4th Generation ECR Ion Sources

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Abstract

The concepts and technical challenges related to developing a 4th generation ECR ion source with an RF frequency greater than 40 GHz and magnetic confinement fields greater than twice B_{ecr} will be explored in this paper. Based on the semi-empirical frequency scaling of ECR plasma density with the square of operating frequency, there should be significant gains in performance over current 3rd generation ECR ion sources, which operate at RF frequencies between 20 and 30 GHz. While the 3rd generation ECR ion sources use NbTi superconducting solenoid and sextupole coils, the new sources will need to use different superconducting materials such as Nb_3Sn to reach the required magnetic confinement, which scales linearly with RF frequency. Additional technical challenges include increased bremsstrahlung production, which may increase faster than the plasma density, bremsstrahlung heating of the cold mass and the availability of high power continuous wave microwave sources at these frequencies. With each generation of ECR ion sources, there are new challenges to be mastered, but the potential for higher performance and reduced cost of the associated accelerator continue to make this a promising avenue for development.

1. Introduction

Electron Cyclotron Resonance ion source performance has progressed steadily since the first successful high charge state ion source called SUPERMAFIOS was developed in Grenoble in the mid 1970's [1]. Beam intensities have increased significantly with O^{6+} going from 15 eμA almost 3000 eμA (2860 eμA) and the charge state distributions for heavy-ions have increased dramatically. The driving force behind has been the development of ECR ion sources that utilize higher microwave frequency and stronger magnetic confinement. A number of technical innovations such as biased probes, wall coatings, high temperature ovens and improved extraction systems have also contributed to the improved performance.

High charge state ECR ion sources have had an enormous impact on the development and performance of heavy-ion accelerators including many cyclotrons, linacs and synchrotrons used for nuclear physics research. As the interest in radioactive beams for nuclear physics research grows, the need for more intense high charge beams to inject into heavy-ion driver accelerators provides new motivation to improve ECR ion sources. This was a major factor in the design to build the VENUS ECR ion source for operation at 28 GHz, which has produced in a short-term test 205 eμA of U^{33+}.[2]

2. Physics and Scaling in ECR ion sources

In an ECR ion source, the plasma density, n_e, the electron energy distribution and the ion confinement time, τ_i, and the neutral density, n_o, all play significant roles in determining the charge state distribution and intensity of the extracted beam. In rough terms assuming the electron energies are sufficient for ionization, the product $n_e\tau_i$

determines the peak of the charge state distribution, while the neutral density limits the maximum attainable charge through charge exchange. High charge state ECR ion sources operate well below the plasma critical density. Since the critical density increases as the square of the microwave frequency used to heat the electrons via electron cyclotron resonance heating, Geller proposed that the extracted ion current from an ECR ion source should scale as the square of microwave frequency. [3] Already in 1976, R. Geller proposed to use a 56 GHz microwave generator to power an advanced version of SUPERMAFIOS to produce U^{50+} ions. [1]

The magnetic fields in an ECR ion source serve both to confine the plasma and to provide a closed surface where the RF power can heat the electrons through electron cyclotron resonance. For an ECR source it is convenient to describe the magnetic field strength relative to B_{ecr}, which is defined as

$$B_{ecr} = f/28$$

where B_{ecr} is the field in Tesla for resonance at an RF frequency f in GHz. In the early ECR sources this ratio of Bmax to Becr was on the order of 1.5. In the late 1980's it was experimentally demonstrated that at a given frequency, it was important to use stronger magnetic fields to confine the plasma. [4] The absolute minimum confinement needed for a high charge state ECR is for the solenoid and sextupole fields combine to form a closed surface defined by ratio of B to B_{ecr} equal to one inside the plasma chamber. For optimum confinement the fields should be sufficient to form a second closed surface at roughly twice the resonance field. Table 1 gives the optimum confinement, fields as a function of B_{ecr}. [5]

3. ECR Development

The development ECR ion sources can be roughly divided into three generations. First generation ECR sources operate between 5 and 10 GHz and were mainly developed during the 1980s. Second generation sources, which operate between 10 and 20 GHz, began appearing in the late 1980s and continue to be the most common type of source used at accelerators. While first and second generation ECR ion sources could be built using either conventional room temperature solenoids with permanent magnet sextupoles or with superconducting coils, full field 3rd generation ECR ion sources require fully superconducting magnet structures. Two superconducting 3rd generation ECR sources, VENUS and SECRAL, are in operation and several other high field superconducting ECR ion sources are either being commissioned, under construction or being designed. [6,7,8]

The VENUS ECR, which began operation at 28 GHz in 2004, uses solenoids and a sextupole made with NbTi superconducting wire arranged in the conventional coil geometry, to produce the optimum magnetic confinement fields for 28 GHz.[9] The coil configuration is shown in Fig. 1. To avoid coil movement and subsequent quenching of the superconducting magnets caused by the forces between the solenoid and sextupole coils in VENUS, a carefully engineered clamping and banding system, which applies significant pre-stress to the coils, was developed With this clamping, the VENUS magnet trained quickly up to its design currents. [10]

The SECRAL source currently operates at 18 GHz, but has demonstrated the magnetic fields strengths needed for 28 GHz. [11] The inverted coil geometry used for

SECRAL is illustrated in Fig 2. This design reduces the forces on the sextupole ends, since the axial fields are smaller at that point than for the conventional geometry. On the other hand, the sextupole must be significantly stronger than one for the conventional geometry, since the field strength of a sextupole depends on the square of radius and in this design the sextupole diameter is significantly larger than that of the plasma chamber wall. To produce the required sextupole field, SECRAL uses a large sextupole coil surrounded by an iron yoke, which adds roughly 30% to the sextupole field strength compared to an air coil.

4. 4th Generation ECR Ion sources

In the remaining sections we will focus on the concepts and challenges associated with developing a new 4th generation of ECR ion sources that could operate at more than 40 GHz. For the purposes of this paper, 56 GHz is chosen as a design goal, but certainly any frequency above 40 GHz would be of great interest. Table 1 gives the optimum confinement fields as a function of B_{ecr} for both 28 and 56 GHz.

The maximum field that can be produced in a superconducting magnet is generally limited by processes that drive the superconductor in to the normal conducting state and cause the magnet to 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. The short sample characteristics of NbTi are shown in Figure 3. The maximum current density, j_c, is plotted as a function of local magnetic field. At 4 K and 7 T the critical current density NbTi is roughly 1500 A/mm^2 . When the local field in the superconductor reaches 10 T, the critical current goes to 0.

The engineering current densities, j_e, which takes account for the additional non-superconducting materials surround the superconducting filaments and coil packing factors, are significantly lower. The typical engineering current densities versus the applied magnetic field for various superconductors are shown in Fig 4.

As a first step to evaluate the requirements for superconducting magnets at 56 GHz, we used a TOSCA model of VENUS to compute the fields generated when the ampere-turns in all coils were doubled. While VENUS has iron bars inside the sextupole coils, this only increases the sextupole strength 10% above an air core design for 28 GHz fields. The VENUS sextupole can produce 2.2 T at the plasma chamber wall and doubling the ampere-turns will produce at least 4T at this point, which meets the magnetic field criterion for 56 GHz. The superconducting current density was estimated by assuming a superconducting fraction of .25 in the coil packs. The fields and current densities were evaluated to determine the operating points for the magnets. The highest B fields occur in the sextupole where current density in the superconductor, j_{sc}, is 1550 A/mm2 and B is 12.7 T as shown in Fig 5. This operating point is below the short sample current limit for commercially available Nb_3Sn RRP conductor from Oxford Superconducting Technologies as illustrated in Fig. 5. New high Tc superconductors such as B2212 offer the potential for operating in even higher magnetic fields. However, it is too early to consider their use for a 4th generation ECR, because the difficulty in constructing coils with them and the potential for burnout in the wire during a quench.

While the model calculations show that the superconducting properties of Nb_3Sn meets the requirements for ECRIS-56, the design of such a magnet requires detailed mechanical and magnetic modeling, especially with respect to calculated the Lorentz forces on the coils and designing an adequate clamping system. One of the most challenging areas for an ECR magnet structure is at the injection end of the where the axial magnetic fields interact with the end currents in the sextupole. The end forces on the sextupole coils are alternately inward and outward, which makes the clamping difficult than for a solenoid, where the Lorentz forces generate an azimuthally uniform radial hoop force. The VENUS ECR, which uses solenoids and a sextupole made with NbTi superconducting wire, was the first source to fulfill these criterion at 28 GHz. The inter-coil forces for a 56 GHz magnet will be roughly four times as great for those at 28 GHz.

The inverted coil geometry used for SECRAL reduces the forces on the sextupole ends, since the axial fields are smaller at that point than for a conventional geometry magnet structure. In addition it would allow for additional space for radial clamping. On the other hand, the sextupole must be significantly stronger than one for the conventional geometry, since the field strength of a sextupole depends on the square of radius and in this design the sextupole diameter is significantly larger than that of the plasma chamber wall.

5. Other Design Considerations

Generating sufficient microwave power, coupling it into ECRIS-56, removing the heat from the plasma walls and dealing with an intense level of bremsstrahlung generated when the hot electrons collide with the plasma walls will be major technical challenges for ECRIS-56. The VENUS ECR has operated up to about 9 kW of RF power so far, which is the most power coupled into an ECR source so far. However, this translates to a power density in VENUS of only about 1 kW/liter and does not appear to be the saturation power density, where the production of high charge state reaches a maximum. This is not surprising as other sources like the 14 GHz AECR-U operate well up to about 2 kW/liter. Since the power density should scale roughly as the plasma density divided by the electron confinement time, it is probably that the saturation power density at 28 GHz could be as much as 8 kW/liter. At 56 GHz the practical limits of microwave power availability and heat removal will probably limit the power density to values significant less than the saturation values. While 28 GHz gyrotrons capable of producing 10 kW of continuous wave power are commercially available, at higher frequencies existing gyrotrons are pulsed. However, gyrotrons at 53, 60 and 70 GHz, which can produce 200 kW for 200 ms, have been constructed and could produce 30 kW CW with the appropriate power supplies. With further R&D these gyrotrons could even be extended to 50 kW.[12]

The question, however, is if it is possible to build a plasma chamber that has enough cooling capacity to dissipate this amount of power. The microwave power is partially coupled into the plasma and partially dissipated on the plasma walls. The microwave heating of the walls is widely distributed, but the hot plasma electrons are dumped back onto the plasma walls along the magnetic flutes defined by the vector field of the sextupole and solenoid fields. This generates localized heating on the plasma wall, which can result in burnout of the plasma chamber. [13] As the operating frequency of ECR ion sources has increased, so has the amount of x-rays observed. A model calculation of ECR heated plasma predicts that mean energy of the electrons increases rapidly with frequency. [14] While the plasma chamber walls, surrounding magnetic structures all serve to reduce the x-ray flux outside of a traditional ECR source, as the mean energy of the electrons increases, additional shielding must be added for personnel protection. In a superconducting ECR ion source, the x-rays cause an additional cryogenic load by depositing energy in the cold mass of the cryostat. One design solution is adding a high liner made from dense high z material such as tantalum between the plasma chamber and the cryostat to attenuate the x-rays .[15] A second option would be to significantly increase the amount of refrigeration available at 4 K and might be the only possibility to operate ECR ion sources at these high frequencies.

So while building a 4th Generation ECR ion source presents challenges, the basic technologies to do so are available. The next step would be to design and build a prototype superconducting magnet structure capable of producing the required magnetic fields. The development cost of such a system is high, but by providing more intense beams with higher charge states a 4th generation ECR ion source could enhance the capability of heavy-ion accelerators now being constructed and reduce the length and cost of future machines now being considered.

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Figure Captions

Fig. 1. Magnetic model showing the coil configuration used in the VENUS ECR ion source. The superconducting sextupole coils are surrounded by three solenoid coils, which produce the axial magnetic fields.

Fig. 2. The coil geometry used in the SECRAL magnet. This inverted geometry uses compact solenoid coils surrounded by large sextupole coils.

Fig. 3 shows a plot of the critical current, j_c, in NbTi for 4 K. To the left of the curve, the material is superconducting, to the right normal conducting. The maximum magnet aperture field in this case is roughly 5 T, when the local field in the superconductor reaches 6 T.

Fig 4. Engineering current densities for various types of superconductors. The cross indicates the operating point for the VENUS sextupole at 28 GHz.

Fig 5. Model calculations based on the VENUS coil geometry to determine the operating points for a when the ampere-turns are doubled. The small dot shows the highest field location in the sextupole coil (12.7 T) when the currents are set to produce the optimal fields for 56 GHz. Field and current values in the other coils are well below the critical current of this type of Nb_3Sn.

TABLES

Table 1
Optimum fields for ECR operation

		28 GHz	56 GHz
B_{ecr}		1 T	2 T
B at wall	$\geq$ 2 B_{ecr}	2 T	4 T
B_{inj}	$\geq$ 3.5 B_{ecr}	3.5 T	7 T
B_{rad} plasma wall	~ 2 B_{ecr}	2 T	4 T
B_{min} on axis	~.4 -.8 B_{ecr}	.4-.8 T	.8-1.6 T
B_{ext}	~ 2 B_{ecr}	2 T	4 T

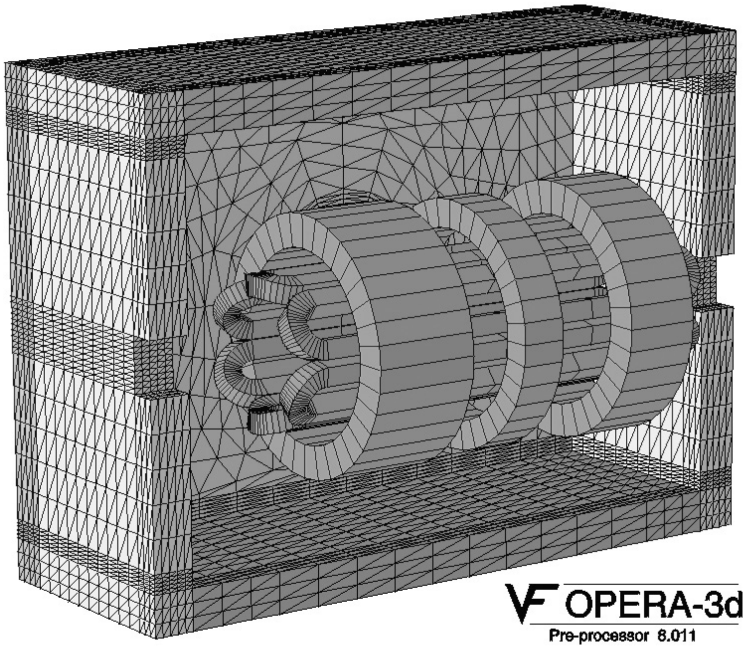

Fig. 1

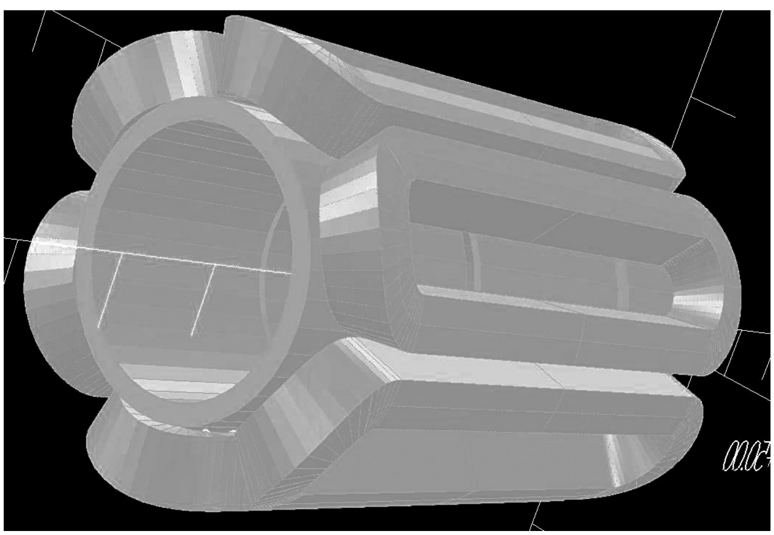

Fig. 2

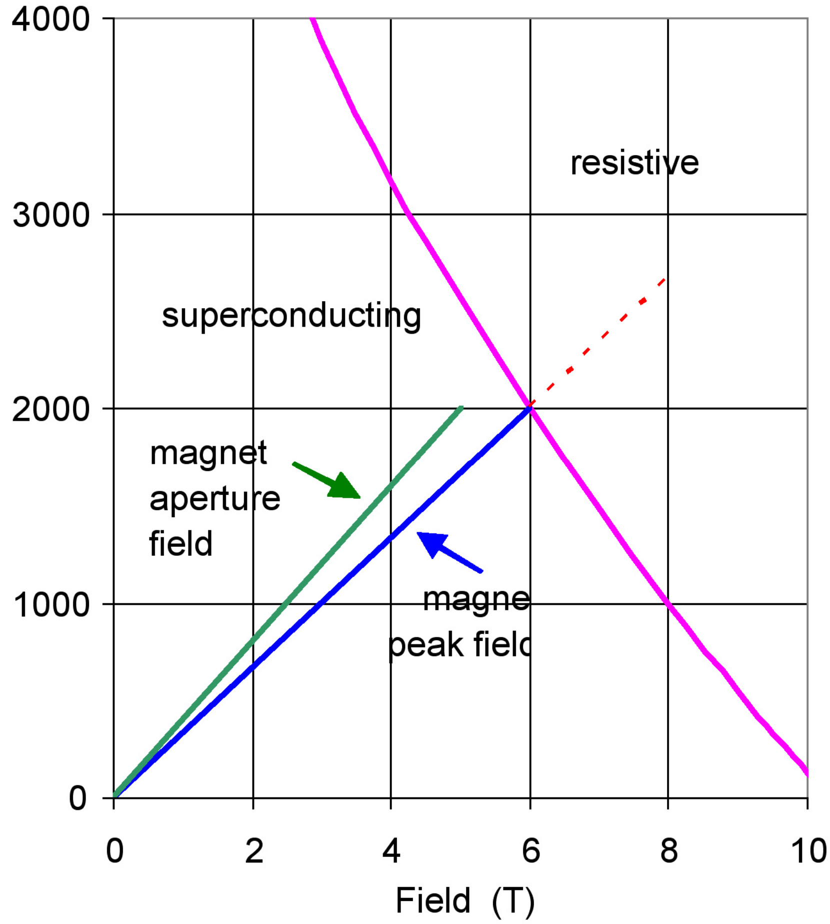
4000
3000
2000
1000
0
0
2
4
6
8
10
Field (T)
resistive
superconducting
magnet
aperture
field
magne
peak field

Fig. 3

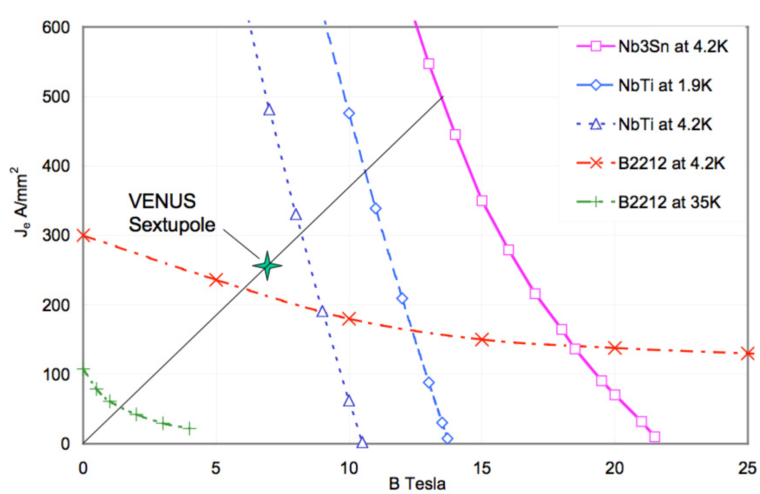
600
500
400
300
200
100
0
J_e A/mm^2
0
5
10
15
20
25
B Tesla
VENUS
Sextupole
Nb3Sn at 4.2K
NbTi at 1.9K
NbTi at 4.2K
B2212 at 4.2K
B2212 at 35K

Fig. 4

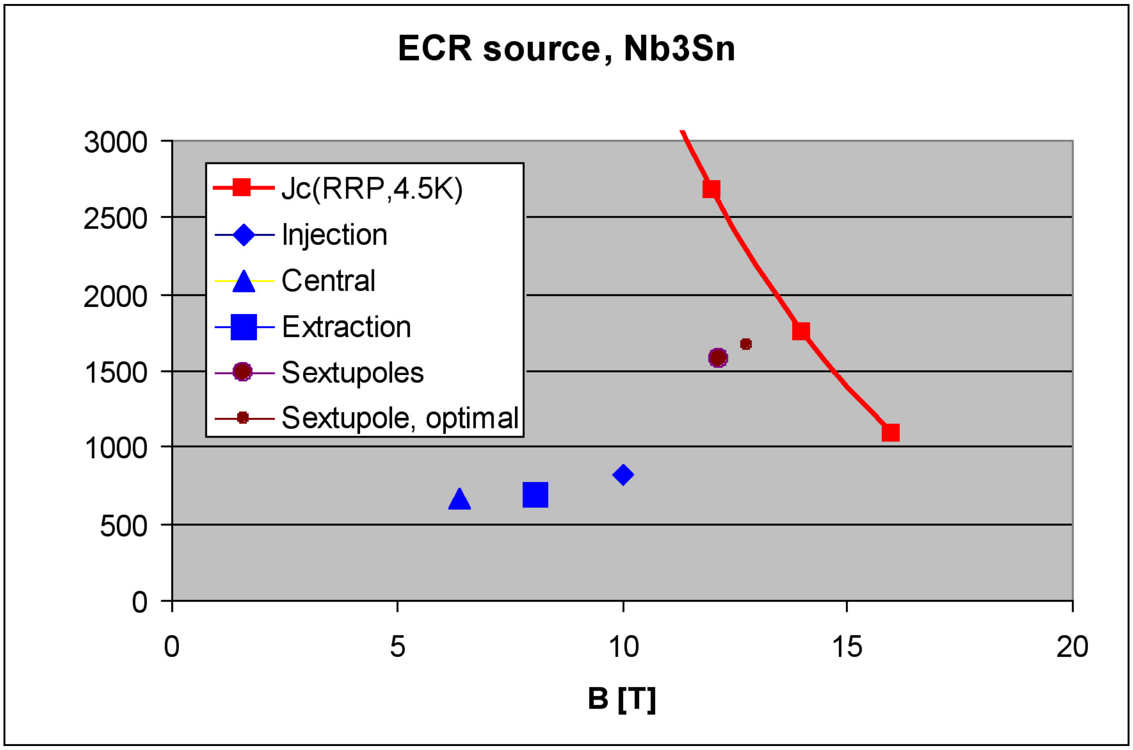
ECR source, Nb3Sn
3000
2500
2000
1500
1000
500
0
0
5
10
15
20
B [T]
Jc(RRP,4.5K)
Injection
Central
Extraction
Sextupoles
Sextupole, optimal

Fig. 5