BEAM SIMULATIONS IN COMPUTER-MODELLED 3D FIELDS FOR RIKEN AVF CYCLOTRON UPGRADE

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Abstract

A highly advanced upgrade plan of the RIKEN AVF cyclotron is underway. The present study is to expand the region of its available acceleration energies as well as to increase the beam intensity with the help of detailed orbit simulations. The computer model of the AVF 3D electromagnetic fields was prepared and successfully checked against the measurements. Electric and magnetic field distributions and mechanical structures were transmitted to the beam dynamics code for simulations, and particle losses during the injection, acceleration and extraction were estimated. Some experiments already conducted with the beams confirmed the selection of the machine parameters based on the beam dynamics simulations. The new inflector geometry and the optimized central electrode structure have been formulated for the upgrade.

INTRODUCTION

In order to meet the requirements from users on the expansion of the region of its available acceleration energies as well as the increase in its beam intensities, the project to upgrade the RIKEN AVF cyclotron [1] has been being conducted by a collaboration of the Center for Nuclear Study (CNS) of the University of Tokyo, RIKEN Nishina Center, and the Joint Institute for Nuclear Research (JINR) [2], [3].

The present study in this upgrade is focused on the beam dynamics investigation using the completely computed AVF 3D electromagnetic fields. The characteristic feature of this study is that particularly the 3D electric fields of the center region as well as the inflector, for which analytical or approximated ones were adopted in the original design, are used in the present beam simulation to obtain more reliable results.

ACCELERATION REGIMES

Fig. 1 shows a performance of the AVF cyclotron. The RF frequency range is 12-24 MHz and the average magnetic field range at the extraction is 0.5-1.76 T. The acceleration harmonics presently operated is 2. The colored pentagon-shaped region indicates the one inside which ion beams are designed to be available; the inclined line is the limit that was determined in the original design by the condition of constant orbit along

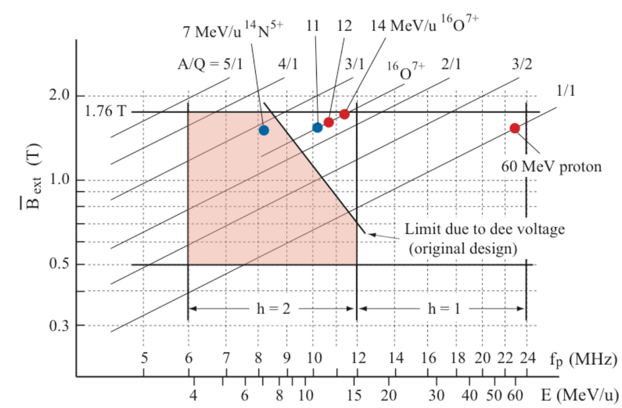

Figure 1: Acceleration performance of the AVF cyclotron. See the text for detail.

with the characteristics of the available dee voltage. The 7 MeV/u $^{14}N^{5+}$ ion beam, which is typical in this region as an injected beam to the booster, RRC, and studied in detail by the present simulation, is indicated by a blue point.

The new acceleration regimes of interest that were studied in the present simulation are: 11, 12 and 14 MeV/u $^{16}O^{7+}$ ion beams as well as 60 MeV protons. The 11 MeV/u $^{16}O^{7+}$ ion beam (indicated by a blue point in Fig. 1) has already been successfully accelerated in the existing geometry of the center region according to the simulation, while 12 and 14 MeV/u beams (indicated by

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red points) are expected to be accelerated in its newly designed geometry as shown later. For 60 MeV protons, which are to be accelerated in the acceleration harmonics of 1, only the feasibility of its isochronous field was checked.

MECHANICAL AND FIELD MODELS

The computer model of the electromagnetic fields was prepared and successfully checked against the measurements. It comprises the following structural elements: part of the injection line including a beam buncher and Glazer lenses, a magnet yoke, spiral sectors, center plugs, main/trim and harmonic coils, an inflector, an RF shield, RF dee electrodes, a deflector (ESD) and a magnetic channel (see Fig. 2 and Fig. 3).

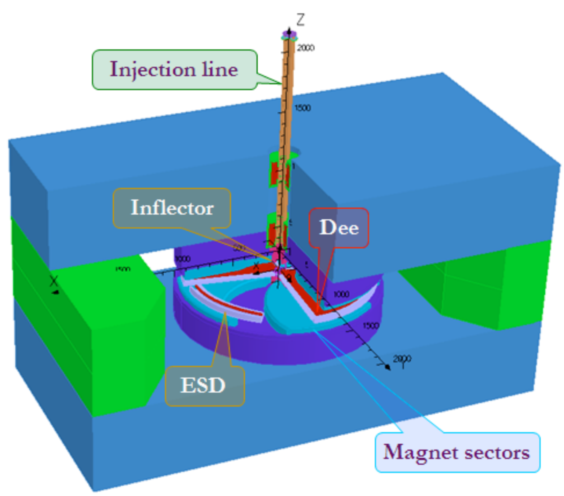

Figure 2: General view of the cyclotron computer model.

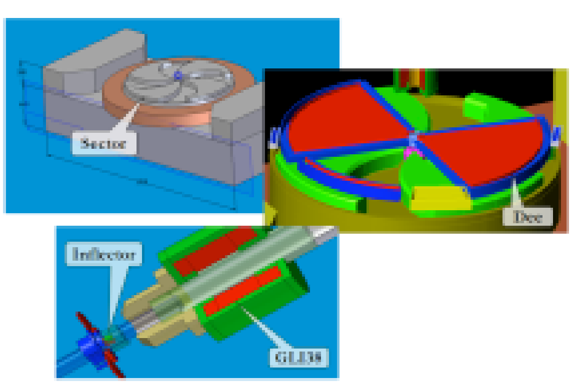

Figure 3: Some detailed parts of the cyclotron computer model.

The magnetic and electric field distributions, calculated with the TOSCA program [4], and the mechanical structures of the computer model were transmitted to the beam dynamics code CBDA [5], [6], with which particle losses on the surfaces of the system elements were estimated. The generation of the fields and structures for any acceleration regimes is now possible with the proved accuracy and without any additional magnetic field measurements. Detailed description of the models is given elsewhere [7].

BEAM DYNAMICS STUDY

At first, the simulation of injection and acceleration of 7 MeV/u $^{14}N^{5+}$ ion beam was performed in order to obtain better calibration of the simulations vs. the experiments [3]. Fig. 4 shows an example of the simulation in which beam bunches are injected onto the mid plane of the cyclotron through the inflector and accelerated in the cyclotron. Assessment of beam losses from the beam buncher up to the initial 20th turn in the cyclotron was carried out. The emittance of the injected beam was assumed to be 100 π.mm.mrad. In Fig. 5 is shown an example of the simulation in which the particles lost on the inner surface of the dee electrodes etc. are indicated by black dots. The simulation showed that about 60 % in total of the particles were lost: ~30 % during injection (at the entrance of the inflector) and ~30 % after injection. This value corresponds to the measurement of 60-70 %. The simulation also revealed that the inflector electrode was too short (by 2 mm at both the entrance and exit) to

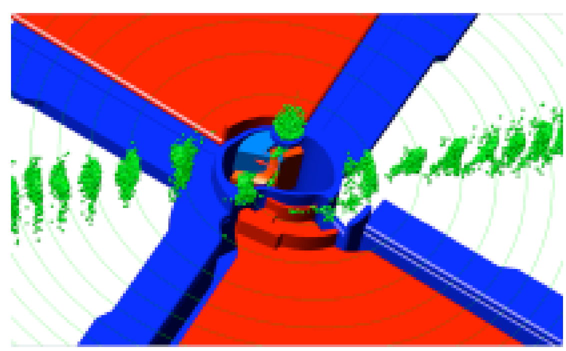

Figure 4: Example of beam simulation in the center region.

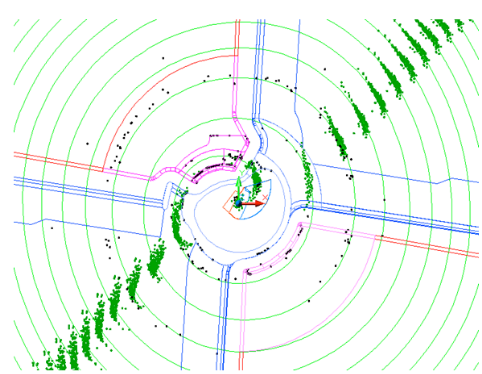

Figure 5: Example of the simulation for beam losses. Green dots: survived particles; black dots: lost particles.

introduce the beam onto the median plane of the cyclotron, and that this caused vertical beam oscillation, also resulting in the beam loss.

Next, the simulation was carried out in order to increase the $^{16}O^{7+}$ ion energy, which had been limited to less than 10 MeV/u due to the voltage available (below 50 kV), up to 11 MeV/u. Changing the injection beam phase at the 1st acceleration gap from the original design value of – 30°RF to – 8°RF as well as the corresponding currents of the innermost trim coil was proposed by the simulation. In this way the energy gain at the 1st turn could be increased, permitting the beam to clear the channel of the dee-electrode tip immediately after passing through the exit of the inflector. In the actual beam test, 11 MeV/u was successfully achieved with the presently available voltage of 49 kV. In order to further increase the $^{16}O^{7+}$ ion energy, the renovation of the geometry of the center region has been proposed in such a way as shown in Fig. 6. The point is that the side walls of the two dee-electrode tips as well as the wall of the rf shield are to be moved as to the inner radius as possible from the original geometry shown by white curves. The simulations have confirmed the possibility to increase the energy up to 12 MeV/u with the realistic dee voltage and even up to 14 MeV/u with a slightly increased dee voltage that is expected to be feasible in the near future.

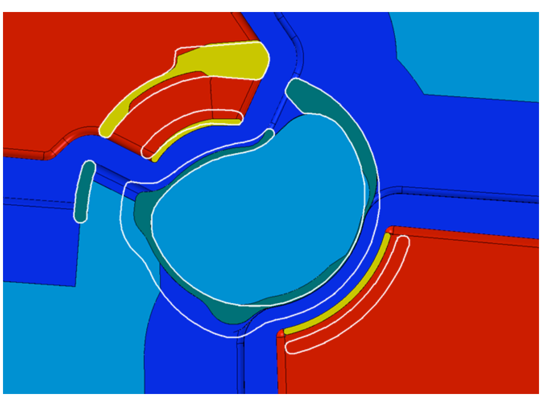

Fig 6: Renovation of the centrer region. White line: before renovation; yellow and green part: after renovation.

The simulation of the $^{14}N^{5+}$ extraction was also carried out. Although in the actual operation a single-turn extraction is possible by producing off-centering with harmonic coils at the extraction, the extraction in the well-centered-orbit acceleration mode was simulated. Upstream of the ESD the turn pattern showed that some overlapping of the bunches at the neighbouring orbits took place. As a result, the beam was extracted with multi-turn extraction as shown in Fig. 7. The transmission efficiency through the ESD was approximately 80 %.

The first attempt to simulate the acceleration of 60 MeV proton beam in the 1st acceleration harmonics mode was carried out. The substantial redesign of the central electrode structure is needed to accelerate protons with reasonable values of the dee voltages, since the existing structure of the center region was designed for the 2nd harmonics, not for the 1st one. Nevertheless, to see how protons will be accelerated, the RF phase excursion during the acceleration up to the final energy was simulated using the realistic dee voltage. The simulation demonstrated a good quality of the magnetic field generated.

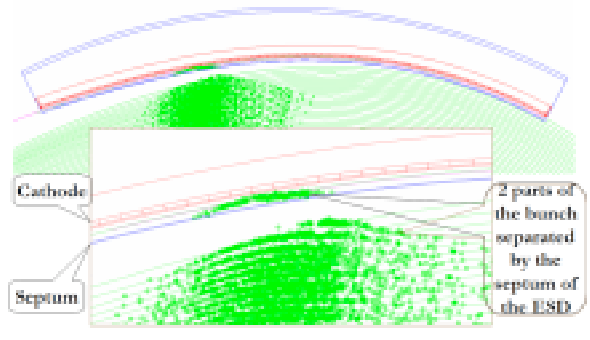

Fig 7: Simulation of the beam bunches in the extraction region.

CONCLUSIONS

Beam dynamics simulations for the RIKEN AVF cyclotron upgrade have been performed using the completely computed 3D electromagnetic fields. Particle losses during the injection, acceleration and extraction were estimated.

It was found that the simulation of typical beam of 7 MeV/u $^{14}N^{5+}$ ions under the existing geometry of the elements corresponded to the experiments in terms of beam losses. The new geometry of the inflector has been proposed in this simulation. The energy of $^{16}O^{7+}$ ion beam has been increased from 10 to 11 MeV/u, and is expected, with the help of the simulation, to be further increased up to 12 MeV/u (even 14 MeV/u) with a new geometry of the central electrode structure, which is planned to be installed this summer. The simulations for beam extraction as well as acceleration of 60 MeV proton beam were also performed.

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