RF SYSTEM WITH ROOM-TEMPERATURE CAVITY OF THE TRISTAN e^+e^- STORAGE RING

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Summary

In the TRISTAN $e^+ e^-$ storage ring an active length of 276 m of the 3 km circumference will be occupied by room-temperature cavities of an alternating periodic structure (APS) operating at 508.58 MHz. General features of the RF system are described including the low-level RF circuit complex, 1 MW cw klystron and circulator, and APS cavity. Also considerations are given for suppressing beam instabilities due to such long RF sections. By this system a peak cavity voltage as high as 330 MV would be possible which is adequate to the beam energy E_b = 29 GeV.

Introduction

At the initial stages of operation of the ring, the beam energy around 27 GeV with a current of 7.5 mA per beam is aimed at by using only room-temperature cavities operating at 508.58 MHz. The total active RF length 276 m (468λ) is 9.1 percent of the 5120λ circumferential length. The peak cavity voltage required for many-hour operation at E_b = 27 GeV is 253 MV and at 29 GeV 330 MV. The synchrotron radiation loss per turn is 191 MV and 254 MV respectively.

Of 8 straight sections adjacent to each of 4 collision points in the ring, 6 are for the room-temperature cavities and the others are left for superconducting cavities. Each section is divided into 10 sub-sections 12λ (7074 mm) long by Q-magnets. 2 straight sections are used also for the beam injection which requires 4 sub-sections per beam. Therefore a total of 52 sub-sections are available for installation of the room-temperature cavities.

An APS cavity unit 5365 mm long is composed of two 9-accelerating-cell structures operating at the π-mode with a shunt impedance of about 22 MΩ/m. The required RF power both for the wall loss and beam loading would be at least 22 MW at E_b = 29 GeV. This is supplied by 26 klystrons rated at 1 MW cw output power, each of which feeding four 9-cell structures. The conversion efficiency is better than 60% and hence the total wall-plug power is less than 50 MW for the RF system. The high-power RF system is installed in a hut on the ground 10 m above each straight section.

At the commissioning of the ring in the autumn of 1986, only 32 APS-cavity units will be used. The remaining 20 units are to be installed in spring 1987. The beam energy at first would be therefore about 25 GeV.

Klystron

Of the 26 tubes half are being supplied by the Valvo works, Hamburg, Philips GmbH and the other by Toshiba Corp., Japan. Main specifications of the tube are: 1 MW cw output power with efficiency better than 60%; dc beam current and voltage less than 20 A and 95 kV respectively; modulation anode electrode to control beam current; vertical tube position with the collector vapor-cooled.

The output power, halved twice by magic-tees, is fed through WR1500 waveguides to 4 input ports of 2 APS cavity units. 3 to 5 klystrons are installed in one RF hut with a spacing of 14 m. Steam from the boiler casing enclosing the collector of the tubes is gathered by a common pipe line 250 mm in diameter, condensed into water in a cooling unit on the roof of each hut and fed back to each tube. The cooling unit with a capacity of 7 MW maintains the vapor pressure rise at the collector within 0.1 atm for a collector loss of 0.8 MW per tube.

Typical parameters of the tubes of the both companies are as follows:

company	Valvo	Toshiba
type	YK1303	E3786
height	4250 mm	4700 mm
heater power	23A × 24V	24A × 12V
number of cavity	5	6
beam power for 1 MW output	19A × 87kV	18A × 86kV
efficiency for 1 MW output	61 %	64 %
driving power for 1 MW output	~ 60 W	~ 2 W
number of 8 l/s ion-pump	1	2

While the normal rating is 1 MW cw at most, the maximum cw output power during conditioning has reached 1.10 MW for Valvo tubes with the 1.88 MW dc input and 1.20 MW for Toshiba tubes with 1.80 MW dc.

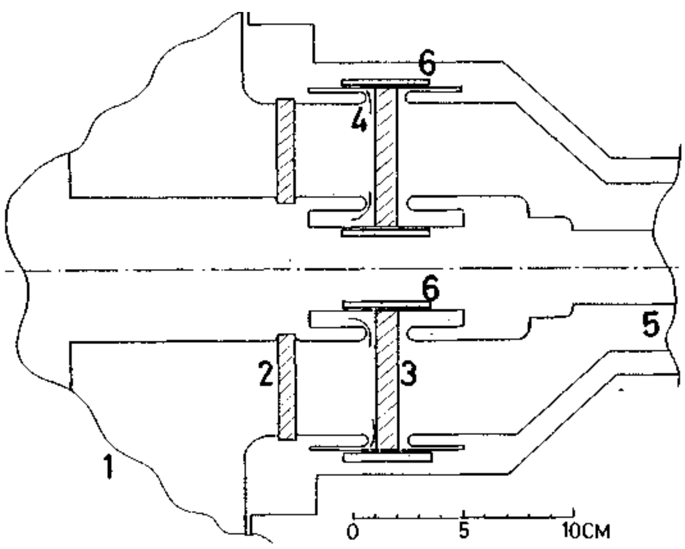
In the development of the E3786 tube partly in collaboration with the KEK staff[1] the following technical points have had to be overcome. First is treatment of the cathode. It is a dispenser one, 70 mm in diameter, of the type S made by Semicon. Associates Inc. USA. For early tubes reduction of excess barium-oxide impregnated in the cathode was not enough before assembling of the tube and they could not stand the designed dc high voltage. This has been remedied by keeping the cathode at 1160°C for 6 hours in an RF furnace with an oil-free pumping system and, after mounted on the gun assembly, at 1015°C about half an hour.

Second is the design of the wehnelt electrode on the surface of which the highest dc electric field exists in the gun assembly. The cathode being normally kept at 1050°C heats up the electrode, and barium and barium oxide deposited on its surface cause unwanted electron emission leading to high-voltage breakdown. Though the excess barium oxide is removed as described above, very small amount of barium continues to evaporate from the cathode surface and therefore the temperature of the wehnelt electrode should be lowered. One way tried was to make it out of OFHC copper block into a shape with good thermal conduction. With the heater off, the current between the wehnelt electrode and modulation anode obeyed very well the Fowler-Nordheim law of cold emission. At the operation of 1.8 MW dc input, the modulation anode current, most of which would be the emission from the wehnelt, was only 0.2 mA. Copper and barium however tend to form a binary alloy of a relatively low melting temperature and hence the electrode temperature should be kept low enough. Another choice for the electrode material was vacuummelted, especially low-carbon stainless steel, SUS316L. Though the modulation anode current is one order of magnitude larger than that of the copper wehnelt, there is no breakdown up to the highest operating voltage. The excellence of stainless steel over copper is in the mechanical strength and also endurance at higher baking-temperature in pre-treatments, which greatly reduces the out-gas from the material itself.

The third point was the choice of materials for welded parts where the cooling-water flows by. Copper should be used as far as possible. When stainless steels are necessiated, it should be of very low carbon content such as SUS304L and 316L. Otherwise the welded area becomes corrosive during the final baking of the tube above 500°C for 165 hours and pin-holes are often made by halogens in water.

Finally of the most concern was the output window in respect of surface treatment of ceramic and its shape. The window is a transition between an air-filled WR1500 (15" × 7.5") waveguide and a 50 Ω vacuum coaxial line 77 mm in diameter connected to the output cavity of the tube. The ceramic partition is made of pure alumina of about 95% content. The shape first tried was of a cylinder type just like that of the PEP tube.[2] It encloses a probe antenna at the end of the coaxial line. The ceramic temperature rise ΔT, monitored by an infrared thermometer, is 5°C per 100 kW of transmitted power P and may be solely due to the dielectric loss of the ceramic ~ 6×10^{-5}. But there is a threshold around P = 200 kW above which $\Delta T = P^{-10}$ and red or blue glow is observed on the inside surface of the ceramic window. By ceramic sample tests in very high RF fields this phenomena was concluded to be a one-side multipacting due to high secondary-electron-emission coefficient S of alumina. Then the inside surface was coated with titanium nitride film 60 Å thick by dc sputtering in a mixture of argon and nitrogen gas. ΔT became only P^{-2} above the threshold power, which also rose up to ~ 400 kW. Though the multipacting is much suppressed by this coating, RF field distribution is not so uniform and causes localized temperature rise in the ceramic. The cw power safely transmitted by this type of window has been 850 kW at most. The ceramic shape adopted now is of a disk type shown in Fig. 1.

Fig. 1 E3786 Klystron Window. 1. transition to WR1500 waveguide 2. supporting teflon disk 3. alumina window 4. air flow 5. coaxial line to the output cavity 6. water channel



The vacuum-side surface is coated in the same way. Both the inner and outer peripheries of the disk are water-cooled and the flat face is cooled by air flow of ~ 1 m^3/min. This type has a very uniform field distribution and there is no abnormal temperature rise. At the maximum cw output 1.20 MW ΔT is only 40 ~ 50°C.

Waveguides

Waveguides are of the size WR1500 (15" × 7.5") made of the 6063-T5 aluminum whose content is 98.8%. The electrical and thermal conductivities are 3.2×10^{7} Ω^{-1} m^{-1} and 1.95 W/cm°C respectively which are almost 90% of the pure aluminum. The tensile strength is twice that of the pure aluminum. The straight waveguide, made by an extrusion method, is a seamless one with a wall thickness of 6 mm. The flexible waveguide is made of a phosphorus-deoxidized copper plate 0.3 mm thick and has corrugation with a pitch of 10 mm and depth of 10 mm.

The size WR1500 is relatively small for our RF frequency. Therefore the wave guide temperature was measured for various conditions at high transmission power levels. For the power 600 kW, the calculated loss per unit length is 300 W/m. The temperature rise at this power was typically 30 ~ 35°C after many-hour operation. It depends very much on air convection around the guide. Though WR1800 and Cu-plated WR1500 waveguides which have 2/3 smaller attenuation were also tested, the present WR1500 type has been chosen from the practical point of view and is used up to 1.2 MW cw power levels.

Circulator

The circulator is of the 4-port type. The 1.2 MW input power is halved by a magic-tee, transmitted through a pair of phase-shifter waveguides and combined again by a 3-dB coupler. The reflected power is absorbed by a water-load at the E-plane arm of the magictee. The phase shifter is 2300 mm long with a cross section of 417 mm × 70 mm. To obtain 45° phase shift, 256 pieces of ferrite plate 69 mm wide, 53 mm long, 8 mm thick are attached both on the upper and lower surface of the waveguide with an external field of 1200 gauss applied. The ferrite material supplied by Mitsubishi Elec. Corp., Japan, is a gadolinium and aluminum doped yittrum-iron garnet (Y, Gd)3(Al, Mn, $Fe)_5O_{12}$ which has the saturation magnetization $4\pi M_s$ = 800 gauss, curie temperature T_c = 250°C, dielectric loss $6 = 3 \times 10^{-4}$ and thermal conductivity 3.2×10^{-2} W/cm°C. As the RF loss for each ferrite plate is about 130 W at 1.2 MW cw operation, the adhesive agent for the ferrite plate should have a good thermal conductivity and also a flexibility for the different thermal expansion rates of the ferrite 9.5×10^{-6}/°C and aluminum 2.3×10^{-5}/°C. The agent used is a flexible epoxy resin ECCOBOND45 supplied by Emmerson & Cuming, Inc., USA. Its thickness is kept at ~ 50 μm. The ferrite piece is fixed besides this resin by a teflon screw 5 mm in diameter. Typical data for a transmitted power of 1.0 MW are: insertion loss ~ 0.22 dB, isolation > 20 dB, VSWR < 1.05.

APS Cavity[3]

The accelerator unit and details of one period of APS are shown in Fig. 2 and 3. The whole structure is made of the low-carbon steel SS41 with the inner surface copper-plated 200 μm thick in a pyrophosphorous-acid bath. It has 2 input couplers in vertically up position, four 400l/s-ion-pumps vertically down, and 18 tuners in horizontal position for accelerating cells.

One unit period of half λ length (294.74 mm) is composed of the accelerating cell gap 224.74 mm long and coupling cell gap 30 mm with the disk 20 mm thick having the 100 mm diameter beam ir.is. For the conflu-

Fig. 2 APS Cavity Unit with 2 Input Couplers.

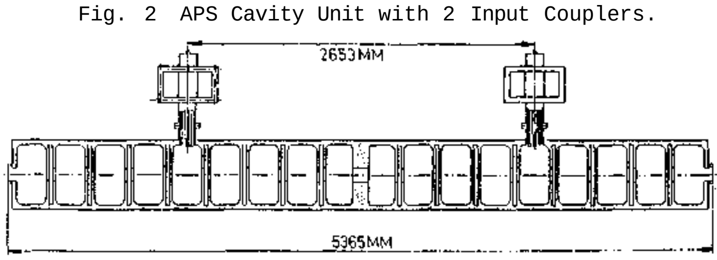
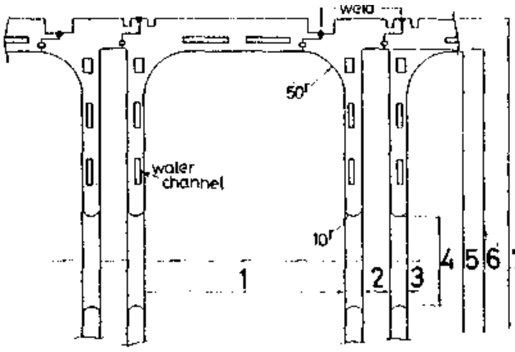


Fig. 3 Unit Period of the APS.
1. g_a = 224.74 mm 2. g = 30 mm
3. t = 20 mm 4. 2a = 100 mmØ
5. $2r_a$ = 464.9 mmØ 6. $2r_c$ = 470.5 mmØ
7. $2r_0$ = 540 mmØ



ent structure i.e. the accelerating π mode frequency fa = the coupling π mode frequency fc, typical calculated parameters are: fπ = fa = fc = 508.58 MHz, f2π - fπ = 2.9 MHz, fπ - fo = 3.1 MHz, Q = 42,400 and R = 26.7 MΩ/m for $\rho_{Cu} = 1.70 \times 10^{-8}$ Ω m.

RF coupling between two 9-cell structures is made so small as 1.2 kHz by a rather long (130 mm) beam hole between them and making the end accelerating cells shorter by 30 mm. This coupling induces a phase error of only 2.1° in one structure even when the other is completely detuned.

The most important was to make the structure stable against thermal detuning.[4] The wall loss per period is 20 kW normally and 35 kW at conditioning. The thermal detuning amounts to a few hundred kHz which is almost comparable with frequency spacings between the π mode and its nearest neighbor modes of the 9-cell structure. Though this is compensated by the tuner, the following points should be taken into account lest the field uniformity should be lost and the coupling cell excited: every accelerating cell should have the tuner; fc higher than fa in any case; the coupling cell gap g_c as wide as possible. When only every other accelerating-cell has the tuner, the coupling cell is slightly excited. For instance SUPERFISH calculations show that Q is lowered 1% by a thermal detuning of 160 kHz for g_c = 30 nun, but only 60 kHz for g_c = 15 mm. The calculated R for g_c = 30 mm is only 2.3% lower than for g_c = 15 mm. Therefore in the final design g_c is chosen to be 30 mm and every accelerating cell is accomodated with the tuner. Furthermore fc should be higher than fa. Otherwise more field energy is stored in a cell with a larger inductance as equivalent circuit analysis shows and, as this cell suffers from more wall loss, the thermal detuning is obviously unstable. Therefore in the present design, fc is made 600 kHz higher than fa in the cold test for every cavity unit. This value is chosen because fc and fa are measured to be - 300 kHz and - 90 kHz respectively for the normal input power 150 kW per 9-cell structure with a cooling water flow of 150 l/min and the power is still doubled during conditioning.

The fabrication method is described in a previous paper.[4] Q at 30°C is 36,800, which is 88.6% of the SUPERFISH calculation, and R is 22.5 MΩ/m. Before the high-power conditioning, frequency errors of the accelerating cells are adjusted by presetting each tuner position in such a way that signals from the pick-up antennas of the coupling cells are made null for the π mode. Afterwards all 9 tuners are drived by the same amount by a common bar. Each cavity unit is conditioned up to 300 kW per 9-cell structure within 15 hours by a computer program controlling the input power level lest the vacuum pressure should exceed 5×10^{-6} Torr (Fig. 4). After conditioning, the unit is baked for 10 days by circulating 145°C water in the channel. The permeation of hydrogen from the water channel through iron into the vacuum is avoided by adding 2% in volume of an anti-corrosion agent. The final outgas rate from the cavity surface at 30°C is about 5×10^{-13} Torr·l/s cm^2. After these processings, the units are installed in the tunnel.

The tuner and input coupler are schematically shown in Fig. 5 and 6. The tuner is a copper plated cylinder 70 mm in diameter. But it is chromium plated in the part where copper plated spring contactors slide. The coupler has a cylindrical alumina window 152 mm in diameter, 190 mm long, 6 mm thick. The inside surface is also coated 60 Å thick with titanium nitride. As the figures show, the gap between the tuner or coupler and the cavity port forms a coaxial section. Its length is so chosen that the TEM mode impedance becomes 0 at the cavity surface at 508 MHz. The accelerating mode still penetrates into this coaxial section in the form of the TE_{11} mode about $\lambda_c/2\pi \sim 4$ cm and cooling by water is necessary. The coaxial gap is chosen to be 1.5 mm lest the leakage field should cause multipacting.

Fig. 4 High Power Conditioning of a Cavity Unit.

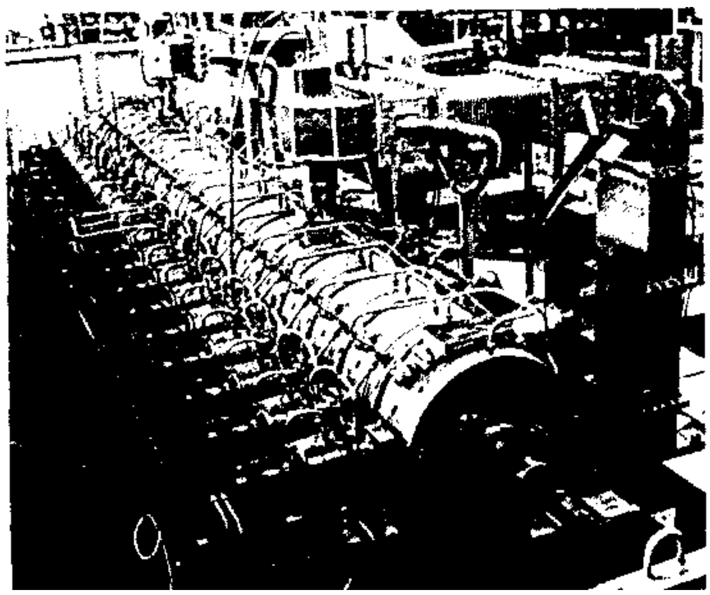


Fig. 5 Tuner for the Accelerating Cell.

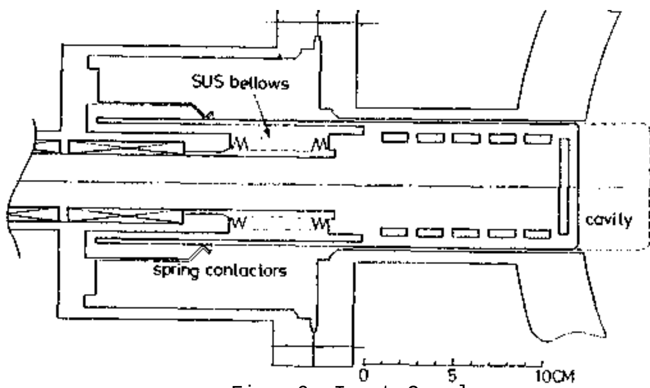
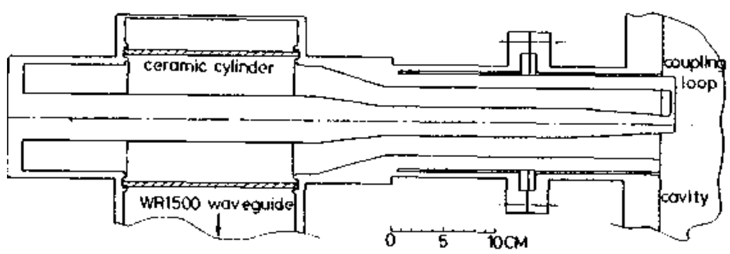


Fig. 6 Input Coupler.



Beam Instabilities Due to Cavity

In considering beam instabilities due to the cavity, essential factors are the higher order modes (HOM) and deviation of cavity shape from axial symmetry. The former will cause coupled bunch instabilities while the latter strengthening of synchrobetatron resonances.

Characteristics of the typical HOM impedances per 9-cell APS are summarized in the following table:

Mode	Frequency (MHz)	Calculated Q	Calculated R(MΩ) or R(MΩ/m)	Measured Q	Measured R(MΩ) or R(MΩ/m)
TM011 π/4	865	37,000	7.7		
TM110 H π/2	794	48,000	61	35,000	47
V π/2	793	48,000	61	23,000	31
TM111 H 0	1039	39,000	108	16,000	44
V 0	1041	39,000	108	9,000	25

To suppress the coupled bunch instabilities a feedback damper with a damping time of 500 μs will be installed. However, if the 52 cavity units have the same resonant frequencies for the HOM, the accumulated HOM impedance is still too large to store the designed current of 4 mA × 2 bunches per beam at the 6.5 GeV injection energy. The total HOM impedance should be reduced by a factor of 5. For this purpose the resonant frequencies of the HOM have been distributed by varying the inner diameter of the accelerating cell $2r_a$ unit by unit. A simulation calculation shows that a random diameter distribution corresponding fa = 160 kHz for 52 units results in reduction of at least 1/5 for the impedance of every mode of the concern. A further damping of the instability will be accomplished by damping antennas attached at the 5-th accelerating cell of a 9-cell structure in 45° direction from the vertical. Q of the pair of TM_{111} modes are reduced to 4,000 and the threshold current will be increased by a factor of more than 5.

The axial symmetry is mostly broken by the tuner plunger 70 mm in diameter and intruding itself 20 mm typically. All the 18 tuners in a cavity unit are on the horizontal median plane and either inside or outside of the cavity center for the sake of simpleness in driving them. To prevent the asymmetry effect on the synchrobetatron resonance from being cumulative, two types of cavity unit are prepared. One type has the tuner position inside the cavity and the other outside. In installing the cavities, a cavity unit of one type is followed by that of the other type. As the phase advance of the betatron oscillation is only 38° per cavity unit, this arrangement would greatly reduce the asymmetry effect.

Low-Level RF System and Operation

The low-level RF circuit complex for operation of the whole RF system is similar to that for the TRISTAN accumulation ring.[5)] The master oscillator is a synthesizer, MG655A, Anritsu Co. Ltd., JAPAN, which has a frequency stability of 5×10^{-10} per day and noise level of - 120 dB at 1 kHz deviation. The signal, transmitted through phase shifters, fast switch and amplitude modulator, is fed to a 100 W transistor amplifer and then to the klystron. The fast switch is activated by the following signals: reflection from the cavity, arcs in the klystron window and waveguides, abnormal levels of water flow, vacuum and temperature of devices.

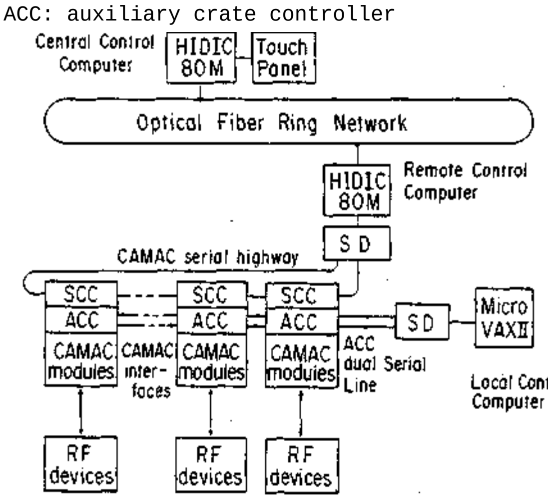
The cavity voltages picked up from the four 9-cell APS connected to a klystron are vector-summed. The sum and an external programmed voltage are compared and a resultant difference signal drives the amplitude modulator to set the cavity voltage at a prescribed level. This feedback loop contains an additional circuit to control the klystron modulation anode voltage. It minimizes the klystron beam current for a given RF output power and also protects the tube from overheating of the collector. A function generator converts the signal linearly detected at the output of the driver amplifier into a control signal for an HV generator for the modulation anode. The generator incorporates a limiter which ensures the anode voltage always lower than the beam voltage and also the collector dissipation less than a prescribed value.

In order to supply a phase-stable RF signal to all RF stations, each station is linked by a phase-locked line to its neighbour 800 m apart. The 508.6 MHz signal sent to its neighbour is converted there to 254.3 MHz signal and sent back through the same cable. Thus, after the frequency doubled, the signal is phase-locked to the reference signal. This system has the advantage of easiness of separating the sent-back signal from the 508.6 MHz signal.

All RF devices in an RF station is controlled via CAMAC crate controllers by a computer Micro VAX II, Digital Equipment. Corp.. This local system is further controlled by a local computer HIDIC 80M, Hitachi, which is linked by a optical fibre ring network to the central control computer of the same type (Fig. 7). Though the HIDIC 80M network offers an easily manageable NODAL system for remote control of the whole accelerator, its capacity is not sufficient for local jobs to run each klystron system independently, which is often necessary in initial conditioning stages. Therefore the Micro VAX II was introduced to back it up.

By this system 10 cavity units with 5 klystrons have been successfully operated at high-power levels.

Fig. 7 Computer Control of the RF System.
SD: serial driver
SCC: serial crate controller
ACC: auxiliary crate controller



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