45 GHz Microwave Power Transmission and Coupling Scheme Study With Superconducting ECR Ion Source at IMP


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Outline

◆ Background

◆ Gyrotron system for 3rd Gen ECRIS

◆ 45 GHz microwave solutions

◆ Summary
Project HIAF

High Intensity heavy ion Accelerator Facility

HIAF requires source to deliver:
- Pulsed $238\text{U}^{35+}$: 50 $\mu$A
- CW $238\text{U}^{35+}$: 20 $\mu$A

Ion source be able to produce:
- Pulsed $238\text{U}^{35+}$: >50 $\mu$A
- CW $238\text{U}^{35+}$: >30 $\mu$A

Only an 4th generation ECRIS might meet the requirements

LBNL VENUS: CW $238\text{U}^{35+}$: 10-12 $\mu$A
45 GHz Fourth generation ECR ion source

FECR key parameters

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Unit</th>
<th>FECR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>GHz</td>
<td>45</td>
</tr>
<tr>
<td>$B_{\text{ECR}}$</td>
<td>T</td>
<td>1.6</td>
</tr>
<tr>
<td>$B_{\text{inj}}$</td>
<td>T</td>
<td>&gt;6.4</td>
</tr>
<tr>
<td>$B_{\text{extr}}$</td>
<td>T</td>
<td>3.2</td>
</tr>
<tr>
<td>$B_r$</td>
<td>T</td>
<td>&gt;3.2</td>
</tr>
<tr>
<td>Mirror Length</td>
<td>mm</td>
<td>500</td>
</tr>
<tr>
<td>Chamber ID</td>
<td>mm</td>
<td>150</td>
</tr>
<tr>
<td>Warm bore ID</td>
<td>mm</td>
<td>170</td>
</tr>
<tr>
<td>Extra. voltage</td>
<td>kV</td>
<td>50</td>
</tr>
</tbody>
</table>

FECR expected beam intensities

| $^{238}\text{U}^{35+}$ | >1000 $\mu$A  |
| $^{238}\text{U}^{41+}$ | 200-400 $\mu$A |
| $^{238}\text{U}^{56+}$ | 30-100 $\mu$A  |

What kind of microwave coupling for the 4th generation ECR?

See H. W. Zhao talk on Wednesday for details.
3rd Gen ECRIS microwave system

First demonstration of 28 GHz RF transmission and coupling system to ECR

Features:
- Low ohmic loss over distances
- Good for 24/28 GHz microwave power

Problems:
- ECRH efficiency ??

Gyrotron frequency boosts beam intensities

- Beam intensity increase more like μW power scaling
- Frequency effect not obvious

Similar results have also been observed with VENUS and SUSI
Exploration of μW coupling with SECRAL

D.Hitz ECRIS2006

电场线

\[ \text{TE}_{02} \rightarrow \text{TE}_{01} \rightarrow \text{TE}_{11} \rightarrow \text{HE}_{11} \]

rf power distribution

97% HE_{11}

SNAKE \text{TE}_{01} \rightarrow \text{HE}_{11}

18 GHz waveguide

\text{TE}_{11}-\text{HE}_{11} \text{ converter}

SECRAL Injection Parts

Designed by B. Plaum, W. Kasparek from Stuttgart University
Exploration of μW coupling with SECRAL

SECRAL Injection Parts
- Flexible choice of injection modes
- Flexible choice of WG openings

Compact Design:
- Waveguide ID: Ø32.6 mm → Ø20 mm
- Convector length: 745 mm → 330 mm
Exploration of $\mu$W coupling with SECRAL

Baseline design for 45GHz microwave coupling
- **TE$_{01}$** with $\Phi$32mm circular waveguide
- Launching schemes are adjustable in the injection section

- **TE$_{11}$** @ $\Phi$8 mm: Plasma is less stable at the power level over 5 kW
- **HE$_{11}$** @ $\Phi$20mm mode did not show any sign of advantage over TE$_{01}$
- **TE$_{01}$** @ $\Phi$16 mm: it is possible to couple high level of $\mu$W power, but not too much gain
- **TE$_{01}$** @ $\Phi$26 mm: output tends to saturation at the power level over 5 kW

- **TE$_{01}$** @ $\Phi$20 mm shows obvious advantage in HCl production at high power level, No sign of saturation even at high power level
## 45 GHz/20 kW microwave system

<table>
<thead>
<tr>
<th>Parameters</th>
<th>SECRAL-II</th>
<th>FECR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>28 GHz</td>
<td>45 GHz</td>
</tr>
<tr>
<td>Operation Mode</td>
<td>CW</td>
<td>CW/Pulsed</td>
</tr>
<tr>
<td>Gyrotron output Mode</td>
<td>TE\textsubscript{02}</td>
<td>Gaussian beam</td>
</tr>
<tr>
<td>Ion source input mode</td>
<td>TE\textsubscript{01}</td>
<td>TE\textsubscript{01}</td>
</tr>
<tr>
<td>Mode Purity</td>
<td>&gt;95%</td>
<td>&gt;95%</td>
</tr>
<tr>
<td>Max. Power</td>
<td>10.0 kW</td>
<td>20 kW</td>
</tr>
<tr>
<td>Transmission line</td>
<td>Circular waveguide</td>
<td>Combined mirror and waveguide</td>
</tr>
<tr>
<td>Waveguide Size</td>
<td>~Ø32.6 mm</td>
<td>~Ø32.6 mm</td>
</tr>
</tbody>
</table>

**Pulse mode operation specifications**

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
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</thead>
<tbody>
<tr>
<td>Fall Time</td>
<td>&lt;10 µs</td>
</tr>
<tr>
<td>Rise Time</td>
<td>&lt;200 µs</td>
</tr>
<tr>
<td>Pulse Duration</td>
<td>5-200 ms</td>
</tr>
<tr>
<td>Repetition Rate</td>
<td>1~10 Hz</td>
</tr>
</tbody>
</table>
24/28 GHz (<35 GHz) Features:
• longitudinal output in TE_{mn} mode
• Normal electromagnet (on the second harmonic of electron cyclotron resonance)
• Transmission line: Smooth wall circular waveguide

45 GHz (>35 GHz) Features:
• lateral output in Gaussian mode.
• Cryogenic superconducting magnet (liquid helium cooled or liquid helium free)
• Transmission line: Quasi-optical mirror, corrugated waveguide
FECCR 45 GHz μW Power Schematic

Courtesy of A.I. Tsvetkov
Gyrotron microwave source main components

45 GHz/20 kW microwave generator is manufactured by GYCOM, Russia.
Commissioning test of 45 GHz system

Frequency: 44.991 GHz
Bandwidth (-1dB): < 50 kHz

Long-term CW mode stability test at 20 kW

Pulse mode operation test

Microwave mode test
<table>
<thead>
<tr>
<th>Parameters</th>
<th>SECRAL-II</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\omega_{rf}$ (GHz)</td>
<td>18-28</td>
</tr>
<tr>
<td>Axial Field Peaks (T)</td>
<td>3.7 (Inj.), 2.2 (Ext.)</td>
</tr>
<tr>
<td>Mirror Length (mm)</td>
<td>420</td>
</tr>
<tr>
<td>No. of Axial SNs</td>
<td>3</td>
</tr>
<tr>
<td>$B_r$ at r=63 mm (T)</td>
<td>2.06</td>
</tr>
<tr>
<td>Coldmass Length (mm)</td>
<td>810</td>
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<tr>
<td>SC-material</td>
<td>NbTi</td>
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<tr>
<td>Magnet Cooling</td>
<td>LHe bathing</td>
</tr>
<tr>
<td>Warm bore ID (mm)</td>
<td>142.0</td>
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<tr>
<td>Chamber ID (mm)</td>
<td>125.0</td>
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</tbody>
</table>
The Layout of the setup for 45 GHz test with SECRAL-II
Design of the 45GHz transmission line for SECRAL-II

Gaussian mode Purity > 95%

BN Widow

3850 mm

350 mm

1100 mm

4100 mm

Mirror1

Mirror2

Mirror3

Mirror4

Mirror5

Gyrotron MOU

MOU
Transmission line installation and test

- Stringent alignment
- Total efficiency of quasi-optical transmission line and mode converter is about 97%.
First 45 GHz ECR plasma

Quasi-optical transmission lines work well in the early tests up to 4 kW of power.

ω<sub>r</sub>: 48 GHz, P<sub>w</sub>= 4.0 kW, HV= 20 kV, Slit-x= 24 mm
Io= 5.0 emA, B: 3.4 T, 0.75 T, 2.04 T, 1.87 T
2017/10/12

ω<sub>r</sub>: 45 GHz, P<sub>w</sub>= 4.0 kW, HV= 20 kV, Slit-x= 24 mm
Io= 3.6 emA, B: 3.4 T, 0.6 T, 1.8 T, 1.87 T
2017/10/12

◆ Quasi-optical transmission lines work well in the early tests up to 4 kW of power.
Summary

- TE_{01} with Φ32mm circular waveguide coupling scheme can work for 45 GHz
- Quasi-optical transmission lines work well in the early tests up to 4 kW of power
- First 45 GHz plasma was obtained with SECAL-II

- What is the optimized microwave power injection scheme for 45GHz needs better understanding and more investigation
- Further detailed tests on SECAL-II with 45 GHz are planned, especially a systematic study of the magnetic field and measurements of the plasma bremsstrahlung at different conditioning parameters.
Thanks for your attention!
45 GHz Gyrotron at IMP
Gyrotron Magnetic System

The system based on JMTD 4T140 liquid helium free magnet (up to 4 T, warm bore Ø140 mm)
Operating magnetic field ~ 1.7 T
Microwave mode test
45GHz quasi-optical transmission line installation
1st pass absorption is important

Waveguide: Antenna

High directivity

Low directivity

Radiation with chamber wall

Ø32 mm $TE_{01}$

Ø20 mm $TE_{01}$

Ø20 mm $HE_{11}$