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Introduction of the Heavy Ion Research Facility in Lanzhou (HIRFL)

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Abstract: The Heavy Ion Research Facility in Lanzhou (HIRFL) is a multi-disciplinary research facility that provides heavy ion beams for physical, biomedical and material sciences. It is a major academic facility of China and one of the world's important centers in nuclear physics and accelerators. The facility was built step by step at Institute of Modern Physics (IMP) over a half century. The first cyclotron was built with great assistance from the former Soviet Union in 1960s, and the newest linear accelerator was tested successfully in 2019. The HIRFL accelerator can provide beams from proton to Uranium with energies of hundreds MeV/u, and hence diverse fundamental sciences and applied researches were carried out at IMP. In this paper, an introduction of the HIRFL accelerator complex was presented. Details of the HIRFL components including ion sources, cyclotrons, synchrotrons, linac and experimental terminals were described. The current operation status and upgrade plans were reported.

Keywords: Accelerator Subsystems and Technologies; Low-energy ion storage; Instrumentation and methods for time-of-flight (TOF) spectroscopy

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1 Introduction

Particle accelerators, especially large-scale accelerator complexes are the most important facility used in fundamental science research. In China, several facilities such as Beijing Electron-Positron Collider (BEPC), Shanghai Synchrotron Radiation Facility (SSRF), China Spallation Neutron Source (CSNS) and Heavy Ion Research Facility in Lanzhou (HIRFL) were constructed over the past decades. The HIRFL device is the one of them which is used to provide heavy ion beams. HIRFL is the core facility at IMP and the largest heavy-ion accelerator complex in China [1]. A layout of the HIRFL accelerator was shown in figure 1. Electron-cyclotron-Resonance (ECR) ion sources are used to provide highly-charged heavy ions. The Sector-Focusing-Cyclotron (SFC) was the first accelerator at IMP built in 1960s and then modified in 1970s. The Separated-Sector-Cyclotron (SSC) was commissioned successfully in 1988. The Cooling-Storage-Ring (CSR) was constructed at the beginning of 2000 and put into operation in July 2008. In 2019, a linear accelerator was constructed completely as an injector of SSC, which was named SSC-Linac. Besides, more than 20 experimental terminals were constructed around those accelerators. At present, stable isotopes from proton to uranium with different energies and charges can be provided by HIRFL accelerators and delivered to different experimental terminals for various experiments. The purpose of this paper is to present a general introduction of HIRFL. The acceleration structure and its feature are described in section 2. The experimental terminals and related research works are presented in section 3. A summary of the HIRFL operation is listed in section 4. A plan of the HIRFL upgrade is introduced briefly in section 5.

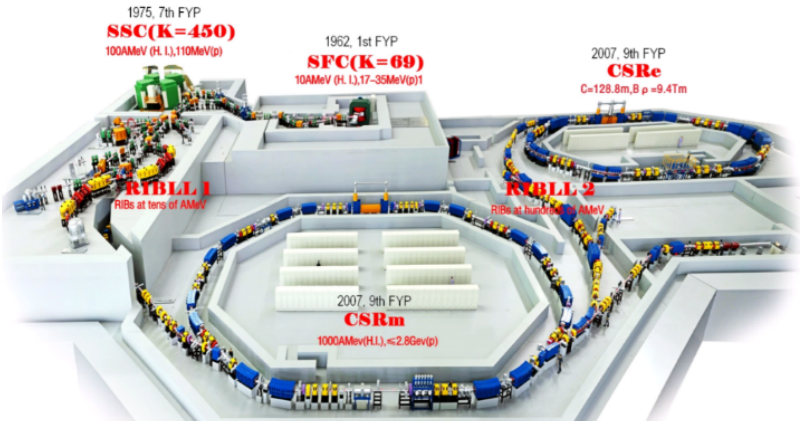

Figure 1. Layout of Heavy Ion Accelerator Research Facility in Lanzhou (HIRFL).

2 HIRFL accelerator structure

The HIRFL accelerator consists of ion sources, linear accelerator, cyclotrons, synchrotrons, beam lines and experimental terminals. Highly charged Electron-Cyclotron-Resonance (ECR) ion source development plays an important role in HIRFL [2]. The first ECR ion source was applied in HIRFL around the end of 1980s, which was a Caprice type 10 GHz machine bought from Grenoble, France [3]. This ion source was lately modified and became the so called LECR0 source in HIRFL. Based on the experience of LECR0, a 10 GHz ECR ion source that was lately renamed as LECR1 had been developed and also put into routine operation during the years from 1995 to 2005. Later, the development of superconducting ECR ion source is fundamentally boosted by the needs from the HIRFL upgrade. First superconducting ECR ion source SECRAL is operated typically with the microwave power from a 24 GHz gyrotron generator and an 18 GHz klystron amplifier. SECRAL was fully on-line for HIRFL operation since 2007. After that, another superconducting ECR ion source SECRAL-2 was designed and operated in HIRFL, which is a close copy of SECRAL. The main difference is in the cryogenic system. The high intensity and highly charged ion beams provided with SECRAL series are listed in table 1 [4].

Table 1. High intensity and highly charged ion beams production with SECRALs.

Ion	VENUS (2018)	SECRAL (2016)	SECRAL-2 (2018)
$^{16}O^{6+}$	4750	2300	6700
$^{40}Ar^{12+}$	1060	1420	1190
$^{78}Kr^{18+}$	770		1030
$^{129}Xe^{34+}$	104	120	102

There are two cyclotrons operated in HIRFL, a Sector Focusing Cyclotron (SFC) with K-value of 69 and a Separated Sector Cyclotron (SSC) with K-value of 450 [5]. The pole diameter of SFC is 1.7 m with the maximum magnetic field of 1.6 T. Typically, light ions (e.g. C^{6+}) can be accelerated up to 100 MeV/u with intensity of 1012 pps and heavy ions (e.g. U^{22+}) can be accelerated up to 1.2 MeV/u with intensity of 10^{10} pps, respectively. The diameter of the SSC magnets is about 12 m

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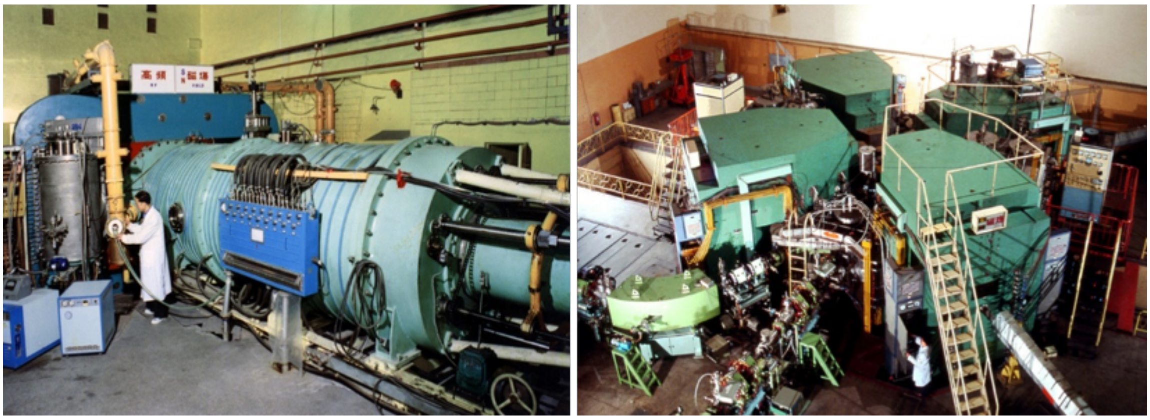

Figure 2. The small cyclotron SFC (left) and the big one SSC (right) in HIRFL.

and the maximum field is up to 1.6 T. The sector angle is 52 degrees with a pole gap of 100 mm. The photos of SFC and SSC are shown in figure 2. Generally, SFC is used as an injector for SSC operation.

To improve the HIRFL beam delivery capabilities, a new heavy ion linear accelerator as a new injector for SSC was constructed in recent years [6]. The first commissioning of the linac together with SSC was done successfully in the end of 2019. The SSC-Linac consists of a 4-rod RFQ and three IH-DTL cavities which can accelerate ions of $A/q < 7$ from 3.73 keV/u up to 1.025 MeV/u. At the beginning of SSC-Linac, a room temperature ECR ion source is used to provide heavy ions. The layout of SSC-Linac was shown in figure 3. Various species ion beams up to uranium have been delivered successfully recently.

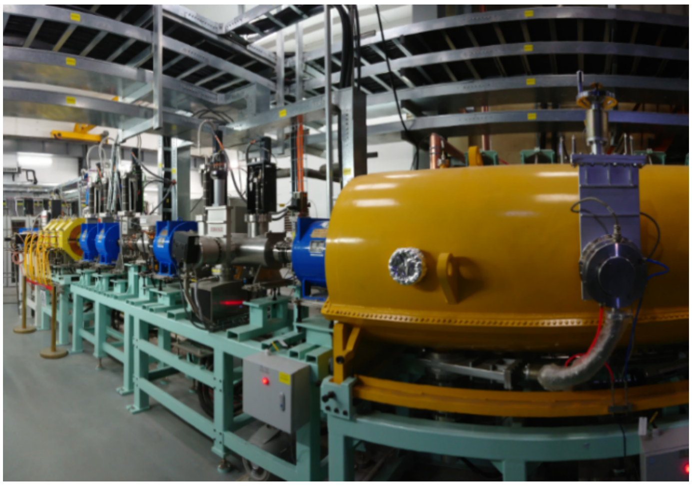

Figure 3. General view of SSC-Linac.

The cooling storage rings including the main ring (CSRm) and the experimental ring (CSRe) are the post-acceleration system of HIRFL [7]. It was a most important upgrade of the HIRFL facility in 1990s. The heavy ions provided by both cyclotrons could be accumulated, cooled and accelerated in CSRm, then extracted to produce radioactive ion beams (RIB) or highly charged heavy ions. Those secondary beams will be accepted and stored in CSRe for many internal target experiments. The proposal of CSR was proposed in 1993 and approved in 1998. The construction work was started in December 1999. The first stored beam signal was observed in CSRm in 2005. In 2008, the CSR storage rings started to provide ion beams for experiments. The main parameters of CSR are listed in table 2.

Table 2. Main parameters of the CSR machine.

Parameters	CSRm	CSRe
Circumference	161.0 m	128.8 m
Ion species	Proton to uranium	Stable nuclei or RIBs
Magnetic rigidity	11.4 Tm	9.4 Tm
Acceptance	$150\pi/30\pi$ ($\Delta p/p = \pm 0.15\%$)	$150\pi/75\pi$ ($\Delta p/p = \pm 0.5\%$)
Tunes	3.63/2.62	2.53/2.58
Electron cooler	35 keV	300 keV
Vacuum condition	$< 10^{-11}$ mbar	$< 10^{-11}$ mbar
RF cavity	0.24–1.7 MHz, 7 kV	0.5–2.0 MHz, 10 kV
Injection	Multi-turn injection or strip injection	Single turn injection
Extraction	Fast or slow	None extraction

3 Experimental terminals

More than 20 experimental terminals are operated at HIRFL for physical, biomedical and material sciences. In this paper, the most popular experimental terminals are introduced briefly, including a gas-filled recoil separator SHANS (Spectrometer for Heavy Atom and Nuclear Structure), a double time-of-flight (TOF) for Isochronous Mass Spectrometry (IMS) and an electron target for Dielectronic Recombination (DR). The description of other terminals can be found in references.

3.1 Gas-filled recoil separator

The schematic view of the gas-filled recoil separator, SHANS [8], is shown in figure 4. The separator consists of four magnets in a $Q_v D_h Q_v Q_h$ configuration, where D refers to a dipole and Q to a quadrupole, as well as the subscripts h and v stand for horizontally and vertically focusing, respectively. Pure helium gas at about 1 mbar pressure is filled in the separator to achieve the required charge state exchange statistics. A differential pumping system is installed upstream of the target to isolate the vacuum region of accelerator side and the gas-filled region leading to window-less operation. A rotating target system is installed at the target position for preparing the experiments with low melting point target. A beam chopper is used to avoid irradiating the target frame, and the chopping signal is recorded by the data acquisition system in order to distinguish between beam-on and beam-off events. SHANS is dedicated to the studies of heavy nuclei produced in heavy ion induced fusion reactions. The research activity is mainly concentrated on the study of the very neutron-deficient isotopes in the actinide or transactinide region. For example, the observation of a new neutron-deficient α-emitting isotope ^{222}Np [9].

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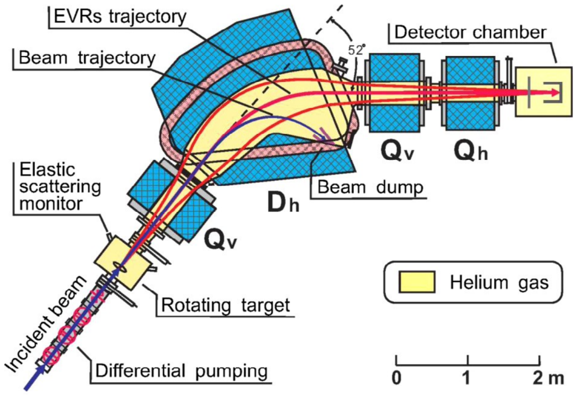

Figure 4. A schematic view of the gas-filled recoil separator SHANS.

3.2 Double TOF detector for IMS

The IMS is a powerful toll for mass measurements of exotic nuclei with lifetime as short as several tens of micro-seconds in storage rings. With the IMS masses of exotic nuclei can be deduced from precise revolution time measurements of the ions circulating in the isochronous storage ring. The basic principle of IMS measurements can be found in reference. A novel way to increase the mass resolving power was first proposed at GSI in 2005. The idea is to measure the velocity for each stored ion with two TOF detectors in the ring, thus the revolution time spread can be reduced by using the velocity information in the off-line data analysis. The first experiment with double TOF detectors has been carried out at CSRe [10]. The schematic view of the double TOF detectors at CSRe is shown in figure 5. With the double TOF detectors, a time resolution has been improved by a factor of at least two compared to the previous single TOF detector under the same condition. A pilot experiment to test the feasibility of the IMS with double TOF detectors was performed with a primary beam of ^{78}Kr beam at the energy of 456.8 MeV/u. The preliminary results are shown in reference [11].

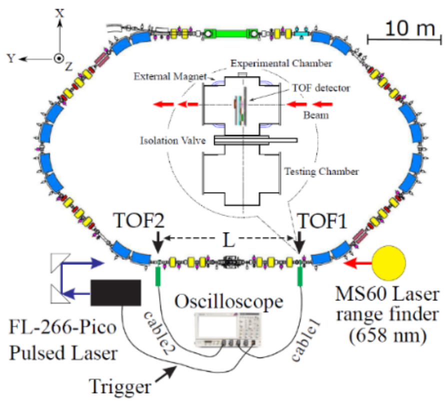

Figure 5. Schematic view of the storage ring CSRe and its double TOF detectors.

3.3 Electron target for DR experiments

DR experiments of highly charged ions at storage rings have been developed as a precision spectroscopic tool to investigate the atomic structure as well as nuclear properties of stable and unstable nuclei. A schematic view of the DR experimental setup at HIRFL is shown in figure 6. The electron cooler with a detuning high voltage system is used as well as an electron target. In the experimental cycle, the ion beam is injected into CSR and cooled for several seconds until the high-quality ion beam was obtained. Then the high voltage detuning started to scan the electron beam energy according to a preset timing sequence. Down stream of the electron cooler, the recombined ions were separated from the primary ion beam in the first dipole and detected by a movable scintillator particle detector. Finally, the DR rate coefficients versus the collision energies are measured by changing of detuning voltages. There are two electron coolers with the maximum energy of 35 kV and 350 kV at CSRm and CSRe, respectively. Several DR experiments have been performed on them with different energies. The details of those experiments were published as reference [12].

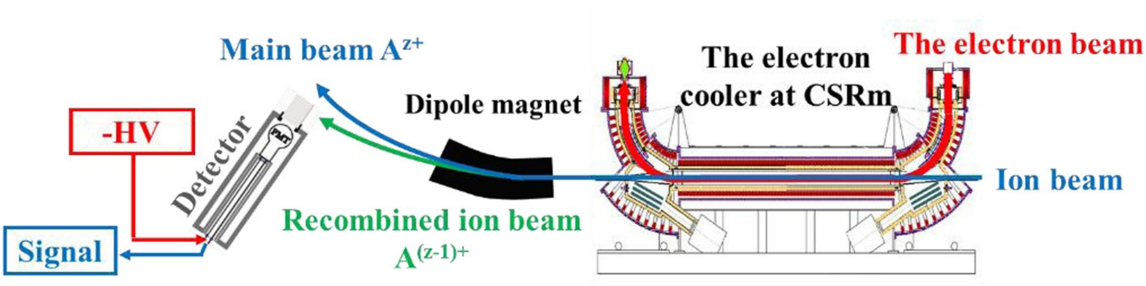

Figure 6. Sketch of the DR experimental setup at HIRFL.

4 HIRFL operation status

HIRFL is always running over 7000 hours and delivering more than 5000 hours of beam for targets every year. A summary of typical ion beam parameters provided by HIRFL in recent years is listed in table 3, including the energies and intensities extracted from different accelerators. Several hundreds of domestic and international users perform research works at HIRFL every year. Generally, more than 50% of beam time is used for the fundamental research, such as nuclear and atomic physical experiments, about 30% of beam time is used for application science [13]. A summary of HIRFL operation time in 2019 is listed in table 4.

There are several operation modes used in HIRFL. Generally, the cyclotron SFC can be used as a main accelerator to accelerate ions up to ten MeV/u. Those ion beams can be delivered for low energy nuclear experiments, such as neutron-deficient isotopes study at SHANS. In addition, the cyclotron SSC can be used as a main accelerator to accelerate ions provided by SFC or SSC-Linac up to hundred MeV/u. those ion beam can be used for material research or cancer treatments study. Furthermore, the both cyclotrons can also be used as an injector of the synchrotron CSRm. In this operation mode, those ions can be injected into CSRm with multi-turn or strip injection methods. An electron cooling at injection energies is applied to shrink beam size. By a combination of injection and fast transverse cooling the number of ions in a synchrotron pulse can be increased by

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Table 3. Typical ion beams provided by HIRFL in recent years.

Ions	SFC		SSC		CSR	
	Energy	Intensity	Energy	Intensity	Energy	Stored Ions
	MeV/u	eμA	MeV/u	eμA	MeV/u	ppp
H_2^{1+}	10.0	7.0			400.0	1.4×10^8
$^9Be^{3+}$	6.89	0.55				
$^{12}C^{4+/6+}$	7.0	10.0			1000.0	1.0×10^9
$^{14}N^{5+/7+}$	6.957	6.0	80.0	0.4		
$^{18}O^{6+/8+}$	7.0	4.0			305.4	1.1×10^9
$^{19}F^{7+}$	6.6	3.0				
$^{22}Ne^{7+/10+}$	6.17	9.0			70.0	2.7×10^9
$^{26}Mg^{8+/12+}$	6.17	3.5	70.0	0.35		
$^{28}Si^{9+/14+}$	6.645	2.2	76.0	0.15		
$^{36}Ar^{8+}$	2.0725	16.0	22.0	3.3	368.0	3.9×10^8
$^{35}Cl^{12+}$	6.0	1.0				
$^{32}S^{11+/16+}$	7.112	4.8	82.0	0.2		
$^{22}Ne^{7+/10+}$	6.17	9.0			70.0	2.7×10^9
$^{40}Ca^{12+}$	5.625	3.5				
$^{58}Ni^{19+}$	6.3	2.4			463.36	8.3×10^7
$^{78}Kr^{19+/28+}$	4.0	4.2			487.9	9.5×10^7
$^{129}Xe^{27+}$	3.0	4.5			235.0	7.2×10^7
$^{209}Bi^{36+}$	2.0	2.0			170.0	1.2×10^7
$^{238}U^{32+}$	1.22	1.0			100.0	4.4×10^7

Table 4. HIRFL operation time in 2019.

Operation time	Time (h)	Percentage (%)
Total operation time	7392	100
Machine failure time	208.5	2.8
Preparation of beam	1416.5	19.2
Other time	16.5	0.2
On target beam time (total)	5750.5	77.8
Nuclear physics	2671.5	46.5
Irradiation	2065	35.9
Biophysics	191.5	3.3
Space	384	6.7
Machine study	438.5	7.6

more than one order of magnitude. These multi-injection process usually takes about 10 seconds. Then, those ions will be accelerated to the top energies for experiments. Due to the limitation of RF cavities, the harmonic number is reduced from 2 to 1 at the medium energy of acceleration.

At the top energies, these ions will be kicked out from CSRm within 100 ns and transferred to experimental terminals, or extracted slowly with several seconds to terminals. Figure 7 shows a standard operation cycle of CSR [14]. The beam current measured by DCCT and the horizontal profile measured by IPM in CSRm are shown in figure 8.

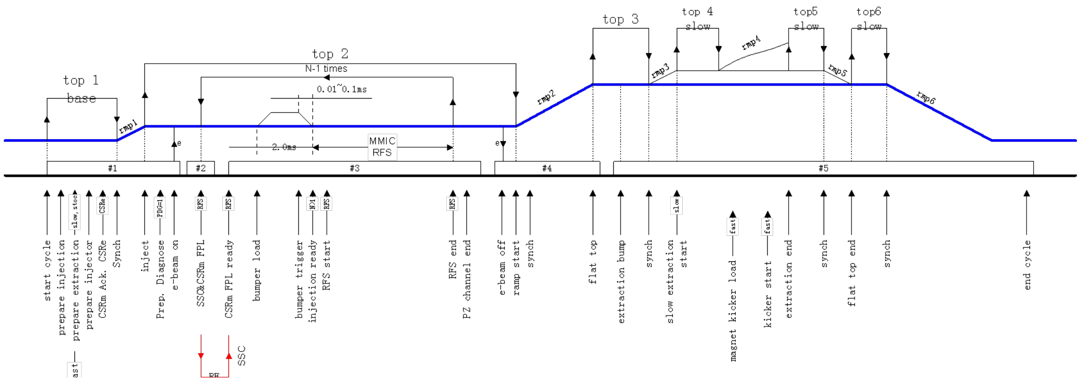

Figure 7. Operation cycle of CSR.

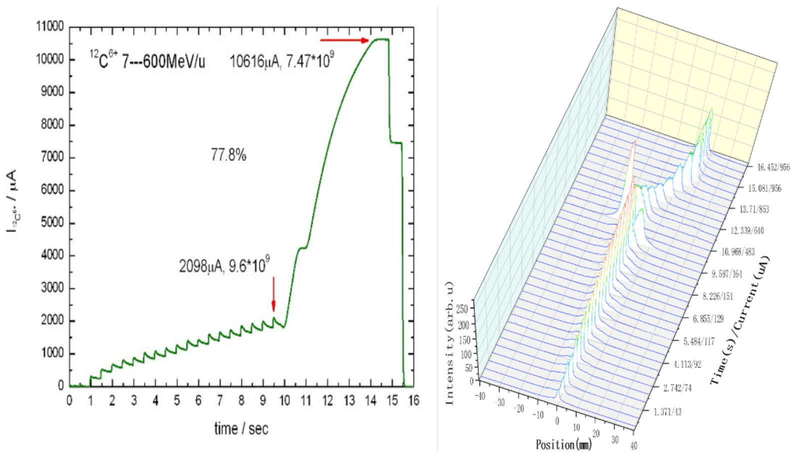

Figure 8. Beam current and horizontal profile measured in CSRm during one operation cycle.

5 Future of HIRFL

Over the past decades, the HIRFL accelerator complex have been constructed step by step. In the future, the most important upgrade is to improve the hardware stabilities and beam qualities of existing accelerators. The digital power supplies will be used to replace old analog ones, in order to improve the stabilities and efficiency of the operation. Related to the power supplies and other electrical equipment, the electromagnetic compatibility (EMC) which is the interaction of electrical and electronic equipment with its electromagnetic environment and with other equipment, becomes the main factor that influence on the beam qualities and experimental accuracy. It is planned to do EMC test and upgrade the connection of an earth electrode system. In addition, a new operation software focusing on heavy ion synchrotrons was developed based on HIRFL. The software has a good communication with accelerator physical codes such as MAD-X and control system such as EPICS. In the operation, operators only need to calculate and set the accelerator physical parameters, such as tune value, acceptance and so on. The operation software will calculate the hardware parameters according to those physical parameters and communicate with hardware by EPCIS system. The new operation software was tested at HIRFL in middle of 2020. The further developments will continue to carry out.

Furthermore, the beam time on target is limited by the chain of HIRFL accelerators, which means only one experimental terminal can be delivered beam in the operation cycle. For example, if an experiment was done at extraction of CSRm with injector of SFC, the cyclotron SSC and its injector Linac should be shut down because no beam lines can be used to deliver ion beam extracted from SSC to any experimental terminals. In the future, it is planned to build some by-pass beam lines, as shown in figure 9. With these beam lines, the cyclotron SSC and the storage ring CSR can be used as the main accelerators simultaneously. It would be a great upgrade to improve the beam time on the target at different terminals.

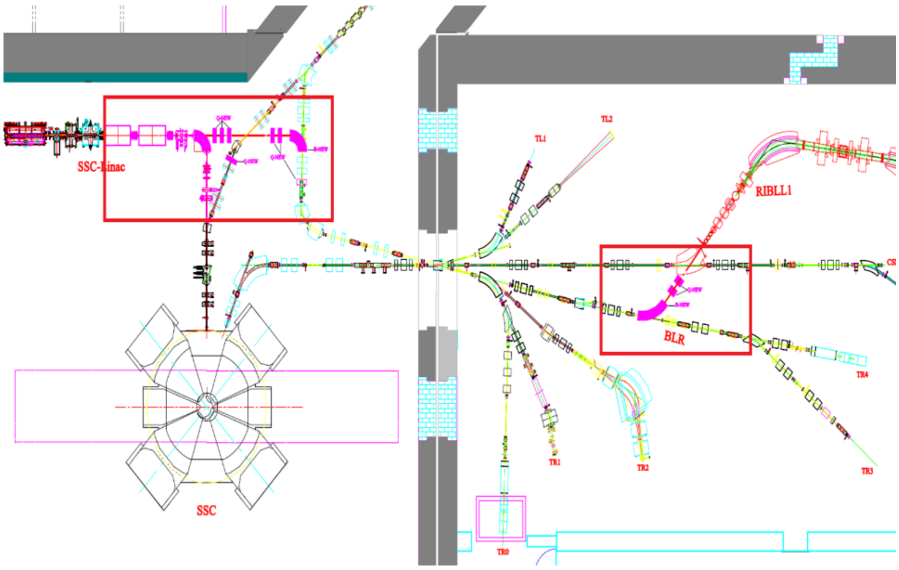

Figure 9. By-pass beam lines (in red box) will be constructed to improve the operation efficiency.

6 Conclusions

The main structure of the HIRFL accelerator complex and its machine parameters are described in this paper. Based on HIRFL, fundamental research works in nuclear physics, nuclear astrophysics and atomic physics are conducted. The major research subjects are the precision mass measurement of short-lived nuclides, nuclear structure and reaction mechanism, property of nuclear matter, synthesis of new super-heavy isotopes, chemistry of super-heavy elements, nuclear reaction in stellar environments, and spectroscopy and interaction of highly charged ions. In addition, heavy ion application researches such as cancer therapy have been developed at HIRFL in recent years. In the future, more works related to the existing accelerator complex will be done to improve the hardware stabilities and beam qualities.

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