CALCULATIONS OF THE BEAM TRANSMISSION AND QUALITY IN THE RIKEN AVF CYCLOTRON

S. B. Vorozhtsov, A. S. Vorozhtsov, E. E. Perepelkin, JINR, Dubna, Russia
S.Watanabe, S. Kubono, CNS, Japan
T. Mitsumoto, SHI, Japan
A. Goto, RIKEN, Japan

Abstract

The highly advanced plan of the RIKEN AVF cyclotron (Japan) is under way. The intensity of the $^{14}N^{5+}$ ion beam more than 10 pμA is required to obtain a sufficient yield of secondary particles. The computer model of the AVF electromagnetic field has been prepared and successfully checked against the measurements. The focus of the present study is on the 2nd RF harmonic regime. The intermediate goal of the upgrade is improvement of the transmission efficiency and the beam quality of the regime. Measured Hyper ECR output emittances were 64 and 135π·mm·mrad, from which the emittance of 100π·mm·mrad was assumed for both transverse oscillations in the simulation. The detailed account of the transmission efficiency and incremental losses are given. The optimization of the starting beam parameters for the existing electrode structure was considered first. The goal is to obtain a sufficiently small axial angle at the exit from the inflector to decrease axial losses in the initial turns. To this end, a new regime was formulated. The ECRIS voltage and the dee voltage were decreased by 15 % to 9kV and 40 kV, respectively. The modification is needed to ensure the beam passage through the puller with the crossing of the 1st acceleration gap at the positive RF phase that gives the electrical focusing there. Accordingly, the buncher voltage should be changed to 125 V. As a result, the RF phase range of the bunched beam became ±12° and energy spread ±0.8keV with the tails of ~ 25% of the beam intensity. The magnetic field variation by ~50 % of the maximal contribution of the 1st trim coil is needed to ensure acceleration at the top of the dee voltage. The RF frequency 16.2 MHz was assumed. The particle losses in the range from the inflector ground to the ESD mouth became ~ 35% instead of previous ~ 60%. The obtained regime was tested experimentally at the AVF cyclotron before proceeding to a more radical modification of the central region as the next step.

AVF CYCLOTRON UPGRADE

Experimental studies in such fields as nuclear physics of unstable nuclei and nuclear astrophysics are performed using the AVF cyclotron. To continue such research activities, the upgrade project of the AVF cyclotron is being implemented by a collaboration of the Centre for Nuclear Study (CNS) of the University of Tokyo and RIKEN. One of the issues in this project is to increase the intensity of $^{14}N^{5+}$ ion beams up to 10 pμA, which is required for obtaining sufficient yields of secondary particles [1]. The present study is thus focused on the improvements in the beam transmission efficiency and beam quality in the AVF cyclotron by detailed orbit simulations.

FIELDS

The computer model of the AVF electromagnetic field was prepared and successfully checked against the measurements. It comprises the following structural elements: a magnet yoke, spiral sectors, center plugs, trim and harmonic coils, an inflector, an RF shield, RF Dee electrodes, a deflector and a magnetic channel (see Figure 1 - Figure 3). Electric and magnetic field distributions and mechanical structures were transmitted to the beam dynamics code CBDA [2] for simulations, and particle losses on the surfaces of the system elements were estimated.

ACCELERATION

First, the simulation with respect to the beam injection and acceleration was performed for the existing geometry and originally designed operational parameters. The focus of the present study is on the 2nd RF harmonic regime upgrade: improvement of the transmission efficiency and the beam quality of the existing regime (accelerated particle energy is 7 MeV/u, beam intensity ~1 pμA and Dee voltage 46.7kV). Measured Hyper ECR output emittances of 100π·mm·mrad was taken for both transverse oscillations in the simulations as an approximation. The source potential is 10.4 kV. The CW beam after the ECRIS was assumed. The RF amplitude Vmax = 150 V for the buncher was selected to provide a longitudinal focus of the beam at the entrance of the inflector (~ 2m from the buncher). The resulting RF phase range after the buncher was obtained to be ±10° RF at the entrance of the inflector. The energy spread after the buncher was 1 keV. Considering the results of the beam bunching upstream the inflector and the measured transverse emittances the corresponding 6D upright ellipsoid in the phase space was generated to represent the injected beam at the entrance of the inflector.

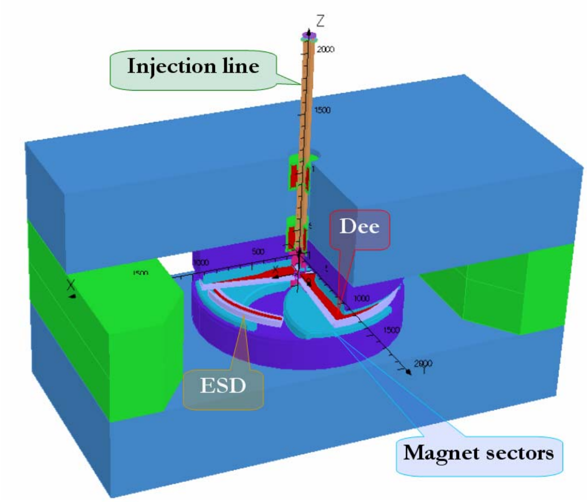

Figure 1: Computer model of the cyclotron.

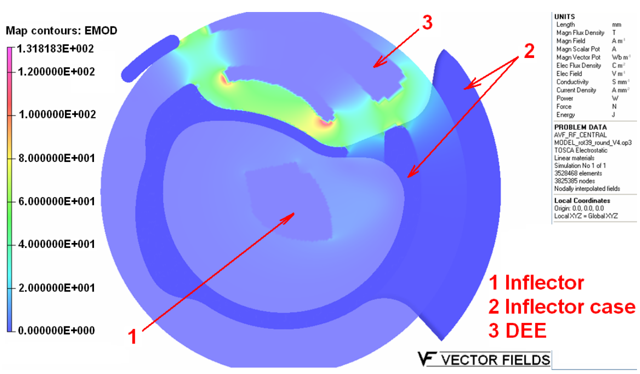

Figure 2: Computer model of the electric field distribution in the center region.

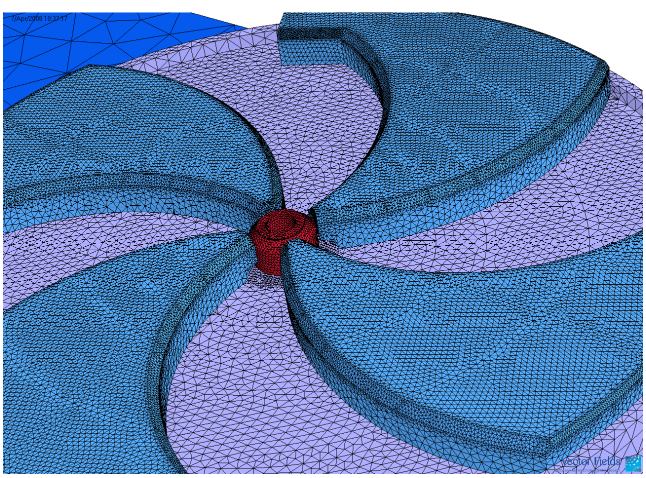

Figure 3: Computer model of the magnetic field distribution.

At the exit of the inflector a substantial increase in the longitudinal beam emittance (RF phase range by a factor of ~ 3 and energy spread by a factor of ~ 2) takes place. This can be a consequence of the electrical fringe field effects at both sides of the inflector due to not quite optimal cutting of the inflector plates by 4 mm (half gap between the inflector potential electrodes).

In the 1st reference particle orbit the matching to the center region electrodes was provided. The 1st gap crossing at the prescribed –30°RF phase was also ensured. A comparison of the central track with the previous simulations [3] shows almost full coincidence of the curves. In the initial orbits of the cyclotron heavy losses of the particles at the electrode surfaces take place.

TRANSMISSION

A comparison of the overall transmission from the ECRIS exit to the point downstream the deflectors (extracted beam position) demonstrates good agreement with the experimental results. According to the simulations, the major particle losses are in the central region due to particles at the RF system surfaces. The detailed account of the transmission efficiency (calculated and measured) is given in Figure 4. The results showed that the beam transmission efficiency agreed with the measurement despite the adopted approximations; the major particle losses occurred in the centre region during several turns due to the vertical broadening of the beam. The simulation also indicated that the inflector electrode was too short to introduce the beam onto the median plane of the cyclotron, and that this caused vertical beam oscillation, also resulting in the beam loss.

OPTIMIZATION

The easiest way to improve the above situation is to determine better operational parameters instead of changing the present geometry of the centre region.

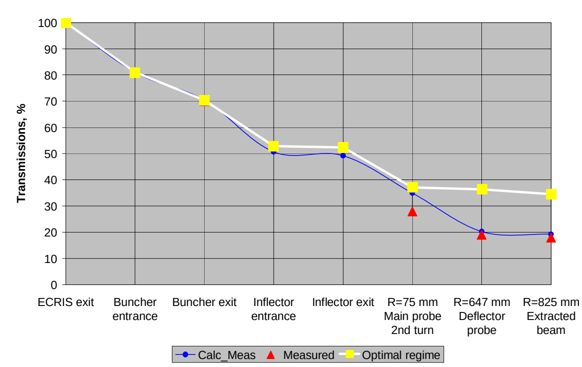

Figure 4: Beam transmission

A preliminary calculation showed that the broadening of the beam could be mitigated and the beam transmission efficiency could be improved by changing the beam the injection energy and the RF Dee voltage. In the simulation for 7 MeV/nucleon $^{14}N^{5+}$, the extraction voltage of the ECR ion source was decreased from 10.4 kV to 9 kV and the RF Dee voltage from 46.7 kV to 40 kV. These values were adopted in order to obtain a sufficiently small vertical angle at the exit of the inflector as well as to ensure the beam passage through the puller with the beam crossing the first acceleration gap at the positive RF phase that allows the electric focusing. It is noted that a negative phase (defocusing) at this gap was adopted in the original design in order to avoid overfocusing [3], [4]. The magnetic field amplitude of the first trim coil was also changed by approximately 50 % to ensure beam sitting at the zero RF degree in the isochronous field region. The result obtained in the calculations [5], [6] indicated that the beam transmission efficiency in the range from the inflector entrance to the electrostatic deflector was improved from 40 % to 65 % (Figure 4).

EXPERIMENTS WITH THE BEAM

The results of the measurement at the AVF are as follows: actually higher intensities were obtained in the optimal regime though the improvement was not drastic. The statistics of the operation for 7 MeV/nucleon $^{14}N^{5+}$ ions indicates that the beam intensity increased by ~ 17 % in the machine study performed with the Dee voltage and injection voltage being lower than the nominal values by ~15 %. The beam transmission efficiency is still low compared to the simulation result, which is mostly the effect of the rather large uncertainty of the input beam parameters in the calculations.

Further studies were motivated by the recent beam dynamics simulations and the past operational data, where the beautiful beam pattern (well-centered beam) was obtained as shown in Figure 5. This time the transmission efficiency through the AVF cyclotron was ~ 35 %. It is noted that such good results were obtained by taking the imbalance of the two dee voltages to be 91 % and 108 % of the designed values, respectively, as well as by adjusting the currents of the two innermost trim coils.

The beam transmission efficiency through the AVF cyclotron has recently increased to 30 ~ 35 % at the maximum in routine operation. This improvement owes mainly to the increase in the extraction efficiency (from 50 % to 80 %) by careful tuning and adjustment of RF dee voltages (the voltages of two dees are changed to 90 % and 110 % of the designed values for dees No. 1 and No. 2, respectively).

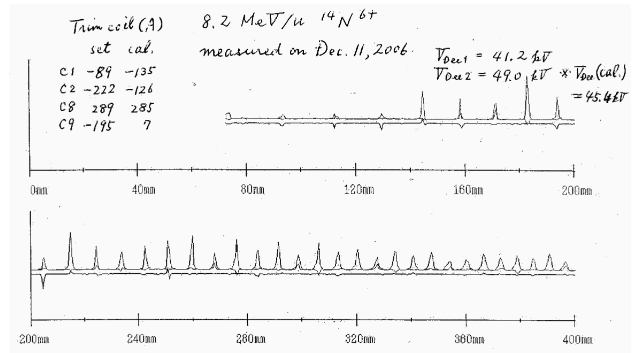

Figure 5: 8.2 MeV/nucleon $^{14}N^{6+}$ beam pattern measured on December 11, 2006

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