CYCLOTRON 13

ECR SOURCE DEVELOPMENT

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LBL from 08/12 to 08/13
Preamble

• The ECRIS’12 Workshop and the ICIS’13 Conference demonstrated that the ECR Ion Source field is still very active

• Many interesting new developments have been presented in the last years, but it’s unfortunately impossible to summarize all of them in 25 minutes

• The philosophy retained for this presentation is to focus on some
  • new challenging projects
  • newcomers
  • Original/exotic developments
OUTLINE

• ECRIS DEVELOPMENT FOR (non cyclotron) ACCELERATORS
  • FRIB (MSU)
  • SPIRAL2 (GANIL)
  • RISP (IBS) newcomer
  • KBSI (KBSI Busan) newcomer

• SOME ORIGINAL/EXOTIC ECRIS DEVELOPMENT
  • INTENSE PULSED PROTON BEAMS AT IAP (IAP RAS)
  • INDUSTRIAL APPLICATIONS WITH THE COMIC SOURCES (LPSC)
  • $TE_{01} \rightarrow HE_{11}$ MODE CONVERTER FOR THE VENUS ECR ION SOURCE (LBL)
  • MASS SPECTROSCOPY (ANSTO) newcomer
ECR developments for the FRIB project

- A facility to study nuclei synthesis and properties far from stability by means of radioactive ion beams
- Accelerate ion species up to $^{238}$U with energies of no less than 200 MeV/u
- Provide beam power up to 400 kW to the target

- 450 µA of $^{238}$U$^{33+}$+$^{238}$U$^{34+}$ required from the source
- Beam norm. emittance (99%):
  - <0.9 $\pi$.mm.mrad (for single charge)
  - <0.6 $\pi$.mm.mrad (for dual charge)
**ECR Developments for the FRIB Project**

**FRIB ECR systems**

- Two ECR on two 100 kV HV platforms:
  - Existing ARTEMIS ECRIS (room temp.)
    - For commissioning
  - An upgraded version of VENUS
    - For high intensity beam operation
    - Under design

- A complex achromatic LEBT to transport simultaneously $^{33+}U$ and $^{34+}U$ beams
  - The LINAC is one floor below (not shown here)
Uranium production test with VENUS (LBNL+MSU)

- Impressive Uranium spectrum!
- Oven with a Rhenium crucible
  - \( U \) consumption \( \sim 9 \text{ mg/h} \)
- 2 kW 18 GHz + 6.5 kW 28 GHz
  - VENUS tuned to its maximum experimental power
- LEBT transmission limited at 22 kV
  - HV drain 9 mA, FC tot \( \sim 5 \text{ mA} \)
- No production limitation observed: source still responsive with power and oven temperature

- Emittance compatible with FRIB specification

Validates the FRIB operation

With 220 µA \( U^{33+} \) + 220 µA \( U^{34+} \)
VENUS upgrade for FRIB

- VENUS original design

- Cold mass of FRIB SC-ECR essentially identical to VENUS
  - re-design entrusted to LBL Superconducting Group (see next slides)

- Original VENUS Cryostat extensively modified (MSU)
  - Cooling rely only on cryocoolers
  - Added cooling capacity at 4.2 K (8 to 9W total vs. 5 to 6 W for VENUS)
  - Optimized material, and design to minimize heat leak and simplify maintenance
FRIB / VENUS upgrade: possible new cold mass design

- New cold mass mechanics design for the coils
  - Bladders and Keys
- Each sextupole coil is dismountable
- Pre-stress can be modified/optimized
  - By changing the keys size

*OPTIMIZATION:
Yoke keyway features can be incorporated in the Solenoid Bobbin – eliminating a thin, cylindrical machining. Also, the Load Pads can be made thicker and structurally stable.
FRIB / VENUS upgrade: possible new cold mass design

• Exploded View

ECR Developments for the FRIB Project
ECR development for the Spiral2 project

- GANIL extension to produce radioactive ion beams (RIB)
  - 5 mA Deuterons on target
  - Re-acceleration of RIBs in existing cyclotron
- Stable Heavy ion program with the LINAC
  - Super Separator Spectrometer
  - Neutron for Science

**ECR challenge:**
- Produce 1 mA A/Q=3 beams up to the argon mass at 60 kV
- Produce high intensity Metallic beams (Ni, Ca, S, Si, C…)
- Emittance $1\sigma$ norm. RMS<0.4 $\pi$.mm.mrad
Deuteron Spiral2 LEBT commissioning

- A variation of the SILHI (Taylor) source
  - Permanent magnets
  - The source produces up to 100 mA of D+
  - 0.1 to 5 mA required @ 40 kV OK (see plot)
  - Emittance OK

- Source ant LEBT commissionned at CEA/IRFU Saclay

- Now under assembly at GANIL
A/Q=3 ECR and LEBT commissioning

• Source and LEBT commissioned at LPSC, Grenoble
  • Excellent transmission (T>90%)
• Starter source is PHOENIX V2
  • Room temperature 18 GHz ECRIS
  • OK for LINAC commissioning at GANIL and first year experiments
  • Emittance OK
• But a new high performance ECRIS should be built (and financed) to fulfill the final beam requirement

<table>
<thead>
<tr>
<th>Ion</th>
<th>Required (µA)</th>
<th>PHOENIX V2 (µA)</th>
<th>World record (µA)</th>
<th>Ref.</th>
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<tbody>
<tr>
<td>O(^{6+})</td>
<td>1000</td>
<td>1300</td>
<td>3000</td>
<td>VENUS</td>
</tr>
<tr>
<td>S(^{12+})</td>
<td>240</td>
<td>55</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
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<td>420</td>
<td>50</td>
<td>514</td>
<td>VENUS</td>
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<tr>
<td>Ca(^{16+})</td>
<td>160</td>
<td>16</td>
<td>70</td>
<td>SECRAL</td>
</tr>
<tr>
<td>Ni(^{19+})</td>
<td>57</td>
<td>19</td>
<td>50</td>
<td>SUSI</td>
</tr>
</tbody>
</table>

Heavy ion LEBT @ LPSC
Spiral2 ECR A/Q=3 upgrade and prospect

- PHOENIX V2 → PHOENIX V3 upgrade
  - Increase the plasma chamber volume: 0.7 → 1.4 litre
  - ECR Magnetic confinement kept identical
  - Expected shift of CSD: Gain expected +50-100% on A/Q=3
  - Under design, to be assembled and tested in 2014

- Long term upgrade: design and build a superconducting 28 GHz ECRIS
  - Pending funding
The Rare Isotope Science Project (Institute of Basic Science)

- A new RIB facility to study nuclei far from stability in Rep. of Korea
- Project approved in 2009
- The beam requirement is to accelerate ion from H to $^{238}$U.
- ECRIS requirement:
  - 400 $\mu$A of $^{238}$U$^{33+}$+$^{238}$U$^{34}$ (déjà vu)
  - 1 $\sigma$ norm. Emittance <0.1 $\pi$.mm.mrad
ECRIS development for the RAON accelerator

- A Newcomer team in the ECRIS community from Daejeon
- A 28 GHz superconducting ECRIS is under development
  - Overall dimension and cryostat technology similar to VENUS
  - 4 axial coils instead of the usual 3 (inspired by the SUSI SC (MSU) with its 6 coils)

Boundary condition:

$B_{\text{inj}} > 3.5B_{\text{ecr}}$, $B_{\text{ext}} \approx 2B_{\text{ecr}}$, $B_r \approx 2B_{\text{ecr}}$, $B_{\text{min}} \approx 0.8B_{\text{ecr}}$

Design result:

$B_{\text{inj}} = 3.61$ T, $B_{\text{ext}} = 2.07$ T, $B_r = 2.17$ $B_{\text{ecr}}$, $B_{\text{min}} = 0.545$ T
Superconducting coil prototyping

• 3 single hexapolar coils prototype have been built
  • Rectangular wire 1.9x1 mm² with Cu:NbTi ratio of 3:1
  • 1 saddle coil wet winding, no fiber cloth
  • 1 racetrack coil pre-preg impregnation (wet winding, fiber cloth)
  • 1 saddle coil, pre-preg impregnation => validated
Superconducting coil test performed in LHe

- The final saddle prototype reached 95% of wire Ic current data
  - Validation of the design
- Other coils under construction
- Final assembly and test will follow
A new compact LINAC at the Korean Basic Science Institute, (KBSI), Busan, South Korea

- Project started in 2009
- The goal is to produce intense fast neutron flux up to $5 \times 10^{13}$ n/s applied to neutron radiography
- A LINAC accelerates 1 mA of $^7\text{Li}^{3+}$ to produce fast neutron flux in a windowless hydrogen target
  - LEBT equipped with a 28 GHz SC ECR Ion Source
  - RFQ 500 kV/u
  - DTL 3 MeV/u

Unfortunately only a few papers available on the topic…
A new 28 GHz ECRIS at KBSI

- Another Newcomer Team in the ECR community
- The ECRIS construction is well advanced
  - The ECRIS design and technology is close to VENUS (LBNL)
  - Except for the hexapole coils which are more inspired from SECRAL (IMP Lanzhou)
    - Racetrack coils with a trapezoid section
A new 28 GHz ECRIS at KBSI

- Individual Coil test in a vertical cryostat
  - Axial coils OK
  - Hexapole reacetrack at 70% of design
    - At least suitable for a high performance 18 GHz operation (1.5T)
  - Tests stopped because of LHe shortage
A new 28 GHz ECRIS at KBSI

- The source has been assembled recently:
  - We wish them good luck with the final global magnetic test!
SMIS 37 is a pulsed ECR operated at 37.5 GHz

- RF power up to 100 kW
- Pulse duration ≤ 1.5 ms
- Optical microwave coupling
- Gaussian beam (linear polarization)
- Fast pulsed gas valve (5 ms pulse)
- Water cooled pulsed coil
  - Capacitor discharge (T/2=11 ms)
  - Bmax~4 T
- HV ≤ 65 kV
- Beam Current measured right at the extraction in a Faraday cup
- Or current analyzed in a bending magnet
- Beam emittance measured with a pepper pot
- Gasdynamic regime (collisional plasma), P~10^{-3}-10^{-4} mbar
450 mA of H⁺

- SMIS 37 produces pulses up to 450 mA of H⁺
  - Diode Ion Extraction:
    - HV electrode Ø10 mm
    - ground electrode Ø22 mm
  - Proton fraction ~95%
H$^+$ Emittance measurement

- SMIS 37 Beam emittance
  - 450 mA H+
  - Current density~600 mA/cm$^2$
  - 90% norm. Emittance is $0.3 \, \pi \, \text{mm.mrad}$
    - So RMS norm. Emittance~0.06 $\pi \, \text{mm.mrad}$

- Why is the emittance so small?
  - Because the magnetic emittance is small!
  - Plasma drifts far out of the magnetic trap and the beam is accelerated where $B \ll B_{\text{max}}$
COMIC sources at LPSC

- COMIC 2.45 GHz
  - Compact ECR source operated at low power
  - 10 W solid amplifier

Industrial applications with the COMIC sources at LPSC
Industrial applications with the COMIC sources at LPSC

**COMIC 2.45 GHz**

- 1W vacuum ECRIS

Diagram with labels:

- Faraday cup
- ground electrode
- Intermediate electrode
- COMIC source
- 1W isolator
- 1W 2.37-2.51 GHz
- 12 V/ 500 mA

Ar - 24 µA - Φ 1 mm - 20 KV (18 KV) - 1 W - ~ 3 mA/cm²
COMIC 2.45 GHz

- Emittance - Xenon – 1.8 µA tot / 3 W / Ø 0.3 mm / 15 kV

1 σ RMS
1.2 π.mm.mrad
15 KV
3/10 mm ext.
Industrial applications with the COMIC sources at LPSC

COMIC Application on a Focusing Ion Beam

- Orsay Physics FIB

COMIC source inside

Microsurgery Of an ant head
COMIC Application for Implantation

• Multi-beam implanter  10 sources (HV>30 kV)
COMIC Application for thin film deposition

- Multi-Beam Sputtering with 20 ECR sources
COMIC 5.8 GHz

- The Goal is to improve the current density (ECR scaling law)
  - Quarter wave cavity down-scaled from 2.45 to 5.8 GHz
  - A clear current increase is observed
    - Higher plasma density

15 kV - Ø 0.3 mm extraction - Ar gas pressure:
2\times10^{-6} \text{ mbar at 2.45 GHz}
1\times10^{-5} \text{ mbar at 5.8 GHz}
TE$_{01}$ to HE$_{11}$ Mode Converter for the VENUS ECR Ion Source

**Motivations:**

- The usual 18 GHz mode injected in an ECRIS is the TE$_{10}$
  - Transverse Electric, linearly polarized
  - Rectangular waveguide
  - Efficient plasma coupling
  - Excellent performance vs RF power
- The 24/28 GHz mode injected in new generation ECRIS is the TE$_{01}$
  - Oversized circular waveguide
  - Transverse Electric circular polarization
  - The RF power density profile is hollow
  - Weaker performance vs power observed /18 GHz
- Is this weaker performance coming from the TE$_{01}$ mode used?
**HE\textsubscript{11} mode vs TE\textsubscript{01}**

- The HE\textsubscript{11} mode is used in fusion research since the 80’s
  - HE\textsubscript{11}=Hybrid Electric~85\%TE\textsubscript{11}+15\%TM\textsubscript{11}
  - Quasi gaussian beam profile with a linear polarization

- The HE\textsubscript{11} @ 28 GHz is nearly equivalent to the TE\textsubscript{10} @ 18 GHz
HE\textsubscript{11} conversion steps

• The mode conversion is done into two steps:

1) Convert the TE\textsubscript{01} to TE\textsubscript{11} using a circular waveguide whose center is wiggling in a direction perpendicular to the waveguide axis. This is the « Snake ». 

2) Convert partially the TE\textsubscript{11} to TM\textsubscript{11} to build up the HE\textsubscript{11} in a corrugated waveguide whose groove depth is following a special curve from \(\lambda/2\) to \(\lambda/4\)
Snake optimum profile

- Obtained by a simulation program

Length 650 mm

X (m) vs. Axis location (mm)

-4.7 mm

+1.0 mm

TE01 → HE11 mode converter for the VENUS ECRIS at LBL
**Snake calculated mode conversion profile**

**Modes**

<table>
<thead>
<tr>
<th>Curvature Coupling Coefficients</th>
<th>Energy (normalized to 1)</th>
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<tbody>
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<td>TM11-TM21</td>
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</tbody>
</table>

97% into TE11

T. Thuillier, LPSC, CYC’13, Vancouver, Canada, September 17, 2013
New VENUS Injection Assembly

18 GHz waveguide

SNAKE $\text{TE}_{01}$ to $\text{HE}_{11}$

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

Plasma Screen

$\text{TE}_{01} \rightarrow \text{HE}_{11}$ mode converter for the VENUS ECRIS ECRIS at LBL
Initial tests with the HE11 mode launcher

- Installation beginning of August 2013
- It has preformed 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)
  - Maximum $\text{Xe}^{27+}$ test at 5 kW of 28 GHz only
    - $\text{TE}_{01}$ mode launcher 330 $\mu$A
    - $\text{HE}_{11}$ mode launcher 370 $\mu$A
  - Some indications of improvements when used in two frequency mode with the 18 GHz
- Further development is needed see if $\text{HE}_{11}$ mode launching has significant advantages over $\text{TE}_{01}$ mode
  - VENUS has an enormous range of settings, ions and power levels
  - As Geller said, “Tuning an ECR ion source is searching for an island of stability in a sea of turbulence.” This will take some time.
The Ion Charge Exchange Spectroscopy at ANSTO

- 7 GHz ECRIS
  - Quartz tube
  - Volume 300 ml
  - P<100 W
- $^{14}\text{C}:^{12}\text{C}$ ratio measurement down to $10^{-9}$
- Charge 3+
  - $^{14}\text{N}^3+$ rejection
  - Molecule rejection ($^{13}\text{CH},^{12}\text{CH}_2$..)
- Online transient $^{14}\text{C}:^{12}\text{C}$ ratio count foreseen for medical application
- Limitations:
  - Reproducibility
  - Ion residence time in plasma chamber
  - background

Mass spectroscopy at ANSTO

ICE-MS
Source upgrade

- Hexapole rotation to enhance desorption from the plasma chamber walls
Thank you for your attention!