HIGHLIGHTS FROM JAPAN
— TRISTAN AND POST-TRISTAN ACCELERATORS —

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Abstract

TRISTAN is a high energy electron-positron colliding beam accelerator in Japan. The first year of the TRISTAN operation for physics experiments is reviewed with an emphasis on the accelerator performances. Also presented are high energy accelerator projects following TRISTAN, which are under discussion in the physics community of Japan.

Introduction

The TRISTAN electron-positron colliding beam accelerator was successfully commissioned in November 1986 after the five-year construction period.[1] The full scale experimental run was started in May 1987 with the main colliding beam ring equipped with four experimental detectors nicknamed VENUS, TOPAZ, AMY, and SHIP. The maximum beam energy and peak luminosity achieved were 28 GeV and 1.4 x 10^{31} $cm^{-2}\cdot sec^{-1}$, respectively. In the first year TRISTAN was operated for about 3900 hours in total and 2300 hours for colliding beam experiments. The integrated luminosity collected by each experimental group amounted to 12 ~ 16 pb^{-1}.

Following the completion of TRISTAN, post-TRISTAN accelerator projects have been under discussion in the physics community of Japan. In the field of high energy physics, the High Energy Committee, an organization of high energy physicists, has proposed, as a first priority item, to initiate a coherent R&D work aiming at construction of a TeV class electron-positron linear collider as a possible home based facility. While, in the field of nuclear physics, a new research facility, so called the Japanese Hadron Facility, has been proposed to expand the experimental opportunities for intermediate energy nuclear physics and interdisciplinary science.

TRISTAN

Accelerator System

The TRISTAN accelerator complex consists of four separate accelerator systems as illustrated in Fig. 1. A 400 m long main linac accelerates electrons and positrons to 2.5 GeV. Positrons are produced by bombardment of a tantalum target with high-current electron beam of 200 MeV from a linac constructed at the upstream end of the main linac and, then, accelerated to 250 MeV by another linac located downstream of the conversion target prior to the transfer to the main linac.

Electrons and positrons accelerated in the main linac are injected and accumulated in the TRISTAN Accumulation Ring (AR). The AR is a storage accelerator ring of 377 m in circumference and accelerates the accumulated beam to 7.5 GeV for the transfer to the main colliding beam ring.

The TRISTAN main colliding beam ring (MR) has a circumference of 3018 m and such a shape that four quadrant arcs of 347 m in the mean curvature radius are connected together by four 194 m long straight sections. Two electron and two positron bunches circulating in opposite directions collide with each other at the midpoints of the straight sections,where the colliding beam detectors are located. RF cavities to accelerate beams are aligned on the both sides of the detector regions in the straight sections.

The latest parameters of the TRISTAN accelerators are listed in Table 1. The present beam energy for the colliding beam experiments is 28 GeV compared with the target of 30 GeV. As described below, this is to be reached shortly by installation of a superconducting RF cavity system which is scheduled in this summer. As for luminosity,the peak value has already exceeded the target of 1 x 10^{31} $cm^{-2}\cdot sec^{-1}$ and reached 1.4 x 10^{31} $cm^{-2}\cdot sec^{-1}$.

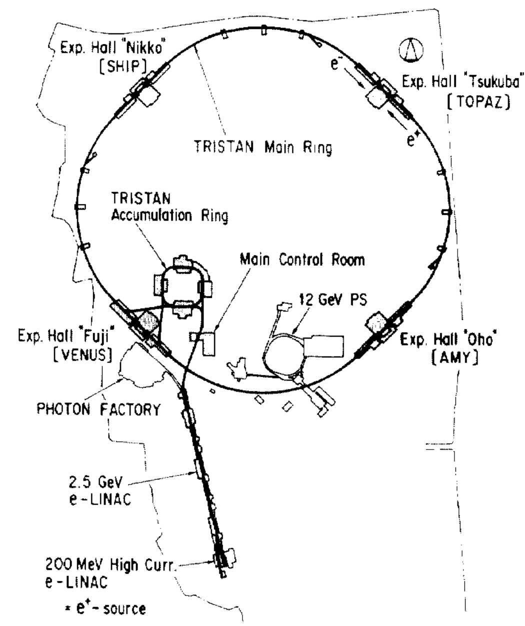

Fig. 1 Site layout of the TRISTAN accelerator complex.

Table 1 Performance parameters of the TRISTAN accelerators

Main linac		
Energy	2.5	GeV
Repetition rate	25	pps
Peak current, e^-/e^+	100/15	mA
Positron generator		
Bomberding e^- energy	200	MeV
Bomberding e^- peak current	10	A
Post-accelerated e^+ energy	250	MeV
Post-accelerated e^+ peak current	20	mA
TRISTAN-AR		
Maximum energy	7.5	GeV
Injection energy	2.5	GeV
RF frequency	508.6	MHz
RF voltage at 7.5 GeV	20	MV
Maximum single bunch current	50	mA
TRISTAN-MR		
Maximum energy	28	GeV
Injection energy	7.5	GeV
RF frequency	508.6	MHz
Number of cavity cells	936	
Total cavity impedance	5900	MΩ
Maximum accelerating voltage	320	MV
Maximum single bunch current	4.8	mA
$2e^+ + 2e^-$ beam current	14	mA
Filling time	20 ~ 30	min.
Beam life time	2.5 ~ 3.5	hr.
Beam emittance	1.0 x 10^{-7}	m·rad
Emittance ratio, $\varepsilon_V/\varepsilon_H$	1 ~ 2	%
Beta-functions at collision point, β_V/β_H	0.1/1.8	m
Peak luminosity at 28 GeV	1.4 x 10^{31}	$cm^{-2}\cdot sec^{-1}$

First Year of the TRISTAN Operation

The TRISTAN accelerator operation after the beam commissioning is summarized in Fig. 2. About 60 % of the total operation time were allocated to the colliding beam experiments and about 30 % for the accelerator beam development works.

A typical operation pattern of the MR is shown in Fig. 3. The total beam current and the beam life time were recorded through 24 hours on February 28, 1988. The terraced increase of the current indicates the beam injection. The MR was filled with two positron bunches first, then with two electron bunches. To accumulate beams of about 13 mA in total current, the AR transfers beams of 15 ~ 20 mA in the AR current to the MR 8 ~ 12 times. A whole injection process takes about 20 ~ 30 minutes. The positron and electron beams injected were accelerated to the top energy in about two minutes and brought to collision after the beam optics was changed from an injection one to a low-beta one. In the latter the beta functions at the collision points were squeezed to 1.8 m horizontally and 0.1 m vertically. This optics transfer was performed by changing the strengths of the insertion quadrupoles in many small steps so that the betatron tunes did not cross the stop-bands on the tune diagram. As seen in Fig. 3, the present acceleration and optics transfer processes are not accompanied by any loss of the circulating beam. The electron and positron beams under collision for the physics experiments in the MR had a life time of 2.5 ~ 3.5 hours. The MR, then, was re-filled with beams every 1.5 ~ 2 hours. The present beam life is governed by the vacuum pressure in the beam duct, which is about $0.5 \sim 1 \times 10^{-8}$ Torr.

A remarkable luminosity improvement was achieved through extensive accelerator beam development works, which were aimed at increasing the injection beam current, reducing the beam emittance, and making the vertical to horizontal emittance ratio as small as possible.[2] The injected beam was primarily stabilized by use of eight wiggler units. Each unit consists of three horizontally deflecting dipole magnets installed in the wiggler straight sections at the symmetry points of the MR quadrant arcs. The wiggler system has a strength that can halve the radiation damping time and increase the energy spread by three times and the emittance by ten times at the injection energy.

The injected beam was observed to become unstable due to synchro-betatron resonance. Therefore the beam current limit could considerably be improved by finding a set of three parameters, horizontal and vertical betatron frequencies and synchrotron frequency, to avoid the resonances. Such a parameter optimization encountered a difficulty that the parameters which gave the highest current limit were slightly different for electron and positron beams corresponding to their slightly different closed orbits. Fortunately the difficulty was experimentally resolved by skillfully deforming the closed orbits using the vertical orbit bump generators.

As is well-known,the beam emittance of the electron storage ring can be controlled by shifting the RF accelerating frequncy through modification of the damping partitions. At energies for the colliding beam experiments, the MR was operated at an RF frequency shifted from the nominal one by 1.5 ~ 2.5 kHz. This made the emittance about half of the nominal one.

Measurements of the tune shift due to beam-beam interactions show that the present electron and positron beam currents in the MR are still below the limit imposed by the beam-beam effect. Then, reduction of the vertical to horizontal emittance ratio directly leads to increase of the luminosity. This was also done by skillfully deforming the closed orbits using the vertical orbit bump generators. The emittance ratio of 6 ~ 10 % naturally arising in the present MR could be reduced to 1 ~ 2 %. Figure 4 shows a beam current dependence of the horizontal and vertical betatron tunes, beam-beam tune shift parameters, and vertical to horizontal emittance ratio. It seems to be noteworthy that the vertical beam-beam parameter measured still shows a linear current dependence beyond 0.03 which is generally believed to be a universal limit.

Energy Upgrade by Superconducting RF Cavities

The present TRISTAN beam energy of 28 GeV is almost the highest which will be attainable with the installed RF accelerating system. It consists of 104 nine-cell cavities of Alternating Periodic Structure (APS) type driven by 26 klystrons of 1 MW cw-power at 508 MHz. Therefore, to upgrade the TRISTAN energy further within an available wall-plug power of about 100 MW, KEK started a two-year program of constructing a superconducting cavity system in 1986. This is entirely based on the very successful R&D work on

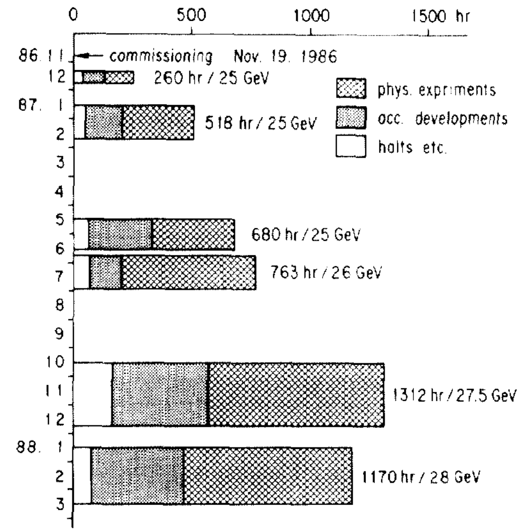

Fig. 2 Summary of the TRISTAN accelerator operation after the beam commissioning in November 1986.

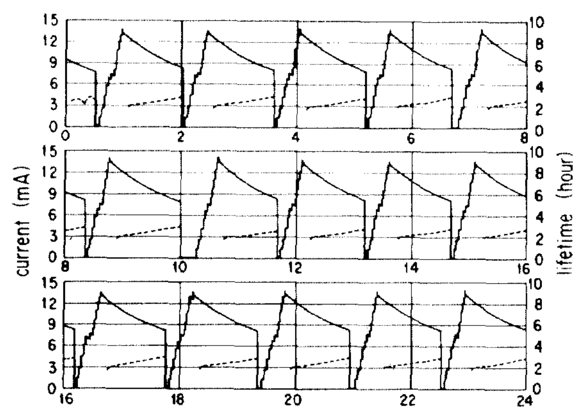

Fig. 3 Total beam current (solid line) and beam life time (dotted line) in the TRISTAN-MR recorded through 24 hours on February 28, 1988.

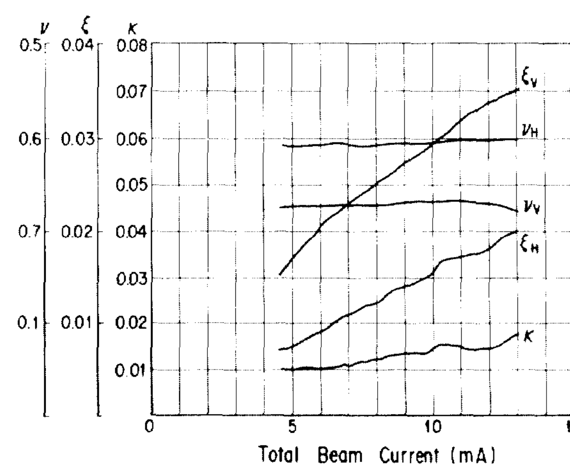

Fig. 4 Horizontal and vertical betatron tunes, ν_H, ν_V, beam-beam parameters, ξ_H, ξ_V, and vertical to horizontal emittance ratio, κ, as a function of the total beam current in beam collision at 28 GeV.

the superconducting cavity at KEK extending over 15 years.[3] The system consists of 32 units of five-cell niobium cavities and a low temperaure system to cool the cavities down to 4.2 K. The cavities are to be installed in the Nikko RF section of the MR, 16 cavities in the summer of 1988 and the remainings in the summer of 1989. The present accelerating voltage of 320 MV, which is generated by 104 units of the nine-cell APS cavities, then, will be increased to about 440 MV and further to 560 MV after the summer of 1988 and 1989, respectively. Corresponding upgrade of the MR energy will be from 28 GeV for 320 MV to 30 ~ 31 GeV for 440 MV and to 32 ~ 33 GeV for 560 MV.

Extensive beam acceleration experiments have been carried out for the superconducting cavities by utilizing the TRISTAN-AR since 1983. Four prototype cavities, one three-cell and three five-cell types, have been constructed and tested so far. As for the acceleration of stationary beams, all exhibited satisfactory behavior or the accelerating gradient greater than 4 ~ 5 MV/m. In the low-level RF control system, however, a problem was encountered in association with transient behavior of the cavity. It is a phenomenon that the auto-RF level control system becomes unstable when the cavity is loaded with beams heavily and transiently. This has eventually been resolved in the recent experiment. The RF level control system was found to be stabilized by detuning the cavity slightly, about 20 ~ 30 degrees, and also implementing a beam loading compensation control loop with a fast response.

Sixteen five-cell cavities which are to be installed in the MR this summer have been completed and tested for the RF properties in a vertical cryostat. The techniques of the cavity fabrication have been well-established. The whole process is summarized as hydroforming of half-cells from 2.4 mm thick Nb sheets, electron-beam-welding (EBW) to form cavity cells, electropolishing (EP) for about 80 μm, annealing in a Ti-wall box, frequency tuning by the permanent deformation, EP of about 5 μm, and rinsing with pure H_2O and H_2O_2. Parameters of the present cavity are listed in Table 2. Figure 5 shows typical Q-values as a function of the accelerating field for the two five-cell cavities fabricated. Figure 6 summalizes the measured max-imum accelerating fields, Eacc, and Q-values at Eacc = 5 MV/m of the all sixteen five-cell cavities. Two five-cell cavities are joined together only mechanically and assembled into a horizontal cryostat as shown in Fig. 7.

A low temperature system of the present superconducting RF cavities has been completed. Its main constituents are a 6.5 kW helium cold box, a 10,000 Nm^3 liquid helium storge, six screw-type compressors of 10,000 Nm^3/hr at 17 $kg/cm^2 \cdot G$, and liquid helium and nitrogen transfer lines. The cold box in the installation work is shown in Fig. 8.

Table 2 Parameters of the TRISTAN 5-cell superconducting cavity

Frequency	508.58	MHz
Effective length	1.473	m
Accelerating field, Eacc	5	MV/m
Q-value at Eacc = 5 MV/m	2×10^9	
R/Q	600	Ω
Geometrical factor	269	Ω
Cell to cell coupling coefficient	1.5	%
Surface peak electric field /Eacc	1.97	
Surface peak magnetic field /Eacc	40.6	Gauss/MV/m
Number of beam pipe HOM-couplers	2	
Q-value of beam pipe input coupler	1×10^6	
RRR	100 ~ 120	

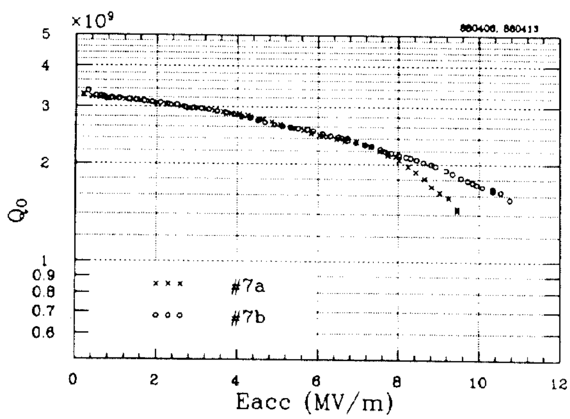

Fig. 5 Q-values of the two five-cell superconducting cavities as a function of the accelerating fields, Eacc.

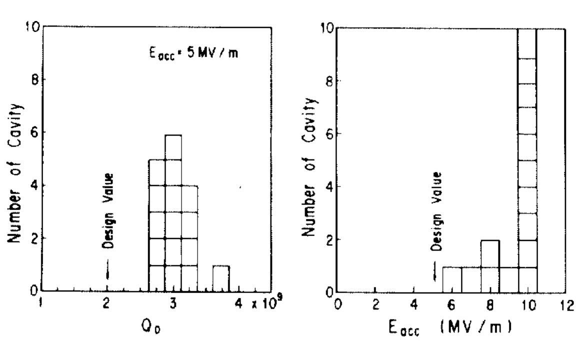

Fig. 6 Maximum accelerating fields, Eacc, and Q-values at Eacc = 5 MV/m of the 16 five-cell superconducting cavities tested in a vertical cryostat.

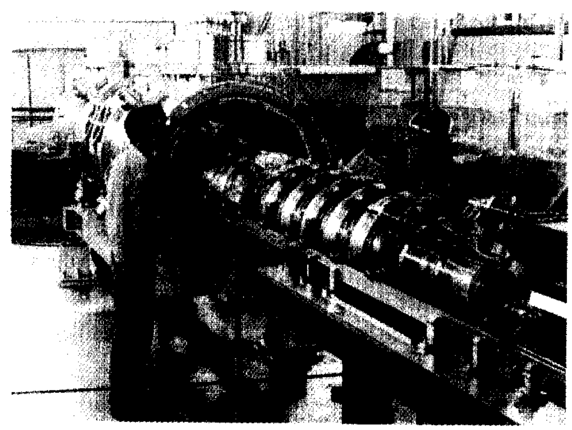

Fig. 7 Assembling of the two five-cell superconducting cavities into a unit and the installation in a horizontal cryostat.

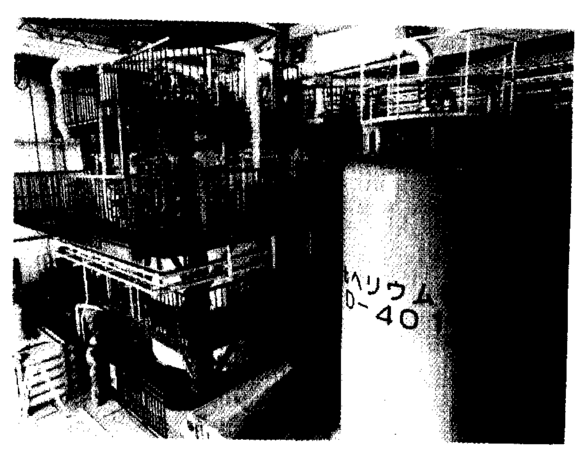

Fig. 8 Cold box (6.5 kW) for the TRISTAN superconducting RF cavity system.

Post-TRISTAN Accelerator Projects

Linear Collider R&D

In 1986 the community of high energy physics in Japan decided a direction of the post-TRISTAN that a possible construction of a TeV class electron-positron linear collider should be pursued for new energy frontier physics. Responding to it, KEK, in collaboration with the university's high energy physics laboratories, organized a study group and initiated a coherent R&D work on lienar colliders in 1987.[4] The tasks imposed on this group are to make and execute an R&D program to determine the feasibility of a TeV class linear collider in approximately five years.

As is well-known, many technical difficulties should be over-come before the TeV class lienar collider project becomes realizable. Listed in Table 3 are the general parameters of a 0.5 TeV + 0.5 TeV linear collider tentatively designed at KEK. Investigations of the parameters generally specify areas which the R&D should encompass as follows.

1. Theoretical works on system design including injection damping rings, linacs, and final focuses, and beam dynamics such as beam-beam disruption, beam-strahlung, and instabilities of an intense bunch accelerated in the linac.
2. Development of high gradient accelerating structures which can attain the accelerating field higher than 100 MV/m in practical operations.
3. Development of highpower sources of the output larger than that presently realized by an order of magnitude.
4. Development of final focussing device.

Table 3 Parameters of the linear collider tentatively designed at KEK

Energy	0.5 TeV + 0.5 TeV	
Luminosity	1×10^{33} $cm^{-2} \cdot sec^{-1}$	
Linac length	5 km + 5 km	
RF frequency	11.4 GHz	
Accelerating gradient	100 MV/m	
Beam power	2.5 MW	
Disruption parameter	2	
Aspect ratio	1	100
Number of particles per bunch	1.9×10^{10}	4×10^{9}
Bunch frequency	1.6×10^{3}	7.8×10^{3}
Bunch height at collision point	0.17 μm	0.003 μm
Bunch length	1 mm	0.08 mm

Table 4 Design parameters of the KEK-TAF linacs

	S-band linac		X-band linac
	Phase I	Phase II	
E_b (GeV)	0.3	1.5	1
E_a (MeV/m)	50	50	100
f_{RF} (GHz)	2.856	2.856	11.42
P_o (MW/structure)	200	200	50
N_k (klystrons)	4	24	8
N_s (structures)	2	12	16
L_s (m/structure)	3	3	0.5
N_e (e^-/bunch)	5×10^{10}	5×10^{10}	1×10^{10}

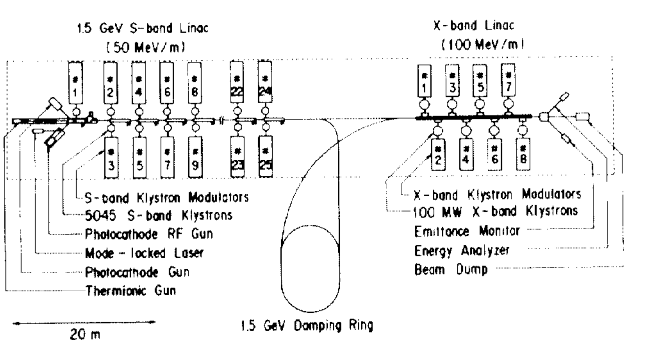

Fig. 9 Test Accelerator Facility for the linear collider R&D at KEK.

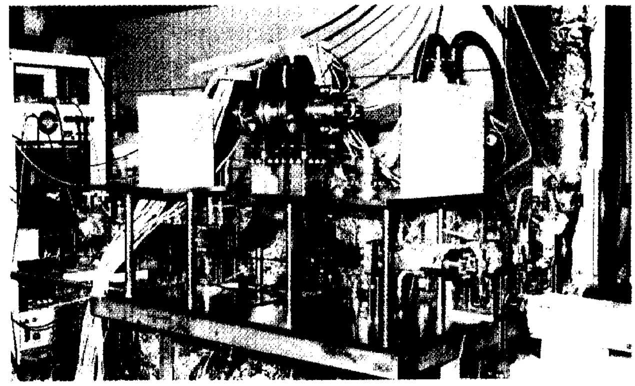

Fig. 10 An S-band model structure under high gradient tests by use of a resonant ring.

5. Investigation of ground motion and development of static and dynamic methods to install and align accelerator structures with an accuracy better than sub-micron meters.

Numerous new ideas on linear colliders have been proposed to solve such technical problems. On a relatively short time scale, however, the solutions should be sought among the fairly conventional approaches. The KEK R&D group decided as a major experimental R&D program to build a Test Accelerator Facility (TAF). The TAF consists of two test linacs of S-band and X-band as illustrated in Fig. 9. The energy of the first-phase S-band linac will be 300 MeV. The accelerating structure is composed of two wave guide units of 3 m in length and driven by four 5045 type klystrons supplied by SLAC. A short prototype structure has already been developed at KEK. It was tested for the accelerating gradient as high as 100 MV/m. Figure 10 shows a model structure under high gradient tests by use of a resonant-ring system. The main purpose of this linac is to develop the basic technologies on high gradient structures, instrumentation and control, and structure alignment which would be required for a future TeV class linear collider. In the second-phase the linac is intended to be extended to about 1.5 GeV. This, with a damping ring at the end, will be integrated into a future linear collider as an injector part of it. The X-band linac is assumed to be a main structure of the TeV class linear collider. The TAF X-band program is, however, limited to R&D's for the sub-systems because of no available power source presently. Those underway at KEK are design studies of the waveguide structure, developments of the structure fabrication, design studies of the 100 MW-calss klystron, and the construction of a facility to build the designed klystrons. It is planned to install the X-band structure without equipping with RF sources at the rather early R&D stage. Transmission of the beam accelerated in the S-band linac through the X-band structure will make it possible to investigate interactions between the beam and structure.

Design parameters of the TAF linacs are summarized in Table 4.

Japanese Hadron Facility

The Japanese Hadron Facility (JHF), a new accelerator-based facility in Japan, has been proposed to expand the experimental opportunities in the fields of nuclear physics, elementaly particle physics, and interdisciplinary researches by use of pulsed neutron and muon beams.[5] The JHF accelerator complex is thought to be built as a phased program. The first-phase will consists of a 1 GeV proton linac, a separate linac for heavy ions, and a 1 GeV compressor/stretcher ring. In the later phase the program proposes to add an intermediate energy ring of about 5 GeV and further a high energy ring of a few tens of GeV for a kaon-factory. For the experimental researches, four science arenas are to be set-up as summalized in Table 5. The kaon-experiments will be done at the existing KEK 12 GeV proton synchrotron which is expected to be upgraded considerably in its intensity by converting its injector from the present 500 MeV rapid cycling booster to the 1 GeV proton linac of the JHF. The compressor/stretcher ring will provide 1 GeV short pulse (20 nsec) proton beams for the spallation neutron and μSR experiments in its compressor mode, and 1 GeV long spill (70 % duty factor) slow-extracted beams for the low energy pion physics in its stretcher mode. The experiments on exotic nuclei will be done by use of the heavy ion linac with the maximum energy of 6.5 MeV/u. A very intriguing feature of this linac facility will be an acceleration of unstable nuclei produced by high intensity 1 GeV proton beams in the ISOL (Isotope Separator On-Line) ion source.

In 1987 a joint R&D group was formed in KEK and INS (Institute for Nuclear Study, University of Tokyo) to make design and construction studies of the JHF accelerators. The accelerator scheme proposed by the R&D group is illustratd in Fig. 11. Table 6 and 7 shows the design parameters of the 1 GeV proton linac and heavy ion linac, respectively.

Acknowledgement

The author wishes to thank Professors T. Nishikawa, S. Ozaki, M. Kihara, K. Takata, and S. Takeda for their help for preparing this paper.

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Table 5 Science arenas of the JHF

Kaon arena —	Rare kaon decay experiments and hyper-nuclei experiments with kaons
Neutron arena —	Condensed matter physics with pulsed spallation neutrons
Meson arena —	μSR with muons and nuclear physics with low energy pions
Exotic nuclei arena —	Exotic nuclei physics and acceleration of exotic nuclei

Table 6 Design parameters of the JHF 1 GeV proton linac

Energy	1	GeV
Total length	500	m
Average beam current	400	μA
Repetition rate	50	Hz
Pulse length	400	μsec
Ion source (H^-)	50	keV
RFQ (432 MHz)	3	MeV
Drift tube section (432 MHz)	150	MeV
Coupled-cell section (1296 MHz)	1	GeV

Table 7 Design parameters of the JHF heavy ion linac

Charge to mass ratio	1 ~ 1/60
Energy	6.5 MeV/u
Total length	120 m
Ion source for stable nuclei,	ECR
for unstable nuclei	ISOR
Split-coaxial RFQ (17 MHz)	170 keV/u
Interdigital-H type linac (51 MHz)	1.4 MeV/u
Alvarez linac (102 MHz)	6.5 MeV/u

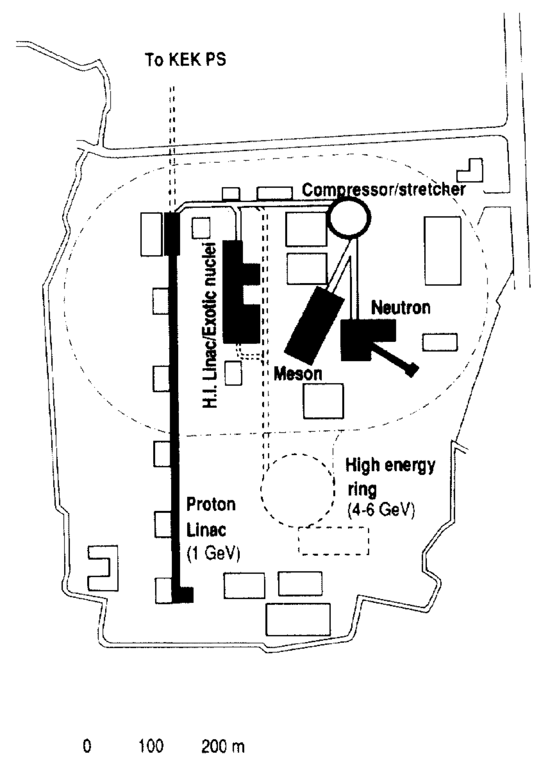

Fig. 11 Accelerator layout of the Japanese Hadron Facility.