TRISTAN PROJECT AND KEK ACTIVITIES

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Summary

Present status of the accelerator construction and operation at KEK is described with an emphasis on the TRISTAN project. TRISTAN, which stands for Transposable Ring Intersecting Storage Accelerator in Nippon, aims at achieving electron-positron colliding beam experiments at a total collision energy of about 60 GeV. The construction of the TRISTAN accelerators, which began in 1981, is progressing on schedule towards the commissioning, which is planned to take place in November 1986. Incidentally, a great deal of R/D effort on the superconducting rf cavity and superconducting magnet is being made to upgrade the beam energy and luminosity of TRISTAN.

1. General Description of the KEK Accelerator Facilities

KEK is operating four accelerator facilities as illustrated in Fig. 1.[1] Those are PS, a high energy physics facility with a 12 GeV proton synchrotron, BSF, a facility which utilizes the 500 MeV beam from the PS booster synchrotron, Photon Factory, a synchrotron radiation research facility with a 2.5 GeV electron storage ring, and TRISTAN, an electron-positron colliding beam facility. Figure 2 shows a recent areal view of the KEK site.

1.1 PS

The PS accelerator includes a 750 keV Cockcroft-Walton preinjector, a 40 MeV drift-tube linac, a 500 MeV fast-cycling booster synchrotron, and a 12 GeV main ring.

The preinjector supplies 15 - 20 mA H^- beams with a pulse width of about 50 μs to the linac at a repetition rate of 20 Hz.[2] The H^- ion source is a multicusp type with a directly heated LaB_6 cathode which has newly been developed. Owing to a relatively low working temperature, about 1400°C, of the LaB_6 filament, the present cathode can provide very stable current through more than 3000 hours.

An R/D on the polarized H^- ion source is also underway for acceleration of polarized proton beams in the booster and main ring. An optical pumping type ion source has been developed. It can produce a beam with a polarization of about 50 % in a thick sodium vapour by use of three CW dye lasers. The polarization is ex[illegible]ted t[illegible] be [illegible] 100 % sh[illegible]rtl[illegible] [illegible] the CW dye laser by a flash-lamp-pumped pulsed dye laser with very high peak intensity.

The proton linac was upgraded from 20 MeV to 40 MeV in 1985 by adding a new drift-tube linac.[2] The new 200 MHz cavity is 13 m long and has 35 cells with post-couplers to flatten the field distribution. The drift-tubes are equipped with Alnico-9 permanent quadrupole magnets. The linac accelerates 10 mA H^- beams at a repetition rate of 20 Hz.

The booster is a combined function type synchrotron with a circumference of 36 m and a repetition rate of 20 Hz. The 40 MeV H^- beam transported from the linac is injected into the booster by the charge exchange method.[3] For charge exchange, a stripping foil with a thickness of 33 μg/cm^2 is used. The beam intensity at the injection almost reaches the space charge limit. About 70 % of the injected beam, 1.5×10^{12} protons, can be accelerated to 500 MeV in a single bunch.

The main ring is a separated function type slow cycling synchrotron with a circumference nine times as large as that of the booster. One magnet cycle of the main ring takes about 2.5 s for the flat top period of 0.5 s. Nine booster bunches are successively injected into the main ring by the bunch-by-bunch method and accelerated to 12 GeV. For the moment, the main ring cannot accelerate full intensity booster beams due to blow-up of the longitudinal and transverse emittances which may be attributable to a high charge density of the beam bunch. To cope with this difficulty, several improvement programs, such as an experiment to move the transition to an energy region beyond 12 GeV by use of a set of auxiliary quadrupole magnets, are in progress. The present beam intensity of the main ring is about 4×10^{12} ppp, twice the design intensity. At the flat

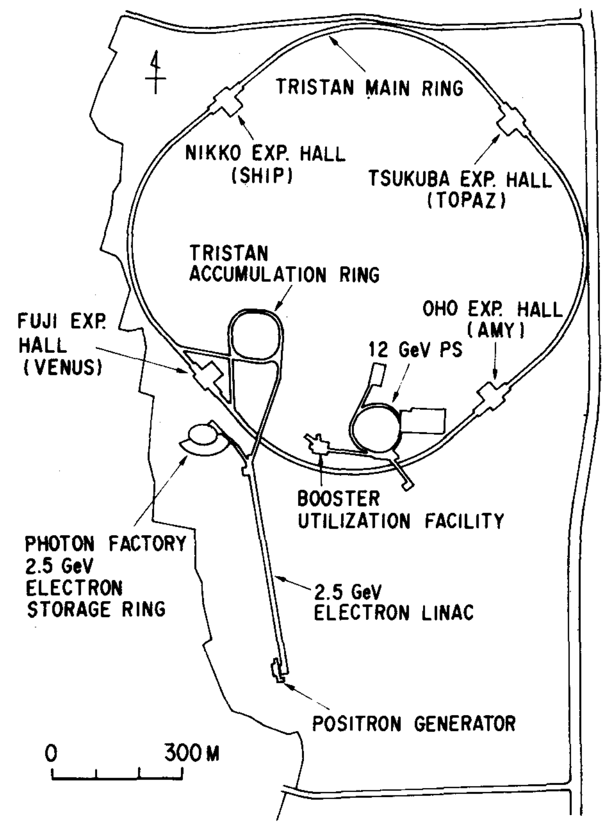

Fig. 1 Accelerator facilities in the KEK site.

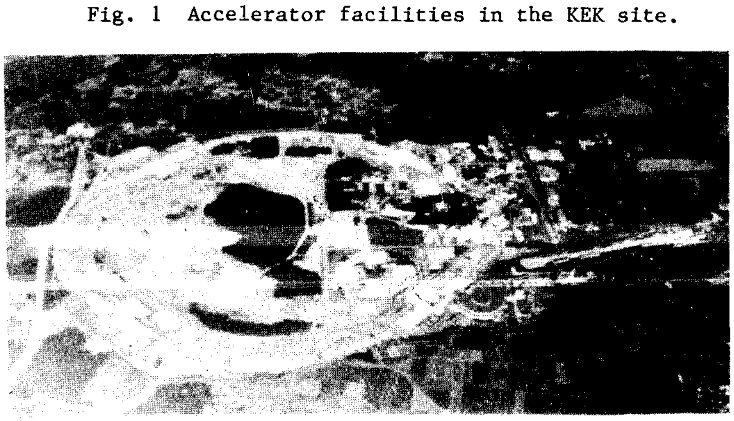

Fig. 2 Recent areal view of the KEK site.

top, more than 80 % of the accelerated beam is slow-extracted and the rest are used to produce internal target beams. Counter experiments on elementary particles and nuclear physics have been proceeding extensively by using seven channels of $\bar{p}$, k, π, and μ beams produced with 12 GeV protons. Further, a study of a future plan to upgrade the PS facility has started aiming at an increase of the main ring intensity by an order of magnitude.

Accelerator experiments to accelerate polarized protons in the booster and main ring are being performed and giving promissing results which indicate the possible use of the polarized beam for counter experiments.

The yearly operation time of the PS facility was about 3500 hours through the past ten years.

1.2 BSF

The PS booster supplies 500 MeV proton beam to BSF during the acceleration, flat top, and decceleration periods of the main ring. An average beam current which BSF receives is about 5 μA corresponding to 40 booster pulses in the main ring cycle time of 2.5 s.

BSF consists of three facilities; KENS, a KEK facility to make neutron scattering experiments with a pulsed spallation neutron source, BOOM, a pulsed-muon facility of the Tokyo University, and the Particle Radiation Medical Science Center of the Tsukuba University.[4] Recently, BSF has made further progress by introduction of new systems. For instance, KENS has succeeded in doubling the neutron intensity by replacing the tungsten target with a depleted uranium target, and BOOM has developed a surface muon beam channel consisting of permanent magnets, which promises many interesting experiments on generation of thermal muonium in vacuum.

1.3 Photon Factory

The Photon Factory is a facility dedicated to scientific researches which use intense synchrotron lights generated by an electron storage ring.[5] It consists of a 2.5 GeV injector linac and a storage ring with the same energy.

The injector linac, which also plays a role of the TRISTAN injector, is a 400 m long conventional traveling wave type. In the ordinary beam injection into the Photon Factory storage ring, it delivers an electron beam with a pulse width of 0.2 - 0.8 μs and a current of 30 - 50 mA at a repetition rate of 1 Hz.

The electron storage ring has an elliptical shape with a circumference of 187 m, and can provide 15 synchrotron light channels for experiments, including three special channels whose sources are a 5 T superconducting vertical wiggler, a 54-pole permanent magnet wiggler, and a 120-pole permanent magnet undulator.

In the ordinary operation, a beam current of about 200 mA is stored in the storage ring at the injection. The beam life is about 30 hours at 150 mA. To avoid the two stream instability caused by ion trapping, two-thirds of the 500 MHz RF buckets are filled nonuniformly with beams, leaving the rest empty. A fine temperature control system of the cavity cooling water and an octapole magnet system have been introduced in the storage ring. They play important roles in reducing the coupled bunch instabilities arising from the parasitic cavity mode excitation and in stabilizing the transverse coherent beam instabilities.

The operation time of the Photon Factory was increased yearly since 1983 and reached about 2700 hours in 1985.

1.4 TRISTAN

The objective of the TRISTAN project is to build an electron-positron colliding beam accelerator with a beam energy of about 30 GeV and to investigate elementary particle phenomena using high energy electron-positron interactions.[6] The construction of TRISTAN accelerators and detectors began in 1981 and is to be completed at the end of 1986.

The accelerator complex of TRISTAN consists of an injector linac system, an accumulation ring, AR, and a main colliding beam ring, MR. The injector system includes a 2.5 GeV main linac, which is also used as an injector for the Photon Factory electron storage ring, a 200 MeV high current electron linac to produce positrons, and a 250 MeV linac to preaccelerate positrons before injection into the main linac. AR, which is a storage accelerator with a circumference of 377 m, accumulates electrons and positrons from the injector linac and accelerates to 6.5 - 8 GeV to transfer to MR. MR has a four-fold symmetrical structure that four quadrant arcs of 347 m in average radius are joined by four 194 m-long straight sections.

Two electron and two positron bunches, circulating in clockwise and in counter-clockwise, respectively, collide to each other at the middle of the four straight sections, where the experimental detectors are to be installed. There are four experimental halls corresponding to each collision point. As shown in Fig. 1, each hall is named after the famous land mark located in respective direction.

The TRISTAN Physics Program Advisary Committee has approved four experiments, which were proposed by VENUS, TOPAZ, AMY, and SHIP collaboration groups.

The civil construction for the TRISTAN accelerators and experimental facilities was completed in 1985.

2. TRISTAN Accelerators

2.1 Injector Linac System

The main injector linac of 2.5 GeV was constructed in 1982 and has been supplying beams to both the Photon Factory electron storage ring and the TRISTAN AR.[5] Its general parameters are given in Table 1. As AR is operated in the single bunch mode, in which only one of the 508 MHz RF buckets is filled with beam, the linac should produce beam pulses as short as 1.5 ns, synchronizing with the AR RF clock. The present 2.5 GeV electron short pulse beam has a peak current of 50 - 100 mA, an energy spread of about 0.1 %, and an emittance less than 30 π cm·mrad in normairzed unit.

The positron generator system, which was completed in 1985, consists of an electron gun, electron accelerating wave-guides with a total length of about 26 m, an electron to positron conversion system, and positron accelerating wave-guides with a total length of about 24 m. General design parameters of the electron and positron linacs of the positron generator system are given in Table 2. A high current electron bunch with a pulse width less than 2 ns is obtained by a sub-harmonic buncher. It is operated at a frequency of 119 MHz, 24th subharmonic of the RF frequency of the accelerating wave-guides, and forms a gun pulse with a width

Table 1 General parameters of the main injector linac

Energy	2.5 GeV
Pulse width for AR injection	1 - 1.5 ns
Peak current, electron/positron	50 mA/10 mA
Repetition rate	50 pps
Energy spread	0.1 %
Normalized emittance	10 cm·mr
Accelerating RF frequency	2856 MHz
Type of acceleration mode	T.W.2/3π
Wave guide length	2m × 160
Max. klystron power	30 MW
Number of klystrons	42
Master osc. frequency	476 MHz

of about 5 ns into a short pulse with a width of 2 ns and a peak current of about 7 A. The electron beam thus obtained is accelerated to 200 MeV. The conversion target is a tantalum plate with a thickness of two radiation lengths. The produced positrons are focussed with a so-called quater-wave-transformer which consists of a set of two uniform solenoids, a high-field and short-range type followed by a low-field and long-range type, and are accelerated to 250 MeV by the positron linac before injection into the main linac. Positron beams with a peak current of about 5 mA have been accelerated to 2.5 GeV so far. Although this is about half of the design figure, it is expected to increase considerably by improving the gun and sub-harmonic buncher operation.

Table 2 Linac parameters of the positron generator

Linac beam	electron	positron	
Energy	200	250	MeV
Pulse width	1 - 1.5	1 - 1.5	ns
Peak current	10,000	10	mA
Repetition rate	50	50	Hz
Acc. RF frequency	2856	2856	MHz
Type of acc. mode	T.W.2/3π	T.W.2/3π	
Wave guide length	1.5m×1 + 2m×2 + 4m×5	2m×4 + 4m×4	
Max. klystron power	30	30	MW
Number of klystrons	3	3	

2.2 Accumulation Ring, AR

The TRISTAN AR is primarily a beam accumulator and energy booster for the TRISTAN MR. Therefore, the basic parameters of AR were determined so that the radiation damping of the injected beam in AR is fast enough to accept the 2.5 GeV electron and positron beam delivered from the injector linac with a repetition rate of 50 Hz, while the maximum energy is high enough to avoid instability problems which may happen when the AR beam is transferred to MR. Additionally, AR can be operated as an independent electron-positron beam collider with a total collision energy of 10 - 13 GeV, and be utilized as a storage ring for the synchrotron radiation research. Listed in Table 3 are the AR general parameters and beam parameters for its colliding beam mode operation. Figure 3 illustrates the magnet lattice configuration and the betatron and dispersion functions in a quadrunt of AR. AR has four long straight sections, two for RF cavities and two for colliding beam experiments. Corresponding to each collision point, two experimental halls are prepared. For the synchrotron radiation research, another experimental hall are also built on one of the four arcs.

The construction of AR began in 1981 and finished in 1983. After the commissioning, which took place in November 1983, AR was mainly operated for accelerator developments and for providing two bremsstrahlung beams generated with internal molybdenum targets to experimental stations. These beams were used for energy calibration of the lead-glass counters for the colliding beam experiments in MR.

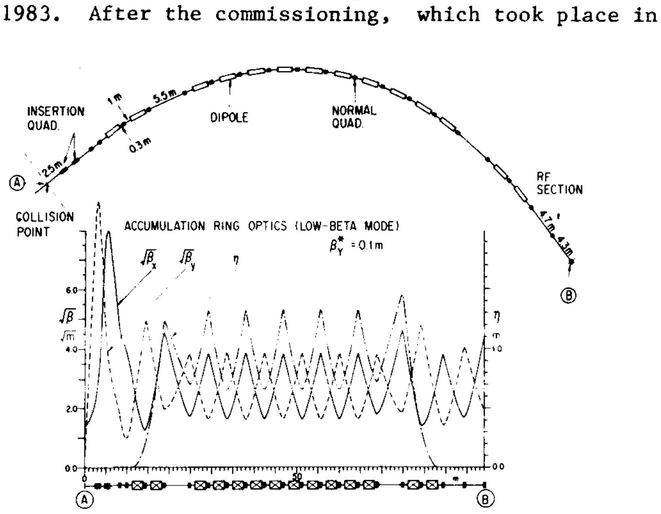

Fig. 3 A quadrant of the TRISTAN AR lattice.

Following the completion of the positron generator system, an experiment to accumulate positrons in AR was started in October 1985. As mentioned above, a 2.5 GeV positron beam with a pulse width of 2ns and a peak current of 5 mA has already been obtained at the downstream end of the injector linac. About 50 - 60 % of this beam reached the AR injection point. The rest were lost through matching the beam emittance and momentum spread with the acceptance of AR. The present accumulation-rate of positrons in AR is about 1.5 mA/min, when the injector linac system is operated at a repetition rate of 10 Hz. The accumulation efficiency was measured to be rather high, more than 75 %.

An experiment to collide an electron bunch with a positron bunch was also made in AR. The collision luminosity was measured with a luminosity counter developed for use in MR. For the magnet lattice tuned to a low-beta optics of $\beta_H = 2$ m and $\beta_V = 0.1$ m for the horizontal and vertical beta-functions at the collision point, the luminosity of $1 - 5 \times 10^{29}$ $cm^{-2} \cdot s^{-1}$ was achieved in the beam energies ranging from 2.5 GeV to 5 GeV. As electrostatic beam separators were not yet installed in AR, the accumulated beam current could not exceed a few mA per beam due to the beam-beam instability at the injection.

In March 1986, a new facility was constructed to

Table 3 Design parameters of the TRISTAN AR

General parameters:		
Circumference	377	m
Average machine radius	60.0	m
Average radius of curved section	47.6	m
Bending radius	23.173	m
Length of long straight section	2 × 19.45	m
Length of RF section	2 × 19.05	m
Length of dispersion suppressing straight section	8 × 5.5	m
Number of cells in arc	28	
Length of a normal cell	8.8	m
Betatron oscillation tune in curved section (hori/ver)	7/7	
Momentum compaction factor	0.013	
Revolution frequency	0.795	MHz
RF frequency	508.58	MHz
Harmonic number	640	
Length of cavity section	8 × 3.7	m
Injection energy	2.5	GeV
Extraction energy	6	GeV
Beam parameters at 6 GeV:		
Bending field	0.86	T
Energy loss per turn	4.9	MeV
Transverse radiation damping time	3.2	ms
Natural energy spread	1.1×10^{-3}	
Natural horizontl emittance	2.7×10^{-7}	m·r
Over voltage ratio for 24 hrs life	2.09	
RF peak voltage for 24 hrs life	10.3	MV
RF bucket height for 24 hrs life	7.0×10^{-3}	
Synchrotron oscillation frequency	35	kHz
Natural bunch length	1.8	cm
R.M.S. Beam size in normal cell hori(zero coupling)/ver(full coupling)	2.4 mm/1.4 mm	
Length of magnet free area at collision point	5	m
Beta functions at collision point(hor/ver)	2.0 m/0.1 m	
R.M.S. beam size at collision point for optimum coupling (hori/ver)	0.71 mm/0.036 mm	
Number of bunches per beam	1	
Luminosity	1×10^{31}	$cm^{-2} \cdot s^{-1}$

make the synchrotron radiation research with AR. For the moment, it has one photon beam channel which can accommodate two experimental set-ups, one for studies on X-ray diffraction under super-high pressure and the other for medical applications. The test experiments performed at 6 - 6.5 GeV have given very promissing results.

The design of the TRISTAN MR required development of many new accelerator components. Therefore, we have used maximaly the AR construction and operation to test such new apparatuses and to accumulate experiences for the beam collider. Here we briefly describe the results of R/D on the RF, vacuum, and control systems.

Main subjects of the present development work for the 500 MHz RF system were to build a multi-coupled cell cavity with a shunt impedance as high as possible and a structure as simple as possible to be suitable for mass-production, and a klystron with an out-put RF power larger than 1 MW.[7] As candidates of the cavity, we studied two types of the structures, one is a disk and washer structure, DAW,[8] and the other is an alternating periodic structure, APS.[9] DAW was first developed. With the aid of the computer program SUPERFISH, its impedance was optimized to about 44 MΩ/m at 508 MHz for a structure with a beam hall, disk, and washer diameters of 100, 805, and 450 mm, respectively. Two twelve-cell DAW cavities were constructed and tested in AR. To minimize the degradation of the shunt-impedance due to the washer supports, a single stem structure was adopted. Nevertheless, the impedance of the cavity was degraded to 27 MΩ/m. Those cavities could be used to accelerate beams in AR. But we did not adopt this structure because of the experimental result that a lot of higher as well as lower harmonic modes with high impedances were excited by the beam. Those modes are considerably larger in number compared to that of a conventional structure due to the bigger inner diameter of DAW, and will cause serious longitudinal and transverse beam instabilities. After-all, an APS cavity which has the mechanical dimensions and RF parameters as given in Table 4 was developed and adopted as the TRISTAN RF cavity. A unit of the TRISTAN APS cavity has nine-accelerating-cells which are RF-coupled each other with short coupling cells. The APS cavity has a finite group velocity of TM_{01} mode at the accelerating frequency and has wide mode-separations compared with ordinary slot-coupled cavities. Further, the present structure has a perfect axial symmetry and behaves in accordance with the computer calculations as noted in Table 4. Undesirable excitation of the coupling-cell due to the thermal detuning of the cavity is removed by equipping every accelerating-cell with a tuner and keeping the coupling-cell frequency slightly higher than that of the accelerating-cell. The cavity tuners are preset one by one to make the coupling-cell excitation minimum in the cold condition and driven together with a common adjusting mechanism in the high power operation. The cavity body is made of a low carbon steel, and a copper layer of about 0.2 mm in thickness is electroplated on the inner surface in a pyrophosphorous acid bath.

Table 4 Parameters of the TRISTAN APS cavity

Length of accelerating cell	209.74 mm
coupling cell	30.00 mm
Radius of accelerating cell	232.28 mm
coupling cell	235.20 mm
Beam hall radius	50 mm
Freq. of accelerating cell	508.58 MHz
coupling cell	508.58 MHz
Operating mode	π-mode
Band width $(f_{2\pi}-f_{0})/f_{\pi}$	1.04 %
Q of accelerating cell (SUPERFISH/achieved)	42,450/36,800
coupling cell (SUPERFISH/achieved)	9,083/7,940
Shunt impedance (SUPERFISH/achieved)	27.0 MΩ/m/23.4 MΩ/m
Max. accelerating field achieved	1.5 MV/m

The development of the 500 MHz klystron has been underway in cooperation with industries. We require the following specifications for the klystron, i.e., the tube is a vertical mount type with a collector of evaporation cooling structure, and is operated at the maximum output RF power of 1 - 1.2 MW with an efficiency larger than 60 %. Two companies have succeeded in fabricating the tubes and already supplied about twenty pieces of them to KEK. A prototype of the RF system, which includes the APS cavities and klystrons, has been installed in AR and routinely used for the beam acceleration showing very satisfactory performances.

Many technical innovations have been introduced in the TRISTAN vacuum system.[10] First of all, aluminum alloy materials were applied to all the vacuum components, e.g., vacuum pipes, corrugated bellows, gate valves, ion pumps, and electrostatic beam separators. This, so called all-aluminum system, also means that no material transition exists between the components. The main vacuum pump is a distributed sputter ion pump of a built-in type, which has an anode consisting of five layers of a polished and perforated aluminum plates and a cathode made of Aℓ-Ti-Zr alloy rods with a diameter of 3 mm. At special places where both distributed and ordinary ion pumps can not be used, a cartridge non-evaporable getter pump is used mounted on aluminum conflat flanges. For instance, a NEG-ST-707 type pump module is installed in the vacuum pipe inserted in the long insertion quadrupole magnet. For the vacuum system installed in AR, the best pressure of about 10^{-8} Pa was achieved without any baking or discharge cleaning. This is mainly due to adoption of a special extrusion technique in manufacturing the pipes and chambers. The new extrusion process is performed in an atmosphere of oxgen and argon, and proves to be very effective in preventing a growth of a porous aluminum oxide film with trapped contaminations that causes gas desorption later. The pressure rise due to the beam was measured in AR to be about 6×10^{-9} Pa/mA for a beam current-time integral of 1.8×10^{8} mAh.

Considering the complexity and size of the TRISTAN accelerators, we adopted a distributed computer control system which works with a software system, so called KEK-NODAL.[11] There exists only one common control system for both AR and MR, and only one control center covers both accelerators. Twenty-five 16 bit minicomputers, HIDIC 80E's and 80M's, are distributed around the accelerator facilities, and linked together by optical fiber cables to form a node to node token-passing ring network. The transmission speed on the optical fiber cable is 10 Mbps and the overall transmission capacity is about 600 kbytes/s. To manage large tasks, this network is also connected directly to the KEK central computer system. A CAMAC system is used as standard interface for the present control system. Devices to be controlled are connected to the minicomputers through a CAMAC highway of a 2.5 Mps bit-serial type. Operations of the accelerators are done through five operator consoles, each of which is managed by one minicomputer in the network. An operator console contains two 20-inch high resolution color graphic displays, a pair of touch-panels, and ten small TV monitors. One touch-panel is used to select a program and a piece of equipment to be controlled, and the other is used mainly to perform the control actions. The present control system has been working satisfactorily since the very beginning of the AR operation.

In the past two years, about 30 - 40 % of the AR operation time were allocated to accelerator studies and developments. For instance, to study a mode-coupling type beam instability, the accurate bunch length measurement with a streak camera was made extensively by changing various machine parameters. The results showed that the mode-coupling theory can interprete the present bunch lengthenning phenomena with the impedance parameters calculated for the RF cavities and bellows in AR. The present results were applied to the analysis of the beam instabilities in MR and fed-back to the design of the MR lattice, RF cavities, and vacuum pipes and chambers. In the course of the accelerator developments in AR, we also devised several techniques and instruments to control beams. Those are betatron and synchrotron tune monitors, tune-feed-back systems to keep the tunes constant, and transverse and longitudinal beam dampers to stabilize coherent betatron and synchrotron oscillations.[12]

2.3 Main Colliding Beam Ring, MR

The TRISTAN MR was designed to achieve a beam energy as high as possible beyond 25 GeV for the given KEK site of 1 km × 2 km. Due to very high rate of synchrotron radiation loss, this necessarily leads to such a ring structure that a considerable part of the ring circumference is allocated to straight sections for RF cavities. The present MR lattice has a four-fold super-periodicity and is devided into four equivalent parts bounded by two of the beam collision points. The quadrant is further sub-divided into two mirror-symmetrical octants. Each octant, starting from the center of the quadrant arc, is composed of a wiggler section, normal cells, dispersion suppressor cells, RF cells and an experimental insertion. Such a configuration was adopted to fulfill a requirement that the dispersion function and its delivative should be zero both in the RF cells and experimental insertion. Figure 4 illustrates the calculated beta- and dispersion-functions in the octant. Also indicated is the arrangement of the main dipole and quadrupole magnets. The wiggler straight section is 9 m long and accommodates a set of dipole wigglers to enhance the radiation damping during the injection process. The dispersion function here is made large to be suitable for the wiggler function. The normal cell has a periodic FODO structure and is designed to make the betatron phase advance per cell 60 degrees in both horizontal and vertical planes. A dipole magnet located at the end of the dispersion suppressor section is a so-called weak-bend to avoid a direct hit of the experimental detector by strong synchrotron radiation generated in the up-stream normal-bends. Its strength is about 4 % of the normal one. The RF cell is designed to be shorter by about 15 % than the normal cell, so that the vertical beta-function can be made smaller by about 30 % than that in the normal cell. This is intended to ease instability problems arizing from beam-cavity interactions. A threshold beam current of such instabilities is predicted to be inversely proportional to the beta-function at the RF cavity. The design of the experimental insertion is mainly governed by a requirement for beta-functions at the collision point, which should be as low as possible for the highest luminosity, and by restrictions imposed by the chromaticity correction, which is largely affected by such a low-beta insertion. In the present design, two schemes are prepared, so-called low-beta and mini-beta optics. The low-beta optics includes two pairs of normal iron-core quadrupole magnets, QC1 and QC2, and gives the beta-functions at the collision point of β_H = 1.6 m and β_V = 0.1 m for QC1 located 4.5 m from the collision point. While the mini-beta optics includes a pair of superconducting quadrupole magnets, QCS, and QC1's, and gives β_H = 0.8 m and β_V = 0.05 m. Therefore, the latter can double the luminosity compared with the former. The operation of MR is to start with the low-beta optics first. The beta- and dispersion-functions in the low-beta insertion are shown in Fig. 5. Also indicated is the location of auxiliary components such as skew quadrupole magnets, SKQ, and beam separators, DCS. Figure 6 shows a cross-section of the VENUS colliding beam detector along with the insertion quadrupole magnets QCS, QC1 and QC2. Correction schemes of the chromaticity for the designed lattice were studied by using beam tracking computer programs. Basically a sextupole magnet system of six families has been found to give a statisfactory solution. The MR design parameters for the geometry, lattice, beam, and RF are summarized in Table 5.

The construction of MR, which began in 1982 as a four-year program, is near completion. Most of the accelerator components for MR were fabricated following the models or prototypes developed and tested in AR.

All the magnets have been installed in the accelerator tunnel and cabled to the corresponding power supplies, Fig. 7. After the successful full-excitation tests, a fine alignment work of the magnets

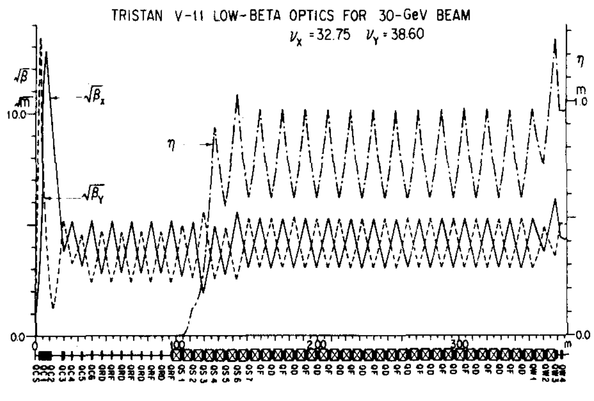

Fig. 4 An octant of the TRISTAN MR lattice.

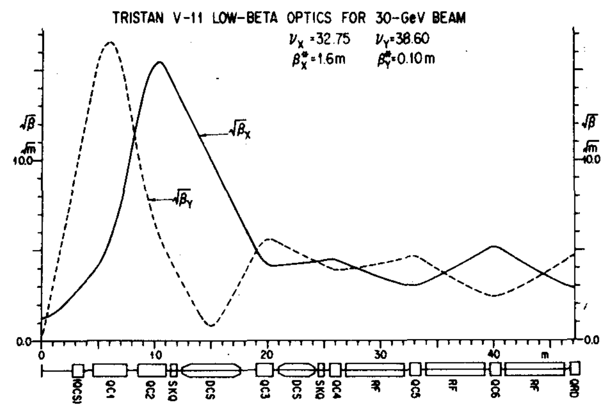

Fig. 5 TRISTAN MR lattice near the collision point.

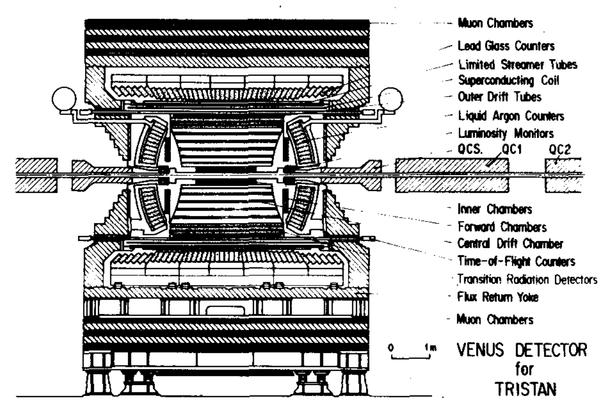

Fig. 6 VENUS colliding beam detector and the insertion quadrupole magnets. QCS is a superconducting type and QC1 and QC2 are normal iron-core types.

Table 5 Design parameters of TRISTAN MR

Gesmetrical parameters:	
Circumference	3018.08 m
Average radius of ring	480.34 m
Average radius of arc	346.69 m
Length of long straight section	4 × 194.35 m
Length of wiggler straight section	4 × 15.59 m
Number of colliding points	4
Length of magnet free area	
at collision point with QCS	5.4 m
without QCS	9.0 m
Lattice parameters:	
Number of normal cells	116
Length of normal cell	16.12 m
Phase advance in a normal cell	60 deg
Beta-function in normal cell (max/min)	27.7 m/9.38 m
Dispersion function in normal cell (max/min)	0.961 m/0.585 m
Number of dispersion suppressor cells	20
Length of dispersion suppressor cell	15.42 m
Number of RF cells	40
Length of RF cell	14.15 m
Phase advance in a unit RF cell (hori/ver)	57 deg/78 deg
Beta-function in RF cell (hori/ver)	
maximum	26.8 m/21.6 m
minimum	8.2 m/5.8 m
Beta-function at collision point (hori/ver)	
in mini-beta optics	0.8 m/0.05 m
in low-beta optics	1.6 m/0.1 m
Maximum beta-function (hori/ver)	
in mini-beta optics	164 m(QC1)/180 m(QCS)
in low-beta optics	240 m(QC2)/274 m(QC1)
Beam parameters at 30 GeV:	
Number of bunches per beam	2
Radiated energy per revolution	290 MeV
Transverse radiation damping time	2.08 msec
R.M.S. natural energy spread	1.64×10^{-3}
Natural horizontal emittance	1.794×10^{-7} rad·m
Maximum r.m.s. beam size in normal cell	
horizontal (zero-coupling)	2.72 mm
vertical (full-coupling)	1.57 mm
Maximum r.m.s. beam size in RF cell	
horizontal (zero-coupling)	2.19 mm
vertical (full-coupling)	1.39 mm
R.M.S. beam size at collision point optimum coupling (hori/ver)	
in mini-beta optics	0.367 mm/0.023 mm
in low-beta optics	0.520 mm/0.032 mm
Luminosity ($I^- = I^+ = 10$ mA)	
in mini-beta optics	2×10^{31} $cm^{-2} \cdot s^{-1}$
in low-beta optics	1×10^{31} $cm^{-3} \cdot s^{-1}$
RF parameters at 30 GeV:	
Revolution frequency	99.33 KHz
RF frequency	508.58 MHz
Harmonic number	5120
Unit cell length of RF cavity	0.2947 m
Number of RF cavity cells	
for conventional RF cavity	936
for super-conducting RF cavity	160
Over voltage ratio for 24 hrs life	1.314
Peak RF voltage for 24 hrs life	383 MV
RF bucket height for 24 hrs life	1.09×10^{-2}
Synchronous phase angle	130.5 deg
Synchrotron oscillation frequency	9.98 MHz
Natural bunch elgnth	1.17 cm

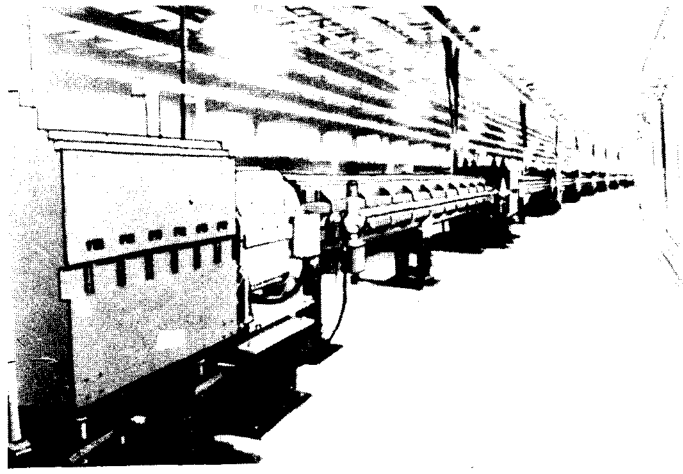

Fig. 7 Recent photograph of the TRISTAN MR tunnel.

in the tunnel is underway. Vacuum pipes and chambers equipped with beam monitors have been installed in the magnets and interconnected along the whole ring. The beam lines to transfer electrons and positrons from AR to MR were completed. The test experiment demonstrated a successful extraction of electron and positron beams from AR without loss. MR is controlled with the existing computer control system with which AR is being operated.

Ten magnet free sections are allocated for installation of RF cavities in each octant of the MR lattice, see Fig. 5 and 6. As the electron and positron injection systems occupy eight such sections, four for each beam, on both sides of the Fuji experimental area, 72 sections in total are available for RF cavities. Two quadrupole magnets at the both ends of the cavity section is separated by 7.07 m, twelve times the wave length of the 508 MHz RF, to prepare a net cavity space of about 5.5 m. This space can accommodate two nine-cell APS cavities or two five-cell superconducting cavities, which are described in the previous and next sections, respectively.

The construction of the present RF system is planned to be splitted into three phases as follows. First, at the initial stage of operation following the commissioning, 64 nine-cell APS cavities are installed in the RF section at the Fuji and Tsukuba experimental area. This system will generate a total accelerating voltage of about 200 MV and accelerate an MR beam to about 25 GeV. In March 1987, additional 40 APS cavities are to be installed in the RF section at the Oho experimental area towards the start of the regular MR operation for colliding beam experiments scheduled in May 1987. At this stage, the whole APS cavity system has 104 nine-cell structures, about 280 m, and is expected to extend the MR beam energy to about 29 GeV with a total accelerating voltage of 330 MV. In the remaining 40 cavity sections at the Nikko experimental area, we plan to install superconducting cavities aiming at the MR beam energy as high as possible. This program is described in the next section.

To use the MR cavity space effectively, an MR APS unit is composed of two independent nine-cell structures linked together with a separation of 130 mm for RF decoupling. A schematic drawing of the MR unit is shown in Fig. 8. An RF power of 1 MW is generated by a klystron which has been newly developed for TRISTAN, and fed to four nine-cell structures, i.e. two MR units, through a circulator. A very high impedance of the present RF cavity system requires us to take measures against beam instabilities caused by beam-cavity interactions. As one of the measures, we have made 52 MR APS units to have a slightly different higher order mode frequency by varying the inner-diameter of the accelerating-cell unit by unit. This reduces the total higher order mode impedances by a factor of five and should be effective to avoid a coherent excitation of the modes with high Q-values. The present nine-cell cavity is also equipped with a damping antenna at the middle of the cavity to couple out the higher order modes excited by beams. At present, about half of the APS units required for the initial stage operation have been installed in the MR tunnel after vacuum tested, heat treated for 10 days at about 140°C, and RF aged to an input power level of 300 kW.

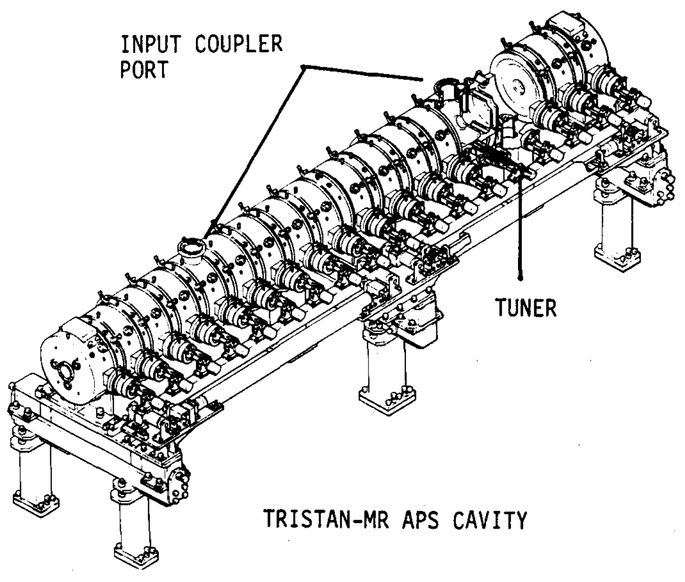

Fig. 8 Schematic drawing of the TRISTAN APS cavity.

2.4 TRISTAN Upgrade Program

2.4.1 Superconducting RF cavity. Based on the very successful R/D on the superconducting cavity at KEK, we decided to construct a superconducting RF system for MR. The system consists of 32 five-cell superconducting cavities to fill two out of eight long RF sections of MR and a high power helium refrigerator for them. Following the authorization of the proposal as a two-year program in April 1986, we have started the construction of the cavities and refrigerator in cooperation with industries. The system is scheduled to start working after the summer shutdown in 1988, and expected to upgrade the MR beam energy to about 33 GeV.

A five-cell 508 MHz superconducting cavity for MR was designed based on the technical and operational experiences accumulated through the single-cell and three-cell cavity constructions.[13] As illustrated schematically in Fig. 10, an MR cavity unit consists of

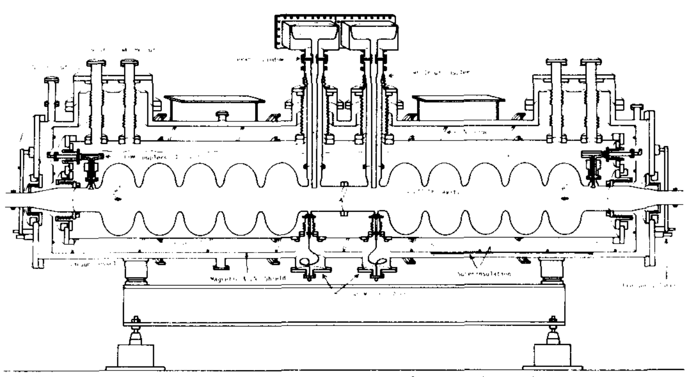

Fig. 9 Schematic drawing of the TRISTAN superconducting cavity.

two independent five-cell structures which are coupled together only mechanically and enclosed in a liquid helium cryostat with an inner diameter of 700 mm. An RF power is fed to the cavity through a coupling port on the beam pipe of 180 mmϕ at the cavity end where antenna type coupler is mounted. To couple out undesirable cavity modes excited by beams, also attached to the cavity are two higher order mode couplers on the beam pipe at the other side of the input one. They reduce loaded Q-values of the cavity to 10^4 - 10^5 for the most dangerous modes, a longitudinal TM_{011}'s, and transverse TE_{111}'s, TM_{110}'s, and TM_{111}'s. The frequency tuning is done by adjusting the cavity length with two mechanical and one piezo electric tuners. The tuning sensitivity is 90 kHz/mm. One of the mechanical type is for rough tuning, and the other for fine tuning. The piezo type works in series with fine mechanical tuner and compensates for fast frequency modulations, ∿ 100 Hz. Table 6 gives the design parameters of the present cavity.

A prototype of the MR five-cell cavity was constructed and tested with the AR beam in February 1986. The Q-value of the cavity was measured to be 3.5×10^9 at a low field and 1.8×10^9 at 4.1 MV/m. The maximum accelerating field of 4.5 MV/m was achieved at 4.2 K after RF aging. The beam acceleration experiments proved that the input and higher order mode couplers and the tuner system worked as designed. The input coupler was tested up to 80 kW under the total reflection condition.

Table 6 Design parameters of the five-cell TRISTAN superconducting cavity

Frequency	508.581	MHz
Effective length	1473.7	mm
Effective shunt impedance	18.9	MΩ/m (Cu)
R/Q	600	Ω
Geometrical factor	269	Ω
Band width $2(f_\pi - f_0)/(f_\pi + f_0)$	1.5	%
Field strength		
E_{acc}	$\sqrt{P_L \cdot Q}$	V/m
E_{sp}/E_{acc}	1.97	
H_{sp}/E_{acc}	40.6	Gauss/MV/m

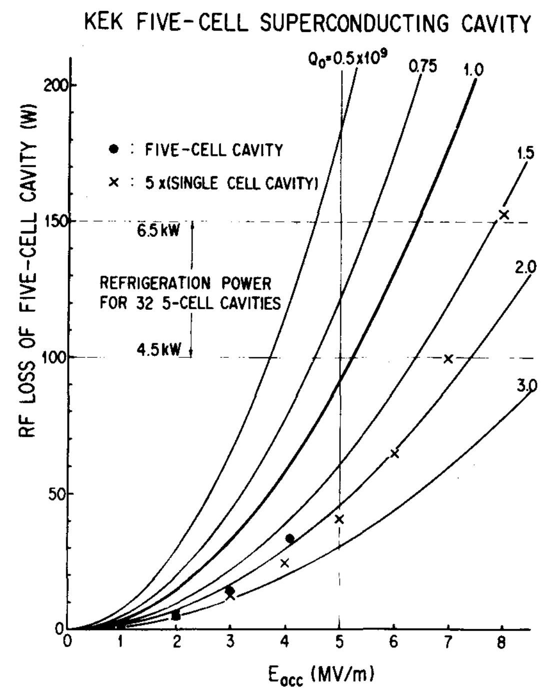

Fig. 10 RF loss of the TRISTAN five-cell superconducting cavity as a function of the Q-value and accelerating field.

Figure 10 shows an RF loss of the five-cell cavity as a function of the Q-value and the accelerating field. Also plotted are the experimental results for the cavities constructed so far. In designing the helium refrigeration system, we assumed the minimum Q-value of the cavity to be 1×10^{9} at the target accelerating field of 5 MV/m and obtained an estimated refrigerator cooling power of 4.5 kW including heat leaks at the transfer lines and chambers and a safety factor. A flow diagram of the refrigerator system is illustrated in Fig. 11. The system consists of a helium cold box, a 12 m^3 liquid helium dewar, three 100 m^3 medium pressure gas storages, and a compressor system. The present system is designed to be easily upgraded to 6.5 kW with an addition of expansion tur bines.

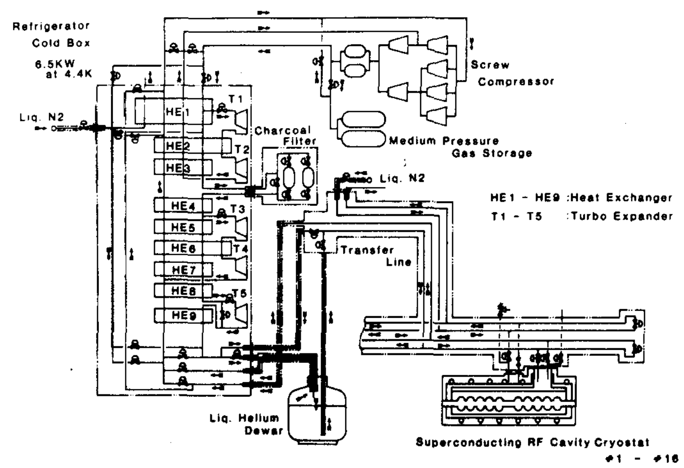

Fig. 11 Flow diagram of the helium refrigerator system for the superconducting RF cavity.

Table 7 Parameters of the TRISTAN sueperconducting insertion quadrupole magnet

Field gradient	70 T/m
Coil current	3400 A
Coil inner diameter	140 mm
outer diameter	217 mm
Physical length	1430 mm
Magnetic length	1100 mm
Stored energy	341 kJ
Bursting force	9.4×10^4 kg/m
Cross-section of NbTi SC cable	$9.09 \times (1.35 - 1.19)$ mm^2
No. of strands	27
Strand diameter	0.68 mm
Cu/SC ratio	1.1
No. of filaments	3000
Filament diameter	9 μm
Copper resistivity ratio	107
Ic at 7 T and 4.2 K	5290 A

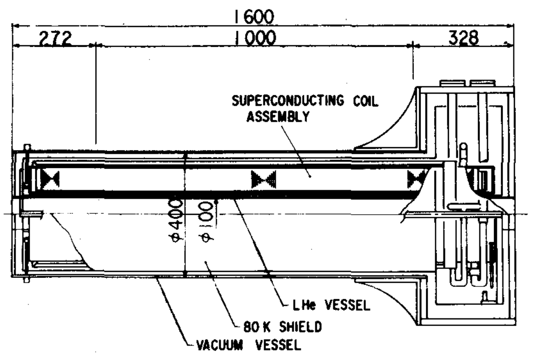

Fig. 12 Superconducting insertion quadrupole magnet and the cryostat.

2.4.2 Superconducting insertion quadrupole magnet. As explained in the previous section, the mini-beta insertion optics for an upgrade of the MR luminosity requires a set of superconducting quadrupole magnets located symmetrically with respect to the collision point. The design of the magnet is mainly governed by a space allocated, i.e., almost inside the colliding beam detector. The main design parameters of the magnet are given in Table 7 together with those for the conductor cable. An iron-free structure was chosen by considering its magnetic interference with the detector magnet.

Two prototypes were constructed and tested in a vertical cryostat.[14] The first quench occured at a field gradient of 64 T/m, corresponding to a peak field of 4.8 T. After five quenches, it exceeded the design figure and reached 80 T/m, corresponding to about 80 % of the short sample limit. One of the magnets is now assembled in a horizontal cryostat as illustrated in Fig. 12. An overall excitation test of the magnet, including a precise field measurement, is going to start soon to finalize the system design.

Acknowledgement

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References

1. T. Nishikawa et al., Survey in High Energy Physics 3, 161 (1983).
2. S. Fukumoto et al., presented to this conference.
3. T. Kawakubo et al., presented to this conference.
4. H. Sasaki, Proc. of ICANS-7, 15, Chalk River (1983).
5. T. Nakajima et al. ed., Photon Facotry Activity Report, KEK (1986).
6. S. Ozaki et al. ed., General Description of the TRISTAN Project, KEK (1986).
7. K. Akai et al., presented to this conference.
8. Y. Andreev et al., Proc. Linac Conf. AECL-5677 (1968).
9. T. Nishikawa et al., Rev. Sci. Instr. 37, 652 (1966).
10. H. Ishimaru et al., J. Vac. Sci. Technol. A4 1762 (1986).
11. S. Kurokawa et al., Nucl. Instr. and Meth. A247, 29 (1986).
12. T. Ieiri et al., presented to this conference.
13. T. Furuya et al., presented to this conference.
14. K. Tuchiya et al., Proc. of the Cryog. Eng. Conf. MIT(1985).

Discussion

Э.А.Мяэ. Раньше энергия инжекции в бустер протонного синхротрона была 20 МэВ. Какой выигрыш в интенсивности бустера и протонного синхротрона вы имеете, перейдя на 40 МэВ энергии инжекции?

Y.Kimura. In the booster we could double the intensity. Before the upgrade the booster intensity was $6 \cdot 10^{11}$ per pulse; now it's $1.5 \cdot 10^{12}$ per pulse. In the case of the main ring it increased not so much, maybe 40% or so.

А.В.Самойлов. Вы говорили о хорошем согласии расчетных и экспериментальных характеристик ваших резонаторов. По каким программам вы рассчитывали свои резонаторы?

Y.Kimura. "Superfish".

Yu.K.Pilipenko. What about polarized beam?

Y.Kimura. Yes. We had a good polarized beam at the booster stage. But in the main ring for the moment the polarization obtained is about 30%. So now we are developing further.