AN ADVANCED SUPERCONDUCTING ECR ION SOURCE SECRAL AT IMP: FIRST RESULTS AND OPERATION AT 18 GHZ

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Abstract

An advanced superconducting ECR ion source named as SECRAL was successfully built to produce intense beams of highly charged ions for HIRFL in Lanzhou. A unique feature of SECRAL is that the three axial solenoid coils are located inside of the sextupole bore in order to reduce the interaction forces between the sextupole coils and the solenoid coils. For 28 GHz operation, the magnet assembly can produce peak mirror fields on axis 3.6 Tesla at injection, 2.2 Tesla at extraction and a radial sextupole field of 2.0 Tesla at plasma chamber wall. During the commissioning phase at 18 GHz with a stainless steel chamber, tests with various gases and some metals have been conducted with microwave power less than 3.5 kW by two 18GHz rf generators. Record beam intensities of some highly charged ions have been produced, for instance, 810eμA of O^{7+}, 505eμA of Xe^{20+}, 306 eμA of Xe^{27+} and so on. Dependences of the rf power, the magnetic field configuration on the ion source performance and bremsstrahlung spectra have been studied experimentally. Beam emittance from SECRAL was measured and preliminary results are given. SECRAL has been put into operation to provide highly charged heavy ion beams for HIRFL cyclotrons since May 2007. Operation status is presented.

INTRODUCTION

HIRFL (Heavy Ion Research Facility in Lanzhou) is a cyclotron and storage ring complex which consists of two cyclotrons and a heavy ion cooling storage ring (HIRFL-CSR)[1]. Heavy ion beams with intensity 5×10^{11} — 8×10^{12} pps for Ca, Ni, Xe, Pb, U are requested from the cyclotrons for radioactive ion beam physics, super-heavy element research and injection to HIRFL-CSR. To satisfy the requirements, 50-100 eμA stable DC beams and 100-200 eμA pulsed beams for highly charged ions such as Ni^{17+}, , Xe^{33+}, U^{41+} are expected from ion source. So a new fully superconducting ECR ion source named SECRAL (Superconducting ECR ion source with Advanced design in Lanzhou) was designed and built at IMP to achieve the performance enhancement of HIRFL.

Geller's ECR scaling laws suggest that an advanced highly charged ECR ion source requires stronger magnetic fields and larger microwave heating frequency to increase the plasma density and the ion confinement time [2]. The new magnetic scaling laws, proposed by ECR groups at CEA/Grenoble and LNS/Catania through a systematic study with a superconducting ECR ion source SERSE, demonstrate for example that the axial magnetic field at injection mirror throat should be about four times of the ECR resonance field to get a high performance ECR source [3-4]. These guidelines have resulted in utilization of superconducting magnet technology for higher frequency ECR ion source such as 28-56 GHz. A few of fully superconducting ECR ion sources are in operation, such as SERSE in Catania [4], VENUS in Berkeley[5] and SECRAL in Lanzhou[6]. Some other fully superconducting ECR sources are under construction or test, such as European MS-ECRIS [7], RIKEN SC-ECRIS [8] and MSU SuSI [9]. The construction of SERSE and VENUS has addressed a number of technical challenges in building a high-magnetic-field superconducting ECR source. Particularly tests of VENUS prototype magnet had demonstrated that it is very difficult to harness the high interaction forces between the axial superconducting solenoids and the radial superconducting sextupole at high magnetic fields of some teslas[10]. Excluding SECRAL, at present all existing or under development high-magnetic-field superconducting ECR ion sources utilize the conventional ECR magnetic structure, where the sextupole magnet being located inside the axial solenoid coils.

An unconventional magnetic structure was proposed during design of the SECRAL in 2001[11]. The key point of this innovative design is that all the axial superconducting solenoid coils are now located inside the superconducting sextupole, the opposite to the conventional ECR magnetic structure. This new magnetic structure results in many significant advantages for a high-magnetic-field superconducting ECR ion source [6]. Firstly a more favorable magnetic configuration for highly charged ion beam production is achieved. In addition, the magnet assembly can be much more compact in size as compared to other same high field ECR sources with conventional magnetic structures. This novel magnetic structure has made SECRAL one of the best ECR ion sources. Even operating at 18 GHz with frequency-matched magnetic fields and microwave power of about 3 kW, its performance in some cases exceeds the performance of the high-magnetic-field ECR ion source operating at 28 GHz.

The first beam of SECRAL at 18 GHz was extracted and analyzed in August 2005. The ion source commissioning at 18GHz for optimization of highly charged intense beam production was conducted from August 2005 to June 2006. Some record ion beam intensities were achieved during the source commissioning. In May 2007, the first beam produced by

SECRAL, $^{129}Xe^{27+}$ with 22 kV extraction voltage, was delivered to HIRFL accelerator complex for more than one month continuously. Since then SECRAL has been put into operation to provide highly charged ion beams for HIRFL facility.

SECRAL ECR ION SOURCE

SECRAL design and its beam transport line are illustrated in Fig.1. The SECRAL design has been optimized for maximum ion source performance at 28GHz rf frequency for high charge state heavy ion beam production. A detailed description of the source design and the superconducting magnet assembly can be found in references [6]. The experiences from SERSE and VENUS were very helpful for design of conventional components of the SECRAL ion source.

Unlike the conventional layout of an ECR ion source, the SECRAL sextupole magnet is located outside of the mirror solenoids in order to reduce the interaction forces. The purpose of this innovation design is to develop a compact fully superconducting ECR ion source while still keeping the suitable magnetic profile of a powerful 28 GHz machine. At full excitation, SECRAL can produce 3.6T and 2.2 T at injection and extraction mirror throats respectively. The achieved radial sextupole field is 2.0 Tesla at plasma chamber wall with inner radius 63 mm. The distance of mirror to mirror is 420 mm. Such distance, combined with a minimum-B value ranging from 0.4-0.8 Tesla gives appropriate plasma volume. The SECRAL magnet assembly is cooled by a one-stage cryo-cooler and 4.2K liquid helium. SECRAL has been tested and is in daily operation at 18 GHz in its first phase development. In the second phase SECRAL will be tested and operated at 28 GHz when the 28 GHz rf generator is available.

Today available microwave generators for 28 GHz can deliver up to 10 kW of rf power, however, launching such a huge power into an ECR ion source leads to some technical problems. Firstly one would have to cope with a very good plasma chamber cooling and secondly too much power leads to plasma instabilities. Anyhow, even if the plasma cooling is rated to evacuate 10 kW, at such huge rf power, it is very difficult to achieve a good stability for long term operation of the ion source as required by today's accelerator. Too much power on the plasma chamber wall considerably reduces the mean time between failures. For this reason, SECRAL has fixed a maximum rf power of 5kW without loosing any capability of a fully superconducting source at 28 GHz having an extraction voltage of 20-30 kV.

PRODUCTION OF HIGHLY CHARGED ION BEAMS BY SECRAL

After conditioning of the ion source, we focused on commissioning for production of high charge state O, Ar and Xe ion beams. Typical vacuum without plasma is 4.0×10^{-8} mbar at injection side, 3.0×10^{-8} mbar at

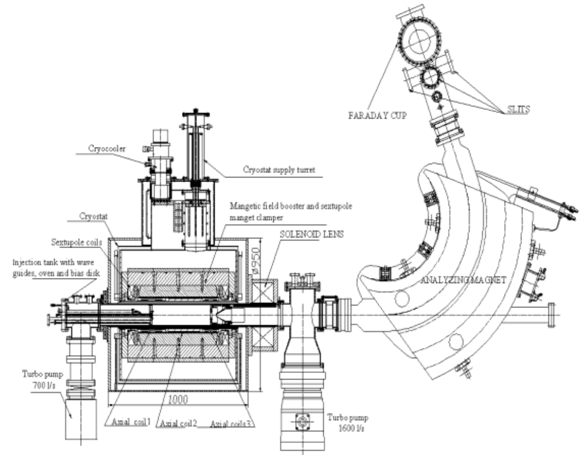

Figure 1: Layout of SECRAL ion source and its beam transport line.

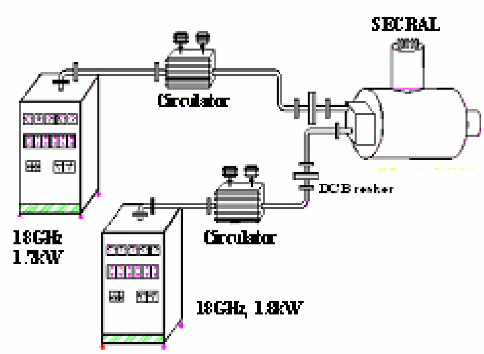

Figure 2: The SECRAL microwave feeding system.

extraction side and 1.0×10^{-8} mbar at the beam line. Typical extraction voltage is 25 kV for optimization of most highly charged ions. During the first stage of the commissioning, a single 18GHz microwave generator with maximum output power 1.7 kW was used. To reach better results, a fraction of the microwave power was fed into the ion source simultaneously from the second 18 GHz microwave generator with maximum output power 1.8 kW as shown in Fig.2. The second circulator between the generator and the SECRAL source has not been used in the final commissioning. The total maximum 3.5 kW power could be fed into the source. With total input power about 3.0 kW from the double 18GHz microwave generators, a number of record ion beam intensities were achieved, even with a basic stainless steel plasma chamber, thanks to an optimum magnetic field configuration and a fine tuning of classical "ECR knobs" such as gas flow rate, biased disk, gas mixing and beam focusing, for instance, 810 eμA of O^{7+}, 505eμA of Xe^{20+}, 306 eμA of Xe^{27+} and son on. Table 1 summarizes some of the commissioning results for highly charged ion beam production from SECRAL. Fig. 3 shows the CSD (charge state distribution) spectrum with the source optimized on $^{129}Xe^{30+}$. The spectrum was obtained by an oscilloscope and the analyzing magnet power supply was operated manually, that is why some of the peaks are narrow and some of the peaks are rather broad even with some noise signals. 95% enriched Xenon-129 was used during the xenon beam tests. The spectrum demonstrates that SECRAL has a good confinement for highly charged ECR plasma and also the mass resolution of the analyzing beam line is nice.

Table 1: Commissioning results of SECRAL at 18GHz in comparison with other high performance ECR ion sources (beam intensity: eμA).

f (GHz)	Q	**SECRAL**[12] *18*	**VENUS**[13] *28 or 28+18*	**GTS**[14] *18*
O	6^+	2300	2850	1950
	7^+	810	600	
Ar	11^+	810		510
	12^+	510	860	380
	14^+	270	514	174
	16^+	73	133	50
	17^+	8.5	14	4.2
Xe	20^+	505	320	310
	26^+	410	290	228
	27^+	306	270	168
	30^+	101	116	60
	31^+	68	67	40
	33^+	31		15
	34^+	21	40	8
	35^+	12	28	5.4
	37^+	5	12	2.3
	38^+	2.4	7	1

To demonstrate SECRAL capability for metallic ion beam production as requested by an official acceptance test, within 10 days we quickly tested productions of highly charged Ca, Ni and Pb ion beams with a high temperature oven dedicated for SECRAL, which can reach more than 1600 ℃. With the high temperature oven inserted into the SECRAL source, the coupled microwave power is limited to maximum 1.7 kW because only one waveguide from single microwave generator is available. However, some promising results were achieved for metallic ion beam production, for instance, 287eμA Ca^{11+}, 75eμA Ca^{16+}, 18eμA Ca^{18+}, 2.25eμA Ca^{19+}, 173eμA Pb^{27+}, 143eμA Pb^{28+} and 90eμA Pb^{30+}. Anyway, it is impossible to have very good results for three kinds of metallic ion beam productions within only 10 days. So the results of metallic ion beam production remain very preliminary.

STUDY OF SECRAL PERFORMANCE AND BREMSSTRAHLUNG SPECTRA IN DEPENDENCE OF THE RF POWER AND THE MAGNETIC FIELD CONFIGURATION

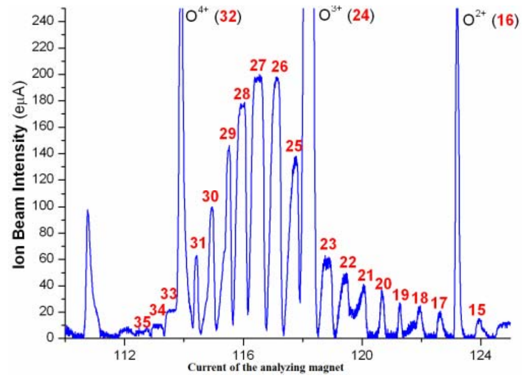

Figure 3: CSD spectrum with the SECRAL source optimized on Xe^{30+}.

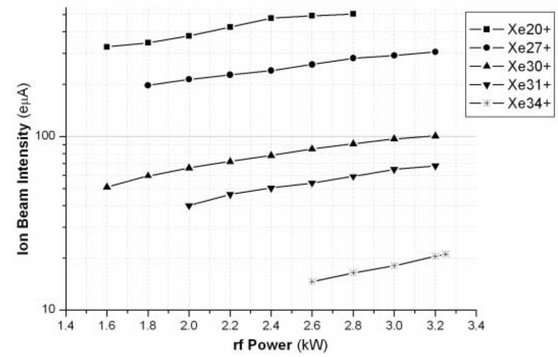

Figure 4: Dependence of Xe ion beam intensities on the coupled microwave power.

One of the most important tuning parameters for the SECRAL ion source is the coupled rf power. SECRAL ion source is equipped with two 18 GHz rf generators with two separated waveguides. For the same level rf power such as 2 kW, it is still an open question whether the effect to the ECR plasma with 1 kW from each rf generator is the same as that of 2 kW from a single rf generator. Anyway, during the tests, obviously the achieved beam intensity with two rf generators is much more stable than that of the same total power from a single generator, which may be resulted from out-gassing effect of the waveguide. On the other hand, many tests from SECRAL show the total reflected power from two generators is much less than that of a single generator with the same power. With the two 18GHz rf generators, the SECRAL performance for highly charged ion beam production in dependence of the rf power has been studied experimentally. Fig. 4 illustrates the beam intensity dependence of different charge state Xe ions on the coupled microwave power. It demonstrates that the highly charged xenon beam intensities keep increasing with the coupled microwave power, and it is far from saturation. Fig.4 implies SECRAL needs higher power to achieve higher beam intensity. In Fig.4 the magnetic field configuration, gas flow rate and biased voltage are different for the different charge state beams, but for the same charge state, the magnetic field distribution was kept constant during the experiments, the gas flow rate and the biased voltage were slightly optimized for the different rf power.

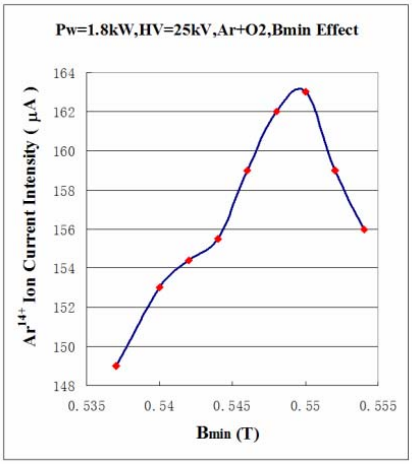

Figure 5: Dependence of the minimum axial magnetic field B_{min} on Ar^{14+} beam intensities at the rf power 1.8 kW.

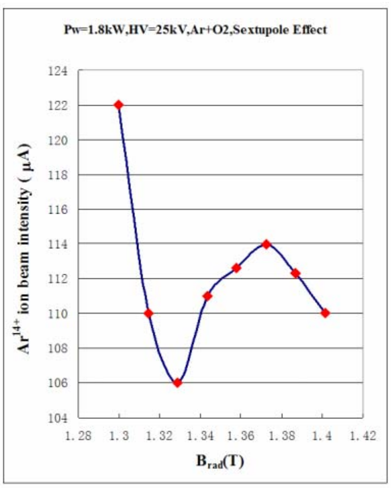

Figure 6: Dependence of the sextupole field at the chamber wall B_{rad} on Ar^{14+} beam intensities at the rf power 1.8 kW.

Optimizing the magnetic field configuration at different plasma conditions is a key process during SECRAL commissioning. By varying the currents of the three solenoid coils and the sextupole coil independently, a study of the magnetic field configuration dependence on highly charged ion beam production was performed. Fig.5 and Fig.6 shows dependence of the minimum axial magnetic field B_{min} and the sextupole field at the chamber wall B_{rad} on Ar^{14+} beam intensities by varying the central solenoid current and the sextupole coil current respectively, while keeping the other parameters constant. The coupled rf power is 1.8 kW during the experiments. Fig.5 and Fig.6 demonstrate that SECRAL is very sensitive to B_{min} and B_{rad}. SECRAL tests also support the idea that the magnetic field configuration is dependent on the coupled rf power for optimizing the same charge state ion beam. Generally speaking, optimized magnetic field distribution for SECRAL is in a good agreement with Hitz's magnetic scaling laws [3].

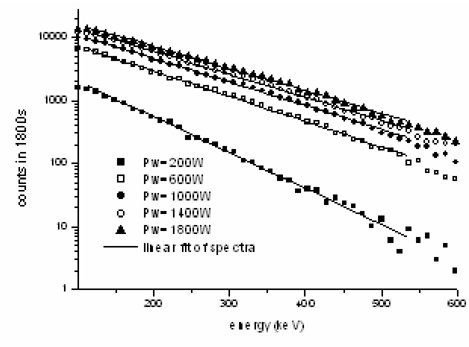

Figure 7: The measured and the fitted bremsstrahlung spectra for microwave power from 200W to 1800W.

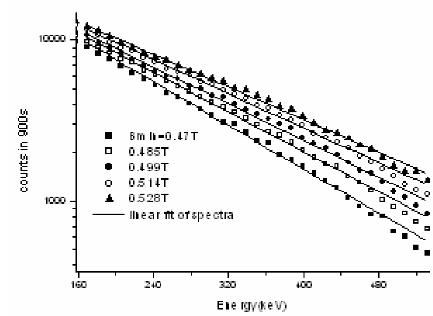

Figure 8: The measured and the fitted bremsstrahlung spectra for B_{min} from 0.47T to 0.528T

Bremsstrahlung measurements have frequently been used as a diagnostic to characterize the hot electron density and temperature distribution from high charge state ECR ion source[15]. In order to study the hot electron energy produced by SECRAL plasma and its dependence on the microwave power and the magnetic field configuration, the axial bremsstrahlung spectra were measured with a high purity Germanium detector [16]. Similar measurements were done previously at VENUS ECR source [15]. The detector is located just after the analyzing magnet and connected with a lead collimation system to keep the detector count rate low enough to minimize detector dead time. The spectra were measured with argon plasma mixing oxygen gas at different microwave power and different magnetic field configuration. Fig.7 shows dependence of the detector count rate on the microwave power in semilog coordinate with a linear fit. The spectral temperature derived from the spectra of Fig.7 ranges from 76 keV at 200 W rf power to 125 keV at 1800 W. Dependence of the count rate on the rf power shown in Fig.7 might imply a dependence of the electron density on the rf power, strong increase with low rf power and such increase of the electron density becomes less with high rf power. By varying the current of the middle solenoid coil, the axial bremsstrahlung spectra were measured in dependence of the minimum axial magnetic field B_{min} at rf power 1.6 kW, as shown in Fig.8. The spectra temperature in Fig.8 increases from 128 keV for the lowest B_{min} 0.47 T to 172 keV for the highest B_{min} 0.528 T. Dependence of the spectra temperature on the B_{min} might provide an evidence that the hot electron energy gain in a highly charged ECR ion source depends on the gradient field near the resonance, as pointed out in ref [15,17-18]. Further studies of bremsstrahlung measurements in dependence of the various conditions at SECRAL will be done.

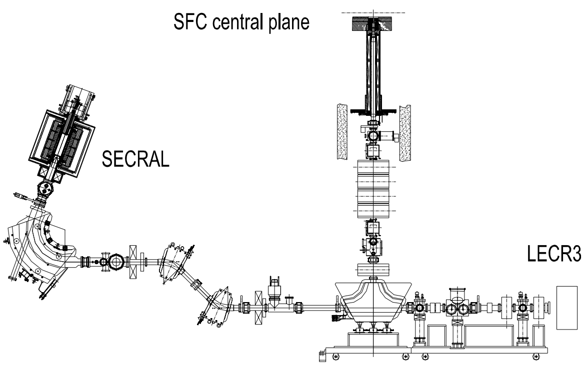

Figure 9: The axial injection beam line of SFC with two ECR ion sources SECRAL and LECR3

SECRAL OPERATION AND BEAM EMITTANCE MEASUREMENT

SECRAL has been put into operation to provide highly charged ion beams for HIRFL facility. In May 2007, the first beam produced by SECRAL,140-160 eμA of $^{129}Xe^{27+}$ with 22 kV extraction voltage, was delivered to HIRFL accelerator complex for more than one month continuously. The beam was dedicated for commissioning of HIRFL cooling storage ring. $^{129}Xe^{27+}$ beam produced by SECRAL was injected into the HIRFL injection cyclotron SFC through an axial injection beam line as shown in Fig.9. The accelerated beam 2.9 MeV/u $^{129}Xe^{27+}$ from the SFC was directly injected into the HIRFL-CSRm through multiple multi-turn injection. After accumulation and cooling down by an electron cooler device, the beam was accelerated to 235 MeV/u and the accumulated beam intensity reached to 500 eμA (1×10^8 pps), which is the heaviest ion beam with the biggest accumulated beam intensity for a heavy ion synchrotron with a cyclotron injector. However, the beam transmission efficiency from the ion source SECRAL to the exit of the SFC is not good, in particular, the injection efficiency is low. The extracted beam intensity of 2.9 MeV/u $^{129}Xe^{27+}$ from the SFC was only 5-6 eμA although the beam intensity from the SECRAL source was about 150 eμA. One of the main reasons for the low injection efficiency could be strong longitudinal space charge effect at the axial injection beam line that reduces the buncher efficiency. If the extraction voltage of the SECRAL source could be raised up to 60 kV, the buncher efficiency should be improved a lot. Fig.10 shows dependence of the calculated buncher efficiency on the beam intensity at different extraction voltage for the beam $^{129}Xe^{27+}$. Another reason for the low extracted beam intensity from SFC is lower extraction efficiency less than 40% for 2.9 MeV/u $^{129}Xe^{27+}$.

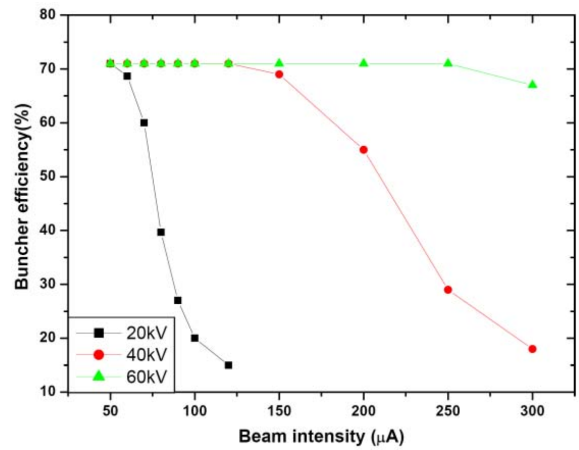

Figure 10: Dependence of the calculated buncher efficiency on the beam intensity at different extraction voltage for the beam $^{129}Xe^{27+}$. Longitudinal acceptance of SFC: $\Delta\varphi=10^o$, $\Delta W/W=4\%$.

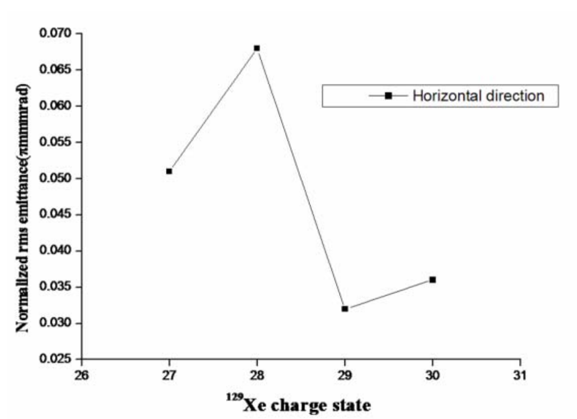

Figure 11: Preliminary measurements of normalized rms emittance in horizontal direction for Xe^{27+}, Xe^{28+}, Xe^{29+} and Xe^{30+} at 15 kV extraction voltage.

The sextupole field region at the extraction side of SECRAL is much shorter than that in a conventional superconducting ECR ion source. This might be advantageous for efficient extraction of highly charged ion beams with a smaller emittance. In order to study beam emittance from SECRAL. emittance measurements were done by an Allison emittance scanner developed by IMP[19]. Very preliminary measurement results illustrate that emittance of highly charged ion beam produced by SECRAL is as small as expected. Fig.11 gives measurement results of normalized rms emittance in horizontal direction for Xe^{27+}, Xe^{28+}, Xe^{29+} and Xe^{30+} at 15 kV extraction voltage and low beam intensity. Fig.12 shows measured phase space distribution of Xe^{27+} in horizontal direction with beam intensity 37 eμA. Further detailed studies on the SECRAL beam emittance will be under way.

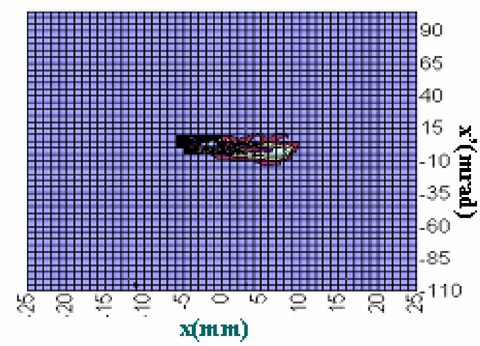

Figure 12: Measured phase space distribution of Xe^{27+} beam in horizontal direction.

COMPARISON WITH OTHER HIGH PERFORMANCE ECR ION SOURCES AND DISCUSSIONS

Table 1 lists some of the commissioning results from SECRAL and comparison to recently published data from other high performance ECR ion sources. Table 1 clearly shows that SECRAL has produced a number of world record intensities of highly charged heavy ion beams, for instance, 810 eμA of $^{16}O^{7+}$, 505 eμA of $^{129}Xe^{20+}$, 410 eμA of Xe^{26+}, 305 eμA of Xe^{27+} and 68 eμA of Xe^{31+}, while the other record beam intensities listed in Table 1 are produced by VENUS. But it should be kept in mind that a 28 GHz frequency would boost SECRAL results by a factor 2.5 since the electron density and consequently the beam intensity scales with the square of the frequency. In addition, we expect that the performance of SECRAL will be improved with an aluminum plasma chamber that is under fabrication and should be completed soon.

The SECRAL magnetic structure considerably reduces the interaction forces between the sextupole and the three solenoids through smaller solenoids and shorter sextupole coils which results in smaller ion source body. A compact ECR ion source results in a short plasma chamber, that is advantageous for several reasons. The level of needed rf power is much less than that in conventional superconducting ECR ion source (SC-ECRIS), while the rf power density is higher, which could make a microwave coupling and power absorption more efficient. Further more, the ion beam production and extraction can be more efficient. While a traditional SC-ECRIS has to utilize a much longer sextupole so as to reduce the interaction forces, which inevitably leads to a longer plasma chamber and lower rf power density.

An obvious disadvantage for the SECRAL magnetic structure is its lower sextupole field compared to a conventional SC-ECRIS, such as VENUS. But 2.0 Tesla of the sextupole field at the chamber wall may be enough for 28 GHz operation. However, for the rf frequency more than 28 GHz, it might be a challenge for the SECRAL magnetic structure.

SECRAL has been put into operation to provide intense highly charged ion beams for HIRFL facility since May 2007. But the beam transmission efficiency is still low. How to inject intense beam from a SC-ECRIS into a cyclotron with high injection efficiency is a key issue to be studied in near future.

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