

HIRFL-CSR COMMISSIONING STATUS AND FUTURE UPGRADE*

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Abstract

CSR is a new ion cooler-storage-ring system in IMP, Lanzhou, China, which consists of a main ring (CSRm) and an experimental ring (CSR_e) with two previous cyclotrons SFC (K=69) and SSC (K=450) as the injectors. The main construction of CSR was completed in 2005. It was being commissioned in the following two years. In 2008 the main purposes of CSR was focused on the primary ⁷⁸Kr beam with kinetic energy up to 500MeV/u for precise mass spectroscopy at CSR_e at isochronous mode. The cancer therapy phase-II in IMP with 100-250MeV/u carbon beam from CSRm was tested and 6 patients with tumors in the heads were treated successfully.

INTRODUCTION

HIRFL-CSR (Heavy Ion Research Facilities in Lanzhou, Cooler Storage Ring) consists of a main ring (CSRm), an experimental ring (CSR_e) and RIB production and transfer line (RIBLL2) in between [1][2], shown in Fig. 1. The two previous cyclotrons SFC (K=69) and SSC (K=450) of the HIRFL are used as the injectors, offering lighter ion beams like ¹²C⁴⁺ at maximum 7 MeV/u with SFC, or heavier or higher-energy ion beams with SFC+SSC combination. The heavy ion beams from the cyclotrons are injected first into CSRm for accumulation with e-cooling, consequently accelerated, and finally either fast-extracted via RIBLL2 into CSR_e for internal-target experiments or mass measurements of radioactive ion beams (RIBs), or slow-extracted for external-target experiments or cancer therapy.

In 2005 the main construction of CSR was completed. It was being commissioned in the following two years. Main features of CSR were realized and examined by the national testing team, including the stripping injection (STI), electron-cooling with hollow electron beam, carbon beam stacking with the combination of STI and e-cooling, the wide energy-range acceleration from 7 MeV/u to 1000 MeV/u with the RF harmonic-number changing at the mid-energy, the multiple multi-turn injection (MMI) and the beam accumulation with MMI and e-cooling for heavy-ion beams of C, Ar and Xe, the fast and slow extraction from CSRm, the commissioning of CSR_e with two lattice modes and testing RIB mass spectroscopy at CSR_e at isochronous mode with time-of-flight (ToF) method.

In 2008 the main commissioning purposes was focused on the primary ⁷⁸Kr beam with maximum kinetic energy up to 500MeV/u for production of proton-rich drip-line nuclei and precise mass spectroscopy at CSR_e at

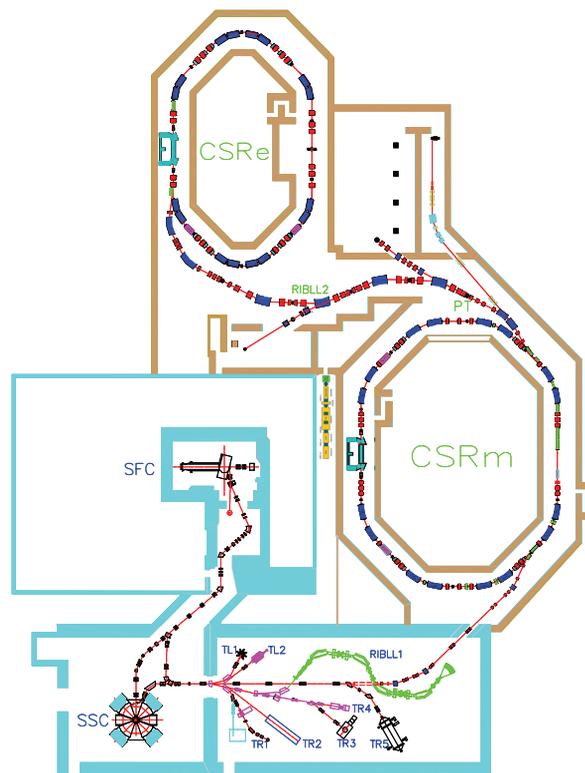


Figure 1: Layout of present HIRFL-CSR.

isochronous mode. Great effort was made to accumulate injected $\delta 600 \text{ nA } ^{78}\text{Kr}^{28+}$, which was actually hard to see at the ring at first, to the ultimate current $80 \mu\text{A} (1 \times 10^8)$.

The cancer therapy phase-II in IMP with 100-250 MeV/u stepped by 5 MeV/u with carbon beam from CSRm was performed and 6 patients with tumors in the heads were treated successfully. Stripping injections with and without accumulation with e-cooling were tested for the possible miniaturization of this type of cancer-therapy machine-complex.

COMMISSIONING AND TEST EXPERIMENT

The first stored beam in CSRm was obtained with charge stripping injection for carbon beam ($\text{C}^{4+} \rightarrow \text{C}^{6+}$) in Jan. 2006, with much effort due to the low injected beam current of only a few μA and still improving beam diagnostics and control system at the very beginning of commissioning. Later on the remote control system and tune measurement [3] were available, which assured the commissioning on the right way.

Successful acceleration of injected ¹²C⁶⁺ at 7 MeV/u (0.76T m/0.1 T) to 1GeV/u (11.3T m/1.5 T) with a beam intensity of 2.8×10^8 pps was achieved in Oct. 2006. It

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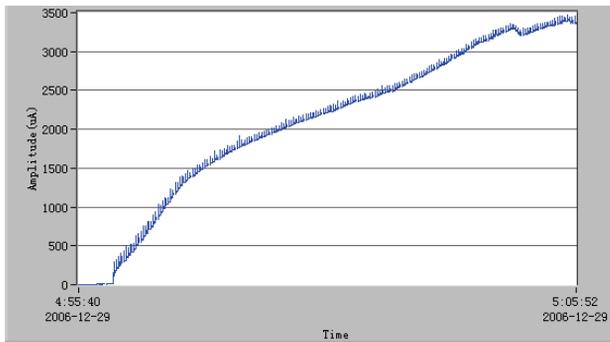


Figure 2: Measured beam current of $^{12}\text{C}^{6+}$ at 7MeV/u, with stripping injection and accumulation with electron cooling.

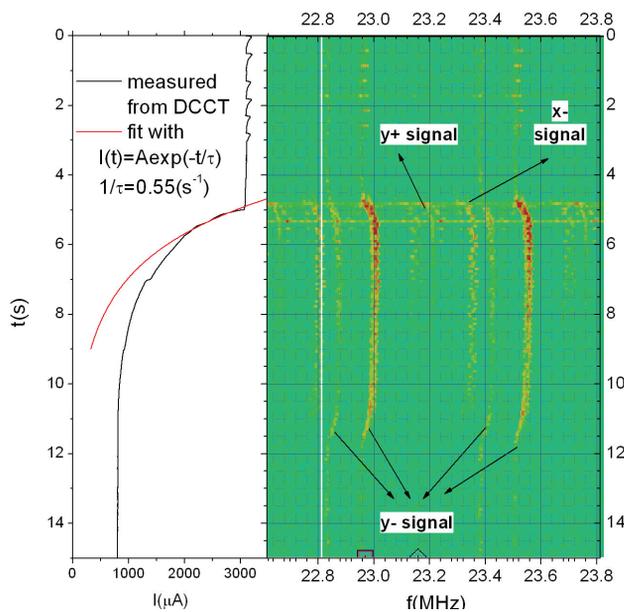


Figure 3a: Measured beam current and longitudinal spectrum of cooled $>2.5\text{mA}$ $^{12}\text{C}^{6+}$ beam at 7MeV/u during the beam break-up.

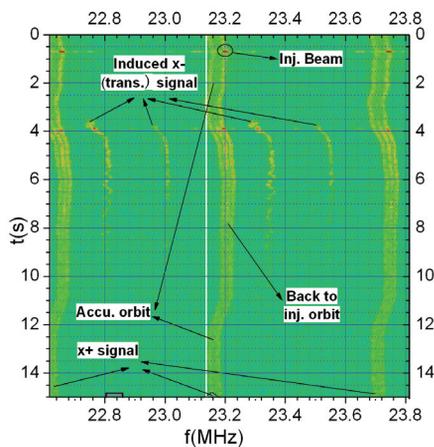


Figure 3b: Measured transverse spectrum during the beam break-up.

relied on the techniques of modification of ramping curve against systematic error in the measured magnet-field data, and with the high-efficiency harmonic-transfer RF-acceleration. The latter is to divide the acceleration into

two or more ramping parts, each with different RF-harmonics. The RF-harmonics transfer is applied in most of the CSRm operations, shown in Figs. 7 and 11 at about 3.5 s and 2.5 s respectively. It is of great importance for CSR because the lower-energy $^{12}\text{C}^{4+}$ beam from SFC beam is thus acceptable for CSRm to be accelerated to 1GeV/u. So the efficiency of carbon beam is greatly enhanced with the absence of SSC.

As a key point for the accumulation of ion beam, the electron cooler system at CSRm was in function by the end of 2006 [4]. The availability of beam current monitor DCCT helped to realize the accumulation of stripping-injected carbon beam with electron-cooling. The new generation of electron cooler system with adjustable electron-beam distribution dramatically improved the $^{12}\text{C}^{6+}$ beam intensity with normal accumulation time of 10 seconds to 7×10^9 pps at 1GeV/u in Sep. 2007 [3].

Experiments were made for the no-time-limit accumulation of carbon beam with stripping injection. With injected C^{4+} beam of 10 μA , a saturated maximum current of 3.4 mA of C^{6+} beam was achieved, i.e. 1.6×10^{10} at CSRm, which is a factor of ~ 300 , in 8 minutes, as was shown in Fig. 2.

Instabilities and beam break-up were observed for such long-stored cooled beam, as shown in Fig. 3. When the beam current reached a certain level, ~ 2.5 mA in this case, and when the coming of “hot” injected beam was stopped, the injection-cooling-decay balance would be broken. Then the stored beam got more deeply cooled until certain resonances were met.

Coherent modes were developed and after about 2 s the beam loss began. A new equilibrium was reached at last with a remained current of ~ 0.8 mA.

The mechanism behind is related to the angle between electron-beam and ion-beam. Perturbation or the incoming “hot” beam can maintain the equilibrium.

From the above results it is clear that the stripping injection proved to be so successful to make the planned RF-stacking no more necessary at CSRm.

However, the stripping injection is not fit for elements heavier than argon, for which multiple multi-turn injection (MMI) scheme is required. The MMI was first realized in Apr. 2007 with carbon beam. Soon after the first beams of argon (4×10^8 pps) and xenon (1×10^8 pps) were successfully accumulated and accelerated at CSRm [3].

In Aug. 2007 the first fast extraction from CSRm was carried out. After struggling with the beam line the first beam was stored in CSRe in October, with the stored beam of 7×10^9 pps for $^{12}\text{C}^{6+}$ and 1.2×10^8 pps for $^{36}\text{Ar}^{18+}$ after optimization.

A last testing experiment was performed to exam the CSR overall ability and readiness. Operation with the combination of SFC+SSC+CSRm+RIBLL2+CSRe was applied, for primary $^{36}\text{Ar}^{18+}$ beam at 368 MeV/u up to 400 MeV/u, producing RIB fragments with mass of $A=2Z$ and $A=2Z-1$, respectively, at transition energy of CSRe at 368 MeV/u, i.e. $\gamma_{tr} = 1.395$, at isochronous mode. The resolution of mass was better than 10^{-5} .

The first slow extracted beam was seen on detector in Jan. 2008, but the 50 Hz ripple of power supply was obvious, estimated to be around 5×10^{-4} . Efforts were made to improve it after this test, shown in Fig. 8.

FIRST OPERATION OF CSR FOR MASS SPECTROSCOPY EXPERIMENT

The first operation of CSR for mass spectroscopy was similar to the testing experiment, with the primary beam of $^{78}\text{Kr}^{28+}$, aiming at proton-rich drip-line nuclei of germanium, arsenic and selenium with the life-time of ~ 100 ms. The experiment was taken in two time periods in 2008.

The resolution and even the feasibility of the mass spectroscopy at CSRe at isochronous mode are highly dependent on the relevant reproducibility, efficiency and stability and ripple of power supplies of the combination of SFC+SSC+CSRm+RIBLL2+CSRe, with iteratively changing and testing the energy settings, as shown in Table 1.

The real challenge was the weak injected beam from SSC. The most critical point is to see the very first storage of the beam to tune the machine. In this case the maximum injected $^{78}\text{Kr}^{28+}$ beam current was ~ 600 nA. It is difficult for the DCCT at CSRm to distinguish the small current below $1 \mu\text{A}$. It is also difficult for BPM which requires rebunching the first weak stored beam.

During the first period in the middle of 2008 $^{78}\text{Kr}^{19+}$, $^{78}\text{Kr}^{29+}$ and $^{78}\text{Kr}^{28+}$ were tested for several times to ensure the ring status and to pursue the best chance. Finally the first storage was found by averaging the long-time DCCT data. After this breaking point the accumulation was just consequence with the powerful electron cooling. Maximum currents of $55 \mu\text{A}$ (7×10^7) and $80 \mu\text{A}$ (1×10^8) at injection level were achieved respectively for the two periods. The experiment succeeded to count enough events of aimed-nuclei for reliable mass spectroscopy measurements. Some of the results are shown in Fig. 5 for a measurement of signal with only one particle, and Fig. 6 for the total event-counts.

Table 1: Energy Setting Steps for Mass Spectroscopy at CSRe at Isochronous Mode with primary $^{78}\text{Kr}^{28+}$ Beam

Ext. Energy from CSRm (MeV/u)	Bp Conditions	RIBLL2 settings
198.98	$B\rho(^{78}\text{Kr}^{28+}) = B\rho(^{63}\text{Ge}^{32+} _{\text{iso}})$	Passing through
~ 371.71	$B\rho(^{78}\text{Kr}^{36+}) = B\rho(^{63}\text{Ge}^{32+} _{\text{iso}})$	Energy degrader
~ 450.86	$B\rho(^{78}\text{Kr}^{36+}) = B\rho(^{63}\text{Ge}^{32+} _{\text{iso}})$	Energy degrader +Target
~ 499.78	$B\rho(\text{RIB}) = B\rho(^{63}\text{Ge}^{32+} _{\text{iso}})$	Energy degrader +Target

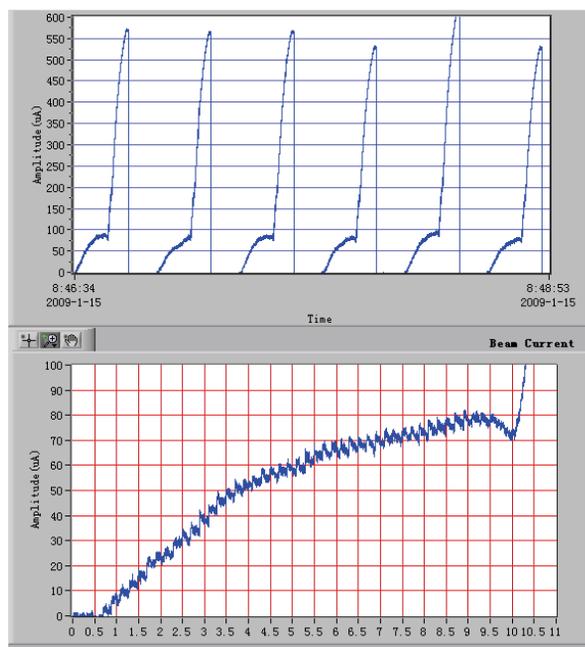


Figure 4: Accumulation, zoomed in the lower graph, and acceleration of $^{78}\text{Kr}^{28+}$ at CSRm.

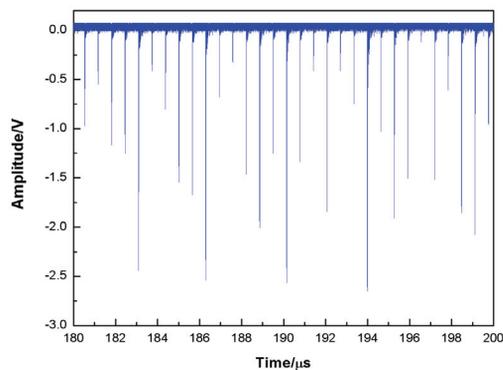


Figure 5: Single particle signal at ToF detector with isochronous mode in CSRe.

FIRST OPERATION OF CSR FOR CANCER THERAPY

The first operation of CSR for cancer therapy was carried out in Mar. 2009. In the treatment phase the

stripping injection of carbon beam accumulated with e-cooling was applied for more insurance of current and stability of slow-extracted carbon beam of $\sim 1 \times 10^9$ at CSRm with energy ranged from 100 MeV/u to 250 MeV/u. At the treatment terminal the scan magnets was used for expansion of beam profile, offering an enough field of $\pm 5 \text{ cm} \times \pm 5 \text{ cm}$ with uniformity better than 95% at the multi-leaf collimator. Beam energy was changed passively with energy degrader.

The main results were shown in Fig. 7 for the beam-current measurement from accumulation to slow-extraction, Fig. 8 for extracted beam measured at scintillation detector at the beam line, Fig. 9 for the expansion uniformity of the irradiation field. Fig. 10 shows the 3D and 2D irradiation field distribution.

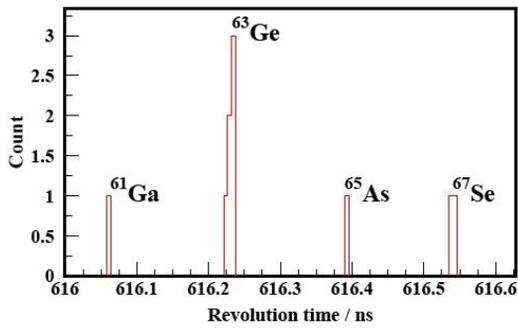


Figure 6: Experiment counts of the aimed target nuclei ^{63}Ge , ^{65}As , ^{67}Se .

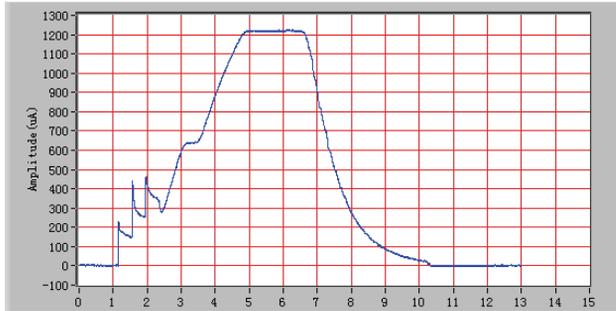


Figure 7: DCCT measurement at CSRm for cancer-therapy operation.

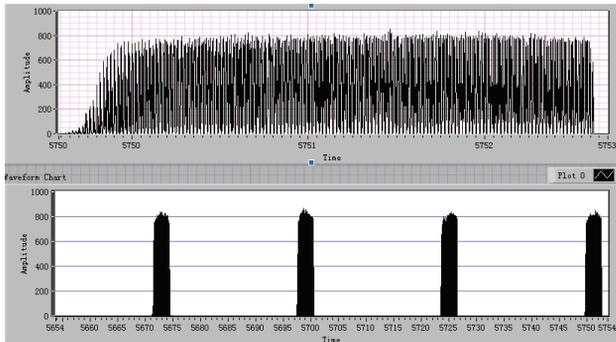


Figure 8: Extracted beam measured at beam line with scintillation detector.

In this operation 6 patients, who were all suffering from recrudescence after normal treatments, with focus-depth of 3-10 cm, were treated and the preliminary clinic results indicated the success of the therapy.

After the treatment several issues were tested. Beam delivering with energy actively changed by CSRm was successfully tested.

The other issue is if the single stripping injection without e-cooling can be enough, efficient and stable for cancer therapy. Fig. 11 shows the positive tested results after optimization. CSR m settings for single stripping injection differ from accumulation mode which requires large accumulation space with dipole magnet fields ~0.5% higher.

CONCLUSIONS AND PROSPECTS

Present commissioning and operation status of HIRFL-CSR were listed in Table 2. From the commissioning and

first operations experiences were gained and concluded as follows.

The first one is the extraordinary performance of stripping injection, especially for our cases with low injection current. Optimized “gain” factors of 25, 150 and 300 were achieved for stored beam with operation modes of single stripping injection, 10 s and no-limit accumulation, respectively, for carbon beam with injection of ~10 μA , which managed to meet the current and emittance requirements of cancer-therapy and other applications.

For cyclotrons the CW-mode is normally not a problem. So it is really flexible to inject and accumulate to the ring at desired repetition rate, depending on the chopper and the injection bumpers. It was also shown a scheme with single stripping injection from a cyclotron like SFC can offer carbon beam with 10^9 pps in a relevant small synchrotron, which can be a possible miniaturized candidate for cancer-therapy.

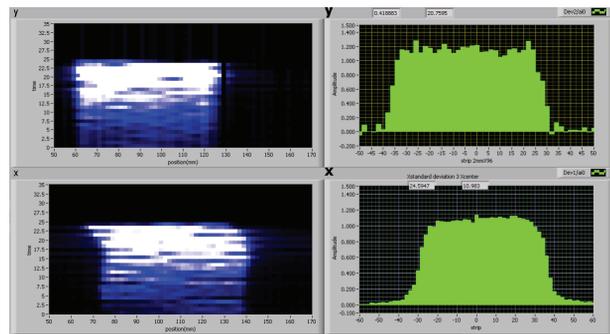


Figure 9: Contour historical (left) and total counts (right) plots for horizontal (up) and vertical (down) scanning for expansion of irradiation field.

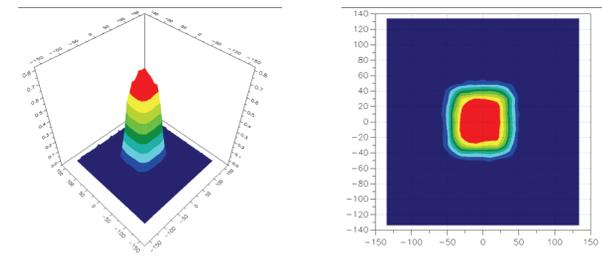


Figure 10: The measured 3D and 2D irradiation field distribution.

Table 2: CSR Commission and Operation Status

Ion	$^{12}\text{C}^{6+}$, $^{36}\text{Ar}^{18+}$, $^{78}\text{Kr}^{28+}$, $^{129}\text{Xe}^{27+}$
Energy	1 GeV/u for C & Ar in CSRm
Intensity	10mA (7×10^9) for C-660MeV/u in CSRm
	1.2mA (4×10^8) for Ar-368MeV/u in CSRm
	0.6mA (1×10^8) for Kr-480MeV/u in CSRm
	0.5mA (1×10^8) for Xe-235MeV/u in CSRm
	15mA (8×10^9) for C-660MeV/u in CSRc
Experiment	RIBs mass-measurement, isochronous mode of CSRc, $\Delta M/M \sim 10^{-6}$

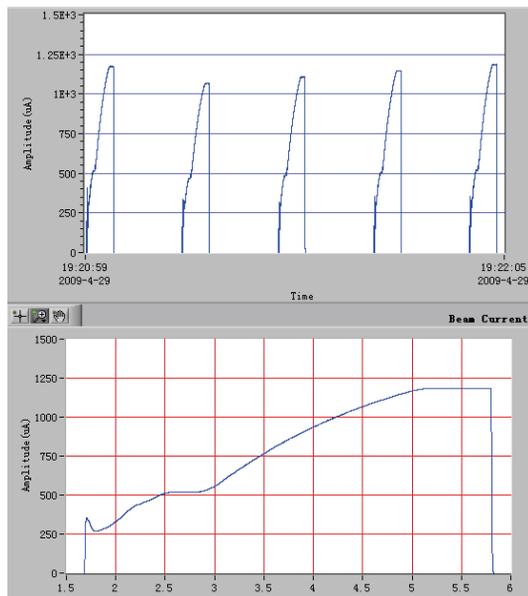


Figure 11: Testing of optimized single stripping injection.

It is shown the RF harmonic-transfer scheme can be applied with high efficiency to simplify the RF of the ring.

It is also clear that if there is a new and more powerful injector besides the present cyclotron injection system the performance of CSR will be great enhanced. Cooperation has been started with IAP, University of Frankfurt, for a dedicated heavy-ion LINAC injector for CSR [5], the first part of which consists of an RFQ and IH-DTLs. Heavy ions with charge to mass ratio from 1:3 to 1:8.5 are to be accelerated to 3.5 MeV/u. In the future it is planned to extend the LINAC to beam energies of up to 10 MeV/u. The main parameters are listed in Table 3, and the layout is shown in Fig. 12. In the HIRFL layout, the position of the new injector can be found in the small hall beside the CSRm cooler, as shown in Fig. 1.

With the new LINAC scheme it is prospected that the injected beam for $^{12}\text{C}^{4+}$ will be increased by 50-100 times. It is hoped that the previous 8-minute accumulation can be shortened to within 5 s. Furthermore, the increased injection current will for sure improve the accumulated beam current. For heavier ions with ~ 1000 times more current will offer much more possibilities at CSR with the new injector. The HIRFL will also gain much flexibility with the multi-injector system.

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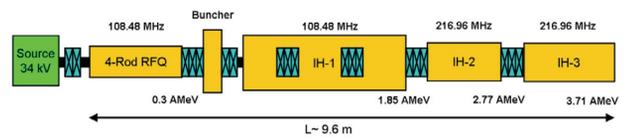


Figure 12: Preliminary LINAC layout.

Table 3: Briefed Parameters of CSR New Injector Scheme

Ion source	Parameters
Super-Conducting 28 GHz ECR	$^{12}\text{C}^{4+}$, $^{40}\text{Ar}^{12+}$, $^{129}\text{Xe}^{27+}$, $^{208}\text{Pb}^{27+}$, $^{238}\text{U}^{28+}$
Beam Current (emA)	0.5 - 1.0
Emittance(π mm mrad)	0.4 - 0.8 (normalized, 90%)
Extraction Voltage (kV)	25 - 40
RFQ	Parameters
Inj. Energy (keV/u)	3 - 5
Ext. Energy (keV/u)	300
Charge-Mass Ratio(q/A)	1/8.5 - 1/3
RF Frequency (MHz)	108.48
Max. RF Power (kW)	250
Ext. emittance (π mm mrad)	< 0.8 (normalized, 90%)
IH-DTL	Parameters
Inj. Energy (keV/u)	300
Ext. Energy (MeV/u)	3.5
Charge-mass Ratio (q/A)	1/8.5 - 1/3
RF frequency (MHz)	108.48/216.96
Ext. Emittance (π mm mrad)	0.8 (normalized, 90%)
Ext. momentum Spread (%)	< ± 0.15

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