In 2022, the HIRFL facility delivered beams to 12 experimental terminals. The main users were from material science at TR5 and nuclear science at RBILL, as listed in Table 3. In addition, the cooling storage ring provided about 1 500 h beam for nuclear and atomic physics experiments.

Table 3 Experimental terminals and beam time distribution.

SFC-T1	RIBLL1	TR0	TR1	TR2	TR4	TR5	CSRm	CSRm-ET2	CSRm-ET3	HERE	CSRe
1173	1001.5	150	128	328	241	1126	296	514	29	329	327.5

Over the year, several machine studies have been performed in order to improve the operation efficiency. The main contributions are listed as following:

The new linac sections DTL3 and DTL4 were installed in the SSC-Linac beam line, in order to increase the ion beam energy from 0.58 to 1.48 MeV/u at the end of linac. Together with the cyclotron SSC, uranium beam can be accelerated up to 15 MeV/u and then stripped and injected into the cooling storage ring CSRm. The acceleration of 500 MeV/u uranium ion beam will be tested in the next year.

The SSC-Linac and CSR were operated in the parallel modes to increase the beam time on the targets. With the upgrade of beam-lines, it is possible to have 4 different parallel operation modes in HIRFL.

The extraction beam current up to 12 eμA of Xenon ($^{129}Xe^{22+}$) beam was obtained firstly in the cyclotron SSC of HIRFL. The improvement of the heavy ion beam current is important for material research. In addition, the stored Krypton ($^{78}Kr^{26+}$) particle number of 1.25×10^9 is obtained.

The afterglow mode of ECR ion source was tested to provide high intensity pulsed heavy ion beams for the cyclotron SFC and consequently the storage ring CSR. Compared with the CW mode, the final beam current has an increase of 80% in CSRm.

New vacuum pumps were installed and operated in the cyclotron SSC. The vacuum condition was improved up to 3×10^{-8} mbar.

The new main magnet power supply of the cyclotron SFC was installed and operated. The stability of $\pm 2 \times 10^{-5}$ was obtained.

8 - 2 Operation and Commissioning of $^{78}Kr^{26+}$ with HIRFL

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In 2022, the $^{78}Kr^{26+}$ beam was used for experiments at the PISA Terminal and the Single Event Effect Terminal of HIRFL. During the routine operation, a primary beam of $^{78}Kr^{26+}$ at 6.05 MeV/u provided by SFC were accumulated, cooled, and further accelerated to extraction energy at the CSRm. The multiple multi-turn-injection (MMI) with electron cooling was utilized in operation. Beam acceleration at CSRm relied on the technique of the high efficiency radio-frequency (RF) harmonic number transfer acceleration. The acceleration process was divided into two ramping parts to avoid the lower limit of the RF frequency. Each ramping part has different RF harmonic number, the first ramping part is 3 and the second is 1. The fast extraction mode was used for the PISA Terminal at the beam energy of 460 MeV/u, and 1/3 integer resonance slow extraction mode for the Single Event Effect Terminal at 70 MeV/u.

The highlights of the operation of $^{78}Kr^{26+}$ are summarized as follows:

(1) The infinite accumulating intensity reached 2 000 eμA, and the 10 second injection intensity reached 1 250 eμA at the CSRm, as shown in Fig. 1.

(2) By adjusting the relative delay time between the magnet and the RF, as well as the capture parameters of the RF, the higher efficient capture and acceleration of 20 s injection is successfully completed. The acceleration intensity was increased from 5 000 to 7 100 eμA and the corresponding ion number was up to 1.23×10^9, as shown in Fig. 2.

(3) The influence of plate gap of 20MS01 on beam injection intensity was investigated. By adjusting the plate gap in the range of 21.01~34.41 mm of 20MS01, the injection intensity of the CSRm did not change significantly, as shown in Fig. 3. This proves the current power supply of 20MS01 could satisfy the demands of $^{238}U^{46+}$ beams injection at 3Tm.

(4) The performance of the non-intercepting current diagnostics was validated, which can measure the beam intensity and position simultaneously. Compared with BPM (Beam Position Monitor) of CSRm, whose detection beam intensity lower limit is of 3 eμA, the non-intercepting current diagnostics can detect 5 cycles of beam circulation signal at the beam intensity of 0.8 eμA, as shown in Fig. 4. Therefore, the current BPM can be replaced by non-intercepting current diagnostics for minimal beam intensity operation.

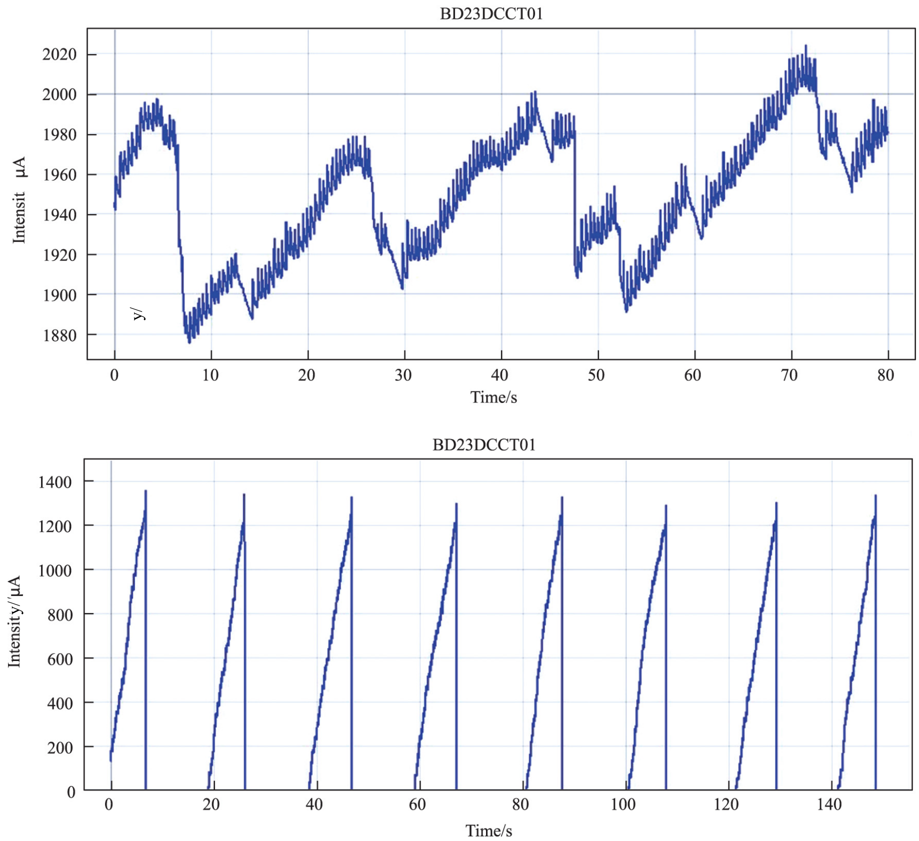

Fig. 1 (color online) The multiple multi-turn-injection (MMI) accumulation of $^{78}Kr^{26+}$ beam in the CSRm. (up) the infinite accumulating, (down) the injection time is 10 s.

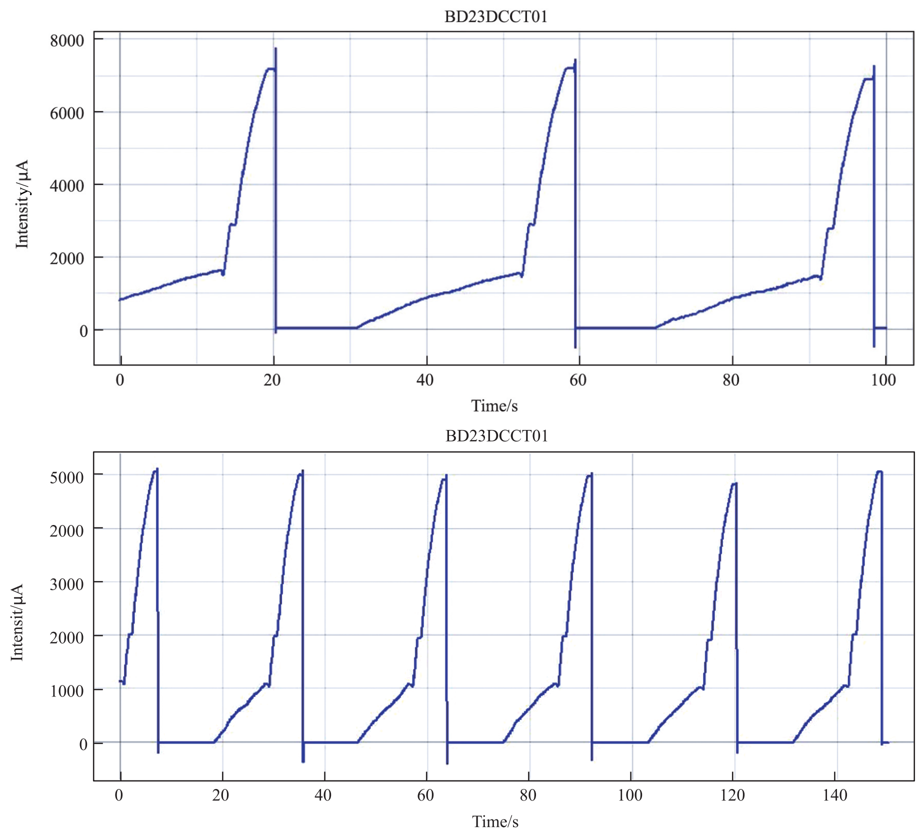

Fig. 2 (color online) The accumulation and acceleration of $^{78}Kr^{26+}$ beam in the CSRm. (up) the injection time is 20 s, (down) the injection time is 10 s.

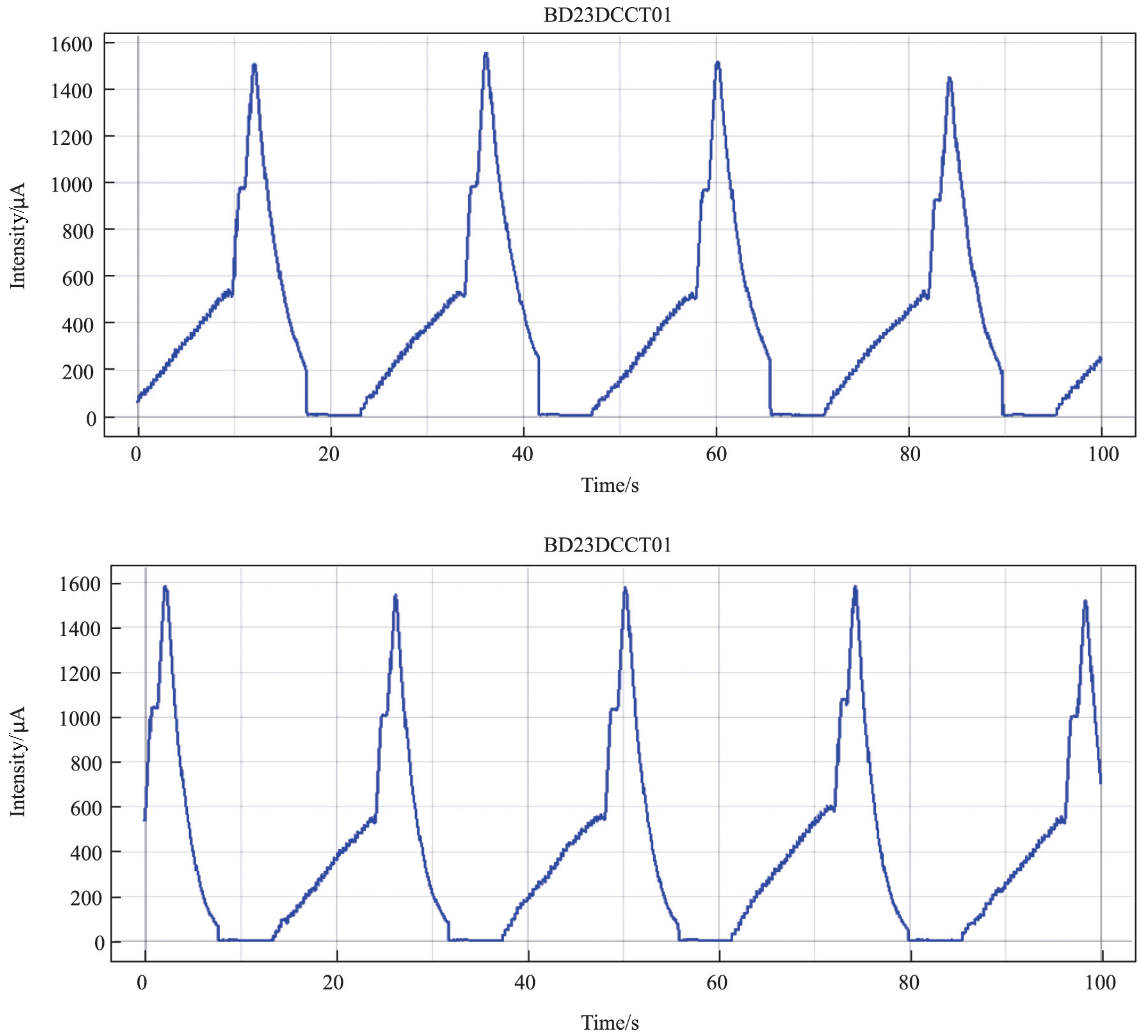

Fig. 3 (color online) The accumulation and acceleration of $^{78}Kr^{26+}$ beam in the CSRm. (up) the plate gap is 34.41 mm, (down) the plate gap is 21.01 mm.

Beam/K		Beam	K Value	Background
Amp_1M_1st	–3.433	–5.150	1.500	0.000
Amp_1M_2nd	–5.230	–7.165	1.370	0.000
Amp_10M_1st	4616.013	2308.007	0.500	0.000
Amp_10M_2nd	3637.570	6547.627	1.800	0.000

Phase	
Phase_1st	198.829
Phase_2nd	178.350
Phase_10M_1st	194.221
Phase_10M_2nd	162.788

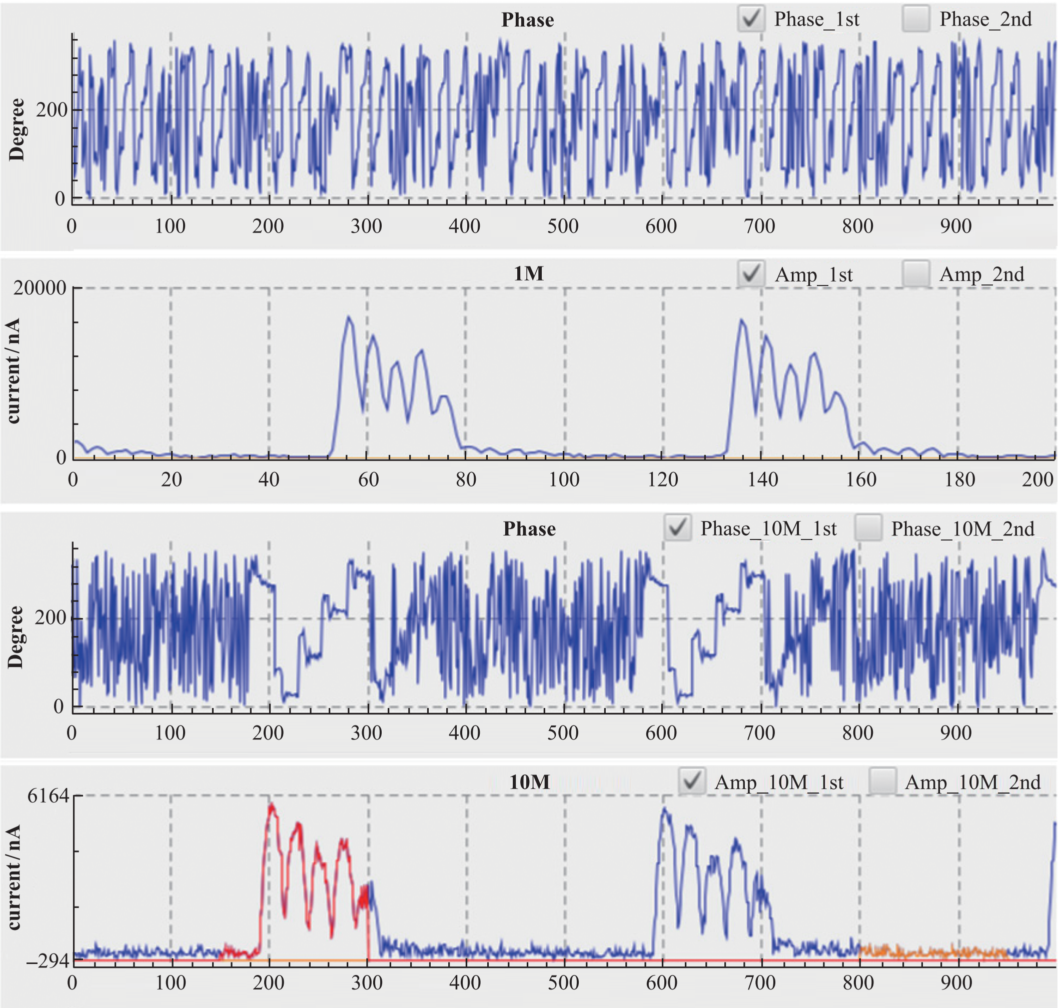

Fig. 4 (color online) The $^{78}Kr^{26+}$ beam signal of the non-intercepting current diagnostics in CSRm.