A PRELIMINARY DESIGN OF TRI-RING INTERSECTING STORAGE ACCELERATORS IN NIPPON, TRISTAN

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Introduction

When the present KEK proton synchrotron project was originally proposed, it was expected to bring up the Japanese high-energy physics program to the present frontier of the world high energy physics. However, a shortcut of the budget forced the project to start with a lower energy accelerator and extend it to a higher energy range. Thus the future extension of the presently constructing 12 GeV proton synchrotron is taken into consideration even at the initiation of the present project.[1] Several possible extension schemes such as a large conventional synchrotron in the energy region of 80 ~ 100 GeV have been considered as a long range plan of the KEK project. At present, however, the future plan of the KEK synchrotron is concentrated on a plan of tri-ring intersecting storage accelerators for various types of colliding beam experiments as e±p, pp, e^+e^- and $\bar{p}p$ at very high center of mass energies. This project is nicknamed as TRISTAN (Tri-Ring Intersecting Storage Accelerators in Nippon) and a preliminary design study is undertaken in the KEK Accelerator Department in cooperation with the university scientists and the cryogenic specialists. This is a report on the present status of the preliminary design study of the TRISTAN.[2]

Outline of TRISTAN

The site of KEK is a land area of approximately 220 hectares in Tsukuba District, Japan. The present 12 GeV proton synchrotron project is in progress at the middle of the site, so that there remains a space enough to build a larger ring with more than 2 Km in its circumference. Thus, as ISABELLE,[3] PEP,[4] and EPIC[5] projects, with a superconducting magnet system we will be able to construct a proton storage ring of 150 ~ 200 GeV inside the site boundary.

The presently constructing synchrotron will be used as the injector of the storage accelerator. Since, however, to raise up the proton energy from 12 GeV to a 100 GeV range a large superconductor magnetization is required, the application of superconducting magnets to the storage accelerator would suffer from technical difficulties unless a new superconducting technique could be developed. Therefore, we are planning to install another conventional ring in the same enclosure as a booster between the present synchrotron and the superconducting rings. It accelerates protons to about 50 GeV and its guiding field is inverted in order to provide the protons for another intersecting ring so as to run in opposite direction. The conventional ring will also be used as an electron or a positron storage ring after it acted as a proton booster between the present main ring and the superconducting rings. Furthermore, as a future option, this ring may be used to produce antiproton beams which will be accelerated and stored in one of the superconducting rings. So we will be able to carry out various types of colliding beam experiments as pp, e±p, e^+e^-, $p\bar{p}$ and e±$\bar{p}$ by choosing different sets of three rings. The particles accelerated in a ring which is free of colliding beam experiments can be extracted toward an experimental hall and used for stationary target experiments.

A preliminary outline plan of the TRISTAN is shown in Fig.1. Two diamond-shape rings (solid lines) are superconducting proton rings intersecting each other at four interaction points in a horizontal plane. The conventional ring (broken line) will be installed above or below the two superconducting rings and intersect them vertically at the beam-transfer or interacting points. Several experimental halls for stationary target experiments are also shown.

Table I. PRELIMINARY PARAMETERS OF TRISTAN pp RINGS

Injection Energy	12~50 GeV
Maximum Final Energy(Each Ring)	180 GeV
Number of Intersecting Points	4
Average Radius(Curved Section)	204 m
Long Straight Section Length	150 m
Short Straight Section Length	30 m
Total Circumference(6×12 GeV Ring)	2035 m
Maximum Magnetic Field	50 kG
Total Stored Energy	~70 MJ
Acceleration Time	~100 sec
Number of Betatron Oscillations	22.25
Cell Structure Separated Function	FODO
Number of Cells(Each Ring)	80
Cell-Length	~16.4 m
Full Vacuum Chamber Aperture	6 cm
Crossing Angle	40 mrad
Total Charge(Each Ring)	6×10^{14}
Circulating Current(Each Ring)	15 A
Luminosity(180 GeV)	7.5×10^{31} cm^{-2}sec^{-1}
Maximum Luminosity for Collinear Crossing	10^{34} cm^{-2}sec^{-1}

TRISTAN pp System

A set of preliminary parameters of TRISTAN pp rings is given in Table I. The average radius of TRISTAN rings is taken as six-times of the present main ring or approximately 324 m.

First, six pulses from the present main ring are injected into the TRISTAN conventional ring to fill up its total circumference leading to 6×10^{13} particles per turn. Then the protons are accelerated upto about 50 GeV and transfered into one of the superconducting rings. From the expected beam characteristics of the present synchrotron, the emittances of the 50 GeV beam would be 0.4 and 2.8 πmm·mrad in vertical and horizontal directions, respectively. Using a set of skew quadrupoles in the beam transport line, we interchange horizontal and vertical phase space of the 50 GeV beam before injection. By means of transverse stacking method we can accommodate some ten pulses of the 50 GeV beam in a useful half-aperture of about 3 cm. Thus 6×10^{14} protons or a 15 A proton beam will be stacked and accelerated in each superconducting ring. The filling time needed for the whole stacking process is about 100 seconds for each, and acceleration takes place in the following ~100 seconds. The vertical and horizontal emittances at 180 GeV are estimated to be $\varepsilon_V = 0.8$ πmm·mrad and $\varepsilon_H = 0.35$ πmm·mrad.

In Fig.2 and Fig.3 we show the proposed lattice for TRISTAN superconducting rings with the cell structure of a separated function FODO system. Taking the length of each long straight section as 150 m, we get the average radius of curved section as 204 m. The total cell number of 80 is chosen with betatron oscillation frequency in neighborhood of 20 and the phase advance of each cell of about 90°. A quadrant of each ring consists of 19 normal cells and one half bending-magnet cell (HBM cell). As is shown in Fig.2, the HBM cell of either ring is located in the down- (or up-) stream in a quadrant of two intersecting rings. Thus the superperiod of each ring is 2 forming a diamond-shape lattice in which each diamond crosses another diamond at a crossing angle of 2°14'. However, the crossing angle can be taken at any degrees by using an appropriate set of deflecting magnets in the position of the missing magnets of the HBM cells or in the long straight sections. In these lattice configurations, we can obtain proton energies of 150 GeV at the bending field of 40 kG and 180 GeV at 50 kG.

The luminosity for a horizontal crossing of the unbunched beams is given by

$$L_{pp} = \frac{fN_p^2}{b_p \theta C} ,$$

where N_p is the total number of protons stored in each ring, $2b_p$ the full vertical beam height, θ the crossing angle, C the circumference and f the revolution frequency. Letting $N_p = 6 \times 10^{14}$, $b_p = \sqrt{\varepsilon_V \cdot \beta_V} = 0.9$ mm (β_V = 1m), $\theta = 2°14'$ and C = 2035 m, we obtain

$$L_{pp} = 7.5 \times 10^{31} \mathrm{cm}^{-2} \mathrm{sec}^{-1} .$$

If we use a quasi-collinear crossing of the bunched beams, then the luminosity will be improved leading to the maximum luminosity corresponding to the maximum allowable tune shift of $\Delta\nu_0$,

$$L_{pp\ max} = \frac{fN_p\gamma_p}{2\beta_p r_p} \Delta\nu_0 \doteqdot 10^{34} \quad \mathrm{cm}^{-2}\mathrm{sec}^{-1} , \quad (1)$$

where we take the β-function as $\beta_p(\beta_V = \beta_H) = 1\mathrm{m}$, γ_p = 190 (180 GeV), the classical proton radius $r_p = 1.5 \times 10^{-18}$ m and $\Delta\nu_0 = 0.02$. In this expression, the proton bunch length ℓ_p is assumed to be $\ell_p \ll 2\beta_p$.

Table II

PRELIMINARY PARAMETERS OF TRISTAN ep RINGS

Maximum Electron Energy	17 GeV
Maximum Proton Energy	180 GeV
Length of Interaction Region	150 m
Bending Radius (Electron)	124 m
Maximum Bending Field (Electron)	4.5 kG
Total Circumference	2035 m
Center of Mass Energy	110 GeV
R.F. Frequency (Electron)	~1200 MHz
Maximum R.F. Voltage (Electron)	100 MV/turn
Electron Current	30 mA
Power radiated by Electrons	1.5 MW
Maximum Luminosity	1.5×10^{31} $\mathrm{cm}^{-2}\mathrm{sec}^{-1}$
Crossing Angle	≲30 mrad
Injector	1 GeV Electron Linac
Injection Field (Electron)	265 G

TRISTAN ep SYSTEM

In Table II are shown preliminary design parameters of TRISTAN ep system. The center of mass energy of the ep colliding system is 110 GeV with the electron energy of 17 GeV and the proton energy of 180 GeV.

We have considered several schemes for storage of electrons including its injector and RF acceleration system. Because of strong synchrotron radiation along a curved orbit, energy and intensity of the electron beam is limited by feasible RF techniques. In this respect, of the schemes proposed the one preferable is that in which an electron linac is used both as the injector and the ring RF acceleration system.[5] The total length of the electron linac is about 100 m and it is installed in one of the long straight sections of the TRISTAN conventional ring. As the injector the linac works at a pulsed operation and provides about 10^{12} electrons with a single turn injection. Immediately after this the electron linac is turned into a ring RF system which works, in a sense, at a CW operation. The energy loss per turn for an electron circulating the storage ring is about 35 MeV for a 15 GeV beam and 50 MeV for a 17 GeV. Including effect of quantum fluctuations, about twice of these figures are required for the RF peak voltage. Considering the power and aperture requirements, we tentatively choose the RF frequency of the linac at L-band region and divide the total length into 10 sections. With a shunt impedence of about 50 MΩ/m, values of necessary RF power are listed in Table III both for the injector and the storage ring operations. It is shown that RF power tubes with a peak RF power of ~30 MW and with an average power of ~350 kW are required, which, however, would not be far beyond from the present available techniques.

In addition to the RF power requirements, some problems associated with this system should be mentioned. First, the linac RF system has the advantage of achieving a 100 % RF capture of the injected beam. However, about 200 mA·μs peak current of the linac at injection is required for providing a 30 mA circulating current in the ring since the revolution frequency of electrons is 150 kHz. This figure is around the maximum current achieved up to the present in the existing linacs. Furthermore, for obtaining a higher luminosity it is favorable that the electron bunches are arranged so as to be separated from one another at a distance equal to the separation of proton bunches. During the period of synchrotron accelerations, the RF acceleration voltage has to be programmed in a range from some hundred kV to a hundred MV. For this, we probably need to excite each section successively with a feed-back RF control system. In addition, a transverse focusing system along the linac should be matched to the ring lattice system. Preliminary orbit analysis shows that the transverse motion is quite feasible throughout the whole process including injection, acceleration and storage. Finally, if we wish to storage positrons as well as electrons in the same ring, we may need to build another relatively small ring which is provided for injection of positrons at a sufficient intensity.

Table III RF POWER OF ELECTRON LINAC PROPOSED FOR TRISTAN INJECTOR AND RF ACCELERATING SYSTEM

Function	Injector	Storage Ring RF (15 GeV)	Storage Ring RF (17 GeV)
Energy Gain	1 GeV	35 MeV	50 MeV
Operation Mode	Pulsed	CW	CW
Peak RF Voltage (Each Section)	100 MV	6 MV	10 MV
Wall Loss (Each Section)	20 MW	70 kW	200 kW
Beam Loading (Each Section)	10 MW	100 kW	150 kW
RF Power (Each Section)	30 MW	170 kW	350 kW
Total Power	300 MW	1.7 MW	3.5 MW

The maximum luminosity for ep colliding experiments will be determined by the maximum allowable tune shift for electrons per intersection. For a quasi-collinear crossing, following relations between the length parameters may be assumed as a practical case.

i) The electron bunch length is short enough while the possible shortest proton bunch length could be 0.3 m.

ii) The β function are assumed to be $\beta_V = \beta_H$ and vary as $\beta_{e,p}(s) = \beta_{e,p} + \frac{s^2}{\beta_{e,p}}$ *in the interaction region.* The β-function for the electron ring at the center of the interaction region is much shorter than that for the proton ring or $\beta_e \ll \beta_p$.

iii) The proton bunch length (or the length of the interaction region of an unbunched proton beam), ℓ_p, could be longer than or comparable to the β_e value, while it is short enough compared to the β_p value, i.e. $2\beta_e \leq \ell_p \ll 2\beta_p$.

iv) The electron beam radius is narrower than the proton beam radius.

On the assumption of these relations, it is shown[2] that the tune shift, $\Delta\nu_e$, has a minimum when the following condition is satisfied between the proton bunch length (or the interaction length) and the electron-ring β-function as

$$\ell_p = 2\sqrt{3}\,\beta_e \quad . \qquad (2)$$

Taking $\Delta\nu_{e\,min} = \Delta\nu_0$ (maximum allowable tune shift), we can obtain an expression for the maximum luminosity,

$$L_{ep\,max} = \frac{fN_e\gamma_e}{4\beta_e r_e}\,\Delta\nu_0 \;, \qquad (3)$$

where N_e is the total number of stored electrons and r_e the classical electron radius. It is noted here the luminosity is one half of the usual expression for extremely short bunches, because the proton bunch length (or the optimum interaction length of an unbunched proton beam) is longer than β_e-value (see equ.(1)). For an unbunched proton beam as given in the pp colliding system, the optimum interaction length is estimated to be $\ell_p = 1$ m and, from equ.(2), the optimum β_e-value is about 0.3 m. Letting $f = 1.5 \times 10^5$ Hz, $Ne = 1.3 \times 10^{12}$ (30 mA), $\gamma_e = 3.3 \times 10^4$ (17 GeV), $r_e = 2.8 \times 10^{-15}$ m and $\Delta\nu_0 = 0.025$, we get

$$L_{ep}\ (\text{unbunched p}) \doteqdot 5 \times 10^{30}\ \text{cm}^{-2}\text{sec}^{-1} \;.$$

If we can bunch the proton beam as short as 0.3 m, then the corresponding optimum β_e-value is about 0.1 m and the maximum luminosity will become three-times higher, or

$$L_{ep\,max} \doteqdot 1.5 \times 10^{31}\ \text{cm}^{-2}\text{sec}^{-1} \;.$$

Time Schedule and Possible Phase I Project

The time schedule and cost estimates of the TRISTAN project should depend upon many unknown factors as the operation experience of the present machine, the future development of accelerator arts, the national economy, the man-power plan, the supply and power problems, etc. A tentative schedule presently seen is as follows:

1973 ~ 1975	Design study and fundamental research on superconducting magnets.
1975	Completion of the present machine.
1975 ~ 1977	Developments of superconducting magnets for storage rings and technical feasibility study.
1978	Construction started
1982	Completion of the conventional ring.
1985	Completion of the superconducting rings.

A rough total construction cost is estimated to be around 10^4 M yen, and, since this figure may be beyond a growth rate of our research budget, we had better divide the TRISTAN project into two stages, Phase I and Phase II. At present, we are considering two possible courses on the process from Phase I to Phase II. The one is that in which we construct the conventional ring in Phase I and use it as a storage accelerator both for protons and electrons. The construction of the accelerator enclosure for the whole project should also be included in Phase I. The conventional ring will accelerate protons to some ten GeV and electrons over ten GeV. Besides, this ring itself may be used as a 12 GeV electron-proton colliding beam machine. In this option, electrons as a starter are injected, accelerated and stored at about 13 GeV. Subsequently, 12 GeV protons accelerated by the presently constructing synchrotron are injected and stored in the same ring rotating in opposite direction. By a small momentum difference or an application of an electric field, we could separate electron and proton orbits except the interaction regions, so that we can devise a bypass or an interacting region without difficulty (Fig.4).[2] The ep colliding experiments at 25 GeV in center of mass energy will be performed with a maximum attainable luminosity of about 10^{31} cm^{-2}sec^{-1}.

The other course from Phase I to Phase II is to build double conventional rings in Phase I and replace one of them by a superconducting ring in Phase II. By means of taking this course, we can perform ep colliding experiments at a center of mass energy as high as 50 ~ 60 GeV; i.e. the energy at which weak processes involving neutrinos would become comparable to electromagnetic processes or large momentum-transfer strong interactions. Design of accelerator and the experimental facilities in Phase I will also become simple and more flexible, provided a little additional construction money should be financed.

Acknowledgement

Many colleagues in the KEK Accelerator Department and other laboratories have contributed to promote the design study reported here. In particular, the discussions with Professor K. Huke, Institute for Nuclear Study, University of Tokyo, Professor K. Kikuchi and Dr. T. Suzuki, KEK Accelerator Department should be acknowledged.

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KEK FUTURE PROJECT

	Present PS	TRISTAN Step 1 (Ring 1)	TRISTAN Step 2 (Ring 2,3)
Energy	12 GeV	p . 50GeV e . 17 GeV	p . 180 GeV
		12GeV, p + 12GeV, e	180 GeV, p + 180 GeV, p
Intensity	5×10^{12} ppp	p . 6×10^{14} e . 10^{13}	p . $6\times10^{14}\times2$ e . 10^{13}
Radius	54 m	324 m	324 m
Magnetic Field	18.5 kG	p . 13 kG e 4.5 kG	p 50 kG e . 4.5 kG
Total Electricity	15 MW	30 MW	40 MW

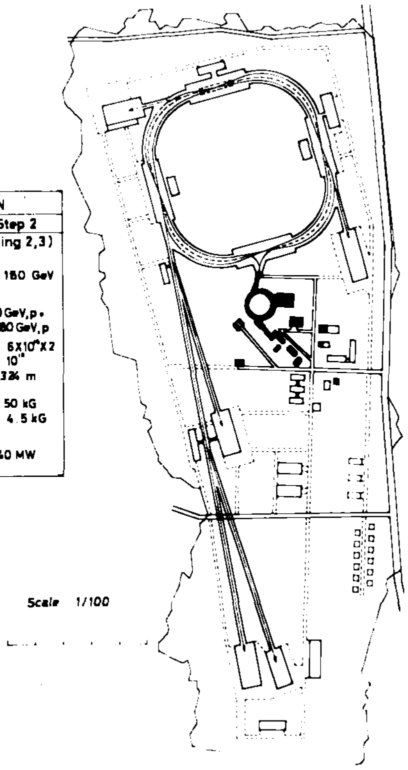


Fig.1 Plan View of TRISTAN

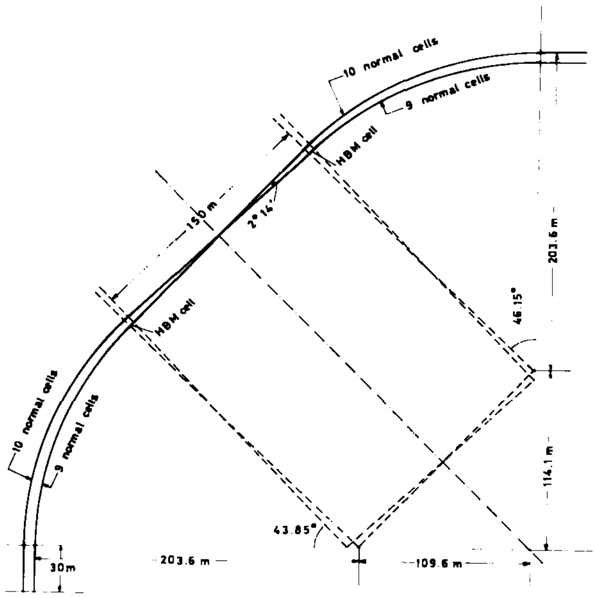
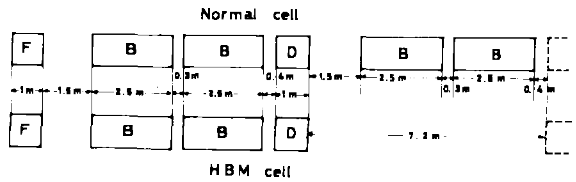


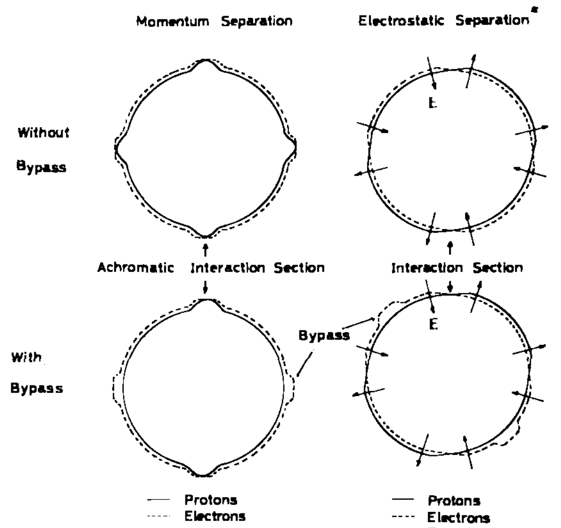
Fig.2 Quadrant of TRISTAN pp Rings



Cell Length		16.4 m
Cell Numbers	Normal cell	76
	HBM cell	4
Radius of Curvature in Bending Magnet		124.0 m
Maximum BM Field (180 GeV)		50 kG
Maximum QM Gradient (180 GeV)		10.4 kG/cm
Phase Advance per cell		82° 7'
β Functions and X_p in regular cell		
β_{max}		26 m
β_{min}		6 m
$(X_p)_{max}$		2.4 m

Fig.3 Cell Structure of TRISTAN pp Rings

$T_e \sim cp_p \sim 12.9$ GeV ($B \sim 3.5$ kG) , $\beta_e - \beta_p \sim 2.6\times10^{-3}$



$\frac{\Delta P}{P} \sim \frac{\nu^2}{R}\Delta x \sim 1\%$ for $\Delta x \sim 1$ cm, $\nu \sim 20$

$E \sim \frac{T}{e}\frac{\nu^2}{R^2}\Delta x \sim 8$ kV/cm for $\Delta x \sim 1$ cm, $\nu \sim 10$

* In this Figure, electric fields are indicated in the horizontal plane, while in practice one had better apply in the vertical directions.

Fig.4 Possible Single Ring ep Colliding Beam System for TRISTAN Phase I.