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ACCELERATION TESTS OF THE JAERI TANDEM SUPERCONDUCTING BOOSTER

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Abstract

An independently phased heavy ion linac composed of 46 superconducting quarter wave resonators has been built for the booster of the tandem accelerator at Japan Atomic Energy Research Institute, Tokai. Several kinds of heavy ions of Si to Au have been accelerated. The performances of the resonators and the results of the beam acceleration are described.

1. Introduction

An upgrade project of the JAERI tandem accelerator with a superconducting booster has been completed after a R&D of a superconducting quarter wave resonator from 1984[1], fabrications and testing of prototype units composed of two superconducting resonators from 1986 and a full scale construction of the booster from 1988[2-4]. Heavy ion beams of Si to Au have been accelerated by the tandem and the booster for the commissioning test in 1994.

For heavy ion beams up to around Au, a bombarding energy higher than nuclear reaction threshold has become available at the new target room.

2. Outline of the Tandem Booster

The diagram of the JAERI tandem booster is shown in Fig.1. The continuous beam from the tandem is injected into the booster. The booster starts off with a double drift bunching system composed of two 129.8MHz QWRs and two 259.6MHz QWRs. One of the two for each frequency is used, while the other stands by. The linac comprises ten acceleration units, each of which contains four 129.8 MHz QWRs in a cryostat and a quadrupole doublet lens outside. After the linac, there is a debunching unit composed of two 129.8MHz QWRs. The debunched beams are analyzed by a double focusing bending magnet. The beams obtained from the booster are, then, 129.8 MHz CW beams.

With respect to the beam transport system, the beam waists should be located at the middle of the two bunching units, at the entrance of the linac, in the middle of the linac, at the exit of the linac, at the object and image points of the analyzing magnet and finally the target position in a target beam line. At or near the waist points, apertures or slits, beam profile monitors and Faraday cups are placed. Beam baffle apertures of 16mm in diameter are put at the entrances of all the acceleration units to protect resonator surfaces from stray beams.

The longitudinal beam diagnostics are important to an independently phased linac. Energy and time detectors are placed before and after the linac and after the debuncher. Those are compact scattering chambers that ions scattered from a Au foil are detected by a solid state detector. Three beam bunch phase detectors, 129.8 MHz normally conducting QWRs, are used for the phase setting of the linac resonators.

The booster is equipped with two identical refrigerators of Claude cycle with two expansion turbines. Each system has two loops, a liquid helium loop and a 80K gaseous helium for the radiation shielding in the transfer line and in the cryostats.

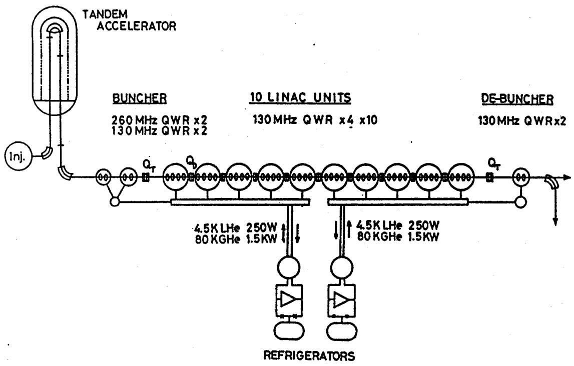

Fig. 1 Diagram of the JAERI tandem booster.

3. Cryogenics

The flow diagram is shown in Fig. 2. Liquid helium passes through heat exchangers cooling four resonators, flows into the Dewar and inside the resonators and returns to the transfer line. The pressure in the Dewar was about 0.35 kg/cm^2 during operation.

Each cryostat is connected to a valve box through four retractable transfer tubes. Remotely variable valves are used in liquid supply lines to cryostats, and locally variable valves in gas supply lines.

The refrigeration power necessary for the booster was estimated to be more than 300W for the liquid loops if an rf power of 4 W is dissipated in a resonator and 2500 W for the 80 K gas loops. The refrigeration power designed for one system is, then, 250 W for the liquid loop and 1.5 kW for the 80K gas loop. In the cold box, there is a small sump of a volume of about 10 litters. The liquid level is controlled by the heater in the sump. The helium liquefied by the heat exchanger in the sump is supplied to the resonators. The returning gas and liquid from the resonators flow into the sump. We obtained the refrigeration powers 10% more than those in the commissioning test.

The operation can be done semi-automatically. We have several operation modes, COMPRESSOR MODE, CIRCULATION MODE, COLD BOX MODE, CRYOSTAT MODE, RECOVERY MODE and WARM-UP MODE. The cold box and 80K radiation shields are cooled in COLD BOX MODE before the resonators. The CRYOSTAT MODE starts to cool the resonators when the radiation shields are cooled to 150K. It took 2.5 days from a start of COLD BOX MODE to cool the resonators and 12 to 15 hours to fill all the Dewars with liquid. Liquid filling was excellent except an acceleration unit, no.5. The unit needed to open the variable valve a lot more than others. The rf power dissipation was limited to about 80W/system(4 W per resonator) for the

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stable resonator operation that the helium pressure was stable or the liquid levels were kept full during the operation of all the resonators. Power of as much as 120 W was supplementary dissipated by the heater in the sump for stabilizing the system.

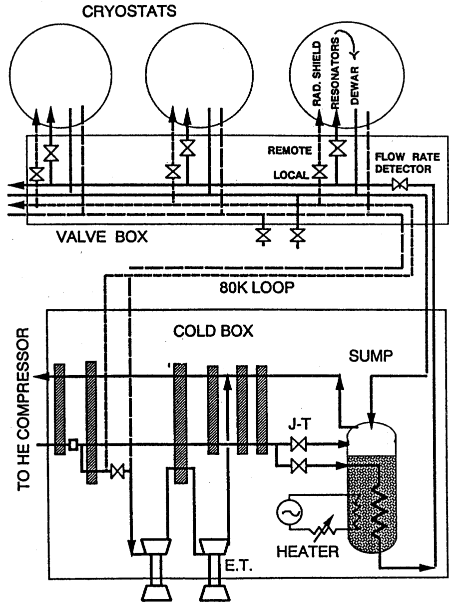

Fig.2 Diagram of gas and liquid flows in a cold box and a valve box.

4. Resonator Performances

The resonator performances were measured in an off-line test cryostat. Fields of about 7 MV/m were obtained at an rf input of 4 W[4, 5]. For most of the resonators, the Q-decrease due to electron field emission at high fields was not so much that high maximum fields were obtained without high power pulse conditioning. This result is due to that the resonators were cleaned well in the final surface treatment.

We have found the Q-degradation with the resonators which absorbed much of hydrogen (an order of a few wppm) in the electro-polishing and were cooled slowly around 120K[4,5]. This phenomenon is understood as a precipitation of a niobium-hydride weak superconductor onto the niobium surface[6]. The cooling rate at 120K was 10K/h when the resonators on line were cooled by the refrigerators. The rate is approximately one-fourth of that in the off-line test cryostat. The Q-values at low fields measured for the resonators in off-line and on-line are shown in Fig.3. A strong Q-degradation happened to most of the resonators from no.1 to no.16. Hydrogen absorption was not prevented enough for them. But, the following improvement was given to the resonators from no.17 in the surface treatment. The hydrogen gas coming out during electro-polishing was brought away as much as possible from the polishing solution by passing nitrogen gas bubbles. The bubbling seemed to be efficient for preventing hydrogen absorption into the niobium for the closed cavity structure.

Fields gradients obtained for the on-line resonators are shown in Fig.4. The resonators of no.1 to no.16 needed the present allowable rf power input of about 4W per resonator mentioned above to obtain their maximum field gradients. Many of them were lower than the design value of 5 MV/m. For those from no.17 to no.40, the degradation was not so severe that field gradients higher than 5 MV/m were obtained within 4 W.

The Q-degradation can be reduced by increasing the cooling rate at the precipitating temperature, around 120K. The cooling rate from 130K to 90K was increased to about 15K/h in a test that we split the16 resonators into two groups and used the whole gas from the cold box to cool down one of two groups at a time over the temperature range. The increases are also shown in Fig. 4. An increase of about 0.5 MV/m was obtained. The acceleration voltage summed over all the resonators finally passed 30 MV.

With respect to the frequency stability, the frequency oscillation was only a few Hz when the cryogenic system was stable. A frequency deviation of about 10 Hz or more happened at the time that the liquid levels fell down from 100% or came back to 100 %, and the pressure deviated by about 0.05 kg/cm^2. The rf input coupling was set to give a band width of more than 20 Hz for stable phase lock.

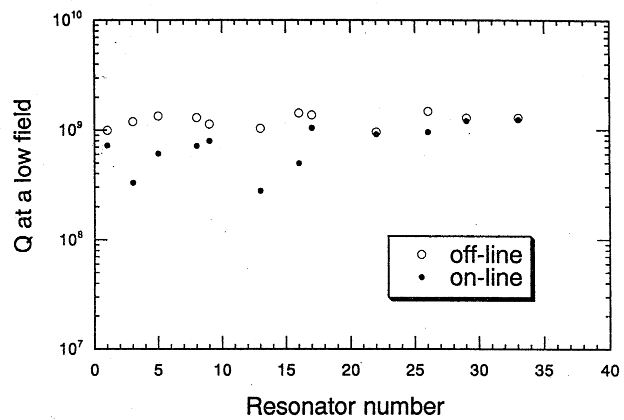

Fig.3 Resonator Q-values at low fields measured for the resonators in off-line and on-line.

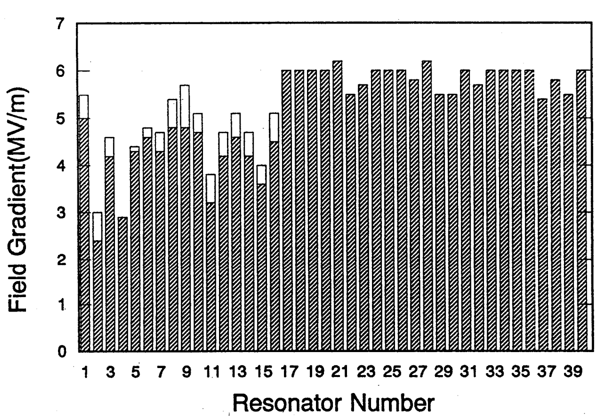

Fig.4 Accelerating field gradients obtained for the on-line resonators. Open bars indicate the increase of the fields after a faster precooling around 120K.

5. Resonator Control with Beam Diagnostics

Each resonator is controlled in a self-excited resonant loop which is composed of a resonator with a variable rf input coupler and a signal pick-up probe, a resonator control circuit and a 120 W rf power amplifier. The rf signal and the rf power are transmitted through heavy doubly shielded coaxial cables. We use control stations made by Applied Superconductivity Inc., in each of which control circuits for 8 resonators are assembled.

For setting the buncher resonators of a1ω (129.8 MHz) QWR and a 2ω (259.6 MHz) QWR, the energy and time detector located at the entrance of the linac was mainly used in the beam acceleration tests. Next to the detector, a beam bunch phase detector, a 2ω normally conducting QWR, is placed. The phases of the beam bunches respectively bunched by the 1ω QWR and the 2ω QWR were measured by using the phase detector and a vector volt meter. This was useful for quick phase setting.

For the phase setting of the linac resonators, three beam bunch phase detectors, 1ω normally conducting QWRs are located after the 3rd acceleration unit, after the 6th unit and after the last unit. Their optimum βs are 0.08, 0.1 and 0.11 and their sensitivities are 7, 10 and 12mV/nA, respectively. The signals are amplified by about 40dB and inputted to vector volt meters. Computer aided measurements were done to display a curve of beam bunch phase as a function of resonator phase in an instant.

A beam bunch phase shift due to the change of time of flight is given as

$$\Delta\varphi = \omega\Delta T = -\omega L/(2 v_0 E_0) q\, E_{acc}\, L_a\, f(\beta) \cos\phi$$

where L is the flight length from the resonator in operation to the phase detector, E_0 the incident beam energy, $\beta = v_0/c$ the incident beam velocity, q the charge state, E_{acc} the field gradient, L_a the acceleration length, f(β) the transit time factor and φ the synchronous phase. By measuring a curve of the phase shift as a function of resonator phase, one can find the value of the resonator phase which corresponds to f=0 or the synchronous phase to be set.

The measurements were so quickly done that this method was suitable to repeat 40 times of resonator phase setting. At each resonator setting, the beam energy was checked by using the energy detector located after the linac.

With respect to the debuncher, one of the two QWRs was enough. Phase and field gradient were set, after bending beams 90°, by looking at the beam profile at the image of the analyzing magnet.

6. Acceleration Test Results

We have accelerated various heavy ions of ^{28}Si, ^{35}Cl, ^{58}Ni, ^{74}Ge, ^{107}Ag, ^{127}I and ^{197}Au from the tandem accelerator. The results are shown in table 1. The injection beam intensities were not the maximum.

In many cases, the total acceleration voltage was about 28 MV because a few resonators were not used because of problems in control circuits. The beams of I and Au in the last two lines were accelerated after the improvement of field gradients by the fast precooling mentioned above. For Si and Ge, which were the latest cases, field gradients were set at 3 MV/m for nearly all the resonator. The synchronous phases were set to the values calculated to give a good condition for debunching. The values were the same among all the resonators from no. 1 to no. 40. The final energies were in good agreement with calculated ones.

According to the beam optics[3,7], the ideal beam transmission efficiency is about 60 %. A satisfying beam transmission was obtained in the cases of $^{58}Ni^{20+}$ and $^{74}Ge^{11+}$ but not in other cases. It seemed partly due to our skill of the beam transport, because we had to transport the beams through many small apertures using many quadrupole lenses and steering magnets. For example, in the adjustment of the 9 quadrupole doublets, the transmission could not be improved by adjusting one by one. We finally obtained a good feasibility in the case of $^{74}Ge^{11+}$ as a result of simultaneously varying the field parameters of all the doublets. There could be partly other possibilities such that some resonators were out of alignment.

As long as the rf load to the cryogenic systems was within the limit and the liquid levels in the Dewars were kept full, all the resonators were locked in phase and stable beams were obtained for a long time with a phase stability of about ±0.5°.

Table.1 Results of beam acceleration tests

Ions	Energy(MeV) initial	final	Current(nA) in	out	Total acceleration voltage(MV)	Synchronous phase (deg)
$^{28}Si^{10+}$	180	327	80	20	17.3	-22
$^{35}Cl^{10+}$	164	351	130	40	24.6	-30
$^{35}Cl^{14+}$	164	446	80	16	27.6	-25
$^{58}Ni^{20+}$	190	628	80	30	28.2	-30
$^{58}Ni^{20+}$	190	658	170	100	27.7	-18
$^{74}Ge^{11+}$	180	326	110	60	17.3	-35
$^{107}Ag^{25+}$	231	798	45	15	27.6	-21
$^{127}I^{27+}$	225	812	20	4	28.3	-25
$^{127}I^{27+}$	225	880	100	23	30.2	-18
$^{197}Au^{25+}$	340	912	19	3	30.7	-22

7. Conclusion

The superconducting booster for the JAERI tandem accelerator was tested with many species of heavy ion beams.

A total acceleration voltage of 30 MV was obtained as expected, although a severe Q-degradation occurred with many resonators. The cryogenic systems worked well. The rf load was limited to about 4 W per resonator in stable operation. The measurement of beam bunch phases was successfully done by using beam bunch phase detecting resonators. The beam transmission was satisfactory in a few cases. It is promising to improve the transmission for others.

Various heavy ions from C to Au can be available with enough energy for nuclear reactions from the tandem booster from now on.

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