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FIRST ION BEAMS EXTRACTED FROM A NEW JYFL 18 GHz ECRIS: HIISI*

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Abstract

A new 18 GHz ECR ion source HIISI is under commissioning at the Accelerator Laboratory at the University of Jyväskylä (JYFL). The main purpose of HIISI is to produce high-intensity ion beams for nuclear physics programme and high-energy beam cocktails for radiation effects testing of electronic components. The initial commissioning results in (18+14) GHz operation mode using 24 segment sextupole (1.3 T) were performed in autumn 2017. A stronger 36 segment sextupole (1.42 T) was constructed and tested during the spring 2018 demonstrating improved performance of HIISI. As an example, Ar^{12+} intensity of 0.57 mA was reached with 19.5 kV extraction voltage and total microwave power of 2.35 kW. In this article we will present the latest development work, ion beam intensities of oxygen, argon and xenon, and future prospects of HIISI.

INTRODUCTION

The K130-cyclotron [1] at JYFL is equipped with an AECR-U type, room temperature (RT) 14 GHz ECR ion source [2] for heavy ion production. The old 14 GHz ECR ion source has worked reliably for more than 60000 plasma-on hours since its construction in 1999. Most of the beams have been produced from natural or enriched gases or by using the MIVOC method [3]. Typical requested energy of the projectile is 5 MeV/u, which requires a q/A-ratio of 0.2. For example, in the case of argon and xenon ion beams charge states of 8+ and 27+ are often needed. Due to the demand for more intensive beams of highly charged ions and also for higher energy for irradiation tests of space electronics the project for a new ECR ion source was initiated in 2013. At the end of 2013 the Academy of Finland funded the JYFL Accelerator Laboratory to design and construct an 18 GHz ECR Heavy Ion Ion Source Injector (HIISI, ref. [4-6]). The objective of HIISI was two-fold: 1) the intensity of medium charge state ion beams, such as Ar^{8+} and Xe^{27+} (E ≈ 5 MeV/u), has to be increased by a factor of 5 and 2) the energy of heavy ion beams (A > 100) has to exceed the value of 15 MeV/u. The first requirement is set by the nuclear physics program and the latter one by the irradiation testing program for the space electronic components. The testing program requires 10^6 particles/s/cm^2 on the irradiation target station. In the case of xenon, which is the heaviest element in 16 MeV/u cocktail, this corresponds to charge state of 44+, and the extracted ion beam intensity of about 10 nA when the total transport efficiency of accelerator facility is taken into account. In 2013, the presented requirement was beyond any existing RT-ECRIS, which forced us to design and construct a new room temperature 18 GHz ECRIS. In this article the present status of HIISI will be given.

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HIISI SPECIFICATIONS

In 2013 only three ECRISs were able to produce the xenon ion beam intensity (Xe^{44+}/10 nA) required by the irradiation testing program at JYFL. Those ECR ion sources are VENUS [7], SECRAL [8] and SUSI [9]. The experimental data and operation parameters revealed that SUSI is able to produce the Xe^{44+} ion beam intensity of about 100 nA in 18 GHz operation mode (B_{inj} = 2.8 T/B_{ext} = 1.3 T and B_{rad} = 1.35 T) and at the microwave power of about 4 kW. In addition, it has produced 730 μA of Ar^{12+} with total microwave power of 3.8 kW. The afore-mentioned magnetic field configuration can be obtained by using normal conducting solenoids and permanent magnets. Consequently, it was decided that SUSI magnetic field configuration and plasma chamber dimensions will be used as the design goal of HIISI.

HIISI has two innovative features, which make it special compared to any other RT ECR ion source: 1) its permanent magnet array is vacuum insulated and 2) cylindrical symmetry of the plasma chamber has been broken. Both features have thoroughly been described in ref. [4 – 6]. The vacuum insulation allows the cooling of the permanent magnets, which improves the properties of the permanent magnets. The intrinsic coercivity H_{cJ} and residual magnetic induction B_r for the selected magnet grade (N45SH) increase 0.55 %/˚C and 0.12 %/˚C, respectively, when the temperature of the permanent magnet decreases. The HIISI design allows cooling of the permanent magnets to -20 C˚. This will increase the H_{cJ} and B_r values from 1595 kA/m and 1.35 T (at 20 ˚C) to about 2100 kA/m and 1.42 T (at -20˚C), respectively. According to demagnetization analysis HIISI is safely operated as long as the permanent magnet temperature does not exceed room temperature.

The cooling capacity of the HIISI plasma chamber allows the use of microwave power of up to 4 kW. The cooling geometry of the plasma chamber and the refrigerated PM array have been presented thoroughly in references [4-6]. Further development of the refrigerated permanent magnet array could make the construction of 1.5 T ECR ion source sextupole possible. This would

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allow plasma heating at the microwave frequency of 21 GHz.

Two complete sextupoles have been constructed for HIISI: 1.32 T (24-segm.) and 1.42 T (36-segm.) sextupoles. The 24-segment sextupole was constructed for the testing and mastering of the new technology and subsequent transfer of the new experience and know-how for a more advanced and complicated 36-segment configuration. The magnet grade of N45SH was used in both configurations. The HIISI specifications are presented in Table 1.

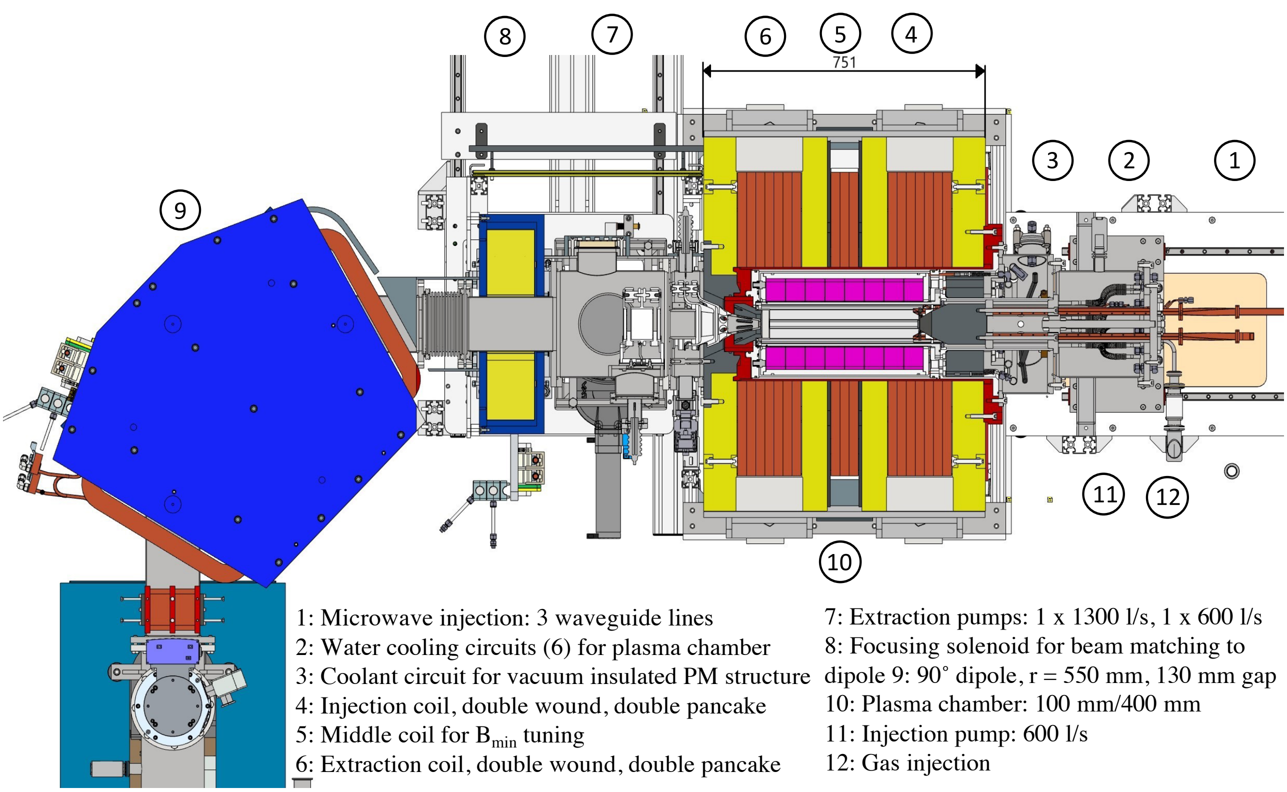
The layout of the HIISI ion source is presented in Fig. 1. The main design objective, to match the magnetic field configuration of HIISI with that of SUSI, was met with the aid of the afore-mentioned innovative solutions for the permanent magnet array and for the plasma chamber.

The microwave power is injected using 3 separate waveguide lines: 1) WR-62 waveguide for 18 GHz/2 kW klystron, 2) WR-62 waveguide for 14.5 GHz/2 kW klystron and 3) WR-75 waveguide for 8-18 GHz TWTA/250 W. So far, HIISI has been operated in (18 + 14.5) GHz operation mode at the power of up to 2 kW and 0.4 kW, respectively. In accordance of an updated plan the TWTA waveguide line will be dedicated for 2nd 18 GHz/2kW klystron increasing the total capacity at this frequency to 4 kW.

The ions are extracted through an 8 mm plasma electrode aperture and through a 25 mm acceleration gap at the voltage ranging from 10 kV to 20 kV. Downstream from the puller the beam is focused by two accelerating einzel lenses. The beam is further focused and matched into the double focusing, 90-degree, r = 550 mm, bending magnet using a large aperture (144 mm) solenoid magnet.

Table 1: HIISI Specifications

Main frequency	18 GHz/2 kW
Secondary frequency	14.5 GHz/2 kW
TWTA	8-18 GHz/250 W
$B_{inj}/B_{min}/B_{ext}$ (nominal)	2.7/0.43/1.3 T
B_{rad} (24/36-segm.)	1.32T/1.42 T
V (inside resonance surface)	0.36 litres/18 GHz
Resonance length (on axis, nom. B field configuration)	130 mm (18 GHz)
Plasma chamber dimensions	d = 100 mm / L = 400 mm
Cooling capacity of plasma chamber	4 kW
HV (presently limited to)	≤ 20 kV/5 mA
Plasma electrode aperture	8 mm in diam.
Power consumption of coils (nom. B fields)	150 kW
Inj./Ext. pressure	$1.7 \times 10^{-7}/2 \times 10^{-8}$ mbar



1: Microwave injection: 3 waveguide lines
2: Water cooling circuits (6) for plasma chamber
3: Coolant circuit for vacuum insulated PM structure
4: Injection coil, double wound, double pancake
5: Middle coil for B_{min} tuning
6: Extraction coil, double wound, double pancake
7: Extraction pumps: 1 x 1300 l/s, 1 x 600 l/s
8: Focusing solenoid for beam matching to dipole 9: 90° dipole, r = 550 mm, 130 mm gap
10: Plasma chamber: 100 mm/400 mm
11: Injection pump: 600 l/s
12: Gas injection

Figure 1: Layout of the HIISI ion source and beam transport line.

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HIISI PERFORMANCE

The testing of HIISI was started in September 2017 by producing highly charged ion beams from oxygen and argon plasmas. During the first days the intensity of 0.5 mA was reached for O^{7+} and Ar^{12+} ion beams demonstrating a performance of HIISI. The source was operated with total microwave power up to 2.4 kW (18 GHz + 14.5 GHz). The refrigerated permanent magnet structure was kept at 10˚C. It was also found out that the cooling of the vacuum chamber, which provides the vacuum insulation for the permanent magnet sextupole was inadequate: we were able to operate the ion source only about 2 hours, at around the microwave power of 2 kW, before the set value for the temperature interlock was reached. This problem was solved for the 36-segment PM sextupole. The record intensities for oxygen, argon and xenon are presented in Table 2. The results were obtained regardless of relatively high background pressure inside the injection chamber of HIISI (1.7 x 10^{-7} mbar).

Table 2: Record Intensities for Oxygen, Argon and Xenon.

oxygen		argon		xenon	
q	I [μA]	q	I [μA]	q	I [μA]
6+	1320	11+	680	26+	300
7+	620	12+	570	27+	196
		13+	330	29+	60
		14+	195	30+	46
		16+	54	31+	27

HIISI vs JYFL 14 GHz ECRIS

The 36-segment sextupole (1.42 T) and the modifications for the HIISI injection geometry were completed in spring 2018. This allowed us to start an active testing campaign of HIISI to better define its performance and the subjects for further development. Figure 2 shows the argon charge state distribution when HIISI was tuned for Ar^{12+} ion beam. The figure also shows the record argon ion beam intensities produced by the JYFL 14 GHz ECRIS. The comparison demonstrates that the requirement set by the nuclear physics program has been met.

The HIISI extraction optics has been designed for the total ion beam current and the extraction voltage of up to 5 mA and 20 kV, respectively. The first experiments have demonstrated that the extraction design does not allow to exploit the full potential of HIISI. The argument is supported by three observations: the intensity of Ar^{12+} ion beam increased as a function of 1) the acceleration voltage, 2) the argon feed rate and 3) microwave power. The intensity of Ar^{12+} increased 5-10 μA per an increment of 0.5 kV. The acceleration voltage was limited to 19.5 kV because at higher values high voltage sparking was observed inside the extraction region. It was also noticed that the Ar^{12+} ion beam intensity increased with the feed rate of argon. After the scanning of the spectrum shown in Fig. 2, the feed rate or argon was increased by a single step of the gas valve. The intensity increased about 20 μA resulting in an immediate high voltage spark destroying for example a HV power supply. The extraction has to be upgraded before the high intensity ion beam testing is continued.

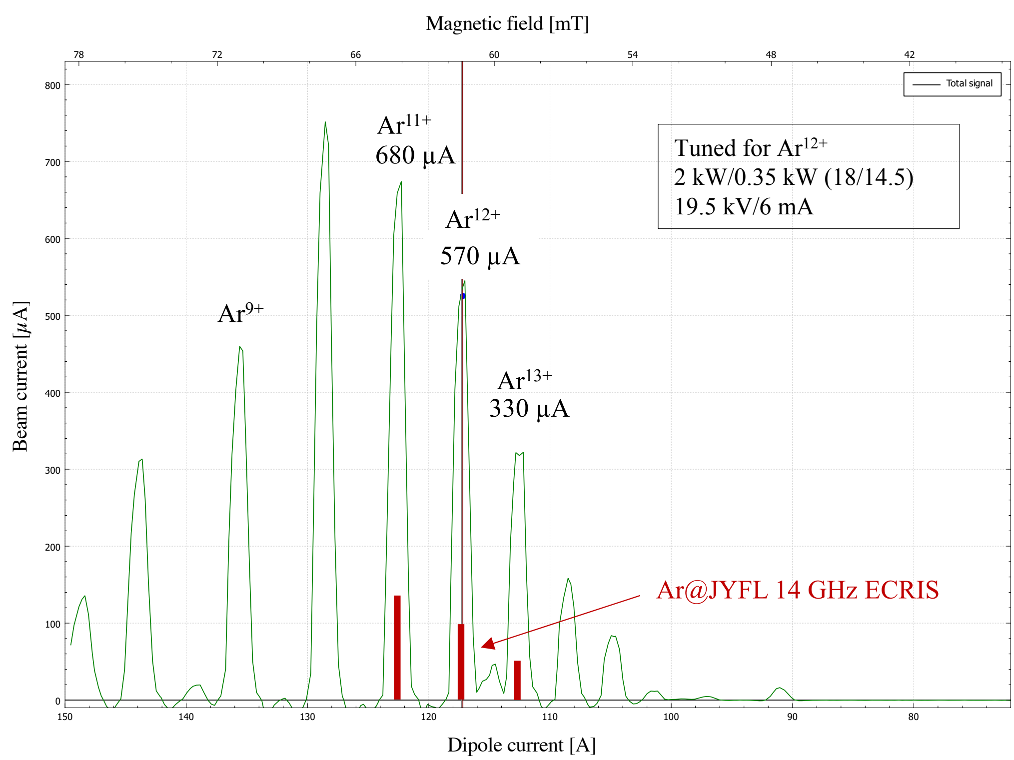

Figure 2: Argon charge state distribution produced by HIISI ion source at JYFL.

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Performance vs Space Electronics Irradiation

In order to meet the other requirement of the project (≥ 16 MeV/u) the charge state of at least 44+ has to be produced in the case of xenon. Due to the extremely challenging nature of the project the ultimate goal set by the irradiation testing program was decided to be pursued via an intermediate step (12.5 MeV/u, Xe^{40+}). The first tests were realized at the end of 2017 using the 24-segment sextupole (B_{rad} = 1.32 T). Figure 3 shows the intensity of Xe^{40+} ion beam, measured at the irradiation effect testing station, as a function of the microwave power (18 GHz). As the figure shows the required intensity level of 10^6 counts/s/cm^2 was easily reached. The figure also shows that the intensity increased vigorously as a function of the microwave power and does not show any sign of saturation below the maximum available microwave power of 2 kW. The test was later realized with the 36-segment sextupole (B_{rad} = 1.32 T) resulting in about 3-fold ion beam intensity.

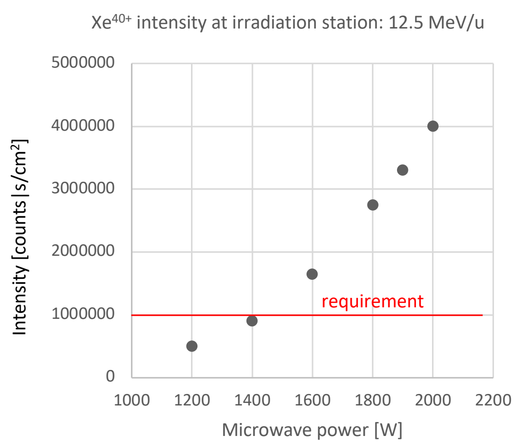

Figure 3: Xe^{40+} particle intensity (12.5 MeV/u) on the irradiation target as a function of the microwave power. The red horizontal line shows the intensity requirement.

CONCLUSION AND FUTURE PROSPECTS

The first experiments have already demonstrated a high performance and potential of HIISI. The experiments also demonstrated that HIISI accepts the microwave power of 2 kW (18 GHz) without any sign of saturation. Consequently, a new 18 GHz/2 kW klystron was purchased in order to duplicate the plasma heating power. The experiments have also given valuable information about the most critical factors limiting the beam intensities extracted from HIISI. During the coming months, i.e. during the first half of 2019, two important upgrades will be realised: 1) the microwave power upgrade and 2) the extraction upgrade. The new 18 GHz/2 kW klystron has arrived and will be connected to HIISI in the beginning of 2019. The new klystron will be connected to the waveguide line originally reserved for the TWTA. This allows us to measure the intensity of Xe^{40+} and Xe^{44+} ion beams as a function of the total microwave power up to 4 kW. During the test, the total ion beam current extracted from the ion source will be limited to 5 mA. The design work for the extraction upgrade will be started in the beginning of 2019. The upgraded extraction has to be capable of extracting the total beam intensities of up to 10 mA. In addition, the high voltage capabilities of HIISI will be improved to make the testing and operation at the acceleration voltage of at least 25 kV possible. The HIISI waveguide lines and the injection side will be modified later to maximize the source performance in 3 and 4-frequency operation modes.

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