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MODEL DEVELOPMENT FOR THE AUTOMATED SETUP OF THE 2 MeV ELECTRON COOLER TRANSPORT CHANNEL

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Abstract

The 2 MeV electron cooler allows for cooling the proton and deuteron beams in the entire energy range of COSY and thereby study magnetized high energy electron cooling for the HESR [1] and NICA [2]. Manual electron beam adjustment in the high energy, high current regime proves a cumbersome and time consuming task. Special difficulties are presented by the particular geometry of the e-beam transport channel, limited beam diagnostics and general technical limitations. A model has been developed to track electrons through the transport channel of the cooler. This allows the offline study of response schemes around any particular setting of the cooler. It is envisaged to control linear, dipole and quadrupole behavior of the e-beam. Application of the model will result in optimized e-beam transport settings for a lossless and cool beam transport. This will improve cooling and recuperation efficiency and allow quick adjustment of the e-beam to the various operational modes of the machine. A good relative agreement of the model and the cooler could be shown. Main focus lies now in overhauling the software and finding suitable initial conditions to improve the agreement to an absolute degree.

MOTIVATION

In need of support for setting up the electron cooler, the model based approach offers a vast amount of advantages to the current manual way of operation. The model will at one point be able to predict the electron trajectory for any given machine setting. Additionally It will be able to calculate beam responses much faster than obtainable by measurements. The speed of obtaining responses scales progressively with the order of motion of the parameter of interest. Thus setting up the cooler will be faster, more reliable and will offer more information on the beam behavior throughout the transport channel, compared to the manual operation. The main objective of the model based adjustment is to achieve a brilliant electron beam quality for high cooling rates and optimal recuperation conditions. With respect to the safety during operation, this will result is improved vacuum conditions and causes less x-ray radiation. The model is embedded in a software suit that reads inputs from the cooler and is able to apply changes to the transport channel settings. With proper procedures and algorithms one will be able to compensate coupled effects between the different orders of beam motion types and to predict beam behavior also for yet unexplored beam regimes.

OVERVIEW

Machine Characteristics and Limitations

There are certain in and outputs available to handle the electron beam. The beam responds to the set currents i.e. the main currents and corrector currents. Main currents are internally called, “Cooling section”, “Longitudinal field”, “Bending field”, “Toroid 45° field”, and “Straight field”. Where it should be pointed out that the shown elements share the same current, as shown in Fig. 1. About 50 corrector currents are used to supply mostly diploes, distributed along the transport channel and some more particular ones [3]. Feedback on the beams behavior is obtained by the Beam Position Monitor (BPM) system, and by the readouts from the vacuum system, leakage current and radiation monitors. Information on the beam shape can be obtained as the electron gun is capable of modulating the beam quadrant-wise [4], as only the modulated portion of the e beam is visible to the BPM system.

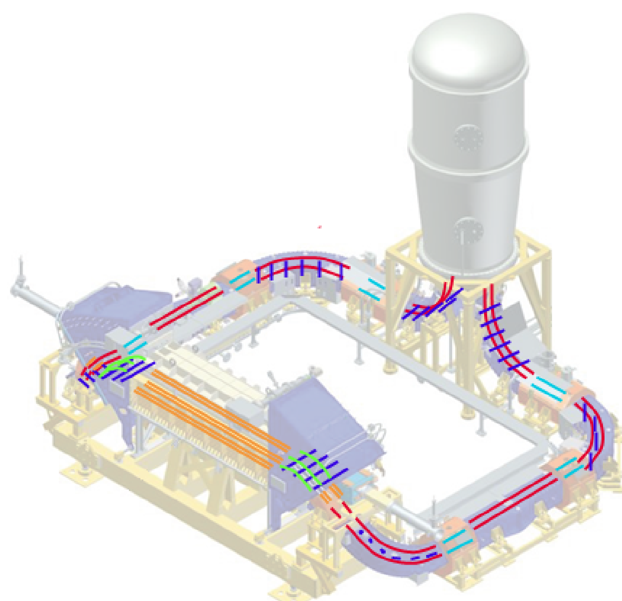

Figure 1: Image of the 2 MeV electron cooler. Equally colored symbolic field lines represent coils that share the same power supply. Orange: “Cooling section”, red: “Longitudinal field”, blue: “Bending field”, green: “Toroid 45° field”, and cyan: “Straight field”.

E Beam Parameters

The e beam parameters of interest for the transport channel setup are the parameterized orders of motion, i.e. linear, dipole and quadrupole. There is only the possibility for an

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orbit (linear) in-situ measurement, with the BPM system. The dipole motion, from now on called larmor rotation, is inevitably excited by the given geometry of the transport channel. The specal condition of an integer number of larmor oscillations [3] to minimize the larmor excitation cannot be kept through all bending sections. Adjasing elements of different field straight distort the longitudinal profile so that a common optimal setting cannot be found. The larmor rotation can only be measured indirectly by sweeping the current of a straight section around the operating point and observing the resulting beam position shift over the set current or B-field. The amplitude of the motion is the larmor radius, which quantifies its magnitude. The highest order of motion is the so called galloping motion (quadrupole motion). It results from the passage of a non-adiabatic e beam trough a B-field gradient section. Individual electrons are excited to carry out larmor rotation, whereas the envelope of the beam is wobbling as a result, because the individual larmor phases vary with their location within the beam as well as the larmor radius increases with distance to the center of charge of the beam. While the center of gravity is unaffected by the galloping motion on can measure the larmor rotation of the center as well as of one quadrant and simply subtract the coherent component to single out the pure galloping motion. The projections of the superposition of larmor rotation and galloping motion is shown in Fig. 2 For the currently foreseen scope of the model software, auxiliary data on the vacuum, leakage current, radiation signal will not be used for feedback schemes by default.

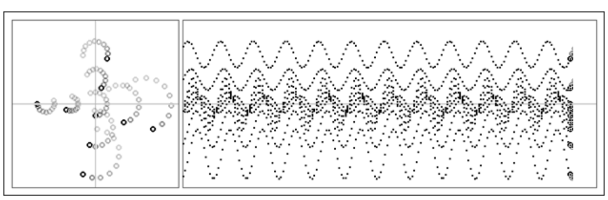

Figure 2: Trajcectory cross sections to visualize the superposition of Larmor and galloping motion. Left in XY-Plane, right in YZ-Plane.

Current Way of Operation for Beam Setup and Adjustments

The initial setup for the transport channel is found by setting main currents to empirically known values scaled by the beta-gamma relation for the given energy. Orbit optimization with focus on the reduction of leakage current as well as stable vacuum conditions is obtained at low e beam current. Larmor and orbit corrections are iteratively performed as the e beam current is slowly increased. The orbit changes are preformed manually as for the operating needs by setting the currents of certain dipole correctors. As the shift translates throughout the transport channel, greater shifts have to be compensated further downstream. The Larmor rotation compensation is only carried out in the cooling section. There is only one pair of short dipole corrector kickers to induce a larmor excitation that counteracts the accumulated larmor rotation in one selected section, in which the larmor radius is measureable. There is a set of seven corrector solenoids to counteract galloping motion in one of the so called matching sections. These coils ought to deliver such a field configuration to bridge the gradient region between the weaker magnetic field in the accelerator column and the strong longitudinal within the first bending section. There is no practical compensation scheme in place for the galloping motion as its measurement is a lengthy procedure and there are seven currents to sweep independently to find an optimal setting.

MODEL

Implementation

The model is embedded in a Java software package specifically in development for the operation of the 2 MeV electron cooler. At its core there are magnetic field maps calculated obtained from COMSOL Multiphysics 5.0 calculations, translated into equidistant grids for an eased access to specific field values at given coordinates. The equation of motion of the electron in such an environment is utilized in the integration of the instantaneous velocity of the particle. Special simplex arguments prevent blowup of the integration. Quantization of beam parameters from the model is taken care of by the trajectory fit of individual electrons with respect to the center of charge representing electron. This way one obtains linear, dipole and quadrupole terms for the entire beam and can compare those with measurement results.

Quality of Agreement

During the proof of principle stage of the model software, it could be shown that there is a satisfying qualitative agreement between the model and the 2 MeV electron cooler. In the first order calibration deviations in the response behavior between the measured electron beam and calculated trajectories are used to scale the dipole magnets in the model. This accounts for errors and simplifications during modelling the coil configurations in COMSOL or installation misalignments of the coils. A quantitative comparison of a measured orbit response matrix and a calculated one showed after calibration RMS deviations of about 10 %. Although there is room for improvement for example by properly scaling also the longitudinal fields, such a deviation is small enough to still allow application of calculated orbit response schemes in feedback scenarios. The qualitative agreement can also be seen in the existence of anticipated effects of the short dipole kickers used for larmor excitation. Galloping motion can also be compensated within the model utilizing the previously mentioned matching section, consisting of seven coils. A simple algorithm sweeps the current of each coil slightly to determine the gradient of the galloping response. The current of each coil is successively set in the direction of the negative gradient. Progressing through several iterations the galloping growth rate is decreased significantly. This shows that the model is capable to find suitable settings for the matching section. The ability to compensate the galloping motion within the model is another solid hint for the good qualitative agreement. The compensation procedures can be carried out within the model, using its response to find optimised settings. Intermediate and final results of the stepwise procedure can be comprehended by means of the Fig 3.

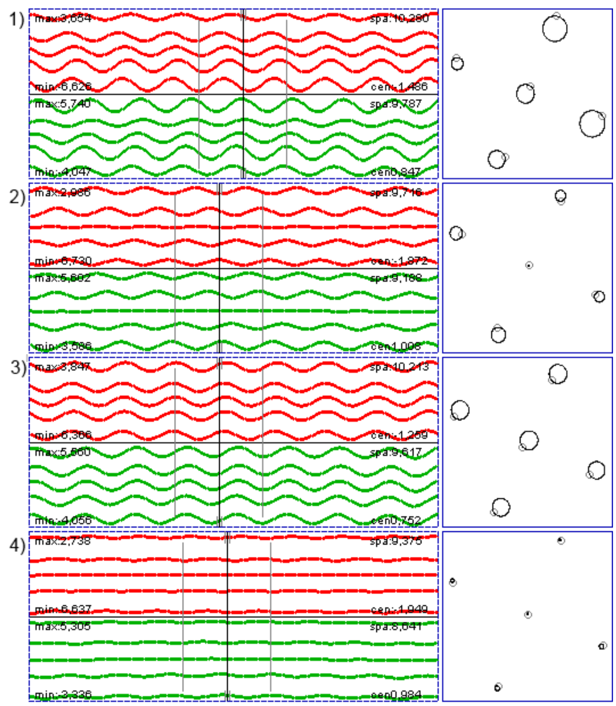

Figure 3: Trajectories in straight section. Red is projection in x, green is projection in y. First initial uncompensated beam, second larmor corrected, third galloping corrected, final larmor corrected again.

The corrector coils in the bending sections consists of two separate coil usually supplied with an equal current to satisfy a magnetic index of 0.5 in the bending sections, which ensures that there is no influence of the beam shape. As there are mismatches, beam shape influence can be seen. There is however the capability for beam shape restoration by applying antiparallel changes to the inner and outer bending corrector coil. The measured shape influence has been also compared to that of the model. The results show qualitative agreement only separated by a factor of two, which will be investigated in the near future.

Space for Improvement

The model calculations are sensitive to the chosen time step width of the integration. Improvements of the underlying physics implementation could allow wider time steps which would speed up the calculation and guarantee its reliability. The included field maps extend partially up to one meter out from the magnetic element to reflect the diffusing fringe field. It has been observed that the electron motion in the order of micro meters is even sensitive to abruptly cut off weak fringing field maps. To reflect the proper electron behavior the diffusion of the fringes as well as even wider extended regions could be implemented into the model. The transport channel is almost completely covered in a magnetic shielding. This acts additionally as a yoke, why its contribution has to be considered not only linearly but also as it can saturate or even pose with a remanence field due to hysteresis. Including saturation and hysteresis of the magnetic shielding would reflect a more accurate environment and improve the model.

Calibration Schemes

As there is a relative agreement of the model and the electron cooler's beam behavior, one could already implement feedback loops to counteract coupled effects during manual or automated changes to the transport channel setup. But this has to be accompanied with steady measurements to verify the beam parameters. The relative calibration is simply given as the rescaling of magnetic field maps according to the deviations of measured and calculated response schemes. An absolute calibration of the model would allow for predictions of the trajectory and thereby all beam parameters. Key to the absolute calibration is the exact starting point of the electron. There are two approaches to determine proper injection conditions for the model calculation that will be presented. The general approach can be described as a least square fit to all measured beam positions. The variations lie within a positional spread and angular spread at each BPM location from where the electron trajectory is traced down- as well as upstream. The error of this error calibration lies within the BPM misalignments. The second approach is more specialized reflecting the transport channel geometry. It also focuses on calibrating the longitudinal model fields. As the larmor rotation can be measured in three straight sections, the position and angle of the e beam is known at the end of these sections. Tracing along straight sections is least prone to error. Because of that, position and angle of the e beam in the beginning of the straight sections can easily be determined. This gives additionally the special relation between the offsets of the present BPMs. In between these straight sections the model trajectory can be traced from one section to the next down- and upstream. Phase propagation differences between the model and the measurement can be picked up and corrected by repeating this procedure at varied settings for the inner magnetic bend elements and determination of scaling factors to calibrate the longitudinal model fields. The remaining trajectory can be traced upstream from the beginning of the first straight section and downstream from the end of the last straight section. This way one knows the most precise starting and end point of the model trajectory, which can be used for the model application and beam predictions.

OUTLOOK

As the model offers plenty of new opportunities one can think of many adaptations, refinements and add-ons. One of

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these is the implementation of the electron gun environment model or some of its crucial parameters. This way one could make use a better an understanding of the beam shape as well as to determine its absolute temperature. Collector components could also be included to the model to achieve and verify higher recuperation and collector efficiencies for higher currents. /newline The hard coded model could be generalized to support a sand box like feature. With help of such a feature any transport channel geometry could be constructed virtually on the fly. It could provide aid during the design of an electron cooler or be adapted to existing ones. This would include the possibimity to plug in generic, numeric and analytic field maps. A step into a more analyitc approach to find and optimize transport channel settings is the look at optics functions. For generalized adjustment schemes transfer functions could be obtained. Inversions of transfer matrices will eventually lead to optimized solutions. This way the entire trajectory could be described analytically.

CONCLUSIONS

A model is under development to aid the transport channel setup of the 2 MeV electron cooler. The model is embedded in a Java software suit with a GUI to monitor beam parameters and set transport channel parameters. The model satisfies a qualitative agreement with the cooler and shows in this way the expected physical behavior. Properly scaled corrector dipoles within the model allow already application of the model for orbit feedback loops. Successful use has been demonstrated during the proof of principle stage of the model. Absolute calibration is yet required to properly reflect the actual e beam trajectory with the model for each magnetic setting of the cooler. For this matter, calibration schemes are under development and will be implemented and tested soon. After successful calibration the core of the model will be operational.

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