PARTICLE-TRACKING STUDIES IN THE PROSCAN CYCLOTRON COMET

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For the new medical cyclotron COMET, three dimensional particle tracking calculations are performed with the code TRACK. We discuss some examples, such as the effects of coil misalignment, the crossing of betatron resonances and off-centring of the orbits.

INTRODUCTION

The 250 MeV SC compact cyclotron (original design by H. Blosser, NSCL, USA and manufactured by ACCEL, D) has arrived in March 2004 and is now ready for tests on site. The cyclotron, *COMET*, will provide beam for the PSI proton therapy project *PROSCAN*. For this cyclotron, three dimensional particle tracking calculations have been performed with the code *TRACK* [1], as an independent verification of the shimming procedures proposed and/or performed by ACCEL and to prepare for the commissioning of the cyclotron. Input fields are obtained from calculations or field measurements.

COIL MISALIGNMENT: TILTED COIL

In several SC-cyclotrons, it appears that the orientation and position of the main coil have a very big impact on beam losses in the vertical plane [e.g. 2-4]. The effect of the coil on the total field is obtained by assuming that the magnetic field of *COMET* can be split into one contribution from the iron and one from the coil [5]. We saved the two field contributions in separate 3D-field maps, so that they can be added with any desired relative spatial shift and/or tilt.

Last year we reported on the effects of a vertical shift of the coil, which causes a shift of the beam in the direction opposite to the coil displacement, with a magnitude of 25 times the shift magnitude [5]. Here we report on the effects of a coil tilt. The result of the coil tilt is a horizontal field component, which is more or less homogeneous over the volume between the poles. The particles experience an azimuthally varying field component, which gives a vertical force in the upward direction during half a turn and a downward force during the other half of the turn. Together with the restoring force due to the AVF field of the iron, oscillations may start and resonances might be excited. Fig. 1 shows the effect of a tilted coil on the vertical beam position. The beam plane is tilting in the same direction and with roughly the same amount as the coil is tilting. Around *r*=75 cm and *r*=78 cm strong vertical oscillations start, just where ν_z has its minima. This correlation with $1/\nu_z^2$ (the focussing power coming mainly from the iron field) has also been observed in the case of the coil shift [4]. The amplitude of the oscillations, however, seems not to depend on the vertical beam size.

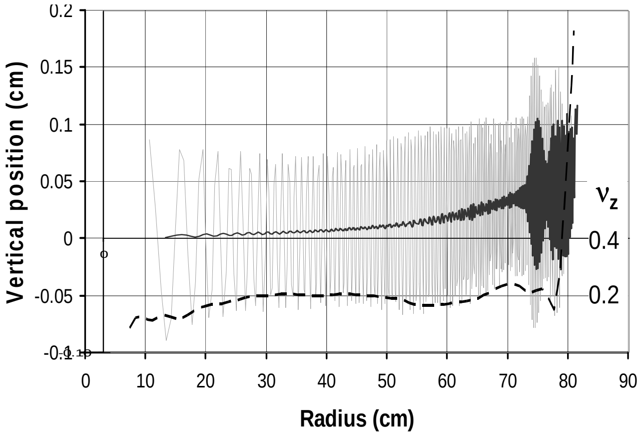

Fig. 1: Vertical particle position as a function of radius when the coil is tilted 0.38 mrad. Dark line: particle starts at centre of iron gap, grey line: particle starts 1 mm above centre. Dashed line: ν_z.

BETATRON RESONANCES

From the field map obtained from the measurements, we derived the equilibrium orbits and the frequencies of the betatron oscillations ν_r and ν_z. Fig. 2 shows the $\nu_z(\nu_r)$ plot obtained, together with some possible betatron resonances. Since especially the coupling resonance ν_r-$2\nu_z$=0, located at 246 MeV, is notorious for causing beam losses, we used *TRACK* to investigate the “width” and the effect of this resonance. First we mapped the equilibrium orbits between 244 and 247 MeV, with a spacing of 1 mm in radius. Around each equilibrium orbit several rays were tracked. These rays had initial offsets of 1 mm or 1 mrad in radial and/or vertical direction. We tracked these rays for 10 turns and recorded their deviation

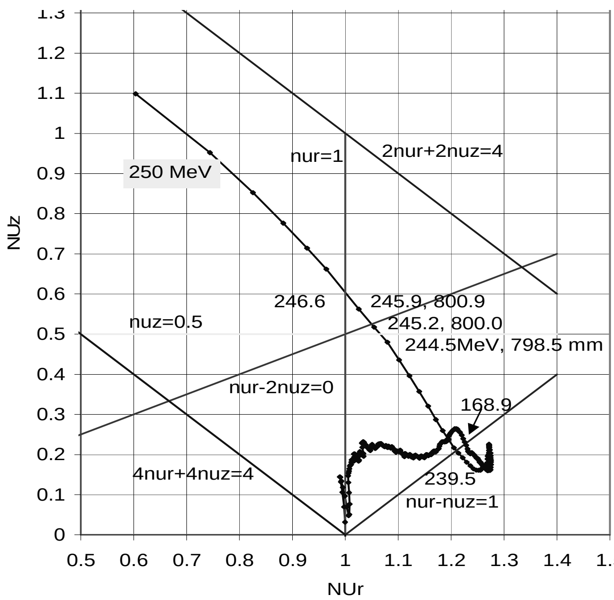

Fig. 2: Plot of the betatron frequencies and resonances in the measured field of *COMET*. Some key energies and average orbit radii are indicated.

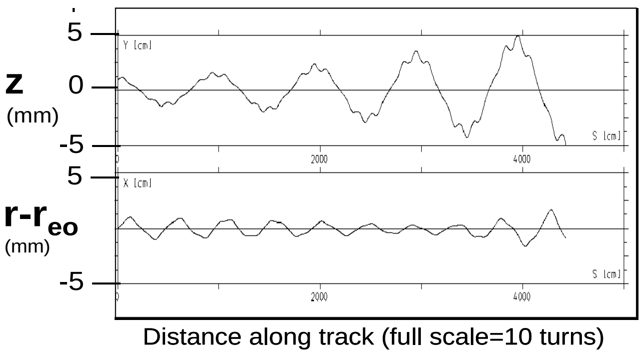

Fig. 3: Track of a particle relative to the 246 MeV equilibrium orbit in the vertical plane (top) and in the horizontal plane (bottom).

from the equilibrium orbit as a function of the distance covered. In Fig. 3 an example is shown of a particle near the 246 MeV equilibrium orbit. For tracks near this energy we could observe increasing amplitudes, both in the radial and in the vertical direction, which suggests the excitation of the coupling resonance. The effect of the resonance also depends on how many turns the accelerated beam experiences its effect. We found that tracks showing amplitude increases of >150 %, occur only between an average equilibrium-orbit radius of 800 mm and 803 mm. This corresponds to ~4 turns. The tracks such as shown in Fig. 3, all indicate that an amplitude increase to ~150 % builds up in approximately 5-7 turns. It can therefore be expected that the accelerated beam passes fast enough through this resonance. To test this, we also performed tracking with the acceleration field switched on. First, a reference track starting at 239 MeV was searched, and then 8 rays with slightly changed starting conditions were traced. Fig. 4 shows the deviation of one of these rays with respect to the reference track. At approximately 246 MeV, one observes an increase in radial amplitude and a decrease in vertical amplitude. It is remarkable, that we have not observed an amplitude increase in the vertical direction in any of the accelerated particles. Although for those rays tracked, the amplitude change is about the expected value, more tracking calculations are to be performed to obtain a complete view of the consequences of the resonance crossing.

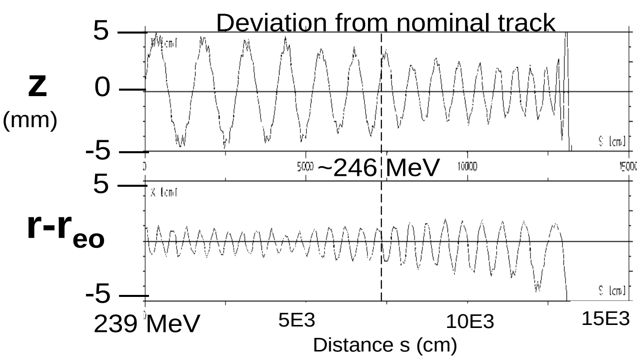

Fig. 4: Track of an accelerated particle relative to the reference particle starting at 239 MeV. The vertical deviation (top) and the horizontal deviation (bottom) are shown as a function of covered distance. The horizontal scale covers ~30 turns.

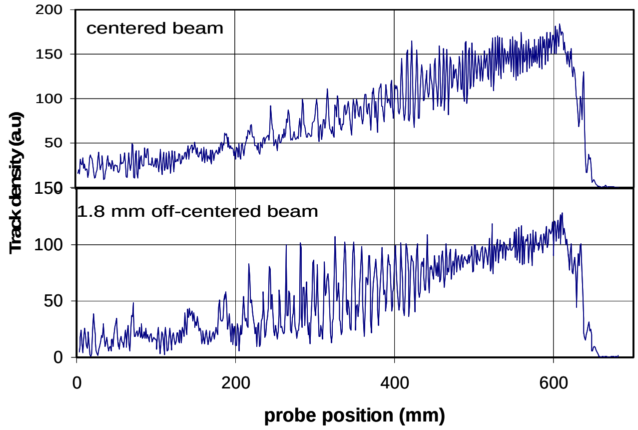

Fig. 5: The simulated track density (tracks per mm radius) for a well centered phase space (r_{start}=10 mm) and one for a phase space that started 1.8 mm to far outward. The actual probe trajectory runs from 200 to 670 mm in the plot, which corresponds to r=390 to 830 mm.

RADIAL PROBE SIGNAL

The radial probe will be equipped with a solid block and a wire. The signal observed at the block shows more or less the beam intensity, minus a fraction proportional to the track density (i.e. minus particles that are scattered by the wire). With *TRACK* we calculated the track density as a function of radius along the radial probe trajectory. The traced particles all started around a reference particle at r=10 cm. The accompanying particles covered a phase space of ±1 mm in radial as well as in axial direction and had an RF phase width of ±21°. Apart from a correction for the stopping power, the obtained track density profile (fig. 5) will give an indication of how the radial probe profile will look like. Note that the radial probe trajectory does not run along a radius, but along a more inclined path.

It can be seen that the track density smoothly increases with radius, as can be expected. However, when the beam starts with a momentum that is 1.8 % too low (i.e. the beam is 1.8 mm off centred), strong oscillations are observed between 200 and 400 mm (r≈400-600 mm) due to precession. This indicates that the signal of a badly centred beam can be well recognized by the radial probe.

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