



An RF-only ion-funnel for extraction from high-pressure gases



T. Brunner^{a,*}, D. Fudenberg^a, V. Varentsov^{b,c}, A. Sabourov^{a,1}, G. Gratta^a, J. Dilling^d, R. DeVoe^a, D. Sinclair^{d,e}, W. Fairbank Jr.^f, J.B. Albert^g, D.J. Auty^{h,3}, P.S. Barbeauⁱ, D. Beck^j, C. Benitez-Medina^f, M. Breidenbach^k, G.F. Cao^l, C. Chambers^f, B. Cleveland^m, M. Coon^j, A. Craycraft^f, T. Daniels^k, S.J. Daugherty^g, T. Didberidze^h, M.J. Dolinskiⁿ, M. Dunford^e, L. Fabris^o, J. Farine^m, W. Feldmeier^p, P. Fierlinger^p, R. Gornea^q, K. Graham^e, M. Heffner^r, M. Hughes^h, M. Jewell^a, X.S. Jiang^l, T.N. Johnson^g, S. Johnston^s, A. Karelin^b, L.J. Kaufman^g, R. Killick^e, T. Koffas^e, S. Kravitz^a, R. Krücken^d, A. Kuchenkov^b, K.S. Kumar^t, D.S. Leonard^u, F. Leonard^e, C. Licciardi^e, Y.H. Linⁿ, J. Ling^j, R. MacLellan^v, M.G. Marino^p, B. Mong^m, D. Moore^a, A. Odian^k, I. Ostrovskiy^a, C. Ouellet^e, A. Piepke^h, A. Pocar^s, F. Retiere^d, P.C. Rowson^k, M.P. Roze^e, A. Schubert^a, E. Smithⁿ, V. Stekhanov^b, M. Tarka^j, T. Tolba^q, D. Tosi^{a,2}, K. Twelker^a, J.-L. Vuilleumier^q, J. Walton^j, T. Walton^f, M. Weber^a, L.J. Wen^l, U. Wichoski^m, L. Yang^j, Y.-R. Yenⁿ

^a Physics Department, Stanford University, Stanford, CA, USA

^b Institute for Theoretical and Experimental Physics, Moscow, Russia

^c Facility for Antiproton and Ion Research in Europe (FAIR GmbH), Darmstadt, Germany

^d TRIUMF, Vancouver, BC, Canada

^e Physics Department, Carleton University, Ottawa, ON, Canada

^f Physics Department, Colorado State University, Fort Collins, CO, USA

^g Physics Department and CEEM, Indiana University, Bloomington, IN, USA

^h Department of Physics and Astronomy, University of Alabama, Tuscaloosa, AL, USA

ⁱ Department of Physics, Duke University, and Triangle Universities Nuclear Laboratory (TUNL), Durham, NC, USA

^j Physics Department, University of Illinois, Urbana-Champaign, IL, USA

^k SLAC National Accelerator Laboratory, Menlo Park, CA, USA

^l Institute of High Energy Physics, Beijing, China

^m Department of Physics, Laurentian University, Sudbury, ON, Canada

ⁿ Department of Physics, Drexel University, Philadelphia, PA, USA

^o Oak Ridge National Laboratory, Oak Ridge, TN, USA

^p Technische Universität München, Physikdepartment and Excellence Cluster Universe, Garching, Germany

^q LHEP, Albert Einstein Center, University of Bern, Bern, Switzerland

^r Lawrence Livermore National Laboratory, Livermore, CA, USA

^s Amherst Center for Fundamental Interactions and Physics Department, University of Massachusetts, Amherst, MA, USA

^t Department of Physics and Astronomy, Stony Brook University, SUNY, Stony Brook, NY, USA

^u Department of Physics, University of Seoul, Seoul, Republic of Korea

^v Physics Department, University of South Dakota, Vermillion, SD, USA

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ABSTRACT

An RF ion-funnel technique has been developed to extract ions from a high-pressure (10 bar) noble-gas environment into a vacuum (10^{-6} mbar). Detailed simulations have been performed and a prototype has been developed for the purpose of extracting ^{136}Ba ions from Xe gas with high efficiency. With this prototype, ions have been extracted for the first time from high-pressure xenon gas and argon gas. Systematic studies have been carried out and compared to simulations. This demonstration of extraction

* Corresponding author. Tel.: +1 650 723 4612.

E-mail address: tbrunner@stanford.edu (T. Brunner).

¹ Now at Patrick AFB, FL, USA.

² Now at University of Wisconsin, Madison, WI, USA.

³ Now at University of Alberta, Edmonton, AB, Canada.

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of ions, with mass comparable to that of the gas generating the high-pressure, has applications to Ba tagging from a Xe-gas time-projection chamber for double-beta decay, as well as to the general problem of recovering trace amounts of an ionized element in a heavy ($m > 40$ u) carrier gas.

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1. Introduction

Ion extraction from gas environments at pressures ≥ 1 mbar is challenging since collisions dominate ion motion [1]. Conventional mass-spectrometry techniques use a combination of skimmers and orifices to reduce the gas flow across differential pumping stages. Similar ion-extraction techniques are applied in ion source assemblies at radioactive ion beam facilities, e.g. IGISOL LIST [2]. Such techniques achieve low downstream pressures at some cost of efficient ion transport [1,3,4].

Radio-frequency (RF) ion funnels have been developed for ion extraction with increased ion-transmission efficiency; typically, RF funnels extract from air into vacuum and improve ion extraction efficiency by more than an order of magnitude (see [1,5] and references therein). RF funnels have also been developed for ion transport in gas stopper cells [6]. Technical improvements have included blocking the gas jet with a jet disrupter electrode [7] and a DC ion carpet at the exit [8]. Various funnel designs have been realized, including a recent design using electrodes etched on PCBs [9]. Typically, RF funnels are used with electrospray ion sources where gas is injected through a capillary. Capillary inlet pressures reach an atmosphere and pressures inside the funnel reach ~ 40 mbar. However, owing to the nature of this ion source, such funnels are not optimized for single ion extraction at close to 100% efficiency and require a longitudinal DC potential gradient to transport ions through the funnel, adding complexity and components that can contaminate the vacuum. To overcome these limitations and extend the use of RF-funnels to heavy-mass gases at a high-pressure, an RF-only ion funnel prototype has been developed. It aims to investigate the feasibility of extracting ions from 10 bar Xe gas into a 1 mbar vacuum in only one stage with high efficiency. This prototype realizes a novel concept of ion transport via carrier gas flow instead of via applied DC-drag potentials that was suggested [10] and described in detail [11,12].

The realization and trial of this RF-only funnel is an important step towards its application in the search for neutrinoless (0ν) double-beta ($\beta\beta$) decay in ^{136}Xe . Over the past decades, experiments searching for the lepton-number non-conserving $0\nu\beta\beta$ -decay [13] have excluded half lives (at 90% CL) shorter than $T_{1/2}^{0\nu\beta\beta} \gtrsim 10^{25}$ yr (in ^{136}Xe [14–16] and in ^{76}Ge [17]). In order to extend experimental sensitivity, the development of larger detectors with reduced background is required. For the detection of the $0\nu\beta\beta$ decay signal such a detector would ideally have no backgrounds. The identification (Ba-tagging) of the atomic species produced in the decay, ^{136}Ba for $\beta\beta$ -decay of ^{136}Xe , would drastically reduce the backgrounds that are dominated by radioactivity unrelated to the production of Ba in the detector. The association of decay energy and event topology to the Ba-tagging technique [18] would allow for the discrimination between the 2-neutrino decay, which produces a continuum spectrum, and the interesting neutrinoless decay, which produces a mono-energetic line at the sum energy of the two electrons.

Among the $\beta\beta$ -decay candidates, the possibility of tagging the final atomic state appears to be possible only for the case of ^{136}Xe [18]. The nEXO collaboration is developing a multi-ton $\beta\beta$ -decay experiment using liquid ^{136}Xe (LXe); Ba-tagging technology

appropriate for LXe is being developed [19,20] for possible use in a second phase of detector operation with sensitivity into the region of the normal hierarchy of neutrino mass [21]. A multi-ton detector using gaseous xenon (GXe) may be appropriate at a later stage to investigate the physics of $0\nu\beta\beta$ -decay, should it be discovered by the LXe detector; the relatively low-density gas would allow visualizing the tracks of low energy final state electrons. Such a detector calls for the development of Ba-tagging for gas phase operations [22].

Schematically, tagging of the Ba^{++} daughter from gas xenon will be implemented in the following consecutive steps: (i) The energy deposited and topology of each event is measured to determine whether it has a $\beta\beta$ -like signature. (ii) If it does, the electric fields inside the time-projection chamber are modified such that ions from the previously determined decay volume are drifted to an appropriate extraction port where they are flushed out by the Xe gas. (iii) Ions are separated from the Xe gas and guided into vacuum. (iv) Ba^{++} is converted to Ba^+ by electron exchange (e.g. in triethylethane gas [23]). (v) The ion is captured in a linear Paul trap and is unambiguously identified by means of laser spectroscopy [24]. The main challenge of this Ba-tagging method is the extraction of Ba-ions from a high-pressure Xe environment with near 100% efficiency.

This paper describes the RF-only funnel apparatus built to investigate the extraction of Ba ions from xenon gas for application in Ba tagging and its tests. The new technique is optimized for highly efficient extraction of single ions from an equal-mass carrier gas.

2. Apparatus

A schematic of the system is shown in Fig. 1. It has been optimized in gas dynamic calculations described in Section 3. Ions are created in a high-pressure noble-gas environment at the entrance of a converging-diverging supersonic nozzle. The ions are injected through this nozzle via the supersonic gas flow into the conical cavity of the RF-funnel. RF-voltage confines the ions while the majority of gas escapes and is pumped by a high capacity cryopump. Exiting the RF-funnel ~ 0.5 ms later, the ions cross into a second differential pumping stage where they are captured by a sextupole ion guide (SPIG). This guide transports the ions to a downstream chamber for detection, currently by a channel electron multiplier (CEM). Details of the individual subsystems follow.

2.1. Vacuum and gas handling system

The vacuum and gas handling systems are designed to ultra-high vacuum (UHV) standards. Only UHV compatible materials (with the exception of O-rings at apertures, in vacuum pumps and along forelines) were used in the funnel and the system, and trapped volumes were vented to avoid virtual leaks. Great effort is taken to avoid contamination of the system that could affect ion extraction or transport. Each part was ultrasonically cleaned for ≥ 15 min each in acetone and then ethanol. A schematic of the gas handling and vacuum setup is shown in Fig. 2. The vacuum system has four chambers: (A) high-pressure chamber with ion source installed at the nozzle entrance, (B) cryopump chamber with RF-funnel

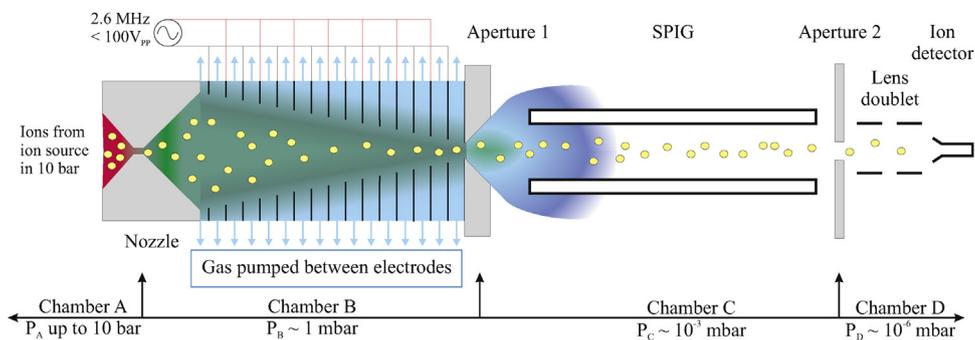


Fig. 1. Concept of the RF-only funnel prototype. See text for explanation.

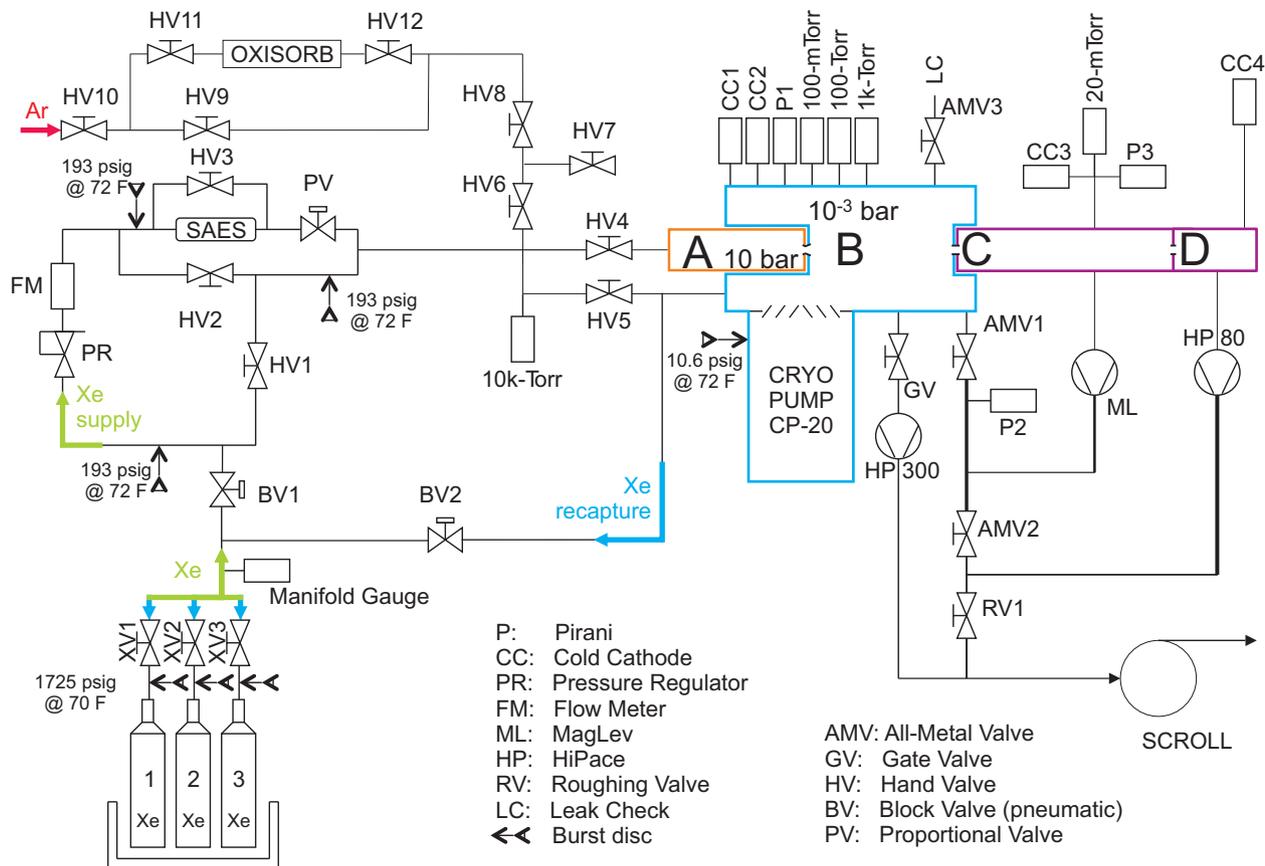


Fig. 2. Vacuum and gas system schematic. The vacuum system consists of four chambers: (A) high-pressure chamber, (B) cryopump chamber with the RF-funnel installed at its center, (C) SPIG chamber and (D) detection chamber. The chambers are separated by small apertures or the nozzle. Arrows depict the flow direction of the gas. Either argon (red arrow) or xenon (green arrows) gas can be supplied to chamber A. Xenon is recaptured (blue arrows). The baratron gauges are labeled by range. See text for details. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

installed at center, (C) SPIG chamber and (D) detection chamber. The converging-diverging nozzle separates chambers A and B, a $\varnothing 1$ mm aperture separates chambers B and C, and a $\varnothing 2$ mm aperture separates chambers C and D; these act as differential pumping barriers. The aperture between chambers C and D can be biased whereas the others are at ground potential.

During pump down, chambers A and B are evacuated by a turbo-molecular pump (TMP),³ chamber C by a magnetically levitated (ML) TMP,⁴ and chamber D by a third TMP.⁵ All TMPs are backed by the same scroll pump.⁶ The system's base pressures

achieved with only the TMPs, are 1.1×10^{-8} mbar, 2.3×10^{-9} mbar, and 3.9×10^{-9} mbar in chambers B, C, and D, respectively. These base pressures decrease to 7×10^{-10} mbar, 2.0×10^{-9} mbar, and 3.1×10^{-9} mbar in chambers B, C, and D, respectively, when the cryopump⁷ is activated. The TMP on chamber B is only used to evacuate the system; during gas-jet operation, a gate valve (GV in Fig. 2) separates it from the system.

During Xe operations and after pump down, the bulk of the Xe gas is pumped by the large cryopump in chamber B so that the gas can be recycled and kept clean. The setup can also be operated with Ar gas. Various stagnation pressures in chamber A, referred to as P_A , have been used.

³ Pfeiffer HiPace300.

⁴ Edwards STP-A803C.

⁵ Pfeiffer HiPace80.

⁶ Edwards XDS35i.

⁷ Sumitomo Marathon CP-20 Cryopump.

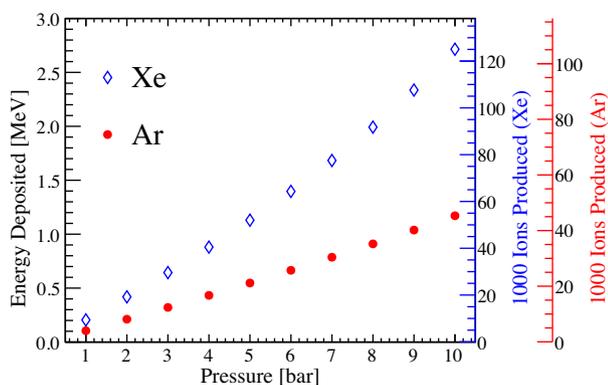


Fig. 3. Simulated energy deposition through ionization by a 3183 keV α -particle in 0.91 mm for xenon and argon. On the right hand side, separate axes for xenon and argon show the number of estimated ion-electron pairs produced.

The system is operated in either recovery or non-recovery mode. In recovery mode, all gas injected is captured by the cryopump in chamber B, which also backs the TMPs on chambers C and D. This is achieved by closing valves GV and RV1 and opening valves AMV1 and AMV2 in Fig. 2. In this mode the background pressure in chamber B, P_B , is limited to protect the TMPs. In non-recovery operation, the scroll pump is coupled to the TMPs on chambers C and D by opening RV1 and AMV2 while closing AMV1 and GV. In this mode of operation the pressure in the foreline of the turbo pumps is independent of P_B thus allowing higher P_B . All gas entering chambers C and D is exhausted to atmosphere. For reasons of cost-saving, recovery mode is always used for Xe. Typically, non-recovery mode is chosen for Ar.

Xenon gas is supplied from three stainless steel cylinders and is purified by a SAES⁸ getter. BV1, PV, and HV4 are open to operate with a xenon jet. To recover the xenon accumulated in the cryopump, the xenon storage cylinders are cooled by immersion in LN₂ and then the pump is warmed up with BV1 closed and BV2 open. A final ≤ 10 g of Xe cannot be recovered from the vacuum system.

Operation with an Ar gas jet is more convenient since not recovering the gas allows for faster turnaround time between tests. Argon is supplied from a cylinder.⁹ Tests have been performed where the Ar was passed through an OXISORB¹⁰ purifier before flowing into chamber A. However, the studies found that this purifier did not improve ion extraction stability; thus all count-rate measurements with argon presented in this manuscript were performed using gas supplied directly from the cylinder. The Ar supply is indicated by a red arrow in Fig. 2.

Burst discs¹¹ protect the gas lines; this limits the maximum pressure in chamber A to 14.3 bar. The maximum operating pressure used in chamber A is 10 bar. The vacuum system is protected by a 1.7 bar burst disc.¹²

2.2. Ion source and gas nozzle

A custom built ¹⁴⁸Gd-driven Ba-ion source, similar to the one in [25] is used to produce Ba ions. The source is made by electroplating ¹⁴⁸Gd onto a stainless steel plate (9.5 mm \times 6.4 mm \times 0.5 mm) for a total activity of ~ 144 Bq. A layer of 20 nm of BaF₂ was evaporated over the ¹⁴⁸Gd. The Sm nucleus recoiling from the ¹⁴⁸Gd α decay

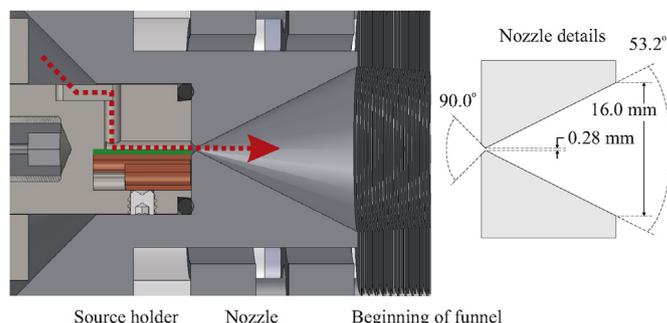


Fig. 4. (Left) Section view of source holder and (right) nozzle details. Gas (red, dashed arrow) flows across the surface of the source plate (green line). Ions from the ion source are injected into the RF-funnel through the nozzle. The start of the RF-funnel is shown at the exit of the nozzle. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

($Q = 3182.69$ keV [26]) knocks out Ba or BaF ions from this layer. Based on α rate and [25] a Ba⁺ rate of ~ 59 Hz is calculated.

This source is installed in the carrier gas flow. Alpha-particles from the source ionize the gas, so that ions other than ¹³⁶Ba are expected to be produced. The energy deposited along a 0.91 mm travel distance in gas at 20 °C by such an α -particle was calculated in SRIM2013 [27] for various pressures of xenon and argon and is shown in Fig. 3. The calculated number of ion-electron pairs produced is also shown (right axis) using (the mean energy required to produce an electron-ion pair) $W = 21.7$ eV for xenon and $W = 25.8$ eV for argon [28]. An experimental verification of these results is not possible for a number of reasons: (1) The source geometry is complex; for an α -particle traveling perpendicular to the gas flow, the minimum distance through the gas is 0.48 mm, the maximum distance is 2.1 mm, and the average distance is 0.91 mm. (2) It is not known how many of the electron-ion pairs recombine nor the pressure dependence. (3) The ratio of ion-electron pairs created in the gas versus Ba ions knocked out of the BaF₂ depends on pressure.

A schematic view of the nozzle region with the source installed is shown in Fig. 4. A holder fixes the position of the source plate at the entrance to the nozzle in chamber A. An O-ring seals the holder to the nozzle, forcing gas through the holder and parallel to the surface of the source plate. The atoms and ions created by the source are thus carried by the gas flow and injected into the funnel through the nozzle. The converging-diverging nozzle has a subsonic half-angle of 45° and a supersonic half-angle of 26.6°. These two cones were machined using electric discharge machining¹³ in a DN40 (CF2.75") flange. The design value for the throat diameter was 0.30 mm, however, the machined diameter is only 0.28 mm. The design values for subsonic and supersonic part lengths are 0.5 mm and 15.7 mm, respectively, and the exit diameter of the supersonic nozzle is 16.0 mm.

2.3. RF-only funnel

In an RF-only funnel, no DC drag field is applied to assist in longitudinal ion transport; only residual gas flow along the RF-funnel axis transports ions into the downstream chamber while an applied RF-field creates a radially confining potential. This method was originally designed to extract ions from an He-buffer gas; here, ions of mass 136 u are to be extracted from Xe gas of very similar or equal mass. The extraction of ions with mass equal to that of the carrier gas has never been tried for $m > 40$ u. Detailed gas-dynamic and ion-trajectory Monte-Carlo simulations have been performed to optimize the design of the RF-only ion-funnel device for this

⁸ SAES MC400-903: acids, bases <1 ppbV; organics, refractory compounds <1 ppbV; O₂, H₂O, CO, CO₂, H₂ <10 pptV.

⁹ Praxair AR 6.0RS 99.9999% pure.

¹⁰ OXISORB: O₂ <5 ppb, H₂O <30 ppb.

¹¹ Continental Disc Corporation: 193 psig @ 72 °F.

¹² MDC BDA-275-ASME: 10.6 psig @ 72 °F.

¹³ EDM Labs Ltd., www.edmlabsltd.com.



Fig. 5. Picture of the first (ID 16.0 mm) and last electrodes (ID 1 mm). A US quarter (OD 24.3 mm) is shown for scale.



Fig. 6. Picture of RF-funnel assembly prior to installation on the nozzle, view from base to exit. The conical cavity ending with diameter 1 mm (ID of electrode #301) is visible. [Fig. 7](#) shows this assembly (left) mounted to the nozzle (right).

purpose. This design was initially reported in [29]. Some results of these simulations are discussed in [Section 3](#).

The RF-funnel consists of 301 individual electrode foils made from 0.102(3) mm thick high-tolerance, stainless steel sheets.¹⁴ The electrodes and inter-electrode spacers were manufactured using photo-etching¹⁵ to obtain high tolerances and low stress. The electrodes are annular with outer diameter (OD) of 28 mm and an inner diameter (ID) decreasing from 16.0 mm to 1.0 mm in constant steps of 0.05 mm per electrode. The electrodes have three mounting tabs that provide maximal spatial rigidity in the stack and allow for the required tolerances. Prior to installation, each electrode was checked for flatness against a polished stainless steel surface and was flattened as required. Each electrode is individually numbered for ease of assembly, as shown in [Fig. 5](#).

Alternating electrodes were fed onto each of two electrically isolated sets (odd and even numbers) of mounting rods, 60° apart from each other. Each set consists of three, 3 mm diameter rods spaced equidistantly 16 mm off the funnel axis. On each set (odd or even)



Fig. 7. Picture of assembled RF-funnel mounted on the nozzle flange. Gas is injected from right.



Fig. 8. Picture of RF-funnel in chamber B above cryopump during a run. Frozen xenon appears as a white coating.

the electrodes are spaced by $0.610^{+0.005}_{-0.010}$ mm thick stainless steel spacers¹⁴ of OD 5 mm that were manufactured using photo-etching to achieve the required tolerances. This results in an average separation of 0.25 mm between the faces of neighboring electrodes (even to odd). The conical cavity formed by decreasing electrode ID and the slot-vented screws that mount the supports are visible in [Fig. 6](#). After all electrodes were mounted, a glass-ceramic spacer was added after the last electrode to fix the radial position of the six mounting rods. End caps are installed on each mounting rod to provide constant pressure to the electrode stacks.

The RF-funnel assembly is a stand-alone unit that is mounted onto and electrically isolated from the downstream side of the nozzle flange. [Fig. 7](#) shows the nozzle-funnel assembly consisting of the nozzle-flange and RF-funnel assembly; the electrically insulating glass-ceramic disk is visible at the RF-funnel's base (center-right). The distance between the exit of the diverging nozzle and the first funnel electrode is 0.25 mm.

[Fig. 8](#) shows a picture of the RF-funnel assembly installed inside chamber B between downstream chamber C (left) and high pressure chamber A (right). The nozzle-funnel assembly is mounted onto chamber C by three silver-plated threaded rods (3/8"-24). This assembly was aligned with respect to chamber C by adjusting the position of the nozzle flange mounting ears (center in [Fig. 8](#)) on the mounting rods at STP. The last funnel electrode and aperture 1 are coaxial (with under 0.03 mm eccentricity) and separated by 0.233(8) mm. Aperture 1 is sealed to the surface of the downstream chamber C with an O-ring. Chamber A is mounted on the upstream side of the nozzle-funnel assembly. A bellows is welded around chamber A to compensate for tolerances in the assembly and mounts to chamber B via an inverted conflat flange. A section view of an engineering model is shown in Figure 2 of [29]. Visible

¹⁴ 316 stainless steel alloy, ESPI Metals.

¹⁵ Newcut Inc., New York.

below the RF-funnel are metal louvers in the cryopump's first stage with a white coat of frozen xenon.

The capacitance of the RF-funnel installed in chamber B is found to be 6.014 nF at 3.6×10^{-7} mbar when the cryopump is off. This has a capacitive reactance of $\sim 10 \Omega$ at the typical operating frequency of 2.6 MHz. A frequency generator supplies a sinusoidal waveform to a broadband amplifier.¹⁶ A 1:4 balun¹⁷ is used to impedance match. Due to a maximum amplifier output power of 120 W, the highest RF-frequency where 100 V_{pp} can be coupled to the funnel is 2.6 MHz. The applied voltages are lower than the break-down voltages in argon and xenon, i.e. they are lower than the Paschen minimum.

A set of baffles (not pictured in Fig. 8) has been installed underneath the funnel to reduce radiative cooling by the cryopump. They are designed to block direct sight between the two elements while allowing a high gas flow conductance. All ion-extraction measurements presented in this work have been carried out in this configuration; only the pressure measurements presented in Fig. 14 were recorded without it.

2.4. SPIG

The gas flow through the exit of the RF-funnel generates pressure in chamber C, P_C , which is too high to operate a CEM safely. Thus, chamber C is used as an additional differential pumping stage and ions are transported through to chamber D where the CEM is located. As the funnel is centered in chamber B for maximum cryopumping speed, chamber C is 0.5 m long. During gas operation, the pressure in this chamber is on the order of a μ bar; for xenon this corresponds to a mean-free path of about 40 mm. The pressure is highest immediately after the entrance to C where the gas flow regime changes from viscous to molecular flow. Thus, the ions have to travel a length corresponding to at least 10 mean-free-path lengths to cross C, which requires an ion transport robust to collisions.

In RF-ion guides, losses of ions lighter than the buffer gas are expected to occur through RF-heating [30]. However, for ions of mass equal to that of the background gas, e.g. Ba in Xe, on average no RF-heating is expected to occur [31]. For equal ion masses, losses will still occur from non-Gaussian fluctuations when consecutive collisions occur at RF-heating maxima [32]. This heating only happens near the electrodes where the electric field is larger [33]. The effective potential of a multipole guide, $\Phi_{\text{eff}}(r) \propto (r/r_0)^{N-2}$, has radial dependence of order two less than the number of poles, N , thus guides with a higher number of poles exhibit a flatter potential at the center of the ion guide (for the same inscribed diameter $2r_0$) [34]. This minimizes the RF heating over most of the transport volume. On the other hand, for a given r_0 , the rod diameter ($2R$) decreases with increasing number of poles. Thus the mechanics of mounting multipoles increase in complexity; in particular, if the 0.5 m long rods cannot support themselves. These opposing considerations led to the choice of a sextupole ion guide (SPIG) for ion transport through chamber C.

Multipoles were simulated in SIMION [35] with pressure response added from pre-built hard-sphere collisions model.¹⁸ The most conservative estimate of pressure at the entrance of C, with the least favorable ion transmission efficiency, was used; this was obtained by solving the Navier–Stokes equations¹⁹ in the entrance region. In addition to the RF, a DC bias was determined to be necessary to collect the ions into the SPIG. SIMION calculations showed

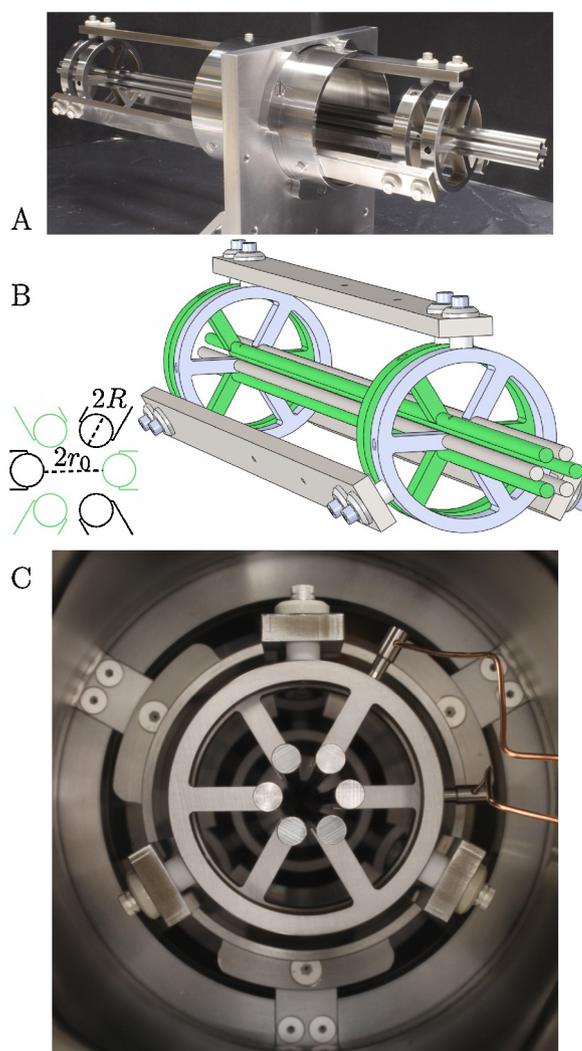


Fig. 9. (A) Picture of the initial SPIG assembly. (B) Rendering of the SPIG's two electrode sets (one set colored green). Each set consists of three rods mounted between two circular positioning holders. (C) View down the installed SPIG.

that without a longitudinal DC potential gradient (i.e. with equal DC bias at both ends of the SPIG), ion-transmission efficiencies of up to 0.8 can be achieved, and so the additional complexity of implementing a DC potential was avoided.

Great care was taken in the design of the SPIG to ensure mechanical rigidity and to create well defined reference features with tolerances less than 0.1 mm. The SPIG (see Fig. 9) consists of two electrode sets, each including three 480.5 mm long rods of $2R = 4.76$ mm ($3/16''$). These sets are mounted at both ends on circular positioning holders that maintain the rods 120° apart on an inscribed circle of radius $r_0 = 4.23$ mm from the axis (see Fig. 9). This corresponds to the optimum ratio of the radius of the rods to the radius of the circle inscribed between the rods of 0.563 for the ideal sextupole field using cylindrical rods [36]. The two sets of rods are mounted 60° apart onto three support bars. The rod sets are insulated from the bars and positioned with precision ceramic spacers that insert into wells in the bar and holders. The bars are mounted to a cylindrical center mount with three lobes that mount to a double-faced DN160 (CF8'') flange in chamber C to ensure that the SPIG is radially centered. A picture of the SPIG mounted in chamber C is shown in Fig. 9C, the lobes are visible at 60° , 180° , and 300° . The entrance to the SPIG lies 6.6 mm after the aperture into chamber C (Aperture 1 in Fig. 1); the aperture widens from 1 mm diameter to

¹⁶ ENI A150.

¹⁷ Balun Designs Model 1413t 1:4/3 kW.

¹⁸ simion.com/info/collision_model.hs1.html.

¹⁹ SolidWorks 2012 Flow Simulation.

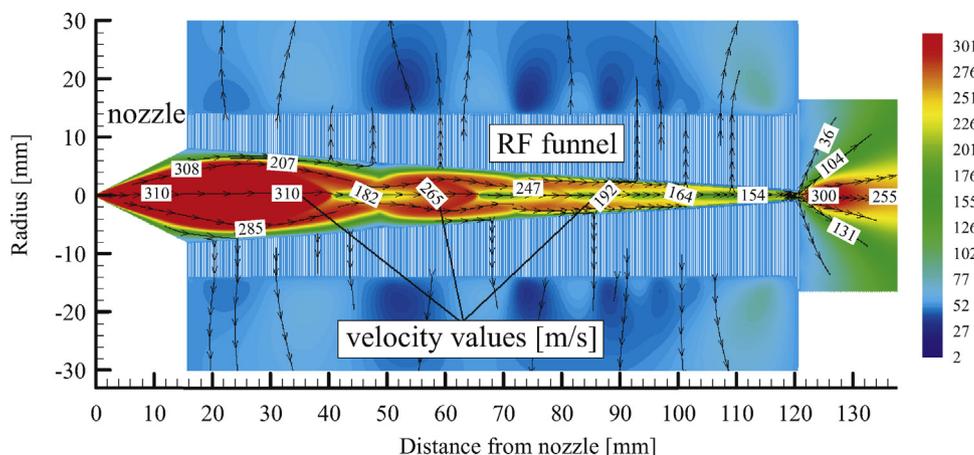


Fig. 10. Simulated velocity field for xenon with $P_A = 10$ bar, $P_B = 8 \times 10^{-3}$ mbar, and $P_C = 1.5 \times 10^{-3}$ mbar. The color scale indicates velocity in m/s.

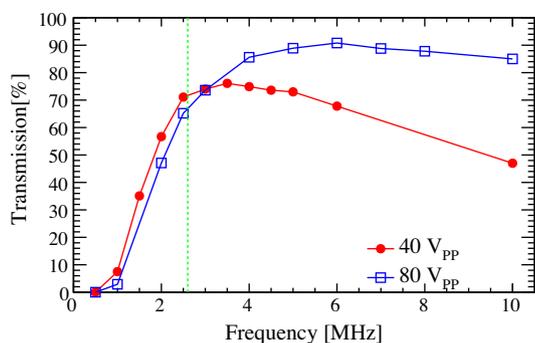


Fig. 11. Simulated, singly-charged, ^{136}u ion transmission in xenon versus RF-frequency for 40 and 80 V_{PP} . $P_A = 10$ bar, $P_B = 3.5 \times 10^{-3}$ mbar, $P_C = 1.5 \times 10^{-3}$ mbar, nozzle diameter of 0.3 mm and inter-electrode spacing of 0.3 mm. The vertical dashed line is at 2.6 MHz, the frequency most commonly used.

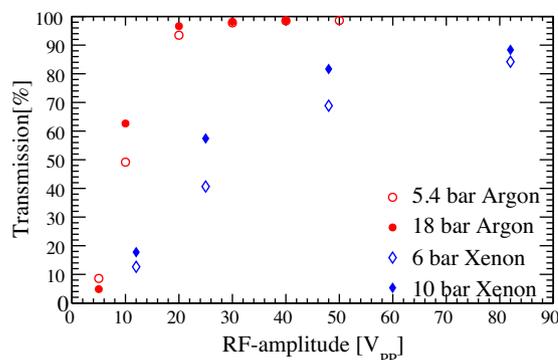


Fig. 12. Simulated transmission at $P_B = 3.5 \times 10^{-3}$ mbar and $P_C = 1.5 \times 10^{-3}$ mbar, for P_A of 5.4 bar and 18 bar Ar and of 6 bar and 10 bar Xe with a nozzle diameter of 0.28 mm.

20.3 mm over a distance of 5.58 mm. The exit of the SPIG is 4 mm in front of chamber D (Aperture 2 in Fig. 1).

The installed SPIG has a capacitance between rod sets of 90 pF at 10 kHz. In order to drive the SPIG, a sinusoidal waveform is generated, amplified and coupled to the SPIG through a toroidal transformer. The secondary of the transformer can be biased to float the SPIG to various DC voltages. The SPIG is typically operated at 2.0 MHz and 400 V_{PP} with a $-5.2 V_{DC}$ bias.

2.5. Ion detector

A differential pumping barrier (Aperture 2 in Fig. 1) separates chambers C and D downstream from the SPIG. This aperture is electrically isolated by a ceramic disk and sealed by two O-rings. This sandwich configuration allows biasing of the aperture to extract ions from the SPIG. The aperture is tapered and its shape has been optimized using SIMION simulations for ion extraction into chamber D. Downstream of this aperture a CEM²⁰ detects the ions. Two lenses focus the extracted ions onto the CEM. The front of the CEM is biased to -2.4 kV, while the rest is at ground. The CEM's signal is capacitively coupled to a high bandwidth amplifier²¹ and recorded.²²

2.6. Data acquisition system

A LabVIEW²³ program controls and monitors the gas handling, vacuum systems and the cryopump; all data is recorded at 1 Hz. Several pressure gauges²⁴ (Fig. 2), CC1²⁵ and P1^{26,27} are digitized.²⁸ The controller²⁹ that reads out CC3 and CC4²⁵ as well as P2 and P3²⁶ communicates via an RS485 connection. The proportional valve (PV) and the pneumatic block valves³⁰ (BV1 and BV2) are controlled by NI modules.³¹ A mass-flow meter³² (FM) measures xenon gas flow before the SAES purifier.

A separate data acquisition program controls and reads the counter,²² and simultaneously records pressure data. This program also controls the RF generator for the funnel, allowing scans of the applied RF amplitude.

²³ National Instruments (NI), LabVIEW 2000.

²⁴ 10 Torr (MKS 722B), 1 Torr (MKS 722B), 100 Torr (MKS 627D), 20 Torr (MKS 627D), and 100 mTorr (MKS 690A read by MKS 270).

²⁵ MKS model 431 cold cathode gauge.

²⁶ MKS model 317 pirani gauge.

²⁷ CC1 and P1 read by the same MKS 937A controller.

²⁸ NI cFP-AI-112.

²⁹ MKS 937B.

³⁰ AP Tech: AP3000SM.

³¹ NI cFP-AO-210 and NI cFP-DO-400.

³² MKS 179A.

²⁰ DeTech 2403.

²¹ ORTEC VT120A.

²² Stanford Research SR620.

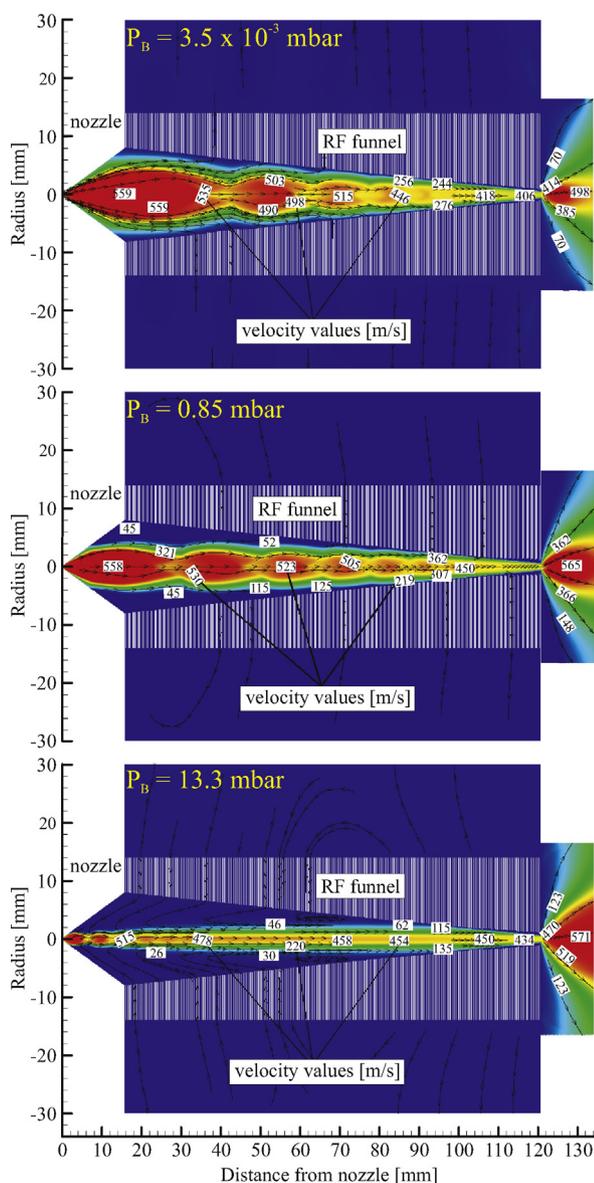


Fig. 13. Simulated velocity fields with $P_A = 5.4$ bar argon for background pressures $P_B = 3.5 \times 10^{-3}$ mbar (top), 0.85 mbar (middle), and 13.3 mbar (bottom).

3. Ion extraction simulations

Numerical simulations, similar to [12], have been performed to optimize the design of the nozzle–funnel system for a xenon stagnation pressure in chamber A, P_A , of 10 bar with mass-flow restrictions posed by the cryopump. These gas dynamic simulations resulted in nozzle and funnel dimensions that are presented in Section 2.3. The simulations are axisymmetric and ignore the electrode mounting features (legs, rods and washers), which might affect the conductivity of the funnel for vacuum pumping in chamber B. Detailed information about gas flow fields of pressure, temperature, density, velocity, and Mach number in the nozzle and chambers A, B, and C has been obtained by means of the VARJET code [37]. This code is based on the solution of a full system of time-dependent Navier–Stokes equations. For the boundary condition in chamber B, a fixed background pressure, P_B , is used. This boundary was set at a radial distance of 50 mm from the funnel axis, after comparison to a distance of 30 mm showed no noticeable differences in the gas flow inside the funnel nor in ion transmission.

Gas dynamic calculations were performed for xenon gas (136 u) and argon gas (40 u). The mass-flow rate through the nozzle equals 45.3 mbar l/s at $P_A = 10$ bar xenon and at $P_A = 5.4$ bar argon. The Reynolds number at the nozzle throat (the critical cross section) equals 6.4×10^4 for $P_A = 10$ bar xenon and $P_A = 18$ bar argon; here, the calculated gas flow shock-wave structures look the most similar. The calculated velocity field for $P_A = 10$ bar xenon is shown in Fig. 10.

The results of these gas dynamic calculations were used as input to ion-trajectory Monte-Carlo simulations. The ion transport efficiency of the RF-funnel was determined as the number of ions passing through the 1 mm diameter exit electrode versus the total number of ions injected into the nozzle. Typically, between 1100 and 7500 simulated $^{136}\text{Ba}^+$ ions were injected into the funnel. Initial simulations with 10 bar xenon were performed for selected frequencies between 0.5 MHz and 10 MHz. The simulated transmission at 10 bar xenon as a function of the applied RF-frequency is shown in Fig. 11.

For increasing RF amplitudes, the maximum calculated transmission efficiency increases and occurs at an increased RF frequency. However, most simulations were performed at a frequency of 2.6 MHz which is typically used in measurements. The use of 136 u for ion and gas is motivated by barium tagging; using instead natural xenon and barium for transport gas and ion, respectively, results in similar, but negligibly enhanced, transmission efficiencies.

The influence of RF-amplitude at 2.6 MHz on transmission efficiency has been calculated for argon and xenon at selected P_A at $P_B = 3.5 \times 10^{-3}$ mbar and $P_C = 1.5 \times 10^{-3}$ mbar, as shown in Fig. 12. With an argon transport gas, the large mass difference between ^{136}Ba and Ar results in almost loss-free ion transport at RF amplitudes larger than $\sim 20 V_{pp}$. In the case of the equal-mass transport gas xenon, the losses inside the funnel increase. Thus, higher RF amplitudes are required to create a stronger confining potential. Furthermore, an increase in P_A at fixed P_B and P_C increases the gas flow and thus the transmission of ^{136}Ba ions in xenon. Comparisons of simulated RF-funnel behavior with data are presented in detail in the next section.

4. Measurements

The measurements presented here focus on benchmarking the Monte-Carlo and gas dynamics calculations as well as on developing practicable modes of operation. The key measurements performed include those of gas pressures during gas-jet operation, and ion extraction with respect to RF-funnel operation. Measurements were performed using argon (Section 4.1) or xenon (Section 4.2) gas.

The pressure gauges used for the measurements (see Section 2.6 and Fig. 2) were found to agree within 10% in common ranges. For ion-extraction and transmission measurements the ion-count rate at the CEM (see Section 2.5) was read out with 1 s integration time and then averaged over three to eleven values. Only statistical uncertainties are shown for all plots. The CEM trigger threshold was optimized for each gas individually; this however, and the different ion production rates (see Fig. 3) complicate objective comparison of measurements between argon and xenon gas operation.

Before each set of measurements, it was verified that all ions measured by the CEM originated in the ion source. Firstly, the SPIG's RF amplitude was reduced to a few mV. This eliminated the CEM signal, ruling out ion creation downstream of the SPIG. Secondly, the funnel's RF-amplitude was varied, altering the CEM-count rate, ruling out the production of secondary ions in the SPIG or chambers C or D. No indication of SPIG or RF-funnel sparking or arc discharge was observed.

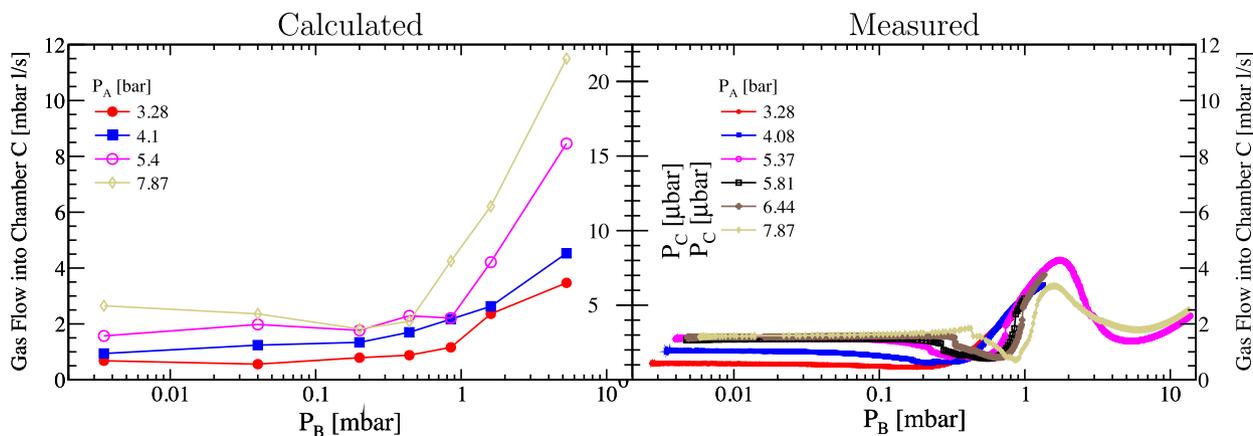


Fig. 14. Calculated argon gas flow into chamber C and measured pressure in C as a function of background pressure, P_B . Selected argon stagnation pressures, P_A , from 3.28 bar to 7.87 bar were applied. A 5341/s Ar-pumping speed in C is used.

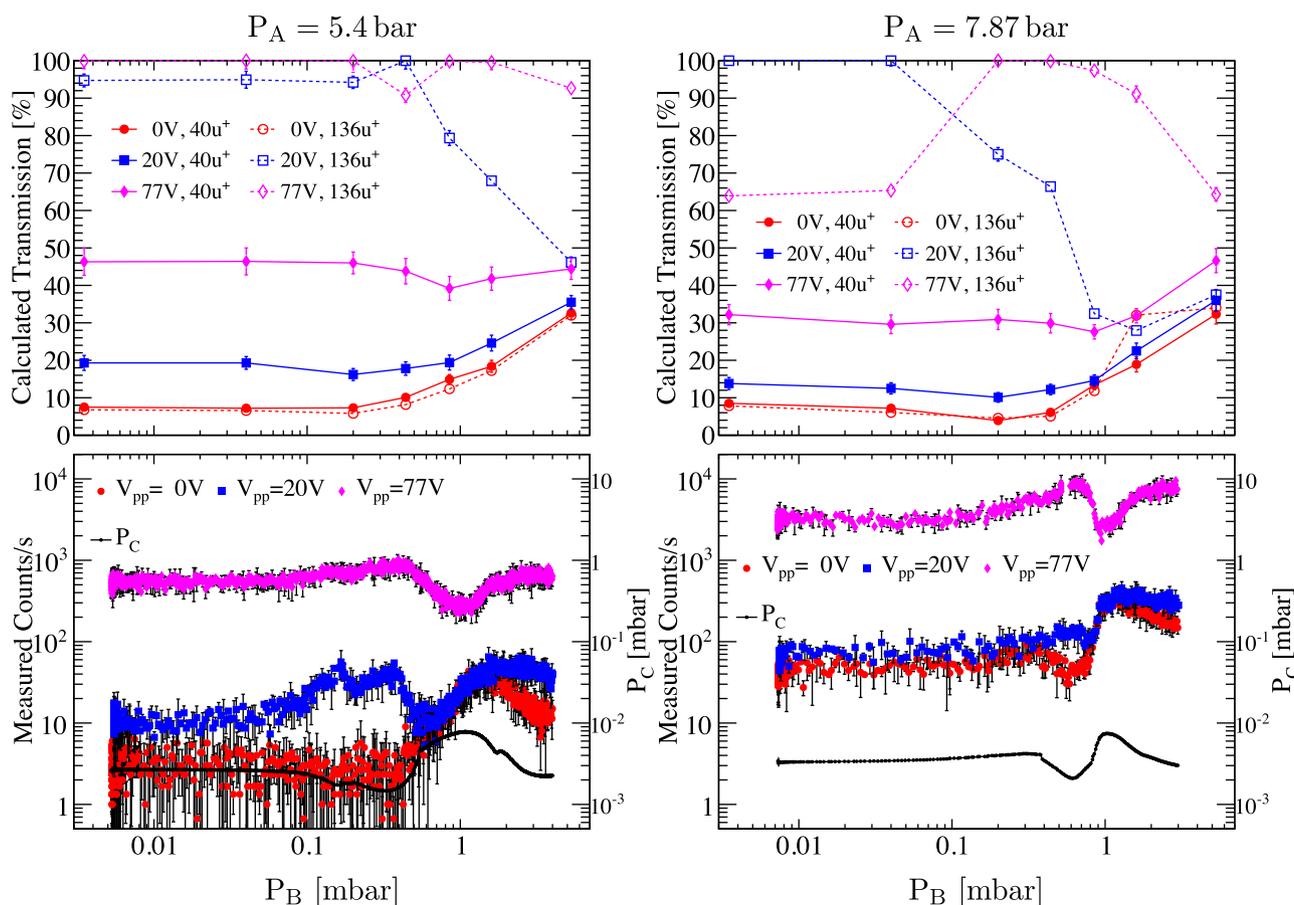


Fig. 15. Calculated transmission (top) and measured count rate (below) at 5.36 bar (left) and 7.87 bar (right) argon stagnation pressure as a function of background pressure in chamber B. The RF-amplitude at 2.6 MHz was set to $0V_{pp}$ (red dot), $20V_{pp}$ (blue square) and $77V_{pp}$ (magenta diamond). The shown pressures, measured in chamber C during the $0V_{pp}$ run, are representative. Calculations were performed with singly-charged ions of mass 40 u and 136 u. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

4.1. Systematic studies with argon

Gas-dynamic calculations show that the behavior of the flow inside the funnel depends on P_A as well as on the pressure surrounding the funnel, P_B . This effect has been investigated in detail at selections of P_A for P_B between 3.5×10^{-3} mbar and 13.3 mbar. In calculations, P_B sets a boundary condition at 50 mm off-axis in chamber B. The velocity fields for an illustrative set of calculations for $P_A = 5.4$ bar argon at $P_B = 3.5 \times 10^{-3}$ mbar, 0.85 mbar, and 13.3 mbar is shown in Fig. 13. An increase in P_B results in the gas

jet being closer to the axis of the funnel; this compression of the gas jet changes the gas flow and thus the ion transmission into chamber C.

Fig. 14 compares the calculated gas flow (left) into chamber C to the measured pressures (right). The TMP on chamber C operates at a pumping speed of 5341/s at 10×10^{-3} mbar argon³³; this nominal speed was used to convert between gas-flow and pressure.

³³ D. Steele, Edwards, private communication (September 2014).

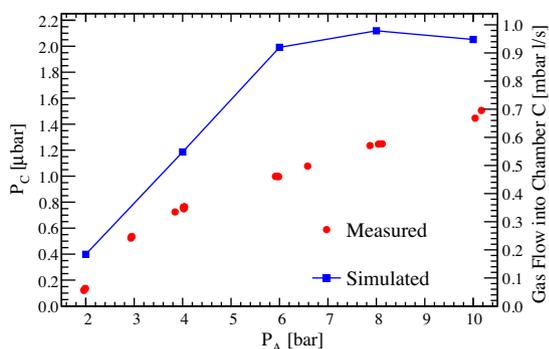


Fig. 16. Measured xenon pressure in chamber C (left axis) as a function of P_A . Calculated gas flow is shown on the right axis. The Xe-pumping speed is 462 l/s.

The gas-flow rate into chamber C was calculated at a selection of P_A and P_B . For direct comparison, similar P_A were applied in the experiment. The experimental measurement was performed dynamically, increasing P_B by virtue of the gradual heating of the cryopump subject to a long term (~ 30 min) continuous gas load. During each run, P_A was kept constant. Runs and calculations were performed at P_A between 3.28 bar and 7.90 bar.

For $P_B \lesssim 1.5$ mbar the general trend in calculated and measured shape and pressure agrees within a factor of ~ 2 . However, the calculated gas-flow rate for $P_B \gtrsim 1.5$ mbar does not agree with the observed pressures; P_C steeply decreases with increasing P_B and has a second local minimum at ~ 5 mbar. This minimum is reproducible and present in all pressure measurements that were performed for background pressures up to 10 mbar. We conclude that in the regime ($P_B \lesssim 1.5$ mbar) where the funnel was optimized its behavior is predicted by calculations. At higher P_B thermal effects inside the vacuum chamber that are not included in calculations might cause the observed behavior. In the following measurements, only the region $P_B < 1$ mbar is considered.

The ion-extraction efficiency in argon has been calculated for $^{40}\text{Ar}^+$ and $^{136}\text{Ba}^+$ and is shown in Fig. 15. The ion transmission was calculated for selected background pressures for $P_A = 5.40$ bar and 7.87 bar and RF amplitudes $0 V_{pp}$, $20 V_{pp}$, and $77 V_{pp}$. Without any applied RF voltage ($0 V_{pp}$), ions are flushed into the downstream chamber C by the gas flow. Here, calculated ion transmissions are comparable for Ar^+ and Ba^+ and increase with the gas flow rate (see Fig. 14). Applying RF voltage to the funnel boosts transmission of Ba^+ to almost unity. The transmission of Ar^+ is reduced as expected due to the equal mass transport gas and the corresponding

increased loss rate from collisions. Higher RF-amplitudes generally led to better confinement of the ion and thus result in higher ion transmission.

Measurements were performed applying the same parameters as those used in calculations of Fig. 15. The measured ion-count rate along with pressures P_C and P_D for selected pressures P_B is shown at the bottom of Fig. 15. Due to the nature of the ion source, Ar^+ is expected to be the dominant ion species (see Section 2.2).

For an RF-amplitude of $V_{pp} = 0 V$ the ion count rate follows the gas flow rate and increases with increasing flow rate. For low background pressures (0.01–0.1 mbar), applying an RF amplitude of $20 V_{pp}$ increases the ion transmission by a factor of 3.5 ($P_A = 5.40$ bar) and 1.5 ($P_A = 7.87$ bar) and is comparable to the calculated (0.04 mbar, Ar^+) increase in transmission of 2.7 and 1.7. In this pressure region, applying $77 V_{pp}$ causes an increase in ion-count rate compared to $0 V_{pp}$ of 170 and 78 for $P_A = 5.40$ bar and $P_A = 7.87$ bar, respectively; this increase is higher than the calculated increase of 6.4 and 4.1.

4.2. Systematic studies with xenon

The funnel operation was investigated for various P_A of xenon. The calculated xenon-gas flow rates into chamber C for various stagnation pressures, using measured P_B for boundary conditions, are shown in Fig. 16 (right ordinate). The measured pressures P_C are also shown in Fig. 16 (left ordinate). The gas-flow rate into chamber C is obtained from P_C using a nominal xenon-pumping speed of 462 l/s at 1.3×10^{-3} mbar.³³ For increasing P_A the calculated flow rate increases before it levels off at ~ 0.95 mbar l/s for $P_A \gtrsim 6$ bar while the measured pressure continuously increases. Despite this disagreement in the general shape of calculated gas flow into chamber C and the gas flow from measured pressure in chamber C, the calculated flow rates agree with the measured pressures to better than a factor of 2 under the assumed pumping speed.

The effect of varying RF-amplitudes at 2.6 MHz was simulated and measured for various P_A shown in Fig. 17. The highest calculated ion transmission reaches 93% at a xenon pressure of 2 bar. At this pressure, relatively low RF-amplitudes of $\gtrsim 30 V_{pp}$ are sufficient to confine the Ba ions. At higher P_A , a given RF-amplitude is less efficient at confining ions. At $P_A = 10$ bar, the maximum transmission efficiency for 2.6 MHz is calculated to be 58%; higher transmission efficiencies have been calculated, reaching 85% for 6 MHz at $160 V_{pp}$. Due to hardware limitations, these RF settings could not be realized in this setup.

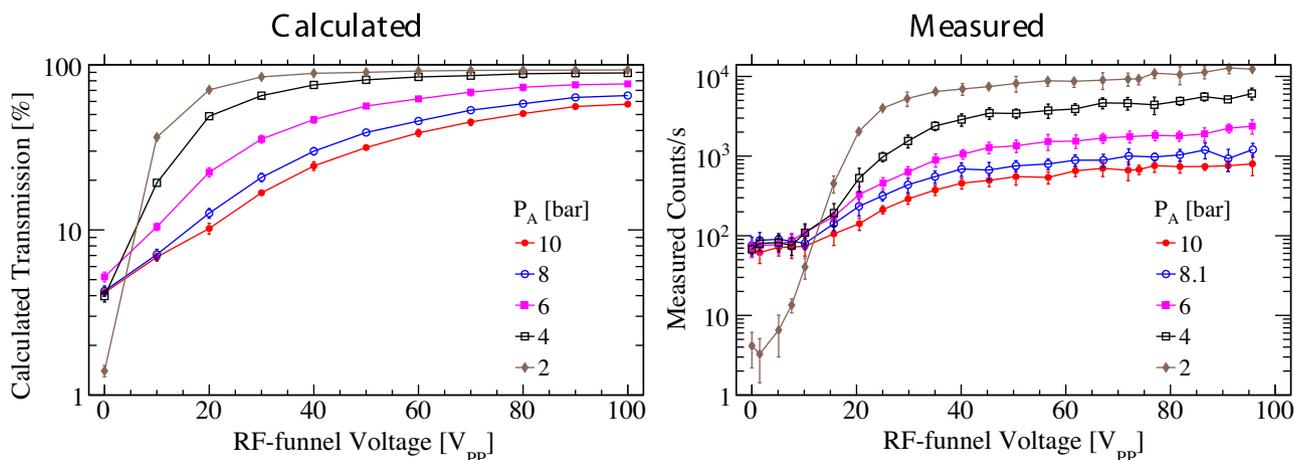


Fig. 17. Calculated ion transmission (left) and observed ion-count rate (right) as function of RF-amplitude at 2.6 MHz for selected xenon P_A . In these calculations, measured $P_B = 8 \times 10^{-3}$ mbar and $P_C = 1.5 \times 10^{-3}$ mbar were used for boundary conditions.

The measured ion-count rate in Fig. 17 for $P_A = 2$ bar increases by up to 4.5 orders of magnitude while the calculated transmission only increases from 1.4(1)% to 93.1(29)%. However, the observed decrease in ion transmission at low RF-amplitudes is predicted by calculations. Better agreement between calculated and measured ion-count rate is observed for higher P_A . Overall, the general trend and shape of both plots agree. It is pointed out, that count rates at different P_A cannot be compared quantitatively with each other due to the different ion production rates and the lack of ion identification. Nevertheless, the shapes of calculated and measured ion extraction in Fig. 17 show similarities and indicate agreement.

5. Conclusion and outlook

We designed and built a setup to extract ions from a high pressure noble gas. With this setup we demonstrated ion extraction from both xenon gas and argon gas at pressures up to 10 bar. Experimental pressure data have been compared to gas dynamic calculations and agreement was found within a factor of 2.

An extension of the presented system is being developed to allow ion identification through a mass-to-charge (m/q) measurement technique, e.g. a quadrupole mass filter (QMF) or a 2-D Paul trap [38]. With such m/q established, the extraction efficiency of Ba ions and other ions from high pressure noble gases will be investigated. In a later step, the presented setup will be coupled to a buffer-gas filled Paul trap to unambiguously identify Ba ions through laser spectroscopy [24] and demonstrate the full process of ion extraction and spectroscopic detection.

Applications, other than Ba tagging are under investigation for RF-only funnels. The combination of a laser with an RF-only funnel as an ion source has been proposed in [39,40]. A selected species can be ionized using multiple lasers, which potentially allows contamination measurements in low-background noble gas detectors. Such a system is best suited to measure contamination concentrations of isotopes heavier than the detector medium, e.g. radon in xenon gas or krypton in argon gas, and complements other contamination measurement techniques such as using an atom trap for trace analysis [41,42] or a cold trap [43].

Another application for an RF-only funnel is the extraction of radioactive ions from stopper cells at fragmentation facilities. Such a use is under investigation to improve ion extraction from the Cryogenic Stopping Cell for the Super-FRS at FAIR [44].

Since their introduction in the 1980s, RF-funnels have been improved constantly and find a wide application in mass spectrometry. Due to their high efficiency and simple application they are well suited for application in future high precision low background experiments.

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