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Diagnostics Requirements for the ARIEL Low Energy Beam Transport

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02	2017-03-22	Collimators, Attenuators, Slits, and CANREB Unique Diagnostics including RFQ and Nier Emittance, HRS Emittance, HRS slits, and Multipole diagnostics	S. Saminathan M. Marchetto C. Barquest

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1 Overview

Rare Isotope Beams (RIB) extracted from the ARIEL target ion sources will be delivered to the experimental facilities at the ISAC through the ARIEL Low Energy Beam Transport line (LEBT). The ARIEL LEBT facility includes the following sub-systems [1]: four basic electrostatic modules [1], matching sections [1], pre-separator [2], high resolution separator [3], RFQ cooler [4] and LEBT for charge state breeder [5, 6]. The low energy beamline that connects different sub-systems consist of matching sections and four basic electrostatic modules [1] similar to ISAC LEBT beamline [7], namely: the periodic section, the 90° achromatic bend section, the low-β insertion, and the order-reversing section.

We require appropriate diagnostic equipment in order to ensure the beam is properly matched out of the separator, through the transport system, and into the experiment. Many diagnostic requirements are ubiquitous: these general diagnostic requirements that apply to all ARIEL beamlines are specified in Section 2. Other diagnostic requirements are particular to each individual subsystem: these unique diagnostic requirements are specified in Section 3.

The general diagnostic elements described in this document include beam intensity, position and profile measurements in the ARIEL LEBT transport system. Unique diagnostic elements for sub-systems such as the ARIEL Pre-separator and CANREB RFQ, HRS, and Nier Spectrometer, include beam attenuators, collimators, slits, emittance rigs, "centering" diagnostics, and beam pulse shape measurement devices. The total number of diagnostic elements, their location, and the overall beamline layouts are described in references [1] and [10].

Basic beam parameters of an ion beam (CW beam) transported through the ARIEL-LEBT beamline is shown in Table 1. A pulsed beam is transported in some part of the LEBT beamlines. The timing structure of those pulsed beams is described in reference [8]. The diagnostic requirements for sub-sytems which tranport pulsed beams derive from the beam parameters shown in Table 2.

Maximum beam energy	60 keV
Mass range (m)	1 – 250 amu
Charge state (q)	Singly charged
Beam intensity range (I)	10^{-19} – 10^{-5}A
Beam operation mode	CW beam

Table 1: Basic beam parameters of a continuous ion beam transported through the ARIEL-LEBT beamline.

Maximum beam energy	20 qkeV
Mass range (m)	1 – 250 amu
Charge state (q)	Multiply charged
Mass-over-charge (m/q)	1 – 7
Beam operation mode	Pulsed beam
Beam frequency range	1 – 200 Hz
Normal operating frequency	100 Hz
Pulse length range [8]	100 ns – 2 ms
Pulse resolution	100 ns
Charge per bunch range [4, 6]	1 – 10^8 ions/bunch

Table 2: Basic beam parameters of a pulsed ion beam transported through the ARIEL-LEBT beamline.

2 General Diagnostic Requirements

RS-1: Diagnostic devices are required to determine the ion beam profile, transverse beam position, beam intensity, emittance and pulse length of a transport beam through the ARIEL LEBT beamline. Diagnostic devices also cut and shape the beam through attenuators, fixed-width collimators, and adjustable slits.

Rationale: In order to achieve a matched condition and a reliable beam transport, these basic beam property measurements and manipulations are necessary. Beam properties of a typical beam are given in table 1 and 2.

Comment: In table 2 the charge per bunch is same as the charge per pulse.

RS-2: Diagnostic devices shall be compatible with a transported beam (see table 1 and 2) having a full width of 25 mm.

Rationale: The measurement width must be sufficiently large to cover an off-centered and de-focused beam.

Comment: The intensity range (see table 1 and 2) can be covered by multiple devices (example channeltron for low intensity and FC for high intensity). Emittance measurements, see Section 3.4 for instance, will need to be performed with both low and high intensity beams.

RS-3: Diagnostic devices shall be integrated with EPICS control system. Data processing and display should be accessible from epics page.

Rationale: The ARIEL LEBT beamline elements shall be integrated with EPICS control systems.

RS-4: Beam intensity measurement shall provide an absolute beam current.

Rationale: Absolute beam current measurement is necessary for tuning the beamline in order to estimate the beam transmission. It is necessary to consider secondary electron emission, leak currents, etc. in the diagnostic design.

RS-5: The accuracy of the beam intensity measurement should be 1% or better.

Rationale: In order to diagnose a transmission $\geq 90\%$ through a beamline section it is required to have an accuracy level of beam intensity measurement within the specified level. Note that the diagnostic devices shall be installed in the HV and RF environment.

Comment: If we were measuring in the range $1 - 10$ nA and we wanted an accuracy of 1% for the full range then a 0.1% accuracy (± 0.01 nA) for the full scale (10 nA) is required in order to achieve a 1% accuracy at 1 nA.

RS-6: Diagnostic devices should be made from material that minimizes the effect from deposition (radio-active, chemical and sputtering process).

Rationale: Ion beam delivery includes RIB of heavier mass (> 100 amu) and alkali metals.

Comment: Slits and collimators especially can be bombarded with heavy ion beams during normal operation, so choosing a material which reduces deposition is important.

RS-7: Diagnostic devices should be capable of continuous operation over several days.

Rationale: Diagnostic devices may be used continuously for more than a few hours to a few days, especially during the beamline tuning. If a FC is proposed for the beam intensity measurement, very often it may be used as a beam stopper as well. Design should consider the maximum beam power given in table 1 and 2.

RS-8: The diagnostic system design should be compatible with the overall beamline design.

Rationale: The diagnostic system design should fit into the vacuum envelope of the beamline and support structure of the beamline.

Comment: The vacuum envelope inside the target hall has remote handling capability and differ from the rest of the ARIEL LEBT beamline [1].

RS-9: Diagnostic devices shall be compatible with a high vacuum environment.

Rationale: Beamline will be designed to achieve a vacuum $\approx 1 \times 10^{-8}$ torr [1].

RS-10: The retracted (park) position of any diagnostic device shall provide a clearance > 25 mm from the beam axis.

Rationale: The acceptance of the optics should not be compromised at the locations of the diagnostics.

RS-11: Error in the absolute beam position measurement shall be 0.33 mm or better and the repeatability in the beam position measurement shall be 0.1 mm or better. The resolution of the beam profile measurements shall be 0.1 mm or better.

Rationale: The optical elements are aligned within the same tolerance.

RS-12: Error in the absolute slit center positions shall be 0.33 mm or better and the repeatability in the slit center position measurement shall be 0.1 mm or better. The resolution of the slit gap shall be 0.1 mm or better.

Rationale: The optical elements are aligned within the same tolerance.

RS-13: The slit and collimator plates should be easily replaceable.

Rationale: The slits and collimators can erode during normal operation and could need replacement once per year. Therefore ease of maintenance and replacement is important.

RS-14: The beam's horizontal and vertical offset relative to the center of an emittance rig's entrance slit should be measured.

Rationale: Knowing the beam's relative position to the center of the first slit greatly reduces the amount of time spent taking emittance scans.

Comment: Read-backs on the first slits in a four vane configuration provides one solution.

Comment: This hardware implementation would be desirable in addition to complementary software-based solutions that will be considered. The software-based solutions can aim to roughly determining the center of the emittance scan before a detailed scan is taken, however this method will be much improved with a well centered initial beam.

3 Unique Diagnostic Requirements

3.1 ARIEL Pre-separator

There are two ARIEL Pre-separator beamlines (East and West). These lines have identical diagnostic requirements.

The ARIEL Pre-separator unique diagnostics include collimators, and a set of horizontal slits. The collimators are positioned upstream of the dipole magnet. The horizontal slits are positioned downstream of the dipole magnet at the mass selection location[2].

For the purpose of this document, unique diagnostics located in the RIB LEBT lines downstream of the ARIEL Pre-separator have also been included in this section. These diagnostics include horizontal slits, vertical slits and attenuators. These diagnostics are located downstream of the Pre-separator in the Mass Separator Room.

Pre-separator Collimators

RS-15: ARIEL Pre-separator fixed-width collimators shall intercept the beam with three aperture sizes as defined by Table 3. The minimum edge-to-edge separation between each aperture is 10.0 mm. This also corresponds to the minimum distance between apertures edges and collimator plate edges. The shape of the apertures is rectangular with 0.3 mm radius rounded corners.

Rationale: These collimators will be used to define the size and position of incoming beams. The collimator dimensions are specified according to the beam transport requirements with a reference 4rms emittance of 9 μm at 60 keV.

Comment: A fourth aperture size is also defined in Table 3. This collimator aperture should be considered, but is able to be omitted if necessary.

Comment: The collimators shall provide the same clearance from the beam axis in their retracted position as specified above in **RS-2:**.

Comment: ARIEL Pre-separator collimators must be compatible with the Target Hall RIB modules assembly.

Comment: The collimator widths shall be machined to 0.05 mm precision, and their centers shall be aligned to the beam pipe center within 0.1 mm.

ARIEL:Pre-separator [2]	Horizontal Width [mm]	Vertical Width [mm]
Collimator 1	1.7	5.6
Collimator 2	2.0	6.6
Collimator 3	2.4	7.9
Collimator 4*	2.8	9.2

Table 3: Collimator full width requirements for the ARIEL:Pre-separator. Collimator 4 is optional (space permitting).

Pre-separator Horizontal Slits

RS-16: The ARIEL Pre-separator horizontal slits shall provide a variable gap of the width ranging from fully closed to fully open to 50 mm with a minimum step size of 0.1 mm. The horizontal slits shall be capable of positioning the center of the gap in the range of ±10 mm around the beampipe center with a minimum step size of 0.1 mm.

Rationale: The horizontal slits at the ARIEL Pre-separator require the same resolution as the HRS "mass selection" horizontal slits, with the additional capability of moving its gap center away from the beampipe center.

Comment: The tolerances for these horizontal slits are given in **RS-12:**.

Comment: The Pre-Separator horizontal slits must be compatible with the Target Hall RIB modules assembly.

RIB LEBT Slits

RS-17: The RIB LEBT horizontal and vertical slits shall have the same specification as the ARIEL Pre-separator horizontal slits.

Rationale: At the locations of these RIB LEBT slits, the vertical beamsize is similar to the horizontal beamsize.

RIB LEBT Attenuators

RS-18: The RIB LEBT attenuators shall provide 10x, 100x, and 1000x beam attenuation.

Rationale: Attenuators bridge the gap between high and low intensity diagnostics. Additionally, some experiments require up to 1000x attenuation of the beam. Comparable with ISAC operations, variable attenuators provide the flexibility to ensure that the appropriate beam intensity is delivered.

Comment: Attenuation of 1000x can be achieved by combination of a 10x and 100x attenuator provided in sequence (with the second attenuator's position having a 90° phase advance along the beamline).

Comment: The beam is round at the location of the attenuators, with a 2 rms beamsize of 5 mm, corresponding to a full width of 10 mm.

3.2 CANREB RFQ

The CANREB RFQ unique diagnostics include a beam pulse measurement device and emittance rigs.

RFQ Beam Pulse Measurement

RS-19: The pulse shape of the beam shall be measured with better than 10 ns resolution.

Rationale: The minimum expected pulse length of the beam is 100 ns, as seen in Table 2.

Comment: An oscilloscope for viewing the beam's pulse shape provides one solution.

RFQ Emittance Rigs

RS-20: From the controls side, the emittance rigs shall interface with the CANREB timing system, as these diagnostics measure the emittance of a pulsed beam (see Table 2).

Rationale: The data acquisition system will need to be synchronized with the beam bunch arrival. The release of the ion bunch from the RFQ buncher will be triggered by a pulse from the CANREB master trigger, so the emittance measurement must be similarly triggered with the appropriate delay to account for ion bunch propagation.

Comment: In addition, any changes in the measurement device, such as stepper motor position or voltage, must be made within integer intervals of the same repetition period as the master trigger so that the changes occur between bunch arrivals.

RS-21: The CANREB RFQ emittance rig shall measure horizontal emittances, and should measure vertical emittances.

Rationale: The beam's horizontal and vertical phase spaces should be diagnosed before injection into the CANREB EBIS.

Comment: Either one emittance meter capable of rotating or two identical emittance meters installed on the same cross would be acceptable for the CANREB RFQ emittance rig.

RS-22: The emittance rigs shall be able to measure a position range of ±10 mm across with a resolution better than 0.1 mm.

Rationale: The largest expected beamsize here is 14 mm across.

RS-23: The emittance rigs shall be able to measure an angular divergence range of ±50 mrad with a resolution better than 0.15 mrad.

Rationale: The largest expected angular divergence of the beam here is 30 mrad.

Comment: The expected emittances vary from 0.5 to 10 μm, with the more intense beams having the higher emittance. Intensities can vary from few to 10^7 ions/bunch. Note that the maximum beam energy is 60 keV.

Comment: A suitable emittance rig design for reference is described in the paper *Allison Scanner Emittance Diagnostic Development at TRIUMF* [9].

3.3 CANREB Nier Separator

The CANREB Nier Separator unique diagnostics include horizontal and vertical slits and a horizontal emittance rig. Space permitting, a pair of both horizontal and vertical slits are desired in locations both upstream and downstream of the CANREB Nier Separator magnet.

Nier Horizontal Slits

RS-24: The CANREB Nier horizontal slits shall provide a variable gap of the width ranging from fully closed to fully open to 50 mm with a minimum step size of 0.1 mm. The horizontal slits shall be capable of positioning the center of the gap in the range of ±10 mm around the beampipe center with a minimum step size of 0.1 mm.

Rationale: The horizontal slits at the Nier Separator require the same resolution as the HRS "mass separator" horizontal slits, with the additional capability of moving its gap center away from the beampipe center.

Comment: The tolerances for these horizontal slits are given in **RS-12:**.

Nier Vertical Slits

RS-25: The CANREB Nier Vertical slits shall have the same specification as the CANREB Nier horizontal slits.

Rationale: At the Nier Separator, the vertical beamsize is similar to the horizontal beamsize.

Nier Emittance Rig

RS-26: The CANREB Nier emittance rig shall measure horizontal emittances.

Rationale: The beam's horizontal phase spaces should be diagnosed after the CANREB Nier separator.

RS-27: The CANREB Nier emittance rig shall have the same requirements as the CANREB RFQ emittance rigs.

Rationale: The beam conditions here are expected to be similar to the beam conditions which determined the CANREB RFQ emittance rig specifications.

Comment: The maximum beam energy is given in Table 2, 20 qkeV.

3.4 CANREB HRS

The CANREB HRS unique diagnostics include horizontal and vertical slits, emittance rigs, and unique multipole diagnostics. For CANREB HRS "mass selection" and "waist" locations, see Figure 1. The multipole diagnostics are located between the magnetic dipoles.

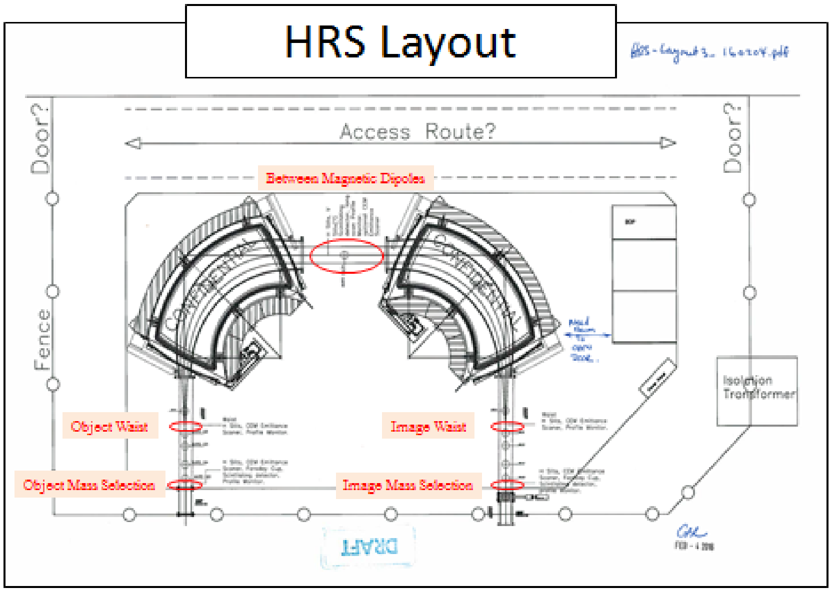

Figure 1: Schematic HRS Layout, including “object mass selection”, “object waist”, “image waist”, and “image mass selection” locations.

HRS “Mass Selection” Horizontal Slits

RS-28: The HRS “mass selection” horizontal slits shall provide a variable gap of the width ranging from fully closed to fully open to 50mm with a minimum step size of 0.1mm. The HRS “mass selection” horizontal slits shall have a fixed center position relative to the beampipe center.

Rationale: These horizontal slits have a 10x relaxed condition from the HRS “waist” horizontal slits for their resolution. Their horizontal center define a fixed central trajectory for the HRS.

Comment: There are two sets of these horizontal slits: one at the “object mass selection” location and one at the “image mass selection” location.

Comment: The slit tolerances are given in **RS-12:**.

HRS “Waist” Horizontal Slits

RS-29: The HRS “waist” horizontal slits shall be capable of measuring a position range of ±10 mm across with a minimum gap and minimum step size of 10 μm. The HRS “waist” horizontal slits shall be capable of adjusting their center position ±5 mm from the center of the beampipe with a resolution better than 10 μm (their minimum gap size).

Rationale: The expected horizontal beamsize here is 0.25 mm across for an emittance of 3μm. These horizontal slits need to be able to be operated across a range during initial set up and tuning. The center of the gap is set to account for beamline misalignments or to select an off center beamlet in the case where contaminants are predominantly to one side of the desired beam.

Comment: There are two sets of these horizontal slits: one at the "object waist" location and one at the "image waist" location.

Comment: For a horizontal "waist" slit with a given position range of ±10 mm, the horizontal slits will actually cover a distance of ±15 mm in order for the center of the gap to be able to be positioned at any point within ±5 mm of the center of the beampipe.

Comment: These horizontal slits' absolute center error is the same as given in **RS-12:**.

HRS "Vertical Collimation" Slits

RS-30: The HRS vertical collimation slits shall be capable of measuring a position range of ±5 mm across maintaining a minimum gap width of 0.1 mm. The resolution for position and gap width shall be 0.1 mm. The gap ranges from fully closed to fully open at ±25 mm from the beamline center.

Rationale: The beam must be centered vertically before entering the HRS. The expected vertical beamsize here is 1 mm across for an emittance of 3μm.

Comment: This single set of vertical slits is located near the upstream ("object") set of "mass selection" horizontal slits, but are not required to be at exactly the same beamline location.

Comment: The slit tolerances are given in **RS-12:**.

HRS "Waist" Horizontal Emittance Rigs

RS-31: The CANREB HRS emittance rigs shall measure horizontal and vertical emittances.

Rationale: The beam's horizontal and vertical phase spaces should be diagnosed before and after the CANREB HRS.

Comment: The CANREB HRS emittance measurements should take place at "mass selection" and "waist" locations. Only the "waist" location emittance rigs are specified at this time to meet the minimum required for commissioning. High resolution mode tuning would be facilitated by emittance measurements at the "mass selection" locations.

Comment: Either a CEM Allison-type scanner or a Pepper Pot design could be considered.

RS-32: The CANREB HRS emittance rigs shall be interchangeable with the horizontal slits at the HRS "waist" locations.

Rationale: The entrance slits of these emittance rigs must operate at the same beamline location as the horizontal "waist" slits.

Comment: Each device shall retract to allow the other devices to be inserted at the same location.

RS-33: The CANREB HRS vertical "waist" emittance specifications shall be the same as the CANREB RFQ emittance specifications.

Rationale: The vertical beam parameters are comparable to the beam parameters at the CANREB RFQ.

Comment: The horizontal emittance specifications are more stringent, as defined below.

RS-34: The CANREB HRS horizontal "waist" emittance rig shall measure a position range of ± 10 mm across with a resolution better than 20 μm.

Rationale: The expected beamsize here is 0.25 mm across for an emittance of 3 μm.

RS-35: The CANREB HRS horizontal "waist" emittance rig shall measure an angular divergence range of ± 120 mrad with a resolution better than 1 mrad.

Rationale: The expected angular divergence of the beam here is 48 mrad for an emittance of 3 μm.

RS-36: The minimum required measured intensity shall be 1 fA with a resolution of 0.5 fA.

Rationale: The position resolution of 0.02 mm and angular resolution of 1mrad give a scanner resolution of 0.02 μm. A 3 μm emittance beam of 1 pA would measure on average 0.007 pA (7 fA) across 150 steps.

Comment: The expected emittances vary from 3 to 30 μm. The lowest total beam current to measure emittance is 1 pA.

HRS Multipole Diagnostics

RS-37: The HRS Multipole vertical slits shall operate from fully closed to fully retracted at ±30 mm, opening the gap in steps of 0.1 mm with a resolution of 0.1 mm. The center of the vertical slits shall be aligned to the vertical center of the multipole with a precision of ±1 mm.

Rationale: Vertical slits before the HRS multipole ensure proper vertical centering of the beam, as it is important for the beam to experience the multipole field along the midplane. The beamsize at the multipole is expected to be ±2.5 mm vertically.

RS-38: A metallic grounded "centering" wire, 7 mm thick and 60mm long requires two positions: centered with the beampipe's center, and fully retracted. This wire shall be aligned to the horizontal center of the multipole with a precision of ±1 mm.

Rationale: These wires will be required for tuning the multipole with the emittance scans, allowing the horizontal center of the multipole to be seen in the phase space plot.

Comment: Having two of these wires, one before and one after the multipole, is optimal.

Comment: These wires should be well grounded, and do not require a current readback.

RS-39: Measuring the beam's horizontal profile at the exit of the multipole would be desirable if possible.

Rationale: The expected beamsize at the multipole measures approximately 27 cm horizontally and 5 mm vertically for an emittance of 6 μm. Measuring the horizontal profile between the dipoles could aid in HRS commissioning and setup.

Comment: Additionally, the "centering" wire could be combined with this profile measurement device as long as the repeatability of the absolute position of the "centering" wire when inserted is not compromised.

A Abbreviations

- **ARIEL:** Advanced Rare IsotopE Laboratory
- **RIB:** Rare Isotope Beam
- **ISAC:** Isotope Separator and ACcelerator
- **LEBT:** Low Energy Beam Transport
- **FC:** Faraday Cub
- **RS:** Requirement Specification
- **CANREB:** CANadian Rare isotope facility with Electron Beam ion source
- **HRS:** High Resolution Separator
- **EBIS:** Electron Beam Ion Source
- **RFQ:** Radio Frequency Quadrupole
- **CW:** Continuous Wave
- **RF:** Radio Frequency
- **HV:** High Voltage

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