SUPERCONDUCTING ECR ION SOURCE DEVELOPMENT AT LBNL*

D. Leitner[#], S. Caspi, P. Ferracin, C.M. Lyneis, S. Prestemon, GL. Sabbi, D. Todd, F. Trillaud
Lawrence Berkeley National Laboratory, Berkeley, CA 94720, U.S.A.

Abstract

The development of the superconducting 28 GHz ECR ion source VENUS at the Lawrence Berkeley National Laboratory (LBNL) [1] has pioneered high field superconducting ECR ion sources and opened a path to a new generation of heavy ion accelerators. Because of the success of the VENUS ECR ion source, superconducting 28 GHz ECR ion sources are now key components for proposed radioactive ion beam facilities. This paper will review the recent ion source development program for the VENUS source with a particular focus on the production of high intensity uranium beams.

In addition, the paper will discuss a new R&D program started at LBNL to develop ECR ion sources utilizing frequencies higher than 28 GHz. This program addresses the demand for further increases of ion beam intensities for future radioactive ion beam facilities. The most critical technical development required for this new generation of sources is the high-field superconducting magnet system. For instance, the magnetic field strengths necessary for 56 GHz operation produce a peak field in the magnet coils of 12-14 T, requiring new superconductor material such as Nb_3Sn. LBNL has recently concluded a conceptual, comparative design analysis of different coil configurations in terms of magnetic performance and has developed a structural support concept compatible with the preferred magnetic design solution. This design effort concludes that a sextupole-in-solenoid ECR magnet structure (VENUS type) is feasible with present Nb_3Sn technology, but that an inverted geometry (solenoid-in sextupole) exceeds the capability of Nb_3Sn superconductors and can be ruled out as candidate for a 56 GHz ECR ion source.

INTRODUCTION

Electron Cyclotron Resonance (ECR) ion sources are an essential component of heavy-ion accelerators. Their ability to produce any low to high charge state ion beam from hydrogen to uranium has made them the injector of choice for many applications. Over the last few decades advances in magnet technology and an improved understanding of the ECR ion source plasma physics have led to remarkable performance improvements of ECR ion sources. At the same time, the demand for increased intensities of highly charged heavy ions continues to grow. The path for further improving the ECR ion source performance includes the use of higher magnetic fields and higher heating frequencies as formulated in Geller's famous ECR scaling laws [2]. Following these guidelines several generations of ECR ion sources have been developed. Qualitatively, if the microwave heating frequency is doubled, the ion beam intensities are enhanced by a factor of four on average and even more for the highest charge state ions. When the ECR heating frequency is increased the magnetic confinement field has to be scaled accordingly. The magnetic confinement structure used for ECR ion sources utilizes a combination of solenoid fields for axial and multipole fields (typically sextupole) for radial confinement. ECR ion sources that utilize normal conducting electromagnetic coils in combination with a permanent hexapole are limited to operating frequencies of up to about 20 GHz due to the maximum achievable field strength. Beyond these frequencies only fully superconducting magnetic confinement structures can reach the field strengths required for optimum performance.

VENUS ECR ION SOURCE PERFORMANCE

Table 1 shows a summary of the VENUS ion source performance. The source can be operated with two frequencies. In addition to 28 GHz, 18 GHz can be injected either as a second frequency for double frequency heating or used alone for single frequency heating. The VENUS ECR ion source has been developed with two applications in mind. First as a prototype ECR ion source for the Facility for Rare Isotope Beams (FRIB) the emphasis of the R&D is the production of medium high charge states such as U33+ (Figure 1). Second as an injector into the 88-Inch Cyclotron the emphasis is on the production of high charge state ions, in particular U47+(Figure 2). Uranium beams are especially challenging to produce because of the chemical properties of uranium and the high temperature required to evaporate enough feeding material for the plasma. In addition, chemical reactions (between the oven, the crucible and uranium or uranium compounds) at higher temperatures complicate operation [3].

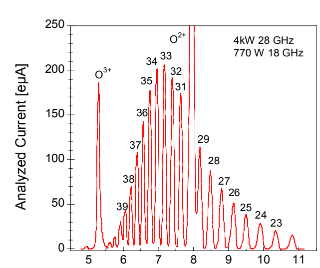

Figure 1: Uranium charge state distribution for a high intensity medium charge state tune optimised for 33 to 34+.

This work was supported by the Director, Office of Energy Research, Office of High Energy and Nuclear Physics, Nuclear Physics Division of the U.S. Department of Energy under Contract DE AC03-76SF00098
[#]dleitner@lbl.gov

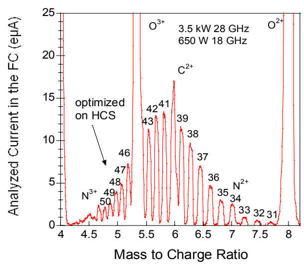

Figure 2: High charge state (HCS) Uranium beam distribution

At LBNL, Uraniumdioxide (UO2) is currently pursuit as feed material. It is an ideal compound since it is chemically stable and sublimes. In addition, its oxygen component serves as an ideal mixing gas for the plasma [3]. The only drawback is the high oven temperature required. UO2 has a vapour pressure of about 1·10-2 mbar at 2000°C. Therefore, the VENUS oven has to be operated at temperatures between 1900 and 2100°C in order to provide enough vapour flow into the plasma through the 2.6 mm2 aperture area. Building a furnace within the restricted space of an ECR injection flange that can reliably reach such high temperature is a major challenge. Over the last years LBNL has developed compact high temperature ovens to meet these temperature requirements in the presence of the high axial magnetic field at the oven position. The latest is a coaxial design which allows the heater current flow to be parallel with the axial magnetic field thus eliminating any IxB forces that might limit the lifetime of the hot oven. Testing of this new oven concept will be the focus of the near term R&D program.

Table 1:Recently Extracted VENUS Ion Beam Intensities in eμA

VENUS 28 GHz or 18 GHz +28 GHz							
CS	^{16}O	^{40}A	CS	^{84}K	129	209	238
6^+	285		25^+	223		243	
7^+	850		26^+			240	
8^+			27^+	88		245	
12^+		860	28^+	25	222	225	
13^+		720	29^+	5	168	203	
14^+		514	30^+	1	116	165	
16^+		270	31^+		86		
17^+		36	33^+		52		205
18^+		1	34^+		41		202
			35^+		28.		175
			37^+		12		
			38^+		7		
			41^+			15	
			42^+				.4
			47^+			2.4	5
			50^+			.5	1.9

MAGNETIC FIELD REQUIREMENTS

Over the last few decades clear guidelines have been established for the optimum confinement field strength for a given microwave heating frequency. The recommended field relationships between the confining fields at the injection end (B_{inj}), extraction end (B_{ext}), and in the radial direction (B_{rad})and the resonant heating field (B_{ECR}) are summarized in table 2. The resonant heating field is related to the microwave frequency f_{rf}, by $B_{ECR}=2\pi f_{rf}\, m/e$, where m the electron mass, and e the electron charge. For example, the corresponding resonant magnetic field for 28 GHz heating is 1 Tesla.

Table 2: 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

The VENUS ECR ion source at LBNL[1] has been optimised for operation at 28 GHz by following the guidelines given in table 2. Its magnetic field values for the axial mirror field created by three solenoid coils and the radial sextupole fields are shown in Figure 3.

In terms of confinement and heating an important feature of the superimposed solenoidal and hexapolar magnetic fields is the magnitude of the last closed surface created within the plasma chamber. For high performance ECR ion source a typical value for the last closed surface is about two times B_{ECR}, which corresponds to 2 Tesla in the case of VENUS. Beyond this value (for example three or four times B_{ECR}) the gains due to the enhancement of the magnetic confinement are much less than the gains achievable by using higher frequencies with a closed surface of 2 B_{ECR} instead.

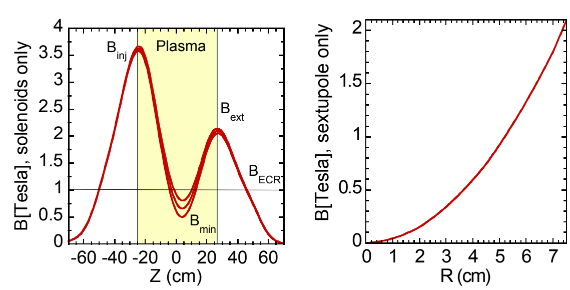

Figure 3: The axial and radial fields of the VENUS ECR ion source. The minimum B field using the middle solenoid coil.

As an example, the magnetic iso-surfaces of the VENUS ECR ion source are shown in Figure 4 in an axial cut through the plasma chamber. The number 2 indicates the two Tesla line, the number 1 indicates the one Tesla line which corresponds to the 28 GHz resonance zone.

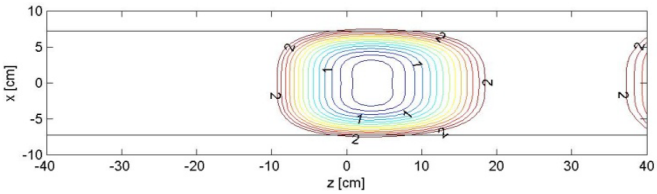

Figure 4: The closed magnetic field surfaces inside the VENUS plasma chamber in 10% increments of the ratio between B/Becr. The axial field peaks are roughly at z = -24 cm and at z = 26 cm.

When the optimum magnetic field values inside the plasma chamber are achieved, the peak fields on the conductor will be much higher. For example, to achieve a sextupole field of 2 Tesla on the plasma chamber wall the maximum field on the sextupole conductor is 6 to 7 Tesla in the case of the VENUS ECR ion source. The maximum field that can be produced in a superconducting magnet is limited by processes that drive the superconductor into the normal-conducting state (magnet quench). To avoid quenching, the magnet design must keep the current densities and local magnetic fields at the coils below the short sample critical current in the superconductor, which depends on the type of superconductor used, the local magnetic field and the temperature. All modern superconducting ECR ion source use NbTi superconducting wires. The performance of NbTi magnets is limited by its upper critical field of about 10 T at 4.2 K, which limits these ion sources to maximum microwave frequencies between 20 and 30 GHz (see Figure 5).

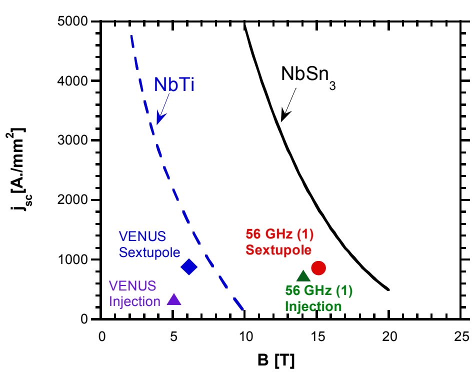

Figure 5: Critical current density in a NbTi and a Nb_3Sn superconductor wire (A/mm^2) vs. total magnetic field (T). The operating points for the VENUS ECR and the proposed 56 GHz ECR ion source (sextupole-in solenoid) for the sextupole magnet and the injection solenoid are indicated. The current density j_{SC} is quoted inside the superconductor and is not the engineering current densities through the total cross section of the wire or cable.

To extend ECR ion sources to frequencies well above 28 GHz, new superconductor technology will be needed in order to fabricate the magnet structure. Presently, the most advanced material for high-field applications is Nb_3Sn, for which the upper critical field limit increases to about 20 T at 4.2 K. The critical current densities for both materials (NbTi and Nb_3Sn) are shown in Figure 5 for a temperature of 4.2 K.

Table 3 summarizes the magnetic field requirements for a 28 GHz and a 56 GHz ECR ion source. In addition, to the maximum field inside the plasma chamber, the peak field on the conductors is shown.

Table 3: Magnetic Field Requirements for a 28 GHz and a 56 GHz ECR Ion Source

Magnetic Design		**28 GHz**	**56 GHz**
Max solenoid field	on the coil	6 T	12 T
	on source axis	4 T	8 T
Max sextupole field	on the coil	7 T	15 T
	on plasma wall	2.1 T	4.2 T
Superconductor		**NbTi**	**Nb_3Sn**

SUPERCONDUCTING MAGNET R&D

Two very distinct options can be pursued to design a fully superconducting ECR ion source magnet structure: The sextupole coils can be placed inside the solenoids (sextupole-in solenoid, geometry 1 in Figure 6) or outside the solenoids (solenoid-in-sextupole, geometry 2 in Figure 7). Both design options have been pursued for third generation ion sources. The VENUS source follows the sextupole-in-solenoid design concept[4], the SECRAL source in Lanzhou[5, 6] follows the solenoid-in-sextupole design concept. There are advantages to each design concept:

Both options have been analysed as possible design solution for a 56 GHz Nb_3Sn magnet structure[7]. To compare the two geometry options specific field requirements at different spatial locations were imposed as summarized in Table 2.

Table 4: Radial Dimensions (ID and OD) for the two Geometry Options (sextupole-in-solenoid and solenoid-in-sextupole) used

Sextupole-in-Solenoid (geometry 1)				
	Sext.	Inj.	Middle	Extr.
r1/r2	100/162	194/253	194/244	194/253
Jsc[A/mm^2]	860	727	-542	595
peak fields	15.1	13.35	8.57	10.31
Solenoid-in-Sextupole (geometry 2)				
	Sext.	Inj.	Middle	Extr.
r1/r2	106 /146	92/106	101/106	92/106
Jsc[A/mm^2]	1083	1924	-227	1657
peak fields	16.9	16.5	13.97	15.25

Table 4 summarizes the dimensions used for the models. These dimensions were chosen following the design of the existing ECR ion sources VENUS and SECRAL. A detailed description of the magnetic analyses and the structural magnet implications can be found in Ferracin et al.[8] and Prestemon et al [7].

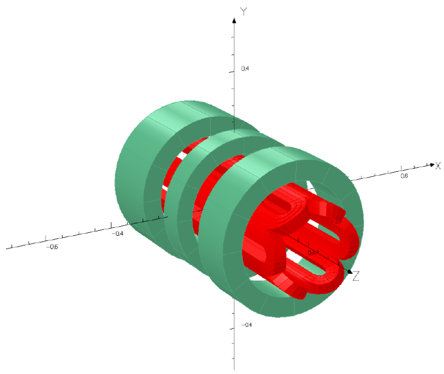

Figure 6: VENUS: Sextupole-in-Solenoid Geometry (1). The sextupole-in-solenoid VENUS geometry leverages proximity of the sextupole to the plasma chamber, minimizing peak fields in that coil.

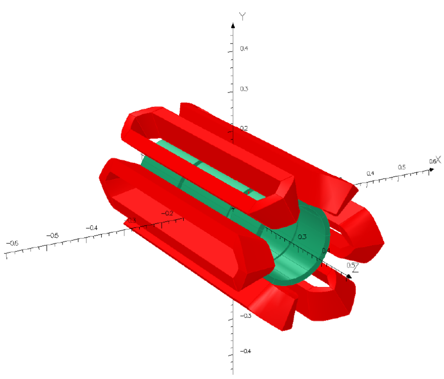

Figure 7: SECRAL Solenoid-in-Sextupole Geometry (2). The solenoid-in sextupole geometry minimizes the influence of the solenoid on the sextupole field, at the expense of significantly higher field on the sextupole magnet surface due to the larger radius of the coils.

The magnetic analyses show, that the solenoids in configuration 2 (Solenoid-in-Sextupole) are subjected to large sextupole fields, resulting in high peak fields in all coils for that configuration. These high current densities in the solenoids stem from the need to minimize the radius of the sextupole and exceed the capabilities of the Nb_3Sn superconductor. In addition, the sextupole field generates a large radial field on the solenoid that alternates sign azimuthally; the resulting Lorentz force distribution leads to sizable shear stresses within the solenoid coils. Based on the magnetic analysis, the solenoid-in-sextupole configuration can be ruled out as a candidate for a Nb_3Sn 56GHz ECR source.

For configuration 1 (Sextupole-in-Solenoid), there are two limits to consider: the peak field at the conductor and the location of the maximum force. The peak field on the sextupole occurs in the middle of the injection coil. However, at this location the solenoid field contributes predominantly a B_z field component on the sextupole, which is parallel to the sextupole current flow. Therefore this field component contributes less to the maximum (critical) field strength at which the superconductor quenches. In order to be more conservative, the total field strength was used for this analysis and for the operation point indicated in Figure 5. The operation points of the VENUS ECR ion source are also shown as a reference. The maximum forces are located at the sextupole ends. A solution for this issue is to lengthen the sextupole coils which results in the extended sextupole structure typical for superconducting ECR ion sources.

It can be concluded from the magnetic analysis that the design is challenging, but feasible, with current Nb_3Sn technology. The design operates at about 86% of the current limits corresponding to a temperature margin of about 2.5K.

OTHER CHALLENGES FOR SUPERCONDUCTING ECR ION SOURCES

Besides the size and weight of the high field superconducting ECR ion source cryostat, the energy stored in the magnet, the quench protection system and cryogenic engineering challenges, other issues in connection with the operation of the ECR ion source plasma have to be considered in the design.

Plasma Chamber

The required microwave power densities injected into the plasma constitutes a major challenge for the design of the plasma chamber cooling circuits. The superconducting structure implies a relatively large plasma volume and this requires a large amount of microwave power to achieve sufficient plasma heating. In addition, as the frequency is increased, more power can be coupled into the plasma without causing instabilities. Taking VENUS as a reference, this source has been operated so far with up to about 9 kW of RF power (about 1 kW/liter) and is clearly not yet at the power saturation point of the ion source. The main danger for the high power source operation is local melting of the plasma chamber due to the inhomogeneous heating distribution onto the plasma chamber walls due to localized particle losses. The weakest regions of the magnetic confinement field are three local magnetic field minima at the inner edge of the injection and extraction solenoid, where the large gradient in the solenoid field produces a radial component that partially cancels the radial field produced by the sextupole. At these spots the plasma confinement is weakest and localized heating of the plasma chamber walls occurs which can lead to local melting of the plasma chamber. Therefore, the engineering design of the plasma chamber cooling needs to be carefully optimised to withstand this localized heat load. As and example, the VENUS plasma chamber is made out of aluminium and has been optimised to maximize the water flow around the plasma chamber. A similar or more advanced design will be needed for the 4th generation ECR ion sources.

Ion Bam Etraction

Transport of the high intensity, space charge dominated, heavy ion beam extracted from the outlet aperture located at the peak of the mirror field is also a major challenge. 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. Therefore, as the extraction field is increased to operate the source at higher frequency some emittance growth will be observed. However, since the highly charge state ions are believed to be concentrated near the source axis the actual, this emittance growth is less than what could be expected from the increase in the magnetic field [9]. In VENUS, the average emittance growth for the same charge state produced with 18 GHz fields and 28 GHz fields is about 20% while the simple field extrapolation would predict 40%. In addition, due to the size of the cryostat, the beam has to be extracted from a long channel (at least .5m) before the first focusing element can be placed.

X-Ra Hat Load and Bremsstrahlung from the Plasma

Finally, the x-ray load from the plasma adds a sizeable heat load to the cryostat. X-rays that are produced by the hot plasma electrons colliding with the plasma walls are particularly troublesome for SC ECR ion sources. The x-rays produced by electron-ion collisions or electrons colliding with the plasma chamber walls can penetrate through the plasma chamber wall and are the cause of x-ray radiation in the vicinity of ECR ion sources. The x-rays can add a substantial heat load to the cryostat and cause localized heating in the superconducting coils (particular at the location of the three magnetic field minima) that may lead to quenches. In addition, they can lead to the degeneration of the synthetic high voltage insulator located between the warm bore of the cryostat and the plasma chamber [10]. During the development of the VENUS ECR ion source it had been recognized that it is crucial to add x-ray shielding in between the cryostat and the plasma chamber to reduce the heat load. A 2mm Ta cylinder was added between the plasma chamber and the cryostat, which reduced the x-ray flux roughly by a factor of 10. However, it can be expected that the electron temperature will increase significantly when the heating frequency is doubled from 28 GHz to 56 GHz. A comparison of the axial x-ray energy spectra at 18 GHz and 28 GHz in VENUS clearly shows that the high energy tail of the x-ray spectrum which is difficult to shield increases substantially at the higher microwave frequency[11], as shown in Figure 8.

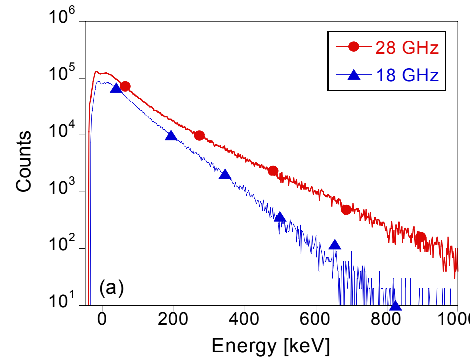

Figure 8: Comparison of the bremsstrahlungs' spectra for 28 GHz heating to 18 GHz heating using scaled (28/18)magnetic fields [11]

In addition, preliminary measurements on the LBL ECR suggest a higher radial energy component of the x-ray energy spectrum. This observation is not surprising and can be qualitatively understood by the transverse ECR heating process. However, it has important implications for the design of future superconducting ECR ion sources and it will be crucial to characterize the frequency scaling of the x-ray emission and its angular dependence.

REFERENCES

[1] D. Leitner, C. M. Lyneis, T. Loew, et al., Rev. Sci. Instrum. 77, 03A303 (2006).

[2] R. Geller, Electron Cyclotron Resonance Ion Source and ECR Plasmas (Bristol, Institut for Physics Publishing, 1996).

[3] D. Leitner, M L Galloway, T. J. Loew, et al., RSI 79 (2008).

[4] C. E. Taylor, S. Caspi, M. Leitner, et al., IEEE Transactions on Applied Superconductivity 10, 224 (2000).

[5] H. W. Zhao, L. T. Sun, X. H. Guo, et al., High Energy Physics and Nuclear Physics 31, 8 (2007).

[6] H. W. Zhao, L. T. Sun, X. H. Guo, et al., in CYCLOTRONS 2007, Giardini Naxos, Italy, 2008).

[7] S. Prestemon, F. Trillaud, S. Caspi, et al., IEEE. Trans. Appl. Supercon 19 (2009).

[8] P. Ferracin, S. Caspi, H. Felice, et al., in PAC'09, Vancouver, 2009).

[9] D. Leitner, J.Y. Benitez, M L Galloway, et al., in CYCLOTRONS 2007, Giardini Naxos, Italy, 2008).

[10] C. M. Lyneis, D. Leitner, O. Tarvainen, et al., Rev. Sci. Instrum. 77, 1 (2006).

[11] D. Leitner, C.M. Lyneis, H. Koivisto, et al., RSI 79, 033302 (2008).