Intensity Doubler: A Proposal for a Major Upgrade of the KEK 12GeV-PS

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Abstract

A proposal for a major upgrade of the KEK 12GeV-PS is presented. The proposal involves a combination of beam stacking in a 500MeV accumulator ring (AR) and acceleration of a superbunch in the 12GeV main ring (MR), referred to as the Intensity Doubler (ID). A super-bunch is created in the AR by barrier-bucket stacking of 12 bunches injected from the booster ring (BR), and is transferred to the MR in one turn. By introducing the AR in the 12GeV-PS accelerator complex, it is possible to reduce the present injection time of about 500msec and increase the machine duty-cycle. Superbunch acceleration is achieved by rapidly switching induction units. Through the final two years of the K2K experiment, the ID could supply proton beams that would be two times higher than the present levels in terms of averaged intensity. The scheme is based on the concept of induction synchrotron [1]. A quite unique features of superbunch acceleration such as bunch-stacking in the barrier bucket is discussed with actual parameters of the KEK-PS. The present status of R&D works for the ID are reported.

1 INTRODUCTION

Since June 1999, the MR has been delivering proton beams to the target in excess of 6×10^{12}ppp for the K2K experiment. The extensive effort to increase the beam intensity is reviewed in the reference[1]. A beam intensity of 8×10^{12}ppp was achieved after acceleration in 2000, March, and the MR is currently operating with a nominal beam intensity between 7.2 to 7.5×10^{12}ppp. However, from a statistical accuracy perspective, further increases in beam intensity are clearly desirable. If the ID were to begin operating in the beginning of 2004, it is estimated that the number of neutrino events would increase by 40% before the scheduled run-end. It is essential to upgrade the KEK 12GeV-PS before the MINOS and the CERN-Gran Sasso experiments commence with higher energy and appropriate beam intensities.

According to our extensive machine studies[2], it seems that proton beams with substantially higher local densities than those under the present operation are not acceptable with the aperture of the MR. The only way to achieve more protons is to stack them in the longitudinal phase space, in other words, along the time coordinate. An accumulator ring placed between the BR and MR is quite effective for this, and effectively reduces the acceleration period by about 500msec. As a result, the acceleration period can be reduced from 2.2sec to 1.6sec, with further effort to eliminate another 100msec. The accumulator will be installed in the MR tunnel. Taking advantage of the fact that the ring operates at a fixed momentum, the magnets are built using permanent strontium ferrite magnets. In conventional synchrotrons, a number of protons being accelerated is simply in proportional to the stacking number of pulses in one acceleration cycle, with the maximum stacking number being a function of the harmonic number of RF. Each pulse delivered from the BR is injected into the central position of the RF bucket with temporal gaps between adjacent bunches, which must be sufficient to allow the injection kicker-fields to reach the flat-top level. In the MR, this temporal gap represents half of the total time of 1.5μsec required for 9 injected Booster bunches (80nsecx9=720nsec), with remaining time being unavailable for stacking. However, it is possible to overcome this fundamental restriction associated with the conventional RF acceleration by applying the concept of induction synchrotron (IS)[3], which employs induction accelerating modules instead of RF cavities. The combination of dual-harmonic RF acceleration in the BR with superbunch stacking in the AR, together with acceleration of the superbunch in the MR should increase beam intensity per pulse by at least 60% and eventually makes the ID attainable.

2 SUPERBUNCH ACCELERATION

Unlike a conventional RF synchrotron, acceleration and longitudinal focusing in an IS are independently provided by two kinds of induction cell (IC), as schematically shown in Fig.1. A dc-like induction acceleration is provided by the IC, which is energized with a long voltage-pulse and a short reset-pulse. The other IC which is excited by short-pulses generates a moving barrier bucket (BB) in the longitudinal phase-space, which, rather than being fish-like, is almost rectangular in shape. The moving rectangular bucket can accommodate particles to its full capacity. The bucket shape tends to create a uniformly diffused longitudinal distribution of the particles apart from both edges of the bucket. The uniformity is important in diminishing the space-charge effects in the transverse and longitudinal directions. The frequency or phase feed-back in RF acceleration, which makes tracking against the ramping magnetic guide-field possible, is replaced by an induction voltage feed-back and a programmable change in the trigger-timing. These feedbacks should be rather simple, unlike that in RF acceleration where the feedback gain depends on the beam intensity and requires careful adjustment.

In order to create a superbunch in the AR, two kinds of barrier buckets are employed, as illustrated in Fig.2. The bunches injected from the BR into the AR are captured by a matched capture bucket. Each bunch is moved adiabatically toward the edge of the stacking bucket and is then released into the stacking bucket in such a way that the reset timing for the edge voltage of the stacking bucket is delayed by the bunch-length of the fresh bunch. Thus the fresh bunch merges into the stacked beam-core. After this process is repeated 12 times, resulting in a 1 μsec-long superbunch, this is extracted in one turn and injected into the MR. This is immediately trapped in the BB in the MR, as described above, and is quickly accelerated by an integrated induction-voltage of 25kV. An important point to note here is the fact that a bunch in the BR is accelerated with dual harmonic RF so that they are well-matched to the capture bucket, which, in tern, helps keeping the line-density low.

3 500MEV ACCUMULATOR RING

The AR is to be located in the existing 12GeV-PS tunnel, which is almost circular in order to match the 12GeV-PS with a super-periodicity of 4, each consisting of 7 FODO cells. Although the tunnel is 4 m wide, much of this considerably large cross-sectional space is occupied by the MR lattice magnets, together with their cable racks and cooling-water pipes along the inner wall. This means that the only space available to accommodate the AR is in the passage between the lattice magnets and the outer wall, but given the limited space too, it will be necessary for the AR lattice to closely mimic the 12GeV-PS lattice. Two sets of induction devices generating 140kV per set are required to generate the BBs for capture/stacking. Sufficient space must also be reserved for these devices.

A combined FODO lattice is being considered to ensure that (1) gradient magnets, the cross section of which is given in Fig.3., are almost uniformly distributed so as to satisfy the constrains discussed above, (2) the total cell number is fixed at 28(4x7), and that (3) the betatron tunes are nearly identical to those of the MR.

The 1.5m-long gradient magnet has a bending angle of 3.75 degrees. A super period with mirror symmetry consists of 5 regular FODO cells and 2 FODO insertion cells (long straight section), as seen in Fig.3. These missing-bend cells are used to inject, extract, and capture the proton beams. The AR must be capable of being adjusted in order to correct for the COD and to adjust the betatron tunes. This will be achieved by utilizing electromagnetic dipole and quadrupole magnets which will be positioned between the split gradient magnets. The lattice functions are shown in Fig.4.

Because the magnetic field is permanent, no power supplies, cooling systems, power distribution cables, or electrically safety systems are required. From the extensive experience at Fermilab[4], it is also clear that the permanent magnets are very stable over time and against temperature fluctuations. The basic design of the permanent magnet was done. This is a 1.586kG gradient dipole with a 7cm gap at the center, a 26cm horizontal aperture and a 10cm horizontal good-field aperture. The overall dimensions are 30cm in height by 45cm in width by 1.5m in length. The magnets are straight and the sagitta of the beam inside a magnet is typically 1.23cm. In the design of the so-called "hybrid" permanent magnet, the field is driven by permanent magnet material and the shape of the field is determined mainly by steel pole elements. This is similar to the gradient magnet employed in the Fermilab Recycler Ring. The field quality is designed to give a vertical magnetic field error of less than 1×10^{-3} across the designated good-field region.

4 CURRENT R&D WORKS

The key components of the ID are the gradient magnet, the induction cell excited to MHz rates, and the MHz repetition rate solid-state driver. The R&D gradient magnet was manufactured according to their basic design specifications and subject to field measurements. Results is reported in an accompanied paper [5]. The original design for the power system was based on the simple idea of using an array of field effect transistors (FETs) or static induction thyristor (SIT) to switch energy from a pre-charged capacitor bank to an induction cell. The performance of the induction modules required for acceleration and BB trapping is common, apart from the pulse length. The output voltage is 2.5-3kV per cell and the repetition rate is 670kHz at 500MeV and 880kHz at 12GeV. The induction cell for acceleration is excited with a 0.5 μsec-long pulse and is reset with a 100 nsec-long pulse, while the induction cell for BB trapping is excited and is reset with a 30-40nsec short pulse. In order to produce a net 1 μsec-long accelerating voltage, 0.5 μsec-long pulses generated independently on two accelerating units are combined into a 1 μsec-long pulse. As both Finemet and Co-Fe ferrite are possible candidates for the core-material of the induction units, core-loss measurements have been conducted for minor-loop operation at the test bench. From these results, it turned out that the core-losses in both materials are dominated by the eddy current loss, but that their magnitude are within manageable. Although technical details of a prototype of a

2.5-3kV, 100nsec induction unit have been presented elsewhere [6], typical examples of pulse shapes of induced voltage and a sigle pair obtained by employing SITs as switching elements are shown in Fig. 5.

5 CONCLUSION

The AR can be constructed at quite a low cost by utilizing well-established permanent magnet technology. Although superbunch acceleration represents a challenge, the technology needed for this is steadily being developed, and there is a high degree of confidence that the performance levels required for the ID are attainable with the technology currently available. The results of neutrino oscillations may become more solid with twice as much statistics. The physics impact of the ID will be discussed in details at any other physics workshop.

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FIGURES

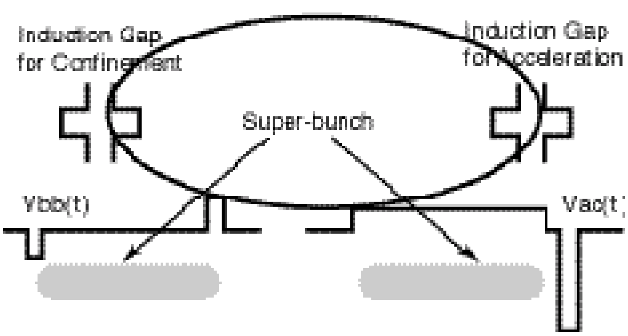

Figure 1: Capture of a super-bunch in the BB and its acceleration with induction voltage Vac(t)

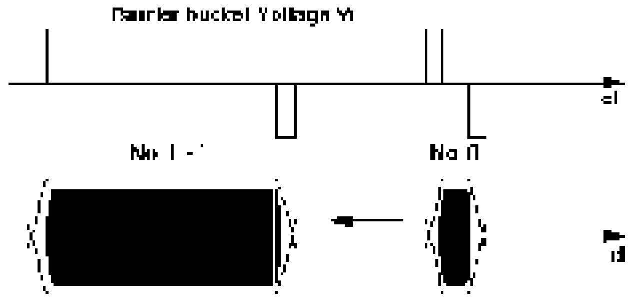

Figure 2: How to create a super-bunch in the AR

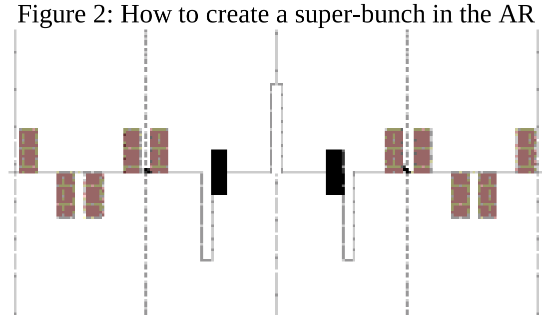

Figure 3: Four cells in the super-periodicity. Gray: the gradient focusing and defocusing magnets, Black: the bending magnets, White: the normal Q-mag

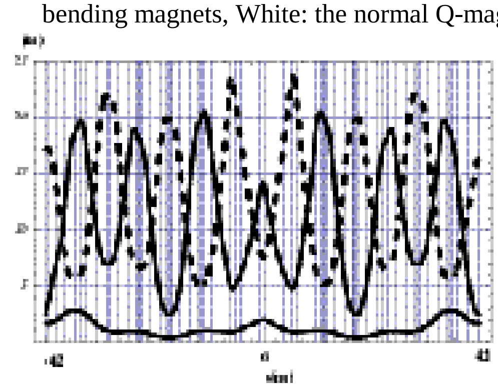

Figure 4: The lattice functions. Solid line (upper): β_x, Broken line: β_y, Solid line (lower): D(s)

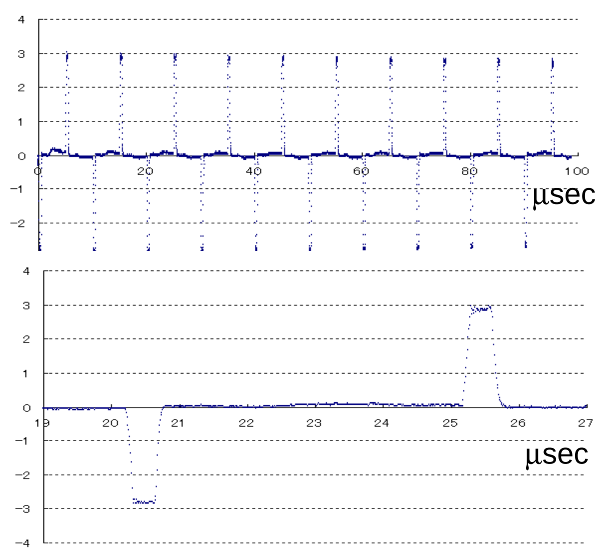

Figure 5: (upper) Pulse shapes of induced voltage (kV/div); (lower) a single pair