WORLD-WIDE DEVELOPMENT OF INTENSE HIGHLY CHARGED SUPERCONDUCTING ECR ION SOURCES

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Abstract

Advancement of nuclear physics and high power heavy ion accelerator is always a driving force for persistent development of highly charged ECR ion source. Increasing demands for more intense and higher charge state heavy ion beams have dramatically promoted development of ECR ion source technology and physics. This talk provides an overview of intense highly charged superconducting ECR ion sources built by the world-wide laboratories in the last years. The key technologies, challenges and main issues related to construction and operation of high performance superconducting ECR ion source are reviewed. The latest results of intense highly charged ion beam production from the superconducting ECR ion sources are presented. Future development and the next generation highly charged ECR ion source are discussed.

INTRODUCTION

Increasing demands for more intense and higher charge state heavy ion beams by high power heavy ion accelerator have dramatically promoted development of highly charged ion source technology and ion source physics study. Many of existing or under-construction high power heavy ion accelerators request ion source to produce very intense highly charged heavy ion beams, for example, pulsed Pb^{27+} beam 1 emA current at CERN LHC[1], pulsed U^{28+} beam 1 emA at FAIR project[2], CW(continuous wave) U^{33+} and U^{34+} mixed beam 12 pμA at FRIB project[3], CW Ar^{12+} 1 emA at GANIL SPIRAL2[4], CW U^{35+} beam 500 eμA at RIKEN RIBF[5], and CW U^{41+} beam 100 eμA at IMP HIRFL[6]. However, these beam intensities with a good long-tem stability required by those projects have not yet been achieved by any existing ion sources. It is well known that the heavy ion accelerators always prefer high charge state beams because accelerator can get higher energy and higher energy gain, which makes accelerator more compact with lower cost. On the other hand, if an ion source can directly provide high enough charge state, the charge striping would not be necessary which implies that injected beam intensity could be higher because stripping efficiency is always low for heavy ions. There are three kinds of ion sources which are able to produce intense highly charged ion beams, ECR (Electron Cyclotron Resonance) ion source, electron beam ion source and laser ion source. Only ECR ion source is able to produce both CW and pulsed highly charged ion beams.

ECR ion source is a plasma device. The plasma is produced and heated by microwave power through electron cyclotron resonance, where the electrons oscillate in the magnetic mirror trap with a "minimum-B" and can absorb energy from the microwave when the electron gyro-frequency is equal to the microwave frequency:

$$\omega_e = \frac{q \cdot B_{ECR}}{m} = \omega_{rf}$$

Where m is the mass of the electron, q is the electric charge of the electron, B_{ECR} is the resonant magnetic field, ω_e and ω_{rf} are the electron gyro-frequency and the microwave frequency, respectively. The energetic electrons ionize the atoms or low charge state ions through sequential impact ionization process to produce highly charged ions. The ECR plasma is confined and stabilized by the "minimum-B" magnetic field configuration which is realized by superposition of an axial solenoid magnetic field and radial sextupole field. The key plasma parameters to determine yields of the highly charged ions are density of hot electrons n_e , ion confinement time τ_i, electron temperature T_e and the neutral atom density n_0, respectively. For highly charged ion beam production, the product $n_e\tau_i$, should be as high as possible. Long ion confinement time can make the ions have enough time to be ionized to the high charge state. The density of hot electrons n_e is related to rf frequency, rf power and the magnetic field. The neural gas density determines the loss of high charge state ions. Geller's scaling law proposed in 1986 [7] pointed out that the electron density and the intensity of highly charged ions are proportional to square of the microwave frequency ($n_e \sim \omega_{rf}^2$, $I \sim \omega_{rf}^2 M_i^{-1}$), respectively, and the ion confinement time is related to the magnetic mirror ratio ($\tau_i \sim B_{max}/B_{min}$).

Design of the magnetic field values for a high performance ECR ion source is based on a new semi-empirical magnetic-scaling law which was proposed by ECR groups at CEA/Grenoble and LNS/Catania through a systematic study with a superconducting ECR ion source SERSE [8-9]. The new scaling law points out that the key magnetic field values of a high performance ECR ion source for intense highly charged ion beam production should follow the following rules: the peak magnetic field at the injection side $B_{inj} \approx 4B_{ECR}$, the peak magnetic field at the extraction side $B_{ext} \approx 2B_{ECR}$, the minimum magnetic field $B_{min} \approx 0.8B_{ECR}$, the radial sextupole magnetic field at the plasma chamber wall $B_{rad} \approx 2.2B_{ECR}$, and the magnetic field at the last close surface $B_{last} \approx 2.2B_{ECR}$. So to produce intense highly charged ion beams, high rf frequency and high field superconducting magnet technology have been utilized. For 28GHz operation, typically, $B_{ECR}=1T$, $B_{inj}\approx 4T$, $B_{ext}\approx 2\ T$, $B_{rad} \approx 2.2\ T$.

There have been three "generations" of highly charged ECR ion source in terms of the rf frequency, the magnetic field and the performance since the first successful high charge state ECR ion source named as SUPERMAFIOS was developed in Grenoble in 1976 [10]. The third generation ECR ion sources are those with rf frequency more than 18GHz and superconducting magnet of the axial field on the axis more than 3 Tesla. A few of high field fully superconducting ECR ion sources (SC-ECR) are in operation, such as SERSE in Catania [9], VENUS at LBNL in Berkeley[11-12], SECRAL at IMP in Lanzhou[13-15], SuSI at NSCL/MSU[16-17]. Some other fully superconducting ECR sources are under commissioning or construction, such as RIKEN SC-ECRIS [18] and European MS-ECRIS [19]. There has been a significant progress for highly charged ECR ion source in terms of beam intensity and charge state in the past 15 years. Table 1 shows an evolution of a few typical beam intensity enhancement in the past years, for example, the beam intensity of Xe^{35+} was increased by a factor 30 from 1.5 eμA produced by AECR-U at LBNL in 1997 [20] to 45 eμA produced by SECRAL at IMP Lanzhou in 2009.

Table 1: A few typical beam intensity enhancement in the past years

Ion	**Year Intensity By ECRIS**	**Year Intensity By ECRIS**	**Increased by a actor**
O^{6+}	1974 15eμA Supermafios	2004-2006 >2000 eμA IMP SECRAL LBNL VENUS	>130
Xe^{30+}	1997-1998 10-15 eμA RIKEN 18GHz LBNL AECR-U	2008 >150 eμA IMP SECRAL	>10
Xe^{35+}	1997 1.5 eμA LBNL AECR-U	2009 >45 eμA IMP SECRAL	>30
U^{34+}	1997 20 eμA LBNL AECR-U	2006 >200 eμA LBNL VENUS	>10

DEVELOPMENT OF HIGH FIELD SC-ECR ION SOURCES

The first successful SC-ECR ion source ECREVIS was developed in Louvain-La-Neuve in 1983 and was coupled to the cyclotron CYCLONE [21,12]. The first high field SC-ECR ion source with good performance is SERSE which was developed by collaboration between CEA/Grenoble and LNS/INFN in Catania [22]. SERSE fabrications started in 1994 and the best results were achieved at 18-28GHz in 2000. SERSE ECR ion source was designed to operate at 18GHz, but also tested at 28GHz which was the first time test at 28GHz in the history of ECR ion source although the magnetic fields are much lower than what 28GHz requests. The achieved magnetic fields for SERSE are: $B_{inj} \approx 2.7$ T, $B_{rad} \approx 1.55$T. SERSE successfully demonstrated the frequency scaling law from 14GHz up to 28GHz. On basis of the systematic studies of the experimental results at SERSE, the collaboration group proposed a new semi-empirical magnetic-scaling law in 2000 [8-9]. Meanwhile, the high power 28GHz rf coupling between an ECR ion source and a 28GHz gyrotron system was tested successfully at SERSE. The research work, the results of the new scaling law and some of the technologies developed at SERSE have led a base for development of the 3rd generation ECR ion source.

Table 2: Key parameters of the existing and under-construction 3rd generation SC-ECR ion sources

	VENUS	**SECRAL**	**SUSI**	**RIKEN SC-ECR**	**MS-ECRIS**
f (GHz)	28	18-24	18-24	28	28
B_{inj} (T)	4.0	3.7	3.6	3.8	4.5
B_{rad} (T)	2.1	2.0	2.0	2.1	2.7
Φ(mm)	150	118-126	100	150	180

The high field fully superconducting ECR ion source has been becoming one of the main development trends to produce intense highly charged ion beams in the past years. Table 2 shows the key parameters of the existing and under-construction 3rd generation SC-ECR ion sources. The design, construction and development of those high field SC-ECR ion sources such as SERSE, VENUS and SECRAL have led the way in developing implementations of the 3rd generation ECR ion source, and have addressed many of technologies and challenges, and have demonstrated feasibility and the nice source performances of the 3rd generation ECR ion source, and also have opened a way for further developing the 4th generation ECR ion source to produce more intense and higher charge state heavy ion beams.

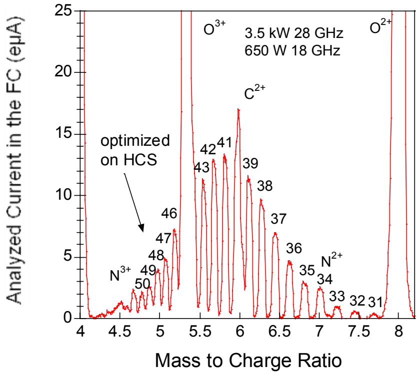

Figure1: VENUS charge state distribution tuned for high charge state uranium beam.

VENUS at LBNL

VENUS is the first 3rd generation high field SC-ECR ion source, and also currently the only SC-ECR ion source operating at 28GHz with coupled rf power more than 9 kW [11-12]. During design, construction and commissioning of the VENUS source, a number of technologies and challenges for the 3rd generation ECR ion source had been addressed, such as the superconducting magnet with cryocoolers, aluminum plasma chamber for high power operation with incorporated tantalum x-ray shielding, bremsstrahlung heating and intense mixed highly charged beam transport.

Some of these technologies have been incorporated into other 3rd generation ECR sources. VENUS produced many of record beam intensities, such as 2850 eμA of O^{6+}, 860 eμA of $Ar1^{2+}$, 205 eμA of U^{33+}, 175 eμA of U^{35+} and 5 eμA of U^{47+} and so on. VENUS had achieved the best uranium beam performance which is more challenging. Fig.1 shows the VENUS charge state spectrum tuned for the high charge state uranium beam. The VENUS superconducting magnet prototype started to build in 1997[23]. VENUS achieved the best results at 28 GHz in 2006-2007. It took almost 10 years from the VENUS prototype magnet to the achieved best results, which indicates the challenges in construction and commissioning of the 3rd generation ECR ion source. However, in January 2008 following a lead quench due to a helium leak in the cryostat and subsequent low helium levels one sextupole current lead got damaged. The cold mass needed to be extracted from the cryostat for repair. It has taken more than two years for repair and recently the cold test is being tested. VENUS will be at online beam test soon [24].

SuSI at NSCL/MSU

SuSI superconducting ECR source was originally designed to operate at 18GHz. After the magnet test, it was to extend to 24GHz operation [16-17]. During initial test and commissioning in 2007-2008, the magnet has experienced a lot of unexpected quenches without any reasonable explanations. No quenches have occurred since the polarity of the sextupole was reversed and the forces applied to the support links were adjusted. SUSI has been under beam commissioning and operation for the MSU cyclotron. Some nice results were achieved, such as 330 eμA of Xe^{20+}, 450 eμA of Kr^{14+} , 150 eμA of Bi^{28+} and 66 eμA of Bi^{33+}[25]. SuSI already provided about 1000 hours beams for the MSU cyclotron [25]. The SuSI unique feature is its flexible axial field distributions with the 6 solenoid coils, and also the plasma volume can be adjusted from 3.1 l to 3.9 l.

MS-ECRIS for FAIR

MS-ECRIS is one of the 3rd generation SC-ECR ion sources which is being built through collaborations of 9 European institutions and finally will be installed at GSI for FAIR project [19]. MS-ECRIS was designed to operate at 28 GHz with currently the highest magnetic fields and the biggest plasma chamber in the existing or under-construction SC-ECR ion sources. Fabrication of the superconducting magnet started in 2006-2007. MS-ECRIS aims to produce the highest charge states for the heaviest species, especially metal ion beams.All the components are ready since 2008, except for the magnets to be refurbished. All single coils already reached the specified demands. But the whole magnet system quenched randomly with different ramping strategies. The whole magnet reached about 50% maximum field. Investigations indicated that most probably a mechanical defect of the straight section caused the failure. Recently some mechanical modifications are being made [26].

RIKEN SC-ECRIS

RIKEN SC-ECRIS is the fastest construction 3rd generation superconducting ECR ion source. The source was designed to operate at 28GH with the achieved maximum axial field on the axis 3.8 T at the injection side [18]. There are six solenoids which enable the source to run at flexible field distribution. It took only about two years from construction to the first beam at 18GHz. The source is under commissioning at 18GHz. The 28 GHz beam test will be conducted in some time of 2010. RIKEN SC-ECRIS can be operated at the flexible axial field distributions with a big plasma chamber 150 mm in diameter. Fig.2 illustrates dependences of Ar^{11+} beam intensity on the field gradient and the ECR surface size which were measured at RIKEN SC-ECRIS at 18 GHz recently [27].

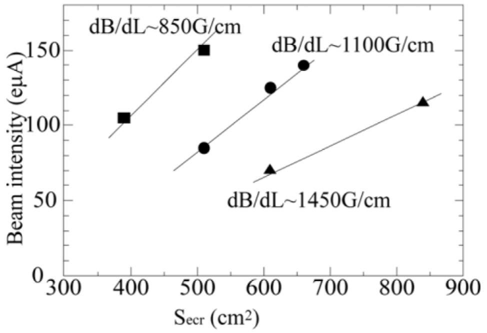

Figure 2: Dependences of Ar^{11+} beam intensity on the field gradient and the ECR surface size at RIKEN SC-ECRIS.

SECRAL at IMP

Excluding SECRAL all existing or under-construction high-magnetic-field SC-ECR ion sources utilize the conventional ECR magnetic structure, where the sextupole magnet being located inside the axial solenoid coils, as shown in Fig.3 [12]. The conventional magnet SC-ECR ion source has some advantages such as higher sextupole field, larger plasma chamber and higher rf power. The main disadvantage of the conventional magnet SC-ECR ion source is very big interaction forces between the solenoids and the sextupole. In order to reduce the interaction forces, the sextupole has to be designed much longer which makes the source body larger.

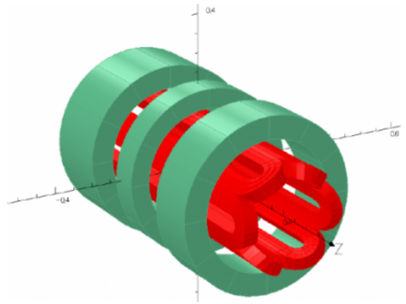

Figure 3: The conventional superconducting magnet structure o ECR ion source.

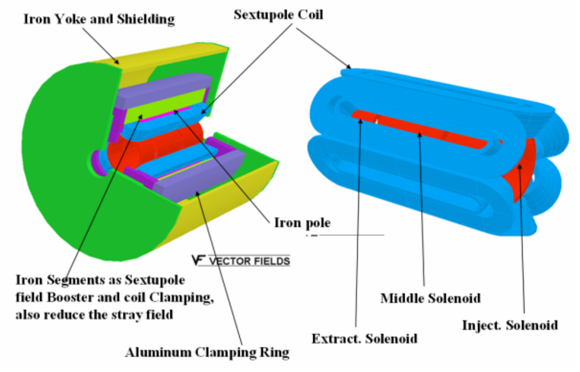

Figure 4: SECRAL superconducting magnet structure

SECRAL is a compact SC-ECR ion source designed to operate at rf frequency 18-28GHz, The most important for SECRAL source is its novel and unconventional magnetic structure which was proposed in 2001 and finally was successfully built in 2005[13-15]. The first beam test of SECRAL at 18 GHz was conducted in 2005 and the 24GHz beam test started in August 2009.

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, as shown in Fig.4. This new magnetic structure results in many significant advantages for a high-magnetic-field SC-ECR ion source. Firstly, this new superconducting magnetic structure significantly reduces the interaction forces between the sextupole and the three solenoids through smaller solenoids and shorter sextupole coils. So a more favorable magnetic configuration for the highly charged ion beam production is achieved and more important, the smaller interaction forces between the superconducting coils can improve the reliability of achieving the necessary high magnetic fields for the third generation ECR sources. 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. A compact source body leads to an efficient rf coupling, higher rf power density and efficient beam transport with smaller beam size in the region between the extraction system and the first focusing element. All these advantages enable SECRAL to produce higher beam intensity and operate at lower rf power that could lead to better long-term stable operation. Secondly, the novel magnetic structure utilizes a cold iron structure of the sextupole magnet with the iron segments as field booster and magnet clamping which reduces the stray magnetic field coming out of the superconducting coils to a very low level (less than 50 Gs). The very low stray field makes support of the magnet inside the cryostat much easier. The key feature for the SECRAL magnet clamping scheme is to utilize the magnetic forces experienced by the six sextupole segments and appropriate tolerances of the four aluminum shrinking rings, which makes the magnet clamping much simple. Simple suspension and clamping of the magnet imply a low construction cost. This novel magnet structure for SECRAL has proven to be quite robust and allowed smooth training and commissioning without any coil design modifications. However, an obvious disadvantage for the SECRAL magnetic structure is its lower sextupole field compared to a conventional SC-ECRIS.

Table 4 lists the latest results achieved by SECRAL at 18GHz and 24GHz and comparison with recently published data from VENUS ECR ion source [11-12]. Currently almost all record beam intensities for highly charged ions were produced by SECRAL and VENUS. SECRAL performance at lower frequency and lower power for highly charged ion beam production could be comparable or even better than those of higher frequency and higher power ECR source. SECRAL with an innovative magnet structure and unique features may open a new way for developing high performance, reliable and compact fully superconducting ECR ion source. SECRAL preliminary results at 24GHz are promising and exciting although commissioning time is too short. Better results should be coming up with long time optimization, aluminum chamber with double frequency heating (24+18GHz) and higher RF power.

SECRAL is the first 3rd generation ECR ion source being operated to delivered thousands-hours-beams for accelerator. SECRAL has been operated to deliver highly charged heavy ion beams for the HIRFL accelerator complex since May 2007, such as ^{129}Xe^{27+}, ^{78}Kr^{19+}, ^{209}Bi^{31+}and ^{58}Ni^{19+}. The total operated beam time from SECRAL for HIRFL has been more than 3000 hours up to January 2010.

Table 3: Latest results of SECRAL at 18GHz and 24GHz in comparison with other high performance ECR ion source (beam intensity: eμA).

		SECRAL	SECRAL	VENUS[11-12]
f (GHz)		*18(+14.5)*	*24*	*28(+18)*
P(kw)		<3.2	3-5	5-9
^{16}O	6+	2300		2860
	7+	810		850
^{40}Ar	12+	510	650	860
	14+	270	440	514
	16+	73	149	270
	17+	8.5	14	36
^{129}Xe	20+	505		320
	27+	306	455	270
	30+	101	152	116
	31+	68	85	67
	35+	16	45	28
	38+	6.6	17	7
	42+	1.5	3.0	0.5
^{209}Bi	28+	214		225
	30+	191		165
	41+	22		15
	44+	15		7.7
	48+	4.2		1.4
	50+	1.5		0.5
^{238}U	33+			206
	34+			202
	35+			175
	47+			5
	50+			1.9

LESSONS AND IMPORTANT ISSUES FOR HIGH FIELD SC-ECR ION SOURCE

The following issues and lessons are important for design, construction and operation of high field SC-ECR ion source.

- To build a high performance SC-ECR ion source, a reasonable compromise has to be achieved among those key issues, such as rf frequency, rf power, magnetic field configuration, plasma chamber size, expertise of SC-magnet and cryogenics, reliability, long-term stable operation, cost, construction time and risk.
- Challenges to build high field SC-magnet for the 3rd generation ECR ion source:

  Need to keep enough safety margin for maximum fields and critical current.

  Try to reduce the interaction forces between the coils and design a reliable clamping system to prevent the wires and the coils from moving.

  Stability and reliability of the SC-magnet are the most important for SC-ECR ion source.
- Challenges to design and operate the cryogenics system for the SC-magnet of the 3rd generation ECR.

  Very strong x-ray with energy tens keV to MeV has to be taken into account in cryogenics design. Keep in mind that additional heat load from x-ray could be 1 W per kW of the rf power, much higher than that from magnet itself. X-ray flux and energy increase with rf frequency and power.

  High power two stage cryocoolers or online close-loop liquefy machine must be installed for long-term operation of the 3rd generation ECR ion source.

Beam quality from the 3rd generation ECR ion source and beam formation, beam transmission should be studied carefully. We only need high brightness beam.

- Reliable interlock and alarm system is very crucial.
- It is hard to build the high field 3rd generation ECR ion source. Sometimes it may take more than 5 years.

FUTURE DEVELOPMENT AND DISCUSSIONS

If we continue to follow up the "semi-empirical" frequency scaling law, we may go ahead to build 50-60GHz ECR ion source to produce more intense and higher charge state heavy ions which could be the 4th generation ECR ion source [12]. No matter what kind of magnet structure might be utilized, the most challenging tasks for the 4th generation ECR ion source are following: (1) SC-magnet with the maximum field at the coil could be 12-17 T, with the axial field on the axis 8-9 T and the sextupole field on the wall 4-5 T. The huge interaction forces between the solenoids and the sextupole could be more than few tens tons. (2) Laboratory available 50-60GHz /10-30 kW gyrotron system operated at both CW and pulse mode. Long-term stability and reliability are crucial. (3) Extremely strong x-ray flux to insulation material and very strong head load from the x-ray to the cryogenics system. Online close-loop LHe liquefy machine may have to be utilized. (4) 40-60 mA mixed highly charged ion beam may be produced and beam transport could be challenging.

However, ECR ion source physics for intense highly charged ion beam formation is far from understanding because it is so complicated. Design of high performance ECR ion source still remains semi-empirical and tricky. ECR physics study is extremely slower than experimental progress. That is why there has been no big significant breakthrough in the past 20 years although great progress has been made. High performance ECR ion source is becoming a very big and complicated machine with high cost which relies on high technology too much instead of new ideas. Original and innovative ideas that may result in great breakthrough for highly charged ion beam production are extremely significant at present.

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