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HIGH POWER OPERATION WITH SECRAL-II ION SOURCE*

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Abstract

SECRAL-II ion source has been successfully developed with the experiences from SECRAL that is another superconducting ECR ion source in operation at IMP. Other than that, SECRAL-II has been intentionally optimized in structure so as to make it optimum for 28 GHz microwave operation. This ion source was available on the test bench in early 2016, and has been used for 28 GHz high microwave power commissioning and tests. With a maximum power 10 kW@28 GHz and 2 kW@18 GHz, very high microwave power density and dense hot plasma could be built in the 5-liter volume plasma chamber. Consequently, very high current density ion beams of high charge states are achievable, which have already exceeded the performance the 24 GHz SECRAL had made couple of years ago. However, there is also the intractable issues stemmed from the hot dense electrons inside the plasma, such as plasma chamber cooling, dynamic heat load to the cryogenic system, and so on. This paper will present the recent results of SECRAL-II operated with high microwave power. The typical consequent issues during the high-power course other than high intensity high charge state ion beam production will be discussed.

INTRODUCTION

Electron Cyclotron Resonance Ion Sources or ECRIS has play an indispensable role in the development of next generation heavy ion accelerators, such as FRIB at MSU, HIAF at IMP, and JLEIC at JLab, and so on [1, 2, 3]. ECRIS is the most efficient ion source in term of the production of dc and long pulse (~ms) highly charged heavy ion beams. After more than 40 years' continuous development by generations of ECRIS sourcerors, the state of the art ECRISs have evolved to 3rd generation, which is represented by superconducting machines, such as VENUS at LBNL, SCECRIS at RIKEN, SECRAL& SECRAL-II at IMP, and so on [4, 5, 6, 7]. High performance superconducting ECRIS provides by far the ultimate conditions for high charge state ion beams production, such as much higher operation microwave frequency, better magnetic field confinement, bigger plasma chamber volume and above all, more flexible conditions for ion source performance optimization. Intense highly charged ion beam production is mainly defined by three key factors, i.e. n_e-plasma density, T_e-electron energy, and τ- exposure time of the ions to a cloud of plasma electrons. State of the art ECRISs can provide flexible conditions for highly charged ion production with quasi-optimum T_e and τ, however, to get high intensity beams, sufficiently high microwave power, or to some extent the effective power density, is required to achieve high enough plasma density inside the plasma chamber. Therefore, high microwave power operation exploration is very necessary and might be mandatory for next generation heavy ion acceleration routine operation, for instance >0.7 emA U^{35+} for HIAF, >0.5 emA U^{35+} for RIBF, and so on.

SECRAL-II is a fully superconducting ECR ion source recently developed at IMP. Its superconducting magnet structure design inherits the features of SECRAL, except the cryogenic system. Table 1 summarizes the main parameters of SECRAL and SECRAL-II in comparison. The improved cryogenic system of SECRAL-II enables high microwave power operation (up to 10 kW) despite of the high bremsstrahlung radiation to the 4.2 K cold mass and the resultant high dynamic heat load, which allows the exploration of the ion source performance at high microwave power. This paper will report the high-power commissioning results and the typical issues of interests in terms of high power stability and beam quality. Challenges to a high power ECRIS are becoming apparent with increasing power density inside the plasma chamber, which are also discussed.

Table 1: Main Parameters of SECRAL-II

Parameters	SECRAL-II	SECRAL
ω rf (GHz)	18-28	18-24
Axial Field Peaks (T)	3.7 / 2.2	3.7/2.2
Mirror Length (mm)	420	420
No. of Axial SNs	3	3
Br (T)	2.0	1.7/ 1.83
Coldmass Length (mm)	~810	~810
SC-material	NbTi	NbTi
Magnet Cooling	LHe bathing	LHe bathing
Warm bore ID (mm)	142 .0	140.0
Chamber ID (mm)	125.0	116.0/120.5
Cooling power@4.2 K (W)	~6	0

HIGH POWER RF SYSTEM

In the high microwave power campaign with SECRAL-II source, several high power microwave generators have been used. 18 GHz CPI DBS-band klystron microwave generator with a maximum microwave power output of 2.4 kW, is used as secondary ECRH (ECR Heating) microwave power source. CPI 28 GHz VGA model CW

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gyrotron microwave generator with a maximum output power of 10 kW, is adopted as the main ECRH microwave power with regards to SECRAL-II design. A 45 GHz/20 kW gyrotron microwave generator from GyCOM Ltd., is incorporated as an auxiliary ECRH microwave source, and additionally to have a proof of principle test of ECRH with the microwave power system for the 4th generation ECR ion source FECR [8]. As 3 different microwave frequencies are available, flexible choices of ECRH schemes for the exploration of high power operation have been made, for instance 18 + 28 GHz double frequency heating, 28 GHz single frequency heating, 18 + 28 +45 GHz triple frequency heating and 28 + 45 GHz double frequency heating. As 28 GHz is always the main ECRH frequency with SECRAL-II, the maximum microwave power injected into the ~5 litters plasma chamber is about 12.4 kW (nominal, transmission loss is not counted), which is equivalent to a power density of ~2.4 kW/l. Generally, a >1.0 kW/l power density will be granted as the criteria as high power operation for most of the 18~28 GHz high performance ECRISs. However, very high microwave power density up to 2.4 kW/l is not always effective during the experiments. Typically, the best performance presented in this paper has been obtained with 7~12 kW (respectively ~1.4-2.4 kW/l) for very intense medium charge state heavy ion (A>40) beam production, and 3~8 kW (respectively ~0.6-1.5 kW/l) for very high charge state heavy ion beams production.

ION SOURCE PERFORMANCE AT HIGH MICROWAVE POWER

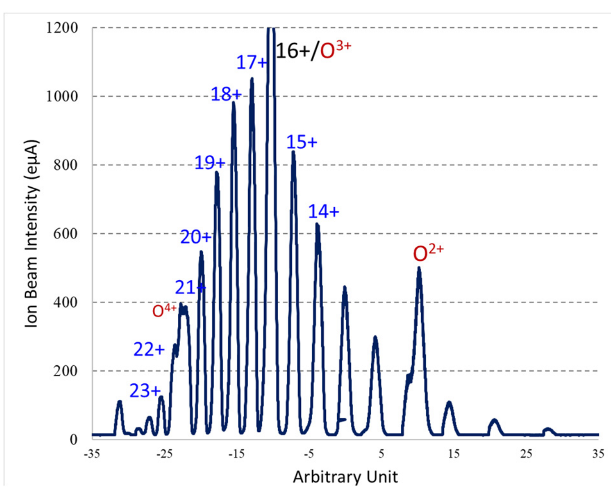

Figure 1: Production of intense Kr^{18+} beam.

At high power ECRH, high density plasma with sufficient energetic electrons are created to strip ions to high charge state. Depending on the source optimization, very intense medium charge state ion beams with the ionization potentials of 0.5~1.0 keV (such as Ar^{14+}, Kr^{18+}…), and very high charge state ion beams with the ionization potentials of >4.0 keV (such as Kr^{33+}, Xe^{44+}, …) are produced and extracted. Similar results are also recently obtained with VENUS ion source during several high power tests, typically 10 kW (~1.3 kW/l), which are also presented at this workshop [9]. Table 2 lists most of recent results with VENUS@28 GHz, SECRAL@24 GHz, and SECRAL-II@28 GHz. As given in the table, emA order ion beams such as Kr^{18+} (Fig. 1) and so on are achievable now, which is a very important benchmark for next generation heavy ion accelerations composed of either SRF linacs or synchrotrons. Very high charge state ion beams production such as Kr^{3n+}, Xe^{4n+} (Fig. 2) and so on, has pushed the M/Q dc beams extracted with an ECRIS from traditionally >4 to presently <3, which is very attractive to cyclotrons and HCI physics, in terms of machine performance and possible physics investigations.

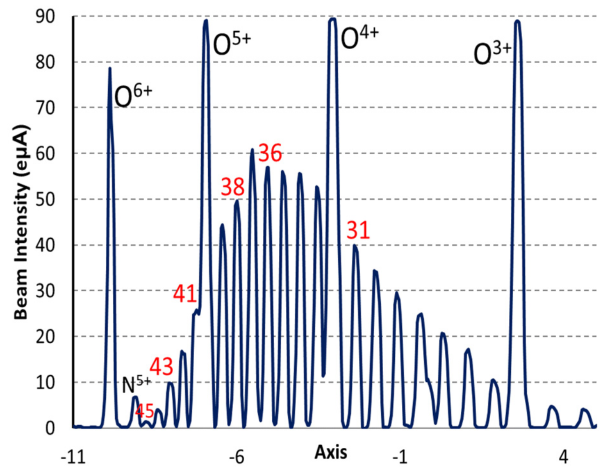

Figure 2: Production of high charge Xe beams.

Table 2: High Intensity and Highly Charged Ion Beams Production With SECRAL-II

Ion	VENUS 2018 10 kW	SECRAL 2016 7~8 kW	SECRAL-II 2018 10 kW
$^{16}O^{6+}$	4750	2300	6700
O^{7+}	1900	810	1750
$^{40}Ar^{12+}$	1060	1420	1190
Ar^{14+}	840	846	1040
Ar^{16+}	525	350	620
Ar^{17+}	120	50	130
Ar^{18+}	4.0	--	14.6
$^{78}Kr^{18+}$	770		1030
Kr^{23+}	420		436
Kr^{28+}	100		146
Kr^{30+}			20
Kr^{31+}	17		7
Kr^{32+}	8.0		0.5
$^{129}Xe^{26+}$		1100	
Xe^{27+}		920	870
Xe^{30+}		360	365
Xe^{34+}	104	120	102
Xe^{38+}	26	22.6	56
Xe^{42+}	6	12	16.7
Xe^{44+}	2	1	3.9
Xe^{45+}	0.88	0.1	1.3

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CHANLLENGES AT HIGH POWER EXPLORATION

Plasma Over-heating to Plasma Chamber (PCO)

Figure 3: Sectional burnt-out chamber wall.

High charge state ECRIS is characterized by a so-called min-B magnetic field configuration, which can not avoid the problem of localized PCO that is still durable for most of the ECRISs in operation, but at a high power operation condition, it is a problematic issue, especially the 3rd generation ECRISs. Min-B structure magnetic configuration that is a superimposition of an axial mirror field and a radial hexapole field always has 6 very weak |B| points, i.e. 3 at source injection and 3 at source extraction. Plasma flux with energetic particles is much easily lost through those points, which high energy electrons dominates the loss process and energy deposition to the plasma chamber wall. With the increase of ECRH microwave power, more plasma energy or lost energetic electron energy will be deposited on tiny areas and result in a very high localized power density, which is estimated to in the magnitude of 1~10 $MW.m^{-2}$ [10]. Such a high power density heat sink to the plasma chamber inner wall can cause immediate boiling of the nearby water inside the cooling channel and isolate the chamber wall from efficient turbulent water cooling. Therefore, only thermal conduction cooling validates for those positions. That's the reason why stainless-steel chamber can only survive much lower microwave power than aluminium chamber. With the increase of ECRH power, temperature at the PCO points will be higher and higher, and eventually the plasma chamber metal will be melted or destroyed by 5~6 kg/cm^2 pressurized water when the chamber metal yield strength becomes very low. As the redial space of an ECRIS is very valuable, not much space is reserved for a complicated cooling water structure that might be useful for the chamber design. This makes it very challengeable when high power operation is desired. VENUS and SECRAL-II have both reported the problem of chamber burnt-out during high power campaign (Fig. 3). When SECRAL-II was tested with a power density of 2~2.4 kW/l, 3 aluminium plasma chambers had been destroyed successively. Improved design with better heat conduction effect and more turbulent cooling water has been made. High power test at the level of >2 kW/l will demonstrate the effectiveness in the near future.

4.2 K Dynamic Heat Load (DHL)

Bremsstrahlung radiation inside ECR plasma has been observed for a long time as researchers tried to do ECRIS plasma investigations, however, dynamic heat load caused by this radiation was only noticed not long time ago during high power ECRH with the 3rd generation ECRIS. Bremsstrahlung radiation X-ray spectrum is quite wide that covers tens of eV to hundreds of keV. Usually, to protect the main high voltage insulator, 1~2 mm Ta shield will be inserted between plasma chamber and the high voltage insulator. X-rays with the energies below 100 keV are mostly filtered by the Ta shield, however, 1~2 mm Ta sheet is almost transparent for X-rays with energies higher than 100 keV. With the increase of ECRH power, the quantity of >100 keV X-rays that can reach the cold mass, mostly composed of iron and copper, will absorb part of the penetrated rays' energy and cause a certain amount of energy sink into the 4.2 K region, and consequently heat load to the 4.2 K system. It has been observed that the ratio between the heat sink and the ECRH power is dominantly related to the B_{min} field. Figure 4 shows the dependence of the measured DHL vs. the B_{min} values at totally 5 kW microwave ECRH. As SECRAL-II has a maximum DHL tolerance of 6 W, it enables its maximum ECRH power of ~12 kW for medium charge state ions, and 6~8 kW for high charge state ion beams, as a consequence of B_{min} optimization. SECRAL-II is obviously qualified for long time operation at the power level of 5~6 kW with regards to DHL, but degradation of the main insulator under high X-ray flux exposure is still unknown even with Ta foil protection, which is also another potential challenge in high power ECRH operation.

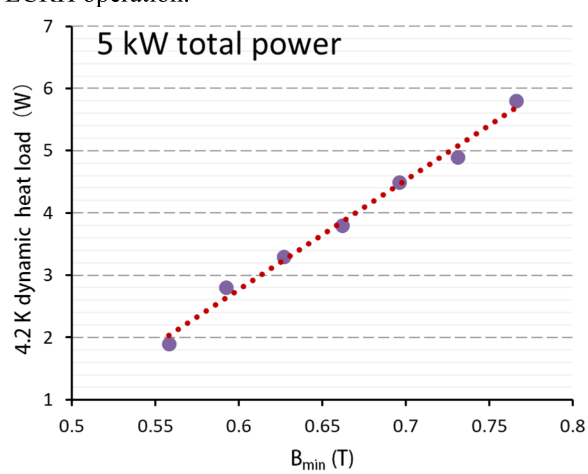

Figure 4: Dynamic heat load vs. B_{min} with SECRAL-II.

Intense Beam Extraction and Beam Quality

Based on traditional understanding of the ion beam behaviour after extraction from magnetized plasma, the emittance is proportional to the ion source field, and therefore the higher the operation frequency, the higher

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the beam emittance [11]. According to the predication, the product is that despite of the obvious beam intensity increment by frequency scaling, ion beam brightness should not have much improvement. And additionally, it has been predicted that with more intense beam extraction at high power ECRH, space charge effect will dominate and degrade the beam quality further more. A triode extraction system has been designed and integrated to SECRAL-II. The highest applicable extraction high voltage was tested up to >30 kV. The extracted mixing beam will be analysed by a high acceptance dipole with double-focusing edges [12]. As the gap is 180 mm, it allows high transmission efficiency of ion beams with big envelope. Second order component of the dipole magnet field has been carefully checked during the magnet design, provided that the beam envelope is not too big (~2/3 of the gap), the influence of sextupole component from the magnet is trivial. Additionally, to have further control of the beam envelope after ion source extraction, a high field solenoid is attached to SECRAL-II magnet. Analysed beams will be monitored by a water cooled faraday cup with the secondary electron suppressor biased to -160 V. A 4-jaw slit system is set upstream of the faraday cup to stop the unwanted beams after beam separation. A set of beam viewer and X/Y allision scanner system is integrated to monitor the beam quality.

Thanks to the 180 mm gap dipole, very high beam transmission efficiency has been observed. For 10 emA total drain current of oxygen beams, a transmission efficiency of ~85% could be made. Even at the total current of 26 emA, ~75% transmission is obtained. Heavy ion beam transmission is always a big challenge. SECRAL-II extraction system can give an estimated transmission efficiency of 85~95% for Xe beams with a total current of no more than 10 emA.

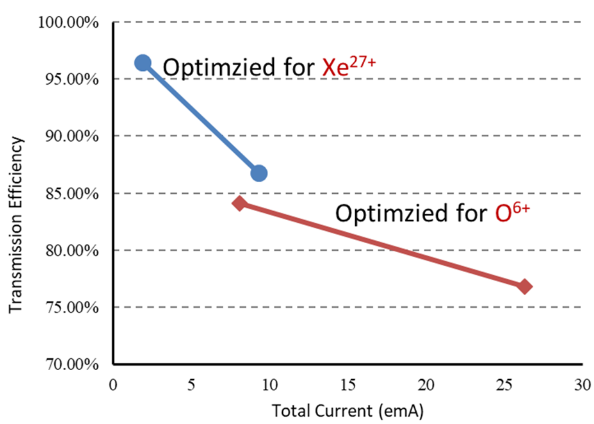

Figure 5: Beam transmission efficiency with SECRAL LEBT at different total beam intensities.

Intense beam extraction and transmission does not indicate obvious degradation of beam quality. With careful handling of the extracted beams, reasonable beam quality could be maintained. Figure 5 gives the evolution total drain current and emittances vs. the extraction ion beams of Ar^{9+} and Ar^{12+}. Obviously, high current beam production is not equivalent to high beam emittances. Medium charge state ion beams, such as Ar^{9+} has slightly worse beam quality with a hollow configuration as indicated in Fig. 6. Ar^{12+} beam quality is better as is given in Fig. 7. It is believed that the space charge actually does not dominate intense beam extraction from a high charge state ECR ion source. SPC compensation at the mixing beam line should be sufficiently high to mitigate the resultant effects. However, the spatial distribution of the ions inside the plasma and the source beam emission meniscus has fundamental impact to the beam formation and quality. Further discussion could be also be found in Ref. [12].

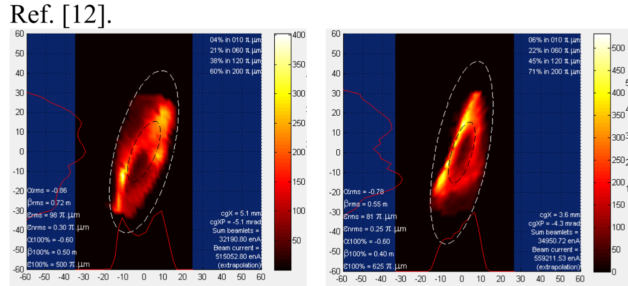

Figure 6: X/Y emittances of ~1.6 emA Ar^{9+}@20 kV.

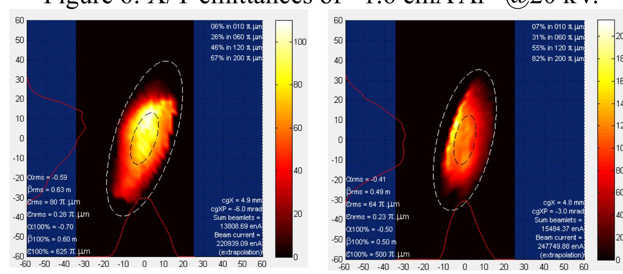

Figure 7: X/Y emittances of ~0.7 emA Ar^{12+}@20 kV.

CONCLUSION

SECRAL-II ion source has been fully commissioned at high microwave power up to 12.4 kW. Under such an ultimate condition, many promising results have been obtained via effective ECRH, for instance 6.7 emA O^{6+}, 1.03 emA Kr^{18+}, 14.6 eμA Ar^{18+}, 16.7 eμA Xe^{42+} and so on. However, these are not the limit of a high performance 3rd generation ECR ion source. Given those critical challengeable problems solved, we may expect better performance:

- Plasma cooling in terms of localized over-heating
- Stable high temperature oven for refractory metal beams
- Dynamic heat load to 4.2 K cryogenic system

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