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STATUS OF THE HIAF ACCELERATOR FACILITY IN CHINA*

L. J. Mao, J. C. Yang†, D. Q. Gao, Y. He, G. D. Shen, L. N. Sheng, L. T. Sun, Z. Xu, Y. Q. Yang, Y. J. Yuan and HIAF project team, IMP CAS, Lanzhou, China

Abstract

The High Intensity heavy-ion Accelerator Facility (HIAF) is under constructed at IMP in China. The HIAF main feature is to provide high intensity heavy ion beam pulse. A rapid acceleration in the booster synchrotron ring (BRing) with the ramping rate of 12 T/s is used. The challenges are related to the systems injector, RF cavities, power supplies, vacuum, magnets, etc. Works on key prototypes of the HIAF accelerator are ongoing at IMP. In this paper, an overview of the status and perspective of the HIAF project is reported.

INTRODUCTION

The High Intensity heavy-ion Accelerator Facility (HIAF) is a new accelerator under construction at the Institute of Modern Physics (IMP) in China [1]. It is designed to provide intense primary heavy ion beams for nuclear and atomic physics. The facility consists mainly of a superconducting electron-cyclotron-resonance (SECR) ion source, a continuous wave (CW) superconducting ion linac (iLinac), a booster synchrotron (BRing) and a high precision spectrometer ring (SRing). A fragment separator (HFRS) is also used as a beam line to connect BRing and SRing. Six experimental terminals will be built in phase-I at HIAF. The layout of the HIAF accelerator was shown in Fig. 1. The main parameters are listed in Table 1.

The construction of the HIAF project was started officially in December 23rd, 2018. Up to now, roughly 50% of civil construction is finished. The first component of SECR is planned to equip in the tunnel in the middle of 2022. The first beam will be accelerated at BRing in the middle of 2025. A Day-one experiment is proposed before the end of 2025. A brief time schedule of HIAF construction is shown in Fig. 2.

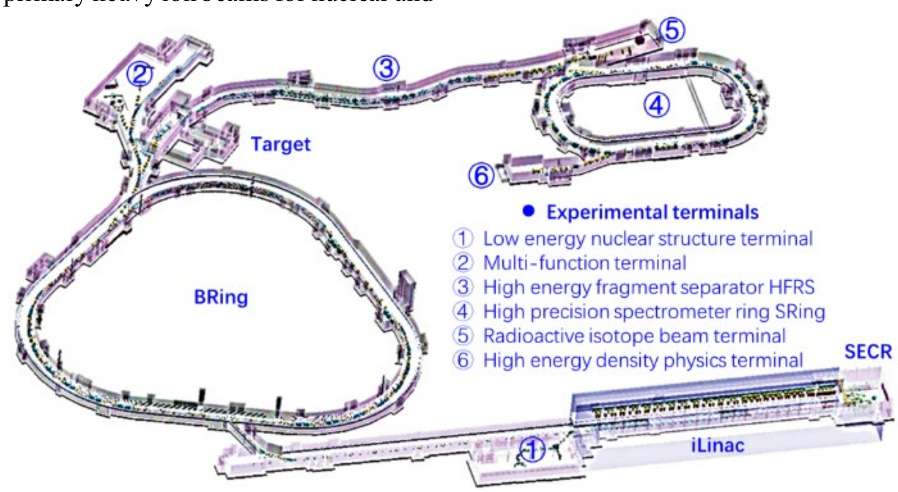

Figure 1: Layout of the HIAF project.

Table 1: Main Parameters of the HIAF Accelerators

	SECR	iLinac	BRing	HFRS	SRing
Length / circumference (m)	---	114	569	192	277
Final energy of U (MeV/u)	0.014 (U^{35+})	17 (U^{35+})	835 (U^{35+})	800 (U^{92+})	800 (U^{92+})
Max. magnetic rigidity (Tm)	---	---	34	25	15
Max. beam intensity of U	50 pμA (U^{35+})	28 pμA (U^{35+})	10^{11}ppp (U^{35+})		10^{10}ppp (U^{92+})
Operation mode	DC	CW or pulse	fast ramping (12T/s, 3Hz)	Momentum-resolution 1100	DC or deceleration
Emittance or Acceptance (H/V, π·mm·mrad, dp/p)		5 / 5	200/100, 0.5%	±30mrad(H)/±15 mrad(V), ±2%	40/40, 1.5%, normal mode

Currently, most of the prototypes related to the HIAF technical challenges have being manufactured or tested. In this paper, the status and perspectives of the HIAF project are presented. The developments and test results of hardware are reported.

* Work supported by the National Development and Reform Commission, China
† yangjch@impcas.ac.cn.

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2019	2020	2021	2022	2023	2024	2025
Civil construction						Day One exp.
		Electric power, cooling water, compressed air, network, cryogenic, supporting system, etc.				
ECR design & fabrication		SECR installation and commissioning				
	Linac design & fabrication		iLinac installation and commissioning			
Prototypes of PS, RF cavity, chamber, magnets, etc.			fabrication	BRing installation & commissioning		
				HFRS & SRing installation & commissioning		
			Terminals installation			

Figure 2: Time schedule of the HIAF construction.

ION SOURCE

Pulsed 50 pμA (~1 ms) U^{35+} ion beam from SECR is required in the HIAF project, which is 5 times higher than the present records of the 3rd generation ECR ion source. It can only be met by sources operating at higher magnetic field and microwave frequency. SECR incorporates with a Nb_3Sn high field superconducting magnet and a quasi-optical 45 GHz gyrotron microwave system, as shown in Fig. 3. The main parameters are listed in Table 2. The biggest challenge lies in the design and fabrication of the Nb_3Sn magnet. A promising cold mass design has been completed by a collaboration with LBNL, as shown in Fig. 3. Up to now, a 1/2 cold-mass prototypes related to critical technologies have be fabricated and tested. The full-sized cold-mass completion is scheduled in 2020 [2].

Table2: Typical Parameters of SECR

Specs.	**Unit**	**SECR**
Frequency	GHz	45
RF power	kW	20
Chamber ID	Mm	>Φ140
Mirror fields	T	≥6.4/3.2
B_{rad}	T	≥3.2
B_{max} in conductor	T	11.8
Magnet coils	---	Nb_3Sn
Cooling capacity at 4.2 K	W	>10

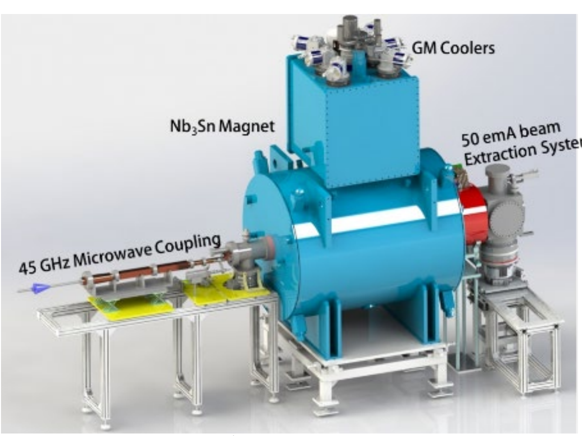

Figure 3: the 4th generation ion source SECR.

The microwave power transmission coupling and ECR heating are critical issues. Based on the present ion source SECRAL-2 at IMP, a study with a 45 GHz gyrotron microwave system by GYCOM Ltd was reported [3]. The transmission lines combined quasi-optical mirror and wave guide mode converter are manufactured. The 45 GHz microwave power at TE_{01} mode has been fed into SECRAL-2 and got the first stable 45 GHz ECR plasma and Xenon beam.

LINAC INJECTOR

The iLinac is used as the injector of BRing and the main accelerator for the low energy nuclear structure terminal. That's why a CW superconducting linac is proposed in HIAF. Two types of accelerating structures in 17 cryomodules are used to achieve the energy of 17 MeV/u for U^{35+} ion beam. The first 6 cryomodules with QWR007 cavities is used to accelerate U^{35+} ions to 5.4 MeV/u. The rest cryomodules are installed with HWR015 cavities. These cavities will be made based on the experience of the CiADS project. A layout of iLinac is shown in Fig. 4. LEBT, RFQ and MEBT locate between SECR and iLinac.

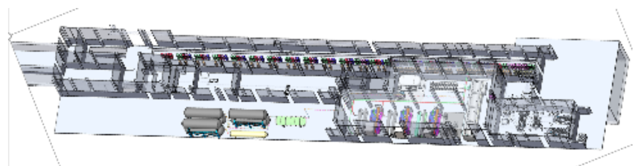

Figure 4: 3-D view of iLinac. SECR locates on left side. The physical design has been finished.

BOOSTER SYNCHROTRON

BRing is the key component of the HIAF project. It is designed with a maximum magnetic rigidity of 34 Tm, which is intended for the storage of U^{35+} ions to an intensity of 2×10^{11} particles with the energy of 835 MeV/u. The BRing lattice and its beta function and dispersion function is shown in Fig. 5. The ionization processes with residual gas particles is the main issue with respect to potential beam loss. Therefore, the lattice design is to localize the beam loss at certain positions to install collimators. It has a three-folding symmetry lattice with DBA (double bend achromat) structure. BRing offers a transverse acceptance of 200 / 100 π·mm·mrad to overcome space charge limits of high intensity beams. It is operated below the transition energy to avoid beam loss by transition-energy crossing [4].

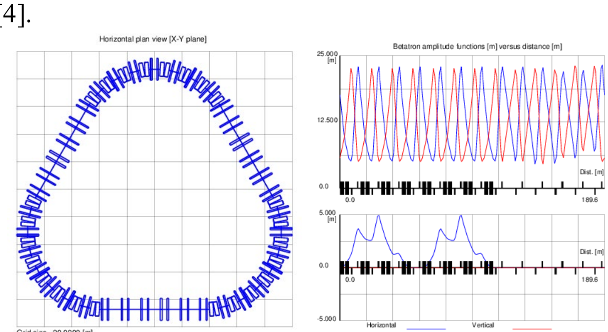

Figure 5: Bring lattice structure and its beta function and dispersion function (one cell).

The present currents reached from the high current source and linac need no stacking by the electron cooling. To obtain a high average beam intensity and avoid space charge limits, transverse phase space painting (4-D) is im-

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plemented for beam accumulation and a rapid ramping cycle is used to reduce the integral ionization cross section. Related prototypes as tilted electrostatic septum, ceramic-lined thin-wall vacuum chamber, fast-cycling power supply and magnetic alloy (MA) acceleration cavities are developed for BRing.

Transverse Phase Space Painting Injection

In the 4-D painting injection scheme, the closed orbit is moved with the horizontal and vertical injection bumps as functions of time. Unlike the injection using charge exchange implemented in proton machine (SNS, J-PARC), a tilted corner septum is used for both transverse phase places simultaneously injection in BRing. Low-loss and low phase space dilution are basic requirements. Injection begins with both horizontal and vertical bump close to the centroid of injection beam, and then gradually move away from it. Both the horizontal and vertical emittance are painted from small to large [5]. Figure 6 shows the particle invariant distribution at the end of injection and its evolution up to 1000 turns. The simulation is performed with U^{35+} ions at the injection energy of 17 MeV/u. The total emittance and momentum spread of iLinac beam are 5 $\pi\cdot$mm$\cdot$mrad and ±0.2%, respectively. The space charge effect is included in the simulation. Due to a small gap between the closed orbit and the injection point, the injection efficiency is small at the beginning. A "hollow" beam in horizontal and vertical phase space is obtained after the injection. However, such a beam profile is susceptible to transverse coupling due to space charge forces in simulation. Finally, the particle emittance reaches a Gaussian-like distribution in both phase spaces.

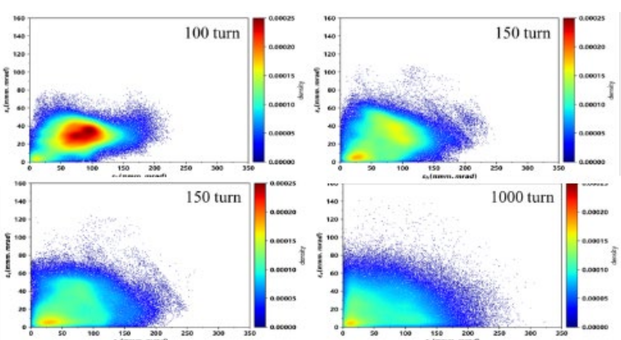

Figure 6: particle invariant distribution after 4-D painting injection.

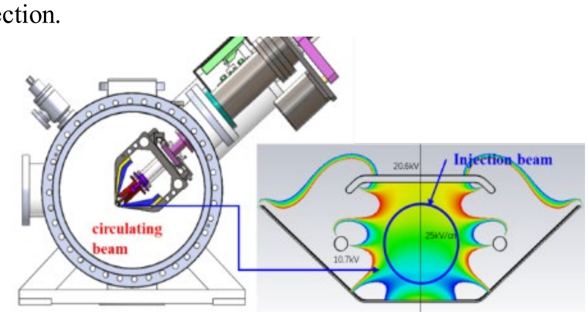

Figure 7: Corner septum cross section and its field map.

A corner electrostatic septum is used to deflect the injection beam to the closed orbit, as shown in Fig. 7. The septum wire with the thickness of 0.1 mm is tilted by 40° to combine the horizontal and vertical injection. To reduce beam loss on the wire, a U-like shape anode is designed. The anode together with two auxiliary electrodes are used to optimize the electric field for injection beam. The field homogeneity better than 5% is achieved in the injection region.

Fast Ramping

Since the cross sections of ionization are decreasing significantly with ion energies, the integral cross section can be kept very small with a fast ramping rate. Rapid accelerating was proposed and tested at SIS18 in 2005, shown an optimistic result for minimum beam loss and dynamic vacuum effect. In BRing, a ramping rate of 12T/s is needed for optimising the space charge limits and collimators. Therefore, a dipole power supply with a rate of 38 kA/s and maximum current of 4 kA is desired. One power supply can be used for 4 dipoles connected in series and 12 groups are needed in BRing. A full-energy storage technology is developed to reduce its power consumption. The analytic modelling optimal control with kinetic inductance fine turning method is used in the control system, to improve the precision of current ramping. A prototype was already tested at IMP. The maximum current of 5.1 kA was obtained in a solenoid load with the ramping rate of 40 kA/s, as shown in Fig. 8. The output current average tracking error is around 5×10^{-4}, which meets the requirements of BRing. Next, the prototype will be tested with BRing dipoles, to study its properties in operation.

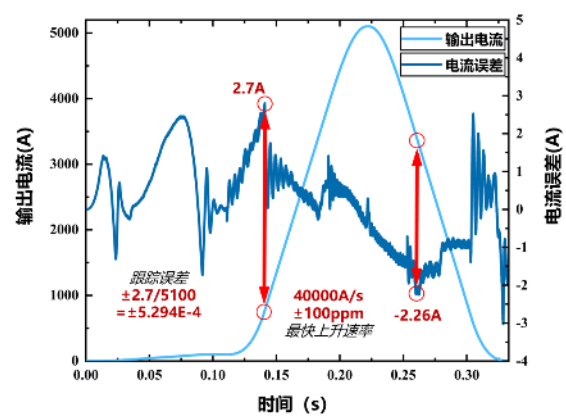

Figure 8: current curve of fast ramping power supply.

High accelerating voltage up to 240 kV is used in the fast ramping of BRing, which will be provided by new MA acceleration cavities. The quality factor (*Q value*) is set at 0.45 to cover a wide frequency range of 0.3 to 2 MHz. A typical acceleration process of $^{78}Kr^{19+}$ is shown in Fig. 9. There are four stages. The first capture stage is used to capture the coasting beam after 4-D multi-turn painting injection. Usually two or even more bunches are obtained in the first capture stage, since a high harmonic should be used at such low injection energies. At the acceleration stage, the maximum ramping rate is 12 T/s, corresponding to the maximum RF voltage of 240 kV. At the de-bunching stage, the RF voltage decreases to zero rapidly, a coasting beam is obtained again in BRing. Two extraction schemes are designed in BRing. The slow extraction mode starts at the end

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of de-bunching. In the fast extraction mode, additional second capture stage is needed, to make only one bunch in BRing. the extraction starts at the end of the second capture stage.

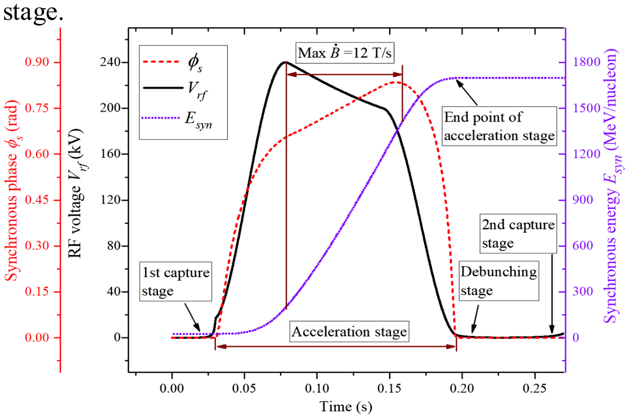


Figure 9: Corner septum cross section and its field map.

The fast ramping of the magnets induces eddy currents in the vacuum chamber wall, which could make a distortion of magnetic field. Ceramic-lined thin-wall vacuum chamber is a good solution to reduce the eddy current effect. A stainless steel with the thickness of 0.3 mm is used for the BRing vacuum chamber. To withstand the atmospheric pressure, the thin wall vacuum chamber is supported by ceramic rings inside. The ceramic rings are made by yttrium stabilized zirconia, which has very good mechanical strength and toughness. the ceramic rings are coated with a 1 µm Au film to reduce the beam impedance and the desorption rate of the ceramic surface. Compared to the similar chamber with reinforced ribs, the gap size of the dipole decreases significantly. A prototype of 3 m length dipole chamber has been tested, as shown in Fig. 10. The pressure is about 1.07×10^{-9} Pa, which basically meets the BRing requirement.

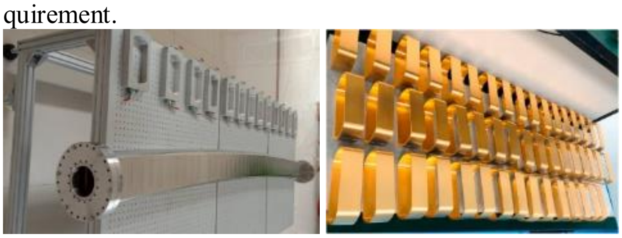
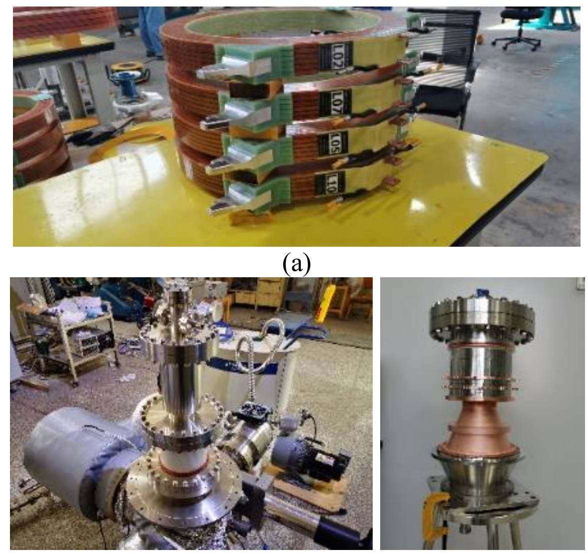


Figure 10: ceramic-lined thin-wall vacuum chamber for BRing dipole (left) and the ceramic rings inside.

SPECTROMETER RING

SRing is designed as a multi-function experimental storage ring, which can be operated in three modes. Firstly, it will be used as an isochronous mass spectrometer (IMS mode) with two TOF detectors for short-lived neutron-rich nuclei. Secondly, it is used to collect and cool long-lived rare isotopes for nuclear experiments, or accumulate and extract highly-charged stable ions for high energy density physics (normal mode). Thirdly, it can be used to store H-like, He-like or other special charge state ions for internal target experiments (target mode). Ions can be decelerated to tens MeV in this mode. Details are available in [6].

A 450 keV magnetized DC electron cooler is used to boost the luminosity of internal target experiments, and proposed to accumulate isotopes with stochastic cooling and barrier bucket system [7]. The cooler is designed based on changes of the 300 keV cooler at IMP, which was made by BINP in 2004 [8]. An 8.0 m cooling section is used with the longitudinal magnetic field of 0.15 T. A pan-cake solenoid is easy to have high precise magnetic field with the homogeneity better than 10^{-4}, but the correct coils will produce transverse components at edges. Figure 11 shows that the coils of the cooling section, the gun and the collector have been tested at IMP.



(a)

(b) (c)

Figure 11: the coils, the gun and the collector for 450 keV cooler.

FRAGMENT SEPARATOR

The High energy Fragment Separator (HFRS) is an in-flight separator at relativistic energy. The schematic layout is shown in Fig. 12. A primary beam from BRing hits the target at PF0. The rare isotopes produced by projectile fragmentation or fission will be collected and purified by the HFRS with the Bρ-ΔE-Bρ method. The magnetic rigidity up to 25 Tm can be operated in HFRS. The large acceptance including the angular acceptances ±30 mrad (H) / ±15 mrad (V) and the momentum acceptance ±2% provides a high collecting efficiency. A two-stage structure is used in HFRS design. The pre-separator is used to dump the primary beams and undesired fragments. The main separator is used to identify the rare isotopes. Details of the HFRS design can be found in [9]. Currently, the target is under-construction at workshop. A prototype of CCT coils is tested at IMP. Figure 13 shows the photos of CCT coils.

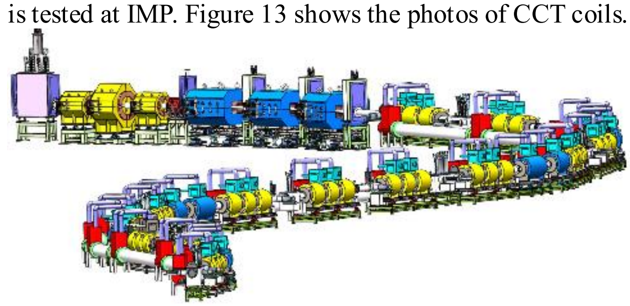


Figure 12: 3-D view of HFRS (a part).

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Figure 13: a prototype of CCT coil.

CONCLUSION

The HIAF project is the biggest heavy ion accelerator project under-construction in China. There are several challenges related to the ion source, the linac, the RF cavities, the power supplies and so on. In past few years, the HIAF project team have developed several prototypes and obtained test results. The HIAF construction will be benefit on these works. The commissioning of the accelerator complex is planned in 2025.

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