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ARIEL Test Ion Source

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History of Changes

Release number	Date	Description of changes	Author
01	2016-11-10	Initial release	S. Saminathan
02	2017–09–25	Updates on the extraction system design to minimize the beam exposure to the HV ceramic insulator (See Fig. 3). Also updates on the beamline design to accommodate a diagnostic chamber (See Fig. 13 and table 3).	S. Saminathan

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Abstract

An off-line ion source called ARIEL test ion source (ATIS) will be used for beam commissioning and tuning of ARIEL low energy beam transport lines. The ATIS is a surface ion source for producing alkali ion beams. In this design note conceptual design of this ion source, beamline layout, element specifications and diagnostic requirements are documented.

1 Introduction

The ARIEL test ion source (ATIS) will be used as an off-line ion source for beam commissioning and tuning of HRS [1], CANREB RFQ/Buncher [2] and ARIEL RIB transport beamlines [3]. The ATIS should be capable of producing stable beams of alkali ions from heavier to lighter ones with an energy up to 60 keV. The basic requirements for the ATIS are listed in table 1 and detailed requirements are given in Ref. [4].

Alkali elements are easily ionizable because of its low ionization potential compared to all other elements. One of the most commonly used ion source for producing alkali beams is a surface ion source. Surface ion sources are very simple to build and operate. It is suited ideally for our requirements because of a high degree of ion beam purity and in this case an additional mass separator is not essential for commissioning RFQ/Buncher and RIB transport beamline. Also the extracted ion beam from this source has relatively low emittance and low energy spread (order of thermal energies) to meet the beam requirements particularly for HRS (see Sec. 2.1).

Beam parameter	**HRS**	**RFQ/Buncher**	**RIB Beamline**
Beam species	Rb^+ or Cs^+, K^+	Cs^+, Rb^+, K^+, Na^+, Li^+	Cs^+
Beam energy (E)	10.0 keV – 60.0 keV	10.0 keV – 60.0 keV	10.0 keV – 60.0 keV
Energy spread (ΔE) [4rms]	< 0.7 eV	< 10 eV	< 10 eV
Emit. (ε) at 60 keV [4rms]	< 6.0 μm	< 12.0 μm	< 12.0 μm
Beam intensity (I)	1 nA – 100 nA	100 fA – 100 nA	1 nA – 100 nA

Table 1: Summary of basic beam requirements.

1.1 Purpose and scope

Purpose of this design note is to provide some basic information about the functionality of the ARIEL test ion source (ATIS). Scope of this document is to present the conceptual design.

1.2 Definitions

- **Coordinate system:** Horizontal axis: x, vertical axis: y and beam axis: z.

1.3 Abbreviations

- **ATIS:** ARIEL Test Ion Source
- **RIB:** Rare Isotope Beam
- **LEBT:** Low Energy Beam Transport
- **CANREB:** CANadian Rare isotope facility with Electron Beam ion source
- **HRS:** High Resolution Spectrometer
- **RFQ:** Radio Frequency Quadrupole
- **HV:** High Voltage
- **EQ:** Electrostatic Quadrupole.
- **PM:** Profile Monitor.

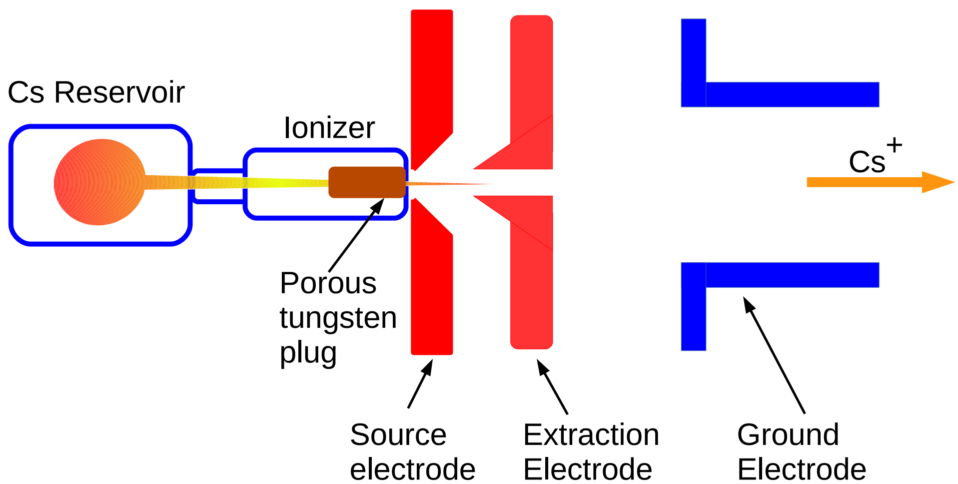

Figure 1: A schematic view of a surface ion source for Cs^+ beams.

2 Surface ion source

Basic principle of a surface ion source is shown in Fig. 1. In a surface ionization process low work function elements such as alkali elements are ionized by contact with a surface of high work function material such as Tantalum, Tungsten, Iridium, etc. The efficiency (η) of a surface ionization is given by the ratio between the number of ions and the total number of particles on the surface. It can be estimated with the Saha-Langmuir equation [5]. From Eq. 1, it is well known that a high ionization efficiencies can be achieved by using an ionizer materials with a higher work function than the ionization potential of elements that needs to be extracted from the source. Therefore, the surface ion source is suited ideally for the alkali elements as they have the lowest ionization potentials of all elements.

Elements	ϕ [eV]
Cs^+	3.89
Fr^+	4.07
Rb^+	4.18
K^+	4.34
Na^+	5.14
Li^+	5.39

Table 2: First ionization potentials ϕ for alkali elements [6].

The efficiency (η) of the surface ionization is given by

$$\eta = \frac{n_i}{n_0 + n_i} = \left[1 + \frac{g_0}{g_i}\exp\Big(\frac{\mathrm{e}(\phi - w)}{kT}\Big)\right]^{-1} \tag{1}$$

Where, n_i, n_0 denote the densities of positive ions and atoms on the surface,
e is the total charge of the of the ion,
ϕ is the ionization potential,
w is the work function of the material,
k is the Boltzmann constant,
T is the temperature of the surface,
g_i, g_0 denote the statistical weights of the ionic and atomic states, respectively.

In the past few decades the surface ion sources are well developed. A simple and compact sources are commercially available, e.g. Ion source model:101139 from HeatWave Labs, Inc. [7]. One such source is being used in the TITAN experimental facility at TRIUMF. The source can typically produce ion currents in the range of few hundred nanoamperes. Similar type of source is proposed for the ATIS with new beam optics design described in Sec. 2.1 and 3. We require an emitter with a diameter about 3.2 mm. The location and the schematic view of the source is shown in Fig. 3. The source consists of a rhenium filament in an alumina insulator assembly. The emitter consisting of an indirectly heated, porous tungsten plug into which the alkali elements has been fused. The filament is heated by passing a current through it which in turn heats the alumina and hence the Tungsten ionizer plug. This causes cesium ions to be released through the process of thermionic emission. The required beam intensity is mainly controlled by controlling the temperature of the source, i.e. controlling the ionization efficiency according to Eq. 1. Ionization efficiency about 90 % and more can be achieved for alkali elements other than Na and Li with a tungsten ionizer at 1000° C (see Fig. 2), whereas ionization efficiency for Na and Li will be around 0.4% and 0.04%, respectively. In this operating regime achieved current densities is about 1–10 mA/cm^2 [7]. For a 3 mm aperture diameter this would still yield about 30–300 nA of Li^+ beams.

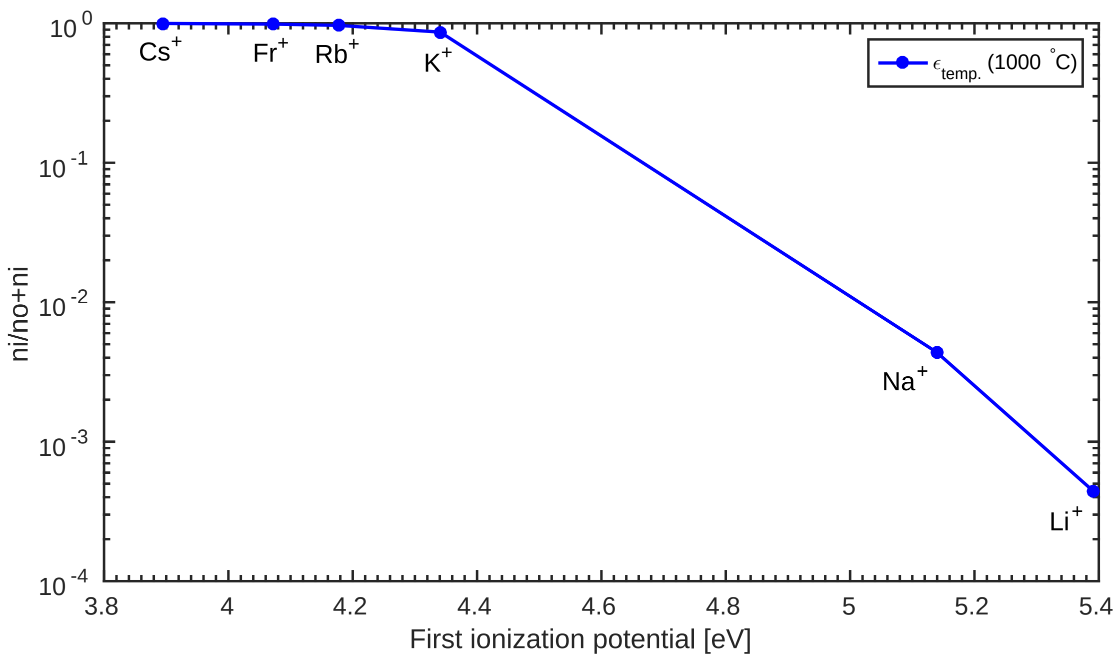

Figure 2: Calculated ionization efficiency for various alkali elements through a tungsten ionizer with a temperature about 1000° C.

2.1 Ion beam extraction

A schematic layout of the proposed ion extraction system with a surface ion source is shown in Fig. 3. The proposed ion source had a diameter of 6 mm and a length of 10 mm, the aperture in the source electrode had a 3.0 mm in diameter (see Fig. 4) in order to achieve the beam emittance $< 12\mu$m (see table 1). The opening aperture in the extraction cone had 9 mm diameter and located 15 mm downstream to the source aperture (see Fig. 5). The ground electrode had an aperture diameter of 50 mm (see Fig. 6). The separation distance between the extraction and the ground electrode is 70 mm. The extraction system geometry and electrode gaps are optimized with the beam optics calculations.

Ions are initialized assuming a Maxwell-Boltzmann energy distribution at the ionizer temperature, which is around 1000° C. For a given initial temperature and the radius of ion emission aperture one can calculate the beam emittance due to the thermal temperature by using Eq. 2. Fig. 7 shows the calculated beam emittance due to the thermal temperature of extracted at various acceleration potential.

Emittance due to thermal temperature is given by [8]

$$\varepsilon_{4rms} = 2R\sqrt{\frac{kT}{2E}} \tag{2}$$

where R is the aperture radius of the source electrode,
k is the Boltzmann constant,
T is the thermal temperature of the ion,
E is the kinetic energy of the ion.

Initially the extraction system is modeled by using the code OPERA3D [9]. Calculated equipotential contour in the xz plane of the extraction system is shown in Fig. 8. Simulations of the ion beam optics were carried out in our in-house code TRANSOPTR by importing the calculated potential from OPERA3D (see Fig. 9). Simulations are performed for extraction and transport of Cs^+ ion beams from the ATIS at an acceleration potential of 60 kV with an initial ion emission energy corresponds to 0.2 eV (see Fig. 10). In this calculations the extraction electrode (1.1 kV) and the emitter (1.0 V) is optimized with beam divergence of the extracted beam. Space-charge effects are not taken into account in order to simulate a typical beam currents of 1 nA from the source. Such currents are sufficiently low that the effects of space charge can be neglected for designing the ion source extraction optics. However, the beam envelope is also calculated by include the space charge effects by assuming an extraction current up to 100 nA at 60 kV (see Fig. 12). According to the analytical calculations for 60 keV extracted beam from the ATIS the 4rms beam emittance and 2 rms energy spread is about 3 μm and 0.2 eV, respectively. These are within the requirements specified in table 1.

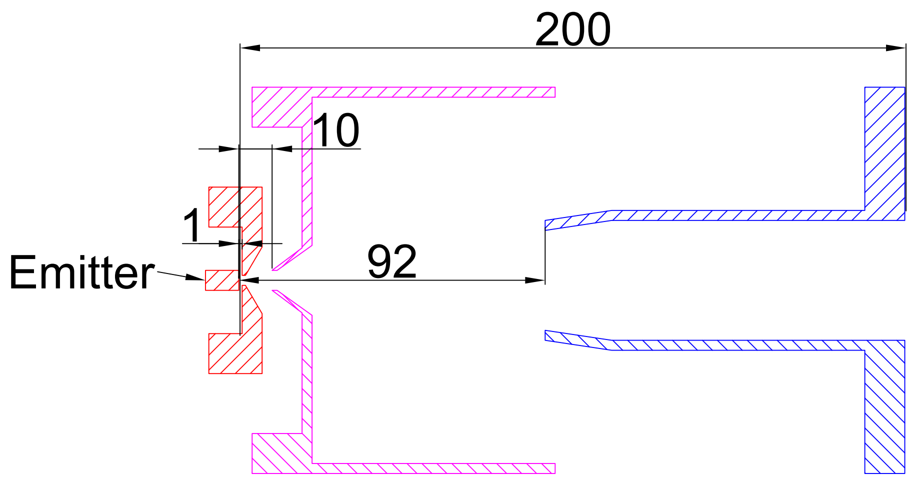

Figure 3: Layout of the ATIS.

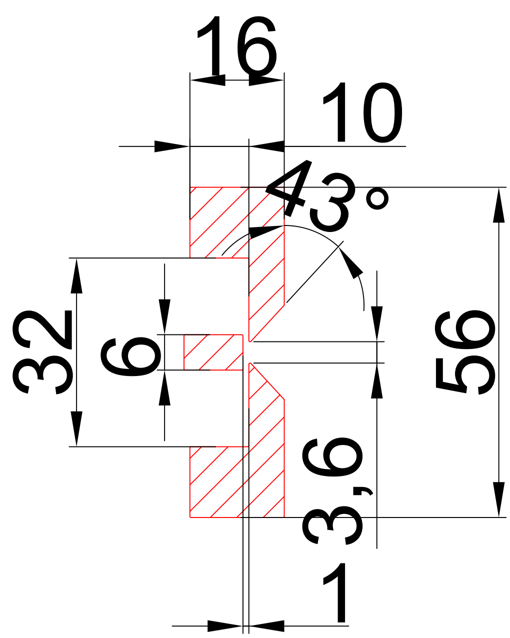

Figure 4: Layout of the source electrode. Remove sharp corners by fillet with radius about 0.25 mm.

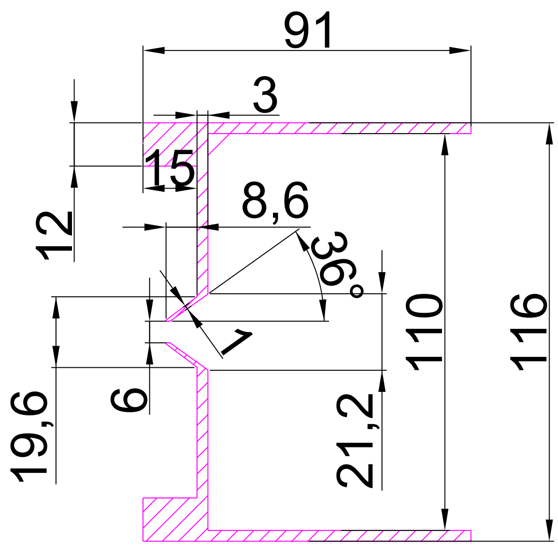

Figure 5: Layout of the extraction electrode. Remove sharp corners by fillet with radius about 0.25 mm.

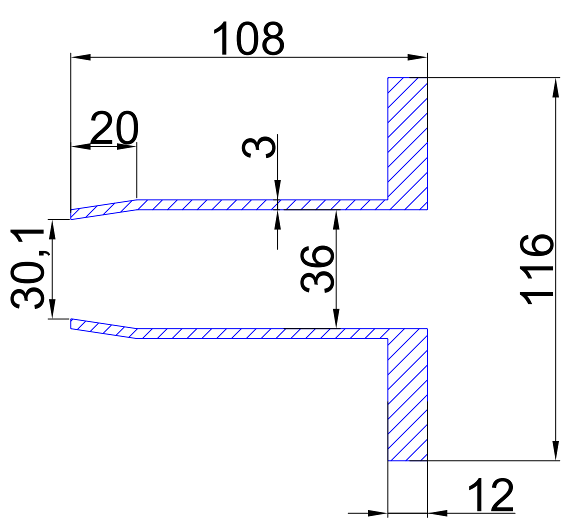

Figure 6: Layout of the ground electrode. Remove sharp corners by fillet with radius about 0.25 mm.

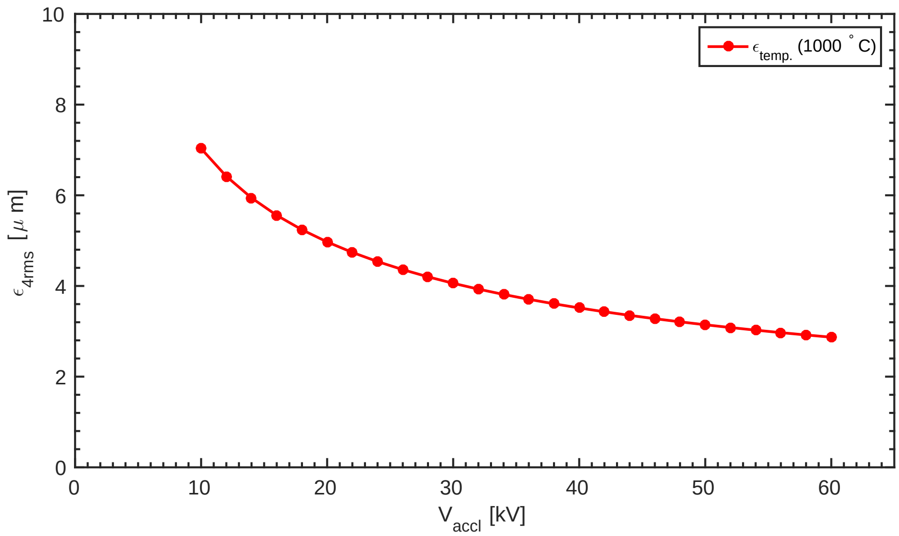

Figure 7: Calculated 4rms emittance of 133Cs$^+$ ion beams due to thermal temperature about 1000° C at various acceleration potential of the extraction system.

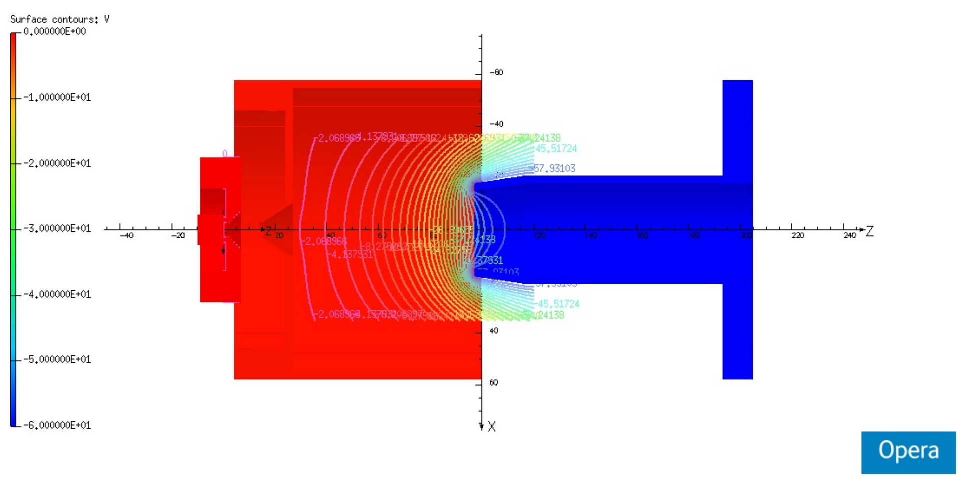

Figure 8: Equipotential contour in the xz plane of the extraction system.

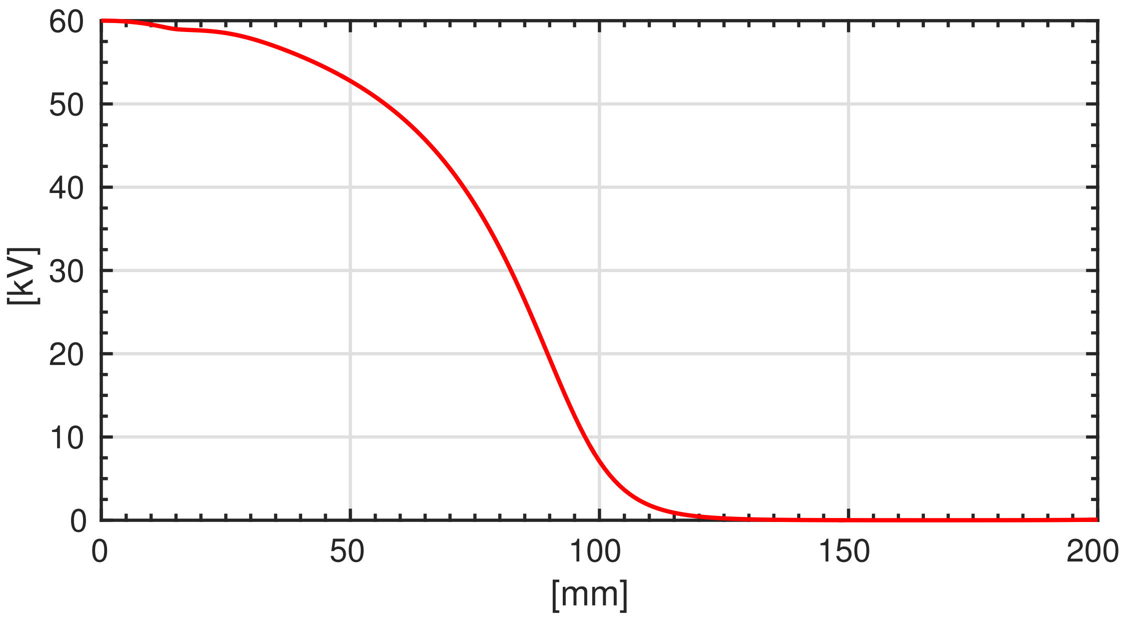

Figure 9: Calculated potential along the axis of the extraction system.

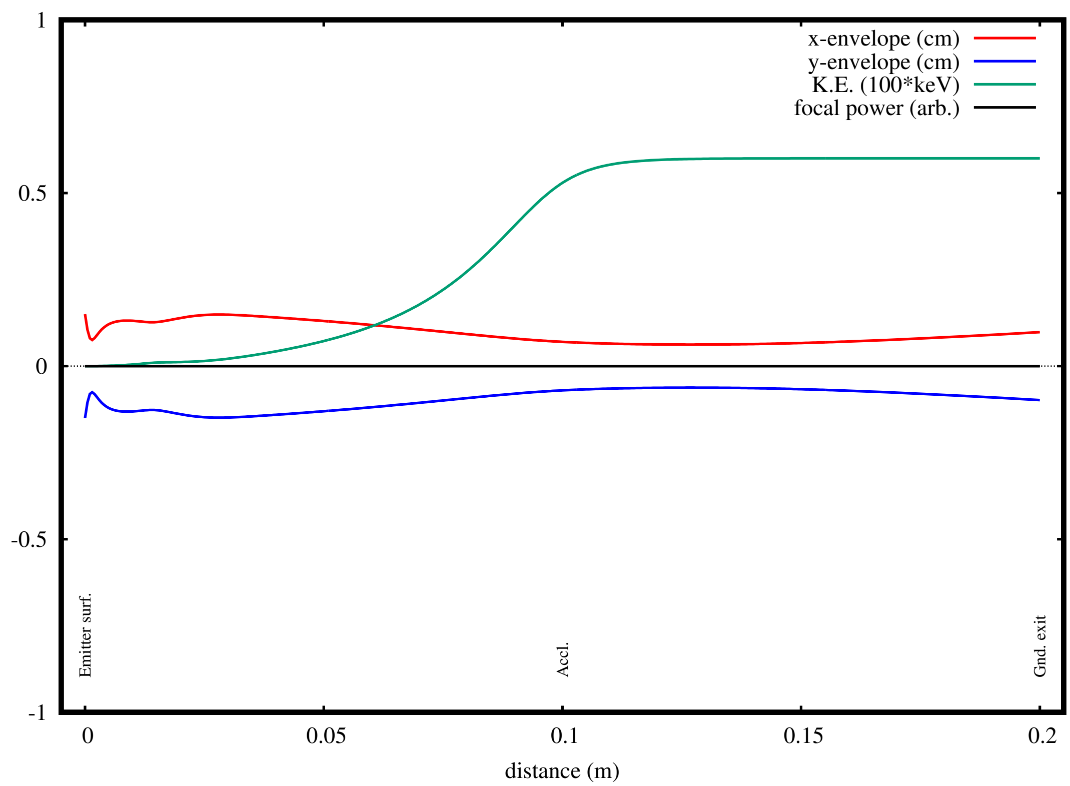

Figure 10: Calculated beam envelope for the 60 keV 133Cs^+ ion beam through the extraction system.

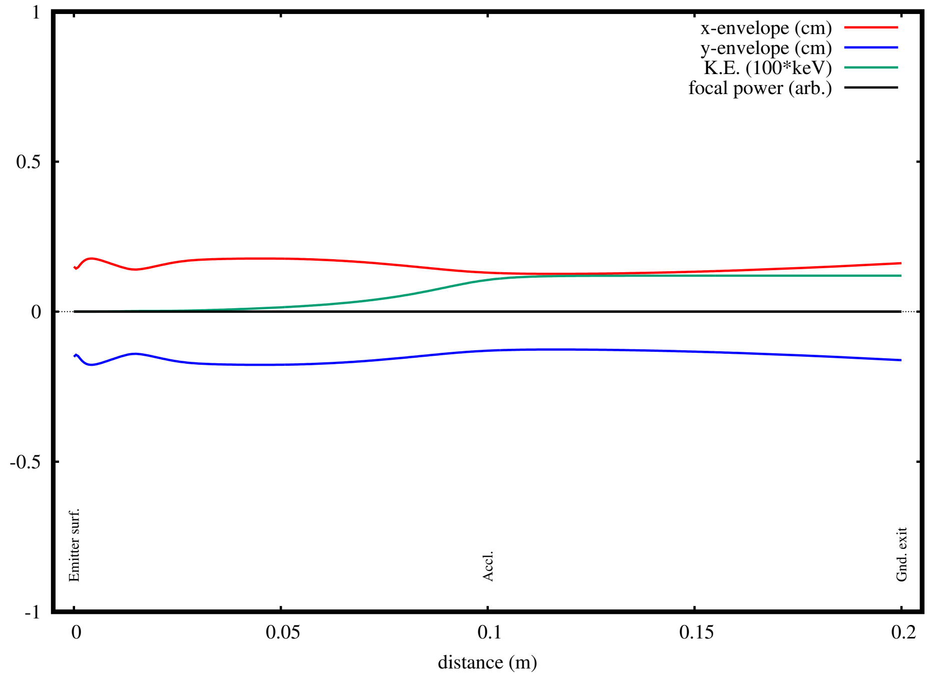

Figure 11: Calculated beam envelope for the 12 kev 133Cs$^+$ ion beam through the extraction system.

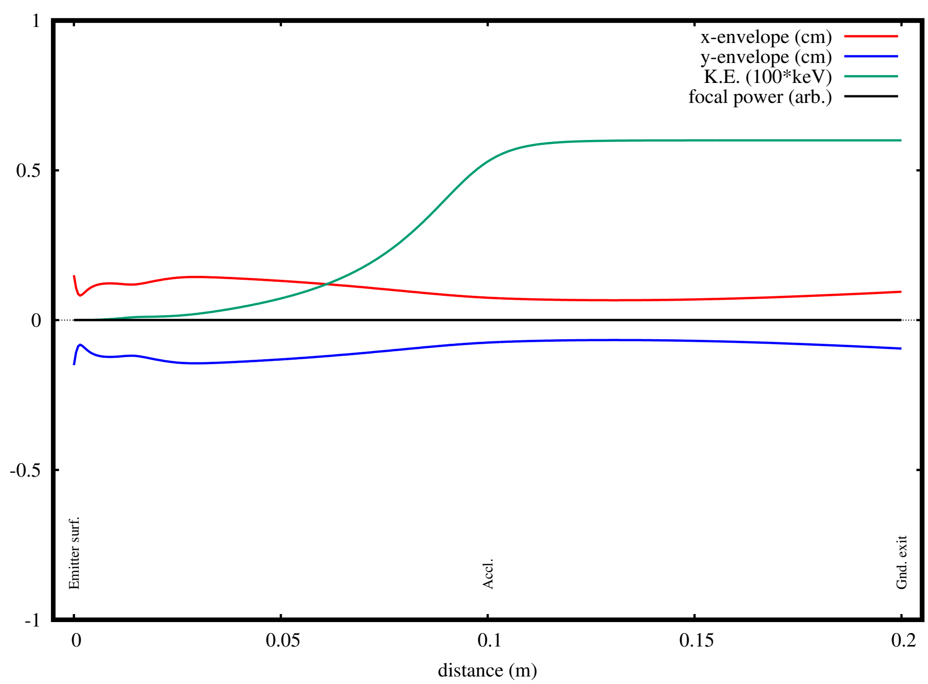

Figure 12: Calculated beam envelope for 100 nA 60 keV 133Cs$^+$ ion beam through the extraction system.

3 Ion beam transport

The ATIS beam transport line basically a matching sections that connects the ATIS and a periodic section in the ARIEL RIB beamline. The calculated beam envelope for the ATIS matching section is shown in Fig. 13. Figures 14 and 15 show the calculated phase-space distributions (up to 3rd order) for various beam emittances at the entrance of a periodic section in the ARIEL RIB transport. These calculations shows that the maximum emittance growth will be less than 1 % in both horizontal and vertical planes for assuming an initial beam emittance of 25 μm at the exit of the ATIS extraction system. Required optical elements and the diagnostic devices are presented in table 3.

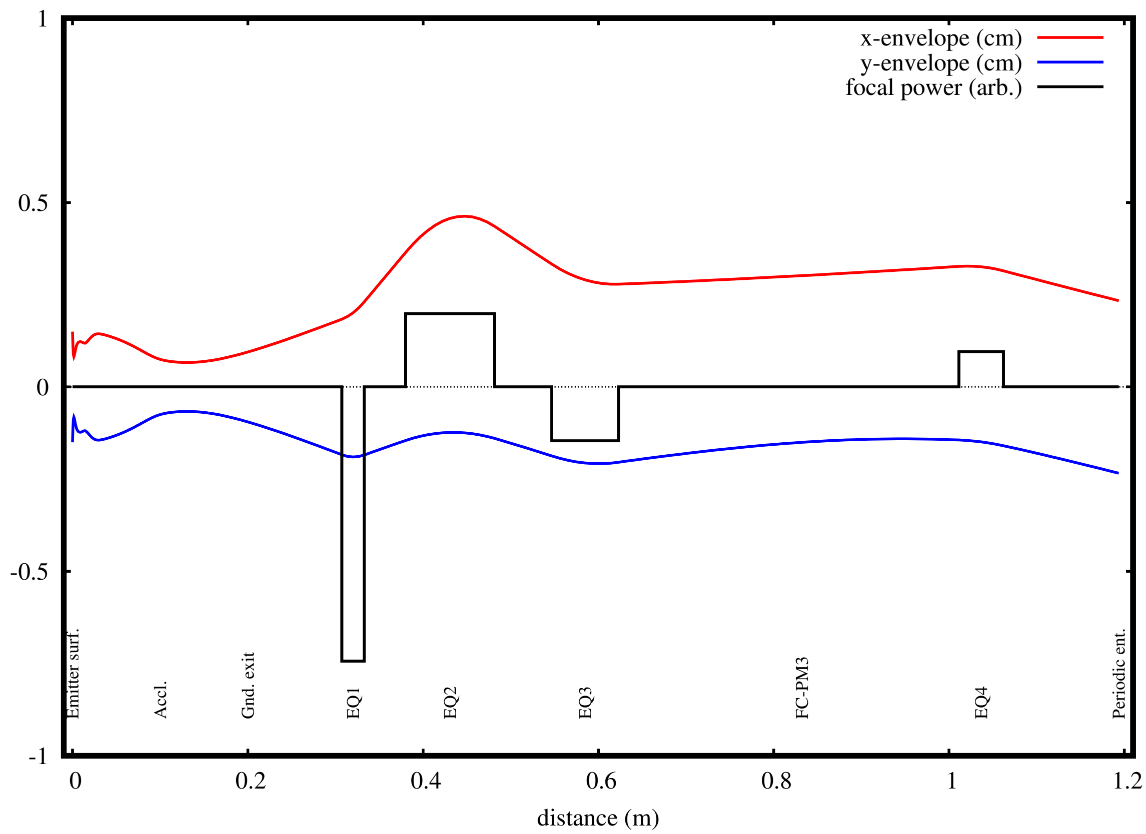

Figure 13: Calculated beam envelope for the 60 keV 133Cs$^+$ ion beam through the extraction and beam transport systems.

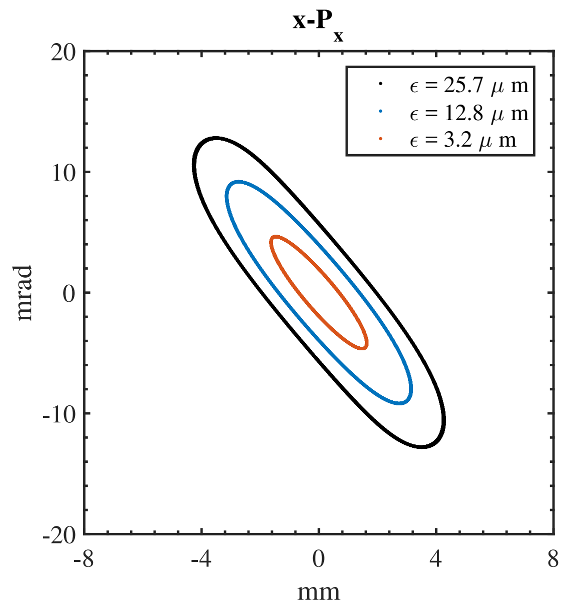

Figure 14: Calculated phase-space profiles by using the code COSY INFINITY for various beam emittances in the horizontal plane at the entrance of a periodic section in the ARIEL RIB beamline.

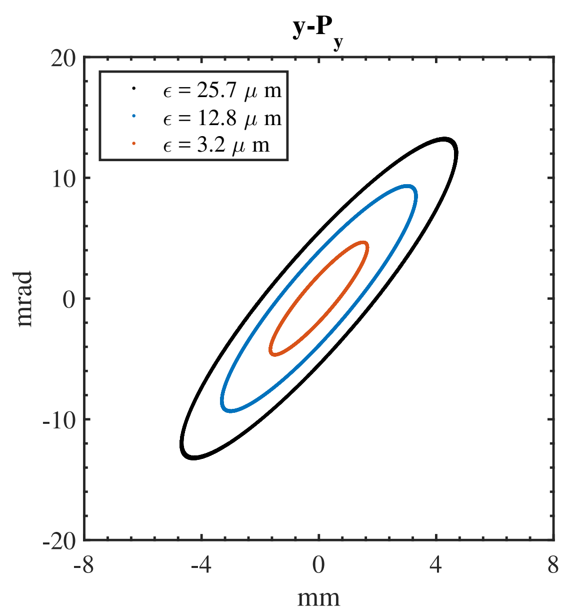

Figure 15: Calculated phase-space profiles by using the code COSY INFINITY for various beam emittances in the vertical plane at the entrance of a periodic section in the ARIEL RIB beamline.

Name	Pot. [kV]	R [mm]	L [mm]	s [mm]	x [mm]	y [mm]	z [mm]
Emitter surface	-	-		000.00	0.00	0.00	000.00
Accel.	60.0	-		100.00	0.00	0.00	100.00
Gnd. exit	-	-		200.00	0.00	0.00	200.00
XY0 st.	-	-		200.00	0.00	0.00	200.00
EQ1	-2.616	12.7	25.4	320.00	0.00	0.00	320.00
EQ2	3.275	25.4	101.6	430.79	0.00	0.00	430.79
EQ3	-2.502	25.4	76.2	584.98	0.00	0.00	584.98
FC-PM3	-	-		832.13	0.00	0.00	832.13
EQ4	1.953	25.4	50.8	1036.67	0.00	0.00	1036.67
Periodic ent.	-	-		1193.67	0.00	0.00	1193.67

Table 3: The coordinates (x, y, z) corresponds to the local position of the mid-point of the each optical element and diagnostic device in the ATIS and its matching section. The 2nd column (pot.) specifies the quadrupole strength and source acceleration potential in kV for a 60 keV ion beam. The 3rd and 4th column specifies the radius (R) and length (L) of the quadrupole in millimeter. The 5th column (s) is the reference trajectory length in millimeter.

4 Summary

Beam optics design for the ARIEL Test ion Source has been done for the production of required alkali ion beams. Beam optics calculations also includes the required matching sections for the ATIS. Optical elements and its design details are presented in this design note.

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