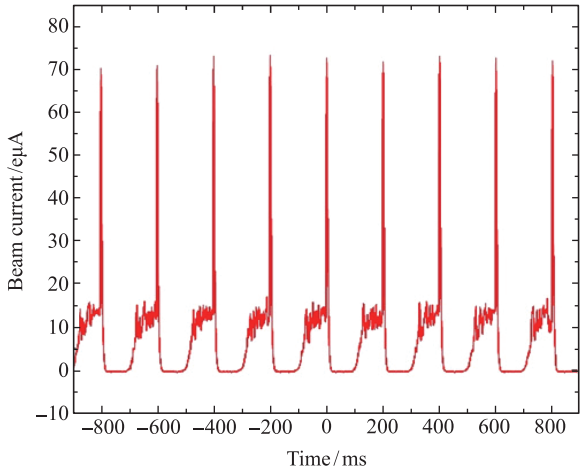

Fig. 3 (color online) Typical afterglow waveforms of U^{37+} produced by LECR4 ion source.

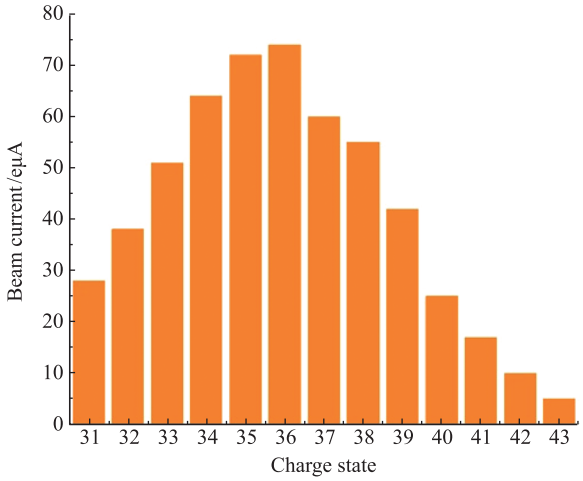

Fig. 4 (color online) Uranium charge state distribution of LECR4 ion source with afterglow mode.

8 - 24 Progress of HECRAL Ion Source

Qian Cheng, Sun Liangting, Lu Wang, Li Libin, Yang Tongjun, Wang Xudong, Zhu Li, Zheng Shijun, Wu Wei, Ma Jindou, Fang Xing, Zhang Wenhui, Zhang Peng, Chang Jianjun, Zhang Zonghu, Ma Hongyi, Li Xixia, Li Xinlu and Zhang Xuezheng

A Hybrid superconducting Electron Cyclotron Resonance ion source Advanced in Lanzhou (HECRAL) has been designed and constructed at IMP. The schematic layout of the ion source is shown in Fig. 1. The axial superconducting magnet of the ion source is optimized and tuned using four sets of superconducting coils, while the radial magnetic field employs a new Non-Halbach structure to achieve better radial confinement. This configuration is advantageous for the generation of highly charged ions. The magnetic field of the ion source allows it operate both at 18 and 24 GHz. The main parameters of the ion source are listed in Table 1.

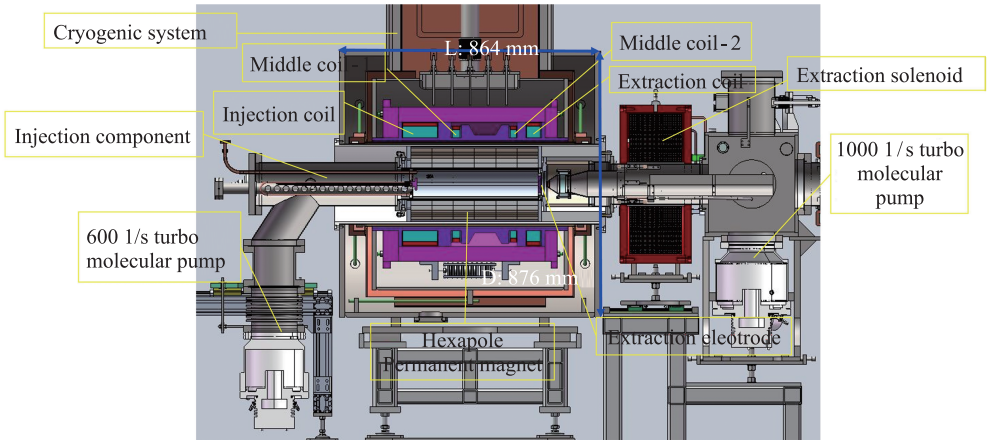

Fig. 1 (color online) The schematic layout of HECRAL ion source.

HECRAL ion source was initially tested in 2021 at a frequency of 18 GHz and a power of 2 kW maximum. The performance achieved was comparable to that of an 18 GHz room-temperature ECR ion source. In 2022, the ion source underwent further testing at a higher power of 3 kW. As a result of this increased power, the proportion of highly charged ion beams was enhanced by more than double. The performance of the ion source reached the level of a fully superconducting ECR ion source operating at the same frequency, as shown in Table 2. Currently, the ion source is operating steadily under an 18 GHz magnetic field frequency, and the low-temperature system is consistently maintaining a zero-evaporation state. Next year, 18∼24 GHz multi-frequency heating and higher microwave power will be used to further explore the performance of HECRAL.

Table 1 (color online) Design parameters of HECRAL ion source.

Parameter	Value
Microwave frequency/GHz	18 ∼ 24
Axial peak field at injection/T	3.4
Axial peak field at extraction/T	1.7
Minimum field at axis/T	0.5
Radial field at chamber wall/T	1.4
Mirror length/mm	400
Resonance length for 18 GHz/mm	100
Resonance length for 24 GHz/mm	134
Plasma chamber ID/mm	100
Warm bore ID/mm	260

Table 2 Comparison of the results of HECRAL ion source with SECRAL@18 GHz.

Ions	**HECRAL-2021/eμA**	**HECRAL-2022/eμA**	**Growth ratio**	**SECRAL@18 GHz**
$^{16}O^{6+}$	1610	2116	31.4%	2300
O^{7+}	496	723	45.8%	810
$^{40}Ar^{12+}$	350	543	55.1%	510
Ar^{14+}	135	224	65.9%	270
Ar^{16+}	45	70	55.6%	73
$^{86}Kr^{19+}$	221	360	62.9%	
Kr^{26+}	65	95	46.2%	
$^{129}Xe^{26+}$	274	430	56.9%	410
Xe^{27+}	202	302	49.5%	306
Xe^{30+}	45	110	144.4%	101
Xe^{34+}	13	31	138.5%	21
Xe^{35+}	9	20	112.2%	12
Xe^{37+}		11		5
Xe^{38+}		6		2.4