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RECENT ADVANCE IN ECR ION SOURCES*

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Abstract

Since their inception in the 1970s, Electron Cyclotron Resonance (ECR) ion sources have been and continue to be used extensively as injector for ion accelerators due in part to the high continuous wave (CW) current of high charge state ions that can be extracted but also because of many operational advantages including current stability, long lifetime and the availability of a wide range of primary beams from many gas and solid elements. Many of the next generation ion accelerators now require very intense beams of highly charged ion and as a result need to develop state of the art ECR ion sources. This paper discuss beam requirements for production of high intensity heavy ions and then focus on the 28 GHz ECR ion source in development for the facility for Rare Isotope beams (FRIB) at Michigan State University and discuss new concept and challenges for developing and operating ECR ion source at frequencies beyond 28 GHz.

INTRODUCTION

The Facility for Rare Isotope Beam (FRIB) built on the campus of Michigan State University (MSU) is based on a superconducting-RF linear accelerator designed to reach a beam power of 400 kW on the production target. Installation and commissioning of the accelerator is making significant progress and a beam energy over 20 MeV/u has already been reached after acceleration through the first linac segment as reported in [1, 2]. Based on the number of secondary beams and reaction products that can be generated, heavy ion beams such as Uranium represent one of the most interesting and important primary beams to develop and it is also the most challenging beam to develop at high intensity from the ion source. The choice of the charge state selected depends on the intensity that can be extracted from the ion source, the final beam energy and the overall acceleration scheme. For FRIB, the Superconducting linac is made of three accelerating sections. A charge stripper is located after the first accelerating section where the beam energy reaches about 20 MeV/u. Because the charge state distribution after the stripper is weakly dependent on the beam energy, the choice of the selected charge state from the ion source is not critical as long as the Q/A meet the injection criteria for the RFQ (Q/A> 1/7). More important is the beam intensity requirement on the ion source of 13 pμA for FRIB in order to reach the final beam power of 400 kW. However, the FRIB accelerator is also designed to accelerate two charge states which lesser the intensity requirement on the ion source. These considerations are important to ensure reliable and long operation from the ion source. Other project like the Heavy Ion Accelerator Facility (HIAF) in China or the Radioactive Isotope Beam Factory (RIBF) in Japan have even higher beam intensity requirement from the ion source which has to deliver 30 pμA of CW $^{238}U^{35+}$ and 50 pμA of $^{238}U^{35+}$ in pulsed operation [3] for HIAF and about 15 pμA of $^{238}U^{35+}$ for RIBF. These intensity requirements combined with the intrinsic advantage of starting with a higher charge state to gain more energy or help lower the cost of the accelerator continues to drive the development of ECR ion source and will be essential for the next generation of heavy ion accelerators.

FEATURES OF AN EFFICIENT ECRIS

Ion Sources for highly charged ions such as ECR or Electron Beam Ion Sources (EBIS) rely on electron impact ionization. Because the cross section for single ionization are much greater than double ionization, high charge states are created in a stepwise process requiring confinement times for the ions, τi of a few ms to tens of ms for very high charge states. Also ionization cross section decrease quickly with charge state while charge exchange cross section are large and mostly depends on the neutral gas pressure. Therefore unlike high current singly charged ions sources which operate at high pressure, ECR have to operate a very low gas pressure. A higher operating pressure has to be compensated by a higher ionization rate to translate into higher current, requiring to increase the electronic density n_e. The product of $n_e \tau_i$ (cm^{3}s^{-1}) represent a fundamental requirement for an ion source to produce highly charged ions [4].

Long ion confinement times in an ECR relies on a magnetic trap achieved by creating a minimum-B configuration using a combination of solenoids along the longitudinal axis and magnetic multipole, usually a sextupole, in the radial direction. Loss cones using the axial magnetic maxima and minima can be defined using the mirror ratio R=Bmax/Bmin. The electrons are heated by interacting with the injected microwave when crossing the closed ECR surface usually referred to as B_{ECR}, where the electron Larmor frequency (ω_L) is equal to the wave frequency (ω_{RF}) according to

$$\omega_L = \frac{eB}{m_e} = \omega_{RF} \tag{1}$$

Increasing the electronic density n_e is usually achieved by increasing the microwave power injected. However there are some limitations as to what density can be achieved for a given magnetic trap and operating excitation frequency

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including the difficulty for the microwave energy to penetrate the plasma above the cutoff density and electron losses due to various mechanism and instabilities [5]. Ideally in order to keep the kinetic pressure of the plasma well below that of the magnetic pressure [6], n_e should scale with the square of the magnetic field B, i.e. $n_e \propto B^2$ or alternatively based on Eq. (1):

$$n_e \propto \omega_{RF}^2 \tag{2}$$

Operating at higher excitation frequency with a suitable magnetic field opens the possibility to operate at a higher microwave power and generate a higher plasma density before the onset of instabilities and electron losses limit the performances. Operating with a stronger magnetic field also helps reach longer confinement times which is very beneficial especially for higher charge states. Over several decades of development and improvement of ECR ion sources, a few design rules regarding the magnetic field trap have emerged which can be summarized as follow:

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

$$B_{min} = \quad 0.4 - 0.8B_{ECR} \tag{4}$$

$$B_{ext} \cong B_{rad} = \quad 2B_{ECR} \tag{5}$$

where B_{inj}, B_{min}, B_{ext} are the magnetic field at the injection peak, the axial B-minimum, and the extraction peak on the ion source axis and B_{rad} the radial field at the wall of the plasma chamber, respectively. Table 1 shows the value of magnetic field based on the operating frequency for various state of the art ECR ion source as well as the technology used to build the magnets. All ECR ion sources shown in the table relies on superconducting magnet to reach the design goal. Building such magnet is very challenging for several reasons. The table shows that the peak field in the conductor is fairly high in most cases resulting in a small temperature margin while at the same time there are large Lorentz forces between the solenoid and sextupole that require good support structure to prevent slippage and conductor motion. Only one ion source is currently under construction with a goal of operating at 45 GHz for HIAF using Nb_3Sn as a conductor (FE-ECR).

Performances of ECR ion sources have improved by several order of magnitude over the last several decades and state of the art 3rd generation of ECR ion sources have gain significant maturity in their operation especially in recent years. New results continue to be presented, demonstrating that optimization of their performance is still ongoing. Table 2 shows some selected results from the ion sources in Table 1. The intensity is also compared to FRIB beam intensity requirements. The best performances are obtained at microwave power close to 8-10 kW at 28 GHz compare to 2-4 kW for ECR from previous generations operating from 14-18 GHz demonstrating the a significant gain in electronic density.

In many cases the performances shown in Table 2 exceed FRIB intensity requirements even for very high charge states. It is also interesting to note how SECRAL 1,2 and VENUS have overall very similar performances despite a very different magnet design but similar plasma parameters.

FRIB 28 GHz ECR ION SOURCE

The construction of the FRIB high performance Superconducting ECR ion source operating at 28 GHz, is progressing well. The cold mass was designed and fabricated by the Berkeley Center for Magnet Technology at the Lawrence Berkeley National Laboratory (LBNL) based on require-

Table 1: Magnetic Field Parameter for Existing, in Construction or Proposed ECR Ion Sources

Parameters	**VENUS** [7]	**FRIB-VENUS** [8]	**SECRAL** [9]	**SECRAL – II** [9]	**RIKEN SC – ECR** [10]	**MARS-F** [11]	**FE – ECR** [3]
$\omega_{RF}/2\pi$ (GHz)	28	28	24	28	28	28	45
B_{ECR} (T)	1	1	0.86	1	1	1	1.61
B_{Inj} (T)	4	4	3.7	3.7	3.8	4.1	6.5
B_{Ext} (T)	2-3	2-3	2.2	2.2	2.2	3	3.5
B_{Rad} (T)	2.1	2.1	1.83	2	2.1	2.2	3.8
B_{Min} (T)	0.4–0.8	0.4-0.8	0.4–0.8	0.4–0.8	~ 0.8		0.5-1
Superconductor	NbTi	NbTi	NbTi	NbTi	NbTi	NbTi	Nb_3Sn
Peak Field (T)	7.3 (Sext) 6.2 (Inj Sol)	6.6 (Sext) 6.15(Inj Sol)		7.8 (Sext) 7.3 (Inj Sol)	7.4 (Sext) 7.2 (Inj Sol)	5.8 ClC 5.9 (Inj Sol)	11.8 (Inj) 11.3 (Sext)
Magnet Structure	Sextupole-in-Solenoid. Radial Bladders	Sextupole-in-Solenoid. Shell based structure.	Solenoid-In sextupole	Solenoid-In sextupole	Sextupole-in-Solenoid	Closed loop coil + solenoids	Sextupole-in-Solenoid. Shell based structure.
Status	Operating (2003-Now)	In Construction	Operating (2005-Now)	Operating (2016-Now)	Operating (2010-Now)	Proposed	In Construction

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Table 2: Selected Beam intensities Obtained from State of the Art ECR ion Sources. FRIB requirement are shown in eμA and are for reaching 400 kW on the target using one charge state acceleration.

Ion	Current (eμA)	Ion Source	FRIB Requirement (eμA)
O^{6+}	6700 4750	SECRAL-2 [3] VENUS [12]	730
Ar^{12+}	1420 1060	SECRAL [3] VENUS [12]	660
Ar^{14+}	1040 840	SECRAL-2 [3] VENUS [12]	770
Ar^{18+}	15 4	SECRAL-2 [3] VENUS [12]	N/A
Ca^{11+}	710 400	SECRAL [3] VENUS [13]	540
Ca^{11+}	270	SECRAL [3]	690
Kr^{18+}	1020 770	SECRAL-2 [3] VENUS [12]	510
Kr^{28+}	146	SECRAL-2 [3]	790
Xe^{27+}	920 705	SECRAL [3] VENUS [14]	540
Xe^{30+}	365 330	SECRAL-2 [3] VENUS [14]	600
Bi^{31+}	680 300	SECRAL [3] VENUS [13]	
U^{33+}	450 202 200	VENUS [13] SECRAL [3] RIKEN [15]	433
U^{35+}	300 202	VENUS [16] RIKEN [15]	460

ments that closely followed the VENUS ECR ion source. More details on the FRIB Superconducting Ion source magnetic parameters and mechanical design can be found in other publications [7]. One of the noteworthy improvement on the magnetic design is the reduction of the peak field on the sextupole coil to 6.6 T at full excitation and to make the pole of the sextupole coil entirely of iron which provide a higher field above 2 T at the plasma chamber wall for a longer section along the longitudinal direction than the original VENUS. Another important difference with VENUS was the use of a shell-based support structure that use bladders and keys technology allowing fine tuning of the sextupole preload. An extensive mechanical analysis was done [17] to define and simulate pre-load parameter from room temperature to cool down and then to full field excitation as well as to define and control contact pressure and manage coil stress levels. This approach for magnet design is already used extensively in the development of the high luminosity upgrade of the LHC Nb_3Sn quadrupoles. In collaboration with the Institute of modern Physics (IMP) in China, a study was done recently with the same approach of using a shell based structure for the mechanical design of magnet structure suitable for operation at 45 GHz but would use Nb_3Sn conductor instead of NbTi [18].

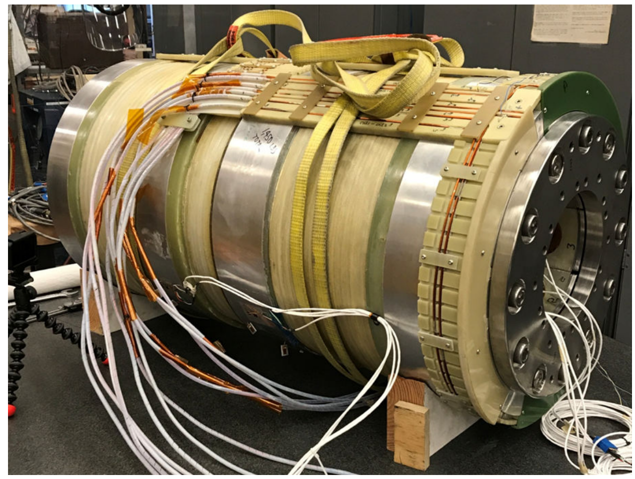

Figure 1: The completed FRIB 28 GHz SCECR coldmass assembly.

The FRIB magnet assembly was completed and tested successfully in 2017 as seen on Fig. 1. The sextupole without the solenoid coils reached the current goal of 450 A after 3 training quenches which correspond at a field of 2.1 T at the plasma chamber wall (r=71.85 mm). After excitation of the solenoids to the required current to reach a magnetic field of 4 T at injection of the ion source and 3 Tesla at extraction, the sextupole current was ramped up and reached a maximum current of 475 A or about 5% above design goal.

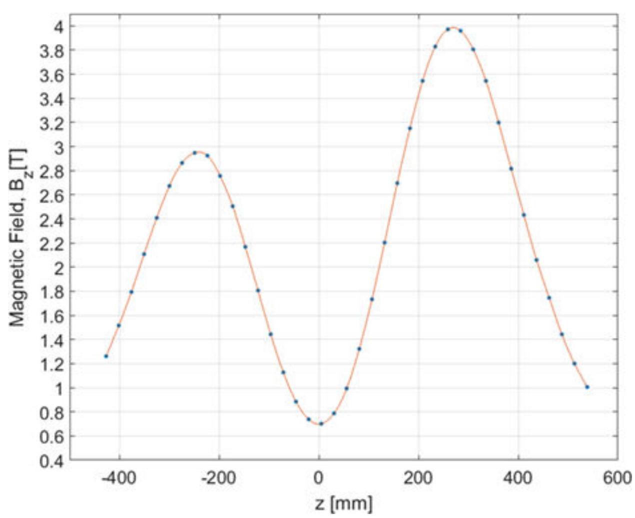

Figure 2: Axial magnetic field profile along magnet axis obtained with the sextupole at 450 A. Coils current were respectively: 215 A (Injection), 172 A (Middle), 215 A (Extraction).

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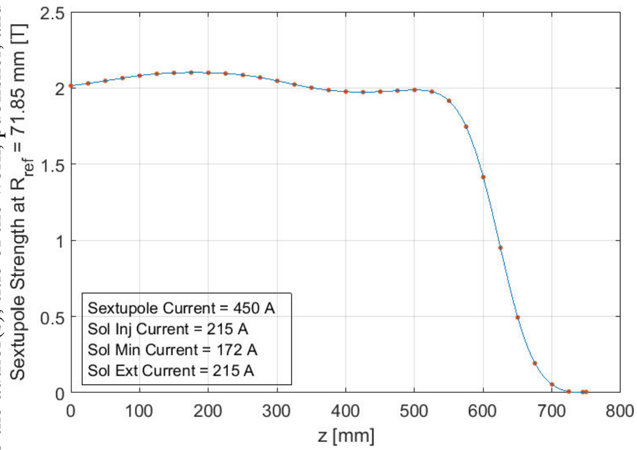

Figure 3: Radial field profile at r=71.85 mm along the longitudinal axis with a sextupole current of 450 A.

One sextupole coil had to be replaced however due to excessive training and the overall assembly was retested successfully with the new sextupole coil. This operation took advantage of the reversibility of installing bladders and keys in the magnet structure. Figures 2 and 3 show the measured field profile during final test of the magnet at LBNL. A more complete report of the magnet test can be found in [19]. The magnet was delivered to FRIB in early 2018.

After reception of the magnet and completing a set of electrical check, the magnet was mounted in the lower cryostat assembly as shown in Fig. 4, which include the helium vessel, thermal shield, vacuum vessel and the support links. Work is now shifting to integrate the upper cryostat vessel which house the cryocoolers, instrumentation, quench protection system and coil leads. The cryostat will be filled with LHe and two GM-JT cryocoolers witch each a cooling capacity of 5W will be used to remove the heat load at 4.2 K. The static heat load at 4.2 K has been calculated to reach 1.3 W with the main contribution coming from the GM-JT cryocoolers and the HTS leads but additional heat load is expected during operation from X-rays generated by the ECR plasma. Fortunately several ECR ion sources operating at 24 to 28 GHz have now clearly established that the dynamic heat load can be controlled for the most part by adjusting the Bmin of the axial magnetic field profile. The first stage of the GM-JT is not available so that the heat shield will be cooled with two independent GM cryocoolers. The Heat shield is made of Al-1100 which has a better thermal conductivity than Al-6061 that was used in the original VENUS. Calculations indicate a maximum temperature at the bottom of the lower cryostat to be about 46.5 K for a temperature of 40 K at the cryocooler head. When not in operation, heaters will be used to keep the heat load constant. The iron yoke around the cryostat has been received and installed on the HV platform. All cryostat components have been delivered and the final assembly is expected to be completed by early 2020.

The design for warm sources components including plasma chamber, injection and extraction assembly has been finalized and procurement and fabrication are also underway. The plasma chamber overall dimension are very similar to the VENUS plasma chamber with an inner diameter of 143 mm. At the thinnest the plasma chamber 1.8 mm thick with a geometry of the cooling lines that follow a spiral pattern with a specific pitch angle and channel depth. Extensive cooling calculations were made for the plasma chamber to optimize the geometry, flow rate and velocity to allow safe operation up to 9 kW. The width of the water channels has been optimized to improve the surface cooling at the expense of larger flow requirement of 5 GPM per channel. The Calculated stress has been estimated to be less than 230 MPa and a maximum temperature of 187°C on the plasma flute at the maximum power of 9 kW. The material for the plasma chamber has been selected to be Aluminum 6061-T6. During the design other aluminum alloys with higher strength at high temperature were considered but it is not clear what impact would be on the production of secondary electron. A 2mm Tungsten tube will be positioned around the outer diameter of the chamber to limit the flux of X-Rays and several layers of 5 mil thick kapton will be used for the chamber electrical insulation. The injection assembly comprise two waveguide for operation at 28 GHz and 18 GHz although initial commissioning will be done at 18 GHz. The design of the 28 GHz microwave waveguide is tapered from 32mm down to 20mm inside the plasma chamber following the recent improvement obtained with both SECRAL and VENUS. The injection end includes space for a sputtering assembly and an oven assembly. The oven assembly will either fit a low temperature cartridge oven or a high temperature resistive oven. Care was taken during the design to optimize maintenance operations. For instance to ensure a very high vacuum and simplify removal of the plasma chamber an helicoflex seal is used between the plasma and the extraction box. Also removal of the plasma chamber won't necessitate disconnection of the cooling water lines.

Figure 4: View of the FRIB SCECR lower cryostat assembly.

The high voltage platform for the 28 GHz ECR ion source is already installed and tested to 100 kV. Overall Supporting systems for the ion source are also ready including: 350 kVA/100 kV isolation transformer, Low Conductivity

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Water skid that will provide 100 GPM of cooling water to the SC-ECR on the high voltage platform. Auxilliaries equipment including racks, power supplies, Cryocoolers compressors and beamline components such as selecting magnet and electrostatic focusing triplets have been installed. The 28 GHz SC-ECR won't be needed for operation until the end of the commissioning of the FRIB linac. The SC-ECR platform is shown in Fig. 5.

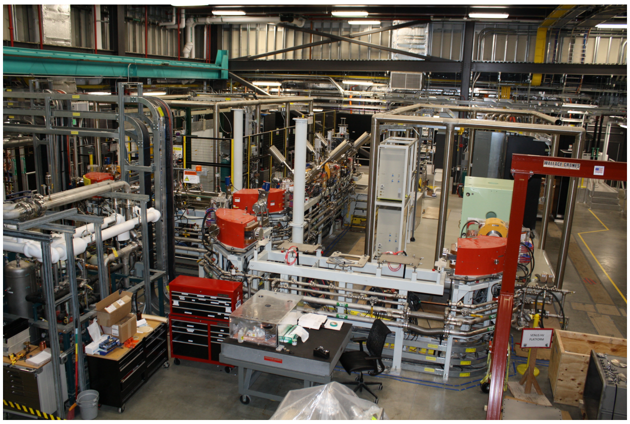

Figure 5: Layout of FRIB ECR ion sources on HV platforms. The 28 GHz source is shown at the forefront while the 14 GHz ECR ion source used for commissioning is shown at the back.

In the meantime a commissioning ion source operating at 14 GHz has been in operation for now 3 years. This source has already provided beam of Argon, Krypton, Neon and Xenon to the linac segment 1 and routinely operates at 900 W for a maximum analyzed beam of 300 eμA of Ar^{9+}.

CHALLENGES AND PROSPECTS FOR 4TH GENERATION ECRs

There are several challenges facing the design, construction and operation of the next generation of ECR ion source aiming for an excitation frequency ranging from 45 GHz to 56 GHz and beyond. The main obstacle remains primarily the construction of a magnet capable of meeting the required field. For operation at a frequency above 30 to 35 GHz, the superconductor has to change from NbTi to Nb_3Sn as the peak field in the coil would exceed the critical field at 4.2 K for NbTi. Nb_3Sn is also difficult to use for superconducting magnet as it is brittle and sensitive to stress. Unfortunately for use in an ECR, the coils also have to be clamped adequately as discussed in the previous section. Another challenge with Nb_3Sn ECR magnet is the design of the quench protection system which need to include a fast detection scheme. The FE-ECR project for HIAF is still progressing [3] and if successful will represents a very important milestone for the development of ECR ion sources at high frequency operation. Another concept developed recently is to use a closed-loop coil geometry [10] that can generate the radial field and some of the solenoidal field in one coil. Additional auxiliary solenoids are needed to reach the required axial mirror ratio but the structure allows for efficient use of the superconductor and minimize interaction forces resulting in a more compact structure and larger plasma chamber. The difficulty of this approach resides in the engineering of the closed-loop coil. Finally the use of high temperature cuprate superconductors could push ion source development to 84 GHz as reported in [20] but will require significant R&D effort.

Beside the magnet structure, one of the major engineering challenge is to design a plasma chamber suitable for operation from 10 to 20 kW CW. ECR plasma chamber are normally designed to be as thin as possible to both maximize the plasma chamber inner volume and minimize the distance from the plasma chamber wall to the coils. At the same time Aluminium remained the preferred material due to its large thermal conductivity and high secondary electron emission. However aluminium has a low melting point and a yield strength that decrease very quickly above 200°C. A thicker plasma chamber design has been proposed previously [21] but would require to either use a smaller chamber or sacrifice

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REFERENCES

[1] J. Wei *et al.*, "Advances of the FRIB project," *Int. J. Mod. Phys. E*, vol. 28, no. 3, pp. 1930003, 2019. doi:10.1142/S0218301319300030

[2] P. N. Ostroumov *et al.*, "Beam commissioning in the first superconducting segment of the Facility for Rare Isotope Beams," *Phys. Rev. Accel. Beams*, vol. 22, pp. 080101, 2019. doi:10.1103/PhysRevAccelBeams.22.080101

[3] H. W. Zhao, L. T. Sun, J. W. Guo, W. H. Zhang, W. Lu, W. Wu, B. M. Wu, G. Sabbi, M. Juchno, A. Hafalia, E. Ravaioli, and D. Z. Xie, "Superconducting ECR ion source: From 24–28 GHz SECRAL to 45 GHz fourth generation ECR," *Rev. Sci. Instrum.*, vol. 89, p. 052301, 2018. doi:10.1063/1.5017479

[4] R. Geller, "ECRIS: The Electron Cyclotron Resonance Ion Sources," *Annu. Rev. Nucl. Part. Sci.*, vol. 40, pp. 15-43, 1990. doi:10.1146/annurev.ns.40.120190.000311

[5] O. Tarvainen, T. Kalvas, H. Koivisto, V. Skalyga, I. Izotov, and D. Mansfeld, "Electron cyclotron resonance ion sources – physics, technology and future challenges", *EPJ Web of Conferences*, vol. 149, p. 01003, 2017. doi:10.1051/epjconf/201714901003

[6] D. Hitz, G. Melin, and A. Girard, "Fundamental aspects of electron cyclotron resonance ion sources: From classical to large superconducting devices," *Rev. Sci. Instrum.*, vol. 71, p. 839, 2000. doi:10.1063/1.1150308

[7] C. Taylor, S. Caspi, M. Leitner, S. Lundgren, C. M. FLyneis, D. Wutte, and S. T. Wang, "Magnet system for an ECR ion source," *IEEE Trans. Appl. Supercond.*, vol 10, no. 1, pp. 224 - 227, 2000. doi:10.1109/77.828215

ISBN: 978-3-95450-223-3 ISSN: 2673-7000 doi:10.18429/JACoW-NAPAC2019-MOYBB2

[8] H. Felice, E. Rochepault, R. Hafalia, S. Caspi, D. R. Dietderich, S. O. Prestemon, G. Machicoane, E. Pozdeyev, N. Bultman, and X. Rao, "Design of a Superconducting 28 GHz Ion Source Magnet for FRIB Using a Shell-Based Support Structure," *IEEE Trans. Appl. Supercond.*, vol 25, no. 3, p. 4101405, 2015. doi:10.1109/TASC.2014.2377730

[9] L.T. Sun *et al.*, "SECRAL II Ion Source Development and the First Commissioning at 28 GHz," in *Proc. ECRIS'16*, Busan, Korea, Aug. 2016, pp. 43–47. doi:10.18429/JACoW-ECRIS2016-TUAO04

[10] T. Nakagawa *et al.*, "First results from the new RIKEN superconducting electron cyclotron resonance ion source," *Rev. Sci. Instrum.*, vol. 81, p. 02A320, 2010. doi:10.1063/1.3259232

[11] D. Z. Xie, J. Y. Benitez, A. Hodgkinson, T. Loew, C. M. Lyneis, L. Phair, P. Pipersky, B. Reynolds, and D. S. Todd, "Development status of a next generation ECRIS: MARS-D at LBNL," *Rev. Sci. Instrum.*, vol. 87, p. 02A702, 2016. doi:10.1063/1.4931713

[12] D. Xie, J. Y. Benitez, C. M. Lyneis, D. S. Todd, and W. Lu, "Recent production of intense high charge ion beams with VENUS," in *Proc. ECRIS'16*, Busan, Korea, Aug. 2019, pp. 142–146, 2019. doi:10.18429/JACoW-ECRIS2016-THAO01

[13] J. Y. Benitez, K. Y. Franzen, C. M. Lyneis, L. Phair, and M. M. Strohmeier, "Current Developments of the VENUS Ion Source in Research and Operations," in *Proc. ECRIS'12*, Sydney, Australia, Sept. 2012, pp. 153-158, paper THXO02, 2012.

[14] D. Xie, Private communication.

[15] T. Nakagawa, Private communication.

[16] G. Machicoane, N. K. Bultman, G. Morgan, E. Pozdeyev, and X. Rao, "Design Status of ECR Ion Sources and LEBT for FRIB," in *Proc. ECRIS'12*, Sydney, Australia, Sept. 2012, pp. 172-176, paper THYO03, 2012.

[17] Heng Pan *et al.*, "Mechanical Study of a Superconducting 28-GHz Ion Source Magnet for FRIB," *IEEE Trans. Appl. Supercond.*, vol. 29, no. 5, p. 4100706, 2019. doi:10.1109/TASC.2019.2901589

[18] M. Juchno, A. Hafalia, W. Lu, E. Ravaioli, G. L. Sabbi, L. T. Sun, W. Wu, D. Xie, H. W. Zhao, "Mechanical Design of a Nb_3Sn Superconducting Magnet System for a 45 GHz ECR Ion Source," *IEEE Trans. Appl. Supercond.*, vol. 28, no. 3, p. 4602806, 2018 doi:10.1109/TASC.2017.2773832

[19] D. Arbaelez *et al.*, "Test Results for a Superconducting 28-GHz Ion Source Magnet for FRIB," *IEEE Trans. Appl. Supercond.*, vol. 29, no. 5, p. 4100605, 2019. doi:10.1109/TASC.2019.2898595

[20] D.Leitner, "High Performance ECR Sources for Next-Generation Nuclear Science Facilities," in *Proc. IPAC'19*, Melbourne, Australia, May 2019, pp. 2224–2229, 2019. doi:10.18429/JACoW-IPAC2019-WEXPLS1

[21] T. Thuillier, J. Angot, J. Y. Benitez, A. Hodgkinson, C. M. Lyneis, D. S. Todd, and D. Z. Xie, "Investigation on the electron flux to the wall in the VENUS ion source," *Rev. Sci. Instrum.*, vol. 87, p. 02A736, 2016. doi:10.1063/1.4935989