PRESENT STATUS OF FLNR (JINR)
ECR ION SOURCES


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FLNR (JINR) CYCLOTRONS WITH ECR ION SOURCES

U400 + ECR4M

U400M + DECRIS-2

CI-100 + DECRIS-SC

FLNR (JINR) CYCLOTRONS

NEW CYCLOTRONS

CI-100 + DECRIS-SC

U400 + ECR4M

U400M + DECRIS-2

CI-100 + DECRIS-SC

MASHA

MT-25

DECRIS-4

ECR4M

U400

DRIBs

DECRIS-SC

DECRIS-2

U200

IC-100

U400M

DRIBs-1
DECRIS - Dubna ECR Ion Sources

DECRIS-2, DECRIS-2m, DECRIS-3, DECRIS-4 are “room temperature” ECR ion sources. The axial magnetic field is created by the coils with independent power supplies. The radial magnetic field is created by permanent magnet hexapole, made from NdFeB.

DECRIS-SC – axial magnetic field is created by superconducting solenoids

DECRIS-2 – U-400M cyclotron – 1995
ECR-4M – U-400 cyclotron – 1996 (collaboration FLNR – GANIL (France))
DECRIS-3 – TESLA Accelerator Installation (Belgrade) -1997
DECRIS-2m – BIONT Inc. (Bratislava) – 2003
DECRIS-SC – CI-100 cyclotron - 2004
DECRIS-3 - DC-60 accelerator complex (Astana, Kazakhstan) – 2006
DECRIS-4 – in operation at the test bench - 2005

DECRIS-2m – tested DC-72 cyclotron (Bratislava)
DECRIS-SC2 – new ion source for U-400M – under commissioning
DECRIS-5 – for DC-110 cyclotron – project/production
The source is in regular operation at the U400M since 1995.

Since 2008 the cyclotron operates in two modes:

**high-energy ion beams** \((A/Z = 3 – 5)\)

**Li, B, C, N, O, Ne, S** ions with energies of 35 -55 MeV/n for generation secondary beams of \(^6\text{He}, ^{15}\text{B}, ^9\text{Li}, ^{11}\text{Li}, ^{12}\text{Be}, ^{14}\text{Be}, ^8\text{He}\).

**low-energy ion beams** \((A/Z = 8 – 10)\)

**Ne, Fe, Kr, Xe, Bi** ions with the energies of 5 – 9 Mev/n for experiments in nuclear physics (SHE) and material physics.
DECRIS-2 at the test bench
Modernization of the U-400M axial injection system, 2007

DECRIS-2

RF source
<table>
<thead>
<tr>
<th>Ion</th>
<th>Li</th>
<th>B</th>
<th>O</th>
<th>Ar</th>
<th>Kr</th>
<th>Xe</th>
</tr>
</thead>
<tbody>
<tr>
<td>2+</td>
<td>300</td>
<td></td>
<td></td>
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<td>3+</td>
<td>70</td>
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<td>4+</td>
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<td>5+</td>
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<td>660</td>
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<td>6+</td>
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<td>450</td>
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<tr>
<td>7+</td>
<td></td>
<td></td>
<td></td>
<td>40</td>
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<td></td>
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<tr>
<td>8+</td>
<td></td>
<td></td>
<td></td>
<td>600</td>
<td></td>
<td></td>
</tr>
<tr>
<td>9+</td>
<td></td>
<td></td>
<td></td>
<td>340</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>18+</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>45</td>
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<tr>
<td>20+</td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td>40</td>
</tr>
</tbody>
</table>
Development of DECRIS
The ECR4M source and the axial injection system were assembled and commissioned in 1996. First accelerated Ar beam – November 1996. First accelerated $^{48}\text{Ca}$ beam – November 1997.

About 66% of the total time since 1997 were used for acceleration $^{48}\text{Ca}^{5+}$ ions for synthesis of new superheavy elements. Within the mentioned period elements with $Z = 113, 114, 115, 116, 117, 118$ were synthesized. Chemical properties of $Z = 112$ were studied. The $^{48}\text{Ca}$ beam intensity on the target is $8 \times 10^{12}$ pps (1.2 pμA).
Operating hours of the U400 cyclotron in 1997-2008

- Hours

- Year

- 209Bi19+
- 136Xe14+
- 84,86Kr8+,9+,12+
- 58Fe6+
- 50Ti5+
- 48Ca5+
- 44Ca6+
- 40Ar4+,5+,6+
- 36S4+
- 24Mg3+
- 20,22Ne2+,3+
- 16,18O2+
- 12C2+
- 6Li1+
- 6He1+
Production of the $^{48}$Ca ion beam

581 samples of metallic $^{48}$Ca were used since November 1997 till July 2010

The screen is heated by microwaves and plasma electrons.

Ca spectrum with hot screen
2002: modernization of the U400 axial injection included sharp shortening the injection channel horizontal part. As the result, the distance from the electron cyclotron resonance ion source to the vertical analyzing magnet became equal to 730 mm. These changes allow us to increase the $^{48}\text{Ca}^{18+}$ ion intensity at the U400 output from 0.9 to 1.4 pμA.
Efficiency of the beam transmission from the ion source to the target at U400.

<table>
<thead>
<tr>
<th>Measurement point</th>
<th>Beam intensity</th>
<th>Ion</th>
<th>Transmission</th>
</tr>
</thead>
<tbody>
<tr>
<td>ECR source, after separation</td>
<td>1·10^{14} pps</td>
<td>84 μAe</td>
<td>48 Ca^{3+}</td>
</tr>
<tr>
<td>Cyclotron center</td>
<td>3.5·10^{13} pps</td>
<td>27 μAe</td>
<td>48 Ca^{3+}</td>
</tr>
<tr>
<td>Radius of beam extraction</td>
<td>2.8·10^{13} pps</td>
<td>22 μAe</td>
<td>48 Ca^{3+}</td>
</tr>
<tr>
<td>Extracted beam (charge exchange method)</td>
<td>9.7·10^{12} pps</td>
<td>28 μAe</td>
<td>48 Ca^{18+}</td>
</tr>
<tr>
<td>Target</td>
<td>8·10^{12} pps</td>
<td>23 μAe</td>
<td>48 Ca^{18+}</td>
</tr>
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Modernization of the ECR4M

The increase of the discharge chamber Ø from 64 to 74 mm
Higher magnetic field in the injection region. New hexapole. New discharge chamber.
All mechanical parts are produced
Waiting shut-down of U-400 for reconstruction to U-400R
DECRIS-4 – was designed as an injector of multiply charged ions for the U-400 cyclotron, which can be transformed to the charge breeder for the second stage of the DRIBs project.

The design of the magnetic structure of the source is based on the idea of the so-called “magnetic plateau”. The axial magnetic field is formed by three independent solenoids enclosed in separated iron yokes. The superposition of the coils and hexapole magnetic fields creates the resonance volume.

Since 2005 the source is in operation at the test bench and is used for the experiments in the solid state physics and for beam development.

This year the source was equipped with the TWT amplifier VZU-6997 (13,75 – 14,5 GHz, 750 W). The first experiments were performed.
The whole magnetic structure is movable along the axis with respect to the plasma chamber to optimize the plasma electrode position during the source operation.
Magnetic structure of DECRIS-4
### RESULTS

<table>
<thead>
<tr>
<th>Ion</th>
<th>O</th>
<th>Ar</th>
<th>Kr</th>
<th>Xe</th>
</tr>
</thead>
<tbody>
<tr>
<td>6+</td>
<td>400</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7+</td>
<td>80</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8+</td>
<td></td>
<td>400</td>
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<tr>
<td>9+</td>
<td></td>
<td>220</td>
<td>80</td>
<td></td>
</tr>
<tr>
<td>11+</td>
<td></td>
<td>125</td>
<td>110</td>
<td></td>
</tr>
<tr>
<td>12+</td>
<td></td>
<td>65</td>
<td>85</td>
<td></td>
</tr>
<tr>
<td>15+</td>
<td></td>
<td>35</td>
<td>55</td>
<td></td>
</tr>
<tr>
<td>18+</td>
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<td>30</td>
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</tr>
<tr>
<td>20+</td>
<td></td>
<td>25</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- **Ar$^{8+}$**
- **Kr$^{12+}$**
- **Xe$^{18+}$**

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[Graphs of current vs. UHF power for DECRIS-2m and DECRIS-4 for different ions.]
Test experiments for production of $^{50}$Ti ion beam

Three methods were used:

1. MIVOC (Metal Ions from Volatile Compounds)
   $\text{(CH}_3\text{)}_5\text{C}_5\text{Ti(CH}_3\text{)}_3$ - (trimethyl)pentamethyl-cyclopentadienyl titanium
   $\text{Ti}\{\text{OCH(CH}_3\text{)}_2\}_4$ - titanium isopropoxide


3. Insertion method – Ti rod.
(CH₃)$_5$C$_5$Ti(CH₃)$_3$

Stable operation
The intensity is enough for experiments
The synthesis is very complicated and with pure efficiency

Ti{OCH(CH₃)$_2$}$_4$ the current of Ti$^{5+}$ less than 1 μA

Stable mode with current of Ti$^{6+}$ $\sim$10 ÷ 20 μA, then unstable.

Relatively stable mode (current variation $\sim$30 40 %) during 0,5 ÷ 1 hour.
Then current drops to zero, or discharge became uncontrollable.
DECRIS-SC ion sources.
**ECR ion source with superconducting magnet system**

Modernization of CI-100 cyclotron:
- **Accelerated ions** - Kr\(^{15+}\), Xe\(^{22+}\) energy 1 MeV/n
  - Kr\(^{20+}\), Xe\(^{30+}\) 2 MeV/n
- **Accelerated beam intensity** > 10\(^{12}\) pps
- The high enough requirements on charge and intensity of accelerated beams (Kr\(^{15+}\), Xe\(^{22+}\)) demand the necessity of using the ion source with the large mirror ratio and a strong magnetic field.

- “Liquid He free” technology
## Parameters of DECRIS-SC

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>UHF frequency</td>
<td>18 GHz, 28 GHz</td>
</tr>
<tr>
<td>Mirror field on the axis:</td>
<td></td>
</tr>
<tr>
<td>Extraction side</td>
<td>2 T</td>
</tr>
<tr>
<td>Injection side</td>
<td>3 T</td>
</tr>
<tr>
<td>Mirror to mirror distance</td>
<td>390 mm</td>
</tr>
<tr>
<td>Max. coil current</td>
<td>60 A</td>
</tr>
<tr>
<td>Radial field at the plasma chamber wall</td>
<td>1.3 T</td>
</tr>
<tr>
<td>Plasma chamber internal diameter</td>
<td>74 mm</td>
</tr>
<tr>
<td>Max. extraction voltage</td>
<td>30 kV</td>
</tr>
</tbody>
</table>
The design of the SC magnet:

1 - superconducting solenoids; 2 - framework of solenoids; 3 - thermal screen; 4 - multilayer screen-vacuum isolation; 6 - support of cold mass; 7 - vacuum casing; 8 - magnetic shield; 9 - current lead; 10 - cryocooler; 11 - heat pipes; 12 - "cold" diodes; 13 - absorbing resistors; 15 - nitrogen heat exchanger.
Electrical power supply and safety system:

Passive protection: sectionalization, “cold” diodes and absorbing resistors. Active protection: three sensor units of the normal zone and eight resistive heaters, installed at the windings.
Thermo control:

In the cold zone of the magnet 16 thermometers are located.
Calibrated TVO carbon resistors are used as thermometers.
DECRIS-SC

Cooling of the solenoids

With LN heat exchanger

With cryocooler only
Hexapole design
General view of the source
DECRIS-SC and axial injection system of CI-100 cyclotron
Since May 2004 the source is in regular operation at the cyclotron for production of polymer membranes and solid state physics.
DECRIS-SC2 ion source for U-400M cyclotron

The main goal of the DECRIS-SC2 source is the production of more intense beams of heavy ions in the mass range heavier than Ar.

Table of main parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operating frequency</td>
<td>14 GHz</td>
</tr>
<tr>
<td>UHF power range</td>
<td>50 – 700 W</td>
</tr>
<tr>
<td>Axial magnetic field (injection/extract)</td>
<td>1.9 / 1.4 T</td>
</tr>
<tr>
<td>Coils power consumption</td>
<td>10 kW (cryocooler)</td>
</tr>
<tr>
<td>Coil current</td>
<td>75 A</td>
</tr>
<tr>
<td>Radial magnetic field</td>
<td>1.0 T</td>
</tr>
<tr>
<td>Plasma chamber diameter</td>
<td>74 mm</td>
</tr>
<tr>
<td>Source diameter / length</td>
<td>690 / 570 mm</td>
</tr>
<tr>
<td>Source weight</td>
<td>~ 700 kg</td>
</tr>
</tbody>
</table>
DECRIS-SC2 is the compact version of the “liquid He free” superconducting ion source. The axial magnetic field is created by superconducting coils and iron plugs. The radial magnetic field is formed by permanent magnet hexapole.
Components of DECRIS-SC2

- Superconducting solenoid
- Cold mass support
- HTSC current lead
- Thermal screen
An electrical circuit of the power supply and protection of solenoids:

1, 2, 3, 4 – windings;
5 – electrical and thermal contacts of the windings ends, current leads conductors and diodes;
6 - HTSC current leads; 7,8,9 - current sources of the windings;
10 – quench detector; H1, H2 – heaters; VD – “cold” diodes.
Tests of the superconducting magnet system

- Cooling
- Axial magnetic field measurement
- Hexapole magnetic field measurement
The superconducting magnet system passed the full test.

The source is assembled and installed at the test bench.

Mechanical problems in coupling the source with the test bench extraction box.
DRIBs (Dubna Radioactive Ion Beams) project

- First phase – production and acceleration of $^6$He и $^8$He beams.
- Second phase – production and acceleration of fission products ($^{132}$Sn).
DRIBs - Project
Transformation of the primary beam into a low energy radioactive ion beam
Magnetic structure of ECR ion source for DRIBs
(operating frequency 2.45 GHz)
ECR ion source for DRIBs

- Permanent magnets
- Shorting plate
- $^6$He atoms
- Beam
- Plasma electrode
- Soft iron

Graph showing He $^1\pi$ transitions.
Maximum extracted $^4\text{He}{}^1{}^+$ current and global efficiency versus the diameter of the extraction hole.

Efficiency for Ar and Kr $\geq 80\%$

Intensity of $^7\text{Li}$ primary beam
U-400M
3 $\mu$A

Intensity of $^6\text{He}$ accelerated beam
U-400
$5 \times 10^7$ pps
MASHA (Mass Analyzer of Super Heavy Atoms)

Mass identification of super heavy nuclei with a resolution better than 1 amu at the level of 300 amu.

Synthesized in nuclear reactions nuclides are emitted from an ECR ion source at energy \( E = 40 \text{ kV} \) and charge state \( Q = +1 \). The setup can work in the wide mass range from \( A \sim 20 \) to \( A \sim 500 \), mass acceptance \( \pm 2.8\% \).
MASHA (Mass Analyzer of Super Heavy Atoms)
Magnetic structure of ECR ion source for MASHA (operating frequency 2.45 GHz)
ECR ion source for MASHA
Total efficiency – 47%
Development and creation of ECR sources for other scientific centers

**DC-72 + DECRIS-2m**

At present, the cyclotron equipment has been produced in full, has passed full testing at the FLNR and is ready for shipment to Slovakia.

**DC-60 + DECRIS-3**

The cyclotron center creation started in the beginning of 2004, and at the end of 2006 the accelerator complex was put into operation, the first accelerated beams were obtained and the first experiments performed.
DECRIS-3, Belgrade
DECRIS-2m, Bratislava
THANK YOU!!