DEVELOPMENTS AT RCNP

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Abstract

Developments at the Research Center for Nuclear Physics (RCNP) in producing ultra-precise beams are surveyed for the decade since 1996 together with findings of key techniques of temperature stabilization of iron cores of cyclotron magnets. In order to understand why beam performance is strongly influenced in a strange manner by deviations of the magnetic field and the frequency and amplitude of the rf accelerating voltage, a two-step nonlinear acceleration theory for spiral orbital motions in cyclotrons is under study and its potential is presented briefly.

INTRODUCTION

The Research Center for Nuclear Physics (RCNP) cyclotron cascade consists of a six-spiral-separated-sector K400 ring cyclotron main accelerator and a three-spiral-compact-sector K140 AVF cyclotron injector. The former is equipped with a flat-topping system but the latter is not equipped with such a system. Both cyclotrons are of variable energies and are able to accelerate various particles including polarized beams of protons and deuterons. Since our report on the performance of the ultra-precise beams at the last 16th conference [1], the performance of the ultra-precise beams is being improved in a further effort toward realizing long-term stability of the magnetic fields of the cyclotrons [2], especially of the AVF cyclotron, using key techniques of temperature stabilization in iron cores. At present, the temperature changes of the iron cores are estimated to be within 0.01ºC over the long term and the field changes are within 2 ppm over the long term after a stationary state has been achieved. For the AVF cyclotron, a quasi-single turn extraction can be achieved without a flat-topping system due to skilful tuning by the operators. An energy spread of, for example, 392-MeV protons extracted from the ring cyclotron is better than 80 keV and its best factor is $\Delta E / E = 1.5 \times 10^{-4}$. A main part of the 80 keV is considered, however, to come from the 64.63-MeV protons extracted from the AVF cyclotron.

The 392-MeV protons are transported to a large high-resolution grand raiden magnetic spectrograph and both lateral matching and angular dispersion matching are carried out [3]. The resultant energy spread observed at the focal plane of the grand raiden is $\Delta E / E = 2 \times 10^{-5}$, a good value, and can be kept stable over the long term.

Based on the achievement of the ultra-precise beams, a renewal of the existing AVF cyclotron, which is 30 years old (the first beam was commissioned in the middle of 1974), was planned and a one-year budget in the 2004 fiscal year has been approved recently. Because of a limited amount of money, only a few components will be replaced with new components to extend the life of the cyclotron and improve its performance. In addition, a few new devices will be installed to open new research fields [4]. In order to upgrade the beam performance, a dee electrode of the AVF cyclotron will be replaced with a new electrode [5], which will have a combined function of both flat-topping and fundamental rf voltages. Perfect single-turn extraction, beyond the currently achieved quasi-single-turn extraction, is expected to be achieved in combination with a well-stabilized magnetic field over the long term.

In order to understand particle motions in cyclotrons, a two-step nonlinear acceleration theory for spiral orbital motions is under study [17] as a natural extension of acceleration theory for synchrotrons and FFAG accelerators at transition energies. We present a framework of the theory here and briefly present longitudinal motions at large radii and high energy.

PERFORMANCE 10 YEARS AGO

Immediately after the ring cyclotron was commissioned at the end of 1991 [6], preliminary experiments with 300-MeV polarized and unpolarized protons were carried out successfully at the grand raiden on the basis of dispersion matching. Single-turn extraction at the ring cyclotron was confirmed and could be ascribed to the flat-topping system. Subsequently, protons with energy of 300 MeV extracted from the ring cyclotron were tuned to an energy spread of 100 keV and a good energy spread of 25 keV was observed at the grand raiden.

In order to get such a high-quality beam, various slits limiting the six-dimensional phase space volume of a beam injected into the ring cyclotron were installed between the ion sources and the ring cyclotron, considerably reducing the intensity by a factor of 10^{-2}. A high quality beam, however, could only be obtained for a short period of half an hour.

A beam intensity upgrade project [7, 8, 9] and a beam stability upgrade project [7, 10] were started in order to improve the performance. Both the upgrade projects were completed in the middle of 1996 and have laid the foundation of the present performance with many fruitful results [7-10]. An energy spread for 300-400 MeV protons was less than 80 keV and an energy spread of 25-40 keV was observed at the grand raiden [7]. At present, the variable energy ranges, for example, from 100 MeV to 416 MeV for protons, and particles from protons to oxygen can be extracted. However, in 1996 a high quality beam could only be obtained for a short time although the best beam performance in 1996 was comparable with the present one. Hence, since a stable high-quality beam over the long term can now be attained, one of the last remaining issues from 1996 has been settled.

Possible procedures used to return a beam under operation to a satisfactory level of performance when the performance of the beam deteriorated, are to tune the amplitude of the rf accelerating voltage and/or the magnetic field strength. In 1996, the amplitude tuning of the rf accelerating voltage was preferably used because its response is faster than that of the magnetic filed strength tuning. However, the reproducibility was not good in both the tuning procedures and a certain satisfactory beam performance did not last long. To achieve long-term stability of high-quality beam performance, the causes of unstable performance must be investigated.

We speculated that unstable performance was due to time-dependent change of the magnetic field distribution and it was difficult to reproduce a magnetic field distribution by tuning of the coil currents. In this respect, a reading of an NMR probe was not a good measure of the magnetic field distribution.

We identified transient eddy currents as a cause at a first supposition and further identified the temperature effect of iron cores. Our ideas of two causes were much indebted to the paper on the field setting for a cyclotron sector magnet studied by Dr. Jungwirth [12].

EFFECT OF TRANSIENT EDDY CURRENT

The coil current tuning procedure possibly produces transient eddy currents that result in time-dependent changes in the magnetic field distribution as they decay. This decay has been known in cyclotrons since Prof. Alvarez found in the first application of accelerator mass spectrometry in 1936 that helium-3 is stable [11]. In his experiment at the Berkeley 37-inch cyclotron, transient eddy currents of a long decay time constant of several seconds helped to produce a magnetic field distribution satisfying the vertical focusing when the magnetic field was turned off from full excitation and then dropped rapidly through the helium-3 region.

In a similar context, if one tunes coil currents to reproduce a beam performance, transient eddy currents appear and then decay, changing the tuning condition at around the decay time constant. In this way, the coil current tuning procedure disturbs the tuning of the beam performance if the decay time constant is long. Consequently, tuning of the coil currents must be repeated to reproduce a certain satisfactory beam performance.

It is necessary to know the time constant, and this has been studied by Dr. Jungwirth for a NAC cyclotron sector magnet [12]. When a coil current of a sector magnet was decreased from full excitation of 1.25 T to some level, it was observed that the time constant depends on the final field. The time constant was longest at 45 min. for a final field of 0 T and was as short as several minutes for higher final fields. However, it was not concluded in the paper that the decay comes from transient eddy currents.

We studied transient eddy currents in an analytical approach to explaining the dependence of the time constant on the final field taking the hysteresis effect of ferromagnetic materials into account [13]. At a poster session of the 15th conference, it was learnt from Dr. Jungwirth that the transient eddy current is an origin of the long decay time constant.

Hence, we can conclude that transient eddy currents produce changes of the magnetic field distribution as they decay after the coil current is changed.

In the case of the RCNP cyclotrons, however, the field strength is now kept constant over the long term for temperature stabilization of the iron cores, and therefore, it is not necessary to tune the coil currents often and thus the chance of producing of transient eddy currents is not serious at present. Hence, transient eddy currents are not a main cause of time-dependent change of the magnetic field distribution now.

EFFECT OF TEMPERATURE OF IRON CORES OF CYCLOTRON MAGNETS

It was pointed out by Dr. Jungwirth in the section of his same paper [12] subtitled “Field Setting” that reproducibility of the magnetic field strength is affected by temperature effects probably. Based on this we further supposed that the temperature effect of the iron cores might be a cause of the time-dependent change of the field strength and field distribution.

We arranged to observe both the effect of transient eddy currents and the effect of the temperature of the iron cores for the ring cyclotron. Four NMR probes were mounted at four different radii of one of the sector magnets. The temperature of the cooling water for the trim coils was changed prior to a change of the coil currents. Field strengths at four different radii were observed to increase immediately after the change of the temperature of the cooling water. They reached peak or bottom field strengths at different times and decayed with different time constants. This complicated phenomenon is believed to be due to a mixture of the effect of non-uniform thermal deformation of the iron cores and the effect of transient eddy currents caused by a field change due to the deformation of the iron cores. In addition, as found at the AGOR cyclotron [14], temperature dependence of the magnetization of the iron cores may contribute to the complicated phenomenon.

It is apparent from our observations that the magnetic field distribution should be kept constant by stabilizing the temperature of the iron cores. It is fortuitous that the response of the ring cyclotron is very fast. Because of this fast response, tuning of the temperature of the cooling water allows reproduction of a certain field strength by using the reading of the NMR probe. As a first trial, with the field strength being monitored by the NMR probe, the temperature of the cooling water of the trim coils of the ring cyclotron was changed with an idling time of one or two days until a smooth decay was attained after the magnet was energized by coil currents. Immediately after the temperature was changed, the field strength changed as expected. After several trials, an appropriate combination of quantities of idling time and temperature change was found for which the field strength became constant within 2 ppm over a time period as long as a week [15]. Under these conditions, stable high-resolution measurements could be made with the grand raiden over a long time period and low background measurements of inelastic scattering at very forward angles without beam halo was soon carried out successfully.

A present method of keeping the temperature of iron cores constant over the long term is that a kind of average of cooling water temperatures at inlet and outlet for the coils is kept constant [1].

We have started to keep the field strength of the AVF cyclotron constant over the long term but we had yet to observe the field strength accurately using NMR probes. Because of the non-uniform field distribution in the AVF cyclotron, it appears difficult to observe the field by NMR probes. However, it was noticed that the cyclotron JULIC could measure it by NMR probes [16]. Encouraged by this, we developed NMR probes [1] that are equipped with gradient coils for a partial cancellation of the non-uniform field distribution at a valley sector in the AVF cyclotron. It should be noted that in this type of NMR probe, a time-dependent change of field strength can be observed at the sacrifice of absolute field strength.

The effect of a change of temperature of the cooling water was observed by measuring the change of the field strength by the NMR probe. Observations showed, however, that the time constant was as long as a week [15] because heat insulation between the coils and the iron core of the AVF cyclotron is very strong, in contrast with that of the ring cyclotron. It is unfortunate that unlike for the ring cyclotron, for the AVF cyclotron there seems to be no inexpensive way to convert from a slow response to a fast one to temperature change of cooling water. This could be achieved by renewal of the iron core and coils of the AVF cyclotron, but rather than this we carefully investigated a water cooling system configuration that could control the temperature effects on the iron core. The most efficient method was to separate the cooling water system for the main coils and the trim coils [1, 2], both of which were formerly connected to a single system. After this separation, the temperature of the iron core of the AVF cyclotron has been more rapidly controllable allowing constant readings of the NMR probes. As a result, a good beam performance for quasi-single-turn extraction is now obtainable.

At present, the readings of NMR probes are good measures of not only the field strength at measuring positions but also the field distribution.

OTHER FINDING ON RF ACCELERATION

Four years ago, it was noticed by operators that the beam performance changed when the three-way valve of the water cooling system for an rf resonator of the AVF cyclotron switched for temperature control. Apparently the position of the temperature sensor was wrong and so it was moved to near the water inlet of the resonator. Since then, not only is a steady beam performance obtainable, but also the capacitive trimmer that keeps the resonant frequency constant now seldom moves. The wrong positioning of the sensor is considered to possibly have caused a thermal deformation of the resonator.

Here, then, is a possible reason that the amplitude of the rf accelerating voltage malfunctions because a structural configuration of a pickup electrode detecting the amplitude deforms due to the thermal deformation of the resonator. The tuning method of the amplitude of the rf accelerating voltage described before might relate to such a malfunction in the amplitude detection. A steady beam performance is attainable from the stable amplitude of the rf accelerating voltage on the basis of the temperature stabilization of the resonator because the resonant frequency is compensated at a fixed frequency by trimmers constantly.

TWO-STEP NONLINEAR ACCELERATION THEORY

It has been well known that beam performance is strongly influenced by deviations of not only the magnetic field strength and the frequency of the rf accelerating voltage but also the amplitude of the rf accelerating voltage [16]. It appears that temperature stabilization of both the magnets and the resonators achieved at the RCNP cyclotrons relates to such a strong influence closely. Our experiences on ultra-precise beams suggest that deviations in the magnetic field strength and the amplitude of the rf accelerating voltage should be 1×10^{-6} and 1×10^{-4}, respectively, for the long term. In addition, a strange response of beam performance to a deviation of the magnetic field strength was observed at the RCNP cyclotrons, as shown in Fig. 1 of Ref. [1] reported at the last 16th conference.

At that time, the stability of the magnetic field of the AVF cyclotron was not good but the stability of the magnetic field of the ring cyclotron was good. The performance of the AVF cyclotron for 64.63-MeV protons dominated the beam performance of the 392-MeV protons extracted from the ring cyclotron. The energy spread of the beam was observed directly by an achromatic mode of the grand raiden and was tuned initially at 80 keV for physics experiments. However, it became worse with time and operators had to tune the magnetic field strength of the AVF cyclotron every few hours to reproduce 80 keV. It should be noted, as seen from the figure, that the field strength always had to be decreased to reproduce 80 keV. For example, the energy spread became worse at 300 keV by a factor of 3.5 and returned to 80 keV by a slight decrease of the field strength of 2 ppm in this case.

This tuning process implies a strange response, in that a positive deviation of the field strength makes the energy spread worse but a negative one does not affect it so much.

In order to understand the strong influence of the deviation and the strange nature of the response, a two-step nonlinear acceleration theory for spiral orbital motions in cyclotrons is under study [17]. For simplicity, cylindrical coordinates are adopted and it is assumed that a magnetic field depends only on radius and rf acceleration is carried out by continuous surf-riding acceleration along a beam path.

The theory consists of two steps. In the first step, a virtual reference of a spiral orbital motion and a relation between the magnetic field distribution and the amplitude of the rf accelerating voltage is determined. The virtual reference motion is assumed to have a constant angular frequency and constant energy gain per turn. A magnetic field distribution is then determined in order to produce a virtual reference motion. It is a solution of a nonlinear ordinary differential equation of order one that is obtainable from the time derivative of the equations of motion. A perfect solution has not yet been obtained because of the complexity of spiral orbits and nonlinearity.

The second step consisting of two stages is a natural extension of the acceleration theory for synchrotrons and FFAG accelerators [18] at transition energies. Particle motion is obtained as a deviation from the virtual reference motion under deviations of the magnetic field distribution and the frequency and amplitude of the rf accelerating voltage from the virtual reference ones.

At the first stage of the second step, transverse motion is separated from longitudinal motion on the assumption that the former is rapidly varying and the latter is slowly varying. Because the longitudinal motion is a nonlinear motion at transition energies [18], particle energy no longer varies rapidly with the transverse motion despite the fact that the phase itself varies rapidly with the transverse motion. At the second stage of the second step, longitudinal motion is obtained as a deviation from the virtual reference motion. The equations of motion for such a deviation are then expressed in a nonlinear form.

All equations to be solved at the second step have been obtained, but perfect solutions have not yet been obtained because of the complexity of spiral orbits and nonlinearity. As a consequence, it is not yet thoroughly understood what happens as a whole from injection at small radii and low energy to extraction at large radii and high energy.

However, longitudinal motion at large radii and high energy is rather easily obtainable. Longitudinal motion (indicated by the suffix L) can be solved for phase and Lorentz factor as a deviation from the virtual reference motion (indicated by the suffix I):

$$\phi_L = \Phi_L\,,\ \gamma_L = \gamma_I + \Gamma_L\,.$$

The independent variable is chosen to be turn number, instead of time. The turn-number derivative of a variable X is expressed as X'. The equations of longitudinal motion at large radii and high energy are expressed approximately by the simultaneous ordinary differential equations of order one for deviations of Φ_L and Γ_L as

$$\frac{1}{2\pi h}\Phi_L{}' = \frac{1}{\gamma_T{}^2}\frac{\Gamma_L}{\gamma_I} - \left(1-\frac{1}{\gamma_T{}^2}\right)\frac{\sqrt{1-\frac{1}{(\gamma_I+\Gamma_L)^2}}-\sqrt{1-\frac{1}{\gamma_I{}^2}}}{\sqrt{1-\frac{1}{\gamma_I{}^2}}}$$

$$+\frac{\Delta f_{rfs}}{f_{rfI}} - \frac{1}{\gamma_T{}^2}\frac{\Delta B_s}{B_I}\,, \tag{1}$$

$$\Gamma_L{}' = \frac{q}{m_0 c^2}V_I\left\{\left(1+\frac{v_s}{V_I}\right)\cos\Phi_L - 1\right\}, \tag{2}$$

where γ_T is a general expression of the transition energy and is defined as

$$\gamma_T{}^2 = \frac{B_I + \Delta B_s}{B_I}\left\{1 - \frac{r}{B_I + \Delta B_s}\left(\frac{dB_I}{dr} + \frac{d\Delta B_s}{dr}\right)\right\}. \tag{3}$$

It is apparent from Eq. (1) that the effect of frequency deviation on beam performance is equivalent to that of magnetic field deviation for the approximation $\gamma_T \approx 1$ as experimental evidence of the full equivalence has been reported from the cyclotron JULIC [16].

The fixed points of motion in (Φ_L, Γ_L) phase space at $\Phi_L{}' = 0$ and $\Gamma_L{}' = 0$ depend on the sign of the deviations. Assuming $\gamma_T = \gamma_I$ and that Eqs. (1) and (2) can be approximated by the squares of Γ_L and Φ_L, respectively, the fixed points are obtained as follows.

When $-\frac{\Delta f_{rfs}}{f_{rfI}} + \frac{1}{\gamma_I{}^2}\frac{\Delta B_s}{B_I} \geq 0$ for positive deviation in the magnetic field, two fixed points of Lorentz factor for $\Phi_L{}' = 0$ appear. The distance between them is given by

$$\Delta\Gamma_L = 2\gamma_I{}^2\sqrt{\frac{1-\frac{1}{\gamma_I{}^2}}{3-2\frac{1}{\gamma_I{}^2}}\left(-\frac{\Delta f_{rfs}}{f_{rf}} + \frac{1}{\gamma_I{}^2}\frac{\Delta B_s}{B_I}\right)}\,. \tag{4}$$

When $\frac{v_s}{V_I} \geq 0$, two fixed points of phase for $\Gamma_L{}' = 0$ appear. The distance between them is given by

$$\Delta\Phi_L = 2\sqrt{2\frac{v_s}{V_I}}\ . \quad (5)$$

It can be seen from Eqs. (4) and (5) that particle motion is strongly influenced by the square root of positive deviations in a strange manner as observed at the AVF cyclotron. It is interesting that a nonlinear oscillation occurs for positive deviations, similar to synchrotron oscillation in synchrotrons and FFAG accelerators, because of the appearance of four fixed points. On one hand, negative deviations do not produce fixed points in contrast to the case of positive deviations.

Many kinds of longitudinal motion, therefore, appear due to the various combinations of positive and negative deviations of the magnetic field and the frequency and amplitude of the rf accelerating voltage. The two-step nonlinear acceleration theory naturally reproduces the strong influence on the beam performance in a strange nature of response.

CONCLUSION

At the 15th conference held in 1998, when we reported the highly stabilized operation of the RCNP cyclotron [15], a representative from AGOR remarked on the importance of temperature stabilization of the magnet [14] to facilitate the removal of one of the last remaining sources of non-reproducibility in modern cyclotrons. In addition to agreeing with AGOR, we remark that temperature stabilization of both the magnets and the resonators produce good, stable beam performance over a long term.

A two-step nonlinear acceleration theory for spiral orbital motions, which is a natural extension of acceleration theory for synchrotrons and FFAG accelerators at transition energies, has the potential to explain the strong influence of deviations on beam performance in a strange manner. In this theory it can be shown that the square root of positive deviations produces longitudinal oscillation at large radii and high energy. However, perfect solutions have not yet been obtained, although the equations to be solved have been obtained. In this respect, further study is needed.

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