PRESENT STATUS OF THE HIMAC HEAVY-ION SYNCHROTRON

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Abstract

The main accelerator of the Heavy-Ion Medical Accelerator in Chiba(HIMAC) of National Institute of Radiological Sciences(NIRS) is two separated-function type synchrotron rings. This paper describes the present status of the HIMAC heavy-ion synchrotron.

Introduction

The HIMAC[1] is an accelerator complex dedicated to medical use consisting of a 100 MHz injector linac cascade[2,3], two separated-function type synchrotron rings[4,5], and a vertical and horizontal beam delivery system[6]. In order to ensure reliable operation, accelerator requirements are optimized at modest values satisfying medical requirements[7].

Two synchrotron rings are installed on the upper and lower underground floors of the building. In order to ensure operational simplicity, two rings have almost identical structure which is of separated-function type with a strong FODO focusing sequence. The both rings have a multi-turn injection channel and a slow extraction channel. For future extension, such capability as a two-stage acceleration of heavier ions, a single-shot beam, and a radioactive beam has been studied by the full use of two-ring facility. It has been studied during these years that the lower ring was designed to have a fast injection channel in addition to a fast extraction channel at the upper ring. Electron cooling devices are considered to be useful for the extension.

Even though we choose the modest accelerator parameters, heavy-ion synchrotrons still encounter some difficulties such as wider dynamic range of magnetic field, rf accelerating voltage, and beam diagnostics in comparison with proton machines. In addition, a high vacuum pressure is required to avoid the beam loss. In order to overcome these difficulties on the HIMAC heavy-ion synchrotron, some devices and components have been fabricated in advance and tests of them have been made to confirm predicted performances.

Based on the test results and the natural extension of well-established technology, the ring layout was completed leaving sufficient space for installation of devices for the future extension. A layout of the injection and extraction beam transport system was also completed. All devices for the first construction phase were specified and most devices are being fabricated.

This paper briefly describes the ring layout, design and status of ring devices, and performance test results, although details of most of the devices are described in companion papers, which include the layout of the injection and extraction beam transport system[8].

Ring Layout

A layout of two rings was studied to allow a fast extraction at the upper ring and a fast injection at the lower ring. Calculations of beam optics in the rings have been made to give a layout in which such devices as fast kicker magnet modules and bump magnets for the extraction and the injection are located appropriately without interference with the existing devices.

These processes generate new bump orbits in addition to bump orbits for the multi-turn injection and the slow extraction. Along the bump orbits, devices with a wide aperture should be located. Critical devices in aperture such as rf accelerating cavities, current transformers, scrapers, and electron cooling devices are located outside the bump orbits. The required aperture of all devices was finally decided.

The basic lattice[5] consists of 12 bending magnets, 12 focusing quadrupole magnets, and 12 defocusing quadrupole magnets. A field monitoring bending magnet to generate a field clock is located outside the ring. Horizontal closed orbit distortion is corrected by 12 horizontal steering magnets. Spaces for 12 vertical steering magnets are reserved to correct vertical closed orbit distortion in occasional deformation of the building floors in future. A set of 6 sextupole magnets is used for chromaticity correction. Spaces for another set of 6 sextupole magnets are reserved to give further flexible tuning if necessary.

A single rf accelerating cavity is equipped for the first construction phase. If the single cavity is insufficient to produce the required accelerating voltage, one more cavity will be installed.

The multi-turn injection channel consists of a septum magnet, an electrostatic inflector, and 4 fast bump magnets. The slow extraction channel using 3rd integer resonance with a tune value of 11/3 consists of 2 sets of 2 sextupole magnets for separatrix control, a quadrupole magnet for precise tune control, 4 bump magnets, 2 electrostatic deflectors, and 2 septum magnets. A space for an air-core type quadrupole magnet is reserved to compensate high frequency components of ripples in tune: while low frequency components are compensated by the quadrupole magnet for the precise tune control. For the fast extraction at the upper ring, spaces for 7 fast kicker magnet modules, an additional bump magnet, and 2 septum magnets are reserved. For the fast injection at the lower ring, spaces for 7 fast kicker magnet modules, 5 bump magnets, and 2 septum magnets are reserved. Spaces for electron cooling devices are reserved in the upper and lower rings, too.

Beam diagnostic equipments in the ring are specified for the first construction phase[9]: 12 horizontal position monitors for horizontal closed orbit control, 2 horizontal position monitors working also as a phase monitor for rf accelerating voltage control[10], 2 profile grid monitors for first turn control, a Faraday cup for for first turn efficiency control, an isolated plate equipped behind a septum electrode of the electrostatic inflector for multi-turn injection control, and scrapers for emittance control working also as a ring beam damper. Beam intensity and multi-turn injection efficiency are measured by a sum of left and right signals

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of a horizontal position monitor. Spaces for 12 vertical position monitors and a current transformer are reserved. Tune measurement in horizontal and vertical directions is made by rf knock-out method in which a decrease of the beam intensity is observed. Chromaticity is measured by the tune measuring system, too.

A profile grid monitor for injection orbit control is located at the entrance of the electrostatic inflector. An ion-chamber profile grid monitor for extraction orbit control and a scintillation monitor for extraction intensity control are located along the extraction beam line.

Magnets

The bending magnet with H-shape gap and saddle-shape coils is of sector type and has demountable pole end pieces at both ends. The upper coil and the lower coil are separated to each other and are connected separately from magnet to magnet in cross-over configuration. Magnet yoke is also connected from magnet to magnet in series. This configuration is expected to form a nice electrical network resulting in suppression of spikes associated with thyristor switching of a power supply.

The first bending magnet has been fabricated after tests of stacking procedure for the sector type magnet and various measurements have been made[11]. Magnetic field distribution shows that the stacking procedure is acceptable and the punched pole cross section shape satisfies the specification on field distribution. Excitation curve shows that the material of silicon steel is adequate. At present, steel punching for all bending magnets are being made.

Electrical characteristics has been measured on self inductance of a coil, a mutual inductance between the upper and lower coils, a resistance of each coil, and interelectrode capacitances between the coils and the yoke. The measured value of inductances and an estimated one agree well. Consequently a power supply for bending magnets was specified.

The quadrupole magnet with saddle-shape coils has a slightly different length in vertical and horizontal directions of a yoke while shapes of four poles are same. It has demountable pole end pieces at both ends. Two upper coils are connected in series and two lower coils are connected in series. This connection is preferred because of mechanical simplicity. Two sets of coils are separated to each other, are called the upper and lower coils, respectively, and are connected from magnet to magnet in cross-over configuration.

The first quadrupole magnet has been fabricated and various measurements have been made. Magnetic field distribution shows that the punched pole cross section shape satisfies the specification on the field distribution. At present, steel punching for all quadrupole magnets are being made.

The electrical characteristics of the quadrupole magnet has been measured similarly to the first bending magnet. In addition, mutual inductances between coils have been measured when four coils were separated. It was found from the measurement that we had made a mistake in the estimation of inductances. The specification of power supplies for quadrupole magnets are fortunately corrected before fabrication.

Power Supplies

A power supply for the bending magnets[12] is 24-pulse thyristor rectifiers consisting of 8 blocks of 6-pulse thyristor bridges each of which is bypassed by a thyristor. These blocks are equipped in symmetric configuration to a neutral point of the power supply and are operated in converter-inverter mode.

In order to decrease amplitude of spikes associated with thyristor switching, the neutral point is physically grounded and the system design of the power supply and the magnets is taken advantage of this neutral point. The neutral point is connected to the wiring for the magnet yoke, and symmetric positive and negative outputs are connected to the cross-over wirings for the upper and lower coils, respectively.

A passive filter of the power supply consisting of a normal mode reactor, a common mode reactor, resistors, and capacitors is equipped in symmetric configuration to the neutral point. For the first construction phase, there is no active filter because a repetitive control of the power supply is expected to reduce low frequency components of ripples while a space for the filter is reserved.

Power supplies for the quadrupole mangets are 24-pulse thyristor rectifiers consisting of 4 blocks of 6-pulse thyristor bridges each of which is bypassed by a thyristor. These blocks are equipped in symmetric configuration to a neutral point and are operated in converter mode only.

In addition to a passive filter similar to that of the power supply for the bending magnets, the power supply for the quadrupole magnets has an active filter consisting of two reactive transformers equipped at positive and negative output lines in symmetric configuration. The primary line of the transformer is energized by power amplifiers to reduce ripples.

This symmetric configuration of power supplies and cross-over coil connection wirings of bending magnets and quadrupole magnets has been proposed at NIRS based on experiences and tests at KEK and INS. At the KEK 12 GeV proton synchrotron, the amplitude of spikes has been decreased by a factor of about 10 when common mode capacitors are added. At the INS cooler-synchrotron ring, TARN2, a resistor bridging across input and output of each coil has decreased the amplitude of the spikes because of bypassing of high frequency components and has eliminated the reflection spikes because of damping nature of the electrical network of magnet coils.

The reactive power is compensated by 12-pulse thyristor controlled reactors in collaboration with capacitors which produce capacitive power and work as harmonic filters, too. The reactive power compensator is also operated to stabilize the primary ac line voltage and to reduce imbalance of primary ac line voltages.

All power supplies for the bending magnets and the quadrupole magnets of two rings and the reactive power compensator are operated by a common clock which is generated by a phase-locked loop to the primary ac line voltage.

The repetitive control which has been developed at the KEK 12 GeV proton synchrotron[13] is applied to operate all power supplies and the reactive power compensator. Due to a synchronous operation by the common clock, large reduction of ripples which have repetitive nature is expected.

Rf Accelerating System

The rf accelerating voltage is required to have a frequency range of 1 to 8 MHz, the maximum amplitude of 11kV/turn at lower frequency around 1 MHz, and an amplitude of 6 kV/turn at higher frequency around 8 MHz. In order to confirm the performance especially for the maximum amplitude, the first cavity has been fabricated and tested[14]. The cavity has been powered at 6 kV for the entire frequency range successfully. However, 11 kV at lower frequency has not been achieved yet. We have encountered two problems. The first is that grounding capacitors of ferrite bias windings are occasionally damaged when the tuning frequency is slowly increased while no damage occurs when it is decreased. The second is that when the amplitude is increased, a shunt impedance of the cavity decreases so as to require a larger rf power. Further tests will be made.

Beam feedback control of the rf accelerating voltage is based on beam phase and horizontal beam position[10].

The fundamental frequency components of both beam signals are processed by heterodyne technique and synchronous detection technique. A position signal is generated by amplitude to phase conversion technique. In order to achieve a high signal to noise ratio and to cancel the rf noise and the white noise, head amplifiers with a high input impedance are chosen and beam signals from beam monitors which are equipped at both ends of the rf cavity are summed after appropriate signal processing.

A digital synthesizer and a phase continuous rf synthesizer have been developed for a master oscillator.

Design study of the beam feedback loop has been made by applying the classical control theory[10]. In order to damp the phase oscillation and the horizontal displacement, a set of transfer functions of components are estimated. As a result, the ferrite material which is one of the components is preferred to be TDK SY-6 because of a low Q value, namely fast response.

The frequency of rf accelerating voltage is controlled by a summation of pattern stored in a memory and the beam feedback loop signals. The frequency is designed to follow such up or down signal as ripples of the bending magnet field. Memory address goes up or down by the field clock which is picked up by a search coil at the field monitoring bending magnet and generates up or down signals.

In order to confirm performance of the rf control system, it had been equipped to the TARN2 rf accelerating system and was tested to accelerate $^4He^{2+}$ ions. The beam with a relatively low intensity has been successfully accelerated from 10 to 160 MeV/u[15]. The digital synthesizer can be operated to accelerate the beam successfully. However the phase continuous rf synthesizer could not. Further precise adjustment is required and will be made at the HIMAC synchrotron.

Injection and Extraction

In the original design for a septum electrode of the first electrostatic deflector for the slow extraction, we were going to use wires with a thickness of 0.1 mm and a spacing of 1.5 mm. However, a stray electric field toward the circulating beam in the ring has been noticed to kick the beam because of a low energy of 6 MeV/u. Instead of the wires, thin plate has been chosen for the septum electrode. It is partly shaved from a 0.5 mm thick plate and is 0.2 mm thick in area of beam aperture. Test of the plate on baking at 200℃ has been made successfully and tests on sparking due to high voltage will be made soon.

Vacuum and Baking

In order to realize a high vacuum pressure around 1×10^{-8} Torr, vacuum ducts, vacuum chambers, and all devices in the vacuum are baked at 200℃. Vacuum pumps consist of turbo-molecular pumps, sputter ion pumps, and titanium getter pumps. The turbo-molecular pumps are always operated even at the final high vacuum pressure.

In order to decrease eddy current on vacuum ducts inserted to the bending magnet gap due to ramping magnetic field, thin wall vacuum duct reinforced by ribs has been developed. The wall is 0.3 mm thick and ribs are 1.5 mm thick with a pitch of 20 mm. Modules which are 194 mm long are welded for the 3.7 m long duct. The prototype duct has been baked at 200℃ several times without trouble. An outgassing rate after baking was measured to be 4×10^{-14} Torr • l/sec/cm^2. We have decided to adopt this type of vacuum duct for the bending magnets. All of the ducts are being fabricated.

The vacuum ducts for the bending magnets are directly heated by dc current flowing on the surface of the thin wall for baking because small amount of the current is enough. On the other hand, vacuum chambers and vacuum ducts for other devices are made of thicker stainless steels than that of 3 mm. They are heated by mineral insulated heaters attached on the surface of the wall for baking.

Computer Control

Main roles of a synchrotron control system are to operate many power supplies with coordinated patterns, to measure beam parameters by monitors synchronously to the patterns, and to correct distortions of beam behavior by the correction devices. These roles inevitably involve the fast and flexible tuning of operating patterns requiring instant change. We have chosen device controllers of which central elements are two memories. Pattern data stored in the memories are output alternatively by an external timing signal synchronized to a given repetition. A prototype controller for magnet power supplies has been developed and its performance tests are being made. Controllers for the rf accelerating devices have also been developed and operated for the beam test at TARN2 successfully.

System design of a synchrotron control computer system is being studied[16] where operation procedures of the rings, the device controllers, and a timing system are also taken into consideration.

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