Study of New Flat-Top Resonator for the RIKEN Ring Cyclotron*

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Abstract

A new flat-top resonator could be inserted into the RIKEN Ring Cyclotron (RRC) to reduce the energy spread of the particle bunches. ANSYS' high-frequency solver is successfully used to determine the geometry of such a resonator. It is found that a two stem, two gap resonator has the most promising characteristics. Preliminary simulations predict a maximum power requirement of less than 15 kW with current-densities and electric fields that should allow reliable operation. ANSYS is also used to calculate the static magnetic field of the RRC sector magnets, as required for beam-dynamics simulations. The effect of the flat-top resonator onto the particle bunches is then investigated.

INTRODUCTION

Flat-top resonators are commonly used in cyclotrons to add a third [1, 2] or fifth [3] harmonic to the accelerating voltage. The resulting broader acceleration voltage reduces the energy spread of particle bunches and hence the extraction losses of the cyclotron, which is usually the limiting factor for beam intensity. Since the beam losses in the RRC might limit the beam intensity of the RIKEN accelerator research facility, a design study for a flat-top resonator was launched.

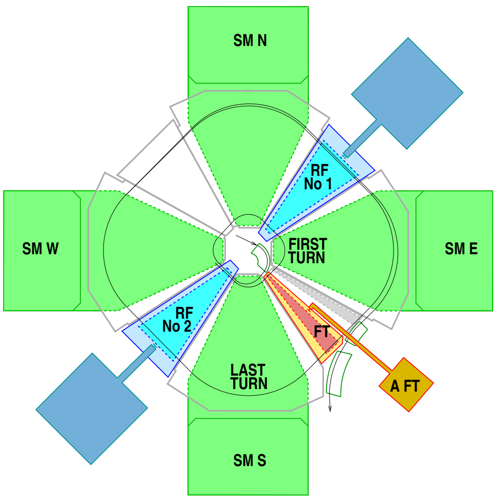

Figure 1: Layout of the RIKEN Ring Cyclotron with sector magnets (SM), main resonators (RF No 1 and 2) and flat-top system. The flat-top resonator is labeled with *FT*, and its amplifier system with *A FT*.

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The flat-top will be achieved by a third-harmonic resonator with a frequency range of 54-120 MHz and a total peak gap voltage of approximately 135 kV. The available space is small and it is challenging to find a resonator shape that fits into the cyclotron.

GEOMETRY OF THE RESONATOR

The three-dimensional electromagnetic eigenmode solver in ANSYS [4] was used to find the geometry of the flat-top resonator. A double gap resonator in the fundamental mode showed the most promising characteristics. Due to mirror symmetry of the geometry with respect to the beam plane, only one half of the structure had to be simulated. This type of simulation used approximately 180,000 elements, 270,000 nodes and the solver required approximately 700 MBytes of memory when second-order tetrahedral elements (ANSYS-type *HF119*) were used. The calculation times were approximately five minutes for preprocessing, including the generation of geometry and meshing, approximately one hour for solving and approximately ten minutes for post processing. It was found that, at higher frequencies, a design with two stems (see Fig. 2) is superior to a design with one stem only. Coarse tuning of the resonator can be achieved by changing the vertical position of the shorting plates. Preliminary simulation results predicted a maximum quality factor of Q_0=13,900 at an operation frequency of 85 MHz and a minimum quality factor of Q_0=12,000 at 120 MHz.

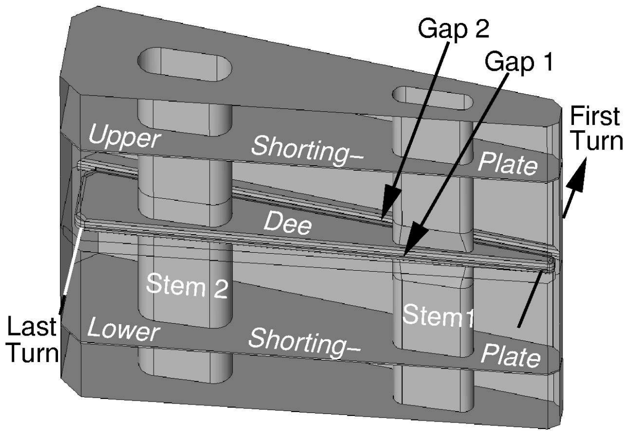

Figure 2: Flat-top resonator with removed sidewall. The shorting plates are set to an operation frequency of 68MHz. The rf-geometry has an approximately 2.64 m maximum length, 0.68 m maximum width and 2 m maximum height.

For the calculation of the power requirement and the gap voltage distribution, the fields were then scaled according to the following procedure. The mean gap voltage is adjusted to be equal to the sum of the mean gap voltage of the main resonators, divided by nine. The calculations are performed for a peak voltage of 300 kV in the gaps of the main resonators. The highest current density in the shorting plate of 23 A/cm was found at an operation frequency of 113 MHz and the maximum electric field in the resonator of 3.7 MV/m at a frequency of 90 MHz. The maximum power requirement is about 15 kW [5].

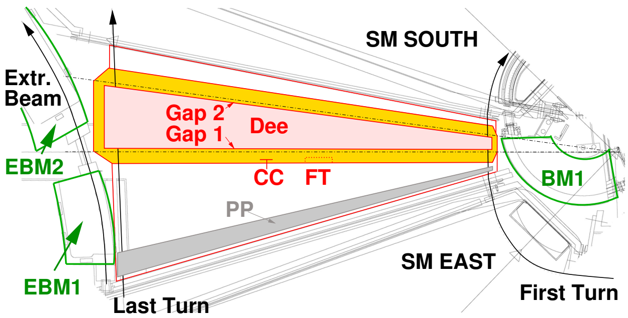

Figure 3: Top view on proposed valley box with flat-top resonator: phase probes (PP), capacitive coupler (CC), fine tuner (FT), injection-, extraction bending magnets (BM1, EBM1, EBM2) and sector magnets (SM).

As indicated in Fig. 3, the injection- and extraction bending magnets (BM1 and EBM2) prevent the standard capacitive coupling and tuning method at the shorter resonator walls. However, preliminary simulations with ANSYS' eigenmode solver [6] indicate that capacitive power coupling could be achieved even if the coupler is located at the sidewall of the resonator. Compared to an inductive coupling loop located close to one of the shorting-plates, it has the advantage of easier manufacturing and maintenance because less movable parts are used. It will be investigated more in detail if the tuning range of the proposed capacitive fine tuner is sufficient for this type of resonator.

FIELD IN SECTOR MAGNETS

For the analysis of the effect of the flat-top resonator onto the ion-beam quality, the focusing properties of the sector magnets have to be known. Since the measured field map data were no longer available, the magnetic field had to be calculated from scratch. ANSYS' magneto static solver with hexahedral mesh (ANSYS element types *SOLID96, SOURC36* and *INFIN111*) was used for this simulation. For the accurate representation of the sector magnet geometry, fine stairs (B-constant profile) and steps (Purcell gap and shims) had to be taken into account. This made the mesh generation very challenging, but it was possible to create a mesh with a total of about 717,000 elements and 679'000 nodes. The particle-tracking program requires accurate field data and derivatives up to third order in the beam plane and special care was therefore taken for the

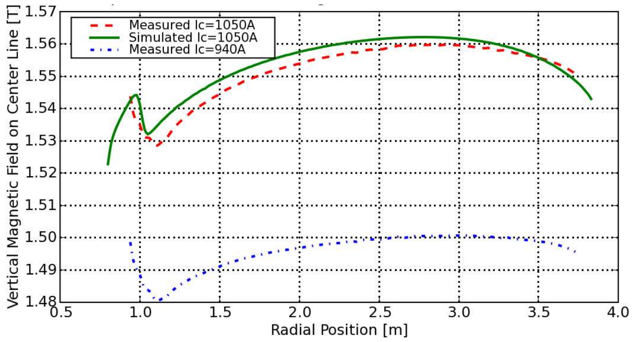

Figure 4: Comparison of calculated and measured magnetic field on the center line of the sector magnet.

meshing in the beam plane and the export of the data. A structured cylindrical mesh was generated in the region of the beam-plane. The nodal solution of the scalar potential on this mesh was exported to a file and the higher order evaluation of the fields and derivatives performed in a different program. Comparison with measured field on the center-line show an error of less than 0.5% (see Fig. 4).

BEAM-DYNAMICS

The beam-dynamics program [7] was written in *C/C++*. *MayaVi* [8] and *PyLab* [9] were used for the visualization of the simulation data. A fourth order Runge-Kutta algo-

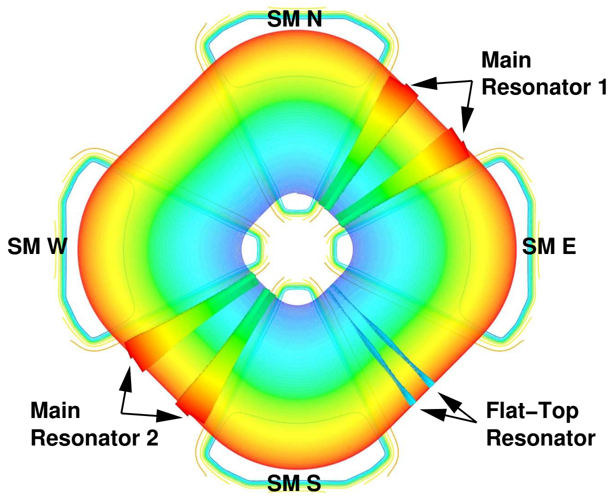

Figure 5: Visualization of the ion trajectory in the RRC with *MayaVi*. The coloring of the trajectory corresponds to the momentum of the particles and the set of arrows indicates the energy kick at the gap-crossings.

rithm with third order interpolation of the magnetic fields was chosen for particle-tracking. The magnetic fields of the sector-magnets were isochronized by a two-step procedure. First, isochronous closed orbits are searched by adjustment of the magnetic fields, then accelerated orbits are calculated for the fine correction of magnetic fields to get good isochrony condition. A simplified description of the electromagnetic fields in the resonator was used for better reproducibility. The gap-voltages were interpolated (in position and frequency) and provided the corresponding energy kick and deflection when the particles crossed one of the resonator gaps.

The formula (Eq. 1) for the prediction of the energy resolution was verified for the case without flat-top resonator and compared to the case with flat-top resonator by numerical simulation. For the cyclotron without flat-top resonator and with a nonuniform radial distribution of the acceleration voltage $V(R)$, the final energy deviation (ΔE_f) of a particle with an initial energy deviation ΔE_i and initial phase φ_i is given by [10]

$$\Delta E_f = a \cdot \Delta E_i + b \cdot \varphi_i^2 \tag{1}$$

where a is the ratio of the final to the initial voltage (V_f/V_i) and b is proportional to the radial integration of $R/V(R^3)$. The final energy resolution strongly depends on the shape of the radial distribution of the gap voltages.

As indicated in Fig. 6, the final energy deviation got reduced significantly when a flat-top resonator was used for the particles with an initial phase deviation. It can be concluded that the flat-top resonator increases the phase acceptance of the cyclotron. On the other hand, there was almost no effect on particles with an initial energy deviation.

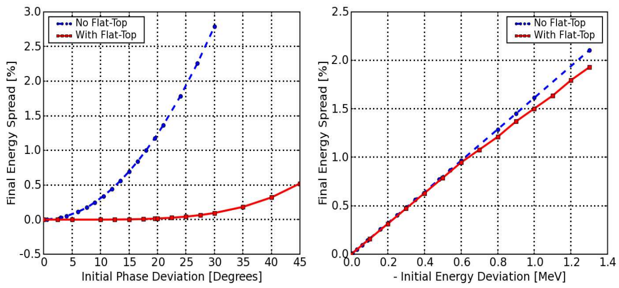

Figure 6: Simulation with four particles for an Uranium-type beam. Relative energy spread in the cyclotron gets reduced if a flat-top resonator is used. This graph was generated with *PyLab*.

Preliminary multi particle simulations showed the same behavior. In Fig. 7, the relative energy spread in the cyclotron is compared to the case with flat-top resonator. About 50,000 macro particles were used for this calculation. At injection location, the macro particles were supposed to be uniformly distributed, to have a phase width of 10 degrees standard deviation and to have all exactly the same energy.

More realistic beam distributions will be simulated and analyzed in future. It is believed that the oblique crossing of gap 2 of the flat-top resonator has a negligible effect on the beam quality. Multi particle simulations will be used to confirm this assumption.

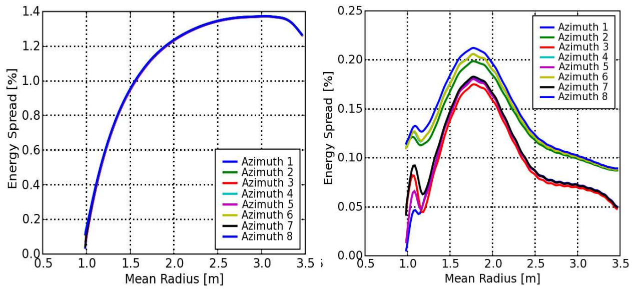

Figure 7: The relative energy spread of an Uranium-type beam (left) in the cyclotron gets reduced if a flat-top resonator is used (right).

CONCLUSIONS

An rf-geometry was found for the new flat-top resonator which should fit into the cyclotron and should allow reliable operation. Preliminary beam-dynamics simulations predict significant reduction of the energy spread at extraction location of RRC.

The parameters of the flat-top resonator will be improved further and more detailed beam-dynamics simulations will be done in future.

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