

# ELECTRON CYCLOTRON RESONANCE SOURCE DEVELOPMENT

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## Abstract

The ECR ion source (ECRIS) is still an active field of research and development, as demonstrated by the numerous contributions to the ECRIS'12 workshop and ICIS'13 conference. It is impossible to present all the interesting ECR development in this paper. Instead, a selection of ECR development for linear accelerator and synchrotrons are presented along with some original recent ECR contributions. A special care is taken to introduce newcomer activity in the ECRIS community.

## ECR DEVELOPMENT FOR ACCELERATORS

### FRIB Project

The FRIB project relies on the simultaneous acceleration of 220+220  $\mu\text{A}$  of  $\text{U}^{33+}+\text{U}^{34+}$  beams. The VENUS ion source demonstrated the feasibility to produce up to 440+400  $\mu\text{A}$  of  $\text{U}^{33+}+\text{U}^{34+}$  (see Fig. 1).[1] FRIB decided to use the VENUS ECRIS and update slightly its original design. The superconducting coil geometry and magnetic field characteristics of VENUS are kept. The cold mass mechanics, entrusted to LBL superconducting group, will be revised to use the modern key and pad scheme: [2] air inflated bladders are used to deform the coils mechanics and allow the insertion of keys that pre-stress the coils once the bladders are removed. The main advantage of this technique is to allow dismounting a hexapole coil independently from others and modify any coil pre-stress at will, by changing the key dimensions. The cryogenics system is simplified: liquid nitrogen is suppressed and replaced by a set of 2 cryocoolers to cool the 30K shield. The 4.2K cooling power is provided by 2x4.3W GM-JT cryocoolers.

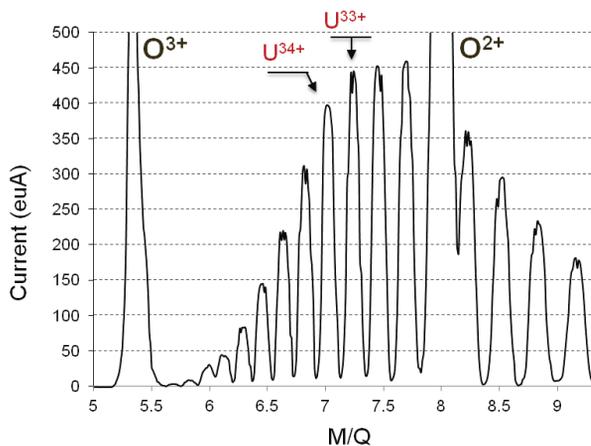


Figure 1: High intensity uranium beam production for  $\text{U}^{33+}$  and  $\text{U}^{34+}$  demonstrated by the VENUS source.

### SPIRAL2 Project

The new linear accelerator construction is under progress at GANIL. The commissioning source to be used for the  $A/Q=3$  heavy ion accelerator is the 18 GHz room temperature PHOENIX V2. This compact source demonstrated the production of 1.3 mA of  $\text{O}^{6+}$ , 1  $\mu\text{A}$  of  $^{40}\text{Ca}^{16+}$ ,  $\text{Ni}^{19+}$ , 7.2  $\mu\text{A}$  of  $^{32}\text{S}^{11+}$ . [3] these intensities are compatible with the first year beam physics experiments. The higher intensities for heavy mass ions required later (1 mA  $^{12}\text{C}^{4+}$ , 100  $\mu\text{A}$   $^{28}\text{Si}^{10+}$ , 240  $\mu\text{A}$   $^{32-36}\text{S}^{11-13+}$ , 280-160  $\mu\text{A}$   $^{40-48}\text{Ca}^{14-16}$  and 60  $\mu\text{A}$   $^{58}\text{Ni}^{19+}$ ) imply the final use a new high performance 28 GHz ECRIS. Funding for such an upgrade is not decided yet. In the meantime, an upgrade of PHOENIX V2, named PHOENIX V3, is under development to increase the plasma chamber volume from 0.7 to 1.4 litre, keeping the overall magnetic confinement unchanged (see Fig. 2).[4] The higher ion confinement time is expected to shift the ion charge state distribution to a higher value, leading to an increase of  $A/Q=3$  ion current. The PHOENIX V3 source is devoted to replace the V2 in 2014/2015 on the LINAC.

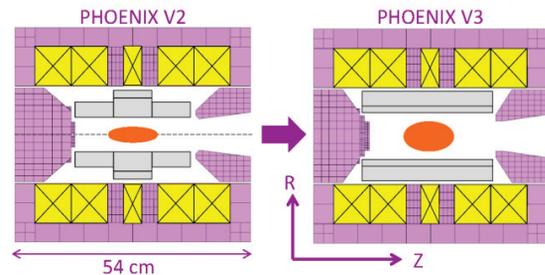


Figure 2: Evolution of the sectional view from PHOENIX V2 to PHOENIX V3.

### Korean Projects

The republic of Korea is currently building several facilities involving multi-charged ECR ion sources. First, a new large heavy ion accelerator facility named Rare Isotope Science Project (RISP) is under construction.[5] This facility, based on a superconducting linear accelerator named RAON, will produce various stable and radioactive ion beams. The accelerator specifications are nearby to the FRIB ones. The project needs a high performance ECR ion source to fulfil the beam requirements. The ECRIS superconducting magnet design features 4 axial coils and a classical set of hexapole coils. The team recently built a saddle hexapole coil prototype which reached the target specifications: the other coils are being built now and final assembly will follow shortly. Second, a compact linear accelerator is under construction at the Korea Basic Science Institute in Busan [6]. The goal is to accelerate 1 mA of  $\text{Li}^{3+}$  beam to 2 MeV/u to produce a fast neutrons flux of  $5.3 \times 10^{13}/\text{s}$  applied to radiography. A new 28 GHz SC ECRIS was designed and recently

assembled for this purpose. The magnetic field is generated by a set of 3 axial coils and racetrack coils have been used to produce the hexapolar field. So far, the hexapole reached 70% of the design goal which is at least comfortable for a high-B mode operation at 18 GHz. Third, a synchrotron is being built by the Korean Atomic Energy Research Institute applied to hadrontherapy. A 14.5 GHz ECRIS has been developed which goal is to produce 20  $\mu\text{A}$  of  $\text{C}^{6+}$ . The first tests reported show the production of 50  $\mu\text{A}$  of  $\text{C}^{4+}$ . [7]

### CERN Argon Test

A 10 weeks run was performed with the Linac3 at CERN to test the long term argon beam production in afterglow mode from the GTS-CERN ion source. [8] This beam will be used in 2015 on the NA51 fixed target experiment. The source was tuned to produce 120-140  $\mu\text{A}$  of  $^{40}\text{Ar}^{11+}$  extracted at 9.5 keV with 500W of 14.5 GHz microwave power. The current at the exit of the linac3 was 55-65  $\mu\text{A}$ . The test was a success but some side effect occurred: pulse to pulse instability reached 20% during some periods of time. A large sputtering was observed on the tantalum bias disk. A sputtering along the plasma loss lines at the chamber wall was observed, leading to a concomitant 15-20  $\mu\text{A}$   $\text{Fe}^{17+}$  charge state production from the source. The test and its feedback will allow preparing safely the next year longer runs required to tune the whole accelerator chain.

### HIGH PROTON INTENSITY AT IAP

New proton beam experiments have been carried out with the SMIS 37 ion source at the Institute of Applied Physics in Nizhny Novgorod. [9] This atypical source, shown on Fig. 3, is composed of two pulsed coils forming a 300 mm axial mirror trap with a peak field up to 4T. The coils current are generated by the discharge of a capacitor bench, providing a 11 ms long sinusoidal shaped pulse current. Hydrogen gas is injected by means of a pulsed gas valve. A 37.5 GHz gyrotron generate a 100 kW microwave pulse up to 1.4 ms which is optically coupled to the central discharge chamber. The very high microwave power and the high gas pressure ( $\sim 10^{-3}$ - $10^{-4}$  mbar) generate a high density collisional plasma (quasi-gasdynamic regime). The plasma diffuses naturally outside of the mirror trap and is finally accelerated  $\sim 170$  mm beyond the magnetic mirror by a simple extraction system composed of a  $\text{\O}10$  mm high voltage plasma electrode hole and a  $\text{\O}22$  mm puller hole set to ground potential. The respective pulse timing of the gas, coil current, microwave pulses were investigated along with the gas pressure to find the best configuration to produce intense hydrogen beams. The total beam current was measured with a Faraday cup located right after the puller. An impressive record beam up to 450 mA of hydrogen was measured at 45 kV extraction voltage. The proton fraction, measured by means of a bending magnet reached 94%. A "pepper pot" was used to measure the total normalized beam emittance which was 0.3  $\pi$ .mm.mrad, including 90% of the beam. The low value of

the emittance is due to the fact that the magnetic emittance, which is usually the dominant term in a ECRIS, is very low here, since the ion extraction is done 170 mm away from the magnetic mirror peak.

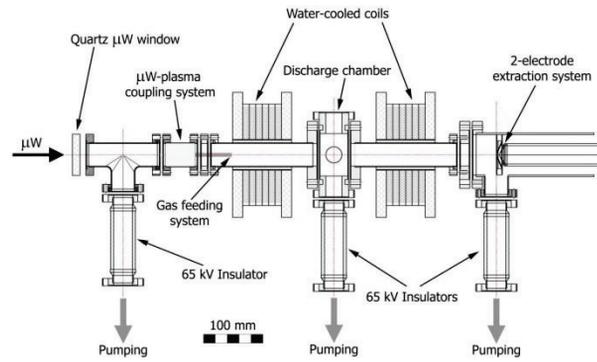


Figure 3: Schematic of the SMIS37 pulsed.

### ECR CHARGE BREEDING

ECR charge breeding (CB) is currently developed in many laboratories: LPSC, ANL, TRIUMF, TexasA&M, GANIL. Recently, a simplified beam injection system was developed at LPSC which increases beam acceptance and allows closing more efficiently the injection plasma chamber by means of a disc with a  $\text{\O}20$  mm hole. [10] Now, the plasma chamber acts more like a closed cavity and RF leaks toward the injection beam line are limited. Experiments have shown a consequent improvement in the efficiency yield with  $\text{Rb}^{15+}$  from 3.6 to 6.5 % with a RF power level reduced from 630 to 360 W. Figure 4 plots CB efficiency for various Mass over charge ions and various ECRIS CB. [11]

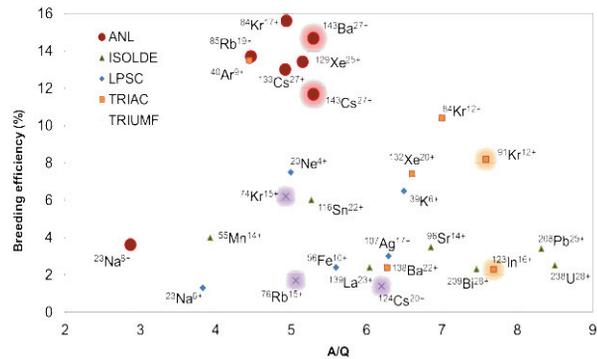


Figure 4: breeding efficiencies for various ECRIS breeder as a function of the A/Q ratio. [12]

The plot shows clearly higher efficiencies obtained with the ANL CB compared to the others. Possible explanations for this higher performance are the better vacuum and a better RF coupling to the cavity in this CB. [12] Early light ion CB studies done with the PHOENIX CB with Na and K shown efficiencies lower than those obtained for heavier mass. This effect was attributed to an excessive velocity of the light ions injected with respect to the mean ion velocity in the plasma, leading to a weaker plasma capture. New experiments performed with the ANL CB on light ions

like K and Na shown that their CB efficiency is finally equal to superior to the heavy mass ions. One can cite for instance efficiencies of 10.3% and 17.9% respectively for  $^{23}\text{Na}^{7+}$  and  $^{39}\text{K}^{10+}$ . [13] These improved performances for light ions are understood as a careful and controlled injection optic and also a symmetric magnetic field on the injection of the ECRIS on the ANL CB, which is not the case on the others. In effect: simulation shows that a single port hole machined in the iron yoke shifts the magnetic center off-axis and degrades the ion beam plasma capture.

The GANIL is currently modifying the former ISOLDE PHOENIX charge breeder to adapt it to the Spiral1 facility. The upgrade will extend the range of elements available for post-acceleration to condensable elements up to  $A < 90$ .

At TRIUMF, an investigation on the booster background reduction was carried out by testing successively a stainless steel plasma chamber and an aluminum one. [14] All the parts in contact with the plasma were changed or plated with aluminum. The gas contamination in both plasma chamber material is identical, whereas the condensable contamination is decreased by two order of magnitude by using aluminum. All ECR CB authors agree that the ideal would be to develop a bakeable UHV charge breeder to reduce significantly the background.

A new charge breeder is under development for the SPES facility. [15] Collaboration between INFN and LPSC is considered to use the PHOENIX CB.



Figure 5: Photograph of the “snake” converter built.

## 28 GHZ HE11 MODE COUPLING AT LBL

The 24-28 GHz plasma heating in new generation ECRIS appears to be less efficient to produce high intensity high charge state ions than the 18 GHz one. The best performance of these sources requires the use of a double frequency heating adding 18 GHz to a large amount of 28 GHz power (4-5kW). The 18 GHz is usually generated by a klystron and injected through a rectangular waveguide using the  $\text{TE}_{10}$  mode which is linearly polarized. On the other hand, the present 24-28 GHz frequency is generated by means of a gyrotron. The

RF power is transported in an oversized circular waveguide using the  $\text{TE}_{01}$  mode. The RF power is zero on the circular waveguide axis and maximum at an intermediate radius. It is thus legitimate to wonder if the lower coupling performance observed at 24-28 GHz is due to an inappropriate coupling mode to the cavity/plasma. In order to tackle this problem, an original RF mode converter has been developed at the LBL to inject directly the quasi-Gaussian  $\text{HE}_{11}$  mode in the plasma chamber, which is practically linearly polarized. [16] The  $\text{HE}_{11}$  mode is a hybrid mode with approximately 85% of the power in the  $\text{TE}_{11}$  and 15% in the  $\text{TM}_{11}$ . A sophisticated mode converter was simulated and designed to make this whole conversion under vacuum, right before the RF injection in the plasma chamber. The mode conversion is achieved into two steps. First, a  $\text{TE}_{10}$  to  $\text{TE}_{11}$  converter, named the “snake”, is composed of a standard 1.25” oversize circular waveguide whose guiding center is wiggling in a direction perpendicular to the waveguide. The curvature forces the  $\text{TE}_{01}$  mode to couple to other modes. A numerical simulation was carried out to find an optimum curvature making the  $\text{TE}_{10}$  to  $\text{TE}_{11}$  conversion with 97% efficiency, along a distance of 650 mm. 16 other modes had to be considered to solve the problem within a few % of accuracy. The following  $\text{TE}_{11}$  to  $\text{HE}_{11}$  conversion is achieved with a corrugated waveguide with a depth profile adapted to convert a part of the  $\text{TE}_{11}$  to the  $\text{TM}_{11}$ . The mechanical assembly was achieved successfully in August 2013. Figure 5 shows a photo of the “snake” converter. The comparison between the  $\text{TE}_{01}$  and  $\text{HE}_{11}$  coupling would require systematic experiments that remain to be done. Qualitatively, the dependence of tuning parameters such as magnetic field and pressure appear to be smoother with the  $\text{HE}_{11}$  mode. The best result obtained using the old injection system for  $\text{Xe}^{27+}$  was 330  $\mu\text{A}$  at 5 kW of 28 GHz; a test with the  $\text{HE}_{11}$  mode produced 370  $\mu\text{A}$ . Further tests are planned, especially to map out the performance for very high charge state ions such as  $\text{Xe}^{43+}$  and  $\text{Bi}^{56+}$  as these charge state beams are important for the cyclotron users.



Figure 6: COMIC 2.45 and COMIC 7.8 ECRIS.

## COMIC SOURCES

Ultra compact ECR ion sources have been developed at LPSC for industrial applications since 2010. [17] The first source named COMIC is an ultra-compact 2.45 GHz quarter wave cavity with a simple gradient magnetic field

generated by a set of permanent magnets (see Fig. 6). The microwave coupling to the cavity was carefully designed to locate the maximum electric field right on the ECR resonance surface. The source operates at very low RF power within the range 0.1-10W, allowing the use of inexpensive solid state amplifiers. Thanks to its compactness, The COMIC was adopted on several industrial machines: focusing ion beam machine, multi-beam implantation, multi-beam sputtering.[18] Recently, the COMIC 5.8 GHz a new ECRIS was developed at a higher ECR frequency in order to increase the extracted beam current. The new source plasma chamber dimension is simply downscaled to match the smaller microwave wavelength. The first comparison tests between the two, applied to FIB, are very promising as the extracted current increased by a factor 4 for a 0.3 mm diameter hole.[19]

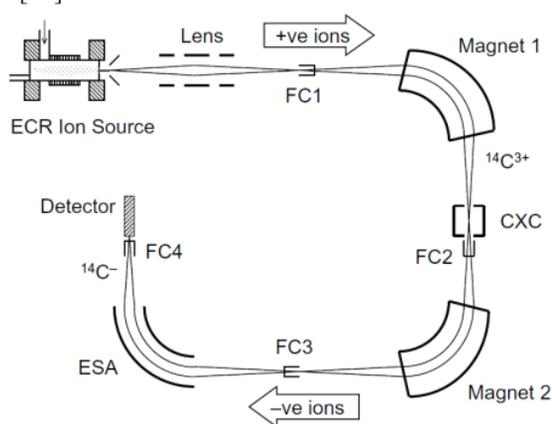


Figure 7: The Ion Charge Exchange Mass Spectrometry developed at ANSTO.

## MASS SPECTROSCOPY WITH AN ECRIS

ANSTO (Australian Nuclear Science and technology Organization) developed several techniques using an ECRIS to perform mass spectrometry to measure rare isotope ratios like  $^{12}\text{C}/^{14}\text{C}$ . One of them is the Ion Charge Exchange Mass Spectrometry shown on Fig. 7.[20] In this system, a 7 GHz ECRIS is designed to produce medium ion charge state distribution. The  $\text{C}^{3+}$  ion beam is selected through a first bending magnet, next passes through a charge exchange cell (CXC) where it is converted to a negative ion beam  $\text{C}^-$ . The negative ions are next passing through a second bending magnet, an electrostatic analyzer and finally a detector counting the ions. One genuine advantage of this technique is that the nitrogen isotope  $^{14}\text{N}$ , the main  $^{14}\text{C}$  beam contaminant, does not convert into a negative ion in the CXC and is thus rejected through the second bending magnet. Another advantage comes from the fact that molecules do not exist anymore on charge state  $3+$  as they dissociate, so no more contamination such as  $^{12}\text{CH}_2$  exists. The ECRIS operates at power levels less than 100W. The magnetic structure is performed with permanent magnets and set to ground potential. The plasma chamber is composed of a quartz tube. The volume is kept small ( $\sim 330$  ml) to reduce the

atoms residence time in the chamber. Only the plasma electrode is set to a high voltage up to 19 kV. Early experiments show that the system is able to measure  $^{14}\text{C}/^{12}\text{C}$  down to the  $10^{-9}$  level, which is suitable for many biomedical tracing applications. The one the authors are focusing on is the capability to measure transient signal of a few seconds duration containing a few  $\mu\text{Bq}$  of  $^{14}\text{C}$  activity. The overall efficiency of this early experiment is  $3 \times 10^{-3}\%$ . But many improvements can be achieved and the final goal is to reach a 1% efficiency, making the technique competitive with classical AMS techniques using tandem accelerators.

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