STATUS OF TRISTAN

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Abstract

After the five years construction period, the TRISTAN electron-positron beam collider was commissioned successfully in November 1986. With three detectors installed at three out of four beam collision areas in the ring, colliding beam experiments have begun in December 1986. The current status of the TRISTAN accelerator operation is presented along with a brief description on the accelerator sub-systems.

1. Introduction

In the last autumn, TRISTAN, a large e^--e^+ collider system in Japan, was commissioned. Since then, TRISTAN has been operated for e^+-e^- collision experiments as well as for machine developments to improve beam intensity, beam quality and luminosity etc.

In Fig. 1, a layout of TRISTAN is shown. TRISTAN, which is a large accelerator complex aiming at achieving e^--e^+ colliding beam experiment at a total energy of more than 50 GeV[1)-4)], is mainly composed of an injector linac of 2.5 GeV, an accumulation ring (AR) of 120 m in diameter and a main ring (MR) of 960 m in diameter. The main design parameters of MR and AR are shown in Table I. A positron generator consisting of a 200 MeV electron linac, an electron to positron conversion system and an accelerator guide of 250 MeV for the positron acceleration is also equipped near the low energy end of the main linac. The MR has four-fold symmetry with four long straight sections of 194 m each. At the center of each straight section, a large experimental hall for the beam collision experiment is provided. The names of these halls are Tsukuba, Oho, Fuji and Nikko in order of clockwise direction. These names correspond to those of famous mountains or a familiar town laying in the direction of the halls as seen from the center of MR. In addition, we also provided in the AR two experimental halls for beam collision experiments and one arced room on one of the quadrants of the ring for synchrotron radiation researches.

2. The Progress of Construction and Operation

The construction of TRISTAN was started in 1981 as a 5-year project of KEK. At that time, the 2.5 GeV linac had almost been completed and been ready to work as the injector of an electron storage ring in the Photon Factory facility. Therefore, only the constructions of AR, MR, the positron generator, beam transporting systems associated with these accelerators and the additional modification of the electron linac were included in the project. That was the modification of the main linac electron gun to be operated both in a long pulse mode of 1 μs and in a short pulse mode of 2 ns or less.

Table I Design parameters of the TRISTAN MR and AR

	Main Electron-positron collider	Accumulation ring
Circumference	3018.1 m	377.0 m
Average radius of curved section	346.7 m	47.7 m
Long straight sections	4 × 194.4 m	2×(19.5m+19.1m)
Total elngth of RF cavity sections	400 m	30 m
RF frequency	508.6 MHz	508.6 MHz
Injection energy	6 - 8 GeV	2.5 GeV
Maximum energy	25 - 30 GeV	6 - 8 GeV
Natural energy spread	1.6×10^{-3} at 30 GeV	1.1×10^{-3} at 6 GeV
Natural emittance	1.8×10^{-7} m•r/30 GeV	2.7×10^{-7} m•r/6 GeV
RF voltage	380 MV/20 GeV	10 MV/6 GeV
Number of interaction	4	2
Max. design luminosity	2×10^{31} cm^{-2} s^{-1}	1×10^{31} cm^{-2} s^{-1}

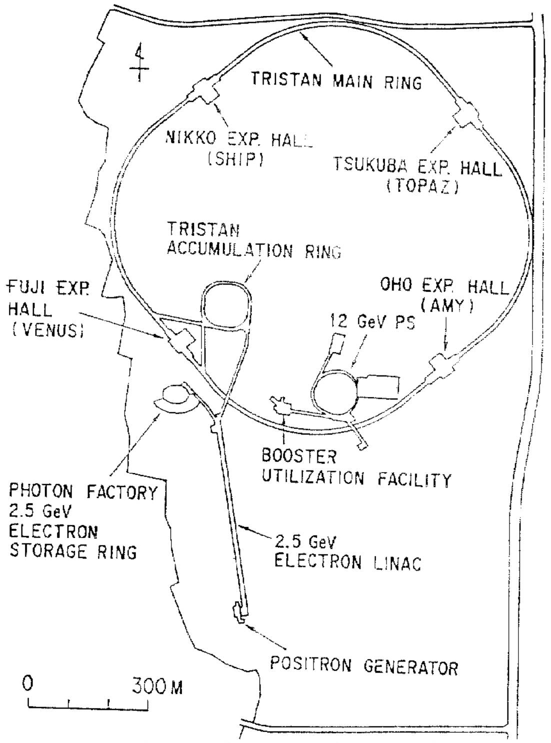

Fig. 1 Accelerators in KEK site.

2.1 Positron Generator

The construction of the positron generator[5)] was started in 1982, and was completed just on schedule and began to work in 1985. A high current electron linac, the first stage of the generator, produces a short pulsed electron beam having a peak current of about 10 A, a pulse width of 2 ns a repetition rate of 20 Hz and an energy of 200 MeV. The pulse width of 2 ns was achieved by means of a 5 ns high voltage pulser and a sub-harmonic buncher to compress the beam pulses. The sub-harmonic buncher is operated at a frequency of 119 MHz, which is the 24th sub-harmonics of the accelerating RF. After a conversion from electrons to positrons by a trantalum target with a thickness of two radiation length, the produced positrons are focussed and collected by a pulsed high field focussing solenoid system and sent to the 250 MeV linac, the second stage of acceleration.

The positron beam accelerated to 250 MeV is transferred to the main linac at the middle point of the first sector where the corresponding energy is just 250 MeV. The 2.5 GeV positron beam with a peak current of 10 mA have been obtained so far. This value almost fulfills the design figure except for the repetition rate. It is expected that the repetition rate will be raised to 50 Hz near future.

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2.2 AR (Accumulation Ring)

Basically, the AR was designed to accumulate the electron or positron beam with a repetition rate of 50 Hz, accelerate and transfer them to the MR. To accept beams at a repetition rate of 50 Hz, the AR was designed to have a short enough damping time at the beam energy of 2.5 GeV. On the other hand, the AR is expected to work as an independent electron (or positron) storage ring or an electron-positron collider. Therefore, the AR and its accompanying buildings are designed as a multi-purpose machine.

The construction of the AR began in 1981 and finished in 1983. The AR was commissioned on 18th of November 1983. Because of an insufficient number of RF cavities and an insufficient RF power for the acceleration, AR was initially operated with a maximum beam energy of 4.2 GeV. With the increase of RF power and the number of RF cavities, the maximum beam energy was increased and, in July 1984, the AR achieved acceleration of electron beams to 6.5 GeV, which is a design value in a storage mode.

The other factor which mainly determines the performance of AR was vacuum. The vacuum system of AR is the so-called all-aluminum system6), i.e., most of vacuum components such as vacuum flanges and corrugated bellows are made of aluminum alloy and, as a result, there is no material transition in the system.

The vacuum ducts are treated by the so-called special extrusion process, and give a fairly small outgassing rate. The base pressure in the beam duct of the AR is in the order of 10^{-7} Pa without baking. The pressure rise due to beam, $\Delta p/I$, decreases rather rapidly with the integrated beam dose. By the end of February 1987, the integrated beam dose amounted to 30 AHr, and $\Delta p/I$ was decreased to as low as 3×10^{-11} Torr/mA, which is a fairly good figure. The main vacuum pump is a new-designed DIP (distributed ion pump) with cathode of titanium rods and anode of a set of parallel aluminum plates with perforations. In addition, NEG's (nonevaporable getter) are also equipped mainly in the beam duct where there is no enough external magnetic field to operate DIP.

The beam life time is about 5 hours at a small beam current (less than several mA) but decreases to about 1 hour with a high beam current. Main factor which determine the beam life time is the pressure rise due to the beam induced gas desorption. The maximum stored beam current of 5 GeV electrons is 60 mA in a single bunch mode.

2.3 MR (Main Ring)

In the period of TRISTAN construction, the first 2 years were devoted mainly to the AR construction and the following three years were to the construction of the MR. As the MR was designed to achieve a very high beam energy for its size, the RF acceleration system and the vacuum system are the main components which are required to work under the most technically difficult conditions. In the following, a short survey of the MR construction and operation test is given forcused mainly on these components.

2.3.1 Magnet: The main magnet system7),8) works as designed. The alignment error distribution of the Q-magnets is shown in Fig. 2. As is seen in the figure, the errors are very small. In Fig. 3 are shown the COD being expected from the above alignment errors and the actual COD measured by the beam monitoring system. The agreement between the two is fairly good. In the figure, a corrected COD is also shown. The COD correction was made by a combination of beam monitoring system and computer controlled correction dipole system. The corrected vertical COD is within ± 0.5 mm and horizontal COD is ± 0.8 mm in average, which show quite statisfactory performances both of the beam monitoring system and of the computer controlled orbit correction system.

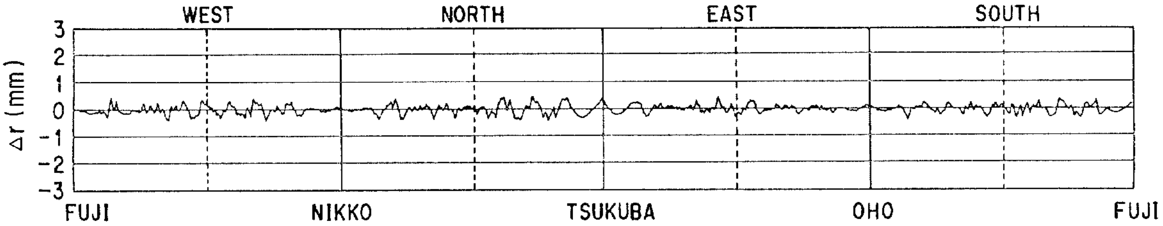

Fig. 2 Setting error distribution of Q magnets in TRISTAN MR.

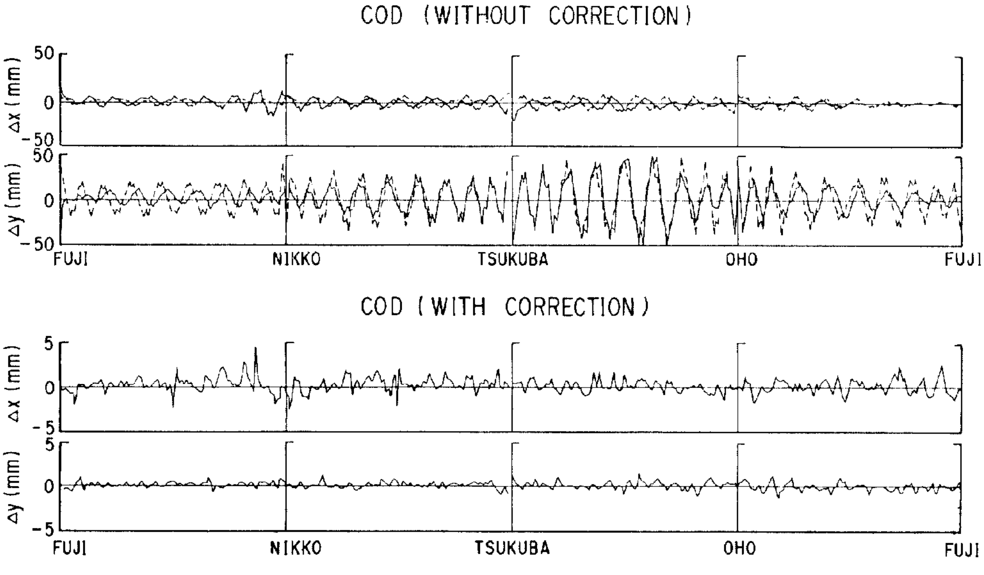

Fig. 3 COD's before and after an orbit correction.

Table II Distribution of RF cavities around MR

Allocation of the Cavities at 8 RF Stations

Klystron Building		RF Section										
		1	2	3	4	5	6	7	8	9	10	
Tsukuba	1	★	★	★	★	★	★	★	★	★	★	
	2	★	★	★	★	★	★	★	★	★	★	
Oho	4	★	★	★	★	★	★	★	★	★	★	NOT FILLED
	5	★	★	★	★	★	★	★	★	★	★	
Fuji	7	★	★	★	★	★	★	inj	inj	inj		
	8	★	★	★	★	★	★	inj	inj	inj		
Nikko	10			✪	✪	✪	✪	✪	✪	✪	✪	NOT FILLED
	11			✪	✪	✪	✪	✪	✪	✪	✪	

★ Two Linked Nine-Cell APS Units
✪ Two Linked Five-Cell SCC Units

2.3.2 RF System: The total accelerating voltage determines the maximum beam energy of TRISTAN. Main part of the long straight sections the total length of which is about 780 m, is allotted to RF cavities. In Table II, the overall distribution of the RF cavities around the MR are given. On both sides of four experimental halls, there are ten sections available for RF cavity insallation or beam injection. Among these 80 sections in all, 8 sections at the Fuji division are allotted to the electron and positron injection systems, and 20 sections at the Nikko division are to the superconducting cavities. The other sections, 52 in all, are for the (normal temperature) RF cavities. At present, only 32 sections of them are occupied by cavities (12 sections in Fuji and 20 sections in Tsukuba division), and 20 more cavities are scheduled to be installed in the Oho division by this summer. The cavity unit is an APS (alternating periodic structure) type of 9 accelerating cells and works at 508 MHz9),10). This type of structure which was developed by a KEK group was chosen because of its high shunt impedance, wide mode separations at the accelerating frequency and the simplicity in the structure. The shunt impedance is about 22 MΩ/m. Each 9-cell cavity unit has one RF coupling port for power feed, and two cavity units are combined to form a "long unit" with 18 cells. This long unit is a fundamental unit to be installed in each section.

KEK has developed a high power klystron with an output power of more than 1 MW (CW) in cooperations with industries11). At present, we have a stationary supply of a 1 MW (CW) klystron from the industry. In the operation of the accelerating system, RF power of 1 to 1.2 MW is divided into 2 × 2, and each RF power of about 250 kW are fed into each 9-cell cavity unit through a coupling port. For the cooling system of the klystron, we have introduced a two-phase heat exchanging scheme. Mixture of hot water and water vapor works as a coolant in the boiler heat exchanger of the klystron beam collector at a temperature level of about 100°C. Most important is the regulation of pressure and the water level in the boiler heat exchanger. A control system keeps the function of the cooling system stable by regulating the pressure and the water level in the boiler.

2.3.3 Vacuum System: The vacuum system of the MR12) works almost well except for one problem. The all aluminum vacuum duct treated by the special extrusion process shows very good vacuum performances. Most of the joints are welded by an automatic welding machine except for those where frequent disconnections will be necessary in the future for the maintenance and rearrangement.

A DIP (distributed ion pump) which has already been confirmed to work well in the AR, is also adopted in the MR as a main pump. The arrangement of electrodes of the DIP of MR is almost the same as those in the AR, but the material of the cathode differs. In the new DIP, a set of cathode assembly of aluminum alloy is mounted in contrast to a titanium cathode in the old DIP. The performance of the new DIP was tested on a test bench and confirmed to have a good pumping speed and a good ultimate pressure. But, in the first operation of the MR vacuum system, the new DIP didn't work well. It turned out that the pumping speed of the new DIP was as small as 1/3 of the old one. The problem why the new DIP is not good is under investigations now, but it is almost clear that the new DIP works well to some kind of gas species but not to another gas species. Although the performance of the main vacuum pump is not adequate, the average pressure in the MR is about 1×10^{-6} Pa without beam and 5×10^{-6} Pa with beam of 4 mA. The pressure is still going down very slowly with the operation time. The life time of the beam is about 1 hr. for the beam current of 4 mA and more than 3 hrs. for zero beam current. If the new DIP would work with the designed pumping speed, the pressure would be decreased by a factor of 1/3 and the beam life time would be increased by a factor of three. A quick replacement work of these DIP's to the ones with titanium cathode are now going on.

Some problems are also in the electrostatic beam separator system. The system is designed to separate electron and positron beams of 8 GeV by a separation of 2 mm with applied voltages of ± 120 kV to the electrode. In the blank test without beam, the electrodes of the separator can hold 100 kV or more, which is enough to separate beams of 7 GeV. But the separator does not work well with beams circulating in the MR. It seems that the structure of the electrode has some defects and the beam induced wake field triggers small discharges inside the electrode structure which lead to the fatal discharge between the electrodes. At present, the separator system is working under a degraded condition with an insufficient beam separation of less than 1 mm. A quick improvement of the separator has begun to be in time with the next machine start in May. In parallel with this improvement, design and construction of a new separator system which is scheduled to be completed by this autumn will be started soon.

3. The Commissioning and Operation of the MR

After careful examinations of each component of the MR, the first overall operation of MR was started on 16th of October, 1986. On 24th, we achieved the first acceleration of electron beam to 25.5 GeV, and on 15th of November, we succeeded the first colliding beam operation at 24 GeV. Some of the main events during these period are listed in Table III. In the initial stage of the commissioning, some of the vacuum gate valves did not work well and we lost a week to repair these valves. But, after this trouble, almost everything went on well and it took only one month in commissioning the MR. On 19th of November, 1986, which is just 5 years after the ground-breaking ceremony, we observed in one of the detectors, VENUS, the first collision event with a total energy of 48 GeV. Since 10th of December, colliding beam experiment has been continued. In Table III, some of the operational statistics are also given.

In the routine operation of TRISTAN in a collision mode, positron beams are first injected and accumulated in the AR. Positron beam of about 10 mA comes from the main linac with a repetition rate of 20 Hz. After about 2 minuts when the accumulated positron beam reaches 10 mA, the beam is accelerated to 7 GeV and is transferred to the MR. The transferring efficiency is about 50 to 80 %. In the two bunches per beam collision mode, next positron beam is injected into another RF bucket being different by π in circulation phase angle. The same procedures are repeated again, and finally, two positron bunches of about 2 mA each are stored in the MR.

Table III Main events in commissioning and operation of MR and future schedule

1986 Oct.16	First try to get a circulating electron beam -unsuccessful-
Oct.22	Retry First 6.5 GeV circulating electron beam
Oct.24	Acceleration of electron beams to 25.5 GeV
Nov.7	Injection of positron beams and acceleration to 25.5 GeV
Nov.15-19	First colliding beam operation at 24 GeV
Dec.10-19	Colliding beam experiments at 24 GeV × 2
Total operation time = 182 Hrs. Machine failure = 8.5 Hrs.	
1987 Jan.22-Feb.20	Colliding beam experiments at 25 GeV × 2
Total operation time = 596 Hrs. Machine failure = 93.2 Hrs.	
May-Jul.	Colliding beam experiments at 25 GeV × 2
Oct.--	Colliding beam experiments at 27-28 GeV × 2

In the next step, the main linac is switched to the electron mode, the electron beam of about 20 mA is injected, accumulated, accelerated to 7 GeV and transferred to the MR. Because the bunch is strong enough, only one injection is enough for each bunch. In Fig. 4, an example of MR operations is shown. In the figure, a positron beam loss at the moment of electron beam injection can be seen. It is considered to be due to the beam-beam interaction. For all these procedures, the injections of positron and electron beams, beam acceleration to 24 GeV and switching off the separator system, it takes about 20 min. The total beam current is about 4 to 5 mA at the beginning of the colliding beam experiment. The beam life time which is determined mainly by vacuum pressure is about 1 hr in the beginning of the experiment and and gradually increases to about 3 hrs at a vary small beam current. In Fig. 5, the rate of pressure rise in MR due to beam, $\Delta I/m$, is shown as a function of beam dose. For a comparison, data of the AR is also given in the figure. Usually, the experiment is continued for about 1 to 2 hrs until the total current reaches to 1.5 mA. In the operation, 16 klystron tubes are operated delivering a total RF power of 12 MW or more to 32 RF cavities. This is the highest RF power being supplied to an accelerator of this type so far in the world.

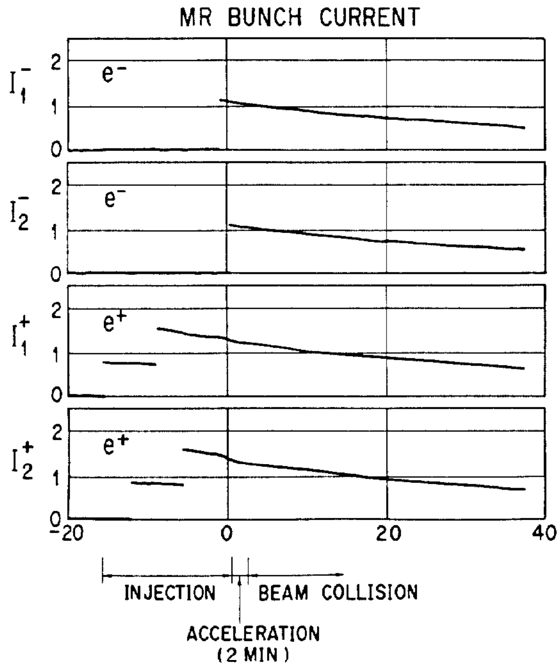

Fig. 4 Beam transferring to MR.

Although the machine time allotted to the machine study is not enough, some results have been obtained in the accelerator studies. In the following, some of them are given.

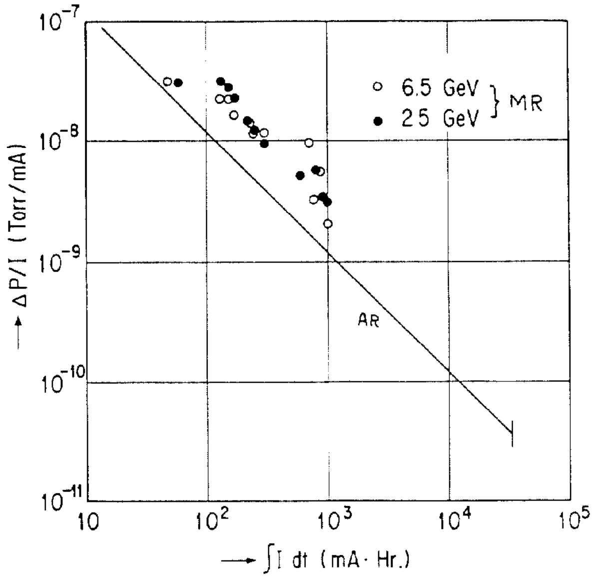

Fig. 5 Δp/I vs. integrated beam dose both in AR (solid time) and in MR.

(i) Current-Life Characteristics

When a beam is injected and stacked in the MR, the beam decays very fast at some instant of time but does not most of the time. Apparently, the beam life time depends largely on the beam current. In Fig. 6, a beam current and the corresponding life time as functions of time are shown. In this case, single bunch electron beam is injected in the MR. It must be noticed that the beam current is limitted at a maximum value of about 2.8 mA. If the beam stacked further, the beam decays very fast to reach 2.8 mA and stored stably. With the time goes on after that the life time increases. But suddenly, when the beam current reaches a value, in this case about 2.4 mA, beam decays very fast. A data of tune shift vs. beam current which is shown in Fig. 7 will help to understand the above "zone structure" of beam life time. This kind of tune shift, it is considered, is due to the beam impedance caused by discontinuities of the beam duct structure and/or accelerating cavities. As the current decreases, the tune changes and the operating point in the tune diagram moves accordingly, which may result in a sudden decrease of beam life time. The calculated total impedance of the accelerating cavities is about 3630 MΩ, which is much greater than the highest of the PETRA, which is about 2300 MΩ.

(ii) Luminosity

In TRISTAN, the luminosity is monitored by a luminosity monitor being built in the detector of beam collision experiment. On the other hand, the luminosity can also be determined from a tune shift in the collision mode operation. In Fig. 8, an example of tune measurement is shown, and in Fig. 9, the tune shift parameters as function of total beam current.

From the tune measurement, we can estimate the highest luminosity achieved to be

$$L \simeq 2 \times 10^{30}\ \mathrm{cm}^{-2}\ \mathrm{sec}^{-1}\ , \qquad (1)$$

with the conditions of beam energy: 25 GeV + 25 GeV, beam current: 2(mA) × 2(mA) and $\beta_H^* = 3.2$ m and $\beta_V^* = 0.07$ m. This agrees well with the result obtained by the luminosity monitor within a measurement errors.

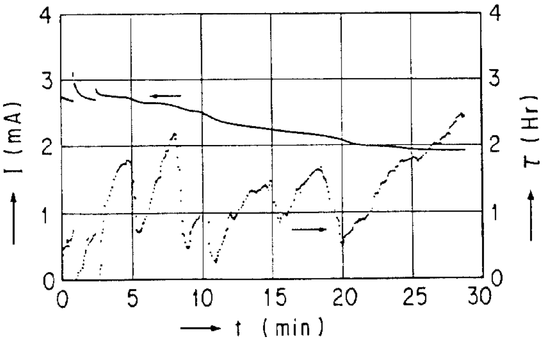

Fig. 6 Beam current and lifetime vs. time in MR.

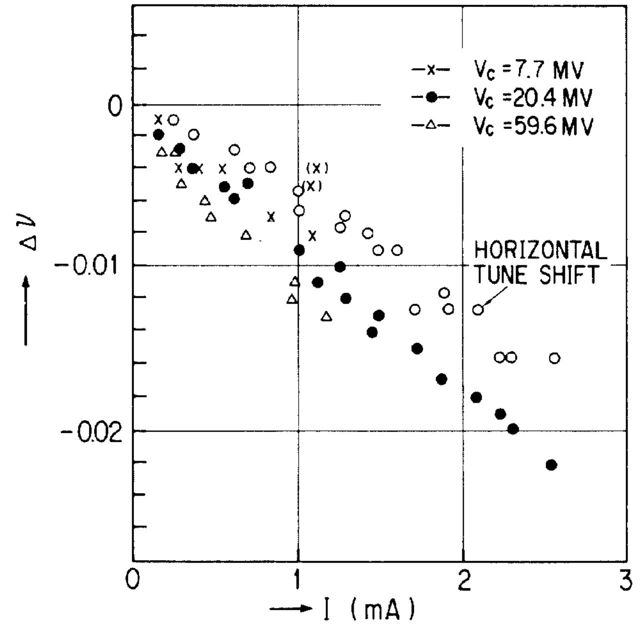

Fig. 9 Tune shift as a function of beam current.

4. Future Upgrading of the MR

Construction works of the RF accelerating system is still going on. Twenty long cavity units and ten klystron tubes will be installed in Tsukuba division by this summer, and be operated from this autumn. It is scheduled that the beam energy of MR will be increased to 27 GeV or more.

For a further upgrading of MR, the construction of superconducting RF cavities[13] and liquid helium refrigerator system is also progressing. The construction has already been approved by the Government as a two-year project, and is scheduled to begin the operation from FY 1988. In the project, 32 five-cell superconducting cavities will be installed in 16 sections of the Nikko division as shown in Table II. Two 5-cell cavities are linked to form one unit which will occupy one section. It is expected that the accelerating field of about 5 MV/m will be achieved, and the present system will allow an increase of the MR beam energy to about 33 GeV. The time schedule of the project is given in Table IV.

Akcnowledgement

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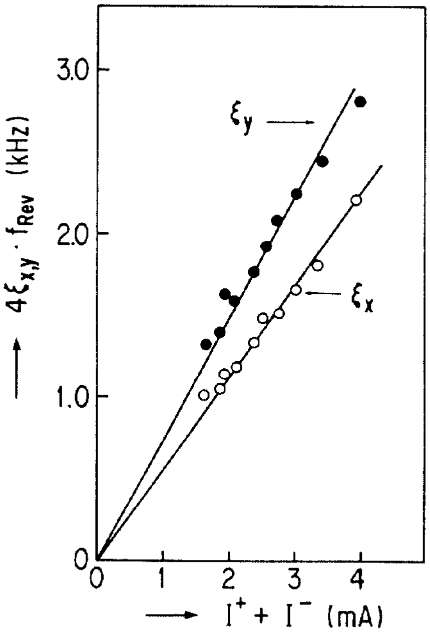
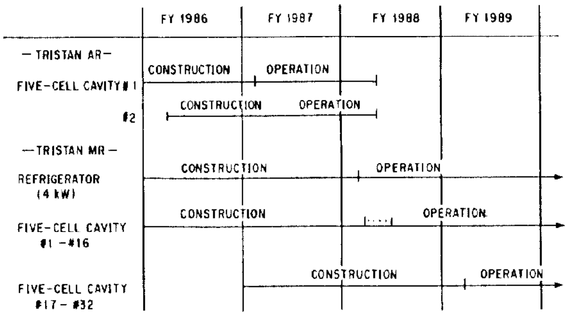


Fig. 8 Tune shift parameters as functions of beam current.

Table IV Time table of superconducting RF system construction



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