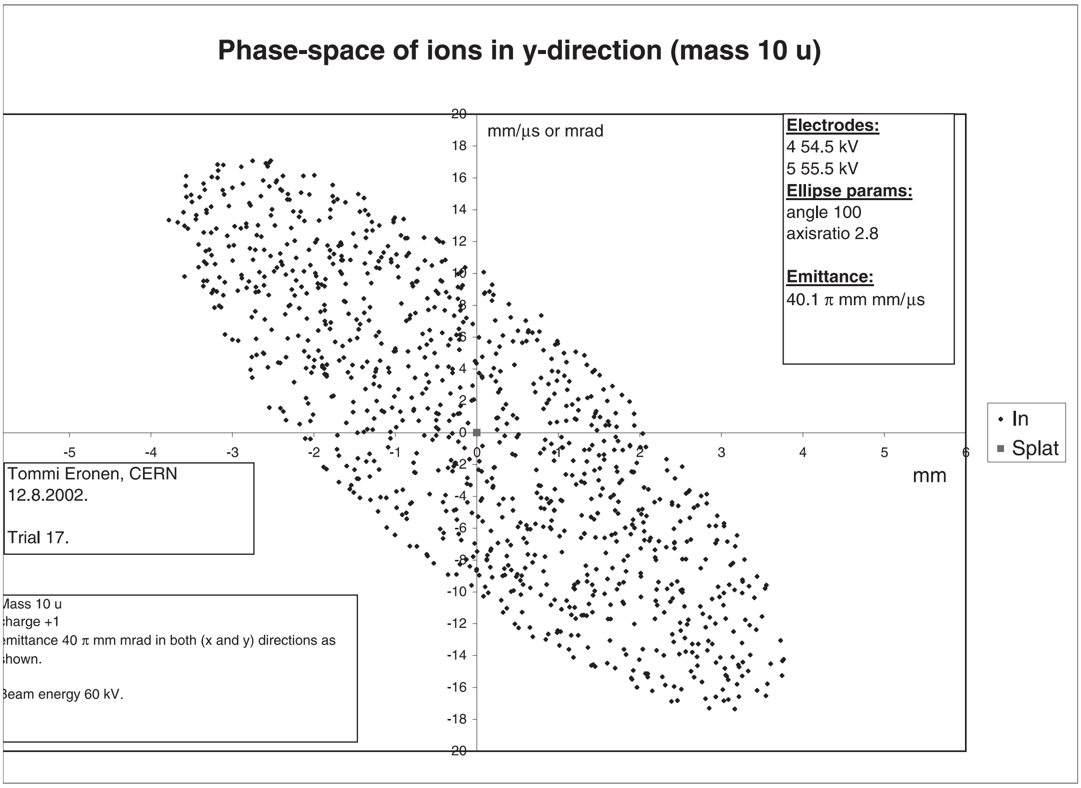

Figure 5.1: Phase space for mass 10 u ions. This phase space can be injected with deceleration voltages 54.5 kV and 55.5 kV. Emittance of the ions is 40 π mm mrad.

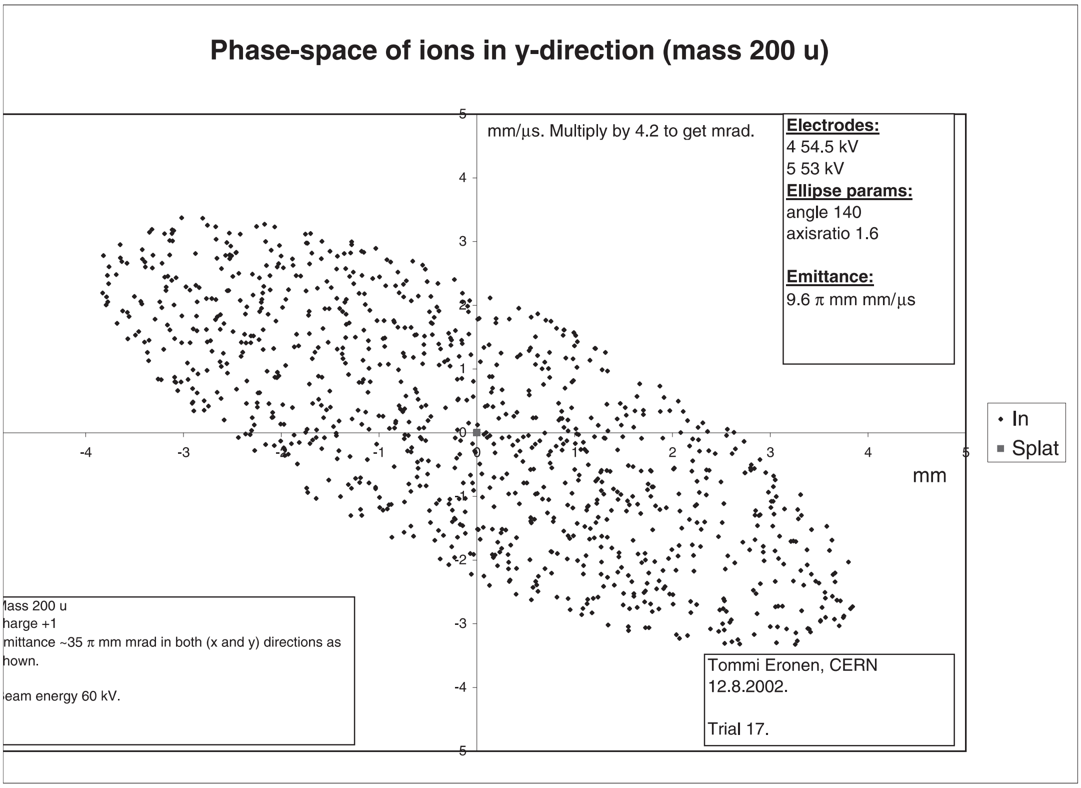

Figure 5.2: Phase space for mass 200 u ions. This phase space can be injected with deceleration voltages 54.5 kV and 53 kV. Emittance of the ions is 40 π mm mrad.