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HIGH PERFORMANCE ECR SOURCES FOR NEXT-GENERATION NUCLEAR SCIENCE FACILITIES

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Abstract

Modern nuclear science ion accelerators require intense high charge state, heavy-ion beams. Electron Cyclotron Resonance (ECR) ion sources are the primary tool for generating such beams. Advances in magnet technology and an improved understanding of ECR ion source plasma physics have led to significant improvements in ECR source performance over the last several decades. The current state of the art is represented by third-generation sources operating at frequencies around 28 GHz and peak coil fields of about 7 T using NbTi conductors. Fourth-generation ECR ion source magnets designed to support ECR ion sources with an operating frequency above 40 GHz are currently under development. This paper will give an overview of the worldwide efforts underway to develop high-performance ECR sources for next-generation heavy ion accelerator facilities.

ECR ION SOURCE DESIGN PARAMETERS

Since the 1980s, Electron Cyclotron Resonance Ion Sources (ECRIS) have been crucial components of heavy ion science facilities [1] . The unsurpassed versatility, stability and high intensity of continuous wave (CW) high charge state ions delivered by these sources make them ideal injectors for these facilities. ECR ion sources use magnetic confinement and electron cyclotron resonance heating to produce a plasma consisting of energetic electrons (up to hundreds of keV) and relatively cold ions (a few eV). The magnetic confinement is typically achieved by a combination of a solenoidal mirror field and a sextupole field (a classical configuration is shown in Fig. 1) that creates a minimum B confinement structure where the field grows from the center of the source in every direction (longitudinally and radially). Within this confinement field a closed magnetic surface exists where the resonance cyclotron frequency of the electrons moving back and forth within the magnetic bottle equals the microwave heating frequency — allowing efficient transfer of energy from the electromagnetic field to the electrons:

$$\omega_e = \frac{e \cdot B_{\mathrm{ECR}}}{m} = \omega_{\mathrm{RF}} \quad (1)$$

where m and e are the electron mass and charge, B_{ECR} is electron cyclotron resonance field, ω_e and ω_{rf} are the electron cyclotron resonance and the microwave frequencies.

High charge state ions are primarily produced by sequential impact ionization, which means that the ions must remain

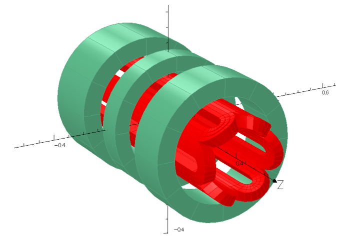

Figure 1: VENUS: Sextupole-in-Solenoid Geometry. The sextupole-in-solenoid VENUS geometry leverages proximity of the sextupole to the plasma chamber, minimizing peak fields in that coil. [2]

in the plasma long enough (tens of ms) to reach high charge states. Therefore, one of the main parameters determining the performance of an ECR ion source is the product of the plasma density and ion confinement time: $(n_e \cdot \tau_i)$. Together with the neutral gas density in the plasma this product determines both the peak of the charge state distribution and the highest charge state that can be produced in the plasma. However, there are many design trade-offs between maximizing density or ion confinement time in the ECR design and this paper will touch briefly on those. In general, ECR development has followed the semi-empirical scaling laws first proposed by Geller [1], which state that the plasma density scales with the square of the frequency $n_e \propto \omega_{\mathrm{rf}}^2$. As the frequency increases, the magnetic fields have to be scaled accordingly to fulfill the resonant heating condition for the plasma electrons. As a consequence the plasma confinement time (τ_i) in the trap improves since it is proportional to the average field strength and the axial and radial magnetic mirror ratios $B_{\mathrm{inj}}/B_{\mathrm{min}}$, $B_{\mathrm{ext}}/B_{\mathrm{min}}$, and $B_{\mathrm{rad}}/B_{\mathrm{min}}$ of the magnetic trap [1].

ECR Ion Source Design Guidelines

Following these fundamental principles, ECRIS designs are aiming for both the highest confinement fields and highest heating frequencies. Compiling results from the best performing ECRIS devices, guidelines for the design of an optimized magnetic confinement field configuration were established that can be scaled to any selected heating frequency F_{rf} of the new ion source [3]. Conveniently for a frequency of 28 GHz the B_{ECR} is 1 T, and can be easily scaled from that number to other frequencies Eq. (2).

$$B_{\mathrm{ECR}}(T) = \frac{F_{\mathrm{rf}}(\mathrm{GHz})}{28(\mathrm{GHz})} \cdot T \quad (2)$$

The established field ratios are listed below with B_{inj}, B_{ext}, B_{min}, the magnetic mirror maximum and minimum fields,

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and B_{rad} the radial field strength on the plasma chamber wall.

$$B_{inj}/B_{ECR} = 4 \tag{3}$$

$$B_{rad}/B_{ECR} = 2 \tag{4}$$

$$B_{ext} \approx 0.9 \; to \; 1.2 \; B_{rad} \tag{5}$$

For the minimum B-field of the trap one can find [3, 4]

$$B_{min} \approx 0.4 B_{rad} \text{ and} \tag{6}$$

$$0.4 < B_{min}/B_{ECR} < 0.8 \tag{7}$$

where B_{min} is a tuning parameter. A target number for the last closed magnetic surface (CS) should be

$$B_{CS}/B_{ECR} \approx 2 \tag{8}$$

Another important parameter for the overall plasma confinement is the electron energy distribution in the ECR plasma, which can be characterized by three components: a cold population (20 eV) — important for the overall plasma density and confinement time; a warm population (up to 100 keV) — responsible for the ionization process; and a hot population with a high energy tail reaching up to several hundreds of keV. The hot electrons are highly confined in the core of the plasma and are quasi collissionless — critical for establishing an electrostatic confinement well for high charge state ions. While the hot electron population does not contribute to the ionization process, their presence is a necessary condition for the creation of high charge state ions [4]. However, one undesired consequence of this hot electron population is the creation of high energy x-rays that penetrate the plasma chamber and, in the case of a superconducting ECR ion source, add a substantial heat load to the cryostat and need to be carefully managed. Some tuning and design trade-offs to manage this heat load are discussed in the next section.

DESIGN TRADE-OFFS

Several engineering and plasma physics design trade-offs need to be considered when a superconducting ECR ion source is designed. Many design parameters are soft and can be adjusted within a relatively large parameter space. The fact that the engineering design parameters for different disciplines (magnet, RF, cryogenic, mechanical) are strongly coupled to each other and cannot be defined independently make their choices more challenging. For example the plasma volume size, magnetic field gradient or field profile will all effect the plasma heating efficiency, confinement time and influence the optimized operational range for the ion source.

Magnetic Field Profile Considerations

By following the general guidelines for the magnetic field listed in the previous section the magnetic confinement field can be optimized for a chosen operating frequency. The bullet list below adds some additional design criteria and trade-offs to consider.

- The average magnetic field will determine the optimum charge state and also the charge state region for which the ECR ion source ionization efficiency will be the highest. The higher the average field and heating frequency the higher the optimum charge state region.
- The field quality is less critical for the performance of an ECRIS than the average field strength. ECR magnets cannot be compared with beam line magnets where multipole field components are an important factor for optimizing the design. Therefore, many coil configuration are equally adequate to achieve the desired field configuration.
- The optimum place for the extraction aperture is located at the peak of the extraction solenoid field. Therefore the extraction beam optics has to be designed to reach into the warm bore of the cryostat — minimizing the lengths between the edge of the cryostat and the extraction aperture will improve the ion beam transport.
- The magnet structure has an uneven distribution of forces due to the radial field components of the mirror field. Design approaches need to carefully manage these stress points/areas and often require extending the sextupole ends well beyond the solenoids to achieve manageable force levels. This design approach needs to be carefully weighed against the disadvantage of increasing the length of the poorly pumped extraction region which increases the risk of high voltage breakdowns and makes the design of the LEBT more difficult. Limiting the maximum extraction voltage can reduce the maximum beam intensity that can be extracted from the source and consequently the ultimate ion source performance.
- The lowest magnetic field points (3 points at the injection mirror) on the plasma chamber wall determine where the maximum heat load to the plasma chamber will be deposited. Therefore, the magnet structure should be reasonably aligned to reduce the risk of this heat load being concentrated on a single point. The heat load management of these points often limits the maximum microwave power that can be coupled into an ECR source.
- The magnetic field strength of the last closed magnetic surface is critical for the confinement in the source and should be kept in mind when designing the magnetic bottle. A good design goal is $2 \cdot B_{ECR}$ (see Eq. 8).
- The extraction solenoid peak field is typically lower than the injection solenoid peak field to establish a preferential drift of ions towards the extraction aperture where they are extracted and formed into the ion beam (see Eq. 5). The typical value of $B_{ext} \approx B_{rad}$ also ensures that the last closed magnetic surface fulfills the criteria listed in Eq. 8.
- The minimum B-field B_{min} should be tuneable within a reasonable time scale (minutes) and a wide range (see also cryostat trade-offs and microwave power trade-offs).

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- Lower magnetic field gradients at the ECR heating zone improve the microwave coupling heating efficiency [5]. This can be achieved by increasing the lengths of the magnetic mirror, which is also beneficial for the overall ion confinement time. However, for a given microwave power system and limited plasma chamber cooling capacity, a higher plasma volume reduces the maximum power density that is available to the plasma and might limit the maximum achievable performance of the source as discussed in the next section.
- Lower gradients can also be achieved by increasing the minimum B field between the mirrors. Raising the minimum B-field improves the microwave heating efficiency [5]. But it will also increase the hot electron temperature in the plasma and consequently the x-ray heat load to the cryostat. This electron temperature depends only on the absolute value of the minimum B-field [6, 7]. Therefore, the available cryogenic cooling power often limits the operational tuning range of this parameter to a less than optimum value for the current superconducting ECR ion sources. This trade-off should be carefully considered (see cryostat considerations).

Microwave Frequency and RF Coupling

- The higher the frequency the higher the microwave power the source plasma can absorb before the onset of instabilities. The threshold density is proportional to the square of the microwave frequency [5–8]. The high frequency large volume sources have not yet reached this point (see plasma chamber cooling).
- Double (or triple) frequency heating improves plasma stability and source performance. The limiting factor on the number of microwave heating frequencies is the available space for waveguide feedthroughs at the injection flange as discussed under auxiliary devices.
- The plasma density increases linearly with power until a threshold density is reached where non-linear phenomena occur [1]. Therefore, for a given confinement configuration the x-ray heat load depends linearly on the microwave power.
- For overmoded waveguides (>24GHz) tapering the waveguide in the injection region increases the power density coupled to the ECR zone [8].
- Off-axis microwave coupling that is placed in-between plasma flutes increases the coupling efficiency.
- The microwave cavity is created between two mirror peak fields and should be closed off by the extraction aperture on one side and the injection flange on the other side.

Plasma chamber (ID) and Mirror Lengths

- The confinement time increases with mirror lengths and radius. These volume parameters are particularly important for sources that are required to deliver the highest possible charge states (such as VENUS). If high intensity low to medium charge states ions are required smaller plasma volumes might be preferred to increase the power density coupled to the plasma chamber.
- To achieve good coupling efficiency the plasma chamber should have a diameter of at least several microwave lengths (>3.5-5). For 24 GHz and 28 GHz the wavelengths are 1.25 cm and 1.07 cm, so a 5-6 cm plasma chamber IDs would be sufficient to satisfy this criteria. Reducing the plasma chamber ID increases the power density in the source for a given microwave power supply and would be advantageous for optimizing a source for medium charge states such as uranium 30-35+. However, a smaller plasma chamber ID makes the design of the injection flange more difficult which needs to accommodate many auxiliary devices.
- Plasma chamber cooling is an engineering challenge. Due to the magnetic field distribution, the plasma heating is concentrated on the lowest magnetic field regions along the field lines that intercept with the plasma chamber. As a consequence, all high performance 3rd Generation ECR ion sources are still power limited. For example for the VENUS source the maximum power density that can be reliably coupled into the source is 1.38 kW/l see Table 1. On the other hand 2.5kW/liter [9] can be coupled into conventional 2nd generation sources before a performance plateau is reached. This would mean more than 30 kW would be needed to reach maximum performance for VENUS.

Cryostat

ECR ion source cryostats are typically mounted on high voltage platforms and cannot be connected to a cryoplant. Therefore, cryocoolers are utilized to maintain the required operating temperature for the magnets. Some design consideration specific to ECRIS cryostats are discussed below.

- The cryogenic loads are dynamic since a major component of the load originates from bremsstrahlung of hot electrons impinging on the plasma chamber walls. The resulting x-rays are absorbed by the cryostat and add a substantial heat load (several (10s of) watts). Therefore, ECRIS cryostats typically have heaters to maintain a constant pressure and temperature in the cryostat when the plasma is off.
- The x-ray heat load to the cryostat is determined by two parameters: the minimum B-field $B_{\min}$ and the total microwave power coupled to the plasma. Since the absorption coefficient of shielding material placed between the plasma and the cryostat decreases logarithmic with x-ray energy while the x-ray energy increases linear with $B_{\min}$, the x-ray heat load increases exponentially with the $B_{\min}$ value.
- On the other hand the plasma density increases linearly with power. Therefore, for a given confinement configuration the x-ray heat load into the cryostat depends linearly on the microwave power.
- Since the x-ray load only increases linearly with power, it is often more beneficial to operate at lower $B_{\min}$

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Table 1: Selected Key Parameters of the Leading ECR Ion Sources

Design Parameter	VENUS	SECRAL	SECRALII	RIKEN	FECR
Superconductor	NbTi	NbTi	NbTi	NbTi	Nb_3Sn
B_{inj} (T)	4	3.7	3.7	4	≥ 6.4
B_{ext} (T)	2-3	2.2	2.2	2.2	≥ 3.4
B_{sext} (T)	2	1.7	2	2.1	≥ 3.4
B_{peak} (T)	7	7.8	7.8	7.4	11.8
Mirror Lengths (mm)	500	420	420	500	500
Plasma Chamber ID (mm)	150	116	125	150	150
$\omega_{rf} primary$	28	24	28	28	45
kW primary	10	7	10	10	20
$\omega_{rf} secondary$	18	18	18	18	45/TBD
kW secondary	2.4	3	2.4	2.4	TBD
Power Density kW/l	1.38	2.1	2	1.38	2

and compensating the reduced heating efficiency with higher microwave power. This tuning restriction is one of the reasons, why none of the 3rd generation superconducting ECR ion sources have reached their performance limits with microwave power yet.

Auxiliary Devices

The main access to the ECR ion source plasma is provided through the injection port of the plasma chamber. The mechanical design of this area is highly complex and congested which limits of how small the plasma chamber ID can be. Space must be provided for: adequate pumping to create high vacuum to ultra-high vacuum conditions in the source, at least two gas lines to feed the plasma, high current feedthroughs for compact high temperature ovens [5] and high voltage feedthroughs for sputter ports for metal ion beam production, waveguides, and a high voltage feedthrough for a negatively biased disk on axis (for improved plasma confinement). Most devices need to be water cooled, electrically isolated from the plasma chamber, and high vacuum compatible. In addition, the injection must reach deep into the warm bore through the fringe field of the injection solenoid magnet and typically has RF springs to electrically close the microwave cavity at the injection side [5].

NbTi ECR ION SOURCES

All high performance 3rd Generation ECRIS utilize Niobium-Titanium alloy (NbTi). It is ductile and allows simple fabrication methods for wires and cables. Since NbTi performance is limited by its upper critical field to about 10 T at 4.2 K, the optimum frequency of these sources ranges from 24-30 GHz operation. VENUS was the first superconducting ECRIS fully optimized for operation at 28 GHz and has a typical field distribution for these kind of sources. IMP followed with the development of the SECRAL I+II sources [8] , RIKEN with the development of two 28 GHz superconducting sources [10], NSCL with the development of SuSI [11], and FRIB with VENUS-II [12]. All these sources feature a combination of a sextupole magnet and a mirror field produced by a series of solenoid magnets with typical peak fields on the coil of 7-8 T. Two coil configurations are used. The VENUS-type, RIKEN, and SuSI sources utilize a configuration where the sextupole coils are placed within the solenoids and the sextupole extends well beyond the solenoid field to minimize the forces on the sextupole magnet ends as shown in Fig 1. SECRAL uses an inverted version where compact solenoids are placed inside the sextupole. The choice of geometry is mainly a matter of optimizing the force distribution of the coils and has little to do with the source performance that can be ultimately achieved. The VENUS field geometry is shown in Fig. 1 and the critical current density in a NbTi wire together with the operational points of VENUS are shown in Fig. 2. The magnet is designed to provide a margin of about 1.5 K at the nominal field of 4 T at the injection solenoid, 2 T at the plasma chamber wall and 3T at the extraction solenoid with a tuneable middle field of 0.2 to 1 T. The comfortable temperature margin and the high copper content of the superconducting wire make the VENUS magnet very stable and robust in operations.

Table 1 lists a few key design parameters of the highest performance 3rd generation ECR ion sources and the first 4th generation source that is under development [8]. Table 2 shows a few selected beam intensities for Argon and Uranium of the two highest performance ECR ion sources VENUS [13], SECRAL [8], and SECRAL-II [14, 15]. The ion beam intensities demonstrate the design trade-offs discussed in the previous section. For Argon the SECRAL type source has produced higher beam intensities taking advantage of the higher microwave power density available for SECRAL and SECRALII (2 kW/L for SECRAL versus 1.4 kW/L for VENUS). For Uranium VENUS is ahead due to its high performance high temperature oven that can produce sufficient vapor pressure to optimize the performance for this high temperature metal. When the performances are compared for low temperature metals such as bismuth where the vapor pressure is not a limited factor SECRAL produces

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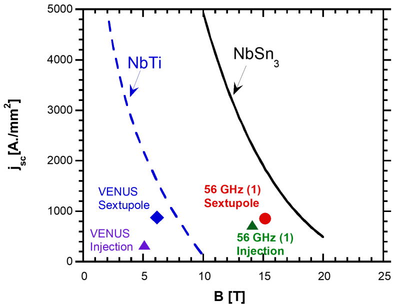

Figure 2: Critical current density A·mm^{-2} in a NbTi and a Nb_3Sn superconductor wire vs. total magnetic field (T). The operating points for the VENUS and a reference design for a 56 GHz ECRIS (sextupole-in solenoid) for the sextupole and the injection solenoid coils are indicated. The current density j_{SC} is quoted inside the super-conductor and is not the engineering current densities through the total cross section of the wire or cable. [2]

Table 2: Selected Beam Intensities μA [8, 13–15]

Ion	VENUS	SECRAL	SECRALII
Ar^{12+}	1046	1420	1190
Ar^{14+}	850	846	1040
Ar^{17+}	120	50	130
U^{32+}	450	200	
U^{33+}	400	202	
Bi^{31+}		680	
Bi^{50+}	50	10	
Bi^{61+}	0.1		

similar intensities as demonstrated in VENUS. On the other hand, for the ultrahigh charge states the larger plasma chamber volume (longer confinement time) is advantageous for the VENUS source where the highest charge states can be extended to Bi^{61+} for bismuth.

Nb3Sn ECR ION SOURCE R&D

To extend ECR ion sources to frequencies well above 28 GHz, new superconducting coil technology will be needed. Presently, the most developed material for high-field applications is Nb_3Sn, for which the upper critical field limit increases to about 20 T at 4.2 K see Fig. 2 for a temperature at 4.2 K. Several years ago LBNL developed a reference design for a 56 GHz ECR ion source based on Nb_3Sn [16]. Building on these earlier conceptual studies, LBNL has recently developed a preliminary engineering design for a 45 GHz ECR ion source (FECR) in collaboration with IMP [17–19]. Some key parameters are listed in Table 1. However, the realization of such a magnet remains challenging. Unlike NbTi, which is ductile and can withstand high compressive force, Nb_3Sn is brittle and strain sensitive. As a result, the current carrying capability of Nb_3Sn coils is affected by mechanical stresses in the windings [16], which makes the design and construction much more difficult than NbTi magnets. An extensive R&D program has been carried out in the context of the LHC high luminosity upgrade to design and several high field quadrupole magnets were built using Rutherford cables [20]. However, a combined magnet as required for an ECRIS is more complex. Due to the limited cooling capacity available with 4 K cryocoolers, Rutherford cables as used for the LHC magnets cannot be used for ECRIS and the current engineering designs are based on single-strand round wires. Even with the substantial experienced gained by the LARP program [20], extensive prototyping might be required before a production magnet can be built. Given the statuts of the R&D it is likely that a Nb_3Sn magnet capable of operating at a frequency above 40 GHz can be developed within the next 5 to 10 years.

HTS ECR ION SOURCE R&D

Nb_3Sn ECR sources could have a strong impact on the accelerator community, but they are ultimately limited to 56 GHz. Therefore, R&D effort is underway to develop high temperature superconductor (HTS) technology suitable for a 5th generation ECRIS either as hybrid magnets with NbTi or Nb_3Sn, or as fully HTS magnet suitable for ECRIS of up to 84 GHz [21]. After three decades of conductor development, high-temperature cuprate superconductors, including Bi-2212 and REBCO, have been fabricated into a practical form of metal/superconductor composites and are commercially available in conductor lengths feasible for making magnets for accelerators. However, the size of a magnet system for this application and the combination of coils as discussed above present unique challenges for HTS conductor and magnet technologies. A preliminary field profile based on a HTS (REBCO) magnet has been recently developed at LBNL [21] as a starting point for systematic R& D to develop such a magnet system. Given that fundamental R&D is required before prototypes can be build, the time frame for such a high field magnet structure is probably 10-20 years away, but research should be pursued to open this path for future 5th generation ECR ion sources.

CONCLUSION

With the current state of the art 28 GHz ECRIS, a limit of what is feasible with established superconducting magnet technology has been reached. Nb_3Sn is the logical next choice for higher frequency sources and will dominate the 4th Generation ECR ion sources development over the next decades. HTS technology, which might open the path to a 5th Generation ECR ion sources is emerging and fundamental R&D should be pursued.

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REFERENCES

[1] R. Geller, in *Electron cyclotron resonance ion sources and ECR plasmas*, CRC Press, UK, 1996, pp. 394-398.

[2] D. Leitner *et al.*, "Superconducting ECR Ion Source Development at LBNL", in *Proc. 11th Int. Conf. on Heavy Ion Accelerator Technology (HIAT'09)*, Venice, Italy, Jun. 2009, paper WE–10, pp. 133–137.

[3] D. Hitz *et al.*, *Rev. Sci. Instrum.*, vol.73, 509 (2002).

[4] D. Leitner, *et al.*, Proc. of Intern. Conf. on Cyclotrons, (CYCLOTRONS'2007), Giardini Naxos, Italy, 2008.

[5] D. Leitner *et al.*,*Rev. Sci. Instrum.*, vol. 79, 033302 (2008).

[6] J. Benitez *et al.*, 22nd Intern. Workshop on ECR Ion Sources, Busan, Korea, (ECRIS'16), MOCO04 (2016).

[7] D. Neben *et al.*, 23rd Intern. Workshop on ECR Ion Sources, (ECRIS'18), Catania, Italy, doi:10.18429/JACoW-ECRIS2018-TUP15 (2018)

[8] Zhao, H. W. *et al.*, in *Phys. Rev. Accel. Beams*, 20,9, pp.094801, Sep.2017 10.1103/PhysRevAccelBeams.20.094801

[9] D. Xie *et al.*, 13th Intern. Workshop on ECR Ion Sources, (ECRIS'97), Texas A&M, College Station, USA, 16-20, (1997).

[10] T. Nakagawa *et al.*,*Rev. Sci. Instrum.*, vol. 81, 02A320 (2010).

[11] G. Machicoane *et al.*, 21st Intern. Workshop on ECR Ion Sources, (ECRIS'14), Nizhny Novgorod, Russia, MOOMMH03 (2014).

[12] G. Machicoane *et al.*, 23rd Intern. Workshop on ECR Ion Sources, (ECRIS'18), Catania, Italy, doi:10.18429/JACoW-ECRIS2018 (2018)

[13] D. Xie *et al.*, 23rd Intern. Workshop on ECR Ion Sources, (ECRIS'18), Catania, Italy, doi:10.18429/JACoW-ECRIS2018 (2018)

[14] L. T. Sun *et al.*, "SECRAL II Ion Source Development and the First Commissioning at 28 GHz", in *Proc. 22nd Int. Workshop on ECR Ion Sources (ECRIS'16)*, Busan, Korea, Aug.-Sep. 2016, pp. 43–47. doi:10.18429/JACoW-ECRIS2016-TUAO04

[15] L. Sun *et al.*, 23rd Intern. Workshop on ECR Ion Sources, (ECRIS'18), Catania, Italy, doi:10.18429/JACoW-ECRIS2018 (2018)

[16] P. Ferracin *et al.*, *Rev. Sci. Instrum.*, vol.81, 02A309 (2010).

[17] M. Juchno *et al.*, *I*EEE Trans.Appl.Supercond., 28, 4602806 (2018).

[18] H.W. Zhao, *Rev. Sci. Instrum.*, vol.89, 052301 (2018).

[19] H.W. Zhao, *et al.*,23rd Intern. Workshop on ECR Ion Sources, (ECRIS'18), Catania, Italy, (2018).

[20] P. Ferracin *et al.*, *I*EEE Trans.Appl.Supercond., 24, 4002306 (2014).

[21] T. Shen, *et al.*,23rd Intern. Workshop on ECR Ion Sources, (ECRIS'18), Catania, Italy,(2018).