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PRESENT STATUS OF HIRFL COMPLEX IN LANZHOU*

Y. J. Yuan†, D. Q. Gao, L. Z. Ma, L. J. Mao, R. S. Mao, J. Meng, Y. W. Su, L. T. Sun, Y. Y. Wang, J. X. Wu, Z. Xu, J. C. Yang, W. Q. Yang, Q. G. Yao, X. J. Yin, B. Zhang, W. Zhang, Z. Z. Zhou, H. W. Zhao, G. Q. Xiao, J. W. Xia, Institute of Modern Physics, CAS, Lanzhou,China

Abstract

Heavy Ion Research Facility in Lanzhou (HIRFL) is a cyclotron, synchrotron and storage ring accelerator complex, which accelerates ions of hydrogen to uranium from low to medium energy. Since the complete of HIRFL-CSR project in 2008, under the support from CAS, efforts have been put to improve the infrastructure for machine performance, including improvement of EMC environments, power distribution stations, PS stations, cooling water system, RF system of cyclotrons and adoption of EPICS control system, etc. New generation SC ECR source-SECRAL2 with high performance is put into operation. Experiments of electron cooling with pulsed electron beam are performed for the 1st time. Stochastic cooling and laser cooling are realized in CSRe. The performance of RIBLL2 and CSRe are gradually improved. The ISO mode of CSRe for precise atomic mass measurements is well studied and reaches state-of-art mass resolution of storage rings. The operation status and enhancement plan of HIRFL will be briefly reported in this paper.

INTRODUCTION

HIRFL[1,2] is one of the largest heavy ion research facility in China. It belongs to the National Laboratory of Heavy Ion Accelerator, which was established in 1991, at Institute of Modern Physics (IMP). HIRFL serves for the scientific researches in nuclear physics, atomic physics and nuclear science related interdisciplinary study.

HIRFL consists of two cyclotrons (SFC and SSC), one synchrotron (CSRm) and one storage ring spectrometer (CSRe), in chain, see Fig. 1. The SFC cyclotron was constructed in 1960s for light ions. It's upgraded in 1980s to accelerate heavy ions from hydrogen to uranium, as required to be an injector of cyclotron SSC. The CSR project, CSRm and CSRe are the major components, was constructed at the turn of this century, for higher energy pulsed beam and precise nuclear physics and atomic physics study at external target and in ring.

Within the half century construction period, the infrastructure of HIRFL has been improved gradually according to the development of technology. In recent years, under the strong support of the maintenance and renovation budget from CAS, we upgraded the power station of HIRFL, LLRF of cyclotrons, water-cooling systems [3] and intra-network; built up the environment control of power supply room of CSR and the monitoring systems of water-cooling, power station and water leakage detection; rearranged and rewired the cables of CSRe to improve the EMC condition of CSRe. Above all, new generation superconductive ECR source SECRAL-II as a back-up of SECRAL with better performance was constructed and put into operation this year [4,5]; EPICS was introduced to take over most of the control system [6].

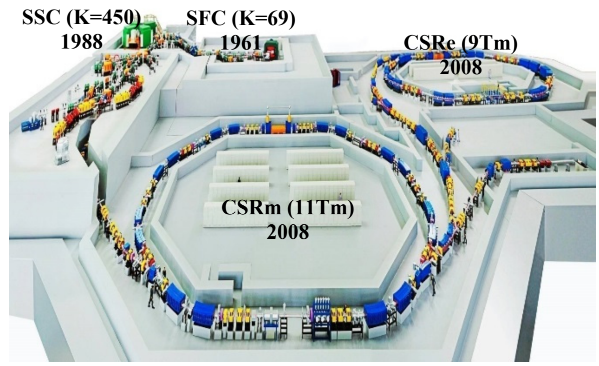

Figure 1: The layout of HIRFL complex.

To improve the performance of HIRFL, new technologies are researched and developed. Experiments of electron cooling with pulsed electron beam are performed for the 1st time for the development of e-coolers at future circular accelerator. The performance of RIBLL2 as on-line separator of secondary beams was gradually improved. The ISO mode of CSRe for precise atomic mass measurements is well studied and reaches state-of-art mass resolution of storage rings with unique two-TOF velocity measurement setups. The Stochastic cooling and laser cooling are realized in CSRe, which will help to extend the research ability of nuclear and atomic physics at CSRe.

Up to now, SFC is the only injector for both SSC and CSRm. This limited the total beam time of the HIRFL complex. To increase the beam time, new injectors are urgently needed. Under the support of CAS and IMP, a DC Linac injector of SSC is being developed since 2012, which will accelerator heavy ion beam to 1.024 MeV/u. New pulse Linac injector for direct injection to CSRm is designed and underdevelopment. With the new injectors the beam time for experiments will be increased dramatically.

OPERATION STATUS OF HIRFL

In last 5 years, the beam time requirement of HIRFL is increasing rapidly. New growth points mainly from anti-radiation testing and reinforcement study of circuits, pile radiation material study, production of super-heavy elements and experiments at storage rings. The machine time and beam time of HIRFL averaged to more than 7500 h/a and 5300 h/a separately. The failure time averaged to less than 250 h/a. With the only injector cyclotron SFC, beam time reached it's up-limit. Among the beam time provided, about 54 % is for nuclear physics and atomic physics, 16

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† yuanyj@impcas.ac.cn

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% is for material science, 13 % is for space science, 8 % is for bio-science, the rest is for the machine study. More than 50 % of the beam time is provided for researchers outside IMP.

As an all-ion accelerator complex, HIRFL provides beams of nature exist ions from Hydrogen to Uranium. The provided ion beams are indicated Fig. 2, including some of their isotopes. According to the design parameters and the working condition limits (range of magnet field and RF frequency) of the cyclotrons, the energy range of available beams from SFC and/or SSC for different A/Q ratios of ions is shown in Fig. 3. It can be seen that the energy range of cyclotrons is still limited by the down-limit of present working field of SFC.

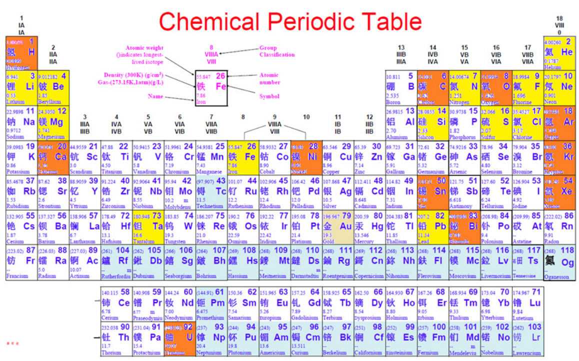

Figure 2: The accelerated primary beams at HIRFL in the chemical periodic table. The red blocked were accelerated in CSRm.

0	Not available by SFC or SSC
1	Available by SFC alone
2	Available by SFC+SSC,same A/Q
	Limited by SFC-RF frequency <15.5 MHz
	Limited by SFC-B >1T
1	Available by SSC after stipping.

E(MeV/u)	SFC 0.4	0.6	1	1.5	2	2.5	3	3.5	4	5	6	7	8	9	10
A/Qs	SSC 4.1	6.2	10.4	15.8	21.2	26.7	32.3	38.0	43.8	55.6	67.9	80.6	93.7	107.3	121.4
8	2	2	1	0	0	0	0	0	0	0	0	0	0	0	0
7.75	2	2	1	0	0	0	0	0	0	0	0	0	0	0	0
7.5	2	2	1	0	0	0	0	0	0	0	0	0	0	0	0
7.25	2	2	1	0	0	0	0	0	0	0	0	0	0	0	0
7	2	2	1	0	0	0	0	0	0	0	0	0	0	0	0
6.75	2	2	1	1	0	0	0	0	0	0	0	0	0	0	0
6.5	1	2	2	1	0	0	0	0	0	0	0	0	0	0	0
6.25	1	2	2	1	0	0	0	0	0	0	0	0	0	0	0
6	1	2	2	1	0	0	0	0	0	0	0	0	0	0	0
5.75	1	2	2	1	1	0	0	0	0	0	0	0	0	0	0
5.5	1	2	2	1	1	0	0	0	0	0	0	0	0	0	0
5.25	1	1	2	2	1	1	0	0	0	0	0	0	0	0	0
5	0	1	2	2	1	1	0	0	0	0	0	0	0	0	0
4.75	0	1	2	2	1	1	1	0	0	0	0	0	0	0	0
4.5	0	1	2	2	2	1	1	0	0	0	0	0	0	0	0
4.25	0	0	2	2	2	1	1	1	0	0	0	0	0	0	0
4	0	0	1	2	2	2	1	1	1	0	0	0	0	0	0
3.75	0	0	1	2	2	2	1	1	1	0	0	0	0	0	0
3.5	0	0	1	2	2	2	2	1	1	1	0	0	0	0	0
3.25	0	0	0	1	2	2	2	2	1	1	1	0	0	0	0
3	0	0	0	1	2	2	2	2	2	1	1	1	0	0	0
2.75	0	0	0	1	1	2	2	2	2	2	1	1	1	1	0
2.5	0	0	0	0	1	1	2	2	2	2	2	1	1	1	1
2.25	0	0	0	0	0	1	1	2	2	2	2	2	1	1	1
2	0	0	0	0	0	0	1	1	1	2	2	2	2	2	1
1.5	0	0	0	0	0	0	0	0	0	1	1	1	2	2	2
1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
F-SFC	5.59	6.85	8.84	10.82	12.49	13.95	15.28	*16.50	5.88	6.57	7.19	7.76	8.28	8.78	9.25
F-SSC	8.39	6.85	8.84	10.82	12.49	13.95	7.64	8.25	8.82	9.85	10.78	11.63	12.43	13.17	13.87
match	0.5	1	1	1	1	1	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5

* possibly availble by SFC-5.49MHz

A/Q	SFC 11	12	14	16	18	20	23	26	30
2.75	0	0	0	0	0	0	0	0	0
2.5	1	0	0	0	0	0	0	0	0
2.25	1	1	0	0	0	0	0	0	0
2	1	1	1	1	0	0	0	0	0
1.5	1	1	1	1	1	1	1	1	1
1	0	0	0	0	1	1	1	1	1
F-SFC	9.691	10.11	10.91	11.64	12.33	12.98	13.88	14.72	15.77

Figure 3: Energy range of beams from SFC and/or SSC for different A/Q ratios of ions.

UPGRADE OF INFRASTRUCTURES

As shown in Fig. 1, HIRFL was built-up in 3 periods, lasting about half century. In recent years, under the strong support of the national maintenance and renovation budget for large scale fundamental science and technology facilities from CAS, many aspects of the infrastructure of HIRFL were upgraded or renewed to improve the operation stability and reduce the failure time.

Power Station The power station for SSC and the beam lines to terminals is replaced using new grid technology, to improve the reliability, safety and energy efficiency.

Water Cooling System The water-cooling systems of HIRFL were upgraded to increase the cooling resistance and heat exchange efficiency, which improved the working stability of power supplies. The resistance of inner circulating water reached above 1.0 MΩ·cm.

Intranet The backbone of intra-network was upgraded from 100 M to 10 G bandwidth according to the requirements for data transmission from control system, beam diagnosis system and physics experiments. With careful design, physical link network topology optimization, application of network expansion with virtualization technology, and rectification of the network cabinet and cables, the new network well meets the growing requirements. An online status inquiry system of network equipment was established along with the upgrading.

EMC Environment The signal cables and power cables of CSRe and RIBLL2 were rearranged and rewired to reduce the electromagnetic radiation interference and improve the EMC environment. The background noise levels of beam diagnosis and experiment detectors were reduced by more than one order.

Environment Control The power supply rooms of CSR were built up inside the CSR hall for more stable and reliable performance of the PS. New monitoring systems of water-cooling [3], power station and water leakage detection were built up to monitor the basic operation condition. The radiation protection system was also rebuilt.

IMPROVEMENTS OF PERFORMANCE

To improve the performance of HIRFL, new technologies are researched and developed.

New Control System The self-developed distributed control system of HIRFL was developed in many years part by part, and based on many kinds of platforms. It's not convenient for the operation and not easy to exchange signals and data. In last years, the open-source Experimental Physics and Industrial Control System (EPICS), developed at LANL and ANL, was adapted to take over most of the control system of HIRFL[6]. The structure of new control system based on EPICS is shown in Fig. 4.

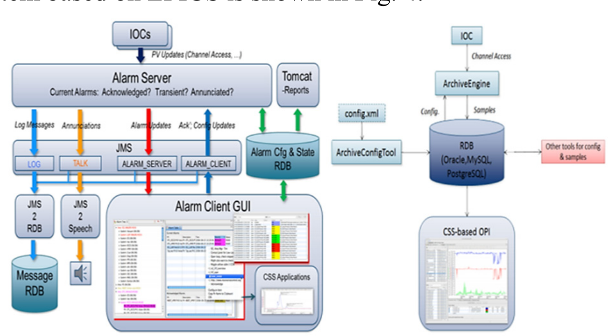

Figure 4: The structure of new HIRFL control system.

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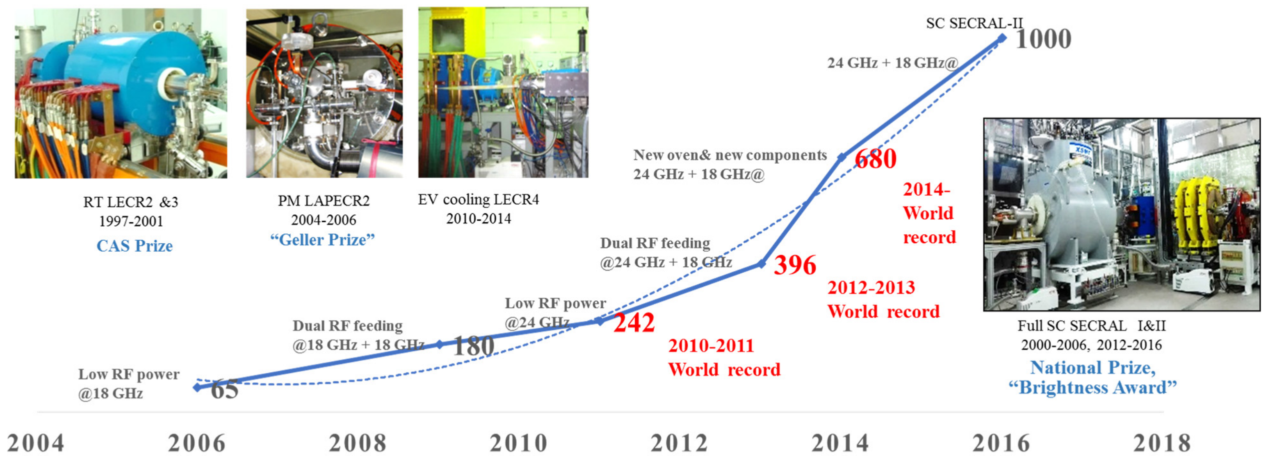

Figure 5: A brief summary of the development of ECR ion sources at IMP.

New control system of electron cooler at CSRm was built to replace the attached one to accommodate the upgraded electron cooler [7]. The LLRF of cyclotron RF systems and the PXI RF controller of CSRm were rebuilt to improve the operation stability, enhance the data-loading speed and reliability.

New SC ECR Ion Source A new generation superconductive ECR source-SECRAL-II as a back-up of the former SECRAL with better performance was constructed and put into operation this year [5]. With new structure, SECRAL-II created higher magnetic field and works at 18 GHz / 24 GHz microwave frequency. It sets a new beam current record of highly charged heavy ion beams. Figure 5 gives a brief summary of the development of ECR ion sources at IMP since 2004. With the state-of-art ECRIS technology, SECRAL-II will enable SFC cyclotron to accelerate heavy ions with higher charge state and intensity to higher energy, which benefits the accumulation and acceleration in synchrotron CSRm.

Pulsed Electron Cooling Experiments of electron cooling with pulsed electron beam are performed for the 1st time at CSRm [8,9]. New phenomena were observed. It was found that the modulation frequency should be near integer or half integer harmonic numbers of the revolution frequency of ions to maintain the life time of ions, otherwise the stored ions will lose rapidly. With the cooling of pulsed electron beam, the ions will be bunched inside the electron bunch and cooled. The experiment phenomena can be explained by space ME field of electron bunches in theory and proved by numeric simulations. The study of electron cooling with pulsed electron beam is important for the cooling of high energy bunched ion beam with high peak current electron cooler, at future ion circular accelerator or colliders.

RIBLL2 Improvement The performance of the 2nd radioactive isotope beam line at Lanzhou - RIBLL2 as an in-flight separator of relativistic projectile fragments was gradually improved. Figure 6 shows the design of RIBLL2 as the connection RIB line between CSRm and CSRe and RIB separation line to external target ETF [10]. There are 8 beam profile detectors newly installed along RIBLL2 for both horizontal and vertical profiles. The core structure of detector is shown in Fig. 7. In the joint efforts of experimental teams, RIBLL2-ETF is capable of identifying clearly all ions up to Z=30, with the combination of the TOF and the MUSIC detectors [10]. Future upgrading of RIBLL 2 was planned.

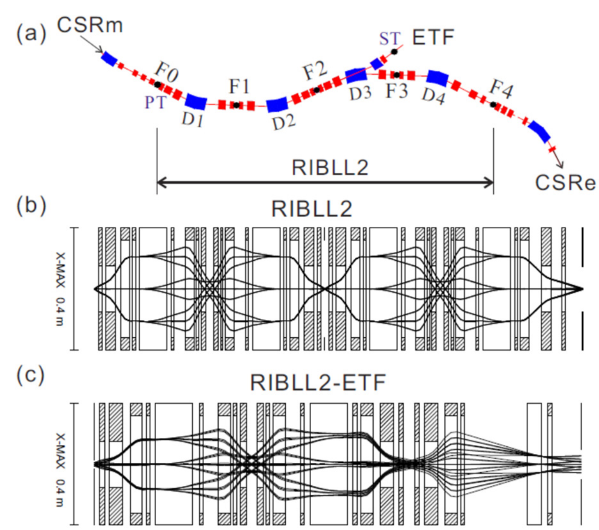

Figure 6: (a) A schematic layout of the RIBLL2 beam line. Horizontal beam trajectories with the first-order optics calculated by the GICOSY for the full RIBLL2 (F0 to F4) (b) and the first half of RIBLL2 and ETF (c).

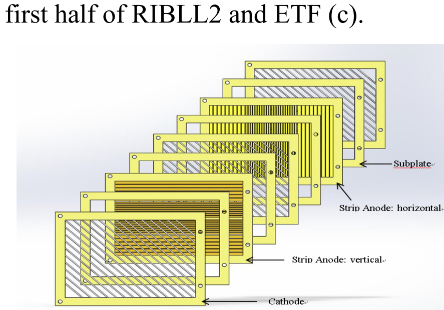

Figure 7: Core structure of BPD at RIBLL2.

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Advanced Mass Spectrometry The ISO mode of CSRe for precise atomic mass measurements is well studied and reaches state-of-art mass resolution of storage rings with unique two-TOF velocity measurement setups (see Fig. 8). Following the ISO mode mass spectrometry at ESR@GSI, we explored deeply the mass spectrometry at CSRe. With the improvement of EMC environment and new dipole PS at CSRe, the signal-noise ratio was significantly improved. With the new idea of two-TOF detector at storage rings to measure the velocity of ions, the transition energy (γ_t), as a function of the closed orbit length or momentum deviation, can be measured precisely using the time spectra data of the ions cycling in CSRe [11]. The transition energy function can be monitored and optimized online to ensure stable and good isochronous condition. With the quadrupole magnets and sextupole magnets corrections, a mass resolution of 1.71×10^5 (FWHM) was reached [12]. Further nonlinear optimization with higher order magnet field was planned.

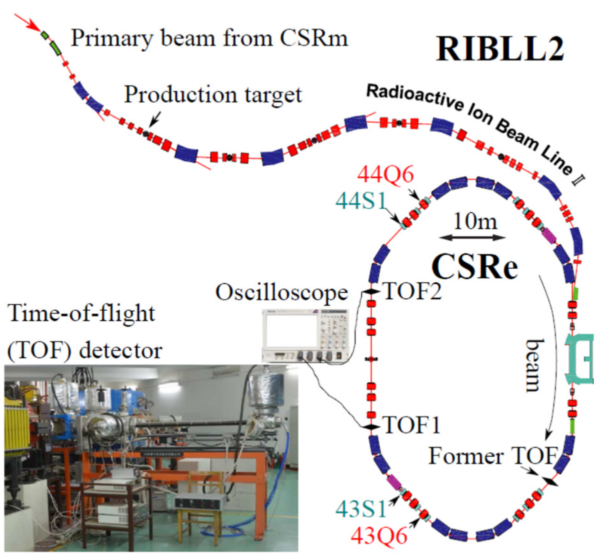

Figure 8: The layout of storage ring mass spectrometry with single TOF and double TOF detectors at CSRe. A picture of installed TOF detector is shown at the left bottom.

Stochastic Cooling and Laser Cooling The Stochastic cooling and laser cooling are realized in CSRe, which will help to extend the research ability of nuclear and atomic physics at CSRe. The beam after target with large emittance and momentum spread can be cooled down in seconds by stochastic cooling with slot line pickup and kickers [13]. Stochastic cooling will be used in the Schottky Mass Spectrometry (SMS) experiments. The relativistic Li-like O^{5+} beam, with energy of 280 MeV/u, was cooled by CW laser of wavelength 220 nm recently. It's up to now heavy ions with highest charge state and highest energy that ever been laser cooled. Figure 9 shows the setup of laser cooling at CSRe.

FUTURE DEVELOPMENTS

Up to now, SFC is the only injector for both SSC and CSRm. This limited the total beam time of the HIRFL complex. To increase the beam time, new injectors are urgently needed. Under the support of CAS and IMP, a CW Linac injector of SSC is being developed since 2012, which will accelerator heavy ion beam to 1.024 MeV/u [14,15]. New pulse Linac injector for direct injection to CSRm is designed and underdevelopment. The operation modes of HIRFL will be enhanced with new injectors (see Fig. 10). With the new injectors the beam time for experiments will be increased dramatically.

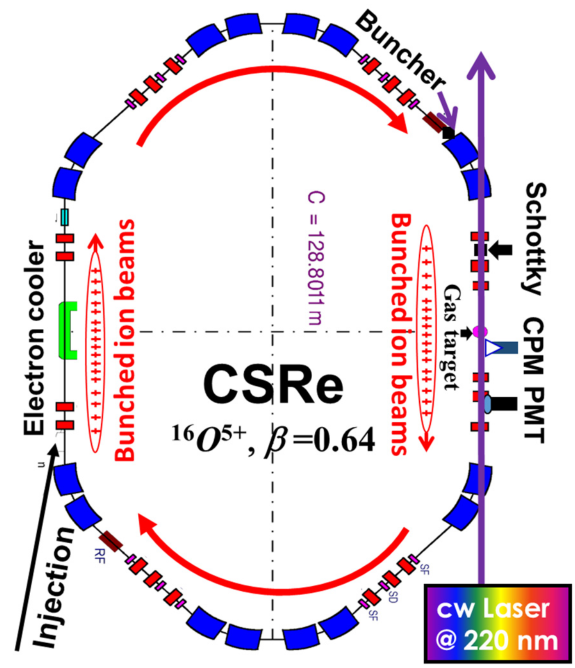

Figure 9: Experimental setup of laser cooling at CSRe.

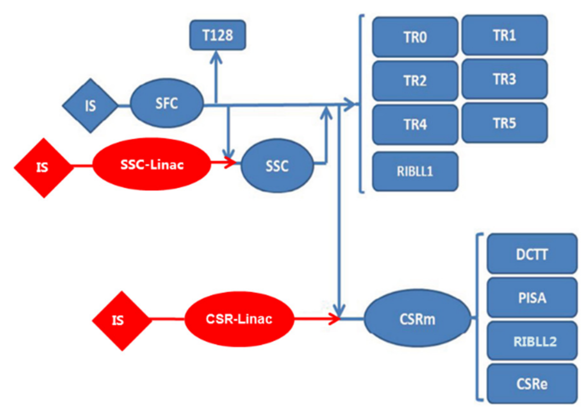

Figure 10: Operation modes of HIRFL with new injectors SSC-Linac and CSRm-Linac.

The first part of SSC-Linac [14,15], energy up to 580 keV/u was constructed off-site. We identified and solved the momentum resolution problem of high intensity heavy ion beam at Q/A selection system [16]. The updated Q/A selection system with additional solenoid reached sufficient Q/A resolution. It will be installed at SSC hall next year. The energy after further acceleration of SSC will be 6 MeV/u, compared with present 1 MeV/u of Uranium from SFC. The intensity will be increased 10~100 times.

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Fig. 11 shows the design location of SSC-Linac and the off-site development of SSC-Linac. The beam lines with crossed vacuum chambers were ready for parallel operation with injectors SFC and SSC-Linac.

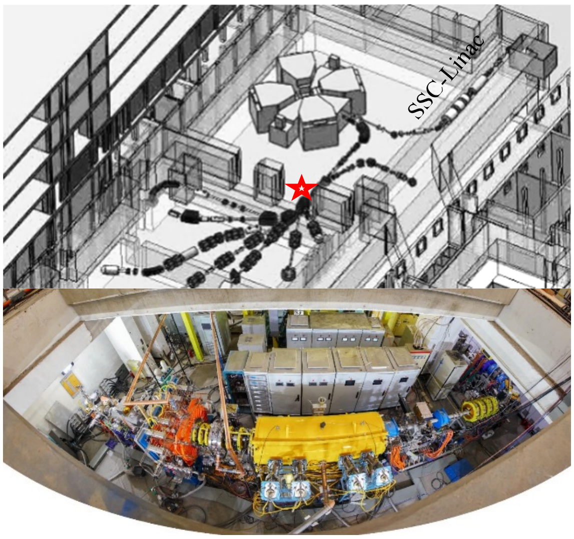

Figure 11: The design location of SSC-Linac (up) and the off-site development of SSC-Linac (down). At the red star position of the beam lines, the vacuum chamber is crossed for parallel operation of injectors.

CONCLUSION

We have detailed the present status of HIRFL complex. To match the increasing beam time and quality requirement of HIRFL, continual improvements of infrastructure remains an important aspect, developments and applications of new technologies are the other. Meanwhile, for the new project HIAF [17], which will break ground in 2018, many aspects of new technology should be studied by the construction group and some of them will be verified at HIRFL.

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