STATUS OF THE CYCLOTRON CASCADE AND FUTURE PROSPECT AT RCNP

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Abstract

The RCNP facility consisting of the AVF-Ring cyclotron cascade and high-resolution experimental apparatuses has advanced the high-precision frontier of nuclear physics in the range of intermediate energies up to 416 MeV for protons.

The best performance of the cyclotron beam has rexently been realized in a long term over a week as the highly stabilized operation of the Ring Cyclotron without any tuning of cyclotron parameters.

This very stable high-resolution operation is realized with a precise adjustment of temperature of the iron core of magnets and has enabled to perform unique nuclear physics experiments.

In order to extend the present activities, we have started studies for a future accelerator towards a new high-precision frontier of quark-lepton nuclear physics in the range of multi-GeV energies.

Despite the fact that the final concept of the future accelerator has not been decided yet, a “figure of 8 configuration” synchrotron is being studied. Such a new multi-GeV high-performance accelerator is characterized as a protons/electrons/light ions/polarized ions cooler-synchrotron-collider. R&D studies for several components of high-performance synchrotrons have been started already.

1 INTRODUCTION

The Research Center for Nuclear Physics (RCNP) was founded in 1971 as a national nuclear physics laboratory in Japan. RCNP is now a laboratory complex which consists of the AVF-Ring cyclotron cascade laboratory, the underground Oto Cosmo Observatory, and the multi-GeV laser electron photon laboratory at SPring-8. All the unique facilities and research programs are open to all domestic and foreign users.

1.1 AVF-Ring Cyclotron Cascade

In the early 1960’s, nuclear physicists in Japan demanded to establish a research center having an AVF cyclotron at Osaka University. At that time, all the working cyclotrons in Japan were of classical type although many AVF cyclotrons had already been constructed in the world.

In a relatively short period after a budget was approved in 1971, the construction of the AVF cyclotron was completed due to extensive preparatory machine studies. The AVF cyclotron with K=140 MeV is of variable particles and variable energies type. The first extracted beam was obtained in 1975 and experimental studies were started in 1976. The capability of the cyclotron and various experimental facilities has greatly been appreciated as unique in the world.

Immediately after the completion of the AVF cyclotron, a study was started to realize a variable particles and variable energies ring cyclotron which can accelerate protons above the threshold energy of pion production towards a new high-precision frontier of nuclear physics in this energy range.

The construction of the Ring Cyclotron was started in 1987. The old AVF cyclotron has been used as an injector without any modification at that time to reduce the construction cost and not to interrupt research activities. The Ring Cyclotron with K=400 MeV was designed to be an energy quadrupler of the AVF cyclotron. The first extracted beam was obtained in 1991 and experimental studies were started in 1992.

After the successful operation of the AVF-Ring cyclotron cascade, several upgrading projects for following developments have been started year by year, especially for the old AVF cyclotron; an axial injection system, high-intensity ion sources for polarized ions and unpolarized ions, and dc power supplies for main coils and trim coils.

A feature of the Ring Cyclotron is to have a flat-topping rf system in order to achieve a high-quality beam with a single-turn extraction. Immediately after the first beam tuning, the flat-topping was obviously known as an effective method to achieve a high-quality beam with a low momentum spread less than 85 keV and a narrow time resolution less than 150 ps for 300 MeV protons.

Such beam performances, however, had been achieved for a short period such as one hour. Over half a decade of operation, it had been difficult to reproduce the same performance everytime in both short and long terms in spite of extensive efforts of tuning of the cyclotrons and beam transport lines.

In order to improve this situation and achieve a high-quality beam stably, a study has been started to find unknown causes of unstable performance of the cyclotrons because all cyclotron components seem to work well due to extensive upgrading projects. In summer, 1996, it was found that the magnetic field of sector magnets of the Ring Cyclotron varied with time depending on temperature of the iron core. In order to keep temperature of the iron core constant, a new procedure based on control of temperature of cooling water for trim coils is noticed to be very effective fortunately due to a special mechanical structure of trim coils and magnet pole of the Ring Cyclotron.

Highly-stable long-term operation of the Ring Cyclotron due to this temperature tuning is reproduced several times since then and has led to remarkable achievements of unique nuclear physics experiments.

1.2 R&D Study for Future Accelerator

Based on the fruitful results of unique nuclear physics experiments around the threshold energy of pion production by the cyclotron cascade, nuclear physicists are expressing their requests for a new high-precision frontier of quark-lepton nuclear physics in the range of multi-GeV energies. In addition, nuclear physicists are always eager to improve their experimental capabilities.

In order to meet these requirements which have to be realized by various accelerator facilities and various experimental methods, we are going to propose a multi-GeV high-performance accelerator which will have multi-functions aiming at flexibility as the highest priority.

2 CYCLOTRON CASCADE [1]

2.1 AVF Cyclotron and External Ion Sources

The AVF cyclotron is of three-sector single-dee type. The magnet with 16 pairs of trim coils has a pole diameter of 2.3 m and weighs 400 tons. The maximum of the average magnetic field is 1.6 T. The resonator associating with the 180-degree single dee electrode is of moving short type and the rf accelerating voltage is variable in frequency from 5.5 to 19.5 MHz with the maximum dee voltage of 80 kV. The beam energy is variable up to a magnetic rigidity limit of 140 q^2/A for heavy-ions lighter than mass 40 although the maximum energy of protons is limited to 80 MeV due to vertical focusing property and the radio frequency range. The beam extraction system is of electrostatic deflector type.

All the ion sources are now located on the second floor outside the cyclotron vault and all the ion beams are axially injected into the center of the AVF cyclotron efficiently through an electric spiral inflector.

A high-intensity polarized ion source (HIPIS) for protons and deuterons is of cold atomic beam type[2, 3, 4]. It consists of a cold 30-degree K nozzle, NEOMAX sextupole magnets and an ECR ionizer. A maximum proton current from the source is 50 - 100 μA. The polarization is 70 % or better after acceleration with the Ring Cyclotron.

In order to obtain a high-intensity unpolarized beam of heavy ions, an old internal ion source of PIG type was replaced by an external ion source of ECR type[5]. It is NEOMAFIOS operating at 10 GHz rf frequency for heavy ions lighter than mass 40. A typical beam intensity from the source is, for example, 110 eμA for $^{14}Li^{4+}$ ions.

The previous axial injection system consisted of electrostatic quadrupole lenses and an electric mirror of wire-grid type. In order to get a higher transmission and a more stable operation, it was replaced by the present system[2, 3, 4] consisting of electromagnetic Glaser lenses, a sawtooth rf buncher, and a spiral inflector. The direction of magnetic field in the Glaser lenses is excited alternately to cancel the depolarization effect of the lenses. The injection energy and injection efficiency into the center of the AVF cyclotron is 15 keV and 14 %, respectively, for 65 MeV protons of the AVF cyclotron.

The power supply for the main magnet was replaced by a saturable reactor with series dropper of transistor type[6]. The previous power supply was a motor-generator with a series dropper. The long-term current stability is much improved from 5×10^{-5} to 2×10^{-6} per day. In addition, current sensors for power supplies for trim coils are being replaced by DCCT's(HOLEC DCCT TOPACC) instead of previous shunt resistors or old DCCT's.

2.2 Ring Cyclotron

The Ring Cyclotron is of six separated sector type with three single-gap rf cavities for acceleration and a single-gap rf cavity for flat-topping. Six spiral sector magnets with 36 pairs of trim coils weigh 350 tons each and have the maximum magnetic field of 1.75 T. Injection and extraction radii of the magnet system are 2 m and 4 m, respectively. Injection and extraction are carried out with a combination of magnetic channels and electrostatic inflectors/deflectors. The rf accelerating voltage is variable from 30 to 52 MHz in frequency with the maximum voltage of 550 kV. The flat-topping voltage is variable in frequency from 90 to 156 MHz which is just three times of the radio frequncy of the accelerating voltage.

Continuous efforts towards upgrading the rf accelerating system have been carried out in order to realize a stable operation and a high performance. Because the Ring Cyclotron is of variable particles and variable energies type, the radio frequency should have a wide range. Such a wide range performance, however, was sometimes affected by parasitic resonances which cause damages on components of cavities, rf power amplifiers, and low level electronics. Trouble shooting on damages has greatly been progressed and a stable performance is being realized.

The amplitudes of both accelerating voltage and the flat-topping voltage are well stabilized at less than 10^{-4}[7]. A phase excursion of both accelerating voltage and flat-topping voltage is also well stabilized at less than 0.1-degree/100hrs. These performances are sufficient for achieving a high-quality beam from the Ring Cyclotron.

2.3 Beam Matching in Cyclotron Cascade

In order to obtain a high-quality beam from the Ring Cyclotron, it is essential to match longitudinal and transverse emittances of the injected beam to acceptances of the Ring Cyclotron at its injection point. Because all the six dimensional phase acceptances of the Ring Cyclotron are so small, a precise matching of the injected beam is needed.

A harmonic number of the radio frequency of an accelerating voltage to a revolution frequency of the circulating beam is 1 or 3 for the AVF cyclotron, and 6, 10, 12 or 18 for the Ring Cyclotron, respectively, because the radio frequency of the Ring Cyclotron is chosen at 3 or 5 times of that of the AVF cyclotron depending on ion species and energies; for example, 3 for protons and 5 for alphas.

The flat-topping voltage is chosen at 11.37 % of the total accelerating voltage in order to obtain the flattened accelerating voltage for phase due to the deceleration effect of the flat- topping voltage[8]. A computation shows in this optimum condition that a small energy devitaion of 10^{-4} from injection to extraction can be obtained for a phase acceptance of 20-degrees.

This phase acceptance requests the phase width of the injected beam from the AVF cyclotron on 7-degree for protons and 4-degrees for alphas, respectively, due to the ratio of the radio frequencies of two cyclotrons. A longitudinal matching due to a dispersion matching at the injection point of the Ring Cyclotron thus results in a high-quality beam without widening the energy spread during acceleration.

In order to achieve the beam with such a narrow phase-width and small emittances from the AVF cyclotron, a longitudinal emittance and transverse emittances should be limited by several kinds of slits installed between the ion source and the injection point of the Ring Cyclotron, although these slits reduce the beam intensity very much. The beam intensity upgrading projects have then been carried out necessarily.

Such slits and some equipments for limiting the beam shape are installed as follows; an rf buncher of the axial injection system, a phase slit at the central region of the AVF cyclotron, a horizontal slit at the exit of the AVF cyclotron, an rf buncher In order to confirm an amount of dispersion at the horizontal slit after the momentum analyzing bending magnets, an Al foil is inserted and a position of the beam is then checked to move as desired.

Although many efforts on tuning of these slits to realize the high-quality beam, the high resolution such as 30 keV with a narrow phase-width of 5 degrees for 65 MeV protons has not been achieved yet.

2.4 Highly-Stable Long-Term Operation

As a result of extensive efforts to find unknown causes of unstable performance of the cyclotrons, we noticed in summer, 1996 that the magnetic field of sector magnets of the Ring Cyclotron varied with time depending on iron-core temperature. Temperatur Such a fast response is considered to arise from a special mechanical structure of trim coils and magnet pole of the Ring Cyclotron because the coils are fixed directly to the pole surface without heat insulators.

In the case of the AVF cyclotron, a slow response was observed; even 2 days after temperature of the cooling water of coils was artificially changed, the field strength did not reach a peak. Therefore, it is difficult to keep the field strength of the AVF cyclotron constant by the same procedure as that for the Ring Cyclotron.

Remarkable achievements were obtained several times since then due to this procedure for the Ring Cyclotron[8]; a small variation of the magnetic field within 2 ppm for 3 days in January, 1997 and a highly-stable long-term operation without any tuning of all cyclotron parameters for 7 days in July, 1997. In the former machine time for experiments, the world's first low-background 0-degree measurement at high-resolution magnetic spectrograph "GRAND RAIDEN", was achieved as shown in Fig. 1. The spectrum features a very low background due to a very little halo of incident beam of 392 MeV polarized protons with an energy spread of 3.6×10^{-4} which is comparable with that of the best performance achieved before. In the latter machine time for experiments, the intensive beam of several hundred nA of 300 MeV protons was supplied stably: the allowed maximum intensity is limited to 1 μA in this facility for radiation safety.

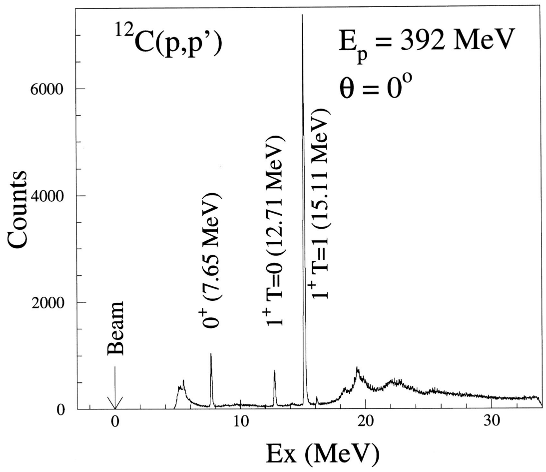

Figure 1: Energy spectrum of inelastically scattered polarized protons of 392 MeV incident energy on very forward angles observed at RCNP GRAND RAIDEN. The unique feature of the experiment is the measurement of polarization transfer coefficient with a focal plane polarimeter at and near 0-degree scattering angle and the low excitation energy of about 5 MeV due to special detector configuration.

The energy spread itself of the beam extracted from the Ring Cyclotron, however, has not been improved significantly in these operations because the quality of the injected beam from the AVF cyclotron to the Ring Cyclotron has not been improved despite the fact that many efforts are being carried out to limit beam emittances by several slits. This performance of ineffectiveness of the slits may come from the fact that the magnetic field strength of the AVF cyclotron varies with time and thus affects the beam quality very sensitively.

3 R&D STUDY FOR FUTURE ACCELERATOR

3.1 A "Figure of 8 Configuration" Synchrotron [9,10]

In order to meet the requirements for a study of quark-lepton nuclear physics, a future accelerator will be a multi-GeV high-performance accelerator aiming at flexibility as the highest priority.

Such an accelerator shall meet the following requirements;

- Two-Ring Configuration,
- Multi-Functions,
- Variable Focusing Modes,
- Multi-Particles, and
- Variable Energies.

Particles should include electrons and polarized ions in addition to usual particles such as protons and light ions. Orbital motion of electrons in synchrotrons for ions is considered to be stable if the synchrotron radiation loss of electrons in bending magnets is compensated by the rf system because a dynamic aperture of synchrotrons for ions is large enough for accomodating the small-size electron beam.

A two-ring configuration is very flexible because various functions are allowed so as to transfer the beam between two rings and to operate independently of each other.

One of the requirements is to accelerate polarized ions stably. A very exciting accelerator of a "figure of 8 configuration" synchrotron was proposed[10] as shown in Fig. 2 in order to accelerate polarized ions stably without intrinsic depolarization. It consists of two rings which have opposite bending directions so that the precession motion of spin of the polarized ions is cancelled when ions make a complete revolution in both rings. In this configuration, a small partial snake with a solenoid is enough for keeping the polarization against a closed orbit distortion.

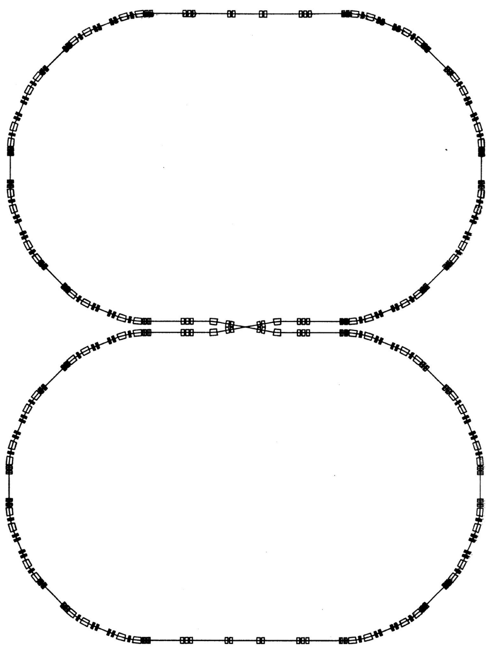

Figure 2: A "figure of 8 configuration" synchrotron with two identical "race track" rings.

This kind of two-ring configuration consists of two identical "race track" rings which can be considered to operate independenly of each other. In addition, a crossing section of a "figure of 8 configuration" synchrotron resembles an intersection of a collider.

For the moment, such a collider due to modification of a "figure of 8 configuration" synchrotron will be studied for a multi-GeV high-performance accelerator characterized as a protons/electrons/light ions/polarized ions cooler-synchrotron-collider.

3.2 R&D Study for High-Performance Synchrotron Components

R&D study of some components for synchrotrons has been started in order to promote a design study for the RCNP future accelerator.

In order to develope high-performance components with a large dynamical range, excellent stability, nice reproducibility, and very low noise, a guiding principle of the R&D study is to realize something new and to be based on physics viewpoints.

- Power Supplies
  - Low ripple synchrotron power supply of Thyristor type[11], and
  - Low noise synchrotron power supply of IGBT type.
- Magnets
  - C-shape bending magnet,
  - H-shape bending magnet,
  - Q-magnet with a normal length, and
  - Q-magnet with a thin length.
- Rf Accelerating System
  - Tuning-free rf accelerating cavity for ions[12],
  - Rf accelerating cavity for electrons of rectangular cross section type, and
  - Study on damping of synchrotron oscillation by simulator circuit.
- Beam Diagnostics and Beam Manipulation
  - Fast betatron-tune controller of RFQ type[13], and
  - Non-destructive dc beam current monitor of DC SQUID type[14].
- Eddy Current Effect in Magnets
  - Study of transient Eddy current effect in solid magnets

In the collider mode of the RCNP future acclerator, high-density high-intensity beams collide or merge each other. The emittance growth of ion beams due to various processes such as intrabeam scattering and non-linearity in large amplitudes should be suppresed to achieve a high luminosity. In the case of electron-ion collider, the ion beam should be cooled down very much. A 2 - 3 MV electron cooling device is essential for multi-GeV ion beams in the collider and its conceptual design will be studied as soon as possible.

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