HIRFL-CSR FACILITY STATUS AND DEVELOPMENT*

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Abstract

The HIRFL-CSR facility come into operation by the end of 2007. During operation in recent years, CSR supplied beam for experiments at several terminals and inside both CSRm and CSRe rings. The experiments covers high resolution mass measurement, cancer therapy research, neutron wall, atomic physics using electron target and internal gas target, using injection beam mainly from the SFC of cyclotron injector. New methods and further developments are required to improve the performance of CSR system including multi-gradients measurement method for beam spot commissioning and beam transfer, nonlinear effect correction and stabilization of isochronous mode of CSRe. For suppling of heverier ion beam with proper ernergy, the cyclotron complex should be enhanced and new injector is proposed to replace SFC as injector of SSC.

INTRODUCTION

The layout of HIRFL-CSR project including injector system is shown in Figure 1[1,2,3]. The main parameters are listed in Table 1. For injection and acceleration of low energy beam(<10MeV/u) directly from SFC, as the span of RF cavity is insufficient, harmonic capture and acceleration (H=2 or 3) is adopt.

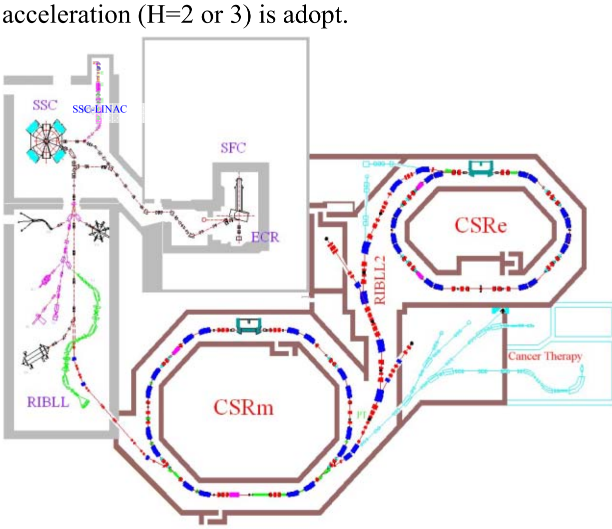

Figure 1: Layout of HIRFL-CSR.

The HIRFL-CSR facility come into operation by the end of 2007. During operation in recent years, CSR supplied beam for experiments at several terminals and inside both CSRm and CSRe rings. The operation parameters of supplied beams are listed in table 2. The operation time with HIRFL-CSR took about half of the total running time of HIRFL.

Table 1: Major Parameters of CSR

	CSRm	**CSRe**
Length	161.0m	128.8m
Ion species	Carbon~Uranium	Carbon~Uranium
Magnet rigidity	0.7~11.5Tm	0.6~9.4Tm
Acceptance		Normal mode
ε_x (π mm-mrad)	200(ΔP/P =±0.15 %) 50(ΔP/P =1.25%)	150(ΔP/P =±0.5%) 10(ΔP/P =±1.3%)
ε_y (π mm-mrad)	30	75
Tunes	3.63/2.62	2.53/2.58
e-Cooler	2-35kV (3-50MeV/u)	50-300kV (70-420MeV/u)
Vacuum Pressure	$<6\times10^{-11}$mbar	$<6\times10^{-11}$mbar
RF cavity	0.24~1.7MHz 7kV	0.5~2MHz 2×10kV
Injection	Multi-turn Charge exchange	Single turn
Extraction	Fast Slow(RF KO)	-

Table 2: Major parameters of CSR operation

Beam	$^{12}C^{6+}$	$^{36}Ar^{18+}$	$^{78}Kr^{28+}$	Xe^{27+}
Injector	SFC	SFC+SSC	SFC	SFC
Accumulation Scheme	Charge exchange	Multi-turn	Multi-turn	Multi-turn
Energy(MeV/u)	150~300/ 600	368~500	300~500	197~ 235
Extraction Scheme	Slow/fast extraction	Fast ext.	Fast ext.	Fast ext.
Intensity(ppp)	$2\times10^8/7\times10^9$	4×10^8	2×10^8	1×10^8
Exp. Terminal	Cancer Therapy/ Neutron Wall	CSRm/ CSRe mass spect.	CSRe mass spect.	CSRe internal target

*Work supported by NSFC(10921504) and National Laboratory of Heavy Ion Research Facility in Lanzhou, China
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OPERATION WITH SLOWLY EXTRACTED BEAM

Basic Design and Performance

In CSRm, the 1/3 integer resonant in horizontal plane is designed for slow extraction[4]. For slow extraction at the energy flattop, the horizontal tune value is set to 3.663, the chromaticity is corrected to zero in both plane and the dispersion function at first extraction inflector is set zero. The area of stable separatrix triangle for all momentum deviation (<0.1%) is designed as 13 π.mm.mrad.

By using RF Knock-out as resonance exciter, the amplitude of horizontal betatron motion increases gradually, finally particles cross the stable separatrix and extracted. The excitation frequency is usually set to 1.663 times of the revolution frequency. The field strength is modulated during extraction to get smooth spill. The main frequency in spill structure is 50Hz due to the power supply ripple, filling factor is about 0.6 presently(Fig. 2). Spill structure will be improved by feedback system later. The extraction efficiency ranges from 15% to 60%, further study of slow extraction is being done to improve it.

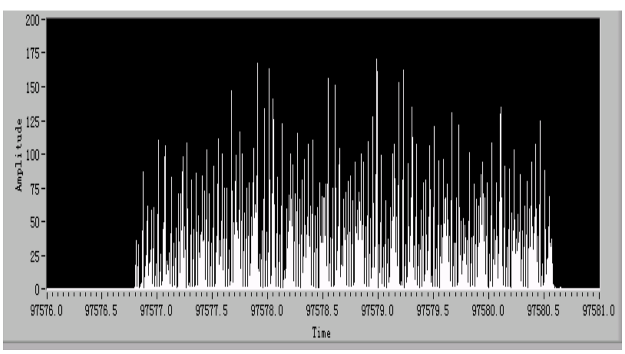

Figure 2: Time structure of slowly extracted beam from CSRm, detected by plastic scintillator. (Spill length is 3.5s)

Beam Spot and Improvement

The time structure of beam spill is not the only one, but the beam spot size is important for cancer therapy to get required dose distribution. The FWHM of beam spot is 10~20mm presently. To reach smaller beam spot in CSR cancer therapy terminal, new method is being developed. The beam parameters, both transverse and longitudinal, can be measured using the multi-gradient method. Figure 3 shows the basic layout of multi-gradient method.

The three-gradient emittance measurement method is well known, but it depends on the assumption of negligible momentum spread and dispersion. When multi-gradient method is used, the longitudinal beam parameters can be easily revealed by fitting of spot sizes to focusing strength of the quadrupole. It's expected to be helpful in target spot forming.

Single-time Charge Stripping Injection

For cancer therapy, single-time charge stripping injection is tested, without electron cooling but with RF bucket on; over 10^9 carbon particles are injected every machine cycle. The result shows the possibility of using cyclotron as injector for HITFiL(Heavy Ion Therapy Facility in Lanzhou, shown in Fig.4), which will be constructed in 3 years.

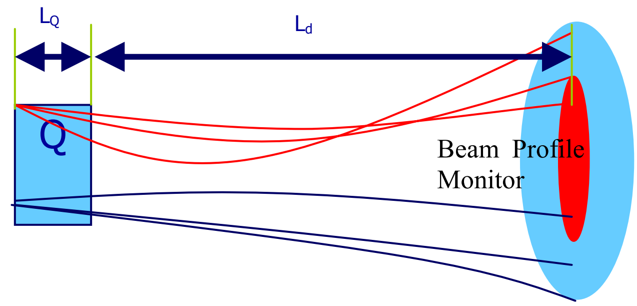

Figure 3: Basic layout of multi-gradient method to measure beam parameters.

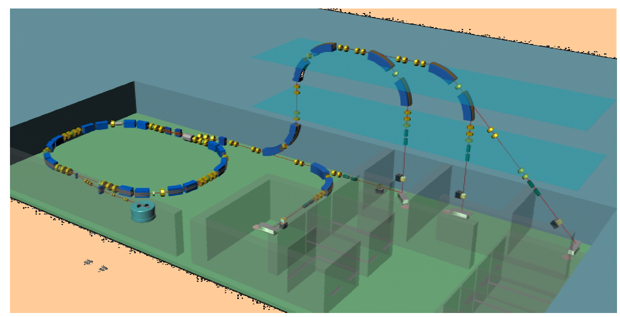

Figure 4: Layout of heavy ion therapy facility in Lanzhou

Conformal Ion Beam Treatment

The treatment in CSR extended the therapy research to deep-seated tumour; two batches including 10 patients were treated. The location depth of tumours was in the range of 3 to 10cm. Most of the tumours were treated with passive energy variation longitudinally and uniform scanning transversely.

The active energy variation and spot scanning technologies are developed and being tested. CSR has the possibility of active energy variation with 255 steps in the energy range of 100~430MeV/u for C^{6+}. It's difficult in commissioning of the energy steps since the hysteresis effect influenced the injection field level (~1%) and efficiency. This effect can be eliminated by ramping of the magnet field to its maximum of treatment every machine cycle. The spot scanning results show good position precision (<1mm) and dose distribution (>80% uniformity, detected by irradiation films). An online dose distribution monitor using 2 sets of slitting ionization chambers (2mm resolution) for both horizontal and vertical direction was built up. A measured particle counting distribution result is shown in Figure 5. The scanning area is 12×12cm^2.

Neutron-Wall Experiment

For testing of the detector matrix at stationary target area, C^{6+}-600MeV/u was slowly extracted and transported through Be foil to a stationary target outside the vacuum chamber. The test experiment observed and distinguished mesons for the first time in IMP. The stability of beam position on the target should be improved to increase the resolution of spectrum.

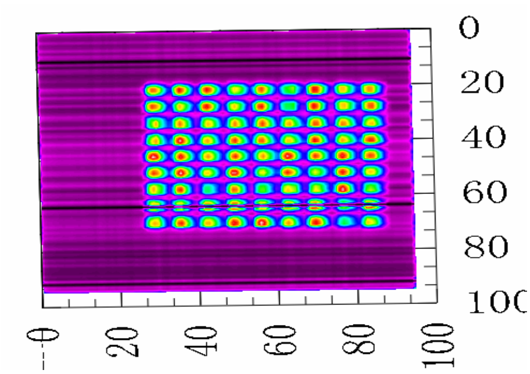

Figure 5: Result of spot scanning test. The black lines show detector failure.

OPERATION OF CSRE MASS SPECTROMETER

The isochronous mode of CSRe is designed with γ_{tr} =1.3953 and acceptance $\Delta P/P \cong \pm 0.35\%$ ($\varepsilon_{x,\,y}$ = 20, 75 π mm mrad). Lacking of proper testing method, the mode is tested with Shottky spectrum of primary beam. Later test experiments with $^{36}Ar^{18+}$ as primary beam[5], the mass resolution reached 10^{-5} for the measurement of ^{32}S, ^{28}Si, ^{34}Cl and ^{30}P.

Aiming at the precise mass measurement of ^{65}As, ^{78}Kr was chosen as primary beam. In every machine cycle (~15s), 2×10^{8} primary particles hit the 15mg/cm^2 Beryllium target. The experiment takes two runs, 10 days for the first run and 15 days for the other. For the first run, 10 target-events are recorded [6], 50 events for the later.

All the data recorded are used to check the whole experiment set. As the first result, by proper fitting method, the magnet rigidity of centre closed orbit is revealed and checked with continuous field measurement of one dipole. Figure 6 shows the fitted centre rigidity offset to the measured data of magnet field in one hour.

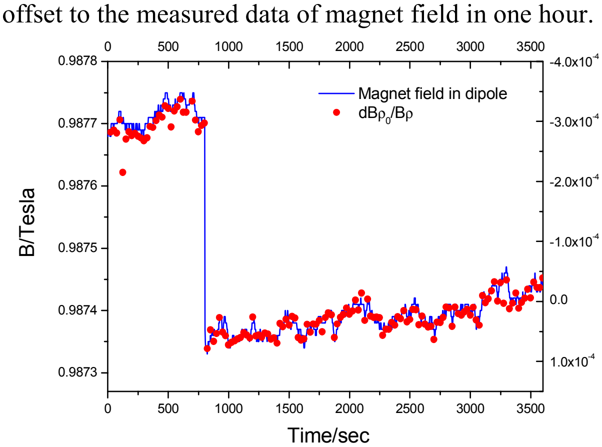

Figure 6: The fitted centre rigidity offset to the measured data magnet field during one hour. The big change is intentional.

The magnet field data are recorded during the second run of 15 days. Figure 7 is the waterfall chart of the data. By removing of the artificial field shift, the field drift is clearly periodic by day, as shown in Figure 8, and reveals the influence of human activity on power supply system. the field drift about 10Gs(0.05%) every day. The influence on experiment is large, this can be seen in the period data. Nine hours of the period data are shown in Figure 9, the period fluctuation is very large. The data are reconstructed to designed condition (red dots in figure 9).

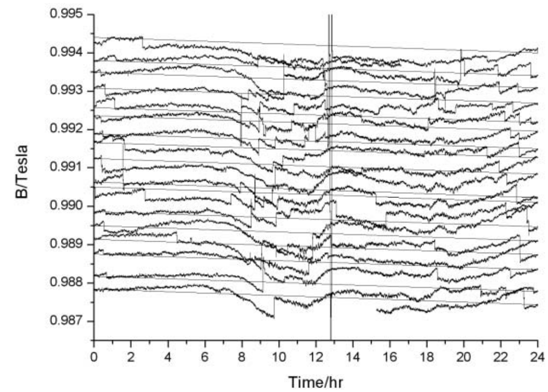

Figure 7: Waterfall plot of recorded field drift of dipole from midnight to midnight.

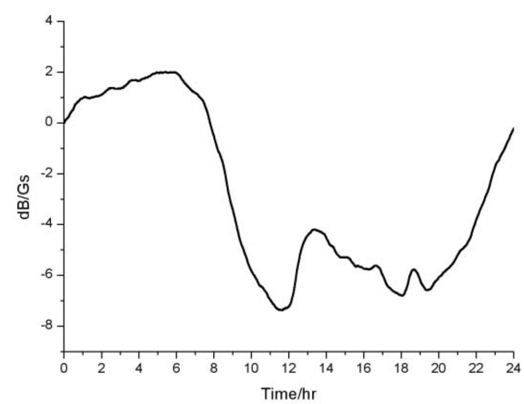

Figure 8: Periodic field drift of dipole field from midnight to midnight.

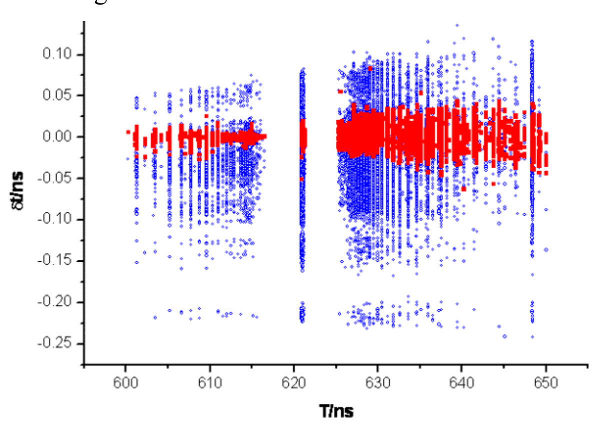

Figure 9: Data of the measured periods of identified nuclides in 9 hrs(blue) and the distribution after reconstruction (red).

Further study of isochronous mode of CSRe shows the correction of nonlinear effect is necessary. The lattice investigation shows the dependence of transition energy on momentum offset at different conditions (Figure 10).

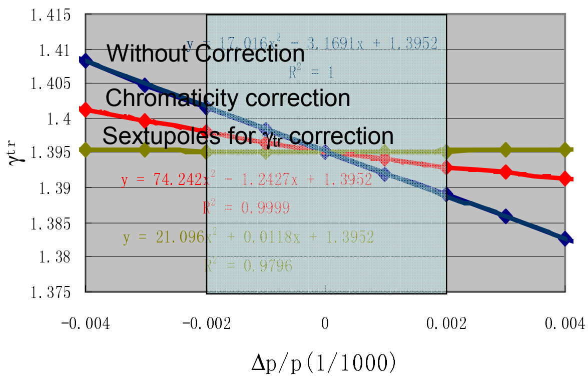

Figure 10: The dependence of transition energy on momentum offset at different conditions.

The experiments up to now were done without transition energy corrections. That's limits the time resolution to 1×10^{-5} for the target nuclei as isochronous mode. With precise corrections, we can expect 1×10^{-7} time resolution. The key point to acheive such a high resolution is the testing method, it's now under investigation.

OPERATION OF ELECTRON COOLER AND EXPERIMENTS OF ATOMIC PHYSICS

The e-cooler for CSRm was in function by the end of 2006[7,8], the performance is very good for the accumulation of heavy ions. However, there is still trouble in the positioning of electron beam and ion beam to be parallel and coaxial between each other; it results in less efficiency of the accumulation.

The modification of high voltage power supply and control system of CSRm cooler is done to change the electron beam energy rapidly. Based on further test of it, modification of the e-cooler in CSRe will be done for atomic physics with higher energy highly charged ions.

The e–cooler of CSRe is now works stably in cooling of high energy heavy ion up to energy of 400MeV/u[9], where it is also difficult to position then electron beam. With the e-cooler of CSRe, the first REC experiment with internal target is done.

In the REC experiment, $^{129}Xe^{54+}$ is produced with thick target in RIBLL2 transfer line, injected in CSRe and hits on the Nitrogen gas target (~$10^{12\text{-}13}$atoms/cm^2). By using of high purity Ge detectors the energy distribution of X-rays is recorded with good resolution (Figure 11).

It's observed from total signals count rate that the beam closed orbit shifts during the target period and affects the brightness and resolution. A slow feedback system should be used to keep the closed orbit and maintain high brightness.

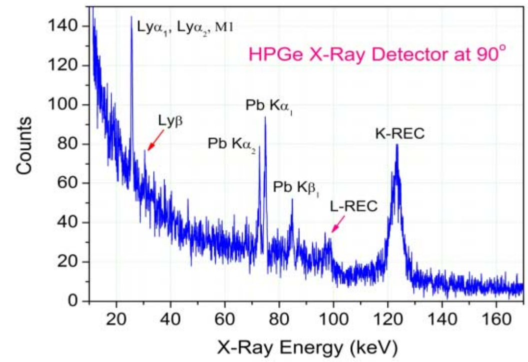

Figure 11: X-ray spectrum detected by HPGe detectors in first REC experiment of CSRe.

THE INJECTOR COMPLEX

By using of cyclotron complex of SFC and SSC as injector system, CSR successfully provided beams of C, Ar, Kr and Xe beams for experiments. But its disadvantage in beam intensity is obvious too.

Usually, the SFC cyclotron alone is used as the injector as its intensity is about one order higher than SSC. But the energy from SFC is not enough to get high charge to mass ratio for heavy ions. It limits the maximum energy can be reached in CSRm.

Bismuth beam is tried this year, the intensity from SSC is about 70~300enA, and is unstable. To get higher intensity of heavy metallic ion beams, the stabilization of machine operation is the first thing to overcome in HIRFL.

It's planned to build a linear accelerator as injector of SSC. The SSC-LINAC is designed to provide heavy ion beam up to Uranium with energy of 1MeV/u. the plan is shown in Figure 12. The major parameters are shown in Table 3.

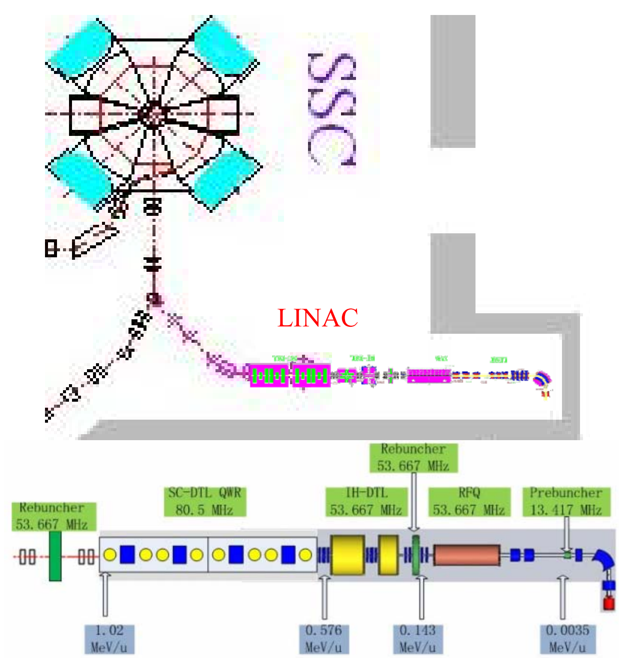

Figure 12: The layout of SSC-LINAC plan

Table 3: Main Parameters of SSC-LINAC

Total Length(m)	18.5
Ions	C~U
Energy(MeV/u)	0.576/1.025
Bunch Frequency (MHz)	13.4167
RFQ Frequency (MHz)	53.6667
Rt-DTL Frequency (MHz)	53.6667
SC-DTL Frequency (MHz)	80.5
$\delta P/P$	$\pm 5\times10^{-3}$
$\Delta\phi$(deg)	± 6
$\varepsilon_h/\varepsilon_v$ (π mm.mrad)	15/15

OTHER ASPECTS OF HIRFL-CSR IMPROVEMENT

An automatic commissioning system is developed and tested for the commissioning of transfer line. By using beam intensity measured from faraday cup, the commission cycle repeated automatically to improve transfer efficiency. It's expected to reduce workloads if the system is spread over the whole HIRFL injector system.

For mass measurement of secondary nuclei with Shottky spectrum, in addition to the existing electron cooler of CSRe, a stochastic cooling system is also proposed to be designed and installed. To make the span wider and cooling time shorter, a new lattice structure is designed to reduce the flipper factor η to about 0.2, meanwhile the acceptance is reduced to $\delta P/P=\pm 5\times10^{-3}$ with emittance $\varepsilon_h=50\pi$ mm mrad. The cooling time simulated is about 4s.

A molecule injector of CSRe is also proposed. It will supply beam of molecule with mass number up to 100 to CSRe. After it's accelerated to maximum magnet rigidity, it will interact with new developed electron target. The injection system, beam detection and diagnosis system will be reformed for this purpose too.

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