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ACCELERATOR PROJECT GEMINI
FOR INTENSE PULSED NEUTRON AND MESON SOURCE AT KEK

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Abstract

A rapid-cycling synchrotron is designed for intense pulsed neutron and meson source at KEK. This 800 MeV accelerator aims to deliver proton beams of 500 μA in time average. This paper describes conceptual design of the accelerator and also points out some technical problems to be overcome in order to realize the project.

Introduction

Five hundred MeV Booster Synchrotron at KEK, which is delivering 2 μA proton beam in time average, is used as a pulsed neutron and meson source of Booster Synchrotron Utilization Facility (BSF) as well as an injector for 12 GeV Proton Synchrotron in a time-shared mode. At present, a project of H^- charge exchange injection is in progress to increase the beam intensity of the booster, and also energy-up of the present 20 MeV injector linac to 40 MeV has been discussed[1]. These correspond to a relatively short term program KENS-I', including the conversion of the present tungsten target to a depleted uranium. KENS-I' program aims to increase the neutron beam intensity by about one order of magnitude by improving the present accelerator and target system. On the other hand, a long-term future program of BSF was discussed informally since the fall of 1980. This is the construction of an intense pulsed neutron source (KENS-II program) and the extension of the present meson science experimental facility BOOM (Super-BOOM project). A tentative program has been presented at the meeting on the BSF future program on March 1982[2]. This was the first formal presentation. The most important part of this program is the construction of a high intensity proton accelerator.

Accelerator Design Principle

An accelerator system for KENS-II and Super-BOOM is called GEMINI, which is abbreviation of "a generator of meson-intense and neutron-intense beam". This is an 800 MeV rapid-cycling synchrotron aiming to deliver the proton beam of 500 μA in time average. Unlike the present meson factories or spallation neutron sources worldwide except those in BSF, GEMINI should deliver equally the pulsed proton beams to each of the meson and neutron experimental facility. And it may be possible that GEMINI will replace the 500 MeV booster as an injector for the present 12 GeV PS. This leads to the determination of the accelerator size to be a half of the circumference of 12 GeV PS, that is, 27 meters in average radius. In BSF, the unique features of the 70 nsec pulsed proton beam are effectively used for the time-of-flight technique in the neutron scattering experiments and for the studies on the relaxation phenomena of condensed matters with μSR. In GEMINI, it is also required that a single bunched beam is simultaneously supplied to each of the neutron and meson experimental facility. This determines uniquely the harmonic number of RF acceleration system is 2. Particularly, some kinds of μSR experiment ask a single short bunched beam less than 30 nsec in bunch length even at the sacrifice of beam intensity.

The accelerator parameters are listed in Table 1. The accelerator will consist of an H^- ion source, pre-accelerator including RFQ linac, 100 MeV Alvarez-type linac, and 800 MeV rapid-cycling synchrotron. The layout of the accelerator is shown in Fig. 1.

Table 1 A New Pulsed Neutron and Meson Source GEMINI

Maximum kinetic energy	800 MeV
Maximum intensity	6×10^{13} p/p
Repetition rate	50 Hz (100/3 Hz & 100 Hz)
Average beam current	500 μA
Injection energy	100 MeV
Injected H^- beam current	30 mA
Number of turns of injected beam	>240
Beam pulse width of injected beam	>330 μs
Magnet radius	7.00 m
Average radius	27.00 m
Number of period	24
Length of straight section	3.008 m
Structure	FBDO
Betatron frequency per revolution	
Horizontal	6.8
Vertical	7.3
Revolution frequency	0.757 - 1.489 MHz
Maximum beta-function	
Horizontal	12.4 m
Vertical	12.9 m
Momentum compaction factor	2.71×10^{-2}
Transition energy/rest energy	6.07
Beam emittance	
800 MeV	0.29×0.16 (mm rad)^2
100 MeV	0.97×0.52 (mm rad)^2
Number of bending magnets	24
Length of bending magnets	1.833 m
Length of quadrupole magnets	
Focussing magnet	0.525 m
Defocussing magnet	0.565 m
Bending magnet field	
800 MeV	0.697 T
100 MeV	0.212 T
Quadrupole magnet peak field gradient	4.18 T/m
Peak energy gain per turn	90.6 keV (60.4 keV)
Harmonic number	2
RF frequency	1.513 - 2.978 MHz
Maximum RF voltage	214 kV (166 kV)
RF bucket area	1.89 eV·sec
Number of RF stations	8
Incoherent space charge limit	7.2×10^{13} protons

Accelerator System

Lattice Structure

Four lattice structures were examined. Finally, a highly symmetric lattice with high tunes was chosen from them; 24 equal FBDO cells with a phase advance of about 90° per cell set the betatron tunes around 7. For a given mean radius of the accelerator, such high tunes lead to smaller aperture magnets for a constant space-charge limit. High tune means a high transition energy, which has advantages to both of the longitudinal and transverse instability of beam. On the other hand, this leads to a large number of unit cells, hence

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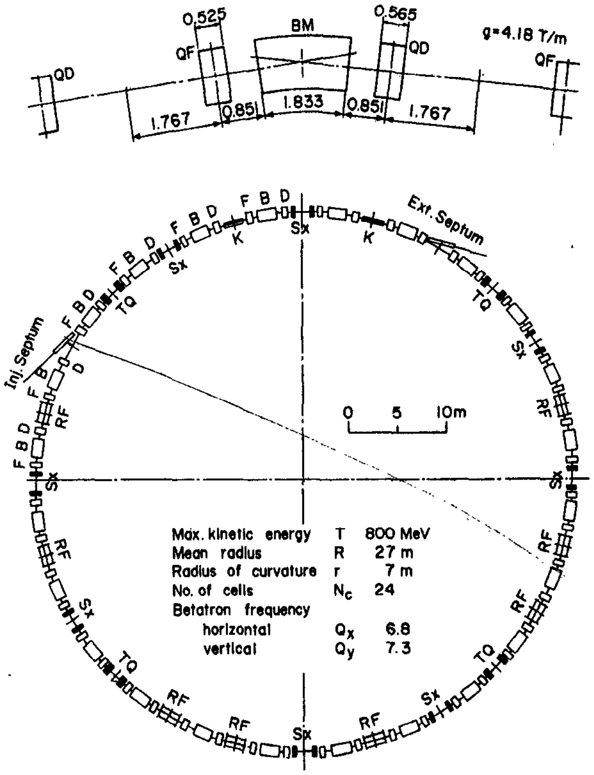


Fig. 1 GEMINI Layout

the shortening of the length of straight section where devices for extraction and acceleration are installed. The choice of horizontal and vertical tune of 6.8 and 7.3 is somewhat arbitrary, and more detailed studies might be considered on x-y coupling, acceptance choice, beam extraction optics, etc. Figure 2 shows amplitude and dispersion function along the beam orbit.

Injector Linac[3)]

100 MeV linac with a 30 mA H^- ion beam is assumed as an injector to the synchrotron. The accelerating structure of this injector system is divided into three stages: 50 ∿ 100 keV H^- ion source, 1 MeV RFQ or APF and 100 MeV Alvarez linac. Even thouth the attainable maximum energy through RFQ linac requires a deliberate study, 1 MeV injection energy will certainly be attainable, which enables us to use klystron working around 400 MHz as RF power source. This will simplify the power system of the linac.

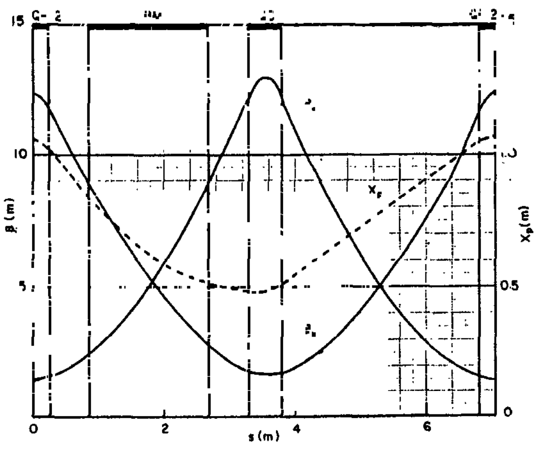


Fig. 2 Amplitude and Dispersion Functions

If the Alvarez linac is excited at 400 MHz, the diameter of cavity is reduced nearly to a half of the present proton linac at KEK, and the average accelerating field can be made higher, say, 3.5 MV/m. With the fixed dimensions of drift tube (bore diameter: 1.0 cm, outer diameter: 9.0 cm) and cavity (diameter: 48 cm), the values of transit time factor, effective shunt impedance, power loss, etc. were calculated as a function of the half-gap length. Table 2 shows accelerating energy by each cavity, cavity length, number of cells contained in a cavity and RF power for 6 partitions at the average accelerating voltage of 3.5 MV/m.

Table 2 Features of 100 MeV Injector Linac

Cavity Number	Energy (MeV)	Length (m)	Number of cells	Power (MW)		
				Cavity	Beam	Total
1	18.37	7.267	81	0.852	0.521	1.373
2	35.57	7.138	41	0.835	0.516	1.351
3	52.68	7.305	33	0.870	0.513	1.383
4	69.93	7.483	29	0.911	0.517	1.428
5	85.38	7.180	25	0.898	0.464	1.362
6	100.39	7.458	25	0.929	0.450	1.379

The momentum spread of the beam at the exit is expected to be ±0.3 %, and the normalized acceptance in the transverse plane is estimated to be 20 mm•mrad with the first quadrupole magnet of 1.5 T/m in field gradient.

The build-up time of the cavity for $Q = 6.5 \times 10^4$ is about 275 μsec. If one adds 100 μsec as a margin to the minimum beam duration 350 μsec, the duty factor becomes 3.6 %. 400 MHz klystron with duty factor of 5 % and peak power of 2.5 MW is expected to be developed without much difficulty.

Injection

Beam injection will be carried out in horizontal plane. In order to store the number of protons of 6×10^{13} into the synchrotron with a 30 mA H^- ion beam, injection would occur at least over 240 turns requiring 330 μsec. We assume the normalized emittance of linac beam of 10 mm•mrad in both transverse planes. A phase-space area of 460 mm•mrad (H) x 246 mm•mrad (V) has to be filled with this beam. For the purpose of filling the horizontal phase space, injection starts with a horizontal bump orbit, which coincides with the injection orbit of the H^- ion beam at the exit of a focussing quadrupole magnet as shown in Fig. 3. A charge stripper of 120 $\mu g/cm^2$ carbon foil is set downstream the Q magnet, whose radial position must be outside the beam envelope at the end of injection. The bump orbit will be provided by means of a pair of bump magnets and a small trim quadrupole magnet. The density distribution of the beam after injection is regulated by choosing a proper decay waveform of the bump field. The maximum amplitude of the bump orbit requires bump field of 0.33 and 0.32 T for the 0.2 m long magnet B1 and B2, respectively. Filling of the vertical phase space will be achieved with a steering magnet introduced into the H^- injection line.

The beam intensity aimed by GEMINI is very huge and expected to be 6×10^{13} protons/pulse. Even though only one percent of the beam is lost, this is equivalent to the full intensity of the present 500 MeV booster synchrotron at KEK. Most of the beam loss in transverse planes at injection will come from the beam blow-up due to the multiple scattering and stripping inefficiency by the charge stripper. The charge stripped proton beam scans radially with decaying

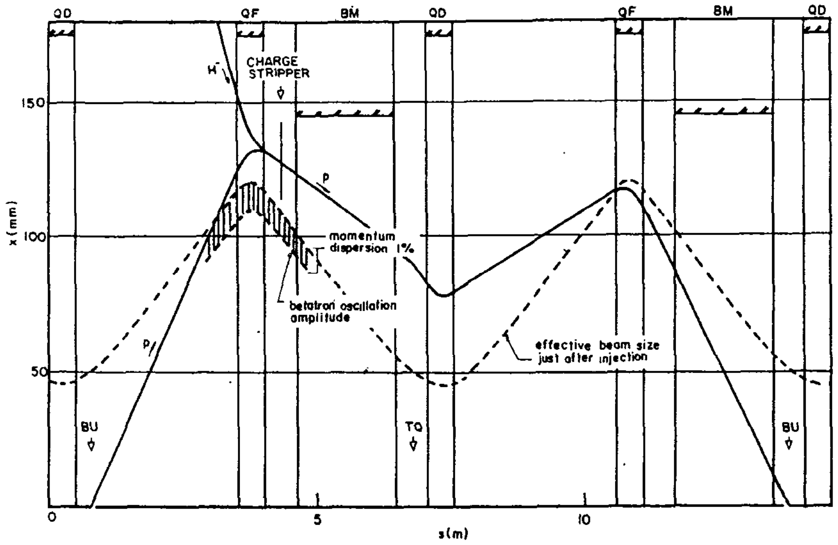
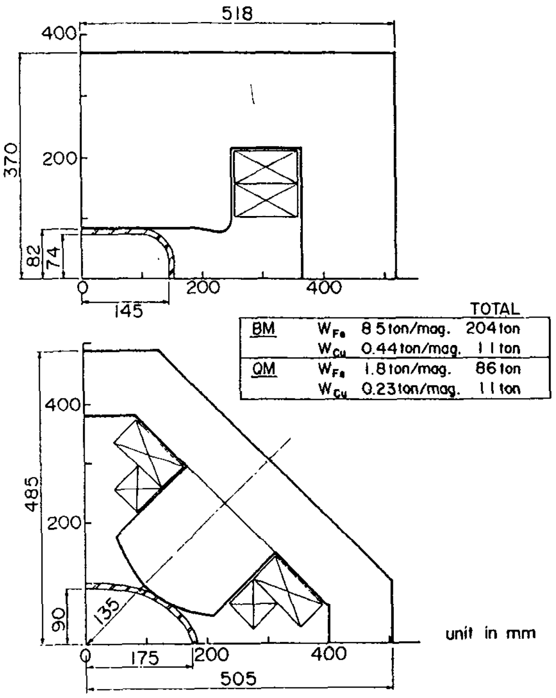


Fig. 3 Injection Optics

closed orbit. The effective number of traverse of the circulating proton beam through the stripper is at most forty times for a 30 mA, 20 % chopped H^- ion beam of 420 μsec in time duration. Using a 120 $\mu g/cm^2$ thick carbon foil, it is possible to keep the beam loss less than a fraction of percent and to localize the most likely unavoidable losses due to the stripping inefficiency by means of proper beam scrapers and collectors.

Ring Magnets

The accelerator ring is made of 24 bending and 48 quadrupole magnets. The required semi-aperture of good-field region is 11.5 cm x 7.4 cm and 13.5 cm x 9.0 cm in the bending and quadrupole magnet respectively. For the vacuum chamber, it is necessary to add 3 and 4 cm in horizontal aperture of the bending and quadrupole magnet respectively to allow the room for injection and extraction of beam. The cross-section of the ring-magnet is shown in Fig. 4.



			TOTAL
BM	W_{Fe}	8.5 ton/mag.	204 ton
	W_{Cu}	0.44 ton/mag.	11 ton
QM	W_{Fe}	1.8 ton/mag.	86 ton
	W_{Cu}	0.23 ton/mag.	11 ton

Fig. 4 Gap and Core Geometry of Ring Magnet

The ring magnet is excited with a repetition rate of 50 Hz. All of the bending and quadrupole magnets are divided into twelve groups. These are connected in series through resonant capacitors and forms a ring circuit. The dc bypass of the capacitors for the dc bias current is provided by installing chokes in parallel to the capacitors. In order to reduce the RF accelerating voltage, the magnet system would be excited by a dual-frequency system with resonant frequency of 100/3 and 100 Hz as proposed by M. Foss and W. Praeg at ANL$^{4)}$. This reduces the peak RF voltage of 214 kV to 166 kV. The switching system of resonant capacitor would be more simplified by replacing ordinary thyristor with GTO (gate turn-off) thyristor, which is capable of self-breaking. The test is under way$^{5)}$.

The maximum voltage imposed on the exciting coil should be kept within 10 kV to the earth. This sets a limit to the number of turns of the coil and leads to a considerable power dissipation due to eddy current circulating in hollow conductor. Reduction of the eddy current loss will be achieved by using hollow conductors of parallel current circuits and by transposing those circuits each other at the connection points between coil pancakes as successfully applied at the KEK booster synchrotron magnet. Even though such a procedure is applied, a considerable amount of the eddy current loss takes place as shown in Table 3. Development of a stranded cable with cooling pipe for coil conductor would make free from eddy current loss, which leads to the reduction of the number of turns of coil and hence the voltage across the coil and the peak voltage applied to GTO thyristor.

RF Acceleration

We assume a 100 MeV injected beam with an effective full momentum spread of 0.75 %. The emittance of such an injected beam is 0.94 eV•sec for the acceleration system with harmonic number of 2. If the RF bucket area has to be twice of this emittance, the

Table 3 Power Consumption of Magnet System (100/3 & 100 Hz Dual Resonant Frequency Mode)

Magnet (24 BM, 48 QM)	BM		QM
P^{dc}_{ohm}	36.4 kW/mag.		19.4 kW/mag.
P^{ac}_{ohm}	5.2		2.7
P_{eddy}	12.5		6.7
P_{iron}	3.8		1.1
Energy-storage Choke (12 meshes)		Condenser (12 meshes)	
P^{dc}_{ohm}	32.5 kW/mesh	P_c	51.4 kW/mesh
P^{ac}_{ohm}	4.6		
P_{eddy}	8.4		
P_{iron}	7.5		
Total Power Loss		Total Stored Energy	
P_{dc}	2.19 MW	U_{dc}	990 kJ
P_{ac}	1.88 MW	U_{ac}	281 kJ

Table 4 Parameters of RF Acceleration System (100/3 and 100 Hz dual resonant freq. mode of guide field)

Harmonic number	2
RF acceleration frequency	1.513-2.978 MHz
Peak RF voltage	166 kV
RF bucket area	1.89 eV•sec
Number of RF stations	8
Number of cavities per station	2
Cavity length	1.2 m
Ferrite inner/outer diameter	0.30 m/0.50 m
Max. flux density of RF field in ferrite	∿100 Gauss
Bias current	550-2,050 A
Shunt impedance of RF cavity	2.7 kΩ
Total average RF loss of ferrite	125 kW
Average power delivered to beam	350 kW

required peak RF voltage through the acceleration period is 166 kV in the 100/3 Hz operation of the guide field magnet. The RF voltage program and relevant parameters of RF bucket are shown in Fig. 5. The required RF voltage will be provided with eight RF stations, each of which is installed in a 3 m long straight section and consists of two reentrant ferrite-loaded cavities. A low impedance cathod-follower is proposed as a final-stage power amplifier in order to compensate for a large beam loading. Parameters of the RF acceleration system are listed in Table 4.

In GEMINI using the H^- charge-exchange injection scheme, the most likely beam loss at around injection will result from the inefficiency of beam trapping in the longitudinal phase space. RF capture efficiency in ordinary methods will be at most 80 % with reasonable parameters. Particularly in a high intensity machine such as GEMINI, therefore, the beam loss at RF capture should be significantly reduced. A chopper will be introduced into the beam line following the preaccelerator. Computer simulation showed that the inefficiency of adiabatic trapping process is less than 1 % in the synchronous injection of a 20 % chopped beam into RF bucket.

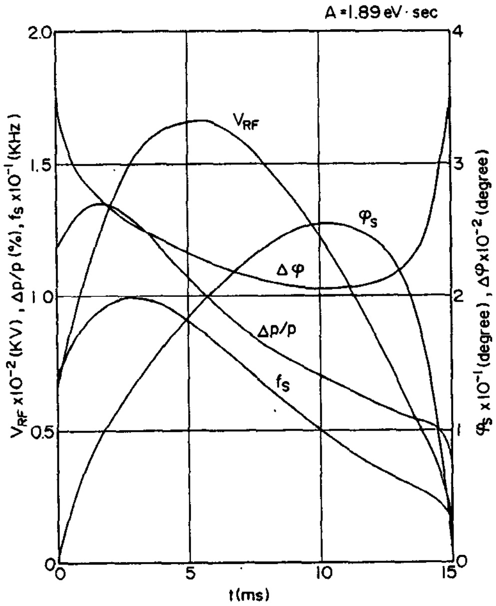


Fig. 5 RF Voltage Program and Relevant Parameters of RF Bucket

While the required bunch length is some 200 nsec or less for the spallation neutron source, special μSR experiments require a very short single bunched beam, say, 30 nsec. This is one of the important options of the accelerator. Assuming typical RF accelerating voltage programs with a limited maximum voltage, the bunch length at the maximum energy was estimated in both cases of adiabatic damping and non-adiabatic method. In the later case, a sudden increase in the RF voltage around the maximum energy will cause the bunch to rotate in longitudinal phase space and the bunch would be upright after a quarter of a synchrotron oscillation period. Extraction should occur when the bunch length is a minimum[6]. It was confirmed by using the present 500 MeV booster at KEK that this method seems to be promising to realize the desired short bunched beam, provided at some sacrifice of beam intensity.

Extraction

Beam extraction is performed by the horizontal single-turn extraction. The emittance of the extracted beam is assumed to be twice of the expected one from adiabatic damping of the initial emittance. Then, the full size of the beam including a dispersion due to the momentum spread of 1 % is estimated to be 74 mm at the entrance of the septum magnet, which is located in a straight section following a defocussing quadrupole magnet. Kicker magnet, therefore, must give a kick sufficient to clear such a beam size plus a 10 mm thick septum. The available space for the kicker magnet is a 3 m long straight section located upstream the septum straight section by an amount of about π/2 radian in phase advance. The required kick angle is 28 mrad, which is too large to be achieved with one kicker magnet located in the 3m long straight section. Another kicker magnet, therefore, is installed at a straight section upstream the first kicker magnet by π radian to realize the required kick angle at the first kicker position. In addition to those kickers, several orbit bump magnets will be used to the purpose of manipulating the beam positions just before the extraction. Figure 6 shows the extraction trajectory of beam. The deflection by the kicker magnet is 15 mrad for the first and second magnet. The septum magnet is divided into two parts, each of which deflects the beam by 150 and 225 mrad, respectively. These bends provide a separation of 80 cm between the central orbit and the central line of the extracted beam at the exit of the septum magnet. This distance is long enough for the

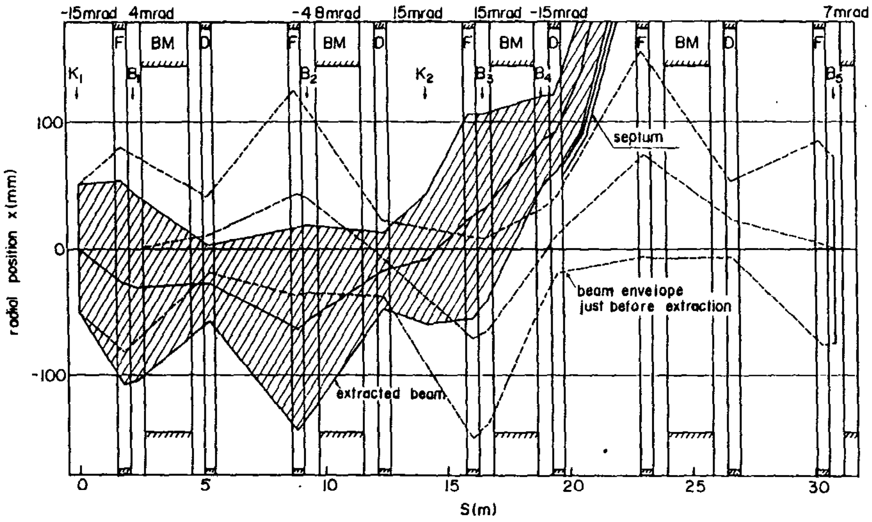


Fig. 6 Extraction Optics

extracted beam to clear the yoke of the quadrupole magnet following the septum magnet. Parameters of the kicker are listed in Table 5. Each kicker magnet, which is installed in a long straight section, is divided into two-different types K_u and K_d located to upstream and downstream side of the straight section according to the difference of beam size.

Table 5 Parameters of Ferrite-loaded Delay-line Type Kicker Magnet

	K_u (2 units)	K_d (3 units)
Deflection angle: Total (mr)	15	
Each (mr)	3	3
Gap height (mm)	180	120
width (mm)	200	200
Magnet length (mm)	600	350
Flux density in gap (T)	0.024	0.042
Exciting current (kA)	3.5	4.0
Impedance (ohm)	10	8.8
Inductance per cell (μH)	0.084	0.110
Capacitance per cell (nF)	0.84	1.4
No. of cells	10	10

Correction Lens System

For the sake of simplifying the power supply for the resonant network, the bending and quadrupole magnets are connected in series. Trim-quadrupole magnet system, therefore, must be introduced to keep the flexibility of tuning in the tune diagram. Assuming the variable range of tune is within ±0.5, four pairs of focussing and defocussing magnet are required, whose length and field gradient are 0.5 m and 1.53 T/m, respectively.

The natural chromaticity $\xi = \Delta Q/(\Delta p/p)$ is considerably high, that is, -9.1 for the horizontal plane and -10.2 for the vertical plane, respectively. If those chromaticities would be eliminated, eight sets of F-type and D-type sextupole magnet are required, whose field is 36.8 T/m^2 and -60.1 T/m^2 for a 0.3 m long magnet. Such quantities will be sufficient in practice to suppress head-tail effects, which might take place.

At present, it is an open question to introduce the octupole magnet for Landau damping.

Layout of the trim-quadrupole and sextupole magnets is shown in Fig. 1.

Vacuum Chamber

The vacuum chamber will be made from about 300 mm long sections of pure alumina, which are joined by metallizing the ends and brazing in vacuum. The lengths of vacuum chamber to be manufactured are within the limits of joining in this method, which enables us to attach directly metal flange at the end of the chamber.

Concluding Remark

The above-mentioned is only a preliminary design, and the design study is still in progress. Many problems are remained to be solved:

1) Design of each accelerator component in more detail,
2) Design studies of the items which have not been set about,
3) Layout including experimental facilities,
4) Cost estimation and time-schedule, etc.

R & D for some of technical problems is in progress; for example, construction of RFQ linac, manufacture of a permanent quadrupole magnet for linac drift tube and beam chopper for output beam of preaccelerator, application of GTO thyristor to the dual-frequency system of ring magnet power supply, development of stranded cable with cooling pipe as magnet coil conductor, etc. And also experiments such as beam bunch shortening test will be carried out by practical use of the existing accelerator and experimental facilities.

References

1) H. Sasaki, presented paper to this meeting.
2) T. Adachi (Ed.), Proc. of the Meeting on BSF Future Prospects, KEK Int. 82-6 (1982).
3) S. Inagaki, et al., Proc. of 7th Meeting on Linear Accelerators, KEK 82-14, 110 (1982).
4) M. Foss and W. Praeg, IEEE Trans. Nucl. Sci. NS-28, 2856 (1981).
5) H. Someya, et al., Proc. 4th Symp. on Accelerator Science and Technology at RIKEN, Japan, 317 (1982).
6) ANL-KFA Study Group, ANL-83-13.