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PROCEEDINGS

Beam-dynamics studies in a 250 MeV superconducting cyclotron with a particle tracking program

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Abstract A 250 MeV superconducting compact cyclotron, based on an original concept from H. Blosser (NSCL) and to be designed and manufactured by ACCEL (D), is being developed for the proton therapy project PROSCAN at PSI. We have used the general purpose three dimensional particle tracking program TRACK, developed at PSI, in the configuration of the 250 MeV cyclotron to perform studies of the beam dynamics and to derive important parameters describing the beam properties. Detailed tracking studies have been performed in the central region and in the extraction region. Examples of our ongoing studies are discussed to demonstrate the capabilities of the program TRACK.

Key words cyclotron • particle-tracking code

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Introduction

The program TRACK has been developed at PSI as a general purpose program for 3-dimensional particle tracking in electric and magnetic fields [3]. The program follows particle trajectories in three dimensions using an algorithm that contains the analytical solution of the equation of motion. The integration is done in small constant field steps of varying size, optimized for the local field variation. The input fields are obtained from commercially available codes, mathematical models or from field measurements. We have introduced time as a new parameter to enable the accelerating RF (radio-frequency) electric and accompanying magnetic fields to be included. Particle histories can now be calculated as a function of position, momentum, mass and time in combined static and alternating magnetic and electric fields. The program provides a visualization of the particle tracks in 3D, evolution of the phase space and marks the particle positions as a function of the phase when a time dependent field is used. The program was originally conceived to facilitate the design and analysis of beam line magnets, spectrometers and separators. However, the built-in command language interpreter allows a broader use of the program, and an application dependent analysis of the particle tracks.

In this paper, we report on the application of TRACK in the analysis of the magnetic and electric field of the new 250 MeV superconducting cyclotron for the proton therapy project at PSI [2]. The cyclotron is based on an original concept from H. Blosser (NSCL, USA) and is being designed and manufactured by the company ACCEL (Germany). 2D and 3D calculated magnetic and electric fields were provided by ACCEL for analysis at PSI.

Applications with static magnetic fields

A search has been made for the equilibrium orbits as a function of energy or average radius R_{aver} for different static magnetic fields. At each equilibrium orbit, cosine and sine-like orbits in the horizontal and vertical plane were tracked, from which the first-order transport matrix of one cyclotron sector was derived. The diagonal elements are then used to calculate the horizontal and vertical betatron frequencies ν_r and ν_z.

Some examples of ν_r–ν_z plots for different magnet layouts, in which the spiral parameters of the hill were varied, are shown in Fig. 1. Based on the calculation of the revolution time of each closed orbit, a study of the isochronicity of the cyclotron has also been made for different magnet layouts. A comparison with the results of other cyclotron codes did not show any significant differences for these two studies.

Applications with dynamic fields

A time dependent electric field was generated by the MicroWave Studio code [1]. This field was added to the static electric field and, starting at a radius of 9.5 cm, particle tracking was made until extraction. In Fig. 2, the energy gain per turn is shown. The shape of this curve is determined by the voltage profile along the dee and the phase at which the particles cross the gap (see also Fig. 3).

It should be noted that the crossing of the acceleration gap is calculated by integrating over small steps and that no "kick"-like approximations are used. In Fig. 3, the particle positions are plotted at the time when the electric field is at zero. This plot provides us with a lot of insight into the optimal frequency setting, isochronicity and phase-width acceptance. When we also add the time dependent magnetic H-field, generated by the currents in the RF cavities, it can be seen that this results in a net kick of the phase of the particles, which grows to approximately 20 degrees (RF phase). This kick occurs mainly near the radius where the dee-stems are located. Here (track 2) the H-fields do not cancel, which results in a small field bump of approximately 0.3×10^{-3} Tesla-meter. Tracks at smaller radii (track 1) experience a decrease in the total magnetic field when entering the dee but this is cancelled by an equal increase of the magnetic field at the dee exit. The effect of the H-field is also almost cancelled at the largest radii (track 3). Due to the spiral shape of the dee, the H-field has a larger impact at the dee exit than at the dee entrance.

The example shown in Fig. 4 shows calculation results at the extraction radius. The radial momentum component p_r and energy are plotted as a function of radius near the location of the extraction septum. Using iron trim-rods located near the extraction radius, a small bump in the field has been added to excite the $\nu_r = 1$ resonance. This yields an increased orbit separation at the septum.

Figure 5 shows the effect of the radial component of the RF field, experienced by the particles, which travel between the dee and outer liner wall after extraction.

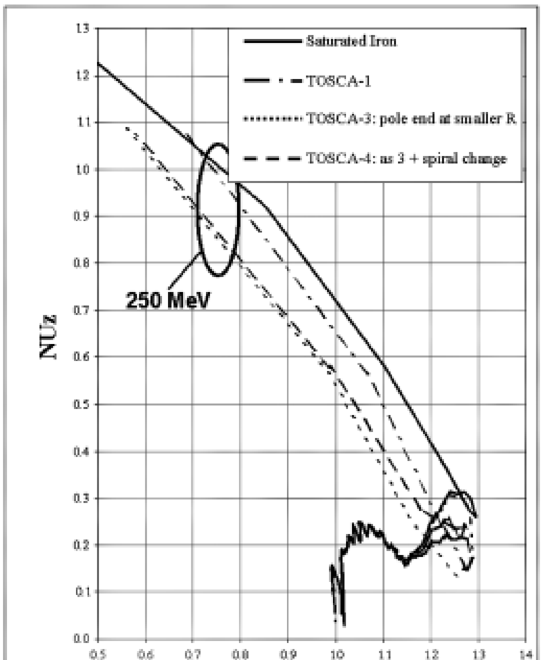

Fig. 1. ν_r–ν_z plot of different magnet designs.

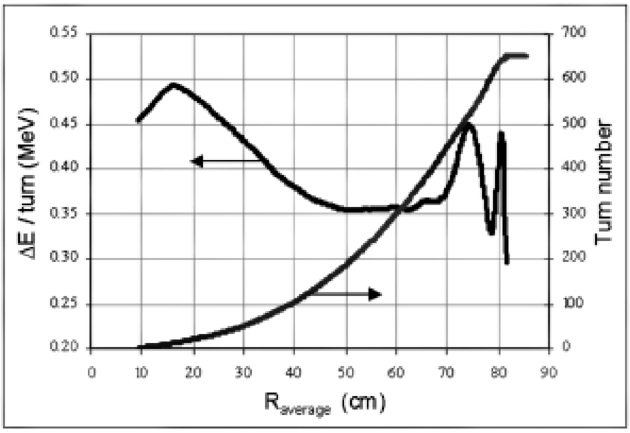

Fig. 2. The calculated energy gain per turn and turn number as a function of radius.

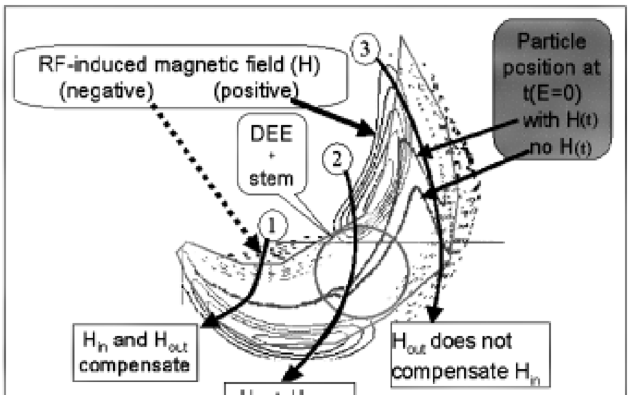

Fig. 3. Isochronicity in TRACK: particle positions at $t(E = 0)$ with and without H(t) field are shown, together with three typical tracks.

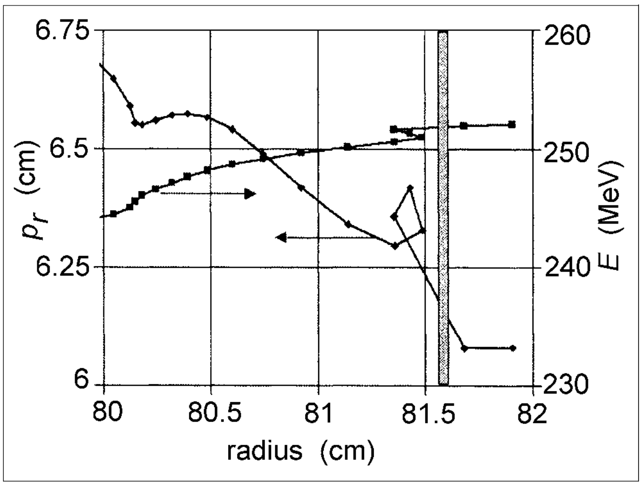

Fig. 4. Radial momentum component p_r and energy as a function of radius near extraction. The datapoints represent all the turns at extraction and the bar at 81.6 cm represents the extraction septum.

A study has been made to examine the distortion of the track, and phase space in the tracks is compared to tracks that have not experienced this RF field. Especially due to the spread in arrival time of the particles, there is an increase of the phase space.

Discussion and conclusions

We have used the program TRACK successfully in the analysis of static and dynamic 3D magnetic and electric fields of a 250 MeV cyclotron. Since the program has not been written for a specific application, its command language interpreter has to be used to extract the relevant data from the particle tracks at specific locations, moments in time or at other conditions specified by the user. The calculations presented here have been done to provide an independent confirmation of the analysis made by the standard cyclotron codes used by ACCEL. Until now, no explicit use of TRACK's 3D possibilities has been made. Currently, we are working on detailed tracking studies in the central region and the extraction region, where we study effects due to asymmetries in the field and e.g. the coupling of resonances in the horizontal and vertical planes. These applications will make more effective use of the 3D possibilities in TRACK. This may prove to be very useful in the commissioning phase of the cyclotron.

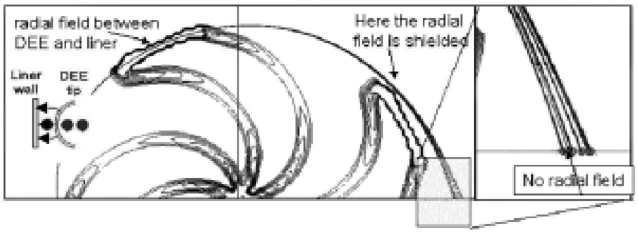

Fig. 5. Electric RF-isofield lines around the dees and location of the extracted orbit between dee and liner. Tracks at different phases are shown, which experience a radial RF field in the extraction path, compared to an undistorted track.

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