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Design, construction and cooling system performance of a prototype cryogenic stopping cell for the Super-FRS at FAIR

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ABSTRACT

A cryogenic stopping cell for stopping energetic radioactive ions and extracting them as a low energy beam was developed. This first ever cryogenically operated stopping cell serves as prototype device for the Low-Energy Branch of the Super-FRS at FAIR. The cell has a stopping volume that is 1 m long and 25 cm in diameter. Ions are guided by a DC field along the length of the stopping cell and by a combined RF and DC fields provided by an RF carpet at the exit-hole side. The ultra-high purity of the stopping gas required for optimum ion survival is reached by cryogenic operation. The design considerations and construction of the cryogenic stopping cell, as well as some performance characteristics, are described in detail. Special attention is given to the cryogenic aspects in the design and construction of the stopping cell and the cryocooler-based cooling system. The cooling system allows the operation of the stopping cell at any desired temperature between about 70 K and room temperature. The cooling system performance in realistic on-line conditions at the FRS Ion Catcher Facility at GSI is discussed. A temperature of 110 K at which efficient ion survival was observed is obtained after 10 h of cooling. A minimum temperature of the stopping gas of 72 K was reached. The expertise gained from the design, construction and performance of the prototype cryogenic stopping cell has allowed the development of a final version for the Low-Energy Branch of the Super-FRS to proceed.

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1. Introduction

The Facility for Antiproton and Ion Research (FAIR) is being built at the GSI Helmholtz Center for Heavy Ion Research in Darmstadt, Germany [1]. At FAIR, the NUSTAR (NUclear Structure, Astrophysics and Reactions) collaboration will study atomic nuclei at the limits of their existence. For this purpose, a secondary beam of exotic nuclei is needed. At FAIR, as at the present GSI facility, such a beam is produced by the in-flight method in which a high-energy beam of stable heavy ions (at GSI and FAIR, energies of up to about 1500 MeV/u are used for the production of secondary beams) passes through a thin target causing the transformation of part of the incident ions into radioactive ones due to nuclear reactions with the target nuclei. The desired radioactive ions are separated from the primary beam and other reaction products by a fragment separator and sent to an experimental setup. The

efficiency of the separation process depends on the momentum and angular acceptance of the fragment separator. The secondary beam intensity delivered by the present FRagment Separator (FRS) at GSI [2] is mainly constrained by its momentum and angular acceptance. In order to gain intensity and to improve the method considerably, the new large-acceptance Superconducting FRagment Separator (Super-FRS) is being constructed [3,4].

The Super-FRS is followed by different experimental branches: the Storage Ring Branch, the High-Energy Branch and the Low-Energy Branch [5]. At the Low-Energy Branch (LEB), the main experimental setups are HISPEC/DESPEC (High-resolution In-flight SPECtroscopy/DEcay SPECtroscopy) [6,7], MATS (Precision Measurements of very short-lived nuclei using an Advanced Trapping System for highly-charged ions) and LaSpec (Laser Spectroscopy) [8]. The operation of MATS and LaSpec requires a low-energy beam (up to a few tens of keV) with a small spread in energy and angle. The high-energy radioactive ion beam from the Super-FRS will be transformed into a suitable low-energy beam in the LEB. The heart of this transformation is a stopping cell filled with a noble gas. It thermalizes the radioactive ions after they have been

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slowed down in solid material as much as possible and with minimal range straggling using an energy buncher device [9,10,5], and extracts them quickly and efficiently using a combination of DC and RF electric fields.

A pioneering experiment with relativistic projectile fragments was performed earlier at the FRS Ion Catcher Facility at GSI, using a stopping cell operated at room temperature [11]. Based on the experience of this experiment, we have developed a second generation stopping cell. It serves as prototype for the LEB at the Super-FRS and allows experiments with stopped projectile and fission fragments at the FRS. Its innovative features are operation at high gas density and cryogenic temperature; this device is thus called the cryogenic stopping cell. It is the first of its type to be constructed, tested and used. The development of cryogenic stopping cells is also being pursued elsewhere [12,13].

Concerning the energy of the projectile fragments to be stopped, the stopping cells required for the FRS Ion Catcher as well as the FAIR LEB facilities are the most challenging as the primary beams used have the highest energy, up to about 1500 MeV/u. The other major new RIB facilities based on projectile fragmentation have substantially lower primary beam energies: the RI Beam Factory (RIBF) at RIKEN delivers beams with energies up to 440 MeV/nucleon for light ions and 350 MeV/nucleon for very heavy ions [14] while the Facility for Rare Isotope Beams (FRIB) at Michigan State University delivers beam energies of 200 MeV/u for uranium ions and higher energies for lighter ions [15].

A short technical description and the results of off-line commissioning of the cryogenic stopping cell have been published by Ranjan et al. [16]. The first results of the on-line performance of the stopping cell at the FRS Ion Catcher Facility (which is discussed by Plaß et al. [17]) are reported by Purushothaman et al. [18]. First mass measurements of very short-lived isotopes extracted from the stopping cell and injected into a multiple-reflection time-of-flight mass spectrometer [19–21] will be reported elsewhere.

In this paper we present a description of the design considerations and construction of a cryogenic stopping cell to be used at the FRS Ion Catcher Facility and to serve as prototype for the LEB of the Super-FRS. More details can be found in [22]. Special attention is given to the cryogenic aspects in the design and construction and to the cryocooler-based cooling system. The cooling system performance in realistic on-line conditions at the FRS Ion Catcher Facility at GSI is discussed in detail.

2. Stopping cell: some basic considerations

In the stopping cell, energetic ions are thermalized in a noble gas (helium or argon is used in practice). The probability that an ion is in an ionic state after slowing-down is tens of percent up to more than 50%, and hence large enough to be of practical use. Near and at thermal energies, ions cannot neutralize in collisions with noble gas atoms due to the high ionization potential of the latter. Thus, provided that the conditions are suitable, these ions can survive long enough to be transported through an exit-hole out of the stopping volume and subsequently be shaped into a low-energy ion beam. This technique was pioneered in the early 1980s in Ion Guide Isotope Separator On-Line (IGISOL) systems [23]. For a recent historic overview of the development of stopping cells, see [24].

For the stopping volumes of $0.5\text{--}2 \times 10^5 \text{ cm}^3$ [11,16,25,26] dictated by the high energies and emittances at in-flight separators, considering practical limits to the gas flow through the exit-hole that can be handled, gas flow is too slow for efficient ion extraction of short-lived isotopes. For example an exit-hole diameter of 1 mm, having a conductance of 0.45 l/s for helium gas at

room temperature, combined with the stopping volume of 190 l for the cryogenic stopping cell described here, gives a helium gas refresh rate of once per 7 min. In this case electric-field guidance of the ions is needed for fast and efficient extraction.

The most common ion guidance uses a static electric field to push ions towards the exit-hole side of the stopping volume where the ions encounter an RF electrode structure in the shape of a carpet or a funnel [25,27–29]. Such structures were pioneered by Masuda et al. [30–32]. The resulting inhomogeneous RF electric field close to the RF electrode structure provides a time-averaged repelling force. Combining this force with a DC electric field forces the ions to travel along the RF structure towards the exit hole. Very near the exit hole, the force generated by the gas flow becomes dominant and the ions are swept out of the stopping cell. Recently, ion transport based on traveling waves [33] has been investigated in the context of gas stopping cells [34,35].

The stopping of energetic ions creates a large number of ion–electron pairs (one for every 41 eV of energy loss in helium and 26 eV in argon). Ions and electrons move in opposite directions under the influence of the applied DC field. As the electrons have a mobility typically 3 orders of magnitude larger than that of the positive ions, the electron density is the same factor smaller than that of the positive ions; recombination of the thermalized ions with electrons is thus of no concern. For a sufficiently large ionization density, the positive ion cloud blows up by space-charge forces. In this case, an RF wall along the body of the cell can be added to contain the ion cloud [29]. If the ionization density is so high as to create a plasma that shields the applied DC field, electrons and ions are not pulled apart and, in addition to the fact that the ions are not transported by the DC field, neutralization will occur [36,29,37,38].

Ions will form undesired molecules/adducts with impurity atoms/molecules. To limit this process to an acceptable level, a stopping gas impurity concentration better than about 1 ppb is needed (see e.g. [39]). Ultra-high-purity stopping cells, aiming at sub-ppb impurity levels, have been constructed employing ultra-high-vacuum technology (see e.g. [40]). Although possible, this is far from trivial. Earlier work by some of us studying the ion survival and transport in a closed cell [41–43] has shown that a sufficient purity level can be achieved by in-situ purification of the noble gas upon cooling the stopping cell to below about 90 K (when operating at a density equivalent to 1 bar pressure at room temperature). The efficiencies measured at low temperature are comparable to those achieved with ultra-high-purity stopping cells at room temperature. However, we consider the construction of a cryogenic stopping cell to be easier. It allows a wider choice of materials, e.g. for an RF carpet. Also, for constant gas density, the mass flow through an exit-hole is proportional to the square root of the temperature. Thus a cryogenic stopping cell allows a larger density for the same pumping capacity at the extraction side. Finally, from an operational point of view, reaching ultra-pure conditions by cooling down is faster and more reliable than by the baking procedure required to reach such conditions at room temperature, an important point for accelerator-based experiments.

3. Cryogenic stopping cell design considerations

3.1. Input from Super-FRS simulations

As the cryogenic stopping cell is developed to serve as prototype for the LEB at the Super-FRS, its design is based on the Super-FRS beam properties. Detailed simulations of the optimized tuning of the Super-FRS facility for use with the stopping cell, thus including range bunching, were performed for two typical but

kinematically different cases: the production of ^{100}Sn by projectile fragmentation of a 1000 MeV/u ^{124}Xe beam on a 6 g/cm² carbon target and the production of ^{133}Sn by projectile fission of a 1217 MeV/u ^{238}U beam on a 3 g/cm² carbon target. We note that recently the design of the Super-FRS range buncher has been updated [5]. The development of a final version of the stopping cell thus needs to be guided by updated simulations.

The simulations performed in the framework of the design of the prototype cryogenic stopping cell show that the range straggling (standard deviation) that needs to be handled by the stopping cell is 2.5 mg/cm² helium for ^{100}Sn and 6.6 mg/cm² helium for ^{133}Sn . Efficient stopping (about 90%) of these ions thus requires areal densities from 8 to 20 mg/cm² helium. Based on these results, we aimed for a stopping cell with areal density of up to 20 mg/cm². We chose a stopping cell length of 100 cm as being quite representative for a final device; as such, the results of the prototype stopping cell will be valid or scaleable if the final device turns out to be a few times longer. For such a length, the maximum areal density deduced from the simulations translates into a density of the helium stopping gas of 0.20 mg/cm³, several times higher than that reached for stopping cells containing RF electrode structures at the time of our design. It corresponds to a helium pressure of about 1200 mbar at room temperature or 250 mbar at 60 K. Other design choices were taken with maximizing the density of the stopping gas in mind.

The full beam widths at the position of the stopping cell are not very different for the two reaction types considered. Based on the simulation results, we chose a stopping volume diameter of 25 cm. As the beam is smaller in the vertical direction, the beam entrance windows in the system are chosen to be 25 (horizontal) × 10 (vertical) cm² in size.

In the case of projectile fragmentation, unwanted isotopes are mostly well separated and, more importantly, more intense fragments stop earlier and thus do not cause extra ionization of the stopping gas. For fission fragments, the situation is not as favorable. Fission gives poorer quality beams because a large energy of about 1 MeV/u is given to the fission fragments in the reaction, isotropically in the center-of-mass system. Also, neighboring, more intensely produced, isobaric isotopes have a longer range and, although they will not be stopped in the stopping cell, they will cause a lot of extra ionization of the stopping gas. For an effective stopping volume of about 5×10^4 cm³, an areal density of the helium gas in the stopping cell of 6 mg/cm², and a primary beam intensity of 5×10^{11} ions per 1.2 s spill (the maximum planned for FAIR), the ionization density rate (electron–ion pairs per cm³ and per second) is 800/(cm³ s) in the case of the ^{100}Sn fragmentation product and $4 \times 10^{10}/(\text{cm}^3 \text{ s})$ in the case of the ^{133}Sn fission product. Definite conclusions concerning the effect of ionization on ion extraction and survival are difficult as the effects depend on e.g. DC field and gas purity. Looking at data from stopping cells at RIKEN [29] and MSU [26], as summarized by [44,45], we conclude that in a typical case of projectile fragmentation, ionization density rates will be low enough so as to not cause problems. What will happen in the case of fission fragments at the highest primary beam intensity planned for the FAIR accelerator is difficult to predict. Eventual adverse effects can be counteracted by applying a higher DC field and/or the use of an RF wall around the effective stopping volume. In order not to add extra complications to the design of the prototype cryogenic stopping cell, an RF wall was omitted; it can readily be added later if required.

3.2. DC field

A large DC field throughout the bulk of the stopping volume is needed for fast ion extraction, required for the study of short-lived isotopes. The travel time of ions is proportional to the areal density

of the gas traversed and inversely proportional to the electric field. The mean ion extraction time from the stopping cell is the time ions stopped in the middle of the cell need to reach the exit-hole side. Fig. 1 shows the calculated mean extraction time as a function of DC field for different helium areal densities. A reduced mobility of 17.5 cm²/V s was used in the calculation. At 2 mg/cm², considered the minimum areal density required for useful operation at both the FRS and Super-FRS, an extraction time of a few 10 s of ms, allowing efficient extraction of the ions needed for the FAIR LEB physics programme, requires a DC field of about 10 V/cm, a value rather easy to achieve. For an areal density of 20 mg/cm², needed for efficient stopping of fission fragments, an extraction time of a few 10 s of ms requires a field of about 100 V/cm, a challenging value but potentially not out of reach.

In practice, the electric field is limited by the breakdown voltage, the so-called Paschen limit. Based on the Paschen curve for helium at a temperature of 77 K [46], the Paschen limit ranges from about 300 V/cm to about 1000 V/cm for the helium density range considered here (0.020–0.20 mg/cm³) when assuming a distance of 1 cm over which the potential difference is applied (note that the breakdown voltage does not exactly scale with this distance). Combining these numbers with Fig. 1 shows that this will not limit fast extraction. However, as the Paschen curve applies to a rather idealized situation, reaching an extraction time of a few 10 s of ms for the highest density considered here represents a significant technical challenge which is beyond the intended reach of the prototype stopping cell described here.

3.3. RF repelling force

The time-averaged repelling force on an ion close to an RF electrode structure, in the high-pressure limit relevant for this work, is given by [47,48]

$$F_{hp}^{avg} = m\mu^2 \frac{V_{RF}^2}{r_0^3} \quad (1)$$

with m being the mass of the ion, μ the ion mobility, V_{RF} the RF amplitude, and r_0 half the electrode spacing. As the ion mobility scales with the inverse of the gas density, the repelling force scales with the inverse square of the gas density. An effective RF repelling electrode structure at high density is thus a challenge. To achieve a large enough repelling force, a large RF voltage and/or a small electrode spacing are needed. What can be achieved in practice is determined by mechanical and electrical limits. In stopping cells, two main types of RF electrode structures are used: funnels and carpets. As we opted for a small electrode spacing, a carpet-type

Fig. 1. Mean extraction time vs. DC electric field for helium areal densities of 2 and 20 mg/cm².

structure was chosen for the cryogenic stopping cell. The electrical limit, i.e. the maximum RF amplitude that can be used, is the Paschen limit. To our knowledge, the Paschen curve for RF fields relevant for our situation is not known. Based on our experience with the cryogenic stopping cell so far, we conclude that the RF carpet discussed in Section 4.5.2 is being operated in the broad minimum of the Paschen curve where the breakdown RF amplitude is rather constant. A smaller electrode spacing thus leads to a larger RF repelling force.

3.4. Operational temperature

The acceptable concentration and type of impurities depends on the chemical reactivity of the ion under study as well as the degree of cleanliness before cooling down. Earlier work with radioactive sources in a closed cell [41] showed that cooling down to below 90 K was needed for maximum ion survival efficiency. On-line experiments with a precursor device, the Cryogenic Ion Guide [49], show that a temperature slightly above 77 K does not completely remove air and other impurities in these situations. In order to ensure sufficient cleanliness for all ions and under all circumstances, we aimed for an operational temperature of the stopping cell of somewhat below 77 K. In order to be able to reliably investigate temperature effects over a sufficiently large temperature range, a cryocooler-based cooling system capable to cool the system to any temperature down to 60 K was designed. Being able to set a desired temperature also allows argon gas as stopping medium (argon liquefies at 80 K at 100 mbar).

4. Construction of the cryogenic stopping cell

4.1. Mechanical construction

A technical drawing of the stopping cell is shown in Fig. 2. The inner cold stopping chamber is surrounded by an outer vacuum jacket at room temperature to provide thermal insulation. The detailed design and construction of the assembly of outer and inner chambers, constructed out of stainless steel, was done by Vacuum Specials B.V. (Woerden, The Netherlands). The electrode structure inside the cold chamber consists of a DC cage (see Section 4.5.1) and an RF carpet (see Section 4.5.2).

In order to assure easy access to the inside of the cold chamber, the cold chamber is attached to the outer jacket only at the beam extraction side. For the same reason, all feedthroughs and connections go through the extraction flange (Fig. 3, bottom). The cold

chamber is supported against the inside of the vacuum jacket by ball bearing supports (see Fig. 4). All in all, this design allows the cold chamber to slide in and out of the vacuum jacket without the need to disconnect any connections, thus allowing easy servicing. It also allows for the shrinking of about 3 mm of the inner cold chamber with respect to the outer vacuum jacket during cooling down. The entrance flanges of both the vacuum jacket and the cold chamber (Fig. 3, top) have a rectangular hole of width 25 cm and

Fig. 3. Flanges of the cryogenic stopping cell. Top: cold chamber entrance flange with heaters installed. The rectangular beam inlet window (closed with a stainless steel cover in the photograph) can be seen. Bottom: vacuum jacket and cold chamber extraction flanges together with the RF carpet. The 5 tubes extending to the right connect to the cooling system via Johnston couplings. The 5 tubes to the left contain all feedthroughs (for RF and DC voltages, temperature sensors and heating elements).

Fig. 2. Technical drawing of the cryogenic stopping cell. Dimensions are in mm. See text for details.

Fig. 4. Inner cold chamber of the cryogenic stopping cell. The twin cooling channels on the outside, with a width of about 7 cm, are clearly visible. Some of the ball bearing supports between the cold chamber and the vacuum jacket are seen sticking out from the surface. On the left and right, close to the bottom of the cold chamber, the cooling channel entrances and exits are seen.

height 10 cm to accommodate the incoming beam from the Super-FRS (Section 3.1). During the on-line experiments at the FRS Ion Catcher Facility, these were covered by 100 μm thick stainless steel windows.

4.2. Design optimization for cryogenic operation

In order to allow easy access to the inside of the stopping cell and flexibility when installing at the fragment separator, an external cooling system was chosen. In this type of cooling application, high-pressure helium gas is the cooling medium of choice. Maximum transfer of cooling power from the circulating cooling medium to the cold chamber is ensured by maximizing the

contact surface area. For this reason, the cylindrical wall of the cold chamber is made out of a so-called thermoplate: a thin stainless steel sheet is welded in the desired cooling channel pattern to a 3 mm thick stainless steel plate and blown up at high pressure, resulting in twin cooling channels winding around it, covering virtually 100% of the surface (see Fig. 4). These two cooling channels are connected via stainless steel tubes to cryogenic feedthroughs with minimal heat loss (Johnston couplings) where the cooling system is connected. Copper strands were added to increase the thermal contact between the stopping cell wall and the entrance and exit flanges.

In order to ensure fast cooling, it is important to minimize the mass to be cooled down. A significant amount of the mass was removed from the extraction flange of the inner stopping chamber. In order not to compromise the structural strength, the removal of material was done after a careful investigation of the deformation due to the pressure inside the cell by means of a finite element calculation. It resulted in a significant reduction of 15% of the total mass to be cooled down. Radiation heat losses were minimized by wrapping the cold chamber in a few tens of layers of super-insulation. Heat losses due to conduction are minimized by careful design and construction of the connections between the cold and room temperature parts of the system. The connections between the extraction flanges of the cold chamber and vacuum jacket by which the two are attached to each other are designed to minimize heat loss: they consist of two thin-walled stainless steel tubes with a ceramic connection in the middle. The ball bearing supports between the cold chamber and vacuum jacket are constructed from thin-walled stainless steel tubes. The heat loss due to conduction for these connections and supports was calculated using the finite element software package FEMLAB. The total heat flow, for temperatures of 60 and 293 K on the cold and warm sides, is 0.65 W per connection and 0.50 W per ball bearing support. For the same reason of minimizing heat conduction, the extraction region is separated from the vacuum jacket insulation vacuum by a thin-walled stainless steel bellows between the cold chamber and vacuum jacket extraction flanges.

4.3. Cooling power requirements

The total weight of the parts to be cooled down is about 160 kg, mostly consisting of stainless steel. Cooling down stainless steel from room temperature to 60 K requires an energy of 90 J/g. In light of operation at accelerator facilities, a cooling down time of the order of 12 h is acceptable. The calculation mentioned in Section 4.4 on which the cooling system design is based assumes uniform cooling down of 160 kg of stainless steel. In practice, such a uniform cooling down of the stopping cell will not be achieved, resulting in a longer cooling down time. In order not to underestimate the required cooling system performance, a cooling down time of 5 h was used in the design calculation. The average cooling power to cool down 160 kg of stainless steel in 5 h is 800 W. The estimated cooling power requirement of 75 W at 60 K consists of

- heat leak due to radiation and conduction: about 20 W,
- cooling of the helium stopping gas: maximum 16 W (for 250 mbar, 60 K, 0.57 mm diameter exit hole),
- heat generated by the RF carpet: estimated at maximum 25 W,
- heat generated by the cooling system itself: about 13 W.

Based on the simulated case of ^{133}Sn fission fragments, the heat input from even the most intense radioactive ion beams at the Super-FRS is estimated to be below 1 W and thus negligible. In conclusion, 800 W of cooling power is needed to cool down to 60 K in an acceptably short time and, at this temperature, 75 W of cooling power is required to keep the device cool.

4.4. Cooling system

The cooling power needed to keep the device cold is about 10% of the power required for fast cooling down, see the previous section. This is a typical situation with cryogenic devices. As the aim is to cool below 77 K, cooling with liquid nitrogen only is not feasible; a cryocooler is thus the cooling device of choice. However, providing 800 W of cooling power with cryocoolers is expensive, and also results in the fact that 90% of the installed cooling power is not needed most of the time. Therefore, a dual cooling power design is chosen: a cryocooler for maintaining the low temperature and added cooling power with liquid nitrogen (LN_2) during cooling down.

Based on our general input, DeMaCo Holland B.V. designed and constructed the cryocooler-based system. The cooling medium circulating in the closed circuit of the cooling system is high-pressure helium gas. The design calculations indicate an optimum helium density translating into a pressure of 5 bar at 60 K. A schematic representation of the cooling system is shown in Fig. 5. The cooling medium is circulated by a cryofan with a diameter of 40 mm, running at 22 000 rpm. The cooling gas returning from the stopping cell flows through a heat exchanger inside a small (3 l) LN_2 vessel to pre-cool the cooling gas before it reaches the cold head of the Leybold Coolpower 140 T cryocooler which provides 140 W of cooling power at 80 K. Before the cooling circuit is split to connect to the two cooling channels on the stopping cell, a heat exchanger pre-cools the stopping gas before it flows into the stopping cell. After the stopping cell, the two channels are recombined before again entering the LN_2 pre-cooler. Obviously, the pre-cooler is only used until either the desired operation temperature or a temperature close to the freezing point of LN_2 is reached.

Temperature tuning can be done using a line bypassing the cold head. Using two tunable cryogenic valves, the fraction of helium bypassing the cold head can be tuned from 0% to 100% and thus any temperature between the lowest achievable and room temperature can be set. To reach a stable temperature, the cryogenic valves are tuned to arrive at a temperature a few degrees below the desired temperature. Then, a LakeShore 340 Temperature Controller is used to control heating elements on the cold chamber flanges for temperature stabilization. For this purpose, three 100 W heaters are attached to both the entrance and extraction flanges of the cold chamber (see Fig. 3). In case quick warming up is needed, the heating elements can be used with a dedicated power supply delivering up to 600 W. In addition, heating bands are wrapped around the outside of the vacuum jacket (heating

Fig. 6. Cooling system for the cryogenic stopping cell. Top: schematic of the cooling system connected to the stopping cell; bottom: photograph of the cooling system.

power 640 W) as well as around the cold chamber underneath the super-insulation (heating power 970 W). This results in a warming up time quite a bit shorter than the cooling down time. Fig. 6 shows a photograph of the cooling system and the way the cooling system is connected to the stopping cell.

4.5. Ion transport electrode structures

For ion transport throughout the stopping cell, a series of DC ring electrodes, called the DC cage, in the bulk of the cell and an RF carpet at the extraction side are used. The DC electric field generated by the DC cage pushes the ions towards the exit side.

Fig. 5. Schematic of the cooling system for the cryogenic stopping cell. In the lower right corner, the helium bottle feeding the stopping gas into the cell is shown. The helium bottle providing the cooling medium is not shown. See text for details.

Fig. 7. DC cage of the cryogenic stopping cell mounted on the exit flange, as used in the off-line commissioning experiments [16]. See text for details.

At the exit side, the ions are guided to the exit hole by the RF carpet.

4.5.1. DC cage

For first commissioning with alpha-decay recoil ions from ^{223}Ra sources [16], a rather simple DC cage was constructed, see Fig. 7. This DC cage consists of an about 1 m tall stack of 34 copper ring electrodes (30 cm inner diameter, 31 cm outer diameter), capped by one curved grid electrode. The electrodes are mounted at 3 cm intervals on four rods made out of G10, a fiberglass epoxy suitable for cryogenic operation. To make the cage mechanically stable, a supporting ring made out of G10 material is placed at the entrance side and the rods are fixed to the RF carpet support ring at the extraction side. The five electrodes closest to the RF carpet are constructed with decreasing inner diameters of 29, 28, 27, 26 and 25 cm. In this way, the grounded RF carpet fastening ring with a diameter of 30 cm is not distorting the shape of the DC field near the carpet. The voltage put on the grid electrode is divided evenly across the electrodes by a resistor chain, except for the 4 rings closest to the RF carpet which each have their own voltage supply in order to be able to shape the DC electric field to provide a “soft arrival” of the ions above the RF carpet. In order to have proper electric field lines at the entrance side, the DC cage needs to be closed by an electrode. The exact shape of this entrance electrode is not critical; a curved grid with a mesh size of 1 cm $\times$ 1 cm and made out of 1 mm diameter wire, thus having a transparency of 81%, was chosen. In the updated version of the DC cage used in the on-line experiments [17], a flat electrode in the form of a 100 μm thick stainless steel foil was used.

4.5.2. RF carpet

The RF carpet developed in this work is made using printed circuit board technology on 0.8 mm thick Rogers 4003^{®1} material.

Fig. 8. Front view of the RF carpet. The full diameter is 30 cm, with 500 ring electrodes over a diameter of 25 cm.

As explained in Section 3.3, the smallest RF electrode spacing was aimed for. In consultation with the manufacturer [51], an electrode spacing of 0.25 mm was chosen as it was the smallest spacing to make the carpet in a reliable way. Given the required stopping volume diameter of 25 cm, the carpet thus has 500 ring electrodes over a diameter of 25 cm, i.e. 4 electrodes/mm. The overall diameter of the printed circuit board is 30 cm to allow for fixing the carpet onto the exit flange of the cold chamber, see Fig. 8. An exit-hole with a nominal diameter of 0.60 mm is drilled in the middle of the carpet, see Fig. 9, left. In practice, the exit-hole diameters have varied between 0.56 and 0.71 mm.

As an RF carpet can operate at a single frequency, suitably chosen depending on the mass and mobility of the ions to be transported, the RF carpet electronics was designed to be of the resonant type. Based on detailed simulations of the ion transport along the RF carpet towards the exit hole [52], an RF frequency of 5 MHz was chosen for designing the carpet electronics. After construction of the carpet, the resonance frequency turned out to be about 5.8 MHz. The functional schematics of the RF carpet electronics is shown in Fig. 10. In addition to the RF voltage, a DC gradient is also applied to the rings. The potential of the outer ring (up to 300 V above the potential of the exit hole can be applied) is divided over the rings by a resistor divider, creating the DC field that guides the ions radially towards the exit hole. In order to make it possible to supply the RF voltage to the rings together with the DC gradient, the RF signal is capacitively coupled to the rings. Every ring has its own capacitor to either the positive or the negative RF terminal. The capacitors (47 nF each) act as a short circuit for the RF frequency, but as an open circuit for the DC gradient. The total capacitance of the carpet was measured to be 5.3 nF. The resonance circuit consists of an inductor (120 nH) in parallel to the capacitance of the ring and two 470 pF capacitors in series to match the circuit to the 50 Ω source at 5 MHz. The RF feed of the carpet has been divided into 3 sections by DC blocking capacitors (220 nF). The 3 sections were designed to be able to attenuate the signal on the inner rings, equalizing the amplitude over all rings. Initially, attenuator circuits were not placed. However, the DC blocking capacitors have a second function: they divide the DC voltage into 3 parts, limiting the DC voltage over the

(footnote continued)

performance due to low dielectric tolerance and loss, and stable electrical properties under frequency variation. They are suitable for low temperature use.

¹ Rogers 4000 Series High Frequency Circuit Materials [50] are glass-reinforced hydrocarbon/ceramic laminates. Their main features are excellent high-frequency

Fig. 9. Zoomed view of the RF carpet center. On the left, the 0.57 mm diameter exit hole, the 4 electrodes/mm and the 0.1 mm vias can be seen. On the right, the electronic components on the back side are shown. The exit hole is visible in the center.

Fig. 10. RF carpet functional schematics. See text for details.

smaller RF feed capacitors on every single ring. In this manner only $\frac{1}{6}$ of the DC voltage will be supplied to the smaller RF feed capacitors.

The Q-factor of the RF carpet depends on temperature and was measured at 300 K and 77 K to be 26.5 and 32.4, respectively. These measurements were done at a resonant frequency of 5.83 MHz. The power dissipated by the RF carpet during the on-line experiments is estimated to be about 10 W, compatible with what was assumed in the cooling system design.

All the electronic components for the RF and DC fields are placed on the back side of the carpet, see Fig. 9, right. Connections with the electrodes are made by 0.1 mm diameter “vias”, see Fig. 9. The DC and RF fields are applied via four connections (two for the DC and two for the RF field) on the back side of the carpet. The RF carpet thus has a simple design because, even with the

large number of electrodes, only four vacuum feedthroughs are needed.

In order to monitor the temperature to prevent damage due to heating by the RF power, a Pt100 temperature sensor is installed inside the coil on the back of the carpet, the warmest area of the electronic components.

5. Results

5.1. DC field

For the prototype stopping cell, a 10 kV power supply was used to provide the voltage on the entrance electrode, thus allowing a maximum DC field of 100 V/cm. With the cell at 1 atmosphere air

or under vacuum, the full 10 kV could be applied. With the cell filled with helium, the maximum voltages that could be applied before breakdown were lower. A systematic study of DC voltage breakdown vs. helium pressure and temperature was not performed in order not to risk damage the electrode system. However, the electric field values mentioned in this section are rather close to the breakdown values. During off-line commissioning, electric fields of up to 12.6 V/cm were applied for helium pressures around 100 mbar at 83 K. The updated DC cage was operated during the on-line experiments with a DC field of up to 27.5 V/cm. For a helium pressure of 49 mbar and a temperature of 74 K (representing an areal density of 3.1 mg/cm²), and a DC field of 22.2 V/cm, the mean extraction time of ²²¹Ac fragmentation products was measured to be 23.9 ms [18]. This value agrees well with the value of 27.5 ms expected from mobility theory calculated as in Section 3.2.

5.2. Performance of the cooling system

Results of off-line and on-line commissioning of the cryogenic stopping cell have been published earlier [16–18]. Here we focus on the cooling system performance in realistic on-line conditions.

During off-line commissioning and the first on-line experiment, cooling with liquid nitrogen was used. This resulted in a temperature of the helium gas of 85 K at a pressure of 125 mbar (density 0.071 mg/cm³) in off-line conditions [16] and 100 K at 100 mbar (density 0.048 mg/cm³) in on-line conditions [18]. The pressure limit is dictated by the pumping capacity in the extraction region just outside of the stopping cell. At the time of the second on-line experiment, the cryocooler-based cooling system (see Section 4.4) was in use and a temperature of the helium gas of 78 K at a pressure of 47 mbar (density 0.029 mg/cm³) was reached [18]. The lower density that could be used was due to the maximum acceptable pressure for experiments downstream of the stopping cell as well as to a somewhat larger exit-hole diameter.

During the second on-line experiment, the performance of the cooling system was studied in detail in realistic on-line operating conditions. The temperature at several locations of both the stopping cell and the cooling system was followed during a cooling-down procedure. The results are shown in Fig. 11.

Considering the cooling system, the temperature drops that are due to the LN₂ pre-cooler and the cryocooler cold head are clearly visible by comparing the relevant temperature traces. At the start of the cooling down process, the LN₂ pre-cooler induces a

temperature drop of the high-pressure helium cooling medium relative to the entrance to the LN₂ pre-cooler (i.e. the return line from the stopping cell) of 135 K ('pre-cooler in' minus 'pre-cooler out'), showing the large boost in cooling power delivered by the pre-cooler. As the stopping cell cools down, the temperature of the return line drops and the effect of the pre-cooler decreases. The temperature drop induced by the cold head ('cold head in' minus 'cold head out') is a bit over 20 K at the start of cooling down, then slowly decreases and reaches a stable value of 10 K for the lowest temperatures reached. The bump in the temperature traces starting at about 7 h after the start is due to the LN₂ pre-cooler running dry after closing its LN₂ feeding line. At about 9 h after the start, the pre-cooler filling is resumed and the temperatures quickly resume their earlier trend. In order to prevent freezing of the LN₂ in the pre-cooler, its supply needs to be closed before the LN₂ freezing temperature is reached (63 K under 1 atmosphere of air). With this in mind, the LN₂ feeding line is once again closed at about 10 h in the cooling down procedure. As the pre-cooler runs dry, the temperatures increase for a few hours, after which cooling continues, now fully on the cooling power of the cryocooler.

At the start of the cooling procedure, the stopping cell was filled with some helium gas (5 mbar) in order to help distribute the cooling power from the stopping cell cylindrical wall (where the cooling lines are) to the entrance and exit flanges. At about 9 h after the start of cooling down, this pressure was increased to 35 mbar. This results in a small jump of the stopping gas temperature as the extra gas added is at room temperature and needs to be cooled down. More interestingly, the RF carpet temperature trace shows a downward kink, indicating the positive effect of the higher pressure in the stopping cell. This effect is however minor: the exit flange, being much more massive, does not show a kink in the temperature trace.

During the design of the cooling system, the optimum pressure of the helium cooling medium at an operational temperature of 60 K was determined to be 5 bar. The maximum pressure that the cooling circuit on the stopping cell can operate at is 10 bar. So at the start of cooling down, the pressure in the cooling circuit was set to 10 bar by tuning the pressure regulator of the helium bottle that supplies the cooling medium to this value. Leaving the valve between bottle and cooling circuit open during cooling down assured a constant pressure of 10 bar and thus optimum performance given the pressure boundary condition. When the temperature of the stopping cell gas dropped below 120 K, the valve between bottle and cooling circuit was closed such that from that point on the pressure in the cooling circuit dropped with temperature, reaching 5 bar at 60 K as needed for optimum performance.

After about 30 hours of cooling, the RF carpet was switched on for about 1.5 h, leading to a substantial rise in the temperature sensor attached to the backside of the carpet. When tuning of the beam upstream of the stopping cell was completed, at about 42 h of cooling, the system was made ready for use by increasing the stopping cell pressure to 50 mbar and putting the carpet in its nominal operating condition with an RF amplitude of 45 V and a frequency of 6.55 MHz (this frequency is slightly higher than the value mentioned in Section 4.5.2 due to fine tuning of the design of the carpet electronics based on the simulations from [53]). Again the carpet temperature rises substantially. However, the stopping cell gas temperature, and thus the stopping cell performance, is not affected by the carpet operation. In full operational mode, a final temperature of the stopping gas, the most relevant temperature for cryogenic operation, reaches 72 K, a value compatible with the design goal of somewhat below 77 K.

Based on the results presented in Section 5.3, we consider the stopping cell to be operational for a stopping gas temperature below about 110 K. Combining this value with the stopping gas temperature trace, we conclude that about 10 hours of cooling is needed before the

Fig. 11. Temperature vs. time at various locations in the stopping cell and cooling system during a typical cooling down in realistic on-line operating conditions. The gaps in some of the curves are due to missing data. See text for details.

Fig. 12. Ion extraction vs. temperature. Left scale and circles: ^{219}Rn intensity; right scale and squares: total ion current extracted from the stopping cell as measured by a channeltron. Both are shown in arbitrary units. The line through the channeltron data indicates the exponential decrease in total ion current with decreasing temperature.

stopping cell can be used, a value acceptable for on-line experiments. Note that the cooling down time required for efficient ion survival will depend somewhat on the chemical nature of the ion and the cleanliness of the system before cooling down starts.

5.3. Performance at low temperature

Fig. 12 illustrates the stopping cell performance at low temperature in terms of the extraction of radioactive ions as well as the total current extracted. Note that a comparison with the performance at room temperature is not possible as the stopping cell is not designed to achieve at room temperature the stopping gas purity required for useful operation. These measurements were performed in off-line conditions, with radioactive ^{219}Rn ions generated as alpha decay recoil ions from a ^{223}Ra source installed at the entrance side inside of the stopping cell. The total ion current extracted is measured using a channeltron. An exponential decrease in total ion current with decreasing temperature is observed. As the total ion current is dominated by impurity ions, this trend is indicative of a decrease of impurity ions with decreasing temperature and thus illustrates the stopping gas purification due to cryogenic operation. The intensity of extracted ^{219}Rn ions is determined by measuring its alpha decay after implantation of the extracted beam on a foil in front of a silicon detector. If the observed trend is extrapolated linearly to higher temperatures, the extracted intensity becomes zero around room temperature. Although the result of an extrapolation over such a large temperature range has to be considered to be rather uncertain, it indicates the usefulness of cryogenic operation. The exact behavior will depend on both the ion and the contaminants in the stopping gas. Note that ^{219}Rn , being a noble gas isotope, is likely not representative of isotopes of most other chemical elements, whose behavior vs. temperature remains to be investigated.

6. Summary and outlook

In this paper, we have given an overview of the design considerations and construction of a cryogenic stopping cell meant as a prototype for the Low-Energy Branch of the Super-FRS at FAIR. It has been incorporated at the FRS Ion Catcher Facility, allowing extensive on-line commissioning as well as first measurements of the mass of short-lived exotic nuclei. In a next on-line experiment, the performance at high ionization density rates will be investigated.

To obtain a suitable stopping gas purity, the goal was to reach an operational temperature somewhat below 77 K. In realistic on-line conditions (see [18] for detailed results), mass spectra acquired with the multiple-reflection time-of-flight mass spectrometer show the excellent cleanliness of the stopping cell. At the stopping gas temperature of 72 K reached, excellent ion survival and extraction efficiencies were observed. With respect to operational temperature, the cryogenic stopping cell has thus reached the design goal. This also means that the present cooling system will likely be suitable for the final Super-FRS stopping cell.

Based on the Super-FRS specifications, a stopping cell with an areal density of 2–20 mg/cm^2 helium allows efficient stopping of medium-mass and heavier fragments. The areal density reached depends on the stopping gas temperature, exit-hole diameter and pumping capacity in the extraction region. In the measurements so far, the exit-hole diameter has been (nominally) constant but the operational temperature, pumping capacity and pressure limit due to experimental equipment upstream of the stopping cell have not. The largest areal density, obtained during off-line commissioning, is 7 mg/cm^2 , about a third of the design value for efficient stopping of projectile fission products. This value is adequate for efficient stopping of medium-mass and heavier projectile fragmentation products. During the on-line commissioning using the cryocooler-based cooling system, a lower value of 3.1 mg/cm^2 was reached due to the maximum acceptable pressure for experiments downstream of the stopping cell and a somewhat larger exit-hole diameter.

To substantially increase the areal density, an increase in the pumping capacity in the extraction region is necessary. Very likely, a substantial gain can also be made by reducing the exit hole diameter. Finally, constructing a longer cell (say up to 2 m) is rather straightforward. Due to the design in which all feed-throughs and connections are at the exit side of the system, extending the cell can be done by simply adding a cylindrical extension to the entrance side. For the same DC field, a longer cell will of course suffer from larger mean ion extraction times. In order to keep the extraction times equal, the DC field will need to scale with the areal density. Considerations based on the Paschen curve (Section 3.2) show no limit to this scaling. However, as the Paschen curve applies to a rather ideal situation, the design of the DC field electrode structure for stopping cells with a higher areal density will require a very careful consideration of actual breakdown voltages and related high-voltage shielding.

For higher densities of the stopping gas, efficient operation of the RF carpet becomes more challenging, as the ion mobility, and thus the effective repelling force, decreases quadratically, see Eq. (1). Extrapolating our experience so far, there is reason to believe that the present carpet can be operated at higher gas densities, provided that the RF power dissipation can be handled. Further measurements will need to establish the limits of the present carpet. Concerning further development of the carpet technology used, an increase in density of the stopping gas can be compensated by a suitably larger factor V_{RF}^2/r_0^3 (see Eq. (1)). Our experience with the RF carpet indicates that it is being operated in the rather broad minimum of the Paschen curve. A somewhat smaller electrode spacing, possible with the technology used to construct the present RF carpet, is thus expected to allow operation at higher gas densities.

The cryogenic stopping cell described in this paper, as part of the FRS Ion Catcher Facility, has opened up new possibilities for spectroscopy of short-lived exotic nuclei. It has fulfilled its purpose as the prototype stopping cell for the Low-Energy Branch of the Super-FRS. The expertise gained from its design, construction and performance allows the development of a final version which is currently underway.

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