THE JAPAN HADRON FACILITY ACCELERATOR

Y. Yamazaki
KEK, High Energy Accelerator Research Organization
1-1 Oho, Tsukuba-shi, Ibaraki-ken, 305-0801, Japan

Abstract

The Japan Hadron Facility (JHF) is to promote various scientific fields by constructing high-intensity, medium-energy proton accelerators. The JHF accelerator complex comprises a 50-GeV main synchrotron, a 3-GeV rapid-cycling booster synchrotron, and a 200-MeV linac. The R&D programs include the following items: 1) a transition-free lattice design, 2) an RF accelerating cavity with low Q, but high μ new material, 3) a magnet power supply without any reactive power, 4) a beam extraction system with low beam loss, 5) a ceramics vacuum chamber to avoid the eddy current problem, 6) a high-intensity, low emittance H^- ion source, 7) a high-energy RFQ linac with a π-mode field stabilizing loop, and 8) a new linac accelerating structure SDTL.

1 INTRODUCTION

The Japan Hadron Facility (JHF) [1] comprises a 50-GeV main synchrotron, a 3-GeV rapid-cycling synchrotron, and a 200-MeV linac [1-4]. The JHF accelerator complex will provide high-intensity, medium-energy proton beams for various scientific fields covering fundamental particle physics, nuclear physics, solid state physics, biology and others.

The 50-GeV synchrotron accelerates a beam of 10 μA with a repetition rate of 0.3 Hz, while the 3-GeV one accelerates a beam of 200 μA with a pulse length of 900 ns and a repetition rate of 25 Hz. The 50-GeV beam is slowly extracted to an experimental hall, referred to as the "K Arena," where experiments are conducted concerning Kaon rare decay, hyper nuclei, and others. The beam is also fast extracted to the neutrino oscillation experimental area. A long base-line experiment will be conducted by making full use of the Super Kamiokande detector located 250 km from KEK.

The beam of the 3-GeV rapid-cycling synchrotron is to be fast extracted to the three experimental areas: a pulsed spallation-neutron experiment area, referred to as "N Arena"; a muon experimental area, the "M Arena"; and an exotic-nuclei experimental area, the "E Arena." The production of 0.6-MW proton beams will make possible the most powerful pulsed spallation neutron source in the world. Both materials science and life science will be substantially promoted by this facility. The muon beam facility will also provide a unique experimental tool for these sciences. The exotic nuclei produced by a typically 10 μA beam will be ionized by an ion source on line (ISOL), and accelerated to 6.5 MeV/u in order to study nuclear reactions, for example, those taking place within stellar matter.

The existing infrastructure will be fully utilized for the JHF. The tunnel in which the present 12-GeV main synchrotron is installed will accommodate the JHF 3-GeV synchrotron. The eastern experimental hall will be used as the N arena, while the northern experimental hall will be the M arena. The beam transport being constructed for the neutrino oscillation experiment will become that from the 3-GeV synchrotron to the 50-GeV one. In addition, all electrical and water-cooling plants for the existing facilities will be made use of.

We are hoping that the project will be approved this year while aiming for construction to start in 1999 and completion in 2003. Since we are challenging for the most powerful proton accelerator in the world, we have many design issues [5] as well as R&D items to consider.

2 ACCELERATOR SCHEME

The H^- ions produced in a volume-production-type ion source with a peak current of 30 mA are accelerated up to 200 MeV by the linac. Then, the ions are injected to the 3-GeV ring through a piece of charge-exchange foil. The large acceptance in the ring is transversely painted in order to maximally ease the space-charge effect. (The longitudinal painting will be done not intentionally, but partly by the sinusoidally varying magnetic fields.) The beam has already been chopped in the linac synchronously with 2-MHz RF acceleration in the ring in order to longitudinally accept all beams from the linac. In this way, we can avoid the beam loss which is inherent in adiabatic capture. Four buckets are thus filled out for 500 μs.

The magnetic fields are to sinusoidally oscillate with a rapid cycle of 25 Hz. Each of the focusing quadrupoles, defocusing quadrupoles and bending magnets is to be driven through its own resonant network in order to maintain a greater number of adjustable knobs. The injection time is to be limited by the approximately flat bottom of the 25-Hz sinusoidal function. In each cycle the ring will accelerate 5×10^{13} protons.

The four bunches thus accelerated are to be injected four times to the 50-GeV synchrotron, in which sixteen bunches are accelerated (2×10^{14} ppp), as shown in Fig. 1. One bucket is left empty in order to allow the rising of the fast-extraction kickers during the time thus opened. After the 0.12-s injection the beam energy is to be ramped up to 50 GeV for 1.9 s, and then the beam will be slowly extracted during a time of 0.7 s. The ramping cycle is to be completed in 3.42 s, including the falling time of 0.7 s.

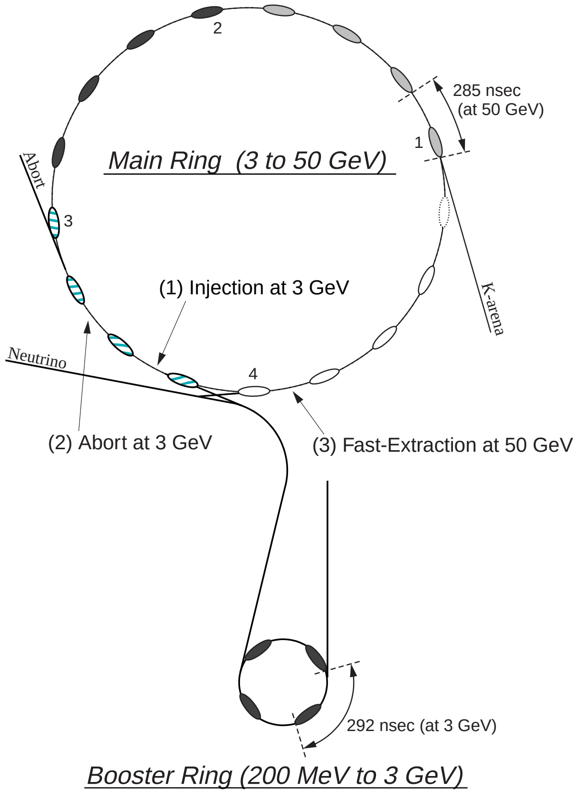

Figure: 1 Injection scheme from the 3-GeV synchrotron to the 50-GeV synchrotron.

3 LATTICE DESIGN

3. 1 50-GeV Synchrotron

The main parameters of the 50-GeV synchrotron are listed in Table 1. Its lattice has been designed in order to meet the following requirements. First, the four long straight sections (60 meters) are respectively necessary for slow extraction to the K Arena, for fast extraction to the neutrino experiment, for RF acceleration, and for the abort channel. Second, the imaginary transition γ (γ_t), that is, negative-momentum compaction factor (α), should be realized in order to make the ring free of the transition. Third, the phase advance has been chosen to be below 90° in order to avoid any strong resonance of the self space-charge force coupled with the beam-envelope modulation. Fourth, the maximum tunability is guaranteed: α, which is nominally - 0.001, is adjustable from $1/\nu_x^2$ to - 0.01, while both horizontal and vertical tunes are adjustable within ± 1 (nominally 21.85 and 15.4, respectively).

The imaginary γ_t is a unique feature of this lattice. The synchrotron oscillation, the frequency of which is proportional to a square root of the slippage factor (η), loses stability at $\eta = 0$, resulting in beam loss. The beam energy and the value of γ which make η vanish are referred to as the transition energy and transition γ (γ_t), respectively. Since α is proportional to an orbit integral of the dispersion function divided by the bending radius (ρ) , we can obtain a negative α if the dispersion function can be made negative at some of the bending magnets. Among various methods, we have chosen the missing-bend method rather than beta-function modulation, which is fairly harmful in any case.

Table 1: Main parameters of the 50-GeV synchrotron.

Energy	50 GeV
Beam Intensity	2×10^{14} ppp
Repetition	0.3 Hz
Average Beam Current	10 μA
Beam Power	0.5 MW
Circumference	1445 m
Lattice Cell Structure	3-Cell DOFO × 6 module + 4-Straight Cell
Typical Tune	(21.85, 15.4)
Momentum Compaction Factor α	– 0.001 (imaginary γ_t)
Total Number of Cells	88
The Number of Bending	96 (5.85 m)
Magnetic Field	0.143 ~ 1.9 T
The Number of Quadrupoles	176 (1.5 m or 2 m)
Maximum Field Gradient	20 T/m
Harmonic Number	17
RF Frequency	3.43 ~ 3.51 MHz
Circulating Current	6.4 ~ 6.6 A
RF Voltage	280 kV
RF Voltage per Cavity	40 kV (10 kV/gap)
The Number of RF Cavities	7
Beam Emittance at Injection	54 π mm·mrad
Beam Emittance at Extraction	4.1 π mm·mrad

For the emittance value of 54 π mm·mrad the maximum space-charge tune shift is – 0.08 (incoherent , vertical). It is noted that the big aperture shown in Table 2 should be prepared for this emittance if a COD of 1 mm is allowed.

Table 2: Apertures of the JHF synchrotrons.

	Horizontal	Vertical
50-GeV Synchrotron		
Bending Magnets	60 mm × 2	50 mm × 2
Quadrupole Magnets	66 mm × 2	60 mm × 2
3-GeV Synchrotron		
Bending Magnets	120 mm × 2	87 mm × 2
Quadrupole Magnets	120 mm × 2	120 mm × 2

3. 2 3-GeV Synchrotron

The strongest constraint on the 3-GeV ring lattice is that everything should be fitted into the existing 12-GeV synchrotron tunnel. Even so, many straight sections (O) are necessary. First of all, they are used for many RF accelerating cavities in order to ensure rapid acceleration. Second, two straight sections are necessary for each of two extraction channels, three straight sections are used for a beam scraper and collector system, and three sections for injection painting, where each straight section is 5.2 m long. No transition is of course preferable for the same reason as the 50-GeV synchrotron mentioned above.

The two lattices, which are respectively referred to as a normal FODO lattice and high γ_t lattice, are being investigated. The former is very similar to that of the present 12-GeV main synchrotron, being the best fit to the tunnel. The parameters listed in Table 3 are based upon this lattice. The latter has the advantage regarding the flexible α and the higher transition energy than 10 GeV.

Table 3: Main parameters of the 3-GeV synchrotron.

Energy	3 GeV
Beam Intensity	5×10^{13} ppp
Repetition	25 Hz (50 Hz in future)
Average Beam Current	200 μA (400 μA in future)
Beam Power	0.6 MW (1.2 MW in future)
Circumference	340 m
Magnetic Rigidity	2.15 ~ 12.76 Tm
Superperiodicity	4
Structure per superperiod	F(1/2O)(1/2B)DO + 5 × FBDO + F(1/2B)(1/2O)DO
Typical Tune	(6.84, 5.81)
Momentum Compaction Factor	0.0222 (no transition)
Total Number of Cells	28
The Number of Bending	48 (1.7 m)
Magnetic Field	0.17 ~ 1.00 T
The Number of Quadrupoles	56 (0.8 m)
Maximum Field Gradient	3.75 T/m
Harmonic Number	4
RF Frequency	1.99 ~ 3.43 MHz
Circulating Current	4 ~ 6.8 A
RF Voltage	400 kV
Beam Emittance at Injection	$\leq 320\pi$ mm·mrad
Beam Emittance at Extraction	54π mm·mrad

4 R & D FOR THE SYNCHROTRONS

The R&D program for the JHF accelerators was formed in order to overcome various difficulties associated with their high-intensity character. It includes [6]:

1) RF accelerating cavities,
2) 50-GeV synchrotron magnet power supplies,
3) 3-GeV synchrotron magnet power supplies, and
4) ceramics vacuum chambers for the 3-GeV synchrotron.

The RF accelerating system should be in stable operation under extremely heavy beam-loading. It should also be able to provide a high field gradient (at lowest 10 kV/m, hopefully higher) in order to realize rapid acceleration. Since the circulating current of each synchrotron amounts to approximately 7 A, the system should incorporate devices to cure any beam instabilities.

The conventional ferrite-loaded accelerating cavities have been suffering from the following difficulties:

1) The value of μQf, which is proportional to the shunt impedance, decreases as the RF magnetic field. This is one of the reasons for limiting the possible RF field gradient.
2) The cavity is tuned to a varying operating frequency by adjusting the permeability through the bias magnetic field. The response to the bias field is sometimes too slow for rapid-cycling.
3) The low Curie temperature, typically 100°C to 300°C, also limits the highest-possible field gradient.
4) A cavity with the a high Q-value, typically 10 to 20, may give rise to a coupled-bunch instability.

Recently, a very promising new material has been applied to the RF cavity in order to overcome the above difficulties [7]. In contrast to the ferrite materials, the fine crystal high-μ metal, sometimes called "FINEMET", and magnetic alloys can be characterized as follows:

1) The μQf value is constant up to an RF magnetic field of several thousand Gauss. Although the μQf value is lower than that of the ferrite at a low RF field, it becomes higher at an operating RF field higher than 100 Gauss.
2) Its extremely low Q-value of typically around 1 makes tuning unnecessary. This eliminates the difficulty inherent to the complexity of tuning the nonlinearly behaving cavity and the possibly unstable behavior of the tuning feed-back system. It should be noted that a high shunt impedance with a low Q-value is ensured by the extremely high permeability.
3) High Curie temperature, typically of 570°C, enables the use of the cavity at a higher field gradient than ever obtained.
4) Since the Q value is very low, the cavity should be more immune against coupled-bunch beam instabilities than the conventional ferrite-loaded cavity.

Since the new material seems to be promising, we fabricated a cavity using this material. A high-power test was successful up to 10 kV/m CW, which is already at a practically useful level. The maximum field gradient is only limited by the ability of the RF power source, but not by any shortcomings in the cavity. The power source will be upgraded in order to further test the cavity.

A plate of the material was tested in order to seek for the possibility of higher field gradient. The water-cooled plate can stand the RF power equivalent to 40 kV/m.

The magnet power supplies of the 50-GeV synchrotron will use insulated gate bipolar transistors (IGBT), the gating time of which is so fast and flexible as to avoid a harmful reactive (wattles) power. This is also a long-waited device, but it is only recent that high-power devices (3.3 kV, 1200 A) have been successfully developed. Since the development is still continuing, we are expecting that the devices can be mass-used for our power supplies.

Three families of the magnets of the 3-GeV synchrotron respectively driven through three resonant networks need precise amplitude and phase controls in order to synchronously operate three systems. Two prototypes of the resonant networks have been fabricated and tested. They were successfully in phase within 1 mrad, which correspond to 0.01 in betatron tune difference.

The rapid cycle of 25 Hz of the 3-GeV synchrotron led us to use ceramics chamber in order to avoid any harmful effect of the eddy current otherwise induced. The chamber, on the other hand, should RF-shield the beam current by means of copper strips or copper plating, or other. The R&D including the fabrication of the ceramics chamber is in progress.

5 200-MEV LINAC

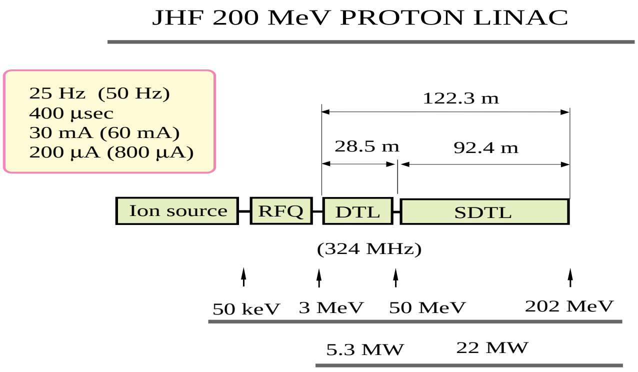

Figure: 2 The scheme of the 200-MeV linac.

The scheme of the 200-MeV linac is shown in Fig. 2, while the main parameters are listed in Table 4. We have been carrying out R&D for the 1-GeV linac [8] of the original Japanese Hadron Project, the accelerator complex of which comprises the full-energy linac and a storage ring (compressor/stretcher ring). The accomplishment of this R&D work includes the following:

1) A volume-production type H^- ion source, which generates a peak current of 16 mA with a normalized 90% emittance of 0.5 π mm·mrad without cesium [9].

2) A newly optimized low-energy beam transport (LEBT) made of two solenoids [9]. The optimization work was based upon careful three-dimensional analyses of various LEBT schemes, while carefully taking into account the geometrical aberration. The beam experiment showed that a very strong space-charge neutralization effect maintained the high brightness throughout the LEBT.

3) The 3-MeV, 432-MHz radio-frequency quadrupole (RFQ) linac with a newly invented field stabilization method: π-mode stabilizing loop (PISL) [9,10]. The world-highest acceleration energy has been accomplished by means of the PISL. However, the transmission of this RFQ linac was only 82 percent, in contrast to the design value of 95 percent. The reason for this discrepancy is now being studied.

4) The 432-MHz drift-tube linac (DTL) with permanent quadrupole magnets (SmCo) therein [11].

5) The first high-power tested annular-ring coupled structure (ACS) [12]. This is made possible by newly devised coupling slots based upon a profound understanding of the RF characteristics of the ACS, both theoretically and empirically.

6) The 5.5-MW, L-band RF power sources with a pulse length of 600 μs and a repetition rate of 50 Hz. The klystrons are driven by a huge line-type modulator [13].

The new design [2,14] of the 200-MeV linac makes full use of knowledge obtained during the course of developing the 1-GeV linac. In addition, the design has been optimized for the new specifications.

First of all, we need a higher peak current of 30 mA for the new design, compared to 20 mA for the old one. In particular, an even higher peak current is essential for the future upgrade. On the other hand, the brightness of the volume-production-type H^- ion source was higher than expected, mainly because the space-charge neutralization phenomena are so common everywhere.

Table 4: Main parameters of the 200-MeV linac.

Energy	200 MeV	
Frequency of RFQ, DTL, and SDTL	324 MHz	
Repetition	25 Hz	(50 Hz in future)
Beam Pulse Length	500 μs	
Chopping Rate	53 %	
Peak Current	30 mA	
Linac Average Current	375 μA (750 μA in future)	
Average Current after chopping	200 μA (400 μA in future)	
Total Length	125m(160 m with a debuncher)	
H^- Ion Source		
Type	Volume-Production Type	
Peak Current		32 mA
Normalized Emittance (90%)		1.5 π mm·mrad
Extraction Energy		50 kV
RFQ		
Type	Four-vane type with PISL's	
Energy		3 MeV
DTL		
Energy		50 MeV
Focusing Quadrupole Magnet		Electromagnet
Total Tank Length		27 m
The Number of Tanks		3
SDTL		
Energy		200 MeV
Total Tank Length		66 m
The Number of Tanks		31
RF Sources		
The Number of Klystrons (including the RFQ and debuncher)		19
Total RF Power		27 MW

Under the condition that we wish to have the peak current as high as possible, while we have no definite answer concerning the highest-possible peak current as a result of the future development, we should design a linac which remains flexible for increases in the peak current. From that viewpoint, we should use quadrupole electromagnets in drift tubes rather than the permanent quadrupole magnets (PQM), the field gradients of which cannot be flexibly optimized to the increasing peak current in the future. Since the frequency of the drift-tube linac (DTL) should be as high as possible from the viewpoint of emittance-growth suppression, we chose the highest-possible frequency of 324 MHz, with which the quadrupole electromagnets can be contained in the drift tubes.

We will use the same type of ion source, the LEBT and RFQ linac, as those developed for the 1-GeV linac, except for its frequency. After understanding the reason for the low transmission, the RFQ linac will be redesigned using the improved design computer program. The obtained brightness mentioned above is promising a peak current of 3×16 mA for the designed acceptance of 1.5 π mm·mrad of the 432-MHz RFQ linac. This value already exceeds the required peak current.

Another new feature of the 200-MeV linac is the use of a separated DTL (SDTL) [15] after around 50 MeV. Its idea is based upon the fact that quadrupole magnets (QM's) are not necessary in every drift tube (DT) after 50 MeV. By taking the QM's outside the DT's, that is, outside of the tank, we can optimize the geometrical shapes of the DT's in order to maximize the shunt impedance. The shunt impedance of SDTL is by 50 to 70 percent higher than that of a conventional DTL with the same frequency.

The chopping is one of the most difficult items to be developed. At present a chopping system has been designed which is compatible with a beam loss of 1 percent in the linac [16].

6 CONCLUSION

We believe that the required specifications can be obtained on the basis of the success of the R&D works described in Sec. 4, except for the beam-loss problems. Even slight beam losses in this kind of powerful proton accelerators would generate an enormous amount of radioactivity, making impossible the hands-on maintenance of the accelerators, which is a more serious problem than shielding. We are trying to localize any significant beam loss at those places especially designed for this purpose. Since the beam-loss mechanisms have not been fully elucidated, it will be a real challenge in the JHF accelerator. We believe that this kind of problem can only be solved based on the experience obtained through empirical beam studies. The development, design, construction, commissioning, and operation of the JHF accelerators will also contribute to our understanding of the mechanisms from this viewpoint.

If we can solve the beam-loss related problems through beam studies and machine improvement, the possibility of future upgrades of the 3-GeV ring to the 1.2 MW machine will be seriously considered. First, we will increase the repetition rate of the 3-GeV synchrotron by a factor of two. For this purpose, the linac should be able to accelerate a peak current of 60 mA, since the injection time will be halved by doubling the repetition rate. The peak current can be increased by adding Cs vapor in the ion source. Although the Cs may decrease the discharge limit in the following RFQ linac, its amount for the volume-production type ion source is significantly smaller than that for surface-production type, easing its harmful effect on the discharge problem. It is noted that this upgrade is made possible, only if the beam loss can be halved by some means.

The further upgrade should include the energy upgrade of the linac to 400 MeV. The upgrade to 2.4 MW will be possible together with the increase by a factor of two in the flat bottom of the rapid-cycling magnetic field by some means or in the peak current via a funneling method or others. For this upgrade we have to decrease the beam loss during the injection by a factor of 6, since the 400-MeV beam is approximately three times as effective as the 200-MeV beam regarding the production of the radioactivity.

The upgrade of the 50-GeV synchrotron will be also possible by two methods: fast ramping and/or barrier bucket. In particular, the current increase by a factor of 3 or more is expected by making a full use of the barrier bucket methods. Together with the fast ramping it will be possible to obtain a slow-extracted beam current of 40 μA and a fast-extracted beam current of 50 μA.

It is our understanding that the potentiality for these upgrades can be only realized through the empirical studies using the real machine as mentioned above.

8 REFERENCES

[1] JHF Project Office, "Proposal for Japan Hadron Facility," KEK Report 97-3 (JHF-97-1).

[2] JHF Project Office, "JHF Accelerator Design Study Report" KEK Report 97-16 (JHF-97-10).

[3] T. Kato, KEK Report 96-17 (1997).

[4] Y. Mori, "The Japanese Hadron Facility", Proc. 1997 Part. Accel.Conference, to be published.

[5] Y. Yamazaki, Proc. 1996 Linac Conf., 592 (1996).

[6] Y. Mori, "Design and Hardware Developments of the JHF 50-GeV Synchrotron," contribution 5D001 to this conference.

[7] C. Ohmori et al., "RF Systems for JHF Synchrotrons," contribution 5E104 to this conference.

[8] Y. Yamazaki and M. Kihara, Proc. 1990 Linac Conf., 543 (1990).

[9] A. Ueno et al., Proc. 1996 Linac Conf., 293 (1996).

[10] A. Ueno and Y. Yamazaki, Nucl. Instr. Meth. A300, 15 (1990).

[11] F. Naito et al., Proc. 1994 Linear Accel. Conf. 134, 137 (1994).

[12] T. Kageyama et al., Proc. 1994 Linear Accel. Conf. 248 (1994).

[13] S. Anami et al., Proc. 1990 Linear Accel. Conf. 174 (1990).

[14] T. Kato and Y. Yamazaki, "Design of the JHF 200-MeV Proton Linear Accelerator," contribution 4D010 to this conference, .

[15] T. Kato, KEK Report 92-10 (1992).

[16] S. Fu and T. Kato, "Design of Beam Transport Line between the RFQ and the DTL for the JHF 200-MeV Proton Linac, " contribution 4D011 to this conference.