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STATUS OF THE HIAF ACCELERATOR FACILITY IN CHINA*

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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 as well as high intensity CW beam. A rapid acceleration in the booster synchrotron ring (BRing) with the ramping rate of 12 T/s is used. The challenges related to the injector systems, RF cavities, power supplies, vacuum system are reported in this paper. The status of the HIAF project construction is presented.

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 mainly consists 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 at HIAF. The layout of the HIAF accelerator is shown in Fig. 1. The main parameters are listed in Table 1.

The construction of the HIAF project was started in December 23rd, 2018. Up to now, roughly 50% of civil construction is finished, as shown in Fig. 2. The first component of SECR is planned to installed in the tunnel in 2023. The first accelerated beam at BRing is expected in the middle of 2025. Day-one experiment is scheduled by the end of 2025. A brief time schedule of HIAF construction is shown in Fig. 3.

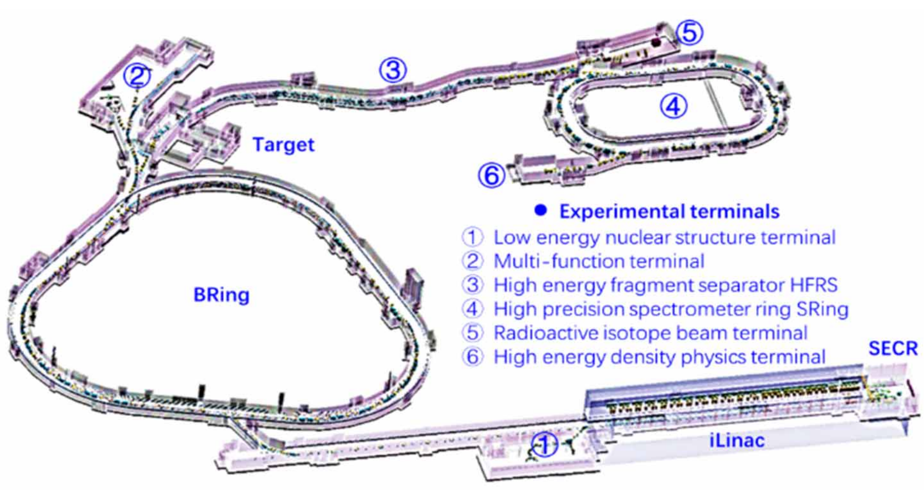

Figure 1: Layout of the HIAF project.

Figure 2: Civil construction of the HIAF project.

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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.

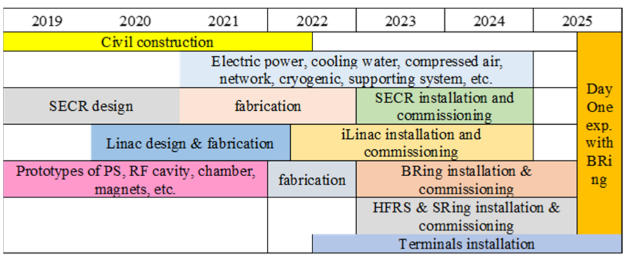

Figure 3: time schedule of the HIAF construction.

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. 4. 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. 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 2023 [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

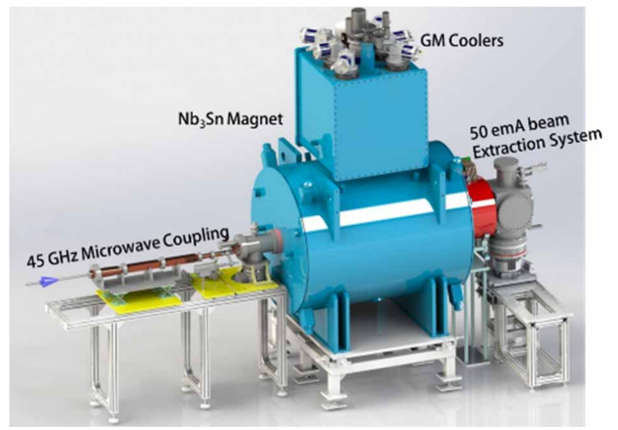

Figure 4: the 4th generation ion source SECR

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 TE01 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. 5. The physics design has been finished.

Figure 5: 3-D view of iLinac. SECR locates on left side.

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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 are shown in Fig. 6. The ionization of residual gas particles is the main concern 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-fold 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].

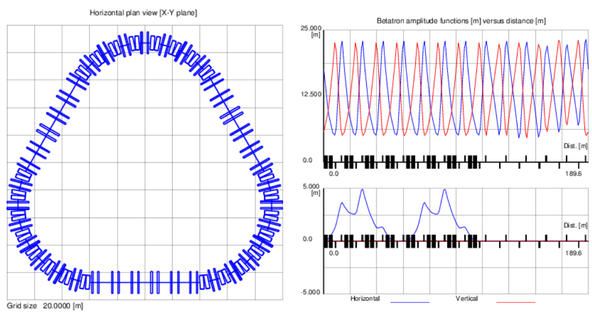

Figure 6: BRing lattice structure and its beta function and dispersion function.

Beam stacking with the electron cooling method is not possible for fast ramping synchrotrons. To obtain a high average beam intensity and avoid space charge limits, transverse phase space painting (4-D) is implemented for beam accumulation and a rapid ramping cycle is used to reduce the integral ionization cross section. Related prototypes as tilted electrostatic septum, 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 spaces simultaneous 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 emittances are painted from small to large [5]. Figure 7 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 π·mm·mrad and ±0.2%, respectively. 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 low 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.

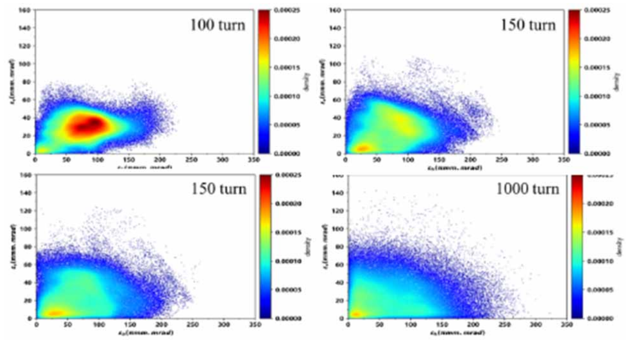

Figure 7: particle invariant distribution after 4-D painting injection.

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 for 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.

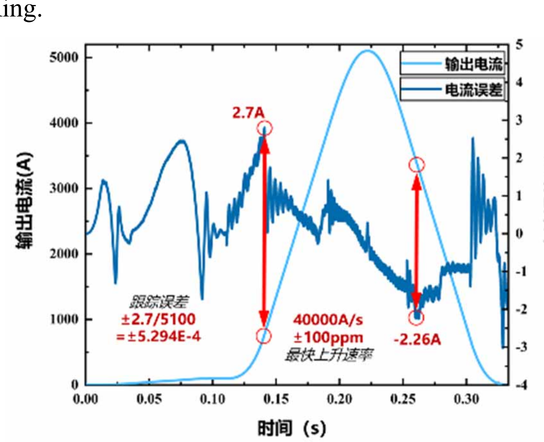

Figure 8: current curve of fast ramping power supply.

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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 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 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.

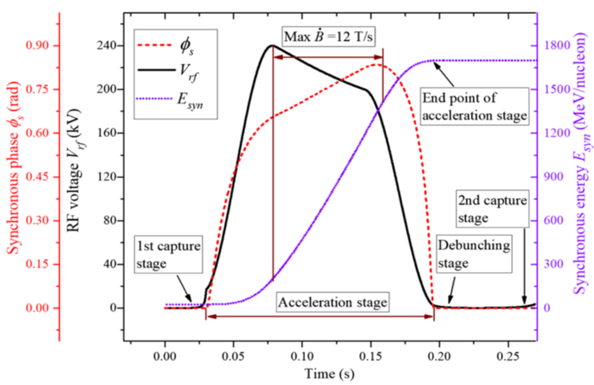

Figure 9: Corner septum cross section and its field map.

The fast ramping of the magnets induces eddy currents in the vacuum chamber wall, which could make a distortion of magnetic field. 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 titanium alloy (TC4) rings inside. Compared to the similar chamber with reinforced ribs, the gap size of the dipole decreases significantly. A prototype of the TC4 rings has been tested, as shown in Fig. 10.

Figure 10: the TC4 rings inside of the chamber.

Fast and Slow Extraction System

To meet the requirements of multi-purpose experiments, fast and slow extraction systems sharing the same extraction channel have been designed in BRing. Fast extraction system is used to provide single-short bunched beam, and it comprises seven kicker cells, three orbit bumpers and four magnetic septa. The phase advance be-tween the first three kicker cells and magnetic septa is optimized to 3π/2, and that of the rest four kicker cells is near to π/2. Together with three orbit bumpers increasing a local bump amplitude of 20 mm, a total horizontal kick angle about 6.42 mrad can be provided by the kicker cells, and it can create a separation about 40 mm in front of the first magnetic septum. The fast extraction beam envelopes are shown in Fig. 11. The zone in green is the acceptance, and the one in cyan and yellow are the circulating and extracted beams with $\varepsilon_{x,total}$= 24 π·mm·mrad and $\delta p/p = \pm 0.2\%$ respectively. The slow extraction is applied for acquiring quasi-continuous beam by third-order resonance and RF-knockout scheme, and it consists of three 1.5 m-long successive electrostatic septa and two kinds of different functional orbit bump magnets. One is four horizontal correctors for raising a height of 10 mm at the entrance of first electrostatic septum to save effective aperture of the elements in the BRing. The other one is the three orbit bumpers also used in fast extraction to reduce the deflection voltage of the electro-static septa. Consequently, a field up to 90 kV/cm with electrode spacing of 15 mm can realize identical entrance position of extracted $^{238}U^{35+}$ with the energy of 835 MeV/u beam at the first magnetic septum.

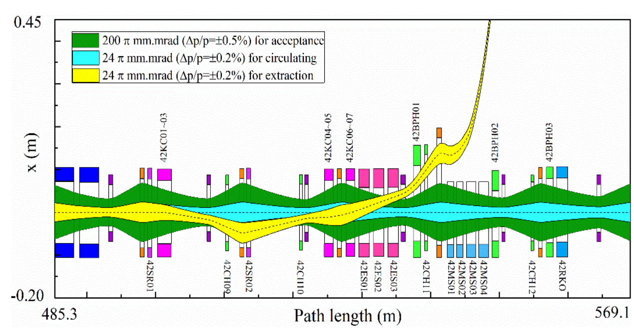

Figure 11: The fast extraction beam envelopes.

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].

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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].

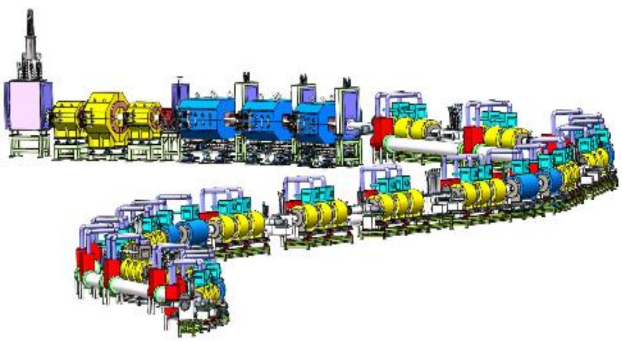

Figure 12: 3-D view of HFRS beam line.

CONCLUSION

The HIAF project is large scale 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, the vacuum system and so on. In the past few years, the HIAF project team have completed the development of several prototypes and obtained test results successfully. The HIAF construction will benefit from those progresses. The systematic commissioning of the accelerator complex is planned in 2025.

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