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ABSTRACT

An innovative 18 GHz HIISI (Heavy Ion Ion Source Injector) room temperature Electron Cyclotron Resonance (ECR) ion source (ECRIS) has been designed and constructed at the Department of Physics, University of Jyväskylä (JYFL), for the nuclear physics program of the JYFL Accelerator Laboratory. The primary objective of HIISI is to increase the intensities of medium charge states (M/Q ≅ 5) by a factor of 10 in comparison with the JYFL 14 GHz ECRIS and to increase the maximum usable xenon charge state from 35+ to 44+ to serve the space electronics irradiation testing program. HIISI is equipped with a refrigerated permanent magnet hexapole and a noncylindrical plasma chamber to achieve very strong radial magnetic confinement with B_{rad} = 1.42 T. The commissioning of HIISI began in Fall 2017, and in Spring 2019, it has met the main objectives. As an example, the intensity of the Xe^{27+} ion beam has improved from 20 μA to 230 μA. In addition, the beam intensity of the Xe^{44+} ion beam has exceeded the requirement set by the irradiation testing program. The performance of HIISI is comparable to superconducting ECR ion sources with the same maximum microwave frequency of 18 GHz and a total power of 3 kW. For example, Ar^{16+} and Xe^{30+} ion beam intensities of 130 μA and 106 μA, respectively, have been obtained with a total microwave power of 3 kW distributed between 18, 17.4, and 14.5 GHz frequencies. The ion beams have been extracted through an 8 mm plasma electrode aperture using 15–17 kV extraction voltage. The latest development work, extracted ion beam intensities, special features, and future prospects of HIISI are presented in this paper.

I. INTRODUCTION

The primary objectives of HIISI[1–3] (Heavy Ion Ion Source Injector) were to (A) increase the intensity of medium charge states, such as Ar^{8+} and Xe^{27+}, by a factor of 10 in comparison with the JYFL 14 GHz Electron Cyclotron Resonance ion source (ECRIS) for ion beams up to 5 MeV/A, required by the local nuclear physics program and (B) increase the ion beam cocktail energy, required by the European satellite industry and radiation effects community, from the present maximum of 9.3 MeV/A to at least 15 MeV/A. In the case of xenon—which is considered to be the heaviest component of the high-energy beam cocktail at JYFL—the latter requirement can be achieved with the Xe^{44+} ion beam. The ion flux, at the irradiation target, should reach 1 Mcounts cm^{-2} s^{-1}. In 2014, the given requirement exceeded the performance of any existing room temperature (RT) ECR ion source.

The technical considerations required to achieve the given goals were formulated by analyzing existing high-energy, high-intensity ion sources. As a result, the technical configuration of SUSI[4] at NSCL/MSU was found to be the most promising as its performance at 18 GHz met the requirements of the ECR ion source at JYFL (see Fig. 3). It was then expected that by using the SUSI geometry, i.e., a similar plasma volume and a magnetic field configuration for the new JYFL design, the new ECR ion source, HIISI, can be realized without the use of expensive and complex superconducting techniques. With the new design, the aforementioned intensity requirements can be met with 18 GHz heating frequency, making the ion source a very attractive and cost effective option for any large-scale accelerator facility.

II. SPECIFICATIONS OF HIISI

The ion beam data of SUSI, when operated at 18 GHz and optimized for the production of very high charge states, suggested that the hexapole field (B_{rad}) should be at least 1.35 T on the surface of the plasma chamber. The value is very challenging to achieve with permanent magnets when, at the same time, the considerations for the strong demagnetizing magnetic field induced by the solenoid magnets have to be taken into account. Two innovative approaches have been adopted to reach the adequate (B_{rad}) value (1.35 T) and to avoid demagnetization of permanent magnets. The permanent magnets of HIISI have been assembled inside a vacuum insulated and refrigerated hexapole magnet chamber avoiding contact between the magnets and the plasma chamber wall. The vacuum insulation allows the cooling of permanent magnets down to −20 °C, which strongly increases the coercivity of the magnets against the demagnetizing field component. The thickness of the plasma chamber wall is minimized at the magnetic pole, i.e., at the plasma loss area, to maximize the radial confinement. The width w of this thinner section, shown in Fig. 1, is 16 mm. The unconventional plasma chamber structure makes it possible to realize the vacuum insulation without compromising the radial confinement. In this approach, the distance between the magnets and the inner surface of the plasma chamber can be kept short, i.e., close to 4 mm, which makes adequate radial plasma confinement possible. The concept of the plasma chamber radius varying with the polar coordinate angle was first tested with VENUS.[5,6] The HIISI plasma chamber is presented in Fig. 1. In the present configuration, the plasma chamber radii R_1 and R_2 at the magnetic pole and between the poles are 54.5 mm and 50 mm, respectively. The thickness of the plasma chamber wall at the magnetic pole is 3 mm. The vacuum gap between the plasma chamber and permanent magnet structure is 1.5 mm. The HIISI plasma chamber has 6 cooling circuits as close to the plasma flux area as possible. The cooling circuit has a pressure drop and water flow rate of about 6 bars and 0.2 l/s, respectively (see Ref. 1 for further information).

The maximum microwave power was defined by thermal simulations. In the simulations, the realistic magnetic field geometry is used to define the electron distribution of radial losses. It was assumed that the entire heat load is transferred to the plasma chamber walls by electrons. According to the thermal simulations, the plasma heating power should not exceed 3 kW. This radial power load results in the maximum temperature rise ΔT of about 55 K on the plasma chamber wall. This power is considered to be safe for the aluminum plasma chamber as well as for the refrigerated hexapole magnets. The electron trajectory simulations also revealed that the width of the electron flux on the chamber wall increases with the electron energy. As an example, 100 keV electrons cover the 18 mm area on the wall of the HIISI plasma chamber. The result indicates that the magnetic confinement of 100 keV electrons, and above, is slightly affected by the geometry of the HIISI plasma chamber. More comprehensive information about the heat load and the electron trajectory simulations and related considerations can be found from Ref. 2.

The HIISI specifications are presented in Table I. The axial magnetic field is produced by three coils. The coil currents to produce the nominal magnetic field values shown in the table are as follows: 1000 A, 0–200 A, and 820 A for the injection, middle, and extraction coil, respectively. The current in the middle coil is reversed from the other two and is used for the tuning of the B_{min} value. The electric power consumption is about 160 kW with the nominal coil currents. The layout of HIISI is presented in Fig. 2.

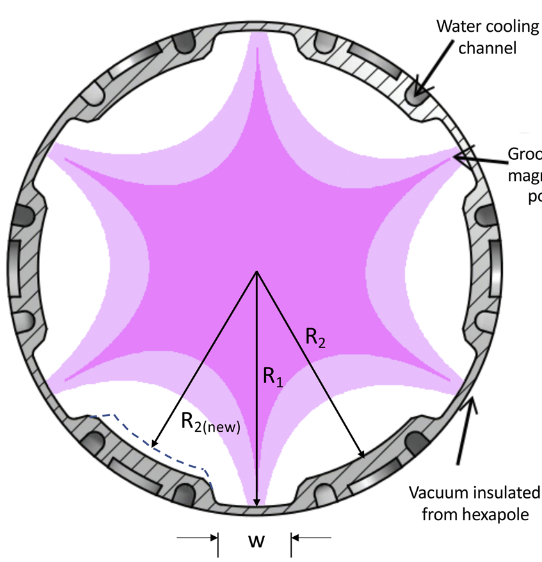

FIG. 1. The cross section of the HIISI plasma chamber: R_1 is 54.5 mm, R_2 is 50 mm, and width w is 16 mm. Different radius values $R_{2(new)}$, between the magnetic poles, will be tested later.

TABLE I. HIISI specifications.

Frequency	18 + 17.4 + 14.5 GHz
Total klystron power	Limited to 3 kW
TWTA 8–18 GHz	P(max): 250 W
B_{rad} (24-segment)	1.3 T
B_{rad} (36-segment)	1.42 T
B between poles (36-segment)	1.0 T
B_{inj}	2.8 T
B_{min}	0.45 T
B_{ext}	1.3 T
P_{inj}	1.5×10^{-7} mbar
P_{ext}	3×10^{-8} mbar
L (plasma)	120–150 mm
V (plasma)	0.36 l
L (plasma chamber)	400 mm
D (plasma chamber)	109 mm (on pole)
D (plasma chamber)	100 mm (between poles)
T (hexapole)	+5 °C
Typical extraction voltage	15–20 kV
D (extraction aperture)	8 mm

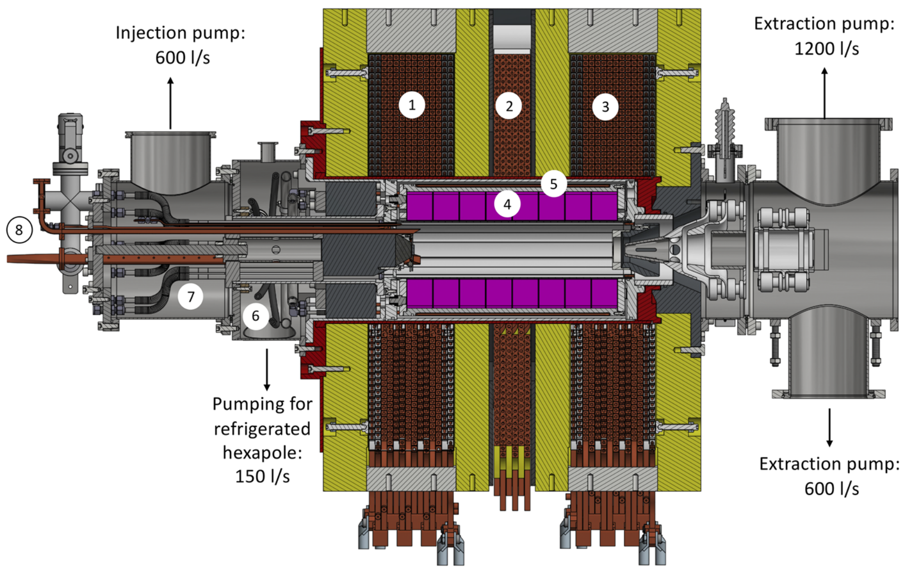

FIG. 2. Layout of HIISI: (1) Injection coil for current up to 1000 A, (2) middle coil for tuning of B_{min}, (3) extraction coil for current up to 900 A, (4) vacuum insulated hexapole, (5) vacuum chamber for permanent magnet array, (6) coolant circuit for refrigerated permanent magnets, (7) six water cooling circuits for plasma chamber, and (8) three waveguide lines for microwaves 14.5/17.4/18 GHz.

III. DEVELOPMENT STEPS OF HIISI

The hexapole magnetic field simulations for the 24-segment and the 36-segment configurations showed that the more complex configuration will boost the B_{rad} value from 1.3 T to 1.42 T with the same permanent magnet grade. The refrigerated hexapole structure can be considered as a prototype with several unknown factors, and therefore, it was decided to construct first the weaker but less complex 24-segment hexapole. This intermediate step allowed us to test the prototype with lower complexity, and especially, it gave us important know-how for the realization of the stronger but more complex 36-segment permanent magnet configuration.

A. 24-segment hexapole

The assembly of the 24-segment permanent magnet hexapole was realized in the beginning of 2016, and the first offline cooling test, for the refrigerated assembly alone, was successfully performed a few weeks later. The commissioning of HIISI was started in the Fall 2017 with the 24-segment hexapole (1.3 T). During two short test periods, high-intensity oxygen and argon ion beams were extracted. The achieved intensities are shown in Table II and denoted by *a*. During the test periods, three bottlenecks were discovered: (1) overheating of the outer part of the refrigerated hexapole structure, (2) inadequate design of the ion beam extraction, and (3) inadequate high voltage (HV) insulation and protection.

TABLE II. HIISI[1–3] commissioning status and comparison to JYFL 14 GHz ECRIS[9] and GTS.[10] Beam currents expressed in μA. The oxygen and argon beam currents of HIISI are measured with a 32 mm collimator located at the front of the Faraday cup, and the xenon beam current is measured with a 25 mm collimator.

Ion species	JYFL 14 GHz ECRIS 1 kW + TWTA (50–100 W)	GTS 18 GHz	HIISI 2017^a HIISI 2019^b
O^{6+}	627	1950	1080^a
O^{7+}	222	...	560^a
Ar^{12+}	103	380	560^a
Ar^{13+}	51	255	330^a
Ar^{14+}	49	174	195^a
Ar^{16+}	10	50	130^b
Kr^{25+}	...	...	121^b
Xe^{29+}	17	...	129^b
Xe^{30+}	12	60	106^b
Xe^{31+}	8	40	72^b
Xe^{32+}	4	...	50^b
Xe^{34+}	...	8	30^b
Xe^{35+}	...	...	27^b

The hexapole structure has four temperature sensors: three of them are assembled on the refrigerated hexapole chamber (15 °C) and one on the permanent magnet vacuum chamber (45°). The interlock set-point for the sensors is shown in the parentheses. The permanent magnets were cooled down to 5 °C. The HIISI was operated up to 2.3 kW without a significant temperature rise of the refrigerated permanent magnet array ($\Delta T \approx 1\,^{\circ}$C). However, it was discovered that the cooling of the extraction electrode is not adequate, allowing heat conduction into the outer structure of the permanent magnet vacuum chamber. This gradual overheating (temperature interlock set to 45 °C) strongly limited the tuning range and operational time of HIISI. Regardless of this problem, the HIISI immediately demonstrated high performance.

The first test period also revealed that the performance of HIISI clearly exceeds the original design specifications (3–5 mA) for the total extracted current. Ion beam intensities above the design value tend to cause charging and sparking in the extraction region. Attempts to minimize the spreading of the beam were done by increasing the extraction voltage. The combination of high total beam intensity (6 mA) and the use of 20 kV extraction voltage eventually caused a serious high voltage failure that damaged the power supplies and other auxiliary devices. The test period with the 24-segment hexapole also revealed that the beam current increased monotonically up to a power of 2.3 kW (14.5 GHz + 18 GHz operation[3]), therefore motivating the use of higher microwave power.

B. 36-segment hexapole

The overheating problem was resolved for the 36-segment hexapole constructed in Spring 2018. The high voltage insulation was improved in Fall 2018 by better grounding, optical separation of control signals, and upgraded HV breaks. In addition, the third heating frequency was enabled and the maximum microwave power limit was increased from 2.3 kW to 3 kW. Most of the experiments have been performed in three frequency operation mode (14.5 + 17.4 + 18 GHz). Due to inadequate extraction capabilities, the total ion beam current and extraction voltage have been limited to 5 mA and 19 kV, respectively. As a result of this, the HIISI has mainly been tested for the production of high charge states such as Ar^{16+} and Xe^{30+}.

IV. CURRENT PERFORMANCE

The current performance of HIISI is presented in Fig. 3 and Table II. The figure also shows a comparison between the JYFL 14 GHz ECRIS, SUSI, and HIISI (2017/2019). The performance of room temperature HIISI and fully superconducting SUSI is practically identical, and the HIISI has exceeded the target intensity set for the 16.2 MeV/u beam (1 Mcounts cm^{-2} s^{-1}). The intensity of the Xe^{44+} ion beam in the irradiation target was measured to be several times higher than the intensity of the Xe^{35+} ion beam produced with the JYFL 14 GHz ECRIS. The improved performance of HIISI from 2017 to 2019 is due to the stronger hexapole (1.3 T → 1.42 T), new klystron with 17.4 GHz heating frequency (14.5 GHz + 18 GHz → 14.5 GHz + 17.4 GHz + 18 GHz), and the higher total microwave power (2.3 kW → 3.0 kW).

The excellent performance of HIISI has encouraged us to develop a new 22 MeV/A heavy ion cocktail for irradiation tests of

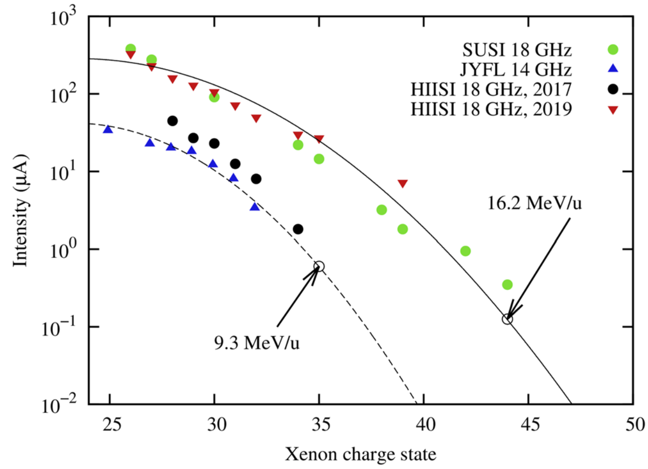

FIG. 3. Intensities of Xe ion beams produced by different ECR ion sources: JYFL 14 GHz ECRIS, SUSI at 18 GHz (4 kW), and HIISI in 2017 (14.5 GHz + 18 GHz/2.3 kW) and 2019 (14.5 GHz + 17.4 GHz + 18 GHz/3 kW). The xenon charge states of 35+ and 44+ required for the currently used 9.3 MeV/u and proposed 16.2 MeV/u beam cocktails are marked on the fitting curves.

space electronics. Krypton will be the heaviest element in the cocktail, and the required energy will be met by the Kr^{32+} ion beam. The first experiment with the HIISI confirmed that the requested energy and fluence specifications can be met. Figure 4 shows the charge states distribution of krypton when the HIISI has been tuned for the Kr^{25+} ion beam. The tuning parameters are as follows: 3-frequency

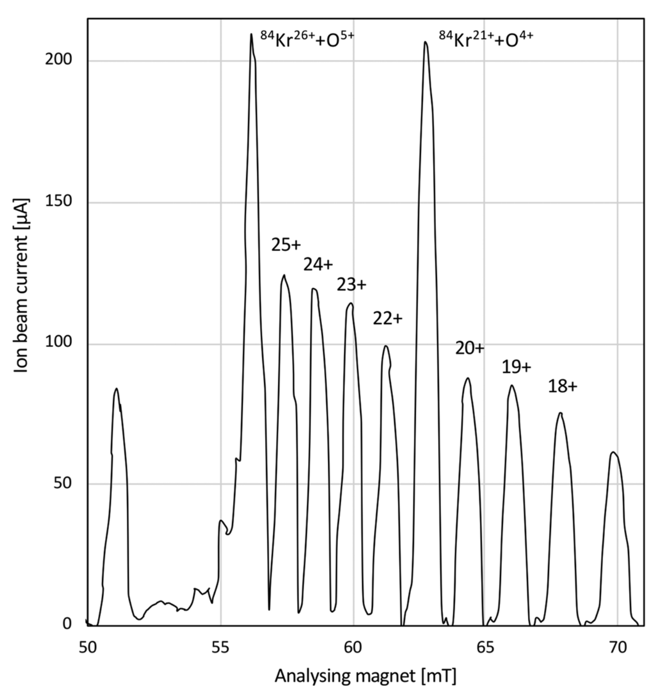

FIG. 4. Charge state distribution of krypton when the HIISI was optimized for Kr^{25+}.

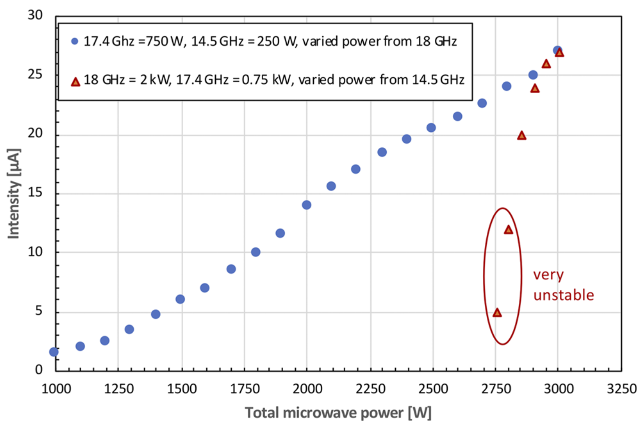

FIG. 5. Intensity of the Xe^{35+} ion beam as a function of total microwave power when the power from the 14.5 GHz or 18 GHz power was altered.

heating is used (14.5/17.4/18 GHz), total microwave power is 3 kW (250/750/2000 W), nominal magnetic field values shown in Table I are used, and oxygen is used as the mixing gas. The ion beam was extracted through the plasma electrode aperture, 8 mm in diameter, using an extraction voltage of 17 kV.

The use of 14.5 GHz as the secondary frequency has been observed to have a strong impact on the performance of HIISI. In all circumstances, it stabilizes the plasma, but especially in the case of highly charged ion beams, such as Xe^{35+}, its effect on the ion beam intensity is dramatic. This is demonstrated by Fig. 5. In this experiment, the ion source was tuned for Xe^{35+} and the beam intensity of about 27 μA was obtained with a total microwave power of 3 kW. In order to demonstrate the stabilizing effect of the 14.5 GHz radiation, the total microwave power was decreased by decreasing the power from either the 14.5 GHz or the 18 GHz klystron, while the power from the 17.4 GHz klystron was kept constant. The total heating power of 3 kW was introduced to plasma as follows: 250/750/2000 W from 14.5/17.4/18 GHz klystrons, respectively. The intensity of Xe^{35+} decreased gradually when the power from the 18 GHz klystron was decreased. The power transmitted from the 14.5 GHz klystron had a much stronger effect: the intensity first drops quickly with decreasing power and the plasma becomes very unstable when the 14.5 GHz power is below 100 W. The multiple frequency heating and plasma stability of HIISI will be studied in more detail during 2020. It is assumed that the evidenced plasma instabilities are of kinetic origin, driven by the anisotropy of the Electron Energy Distribution (EED).[7,8]

V. FUTURE PLANS AND PROSPECTS

The HIISI research and development program that will be taking place during 2020-21 is divided into three different topics: (1) extraction upgrade, (2) optimization of HIISI plasma chamber geometry, and (3) characterization of plasma properties, especially the plasma stability. The experimental campaign to define the extracted beam properties has been started and will be completed by the end of 2019. The data are needed to optimize the extraction optics and geometry for higher total beam intensities (from 3–5 mA to 5–8 mA). The characterization of the plasma, especially the plasma stability experiments, will be started in the beginning of 2020. The instability threshold will be defined in different operation modes using different heating frequencies and their combinations and with different plasma chamber geometries. The plasma chamber geometry will be changed, for example, by varying the width w of the groove on the magnetic pole and by varying the radius $R_{2(new)}$, both shown in Fig. 1. The work will also give important information for further development of the HIISI hexapole and the cooling capacity of the HIISI plasma chamber.

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