Synchrotrons of Joint Project

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Abstract

The construction of Joint Project between KEK and JAERI has started in April 2001. Hardware R&Ds still continues in parallel. Here we focus on mainly the design principle and issues of two synchrotrons, namely 3 GeV Proton Synchrotron (PS) and 50 GeV PS.

1 INTRODUCTION

The Joint Project, formerly JHF at KEK and NSP at JAERI, has been approved and construction started in April 2001 [1-12]. That will be a great outcome of intensive design study and hardware R&Ds for last several years. The goal of the accelerators is to deliver 1 MW pulsed beams from 3 GeV Proton Synchrotron (PS) and pulsed (fast) and continuous (slow) beams of 0.75 MW from 50 GeV PS. It will open various new research fields from atomic energy to biophysics.

Besides the applications with this new facility, the accelerator complex itself is a tremendous challenge. Beam intensity of one or two order magnitude more than the present facilities requires the same or even lower beam loss. Therefore, this accelerator complex demands a very careful beam handling, which was not realized in the other type of accelerators.

In this paper, we will discuss the overview of the accelerator complex, design considerations, and an example of commissioning simulation.

2 TIME STRUCTURE, BEAM INTENSITY, AND EMITTANCE

2.1 Time Structure

Let us first look at the time structure of the two synchrotrons. The 3 GeV PS runs with 25 Hz. Since the excitation pattern of the magnets is sinusoidal and acceleration occurs on the rising side, the beams stay in the ring for 20 ms in one cycle from injection to extraction. Injection requires only around 0.5 ms. It corresponds to about 300 turns revolution. Charge exchange injection is performed during that time. As an injector of 3 GeV PS, it is sufficient to run linac with the same 25 Hz. However, the other function of linac, that is a driver of Accelerator Driven System (ADS), makes it runs with 50 Hz.

Most of the extracted beams from 3 GeV PS are delivered to the neutron facility. However, four batches, which consists of two bunches because of harmonic number of two in 3GeV PS, are transported to 50 GeV PS every 3.42 s, which corresponds to one cycle of 50 GeV PS. In fact, depending on operation modes of 50 GeV PS, 3.42 s can be shorter or longer. After the first batch is injected, only two buckets out of nine is occupied and 50 GeV PS is just waiting for the next batch from 3 GeV PS. Then second batch fills in two of the empty backets and so on. The transfer and injection of 50 GeV PS with four batches takes 0.12 s (= (4-1) x 0.04 s). Once injection is completed, acceleration starts with linearly excited magnets up to the final energy. It takes 1.9 s. When the beam is extracted with slow extraction scheme, firstly RF is turned off and debunched beams are continuously extracted in 0.7 s. After the beam is extracted, another 0.7 s is required to reset the magnetic field for the next injection. When fast extraction mode is taken, one turn extraction takes negligibly short time compared with one cycle. In principle, one machine cycle becomes 2.72 s (=3.42 – 0.7).

2.2 Beam Intensity

The beam intensity at each stage becomes following. The peak beam intensity of linac is supposed to be 50 mA. In fact, pulse trains of linac with 324 MHz structure are chopped with the RF frequency of 3 GeV PS (1.22 MHz) and its existing ratio is 56%. The averaged peak intensity becomes 28 mA. When 3 GeV PS accepts 293 turns of the linac beams, the total accumulated particles are 8.333 x 10^{13} or 333 μA in average. With extraction kinetic energy of 3 GeV, that makes 1 MW beam power.

Four batches of 3 GeV PS injection are injected to 50 GeV PS so that the total accumulated particles are 3.33 x 10^{14} or 15.6 μA in average and that makes 0.75 MW (here, slow extraction scheme and its cycle time are assumed.) Just for comparison, the maximum number of particles per pulse in the existing machines is 7 x 10^{13} in the AGS at BNL. The 50 GeV PS will be the first proton synchrotron with number of proton per pulse of the order of 10^{14}.

2.3 Emittance

The emittance evolution is assumed in the following way. First we show transverse one. Although the 100% emittance from linac (after beam collimation) is 4 pi mm-mrad, because of the injection painting process in 3 GeV PS, it becomes 216 pi mm-mrad (4rms.) We assume further increase of emittance by a factor of 1.5 due to space charge effects and other instabilities but not beyond. That is limited with a beam collimator inside the ring. As a result, most of the particles (99%) should exists in the emittance of 81 pi mm-mrad (adiabatic damping of 216 pi mm-mrad.) at extraction of 3 GeV PS. Then, it is delivered to the neutron facility.

For the batch to the 50 GeV PS, we change painting pattern at injection so that the resulting emittance is between 144 and 216 pi mm-mrad because 81 pi mm-mrad at extraction is almost equal to the physical acceptance of 50 GeV PS and no room is left for further increase. When it starts from 144 pi mm-mrad, adiabatic damping makes down to 54 pi mm-mrad right before injection of 50 GeV PS. Then, we expect again the space charge effects, other instabilities, and optical mismatch at the injection of 50 GeV PS, that makes the emittance growth by a factor of 1.2 to 1.5 but not beyond again by a beam collimator inside. Therefore, it becomes 10 pi mm-mrad at the kinetic energy of 30 GeV, and 6.1 pi mm-mrad at 50 GeV.

3 BEAM LOSS

Practically speaking, operational beam intensity is limited, especially in the early phase, by the level of radio activation or the components. Once the beam loss becomes more than expected, even at a single pinpoint, we must decrease beam intensity so that further activation is prevented. At the same time, a careful study to identify possible reasons that make beam loss should be initiated.

It is important to distinguish controlled and uncontrolled loss. Controlled loss refers to the loss that is expected and localized to specific places. Uncontrolled loss is unpredictable. Although the beam loss is inevitable in any case, it is desirable to have only controlled beam loss to some moderate amount.

3.1 Linac to 3 GeV PS Beam Transport and 3 GeV PS

In each stage, the maximum allowable beam loss is assumed. That is also the basis of shielding plan. Generally speaking, 1 W/m is a rough criterion to keep the machine accessible with hands-on-maintenance. It is therefore the limit of uncontrolled loss. Controlled loss may be more than that. After linac, at the beam transport to 3GeV PS, two different limits are set. One is before arc and the other is in the arc. In the straight section just downstream of linac, not much beam loss is expected because of an enough aperture. The allowable beam loss is 0.1 W/m. In the arc, the nominal limit of 1 W/m is enforced. Both are uncontrolled loss.

When a H^- beam is injected into 3GeV PS through charge exchange foil, some of particles remain as H^- or H^0 instead of becoming protons. We expect that the fraction of those particles is 2% of the total. In fact, it is possible to capture most of them to the dump line since the orbit of those particles is predictable. A dump target that can handle 4 kW will capture them. Nevertheless, some fraction of those, especially protons as a result of decaying H^0 at some excited level, behaves as a circulating beam with large amplitudes and may hit some of components, resulting in uncontrolled loss.

In order to clean up those particles as well as large amplitude particles due to space charge effects and other instabilities, there is a beam collimator. The loss at the collimator is controlled loss. It allows up to 4 kW, which corresponds to 3% of the total at injection energy.

Other than that, loss during acceleration is expected and it should be less than 1 W/m. Beam loss at extraction is another source due to large amplitude particle but not collimated during acceleration or some errors in extraction kicks. Although it is not controlled loss, beam loss of 1 kW around the extraction region is allowed. In fact, aperture of the extraction region has the same amount as that of a collimator, so that there should be no larger amplitude particle than the aperture.

3.2 3 GeV PS to 50 GeV PS Beam Transport and 50 GeV PS

There are several beam collimators in the beam transport line between 3 GeV PS and 50 GeV PS. Since the average beam power going through the beam transport is about 47 kW (= 4/(25 x 3.42) x 1 MW), 1% beam loss at the collimator corresponds to 470 W. The rest of the beam transport is limited to 1 W/m.

The injection of 50 GeV PS is relatively simpler than that of 3 GeV PS. It is the inverse process of 3 GeV PS extraction with fast kicker and septum. The amount of beam loss is expected similar. However, the aperture in injection region is much smaller than the 3 GeV extraction, and more beam loss is expected, that is 0.3% and corresponding to 140 W. Most of the controlled loss in 50 GeV PS occurs at the collimator and it is expected to 1% or 470 W. The loss during acceleration is limited to 0.5 W/m.

The hottest spot in 50 GeV PS is the extraction insertion region, especially for slow extraction. Since the beam energy is 50 GeV, only 1% of the total current is equivalent to 7.5 kW. To make matters worse, the beam loss at septum wires is inevitable for slow extraction scheme and 1% is the best value we have simulated. That is one of the big challenges in the accelerator complex. The loss in the fast extraction region can be less and it is expected to 0.15% or 1.1 kW, still not negligible.

4 DESIGN CONSIDERATIONS

In order to overcome the problems associated with high intensity beams, we emphasize the following design considerations.

4.1 Basic Optics

Both 3 GeV PS and 50 GeV PS have same lattice structure called 3 cell DOFO high transition gamma lattice in the arc. Similar to Chasman-Green or DBA for a synchrotron radiation ring, that structure makes the dispersion function in the bending magnet small and has a small or even negative momentum compaction factor. In 3 GeV PS, although a normal FODO design gives transition gamma high enough so that a beam never cross it, higher transition energy than that of a normal FODO lattice makes more accurate feedback control of RF near the extraction energy and eases the longitudinal matching to 50 GeV PS without too much voltage reduction (60 kV instead of 20 kV compared with the peak voltage of 420 kV.) In 50 GeV PS, it is essential to make the momentum compaction factor negative to avoid transition crossing which has a potential source of beam loss.

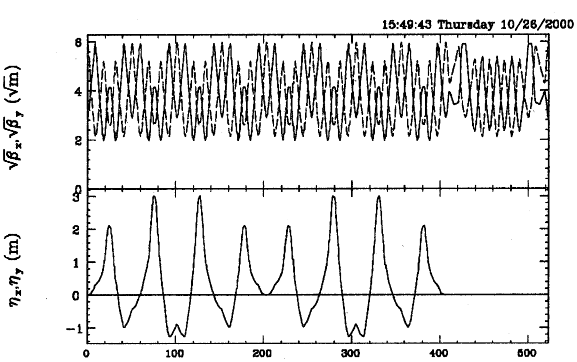

Figure 1: Lattice functions of 50 GeV PS. Solid line is horizontal and dashed line is vertical.

One drawback of those lattice structures is chromatic behaviour, which is relatively inferior to a normal FODO because of localized chromaticity correction sextupoles. However, the tracking study shows dynamic aperture as much as twice of physical one with only two families of sextupoles. In order to make the lattice functions insensitive to momentum deviation, the correction scheme with 4 or more family of sextupoles are under investigation.

The insertion is designed independently of the arc to satisfy basic functions like injection, extraction, RF acceleration, and collimation. Each function is assigned to one of three insertions whereas a basic focusing structure has three-fold symmetry. In 50 GeV PS, there is a section where a beta function is relatively high and alpha is almost zero. We believe it gives optimum place for an electric septum for slow extraction and minimize beam loss associated with the extraction.

The overall structure of both synchrotrons obeys FODO principle and, therefore, flexibility of focusing property is assured. The number of quadrupole family in the arc is four and that in the insertion is seven in both synchrotrons.

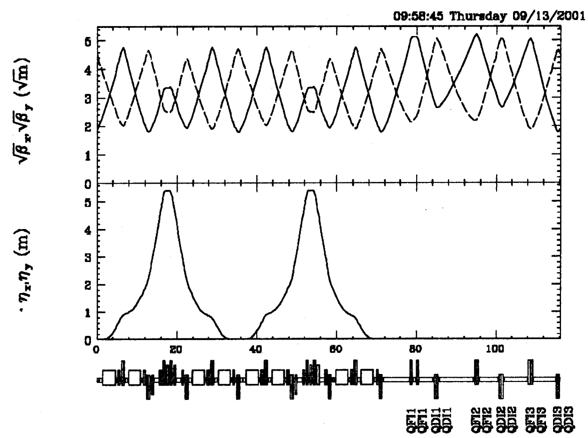

Figure 2: Lattice functions of 3 GeV PS. Solid line is horizontal and dashed line is vertical.

4.2 Emittance Control

Transverse as well as longitudinal emittance at the beginning of 3 GeV PS is enlarged by phase painting to reduce space charge effects. In addition to a bump orbit that makes a H^- beam from linac and circulating beams merge at a charge exchange foil, there is another painting bump orbit in horizontal direction excited during an injection process. Gradual change of bump excitation makes an injection point in transverse phase space shift, resulting in the production of almost uniform distribution. In vertical, a steering magnet located at 180 degree upstream in betatron phase from the injection point change the gradient at injection. As a nominal operation, we plan to fill the beam from the center in horizontal and from the outer edge in vertical, which is called anti-correlated painting. Once emittance exchange due to coupling (most probably due to space charge potential) becomes significant during injection, we fill the beam from the center in both directions, which is called correlated painting.

It is not clear at the moment what kind of combination of collimator aperture and painting emittance minimizes the overall beam loss. Given the physical aperture of 486 pi mm-mrad, which is determined by quadrupole bore and bending gap, there should be optimised setting of collimator and painting. Obviously, small painting emittance increases space charge tune shift and is subject to deteriorate. On the other hand, larger painting emittance removes the margin between emittance and collimator aperture. Similar argument is applied to the ratio of collimator and physical aperture. Larger collimator aperture accommodates more beams without increasing space charge tune shift. However, once a particle hits a primary collimator, not enough margin between collimator and physical aperture makes the particle hit at an unpredictable place before reaching a secondary collimator. Simulation results show the ratio of 1.5 for both cases is optimum and that determines the nominal values, namely collimator aperture of 324 pi mm-mrad and painting emittance of 216 pi mm-mrad. However, those are one of major parameters to be optimised during the commissioning and its necessary knobs are prepared.

In the longitudinal phase space, painting is not so obvious as the transverse. The linac pulse train is chopped such that +-100 degrees in a 3 GeV PS RF bucket is occupied with the particles. Shift of the injection point in the phase space is introduced in the momentum direction because of the ramping of bending fields whereas the incoming beam has the constant energy. That is about 0.1% during the injection period of 0.5 ms. The momentum spread of incoming beams are expected to +-0.2%. In addition, we plan to have an offset of the injection momentum relative to the synchronous momentum determined by bending fields by 0.2%, that forms larger longitudinal emittance than that without the offset and therefore gives larger bunching factor.

Another increase of a bunching factor comes from the introduction of the second harmonics. A low Q cavity realized with magnetic alloy makes it possible to drive one RF cavity with fundamental and second harmonics at once without any extra cost. We certainly plan to use the second harmonic from the very beginning of the commissioning.

Painting emittance of 216 pi mm-mrad together with bunching factor of 0.42 with second harmonic RF reduces the incoherent tune shift due to space charge force down to –0.15, which is moderate.

In the downstream of 3 GeV PS, emittance control is simply done with collimator, one in 3GeV PS to 50 GeV PS beam transport and the other inside 50 GeV PS. The tune shift in 50 GeV PS is about –0.15, just happens to be the same as 3 GeV PS.

4.3 Beam Loss Control

In any accelerator, beam loss is inevitable and it must be pretty small ratio in high intensity synchrotron. If it cannot be avoided, the best possible way is to localize the loss where we make an adequate radiation shielding and assume special cares are necessary once machine failure occurs.

A device to control beam loss is a beam collimator. In the beam transport between linac and 3 GeV PS, there are two kinds of collimators; one for momentum collimation and the other for transverse amplitude collimation. The former is set at the place in the 90 degree arc section where beam size due to momentum spread dominates because of large dispersion function. The latter is set at the place in the straight section where dispersion is zero. A charge exchange foil close to beam tail at each location will strip electron if the incoming H^- particle has more amplitude than the limit, which is 0.1% in momentum and 4 pi mm-mrad in transverse emittance. The proton with large amplitude will be bended in the opposite direction when it goes in the arc or hit aperture limit by secondary collimators (or collectors) in the straight. Since we know the source point of protons, that is the foil, and can predict orbit afterward, it is a controlled loss.

Still there are some drawbacks in those systems. In the momentum collimator, physical size does not reflect magnitude of momentum precisely. Although it is located at the large dispersion region, the size is partially determined by betatron amplitude. A particle with smaller betatron amplitude can survive after collimator with larger momentum. In the transverse collimator, we can only scrape large amplitude particles with some certain phases. For example, four collimators with 45 degree phase advance apart can shape a beam as an octagon, not an ellipse. That is one of fundamental limits of collimator in one pass beam line.

In 3 GeV PS, there are also momentum and transverse collimators. Now circulating particles are already charge exchanged and foil cannot be used to scrape large amplitude particle. Instead, an obstacle called "jaw" is put near the beams. In the transverse collimator, the particle which hits jaw will gain (or lose) transverse momentum. Depending on the sign of additional momentum, secondary collimators downstream with a right phase relation, or even after one or several turns later, will catch the particle. In the momentum collimator, much thinner jaw will slightly change the transverse momentum and let the particle hit the transverse collimator downstream. The 50 GeV PS has transverse collimator from the beginning, but no momentum one. It will be added later if necessary.

Ideally we can expect all the beam loss occurs in those collimators and no other place. However, still some uncontrolled beam loss occurs, for example, at the quadrupole magnets between primary and secondary collimators. There are also some particles which go through the collimator region but cannot circulate in the rest of the ring. Another concern is whether the beam collimated at the injection energy will be adiabatically damped according to acceleration. In fact, as long as all the machine aperture is larger than the collimator one in 3 GeV PS, the aperture limit always exists in the collimator whether beam is damped or not. However, if it is not damped, large amplitude particles will be lost in the beam transport between 3 GeV PS and 50 GeV PS or in 50 GeV PS because we do make the machine aperture as large as 3 GeV PS. We need more study especially on the behaviour of large amplitude particles during acceleration process.

5 SIMULATION OF COMMISSIONING

Although careful choice of lattice and beam parameters is made as much as possible during the design stage, eventually a lot of machine tuning and beam study using the real machine are needed to reach the design goal. From the previous experiences of existing synchrotrons, we have ideas how we tune a machine and what kinds of beam study are necessary to improve beam quality.

Having said that, it should be, however, noted that all the procedures based on the previous experiences may not be performed because of the limitation of radio-activation. For example, with full intensity operation, machine parameters cannot be chosen so that more than 10% of the particles are lost, simply because such as beam loss is prohibited even as controlled loss. In that respect, a dry run of commissioning and machine improvement becomes more serious compared with the existing facilities.

In the following, we show a simulation of a tune survey. That is a typical example which can be done in the existing machines easily, but limited in the high intensity machines. Figure 3 shows the rms emittance as a function of vertical bare tune. The horizontal bare tune is fixed at ν_y=7.35 (this simulation is based on the older verion of the 3GeV PS. Now the nominal tune is ν_x=6.72 and ν_y=6.35.) Taking the tune shift into account, some peaks indicating emittance growth can be attributed to structure resonances. A peak at ν_y=6.20 is due to $4\nu_y$=24, one at ν_y=6.95 is due to $4\nu_y$=27, one at ν_y=6.60 is due to $2\nu_x+2\nu_y$=27, and one at ν_y=5.50 is due to $4\nu_y$=21. A small peak at ν_y=5.70 may be due to $2\nu_x-2\nu_y$=3.

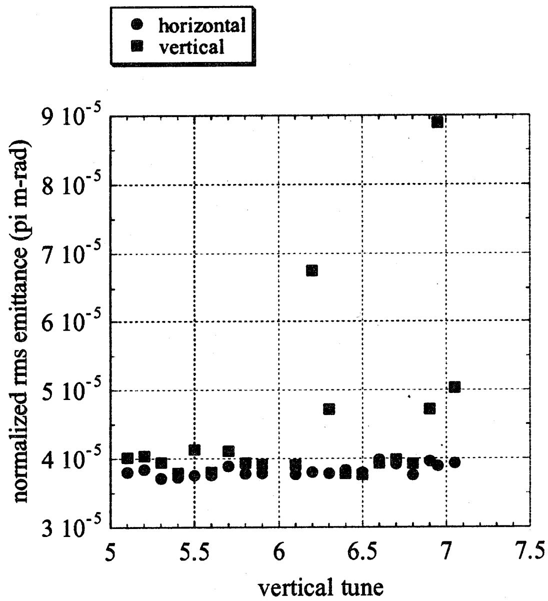

Figure 3: RMS emittance at 1,000 turns after injection when bare tune is surveyed in vertical direction.

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