HIAF front end for transmission and acceleration of 30 pμA $^{238}$U$^{35+}$

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Outline

- Overview
- HIAF Front End: Design and studies
  - High intensity heavy ion beam production and beam quality
  - Beam transport and space charge issues
  - High intensity beam matching with RFQ
  - End-to-End simulation
- Beam commissioning of LEAF
- Summary
**iLinac:** Superconducting linac  
Length: 90 m  
Energy: 17MeV/u (^{238}U^{35+})  
Intensity: 30 µA

**BRing:** Booster ring  
Circumference: 530 m  
Rigidity: 34 Tm  
Beam accumulation  
Beam cooling  
Beam acceleration  
E=0.8 GeV/u,  
I= 1.0x10^{11} ppp (^{238}U^{35+})

**SRing:** Spectrometer ring  
Circumference: 273.5 m  
Rigidity: 15Tm  
Electron/Stochastic cooling  
Two TOF detectors  
Four operation modes

**External target for RIB**

**CEE for HD nuclear matter**  
Hypernuclear  
HE irradition

**HFRS**  
L: 152m  
Bρ: 25 Tm  
RIBs, stable ion beams

**RT Front End**  
Energy: 0.5MeV/u  
Intensity: 30 µA (^{238}U^{35+})

The world highest intensity CW heavy ion linac!
High intensity heavy ion Front End

SPIRAL2/ GANIL, A/Q=3 heavy ion
LEBT up to 1 mA
Typically $\text{Ar}^{12+}$ 1 emA/CW

FRIB/MSU, O-U
LEBT up to 350 eμA
Typically $\text{U}^{33+} + \text{U}^{34+}$ 13 pμA /CW
HIAF Front end

CW mode
For iLinac Operation only
Or iLianc + BRing

- Wide ion species: M/Q: 2~7
- High beam intensity: up to 2 emA, typically >1 emA U^{35+}
- Flexible operation modes

Pulsed mode
BRing injector only

- 16O^{6+} ~ 1 emA
- 129Xe^{27+} ~ 1 emA
- 209Bi^{31+} ~ 1 emA
- 238U^{35+} ~ 0.7 emA

- 16O^{6+} 2 emA
- 129Xe^{27+} 2 emA
- 209Bi^{31+} 1.5 emA
- 238U^{35+} 1 emA

0.3-5 Hz/0.2-2 ms

SC-ECRIS: Superconducting ECR Ions Source
SN: Solenoid
AM: Analyzing Magnet
DD: Diagnostic Device
Q: Quadrupole
CH: Chopper
AT: Accelerating Tube
PSN: Pared Solenoid
MHB: Multi-Harmonic Buncher
Challenges in HIAF Front End

- High Intensity heavy ion beam production
- Intense heavy ion beam extraction
- Intense heavy ion beam transmission with high quality and efficiency
  - Borrowed ideas: Achromatic beam optics, Beam collimation, MHB…
- Intense heavy ion beam matching to RFQ
- High Intensity heavy ion beam RFQ
High intensity heavy ion beam production

SECRAL I-II beam intensities

<table>
<thead>
<tr>
<th>Ion Beam</th>
<th>SECRAL I-II (eμA) (2015-2016)</th>
<th>LBNL VENUS beam Intensity 2016 (eμA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{16}\text{O}^{6+}$</td>
<td>6700</td>
<td>4750</td>
</tr>
<tr>
<td>$^{40}\text{Ar}^{12+}$</td>
<td>1420</td>
<td>1060</td>
</tr>
<tr>
<td>$^{40}\text{Ar}^{16+}$</td>
<td>610</td>
<td>523</td>
</tr>
<tr>
<td>$^{40}\text{Ar}^{18+}$</td>
<td>5</td>
<td>4</td>
</tr>
<tr>
<td>$^{40}\text{Ca}^{11+}$</td>
<td>710</td>
<td>400</td>
</tr>
<tr>
<td>$^{40}\text{Ca}^{14+}$</td>
<td>270</td>
<td></td>
</tr>
<tr>
<td>$^{40}\text{Ca}^{14+}$</td>
<td>270</td>
<td></td>
</tr>
<tr>
<td>$^{110}\text{Xe}_{26}^{26+}$</td>
<td>1100</td>
<td></td>
</tr>
<tr>
<td>$^{110}\text{Xe}_{30}^{30+}$</td>
<td>320</td>
<td>211</td>
</tr>
<tr>
<td>$^{110}\text{Xe}_{42}^{42+}$</td>
<td>10</td>
<td>1</td>
</tr>
<tr>
<td>$^{209}\text{Bi}_{31}^{31+}$</td>
<td>680</td>
<td>300</td>
</tr>
<tr>
<td>$^{209}\text{Bi}_{41}^{41+}$</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>$^{209}\text{Bi}_{50}^{50+}$</td>
<td>10</td>
<td>5</td>
</tr>
<tr>
<td>$^{238}\text{U}_{33}^{33+}$</td>
<td>202</td>
<td>440</td>
</tr>
</tbody>
</table>

The world record beam intensities
High intensity heavy ion beam production

45 GHz FECR

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Microwaves</td>
<td>45 GHz/20 kW</td>
</tr>
<tr>
<td>Magnet conductor</td>
<td>Nb$_3$Sn</td>
</tr>
<tr>
<td>Axial fields (T)</td>
<td>6.5/1.0/3.5</td>
</tr>
<tr>
<td>Sextupole field (T)</td>
<td>3.8@r=75 mm</td>
</tr>
<tr>
<td>Maximum field (T)</td>
<td>11.8 T</td>
</tr>
<tr>
<td>Magnet bore (mm)</td>
<td>Ø161~165</td>
</tr>
<tr>
<td>Extraction (kV)</td>
<td>50</td>
</tr>
<tr>
<td>Typical beam</td>
<td>1.0 emA U$^{35+}$</td>
</tr>
</tbody>
</table>

Typical beam: 1.0 emA U$^{35+}$

$I \propto \omega_E^{2}$

$\omega_{ECR} = \frac{eB}{m_e}$

Goal: >1 emA U$^{35+}$
Beam extraction

Typical issues:
- Emittance growth at extraction
- Beam X/Y phase space coupling
- Space charge influences

FECR beam extraction

- Simulated with IBsimu code.
- Start from an assumed plasma.
- Includes magnetic fields in ECR.

- $I_{\text{total}}$: 20 emA
- $I_{U^{35+}}$: 2 emA

50 kV insulation columns
ECR beam quality: emittance growth

- Triangular shape due to magnetic field of ion source.
- In-homogeneous density distribution in cross-section.
- Large projection emittance due to high magnetic field at extraction.

\[ \varepsilon_{mag} = 0.032 \cdot (R_{extr})^2 \cdot \left( \frac{B_{extr}}{M/Q} \right) \]

50 kV, 23 kV -2 kV grounded

\( \varepsilon_{Nor. \, Rms} = 0.32 \pi \, \text{mm.mrad} \)

\( U^{35+} \)
ECR beam quality: Coupling

**Solenoid**

SECRAI schematic view and the axial magnetic field distribution.

\[ R_{\text{out}} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & -\kappa & 0 \\ 0 & 0 & 1 & 0 \\ \kappa & 0 & 0 & 1 \end{bmatrix} \]

\[ \kappa = \frac{B_{\text{extr}}}{2(B\rho)} \]

\[ C_0 = \begin{bmatrix} \epsilon \beta & 0 & 0 & 0 \\ 0 & \epsilon & 0 & 0 \\ 0 & 0 & \epsilon \beta & 0 \\ 0 & 0 & 0 & \frac{\epsilon}{\beta} \end{bmatrix} \]

\[ C_1 = R_{\text{out}}C_0R_{\text{out}}^T = \begin{bmatrix} \epsilon \beta & 0 & 0 & \kappa \epsilon \beta \\ 0 & \frac{\epsilon}{\beta} + \kappa^2 \epsilon \beta & -\kappa \epsilon \beta & 0 \\ 0 & -\kappa \epsilon \beta & \epsilon \beta & 0 \\ \kappa \epsilon \beta & 0 & 0 & \frac{\epsilon}{\beta} + \kappa^2 \epsilon \beta \end{bmatrix} \]

\[ \epsilon_x = \epsilon_y = \sqrt{\epsilon \beta \left(\frac{\epsilon}{\beta} + \kappa^2 \epsilon \beta\right)} \quad \epsilon_{1,2} = \epsilon_x \pm \kappa \epsilon \beta \]

**Factor ①:** half-solenoid field induced rotational momentum dis-conservation.

**Factor ②:** magnetic field induced beam rotation along axis (non-round beam).
ECR beam quality: Coupling

**Simulation**

![Simulation Diagram]

**Measurement**

![Measurement Diagram]
Paired Solenoid: Avoiding coupling

Paired Solenoid

\[ R = R_{sol+} \ast R_{sol-} = \begin{bmatrix} \# & \# & 0 & 0 \\ \# & \# & 0 & 0 \\ 0 & 0 & \# & \# \\ 0 & 0 & \# & \# \end{bmatrix} \]

![Diagram of paired solenoids and RFQ](image-url)
Objective ion: $^{35+}U$

- $^{35+}U \sim 2$ emA, Total current $\sim 20$ emA.
- Initial mixed beam were simplified to include 20 different ion species
- Assuming all the beams have water-bag distributions with the same Twiss parameters, $\sim 0.24 \pi \text{mm.mrad.}$
Space charge compensation degree has a vital impact on beam transmission and charge separation.

- 70% SCC
- 50% SCC
- 30% SCC

• SCC: Space Charge Compensation

- Space charge compensation degree has a vital impact on beam transmission and charge separation.
- How much is the SCC factor?
The measurements suggest overall low neutralization factors (0%–60%).

Retarding field analyzer

Space Charge effect: How much?

Measurement with SECRAL-II ion source

- Beam emittance does NOT increase with beam intensity.
  → good compensation in ECR Q/A analyzer lines.

- Beam quality is mainly determined by the ion source tuning and plasma conditions.
Space Charge effect: How much?

SECRAL Q/A analyzer

- $I_{\text{total}} = 13 \text{ emA}$,
- $I_{\text{Bi}^{31+}} = 0.65 \text{ emA}$.

![Diagram showing different charge states and their intensities for 70%, 50%, and 30% SCC scenarios.](image-url)
Space Charge effect: How much?

SECRAL Q/A analyzer

- $I_{\text{total}} = 13$ emA,
- $I_{\text{Bi}^{31+}} = 0.65$ emA.
Space Charge effect: How much?

SECRAL Q/A analyzer

- $I_{\text{total}} = 13 \text{ emA,}$
- $I_{\text{Bi}^{31+}} = 0.65 \text{ emA.}$

In realistic beam simulations and Q/A analyzer design it is secure to set the overall space charge compensation factor to **70%** for intense highly-charged ion beams.
Multi-particle tracking

Phase space distribution after charge selection

Simulation @FECR

- $B_{\text{extr}} = 3.53$ T

Measurement @ VENUS

- $\varepsilon_X, \text{rms} = 0.27 \, \pi \, \text{mm.mrad}$
- $\varepsilon_Y, \text{rms} = 0.21 \, \pi \, \text{mm.mrad}$
- $B_{\text{extr}} \sim 2.2$ T
- $I_{U34^+} = 311 \, \text{emA}$
- $I_0 = 7.5 \, \text{mA}$

Thyo03_talk @ ECRIS2012
Necessity of beam collimation

Particle distribution at RFQ entrance

$\varepsilon_x = 0.27 \text{ pi.mm.mrad}$

$\varepsilon_y = 0.31 \text{ pi.mm.mrad}$
LEBT collimation channel

- 3 successive apertures;
- Phase advance of about 45 degrees per drift space;
- Total phase advance of 90 degrees.
LEBT collimation channel

- 3 successive apertures;
- Phase advance of about 45 degrees per drift space;
- Total phase advance of 90 degrees.
Phase space distribution at the 1st aperture
LEBT collimator

Phase space distribution at the 2\textsuperscript{nd} aperture

With 1\textsuperscript{st} aperture cut
LEBT collimator

Phase space distribution at the 3\textsuperscript{rd} aperture

With 1\textsuperscript{st} and 2\textsuperscript{nd} aperture cut
20% of the particle tails contribute more than 69% of emittance.

\[ \epsilon_x = 0.16 \text{ pi.mm.mrad} \]

\[ \epsilon_y = 0.15 \text{ pi.mm.mrad} \]

Particle distribution at RFQ entrance with Collimation cutting in LEBT
Requirements and strategies:

- High acceleration efficiency and high transmission.
- Small Longitudinal Emittance.
  - External 3-harmonic pre-buncher
  - Small longitudinal acceptance of RFQ
- Proper Vane Voltage to minimize the thermal problem for CW beam.
- Length as short as possible.
- Traditional design for easily fabricating and tuning—Sinusoidal modulation, constant voltage, constant average radius.
- Small convergence at entrance for easily matching with LEBT.
High intensity beam matching with RFQ: Longitudinal

Beam pre-bunching with 3-Harmonic Buncher

Without longitudinal space charge

With longitudinal space charge

Voltage (kV) for three Harmonics:

<table>
<thead>
<tr>
<th>Longitudinal Space Charge</th>
<th>1\textsuperscript{st} Harmonics (40.625 MHz)</th>
<th>2\textsuperscript{nd} Harmonics (81.25 MHz)</th>
<th>3\textsuperscript{rd} Harmonics (121.875 MHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NO</td>
<td>2.66</td>
<td>-1.60</td>
<td>1.46</td>
</tr>
<tr>
<td>YES</td>
<td>3.19</td>
<td>-2.26</td>
<td>2.03</td>
</tr>
</tbody>
</table>

- Starting phase and modulation are selected as -60° and 1.02.
High intensity beam matching with RFQ: Transverse

Steep convergence VS Smooth convergence at RFQ entrance

Beam back-tracking from the entrance of the RFQ electrode

(a) RFQ matching TWISS parameters: \( \alpha \approx 0.63 \), \( \beta \approx 5.92 \text{ cm/rad} \)
emittance growth: 4.6%

(b) RFQ matching TWISS parameters: \( \alpha \approx 0.39 \), \( \beta \approx 12.06 \text{ cm/rad} \)
emittance growth: 0.24%
High intensity beam matching with RFQ: Transverse

Steep convergence VS Smooth convergence at RFQ entrance

Steep convergence

\[ \epsilon_x = 0.19 \text{ pi.mm.mrad} \]

\[ \epsilon_y = 0.19 \text{ pi.mm.mrad} \]

Smooth convergence

\[ \epsilon_x = 0.16 \text{ pi.mm.mrad} \]

\[ \epsilon_y = 0.15 \text{ pi.mm.mrad} \]
# RFQ beam dynamics

<table>
<thead>
<tr>
<th>Parameter</th>
<th>HIAF-RFQ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design M/Q</td>
<td>2~7</td>
</tr>
<tr>
<td>Frequency (MHz)</td>
<td>81.25</td>
</tr>
<tr>
<td>Resonance cavity</td>
<td>4-vane</td>
</tr>
<tr>
<td>Input/Output energy (MeV/u)</td>
<td>0.014/0.5</td>
</tr>
<tr>
<td>Max. vane voltage (kV)</td>
<td>70</td>
</tr>
<tr>
<td>Max. Kilpatrick Coefficient</td>
<td>1.57</td>
</tr>
<tr>
<td>$R_0$ (mm)</td>
<td>5.758</td>
</tr>
<tr>
<td><strong>Synchronous Phase</strong></td>
<td>-60° ~ -26°</td>
</tr>
<tr>
<td><strong>Modulation Factor</strong></td>
<td>1.02~2.03</td>
</tr>
<tr>
<td><strong>Acceptance TWISS $\alpha/\beta$ (cm/rad)</strong></td>
<td>0.39/12.05</td>
</tr>
<tr>
<td><strong>Radial Matcher cell</strong></td>
<td>6</td>
</tr>
<tr>
<td>Length (cm)</td>
<td>623.9</td>
</tr>
<tr>
<td><strong>Overall acceleration efficiency</strong></td>
<td>81.3%</td>
</tr>
<tr>
<td>$\varepsilon_{z,\text{rms}}$ (keV/u.ns)</td>
<td>0.33</td>
</tr>
<tr>
<td>$\varepsilon_{z,99.9%}$ (keV/u.ns)</td>
<td>6.40</td>
</tr>
<tr>
<td>$\varepsilon_{x,\text{rms}}/\varepsilon_{y,\text{rms}}$ (π.mm.mrad)</td>
<td>0.152/0.146</td>
</tr>
<tr>
<td>$\varepsilon_{x,99.9%}/\varepsilon_{y,99.9%}$ (π.mm.mrad)</td>
<td>1.407/1.343</td>
</tr>
</tbody>
</table>
RFQ beam dynamics

@ rfqgen

- x (cm) vs cell number
- y (cm) vs cell number
- phi (phi) vs cell number
- W (MeV) vs cell number
End-End Simulation for HIAT FE

- Initial particle distribution from extraction simulation.
End-End Simulation for HIAT FE

- Initial particle distribution from extraction simulation.

- Initial 2 emA $^{35+}$ U
- 80% transmission in LEBT with collimation cut
- Overall 81.25% acceleration efficiency in RFQ with MHB
Simulation with different SCC factor in LEBT

• SCC: Space Charge Compensation

<table>
<thead>
<tr>
<th>SCC</th>
<th>Collimator</th>
<th>(\eta_{\text{LEBT}})</th>
<th>(\eta_{\text{RFQ}})</th>
<th>(\eta_{\text{Total}})</th>
<th>(\varepsilon_x) LEBT</th>
<th>(\varepsilon_y) LEBT</th>
<th>(\varepsilon_x) RFQ</th>
<th>(\varepsilon_y) RFQ</th>
<th>(\varepsilon_z) RFQ</th>
</tr>
</thead>
<tbody>
<tr>
<td>95%</td>
<td>without</td>
<td>100%</td>
<td>68.8%</td>
<td>68.8%</td>
<td>0.23</td>
<td>0.21</td>
<td>0.16</td>
<td>0.15</td>
<td>0.34</td>
</tr>
<tr>
<td></td>
<td>with</td>
<td>80%</td>
<td>79.9%</td>
<td>63.8%</td>
<td>0.16</td>
<td>0.14</td>
<td>0.15</td>
<td>0.14</td>
<td>0.33</td>
</tr>
<tr>
<td>70%</td>
<td>without</td>
<td>100%</td>
<td>67.0%</td>
<td>67.0%</td>
<td>0.27</td>
<td>0.31</td>
<td>0.15</td>
<td>0.15</td>
<td>0.33</td>
</tr>
<tr>
<td></td>
<td>with</td>
<td>80%</td>
<td>81.3%</td>
<td>65.0%</td>
<td>0.16</td>
<td>0.15</td>
<td>0.15</td>
<td>0.15</td>
<td>0.33</td>
</tr>
<tr>
<td>50%</td>
<td>without</td>
<td>100%</td>
<td>65.4%</td>
<td>65.4%</td>
<td>0.28</td>
<td>0.31</td>
<td>0.18</td>
<td>0.16</td>
<td>0.32</td>
</tr>
<tr>
<td></td>
<td>with</td>
<td>80%</td>
<td>80.0%</td>
<td>64.0%</td>
<td>0.18</td>
<td>0.17</td>
<td>0.17</td>
<td>0.15</td>
<td>0.32</td>
</tr>
<tr>
<td>25%</td>
<td>without</td>
<td>100%</td>
<td>62.1%</td>
<td>62.1%</td>
<td>0.31</td>
<td>0.35</td>
<td>0.19</td>
<td>0.17</td>
<td>0.32</td>
</tr>
<tr>
<td></td>
<td>with</td>
<td>80%</td>
<td>76.8%</td>
<td>61.4%</td>
<td>0.19</td>
<td>0.20</td>
<td>0.19</td>
<td>0.16</td>
<td>0.32</td>
</tr>
<tr>
<td>0%</td>
<td>without</td>
<td>99.4%</td>
<td>60.3%</td>
<td>60.0%</td>
<td>1.02</td>
<td>0.92</td>
<td>0.18</td>
<td>0.19</td>
<td>0.30</td>
</tr>
<tr>
<td></td>
<td>with</td>
<td>80%</td>
<td>74.6%</td>
<td>59.7%</td>
<td>0.22</td>
<td>0.21</td>
<td>0.18</td>
<td>0.18</td>
<td>0.30</td>
</tr>
</tbody>
</table>
Protype of HIAF Front End

LEAF (Low Energy Accelerator Facility)

LEBT test chamber 1# (X/Y Allison, FC)

LEBT test chamber 2# (X/Y Allison, FC, Chopper)

ACCT-1

ACCT-2

MHB

Acc. tube

ECR

FECR

BPM-1

BPM-2
LEAF (Low Energy Accelerator Facility)

LEBT test chamber 1# (X/Y Allison, FC)

LEBT test chamber 2# (X/Y Allison, FC, Chopper)

ACCT-1

ACCT-2

MEBT test chamber (X/Y slits; X/Y slits; FC&FFC)

Prototype of HIAF Front End

FECR

Acc. tube

ECR

MHB
LEAF (Low Energy Accelerator Facility)

LEBT test chamber 1# (X/Y Allison, FC)

LEBT test chamber 2# (X/Y Allison, FC, Chopper)

ACCT-1

ACCT-2

MEBT test chamber (X/Y slits; X/Y slits; FC&FFC)

Prototype of HIAF Front End

FECR

Acc. tube

BPM-1

BPM-2

ECR

MHB
First beam test of LEAF

**ECR beam**

- $^4\text{He}^{1+}$
- Beam intensity: $\sim 88.8$ euA
- Pencil beam

LEBT test chamber 1#
@Allison
First beam test of LEAF

**LEBT** beam transmission $\rightarrow$ Axisymmetric beam

Transmission efficiency $\sim$ 100%

LEBT test chamber 2#
@Allison
First beam test of LEAF

RFQ
Beam simulation @ TRACK @ without MHB

- Transmission efficiency ~ 99.2%
- Acceleration efficiency ~ 45.6%

Measurement

- Transmission efficiency ~ 98.5% ($I_{\text{ACCT-2}} / I_{\text{ACCT-1}}$)
- Acceleration efficiency ~ 46.5% ($I_{\text{FC}} / I_{\text{ACCT-1}}$)
First beam test of LEAF

Beam Energy

TOF: Distance $\sim 1.0689$ m
$\rightarrow$ Energy $\sim 0.5 \pm 0.001$ MeV/u

BPM-1
BPM-2

Bunch length

FFC signal
FWHM $\sim 0.83$ ns

FWHM $\sim 0.8$ ns
First beam test of LEAF

Transverse emittance after RFQ

0.08 π.mm.mrad

0.074 π.mm.mrad

Measurement @ slit+slit+FC

0.078 π.mm.mrad

0.062 π.mm.mrad

TRACK simulation
First beam test of LEAF

RFQ CW commissioning @ 200 eμA He$^{1+}$

Transmission ~ 97%, Acceleration ~ 50%

Beam current @ 100 eμA at FC

RFQ vacuum 2E10⁻⁶ Pa

1.9E10⁻⁵ Pa

RFQ Vane temperature

RFQ wall temperature

6 Hr
Design of HIAF front end was completed based on studies of ion source beam quality, space charge effect in low energy beam transport, high intensity beam matching with RFQ.

Beam simulations show that the present design is robust to transport and accelerate very high intensity beams of highly-charged heavy ions.

The LEAF has been successfully commissioned and accelerated beams to the energy as expected, satisfying the design specifications, which provides a good basis for HIAF Front end.
Acknowledgement

- LEAF Team Members
- Brahim Mustapha
Thank you for your attention!

HIAT 2018
Lanzhou, China
Oct. 22-26, 2018
http://hiat2018.csp.escience.cn/dct/page/1