First three year operational experience with the JAERI tandem-booster

S. Takeuchi and M. Matsuda

Japan Atomic Energy Research Institute,
Tokai Research Establishment
Tokai, Naka, Ibaraki 319-11 Japan

Abstract

The JAERI tandem-booster composed of 46 superconducting quarter wave resonators was completed in 1994. The resonators have been running well, without serious troubles which might cause cryomodule opening, for three years since its completion. Improvements done for the superconducting resonators during and after the commissioning and operational resonator performances are described in this paper.

1. Introduction

A prototype superconducting quarter wave resonator(QWR) made of nobium and copper was built at JAERI and the test result was reported[1] in the 3rd Workshop held in 1987 at Argonne National Laboratory where a niobium quarter wave resonator was preliminarily built for the first time[2]. A maximum accelerating field gradient(E_{acc}) of about 5 MV/m was obtained with both resonators. As more QWRs were built, higher performances were obtained. The maximum E_{acc} was improved to 7MV/m, or E_{acc} at an rf input of 4 W(reference rf input power for the QWRs) was 6 MV/m, at a report in the 4th Workshop[3]. The booster project was fully funded in 1988. Many resonators were in fabrication. The maximum E_{acc} further rose to 12.6 MV/m, or the average E_{acc} at 4 W to 6.5 MV/m, at a report in the 5th Workshop[4]. The rise was brought by the improvement of drying method after electro-polishing and rinsing; that is, resonators were finally rinsed with methanol in order to avoid dust particles from depositing during drying resonator surfaces.

On the other hand, a problem called Q-disease was found at Saclay[5]. Such a degradation did not happen to our QWRs for the holding temperature above 130K[4], but it was found later to occur between 130 and 90K as was reported in the 6th Workshop in 1993[6]. The Q-disease is belieaved to be due to hydrogen absorption into niobium and precipitaion as a form of niobium hydrides at about 100K. High RRR niobium does not have densely populated hydrogen trapping centers like nitrogen atoms in it. Niobium with an RRR between 150 and 200 had been used for the QWRs before the Q-disease was found. After an effort to decrease hydrogen absorption during electro-polishing, we found a method of feeding nitrogen gas bubbles through the electro-polishing solution to expel hydrogen gas bubbles. The bubbling could be applied to 24 of 40 linac QWRs. The result was reported in the 6th Workshop[6].

Near the end of 1993, the booster system including cryogenic system was completed and tested with ion beams from the tandem accelerator. All the cryomodules were, once, opened to improve frequency stability and to correct frequency tuning at the room temperature. The booster was tested with various heavy ions and commissioned in 1994[7] . The use of the booster for experiments of nuclear physics and solid state physics started in 1995.

In this paper, described are an outline of the cryogenic system, the improvements on the QWRs at the beginning of commissioning, the recovery of Q by a fast precooling, the operational performances of the QWRs, and the operation with beams since 1994.

2. Outline of the booster and cryogenic system

As is shown in Fig. 1, the booster is composed of a buncher, a sub-buncher, a linac and a de-buncher, which consist of two 129.8MHz QWRs, two 259.6MHz QWRs, 40 129.8MHz QWRs and two 129.8MHz QWRs, respectively[8]. The linac QWRs are separated into ten modules. All the QWRs have an optimum beam velocity of 0.1 and are made of niobium and copper as is shown in Fig.2[9].

The booster is equipped with two identical refrigerators with a refrigeration power of about 270 W for 4.5 K liquid helium loop and 1.6 kW for 80K cold gas helium loop. The flows in these loops are illustrated in Fig. 3. The liquid flowing toward the resonators is liquefied through a heat exchanger in the sump which contains the liquid generated by a J-T valve. There is no liquid reservoir outside the cold box. All the cryomodules have a liquid vessel of about 60 liter in them. The liquid flows into the vessel after

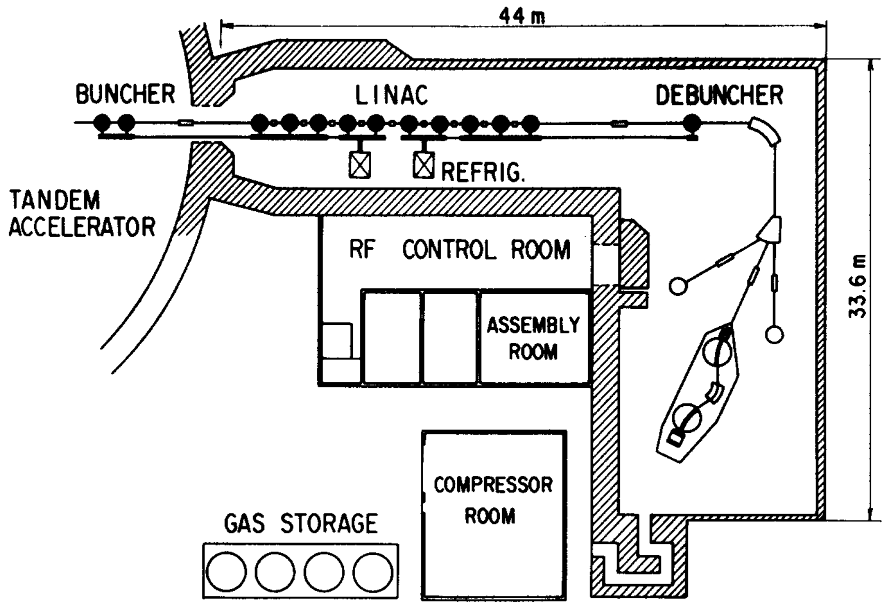

Fig.1 Layout of the JAER tandem booster

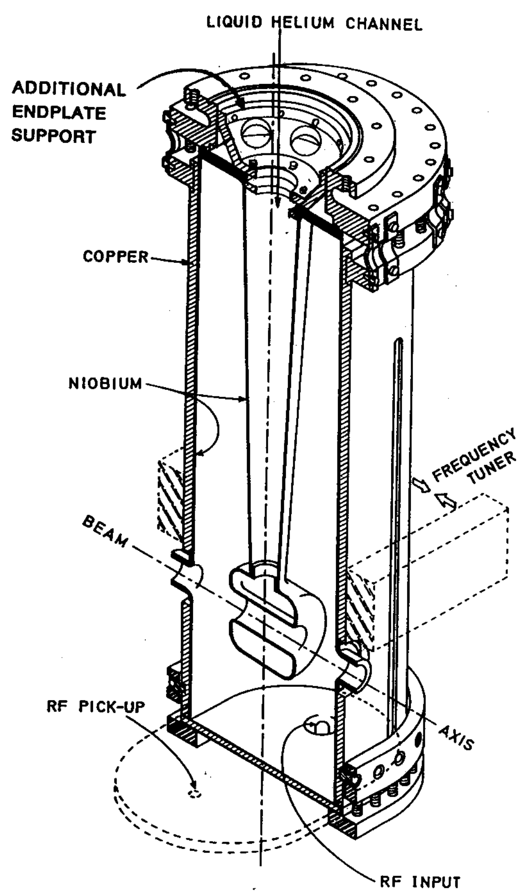

Fig. 2 129.8 MHz superconducting quarter wave resonator with β = 0.1

passing though heat exchangers on top of four resonators. Liquid levels in the vessels are always full in the stationary condition. Two phase fluid returns to the sump container in the cold box. Quiescent loss in the 4.5 K loops is about 70 W. Remaining 200 W is available for cooling resonators and controlling the cryogenic system. In the sump, there is a heater which controls liquid level at 65%. The heater power is balanced at 200W - P_{res}, when a total RF power of P_{res} is dissipated in the resonators. P_{res} is about 80 W at the standard RF loading of 4 W per resonator and its limit was estimated at about 140 W within the stable condition. The pressure fluctuation at the resonator walls is an order of several mbar, when the system is stable.

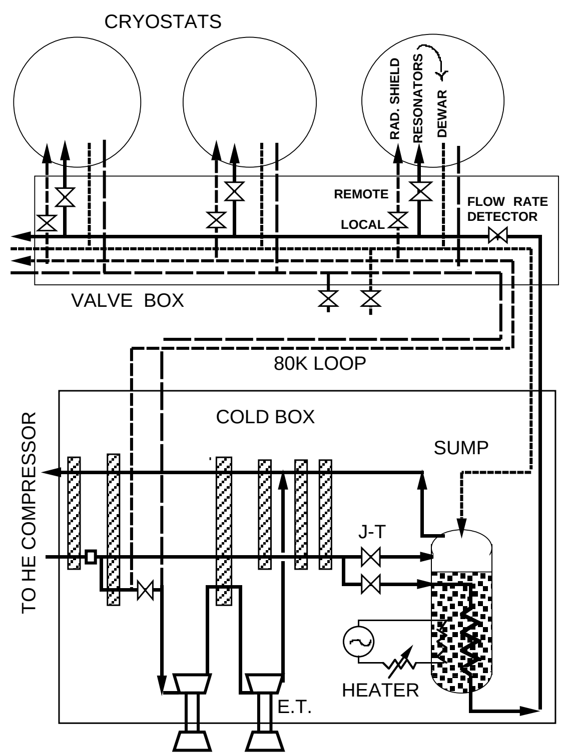

Fig.3 Flow scheme of the 4.5 K and 80 K loops in the cryogenic system

3. Frequency stability and frequency course tuning

During the first beam test carried out in 1993, frequency stability was within several Hz when the cryogenic system was calm, but not good enough against a pressure instability of as much as 50 m bar which was caused by an inappropriate RF power loading and following big liquid level fluctuations. The frequency stability was improved from 1.25 kHz/bar to 270 Hz by putting a support to the top end plate for every 129.8MHz QWR, which is shown in Fig.2. The frequency fluctuation was decreased enough to keep controlling resonators even under a moderate pressure instability.

When the resonators were assembled, their frequencies were tuned within 30 kHz by using set screws on the retractable frange at the resonator bottom(see Fig. 2). The frequencies which had been tuned upwards tended to turn down due to a repetition of thermal cycles. This tendancy was improper because the slow tuners work downwards. The tuning was, therefore, corrected by giving a permanent deformation to the outer conductors themselves, as it was originaly planed. After the correction, the tuning was improved but not perfect. Further corrections will have to be done in the future. It is suggested for a future plan that the bottom structure should be designed more rigid.

4. Fast precooling for Q recovery

The QWRs were made of composite materials, niobium and copper-clad-niobium, so that heat treatments for outgassing hydrogen gas were not applicable to them. Some of them absorbed much hydrogen during electro-polishing so that a severe Q-degradation occurred to them. There is, so far, no effective method of curing the disease for these QWRs other than precooling as fast as possible at the niobium-hydrides precipitating temperature, which was found to be in between 130K and 90K for one of the QWRs[6,10] . The slower the precooling, the more Q-degradation is severe as is seen from Fig.4. The cooling rates are about -12 K/h at the normal precooling procedure, so that it should be increased more than twice. In each cryogenic system of the booster, liquid helium is fed to six or seven cryomodules in parallel, so that an increase can be made by sequentially switching all the flow into a few cryomodules.

The QWRs suffering from Q-disease are in the linac modules of No.1 to No. 4. Sequential precooling was tried according to a procedure shown in Fig. 5 for the first half part of the booster, which includes the buncher and 5 linac modules. The cooling rates from 130K to 90K were increased to -17 to 27

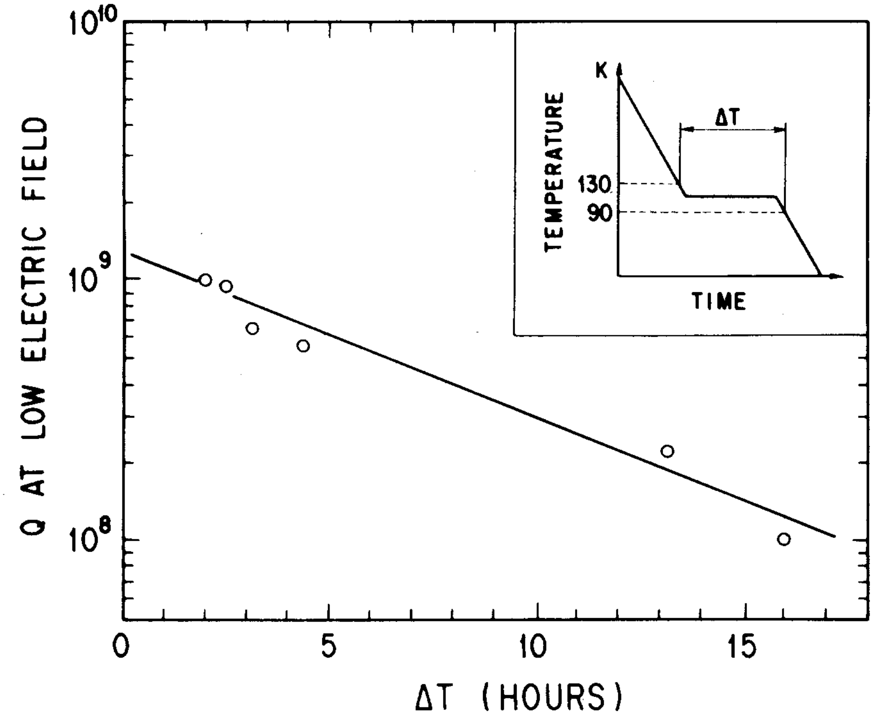

Fig.4 Q-degradation on cooling between 130 and 90K. Q-factors at low fields are plotted as a function of holding time between 130 and 90 K[6,10].

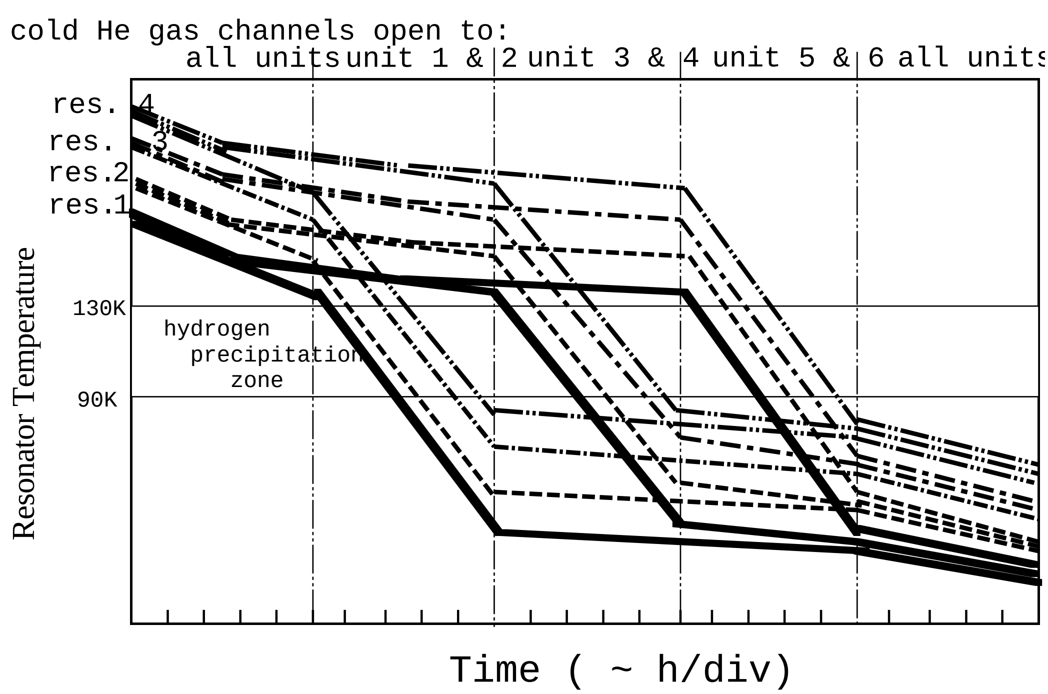

Fig. 5 Scheme of a two-units(cryomodules)-by-two-units sequential precooling over the hydride precipitation zone of 130 K to 90 K.

K/h(20 K/h on average) and -21 to -48 K/h (28.5 K/h on average) in two cases of three modules by three modules and two modules by two modules, respectively. The rates differed depending on the resonator positions because cold helium gas flows in series through four heat exchangers on resonators inside a cryomodule. The Q-factors measured after the fast precooling are shown in Fig. 6. The Q factors degraded to 30- 57 % in on-line from those obtained in off-line tests were recovered to 64 - 79 % for the case of two-modules-by-two-modules sequential precooling.

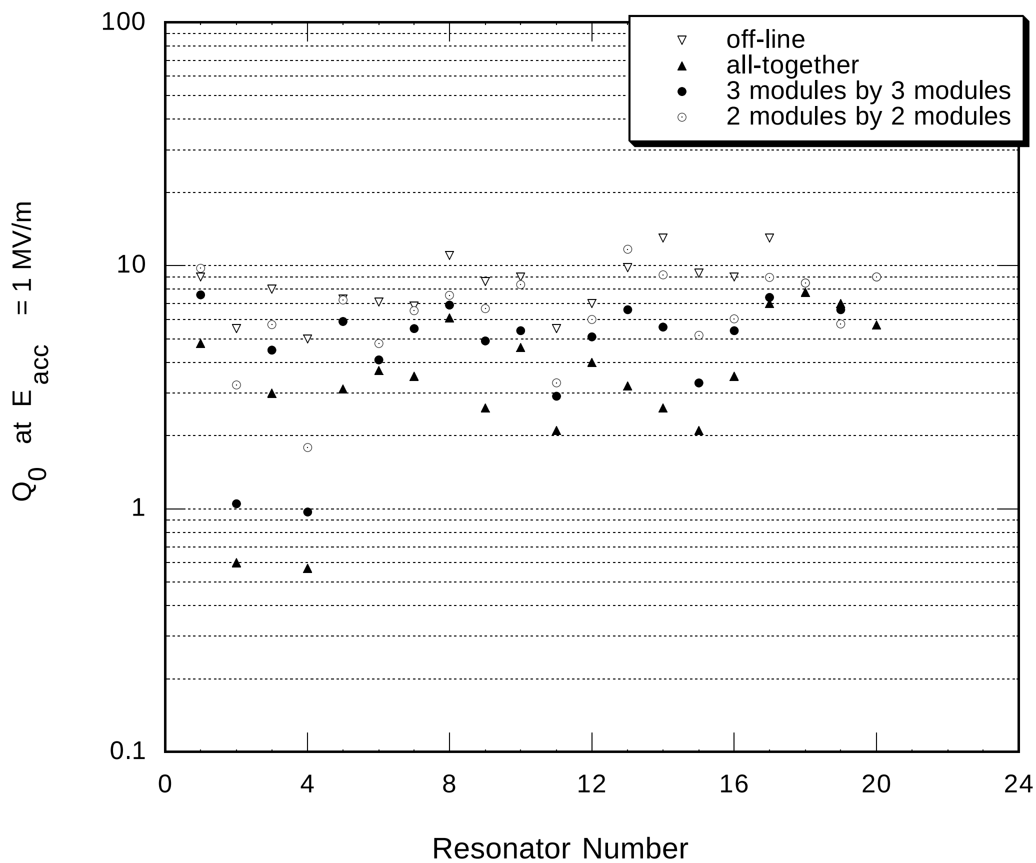

Fig.6 Q-recovery by sequential fast precooling modes

5. Q factors and field gradients

The Q factors of all the forty linac QWRs, which were measured in 1995 and 1997 as well as in off-line(1990-1993), are shown in Fig. 7. The measurements in 1997 were done after the fast precooling for the QWRs from No.1 to No.20. For the QWRs from No. 17 to No. 40, not only there were no significant Q-degradation, but also there were small increases from those in 1995. There might be measurement errors. If not, there is

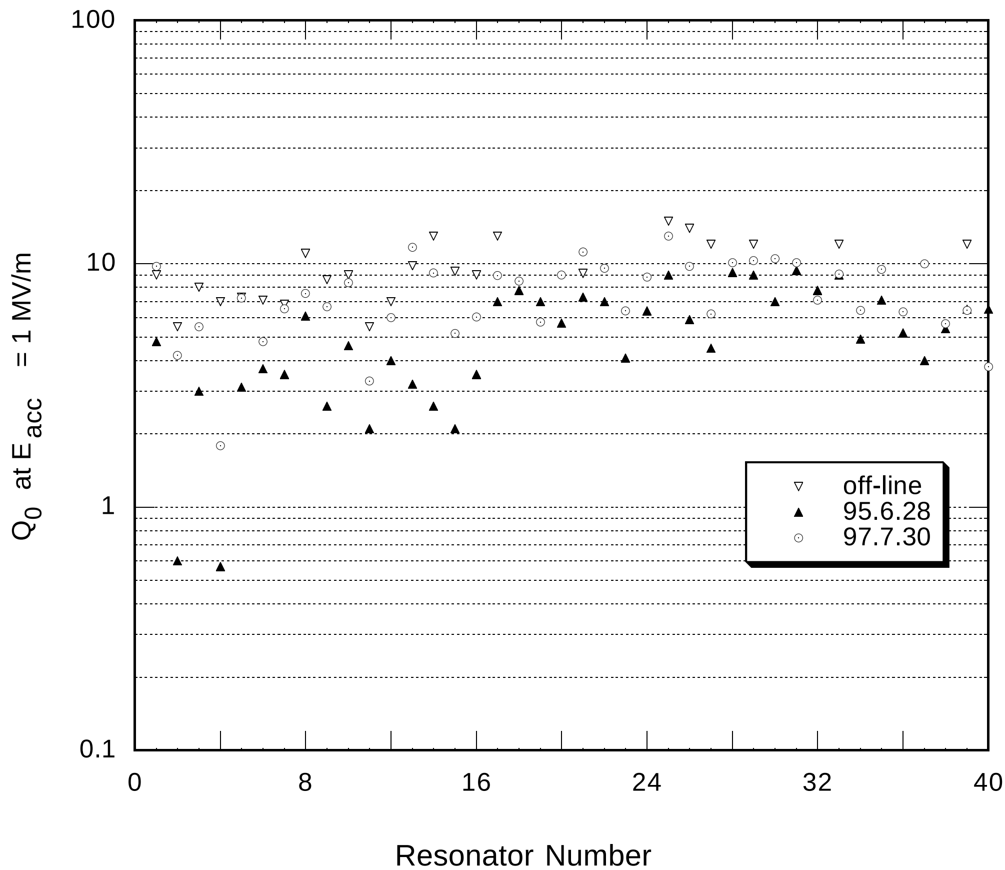

Fig.7 Q factors of the booster linac superconducting quarter wave resonators measured in 1995 and 1997 as well as in the off-line tests.

a possibility that the hydrogen gas contaminating the niobium surfaces was getting out during a long storage in vacuum and during thermal cycles.

The accelerating field gradients of the linac QWRs at an RF input of 4 W, which were measured in 1995 and 1997, were shown in Fig. 8. There was an effect of the fast precooling on field increases, the average of which were about 0.9 MV/m from 4.1 MV/m to 5.0 MV/m, for the QWRs from No.1 to No.20. There were small increases for the QWRs from No.21 to No.40. The reasons seems to be the same as for the case of Q factors described above. On the other hand, electron field emission became appreciable. Pulse conditioning was required for many resonators for a high field operation. RF power amplifiers of 100W(increased to150W recently) for normal operational use were used for moderate pulse conditioning. A 1 kW RF pulse power amplifier was, sometimes, added for more reduction of field emission. High power pulse conditioning using helium gas has not been

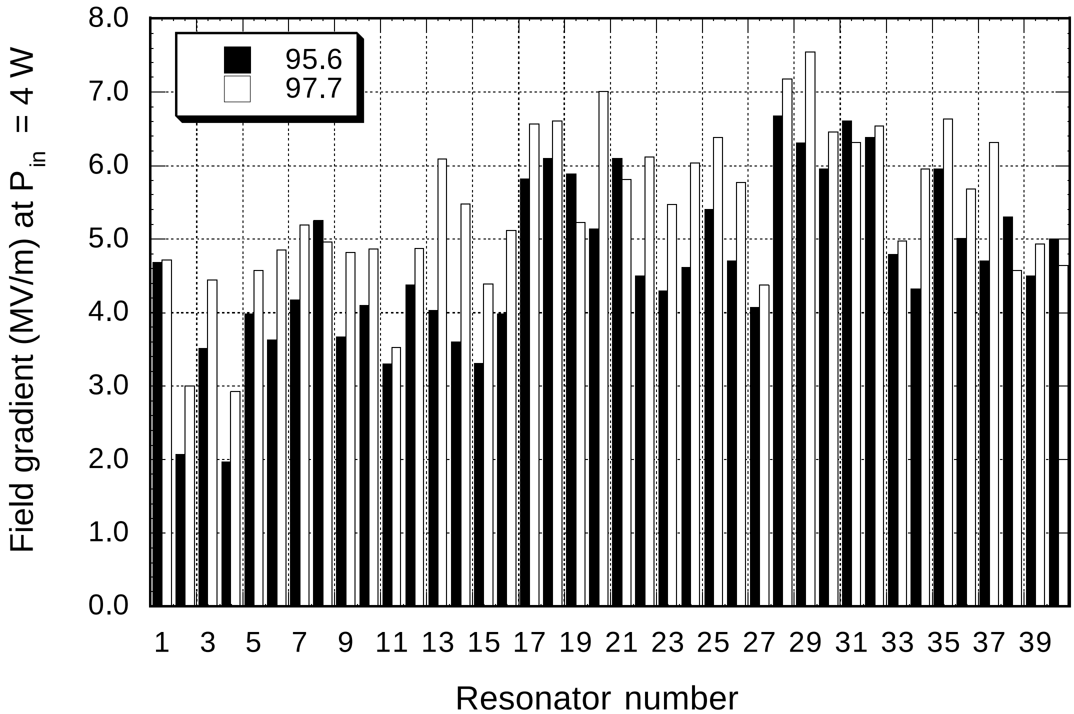

Fig. 8 Accelerating field gradients of the booster linac QWRs at the RF input of 4 W, measured in 1995 and 1997.

applied yet, because the field emission was mostly due to particles on the resonator surfaces. Even though there might exist an affect of field emission on the data of field gradients, the average field level was fortunately 5.4 MV/m in 1997.

6. Operation

The tandem accelerators has been regularly operated for 3 to 4 months and opened for a month for maintenance, in an operation cycle. The booster operation has been cooperative to it. The resonators were cooled down and warmed up once in every 4 or 5 months. Resonator conditioning to remove multipacting barriers could be done in several hours because it took mostly less than 20 minutes per resonator. Problems are related to thermal cycles, such as a frequency de-tuning described above. Fatigue of metals resulting from cyclic stress is also worried about.

The beam time for the booster was about 25% to the total beam time and is tending upwards. Ionized stable isotopes of Si, Cl, Ni, Ge, Zr, Ag, I and Au have been accelerated mostly for nuclear physics experimental studies and partly for heavy ion irradiation studies on high temperature superconductors. Resonators were operated at field levels of around 3.8 MV/m for many experiments; that is, the field levels demanded were lower than those at an RF input of 4W (They were operated at about 5 MV/m during the commissioning[7]). The resonators were stable during a long-run experiment over a weekend without a presence of operating staff, although a few resonators sometimes happened to be out of phase-lock mostly due to some problems with control circuits. Operation at high field levels around 5 MV/m has been planed such as for Coulomb excitation experiments with very heavy ion beams such as Pb beams.

All the slow tuners and variable couplers, which are mechanical components put on the resonators, have been moving smoothly without troubles, so that it has not been required to open any cryomodule.

The cryogenic systems have been working well except troubles with automatically controlled valves at an operating mode change during precooling.

7. Conclusion

The booster which consists of 46 superconducting QWRs has been running satisfactorily for its commissioning and experiments since the improvements of frequency stability and tuning were carried out in early 1994. There have been no troubles to open cryomodules.

The Q factors for the Q-disease affected resonators were sufficiently recovered by increasing cooling rates two or three times over the hydrides precipitation zone of 130 K to 90 K in a sequential gas handling mode. The accelerating field gradients E_{acc} were recently confirmed to be at a high level of 5.4 MV/m for the reference RF input of 4 W per resonator.

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