STATUS, NEW DEVELOPMENT AND UPGRADING PROGRAM AT HIRFL

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Abstract : The operation status and new development including the accelerator and experimental stations of HIRFL facility in the last years, and the upgrading program for the next five years are presented. The new completed radioactive beam line RIBLL, the new axial injection system and the new central region for the injector, the ECR ion source development and the new frame of control system are given in some details. The new project CSR is also presented with its main parameters. A upgrading program is under studying to meet the requirement of RIBLL and CSR towards radioactive beam researches.

1 Introduction

HIRFL has been operating nearly 10 years since the first beam in the end of 1988. The amelioration has been undertaking but with quite modest step, and with the effort the operation efficiency and the beam characteristics such as intensity and ion variety have been improved. But the requirement from the nuclear physicist are becoming stronger to get high beam intensity and ion variety, especially with the new completed RIBLL (Radioactive Ion Beam Line at Lanzhou). The new poster-acceleration project CSR (Cooling Storage Ring) which is under preliminary technical design, asks for the large extending of both beam intensity and ion variety. For the reason of the technical renovation, some subsystems of the machine have been changed and will continue to be changed in the coming years, especially in the domain of computer and beam diagnostics.

2 Operation status

HIRFL have been operating nearly 4500 hours per year and about 3000 hours delivered to experiments in the last years, with about three months shut-down in summer and in winter every year. The long term of shut-down is due to the short of support budget, machine improvement, maintenance and holidays. The beam currents for light ions have been increased from around 50nA to 150nA, and about 40 new beams of different ion species or different final energies have been accelerated during the last nine

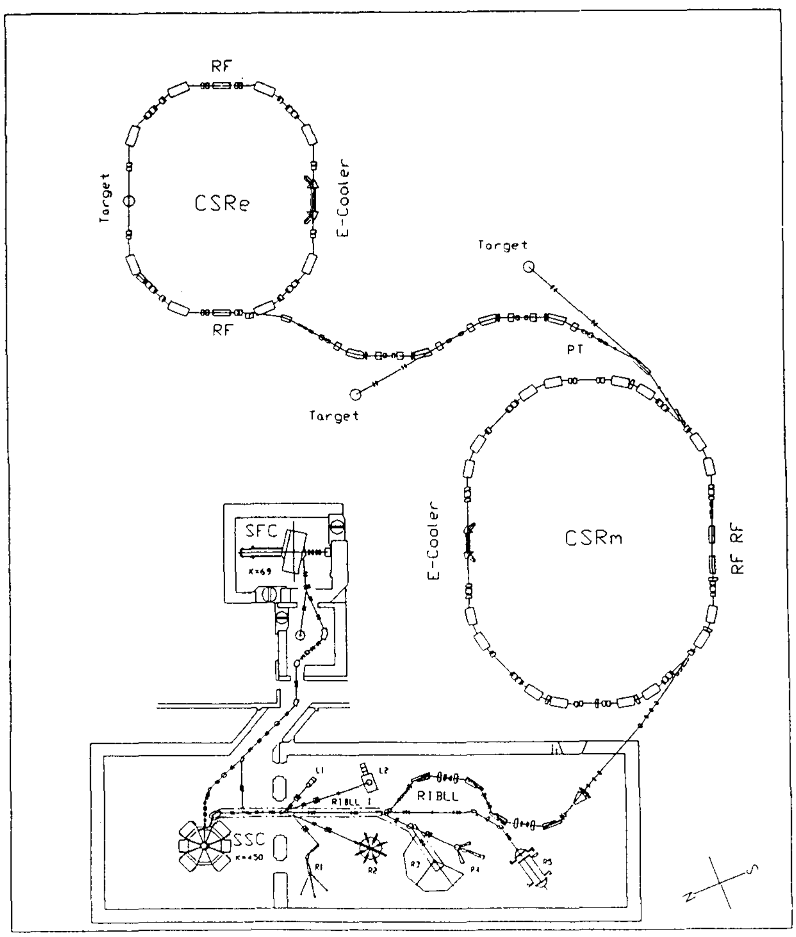

Figure 1, Layout of HIRFL-CSR

years. The operation efficiency (beam time over operation time) has also reached about 70%. The heaviest element accelerated is Xenon. We will try to accelerate metallic ions in the end of the year, and heavier elements up to Uranium in the coming years. Some typical beam characteristics are shown in Table 1.

Table 1, Some Ions Accelerated at HIRFL

Ions	Z1/Z2	E(MeV/u)	I(eμA)	
^{12}C	4/6	75	0.05	
^{16}O	6/8	100	0.01	
^{18}O	6/8	60	0.17	
^{20}Ne	7/10	80	0.13	
^{32}S	9/	5.35	1.1	Injector
^{36}Ar	10/	5.3	1.2	Injector
^{40}Ar	8/15	30	0.1	
^{84}Kr	13/22	16.2	0.04	
^{129}Xe	18/18	8.0	0.003	

3 New developments

3.1 RIBLL radioactive beam line

In July 1997, a radioactive beam line RIBLL (Radioactive Ion Beam Line at Lanzhou) was completed[1], see Figure 1 and Figure 2. Since then, several experiments have been done with the new experiment station, and with ions of ^{18}O 60MeV/u and ^{20}Ne 80MeV/u. The main parameters are listed in the Table 2. This spectrometer with very large acceptances of both transversal and longitudinal means, produces and identifies varied radioactive light ion beams by means of projective-fragmentation method. It has two asymmetric parts of achromatic design which gives the possibility to put the experiment target either at the first object point after the first achromatic section or at the second one after the second section. In the former case, the second part can be played as the ion identification spectrometer of reaction products. It consists of 4 Dipoles, 16 Q-poles and a swinger, and extends about 35m longer.

Table 2, Main Parameters of RIBLL

Solid Acceptance	>6.5
Momentum Acceptance	10%
Magnetic Rigidity(max, Tm)	4.2
Resolution of Magnetic Rigidity	~6×10^{-4}
Element Resolution Z/ΔZ	50~120
Mass Resolution A/ΔA	>500
Primary Beam Incident Angle	0°~5°
RIB Separation Time (μs)	<1

3.2 ECR ion source development

In the last years, two new ECR ion sources (ECR2 and ECR3) have been built in the laboratory. ECR2 is the some similar to the design of CAPRICE type (ECR1) which we bought from CENG laboratory, Grenoble, France, with 10 GHz microwave but better magnetic confinement design[2]. It has been put in operation since 1994. With ECR2, a new working mode was found and that gives about double intensity for high charge states. Some studies with laser was also done to produce metallic ions. ECR1 has also been modified largely to improve the performance. ECR3 still under testing on the testbench, uses 14.5GHz microwave and maybe two microwave frequencies in future[3]. The initial test results with gaseous elements are quite encouraging. The test with metallic elements is foreseen in the late year.

3.3 New axial injection system for SFC[i]

The old axial injection line built in 1992 had several drawbacks such as low charge state analysis power, tight space and difficulty to the maintenance of ECR ion source and the beam line, etc. The new injection beam line was completed in September, 1997, see Figure 3. The main features with the new beam line, called BL0 thereafter, are stated below.

1)Two ECR ion sources are put on line which can act as

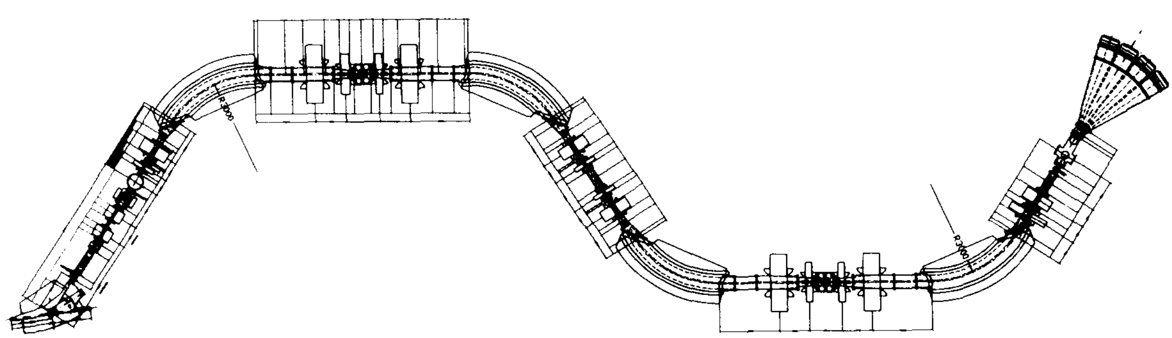

Figure 2, Layout of radioactive ion beam line RIBLL substitute each other. The two sources have their own beam analysis systems, so one can be tested when the other is in operation.

2)Larger space is available for the maintenance and future development. The new beam line was built in the opposite direction to the old one, and the room space was rearranged by changing some supports and walls.

3)The analysis power for charge state is usually 1/65 and can reach 1/125 with the combination of two magnets. The high analysis power is necessary to the tuning of ECR ion source when the heavy ions are accelerated.

4)The buncher system was redesigned[4]. The two bunchers working individually at the moment, are different types, double gap drift-tube for B01 and single gap grid electrode for B02. The buncher B01 designed mainly for harmonic one uses triangular bunching wave, and the buncher B02 mainly for harmonic three uses sawtooth wave with maximum 90% for the bunching slope. The sawtooth wave is generated by direct forming method of charging-discharging and has quite good linearity[5], see Figure 4. Both bunchers are usually set at the half of the injector RF frequency, and this mode can regain the 50% beam loss in the most cases due to the mismatching of the SFC extraction radius and the SSC injection radius.

5)A beam chopper using pulsed electric field was installed on the new beam line BL0, which can be used by both the accelerator tuning and some physics experiments to reduce the beam intensity by a factor 1~10. The applied voltage is fixed at 350V, and the rise time and drop time are around 100ns and 300ns respectively for the frequency range

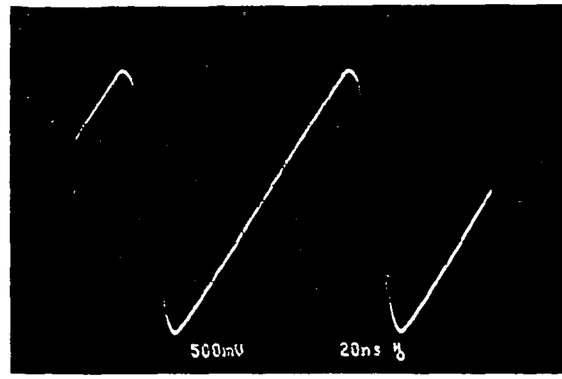

Figure 4, Sawtooth waveform of B02 (f=6MHz)

100Hz~100kHz.

6)The beam diagnostics system on the line BL0 were also renovated. The fluorescent screens with image analysis system are in the place of multiwires, and the beam emittance measurement is possible by three gradients method. More slits were used to define the beam emittance and the beam intensity.

7)The vacuum of SFC was designed to work at the average 1~2×10^{-5}Pa, better than 5×10^{-5}Pa on the old line. The high vacuum is necessary to accelerate heavy ions. There is also some improvement for the pumping inside the axial hole and the spiral inflector.

8)The initial results operated with the new BL0 line were good. The injection efficiency for the low intensity beam was increased largely from 20% to 45%, mainly due to the

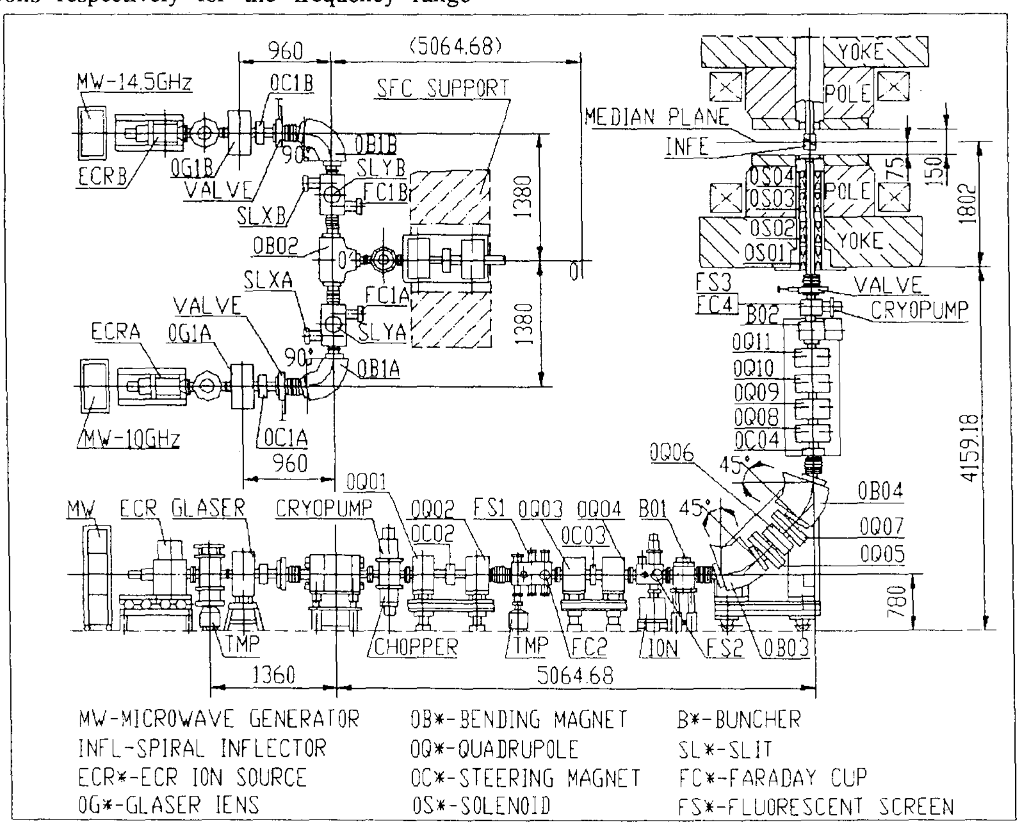

Figure 3, New axial injection beam line for SFC contribution of the new bunchers. The total transmission efficiency at SFC is normally at 5~15%. The poor efficiencies happen at the beam line from the ECR source after analysing the charges and at the extraction from SFC, 40~60% and 40~70% respectively. Due to the strong stray magnetic field on the BL0 line, some about 30Gauss, it is difficult to align the beam on the optical axis. The strong field is considered due to the increased pole radius from 1.5m to 1.7m without changing the yoke when the cyclotron SFC was upgraded in 1984.

3.4 New central region for SFC

The central region was redesigned to use two injection radii instead of one in the past, but with the same geometry of electrode except the use of two different spiral inflectors and their hosts[6]. The injection mode of $R_{inj} = 3.0cm$ is used in the case of accelerating heavy ions, and there harmonic three is usually used for the RF frequency. The injection mode of smaller radius $R_{inj} = 2.5cm$ is used in the case of accelerating light ions with harmonic one. With the two injection modes, we can increase the extraction voltage of ECR ion source for heavy ions (or small charge mass ratio) and keep the maximum tension of 25kV unchanged. The new central region was also designed to decrease the requirement of RF voltage for the high frequency extremity of both harmonics, since the available RF voltage of 70~75kV is not sufficient for the old central region. With the variation to the constant orbit mode, it permits to give the lesser turn number about 110 for H=1 and 80 for H=3 when the RF voltage is easy to obtain, and about 150 for H=1 and 120 for H=3 for the contrary. It was put in operation in January, 1996. We saw the significant gains (>3 times) of beam intensity with the bigger injection radius when accelerating Kr and Xe beams, as the space charge effect was weakened with higher injection energy.

3.5 New computer platform for control system

The HIRFL machine was controlled by a VAX-8350 computer which is outdated and can not be maintained for a considerable period. In 1997, we replaced the central control system by a new system of using distributed mode[7]. All the subsystems are controlled through powerful PC which are connected through Windows 95 network (next Windows NT and some workstations). Although not completed yet, the new control system with the new interface already brings us some advantages for the convenience and the speed.

3.6 Other improvements

We have also improved the other subsystems during the last years. When we accelerated krypton ion at HIRFL in 1994, we observed big beam loss at SFC. The analyse showed that SFC vacuum was not sufficient to accelerate heavy ions. Then we did some studies about the charge exchange process at HIRFL and experiments about the pressure distribution inside SFC[8]. In 1996, the SFC vacuum system was cleaned and some seal parts were replaced or redesigned. The vacuum was improved from $1\sim2\times10^{-6}$torr to $5\sim7\times10^{-7}$torr in the central region.

As the SFC extraction deflectors have some trouble when working long time at the high voltages of 75kV (ESD1) and 90kV (ESD2) corresponding the highest extraction energy, the new electrostatic deflectors were designed and machined. The deflectors which are under testing, were designed by means of new electrode shape, typically the two extremities and materials for SFC. It is expected that they will hold better the high tension. We modified also the mechanism of the position adjusting.

4 Upgrading program

In order to meet the requirements from the undergoing studies with radioactive ion beams and the new project CSR described in the next section, the HIRFL machine must be upgraded to deliver higher beam intensity than present level, e.g. 10 times for light ions and 100 times for heavy ions. We have made a upgrading program to be undertaken in the next five years. Some are described briefly here.

1)Further increasing the injection radius at SFC to 3.6cm for very heavy ions, that means that the central region has to be adapted with three injection modes and with three different spiral inflectors. This modification is the same effort described in the section 3.3 to reduce the space charge effect on the injection line.

2)The axial injection line at SFC will be improved by solving the problem of the strong spray magnetic field on the line and by replacing some solenoids which were not designed correctly.

3)A new rebuncher B1 on the beam line BL1 is to be built and one of the two old bunchers has to improved to be installed at the B2 position. The two rebunchers will be responsible to the augmentation of the beam intensity to the large extent. The new buncher system is designed to work at different harmonic modes. The new B1 works at harmonic 2,3,4,6 respect to SFC-RF instead of harmonic 4 respect to SSC-RF, as the non-linear effect becomes important with transferring low energy heavy ions with a single harmonic mode. The working RF amplitude is set to be 20~100kV instead of the old 40~70kV. The auxiliary rebuncher B2 which will be replaced from the old B1, will be used not only to make a phase length at the SSC entrance smaller than the one at SFC exit, but also used to compensate the energy mismatching caused by the loss in the stripper and the variation from SFC. In the most cases, SFC uses precessional extraction, so it is not convenient to use RF amplitude to adjust the extraction energy. At the moment, B1 is in the stage of technical design, with the help of MAFIA package.

4)At the SSC injection region, there exists a strong residual perturbation of the magnetic field of harmonic one, which is caused by the overcompensation of the iron shim to the field perturbation of the injection element Mi2. The 1st

harmonic magnetic field causes the difficulty to inject the beam by means of strong precession. The studies with MAFIA computation and magnetic measurement are being undertaken to eliminate the residual perturbation to large extent. There is consideration about to increase the maximum magnetic rigidity of the injection system, as the main field can reach 1.7T instead of the design value 1.6T. We are interested in accelerating heavy ions without passing the stripper and that needs higher injection magnetic rigidity. We have only 10~20% ions left for the most probable charge after the stripping. We succeeded to accelerate Xenon beam without stripper in February, 1997.
5)The SFC vacuum has to be increased to 10^{-8} torr level, in order to accelerate very heavy ions such as Pb, U etc. A new vacuum chamber may be necessary to build if the further improvement of the actual one does not satisfy the requirement. The vacuum of RF cavity has to be improved at the same time.
6)The renovation of the beam diagnostics system is also the important and the difficulty work that should be done in the coming years. One reason is that the actual system is totally unsatisfactory and far behind the requirement of machine tuning and the operation. The other reason is that the operation with high beam intensity needs new techniques for the beam diagnostics. The main effort will go to some probes and their electronics such as beam phase probe, beam position monitor, non-interceptive profile monitor.

5 CSR project

The new project CSR (Cooling Storage Ring) as the post-accelerator of HIRFL machine being undertaken preliminary studies[9] and some technical exploration, waits for its official approval from the Chinese government. The project mainly dedicated to the radioactive ion beam physics consists of two cooling rings in cascade. One main ring to accumulate and accelerate ions is called CSRm and one experiment ring called CSRe is for the use of radioactive beam produced at the target between the two rings and of beams of very high charge state asked by the atomic physics researchers. The main machine parameters and beam characteristics are shown in table 3, and the scheme is depicted in Figure 1.

Acknowledgement

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Table 3, Mai10n parameters of the CSR

	C00110SRm		CSRe
Circumference(m)	161.201		120.901
Specific Energy (MeV/u)	25--900(C^{6+}), 10—400(U^{72+})		30--400(C^{6+}), 30—250(U^{90+})
$B\rho_{min}/B\rho_{max}$ (Tm)	1.40/10.64		1.50/6.44
B_{min}/B_{max}(T)	0.18/1.40		0.25/1.40
Ramping rates (Tm/s)	~3		~2.5
Repeating Circle (s)	~17 (10s for Accum.)		
Acceptance	With error		Pure
ε_h(πmm.mrad)	200		470 ($\Delta p/p$=0)
ε_v(πmm.mrad)	20		170
Δp/p (%)	±0.15		±3.5 (ε_h =0)
E-cooler			
Ion Energy (MeV/u)	10-50		30-300
Length (m)	4.0		3.5
RF system	Accel.	Accum.	Capture
Harmonic number	2	16, 32	1
f_{min}/f_{max} (MHz)	0.5/3.3	6.0/14.0	0.6/1.8
Voltages (kV)	1×7.0	1×20.0	2×15.0
Vacuum (mbar)	2×10^{-11}		2×10^{-11}

[i] Partially supported by National Science Foundation, 19675056