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ECR Beam Optimisation & Development of Charge State Analyser

by

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1 ABSTRACT

Electron Cyclotron Resonance Ion Accelerator (ECRIA) is well known to produce low energy, highly charged ions. The accelerated ions from the ECRIA (called projectiles) can be made to collide with target atoms of our interest and the recoil ions can be studied using Recoil Ion Momentum Spectroscopy techniques. The information about the nature of collision is not revealed completely if we were to only observe the target ions, but by building a spectrometer for analysing the projectile beams after collision overcomes this problem. The main objective of this experimental project is to build such a spectrometer called the Charge State Analyser and then using that, analyse the nature of the collision that takes place which depends both on the nature of the projectiles as well as the nature of the target.In this project we have also learned about method of optimisation of the ECR beam.

2 INTRODUCTION

Electron Cyclotron Resonance Ion Sources(ECRIS) are used to perform a wide variety of experiments involving collisions at low velocities. ECR ion sources use a magnetic field to confine the ions and electrons. Electrons moving in the magnetic field perform cyclotron motion with the Larmor frequency. Electrons are heated by resonant transfer of energy from microwaves (MWs). The impact of energetic electrons on neutral atoms (gas or metal) produces ions. ECR ion sources can provide a huge ion current (of the order of tens of μA) with good stability for continuous operations. ECR ion sources are used as an injector in various accelerators for experiments and for radiation therapy.

3 Theory of ECRIS

ECRIS is based on the principle of electron impact ionization of neutral gas molecules. Production of high charge state occurs in a sequence of ionization steps. Ion source has a cylindrical plasma chamber made of copper. This chamber is embedded in a structure with permanent magnets which produce an axial field with maxima (0.8 Tesla and 1.1 Tesla) at the ends and a closed structure hexapolar radial magnetic field as shown in fig 3.1.

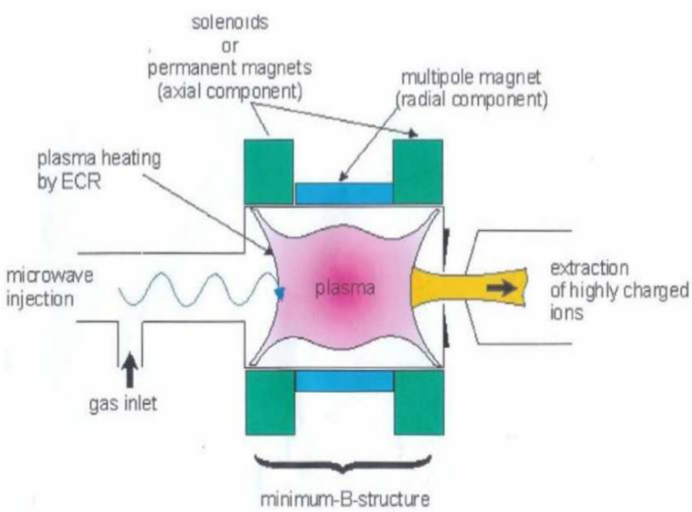

Figure 3.1: Schematic of the ECRIS

In this structure, the minimum B value occurs at the center of the chamber and the value increases in all directions. Such a configuration of magnets is called a "minimum-B configuration". The diagram of the magnetic field is being shown in Figure 3.2 . It has the property of trapping charged particles .In this magnetic field configuration electrons will revolve with different cyclotron frequencies depending on the magnetic field value given by Equation 3.1 .

$$\omega = \frac{e.B}{m} \tag{3.1}$$

In order to make the production effective, it is necessary to provide extra energy to the electron. To energize the electrons, an RF Oscillator(Microwave Source) of fixed frequency (14.5 GHz) is coupled with the chamber through the wave-guide. Then, electrons with cyclotron frequency matched with that of the microwave signal will see an electric field changing with the same

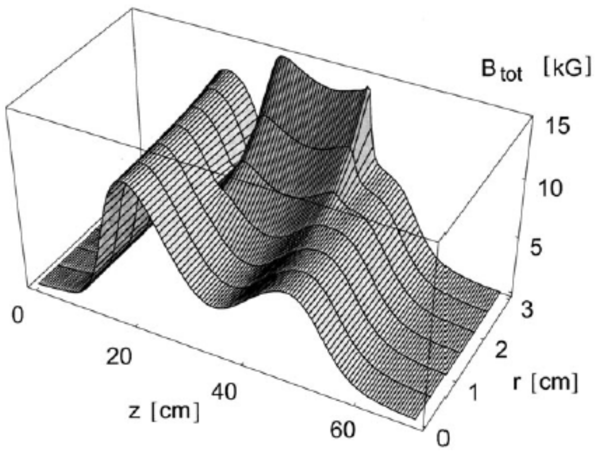

Figure 3.2: "Minimum B" Magnetic field

frequency as their own rotation, then there is resonant energy transfer from Microwave Source to electrons. Now these electrons hit the neutral gas molecules which are put into the plasma chamber through gas inlet. In this process within the minimum- B the energized electrons follow a long helical path, necessary to cause more and more electron-atom collision. Due to this sequential multiple collision, highly charged positive ions can be obtained. Ions obtained in this process are extracted from the source by a positive "Extraction voltage" applied on the source chamber.

4 ECRIA DETAILS

In figure 4.1 we have the schematic of the ECRIA Beam Line

4.1 ELECTRON CYCLOTRON RESONANCE ION SOURCE

TIFR-ECRIS is a "Super nanogan" designed and manufactured by Ms.Pantechnik, France. The ion source is surrounded by permanent magnets (Sm-Co alloy). Plasma chamber is made of copper. In this machine maximum allowed extraction voltage is 30 kV.However the extraction voltage that we set is 20 kV.

4.2 RF SYSTEM

This RF system consists of three units:

- RF oscillator which generates the microwave frequency signal.
- RF amplifier which is a resonator cavity, amplifies the signal.
- Power supply which provides power to the amplifier.

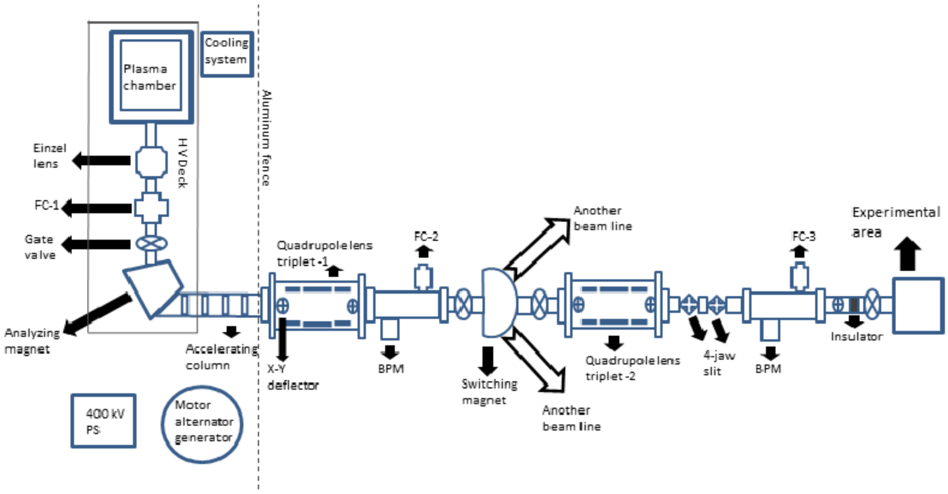

Figure 4.1: Schematic Of ECRIA

In our set-up, RF frequency is 14.5 GHz which corresponds to the resonant magnetic field of 0.51 Tesla and maximum output power is 500 Watt. This RF power is fed to the plasma chamber through the wave-guide. Typically, for lower to higher charge states required power varies from 20 Watt to 250 Watt.

4.3 Einzel Lens

The einzel lens is used for focusing the beam. This lens consists of three metallic (Stain-less steel) cylinders of length 50 mm and inner diameter 50 mm each and separated by 7 mm. First and third are grounded while middle one is given a positive voltage. Typically, this positive voltage lies in the range of 1 kV to 3 kV.

4.4 Faraday Cup

There are three Faraday cups in this system to monitor the current in different positions in the beam line. FC1 is after the Einzel Lens, FC2 is between Qudrupole Lens Triplet-1 and Quadrupole Lens Triplet-2 and FC3 is at the end of the beam line.

4.5 Analysing Magnet

The 90^0 analysing magnet is used to select particular charge state for rest of the beam line by varying the magnetic field. It has the diameter of 40 cm and pole gap 50 mm. It can go up to 0.3 Tesla maximum.

4.6 ACCELERATING COLUMN (AC)

The ECR Deck upto the analysing magnet can be raised to 400 kV. The outlet of the analysing magnet is connected to the accelerating column. The other end of column is joined to Quadrupole Lens. Having one end at high voltage and the other at ground, the potential difference across the column will accelerate the ions further. The AC is made by sealing metal electrodes to insulating ceramic rings. The voltage between the two electrodes is established by resistors. Such a system allows a uniform distribution of electric field along the accelerating column.

4.7 ELECTROSTATIC QUADRUPOLE LENS TRIPLET

There are two Electrostatic Quadrupole Lens Triplet in this beam line. First one is after accelerating column and second one is after the switching magnet. Output beam from the magnets has different emittance in horizontal and vertical planes, and hence a simple Einzel Lens cannot be used to focus it on to a common point. Thus focusing is done by Electrostatic Quadrupole Lens. Electrostatic Quadrupole Lens has four electrodes placed on the sides of a quadrangle with alternating poles having same polarity. This arrangement provides focusing in one plane and defocusing in other plane. Middle Quadrupole arrangement is same as first one but 90^0 rotated in view of polarity and third one is exactly same as first one. First and third elements are of equal size (40 mm long) and of equal strength. Length of the middle elements is nearly 100 mm. And also first and third arrangements are equally separated from the middle one. Thus a triplet has independent control over focusing in two transverse planes.

4.8 X-Y DEFLECTOR

There are four X-Y deflectors at each end of the Quadrupole Lens Triplet. But we only use one which is at the entry end of the first Quadrupole. It is used for better control over the beam.The X-Y deflectors work on the principle of deflection of charged particles in electric field. The deflectors have two perpendicular electric fields generated by voltages on X-Y deflector plates. The voltage can be varied as per the requirement.

4.9 SWITCHING MAGNET

After the first Quadrupole Lens main beam can be directed into three directions at different angles as per requirement. For doing that a switching magnet has been installed.

4.10 BEAM PROFILE MONITOR (BPM)

Beam profile monitor is a device that measures the intensity distribution and position of beam of charged particle. It can be used with both positive and negative ions as well as electrons. In our beam line there are two BPMs. One is after Quadrupole Lens-1 and other one is just before FC3.

4.11 Four-Jaw Slits

Two Four- jaw slits are mounted after the Quadrupole Lens-2, to cut the beam to desired dimensions. The slits are electrically controlled by motor.

4.12 Lead Shielding

The ECR ion source up to analysing magnet is covered with Lead sheets to stop the radiation emitted from ion source and due to beam hitting on the magnet walls. The proper radiation measurements and mappings were done in guidance of TIFR Health Physicist. After the lead shielding radiation level was found under safe limit even with high RF power input.

4.13 Control Panel

Almost all the components of the beam line are being controlled remotely. A Lab-View program has been written to control the Analyzing Magnet, RF tuner, Extraction and Einzel lens voltages as well as the bias rod voltage. Outputs of the Faraday Cups can also be seen in this panel. The gas pressure control is also done remotely. TIFR-ECRIA facility was designed for five separate beam lines. Among these, three are installed and we use the 0^0 beam line for the project.

5 Optimisation of the Beam Current

We used Nitrogen gas to study the optimization of the beam current and the beam current is observed from FC-2 Faraday Cup. The initial base pressure of the ECR Chamber was of the order of 10^{-8} Torr, during optimisation we put the pressure to be at around 2.4×10^{-5} Torr. We then put the analysing magnet's magnetic field around 1100 Gauss (which corresponds to m/q ratio of $\frac{14}{3}$) to select the N^{+3} for the extraction voltage of 20kV. Then by adjusting the Enziel Lens , the quadrupole triplet and the Bias rod voltage we maximize the beam current. After that we vary the analysing magnet's magnetic field from 500 Gauss to 2000 Gauss. We measured this spectra for RF power 20W ,40W ,60W,80W,100W and among these 20W and 100W have been plotted in figure 5.1.

In the spectra we get peaks corresponding to a particular charge to mass ratio that satisfies the radius and the magnetic field of the analysing magnet given by the equation 5.1 .

$$\frac{q}{m} = \frac{2V}{R^2.B^2} \tag{5.1}$$

where V is the potential through which it has been accelerated(extraction potential). The peaks corresponding to the charge states of Nitrogen has been marked in the graph. The unmarked peaks are the impurities that are present in the ECR chamber.

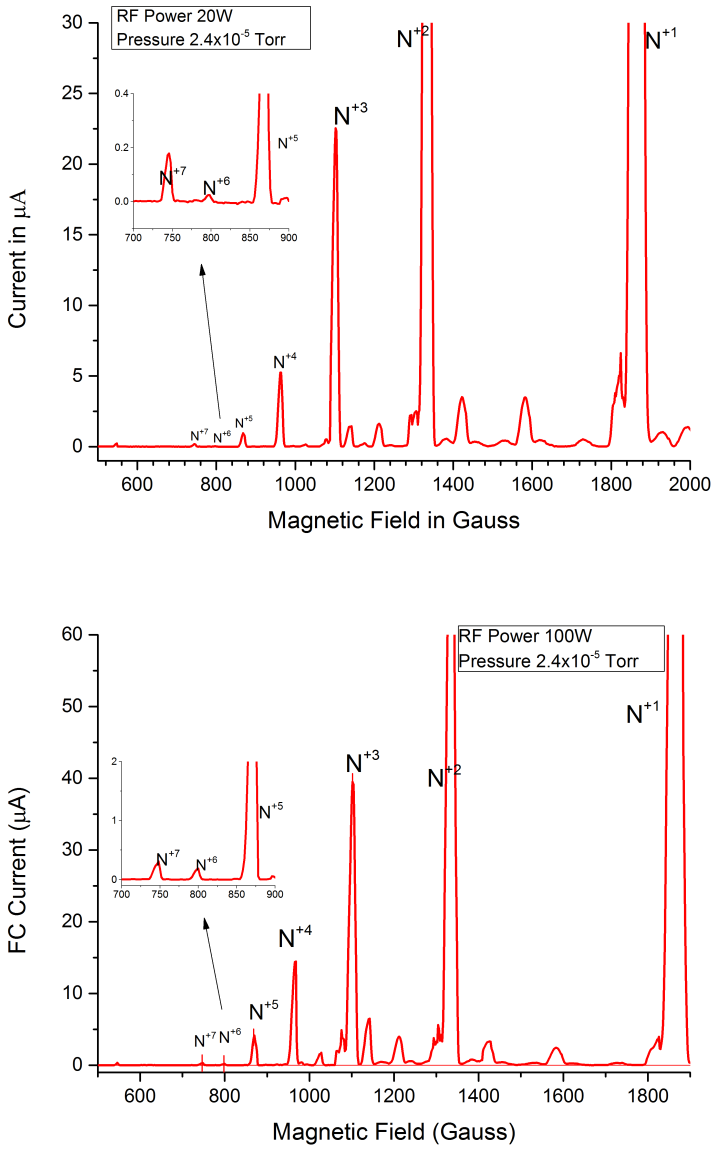

Figure 5.1: Spectra obtained after scanning through analysing magnet at different RF powers

Now, if we plot the FC Current for different charge states at 20W and 100W we get figure 5.2 There are two things that we can note here in these graphs. One is that the higher charge

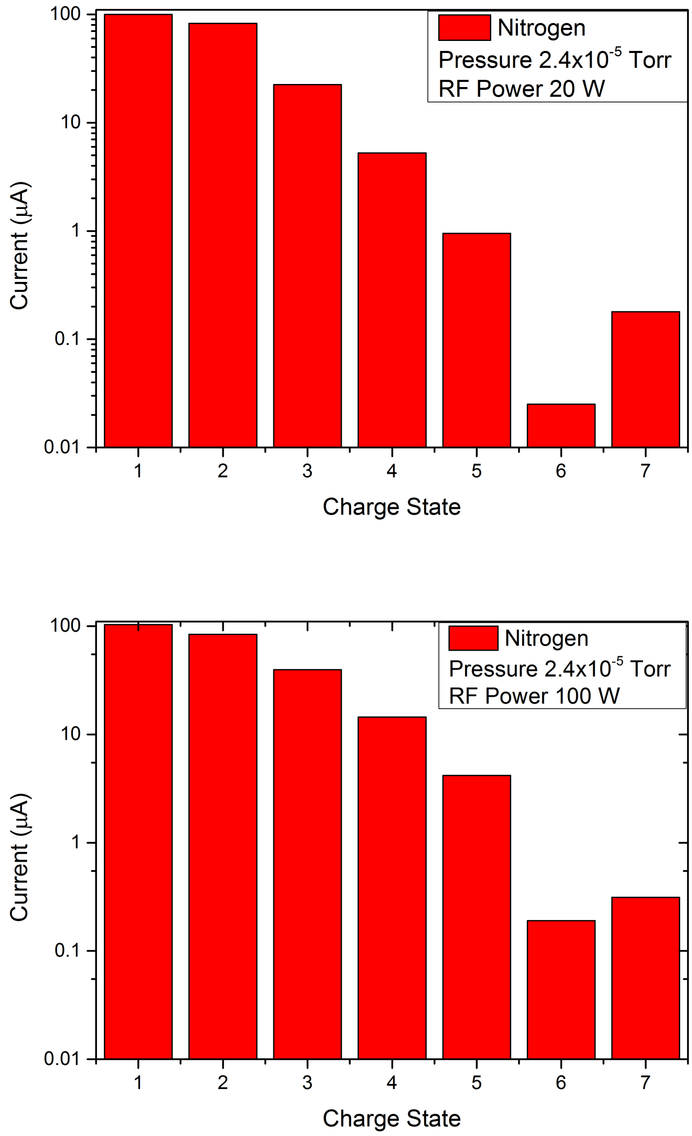

Figure 5.2: Beam Current of Different Charge States of Nitrogen at Different RF Power

state increases as we increase the RF Power. Two , that Beam Current is of the order of μA. Beam current corresponding to N^{+7} charge state is mixed with Beam Current of other species with the same charge to mass ratio. Now if we plot Beam Current of each of the charge state at different RF powers we get the following figure 5.3 . As you can see from the figure that as we

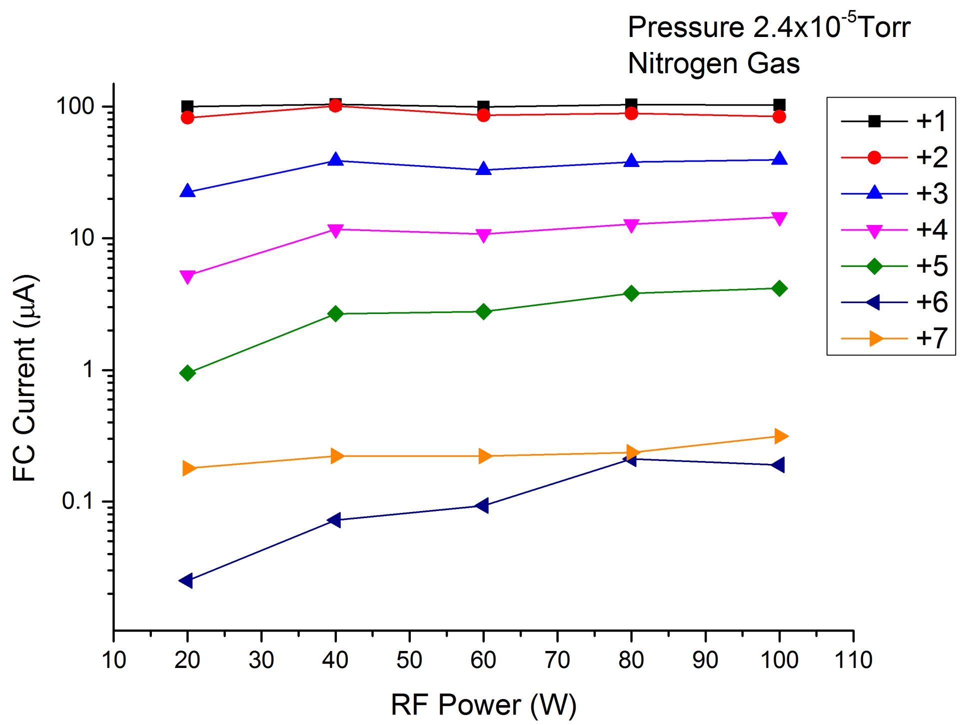

Figure 5.3: Beam Current vs RF Power For different Charge State

increase the power there is a increase in the beam current of higher charge states while lower charge states remain almost same.

6 Development of Charge State Analyser

As we had discussed before, just measuring the momentum and charge states of the recoil target ions will not provides us with the complete information of the electron capture channel would have taken place in the collision. There are three types of ionisation channels namely:

1. Direct Ionisation: Ionisation of the target without the projectile capturing the electron of the target
2. Electron Capture: The target electron is captured by the projectile
3. Transfer Ionisation: Where both capture and direct ionisation can occur.

In the current set-up we can only study the recoil ions that are produced in the collision by measuring their Time of Flight as well as position of impact on the detector. In order to do Time of Flight measurement for the Recoil Ions we need to have the trigger, which is the electron ejected from the target after ionisation.This electron is detected by the Channel Electron Multiplier. But electron capture channel cannot be separated out by the current setup as there is no start trigger corresponding to that channel.

Now if we analyse the post-collision charge state distribution of the projectile, then we can get information about the capture phenomenon.In the present project we have developed a charge state analyser set-up as shown in figure 6.1

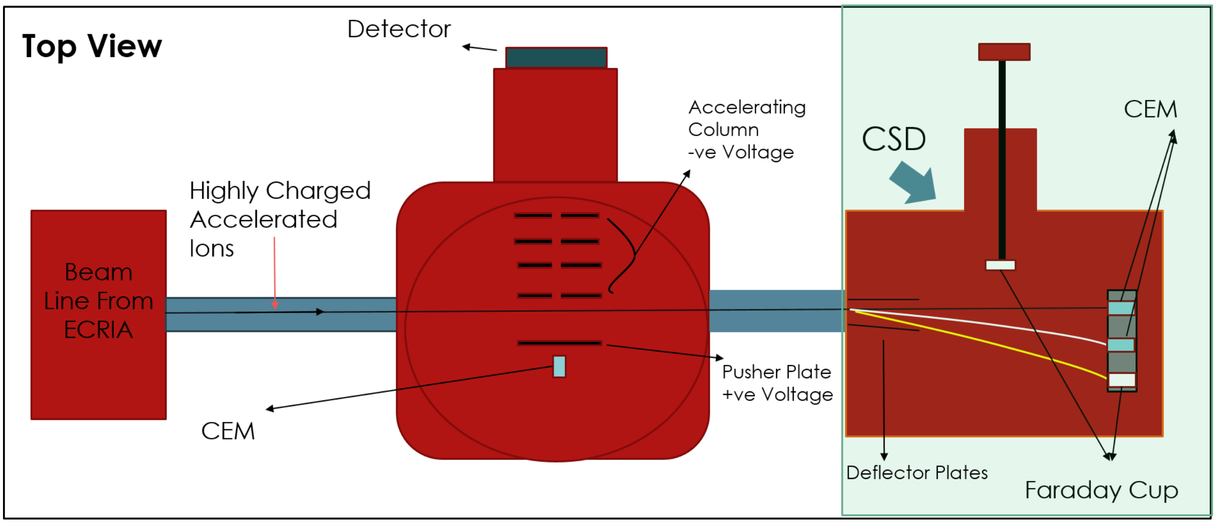

Figure 6.1: Schematics of the Charge State Analyser

To analyse the post collision charge states, the outgoing beam is passed through Electrostatic trapezoidal plate deflectors . Due to capture of electrons the original charge state would be changed to lower values.By applying appropriate voltages to the deflector plates we can control the amount of deflection for different charge states. By measuring their impact position we can get information about the collision channels.The design set-up is optimised for alpha particle or He^{2+} (incoming projectile).So the expected post collision projectiles are He^0, He^{+1}, He^{+2} . We have done a detailed simulation of the design in SIMION 8 software so that we can fix different parameters.Figure 6.2 shows the simulation results.In the actual set-up we are using channeltrons for detection of the charged particles. After assembling all the parts for the Charge State Analyser we tested it for leaks and we got an acceptable leak rate of the order of 10^{-8}Litre/s

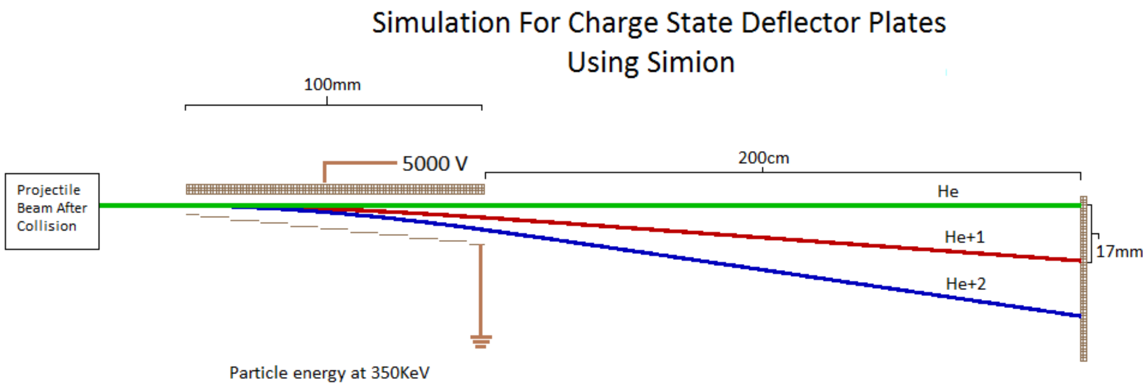

Figure 6.2: Simulation Using Simion

7 Discussion

By adjusting the Enziel Lens,Quadrupole Triplet, Bias rod , Gas Pressure and RF Power we were able to optimize the beam for Nitrogen Gas. We got the different charge states of Nitrogen Gas by scanning with the analysing magnet from 500 Gauss to 2000 Gauss along. Then we looked at the beam current of different charge states and observed that the beam current of ECRIA is of the order of μA. And by varying the power and plotting the beam current for different charge states we were able to infer that increase in power of the RF leads to increase in the higher charge states beam current. Using all these we are able to optimize the projectiles to desired charge states.

In order to capture ionisation process we have designed charge state analyser set-up. It has been vacuum tested and will be installed shortly. For the time being it has been designed from He^{+2} projectiles. In the future it can be modified to study higher charge state projectiles as well.

8 Acknowledgement

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