

SIMULATION OF CIRCULAR RADIO-FREQUENCY CARPETS FOR ION EXTRACTION FROM CRYOGENIC STOPPING CELLS

Adrian ROTARU^{1,2}, Gheorghe CĂȚA-DANIL², Paul CONSTANTIN³, Dimiter.
L. BALABANSKI^{2,3}, Tiberiu SAVA¹, Alex STATE^{1,2}, Anamaria SPĂȚARU^{2,3},
Dragoș NICHITA^{2,3}

At ELI-NP, isotopes of refractory elements and heavy rare earth elements will be investigated by using the ion guide isotope separation on-line technique (IGISOL). A two-chamber cryogenic stopping cell with orthogonal extraction will be used together with RF carpets for the production and extraction of radioactive ions. In the present work, the extraction time of photo-fission fragments is investigated, from the first chamber of the cryogenic stopping cell by implementing RF carpets and gas collision models in the Simlon 8.1 simulation software.

Keywords: RF carpets, IGISOL, cryogenic stopping cell, ion extraction

1. Introduction

The availability of high-brilliance gamma beams at the ELI-NP facility will provide the physics community a new tool for nuclear research [1][2]. Due to the fact that the gamma beams will cover the giant dipole resonance, the facility is ideal for the production and studies of fission fragments.

An experimental program for the production of exotic neutron-rich radioactive ion beams (RIBs) is proposed for the investigation of refractory elements in the Zr-Rh region ($A \sim 100$) and the rare earth region ($A \sim 140$) [3]. For this, the ion guide isotope separation on-line technique (IGISOL) together with the high-brilliance gamma beam at ELI-NP as the primary beam will be used. Thin ^{238}U targets will be placed inside a cryogenic stopping cell. The expected 10^{12} γ/s primary beam flux at energies between 12 and 17 MeV will be used for the photo-fission reaction with a measured cross-section of about 1 b. The resulting fission products need to be collected and delivered as a well-formed ion beam.

The current project aims at building of a High Area Density Orthogonal extraction Cryogenic Stopping Cell (HADO CSC), as first proposed in Ref. [4] and is carried out in collaboration between several research institutions including ELI-NP, GSI and Giessen University. This project is based on the experience

¹ National Institute for R&D in Physics and Nuclear Engineering “Horia Hulubei”

² University POLITEHNICA of Bucharest, Faculty of Applied Sciences

³ Extreme Light Infrastructure – Nuclear Physics, “Horia Hulubei” National Institute for Physics and Nuclear Engineering, Str. Reactorului 30, 077125 Bucharest Magurele, Romania

gained with the CSC prototype operational within the Ion Catcher facility at GSI [5]. A demonstrator unit is being built for testing the RF carpets and is the basis for the large scale IGISOL Facility that will be constructed at ELI-NP.

The scope of this work is to investigate the extraction times of fission fragments from the proposed demonstrator cryogenic stopping cell by using ion optics simulations and ion-gas collision models. For this, we investigate different RF carpets in SimIon 8.1 to determine a good design and to estimate extraction parameters. The purpose of these simulations is to determine the time elapsed from when fission fragments are generated and when they are extracted through the RF carpet and to determine a set of parameters such that extraction time is minimized.

2. Discussions on HADO CSC concept

The key optical component, which is required to make a CSC system work, is a device called a Radio-Frequency (RF) carpet [6]. In the ELI-NP HADO-CSC, the primary gamma beam will hit multiple thin ^{238}U targets to trigger giant dipole mechanism and will result in photofission and release of fission fragments. The photo-fission fragments can have between 20-100 MeV kinetic energy (depending on mass) and very broad momentum spread [7] once the ^{238}U nucleus splits. In Fig. 1, which shows the ELI-NP cryogenic stopping cell demonstrator, this happens in the lower chamber denoted as Chamber 1. This chamber is filled with He gas at 300 mbar and 70 K to thermalize all fragments in 10 cm [8]. It is an excellent choice as a gas moderator because it is an inert gas and it has a high ionization potential. The charge of the fragments should not be neutralized by charge exchange with residual gas impurities, making extraction by electric fields ineffective. Consequently, the chamber must be filled with ultra-pure He and kept at cryogenic temperatures to freeze most impurities to the walls.

There are three main field components of the RF carpet which are considered in this paper. First, there is a DC guiding field that guides the ions towards the carpet. A guiding electrostatic field is created between the carpet, acting as a cathode and an anode layer on the bottom of the chamber such that fragments which have positive charge will flow towards the carpet. After thermalizing, all fragments drift along this guiding DC field upwards. The intensity of this field should be significantly larger than that of the field induced by the space charge generated via gas ionization. A value of about 100 V/cm was calculated as being appropriate [8]. Second, once the fragments reach the surface of the RF carpet, there is a RF repulsion field that acts at short distance and makes the ions hover above the carpet's surface. However, fragments cannot hover

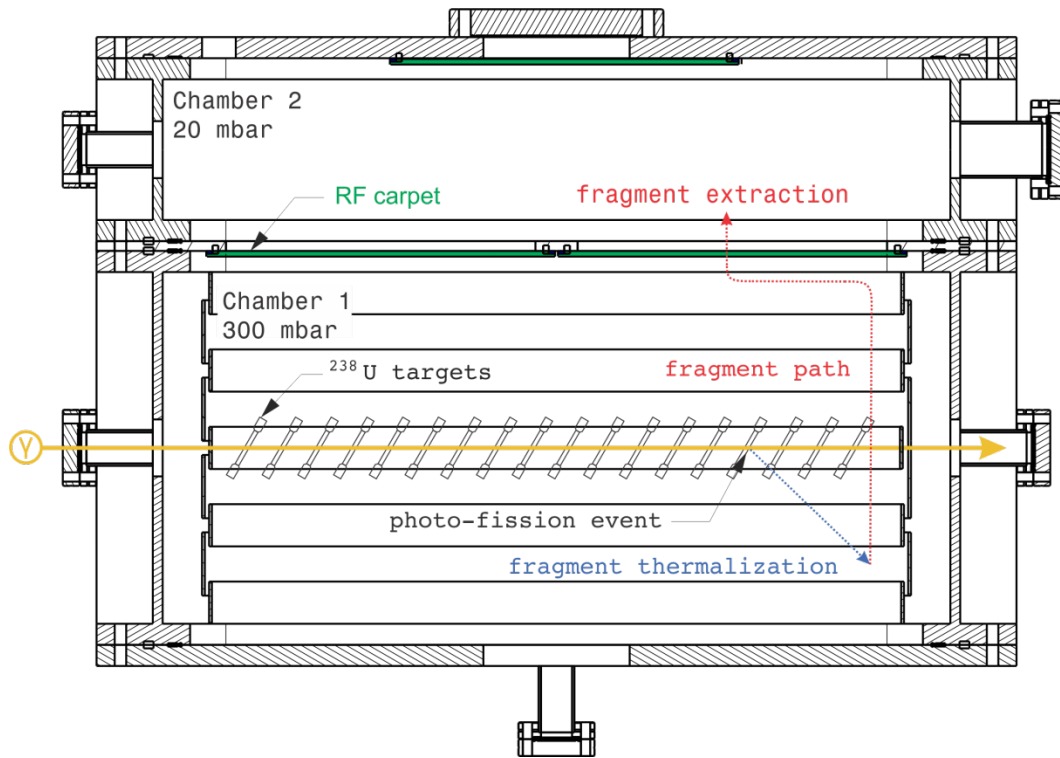


Fig. 1: Illustration of cryogenic stopping cell used to create radioactive ion beams using the (γ, f) reaction. In this illustration, yellow line represents the primary gamma beam and its direction and the blue and red dotted lines represents the path of fission fragments during its three flight phases (thermalisation, drift and drag)

indefinitely and will touch the carpet, at which point they are lost. The geometry of the carpet, the RF frequency and amplitude requires a systematic study to determine the best parameters to catch the fragments and retain them on the surface as long as possible. This is one of the main topics addressed in this work.

Third, there is a DC steering field that drifts the ions towards the centre of the carpet. At the centre, we have a nozzle through which fragments are extracted into the second chamber, denoted as Chamber 2 by He gas flow using differential pressure (20 mbar in the Chamber 2). Here they are again collected using RF carpets and then extracted towards a RF quadrupole where the ion beam is formed. Thus, a RIB is created that can be separated, post-accelerated and sent to experimental stations.

One of the main challenges with our two-chamber design is that while in the first chamber the gas flow is stationary and the processes of ion manipulation are well understood, in the second chamber we face non-linear gas jets and we need to handle the ion transport under these conditions. Ion handling in the second

chamber will be the subject of a future work; the present paper presents solutions for ion manipulation in the first chamber only.

A feature of any kind of optical element is its acceptance that represents the maximum emittance that a beam transport system is able to transmit. The RF carpets can input a population of ions with a wide kinematic spread and outputs a beam with low emittance. At the basic level an RF carpet is a planar arrangement of many electrodes with different voltages applied on them. They can be either arranged as a circular or a linear array to accommodate different geometries. In Fig. 1 we illustrate the use of 2 circular RF carpets in Chamber 1 and one central circular RF carpet in Chamber 2.

Through collisions with neutral gas particles, the fragments are thermalized and the gas acts like a velocity limiter. If electric field lines are present within the volume, the thermalized ions will follow the field lines precisely. Thus, it is possible to extract ions with very wide spread of kinematic parameters. In this method of extraction, the RF carpet acts as a collector for slow ions.

The RF repelling force of a carpet inside a pressure chamber can be approximated as:

$$|F| = m\mu^2 \frac{V_{RF}^2}{r_0^3} \quad (1)$$

where m is the fragment mass, μ is mobility, V_{RF} is the RF amplitude and r_0 half the electrode spacing. Ideally, the repelling force should be as high as possible such that the fragments survive long enough until extraction. This can be done by increasing RF amplitude but only to the point allowed by the breakdown potential. The main problem, however, is that power increases with the square of the amplitude and more heat is generated. The heat diffusion should be maintained as low as possible since the carpet is inside a cryogenic gas chamber and temperature should be kept constant. The second option is to minimize the spacing between electrodes as much as possible which is technologically difficult. Nowadays carpets with 4 electrodes per mm, i.e. 0.1 mm thick electrode and 0.15 mm spacing, can be manufactured with high reliability [5]. The mobility is inversely proportional to the gas density but a compromise can be reached here since decrease of the pressure extends the stopping range.

The way the RF power is applied, is that the potential on every electrode is offset with 180 degrees with respect to his neighbours and oscillates with a certain frequency in the MHz range. The fragments oscillate with the RF signal and prefer to stay in between electrodes and will randomly move along them.

As mentioned, the fragments only hover for a small amount of time before they touch the RF carpet. In order to extract them they have to be forced to move towards the exit nozzle. This can be done with a DC gradient applied directly on the carpet. The innermost electrode can serve as cathode and the outermost can serve as anode. This can be easily achieved simply by connecting the two

electrodes to a voltage source and link the remaining electrodes through a resistor chain. The method is simple and the extraction time is inversely proportional to electric field strength. It is desired to have an applied voltage as high as possible because this decreases flight time, however we are limited by the breakdown voltage and as such our applied value will be slightly below this value.

3. Simulated results

The two most important parameters to consider for an RF carpet to extract photo-fission fragments are the efficiency and extraction times. Thus, the RF carpet must be simulated as accurate as possible to determine a good design and to estimate the extraction parameters. SimIon 8.1 [9] is an excellent software used for electro-optical simulations. Complex geometries can be defined and Lua scripting can be used to add complex physical behaviour.

In the simulations, we consider ions which are generated on the surface of a ^{238}U target with kinetic energy (KE) in the range between 20 MeV and 100 MeV, emitted in random directions, as described in the previous section. After thermalizing, they follow the DC guiding field and drift towards the RF carpet surface.

Fragments are simulated with $A=100$ amu and $q=+1$. Collisions with gas atoms can be simulated by either the hard sphere collision model or by statistical diffusion.

The hard sphere collision model is simple to implement and widely used because of its simplicity. It assumes that all particles are impenetrable spheres and cannot overlap each other. However, they transfer momentum by elastic interaction which happens with an expected frequency measured as mean free path. Unfortunately, this model is very slow to simulate and is suitable only for low pressures.

Statistically simulated diffusion model works to some extent like the hard sphere collision model. It estimates the thermal velocity of the fragment and the mean free path, but it does not model every collision between ions and gas atoms. Instead it calculates the number of expected collisions for each ion in a time step and uses it to calculate a statistical jump radius. Calculations within this model are faster and it works better for higher pressures. Therefore, it is used in the simulations for the 300 mbar chamber.

We model a circular RF carpet with concentric rings of width 0.1 mm and a gap of 0.15 mm [5]. To create the RF repulsion field, the potentials for each electrode on the carpet is given by:

$$U_{\text{electrode}} = V_{\text{RF}} * \sin(t(s) * 2\pi f) \quad (2)$$

Where f is frequency and t is elapsed time (given on each run by the time of flight of the ion). Ions with mass of 100 amu and charge state +1 are generated at a distance d from the carpet. To force the ions to drift towards the carpet we use a DC guiding field of 10V/mm generated between the carpet itself and an anode placed at a certain distance D . This geometry is illustrated in Fig. 2.

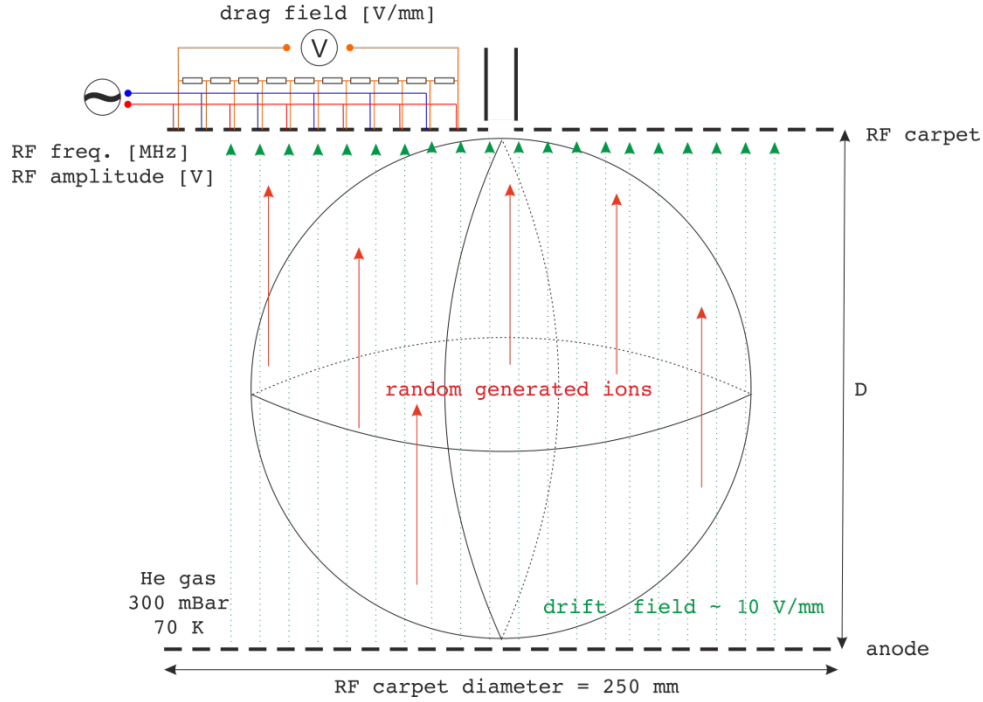


Fig. 2: Illustration of simulation geometry with DC guiding fields (green) to push randomly generated ions towards the surface of the RF carpet

The entire simulation volume is filled with He gas and elastic interactions are modelled using statistically simulated diffusion, the volume pressure is 300 mbar and the temperature is 70K. When ions are generated between the carpet and the anode, the guiding field will push them towards the carpet, they will collide elastically with neutral gas particles such that a constant velocity is reached and when they reach the RF carpet the repulsion field should trap them above the surface at a certain distance. In Fig. 3 we present the volume the ions occupy above the RF carpet for an RF frequency of 6 MHz. Different RF amplitudes were used in the range of 80 V and up to 160V and the vertical position of the fragments above the surface of the RF carpet was recorded. Inside this volume, the ions vertical position oscillates. The optimal RF amplitude is a compromise between the oscillation distance from the carpet and the breakdown voltage that can occur between two electrodes. At 130 V the ions are always at least 100 nm above the surface.

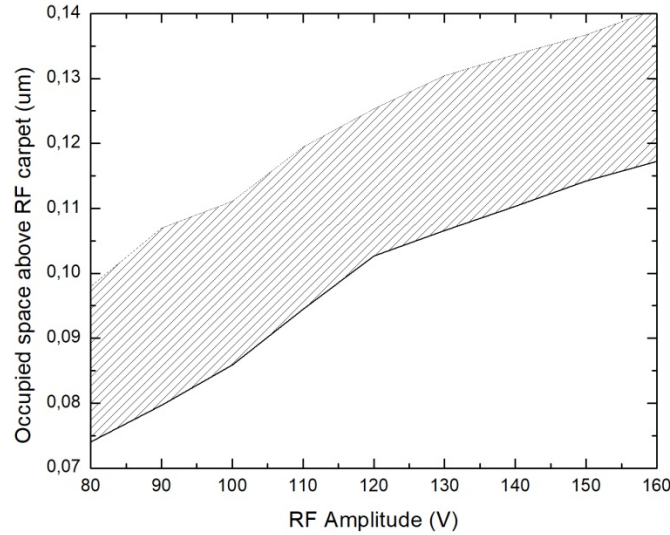


Fig. 3: The vertical space occupied above the RF carpet by fragments oscillating under the influence of the RF repulsion field for different RF amplitudes

After computing the height at which the ions hover, the carpet was tested at 6 MHz and 130V RF amplitude to find out how long a single ion can hover above it without touching the electrodes. After 100 ms of simulated time the ion remained stable and seemed to remain like this for a long time. Ideally, the extraction time should be as short as possible, and in reality, a total extraction time of 30-40 ms is targeted to be able to extract short lived isotopes. Thus, one can assume that a RF carpet with 4 electrodes/mm, operating at 6 MHz and 130V RF amplitude is suitable for trapping the ions of interest.

After we determined the parameters to trap ions with mass of 100 amu and charge +1, we investigated the DC steering field necessary to transport ions above the surface of the RF carpet. Without a steering field the ions will hover randomly and we need to collect them towards the centre where they are extracted through a nozzle by the gas flow.

To simulate this process, ions were generated on the extremities of the RF carpet and a DC field was applied between the outermost electrode, serving as anode and the innermost electrode, serving as cathode. This field is divided equally between the remaining electrodes to form equipotentials. The time of flight was recorded and the velocity was computed for different DC steering fields. These results are presented in Fig. 4. For these simulations, an RF frequency of 6 MHz and a RF amplitude of 130 V were used. Gas conditions remain the same. The ions do not move continuously above the carpet, they hover in-between electrodes where they wait a certain period.

The mechanism by which the ions move above the RF carpet is that they find a position of semi-stability in-between two electrodes – because of the rapidly changing RF field and their reduced mobility because of the gaseous medium, and they tend to wait in this semi-stable position. The effect of the drag field applied along the surface of the RF carpet gives them a push towards the centre nozzle. Statistically, they will wait for a certain period of time in-between two electrodes and then will jump, after which they will wait and jump again. Slowly, they are dragged towards the centre of the carpet.

The average waiting time for an ion to jump between two consecutive electrode gaps was estimated from the total time of flight. It is obvious that when increasing the drag field average waiting time per electrode is reduced such that the total extraction time will be reduced. The practical limit of this is the breakdown voltage. A drag field of 3.6 V/mm results in an average ion speed of 2.38 m/s.

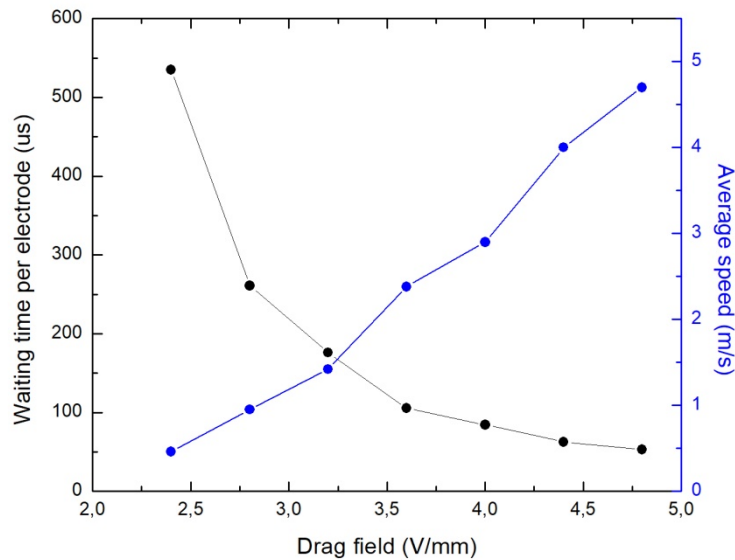


Fig. 4: Ions average speed above the RF carpet and average waiting time per electrode for different drag field voltages

All electrodes must be connected to an RF electronic resonator tuned at some MHz frequency. This electronic resonator is an RLC circuit powered by a signal generator and an amplifier. The RLC circuit is required to be at resonance with the signal generator such that electrical losses are minimized. Since the RF carpet must function inside a cryogenic stopping cell, the heat dissipation must be kept at a minimum. In the case of using a DC guide field all electrodes are also connected to a resistor chain powered by a dedicated voltage source.

The next step in our simulations was to compute the ion average velocity as a function of gas velocity and DC guiding electric field. This is needed to estimate the time it takes for a fragment to reach the surface of the RF carpet while drifting through the gas. For this, two planar electrodes placed at a small distance apart are considered. A voltage drop is applied such that the field lines are perpendicular to the plates. The statistically simulated diffusion collision model is used considering that He at 300 mbar and 70 K fills the volume. An average gas flow velocity is assumed, parallel with and in the same direction as the DC field lines. The average ion velocity is estimated from its time of flight. In Fig. 5, the ion average velocity (ion vx) is presented as a function of the gas velocity (gas vx) for different guiding fields voltages (guiding field voltages are colour coded). The ions velocity vectors are defined as being parallel to the electric field lines.

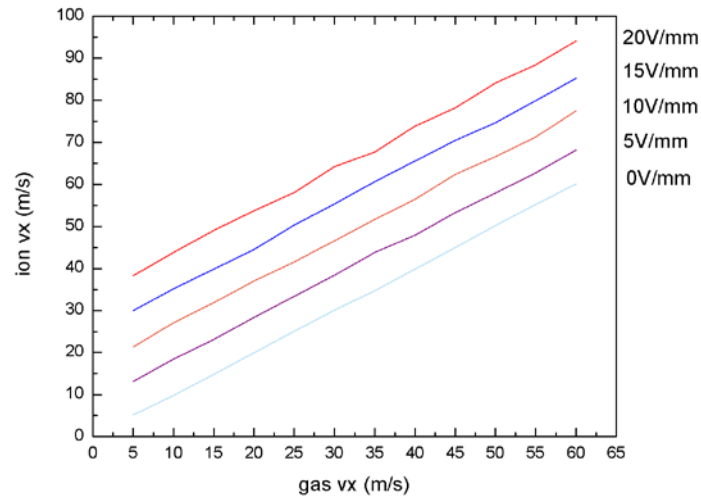


Fig. 5: Ion velocity as a function of gas velocity and DC field gradient

A limiting factor of the CSC performance is the ability of the RF carpet to catch ions coming with different velocities. In the first simulations investigating the ability of the RF carpet to maintain ions hovering above it, the ions were coming with average velocity of around 17 m/s. The simulation was repeated adding a gas flow component which increases the velocity of the ions.

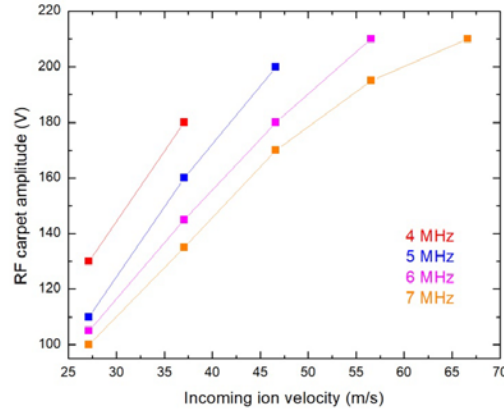


Fig. 6: RF carpet voltage amplitudes needed to catch ions at different incoming speeds

In the plots shown in Fig. 6 the RF amplitude needed to catch the ions and make them hover stable for a minimum of 100 ms is presented as a function of the ion velocity. Obviously, the increase of amplitude is beneficial but a compromise must be reached to maintain electrical consumption as low as possible i.e. to avoid thermal losses. An amplitude of 130V at 6 MHz seems satisfactory for catching ions with velocities up to 33 m/s. This is a very promising result because it is unlikely that ions with greater velocity will reach the surface of the RF carpet due to thermalisation. Continuing this work, we will need to construct a testing chamber for RF carpets and we will make a comprehensive study of how the different parameters addressed in the present paper impacts overall ion extraction time. The experimental results that will be obtained will be invaluable for the development of our experimental cryogenic stopping cell. These simulated results provide a good place to consider starting our future experimental work.

4. Extraction times calculations

The simulations described in this work allow us to specify the working parameters for fragments extractions using an RF carpet. For the CSC demonstrator device, three 25 cm diameter RF carpet with 500 electrodes (4 el/mm) will be used.

In the present paper, we will consider extraction times from the first chamber only. To consider the second chamber we need to take into account non-linear gas flow, which will be the subject of a future work. Furthermore, because the first chamber is symmetric with respect to its centre (both left and right side is mirror identical to one another and each has one RF carpet – see Fig. 1) we will consider one half with width of 250 mm and height of 200 mm. We assume the

results in the other half to be identical because of the mirror symmetry. In the centre of the simulated volume a thin ^{238}U target is placed. It is irradiated with 5×10^{12} γ/s primary beam with energies between 12-18 MeV. This will generate approx. 2×10^6 fragments/s that will be emitted in random directions [3]. The photo fission fragments start with KE between 20-100 MeV and a charge state between +10 and +20. The entire volume is filled with He gas at 300 mbar and 70 K. Through elastic collisions the fragments will thermalize very fast, about 50 ns and will end with KE ~ 1 -2 keV and charge $q=+1$. After thermalizing the fragments have travelled around 100 mm from the ^{238}U target in random directions.

The following are the extreme cases that can be considered. The first case is the fastest possible extraction; ion is emitted straight upwards and lands directly over or very close to the extraction nozzle. In the second case the ion is emitted straight downwards and after thermalizing it is guided by the guide field upwards and lands close to the exit nozzle. In the third case the ion is emitted parallel to the RF carpet in which case it will travel the longest distance across the carpet, thus it will take the longest time to be extracted.

In either case a drift field of 10 V/mm is used which accelerates the fragment to a velocity of ~ 17 m/s towards the RF carpet. If a drag field is used for extraction (3.6 V/mm) this will result in travel velocity above the carpet of ~ 2.38 m/s. The carpet will operate at 6 MHz and 130 V RF amplitude.

The simplest way to compute an average extraction time using these travel speeds is to calculate travel time from travel length for each emission angle. As a good approximation, all ions thermalize in a 100 mm travel length. This correspond to spherical coordinate r . Since we are evaluating a single ^{238}U target placed in the centre of a RF carpet and the carpet has cylindrical geometry, the θ coordinate can be neglected. The ϕ coordinate takes values from 0 to 180 deg. and it is possible to compute a travel length and travel time for each angle.

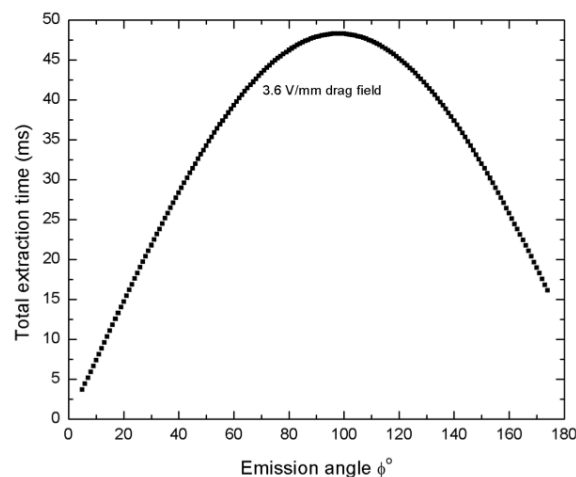


Fig. 7: Total travel time as a function of emission angle ϕ

The UF₄ target is 7x7 cm wide and 3 μ m thick. The total extraction time is given by the thermalizing time, the drift time and the hover time above the RF carpet. The total travel time as a function of each emission angle ϕ is presented in Fig. 7.

Obviously, the longest extraction time occurs for fragments emitted at $\phi \sim 100^\circ$ for a DC drag field. This happens because the hovering above the carpet takes much more time than the drifting through gas. An average extraction time is an arithmetic mean over the different directions since the emission is assumed to be isotropic. Thus, in a simplified assumption, the simulated average extraction time is calculated to be 34 ms.

5. Conclusions and outlook

In order to evaluate the extraction performance of photo-fission fragments from a cryogenic stopping cell, we have implemented a radio frequency carpet and gas collision models in the SimIon 8.1 simulation software. This has allowed us to investigate different aspects of the ion handling and understand the various behaviours under different conditions, fine tune the working parameters in order to optimize the system and calculate the total extraction time for fission fragments from the first chamber.

Obviously, the study needs to be continued to include non-linear gas jets in the second chamber and to calculate the total extraction times for fission fragments from the entire cryogenic stopping cell. Also, in the future we will investigate the method of travelling wave extraction to determine if it is possible to reduce the extraction times by increasing the fragments drift velocities above the surface of the RF carpets.

REFERENCES

- [1] *N.V. Zamfir*: Nuclear Physics News **25**, 34 (2015).
- [2] *D.L. Balabanski et al.*: Eur. Phys. Lett. **117**, 28001 (2017).
- [3] *D.L. Balabanski et al.*: Rom. Rep. Phys. **68**, S621 (2016).
- [4] *T. Dickel et al.*: Nucl. Inst. Meth. B 376, **216** (2016).
- [5] *Plaß et al* NIM (2013)
- [6] *M. Wada et al.*: Nucl. Inst. Meth. B **204**, 570 (2003).
- [7] *P. Constantin et al.*: Nucl. Inst. Meth. B **372**, 78 (2016).
- [8] *P. Constantin et al.*: Nucl. Inst. Meth. B **397**, 1 (2017).
- [9] *D. A. Dahl*: Int. J. Mass Spectrom. **200**, 3 (2000).