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ECR Ion Source Development and Challenges

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Outline

- Intense HCI Beam Needs
- Status of Intense HCI Beam Production
- Perspectives of Next Generation ECRIS
- Status of FECR Development
  - 45 GHz Nb₃Sn Magnet Development
  - Conventional Ion Source Physics & Technologies
- Summary
Intense HCI Beam Needs by Accelerators

Ar^{12+} and U^{3x+} beam intensities evolution over years

HCl beam intensity needs are always one decade ahead of the real production.
Intense HCl Beam Needs of HIAF

**HIAF**
2018-2025

**BRing:** Booster ring
- C: 569 m
- Bρ: 34 Tm
- E: 0.834 GeV/u,
- I: 1.0x10^{11} ppp (U^{35+})

**SRing:** Spectrometer ring
- C: 278m
- Bρ: 15Tm

**iLinac:** Superconducting linac
- L: 100 m
- E: 17 MeV/u(^{238}U^{35+})
- I: 1 emA

**Challenges**
- Intense highly charged heavy ion beams production
- Low β intense heavy ion beam acceleration
- High intensity heavy ion beam accumulation, acceleration in storage ring

- CW: 0.5 emA U^{46+}
- ~50 puA U^{35+}/ ≤5 Hz @0.2~2 ms
Status of Intense HCI Beam Production

2nd G ECRIS
- High $\omega_{rf}$
- High $P_{rf}$

3rd G ECRIS
- 24-28 GHz
- 5-10 kW
- $\Omega$100-150 mm ID Chamber

3rd G ECRIS
- Oven Techniques
- $\mu$W Techniques

Beam Intensity (eµA)

Year

Ar$^{12+}$  Bi$^{31+}$  Xe$^{30+}$  U$^{35+}$
Status of Intense HCI Beam Production

Typical 3rd G. ECRISs for intense $U^{3x+}$ beams
- $U^{3x+}$: 10~15 $\mu$A
- 1/4~1/5 of HIAF needs

4th G. ECRIS
- $U^{3x+}$: 30~50 $\mu$A
- $U^{4x+}$: 5~10 $\mu$A
Perspectives of Next Generation ECRIS

Significance:

Ultimate conditions for physics with low energy HCl beams:
- Material irradiation research
- Highly charged atomic physics
- Low energy nuclear physics

Prototyping for HIAF:
- 45 GHz ECR Ion Source
- 81.25 MHz CW 4-vane RFQ
- Intense heavy ion beam production, transmission and acceleration

(2015-2021)
Funded by NSFC

L. Sun, ECRIS2020, Virtual Conf., 7/32
Perspectives of Next Generation ECRIS

FEKR (First 4th generation ECR ion source)

FECR (First 4th Generation ECR ion source)

- Reliable SC-magnet for 45 GHz plasma confinement
- Effective coupling to the plasma of 20 kW/45 GHz microwave power
- 20 kW microwave heated plasma operation reliability and stability: Plasma chamber and dynamic stability
- Strong bremsstrahlung radiation problems
  - Heat sink in cryostat
  - HV insulator degradation
  - Risk of coil epoxy degradation
- Intense high charge state ion beam (20-40 emA) extraction, transport and beam quality control
- Intense metallic beam production, especially of refractory materials: U, W, Ta, Mo, Ti, Ni...

Liangting Sun, ICFA-Newsletter 73, p34.
Status of FECR Development: Magnet

Cold mass
- High quality reliable Nb$_3$Sn sextupole coil production
- Precise and efficient pretension and clamping structure
- Fast quench detection and active protection

Cryostat
- Safe suspension system for operation and transport of 3.5 tons cold mass
- Precise installation and alignment of cold mass
- High voltage safe instrumentation
- Sufficient dynamic cooling power @4.2 K
The coldmass mechanical structure was designed by collaboration with ATAP magnet group at LBNL (2015~2016).

Bladder & Keys assembly

- COIL-PACK SUBASSEMBLY
- AXIAL-LOAD END PLATE SUBASSEMBLY
- SEPTUPOLE COILS
- COLLARS
- LOAD-KEYS

AXIAL RODS (Strain Gauged)

- YOKE-SHELL ALIGNMENT PINS
- MASTER-KEY PLATES
- SOLENOID STRUCTURE
- SUBASSEMBLY

SHELL-YOKE SUBASSEMBLY (Shell is strain gauged)

½ length prototype

Status of FECR Development: $\text{Nb}_3\text{Sn}$ Coil

- **Prepared Coil**
  - Mechanical mapping
  - Detailed Q/A

**Winding**

- Iron+Ti alloy
- ITER Wire (1000 A@12 T)
- C5100 Alloy
- G10
- 316 LN SS
- Pole
- Coil block
- Injection endshoe
- Extraction endshoe
- Coil insulation plate

**Heat Treatment**

- Prepared Coil
- Potting
Status of FECR Development: \( \text{Nb}_3\text{Sn Coil} \)

Journey of coil R&D

2016.12  \rightarrow  2018.12
Status of FECR Development: \( \text{Nb}_3\text{Sn Coil} \)

- **Al Shell**
- **Upper yoke**
- **Key**
- **Pad**
- **Shim1+shim2**
- **Lower yoke**

A Mirror Structure for sextupole cold test

- **Pole field**: 30 min
- **No Quenches!**

- **Highest field in superconductor**: 10.4 T
- **LF**: 80% of short sample

Status of FECR Development: structure

½ prototype with Al dummy coil mockup

Whole process Strain- Guaged
Status of FECR Development: $\frac{1}{2}$ cold mass

- Sextupole pre-assembly
- Sextupole in collars
- Sextupole & solenoids
- Load pad and wiring
- Instrumentation in Pizzabox
- Axial preload with pistons
- Radial preload with bladder & keys
Status of FEKR Development: Cold Test

- Solenoid only energized to 100% design current 600 A
- No quenches!
- Field consistent with calculated

- Sextupole only energized to 90% design current= 671 A (power supply malfunction)
- No quenches!
- Field consistent with calculated
Status of FECR Development: Quench protection

Sextupole passive quench protection

Active quench protection

- \( I_0 = 673 \, \text{A} \)
- \( R_{\text{EE}} = 2.4 \, \Omega \)
- \( U_{\text{EE}} = 1650 \, \text{V} \)
- Fast quench detection, validation and triggering energy extraction in: 17 ms


Fast quench detection (~20 mV, 10 ms) system based on FPGA

Flux jump adds additional difficulty to quench protection and coil safety

Flux jump signal during coil ramping

1000 A fast quench trigger energy extraction power supply

Fast trigger in 0.25 ms
### Status of FECR Development: Cryogenic system

#### Key parameters of FECR cryostat

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operation Temp. (K)</td>
<td>4.3 K</td>
<td></td>
</tr>
<tr>
<td>Magnet Cooling</td>
<td>LHe bathing and &quot;0&quot; boiling-off</td>
<td></td>
</tr>
<tr>
<td>Stored Energy (MJ)</td>
<td>~1.6</td>
<td>100% currents</td>
</tr>
<tr>
<td>Required heat load (W)</td>
<td>≥ 12</td>
<td>~2 W static at 100% currents</td>
</tr>
<tr>
<td>Warm Bore (mm)</td>
<td>Ø162</td>
<td></td>
</tr>
<tr>
<td>LHe Volume (L)</td>
<td>~330</td>
<td></td>
</tr>
<tr>
<td>Cryocoolers</td>
<td>6 two-stage + 1 single stage coolers</td>
<td>Cold service enabled</td>
</tr>
<tr>
<td>Dimension (mm)</td>
<td>L1456 × Ø1200 × H2690</td>
<td></td>
</tr>
<tr>
<td>Total weight (ton)</td>
<td>~6.1</td>
<td></td>
</tr>
</tbody>
</table>
Status of FECR Development: Cryogenic system

<table>
<thead>
<tr>
<th>Model</th>
<th>1st Stage</th>
<th>2nd Stage</th>
</tr>
</thead>
<tbody>
<tr>
<td>CH-110</td>
<td>130 W@50 K</td>
<td>N/A</td>
</tr>
<tr>
<td>KDE422</td>
<td>~20 W@50 K</td>
<td>≥2.2 W@4.2 K</td>
</tr>
<tr>
<td>RDE-418D4</td>
<td>~42 W@50 K</td>
<td>≥1.8 W@4.2 K</td>
</tr>
<tr>
<td>Total</td>
<td>~316 W@50 K</td>
<td>≥12 W@4.2 K</td>
</tr>
</tbody>
</table>
Localized heat sink strongly related to field homogeneity

Field homogeneity:
- <1% \( \rightarrow \) concentricity \( \Delta r < 0.4 \text{ mm} \)
- <0.5% \( \rightarrow \) concentricity \( \Delta r < 0.2 \text{ mm} \)
## Status of FECR Development: Conventional Parts

<table>
<thead>
<tr>
<th>Parameters</th>
<th>3rd G. ECRIS</th>
<th>45 GHz FECR</th>
<th>Increased by</th>
</tr>
</thead>
<tbody>
<tr>
<td>Microwave Power (kW)</td>
<td>~10</td>
<td>&gt;20</td>
<td>&gt;2</td>
</tr>
<tr>
<td>Ts (keV)</td>
<td>50~60</td>
<td>80~100</td>
<td>&gt;1.5</td>
</tr>
<tr>
<td>Microwave Length (mm)</td>
<td>~10</td>
<td>~6</td>
<td>/</td>
</tr>
<tr>
<td>Max. Plasma Density (cm⁻³)</td>
<td>~1X10¹³</td>
<td>~2.6X10¹³</td>
<td>&gt;2.6</td>
</tr>
<tr>
<td>Total Beam Available (mA)</td>
<td>10~20</td>
<td>26~52</td>
<td>&gt;2.6</td>
</tr>
</tbody>
</table>
Status of FE€R Development: $\mu W$ coupling

45 GHz Microwave System for FE€R

- 45 GHz/20 kW microwave transmission system based on Quasi-optical design
- First 45 GHz ECR plasma with SECRAL-II ion source
- Efficient transmission and coupling demonstrated

About multi-frequency ECRH

- Secondary or multi-frequency ECRH is essential
- Optimum frequencies to suppress kinetic instabilities?
- Needed power? (4~5 kW)

L. Sun, TUA5, ECRIS2018
Status of FECR Development: Plasma Chamber

Chamber burnt with SECRAL-II
Typically: >7 kW

Chamber burnt with VENUS

Typically:
1 kW μW~1.25 MW/m² heat sink

LCW pressure of 6 kg/cm², water BP =150~160℃

T. Thuillier et al., Review of Scientific Instruments 87, 02A736 (2016)
## Status of FECR Development: Plasma Chamber

<table>
<thead>
<tr>
<th>$P_{rf}$ (kW)</th>
<th>$T_{\text{max}}$ on Al wall</th>
<th>$T_{\text{max}}$ of water at the hottest point</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>174°C</td>
<td>88°C</td>
</tr>
<tr>
<td>15</td>
<td>229°C</td>
<td>107°C</td>
</tr>
<tr>
<td>20</td>
<td>299°C</td>
<td>137°C</td>
</tr>
</tbody>
</table>

### Water flow rate:

Water temperature distribution at the chamber wall of weakest plasma confinement point

- **2**: Gaussian distributed, 159°C, 78°C
- **3**: Gaussian distributed, 229°C, 107°C
- **4**: Gaussian distributed, 299°C, 137°C

Micro-channel structure of 0.4 mm $\times$ 20

Please see Guo’s talk 1147 on Tuesday
Status of FECR Development: Bremsstrahlung

If $T_s$ rises linearly with $B_{\text{min}}$

- ~0.6 W/kW@28 GHz, 1~2 W/kW@45 GHz?
- 20 kW@45 GHz ~ >20 W@4.2 K?

Also see two Li’s talks 1122 & 1082 on Tuesday & Wednesday
Yellowish PEEK insulator after high power operation (1.5 mm Ta shielding)

- Main insulator is replaceable
- What if Coil epoxy degrades after long time exposure, which literally needs high quality of insulation property (5 kV standard)

\[
damage = f(n_e \uparrow, T_s \uparrow)
\]
Status of FECR Development: Uranium Beam

Uranium beam production with HTO

- Copper
- Water in
- Water out
- Shielding ($\text{Al}_2\text{O}_3$)
- 1 mm Gaps
- End Cap (Ti)
- End plate ($\text{Al}_2\text{O}_3$)
- Support (Ta)
- Susceptor (Ta)
- Coils (Cu)
- Metal vapor

>2000°C Inductive Heating Oven

- End cap and rod

Crucible, Thermal Shield & Insulator Off-line Test

Wang Lu @ talk 1155, on Tuesday

Max. 450 $\mu$A $\text{U}^{33+}$ produced
Status of FECR Development: Uranium Beam

- Plasma heating contribution obvious
- Oven temperature still has margin
- Potentials at 28 GHz, limited by power limit in 2019 (chamber damage at high power)

![Graph showing $U^{33+}$ (eμA) vs. $P_{rf}$ (kW)]

- Oven
- Biased Disk
- 24 GHz WG
- 18 GHz WG
Higher extraction voltage ==

- Higher beam transmission efficiency
- Better beam quality in terms of SPC
Status of FECR Development: Beam Extraction

- Beam emittance degradation not proportional to $I_q$
- Space charge not dominant at extraction and transmission
- Plasma condition and beam extraction critical

Status of FECR Development: Beam Extraction

Evidence of SPC not dominant in ion source extraction and transmission

- $I_{\text{total}} = 13 \text{ emA}$, $I_{\text{Bi}^{31+}} = 0.65 \text{ emA}$. 
Max. 50 kV extraction voltage
4-electrode extraction system
Variable beam extraction optics
Dural-solenoid solution before dipole magnet
(independent control of beam focusing and matching)

Z. Shen @ talk 1142, on Wednesday
Summary

- **Reliable and safe** SC-magnet for 45 GHz plasma confinement
- **Effective coupling** to the plasma of 20 kW/45 GHz microwave power
- **20 kW microwave heated plasma operation** reliability and stability:
  - Strong bremsstrahlung radiation problems
  - Intense high charge state ion beam (20-40 emA) extraction, transport and beam quality control
- **Intense metallic beam production**, especially of refractory materials: U, W, Ta, Mo, Ti, Ni...
Acknowledgement

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- Nb$_3$Sn Wire
- Wire braiding

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- Mirror structure
- Mechanical mapping

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- Cryogenic system fabrication and integration

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- Gyrotron microwave generator and microwave transmission solutions

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- Coldmass structure design

RIKEN
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Welcome collaborations and Postdoc research !!