THE JAPANESE HADRON FACILITY

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Abstract

The present status of the design and R&D works for the accelerators of Japanese Hadron Facility(JHF) are expressed.

1 INTRODUCTION

The Japanese Hadron Facility (JHF) consists of the following three accelerators;[1]

(1) main ring:50 GeV proton synchrotron (50 GeV PS)

(2) booster:3 GeV proton synchrotron (3 GeV BS)

(3) injector:200 MeV proton linear accelerator (200 MeV linac)

The accelerators will be constructed at the north site of KEK. The first stage of beam acceleration is provided by the linac, which accelerates H^- ions up to 200 MeV. The expected peak beam current in the injector linac is at least 30 mA and the pulse duration and the repetition rate of the beam are more than 400 msec and 25 Hz (50 Hz in future), respectively. The H^- beam is injected into the booster by charge-exchange multi-turn injection and accelerated to 3 GeV. The 3 GeV booster will be constructed in the existing tunnel for the present KEK proton synchrotron (PS) main ring. All of the components of the KEK PS main ring, such as dipole magnets, quadrupole magnets, vacuum chambers and others will be removed. The booster is a fast cycling proton synchrotron with a repetition rate of 25Hz. The expected beam intensity in the booster is $5x10^{13}$ ppp (protons per pulse), therefore, the average beam current becomes 200 mA. The total power of the extracted beam from the booster reaches 0.6MW. The 3 GeV protons are supplied to three experimental facilities; a pulsed spallation neutron source facility (N-arena), a meson facility (M-arena) and an unstable nuclei facility (E-arena), and to the 50 GeV main ring (K-arena).

Protons from the booster are injected into the main ring and accelerated to 50 GeV. The expected beam intensity in the main ring is $2x10^{14}$ ppp and the repetition rate is about 0.3 Hz. The 50 GeV protons are extracted by slow and fast extraction schemes into two experimental areas; one is for experiments using secondary beams (K, pbar, etc.) and primary beams by slow extraction, and the other is for the neutrino oscillation experiment by fast extraction. When it is operated in a slow extraction mode, the average current and duty factor, which is defined as a fraction of a cycle when beam are available, are 9.4 mA and 0.20, respectively. In addition to acceleration of high intensity protons, heavy ion and polarized proton beams are also requested. Using the 500 MeV booster of the KEK PS as an injector of the 3 GeV booster, it becomes feasible to accelerate these particles.

Typical machine cycle structure is illustrated in Fig.1. Four batches from the booster is injected into the main ring when the main ring stays low field. The 16 buckets out of 17 are filled with beams. Then, the main ring starts acceleration while three other facilities start using 3 GeV beams directly from the booster. Table 1 shows the main parameters of the whole accelerator complex.

2 50GEV MAIN RING

2.1 Lattice Design

The symmetry of the lattice is 4 because of the following requirements. There will be two major physics experimental area downstream. One uses slow extracted beams and the other does fast extracted beams. Slow extraction channel needs a long straight section of more than 50 m to realize a low loss extraction. In addition, abort channel of beams at and slightly above the injection energy needs another long straight section. A long straight section is also needed for RF cavities. The total required RF voltage is estimated as at least 270 kV. With an accelerating field of 10 kV/m, a total length for RF cavities is 27 m. The maximum field strength of bending magnets is 1.8 T and its length is 6.2 m. The field gradient of quadrupole magnets is 20 T/m at maximum and its length is 1.5 m and 2 m depending on a family. The coaxial type RF cavities with high permeability material will be used in the frequency range of a few MHz. The beam transfer line from the booster merges the main ring at one of the missing bend cells in an arc. The beams are injected vertically using some kicker magnets.

Table1: Main parameters of accelerator complex.

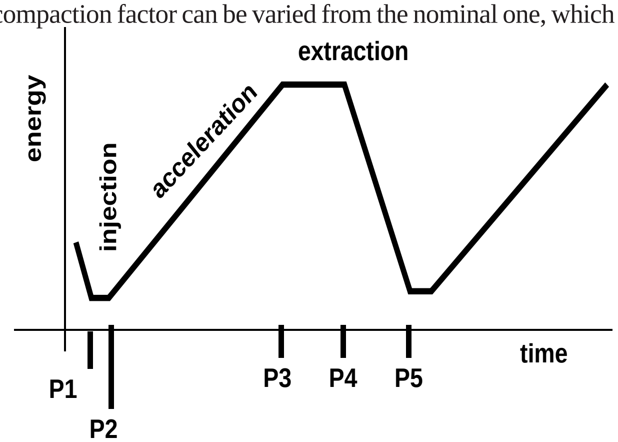
200 MeV linac		
	beam emittance	320 πmm-mrad
	accelerated particle	H^-ion
	peak beam current	>30(50)mA (25Hz,400μs)
3 GeV booster		
	beam emittance	54 πmm-mrad
	intensity	$5x10^{13}$ppp
	repetition rate	25Hz
	beam power	0.6MW
	RF frequency	1.99-3.43MHz
	RF voltage	420kV
	circumference	340m(KEK-PS tunnel)
50 GeV main ring		
	beam emittance	4.1 πmm-mrad
	intensity	$2x10^{14}$ppp
	repetition rate	0.3Hz
	RF frequency	3.43-3.51MHz
	RF voltage	270kV
	momentum compaction	$\sim$-10^{-3}
	circumference	1445m (north site of KEK)

The booster delivers a batch of 4 bunches every 40 ms when it is operated in 25 Hz. Because the circumference of the main ring is 17/4 times that of the booster, 4 booster batches fill 16 buckets of the main ring. One empty bucket is left and it is reserved for necessary time period for excitation of extraction kicker magnets.

In order to achieve high beam intensity and low beam loss in the 50 GeV PS, the following considerations are taken in its design.

(1)Imaginary transition γ lattice

The imaginary transition γ lattice means that the momentum compaction factor is negative and beams never cross transition energy which might cause a large fractions of the beam loss. The betatron oscillation amplitude and dispersion functions are depicted in Fig. 2. We adopted the missing bend scheme which make transition γ imaginary. The basic unit of the lattice is 3 FODO cells. There is no bending magnet in the middle FODO cell, therefore it can be represented as (D/2)BFBDOFODBFB(D/2). We adjust the middle FODO cell length and the strength of 4 quadrupole families, 2 for focusing and 2 for defocusing, to achieve imaginary transition γ. The magnitude of the momentum compaction factor can be varied from the nominal one, which



slow extraction of 50GeV

P1 - P2(injection)	0.12 s
P2 - P3(acceleration)	1.9 s
P3 - P4(extraction)	0.7 s
duty factor	0.20
P4 - P5	0.7 s
total	3.42 s
average current	9.4μA

Fig.1: Typical machine cycle of the main ring.

is determined by horizontal tune, on positive side to slightly less than -0.01 on negative side. When it is too close to zero, higher order effects, such as the momentum compaction factor depending on $(\Delta p/p)^2$ and on space charge tune shift, become relatively large and the lattice is unstable. On the other hand, when its magnitude becomes too large, the betatron oscillation amplitude and dispersion functions tend to diverge, resulting in smaller transverse acceptance. We choose the momentum compaction factor of -0.001 as a nominal value, which gives moderate lattice functions.

(2)Selection of phase advance

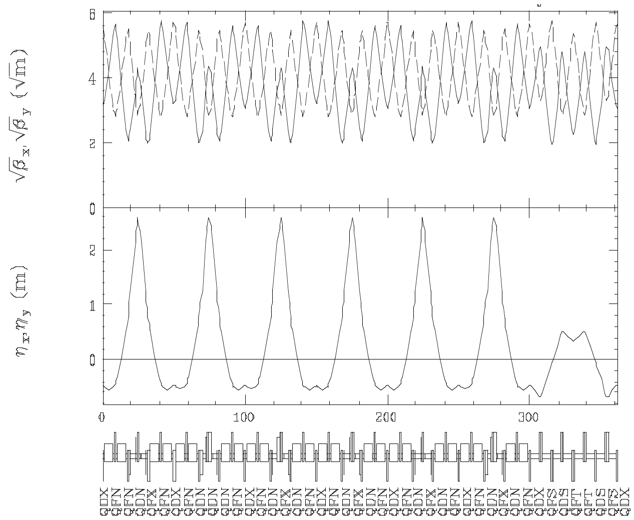


Fig. 2: Betatron oscillation amplitude and dispersion functions in the main ring. The solid line in the top is the horizontal betatron oscillation amplitude and the dashed line is the vertical one. In the bottom picture, the vertical dispersion is zero and the other curve is the horizontal one. One quarter of the ring is depicted.

Self space charge force excites strong resonance coupled with beam envelope modulation if the phase advance is just above 90 degrees[2]. The space charge induced resonances can be cured only by careful tuning of the transverse phase advance. The horizontal phase advance is below 90 degrees and the vertical one is far below 90 degrees making the tune of (21.8, 15.3) in total.

(3)Room for slow extraction hardware

In order to reduce beam loss less than 1 % at the extraction, careful design and simulation are in progress as explained later. At least 50 m long straight section is necessary to put electric and magnetic septa. If that is still not enough, we have an option of putting a pre-septum magnet in the missing bend cell in the preceding arc.

(4)Tunability of the transverse tune

The lattice should have tunability in transverse tunes and stability in lattice functions together. More specifically, the betatron oscillation amplitude and dispersion functions should not change much at least within the tune of +-1 around the nominal tune. In addition, the momentum compaction factor is supposed to be almost constant within the similar tuning range. With the same lattice, by tuning the quadrupole strength such that the phase advance in the arc is equal to integer, the dispersion free long straight can be created.

2.2 Emittance and Acceptance

In order to see whether the main ring has an enough acceptance to accommodate the emittance above, the acceptance is calculated for off momentum particle of 0.5 % with closed orbit distortions (COD) introduced by quadrupole mis-alignments. The distribution of misalignment errors is Gaussian whose rms value is +-0.3 mm. The magnitude of errors more than 2 σ is eliminated. With steering magnets next to each quadrupole magnet, one for each plane, and beam position monitors, one for both planes, the COD correction is performed. The corrected COD is about ±0.5 mm and the acceptance becomes more than 60 π.mm.mrad. Here we assume a beam pipe of 100 mm diameter. It is less than 40 π.mm.mrad without correction.

From the beam instability point of view, the longitudinal emittance should be more than 3 eVs. On the other hand, that of the booster is 0.6 to 1 eVs, which is obviously not big enough. The larger longitudinal emittance also helps reduce transverse space charge effects because of the higher bunching factor. Therefore, we will blow up the longitudinal emittance either during the acceleration of the booster, or right after the injection of the main ring. With the longitudinal emittance of 3 eVs and the RF voltage of 270 kV, the bunching factor becomes 0.28 and the incoherent and coherent space charge tune shifts are -0.08 and -0.04, respectively. That is not negligible, but small enough.

2.3 Chromaticity Correction and Dynamic Aperture

Since the transition energy is imaginary, operation from the injection to the extraction is always below the transition energy, namely the slippage factor is always negative. The zeroth mode of the head tail instability and negative mass instability are stable with negative chromaticity. The natural chromaticity makes the tune spread due to momentum dispersion too high, the order of +-0.1, so that chromaticity correction is planned, even though it is not necessary to correct it to zero. The chromaticity correction introduces strong nonlinearity by the sextupoles. We have looked at tune shift due to amplitude and the dynamic aperture. The dynamic aperture is defined as the maximum amplitude of particle which survives for 10,000 turns at the flat bottom energy. The sextupoles are excited to make the both chromaticity zero in that test. The tune shift is small and the dynamic aperture is more than 200 π.mm.mrad, that is large enough compared with the physical aperture of 54 π.mm.mrad. The momentum dependence of the dynamic aperture within the range of +-0.5 % is negligible.

2.4 Space Charge Effects

Incoherent space charge tune shift at injection is -0.1 at most even though the total number of particles are $2x10^{14}$. At 3 GeV, coherent space charge tune shift becomes not negligible but still less than -0.05. Those value seems not too difficult to deal with, but still careful beam handling is necessary to reduce beam loss. An upgrade plan is already discussed with 2nd harmonic cavities or barrier bucket system. By those additional installations, the space charge tune shift can be even lower than -0.1 and the increase of the beam intensity becomes feasible. More detailed study using multi-particle tracking is in progress.

2.5 Slow Extraction

In an ordinary slow extraction, particles with a large betatron amplitude caused by a resonance are deflected outward by an electric septum. Then, they are extracted from the ring by a chain of magnetic septa. For a high current proton accelerator such as the 50 GeV PS, even a small beam loss in those process will lead to unacceptable levels of radiation. We set a criterion such that tolerable beam loss in the slow extraction process should be less than 1 % for a 10 μA average current. For the present design of the main ring, beam loss process was examined by beam simulations. The third integer resonance was chosen to increase the betatron amplitude of the particles. In this calculation, the septum thickness is chosen to be 50 μm. It is feasible if we consider the deformation of the wires as well as the nominal thickness of the wires. The beam loss less than 1 % is achieved by selecting the septum length less than 1 m and the resonance strength of greater than S=1.5.

There are several new methods to reduce the beam loss. A TRIUMF group has proposed ‘an electric pre-septum’ [3]. A LANL group has proposed a new magnet with two pairs of magnetic poles with opposite magnetization directions [4]. Recently a new extraction scheme has been proposed in Japan and successfully tested in several facilities [5]. In this method, the separatrix is kept in constant by fixing the betatron tune near the resonance and the horizontal emittance of the circulating beam is increased by a transverse RF field. The angular spread of the beam extracted from the constant separatrix is expected to be very small. We would be able to reduce beam loss at the first septum by using this method. The combination of this method and the electric pre-septum scheme mentioned above is also very effective to reduce the beam loss drastically.

2.6 Magnets and Power Supplies

The main ring consists of 96 bending magnets, 176 quadrupole magnets, and 48 sextupole magnets. Main parameters for magnet design are summarized in Table 1. Based on these requirements, a bending magnet, a quadrupole magnet and a sextupole magnet have been designed.[6]

2.7 *RF system*

The RF voltage cycle is calculated by RAMA. It requires 270 kV, for whole injection and acceleration periods. In order to avoid negative mass and microwave instabilities, the longitudinal emittance is increased during injection. The emittance becomes 3 eVs after increasing the longitudinal emittance. [7] The room placed for the RF cavity in the ring is limited. The requirement for RF voltage per unit length has to be at least more than 10 kV/m. As the practical length of the RF cavity is 3 to 4 m, the required voltage per cavity is about 40 kV. The requirements of RF system performance are summarized in Table 2 Since the beam intensity is very high and harmonics number is 17, beam loading effects and coupled bunch instability are significant problems.

A number of wide band cavities using fine-crystallized soft-magnetic core, “FINEMET”, are going to be employed in the main ring. This material is made of a thin layer of soft magnetic tape and has a very high permeability. Although the Q value is relatively small (Q~1), the shunt impedance (=μQf) is fairly large. The characteristics are independent of the RF magnetic field as shown in Fig.3.Since the Curie Temperature of the material is about 600C, a stableoperation at high temperatures is possible.

Development of this new type of the RF cavity has been started and recently, wwe have succeeded in obtaining the RF voltage pwr unit length of about 10kV/m.[8] The

Table 1: Main parameters for design of the main ring magnets

Bending Magnet		
	Magnetic Rigidity	12.76 - 170 Tm
	Field	0.135 T (for 3 GeV)
		1.8 T (for 50 GeV)
	Length	6.2 m
	Number	96
	Active Peak Power	54.0 MW
	Dissipation Power	12.0 MW
	Cooling Water	8.5 ton/min.
Quadrupole Magnet		
	Max. Field Gradient	20 T/m
	Length	1.5 - 2 m
	Total Number (8 families)	176
	Active Peak Power	24.0 MW
	Dissipation Power	7.0 MW
	Cooling Water	5.0 ton/min.
Magnet Aperture		
	B-Magnet 106 mm^h x (106 mm^w for useful)	
	Q-Magnet	132 mm^f

wide band cavity is also suitable to cure the coupled bunch instability as described in the section of beam instabilities.

3 3GEV BOOSTER

3.1 Lattice Design

Since the 3 GeV ring will be constructed in the present KEK PS tunnel, it imposes some geometrical constraints on the lattice. In addition, the high intensity operation requires a few essential cares on the optics. The circumference and superperiodicity should be very similar or the same as the present KEK PS. That is 340 m and 4, respectively. More specifically, the number of the total cells and the local curvature of the arc must be similar to that of the KEK PS, since the width of the tunnel cross section is only 4 m. There should be empty cells to install many rf cavities. The 3 GeV ring repetition is initially 25 Hz and supposed to be upgradable to 50 Hz. The minimum required rf voltage for 25 Hz operation is 420 kV. The straight section of 40 m or more in total is necessary for rf cavities provided that the accelerating field of more than 10 kV/m will be available. For 50 Hz operation, the necessary length of the straight section will be doubled. In order to install injection components including steering magnets for H- painting, one half cell is required. For extraction, 3 half cell is also required for one extraction channel. 6 half cells are then required for N arena and for E, K, and M arenas. In addition, the beam scraper and collector system, those are separated for about

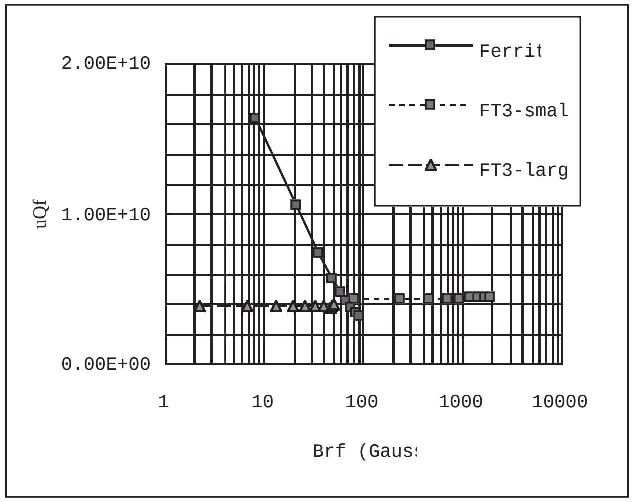


Fig.3: Characteristics of large and small FINEMET(FT3) and typical ferrite cores

180 degree phase advance, needs 4 half cells. The flexibility of adjusting transverse tune with minimum modulation of betatron oscillation amplitude and dispersion functions is desired. The tuning range of a few integer units in both horizontal and vertical planes is expected. Transition energy crossing must be avoided because the beam loss associated with it is inevitable. The higher transition energy, therefore the smaller momentum compaction factor, is also helpful from view point of the longitudinal matching between the 3 GeV and the 50 GeV ring.

In order to satisfy the above-mentioned conditions, a flexible momentum compaction (FMC) lattice has been studied in detail (Fig. 4). The FMC lattice consists of 28 FODO cells as total. The basic unit is 2 FODO cells with 2 bending magnets in the outer half cell. It can be represented as (F/2)BDOFODB(F/2). Three of them together with 1 FODO cell without bending magnets make a superperiod. Consecutive half cell without a bending magnet provides the place for the extraction. The whole ring consists of 4 identical superperiods such that the ring fits in the present KEK PS tunnel. The horizontal phase advance per 2 FODO cells is chosen above 180 degrees, but not too close to 180 degrees, in order to realize FMC. Those adjustments requires 2 focusing quadrupole families and 1 defocusing quadrupole family. The momentum compaction factor can be varied from almost zero to 0.009, which corresponds to 10 or higher in terms of transition gamma. The second order effects on the momentum compaction factor which come from the $(\Delta p/p)^2$ term is also examined and it turns out negligible unless it is too close to zero. We choose 0.006 as the nominal value of the momentum compaction factor. The betatron oscillation amplitude and dispersion functions in the tune range of +-1 around the nominal tune is examined. The tune depen-

Table 2: RF System requirements.

RF amplitude	40 kV (per cavity)
Harmonic Number	17
Number of Bunches	16
RF Frequency at injection	3.4 MHz
RF Frequency at extraction	3.5 MHz
Intensity per bunch	1.25 X 10^{13}
Total Gap Impedance	8 kW
Beam Intensity	6.4~6.6 A
Ib	12.8~13.2 A
Acceleration Time	1.9 s
Max. Beam Power	132 kW
Max. fs	30

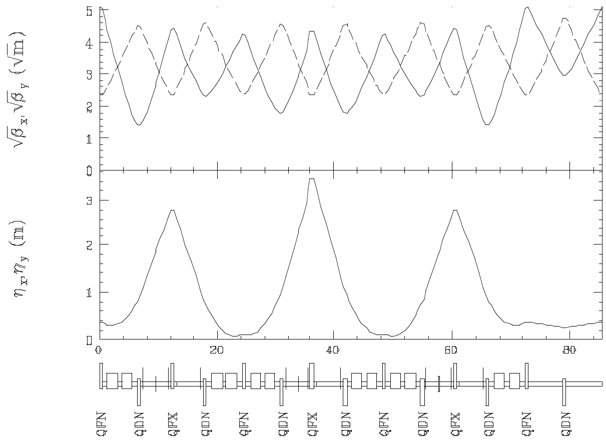


Fig. 4 Flexible momentum compaction (FMC) lattice for the 3GeV booster.

dence of those functions are marginal.

One of the distinguished features of this lattice is that it can provide the additional knob to control the momentum compaction factor. Then it becomes easier to match optically in the longitudinal plane between the 3 GeV and the 50 GeV rings, and to increase synchrotron oscillation frequency to introduce Landau damping. We have also looked into the alternative lattices, namely two options of normal 28 FODO cell lattice, and normal 24 FODO cell lattice. The both normal 28 FODO cell lattices (second and third options) fit most in the KEK PS tunnel simply because the tunnel has originally made for the present 28 cell KEK PS lattice.

3.2 Synchrobetatron Coupling Resonances

Because of the fast cycling nature, the required rf voltage is relatively high, resulting in high synchrotron tune, 0.015 at the injection energy. The synchrobetatron coupling resonance due to dispersion at the rf cavity location becomes one of major concerns to design the 3 GeV ring. Because there is large tune spread due to space charge effects, the transverse tune of some particles in a beam is close on a integer and resonance condition with small number of *m* may be satisfied. We have looked at the rms emittance growth and beam loss due to synchrobetatron coupling resonances by a full 6-D particle tracking. The FMC lattice was taken and multi-particles tracking has been done. When the harmonic number is 4 and synchrotron tune is around 0.015, no rms emittance growth or beam loss has been observed below the horizontal tune of 7.85 even though all the cavities are located at one position so that any cancellation due to symmetry occurs.

4 200MEV LINAC

A 200-MeV proton linear accelerator for the JHF consists of a 3-MeV radio-frequency quadrupole linac (RFQ), a 50-MeV drift tube linac (DTL) and a 200-MeV separated-type drift tube linac (SDTL).[8] An rf frequency of 324 MHz has been chosen for all of the rf structures. An expected peak current of 30 mA for H^- ion beam of 400 μsec pulse duration will be accelerated at a repetition rate of 25 Hz. One of the design features is its high performance for a beam-loss problem during acceleration. It can be achieved by separating the transition point in the transverse motion from that of the longitudinal motion..

The features of the design are as follows:

1. A frequency of 324 MHz has been chosen for all of the rf structures up to 200 MeV.
2. An SDTL has been chosen in an energy range from 50 to 200 MeV.
3. A 3-MeV RFQ has been chosen.
4. A transition energy of 150 or 200 MeV from the SDTL to the ACS has been selected.
5. The klystrons are used for all of the accelerating structures.

Acknowledgment

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