FIRST OPERATING EXPERIENCE WITH THE SUPERCONDUCTING HEAVY ION TANDEM-BOOSTER LINAC AT JAERI

Suehiro Takeuchi, Michihiro Shibata,
Tetsuro Ishii, Hiroshi Ikezoe and Tadashi Yoshida
Japan Atomic Energy Research Institute,
Tokai Research Establishment
Tokai, Naka, Ibaraki 319-11, Japan

Abstract

The superconducting heavy ion tandem-booster which was being constructed at JAERI was completed and submitted to beam acceleration tests in 1993. The booster is an independently phased linac composed of 46 superconducting quarter wave resonators. Acceleration tests have been done with Cl^{10+}, Cl^{14+} and Ni^{20+} at a total acceleration voltage of 28 MV.

Introduction

A superconducting heavy ion linac has been constructed for the booster of the tandem accelerator at JAERI in order to obtain the incident energy higher than the Coulomb barrier for medium heavy or very heavy projectile nuclei in a collision with similarly heavy target nuclei. The development was started with making a proto-type superconducting quarter wave resonator(SC.QWR) in 1984 and followed by construction of bunching and de-bunching units. The construction of the linac part composed of 10 units started in 1988. The installation, including adjustment and testing, of the linac units, refrigerating system and others were made from 1992 and completed in October of 1993. A view of the booster completed is shown in Fig.1. Then, beam acceleration test started with Cl ions from the tandem. The outline of the booster and our experience in the beam test are described in this paper.

Outline of the Booster

The booster has a double-drift harmonic bunching system composed of two units of two 129.8 MHz SC.QWRs and two 259.6 MHz SC.QWRs, ten linac units, in each of which four 129.8 MHz SC.QWRs are housed, and a de-bunching unit composed of two 129.8 MHz SC.QWRs, as is shown in Fig. 2. The structure of the 129.8 MHz SC.QWRs is illustrated in Fig. 3[1]. The optimum beam velocity is 0.1c for all the QWRs. We take an advantage of QWR that the incident velocity acceptance is wide, so that the booster becomes simple[2]. The designed total acceleration voltage is 30 MV. Direct current heavy ion beams are injected into the booster. About 60 % of the beams are bunched and accelerated through the linac in a calculation[2]. The booster is designed to use c.w. quasi-dc beams. De-bunched beams after a drift of about 10 m are compressed in energy and analyzed by a 90 degree bending magnet.

The booster is equipped with two closed loop liquid helium cryogenic systems. Each one has a refrigerating power of 250 W for a liquid helium loop and 1.5 kW for a 80 K gaseous helium loop. These loop lines are branched at booster units through valves.

All the resonators were respectively controlled by a direct phase feedback to the drive line in a self-excited loop with a 120 W RF amplifier. They have movable RF input couplers.

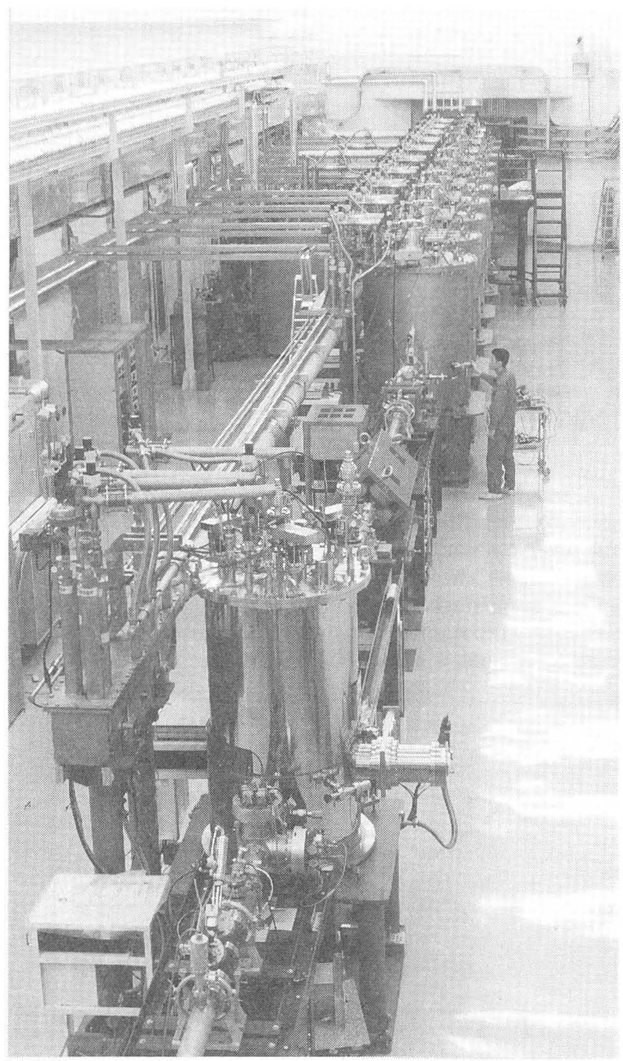

Fig. 1 A view of the heavy ion tandem-booster linac at JAERI

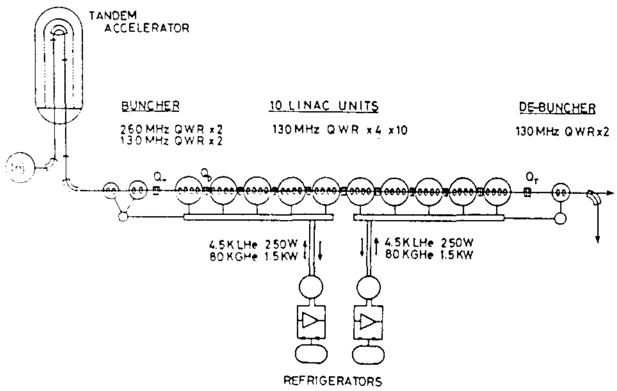

Fig.2 Diagram of the tandem-booster linac

For resonator phase setting, energy and time measurement detectors are placed in front and exit of the linac and beam bunch phase detectors after the third, the sixth and the last linac units. The phase detectors are normal conducting QWRs. Resonator phases are quickly set after sweeping the resonator phase and seeing the beam bunch phase.

Superconducting Resonators

All the resonators were given a final surface treatment at JAERI after the completion of fabrication in the factory. The niobium surfaces were polished by electropolishing, rinsed with HF, H_2O_2, de-ionized water and supersonic wave and then dried in a clean room after the final spray with de-ionized water and methanol. Many of them were tested in a testing cryostat before assembling. The off line resonator performance was as high as 7 MV/m at an RF input of 4 W for most of the resonators[3-5].

Q-disease

A Q-degradation phenomenon during slow precooling was found with high RRR high beta cavities[6,7]. It is called Q-disease and believed to be due to precipitation of hydrides[8]. In our experiment with one of our QWRs, the Q-disease was found if the QWR is slowly cooled between 130 K and 90 K[3]. On-line resonator performances were measured when the cryogenic systems became available for RF testing. The cooling rate in the region of 130 K to 90 K was - 10 K/h for both cryogenic systems. The resonators in the first four units were found to have 30 to 70 % of Q values compared with the off-line Q values[4,5]. Their accelerating fields at an RF input of 4 W were 3 to 5 MV/m. The Q values have not been changed very much by many thermal cycles and were not improved even by three week outgassing at 100C°. With the resonators in the rest six units which were made one year after those in the first four units, such a severe Q-degradation did not happen. We believe that the reason of the difference lies in an improvement of preventing hydrogen from being absorbed to niobium in electropolishing.

Problems and their treatments

We had a problem of frequency drift in thermal cycles. Frequencies of many resonators had been changed lower during cryogenic operation tests. The cause was found in too much adjustment of frequency as much as 50 kHz with screws on the bottom de-mountable flange (see Fig. 3). Such a big adjustment should have been done by giving a plastic deformation to outer conductors. A readjustment was done successfully and all the resonators except one were tuned to 129.800 MHz. The frequency drift in thermal cycles was overcome substantially.

In a test with the cryogenic systems, we found the resonator's frequency stability was not good enough against the instability of the liquid helium pressure in the cryogenic system described below. We put a support to the top shorting endplate for every resonator (see Fig. 3). The supports reduced the frequency change with helium pressure from 1.2 kHz/kg/cm^2 to 0.27 kHz/kg/cm^2. As a result, the frequency change decreased to an acceptable level of 20 Hz at a maximum pressure change.

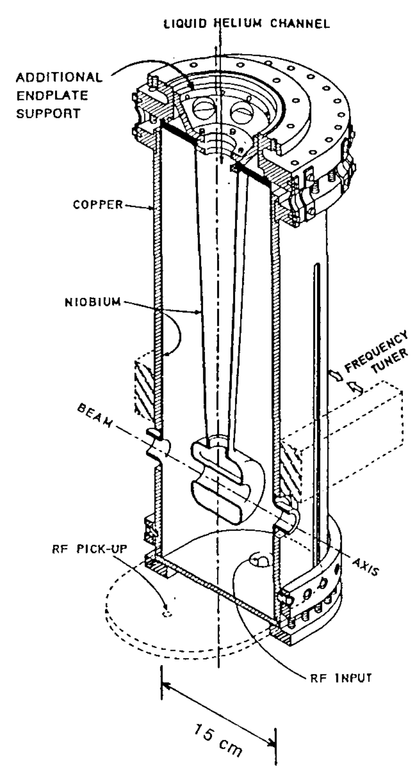

Fig. 3 A cut-away view of superconducting quarter wave resonator

Cryogenic System

The two(A and B) systems were found to have 110 % of refrigerating power compared with the design values in their performance test without transferring liquid into the booster units.

The operating procedure is programmed and automatic. There are several operating modes; compressor mode, cold box mode, cryostat mode, recovery mode and warm up mode. The cold box and radiation shields are cooled down first. The resonators start to be cooled down when the temperature of the shields falls below 150 K. It takes 2 days and a half to precool the resonators and a half day to fill up the cryostat vessels with liquid helium.

A power dissipation of 16W in each cryostat was confirmed in the initial performance test by using heaters put in the cryostat vessels. We had some initial troubles in operating the two(A and B) systems. Trivial ones have been overcome. A serious problem remains in the A system. The liquid flow to the No. 5 linac unit, which is closest to the cold box, is much less than others, even the valve is widely opened. It seems to affect the pressure stability and the allowable power dissipation. The pressure stability of the A system is several times less than the B system. The pressure change as much as 0.1 kg/cm^2 happened when the liquid level in the No.5 unit hit 100% after some decrease, because a return of liquid to cold box caused an exessive cool-down at the final stage expansion turbine. The liquid levels must be always kept at100% to keep resonators phase-locked.

Results of Beam Acceleration Tests

The initial beam acceleration tests were done by injecting the beams of Cl^{10+} 164MeV(β = 0.1) with an intensity of 80 - 130 nA from the tandem. The bunching system worked well. A measured bunch width was 0.33 ns (FWHM). We used 37 or 38 resonators of the linac in the tests(One had a low frequency and some resonator control circuits were out of order). The frequency changes due to the pressure instability were about 20 Hz and 5 Hz at a maximum in the A and B systems, respectively. RF input couplers were set at resonator control band widths of about 40 Hz and 25 Hz for the resonators in the A and B systems, respectively.

At an accelerating field gradient of 3 MV/m for every resonator, everything was stable. At a field gradient of 4.5 MV/m, an overload to the A system happened because the Q-degradation due to Q-disease was severe for many resonators. The field gradients were, then, respectively set within the rf dissipation of 4 W.

For the beams of Cl^{10+}, a final energy of 351 MeV was obtained at the average fields of 3.7 MV/m for the first 15 resonators and 4.9 MV/m for the last 22 resonators. Every resonator phase offset was set at -30°. For Cl^{14+}, a final energy of 446 MeV was obtained at the average fields of 3.9 MV/m for the first 15 resonators and 5.5 MV/m for the last 23 resonators and with a phase offset of - 25°.

Testing with different ion species has started. Beams of Ni^{20+} were accelerated from 190 MeV to 628 MeV and 658 MeV for phase offsets of -30° and - 18°, respectively, and at the average fields of 4.0 MV/m for the first 15 resonators and 5.55 MV/m for the last 23 resonators. The field gradients are shown in Fig. 4. The total accelerating voltage was 28 MV.

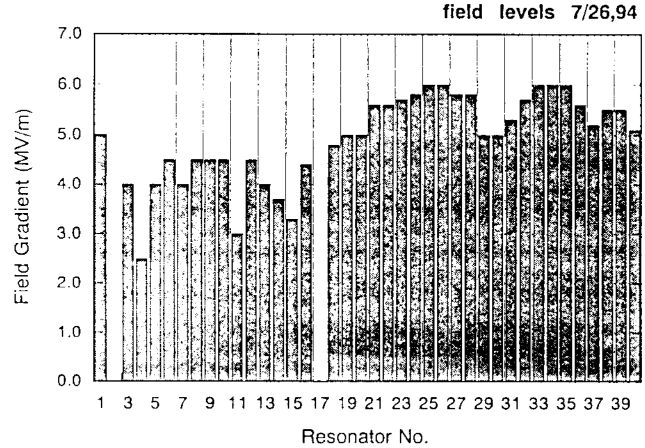

Fig. 4 Accelerating field gradients of the resonators in the linac

Resonator phase setting

We used calculated values for the resonator phase offsets which gave a good beam debunching after the acceleration. The beam bunch phase detectors were quite useful in setting the resonator phases. A typical phase signal from the detector is shown in Fig. 5. Phase setting is quickly done by finding zero-crossing points of the phase shift of a phase detector signal in sweeping the resonator phase reference in the resonator controller. The zero crossing points correspond to a resonator phase offset of +90° or -90°, if the phase signal from the detector is reset to zero before the resonator to be set is turned on. When the phase shift exceeded the range of ± 180°, the field gradient was lowered only during the phase setting. The phase shift was not affected very much by the unbunched off-phase parts of beams.

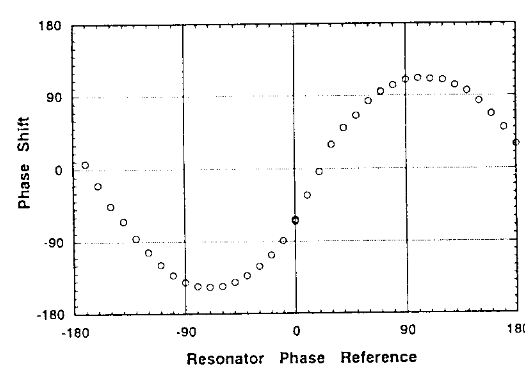

Fig. 5 Phase shift of a phase detector signal as a function of resonator phase reference

Beam transmission

The beam transmission efficiency was between 50% and 100% in the tests. A precise adjustment of beam transport elements was required for a good beam transport, because baffle apertures of 16 mm in diameters are put in front of all the linac units. They are for preventing unbunched largely off-phased particles from hitting resonator walls.

Beam debunching and analyzing worked well. The beam at the image of the 90 degree analyzing magnet was stable as long as the all the resonator phases are locked. Each resonator phase error was as small as ± 0.1°, and each resonator field gradient error was as much as ± 0.1 MV/m. The beam energy spread has not been measured yet, but it was estimated about 0.5 MeV from the beam profile at the image of the analyzing magnet.

Discussion

The accelerating gradients and the total accelerating voltage were hindered by Q-disease very much. We hope to cure it somehow.

Some trials have been done. A long term outgassing at 100°C had no effect as is mentioned above. It has been known that anodizing is effective[9]. A resonator has been anodized and installed in this booster. With it, we did not found appreciable improvement of Q in off-line and on-line tests. The oxide layer is about 0.1 mm. A thick oxide layer, however, is not welcome, because parts of the layer could be damaged by high power pulse conditioning. The conditioning is very useful to recover the Q at high field which has been degraded by electron field emission from dust particles.

It is expected that a part of hydrogen content evaporates when the niobium is warmed up after a hydride is precipitated on the surface. In a sample test with 0.3 mm thick niobium sheets, we found a definite decrease of hydrogen content after an absorption of hydrogen and a thermal cycle in vacuum. In a test with a resonator in a testing cryostat, the Q was improved twice as a result of several thermal cycles across the precipitation zone(90-130K). With the resonators in the booster linac, however, clear improvement has not been observed over the thermal cycles so far. It is still worth trying more thermal cycles by an effective way, such as feeding RF power.

Another idea we want to try is a time serial cooling process across the precipitation zone for two or three groups of resonators by manipulating helium flow control valves. It may increase individual cooling rates.

Conclusions

A heavy ion superconducting booster has been built at JAERI and has started running with beams of Cl and Ni. Bunching, acceleration and de-bunching were as successful as designed. There were no ill effects of unbunched parts of beams in operation.

The Q-degradation called Q-disease was heavy for the resonators in four linac units. Their field gradients were limited to 4.0 MV/m in average. With this limit, the total accelerating voltage of 28 MV was available.

References

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