Design, Construction and First Commissioning results of SuSI

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The Origin of the Elements in the Universe

EGRET All-Sky Gamma Ray Survey Above 100 MeV

Crab Nebulae
Hubble Space Telescope

M82 Starburst Galaxy
Chandra X-Ray Observatory
Motivation for production of highly charged ions

- Intense highly charged ions are used in many accelerator applications.
- Dc beams for RIA/ISL, RIKEN RIB, etc.
- Pulsed beams for injection in synchrotrons such as RHIC, LHC, FAIR, hadron therapy.
- Higher M/Q from an ion source makes the accelerator more compact and less costly.
- There is generally a tradeoff between intensity and charge state from an ion source.

**Stand alone operation**

- Ion source: O^{8+} 5 keV/u
- Accelerator: O^{8+} 200 MeV/u

**Coupled operation**

- Ion source: O^{3+} 5 keV/u
- Accel. 1<sup>st</sup> stage: O^{3+} 16 MeV/u
- Accel. 2<sup>nd</sup> stage: O^{8+} 200 MeV/u

Stripping
ECRIS Basics

- the energy of the electrons should be higher than the ionization potential of the desired charge state
- the ions should be trapped for a time sufficient to reach the desired charge state since step-by-step ionization is the dominant process
- a minimum-B magnetic mirror configuration confines the particles
- electrons are heated by interaction with rf waves at the cyclotron frequency:

\[ \omega_{ce} = \frac{e|B|_{ecr}}{m_e} = \omega_{rf} \]

- the created ions are extracted and accelerated with electrostatic fields

A typical screen output for TrapCAD, a tool to design and study magnetic traps of ECRIS
Key parameters of an ECRIS

- **Magnetic field configuration:**
  \[ B_{\text{inj}} \approx 4 B_{\text{ECR}} \]
  \[ B_{\text{ext}} < B_{\text{rad}} \approx 2 B_{\text{ECR}} \]
  \[ B_{\text{min}} \approx 0.8 B_{\text{ECR}} \]
  \[ I \propto \log B^{1.5} \]

- **Microwave frequency:**
  \[ \omega_e = q B_{\text{ECR}} / m = \omega_{\text{rf}} \]
  \[ I \propto \omega_{\text{rf}}^2 M^{-1} \tau^{-1} \]

- **Extraction voltage:**
  \[ I \propto U_{\text{ext}}^{3/2} \]

- Plasma chamber geometry (length, diameter) and wall material
- Extraction system (gap, voltage, plasma electrode position)
- Biased disc (voltage, position)
Magnetic confinement

ECRIS = magnetic structure with B minimum

\[ B_{\text{last}}^2 = B_{\text{min}}^2 + B_{\text{rad}}^2 \]

Confinement: 5 parameters

\[ B_{\text{inj}} \approx 4 B_{\text{ECR}} \]
\[ B_{\text{ext}} < B_{\text{rad}} \approx 2 B_{\text{ECR}} \]
\[ B_{\text{min}} \approx 0.8 B_{\text{ECR}} \]
Plasma electrode location and biased disc effect

- The beam intensity is strongly dependent on the position of the bias disc.
- Desirable to have an adjustable length of the plasma chamber to be able to change the matching conditions between the plasma and the microwaves.
## B-min ECRIS dynasty

<table>
<thead>
<tr>
<th>Generation</th>
<th>Year</th>
<th>Frequency</th>
<th>Description</th>
<th>Power</th>
<th>Total Current</th>
<th>Q Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st generation</td>
<td>'80s</td>
<td>6 ÷ 10 GHz</td>
<td>SUPERMAFIOS, MINIMAFIOS, ECREVIS, CAPRICE, etc.</td>
<td>P &lt; 1 kW</td>
<td>I_{tot} &lt; mA</td>
<td>Q = 6 ÷ 12 for Argon</td>
</tr>
<tr>
<td>2nd generation</td>
<td>'90s</td>
<td>14 ÷ 18 GHz</td>
<td>ECR4, Hypernanogan, AECR, SC-ECRIS 18 GHz RIKEN</td>
<td>P = 1 ÷ 2 kW</td>
<td>I_{tot} = 1 ÷ 5 mA</td>
<td>Q = 8 ÷ 16 for Argon</td>
</tr>
<tr>
<td>2.5 generation</td>
<td>1998</td>
<td>14 ÷ 18 GHz</td>
<td>SERSE</td>
<td>P = 2 kW dc or pulsed</td>
<td>I_{tot} = 1 ÷ 5 mA</td>
<td>Q = 12 ÷ 18 for Argon</td>
</tr>
<tr>
<td>2.5 generation</td>
<td>2000</td>
<td>28 GHz</td>
<td>SERSE</td>
<td>P = 4 ÷ 7 kW dc or pulsed</td>
<td>I_{tot} = 5 ÷ 15 mA</td>
<td>Q = 12 ÷ 18 for Argon</td>
</tr>
<tr>
<td>2.5 generation</td>
<td>2002</td>
<td>28 GHz</td>
<td>PHOENIX</td>
<td>P = 4 ÷ 7 kW Pulsed</td>
<td>I_{tot} = 10 ÷ 20 mA</td>
<td>Q = 12 ÷ 18 for Argon</td>
</tr>
<tr>
<td>3rd generation</td>
<td>2004</td>
<td>≥ 28 GHz</td>
<td>VENUS, SECRAL, SuSI, MS-ECRIS, SC-ECRIS in RIKEN</td>
<td>P ≥ 10 kW dc or pulsed</td>
<td>I_{tot} = 10 ÷ 50 mA</td>
<td>Q = 14 ÷ 18 for Argon</td>
</tr>
<tr>
<td>4th generation</td>
<td>2010?</td>
<td>60-90 GHz</td>
<td>?</td>
<td>P = 50 ÷ 100 kW dc or pulsed</td>
<td>I_{tot} = 50 ÷ 100 mA</td>
<td>Q = 14 ÷ 18 for Argon</td>
</tr>
</tbody>
</table>
First 28 GHz operation (2000)
Designed for 18 GHz
$B_{\text{rad}} = 1.45$ T

Results of 28 GHz tests
- $I \sim f^2$, verified at 14, 18 and 28 GHz
- $P \geq 3$ kW
- Optimum $B_{\text{rad}}$ at 28 GHz $> 1.45$ T
The LBNL ECR ion source group leads the way to the next generation sources with VENUS

Challenges

- Superconducting Magnet
- 28 GHz microwave heating
- X-rays from the Plasma
- Ion Beam Transport

VENUS (2001)
4.0 T, 14 kW, 18 + 28 GHz

ECR (1983)
0.4 T, 0.6 kW, 6.4 GHz

AECR-U (1996)
1.7 T, 2.6 kW, 10 + 14 GHz

Normal conducting ▸ Super conducting

I_{6GHz} ➤ 4 x I_{6GHz} ➤ 16 I_{6GHz}
VENUS is the first ECRIS to address these challenges

Superconducting Magnets
State of the art cryostat

New Plasma Chamber

Beam Transport

- 28 GHz microwave plasma heating

Ta X-ray shielding

• Because of its unique position, VENUS was selected as prototype injector source for the next generation heavy ion facilities in the US
• 28 GHz operation since 2004
ECR Ion Sources at NSCL/MSU

RT-ECR (1985)
First ECRIS using iron return yoke
The first ECRIS with an integral large volume oven and heated liner
The first dynamically tunable SC ECRIS using the High-B mode

First Vertical SC ECR
Designed for 6.4 and 14.5 GHz
High B-mode demonstration at 6.4 GHz
Sextupole field too low for 14.5 GHz
(Quenching)
ECR Ion Sources at NSCL/MSU

ARTEMIS-A (1999)
- modified version of AECR-U from LBL

ARTEMIS-B (2005)
off-line test bench for ion source development
ECR Ion Sources at NSCL/MSU

**SuSI – Superconducting Source for Ions (2007)**

- **maximum magnetic fields:**
  - *Original Design:*
    - 2.6 T, 1.5 T axial field
    - 1.5 T radial field
  - *Tested (February 2006):*
    - 3.6 T, 2.2 T axial field
    - 2 T radial field
- **plasma chamber diameter:**
  - 101.6 mm (aluminum)
- **superconducting wire:**
  - 2x1 mm NbTi
  - Cu/SC ratio 3.00
- **operating frequency:**
  - *Phase I:* 18 + 14.5 GHz
  - *Phase II:* 24-28 GHz
- **maximum extraction voltage:**
  - 60 kV (ion source at +30 kV, beamline at −30 kV)
- **tunable plasma chamber length**
- **tunable bias disc position**
The Flexible Axial Magnetic Field Concept

\[ J_1 = J_2 = 61 \text{ A/mm}^2 \]
\[ J_3 = J_4 = -60 \text{ A/mm}^2 \]
\[ J_5 = J_6 = 74 \text{ A/mm}^2 \]

- the relative distance between the resonant zone and plasma electrode can be varied

\[ J_1 = 120 \text{ A/mm}^2 \]
\[ J_2 = J_5 = 0 \]
\[ J_3 = J_4 = -27 \text{ A/mm}^2 \]
\[ J_6 = 96 \text{ A/mm}^2 \]

- the distance between the two magnetic maxima can be varied
- the “depth” of the magnetic minimum can be varied
- the position of the magnetic profile can be shifted

\[ J_1 = J_6 = 0 \text{ A/mm}^2 \]
\[ J_2 = 170 \text{ A/mm}^2 \]
\[ J_3 = J_4 = -100 \text{ A/mm}^2 \]
\[ J_6 = 150 \text{ A/mm}^2 \]
SC hexapole coils

Similar technology as used in VENUS construction

High pressure liquid metal bladder to prevent movement

@ R=50 mm
The assembly of the SuSI magnet liquid nitrogen thermal shield.

The SuSI magnet cryostat before the super insulation is applied to the front and back end of the liquid nitrogen thermal shield.
SuSI Magnet Construction II.

- LHe vessel completed, leak checked.
- LN$_2$ shield completed.
- Vertical and horizontal support links installed.
- Cryostat was finished in Sept. 2006.
- Vacuum vessel installation was completed in Dec. 2006.

SuSI commissioning started in January 2007

The SuSI magnet yoke with the injection and extraction hardware and plasma chamber with electrical isolation ready for tests.
SuSI Injection Side and Plasma Chamber

Movable injection hardware with two microwave waveguides

• Testing at high voltage the plasma chamber with the electric isolation around
  • also visible the spare plasma chamber with electric insulator removed
SuSI Extraction Side

-30 kV

0 kV

DC break

-30 kV

puller moving mechanism

Accel-decel 3-element electrode system

+30 kV

-35 kV

puller
90° Analyzing Magnet I.

- vacuum chamber is electrically isolated from the rest of the magnet

Based on the LBL VENUS analyzing magnet design (M. Leitner)
90° Analyzing Magnet II.

Midplane magnetic field contours

${^{48}\text{Ca}^{8+}}$ beam through the analyzing magnet and the decelerator Einzel lens

- initial beam energy: $60 \text{kV} \times 8 = 480 \text{ keV}$
- final beam energy: $30 \text{kV} \times 8 = 240 \text{ keV}$
Beamline Elements

Decelerator Einzel lens

0 kV

+10 kV

-30 kV

55 kV ceramic breaker

Cooling tubes for the jaw

Stepper motor

Faraday cup

4-jaw slit system (max. opening: 90x90 mm) with Faraday cup (mounted in a 6-way cross, 8” CF)
The Floor Layout for SuSI in the Production Area

SuSI

ARTEMIS-A

To K500 cyclotron
SuSI photos
Mapping the magnet I.

Radial Probes

3D Probe

R = 29.1 mm

R = 42.7 mm

R = 56.2 mm

3D Probe

R = 55.9 mm

B_z

B_θ

B_R

Radial Probes

R = 56.2 mm

R = 42.7 mm

R = 29.1 mm
Mapping the magnet II. (solenoids)

Magnetic field maps of the individual solenoids
Lines – calculated values with AMPERE
Dots – measured values
Each coil was mapped at 100 and 300 Amp

Magnetic field maps of all solenoids
Lines – calculated values with AMPERE
Dots – measured values
Black: 290, 0, -50, -50, 0, 210 Amp
Red: 175, 175, -130, -130, 135, 135 Amp
Blue: 0, 390, -220, -220, 320, 0 Amp
Green: 390, 0, -66, -66, 0, 280 Amp
Mapping the magnet III. (hexapole)

I=500 A

R=56.2 mm

I=500 A

R=42.7 mm

Plasma chamber wall

Br = A + B1R + B2R^2
A=0.00457
B1=-0.00709
B2=0.00682

r=50.8 mm
Br_{ECR} = 2B

24 GHz

28 GHz

14.5 GHz

18 GHz
SuSI First plasma ignited on March 29, 2007

SuSI First charge state distribution obtained on June 8, 2007
NSCL People Involved in ECRIS Design and R&D

**Ion Source Physicists:**
- Dallas Cole
- Guillaume Machicoane
- Larry Tobos
- Peter Zavodszky

**Accelerator Physicists:**
- Marc Doleans
- Felix Marti
- Peter Miller
- Jeff Stetson
- Mathias Steiner
- Xiaoyu Wu
- Qiang Zhao

**Mechanical Engineers:**
- Ben Arend
- Jim Moskalik
- Jack Ottarson

**Electronic and RF Engineers:**
- Kelly Davidson
- Bill Nurnberger
- John Vincent

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- Scott Hitchcock
- Al Zeller
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- **T. Nakagawa** – RIKEN, Tokyo, Japan