COMMISSIONING OF CSR IN LANZHOU*

W.L.Zhan, J.W.Xia, H.W.Zhao, Y.J.Yuan, K.D.Man, P.Yuan, D.Q.Gao, X.T.Yang, M.T.Song, G.Q.Xiao,W.M.Qiao, X.H.Cai, X.D.Yang, B.W.Wei, and HIRFL-CSR Group
Institute of Modern Physics, CAS, 730000, Lanzhou, China.

Abstract

HIRFL, is consists of the ECR ion source, cyclotron of SFC, SSC, and CSRm, CSRe, had been installed and started commission from 2005. Two injection modes of the stripping injection and MMI with electron cooling were tuned successful. The typical gains of accumulation from 7 to 60 were obtained by single multi-turn injection or multiple multi-turn injections (MMI) respectively. The beam momentum spread typical from 4×10^{-3} is cooling to 2×10^{-4}. The life time of storage beam with electron cooling are about 10 second for 2.86MeV/u Xe and >1000 s for 7MeV/u C. The beams were accelerated by switching the harmonic number 2 (4) to 1during ramping. So far, three kinds of beams, 10^9ppp of $^{12}C^{6+}$, 10^8 ppp of $^{36}Ar^{18+}$ and 10^8 ppp of $^{129}Xe^{27+}$ were accelerated to 1000MeV/u, 235MeV/u and extracted from CSRm respectively. The beam has past RIBLL-II and inject into CSRe. Detail commissioning of CSRe is ongoing. After test run on CSRe, HIRFL-CSR is reviewed before end of this year and will open for user next year.

INTRODUCTION

The Heavy Ion Research Facility in Lanzhou (HIRFL) has found as national laboratory in 1992 and expanded its capability by upgrading Cooling Storage Ring (CSR) project from 2000[1,2]. Its accelerator complex is consists of ECR ion sources, the cyclotrons of Sector Focus Cyclotron (SFC), Separated Sector Cyclotron (SSC) and the new electron cooler synchrotron (CSRm), the experimental cooling storage ring (CSRe) as fig.1. Its main performances are listed at table.1. Now, CSR is under commissioning and the existing cyclotron system is served as the injectors.

Table 1: Main performances of HIRFL accelerators

Accelerator	**SFC**	**SSC**	**CSRm**	**CSRe**
Ions	H, C-U	H, C-U	H, C-U	H, C-U, RIB, HCI
Energy				
K/Proton(MeV)	70	450	2800	2000
$^{12}C^{6+}$(AMeV)	10	100	1100	760
^{238}U(AMeV)	0.8 $^{238}U^{26+}$	11 $^{238}U^{40+}$	520 $^{238}U^{72+}$	500 $^{238}U^{90+}$
ΔP/P	$\sim10^{-2}$	$\sim10^{-3}$	$\sim10^{-4}$	$\sim10^{-5}$
δP/P (entrance)			±0.15%	±0.25% ~0.5%
emittance			≤5π	≤1π

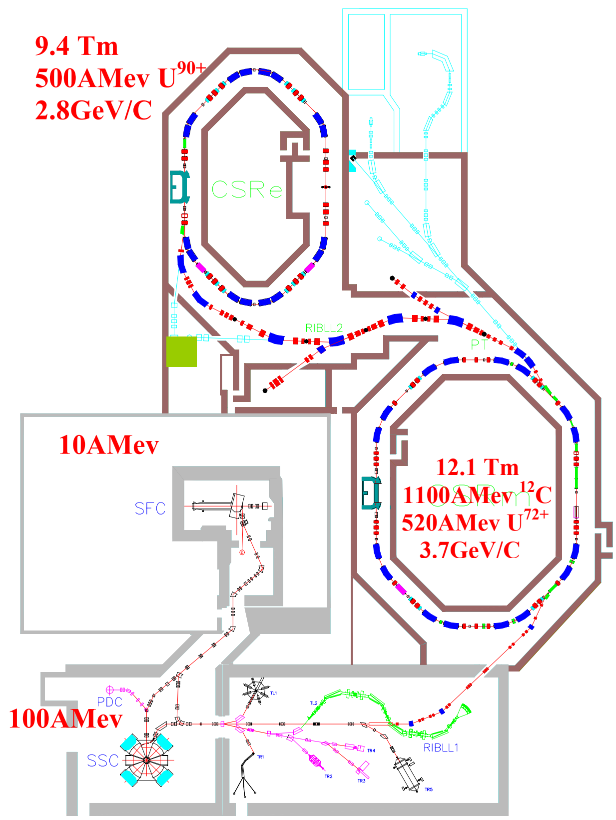

Figure1: Layout of HIRFL System

IMPROVEMENTS OF INJECTION BEAM

In order to provide higher beam quality and intensity, there are many upgrade items starting when HIRFL-CSR project was proposed in last decade. Besides the vacuum, power supplies and rebunch 1 [3,4] had been carried out, the new super-conductor ECR ion source (SECRAL)[5], the beam diagnostic, injection & extraction and others updates are close finished. Therefore, the injection beam quality and intensity to HIRFL-CSR have increased either from SFC or SSC significantly.

HIRFL system has operated about 7000hr/year in past two years. Above 50% the beam time were used for SFC+SSC experiments (include 10% beam time for cancer therapy clinic test by C beam), about 30-40% beam time were used for commissioning of CSR system and others for accelerators developments.

High Charge State Ions from SECRAL

In order to obtain the high intensity of heavy ion with higher charge state to avoid beam loss by stripping, the new Superconducting Electron Cyclotron Resonance ion source with Advanced design in Lanzhou (SECRAL) were proposed to improve the high charge state heavy ion beam for HIRFL system. Its main innovative design is set the three axial solenoid coils inside the radial sextuple bores as fig.2 and obtain the adequate plasma volume with higher microwave power density, easy extract ions and reduce to 1/4 forces amount superconducting coils that dramatically decrease the technical challenge of superconducting. SECRAL started commission in end of 2005, made some new results of highest intensity of heavy ions and started online operation at SFC in 2007.3. It is expected to obtain the better results by using 28 GHz microwave in coming year (details in other invited talk by Dr.Zhao[6] in this conference).

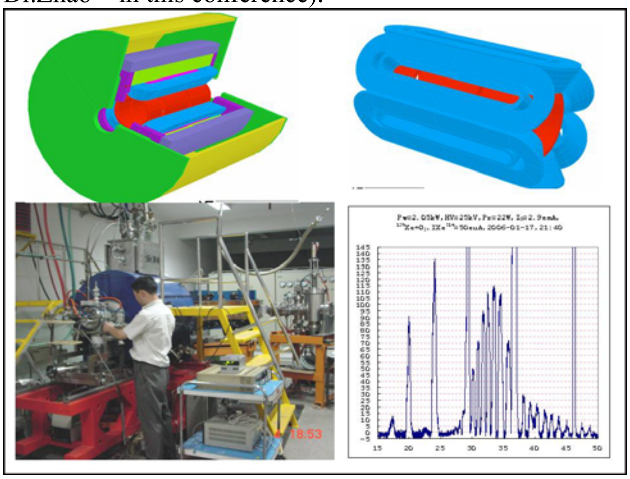

Figure 2: Layout of SECRAL

Beam improvement of SFC

The main improvements of SFC are 1, vacuum of SFC is improved from 10^{-7} to 10^{-8} mbar; 2, reducing the spray magnet field to less than 5 Guass; 3, rebuilt the LEBL of ECR (include SECRAL) to SFC; 4, upgraded the DC PS; 5, upgraded the beam diagnostic and control; 5, new chopper has added to accelerate high pulse beam for CSR operation and others, such as, the stability of RF and beam extraction subsystem. Therefore, the efficiency of the beam from ECR ion source to the beam extracted from SFC cyclotron is about 5%~10%, energy shift is within ±0.8%. Thus, the beam intensity were increased to 10^{13}pps for light ion and about factor 10 higher than before for heavy ion up A~130. Typically, for the commission of CSR, ECR provided ions intensity about 100~180μA; after injection chopper of SFC, the beam is compressed as pulse beam, then, the pulse beam is accelerated and extracted from SFC; finally, beams are ~1.5×10^{13}pps of $^{12}C^{4+}$, ~10^{13}pps of $^{36}Ar^{8+}$ and ~2×10^{12}pps of $^{129}Xe^{27+}$ are obtained respectively.

Beam Improvement of SSC

Besides the improvements of vacuum, power supplier, beam diagnostic and control, the most effective upgrading items are RF, rebunch1 and matching between SFC and SSC cyclotron. The RF high voltage of SSC is increased to 150~200keV and improved acceleration and injection and extraction efficiency., the rebunch1 aims to match two cyclotrons in the RF phase and momentum and gain about factor 2 to 5 the beam intensity extracted from SSC in energy <30 MeV/u (the origin design of matching between SFC and SSC is 1:1 for energy <30Mev/u and only 50% for energy>30MeV/u). By these improvements, the efficiency of SSC injection is about 50%~80%; the acceleration efficiency from SSC diameter 1.3m to 3.2m is about 60%~90%; the extraction efficiency is about 40%~70%; hence, the total efficiency of SSC acceleration is about 25%~50%. Therefore, the beam intensity increases factor 2.5 to 10 and even high for heavier ions.

For example, $^{36}Ar^{8+}$ ion is typical high beam intensity requested for CSR commission. It is provided by ECR ion source with about 150μA; about 10μA 2.08MeV/u $^{36}Ar^{8+}$ beam is obtained after accelerated by SFC; and ~3μA 22MeV/u beam is extracted by SSC.

CSR$_M$ COMMISSION[7,8]

CSRm is electron cooler synchrotron with the function of beam injection, electron cooling, ion accumulation, acceleration, extraction or internal target experiment. It has been installed completely in 2004 as fig.3, its main performances are listed in table 1. The first cast beam accumulation at CSRm was before end of 2005; the C beam acceleration to 1.0GeV/u was in 2006; cooling the beams by electron cooler successful realized the cooler synchrotron in beginning of 2007.

Figure 3: Side View of CSRm

CSRm Stripping Injection Commission

The one of original RF stacking injection mode was replaced by the stripping injection since the stripping injection mode is higher injection efficiency and easy to use for light ions. The arrangement of stripping injection is configure as fig.4.. It consists of 1 injection Magnet Septum (MS1), 4 bumps (BM), a stripping carbon foil and stopper locating inside the first dipole following MS1. The design of stripping range Q_s/Q_i is 1.33~1.5, which Q_s is the charge state after stripping and Q_i is charge state before stripping, for injection beam from SFC. The typical stripping injection orbit of $^{12}C^{4+}$ with momentum spread about ±0.5%, injection beam horizontal emittance about 20πmmmrad and CSRm acceleration acceptance about 80πmmmrad.

The typical 7MeV/u $^{12}C^{4+}$ beam from SFC with intensity of 10^{13}pps is injected in duration 400 μs (corresponding the fall time of bump), then, above 10^9 of $^{12}C^{6+}$ ions were stored inside of CSRm in 2006. By using the electron cooling accumulation, the bunch of injection beam are cooled by electron cooler about 1 second, then, next bunch can inject one by one. So far, carbon beam is only used for stripping injection and the best result of stripping injection is above 7×10^9ppp in 10 second at CSRm. 25 MeV/u Ar beam will be test late.

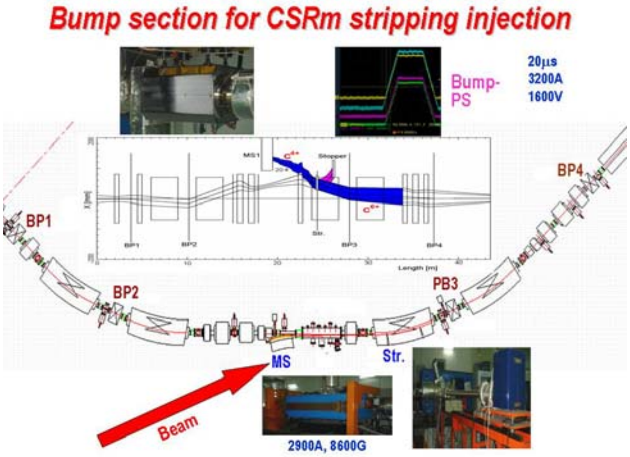

Figure 4: Stripping Injection at CSRm

CSRm MMI Injection Commission

The Multiple Multi-turn Injection (MMI) is more general injection mode designed for CSRm, which can use for ions from light to heavy. The configuration MMI at CSRm is shown in fig.5. MMI devices are most same of stripping injection arrangement, except that the static electric septum is moved in and stripping foil moved out of CSRm injection beam orbit. The static electric septum is 2m long with adjustable gap 23mm, 100µm tungsten coated golden wires plane can be supplied 160kV as fig.5. MMI orbit is also shown in fig.5. The emittance of injection beam is about 20πmmmrad with the momentum spread about ± 0.5% from SFC and ± 0.15% from SSC. After multi-turn injection, the emittance inside of CSRm increase to 150πmmmrad. Except 20πmmmrad is reserved as accumulation core for multiple injection in horizontal, 130πmmmrad is left for next multi-turn injection. Therefore, the horizontal beam emittance should be cooled down to 20πmmmrad before next multi-turn injection.

So far, three kind of ions ($^{12}C^{4+,5+,6+}$, $^{36}Ar^{18+}$, $^{129}Xe^{27+}$) are commissioned by MMI injection mode. 7 Mev/u carbon beam from SFC direct or after stripping are injected into CSRm, above 5×10^8 ions stored inside of CSRm. Comparing the injection beam intensity, the beam intensity measurement by DCCT inside CSRm gain factor 60 at least within 10 second. 22 Mev/u $^{36}Ar^{18+}$ beam is obtained by stripping $^{36}Ar^{8+}$ beam from SSC, then, inject into CSRm by MMI, finally, above 1.5×10^8 ions are stored inside CSRm. This gain is above 60 within 10 second and 80 within 20 second. 2.9 MeV/u $^{129}X^{27+}$ from SFC directly inject into CSRm by MMI, above 1.2×10^8 ions stored inside of CSRm. This gain is above 20 within 10 second and 27 within 20 second.

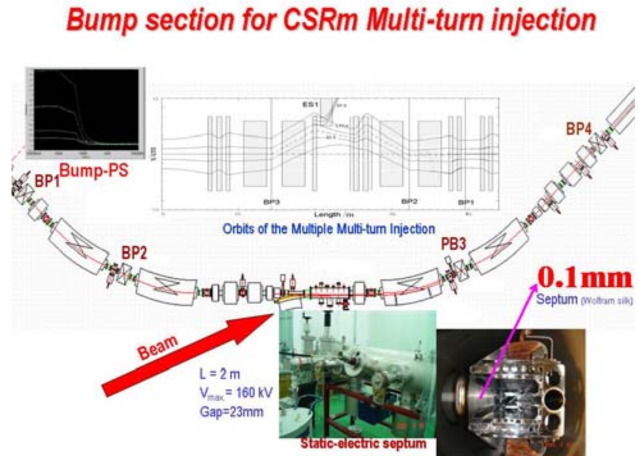

Figure 5: MMI injection at CSRm

Electron cooling

The electron cooler is new generation electron cooler which provides the electron beam with the full and hello electron beam by changing the high voltage of electron gun anode, grid and their ratio[9]. By using this unique feature, the electron cooling effect is test during CSRm commission. The main operation parameters of electron cooler at CSRm are electron energy range of 4~35kV, the cathode diameter 29.0mm, maximum electron beam ~3.0A, magnitude expansion factor 1~4 and high vacuum $\leq3\times10^{-11}$ mbar. This electron cooler can cool the beam momentum spread from 4×10^{-3} to 2×10^{-4} for 7MeV/u $^{12}C^{6+}$ beam as fig.6.

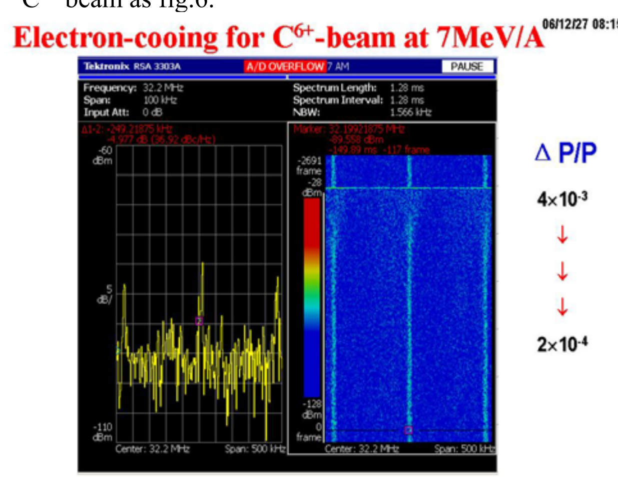

Figure 6: Momentum spread decrease by electron cooling

The three kind of beam were cooled, accumulated and their main performance list in table.2. In table.2, $T_{inj.}$ indicates the duration of beam injection and accumulation, $I_{inj.}$ indicates the injection beam current, I_{10s} means multiple injection within 10 second, I_{long} means maximum beam accumulation inside CSRm for long time, I_e is the electron cooling current. Obviously, the cooling accumulation of $^{36}Ar^{18+}$ beam effect is more stronger since the cooling time is less (0.35sec.) and less influence of ripple component percentage by power supplier in energy 21.7MeV/u. The life time of full stripping ion stored inside of CSRm is longer than partial striping for carbon beam. 7.08 Mev/u $^{12}C^{6+}$ cast beam life time reaches about 1088 second (fig.7) inside of CSRm. It will be improved by reducing the ripple of power supplier in low energy and intensive tuning.

Table2: List of cooling and accumulating results

Ion	$^{12}C^{6+}$	$^{12}C^{4+}$	$^{36}Ar^{18+}$	$^{129}Xe^{27+}$
E_{inj}(MeV/u)	7.08	7.10	21.7	2.87
Inj. Mode	Stripping	MMI	MMI	MMI
T_{inj}(sec.)	1.0	1.0	0.35	0.35
$I_{inj.}$(μA)	10~11	~6	4	2~3
$I_{10sec.}$(μA)	1600	105	250	70
I_{long}(μA)	3500	120	435	70
Livetime(s)	~900	27.3	54.7	12
I_e (mA)	70	124	97	70

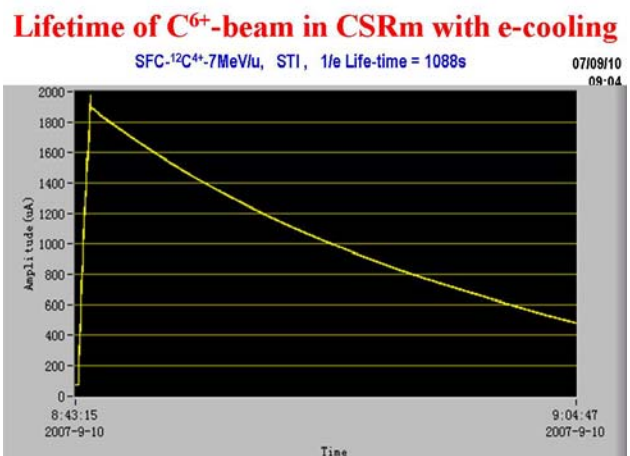

Figure 7: life time of 7Mev/u $^{12}C^{6+}$ at CSRm

The beam store inside CSRm with the lattice as fig.8. This β distribution is measured from beam position monitor by changing the quadruple setting. In fig.8 the squire indicates the design, star indicates the measurement, both agree well. Both x, y emittance are measured about 1 πmmmrad after cooling respectvely.

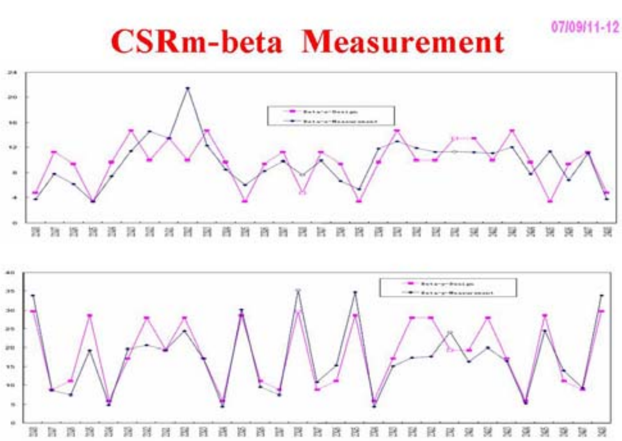

Figure 8: CSRm β measurement by BPM

Acceleration of CSRm

The beam accelerates by ramping the dipole, quadruple power and RF frequency as fig.9. Left of fig.9 is the PS ramping curve, the first plateau is injection beam setting, 2nd plateau is RF switching setting, 3rd is acceleration top energy. RF harmonic number is switched 2 to 1 (or 4 to 1) since the range of RF frequency is limit.

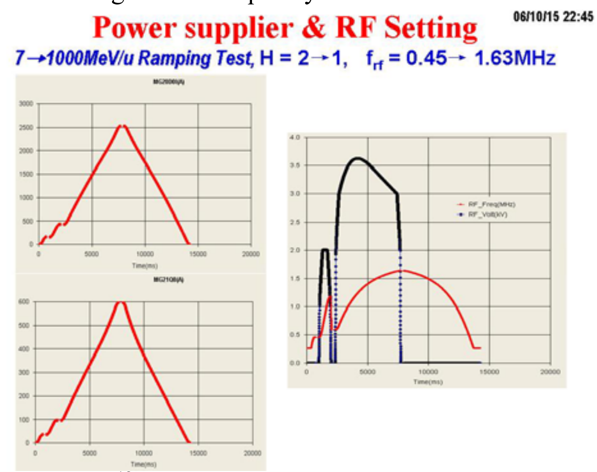

Figure 9: $^{12}C6^{+}$ beam rumping setting of PS and RF

So far, three kinds of beams, >6×10^9 ppp of $^{12}C^{6+}$, 10^8 ppp of $^{36}Ar^{18+}$ and 10^8 ppp of $^{129}Xe^{27+}$ were accelerated to 1000MeV/u, 235MeV/u respectively. Fig.10 shows the 22 MeV/u $^{36}Ar^{18+}$ beam MMI injection, 10 second accumulation, low energy ramping, RF harmonic number switching 2 to 1 and high energy ramping up to 1000MeV/u full procedure.

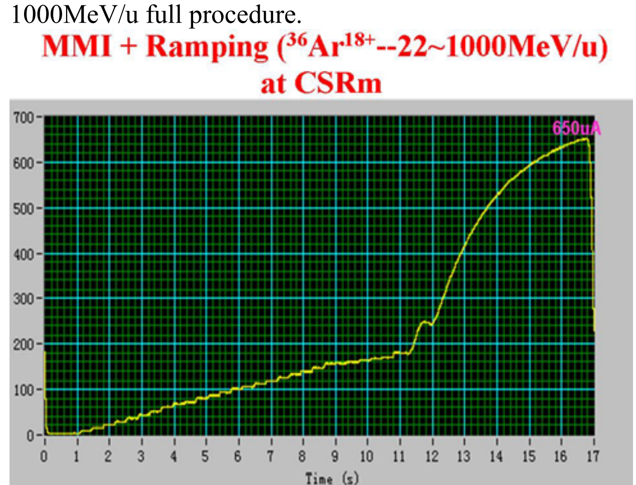

Figure 10: $^{36}Ar^{18+}$ beam acceleration procedure

Fast extract of CSRm

The configuration of CSRm extraction is designed as fig.11. This configuration is consists of 4 coils embedded in neighbour 4 dipoles of the extraction point, one kicker with 4 cells in upstream and 2 magnetic septum in down stream. The maximum current of kicker is 2700 A, Vmax = 60kV, corresponding to extract 1100 MeV/u 12C6+ beam. Its pulse rise time is about 150 ns from 1% to 99% of the amplitude. Two magnetic septum are supplied 2900A current, corresponding 4300 Gs for MS2 and 12800 Gs for MS3 respectively.

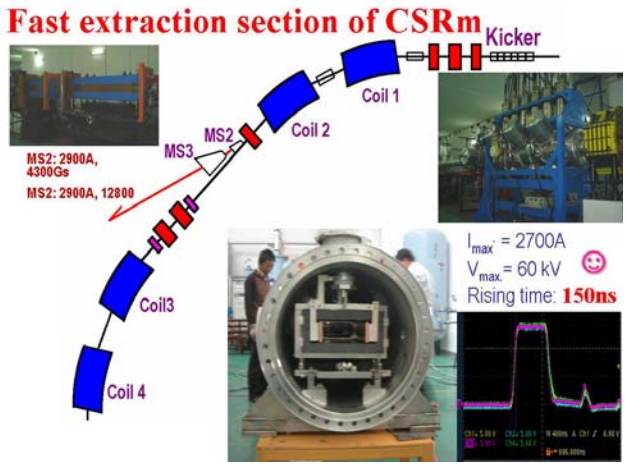

Figure11: The Configuration of CSRm fast extraction

The first extraction beam is 235 MeV/u $^{129}Xe^{27+}$ in Aug. 2007. Late, 600Mev/u or 1000MeV/u $^{12}C^{6+}$ beam were extracted for further commission.

RIBLL2 & CSR$_E$ COMMISSION

RIBLL2 and CSRe were installed completely in 2005 as fig.12 and fig.13.

Figure12: Side View of RIBLL

Figure13: CSRe Electron cooler & Gas Jet Target

RIBLL2 Commission

RIBLL2 is about 100 meters length with function of beam line to transport beam from CSRm to CSRe, some external experimental sites and the separator to produce secondary beam of radioactive ion beam (RIB) or high charge state beam (HCI). So far, the DC or pulse beam is delivered to the entrance of CSRe as fig.14.

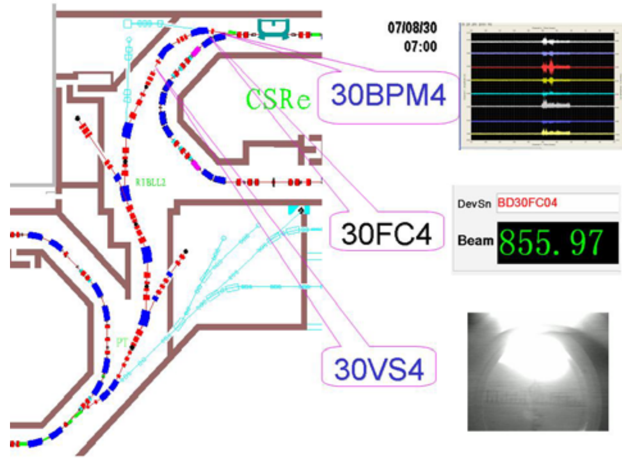

Figure14: Commision of RIBLL2

CSRe Commission

CSRe is high accuracy and high sensitive spectrometer. All setups are test offline in past few years. Now, it is under commissioning and expects to get the result in this October.

CONCLUSION

Many upgrade items at HIRFL are gradually finished from beginning of this decade. Its main performances have been improved in the beam species from light ion to uranium and maximum beam intensities above 10μA from SFC, 3μA from SSC. The big upgrade project CSR is under commissioning successful. Most of CSRm functions are test and three kinds of beams, >6×10^{9}ppp of $^{12}C^{6+}$, ~10^8 ppp of $^{36}Ar^{18+}$ and ~10^8 ppp of $^{129}Xe^{27+}$ were accelerated to 1000MeV/u, 235MeV/u respectively. The momentum spread ~10^{-4} and the beam emittances 1πmmmrad are matching the design. RIBLL2 has delivered beam in the entrance of CSRe. CSRe is under commissioning and plan to finish in end of this Oct.. However, it need to integrate with LINAC injector and modern experimental setup.

ACKNOWLEDGEMENTS

We are grateful for the valuable advices of HIRFL-CSR international advisory committee, especially for Dr.N.Angert, Dr.V.Parkhomchuk, helps of GSI colleagues and the effective collaboration from BINP and the academic exchange with RIKEN colleagues. This work partial support by NSFC grand of A503/10221003.

REFERENCES

[1] B.W.Wei, et.al., Results from Lanzhou K450 Heavy Ion Cyclotron, Proc. Of 1989 Particle Acc., IEEE.

[2] J.W.Xia, et.al., HIRFL Status and HIRFL-CSR Project in Lanzhou, Proc. Of the First Asian Part. Acc. Conf. KEK, Japan, 1998.

[3] H.W.Zhao, et.al., HIRFL Operation and Upgrade, 17th Inter. Conf. on Cyclotrons and their Applications, Tokyo, 2004(121).

[4] W.L.Zhan, et.al., Progress of The Heavy Ion Research Facility in Lanzhou, 17th Inter. Conf. on Cyclotrons and their Applications, Tokyo, 2001 (174).

[5] H.W.Zhao, et.al., Rev. Sci. Inst. 77. 03 A(2006)

[6] H.W.Zhao, et.al., An Advanced Superconducting ECR ion Source at IMP: first results and operation at 18 GHz, 18th Inter. Conf. of Cyclotrons and their Applications, Catania 2007.

[7] J.W.Xia, et.al., Construction and Commisioning of HIRFL-CSR, APAC'2007, Indore, India, Jan. 2007.

[8] W.L.Zhan, et.al., Institute of Modern Physics, CAS, Nucl. Phys. News, V17. No.2 2007(5-).

[9] X.D.Yang, et.al., Commissioning of Electron Cooling in CSRm, Proceedings of COOL 2007, Bad Kreuznach, Deutschland TUM1I02 2007.