ECR Ion Sources-Past, Present and Future

- Production of Highly Charged Ion Beams
  - Physics
  - Technology
  - Challenges
  - Recent experiments at Berkeley
Eugen Goldstein
Sitzungsbericht Berl. Akad. 25. July 1886
Wied. Ann. 64 (1898)38

4. Ueber eine noch nicht untersuchte Strahlungsform an der Kathode inducirter Entladungen; von E. Goldstein.

Das Kathodenlicht der Entladung des Inductoriums durch verdünnte Gase besteht aus mehreren verschieden gefärbten Schichten. In verdünnter Luft ist die der Kathode unmittelbar anliegende Schicht chamosgelb gefärbt, die zweite erscheint blau und lichtschwach, die dritte violettblau und hellleuchtend. Die erste Schicht ist ungeachtet ihrer Helligkeit von der weitaus grössten Zahl von Autoren ganz ignoriert worden; die wenigen, die ihrer gedenken, gehen meist über die Constatirung ihrer Existenz nicht hinaus. Untersuchungen
Incoming electron must have kinetic energy greater than the ionization potential of the electron in the shell. Highest cross section for $E_e \sim 3-5 \times$ ionization potential

Ionization Potential for 1s electron
$E_{ip} = 13.6 \times Z^2 \text{ eV}$
Electron Impact Ionization

- **Low charge states**
  - high cross sections
  - low ionization potentials
  - 0 to 1$^+$
    - $10^{-16}$ cm$^2$
    - $I_p \sim 16$ eV
    - $E_{opt} \sim 60$ eV

- **High charge states**
  - low cross sections
  - high ionization potentials
  - 15$^+$ to 16$^+$
    - $10^{-19}$ cm$^2$
    - $I_p \sim 939$ eV
    - $E_{opt} \sim 3000$ eV

Production of high charge states requires a high density of hot electrons and long confinement time
Atomic Physics is well known and the CSD can be modeled if the plasma parameters are known.

The ion charge state distribution in an ECRIS can be reproduced with a 0 Dimension model including a set of balance equations:

\[
\frac{\partial n_i}{\partial t} = \sum_{j=j_{\text{min}}}^{i-1} n_e n_j \langle \sigma_{j \rightarrow i}^{\text{EI}} v_e \rangle + n_0 n_{i+1} \langle \sigma_{i+1 \rightarrow i}^{\text{CE}} v_{i+1} \rangle - n_0 n_i \langle \sigma_{i \rightarrow i-1}^{\text{CE}} v_i \rangle - \sum_{j=i+1}^{j_{\text{max}}} n_e n_j \langle \sigma_{i \rightarrow j}^{\text{EI}} v_e \rangle - \frac{n_i}{\tau_i}
\]

- \( n_i \) ion density with charge state \( i \)
- \( \sigma \), cross section of microscopic process
  - Electron impact or charge exchange here
- \( \tau_i \) is the confinement time of ion in the plasma
- \(- \frac{n_i}{\tau_i} \) represents the current intensity for species \( i \)
- Free Parameters: \( n_e, f(ve), \tau_i, n_0 \)
- Model can be used to investigate ion source physics

- Needed parameters
  - Plasma density
  - Electron energy dist
  - Ion confinement time
  - Neutral density
The peak of the CSD is mainly determined by the product of the plasma density and ion confinement time $n_e \tau_i$.

Highest charges states are determined by the neutral density $n_0$ (charge exchange).
Golonvaniskii criterion
\[ n_e \tau_i \sim 1 \times 10^{17} \text{ s/m}^3 \text{ at 9 keV for VENUS} \]

Lawson criterion for D-T fusion
\[ n_e \tau_E \geq 1.5 \times 10^{20} \text{ s/m}^3 \text{ at 25 keV} \]
Plasma Properties

- Partially or fully ionized gas consisting of free electrons and free ions as well as neutral atoms and molecules
- Overall neutral: $N_e = \Sigma q_{ion} \cdot N_{ion}$
- Need to be constantly heated to be sustained (fusion in stars, on earth energy must be added)
- Must be confined if it should be sustained for some time (gravity in stars, on earth with magnetic fields)
- Plasma frequency scales as the square root of density
- $\omega_p = \sqrt{\frac{n_e e^2}{\varepsilon_0 m}}$ where
  - $\omega_p$ plasma frequency
  - $n_e$ plasma density
  - $e$ electron charge
  - $m$ electron mass

ECR plasma
Electrons in a magnetic field

- Electron cyclotron frequency
  \[ \omega_{ec} = \frac{eB}{m_e} \]
- 28 GHz ~ 1 Tesla
- Magnetic mirror can trap electrons
- Mirror ratio \( R_m \)
  \[ R_m = \frac{B_{\text{max}}}{B_{\text{min}}} \]

\( \omega_{ec} \) electron cyclotron frequency

\( e \) electron charge

\( B \) magnetic field

\( m_e \) electron mass
The superposition of axial mirrors and a sextupole provide a minimum $B$ magnetic field confinement and a closed ECR resonance zone.

**Solenoid Coils**

**ECR Zone**

$B_{ecr} = \omega_{rf} m_e / e$

**Sextupole**

$B_{radial} = kr^2$

Typical $B$ fields at 28 GHz

- **Axial field**
  - $2.8 \text{ T}$

- **Radial field**
  - $2.0 \text{ T}$
Magnetic field geometry

Field lines crossing the ECR zone and terminating on the plasma chamber walls for VENUS
Plasma marks on VENUS

Injection
(bias probe)

Extraction
Launching Microwave Power into an ECR Ion Source

**Typical B fields at 28 GHz**

**Launching Microwave Power into an ECR Ion Source**

**ECR Zone**

$$B_{ecr} = \omega rf \frac{m_e}{e}$$

Microwaves couple to the electrons at the ECR surface

High density plasma inside The ECR Zone—"Plasmoid"

18 GHz

28 GHz
Simplified Model for Electron Cyclotron Resonance Heating

\[ \omega = \frac{eB}{m_e} \]

RF E field vs time

ECR heating occurs when the electron cyclotron frequency equals the RF frequency. Depending on the phase of the electron and the RF wave the electron can be heated or cooled. If stochastic heating is assumed, on average energy is gained.
Plasma density in High Charge State ECR ion sources

- The plasma frequency $\omega_p$ is the natural oscillation frequency of a plasma with the electrons oscillating against ions … where $n_e$ is plasma density

$$\omega_p = \sqrt{\frac{n_e e^2}{m_e \varepsilon_0}}$$

- Simplest dispersion relation of EM wave in a plasma is

$$\omega^2 = \omega_p^2 + k^2 c^2$$

- EM propagates if

$$n_e < \frac{m_e \varepsilon_0 \omega^2}{e^2}$$

- Plasma critical density $n_{critical}$ when $n_e = \frac{m_e \varepsilon_0 \omega^2}{e^2}$

- Above the critical density many EM waves no longer propagate
- High charge state ECR ion sources are believed to operate below the critical density

- $n_{critical}$ at 28 GHz is $9.9 \times 10^{18} /m^3$
Frequency scaling in ECR ion sources

- Geller proposed scaling for ECR ion sources 1987
  - Plasma density \( n_e \sim f^2 \)
    - Based on the assumption \( n_e < n_{\text{critical}} \) and measurements at 10 to 18 GHz
  - Beam current \( I \sim n_e \sim f^2 \)

\[
B_{\text{ecr}} = m \frac{\omega_{\text{rf}}}{e} \quad \text{(Electron cyclotron resonance condition)}
\]

- In the 1990’s experiments showed there is an optimum magnetic field for confinement
  - \( B \geq 2 \ B_{\text{ecr}} \) at the plasma chamber walls
  - \( B_{\text{inj}} \sim 3 \ B_{\text{ecr}} \) on axis
  - \( B_{\text{rad}} \geq 2 \ B_{\text{ecr}} \) on the walls
  - \( B_{\text{ext}} \sim B_{\text{rad}} \)
  - \( B_{\text{minimum}} \sim 0.4-0.8 \ B_{\text{ecr}} \) on axis
ECR Ion Source Pioneers

Richard Geller  Yves Jongen

6th Workshop on ECR Ion Sources Berkeley 1985
High Charge State Ion Sources—ECRIS

**Supermafios (Geller, 1974)**
- 15 eµA of O$^{6+}$
- Power consumption 3 MW
- Solenoid, Sextupole, Axial Extraction

**VENUS (2011)**
- 3000 eµA of O$^{6+}$
- Power consumption 100 kW
- Solenoid, Sextupole, Axial Extraction
Minimafios Grenoble ~1979 Geller’s group
ECREVIS circa 1983

First successful superconducting ECR ion source

Yves Jongen, Louvain-la Neuve, Belgium
Microwave power for ECR Ion sources

• 6.4 to 18 GHz klystrons are used
  – (2-3 kW CW)
  – narrow bandwidth typically ~100 MHz

• 5 to 18 GHz TWT’s
  – 300—500 W
  – Broadband width ~ several GHz

• Above 18 GHz and below 31 GHz
  – 24 and 28 GHz 10 kW cw gyrotrons can be used
  – 1 kW CW EIO (extended interaction oscillators commercially available)
  – CPI has devices at ~1 kW and frequencies 27-31 GHz

• Above 30 GHz existing gyrotrons are pulsed with peak powers ≥100 kW, but these could be de-rated to operate at CW (~30 kW)
Higher magnetic fields and higher frequencies are the key to higher performance.

**Normal conducting**

**Super conducting**

**Analyzed beam current [eµA]**

<table>
<thead>
<tr>
<th></th>
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<tbody>
<tr>
<td>10</td>
<td>0.4 T, 0.6 kW, 6.4 GHz</td>
<td>1.7 T, 2.6 kW, 10 + 14 GHz</td>
<td>3.5 T, 14 kW, 18 + 28 GHz</td>
</tr>
</tbody>
</table>

**ECR 6 GHz**

**ECR 28 GHz**

**ECR 14 GHz**

**Time, Money, Technical Complexity**
VENUS 28 GHz Superconducting ECR Ion Source

First plasma 2002
28 GHz operation in 2004
**VENUS Magnet Development and Performance**

**28 GHz VENUS**

Main challenge are the forces between the sextupole and solenoid magnet coils.

Special clamping technique has solved this problem for the VENUS source.

The sextupole magnet is routinely run above design currents.

Achieved:
- 4T, 3T (inj,ext)
- 2.2 T plasma wall
VENUS Technology Development
Now Incorporated Into Other 3rd Generation Sources

Advanced cryostat with cryocoolers

Beam transport with high transmission dipole magnet

Aluminum plasma chamber for high power operation with incorporated tantalum x-ray shield

Water cooling for high power

Ta X-ray shield

28 GHz ceramic 30 kV HV break
Overview of VENUS

• **Fully superconducting**, Niobium-Titanium sextupole & 3 solenoids enclosed in LHe
• **LN Reservoir**: 70K, dissipates heat from normal conducting leads
• **LHe Reservoir**: 4.2K
• **Four two stage cryocoolers** which provide 6W total cooling power at 4.2K, recondense evaporated He, 1st stage (45K) cools part of the Cu leads

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
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<tbody>
<tr>
<td>Maximum Injection Field, on axis</td>
<td>4.0T</td>
</tr>
<tr>
<td>Maximum Extraction Field, on axis</td>
<td>3.0T</td>
</tr>
<tr>
<td>Maximum Radial Field, at wall</td>
<td>2.2T</td>
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<tr>
<td>Chamber Diameter</td>
<td>14cm</td>
</tr>
<tr>
<td>Chamber Length</td>
<td>50cm</td>
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<tr>
<td>18 GHz Maximum Power</td>
<td>2kW</td>
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<tr>
<td>28 GHz Maximum Power</td>
<td>10kW</td>
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<tr>
<td>28 GHz Maximum Power Injected</td>
<td>6.5kW</td>
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<tr>
<td>18+28 GHz Maximum Power Injected</td>
<td>8.5kW</td>
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VENUS Recent Results

Uranium Charge State Distribution

<table>
<thead>
<tr>
<th>Ion</th>
<th>Intensity $\mu A$</th>
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<tbody>
<tr>
<td>He$^{2+}$</td>
<td>11,000</td>
</tr>
<tr>
<td>O$^{6+}$</td>
<td>3,000</td>
</tr>
<tr>
<td>Ar$^{11+}$</td>
<td>860</td>
</tr>
<tr>
<td>Ca$^{11+}$</td>
<td>400</td>
</tr>
<tr>
<td>Bi$^{31+}$</td>
<td>300</td>
</tr>
<tr>
<td>Bi$^{50+}$</td>
<td>5</td>
</tr>
<tr>
<td>U$^{33+}$</td>
<td>440</td>
</tr>
<tr>
<td>U$^{50+}$</td>
<td>13</td>
</tr>
</tbody>
</table>
88-Inch Cyclotron Facility

VENUSS Applications
- Heavy element research
  - 70 eµA Ca^{11+}
- Space radiation effects testing
  - 100 enA Xe^{43+}
  - ECR Ion Source R&D

AEGR-U Applications
- Nuclear physics research
- Space radiation effects

\[ \frac{E}{M} = \frac{Q}{M} \times K \]

88 - Inch Cyclotron

K = 130
5 MeV/nuc \quad M/Q \leq 5

4/18/2014 Columbia University
Claude Lyneis LBNL
Demand for increased intensities of highly charged heavy ions from ion sources continues to grow.

- **FRIB, MSU, USA**
  - 270 eµA $\text{U}^{33+}$ and 270 eµA $\text{U}^{34+}$

- **SPIRAL 2, GANIL, France**
  - 1mA $\text{Ar}^{12+}$

- **IMP HIRFL, LANZHOU, China**
  - 525 eµA $\text{U}^{35+}$

- **RAON, S. Korea**
  - 400 µA $\text{U}^{33+}$

- **RIKEN, Japan**
  - 750 µA $\text{Bi}^{35+}$
Research and Applications for High Charge State Ions

• Accelerator Applications
  – Nuclear and High Energy Physics
    • Heavy-ion Accelerators for nuclear physics research
    • Driver linacs for rare isotope beam production
    • Charge breeders for rare isotope post accelerators
    • Heavy-ion synchrotrons (CERN LHC)
    • EIC (Electron Ion Collider—Next Nuclear Physics Initiative)
  – Space Radiation Effects Testing (simulating cosmic ray environment)
    • Testing of electronic devices for space vehicles
  – Particle Therapy
    • Proton Therapy
    • Hadron Therapy (Carbon Beam Therapy)
• Atomic Physics
  • Charge exchange cross section
  • Astrophysics (effect of high charge state plasmas on optical transmission)
• Fusion Materials Testing
  – High intensity proton sources $\geq 100$ mA
  – First wall lifetime studies
Fourth Generation ECR Ion Sources

\[ B_{ecr} = m \frac{\omega_{rf}}{e} \]

For a 56 GHz ECR \( B_{ecr} = 2 \text{ T} \)

Confinement criterion

\( B_{conf} \geq 2 B_{ecr} \) at walls

\( B_{inj} \sim 3 B_{ecr} \) on axis

\( B_{rad} \geq 2 B_{ecr} \) on the walls

GenIV-ECR

- \( B_{inj} \sim 6 \text{ T} \)
- \( B_{ext} = 4 \text{ T} \)
- \( B_{rad} = 4 \text{ T} \)
Starting point—VENUS Geometry
Frequency---56 GHz (twice that of VENUS)
we expect the magnet to go resistive 'quench' where the peak field load line crosses the critical current line *
Operational condition at 28 – 42 – 56 GHz
(B_{injection} = 3.5 \, B_{ecr})
The superposition of solenoid and sextupole magnets in an ECR source leads to very complex forces. Magnets must be prestressed to avoid motion under the Lawrence forces. Maximum stress must be ≤160 MP. Higher stress levels result in degradation of the superconducting material properties.
Shell-based Mechanical Structure

- Primary mechanical support is provided by a thick Aluminum shell
- Assembly (warm) pre-load by pressurized bladders and interference keys
- Pre-load increase at cool-down due to shell-yoke differential contraction
- The coils remain in compression up to the operating point
GenIV-ECR Cryostat Design

- Two 5 W GM-JT cryocoolers at 4.2 K
- One shield cryocooler 6 W at 20 K and 120 W at 77 K
- High Tc leads
- Static heat load 1.5 W
- Magnets on + 0.15 W
- Warm bore 170 mm ID

- Designed for HV platform
- No LN cooling
In the ECR community, much of the experimental knowledge is based to the properties of the extracted ion beams, such as charge state distributions, extracted current intensities and time evolution of the charge state distributions.

However the ions are relatively passive participants, they are cold ~ a few eV, they don’t couple to the RF heating and the instabilities are from the plasma electrons.

To improve our understanding of ECR ion source plasma, we need to focus on the electron dynamics and develop/apply diagnostics to study the electrons.

Questions:
- How strong is the RF coupling/damping in an ECR plasma chamber?
- What limits the plasma density?
- How can we get a handle on these questions?
RF coupling models

• The plasma chamber can be considered a multimode cavity filled with a lossy material.
  – Typical ECR plasma chambers are highly over-moded, so the eigenmodes of the cavity are very closely spaced
  – Models often assume a single mode is excited, but except at very low densities the modes will overlap
  – Models often neglect the plasma loading and assume the chamber has a $Q_0$ similar to an empty chamber ~2000 to 5000 would be typical of an aluminum chamber at vacuum

• The few pass approach assumes strong damping for the RF launched from in injection waveguide
  – Single pass damping is not well know and depends on density
  – RF not adsorbed in the first pass is then reflected by the chamber walls—Complex to model
Pulsed Microwave Transmission Measurements On VENUS at 18 GHz

Time scale 40 ms/cm
Time scale 400 µs/cm
Instabilities after RF On for ~ 300 ms

Transmitted 18 GHz (inverted)

Time scale 400 µs/cm
28 GHz system for VENUS

- Modifications needed to launch 28 GHz quasi-Gaussian microwaves
  - Move injection of 28 GHz closer to the axis
  - Convert from $\text{TE}_{01}$ to $\text{HE}_{11}$ in the injection section
  - Minimize the required changes to the VENUS system
VENUS Injection

18 GHz waveguide

28 GHz waveguide

HV Break
HE$_{11}$ and TE$_{01}$ modes
Calculated mode conversion and excitation of undesirable modes

97% into TE11

<table>
<thead>
<tr>
<th>Modes</th>
<th>Curvature Coupling Coefficients</th>
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<tbody>
<tr>
<td>TE11-TM21</td>
<td>0.2605380</td>
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<tr>
<td>TE11-TE22</td>
<td>-0.0883540</td>
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<tr>
<td>TE11-TM22</td>
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<tr>
<td>TE11-TM02</td>
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<tr>
<td>TE11-TM01</td>
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<tr>
<td>TM11-TM02</td>
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<tr>
<td>TM11-TM01</td>
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<tr>
<td>TE01-TE11</td>
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<td>TE01-TE12</td>
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<tr>
<td>TM11-TM21</td>
<td>2.4503221</td>
</tr>
</tbody>
</table>
Designing $\text{TE}_{01}$ to $\text{TE}_{11}$ mode converter

- To convert $\text{TE}_{01}$ into $\text{TE}_{11}$ with a snake we used a circular over-moded waveguide where the diameter is constant but the center is displaced in the $y$ direction as a function of path length.
- As the microwave power flows down the waveguide the curvature of the waveguide couples the different microwave modes, which are eigenmodes in a smooth waveguide.
- A short corrugated waveguide then converts $\text{TE}_{11}$ into $\text{HE}_{11}$

This technology was developed in the fusion community between 1980 and 2000.
New VENUS Injection Assembly

18 GHz waveguide

SNAKE $TE_{01}$ to $TE_{11}$

$TE_{11}$-$HE_{11}$ converter

Plasma Screen
Initial tests with HE$_{11}$ mode launcher

- Installation beginning of August 2013
- It has performed very well in the early tests.
  - Up to 5 kW of power
  - No problems with arcing or parasitic mode generation
- Compared to the old system
  - Tuning appears to be broader
  - Smoother dependence on 28 GHz power (more monotonic)
  - Some indications of improvements when used in two frequency mode with the 18 GHz
- While it works well, no significant improvement has been demonstrated yet.
Conclusion

• The performance of ECR Ion Sources has steadily improved over the last 40 years
  – Although from 2006 to present performance is relatively flat
• A detailed theoretical picture of the plasma physics is still open for improvement
• More plasma diagnostics for the hot electron parameters and for RF adsorption would be welcome
• Frequency scaling is roughly correct from 6 to 28 GHz and is expected to work for 4\textsuperscript{th} generation ECR’s at ~50 GHz
• The technical challenges at 50 GHz make it attractive to look for new approaches