Progress and new developments of accelerator

High-Intensity Heavy Ion Accelerator Facility-HIAF

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HIAF general design group
1. Background and science motivations
2. General description of project
3. Design concept and unique features
4. Innovative technologies and developments
5. Summary
Next-generation high intensity facilities are required for advances in nuclear physics and related research fields:

- To explore the limit of nuclear existence
- To study exotic nuclear structure
- Understand the origin of the elements
- To study the properties of High Energy and Density Matter

Fascinating and crucial questions

- To explore the limit of nuclear existence
- To study exotic nuclear structure
- Understand the origin of the elements
- To study the properties of High Energy and Density Matter

Next-generation facilities being constructed or proposed worldwide:

- SPIRAL2 at GANIL in Caen, France
- FAIR at GSI in Darmstadt, Germany
- FRIB at MSU in the U.S.
- NICA at JINR, Dubna, Russia
- EURISOL in Europe

High Intensity Heavy-ion Accelerator Facility

HIAF in China
HIAF: background and motivation

**HIAF:** One of 16 large-scale research facilities proposed in China in order to boost basic science, next-generation high intensity facility for advances in nuclear physics and related research fields.

**The HIAF project:**
- Proposed by IMP in 2009.
- Approved in principle by the central government in the end of the 2012.
- The final approval was in the December of 2015
- **Final preparation for starting of construction are under way and will start in coming few months**

**Science motivations:**
- High intensity radioactive beams to investigate the structure of exotic nuclei, nuclear reactions of astrophysics and to measure the mass of nuclei with high precision.
- High charge state ions for a series of atomic physics programs.
- Quasi-continuous beam with wide energy range for applied science.
- High energy and intensity ultra-short bunched ion beams for high energy and density matter research.
- Spontaneous electron–positron pair production
iLinac: Superconducting linac
- Length: 100 m
- Energy: 17-22 MeV/u (U^{35+}\text{-}45+)

BRing-S: Booster ring
- Circumference: 650 m
- Rigidity: 86 Tm
- Beam stacking
- Beam acceleration

BRing-N: Fast cycle ring
- Circumference: 590 m
- Rigidity: 34 Tm
- Large acceptance (250/120)
- Two planes painting injection
- Fast ramping rate (5-10Hz, 20Hz)

SRing: Spectrometer ring
- Circumference: 273 m
- Rigidity: 13-15 Tm
- Electron/Stochastic cooling
- Two TOF detectors
- Four operation modes

MRing: Figure “8” ring
- Circumference: 273 m
- Rigidity: 15 Tm
- Ion-ion merging

These tunnels will be built in a cut and cover method and will be filled with 5 m overlay of soil. This conforms to the requirements of radiation safety.
Facility for world class experiments

Unprecedented parameters and unique features:

**Highest beam Intensity** (Comparison with HIRFL):
- Primary beam intensity increases by $x\ 1000 - x\ 10000$
- Secondary beam intensity increases by up to $x\ 10000$
- Highest heavy ion beam intensity in the world

**Precisely-tailored beams - Precision frontiers**
- 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)

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

Parallel mode
Experiment terminals

External target station
High Energy Density Physics
Nuclear Matter study-CEE
Hypernuclear
High energy irradiation

Low energy irradiation

Low energy nuclear structure terminal

RIBs physics station
High precision spectrometer ring

BRing-S
BRing-N

HFRS
e-ion recombination spectroscopy

SRing
MRing
Ion-Ion Merging

iLinac
SECR

Low energy irradiation
## Budget

<table>
<thead>
<tr>
<th>Items</th>
<th>1st phase (MRMB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>iLinac</td>
<td>360</td>
</tr>
<tr>
<td>BRing</td>
<td>350</td>
</tr>
<tr>
<td>Beam transfer line</td>
<td>50</td>
</tr>
<tr>
<td>Experiment setups</td>
<td>240</td>
</tr>
<tr>
<td>Cryogenics</td>
<td>80</td>
</tr>
<tr>
<td>Civil engineering</td>
<td>190</td>
</tr>
<tr>
<td>Tunnel construction</td>
<td>160</td>
</tr>
<tr>
<td>Contingency cost</td>
<td>100</td>
</tr>
<tr>
<td><strong>Total of facility</strong></td>
<td>1530 (central government)</td>
</tr>
<tr>
<td><strong>Infrastructure &amp; common systems</strong></td>
<td>1000 (local government)</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>2530</td>
</tr>
</tbody>
</table>
## Schedule

### Critical Points

- **Plan**: 20~
- **Approval**: 09
- **Start construction**: 20~
- **Commissioning**: 22
- **Operation**: 24

### Design

- **Idea design**
- **Conceptual design**
- **Design report preparation, submission, approval**
- **Detailed design & prototype**

### Construction and Installation

- **Civil construction**
- **Equipment construction, Fabrication**
- **Installation**
- **iLinac, BRing, CRing commissioning**
- **Combined commissioning**

### Commissioning

- **Start of operation**

### Budget periods

- **BP1**
- **BP2**
- **BP3**
- **BP4**
New campus
Design concept and unique features

- Unprecedented heavy ion beam intensity
- Multi-function storage ring
- Figure-8 shape ion-ion merging ring
Unprecedented heavy ion beam intensity

Concepts for approaching the highest heavy ion intensity

BRing-N
- Novel two planes painting injection scheme - $2.0 \times 10^{11}$ ppp
- Fast ramping rate operation mode - 3-5 Hz

BRing-S
- Innovative timing system of RF synchronization
- 5 times increase of intensity
  - $1.0 \times 10^{12}$ ppp

Barrier bucket stacking longitudinal
Unprecedented heavy ion beam intensity

Two planes painting injection

Simultaneous injection in H and V planes using tilted septum
Conclusions:

- The beam intensity could reach $2.0 \times 10^{11}$ with two planes painting, nearly 10 times over the conventional single-plane injection.
Fast ramping rate mode of BRing-N

Why?

Due to space charge and dynamic vacuum effect, beam should be launched to the high energy as soon as possible.

Repetition rate: 3-5 Hz, 5-10Hz
Unprecedented heavy ion beam intensity

Barrier bucket stacking

- 5 times increase of beam intensity through barrier bucket

800MeV/u ($^{238}$U$^{35+}$)

Barrier bucket stacking

5 times

2.0 $\times$ 10$^{11}$

BRing-N

Innovative RF timing system

2.3GeV/u ($^{238}$U$^{35+}$)

5 times increase of beam intensity through barrier bucket

Challenges:

- Fast e-cooling for high energy heavy ion
- High intensity effect of barrier bucket stacking

Momentum spread

Emittance

Intensity
# Basic beam parameters

<table>
<thead>
<tr>
<th></th>
<th>Ions</th>
<th>Energy</th>
<th>Intensity</th>
</tr>
</thead>
<tbody>
<tr>
<td>SECR</td>
<td>$^{238}\text{U}^{35+}$</td>
<td>14 keV/u</td>
<td>0.05-0.1 pmA</td>
</tr>
<tr>
<td>iLinac</td>
<td>$^{238}\text{U}^{35+}$</td>
<td>17 MeV/u</td>
<td>0.028-0.05 pmA</td>
</tr>
<tr>
<td>BRing-N</td>
<td>$^{238}\text{U}^{35+}$</td>
<td>0.8 GeV/u</td>
<td>$\sim 2.0 \times 10^{11}$ ppp</td>
</tr>
<tr>
<td>BRing-S</td>
<td>$^{238}\text{U}^{35+}$</td>
<td>2.3 GeV/u</td>
<td>$\sim 1.0 \times 10^{12}$ ppp</td>
</tr>
<tr>
<td></td>
<td>$^{238}\text{U}^{76+}$</td>
<td>5.8 GeV/u</td>
<td>$\sim 5.0 \times 10^{11}$ ppp</td>
</tr>
<tr>
<td></td>
<td>$^{238}\text{U}^{92+}$</td>
<td>7.3 GeV/u</td>
<td>$\sim 5.0 \times 10^{11}$ ppp</td>
</tr>
<tr>
<td>SRing</td>
<td>RIBs: neutron-rich, proton-rich</td>
<td>0.84 GeV/u ($A/q=3$)</td>
<td>$\sim 10^{9-10}$ ppp</td>
</tr>
<tr>
<td></td>
<td>Fully stripped heavy ions</td>
<td>0.8 GeV/u ($^{238}\text{U}^{92+}$)</td>
<td>$\sim 10^{11-12}$ ppp</td>
</tr>
</tbody>
</table>
The highest pulse heavy ion beam intensity in the world

<table>
<thead>
<tr>
<th>Institute</th>
<th>Machine</th>
<th>Planned Intensity</th>
<th>Achieved Intensity</th>
<th>Ion species</th>
<th>Repetition rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>BNL</td>
<td>AGS Booster</td>
<td>$5 \times 10^9$</td>
<td>$5 \times 10^9$</td>
<td>Au$^{32+}$</td>
<td></td>
</tr>
<tr>
<td>CERN</td>
<td>LEIR</td>
<td>$9 \times 10^8$</td>
<td>$9 \times 10^8$</td>
<td>Pb$^{54+}$</td>
<td></td>
</tr>
<tr>
<td>JINR</td>
<td>NICA Booster</td>
<td>$4 \times 10^9$</td>
<td>$4 \times 10^9$</td>
<td>Au$^{32+}$</td>
<td></td>
</tr>
<tr>
<td>GSI</td>
<td>SIS18</td>
<td>$1.0 \times 10^{11}$</td>
<td>$3 \times 10^{10}$</td>
<td>U$^{28+}$</td>
<td>$2.7$Hz</td>
</tr>
<tr>
<td>FAIR</td>
<td>SIS100</td>
<td>$4.0 \times 10^{11}$</td>
<td>$4.0 \times 10^{11}$</td>
<td>U$^{28+}$</td>
<td></td>
</tr>
<tr>
<td>IMP</td>
<td>HIAF-BRing-N</td>
<td>$2.0 \times 10^{11}$</td>
<td>$2.0 \times 10^{11}$</td>
<td>U$^{35+}$</td>
<td>$5-10$Hz, $10-20$Hz</td>
</tr>
<tr>
<td>IMP</td>
<td>HIAF-BRing-S</td>
<td>$1.0 \times 10^{12}$</td>
<td>$2.0 \times 10^{12}$</td>
<td>U$^{35+}$</td>
<td></td>
</tr>
</tbody>
</table>
Key devices
- Electron cooling
- Stochastic cooling
- Two TOF detectors
- Electron target

Operation modes
- Isochronous mode
- Normal Mode
- Internal-target Mode
- Ion-ion merging Mode

Experiment programs
- Gas-jet target experiments
- DR experiments
- IMS & SMS
- Laser cooling
- Ion-ion merging experiments

Multi-function storage ring
Precision frontiers machine for in-ring experiments
Multi-function storage ring

Isochronous mode with two TOF

**HIRFL-CSRe**

\[ \frac{df_{rev}}{f_{rev}} = \frac{1}{\gamma} \frac{1}{\gamma_f} \frac{dP}{P} \frac{1}{\gamma_f^2} \frac{d(m/q)}{m/q} \]

\[ \gamma = \gamma_f = 1.395 \]

**HIRAF-SRIng**

Beams: \(^{58}\text{Ni},^{78}\text{Kr},^{86}\text{Kr}\) and \(^{112}\text{Sn}\)

43 masses are measured

Measured for the first time: 16

Precision improved: 27

Precision achieved: \(\Delta M/M \sim 10^{-7}\)

Demonstrated the TOF mode first time in the world

\(\Delta M/M \sim 10^{-7} - 10^{-8}\)
A fundamental question of QED-spontaneous electron-positron pair creation in supercritical Coulomb fields

Theory prediction: occur in the collisions of two very heavy ions with the total atomic number $Z_1 + Z_2 \geq 173$.

Failed to observe in fixed target experiments due to the interference of extranuclear electrons.
First ion-ion merging facility in the world

Unique features:
- “8” shape ring
- Coasting beam merging with itself scheme
- Based on SRing
- Sharing the injection and cooling system
- No powerful RF system

Advantages:
- No electron-electron correlation
- Ultra-low background signals
- Small angle collision provides the energy (6~8MeV/u) to cross column barrier

Bare heavy nuclei, e.g. $^{238}_{92}$U$^{92+}$, $Z_1 + Z_2 = 184 \geq 173$
Figure-8 shape ring for ion-merging

Merging beam parameters - **First phase**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ion</td>
<td><strong>238U</strong>&lt;sup&gt;92+&lt;/sup&gt;</td>
</tr>
<tr>
<td><strong>Energy (MeV/u)</strong></td>
<td>637(800)</td>
</tr>
<tr>
<td>Circumference (m)</td>
<td>483.8</td>
</tr>
<tr>
<td>Frequency (MHz)</td>
<td>0.50(0.52)</td>
</tr>
<tr>
<td><strong>Crossing angle (°)</strong></td>
<td>6.8</td>
</tr>
<tr>
<td>CM energy (MeV/u)</td>
<td>6(8)</td>
</tr>
<tr>
<td><strong>Particle number</strong></td>
<td><strong>7(8) × 10&lt;sup&gt;10&lt;/sup&gt;</strong></td>
</tr>
<tr>
<td>ε&lt;sub&gt;x&lt;/sub&gt;,rms/ε&lt;sub&gt;y&lt;/sub&gt;,rms (π mm mrad)</td>
<td>1/1</td>
</tr>
<tr>
<td>β&lt;sup&gt;<em>&lt;/sup&gt;&lt;sub&gt;x&lt;/sub&gt;/β&lt;sup&gt;</em>&lt;/sup&gt;&lt;sub&gt;y&lt;/sub&gt; (m)</td>
<td>1/0.03</td>
</tr>
<tr>
<td>σ&lt;sub&gt;x&lt;/sub&gt;,rms/σ&lt;sub&gt;y&lt;/sub&gt;,rms (mm)</td>
<td>1/0.173</td>
</tr>
<tr>
<td>Laslett tune shift</td>
<td>-0.1(-0.077)</td>
</tr>
<tr>
<td>Hourglass factor</td>
<td>0.9</td>
</tr>
<tr>
<td><strong>Luminosity (cm&lt;sup&gt;-2&lt;/sup&gt;s&lt;sup&gt;-1&lt;/sup&gt;)</strong></td>
<td>4.4(5.4) × 10&lt;sup&gt;23&lt;/sup&gt;</td>
</tr>
</tbody>
</table>
### Merging beam parameters – **Update- 1000 times**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ion</td>
<td>$^{238}\text{U}^{92+}$</td>
</tr>
<tr>
<td>Energy (MeV/u)</td>
<td>4300</td>
</tr>
<tr>
<td>Circumference (m)</td>
<td>472.7</td>
</tr>
<tr>
<td>Frequency (MHz)</td>
<td>0.624</td>
</tr>
<tr>
<td>Crossing angle (°)</td>
<td>1.93</td>
</tr>
<tr>
<td>CM energy (MeV/u)</td>
<td>8</td>
</tr>
<tr>
<td><strong>Particle number</strong></td>
<td>$3 \times 10^{12}$</td>
</tr>
<tr>
<td>$\varepsilon_{x,\text{rms}}/\varepsilon_{y,\text{rms}}$ (π mm mrad)</td>
<td>1/1</td>
</tr>
<tr>
<td>$\beta_x^<em>/\beta_y^</em>$ (m)</td>
<td>0.1/0.02</td>
</tr>
<tr>
<td>$\sigma_{x,\text{rms}}/\sigma_{y,\text{rms}}$ (mm)</td>
<td>0.316/0.141</td>
</tr>
<tr>
<td>Laslett tune shift</td>
<td>-0.08</td>
</tr>
<tr>
<td>Hourglass factor</td>
<td>0.9</td>
</tr>
<tr>
<td>Luminosity (cm$^{-2}$s$^{-1}$)</td>
<td>$4.1 \times 10^{26}$</td>
</tr>
</tbody>
</table>

**Figure-8 shape ring for ion-merging**

**Update-1:** SC magnet to 4T

**Update-2:** New interaction section with small cross angle