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DESIGN OF THE COMPRESSOR/STRETCHER RING OF THE JAPANESE HADRON PROJECT

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ABSTRACT

A possibility of adopting a racetrack-type design for the compressor/stretcher ring of the Japanese Hadron Project is described. This design has two long straight sections to enable to inject the H^- beam and to produce a high β point for the slow extraction.

I. INTRODUCTION

The proposed Japanese Hadron Project consists of the 1GeV linac, the compressor/stretcher ring(CSR) and three experimental facilities. These facilities are E, M and N arenas for experiments using exotic nuclei, mesons and neutrons, respectively. The functions of the CSR are to accumulate the 1GeV proton beam with an average current of $200\mu A$ and to supply the beams to the M and N arenas with a repetition rate of 50Hz. Two bunches of the proton beam, the time duration of which is normally 200ns, are accumulated in the CSR. The N arena uses the beam of this time duration without any change in time structure. For the M arena, however, in addition to the normal operation mode just described above, two additional operation modes of different time structures are required. One mode is the ultra-short pulse mode for muon experiments, in which a bunch will be compressed to an ultra-short bunch of 20-30ns in length. In this mode, the sequence of operation is:

1. Accumulation of the beam in two RF buckets (the harmonic number h=2),
2. Fast extraction of one of the bunches to the N arena,
3. Compression of the remaining bunch by an RF system of h=1 and
4. Fast extraction of the bunch to the M arena.

Another mode is the stretcher mode for pion experiments. The beam is slow-extracted in a duration of 20ms before the next beam pulse from the Linac arrives. In this second mode, the sequence of operation is:

1. Accumulation of the beam in two RF buckets,

2. Fast extraction of one bunch to the N arena and
3. Slow extraction by a third-order resonance.

The conceptual design work on the CSR began in 1988. The design work has been almost finished and its results have been reported elsewhere[1,2]. The fundamental lattice of the CSR which was designed in this work is a FODB cell, and the whole ring consists of 16 superperiods, as shown in Fig. 1. Each cell is composed of a 2.8m bending magnet with a bending angle of 22.5 degrees, two quadrupole magnets and a 5.7m long drift space. The drift spaces are used to install the equipments for injection, fast and slow extractions, acceleration and beam collimation.

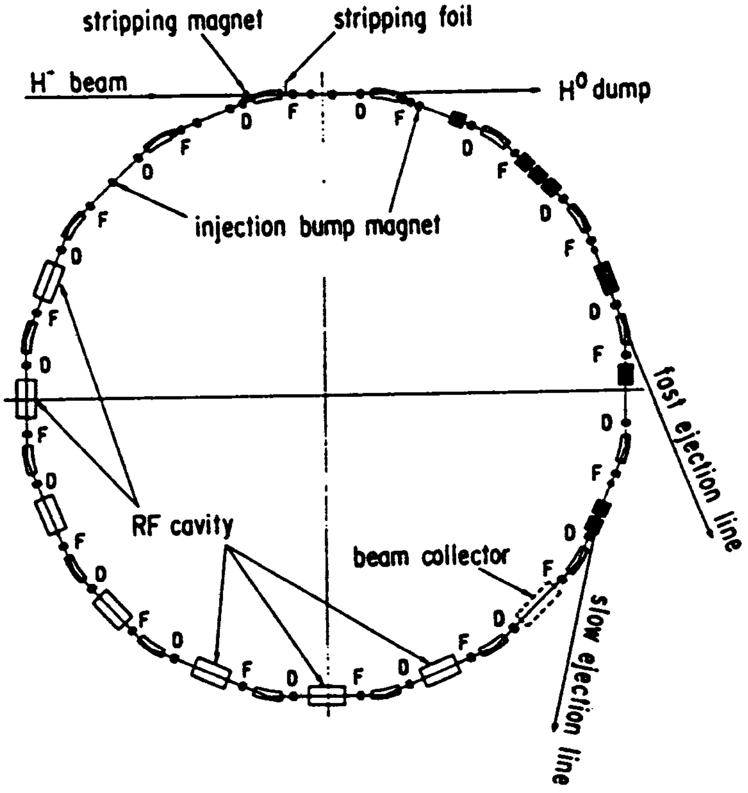


FIGURE 1. Layout of the CSR of 16 superperiod lattice.

One drift space is used to implement the H^0 injection system which is similar to that of the PSR at LANL. The H^- beam is neutralized to the H^0 beam in a stripping magnet with a magnetic field of $1.8T$. The beam is accumulated in the CSR after ionized to protons with a thin carbon foil. The H^0 injection method is simple and has a merit that it is possible to inject the beam even in a short drift space between the bending and quadrupole magnets.

Three drift spaces downstream of the injection point are used to set kickers and septums for the fast extraction. One of characteristics of this fast extraction system is to extract the beam in the vertical direction. The reason of the vertical extraction is that the horizontal beam size becomes too big to extract horizontally in the case of the ultra-short pulse, which has a large momentum spread.

Next two drift spaces include electric and magnetic septums for the slow extraction. Since the repetition rate is as high as 50Hz, the ordinary extraction method of changing the betatron tune with quadrupole magnets is not applicable to the present case. Instead, we have proposed a method to shift the horizontal tune by varying the beam energy with

RF[3]. As the CSR has a natural chromaticity of -4, it is possible to shift the horizontal tune with a momentum variation of 0.8% from 4.30 of injection tune to $4\frac{1}{3}$ of the nearest third-order resonance. The effective thickness of the electric septum seen by the extracted beam mainly determines the beam loss at the extraction point. The beam loss determined by the angular spread of the beam can be minimized by keeping the overlapping condition of outgoing separatricies of different emittances during extraction[4].

There are 17 RF cavities in eight drift spaces. One cavity operated with the frequency of 3.0MHz (h=2) is used to store two beam bunches during accumulation. Other 16 RF cavities are operated with the frequency of 1.5MHz (h=1), since it is suitable to minimize the tail of the bunch caused by non-linear RF wave form[1]. These cavities are designed to generate a voltage of 15kV per cavity. With these cavities, the high voltage of 240kV required to obtain the ultra-short pulse can be generated.

Recently, racetrack lattices which include long straight sections are proposed for special purposes in many accelerators. In the KAON factory at TRIUMF, a racetrack lattice has been proposed for reducing beam loss at the extraction septum. At the septum of the ring named Extender, the beta function is chosen to be 100m. The beam loss ratio is estimated to be about 0.2%. For a second-generation proton storage ring at LAMPF, a racetrack lattice has been also proposed for the direct H^- injection[5]. Also, Rees has pointed out merits of the lattice with long straight sections in his conceptual design of the CSR[6]. Generally speaking, however, there are some demerits when the number of superperiods decreases. For instance, the betatron resonances would be strong and may cause beam loss. Therefore, we have begun the design of a racetrack-type machine and compared it with the high-periodicity machine.

II. DESIGN CONCEPT

The general requirements imposed on the design of the racetrack-type machine are as follows.

1. Both H^- and H^0 injections are possible.
2. Two operation modes of the different time structures mentioned above are possible.
3. Both high β optics for the stretcher mode and normal β optics for the ultra-short pulse mode are possible.
4. The transition energy should not be so high compared with that of the high-periodicity lattice, since higher transition energy requires higher RF voltage for the bunch compression.
5. The fast-extraction in the horizontal direction is possible.

The design layout of the machine is shown in Fig. 2. Main parameters are listed in Table 1. The ring has a racetrack shape. The length of the long straight section is 45m. The numbers of the bending and quadrupole magnets are 24 and 54, respectively. The dispersion in the straight sections is reduced to zero by using the missing bend method. The beta and dispersion functions for the normal β and high β optics are shown in Fig. 3-a and 3-b, respectively. The beam optics near a pre-septum installed for the slow extraction are much different between two operation modes. The horizontal beta functions at the pre-septum are 25m for normal-β optics and 200m for the high β optics. The value of 200m for the high β optics was chosen from a compromise between the turn separation(5cm) of the slow-extracted beam and the horizontal acceptance(±20cm) required for the quadrupole magnets nearest to the pre-septum.

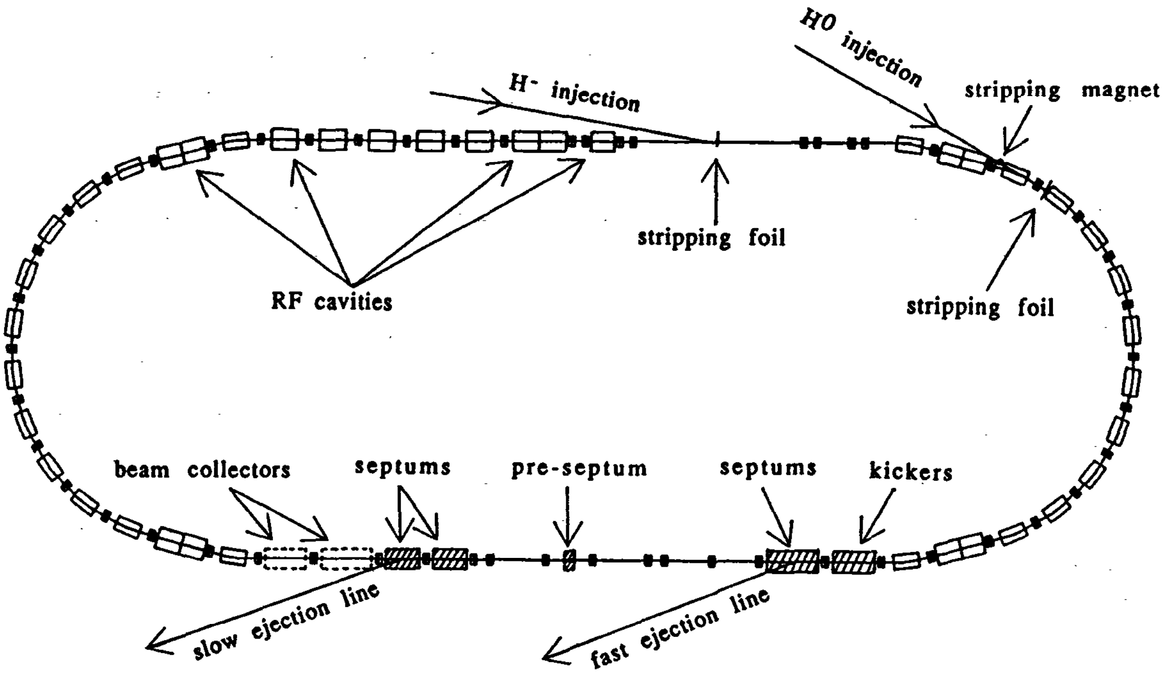
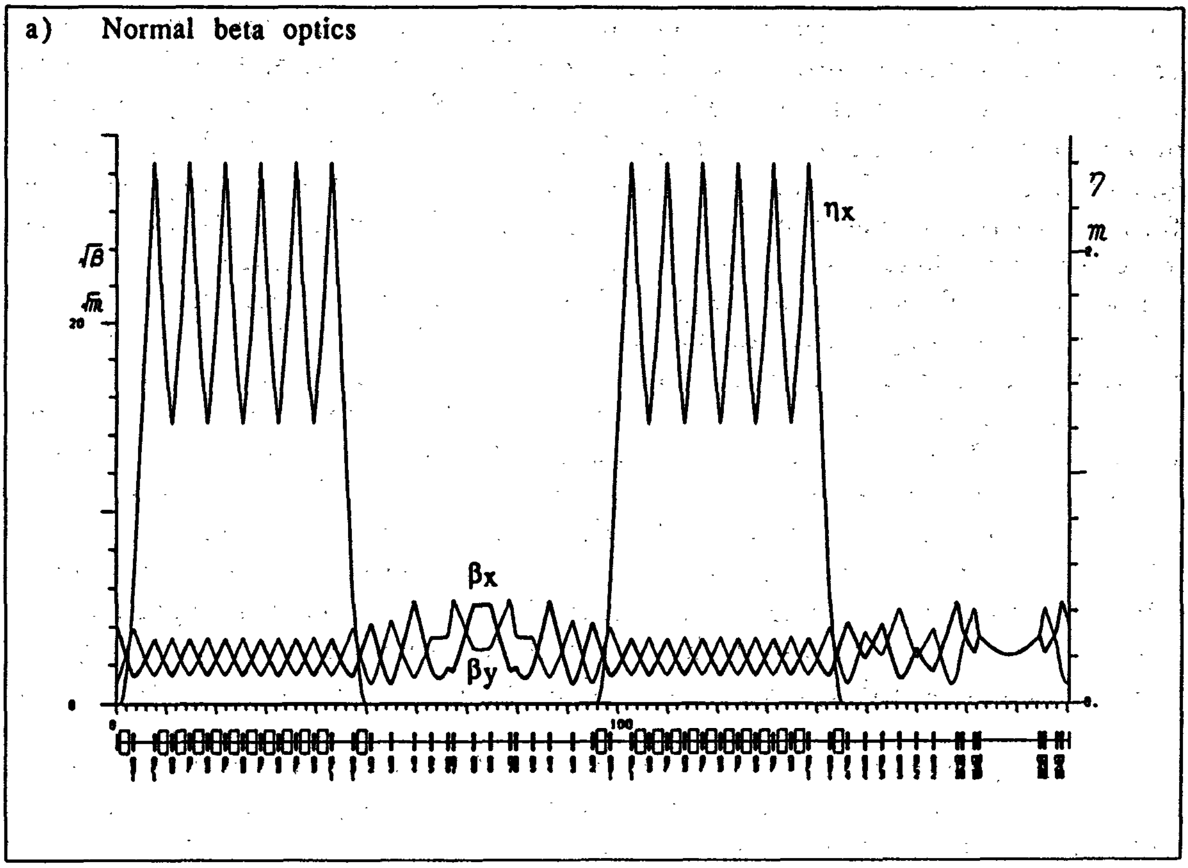


FIGURE 2. The CSR of the racetrack shape

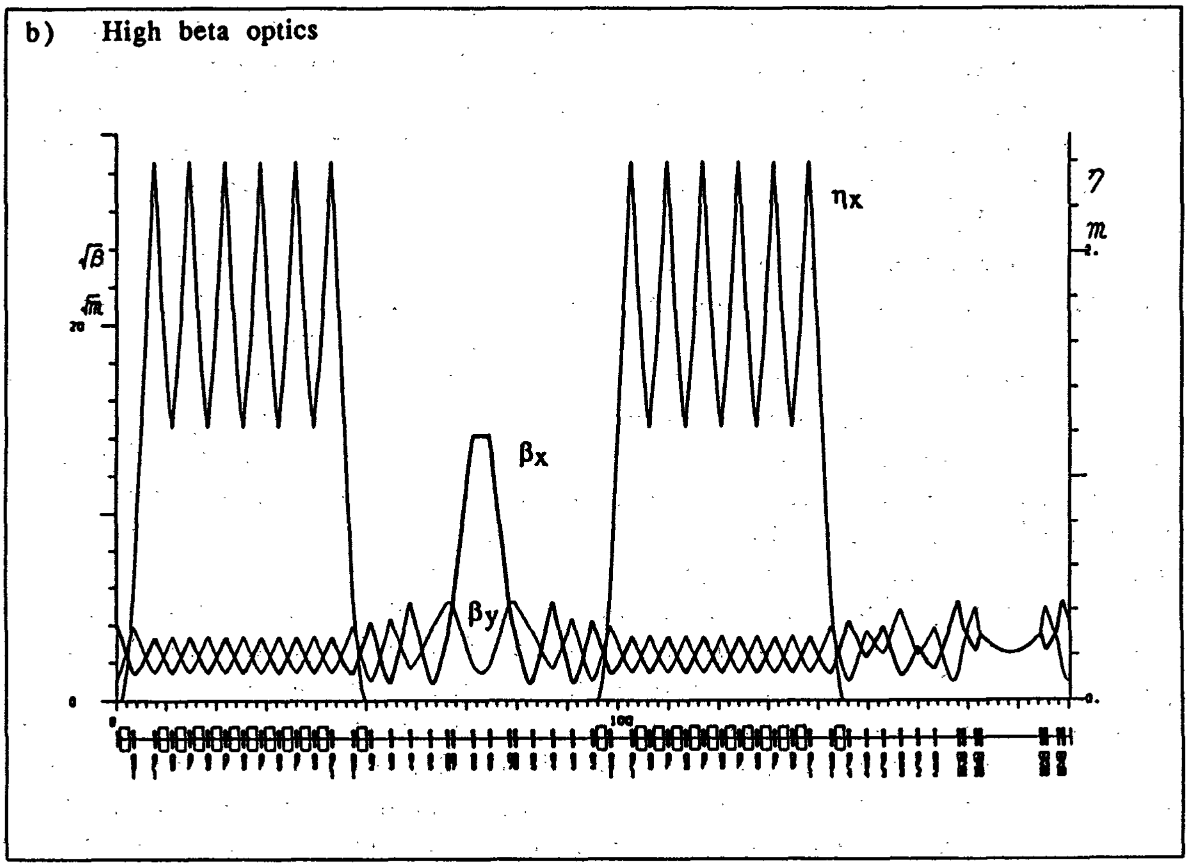
Table 1. Parameters of the CSR of racetrack-type

Energy	$1 GeV$
γ	2.066
Particles per pulse	1.25×10^{13}
Circulation current	$5.5A$
Revolution frequency	$1.4MHz$
Harmonic number (h)	2
Circumference	$190.4m$
RF frequency	$2.8MHz$
Repetition rate	$50Hz$
Average current	$200\mu A$
Horizontal beam emittance(ϵ_x)	$30\pi mm \cdot mrad$
Vertical beam emittance(ϵ_y)	$30\pi mm \cdot mrad$
Horizontal acceptance(A_x)	$120\pi mm \cdot mrad$
Vertical acceptance(A_y)	$120\pi mm \cdot mrad$
Energy spread	±0.2%
Max. momentum spread	±1.0%
Momentum acceptance	±1.5%

Beam optics parameters	High β	Low β
Horizontal tune(ν_x)	6.30(typ.)	6.28(typ.)
Vertical tune(ν_y)	6.21(typ.)	6.23(typ.)
Transition gamma (γ_T)	4.595	4.595
$\eta = (1/\gamma_T^2 - 1/\gamma^2)$	-0.187	-0.187
Horizontal chromaticity(ξ_x)	-13.1	-9.2
Vertical chromaticity(ξ_y)	-9.3	-9.5



a) Normal beta optics



b) High beta optics

FIGURE 3. The beta and dispersion functions in the cases of normal β(a) and high β(b) optics.

When a high intensity beam is stored in a ring, the tune shift arises due to the space charge effect, and it may cause the the beam loss. The horizontal and vertical beam emittances are, therefore, chosen to be $30\pi mm \cdot mrad$(100%), in order to keep the tune shift below an acceptable level of 0.075. The method of phase space painting by means of bump magnets is planned in order to fill the phase space uniformly. The painting method is also useful to reduce the number of foil-hits during injection. Since it is important to decrease the beam loss from the halo of the circulating beam, both horizontal and vertical acceptances are chosen to be $120\pi mm \cdot mrad$, i.e., four times larger than the beam emittance.

One of the two long straight sections is used for injection and RF cavities. A feature of this straight section is that it has a 12m drift space to implement the H^- injection system (an injection septum, a carbon foil, bump magnets etc.). The foil is placed at the center of this drift space. The Twiss parameters, $\alpha_{x,y}$, are chosen to be zero at the foil, because it becomes easy to match the beam optics of the injected beam to that of the ring. With these parameters, the beam is injected parallel with the central orbit of the ring.

If the H^0 injection is adopted, the injection septum is not needed, since the magnetically pre-stripped H^0 beam goes straight in the magnetic field of the bending magnet. Hence, the H^0 injection can be done in a short drift space of the bending section as shown in Fig. 2. In this case, the long drift space can be used to install more RF cavities and some other instruments.

The bending magnet with the bending angle of 22.5 degrees which is designed for the high-periodicity machine is not suitable to use in this racetrack-type machine, since the phase advance per normal cell becomes much larger than 90 degrees if the dispersion is suppressed less than 2.5m. The value of 2.5m is an allowable dispersion in this lattice, as the horizontal beam size increases by 5cm when the momentum spread of the ultra-short pulse becomes ±1% by the compression of the bunch. Therefore, we have adopted the bending angle of 15 degrees. In this case, the phase advance per normal cell and dispersion function become 90 degrees and 2.4m, respectively. Moreover, the horizontal and vertical beta functions in the bend sections become smaller than those of high-periodicity since the distance between two neighboring quadrupole magnets becomes shorter. Therefore, the required magnet apertures also become smaller.

Another long straight section is used for both fast and slow extractions. Kicker and septum magnets for the fast-extraction are located in the drift spaces upstream of the long straight section, as shown in Fig. 2. Since this section is dispersionless, it is possible to extract the beam in the horizontal direction, even for the ultra-short pulse with the large momentum spread. The pre-electric septum for the slow extraction(see Fig. 2) is located at the center of the long straight section where the horizontal beta-function takes the maximum value. The second electric septum and two magnetic septums are located in two free spaces downstream of the pre-septum. Beam collectors in the horizontal and vertical planes would be placed in the remaining two free spaces of the long straight section.

The typical tune values are listed in table 1. The horizontal and vertical tune values of the normal β optics for the ultra-short pulse mode are 6.28 and 6.23, respectively. Since $\eta(= 1/\gamma_T^2 - 1/\gamma^2)$ is smaller by 7% than that of the high-periodicity lattice, seventeen RF cavities are required for bunch rotation. As stated before, the momentum spread is enlarged when the beam is compressed to the ultra-short pulse. Hence, almost zero chromaticity is necessary in order to avoid a large tune spread. However, the dynamic aperture generally becomes narrow, when the chromaticities are corrected with strong sextupole magnets. Therefore, we have checked the effect of the chromaticity correction on the dynamic aperture by using a computer simulation. The result shows that a dynamic aperture is wide enough to store the beam with the emittance of $120\pi mm \cdot mrad$(see Fig. 4-a).

In the high β optics for the slow extraction, the typical horizontal tune value is chosen to 6.30, since it should be near the point of the third-order resonance. The natural horizontal chromaticity of -13.1 is corrected to -8. The value of -8 is taken so as to change the working point easily to the third-order resonance of $6\frac{1}{3}$ with a small energy variation of 0.4%. This energy variation is well inside the momentum aperture of the ring. The dynamic aperture is also larger than the physical aperture as shown in Fig. 4-b.

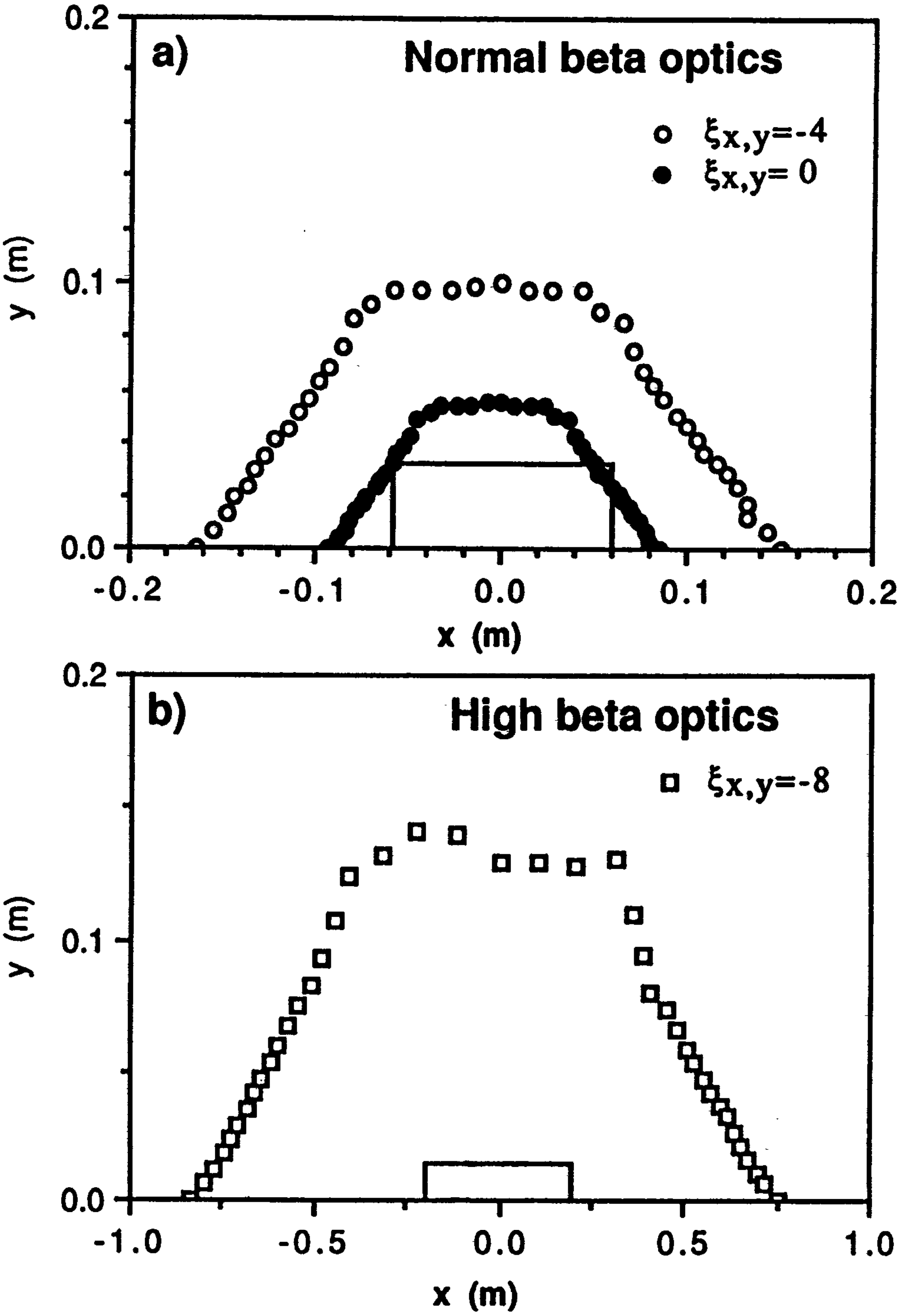


FIGURE 4. The dynamic apertures in normal β(a) and high β(b) optics. The solid line means the acceptance of $120\pi mm \cdot mrad$.

III. INJECTION

Figure 5 shows a scheme of the direct H^- injection[7]. Four bump magnets(B1-B4) are used to produce the bump orbit for phase space painting. The magnetic field of the septum magnet is chosen to be the small value of $0.4T$ in order to prevent H^- from losing an electron with Lorentz stripping during passage through the septum. This weak field requires a drift space as long as 10 to 12m.

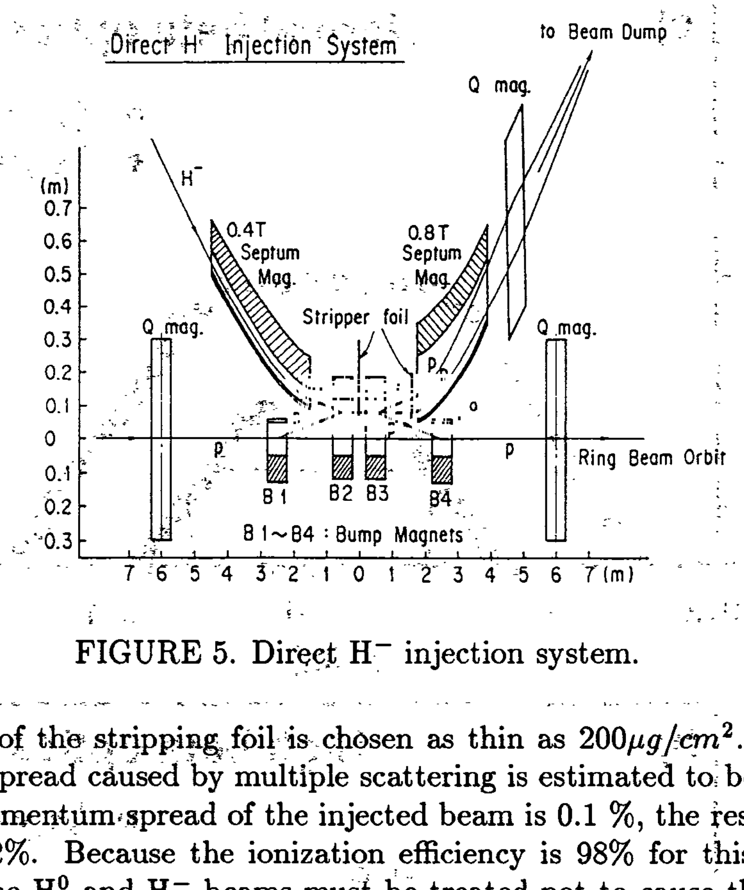


FIGURE 5. Direct H^- injection system.

The thickness of the stripping foil is chosen as thin as $200\mu g/cm^2$. The enlargement of the momentum spread caused by multiple scattering is estimated to be less than +0.1%. Since the initial momentum spread of the injected beam is 0.1 %, the resultant momentum spread becomes 0.2%. Because the ionization efficiency is 98% for this foil, the rest 2% which consists of the H^0 and H^- beams must be treated not to cause the beam loss. The H^0 and H^- beams will be ionized by another foil placed just after the bump magnet B3 and then guided to the beam dump.

IV. FAST EXTRACTION

Figure 6 shows the envelopes of the circulating and extracted beams[8]. As described before, a merit of the ring of the racetrack lattice is that it is possible to extract the beam in the horizontal direction. Five kicker magnets located in the drift space after the bend section deflect the beam into the aperture of the septum magnets in the next drift space. The design value of the total kick angle is $16.3 mrad$. The total bending angle of the septums is designed to be 15.9 degrees. To decrease the beam loss at the extraction septums, the acceptances of the septums are chosen to be 120 $\pi mm \cdot mrad$, which is wide enough for the extracted beam with an emittance of 30 $\pi mm \cdot mrad$.

In the present design, the kickers will generate double-pulsed magnetic fields to fast-extract two bunches for both normal operation mode and ultra-short pulse mode[9]. The interval of double-pulsed excitations is chosen to be about 100μs, and the rise and fall times of the kickers are designed to be 100ns in order to extract one bunch without affecting another circulating bunch[1].

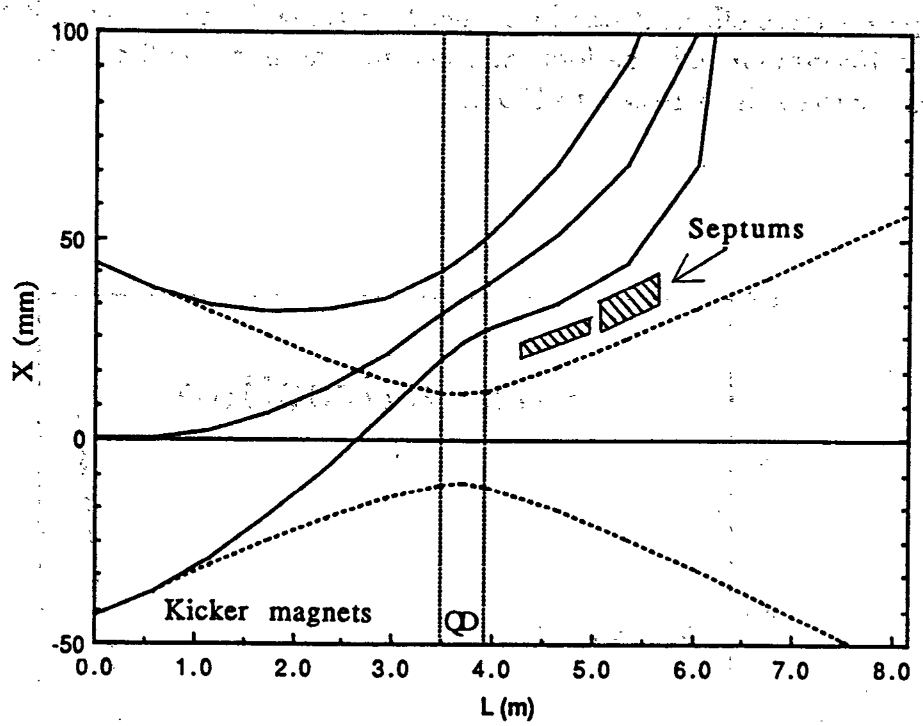


FIGURE 6. The beam envelopes of the kicked(solid lines) and non-kicked circulating(dashed lines) beams near the kickers for the fast extraction.

V. SLOW EXTRACTION

One merit to use high β optics is that it is possible to obtain a large turn separation such as 5cm of the present design. Another merit is that the angular spread of the beam at the pre-septum becomes small, so that the effective thickness of the pre-septum decreases, i.e., the beam loss can be reduced. Since the angular spread of the beam is small for the high β optics, the overlapping condition mentioned above is no longer necessary for the present design.

In the present design, the particles that enter the pre-septum with an electric field of 24kV/cm and go through its full distance are kicked by 0.7mrad. The envelopes of the kicked and circulating beams just before the extraction are shown in Fig.7. The second electric septum and the first magnetic septum are set at the position about $7m$ downstream of the pre-septum. The separation between kicked and circulating beams becomes about 3mm at the second electric septum, by which the kicked beam is further kicked by 8.0mrad and led to the magnetic septums. By the first magnetic septum the beam is kicked by 25mrad, and finally by the second septum it is deflected by 200mrad and then extracted from the ring.

By assuming that the pre-septum is 50μm thick and the angular spread of the extracted beam is 0.35mrad, the ratio of the beam loss during the extraction process is estimated to be 0.45%. This ratio is smaller than 1%, the expected value for the high-periodicity machine. Even with the small ratio of the beam loss, however, for the average current of 100μA the loss current becomes 0.45μA, which is still too much from the point of the accelerator operation and maintenance. If the acceptable loss current is to be less than 0.1μA, the beam current should be less than 22μA. However, the beam loss ratio can be further reduced. For instance, this reduction can be made by decreasing the angular spread of the beam, since the loss ratio mainly depends on the angular spread due to the emittance of the circulating beam. Since the bean emittance is determined by the allowable amount of the tune shift due to the space charge effect, it can be reduced for a low beam current. If the emittance is taken to be $10\pi mm \cdot mrad$, the loss ratio becomes as small as 0.3% and the maximum allowable beam current is increased to 33μA.

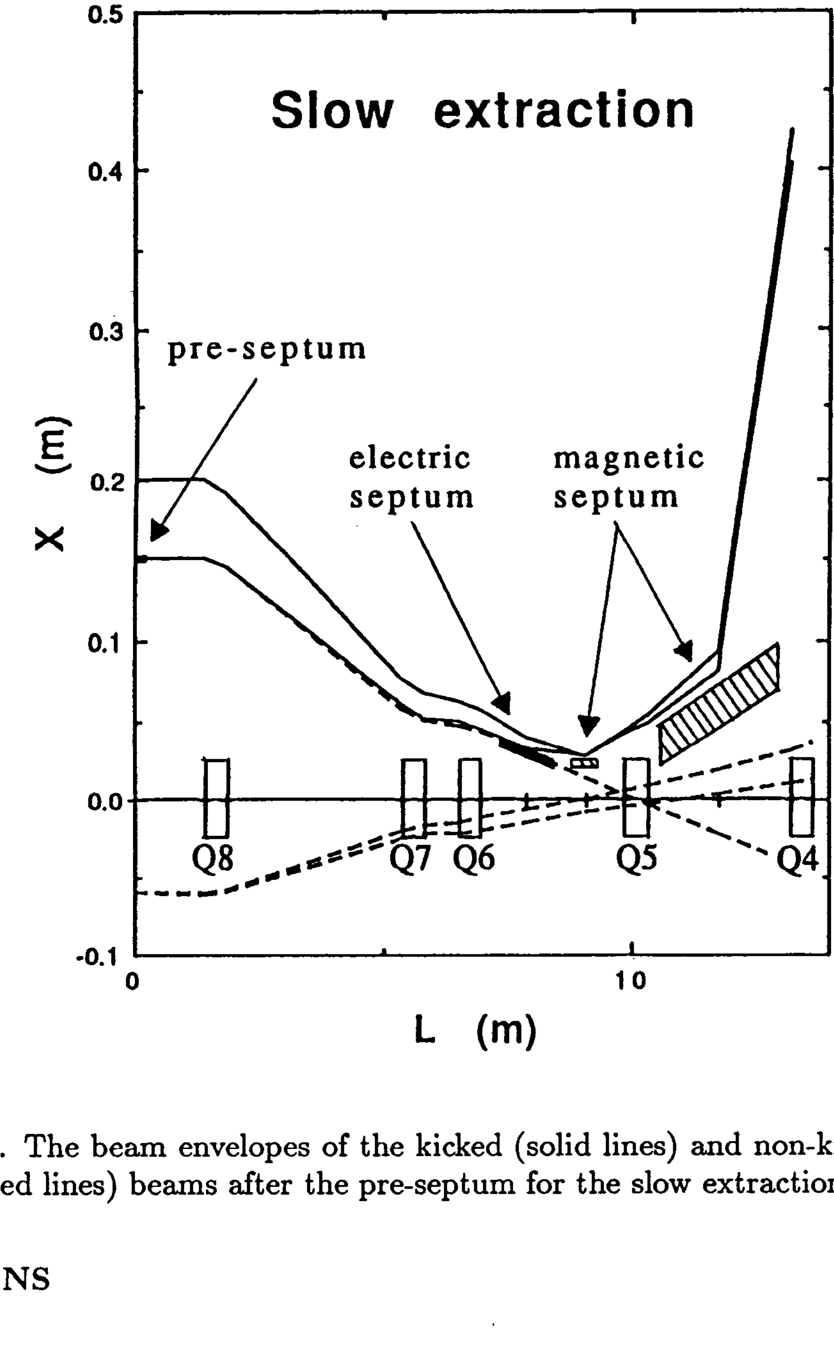


FIGURE 7. The beam envelopes of the kicked (solid lines) and non-kicked circulating(dashed lines) beams after the pre-septum for the slow extraction.

CONCLUSIONS

The design work of the racetrack-type machine has been begun. By changing the machine lattice from high-periodicity to the racetrack-type, we can obtain the following advantages. It is possible to introduce into the ring a long drift space required to implement the direct H^- injection. The beam can be fast-extracted in the horizontal direction, since the long straight section is made dispersionless. By adopting a high β optics, the loss rate for the slow extraction can be reduced.

In the calculation of the dynamic aperture, we can find the suitable operation point to store the beam for both stretcher mode and ultra-short pulse mode. In order to optimize the machine parameters, further studies will be continued.

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