RESEARCH ON SUPERCONDUCTING RF CAVITIES AT KEK

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Summary

Forty eight meters of 508 MHz superconducting RF cavities will be installed in the TRISTAN main ring by the fall of 1988 to increase the energy of e^-e^+ beyond 30 × 30 Gev. The project is based upon the results of research and development on the superconducting cavities at KEK which have been continued since 1967.

This report will give the review of our results of R & D and show the present status of our activity on RF superconductivity.

Introduction

Research activity on superconducting RF cavities at KEK was originally initiated by Y. Kimura, Y. Mizumachi and S. Isagawa since 1967. They have worked at C-band frequency mainly on lead-plated[1] and niobium nitride[2] demountable TE mode cavities for several years.

The author have started to work on RF superconductivity at Tohoku University in Sendai since 1970, and have visited HEPL of Stanford University from 1972 to 1973. At that time HEPL was quite active in this field working on the L-band superconducting linac project[3] and there I have learned lots about RF superconductivity.

After my coming back from Stanford University, we have begun to work on niobium TM mode C-band cavities at KEK from 1973. For several years we have worked at C-band frequency to develop the technique of cavity fabrication, electron beam welding, surface treatments, RF measurements at low temperature and cavity diagnostics. Fifteen single cavities and a three-cell structure have been tested and a nine-cell structure was tested for electron acceleration.[4] The typical results of single cavities showed Q value of 10^{10} and E_{acc} of 10 MV/m at 1.8 K. For the nine-cell structure E_{acc} of 3 MV/m was obtained in the beam test.

From 1979 our research activity has turned to the frequency region of 500 MHz concerning the feasibility of superconducting RF system in the TRISTAN ring. Up to the present six single cavities were tested, a three-cell structure and a five-cell structure were also tested with electron beam in the accumulation ring of TRISTAN.[5,6,7,8,9,10]

Two five cell structures will be installed and operate in the accumulation ring.[11] Construction of thirty two five-cell structure for the main ring of TRISTAN has just started.

Results of Research and Development

Accelerating Field Gradient

Accelerating field gradient E_{acc} is the most important parameter of the cavity about which accelerator people concern. In Fig. 1 improvement of E_{acc} for single-cell 500 ∿ 508 MHz cavities is shown as a function of time. In the figure the values at the first cool down test and the values after guided repair cycles are shown.

These improvements of E_{acc} are due to:

- temperature mapping technique which allows to localize defects,
- improved welding methods and development of the grinding tool to obtain smoother and defect-free welding seams,
- well controlled electro-polishing technique to get clean and smooth surface,
- more effective surface inspection methods to check defects before cool down,
- improved rinsing methods with dust-free pure water and assembling under the clean environment,
- improved electron beam melting and annealing with titanium to get pure niobium material with high thermal conductivity.

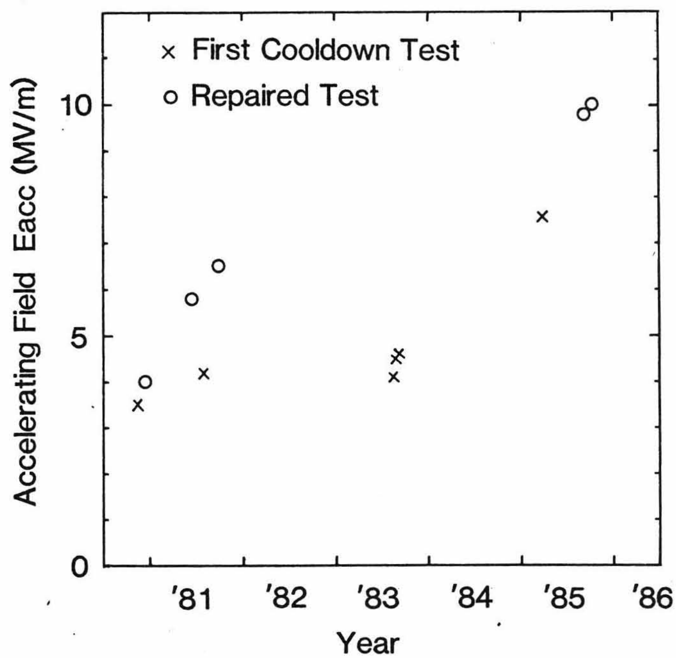


Fig. 1 Improvement of accelerating field gradient for single-cell 500 ∿ 508 MHz cavities.

Niobium Material

One of the recent topics in RF superconductivity is understanding of the breakdown phenomenon which is mostly due to the thermal instability caused by the local heating at the defect. It has been shown by computor simulation[12] and experiments[13] that the improvement of thermal conductivity of cavity wall material helps the cooling efficiency and increase the acheivable field strength. We have made an intense effort to improve thermal conductivity of niobium in collaboration with inductry.

Improvement of niobium material has been performed by:

- increased number of multi-melting,
- improved vacuum of melting furnace,
- slow cooling in vacuo after the last melt,
- raised temperature of melting zone and slower melting rate,
- annealing of sheet material wrapped by titanium sheet[14] to avoid the contamination of oxygen.

In Fig. 2 the effect of multi-melting on the improvement of RRR (residual resistivity ratio) is shown. RRR is commonly used as a measure of thermal conductivity because both are linearly proportional and RRR is available by a simpler measurement.

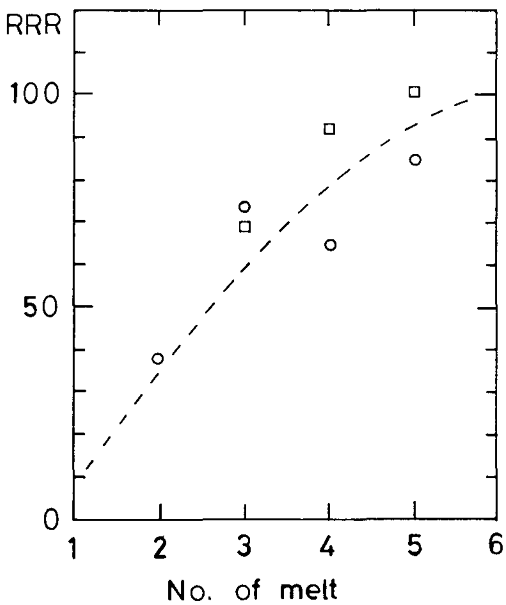


Fig. 2 Improvement of RRR of niobium by multiple electron beam melting.

Nowadays niobium sheet material with thermal conductivity of ∿ 30 watts/m-K is commercially available, it was only ∿ 5 watts/m-K in a few years before.

The property of niobium has been investigated at every step of processing starts from the ingot to the final surface treatment of the cavity. Figure 3 shows the typical change of RRR of niobium during the processing. The effect of mechanical property on RRR is seen from the figure.

Computor simulation shows that the achievable field strength is roughly proportional to the square root of thermal conductivity on the other hand BCS surface resistance goes up with increasing RRR.[15] In Fig. 4 Q_0 at low field and E_{acc} of four different cavities with various RRR are shown. Q_0 behaves reasonably but E_{acc} is not much improved than expected, probably the field is limited by the other factors besides the thermal conductivity. Drop of Q_0 causes the heavier load to the refrigerator and Q_0 value of better than 2×10^9 at E_{acc} of 5 MV/m is desirable in TRISTAN.

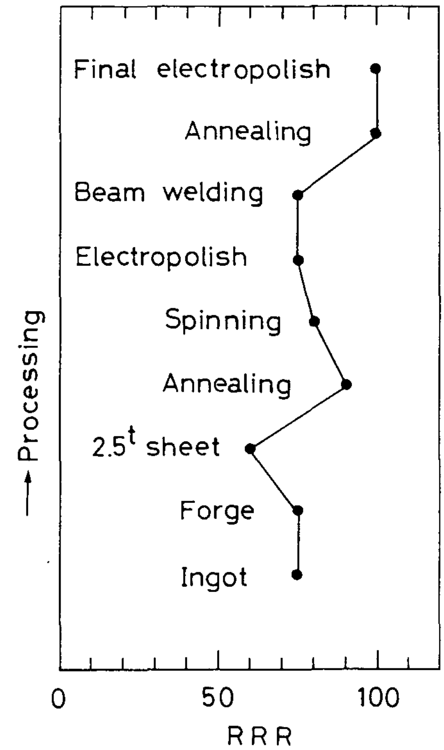


Fig. 3 Change of RRR of niobium starts from ingot to the final surface treatment of the cavity.

Another problem in the purification of niobium is the change of mechanical property with purification. In Japan we have to follow the High Pressure Gas Control Law in construction of SC-cavities, then the cavity wall should have some mechanical stability. It means if we use the purer and softer niobium, cavity wall should become thicker and it will bring the problem of cavity forming technique and increasing cost of material.

Surface Treatments

Electropolishing is the main process of surface treatment of the cavities at KEK. Chemical polishing is also adopted to some niobium parts such as the coaxial filters of higher order mode couplers. Much efforts have been made to investigate the appropriate condition of electropolishing for many years. There are many factors such as voltage, current, bath temperature, acid concentration, shape of electrode and distance between cavity and electrode. Among them, the current density was found to be the most important parameter and it should be kept to the optimum value during the polishing. Measurements of roughness and brightness are quick evaluation of polished surface, Fig. 5 shows the dependence of roughness and brightness on current density. In this case 30 ∿ 100 mA/cm^2 is appropriate and it was also found the optimum current density depends on the property of niobium such as grain size.

Another important parameter of electropolishing is acid concentration. By volume ratio 85 % of H_2SO_4 and 10 % of HF (40 %) are the standard polishing solution[16]. Optimum concentration of HF (46 %) was found to be 60 ∿ 90 cc/liter as shown in Fig. 6. The concentration of HF should be monitored before and during polishing and could be controlled by adding the appropriate amount of HSO_3F and H_2O. In the figure, total amount of active fluoride is shown by the corresponding amount of 46 % HF.

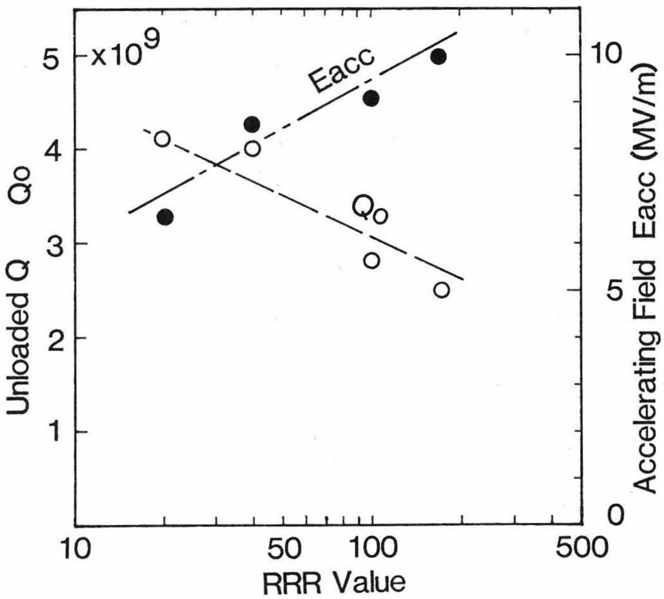


Fig. 4 Q_0 at low field and E_{acc} of four single-cell cavities with various RRR.

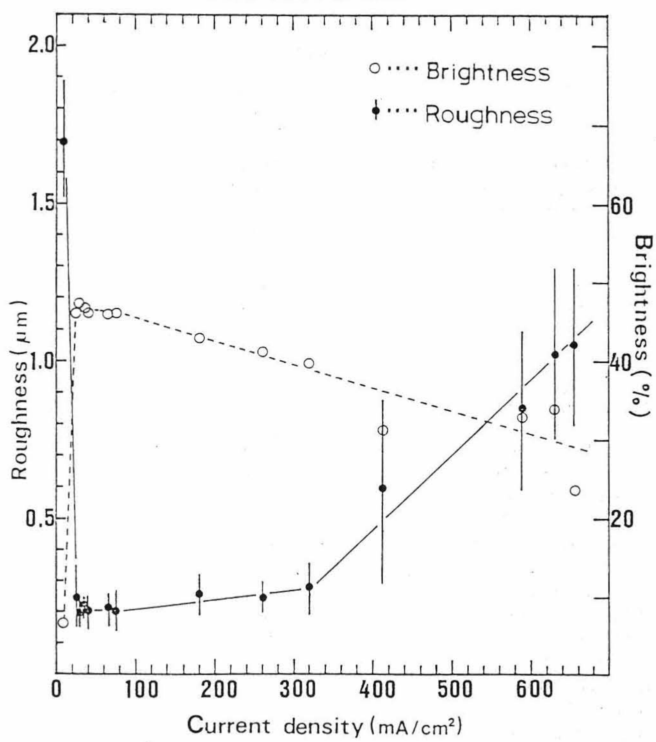


Fig. 5 Roughness and brightness *versus* current density of electropolishing.

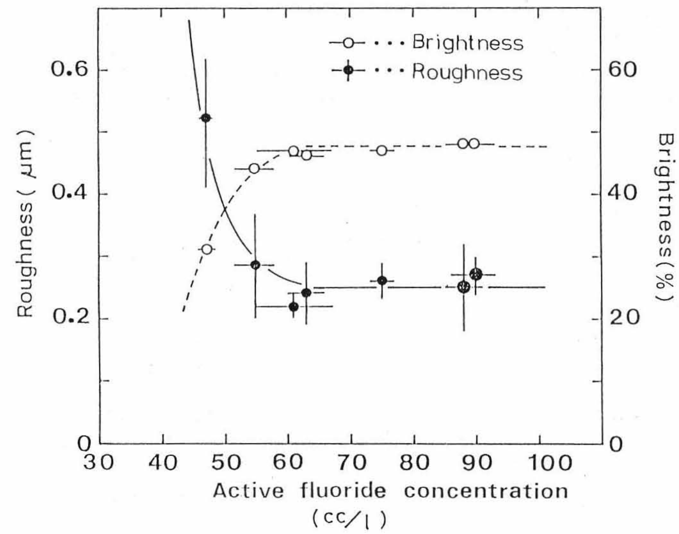


Fig. 6 Roughness and brightness *versus* active fluoride concentration.

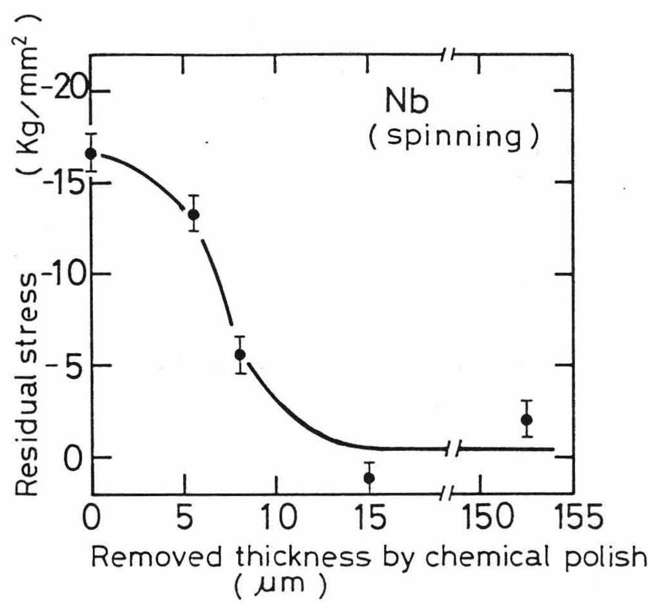


Fig. 7 Residual stress as a function of depth for the cavity made by spinning.

Required removal thickness from the surface depends on the starting material and method of shaping the cavity, reports from various laboratories show the values ranging from 50 μm[17] to 250 μm.[18] Residual stress was measured by X-ray difraction as a function of depth for the cavity made by spinning and shown in Fig. 7.

Surface roughness is usually improved by increasing removal of the surface. Improvement of roughness and brightness is shown in Fig. 8 as functions of thickness removed by electropolishing. In the standard surface treatment at KEK, the typical removal thickness is 100 ∿ 120 μm.

Hydrogen contamination during the polishing has been studied. At first, crude experiments have not shown the sign of the contamination,[7] but more precise experiments have proven the hydrogen contamination in the polished test pieces,[19] also it was found the hydrogen can be removed by vacuum annealing after the polishing.

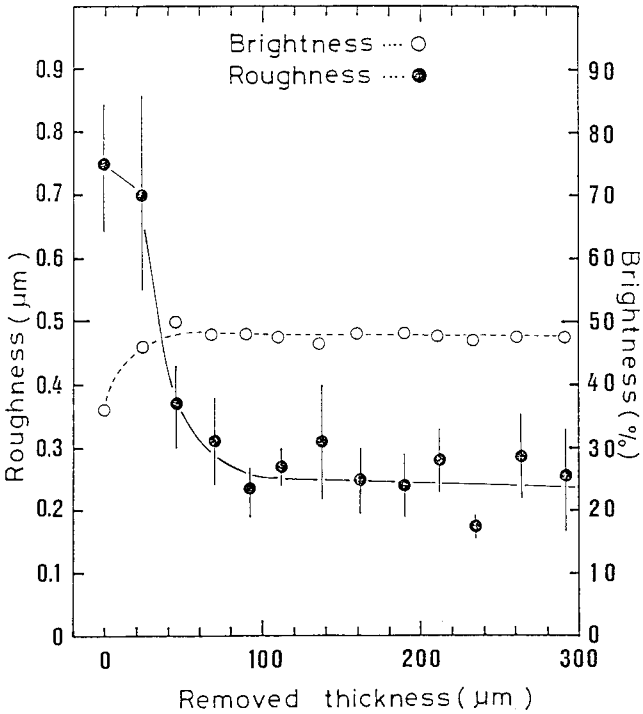


Fig. 8 Improvement of roughness and brightness by electropolishing.

Electron beam Welding

Welding with sharp focussed beam from both inside and outside was adopted in early stage and defects were often found at the welding seam.[6] Improved welding methods such as defocussed beam welding or rhombic raster welding[20] only from outside has also been investigated at KEK and are commonly used at present.

Grinding tools to smoothen the underbead have been developed, one of the grinding machine for the neck of the cavities is shown in Fig. 9. By improved welding and careful grinding, smooth and defect-free welding seam is now available.

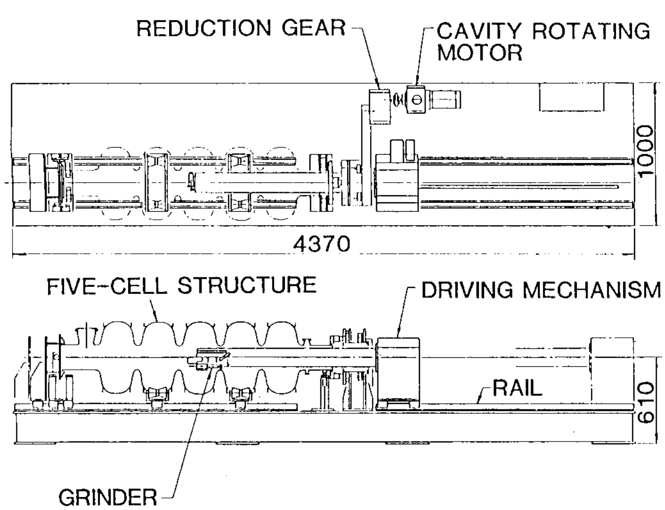


Fig. 9 Grinding machine for smoothening the welding seam.

Multi-cell Structure

For the development of multi-cell structure to be used in electron acceleration, several problems such as high power input coupler, higher order mode (HOM) couplers and frequency tuning system have been investigated.

The first beam test by mulit-cell structure was held at July 1984 with a three-cell structure in the accumulation ring of TRISTAN.[8,10] Major problems left to be solved were the improvements of handling power of the input coupler, Q value of the structure and development of the reliable leak-tight ceramic coaxial connectors. After the beam test, the structure was kept at liquid nitrogen temperature for about six months, cavity vacuum was connected to the ring vacuum of room temperature to test the gas contamination effect onto the SC-cavity. No degradation of Q and E_{acc} was observed after six months.

A five-cell structure was built and tested in July 1986[11], the structure has larger diameters of cavity irises and beam pipes than the three-cell to increase the coupling of fundamental and HOM modes, equipped with an antenna type input coupler and two HOM couplers at the beam pipe.[22] Two additional HOM couplers were on the end cell to ensure the lower loaded Q values for TM_{011} family. According to the results of the beam test, RF power transfered to the beam has reached to 26 KW and the input coupler has been tested up to 82 KW in total reflection mode.

The second five-cell structure was built and the vertical test without couplers was performed in September 1986. The design is almost similar to the first five-cell but the improved surface treatment was adopted and Q was much better. In Table 1 the comparison of these three multi-cell structures is shown.

One of the problems in the electropolishing is hydrogen bubbles coming from the cathode. For the electropolishing of single-cell, a porous teflon cover around the cathode has been used to protect the cavity from the hydrogen bubbles[5], but for the polishing of multi-cell this scheme was found to be insufficient, also the strong convective stream of acid is another problem in the vertical polishing. After the experience of vertical polishing of the three-cell, a horizontal polishing system has been developed and the scheme was adopted to the five-cell structures. The system has successively been improved especially to get enough current density.

The design of ceramic coaxial connectors has been modified and better mechanical property against heat cycle was available now. In the design of SC-structures for the main ring of TRISTAN, all the ceramic connectors will be located at the insulation vacuum of the cryostat but not in the liquid He bath for safety.

In Fig. 10 a three-cell and a five-cell structures and their cryostats, also two five-cell in a cryostat for the main ring TRISTAN are shown.

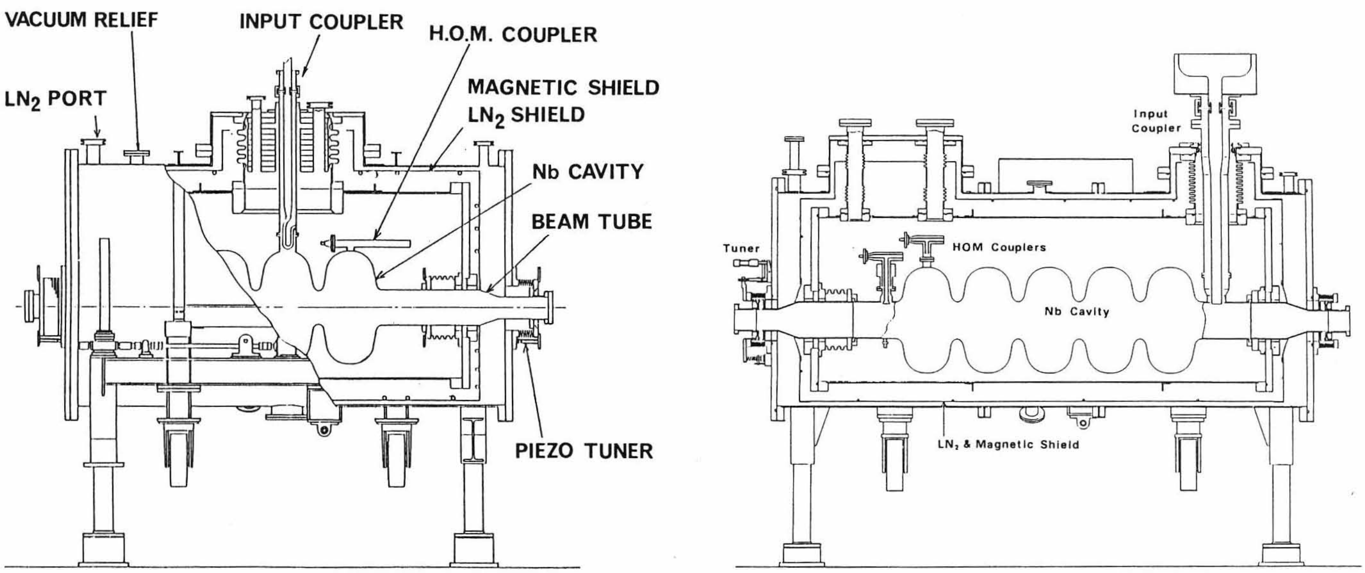
Cryogenics

For the beam test of multi-cell structure in the accumulation ring, a cryogenic system with a 300 watts refrigerator (Turbocool 200) has been prepared and it is to be replaced by a system with a 1 KW refrigerator (TCF 200).

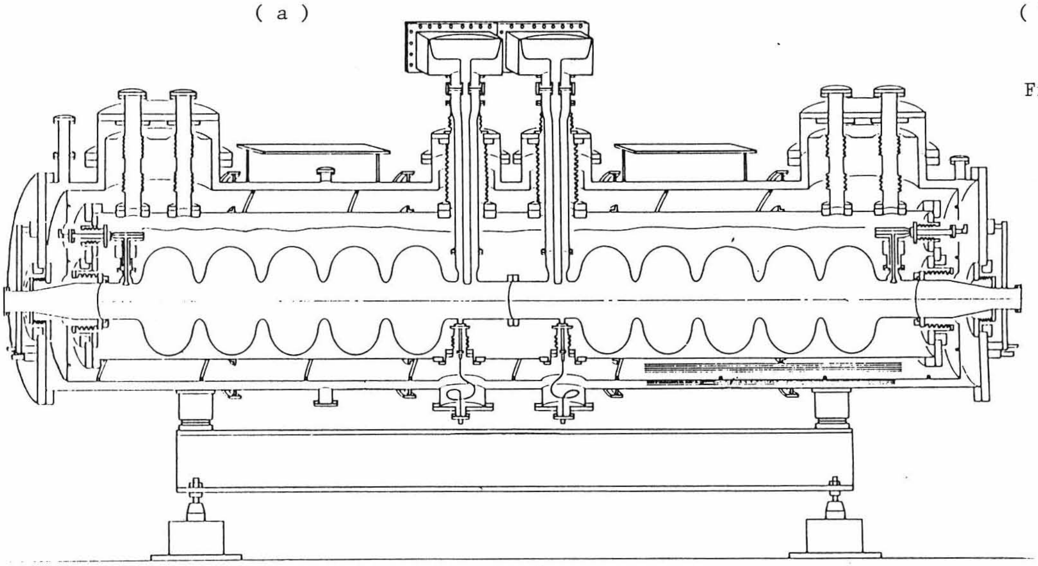
As 48 meters of SC-structure will be installed in the main ring of TRISTAN, a refrigeration system with cooling power of 4.5 KW will be prepared.[21] At present we plan to operate at ∿ 4.2 K, but if in the future accelerating field gradient goes up to much higher level, the operating temperature should be lower to decrease BCS surface resistance of niobium.

Table 1. Comparison of three multi-cell structures.

Cavity No.	#4	#5	#6
Cell number	Three	Five	Five
Final treatment	Vertical EP at 30 mA/cm^2	Horizontal EP at 25 mA/cm^2	Horizontal EP at 50 mA/cm^2
E_{acc} without beam	5.2 MV/m	> 4.5 MV/m	6.4 MV/m
E_{acc} with beam	4.3 MV/m	3 MV/m	Not yet tested
Q_0 at E_{acc}	8×10^8 at 3.7 MV/m	1×10^9 at 4.5 MV/m	2×10^9 at 5.6 MV/m
Input coupler	Loop at the center cell, He gas cooled	Antenna at the beam pipe, Water and gas cooled	Antenna at the beam pipe, Water cooled
HOM couplers	A loop with 1/4 wavelength filter at the end cell, two antennas at other end cell	Two antennas with choke filter at the beam pipe, two antennas at the end cell	Same as #5
Estimated RRR	60	90 ∿ 100	100 ∿ 120
Beam test			
Performed at	July, 1984	February, 1986	Scheduled in Dec., 1986
Stored current	10 mA	25 mA	
RF power to beam	4 kw	26 kw	



(a) (b)



(c)

Fig. 10
Multi-cell structures and their cryostats. (a) A three-cell. (b) A five-cell. (c) Two five-cell in a cryostat for the TRISTAN main ring.

At lower temperature the efficiency of refrigerator is lower and the cost of the system is higher. Figure 11 shows the results of estimated cost of the cryogenic system for TRISTAN including the capital cost and ten years' running cost.

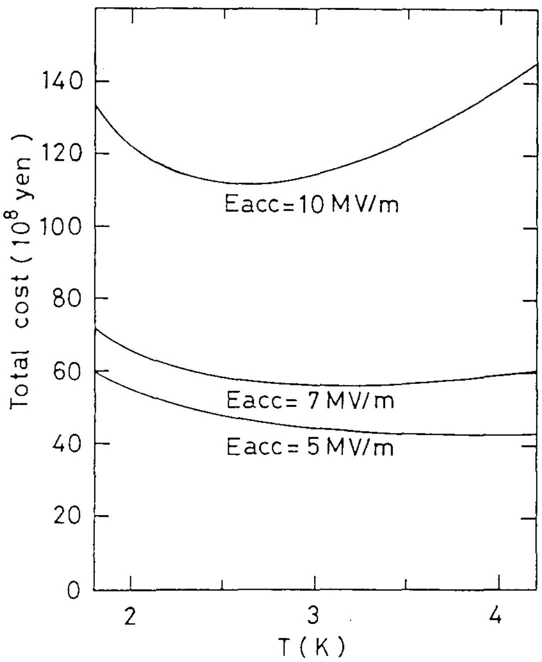


Fig. 11 Estimated total cost for the cryogenic system of TRISTAN SC-RF.

Outlook

According to the encouraging results of multi-cell structures, E_{acc} of 5 MV/m with Q of 2×10^9 will be realised in the five-cell structures for the TRISTAN. Frequency tuning system and HOM couplers have also worked well so far.[10,11] Some uncertainty is in the behavior of beam instability due to the unexperienced length of SC-structure in the storage ring. Our main concern is at present to keep the good relationship with industry and also with the High Pressure Gas Control Law.

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