Status and Upgrades of HIRFL

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• Status of HIRFL

• Activities of Upgrading
  – SSC-Linac injector
  – Isochronous mass spectrometry
  – Electron cooling at CSR
  – Laser cooling at CSRe
  – Stochastic cooling at CSRe
  – Vacuum collimation at CSRm

• HIAF project
Status of HIRFL: overview

SSC (K=450)
100 AMeV (H.I.), 110 MeV (p)

SFC (K=69)
10 AMeV (H.I.), 17–35 MeV (p)

RIBLL1
RIBs at tens of AMeV

CSR(Cooling Storage Ring)

CSRm
1000 AMeV (H.I.), ≤2.8 GeV (p)

CSRe

RIBLL2
RIBs at hundreds of AMeV

Heavy Ion Research Facility in Lanzhou (HIRFL)
### Operation in 2014

<table>
<thead>
<tr>
<th>No.</th>
<th>Ion</th>
<th>SFC MeV/u</th>
<th>Current uA</th>
<th>SSC MeV/u</th>
<th>Current uA</th>
<th>Charge State</th>
<th>Energy MeV/u</th>
<th>Current @ CSRm (uA)</th>
<th>Current @ CSRe (uA)</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>$^{38}$Kr $^{19+}/^{28+}$</td>
<td>4</td>
<td>4.2</td>
<td>432.5,487</td>
<td>600</td>
<td>Secondary beams</td>
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<td>2</td>
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<td>30–50</td>
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<tr>
<td>3</td>
<td>$^{40}$Ar $^{11+}$</td>
<td>4.8</td>
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<tr>
<td>4</td>
<td>$^{15}$O$^{9+}$</td>
<td>7</td>
<td>8.5</td>
<td>8+</td>
<td>265,360</td>
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<tr>
<td>5</td>
<td>$^{12}$C $^{4+/6+}$</td>
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<td>16</td>
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<td>17</td>
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<td>4.906</td>
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<td>18</td>
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<td>8.5</td>
<td>1.9</td>
<td>8.5</td>
<td>300</td>
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<tr>
<td>19</td>
<td>$^{14}$N $^{4+}$</td>
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<td>5</td>
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<td>22</td>
<td>$^{12}$C $^{4+}$</td>
<td>7</td>
<td>10</td>
<td>165, 300</td>
<td>1500</td>
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<td>24</td>
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<td>9.5</td>
<td>0.01</td>
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<tr>
<td>25</td>
<td>$^{58}$Ni $^{19+/20+}$</td>
<td>6.3</td>
<td>1.2</td>
<td>467等多种</td>
<td>280</td>
<td>Secondary beams</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Operation in 2014

- **5199.5h** On targets 71.50%
- **1624.5h** Change ions 22.30%
- **289.5h** Other 4.00%
- **158.5h** Breakdown 2.20%
- **883.5h** Material research 17.00%
- **423h** Atomic physics 8.10%
- **332h** Bioscience 6.40%
- **235h** Machine study 4.50%

- **3326h** Nuclear Physics 64.00%

Operation in 2014
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• HIAF project
New high intensity heavy ion injector of SSC

- Extraction energy:
  1.025 MeV/u → 10.7 MeV/u (SSC) → CSRm
  0.576 MeV/u → 5.97 MeV/u (SSC)
- Beam current: 5~30 eμA for various ions.
- Beam intensity: increase 1~2 order for SSC.
- $^{238}\text{U}^{72+}$ can be accelerated to 487 MeV/u by CSRm after stripping.

Main parameters of SSC_Linac

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Design ion</strong></td>
<td>$^{238}\text{U}^{34+}$</td>
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<tr>
<td><strong>ECR ion source</strong></td>
<td></td>
</tr>
<tr>
<td>Extraction voltage</td>
<td>25 kV</td>
</tr>
<tr>
<td>Max. axial injection field</td>
<td>2.3 T</td>
</tr>
<tr>
<td>Microwave frequency</td>
<td>18 GHz</td>
</tr>
<tr>
<td><strong>RFQ</strong></td>
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<tr>
<td>Frequency</td>
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<tr>
<td>Input energy</td>
<td>3.728 keV/u</td>
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<tr>
<td>Output energy</td>
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<td>Inter-electrode voltage</td>
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<tr>
<td>RF power</td>
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<tr>
<td>Max. current</td>
<td>0.5 eμA</td>
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<tr>
<td><strong>IH-DTL</strong></td>
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<tr>
<td>Frequency</td>
<td>53.667 MHz</td>
</tr>
<tr>
<td>Input energy</td>
<td>0.143 MeV/u</td>
</tr>
<tr>
<td>Output energy</td>
<td>1.025 MeV/u</td>
</tr>
</tbody>
</table>

Layout of SSC-Linac
For planned linac injectors, the maximum stored particle numbers in CSRm will be **2 to 5 times** the case of the cyclotron injector SFC.
High intensity HCI ECR ion source

Evaporative cooling technology

Beam test results of Ion source

<table>
<thead>
<tr>
<th>Ion</th>
<th>charge state</th>
<th>I(μA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{16}$O</td>
<td>6$^+$</td>
<td>2110</td>
</tr>
<tr>
<td></td>
<td>7$^+$</td>
<td>560</td>
</tr>
<tr>
<td>$^{40}$Ar</td>
<td>8$^+$</td>
<td>1717</td>
</tr>
<tr>
<td></td>
<td>9$^+$</td>
<td>1230</td>
</tr>
<tr>
<td></td>
<td>14$^+$</td>
<td>185</td>
</tr>
<tr>
<td>$^{129}$Xe</td>
<td>20$^+$</td>
<td>430</td>
</tr>
<tr>
<td></td>
<td>27$^+$</td>
<td>135</td>
</tr>
</tbody>
</table>
 35kW in CW mode has been fed into RFQ successfully.
 $^{40}$Ar$^{8+}$ ion beam, $E = 142.8$keV/u, $I = 198\mu A$.
 Beam transmission efficiency is 94%.
IH-DTL

RF measured results:
- Frequency [MHz]: 53.667
- Q0: 10200 (Designed 12400)
- Fixed tuner [mm]: 150
- Tuning range [MHz]: 1.4
- Moveable tuner [mm]: 100
- Tuning range [kHz]: 140
- Power [kW]: 18.2 (Calculated)

IH-DTL1

RF coupler
Movable Tuner
Field distribution along the tank
Some beam instruments were developed and applied in the beam commissioning. However, many elements and beam instruments were omitted since the limited funds. The analyzing dipole magnet system and the electrics system for the wire scanner, which were used to measure the energy spread and beam section profile, are not yet available.

The beam current and transmission are measured by three Faraday cups.

The beam energy is measured using the time of flight (TOF) method with two FCTs (Fast Current Transformer) installed after RFQ.

The transverse emittances are measured by scanners located at the downstream of the analyzing magnet.
Solid core beam of O\textsuperscript{5+}, Ar\textsuperscript{8+}

- P\textsubscript{w} = 1 kW
- HV = 25 kV
- I\textsubscript{total} = 7 emA
- I\textsuperscript{O5+} = 1401 euA

- P\textsubscript{w} = 0.1 kW + 0.1 kW
- HV = 18.6 kV
- I\textsubscript{total} = 3.5 emA
- I\textsuperscript{Ar8+} = 210 euA
SSC-Linac injector: LEBT

LEBT hollow beam phenomenon and redesign with PIC multiple beam transmission simulation

- High charge state
- High intensity Ion beam with multiple ion species and charge states
- High current space charge effect
- Extraction voltage: 23 kV
- $I_{\text{total}} = 2.4 \text{ emA}$, $I_{\text{Bi}^{28+}} = 20 \text{ euA}$
Remove a vacuum chamber to decrease the drift distance ~70mm;
Added a new solenoid
Remove a vacuum chamber to decrease the drift distance ~70mm;
Added a new solenoid
SSC-Linac injector: New LEBT

New solenoid 2

Simulation after optimization of LEBT

Beam test will be carried out in coming soon.

$$B_{\text{sol1}} = 0.31 \text{ T}, B_{\text{sol2}} = 0.33 \text{ T}$$
• Status of HIRFL

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• HIAF project
A new beam orbit correction is used to ensure an overlap coaxially between electron and ion beam.
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• HIAF project
Main parameters

**CSRe parameters**

- Circumference: 128.80 m
- Ion species: $^{12}$C$^{3+}$
- Beam energy: 122 MeV/u
- Relativistic $\beta, \gamma$: 0.47, 1.13
- Revolution frequency: 1.088 MHz
- Transition energy $\gamma_t$: 2.626
- Lifetime of ion beam: ~20 s
- Harmonic number $h$: 10, 15, 25

**Laser system**

- Laser source: cw & pulsed laser
- Laser wavelength: $\lambda_{\text{laser}} = 257.5$ nm

**Cooling transition**

- $2s_{1/2} \rightarrow 2p_{1/2}$: $\lambda_{\text{rest}} = 155.07$ nm
- $2s_{1/2} \rightarrow 2p_{3/2}$: $\lambda_{\text{rest}} = 154.81$ nm
Experimental setup

**Experimental Storage Ring CSRe**

- New Schottky Gas target
- Buncher
- Electron cooler
- Gas target
- Experimental Storage Ring CSRe
- Bunched ion beams
- Two PTMs
- Laser
- Pulse laser system, HZDR

**Resonant Schottky**

- UV-sensitive Channeltron

\[ f_{\text{bunch}} = h \cdot f_{\text{rev}} \rightarrow h \text{ bunches} \]
Moving ion energy with RF buncher

Schottky spectrum

\[ \frac{\delta p}{p} \times 10^{-5} \]

Time [s]

\[ f \text{ [kHz]} \text{ (} f_0 \text{ : 244 MHz)} \]

(a) \[ 12 C^{3+} \]

\[ 16 O^{4+} \]

Coasting

\[ \Delta p/p \sim 7.0 \times 10^{-5} \]

(b) \[ 12 C^{3+} \]

\[ \delta p/p \times 10^{-5} \]

RF bunched

\[ \text{Bucket accept. } \Delta p/p \sim 4.0 \times 10^{-5} \]

\[ C^{6+} \]

\[ O^{8+} \]

\[ f_0 - 244 \text{ [MHz]} \]
Experimental setup test

Lorentz transformation

a) access to ground state transitions of heavy ions by huge Doppler shift (@ \( \lambda_{UV} = 257\text{nm} \) )
b) one laser for many ion species
c) Laser cooling force increases with beam energy
d) laser spectroscopy is “free”

\[
\left( \frac{p_{\text{ion}} - p_0}{p_0} \right) \times 10^{-5}
\]

Florescence signals by CPM and PMT

- Lorentz transformation
  - a) access to ground state transitions of heavy ions by huge Doppler shift (@ \( \lambda_{UV} = 257\text{nm} \) )
  - b) one laser for many ion species
  - c) Laser cooling force increases with beam energy
  - d) laser spectroscopy is “free”
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• HIAF project
Overview

Pickup tank

Schottky prober beam signal

Pickup electrode
• Status of HIRFL

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• HIAF project
Overview of experimental results

- Improved precision
- Measured first time
Overview of experimental results

- Improved precision
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Overview of experimental results

Beams: $^{78}\text{Kr}$,
Overview of experimental results

Beams: $^{78}\text{Kr}$,

- **Improved precision**
- **Measured first time**
Overview of experimental results

Beams: $^{78}\text{Kr}$, $^{58}\text{Ni}$, $^{78}\text{Kr}$, 

- Improved precision
- Measured first time
Overview of experimental results

Beams: $^{78}\text{Kr}$, $^{58}\text{Ni}$,

- Improved precision
- Measured first time
Overview of experimental results

Beams: $^{78}$Kr, $^{58}$Ni, $^{86}$Kr,

- Improved precision
- Measured first time
Beams: $^{78}\text{Kr}$, $^{58}\text{Ni}$, $^{86}\text{Kr}$,
Overview of experimental results

Beams: $^{78}\text{Kr}$, $^{58}\text{Ni}$, $^{86}\text{Kr}$, $^{112}\text{Sn}$,
Overview of experimental results

Beams: $^{78}\text{Kr}$, $^{58}\text{Ni}$, $^{86}\text{Kr}$, $^{112}\text{Sn}$,
Overview of experimental results

Beams: $^{78}\text{Kr}$, $^{58}\text{Ni}$, $^{86}\text{Kr}$, $^{112}\text{Sn}$, $^{58}\text{Ni}$,
Overview of experimental results

Beams: $^{78}\text{Kr}$, $^{58}\text{Ni}$, $^{86}\text{Kr}$, $^{112}\text{Sn}$, $^{58}\text{Ni}$,
Overview of experimental results

Beams: $^{78}$Kr, $^{58}$Ni, $^{86}$Kr, $^{112}$Sn, $^{58}$Ni, $^{36}$Ar

- Improved precision
- Measured first time
Overview of experimental results

Beams: $^{78}$Kr, $^{58}$Ni, $^{86}$Kr, $^{112}$Sn, $^{58}$Ni, $^{36}$Ar

Double TOF

Improved precision

Measured first time
Overview of experimental results

Beams: $^{78}$Kr, $^{58}$Ni, $^{86}$Kr, $^{112}$Sn, $^{58}$Ni, $^{36}$Ar

X. L. Tu et al., PRL 106, 112501 (2011)
Y. H. Zhang et al., PRL 109, 102501 (2012)
P. Shuai et al., PL B 735,327 (2014)
H. S. Xu et al., IJMS 349, 162 (2013)

Precision $10^{-6} \sim 10^{-7}$ (20-200 keV)

Double TOF

Improved precision
Measured first time
Highest resolving power of single ToF IMS

\[
\frac{m}{\Delta m_{(FWHM)}} = 250,000
\]

\[E^{(52\text{Co}^m)} = 373(20) \text{ keV}\]

\[E^{(52\text{Mn}^m)} = 377.749(5) \text{ keV}\]
Preliminary results of double ToF IMS

1. intrinsic resolution of TOF detector: 30 ps
2. accuracy of velocity measurement: $10^{-4}$

![Graph showing time-of-flight data with peak at 136.95 ps and RMS of 44 ps.]
Realize real-time data analysis for each injection.

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<th>1870</th>
<th>3543</th>
<th>4177</th>
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• HIAF project
Beam loss mechanism:
Charge exchange of intermediate charge state ions ($^{238}\text{U}^{34+}$) due to collision

\[
\begin{align*}
U^{34+} + X^{n+} & \rightarrow U^{35+} + X \quad \text{Stripping} \\
U^{34+} + X^{n+} & \rightarrow U^{33+} + X \quad \text{Capture}
\end{align*}
\]

Challenges:
- How to get the high collimation efficiency?
- How to optimize lattices for different types of particles?
- How to design the collimator? the mechanical design, control system, vacuum system test.

A dedicated dynamic vacuum simulation code HIAF-DYSD has been developed for the optimization of dynamics design.
Vacuum Collimation at CSRm

Study of collimation efficiency with different parameters

Collimation efficiency – with different parameters

CSRm: U$^{32+}$, at 1.273 MeV/u, U$^{32+}$->U$^{33+}$
First step - Test platform
Desorption measurement
Install at PISA or E-point

Second step –
Collimator prototype of CSRm
Beam loss measurement

The mechanical design has been finished

Fabrication of hardware components

Stepper motor
Control hardware

Vacuum pressure
Data record
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• HIAF project
**CRing: Compression ring**
Circumference: 804 m  
Rigidity: 43 Tm  
Barrier bucket stacking  
Beam compression  
Beam acceleration  
In-beam experiment

**BRing: Booster ring**
Circumference: 402 m  
Rigidity: 34 Tm  
Beam accumulation  
Beam cooling  
Beam acceleration

**ERL: Energy Recovery Linac**
electron machine

**SRing: Spectrometer ring**
Circumference: 188.7 m  
Rigidity: 15 Tm  
Electron/Stochastic cooling  
Two TOF detectors  
Three operation modes

**iLinac: Spectrometer linac**
Length: 180 m  
Energy: 25 MeV/u (U^{34+})

1. Nuclear structure spectrometer  
2. Low energy irradiation target  
3. RIBs beam line  
4. High precision spectrometer ring  
5. External target station  
6. Electron-ion recombination spectroscopy  
7. Electron-Nucleus Collision (ENC)  
8. High Energy Density Physics target  
9. High energy irradiation target
Unprecedented beam Intensity (Comparison with HIRFL):
- Primary beam intensity increases by \( x \ 1000 \) – \( x \ 10000 \)
- Secondary beam intensity increases by up to \( x \ 10000 \)

Precisely-tailored beams
- Beam cooling (Electron, Stochastic, laser; high quality, very small spot)
- Beam compression (Ultra-short bunch length: 50–100ns)
- Super long period slow extraction (Super long, high energy, quasi-continuous beam)

Wide beam Energy:
- Heavy-ion energy: \( x \ 10 \) – \( x \ 15 \)

Versatile operation modes:
- Parallel operation, beam splitting (increase of target time, high integrated luminosity)

### Main Parameters of HIAF

<table>
<thead>
<tr>
<th>Ions</th>
<th>Energy</th>
<th>Intensity</th>
</tr>
</thead>
<tbody>
<tr>
<td>SECR</td>
<td>( ^{34+}U )</td>
<td>14 keV/u</td>
</tr>
<tr>
<td>iLinac</td>
<td>( ^{34+}U )</td>
<td>25 MeV/u</td>
</tr>
<tr>
<td>BRing</td>
<td>( ^{34+}U )</td>
<td>0.8 GeV/u</td>
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<tr>
<td>CRing</td>
<td>( ^{34+}U )</td>
<td>1.1 GeV/u</td>
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<tr>
<td></td>
<td>( ^{92+}U )</td>
<td>4.1 GeV/u</td>
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First phase of HIAF

Budget: 1.53 B RMB ¥
6-7 years project

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</table>

1. Nuclear structure spectrometer
2. Low energy irradiation target
3. Electron-ion recombination spectroscopy
4. RIBs beam line
5. High precision spectrometer ring
6. External target station
Thanks for your attention!