ISBN: 978-3-95450-226-4 ISSN: 2222-5692 doi:10.18429/JACoW-ECRIS2020-MOXZO02

CONCEPTUAL DESIGN OF HEAVY ION ToF-ERDA FACILITY BASED ON PERMANENT MAGNET ECRIS AND VARIABLE FREQUENCY RFQ ACCELERATOR

O. Tarvainen*, A. Letchford, D. Faircloth
STFC Rutherford Appleton Laboratory, ISIS, Harwell, OX11 0QX, United Kingdom
T. Kalvas, J. Julin
University of Jyväskylä, Department of Physics (JYFL), 40500 Jyväskylä, Finland

Abstract

We present a conceptual design of a heavy ion time-of-flight elastic recoil detection analysis (ToF-ERDA) facility based on a permanent magnet (PM) ECRIS and variable frequency RFQ designed to accelerate 1–10 pnA of $^{40}Ar^{8+}$, $^{84}Kr^{17+}$ and $^{129}Xe^{24+}$ ions to 4–7, 10–15 and 13–20 MeV. It is argued that the required beam currents can be achieved using the minimum-B quadrupole CUBE-ECRIS, which is currently being developed at JYFL. Beam dynamics studies demonstrate approximately 95% transmission of the heavy ion beams through the low energy beam transport (LEBT) and 70–80% efficiency through the RFQ. The predicted LEBT and RFQ transmissions of the CUBE-ECRIS with a rectangular extraction slit are almost similar to those of a conventional ECRIS with a circular extraction aperture. It is shown that approximately 10–20% of the ions can be accelerated to the desired energy with an energy spread $\Delta E/E$ below the required limit set by the ToF-ERDA resolution.

INTRODUCTION

Typical ToF-ERDA facilities are based on the concept shown in Fig. 1(a). The heavy ion beams (X^-) are produced with a caesium sputter ion source (see e.g. Ref. [1]). These ions are injected into a tandem-type accelerator where they are first accelerated by the terminal voltage, stripped at the terminal to produce positive ions with a charge state distribution (X^+ ... X^{n+}) and finally accelerated by the terminal voltage into the sample chamber at laboratory ground through an m/q-separation magnet selecting the ion energy.

The concept has benefits and drawbacks. The advantages are: the required beam currents of 1–10 pnA (i.e. particle nanoamperes at the target) can be produced from a wide range of elements; the ion beam energy can be varied over a range of several MeV through the adjustment of the accelerator terminal voltage and selection of the final charge state; the same accelerator can be used for Rutherford Backscattering Spectrometry if equipped with a negative helium (He^-) ion source. By contrast: the stability of the ion source and the lifetime of its cathode can prolong the measurement time and cause downtime of the facility; tandem-based IBA facilities tend to be large in size as the accelerator terminal voltage is on the order of several MV and often needs SF_6-insulation to work, which requires special management (SF_6 is a potent green house gas with an estimated 23,900 times "global warming potential" of CO_2 [2]).

The majority of ToF-ERDA investigations can be carried out with the ion beams (elements) listed in Table 1. All listed beams are halogens, which are easy to produce with the negative sputter ion source from caesium salt targets.

Table 1: Typical Ions (Elements) and Beam Energies Used in ToF-ERDA

Ion	Energy [MeV]
$^{35/37}Cl$	4–10
$^{79/81}Br$	10–15
^{127}I	13–20

PROPOSED ToF-ERDA FACILITY

We introduce an alternative ToF-ERDA concept, shown schematically in Fig. 1(b). The benefits are: increased reliability of the ion source, reduced operational effort and maintenance, lack of SF_6 electrical insulation and smaller

* olli.tarvainen@stfc.ac.uk

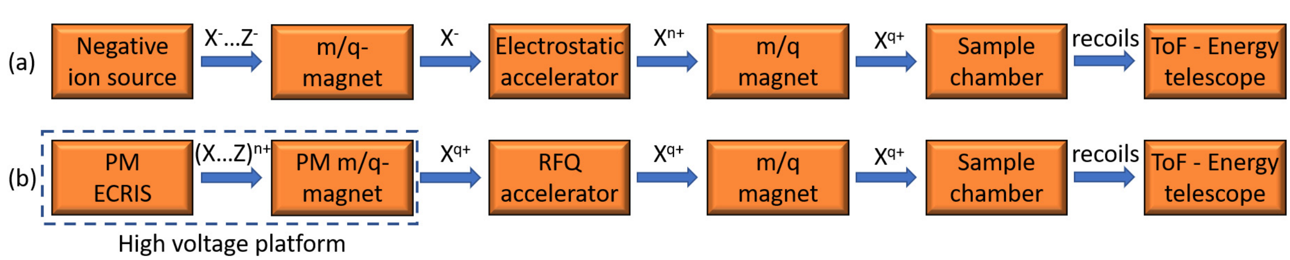

Figure 1: (a) The concept of a typical ToF-ERDA facility based on negative ion source and an electrostatic accelerator. (b) An alternative concept based on permanent magnet ECRIS and variable frequency RFQ accelerator.

ISBN: 978-3-95450-226-4 ISSN: 2222-5692 doi:10.18429/JACoW-ECRIS2020-MOXZO02

laboratory footprint in comparison to most tandem-type accelerators. This conceptual study has been carried out to support the planning of the UK National Thin Film Deposition and Characterisation Centre (led by Daresbury Laboratory). The proposed concept is intended to complement the arsenal of quantitative characterisation methods available for users by allowing the measurement of elemental depth profiles of thin films containing both heavy and light elements in nanometer-scale.

The main components of the proposed TOF-ERDA equipment are

- High charge state permanent magnet electron cyclotron resonance ion source (PM-ECRIS).
- Low energy beam transport (LEBT) with electrostatic focusing and permanent magnet m/q-separator.
- Two-stage low energy acceleration platform.
- Variable frequency RadioFrequency Quadrupole (RFQ) accelerator.
- High energy beam transport (HEBT) with energy dispersive separator, i.e. bending magnet.
- Sample chamber with an option of an auxiliary Rutherford Backscattering Spectrometry (RBS) system.
- Time of Flight – Energy telescope for the detection of recoils.

The design is based on a variable frequency RFQ accelerator, approximately 1.9 m long and with a frequency range of 79–107 MHz. Such accelerator would be an SF_6-free solution producing beams listed in Table 2, i.e. with noble gas ions replacing the halogens. The beam currents listed in Table 2 are the m/q-analyzed electric currents (eμA) through the LEBT required to achieve 1–10 pnA at the target with the desired energy spread ($\Delta E/E$ <0.2‰).

Permanent Magnet ECRIS

The ion beams in Table 2 can be produced with modern PM-ECRISs with an order of magnitude margin in beam intensities (see the literature survey in Ref. [3]). A conventional minimum-B ECRIS with solenoid and sextupole

Table 2: Ions, Beam Energies and Required m/q-analysed LEBT Beam Currents for RFQ-based ToF-ERDA

Ion	Energy [MeV]	Current [eμA]
$^{40}Ar^{8+}$	4–7	0.1–1.0
$^{84}Kr^{17+}$	10–15	0.2–2.2
$^{129}Xe^{24+}$	13–20	0.3–3.0

field components can be considered an overkill for the task. Therefore, the primary candidate for the ion source is the 10 GHz CUBE-ECRIS under construction at JYFL accelerator laboratory. The CUBE-ECRIS is a PM version of the ARC-ECRIS, i.e. it has a minimum-B quadrupole magnetic field topology. The magnet structure is very simple in comparison to conventional PM ECRISs and the resulting field fulfills the semiempirical scaling laws [4] as shown in Fig. 2. The physics design of the CUBE-ECRIS is presented in Ref. [3]. First results from the prototype are expected in 2021.

Low Energy Beam Transport

The expected shape of the beam spot extracted from the CUBE-ECRIS differs from the beam spot of a conventional PM ECRIS. That is because the plasma flux distribution from a quadrupole magnetic field topology favors a rectangular slit instead or a round aperture to extract the beam [3]. Thus, two versions of the low energy beam transport have been simulated comparing the expected LEBT transmissions of the CUBE-ECRIS and conventional ECRIS. The CUBE-ECRIS LEBT is based on a two-stage acceleration with the ion source at approximately +10 kV potential with respect to the LEBT platform, electrostatic quadrupole doublet (EQ1–EQ2), 90° m/q-analysis magnet (DIP) and electrostatic quadrupole triplet (EQ3–EQ5) all on the high voltage platform. Meanwhile, the LEBT design for the conventional ECRIS is based on a 90° m/q-analysis magnet on the platform and a solenoid magnet (SOL) at laboratory ground focusing the beam into the RFQ. The LEBT simulations were

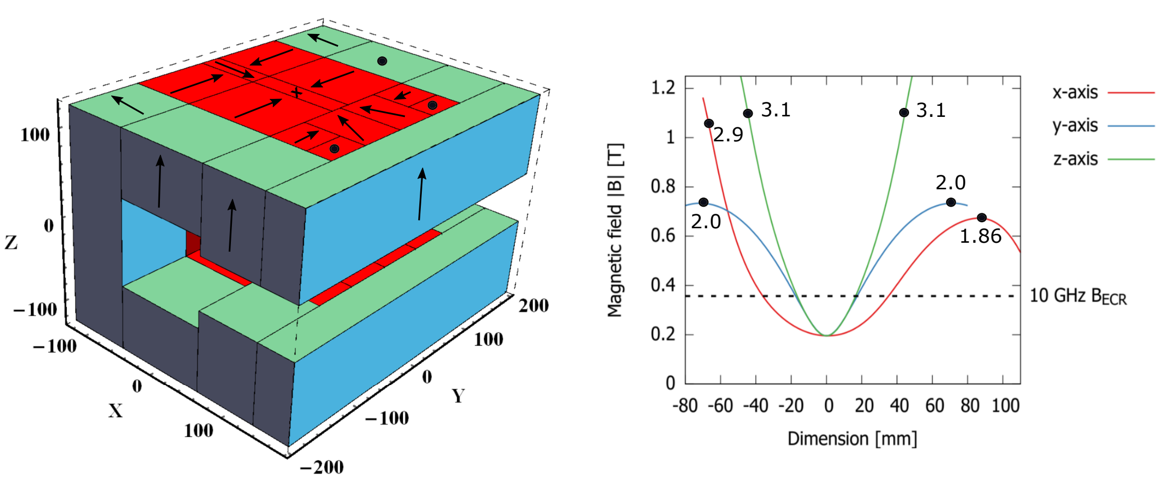

Figure 2: The permanent magnet array and magnetic field of the prototype 10 GHz CUBE-ECRIS. The magnetization vectors are mirrored about the $z = 0$ plane. The mirror ratios (B_{max}/B_{ECR}) on each axis are marked with the black dots.

ISBN: 978-3-95450-226-4 ISSN: 2222-5692 doi:10.18429/JACoW-ECRIS2020-MOXZO02

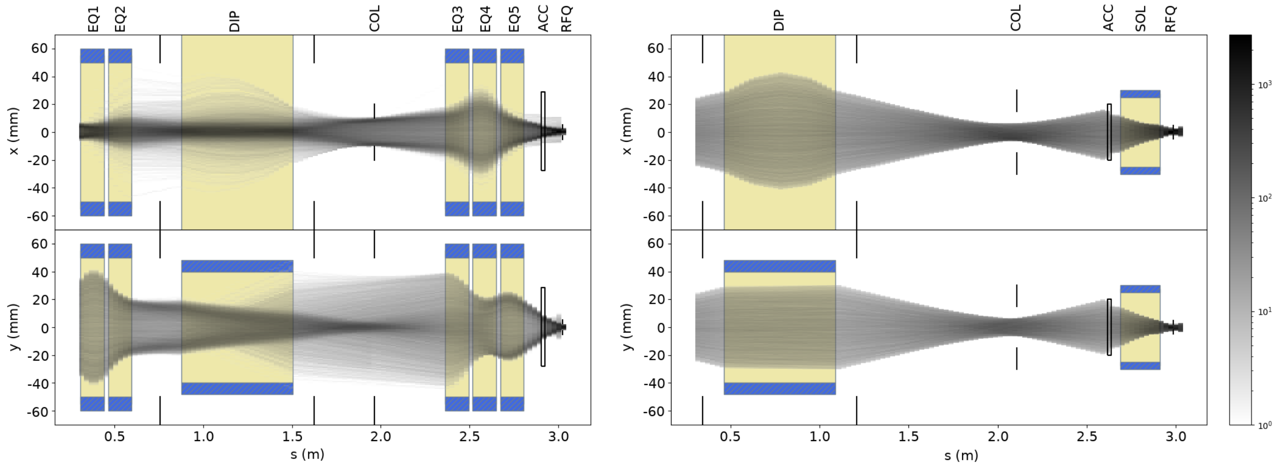

Figure 3: The optimized LEBT solutions for the CUBE-ECRIS (left) and a conventional PM-ECRIS (right).

made with Python-driven Ion Optics Library, PIOL (under development at JYFL), using third order matrices. Figure 3 shows an example of the simulations for Ar^{8+}. The simulation of the conventional ECRIS LEBT assumes similar beam properties to the JYFL 14 GHz ECRIS, i.e. diverging beam with 0.1 mm·mrad normalized rms emittance in both transverse planes. For both LEBT options and beams shown in Table 2 the calculated LEBT transmission is 93–97%. The given number is the total transmission through the LEBT, not the fraction of the beam in the RFQ acceptance, which is discussed later. The expected ~95% transmission is similar to the CUBE-ECRIS prototype beamline with an electrostatic quadrupole doublet and a 135° dipole magnet (loaned from GANIL), under commissioning at JYFL. Thus, the first experimental m/q-analysed beam currents should match those in Table 2 to demonstrate the feasibility of the CUBE-ECRIS concept for the IBA-application.

The two-stage acceleration allows extracting all three noble gas ion species with 10–11 kV ion source potential and using a permanent magnet dipole for the m/q-separation before accelerating the ions into the RFQ. The combined platform + ion source voltage ranges from 18.75 kV to 31.25 kV corresponding to 4 MeV argon and 20 MeV xenon out of the RFQ, respectively. The use of the PM dipole minimizes the power consumption of the LEBT platform. Figure 4 shows a preliminary simulation of a 90° PM bending magnet with 35° entrance and exit angles (used in the LEBT simulation).

The magnetic field can be adjusted in the range of 68–91 mT by moving the "magnet cartridge" radially with respect to the apex of the reference beam trajectory. However, for the IBA-application it is more convenient to adjust the ion source potential to select the beam. In Fig. 4 the dipole field is 83 mT, achieved when the cartridge is moved 25 mm outwards from the position corresponding to the maximum field i.e. when the cartridge is perfectly aligned with the gap in the return yoke. The radial uniformity of the field ($\Delta B/B$) is better than 10^{-3} in the volume occupied by the beam (i.e. -40 mm $< r <$ 40 mm). The uniformity of the field is affected by the volume of the PM material in the thin layers between the magnet pole pieces and the return yoke.

Variable Frequency RFQ

The Radio Frequency Quadrupole (RFQ) is an RF accelerator particularly well suited to the acceleration of low velocity ions due to its use of transverse electric rather than magnetic fields for focussing the beam. The RFQ has four symmetrically placed electrodes inside a resonant cavity which concentrate the TE21 quadrupole mode into a small beam channel. By carefully shaping or modulating the beam facing surfaces of the electrodes a component of the transverse field is directed into the longitudinal direction to provide acceleration.

Because it is an RF accelerator a strict requirement for the RFQ is synchronism between the particles and the RF field.

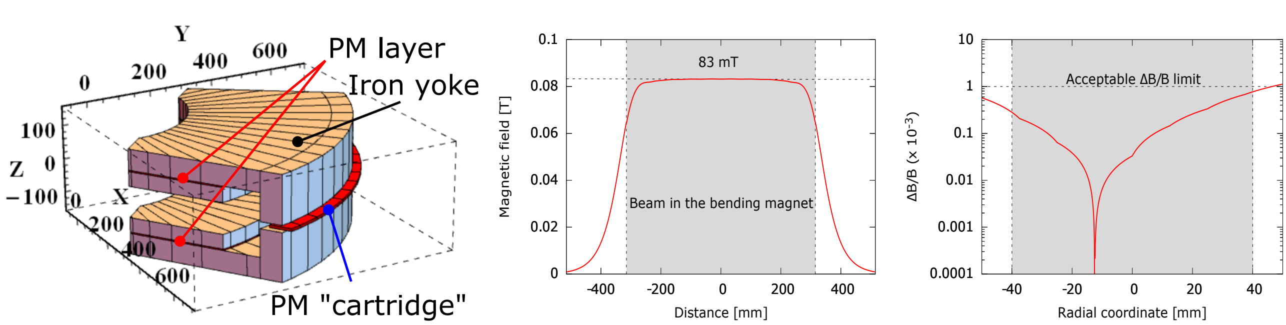

Figure 4: The permanent magnet dipole (left), its magnetic field along the reference particle trajectory (center) and the radial uniformity of the field, $\Delta B/B$ (right).

ISBN: 978-3-95450-226-4 ISSN: 2222-5692 doi:10.18429/JACoW-ECRIS2020-MOXZO02

For a fixed frequency RFQ this translates into a fixed velocity profile. Any ions with the same charge to mass ratio can be accelerated with the final energy being proportional to the mass. Ions with different charge to mass ratios can also be accommodated by varying the strength of the electric field (or RF power level) within the constraint that the maximum surface electric field is not exceeded. In order to achieve variable energy in a single structure it is necessary to adjust the operating frequency. Designing a frequency adjustable, high Q resonant cavity is certainly the biggest challenge in realising a variable energy RFQ however several such devices have been built previously [5–8]. At this stage of the study only the beam dynamics of the RFQ have been considered.

A particular feature of the RFQ is its ability to take a continuous beam from an ion source and bunch it for stable RF acceleration with very high capture efficiency even for high current beams with large space charge forces. This is achieved by a slow, quasi-adiabatic bunching process for which there are well developed design procedures. In the context of low current, high charge state heavy ion beams for IBA this type of design has several disadvantages: (i) Adiabatic bunching can result in a rather long structure. (ii) The slow increase in the electrode modulation can lead to features that are at or beyond the limit of ordinary machining processes. (iii) Constraints on the adiabatic bunching can mean that the longitudinal emittance is not a free parameter resulting in large energy spread.

In order to overcome these disadvantages a different approach has been taken for the IBA RFQ. The long adiabatic bunching section has been replaced by a discrete buncher and drift followed by a capture section. This results in a somewhat shorter RFQ with larger modulation at the beginning and greater control over the energy spread at the cost of reduced total capture efficiency. Figure 5 shows the RFQ parameters. The graphed energy is for the case of $^{129}Xe^{24+}$ accelerated to 20 MeV where the total energy spread is ~0.5%. The total beam transmission η and fraction of beam below 0.2% and 0.5% energy spread are shown in Table 3. These values were calculated by tracking the particle distributions at the end of the LEBT through the RFQ. The total transmission through the RFQ is somewhat better for the conventional ECRIS and its LEBT but the difference to CUBE-ECRIS is very small when the energy spread is restricted (by slits in the high energy beamline).

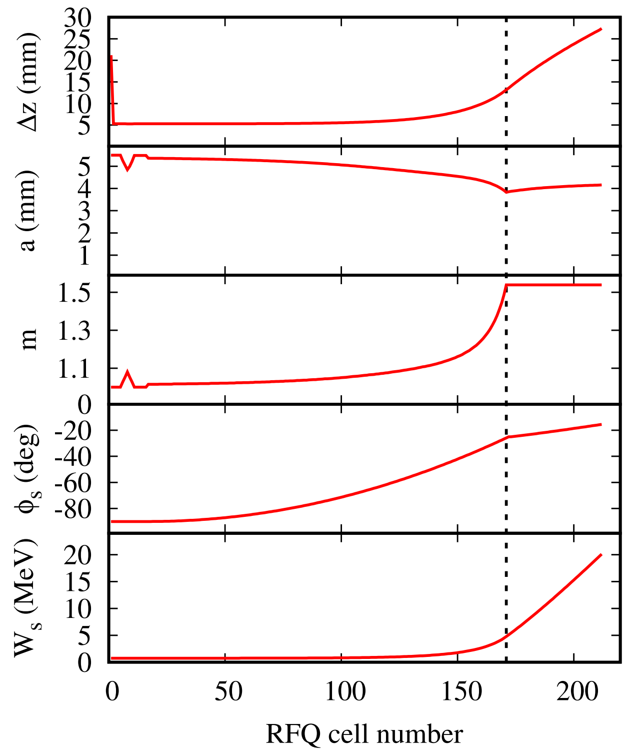

Figure 5: The RFQ parameters along the 1.92 m length of the structure (cell number): Δz is the length of each cell, a the minimum distance of the vane tip from the axis, m the vane modulation, ϕ_s the synchronous phase and W_s the energy of the synchronous $^{129}Xe^{24+}$ ion. The vertical dashed line marks the transition into the accelerating section.

High Energy Beam Transport and Time of Flight – Energy Telescope

The use of the variable frequency RFQ accelerator means that the beam is pulsed at the RFQ frequency with the beam pulses occupying approximately 20% of the time domain, which translates to 2 ns pulses at 10 ns interval for 100 MHz RFQ frequency. The beam can be considered to be semi-continuous if there is sufficient temporal overlap of recoils hitting the first timing detector produced by successive beam

Table 3: The calculated ion beam final energy E, RFQ frequency f and vane voltage V_{vane}, ion source potential V_{source}, total beam transmission η and fraction of beam for which certain $\Delta E/E$. The transmission values are for the CUBE-ECRIS and its LEBT with the corresponding values for the conventional ECRIS and its LEBT in parentheses.

Ion	E [MeV]	f [MHz]	V_{vane} [kV]	V_{source} [kV]	η [%]	$\Delta E/E$ <0.5%	$\Delta E/E$ < 0.2%
$^{40}Ar^{8+}$	4	79.687	56.7	18.75	69 (84)	23 (29)	9 (11)
$^{40}Ar^{8+}$	7	105.416	63.0	32.81	76 (93)	25 (29)	9 (9)
$^{84}Kr^{17+}$	10	86.946	42.4	22.06	70 (87)	20 (27)	8 (13)
$^{84}Kr^{17+}$	15	106.486	63.5	33.09	76 (93)	21 (28)	9 (13)
$^{129}Xe^{24+}$	13	79.995	39.0	20.31	70 (81)	22 (29)	8 (13)
$^{129}Xe^{24+}$	20	99.222	60.0	31.25	70 (87)	25 (29)	8 (10)

ISBN: 978-3-95450-226-4 ISSN: 2222-5692 doi:10.18429/JACoW-ECRIS2020-MOXZO02

pulses. For example, the 100 MHz repetition rate is sufficiently high, depending on spectrometer design, if the recoil times-of-flight span more than 50 ns. Typically, the times-of-flight are in the range of some 100 ns, which implies that for this application the RFQ beam can be considered continuous.

The energy spread of the beam incident on the target can be limited by a high-resolution dipole magnet coupled with a pair of slit plates. The maximum allowed energy spread can be estimated by assuming that the intrinsic ToF spectrometer energy resolution must be greater by some factor than the broadening in recoil spectra caused by incident beam energy variation.

For the proposed beams the energy resolution of the spectrometer for surface recoils can be calculated. One of the figures-of-merit of interest for a ToF-ERDA system is the achievable depth resolution, which is affected not only by instrumentation but fundamental ion-matter interactions like energy-loss straggling and multiple scattering.

Table 4: Relative energy resolution (%) of the proposed time-of-flight spectrometer for various surface recoils, and scattered incident beam ion from ^{197}Au, taking into account timing resolution, kinematic broadening due to finite detector solid angle, and energy loss straggling in the first timing foil.

Ion	**E MeV**	**^{1}H %**	**^{16}O %**	**^{28}Si %**	**^{197}Au (sc.) %**
^{40}Ar^{8+}	4	0.56	0.41	0.39	0.31
^{40}Ar^{8+}	7	0.53	0.42	0.39	0.33
^{84}Kr^{17+}	10	0.54	0.42	0.39	0.29
^{84}Kr^{17+}	15	0.54	0.46	0.42	0.31
^{129}Xe^{24+}	13	0.56	0.41	0.39	0.27
^{129}Xe^{24+}	20	0.53	0.45	0.42	0.28

In Table 4 we have considered effects related to ERD kinematics and intrinsic timing resolution (150 ps), kinematic broadening due to finite detector size or position sensitivity (1 mrad), as well as energy loss straggling in the first carbon foil (thickness 2 µg cm^{-2}) for surface recoils in a ToF spectrometer with a flight path length of 600 mm installed to an angle of 40° relative to the beam. The depth resolution degrades rapidly deeper in the sample especially for heavier recoils, so these values of 0.2–0.6% should be considered optimistic estimates of real world performance. It is concluded that an incident energy spread of 0.2% would be sufficiently small to account for the difference between the optimistic estimate and actual performance of the spectrometer. The assumptions made are based on realistically achievable ToF-ERDA spectrometer design [9, 10].

DISCUSSION AND OUTLOOK

The main advantage of the proposed RFQ based IBA-system over the state-of-the-art negative ion based facilities is the use of (high charge state) noble gas ions, which allows the production of these beams with the PM-ECRIS to be automated into a turn-key system with minimal user involvement. The same applies to the tuning of the RFQ once the correct combination of injection energy, RF frequency and electrode voltage (RF power) for each final ion energy has been determined.

In addition to the RFQ, we have considered the possibility of using a high charge state PM ECRIS on a high voltage platform to produce the desired beams. The benefit of the platform option would be the addition of He^{2+} beam into the arsenal, and hence enabling the use of RBS with the same accelerator. However, the platform voltage would need to be 750–800 kV to achieve the same range of final ion energies as with the RFQ. Such platform would be prohibitively large –its reliable operation would require a laboratory space up to 10 squash courts (in volume) – and the RBS energies of 1.6 MeV as a maximum would be only borderline acceptable for the proposed STFC facility.

The proposed ToF-ERDA concept has been submitted to STFCs internal evaluation as a part of the National Thin Film Deposition and Characterisation Centre with the possible funding decision of a technical design study expected in 2020–2021. Meanwhile the development of the CUBE-ECRIS is ongoing at the JYFL accelerator laboratory. The success of the CUBE-ECRIS prototype will define the choice of the ion source for the project.

REFERENCES

[1] R. Middleton, “A versatile high intensity negative ion source”, *Nucl. Instrum. Methods Phys. Res.*, vol. 214, no. 2–3, pp. 139-150, 1983. doi:10.1016/0167-5087(83)90580-X

[2] P. Forster *et al.*, “Global Warming Potentials ...”, in *IPCC Second Assessment Report*, chap. 2.10. https://www.ipcc.ch/site/assets/uploads/2018/02/ar4-wg1-chapter2-1.pdf

[3] T. Kalvas, O. Tarvainen, T. Toivanen, and H. Koivisto, “Design of a 10 GHz minimum-B quadrupole permanent magnet electron cyclotron resonance ion source”, *J. Instrum.*, vol. 15, p. P06016, 2020. doi:10.1088/1748-0221/15/06/P06016

[4] D. Hitz, A. Girard, G. Melin, S. Gammino, G. Ciavola, and L. Celona, “Results and interpretation of high frequency experiments at 28 GHz in ECR ion sources, future prospects”, *Rev. Sci. Instrum.*, vol. 73, p. 509-512. doi:10.1063/1.1429313

[5] A. Schempp *et al.*, “Development of a Variable Energy RFQ for Cluster Acceleration”, *Conference Record of the 1991 IEEE Particle Accelerator Conference*, San Francisco, CA, USA, 1991, pp. 3053-3055 vol. 5. http://jacow.org/p91/PDF/PAC1991_3053.PDF

[6] K. Stiebing *et al.*, “The Frankfurt ECRIS-RFQ facility for materials research with highly charged ions”, *Nucl. Instrum. Methods Phys. Res., Sect. B*, vol. 113, no. 1–4, pp. 34-37, Jun. 1996. doi:10.1016/0168-583X(95)01413-6

[7] K. Amemiya *et al.*, “Aluminum Ion Implantation using a Variable Energy RFQ Implanter”, in *Proc. EPAC’98*, Stockholm, Sweden, 1998, pp. 2419-2421. http://jacow.org/e98/PAPERS/WEP31C.PDF

ISBN: 978-3-95450-226-4 ISSN: 2222-5692 doi:10.18429/JACoW-ECRIS2020-MOXZO02

[8] K. Amemiya *et al.*, "Development of a continuously variable energy radio frequency quadrupole accelerator for SiC power semiconductor device fabrication", *Nucl. Instrum. Methods Phys. Res., Sect. B*, vol. 188, no. 1–4, pp. 247-250, Apr. 2002. doi:10.1016/S0168-583X(01)01107-7

[9] M. Laitinen, M. Rossi, J. Julin, and T. Sajavaara, "Time-of-flight – Energy spectrometer for elemental depth profiling – Jyväskylä design", *Nucl. Instrum. Methods Phys. Res., Sect. B*, vol. 337, pp. 55-61, 2014. doi:10.1016/j.nimb.2014.07.001

[10] S. Eschbaumer, A. Bergmaier, and G. Dollinger, "A position sensitive time of flight detector for heavy ion ERD", *Nucl. Instrum. Methods Phys. Res., Sect. B*, vol. 371, pp. 125-131, 2016. doi:10.1016/j.nimb.2015.09.036