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ELECTRON CYCLOTRON RESONANCE ION SOURCE RELATED RESEARCH AND DEVELOPMENT WORK AT THE DEPARTMENT OF PHYSICS, UNIVERSITY OF JYVÄSKYLÄ (JYFL)*

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Abstract

Recent research work of the JYFL ion source team covers a wide variety of ion source related projects. The instability measurements have been expanded from the pulse-periodic kinetic instabilities to the cw maser regime, characterized by continuous microwave emissions at high B_{min}/B_{ECR} ratio. It has been observed that with appropriate settings, this regime can offer islands of stability with improved performance.

The ion beam transient studies have focused on developing diagnostics methods for studying the confinement times of highly-charged ions in ECR plasmas utilizing the 1+ injection method with a charge breeder and the sputtering method with a conventional ECRIS. These studies imply that long enough confinement times can exist in the plasma offering a potential explanation for the high ion temperatures measured with the high-resolution plasma optical emission spectrometer setup (POSSU), developed at JYFL. POSSU itself is currently being upgraded to enable time-resolved measurements of the emission line profiles.

The commissioning status of the unconventional CUBE-ECRIS with a minimum-B quadrupole magnetic field topology is also presented. The topology, realized with all-permanent magnet structure, is based on the ARC-ECRIS [1] and is optimized for 10 GHz frequency. The status and operational experience with HIISI is reported as well.

PLASMA INVESTIGATIONS

The plasma instability studies with the 14 GHz ECRIS at JYFL have recently concentrated on exploring the plasma maser regime achieved at high B_{min}/B_{ECR} ratio. This regime, characterized by continuous microwave emission, and the mechanism of the plasma maser formation in the ECRIS plasma was first discussed by Shalashov et al. [2, 3]. It was recently confirmed that the transition from the pulse-periodic instability regime to the cw maser regime is sometimes (with appropriate tuning and plasma heating frequency) accompanied by increased output of high charge state ions [4] exceeding the beam currents achieved below the instability threshold at B_{min}/B_{ECR} of 0.8–0.85. The maser regime corresponds to the "islands of stability" at B_{min}/B_{ECR} of 0.9 or higher. It is argued that the maser regime improves the extracted beam currents by enhancing the hot electron losses through the continuous particle-wave interaction, which in turn increases the ion flux by acting on the electrostatic ion confinement. The experiments in the maser regime have been carried out with plasma heating frequencies of 10.8–12.4 GHz because of the excessively high solenoid coil currents required to reach $B_{min}/B_{ECR} > 0.9$ with 14 GHz operation.

The JYFL-LPSC collaboration has been developing a code that describes the real 3D magnetic field topology of ECRIS by expanding the on-axis field to $r > 0$ with a 6th order polynomial and superimposing it with an ideal sextupole field [5]. The main objective of the work is to extract all relevant field parameters and compare them to the experimentally found plasma instability threshold. The work aims to define the most influential parameter concerning the onset of plasma instabilities. Figure 1 shows, as an example, the distribution of the magnetic field gradient on the ECR surface of the JYFL 14 GHz ECRIS with nominal coil currents. The code has already been used to correlate the magnetic field properties, especially magnetic gradient distribution, and occurrence of plasma instabilities for SECRAL-II [6] and JYFL 14 GHz ECRIS [7].

The JYFL-GANIL-LPSC collaboration has been developing diagnostic methods for measuring and studying cumulative and population confinement times of ions in the ECRIS plasmas. The temporal evolution of the ion populations is defined by ionization and charge exchange processes, and ion confinement time as per the balance equation [8]. The confinement time must be long enough to allow highly charged ion formation via the stepwise ionization process, but also as short as possible to produce high extraction currents. It is a critical parameter especially in the production

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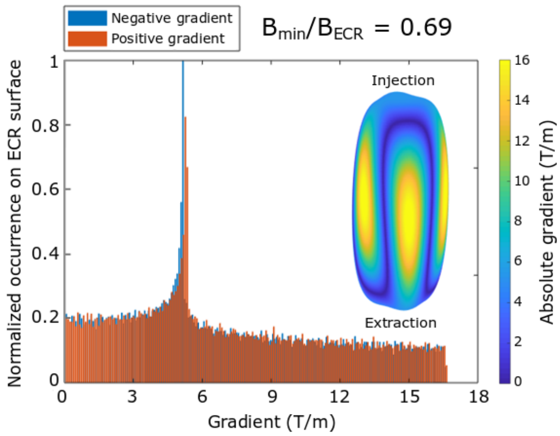

Figure 1: An example of the magnetic field gradient distribution on the (cold electron) ECR surface of JYFL 14 GHz ECRIS with nominal solenoid currents.

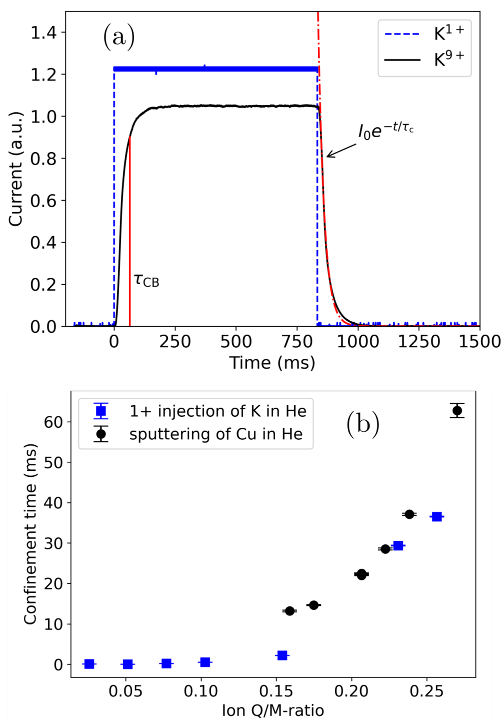

Figure 2: An example of extracted K^{9+} (black line) with pulsed injection of K^+ (dashed line) into a helium buffer (a) and a comparison of obtained τ_c^q using 1+ injection in a CB-ECRIS and sputtering in a conventional ECRIS (b). The exponential fit defining τ_c as well as the conventional charge breeding time τ_{CB} are also plotted.

of Radioactive Ion Beams (RIBs) for nuclear physics studies due to the decay of the injected isotopes.

The confinement time has been studied via transient methods using 1+ injection into a charge breeder and sputtering in a conventional ECRIS. The basic principle of the transient method is to inject material in pulses into a support plasma, and observe the time structure of the extracted ion currents. Figure 2 (a) shows a current transient resulting from injection of potassium into a Charge Breeder ECRIS (CB-ECRIS). The cumulative confinement time τ_c is determined by means of an exponential fit to the decaying current transient as indicated in Fig. 2 (a). It has been argued to represent the total ion lifetime in plasma, as the decaying current is fed by ionization from lower states and charge exchange from higher states and conversely diminished by ionization to higher and charge exchange to lower states [10]. The conventional measure for the charge breeding time τ_{CB} (the 90 % rise time of the current) is also indicated in the figure. Alternative methods for determining the charge breeding time based on short pulse injection have been presented in Ref. [9].

Mutually corroborative results have been obtained from CB and conventional ECRIS as shown in Fig. 2 (b) [10]. The τ_c values obtained from the measurements have been shown to be long enough to allow ion heating via electron drag to temperatures on the order of 10 eV, offering a potential explanation for the observed ion temperatures ranging from 5 eV to 28 eV [11].

A high-resolution spectrometer POSSU, developed at JYFL, has proven to be a very powerful tool for ECRIS plasma diagnostics. It has been used to probe densities of ions and neutral atoms [12], temperature of the cold electron population [13] and ion temperature [11]. POSSU has a Fastie-Ebert type monochromator with two slits (entrance and exit) and rotating diffraction grating. The scanning time of an emission line profile with this configuration is approximately 10 minutes. The ongoing technical development to improve the spectrometer beyond its present capabilities aims to enable time-resolved measurement of the line profiles of relatively strong emission lines such as 488 nm of Ar^+ and 553 nm of Ar^{9+} with ms-level temporal resolution [14]. The modifications required to achieve this include the minimization of the astigmatism with circular entrance slit, optimization of the throughput of the monochromator and replacing the photomultiplier detection system with a high-sensitivity, high-speed, peltier cooled sCMOS detector. The experiments that become available after the ongoing upgrade include time-resolved measurements of the ion temperatures.

SOURCE DEVELOPMENT

The HIISI ECR ion source [15–17] was designed and constructed during 2015-2017. The testing, which was started in Fall 2017, demonstrated the feasibility of an innovative permanent magnet cooling scheme and a capability of HIISI to produce very high charge states, like Xe^{44+}, required by the user community of the JYFL Accelerator Laboratory. The commissioning experiments were started with 24-segment hexapole ($B_{rad} \approx 1.32$ T). As a result of an unexpected overheating problem the tuning range and operational time of HIISI were strongly limited. The problem was resolved for the stronger 36-segment hexapole structure ($B_{rad} \approx 1.42$ T) construction of which was started in the beginning of 2018. Together with the stronger radial confinement and increased

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microwave power (up to 3 kW) available for the plasma heating the intensity of e.g. Ar^{16+} ion beam has increased from 54 µA to 130 µA.

After a short commissioning period, HIISI has been used for the nuclear physics program always when high beam intensity, high charge states or high beam stability is required. Figure 3 shows the injection structure of HIISI: the center of the bias disk is made of magnetic iron (AISI 1006) to maximize the injection magnetic field value (2.8 T). The figure also shows V and Au samples mounted in the plasma flux area on the surface of the non-magnetic part of the bias disk (SAE316). As a result of the arrangement, the ion flux of $1 \cdot 10^5$ particles/s/cm^2 on the experimental target was easily exceeded in the case of $^{51}V^{18+}$ and $^{197}Au^{54+}$ ion beams.

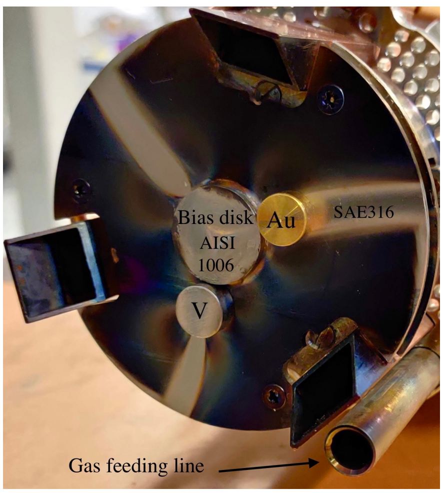

Figure 3: Injection geometry of HIISI including samples for V and Au ion beam production.

Another ion source currently under development at JYFL is the CUBE-ECRIS. It has a minimum-B quadrupole field topology which conforms to the conventional ECRIS scaling laws for 10 GHz microwave operation. A detailed description of the design is presented in Ref. [18]. The magnetic field structure is based on the ARC-ECRIS concept [1], but realized with an all permanent magnet assembly. The aim of the CUBE-ECRIS project is to study the production of highly charged ion beams with a quadrupole field topology and demonstrate beam formation and transport with a slit extraction system, comparing the performance to a conventional ECRIS. Being successful, this alternative topology could have high potential for future ECRIS development, as it has been shown to be scalable to reach appropriate mirror ratios for 100 GHz operation using the existing superconductor technology [19].

The construction of the CUBE-ECRIS was commenced in Spring 2020 and the permanent magnet assembly was completed in September 2020. The assembly is presented in Fig. 4. The resulting magnetic field was verified by measuring the B_y and B_x components of the field along the y direction through the magnetic structure, crossing B_{min} at $y = 0$. The measured and simulated fields are presented in Fig. 5. The first plasma is expected in the first quarter of 2021.

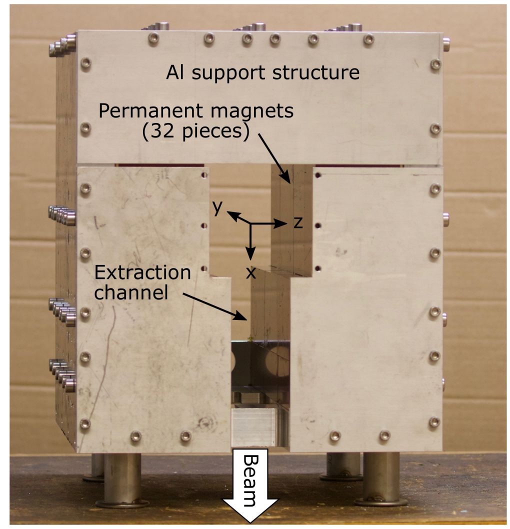

Figure 4: The CUBE-ECRIS permanent magnet assembly inside the Al support structure.

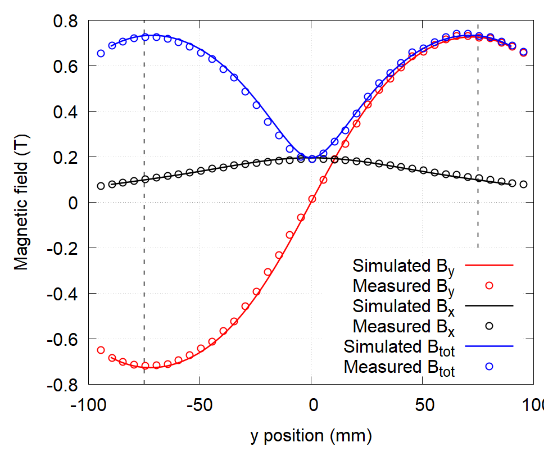

Figure 5: Comparison of simulated and measured magnetic field of the CUBE-ECRIS. Plasma chamber walls are indicated with dashed vertical lines.

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