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FECR ION SOURCE DEVELOPMENT AND CHALLENGES*

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Abstract

FECR or the First 4th generation ECR (Electron Cyclotron Resonance) ion source is under development at Institute of Modern Physics (IMP) since 2015. This ion source is aiming to extract intense highly charged heavy ion beams in the order of 1 emA from the dense plasma heated with 45 GHz microwave power. To provide effective magnetic confinement to the 45 GHz ECR plasma, a state of the art Nb_3Sn magnet with min-B configuration is a straightforward technical path. As there are no much precedent references, it has to be designed, prototyped at IMP through in-house development. Meanwhile, other physics and technical challenges to a 4th generation ECR ion source are also tackled at IMP to find feasible solutions. This paper will give a brief review of the critical issues in the development of FECR ion source. A detailed report on the status of FECR prototype magnet development will be presented.

INTRODUCTION

Heavy ion accelerators are the most powerful tools in modern nuclear physics research. Driven by the needs of large scale heavy ion accelerators, such as FRIB at MSU, RIBF in RIKEN, HIRFL at IMP and so on, ECR ion sources have been continuously supported and improved. The recently started national basic science research project called HIAF or High Intensity heavy ion Accelerator Facility in Huizhou [1], which is composed by high performance superconducting ECR ion sources, SRF (Superconducting Radio Frequency) linac, BRing (Booster synchrotron Ring), HFRS (High energy FRagment Separator) and SRing (Spectrometer synchrotron Ring), will accelerate and accumulate 1×10^{11} ppp U^{35+} of 800 MeV/u in BRing (Fig. 1). For this goal, the injector linac iLinac needs to deliver U^{35+} beam with a beam intensity of ~1 emA at the energy of 17 MeV/u. Consequently, the room temperature front end part will be able to produce and deliver high intensity U^{35+} beams. A 70% efficiency is estimated to transport the intense U^{35+} with high quality to iLinac, and as a result ~40 pμA U^{35+} is literally needed for routine operation if the peak performance of HIAF is desired. Given some margin, the ion source should be able to produce 50 pμA U^{35+} when fully optimized to guarantee the routine operation performance.

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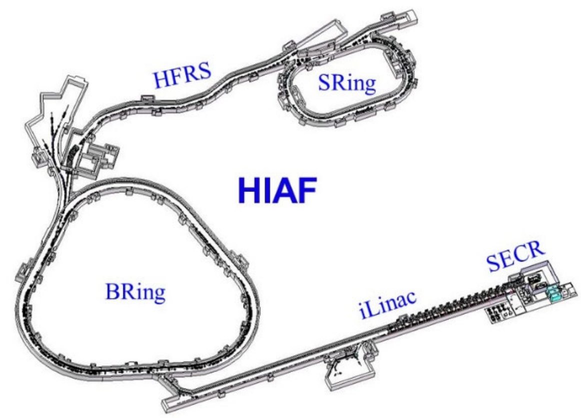

Figure 1: Schematic layout of HIAF.

Modern ECR ion sources with the 3rd generation sources as the iconic machines have been built since 20 years ago. Heated by the microwave of 24~28 GHz and 10 kW maximum power, these sources such as VENUS in LBNL, SCECRIS in RIKEN, SuSI at MSU, SECRAL at IMP and so on, can produce (or potentially) U^{3x+} ion beams of the intensity 10~15 pμA which is more than 10 times the recodes set 20 years ago. But to meet the needs of HIAF, the performance still needs to be boosted by a factor of 3~4. As ECR ion source development is mainly governed by the scaling of $I_q \propto \omega_{ecr}^2$, the straightforward technical path is to develop a 4th generation machine. FECR ion source, which is one of the key components of the LEAF (Low Energy heavy ion Accelerator Facility) project [2], will prototype the first 4th generation ECR ion source in the world.

FECR

The 4th generation ECR ion source concept was proposed more than 10 years [3] when several 3rd generation ECR ion sources had been constructed but seemed to be saturated in performance, which was still not up to the requirements of next generation heavy ion accelerators. FECR ion source is one of the next generation ECR ion sources following the 4th generation concept, which is aiming to be operated the microwave frequency of 45 GHz that can fundamentally increase the ECR plasma density by a factor of 2~3. Table 1 gives the typical design features of FECR. As is mentioned in the table, with the increase of the microwave frequency, the key parameters of the ion source in comparison with a 3rd generation ECR have been obviously changed, which will give the challenges and difficulties in ion source development.

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Table 1: Typical Design Features of FECR

Spec.	Unit	FECR	3rd G ECR
ω_{rf}	GHz	45	24/28
RF power	kW	⩾20	~10
Chamber ID	mm	≥Ø140	Ø100~150
Mirror Fields	T	6.4/3.5	~4/2.8
B_{rad}	T	3.2	1.8~2.2
L_{mirror}	mm	500	420~500
B_{max} in conductor	T	~11.8	~7
Conductor	/	Nb_3Sn	NbTi
T_s	keV	80~100	50~60
$(Ne)_{crit}$	cm^{-3}	$\sim 2.6\times 10^{13}$	$\sim 1\times 10^{13}$
Max. drain	mA	~50	~20

CHALLENGES

To make an operational 45 GHz ECR ion source, FECR has many challenges. As given in Table 1, the key parameters of the ion source will have obvious changes, which might give fundamental impact to the ion source structure or operation conditions. The main expected challenges are given in the following discussions.

Nb_3Sn Magnet

Sextupole Coil Production. A wind and react approach is used in the fabrication of the FECR coils. There are many successful examples of high field solenoids with Nb_3Sn wire, but in terms of sextupole, no much successful information could be the references. The main challenges lie in the precise winding of more than 800 turns single strand in a saddle-like configuration. To have high standard electrical insulation (3~5 kV) of the coil, no damage in the S-glass braided material is allowed during the winding. After successful winding, winded coil will be sent to a programmable oven for heat treatment where the wire will turn into Nb_3Sn conductor. To achieve high quality of electrical insulation and also high RRR value of the superconductor, decarbonization process is mandatory. Finally, the coil will be put in a tooling for Vacuum Pressure Impregnation (VPI) to form the final configuration and more importantly to strengthen the coil and improve the electrical insulation property. To meet the needs of precise installation with bladder and key technology, the 860 mm length sextupole coils should be eventually prepared within a tolerance of ±100 µm.

Cold Mass Structure. There will be complicated forces between the coils. For a 3rd generation ECR ion source, it has already been a big challenge. For FECR, this interaction forces will be more than doubled. Efficient pretension and clamping of all the coils will be the highest priority in the structure design. FECR cold mass design also adopted the state-of-the-art bladder and key technique. The explosive view of FECR cold mass is given in Fig. 2.

Quench Protection. FECR will have totally ~1.6 MJ stored energy at 100% energized currents. Fast and safe extraction of the stored energy when the magnet quenches is crucial. However, compared to NbTi, Nb_3Sn has much slower quench propagation speed that makes fast quench detection and energy extraction more stringent. Passive quench protection widely used on 3rd generation devices is not suitable to FECR. Figure 3 gives the hot-spot temperature for one of the FECR coils. Active quench protection system adaptable to FECR should be developed.

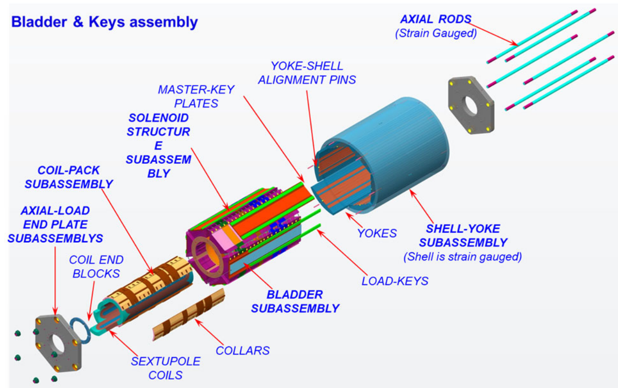

Figure 2: FECR cold mass structure.

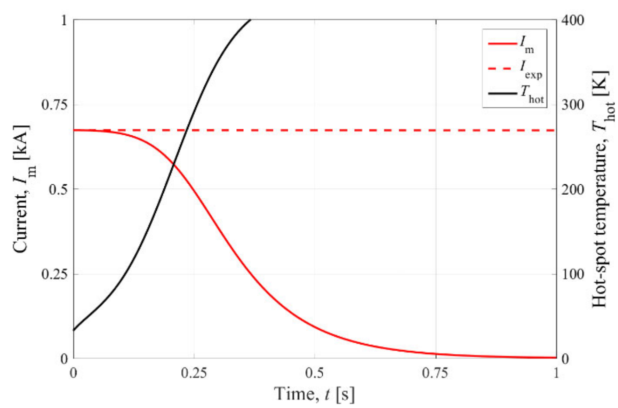

Figure 3: Hot-spot temperature estimation with passive quench protection scheme for one injection solenoid.

Cryogenic System. FECR has a 3.5 tons cold mass. To accommodate it and make it work safely at 4.3 K (liquid helium temperature), many issues should be handled. Radial field homogeneity is very essential for a high performance ECR ion source. Misalignment of the cold mass will possibly cause thermal shortage inside the cryostat, and more importantly, the inhomogeneous radial field on the plasma chamber wall will result in much weaker total magnetic field and consequently much heavier localized heating by plasma flux leakage. Additionally, for efficient energy extraction, active quench protection will use 0.5~2.0 Ω dump resistor which will excite high voltages in the coil circuits. For FECR, a highest voltage of ~1 kV will be seen during the quench energy extraction at 100% design currents [4], which needs a very robust solution to the electrical insulation in the cryostat design and fabrication. Last but not least, much more dynamic heat load is expected to be dumped to the cold mass, and high dynamic cooling capacity is needed at 4.2 K to avoid the loss of boiling-off liquid helium.

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Conventional ECR Parts

20 kW/45 GHz Microwave Coupling. As 45 GHz microwave has a wave length of ~6.7 mm, transmission and coupling of high power microwave to ECR plasma may have the potential risk of arcing inside the circular waveguide. Quasi-optical transmission in air from the generator to the microwave window, and then converted to oversized waveguide after the microwave window is proposed and successfully tested at IMP on the SECRAL-II test bench (Fig. 4). This has basically solved the problem of high power transmission and coupling to ECR ion source. However, the efficient coupling to an ECR plasma in terms of highly charged ion production remains unclear, which needs the real test with FECR. Additionally, in recently years several laboratories have demonstrated that multi-frequency heating is essential to stabilize the plasma when the ion source is fed with high power microwave for highly charged ion beam production. For FECR, it is still hard to make a choice in the auxiliary plasma heating frequency. As a baseline, 45 GHz/20 kW + 28 GHz/10 kW will be applied.

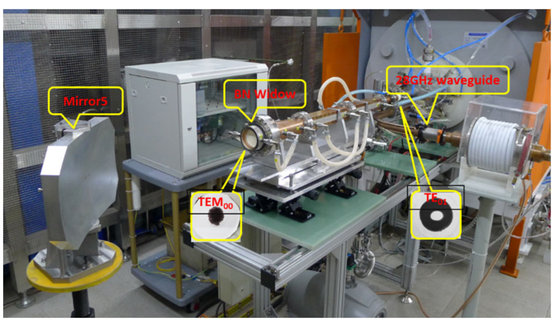

Figure 4: SECRAL-II test bench with 45 GHz microwave coupling system.

Reliability and Stability at 20 kW/45 GHz. Once high power density plasma is built, there will be many challenges. The critical one is the efficient plasma chamber cooling. Many laboratories had the experience of damaged plasma chambers by localized overheating of escaped plasma flux. According to the estimation by T. Thuillier in his paper [5], the peak power sink on the inner wall of plasma chamber can reach to 1.25 MW/cm^2 for 1 kW 28 GHz microwave heating that will cause instant boiling of the cooling water at the weak |B| area on the plasma chamber at high power level. Created bubbles will prevent further cooling with flowing water and plasma chamber damage will happen when chamber material starts to degrade at high temperature. Normally, this damage is an instant process once the heated microwave power reaches the critical value of the chamber (magnetic field configuration, plasma stability also have influences). At 45 GHz, we might face much higher plasma flux density for every kW microwave power launched. Most of the existing plasma chamber can barely take long-time operation at the power level of 10 kW. It is a big challenge for FECR to work at 20 kW/45 GHz.

Strong Bremsstrahlung Radiation. Strong bremsstrahlung radiation is an iconic characteristic of highly charged ECR ion source, which is an evidence of the existence of energetic electrons inside the plasma. For superconducting ECR ion source, this radiation will give additional heat sink to the cryogenic system as mentioned in the former section. This radiation will also cause the degradation of electrical insulators. High voltage (HV) main insulators have been damaged with many 2nd or 3rd generation ion sources. More energetic and dense electrons will be created inside FECR plasma, and the damage to the main insulator column will be devastating. Another possible risk is the radiation to the Nb_3Sn coils. As Nb_3Sn coils have strict requirement on electrical insulation property. Any degradation in the epoxy insulation will affect the performance and even the normal operation of the coils.

Intense Beam Extraction. 3rd generation ECR sources have produced highly charged beams with a total current of 15~20 emA that is 2~3 times the total current from a high performance 2nd generation ECR ion source. FECR is expected to be able to extract 30~50 emA total beam that will raise the challenges in beam extraction, transport and quality control.

Intense Refractory Ion Beam Production. Intense uranium beam is highly desired in most of the heavy ion accelerator laboratories. High temperature oven remains the baseline solution to highly charged intense uranium beam production, despite the sputtering method has also been regarded as an efficient technology in the production of 100 eμA U^{3x+}. As metal uranium is chemically reactive to most crucible materials, UO_2 is favoured for oven application, which needs ~2000°C for intense beam production. At such a high temperature, Lorentz forces, material degradation (or chemical reaction), and thermal stress constitute the challenges in high temperature oven technique. Other than uranium beams, intense beam production of Th, W, Mo, Ca, and so on is also of high challenge with regards to production efficiency and high charge state.

STATUS REPORT

Many research activities oriented to the afore mentioned challenges have been made. In this paper, several typical processes are presented.

FECR Prototype Cold Mass

To validate the cold mass design of FECR, a 1/2 length prototype has been proposed and developed [5]. This prototype is mainly composed by 6 sextupole coils and 2 axial solenoids, which can demonstrate the Nb_3Sn coil fabrication technique, cold mass structure, quench protection and cold mass integration technologies. By the end of August 2020, the prototype cold mass has been developed and recently tested for the 1st round. The prepared prototype cold mass is shown in Fig. 5. In the cold test, we energized the solenoid and sextupole individually. The solenoid was energized to 100 % design current of 600 A without a quench, and the sextupole was energized to 90% design current of 671 A without a quench. But during the training study, we found flux jump signal interference and the power supply stability are problems for stable operation and fast, accurate quench detection.

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Figure 5: Picture of completed FECR 1/2 size prototype cold mass ready for test.

Cryogenic System

An engineering design of the FECR cryogenic system has been made recently based on the final structure design of the cold mass. This cryogenic system will provide the LHe operation condition for the 3.5 tons cold mass. Cold alignment with the assistance of on-line field mapping is enabled in the cryostat design. The typical features of FECR cryogenic system is given in Table 2. The choice of the cryocoolers is specified. As given in Table 3, a combination of 1 CH-110 and 3 RDE-418D4 coolers from Sumitomo Inc., and 3 KDE422 coolers from CSIC Pride (Nanjing) Cryogenic Technology Co., Ltd. has been adopted.

Table 2: Cryogenic System Parameters of FECR

Parameters	Value
Operation Temp. (K)	4.3
Magnet Cooling	LHe bathing
Stored Energy (MJ)	~1.6
Required dynamic cooling capacity (W)	≥12
Warm bore ID (mm)	Ø162
LHe volume (liter)	~330
Dimension (mm)	L1456×Ø1200×H2690
Total weight (ton)	~6.1

Table 3: Cryocoolers for FECR

Model	1st Stage	2nd Stage
CH-110	~130 W@50 K	N/A
KDE-422	~20 W@50 K	≥2.2 W@4.2 K
RDE-418D4	~42 W@50 K	≥1.8 W@4.2 K
Total	~316 W@50 K	≥12 W@4.2 K

High Power Operation

Traditional double-wall water cooling aluminium plasma chamber can only safely work at the ECRH microwave power level of 7~8 kW of 24~28 GHz. A recent breakthrough in plasma chamber design by utilizing a microchannel technology can fundamentally improve the cooling capacity of the plasma chamber. In the recent online test, a total power of 11 kW has been fed into the newly developed plasma chamber installed on SECRAL-II. After 48 hours continuous 11 kW operation, the plasma chamber survived and stable highly charged ion beams are also produced, such as >100 eμA Xe^{34+}. This can't guarantee the safe operation at 20 kW/45 GHz, but is a good baseline for the FECR ion source plasma chamber design.

High Temperature Oven

Enlighted by the successful inductive heating oven (IHO) developed at MSU for the reliable operation under 1800°C, a refined IHO has been recently developed at IMP. With several modifications in the oven structure and material design, this oven can work stably up to 2000°C. Recently, this oven has been used to produce intense uranium beams. At 6 kW/24 GHz, 450 eμA U^{33+} was produced and more importantly the oven survived the one-week high temperature operation [6], which gave us confidence in developing reliable high temperature oven for FECR.

Dynamic Heat Load

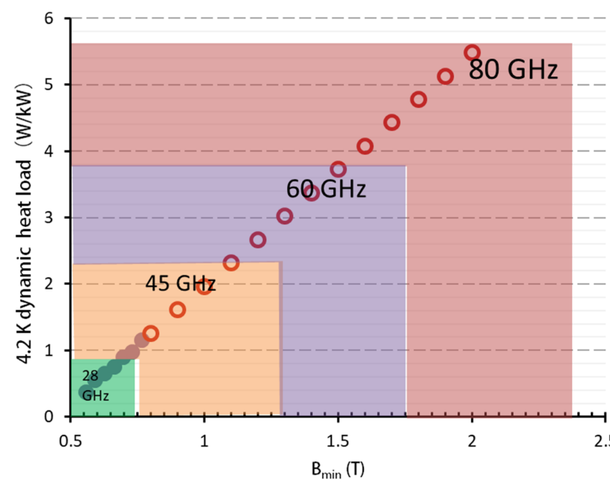

Figure 6: Estimated dynamic heat load to the 4.3 K cryogenic system at different operation B_{min}.

Dynamic heat load to the 4.2 K cryogenic system is mainly caused by the high energy electron bremsstrahlung radiation as most of the existing 3rd generation ECR ion sources have used 1~2 mm Ta shielding that could easily prevent the X-ray of <200 keV from penetration to the cryogenic system. The experimental results from SECRAL-II indicate the dynamic heat load could reach 0.6~1.0 W/kW at 24~28 GHz when B_{min} was set in the range of 0.6~0.7 T, ~0.7 of B_{ecr}. It has been accepted by the community that high temperature electron spectra temperature T_s increases linearly with B_{min} before the cyclotron instability is triggered at B_{min}/B_{ecr}~0.8. For FECR, it will be operated at the B_{min} of 0.9~1.1 T. As illustrated in Fig. 6, 1~2 W/kW dynamic heat load is predicted for FECR which means the cryogenic system will have a total dynamic heat load of 20~40 W during CW operation, which is much beyond the ~12 W design value. Before we can find better solutions, one compromised plan is to lower the operation duty factor by pulsing the microwave power when > 10 kW operation is desired.

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SUMMARY

FECR project was officially started in 2015. After 5 years continuous development, we have tackled most of the envisioned challenges. Most of them have got fundamental progresses recently, but there are still many open questions. To develop an operational FECR ion source, there are still many challenges ahead. According to the updated project plan, FECR assembly is about to be ready in 2021. That will be time to check the feasibility and reliability of our designs towards a high performance 45 GHz ECR ion source.

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We acknowledge the fruitful collaboration work on FECR cold mass design between ATAP/LBNL and IMP. The collaboration with RIKEN ion source group on high temperature oven development is appreciated. We are also graceful that so many people from our community and outside of our community have given us suggestive advice. We thank all the commercial vendors who have been supporting us in this challenging research.

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