THE DESIGN AND R&D WORKS FOR THE 50-GEV SYNCHROTRON OF JAPAN HADRON FACILITY

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Abstract

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

1 INTRODUCTION

The accelerators of Japan Hadron Facility (JHF) will be constructed at the north site of KEK. [1] 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 5×10^{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 2×10^{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.

2 DESIGN STUDY

2.1 Imaginary transition γ lattice

Protons are accelerated from 3 GeV to 50 GeV in the main ring. At the top energy of the 50-GeV main ring, γ is 54.3. In a conventional way of designing a lattice using a regular FODO cell, the transition γ approximately equals the horizontal betatron tune (ν_x). In a machine of this scale, because ν_x is about 20-30, it is difficult to avoid the transition energy in the regular FODO lattice. Although techniques of the transition energy crossing have been developed in many operational proton synchrotrons, it is favorable to place the transition energy, where the phase focusing becomes zero, well above the top energy, avoiding the instabilities and associated beam losses. Thus, an imaginary transition γ lattice, in which the momentum compaction factor is negative, is employed.

The momentum compaction factor is given by

$$\alpha = 1/\gamma_t^2 = 1/C \oint_C \eta(s)/\rho(s)\,ds = \nu_x^3/R \sum_{n=-\infty}^{\infty} |a_n|^2 / (\nu_x^2 - n^2) \quad (1)$$

and $a_n = 1/2\pi \int_0^{2\pi} \beta_x(\phi)^{3/2} / \rho(\phi) \exp(-in\phi)\,d\phi.$ (2)

Here, $\eta(s)$ the dispersion function, $\rho(s)$ the bending radius at the orbit position of s in the ring, C the circumference of the ring, and R the average radius of the ring. ν_x, β_x and ρ are the horizontal betatron tune, the horizontal beta function and curvature, respectively. To make the momentum compaction factor negative, either β_x or ρ should be modulated properly. In order to avoid a bigger beam size, ρ modulation while invoking the missing bend sections in each arc of the ring is better than β_x modulation, although the ring circumference becomes slightly large. In the ρ modulation scheme, the momentum compaction factor and the dispersion function can be estimated analytically.[2] If each arc of the ring comprises periodic modules and each module consists of several FODO lattices, a negative momentum compaction factor can be obtained by choosing the total phase advance of the module as

$$\phi > 2\pi \sqrt{1/\{1 + 2\sin^2(\xi)/\pi^2(1-\xi)^2\}}. \quad (3)$$

Here, ξ is the ratio of the missing bend length to the total module length. If ξ is 1/3, for example, the momentum compaction factor becomes negative when the total phase advance (ϕ) is > 0.83 x 2π. In the 50-GeV main ring, the superperiodicity is four and each arc section consists of six modules. Each module has three FODO cells starting from a defocusing quadrupole. In the center cell of the module, there is no bending magnets (missing bend cell). Thus, ξ is about 1/3.

In order to control the chromaticity, two or three families of sextupole magnets are placed at the middle of the module in the arc. The operation is under the transition energy because the momentum compaction factor is negative, and it is not necessary to correct the machine chromaticity zero.

The acceptance is calculated for off momentum particle of 0.5 % with closed orbit distortions (COD) introduced by quadrupole mis-alignments. The corrected COD is about ±0.5 mm and the acceptance becomes more than 60 π.mm.mrad. [3]

Since the transition energy is imaginary, the zeroth mode of the head tail instability and negative mass instability are stable with negative chromaticity. The sextupoles are excited to make the both chromaticity zero. 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.

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. An upgrade plan is already discussed with 2nd harmonic cavities or barrier bucket system.

3 HARDWARE R&D STUDIES

Various R&D studies of hardwares concerning each accelerator have been going on. Among them, two items of the R&D relating the 50-GeV main ring will be presented in this paper.

(1) High gradient RF cavity using high permeability magnetic alloy and beam loading compensation system
(2) The main ring dipole magnet and the power supply using IGBT for the main ring magnets

3.1 High gradient RF cavity using high permeability magnetic alloy and beam loading compensation system

The required RF voltage is about 270 kV for whole injection and acceleration periods in the 50-GeV main ring. 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. 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 10-13 kV/m. Since the beam intensity is very high and harmonics number is 17, beam loading effects and coupled bunch instability are significant problems.

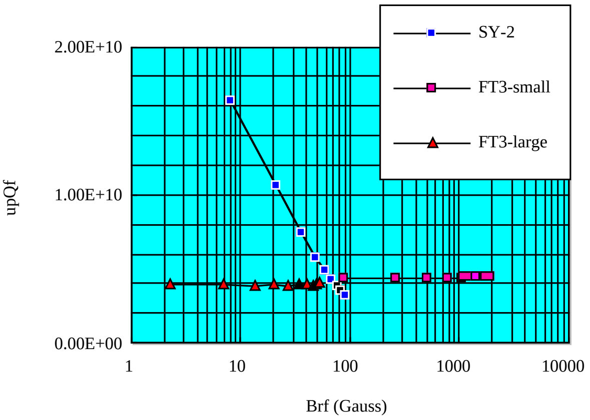

Fig.1 Dependence of the µQf-product on the RF magnetic field strength.

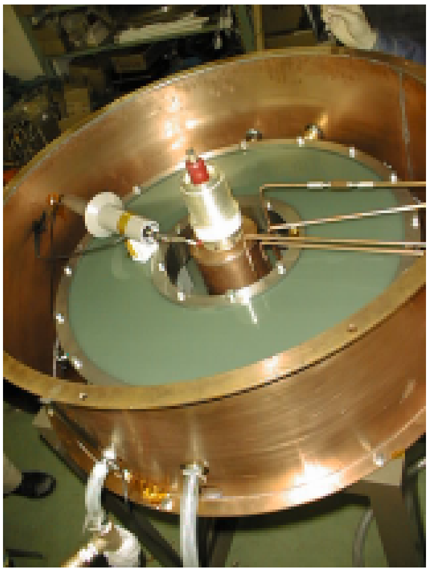

Fig. 2 Photogragh of the single core test cavity. The core is directly cooled by purified water.

A number of the high gradient RF cavities using high permeability soft magnetic alloy core such as “FINEMET” and “METGLAS”, are going to be employed in the main ring. These materials are made of a thin layer of soft magnetic tape and has a very high permeability. Although the Q value is relatively small (Q=1~5), the shunt impedance (=µQf) is fairly large. The characteristics are independent of the RF magnetic field as shown in Fig.1. Since the Curie Temperature of the material is about 600C, a stable operation at high temperatures is possible.

Development of this new type of the high gradient RF cavity has been started and recently, we have succeeded in obtaining the RF voltage per unit length of more than 100kV/m.[4,5] The relatively small Q-value of this type of cavity is also suitable to cure the coupled bunch instability and to avoid the transient beam loading. As shown in Fig.1, one of the advantages of using a magnetic alloy (MA) core is its µQf stability at the very high magnetic RF field of more than 1kG, where the ferrite cores are completely saturated and difficult to be used. In order to clarify this advantage experimentally, a high gradient test cavity has been developed. Figure 2 shows the photogragh of the test cavity. In this test cavity, only one large core was installed in the l/4 cavity. The cavity was driven by a push-pull amplifier. The MA core was dipped in a water chamber which consists of stainless steel and FRP plate. The purified water, whose resistance was more than 10 MΩcm, has been used to cool the core. The maximum RF voltage of about 5.5kV per core(=220kV/m), which is the limit of the maximum plate voltage, has been obtained in the experiment. The maximum voltage was limited by the anode voltage, 11.5 kV and the transformation ratio of 1:2. Because of the shortage of the current from the plate power supply, the amplifier was operated at low duty factor. At the 2kV(=80kV/m) CW operation and the water flow of 60 liters per minute, the temperature rise of the cooling water was less than 4 degree C. The summary of the experimental results are tabulated in Table 1.

Table 1: Summary of the experimental results

Type of test cavity	l/4
Number of core	1
Type of core	FT3M
Size of core	58cm(O.D)X32cm(I.D)X2.5cm
Impedance of core	70 W @ 3MHz
Driving scheme	Inductive coupling
Trans. ratio	1:2
Impedance seen by amplifier	280 Ω @3MHz
Resonant frequency (w/o amplifier)	5.5 MHz
Amplifier push-pull	4CW30,000A X 2
Max. plate voltage	11.5 kV
Max. Gap voltage	5.5 kV/core
Max. Gap voltage	4.7 kV/core @barrier operation, 2MHz

3.2 Dipole magnet and magnet power supply of not-generating reactive power using IGBT

The maximum magnetic field of the bending magnet of the 50-GeV main ring is chosen to be 1.9 T and the cross-sectional structure of a modified window-frame type is adopted. The horizontal and vertical widths of the magnet are 93.4 cm and 59 cm, respectively, and the magnet length is 5.85 m. The pole contour from the side shim to the side slope is carefully determined so as to provide the large required good field region and to avoid partial magnetic saturation in the pole. The turn number of the coil is 32 turns/pole, in which a few turns are inserted into the pole gap. The effective cross-sectional area of the winding is 4.15 cm^2/turn. Since the curvature radius of the bending magnet is 89.41 m and the bending angle is 3.75 degrees, the 5.85 m long bending magnet has a sagitta of 4.8 cm. If the magnet had been constructed as a straight one, it would have a considerably bigger size for the same aperture requirement. Therefore, the bending magnet for the JHF main ring is curved along the central beam orbit. The pole shape of the magnet end will be cut with a Rogowsky curve or a B-constant curve so as to make the effective length uniform with respect to the horizontal position, and to reduce the dependency to the excitation level. The core is constructed with 0.5 mm thick laminations of non-oriented silicon steel with a silicon content of about 0.1% (equivalent to the grade of 50A1300 silicon steel of JIS). The maximum ampere-turn is about 93000 AT for 19 kG.

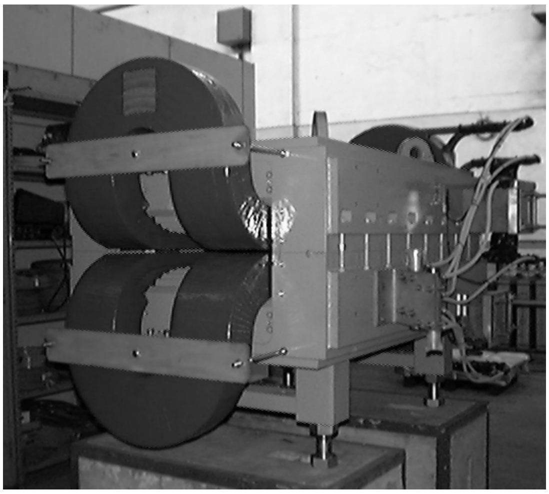

Fig.3: Photograph of the prototype of the dipole magnet of the main ring.

A first prototype bending magnet has been built to study the field quality, performance of the Rogowsky curve or B-constant curve at the magnet end, the effect of an end plate, problems concerning mechanical structures of the core and coil, and many other things concerning the field properties. The magnet has a cross section of full size and length of about one-fourth of the actual size. The picture of the prototype of the dipole magnet is shown in Fig.3.

The JHF 50-GeV ring is operated with an excitation pattern of trapezoidal wave form. The total power rate of the power supplies for the bending magnet and the quadrupole magnet is about 100 MW in peak and 27.5 MW in average, respectively. To reduce the total electric burden to the power supply system, it is expected to construct the power supplies with converter modules not generating reactive power, as much as possible. In this case, there is a possibility to use IGBT's as their converters. To test the possibility of using IGBT's as a converter for the power supply with a power rate of about 5 ~ 10 MW, a power supply with the peak power of 1 MW using IGBT is under construction for R&D study.

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