HIGH INTENSITY HIGH CHARGE STATE ECR ION SOURCES*

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Abstract

The next-generation heavy ion beam accelerators such as the proposed Rare Isotope Accelerator (RIA), the Radioactive Ion Beam Factory at RIKEN, the GSI upgrade project, the LHC-upgrade, and IMP in Lanzhou require a great variety of high charge state ion beams with a magnitude higher beam intensity than currently achievable. High performance Electron Cyclotron Resonance (ECR) ion sources can provide the flexibility since they can routinely produce beams from hydrogen to uranium. Over the last three decades, ECR ion sources have continued improving the available ion beam intensities by increasing the magnetic fields and ECR heating frequencies to enhance the confinement and the plasma density. With advances in superconducting magnet technology, a new generation of high field superconducting sources is now emerging. They are designed to meet the requirements of these next generation accelerator projects. The paper will briefly review the field of high performance ECR ion sources and the latest developments for high intensity ion beam production. The currently most advanced next-generation superconducting ECR ion source VENUS will be described in more detail.

INTRODUCTION

ECR ion sources use magnetic confinement and electron cyclotron resonance heating to produce a plasma made up of energetic electrons and relatively cold ions. The plasma electrons have two components, a cold population (~20 eV) and a hot population that has a high energy tail reaching up to 100 keV or more. Typical ion energies are a few eV. The electrons produce the high charge state ions primarily by sequential impact ionization. The main parameter for the performance of an ECR ion source is the product of the plasma density and ion confinement time ($n_e\tau_i$), since the ECR heating is effective enough to reach sufficient electron temperatures for ionization of high charge ions. The extracted ion beam current (I_{ext}) for a particular ion is proportional to the ratio

$$I_{ext} \propto \frac{n_{ion}}{\tau_{ion}} \quad , n_{ion} \propto n_e , \qquad [1]$$

with n_{ion} the density of the particular ion of interest, n_e the plasma density, and τ_{ion} the ion confinement time of this charge state

So if one could decrease the ion confinement time selectively, it would be easy to increase the extracted ion current. Unfortunately ion confinement time and plasma density are strongly coupled and by decreasing the ion confinement time the plasma density will decrease as well. Therefore it desirable to design an ECR ion source for the highest possible confinement and plasma density (highest frequency and high confinement fields) and carefully balance (tune) between these two parameters and the neutral gas balance in the plasma to optimize an ECR ion source for a desired charge state.

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DESIGN ISSUES FOR HIGH PERFORMANCE ECR ION SOURCES

Over the last decades, the trend to improve the performance of ECR ion sources has been to steadily increase the magnetic confinement field and the magnetic heating frequency following semi-empirical scaling laws formulated by Geller 1980 [1]. These laws state that the plasma density can be increased by increasing the microwave heating frequency ($n_e \sim \omega_{rf}^2$), while the ion confinement time increases with the radial and axial mirror ratio ($\tau_i \sim B_{max}/B_{min}$). Following these guidelines, several high performance ECR ion sources like CAPRICE [2], AECR-U [3], RIKEN 18 GHz [4], and ECR4 [5] have been build and are in use at heavy ion accelerator laboratories around the world. The latest room temperature magnet designs utilize increased permanent magnet strength, like the PHOENIX [6] source or the GTS ECR ion source [7]. Unlike the other traditional sources, the PHOENIX ECR ion source uses 28 GHz heating and produces high currents of medium charge state, but for high charge state production the confinement fields are too low for 28 GHz operation.

Typical confinement field ratios for high performance ECR ion sources are summarized in table 1.

Table 1: Typical magnetic field ratios for high performance ECR ion sources

B_{inj}/B_{ecr}	~ 4
B_{ext}/B_{ecr}	~ 2
B_{min}/B_{ecr}	~ 0.5 to 0.8
B_{rad}/B_{ecr}	≥ 2
B_{ext}/ B_{rad}	≤ 0.9 to 1

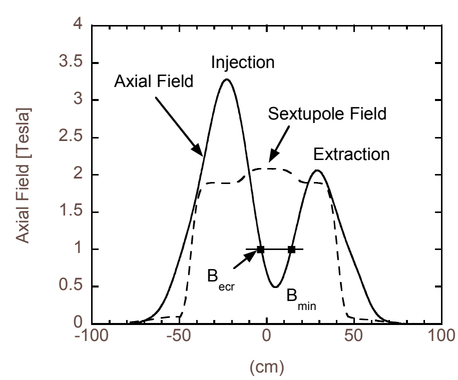

Figure 1: Typical magnetic fields used for VENUS for 28 GHz operation

The next generation sources are designed around 28 GHz microwave frequency, for which 10 kW CW gyrotrons are commercially available. The first 28 GHz heating of an ECR ion source was achieved by the Grenoble/Catania collaboration, which performed a series of tests coupling 28 GHz into the superconducting source SERSE [8]. These tests provided important data for the future design of an optimized 28 GHz ECR ion source. However the magnetic fields in SERSE are not optimal for 28GHz and consequently a new proposal has been developed to design a stronger field version of SERSE called GYRO-SERSE [9].

This choice of frequency has several design consequences. The next section discusses some of the challenges for building and operating these next generation ECR ion sources based on the experiences gained with the SERSE and the VENUS ECR ion source projects. Detail design challenges are discussed in the context of the VENUS source [10], which is the first high B-field 28 GHz source in operation.

TECHNICAL CHALLENGES FOR THE NEXT GENERATION 28 GHZ SOURCES

The magnetic confinement structure

For 28 GHz ECR ion sources the electron cyclotron resonance field strength is 1 Tesla. Following the magnetic field ratio summarized in table 1, about 4 Tesla axial field strength, and at least 2 Tesla radial field strength are required for optimum operation. As an example, figure 1 shows a typical field profile used for VENUS for a high performance tune, which follows closely the relationships summarized in table 1. These high magnetic fields require the use of a superconducting magnet structure, which is technically challenging to build since the superconducting sextupole coils experience strong forces in the axial field of the solenoids. For the VENUS ECR ion source a special clamping technique has been developed utilizing liquid metal filled bladders to prevent any movement of the energized coils [11]. The VENUS magnets have demonstrated an excellent performance and stability and the sextupole magnet is routinely operated above the original design values.

High power microwave coupling

The superconducting structure implies a relatively large plasma volume, which makes coupling of high power 28 GHz microwave a necessity to achieve sufficient plasma heating power density. One challenge for the high power source operation is the inhomogeneous heating distribution onto the plasma chamber walls due to particles losses. The weakest regions of the magnetic confinement field are three local magnetic field minima, where the large gradient in the solenoid field produces a radial component that partially cancels the radial field produced by the sextupole. On these spots the plasma confinement is compromised and localized heating of the plasma chamber walls occurs which can lead to burn out of the plasma chamber [12]. Therefore the engineering design of the plasma chamber cooling needs to be carefully optimized to withstand this localized heat load.

X-ray flux

Bremstrahlung produced by the hot plasma electrons colliding with the plasma walls are particularly troublesome for superconducting ECR ion sources. The high energy bremstrahlung can penetrate through the cryostat walls causing an additional cryogenic heat load [16] and localized heating in the superconducting coils that may lead to quenches[8]. In addition, the high x-ray flux deteriorates the HV insulation between the plasma chamber and the inner bore of the cryostat. Generally, higher frequency sources produce higher x-ray fluxes although the precise scaling has not been measured. Model calculations of electron cyclotron resonance-heated plasmas predict that the mean energy of the hot electrons increases approximately linearly with frequency[13].

Measurements of the x-ray heating on the VENUS ECR ion source at 18 GHz and 28 GHz [12] showed, that the heat loading is on the order of 150 mW per kW of microwave power for 18 GHz, but on the order of 1 W per kW of microwave power for 28 GHz, which is much higher than predicted. In case of the VENUS cryostat [10] only 2W of additional cooling power are available, since it operates in closed loop using 3 cryocoolers. To shield the cryostat from the x-ray flux at high power operation (10 W at 10 kW 28 GHz), a new plasma chamber has been designed for the VENUS source, which incorporates a 2mm thick Ta cylinder to attenuate the x-ray flux. Figure 2 shows axial bremstrahlung test measurements at 28 GHz VENUS operation. Three different spectra are shown: In the first one no attenuation is used, in the second one sheets of aluminum and stainless steel were added to simulate the VENUS plasma chamber and the cryostat wall, and in the third spectrum an additional 1mm thick tungsten sheet was added. The addition of 1 mm of tungsten reduced the total transmitted x-ray flux by a factor of 4.5. Therefore, the 2 mm tantalum should be sufficient to reduce the heating at least a factor of 10. Since without shielding VENUS has operated stably at 4.5 kW and about 5 W of bremstrahlung heating, the new shielding should also provide sufficient protection against induced quenches at high power operation.

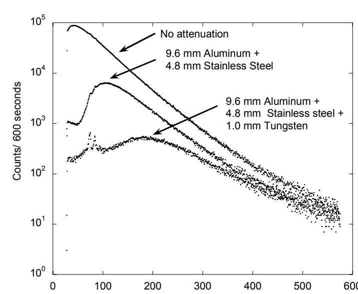

Figure 2: Axial bremstrahlung spectra measured for 2 kW of 28 GHz microwave power on VENUS, using different materials as attenuator.

Low energy beam transport from high field ECR ion source

The third generation superconducting sources can produce several mA of heavy ions, and the extracted ion beams are highly space-charge dominated. Therefore, the beam transport has to be designed as a high current injector system. Figure 4 shows the VENUS beam line as an example of such a high transmission system. In order to minimize beam blow up due to space charge, an intermediate focal point before the analyzing magnet has been avoided and the beam is directly matched into the analyzing magnet. While this approach can transport intense beams, and seems qualitatively simple, the beam dynamics in such a beam line are rather complex. This is due to the fact that the ECR ion source produces a spectrum of ions, and ion beam formation from an ECR ion source occurs in a region of a strong axial magnetic field. As the extracted beam is accelerated through this decreasing magnetic field, an axial rotation is introduced due to canonical angular momentum conservation, which results in transverse emittance growth. The amount of induced rotation depends upon the magnetic rigidity of the constituent ions. To better understand this complexity, LBNL has started the development of advanced simulation tools based on the 3D particle in cell (PIC) codes IMPACT and WARP [14]. These programs have the capability to use a 3D initial beam distribution for multiple species, to take the magnetic field present at the extraction into account, to transport the beam through the extraction electrode and the 3D field distribution of the analyzing magnet, and to take the space charge forces self consistently into account [14].

In addition, due to the radial magnetic confinement field, the ion beam density distribution across the plasma extraction aperture may not be uniform and varies for different charge states, which further complicates simulation efforts. Systematic emittance measurements performed at various ECR ion sources show that the emittance value decreases for higher charge states [15,16]. These results are consistent with a model that the highly charged ions are trapped closer to the axis leading to an inhomogeneous initial beam distribution of all the different charge states across the extraction hole. As an example, figure 3 shows Bi emittance measurements performed on the VENUS ECR ion source, demonstrating this trend clearly.

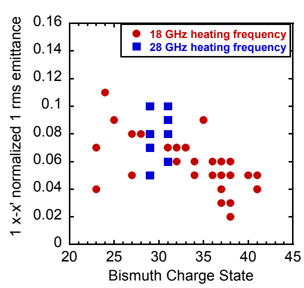

Figure 3: Dependence of the emittance value from the ion charge state for bismuth for the 18 GHz heated plasma and the 28 GHz heated plasma.

Finally, the plasma stability also plays an important role for the absolute emittance value, which can easily vary a factor of three between different source tunes [15] and accounts for the spread in the emittance measurements seen in figure 3.

STATUS OF THE SUPERCONDUCTING ECR ION SOURCE VENUS

The goal of the VENUS ECR ion source project as the RIA R&D injector is the production of 200eμA of U^{30+}, a high current medium charge state beam. On the other hand, as an injector ion source for the 88-Inch Cyclotron the design objective is the production of 5eμA of U^{48+}, a low current very high charge state beam. Figure 4 shows the mechanical layout of the source and its beam transport system [10].

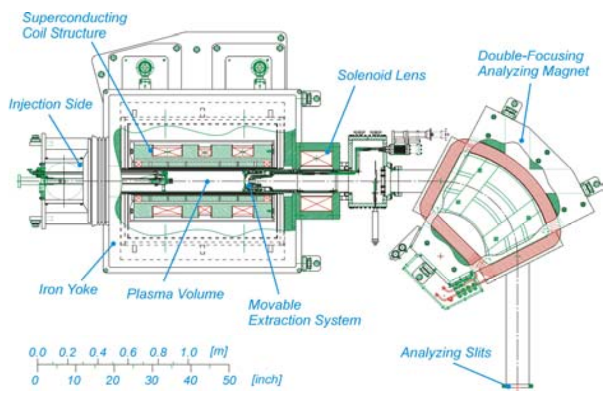

Figure 4: Mechanical layout of the beam transport system for VENUS.

The Venus ECR ion source project was started in 1997 with the development of the superconducting structure and cryostat, which was completed in 2001. At the last PAC conference, the first commissioning results using 18 GHz microwave have been reported. In 2004 28 GHz was coupled for the first time and record ion beam current could be extracted shortly after. Table 2 summarizes the major milestones of the project.

TABLE 2. Major Milestones of the VENUS Project

Date	Milestone
09/1997	Prototype Magnet completed
09/2001	Final Magnet Tests: 4T Injection, 3T Extraction, 2.4 T Sextupole achieved
06/2002	First Plasma at 18 GHz
09/2003	160 eμA of Bi^{24+}, 160 eμA Xe^{20+}
09/03-11/03	Cryostat Modification for 28 GHz operation
01/04-04/04	Gyrotron system assembly at CPI
05/26/04	First 28 GHz Plasma
06/04	320 eμA Xe^{20+}
08/04	245 eμA Bi^{29+}, 15 eμA Bi^{41+}

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COMMISIONING RESULTS AT 28 GHZ

In May 2004, 28 GHz was coupled into the VENUS source for the first time. The VENUS source was tested briefly with various gases in order to be able to compare VENUS to other high performance sources. At initial operation more than 1.2emA of O^{6+} and 320 eμA of Xe^{20+} (twice the amount extracted at 18 GHz) were extracted. More extensive measurements have been performed using bismuth for the Rare Isotope Accelerator (RIA) ion beam development program. Bismuth was chosen since its mass is close to uranium. Therefore, the extraction, and ion beam transport characteristics are very similar. However, bismuth is less reactive than uranium, not radioactive, and evaporates at modest temperatures. More than 240eμA (10 pμA) of Bi^{24+} and Bi^{25+} were produced exceeding the base line requirements for RIA for this particular beam without the necessity of a two charge state LEBT. Further tests showed that even a 5 charge state higher ion Bi^{29+} would still fulfill the RIA intensity requirements using only a single charge state in the LEBT (see figure 5) This opens the possibility to increase the charge state requirement for the RIA accelerator, which would reduce the costs of the driver linac.

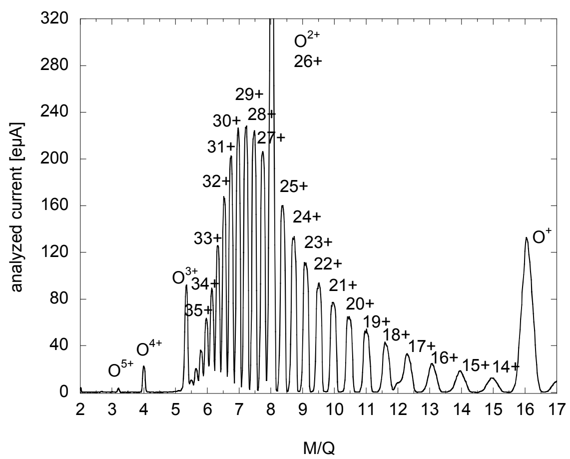

Figure 5: Analyzed Bi current for an ion source tune at 28 GHz optimized for Bi^{29+}.

Since VENUS has a strong plasma confinement very high charge sates can also be produced. Figure 6 shows a high charge state tune for Bi in an M/Q range which is of interest to the 88-Inch Cyclotron operations. Note that compared to figure 5, the medium Bi charge states 29+ have almost completely disappeared from the spectrum and high charge state up to 50+ have appeared.

Table I summarizes the initial performance of VENUS at 18 GHz and preliminary results at 28 GHz for oxygen, xenon, and bismuth in comparison with other high performance sources. Due to the high x-ray loading into the cryostat at higher microwave power (see previous section) only 4.5 kW from the 10 kW available have been injected so far. However, the maximum produced ion beam intensities are still almost linearly increasing with power. After installation of the new plasma chamber tests at higher power levels are planned.

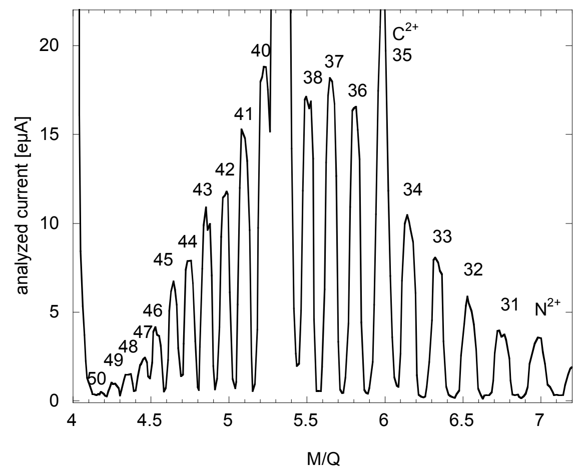

Figure 6: Analyzed Bi current for an ion source tune at 28 GHz optimized for Bi^{41+}.

TABLE 3. Preliminary commissioning results of VENUS at 18 GHz and 28 GHz in comparison with three other high performance ECR ion source, the double frequency heated AECR-U [10] and the 18 GHz ECR ion source GTS [11] and SERSE 28 GHz [12]

		VENUS	*VENUS*	*AECR-U*	*GTS*	*SERSE*
f(GHz)		*28*	*18*	*10+14*	*18*	*28*
^{16}O	6^+	1200	1100	840*	1950	
	7^+	>360	324	360*		
Xe	20^+	320	164		310	380
	27^+	150	84	30	168	
Bi	24^+	243				
	25^+	243	160	70		
	27^+		150	75		
	28^+	240	128	60		
	29^+	245	115	55		
	30^+	225	102	57		
	31^+	203	86	48		
	32^+	165	60	41		
	41^+	15	11	4.4		
	43^+	11.5	5.4	3.0		
	44^+	7.7	4.5	2.2		
	46^+	3.6		1.2		
	47^+	2.4		0.90		
	48^+	1.4		0.60		
	49^+	1.0		0.25		
	50^+	0.5		0.15		

* 3 frequency heating (8.6, 10, 14 GHz)

The next step in the VENUS project will be installation and test of the new plasma chamber that is able to absorb the high power x-ray radiation emitted from the ECR plasma. It will allow us to continue the commissioning at 28 GHz power levels of up to 10 kW. The next major milestone will be the first production of uranium ion beams, which is planned this fall.

OTHER SUPERCONDUCTING ECR ION SOURCE PROJECTS

Several initiatives are underway worldwide to build third generation superconducting ECR ion sources.

The furthest along of these projects is the superconducting source SECRAL (figure 7) at the IMP Lanzhou, China, which is under construction and has recently started commissioning tests of the super-conducting magnets [17]. The magnet design is different from the traditional design by mounting the three solenoid coils inside the sextupole. In this way the magnetic field is not as high as for example for the VENUS, but a more compact design can be built, which reduces microwave power requirements [17].

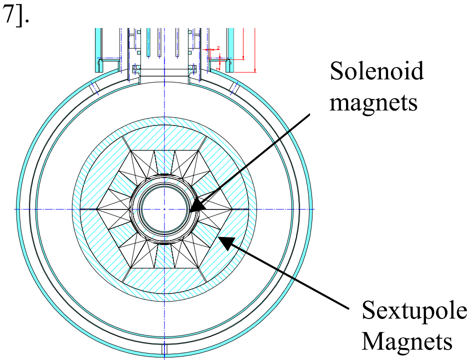

Figure 7 cross section view of the SECRAL source magnets at IMP, Lanzhou.

In RIKEN a new high field superconducting ECR ion source [18] has been proposed with similar design fields as the VENUS ECR ion source. The design uses six solenoid coils to have more control over the shape of the axial mirror field (see figure 8). The goals for this source are very ambitious. For example, 525 eμA of U^{35+} are required for the radiactive ion beam factory under construction in RIKEN.

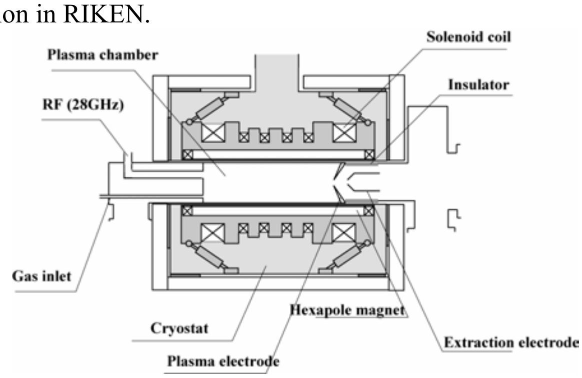

Figure 8: The new 28 GHz RIKEN ECRIS conceptual design with four small inner solenoid coils to have more control over the axial mirror field shape.

In Europe, the GYRO-SERSE [9] proposal has evolved into a multi European collaboration ISIBHI (Ion Sources for Intense Beams of Heavy Ions). This collaboration includes nine major European ECR research groups with the goal to design high performance ECR ion sources that will fulfill the needs of the accelerator upgrades and future projects in Europe. The new high field superconducting source proposed by this collaboration is called Multi-purpose Superconducting ECRIS (MS-ECRIS). The magnetic field design is aiming for an axial mirror field between 4 to 6 Tesla and a sextupole field of up to 3 Tesla.

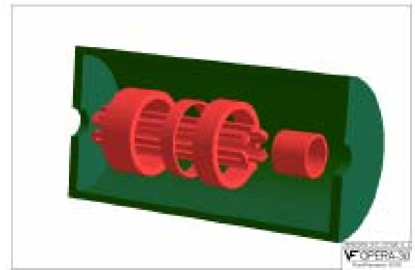

Figure 9: The OPERA-3D model of the MS-ECRIS (GYRO-SERSE) magnetic system. The first focusing solenoid is included7 in the main cryostat [9].

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