COOLER STORAGE RING AT CHINA INSTITUTE OF MODERN PHYSICS*

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Abstract

CSR, a new ion cooler-storage-ring project in China IMP, is a double ring system, and consists of a main ring (CSRm) and an experimental ring (CSRe). The two existing cyclotrons SFC (K=69) and SSC (K=450) of the Heavy Ion Research Facility in Lanzhou (HIRFL) will be used as its injector system. The heavy ion beams with the energy range of 7--30 MeV/nucleus from the HIRFL will be accumulated, cooled and accelerated to the higher energy range of 100--500 MeV/nucleus in CSRm, and then extracted fast to produce radioactive ion beams or highly charged heavy ions. Those secondary beams will be accepted and stored or decelerated by CSRe for many internal-target experiments or high precision spectroscopy with beam cooling. On the other hand, the beams with the energy range of 100--1000MeV/nucleus will also be extracted from CSRm by using slow extraction or fast extraction for many external-target experiments. CSR project was started in the end of 1999 and will be finished in 2006. In this paper the outline and the activities of the project will be described.

INTRODUCTION

Since the end of 1999, a new Cooler Storage Ring (CSR) project [1] has been started to upgrade the Heavy Ion Research Facility in Lanzhou (HIRFL) [2], shown in Fig. 1. CSR will provide Radioactive Ion Beams (RIBs) and high-Z heavy ion beams for nuclear physics and atomic physics. The existing HIRFL complex, consisted by a main accelerator SSC (Separated Sector Cyclotron, K=450) and a pre-accelerator SFC (Sector-Focusing Cyclotron, K=69), will be used as the injector system of CSR. The light heavy ions, example C, N, O etc., can be injected into CSRm directly from SFC, but those heavy ions (A>40) should be accelerated by the combination of SFC and SSC before the injection. The mean extraction radius of SFC and SSC are 0.75m and 3.20m respectively.

GENERAL DESCRIPTIONS

Outline

CSR is a multipurpose Cooler Storage Ring system that consists of a main ring (CSRm), an experimental ring (CSRe), and a radioactive beam line (RIBLL2) to connect the two rings, shown in Fig.1. The heavy ion beams with the energy range of 7~30 MeV/μ from the HIRFL will be accumulated, cooled and accelerated to the high-energy range of 100~500 MeV/μ in the main ring, and then extracted fast to produce radioactive ion beams (RIBs) or highly charged heavy ions (high-Z beams). Those secondary beams will be accepted and stored or decelerated by the experimental ring for many internal-target experiments or high precision spectroscopy with beam cooling. On the other hand, the beams with the energy range of 100~1000MeV/μ will also be extracted from CSRm by using slow extraction or fast extraction for many external-target experiments, and for the future development, the possibility of internal-target mode in CSRm was reserved for those high-energy proton experiments with the energy range of 2~2.8GeV.

Two electron coolers located in the long straight sections of CSRm and CSRe, respectively, will be used for beam accumulation and cooling.

The beam parameters and the major machine parameters of CSR are listed in table 1.

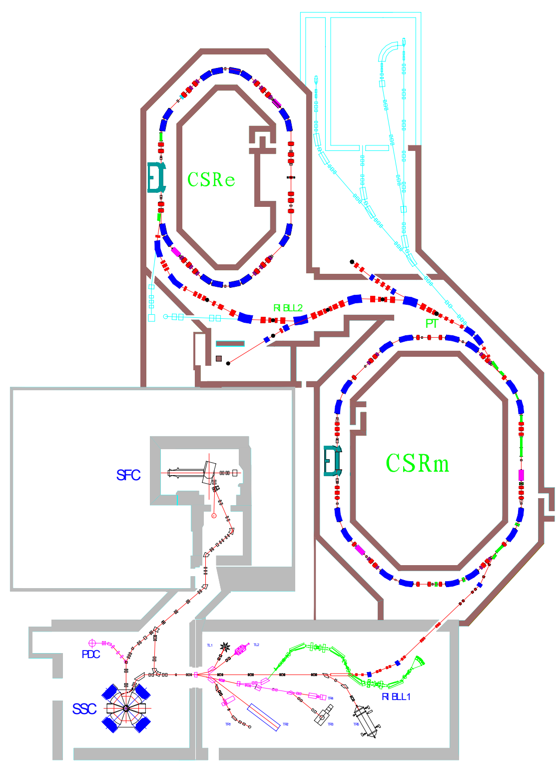

Figure 1: Overall layout of HIRFL-CSR.

Normal Operation Mode

CSR is a double ring system. In every operation cycle, the stable-nucleus beams from the injectors are

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Table 1 Major parameters of the CSR

	CSRm	**CSRe**
Circumference (m)	161.00	128.80
Ion species	Stable nuclei: p -- U, RIBs: A<238	Stable nuclei: p -- U, RIBs :A<238
Max. energy (MeV/μ)	2800(p), 1100 (C^{6+}), 500 (U^{72+})	2000(p), 750 (C^{6+}), 500 (U^{90+})
Intensity (Particles)	10^5---10^9 (stable nuclei)	$10^{3\text{--}9}$ (stable nuclei, RIBs)
$B\rho_{max}$ (Tm)	12.05	9.40
B_{max} (T)	1.6	1.6
Ramping rate (T/s)	0.1--0.4	0.1--0.2
Repeating circle (s)	~ 17 (~ 10s for accumulation)	
Acceptance	Fast extraction mode	Normal mode
A_h (π mm-mrad)	200 (ΔP/P = ±0.15 %)	150 (ΔP/P =±0.5%)
A_v (π mm-mrad)	40	75
ΔP/P (%)	1.4 (ε_h= 50 π mm-mrad)	2.6 (ε_h= 10 π mm-mrad)
E-cooler		
Ion energy (MeV/μ)	7---50	10---500
Length (m)	4.0	4.0
RF system	Acceleration Accumulation	Capture
Harmonic number	1, 2 16, 32, 64	1, 2
f_{min}/f_{max} (MHz)	0.24 / 1.81 6.0 / 14.0	0.4 / 2.0
Voltages (n × kV)	1 × 7.0 1 × 20.0	2 × 10.0
Vacuum pressure (mbar)	3.0×10^{-11}	3.0×10^{-11}

accumulated, cooled and accelerated in the main ring (CSRm), then extracted fast to produce RIBs or highly charged ions. The experimental ring (CSRe) can obtain the secondary beams once for every operation cycle. The accumulation duration of CSRm is about 10s. Considering the ramping rate of magnetic field in the dipole magnets to be 0.1~0.4 T/s, the acceleration time of CSRm will be nearly 3s. Thus, the operation cycle is about 17s.

In CSRe, two operation modes will be adopted. One is the storage mode used for internal-target experiments or high precision spectroscopy with electron cooling. Another one is the deceleration-storage mode used for atomic-physics experiments. Fig. 2 shows the magnetic field exciting procedure of the two rings.

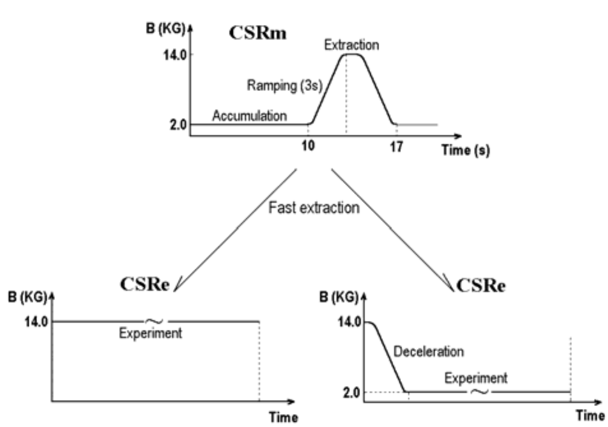

Figure 2: Magnetic field exciting procedure of CSR.

Beam Accumulation

Three modes will be used in CSRm to accumulate ions up to $10^{6\sim9}$ in a short duration of 10s. The first is the Stripping Injection (STI) for those light heavy ions (A<24). The second is the Multiple Multi-turn Injection (MMI) in the horizontal phase space with the acceptance of 150π mm mrad. The third one is the combination of the horizontal MMI and the RF Stacking [3] (RFS) in the momentum phase space. In the third one the horizontal acceptance is 50π mm mrad used for the multi-turn injection and the momentum acceptance is 1.25% for the RF stacking. During the accumulation, electron cooling will be used for the cooling of beam in order to increase the accumulation ratio and efficiency. Table 2 is the accumulation parameters for several typical ions.

Table 2 Parameters of the beam accumulation in CSRm

	C^{4+}	**O^{7+}**	**Xe^{48+}**	**U^{72+}**
Injector	SFC	SFC	SSC	SSC
Energy (MeV/μ)	7	10	20	10
Current (pμA)	2	0.5	0.01	0.01
Current (pps)	1.2×10^{13}	3×10^{12}	6×10^{10}	6×10^{9}
Particles/Turn	5×10^{7}	1×10^{7}	1.5×10^{5}	2×10^{4}
Efficiency of str.	68%		19%	15%
Method	STI	RFS	MMI	MMI
Injection pulse (ms)	1--5	0.1	0.1	0.1
Cycle (ms)	2500	100	250	100
Period (s)	3	10	10	10
Gain factor of MMI	30	2.8	5	5
Particles	1.5×10^{9}	2×10^{9}	5×10^{6}	1×10^{6}

STORAGE RING LATTICE

CSRm Lattice

CSRm is a racetrack shape, as shown in Fig. 3, and consists of four arc sections. Each arc section consists of four dipoles, two triplets and one doublet. The lattice of each arc section is given as follows,

----- L_1-----FDF--B--B--F---- L_2---DF--B--B—F (1/2D)

Where, $2L_1$ is a long-straight section with dispersion free for e-cooler or extraction kicker and internal target. L_2 is a dispersion drift for beam injection, extraction and RF cavity. Fig. 4 is the distributions of the β-functions and the dispersion for this lattice, and Table 3 is the lattice parameters of CSRm.

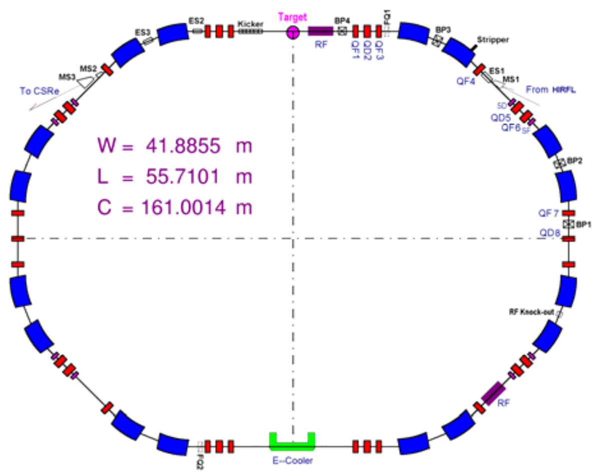

Figure 3: Lattice layout of CSRm.

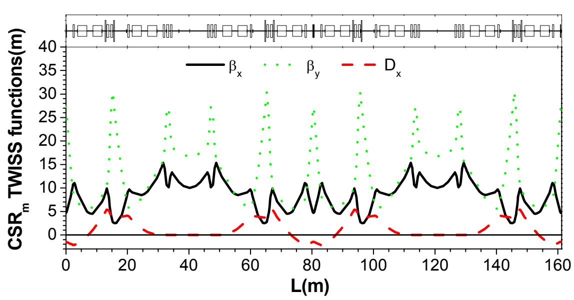

Figure 4: β and dispersion of CSRm

CSRe Lattice

The layout of CSRe is shown in Fig. 5. It has a race track shape and consists of two quasi-symmetric parts. One is the internal-target part and another is the e-cooler part. Each part is a symmetric system and consists of two identical arc sections. Each arc section consists of four dipoles, two triplets or one triplet and one doublet. 11 independent variables for quadruple are used in CSRe. The lattice of the half ring is given as follows,

--L_T--FD-F--B-B--L_R--FD-F-B-B--B-B-F-DF--L_R--B-B--FD--Lc--

Where, $2L_T$ and $2L_C$ are the long-straight sections with dispersion free for internal target and e-cooler. L_R is the dispersion drift for RF cavities. Table 3 shows the lattice parameters of CSRe, and Fig. 6 denotes the distributions of the β-functions and the dispersions for the lattice.

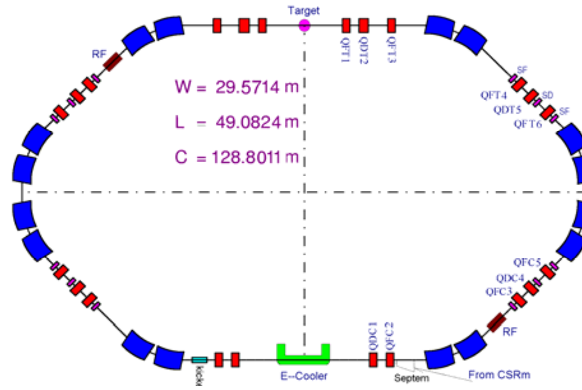

Figure 5: Lattice layout of CSRe.

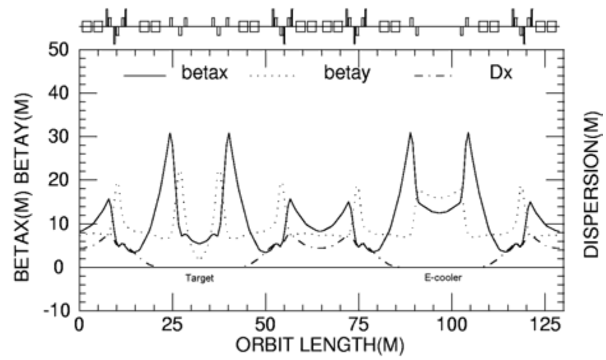

Figure 6: Tiwiss functions of CSRe.

Table 3 Lattice parameters of CSRm and CSRe

	CSRm	**CSRe**
Transition gamma	γ_{tr} = 5.418	γ_{tr} = 2.629
Tune values	Q_x / Q_y = 3.64 / 2.61	Q_x / Q_y = 2.53 / 2.57
Chromaticity	Q'_x / Q'_y = -3.17 / -5.37	Q'_x / Q'_y = -3.10 / -3.74
Max. β (m)	β_x/β_y=12.1/13.5 (B) β_x/β_y=15.3/30.5 (Q)	β_x/β_y=17.6/8.2 (B) β_x/β_y=30.9/22.3 (Q)
Dispersion (m)	$D_{max}(x)$=3.1(B, β_x=9.0) $D_{max}(x)$=5.4(Q , β_x=9.9)	$D_{max}(x)$=6.5(B, β_x=13.0) $D_{max}(x)$=7.8(Q, β_x=16.0)
Injection (m)	β_x= 8.0 , D_x = 4.1 (SM) β_x= 9.7, D_x =3.9 (Q)	β_x=30.4 , D_x = 0 (SM) β_x=30.9, D_x = 0 (Q)
E-cooler (m)	β_x/β_y=10.0/16.7, D_x=0	β_x/β_y=12.5/16.0, D_x = 0
Target (m)	β_x/β_y=10.0/16.0, D_x=0	β_x/β_y=5.4/1.5, D_x=0
RF station (m)	β_x/β_y=8.0/22.5, D_x=4.0	β_x/β_y=4.0/8.4, D_x=4.0

MAJOR SUBSYSTEM

Magnets and Correlative Sub-systems

All magnet cores of CSR will be laminated of 0.5mm-thick sheets of electro-technical steel with high induction and cold-rolled isotropy. Coils will be made of T2 copper conductor with hollow and insulated with polyimide stick tape and vacuum epoxy resin impregnating. In order to reach the necessary field uniformity at the

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different levels of the range of 1000Gs ~ 16000Gs, a so-called modified H-type dipole was designed for CSRm. In CSRe the C-type dipole with large useful aperture will be adopt for physics experiments.

All power supplies of the ring magnets need DC and pulse operation modes, and high current stability, low current ripple and good dynamic characteristic were required. Two types of supply, traditional multi-phase thyristor rectifier for dipoles and switching mode converter for quadruples, were adopted. Table 4 is the major parameters of magnets and its correlative power supplies and vacuum chambers.

Table 4 Major correlative parameters of the magnets

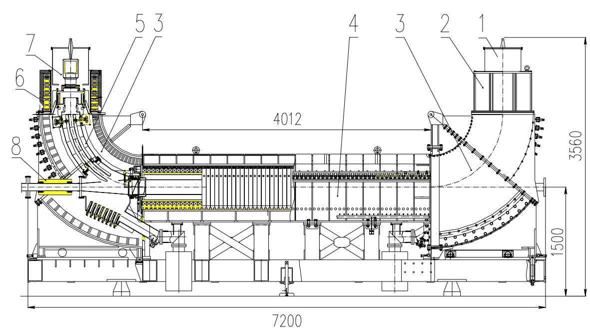
	CSRm	CSRe
Dipole		
Number×angle (deg.)	16×22.5	16×22.5
Bending radius (m)	7.6	6.0
Field range (T)	0.1--1.4	0.1--1.4
Ramping rate (T/s)	0.1--0.4	0.1--0.4
Air gap (mm)	80	84
Useful aperture (mm^2)	140×60	220×70
Homogeneity ($\Delta B/B$)	$\pm 1.5\times 10^{-4}$	$\pm 1.5\times 10^{-4}$
Vacuum. Chamber		
Inner aperture (mm^2)	156×61	236×70
Cross section	Rectangular	Rectangular
Supply of dipole		
Number	1	1
Feeding mode	Series	Series
Stability (at low cur.)	$\pm 1\times 10^{-4}$/8h	$\pm 1\times 10^{-4}$/8h
Ripple (at low cur.)	5×10^{-5}	5×10^{-5}
Tracking precision	$\pm 3\times 10^{-4}$	$\pm 3\times 10^{-4}$
Quadruple		
Number	30	22
Gradient range (T/m)	0.3—10.0	0.3—6.5
Bore diameter (mm)	170	240
Useful aperture (mm^2)	160×100	280×140
$\Delta K/K$	$\pm 1.5\times 10^{-3}$	$\pm 1.5\times 10^{-3}$
Ideal length (m)	0.5, 0.65	0.65, 0.75
Vacuum. Chamber		
Aperture (mm^2)	180×110	285×150
Cross section	Octagonal	Octagonal
Supply of quadruple		
Number	30	22
Feeding mode	Independent	Independent
Stability (at low cur.)	$\pm 1\times 10^{-4}$/8h	$\pm 1\times 10^{-4}$/8h
Ripple (at low cur.)	5×10^{-5}	5×10^{-5}
Tracking precision	$\pm 5\times 10^{-4}$	$\pm 5\times 10^{-4}$

Electron-cooler System

Two electron coolers will be equipped in CSRm and CSRe respectively for heavy ion beam cooling. In CSRm the E-cooling will be used for the beam accumulation at the injection energy range of 7~30 MeV/μ to increase the beam intensity. In CSRe the e-cooling will be used to compensate the growth of beam emittance during internal target experiments or provide high quality beams for the high resolution mass measurements of nuclei. Table 5 is the major parameters of the two e-coolers, and Fig. 7, Fig.8 are the general view of them. The two coolers are almost same with the only difference of the high voltage unit in order to reduce the time of development and the production cost of the devices.

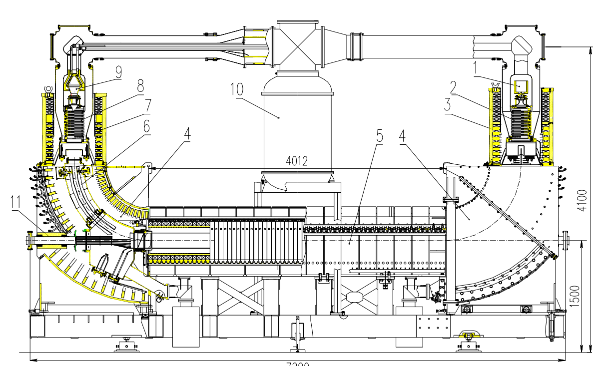
Table 5 Major parameters of the two e-coolers

Parameters	**CSRm**	**CSRe**
Ion Energy [MeV/u] Electron Energy [keV]	7-50 4-35	10-500 5-300
Electron beam current [A]	3 (1.0A@5.5keV)	
Cathode radius [cm]	1.25	1.25
Magnetic expansion factor	1- 4	1- 10
Max. field of gun [kG]	2.4	5
Field of collector [kG]	1.2	1.2
Field of cooling section [kG]	0.6-1.5	0.5-1.5
Length of cooling section [m]	4.0 ($L_{eff.}$= 3.4m)	
Installation length [m]	7.2	7.2
Bending angle of toroid	90°	90°
bending radius of toroid [m]	1.0	1.0



1. E-gun, 2. Solenoid of gun, 3. Toroid, 4. Main solenoid, 5. Electrostatic deflector, 6. Solenoid of collector, 7. Collector, 8. Dipole corrector.

Figure 7: Layout of the CSRm e-cooler.



1. E-gun, 2. Accelerating tube, 3. Solenoid of gun, 4. Toroid, 5. Main solenoid, 6. Electrostatic deflector, 7. Solenoid of collector, 8. Decelerating tube, 9. Collector, 10. 300KV-HV System, 11. Dipole corrector.

Figure 8: Layout of the CSRe e-cooler.

MAGNET TEST RESULTS OF CSRm

Results of CSRm Dipole Field

The dipole field of CSRm was measured in the range of 500Gs to 1.65T with the exciting current from 76A to 3000A. It is larger than the used range of 0.1T to 1.6T. According to the measurement, the homogeneity of field is less than 4×10^{-4} in the required good-field width of 140mm, the multiple components error are less than 8×10^{-4} , and the dipole-field reproducibility is less than 3×10^{-4} between 16 dipoles and reference dipole. Fig. 9 is the dipole integral-field distribution versus the radius at the field level of 1000Gs. Fig. 10 is the multiple component errors versus the whole exciting current. Fig.11 is the reproducibility of CSRm dipoles at the 1000Gs level.

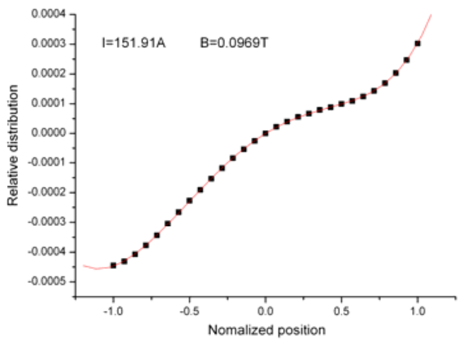


Figure 9: Dipole field distribution versus the radius.

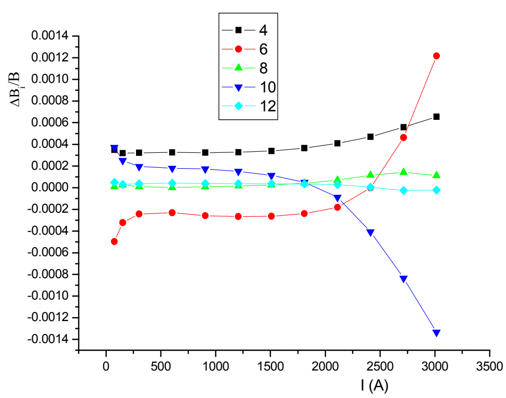


Figure 10: Multiple component errors in CSRm dipole.

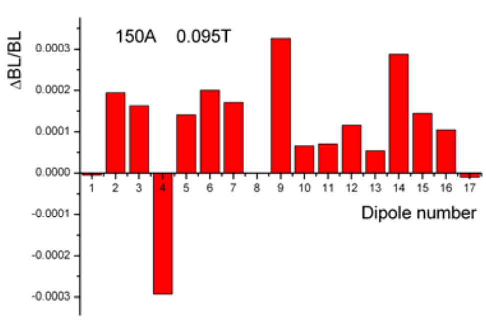


Figure 11: Reproducibility of CSRm dipole.

Results of Quadruple Field

The maximum quadruple gradient of CSRm is reached to 10 T/m with the exciting current of 690A, and the multiple components error are less than 5×10^{-4}. Fig. 12 is the multiple-component errors versus the whole exciting current from 15A to 700A.

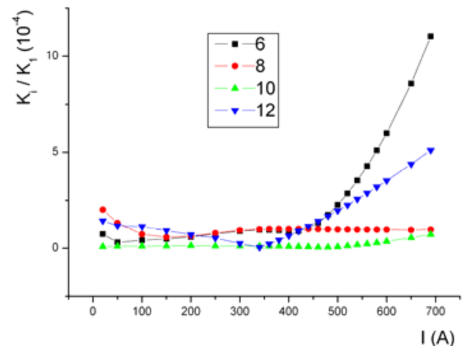


Figure 12: Multiple component errors of quadruple.

PROJECT STATUS

In the summer of 2001 the building construction was over, and in the beginning of 2004 the major fabrication and installation for CSRm and the injection line from HIRFL were finished. Up to the spring of 2005, the fabrication and installation of CSRe and those beam lines between the two storage rings will be completed.

Since 2003 many offline tests have been done. For example, e-cooler, RF station, power supply, Ultra-high vacuum, magnetic field measurement, etc. For the e-cooler, the hollow electron beam can be obtained to partially solve the problems due to space charge effect and reduce the effect of recombination between the ions and the e-beam. In CSRm the vacuum pressure already reached to 5×10^{-12} mbar.

Several subsystems will be delayed, for example, control and diagnosis systems, injection bumps and fast extraction kicker.

At February 3 of 2005, the first-turn of CSRm was obtained without any adjusting. 2005 is the first commissioning time for CSRm, and in the end of 2006 the whole fist commissioning of CSR will be finished.

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