BEAM-CAVITY INTERACTIONS IN HIGH-INTENSITY CYCLOTRONS

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Measurements on the main cavities of the PSI 590 MeV ring cyclotron revealed a higher-order mode excitation at 1.8 mA operation that coincides with the 10th beam harmonic. The presence of such field-perturbations could affect the beam quality of high-intensity cyclotrons and are therefore studied in more detail. First results of analytical methods, numerical calculations with the MAFIA time-domain solvers T3 (rigid beam model) and TS3 (particle in cell model) for the case of the main-cavities of the ring cyclotron, show the limitations of these methods. The deformation of the cavity due to the atmospheric pressure and the heat load induced by the wall currents of the fundamental mode is calculated with ANSYS. The data of the deformed geometry is then imported to SLAC's parallel eigenmode solver Omega3P on unstructured grids for the computation of the mean shunt impedance of the beam harmonic modes.

INTRODUCTION

The inductive pickup probes of the ring cyclotron main cavities detect a signal spike at the tenth beam harmonic ($\approx$ 560 MHz), 29 dB below the level of the fundamental mode. The signal was present at beam currents of 1.8 mA and vanished when the beam was off.

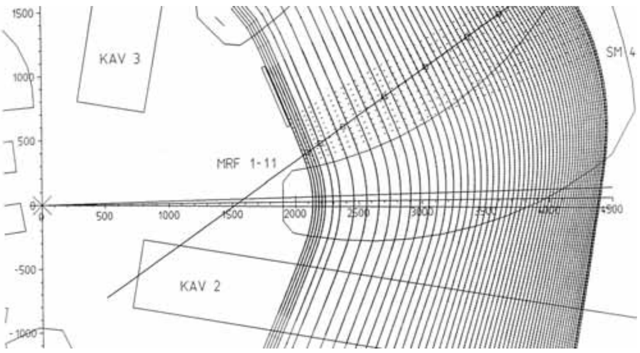

Fig. 1: Top view of the ring cyclotron. The main cavities 2, 3 (KAV 2 and 3) and sector magnet 4 (SM4) are indicated. The first five, then the 10th and 15th particle trajectory are drawn followed by each 10th. The angle of incidence depends on the radius.

The absence of this frequency spike in the spectrum of the directional couplers and in the anode probes of the amplifiers confirms the presumption that this mode is excited by the beam. The detailed analysis of the excitation of these Higher Order Modes (HOM) is interesting for beam quality studies. HOMs may perturb and deteriorate the beam, spread the bunches at extraction and therefore contribute to the activation of the cyclotron. Fig. 1 shows the beam trajectories in the ring cyclotron, calculated with FIXPO [1]. FIXPO is the standard orbit integration program of PSI with an option to search for closed orbits (fixpoint orbits).

TIME DOMAIN CALCULATION WITH MAFIA

Time domain analysis was performed with MAFIA's three-dimensional Cartesian time domain solvers. The import of the particle positions and velocities from the FIXPO file, interpolated onto the grid of MAFIA's solver, gives a realistic excitation model. Each of the 221 bunches acts in the T3 module as a one-dimensional, rigid current distribution which excites an electromagnetic field in the cavity. The simulation in the T3-module has the advantage of being much faster than a fully self consistent PIC calculation and uses much less memory. A first idea about the effect of wake fields was gained by calculating the field excited by the 221 driving bunches crossing the cavity at the positions according to the FIXPO file and the wake-integral. The longitudinal component of the wake-potential describes the total voltage at the test particle divided by the charge of the wake-field generating charge q. The transversal components of the wake-potential give the change in the transversal test particle voltage divided by q. The Fourier transform of the wake-potential of a 590 MeV beam is shown in Fig. 2. Its value depends only on the transversal coordinates and the frequency, and is a measure for the interaction between the particle beam and the accelerator structure. The spectral resolution in the rigid bunch model of MAFIA's T3 solver is achieved by choosing a very long wake integration length of 1000 m. This allows modes at frequencies higher than 100 MHz to be distinguished, but results in computation times of about one month on a DEC-alpha Tru64 machine.

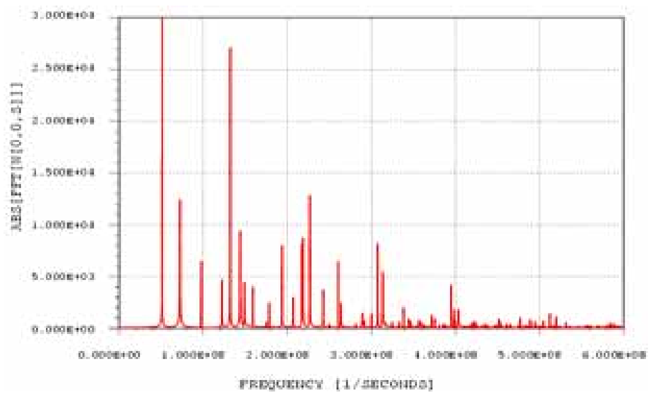

Fig. 2: Fourier transform of a wake integral with an integration length of 1000 m.

In order to get an estimate of the short range effect on the phase space as well, the fields found in the T3-calculation are imported as initial field values into the self-consistent PIC solver (MAFIA's TS3 module). Bunches with a low velocity of 0.1c are propagated through the cavity. The particle monitors are set to register the phase space before and after cavity crossing for comparison. Space charge effects and field deformation due to the close vacuum chamber wall can be observed. The effects of the short range wake-fields on the neighboring bunches are relatively low. More accurate simulations in MAFIA's time domain modules are excluded by the structured grid, the long computation times and memory limitations.

FREQUENCY DOMAIN CALCULATION WITH MAFIA

MAFIA's select eigenmode solver finds, for the initial guess of 556 MHz, a mode with a resonance at 554 MHz. This mode has a magnetic boundary condition in the beam plane. The amplitude was then scaled to 10$\%$ (-20 dB) of the fundamental mode and imported as the initial field into the PIC solver (MAFIA's TS3 module). The subsequent PIC calculation for one bunch propagating with a velocity of 0.1c, indicated a strong deformation of the phase space (Fig. 3) after cavity crossing.

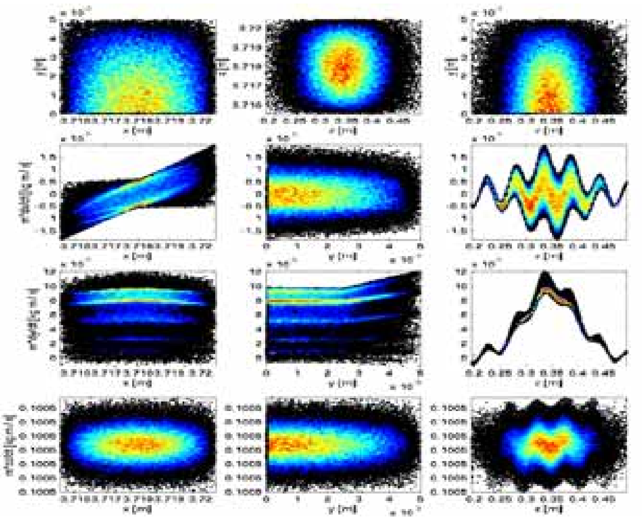

Fig. 3: Phase space after cavity crossing for a bunch propagating with 0.1c. The location of the beam is close to the vacuum chamber wall. Only the upper part is simulated and the magnetic symmetry condition applied.

MAFIA's structured grid unfortunately prevents the simulation of the real geometry necessary to find the appropriate mode in the dense spectrum. The PIC calculation is time consuming even for one single bunch, but we would need to simulate the perturbation for up to 221 bunches with different velocities, locations and angles of incidence.

CALCULATION WITH OMEGA3P

The deformation data, due to the atmospheric pressure and the heat load acting on the cavity, as calculated by ANSYS [3], is now used to get a more realistic mesh of the aluminum cavity. The initial mesh is constructed in CUBIT for the undeformed geometry. The deformation data is then interpolated linearly onto the mesh and the nodes moved accordingly. This permits the use of a much finer mesh, which is independent of the ANSYS mesh, for the subsequent eigenmode calculation. Omega3P's new target deflation solver is then used to find clustered eigenmodes. Several modes in the neighborhood of a target value can now be found, even in a dense spectrum. Tab. 1 shows some modes with a resonance frequency close to the tenth beam harmonic. According to the experience of the beam dynamics group, the bunch phases at the cavity are not yet exactly known. They estimate the phase error of the bunch to be in the range of about 2-3% compared to the phase of the fundamental cavity mode. This uncertainity of the real phase of the 221 bunches prevents an exact prediction of the resulting shunt impedance because of the relatively short period of the tenth beam harmonic mode. Only an upper limit is therefore indicated in Tab. 1.

Harmonic Modes with $\mathbf{f_n \approx (n+1)f_0}$			
n	f_n[MHz]	Q_{0AL}	$\overline{Z}_C[k\Omega]$
0	50.633	29E3	796
10a	555.69	63E3	$\leq$ 0.1
10b	555.93	66E3	$\leq$ 0.9
10c	556.04	66E3	$\leq$ 1.5
10d	556.24	66E3	$\leq$ 1.4
10e	556.94	70E3	$\leq$ 0.1
10f	557.23	72E3	$\leq$ 0.1

Tab. 1: Resonance frequencies f_n, unloaded quality factors Q_0 for aluminum and mean shunt impedance $\overline{Z}_C$, calculated with Omega3P.

Preliminary Conclusion: The high shunt impedance of some harmonic modes suggests that they could significantly interact with the beam.

NEXT STEPS

Omega3P will be used to calculate an appropriate set of HOMs. The excitation of these modes should then be calculated and the simulated signals at the pickups compared with the measured values. Particles are then tracked through the calculated field distribution in order to get information of the effect on the phase space of the beam.

ACKNOWLEDGMENTS

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REFERENCES

[1] G. Rudolf, FIXPO Bedienungsanleitung, PSI.

[2] J.P. Blaser, *Strahlbelastung der Kavitäten und Phaseninstabilitäten* PSI Note (1967).

[3] M. Bopp et al., *Coupled Field Analysis of the New Ring Cyclotron Cavity* PSI Scientific and Technical Report 2001, VI.