BEAM-CAVITY INTERACTIONS IN THE RING CYCLOTRON

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Beam excited Higher Order Modes (HOMs) are observed in the cavities of the Ring Cyclotron. Since a self consistent simulation is not feasible, a simplified computation method is developed: The parallel eigensolver Omega3P of the Stanford Linear Accelerator Center (SLAC) allowed us to calculate the eigenmodes of the entire Ring Cyclotron for the first time ever. The RF fields are expanded onto a superposition of these modes and the excitation is calculated in the frequency domain. Trajectories of the particles in the static magnetic field, superimposed with the space charge fields and the beam excited HOMs, are then simulated. The simulation results confirm that only a small deformation of the charge distribution appears up to proton beam currents of 2 mA.

INTRODUCTION

The dependence of the HOM amplitudes in function of the proton beam current can be measured with a spectrum analyzer connected to inductive pickup loops of the main cavities. An almost linear dependence of the most pronounced signal at 557 MHz in cavity 2 suggests that this HOM is excited by the beam.

MODE EXPANSION TECHNIQUE

A self consistent calculation of the beam-cavity interaction in the cyclotron is currently out of scope due to the following problems:

- More than 1000 proton bunches with different energies propagate simultaneously through the cyclotron and interact mutually and with the excited HOMs. The huge amount of interacting proton bunches would lead to a tremendous number of macro particles.
- In order to reach steady state, about 45'000 particle crossings have to be calculated, leading to more than 8 million time steps and consequently to numerical noise problems (Courant-Friedrich-Lévy Condition).

A mode expansion method [4, 5] is therefore used for the representation of beam excited fields in the frequency domain. The parallel Exact Shift Invert Lanczos (ESIL) eigenmode solver in Omega3P [3] allows to calculate Higher Order Modes (HOMs) of the entire cyclotron structure as basis functions for the mode expansion. The cyclotron geometry has no exact symmetry in azimuthal- or vertical direction and the lower cut off frequency of 56.4 MHz for the beam slot opening in the main cavities causes propagation of eigenmodes around the cyclotron structure. As a consequence, the eigenmodes must be solved for the entire cyclotron structure. The cyclotron geometry is simplified in order to get a reasonable problem size. It is intricate to calculate the eigenmodes in such a complex structure, where the modes are tightly clustered. SLAC's ESIL solver in Omega3P was chosen for this purpose because it guarantees safe numerical convergence to the desired eigenmodes. Omega3P uses unstructured tetrahedral elements for the discretization of the simulation volume. This mesh can be generated with the

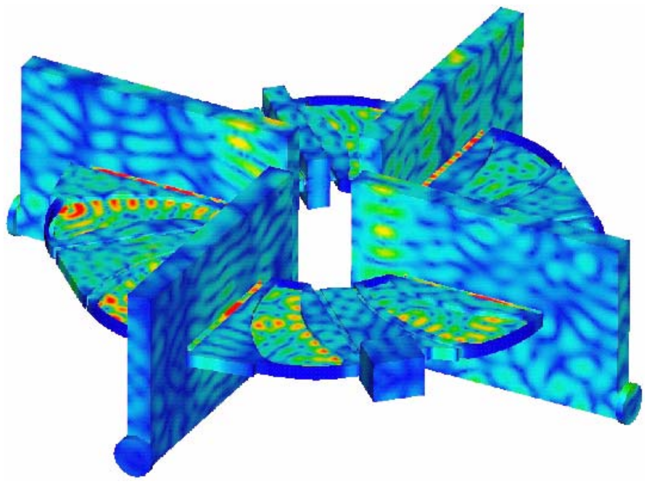

Fig. 1: Example of a typical mixed mode. Contour plot of the absolute value of the magnetic field for the 505.391 MHz mode.

CUBIT [1] program and consists of 1.2 million elements and roughly 246'000 nodes. Using curved second order elements, the average edge length of 6.4 cm yields an upper frequency limit above 700 MHz. Omega3P was run on the IBM-SP4 of the *Swiss National Supercomputing Centre* to find 280 eigenmodes with a resonance frequency close to a beam harmonic. The typical solution time for 20 modes with 6.4 million degrees of freedom was about 45 minutes, using 32 CPUs and required a total memory of about 120 GB. The modes in a cyclotron structure can be classified into three groups: *Cavity modes* have their field energy localized in one of the cavities. *Vacuum chamber modes* have most of the field energy in the vacuum chamber and almost no field energy in the cavities. All other modes are *mixed modes* where energy is located in the vacuum chamber *and* in the cavities. For the determination of the mode amplitudes and phases it is required to calculate the parameters of zero beam current trajectories from cyclotron injection to extraction. These particle motions are integrated by a fourth order Runge-Kutta algorithm based on a third order Taylor expansion of the static magnetic fields. In order to get an estimate of the beam-cavity interaction in the Ring Cyclotron, the longitudinal and transverse "gap"-voltages can then be calculated. The relevant gap for the particles in this case is the trajectory from injection to extraction. Comparison with the measured beam loading of the fundamental cavity modes shows good agreement with the simulation results.

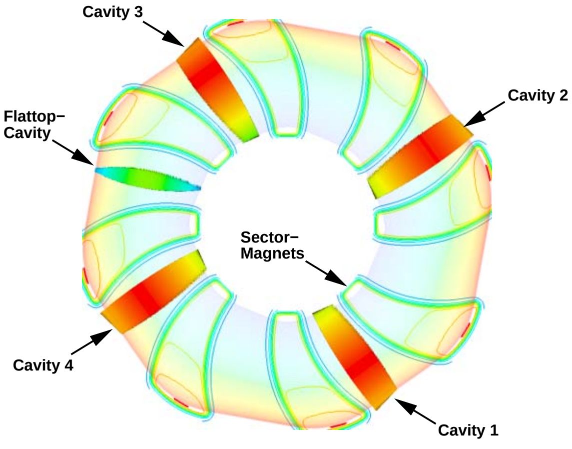

Fig. 2: Geometry of the Ring Cyclotron for orbit calculation. At the cavity location, the glyph represents the voltage distribution considered in the calculation.

EFFECT OF HOMS ON BEAM QUALITY

Subsequent tracking of about 100'000 macro particles with a Particle In Cell Needle (PICN) model [2] for fast space charge corrections is used for the calculation of the evolution of the charge distribution in the cyclotron. The parallelization with OpenMP yields typical execution times of one minute per turn on a HP-superdome, using about eight CPUs. Figure 3 illustrates the effect of HOMs onto the charge distribution. There are 30 particularly critical beam excited modes selected and the resonance frequencies are shifted to exactly the nearest beam harmonic frequency. This bunch deformation therefore presents a "worst case" situation because the mode damping will be more important in the real cyclotron, and because the resonance frequencies do not necessarily fall exactly on a beam harmonic. There is no significant deformation visible if the modes are not shifted exactly to a beam harmonic frequency.

FUTURE EFFORTS

As soon as the phase space at injection and extraction, as well as the effects of neighboring turns are known from 6d beam dynamics simulations, it can be decided whether the PICN model has to be improved or not. One small modification would be, for example, the introduction of a varying rod length according to the vertical beam size. Refined simulations with this method are interesting for intensity upgrade studies of the Ring Cyclotron and the design of future high power cyclotrons, e.g. for Accelerator Driven Systems. Strong deformation of the bunches appearing at higher intensities might require to go beyond the limits of the rigid bunch model. The easiest approach is to just rerun the calculation of the mode amplitudes and phases with the previously calculated beam parameters of the bunch in the

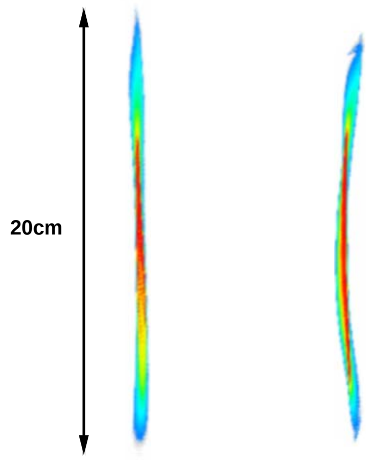

Fig. 3: Horizontal Charge distribution at extraction location (214 turns) without (left) and with beam excited HOMs (right) corresponding to the worst case situation. Propagation direction is upward, the center of the cyclotron is to the left. The beam current is 1.8 mA.

beam excited HOMs. This can be repeated until the required convergence is reached. A self consistent calculation could be performed by a time domain integration of the bunches with a mode expanded representation of the electromagnetic fields at each time step. The accuracy of the eigenmode calculation could be improved in several ways: As soon as increased computing resources or improved numerical methods become available, more details should be added to the RF structure of the Ring Cyclotron and effects of absorbing boundaries (like vacuum pump port, magnets and windows) should be included. Unfortunately, simulations with absorbing boundaries lead to eigenmodes which are no longer orthogonal, and couple mutually.

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