Operation report on the RIKEN AVF cyclotron for 2023

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The annual report on the operation of the RIKEN AVF cyclotron (hereafter denoted as AVF) for the period of January-December 2023 is presented. AVF delivers beams to the following experimental courses as a standalone operation: C01 (machine study; MS), C03 (RI production), E7V (CNS experiments and RI production), E7A (CRIB experiments), and E7B (student experiments and RI production). In addition, AVF is operated as an injector of the RIKEN Ring Cyclotron (RRC).

The yearly changes in operation statistics since 2020, and the beams accelerated using AVF in the period are summarized in Tables 1 and 2. The operation times for the standalone operation and injection to RRC in the period were 2103 hours and 739 h, respectively. The beam service interrupt time caused by trouble of AVF was 79 hours in total. AVF-RRC-SRC experiments were not scheduled or performed.

Table 1. Comparison of AVF operation statistics with that in previous years.

AVF standalone operation		Year 2020	2021	2022	2023
Tuning of AVF	[h]	744	1149	1212	1025
Trouble of AVF	[h]	1	5	0	77
C01 MS	[h]	12	35	32	0
C03 Exp.	[h]	631	672	491	634
E7V Exp.	[h]	18	95	94	106
E7A Exp.	[h]	12	48	302	64
E7B Exp.	[h]	101	96	155	197
Sub total		1519	2100	2287	2103
AVF operation as injector of RRC		Year 2020	2021	2022	2023
Tuning of AVF	[h]	178	214	273	235
Trouble of AVF	[h]	5	1	1	2
RRC-Exp. & RRC-IRC Exp.	[h]	999	834	1300	502
RRC-SRC-Exp.	[h]	0	767	0	0
Sub total		1182	1816	1574	739
Total		2702	3916	3861	2842

Following the development of a Xe beam with an energy of ∼36 MeV/nucleon last year, we performed an acceleration test of ^{129}Xe.[1] $^{129}Xe^{25+}$ ions, instead of $^{136}Xe^{27+}$, because of an expected higher ion yield after charge-stripping (CS), were accelerated by AVF in the harmonics H = 3. After CS, a $^{129}Xe^{35+}$ beam of 72 electric nA (enA) was transported to RRC. Beam intensities before injection to RRC and after extraction were 39 electric nA (enA) and 20.5 electric nA (enA), respectively. A stable beam with an intensity of 15 electric nA (enA) was delivered to the E5 experimental hall. In the experiments performed in June and December, we successfully supplied stable beams of 45v and 50 electric nA (enA), respectively, by improving transmission efficiencies of the cyclotrons and beam transport lines.

Table 2. AVF beam list in 2023.

AVF standalone operation

Particle	Energy [MeV/nucleon]		Experimental Course
	1st beam	17	E7V
$^{1}H^{+}$		19	E7V
		30	C03
$^{2}H^{+}$		12	C03
		6.5	E7B
$^{4}He^{2+}$		7.3	C03
		13	C03
$^{7}Li^{2+}$		6	C03
$^{7}Li^{3+}$		8.3	E7A
		10	C03
$^{14}N^{6+}$		8.4	E7A
$^{18}O^{6+}$		7	E7V

AVF operation as injector of RRC

Particle	Energy [MeV/nucleon]		Experimental Course
$^{12}C^{4+}$		7	RRC-RARF
$^{14}N^{5+}$		7	RRC-RARF
$^{40}Ar^{11+}$		3.8	RRC-IRC-E5B
$^{40}Ar^{11+}$		5.2	RRC-RARF
$^{56}Fe^{15+}$		5	RRC-RARF
$^{84}Kr^{20+}$		4	RRC-RARF
$^{129}Xe^{25+}$	1st beam	2.5	RRC-RARF

During the tuning time in June, we also performed an acceleration test aiming to provide beams with an energy of 60 MeV/nucleon to the E5 hall in the AVF-RRC-IRC mode. A $^{129}Xe^{31+}$ beam with an energy of 1.61 MeV/nucleon and intensity of 100 electric nA (enA) was produced by increasing the thickness of the charge-stripper from 0.5 mg/cm^2 to 1.2 mg/cm^2. However, the momentum spread of beam bunches was increased to approximately ±1%, and the beam emittance was deteriorated. Due to the poor transmission efficiency, the injection intensity to RRC was expected to be ∼20 electric nA (enA), which is extremely low for acceleration in RRC and IRC because a certain intensity is required to optimize the isochronous magnetic field for each cyclotron. Although acceleration is difficult, we are considering the use of the second charge-stripper after RRC, which can be expected to have a high CS efficiency of 30% or more due to the increased beam energy.

In April, a vacuum leak occurred from the sub-vacuum chamber of AVF, which was caused by heat hardening of the O-rings attached to the feed-through pipes for the trim coils.[1,2] The O-rings were replaced by new ones to recover the vacuum. During the repair, when an upper yoke of the main magnet was lifted up, abnormal vibrations and noises occurred in the drive

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mechanism several times. Considering safety, parts including gears were overhauled by the manufacturer in July during a maintenance period. Although it is not practically problematic, very slight vibration and noise remain. Therefore, we are considering to replace these parts in the future.

References

1) M. Nishimura *et al.*, Proc. of PASJ2023, (2023), pp. 1049–1053.
2) Y. Watanabe *et al.*, "Vacuum Leak at Feed-Through of Trim Coils in AVF," in this report.