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FAST ELECTROMAGNETIC MODELS OF EXISTING BEAMLINE SIMULATIONS

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Abstract

The AD-ELENA complex decelerates antiprotons to energies of 100 keV before transport to experiments through electrostatic transfer lines. Transfer line optics are traditionally designed from a lattice based approach and are unaffected by external effects. Presented is a method of rapidly prototyping MAD-X simulations into G4Beamline models which propagate particles via electromagnetic fields rather than idealised optical lattice parameters. The transfer line to the ALPHA experiment is simulated in this approach. Due to the presence of fringe fields disagreement is found between the two models. Using an error minimisation technique, revised quadrupole strengths are found which improve agreement by 30% without any manual adjustment.

INTRODUCTION

The AD-ELENA (Antiproton Decelerator - Extra Low ENergy Antiproton) complex decelerates anti-protons ($\bar{p}$) down from 5.3 MeV to energies of 100 keV. After deceleration $\bar{p}$ are then transferred to and subsequently trapped by experiments, however experiments require energies in the sub 10 keV range to trap $\bar{p}$ efficiently. To achieve this, experiments routinely use destructive degrader foils which significantly impact the number of available $\bar{p}$ in the traps. Work is ongoing to model degrader foils using density functional theory in combination with molecular dynamics [1] to fine-tune foil degrader thickness, maximising the number of $\bar{p}$ available for trapping. In the process of this modelling it is important to have accurate simulations of the beam profile at the point of handover between ELENA transfer lines and experimental setups, as such the electrostatic transfer line which carries $\bar{p}$ from ELENA to ALPHA (Antihydrogen Laser PHysics Apparatus) is simulated in G4Beamline [2]. Previous work has shown the approaches used in modelling the electrostatic optics as well as the static bending elements within the beam to be effective [3].

Presented in this work is a new method of rapidly prototyping realistic simulations from existing MAD-X [4] models which use lattice based structures, into one which models a voxelised world space whereby electromagnetic fields determine the motion of particles. Electromagnetic fields are generated by realistically modelled structures, with quadrupole field gradients calculated directly from integrated field strengths returned from MAD-X. Whilst current work focuses on the ALPHA transfer line, with some user modification the method presented is extensible for any transfer line that uses repeated optical structures.

By utilising Enge style functions to model fringe fields [5], quadrupoles are modelled in a more realistic manner. The impact of these is seen as an increase in the quadrupole's effective length in G4Beamline simulations, causing a discrepancy between the beta values returned by MAD-X and those from G4Beamline. Similarly with sufficient modelling, the impact of any stray fields can be included and suitably accounted for [6].

The effects of fringe fields are reduced by development of a beta matching minimisation algorithm, resulting in significantly greater agreement between the two models.

TRANSFER LINE MODELLING

A number of transfer lines exist after ejection from ELENA. Extraction from ELENA is handled by a small kick fast deflector, similarly these are used for the shifting between beamlines. A number of static deflectors handle larger bends and are often situated directly after a fast deflector to produce a larger bend than the fast deflector could handle alone.

Optical Structures

Optical structures are built in a modular fashion, with each FODO cell (A repeated optical structure consisting of focusing and defocusing quadrupoles with drift spaces) consisting of 2 quadrupoles, and 2 corrector magnets sat in the space between each quadrupole. Although the geometrical structure of each FODO cell is identical to another, the electrostatic quadrupoles can be fine-tuned to aid in the focusing of the beam.

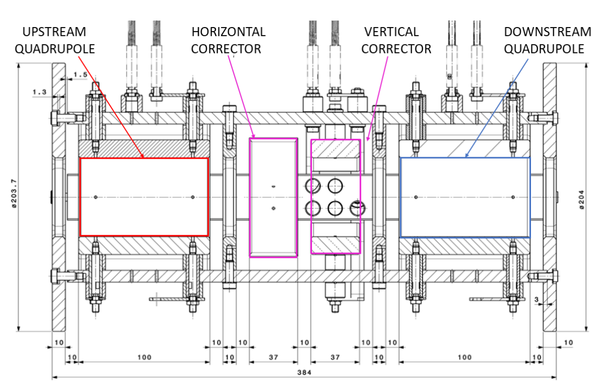

Figure 1: Schematic of a modular FODO cell utilised in the transfer lines.

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In Fig. 1 the blue and red bounding boxes indicate the positions of the up and downstream quadrupoles, pink bounding boxes highlight the horizontal and vertical correctors. By utilising MAD-X simulations the strength of the focusing magnets required can be determined.

MAD-X Object Extraction

By utilising the TWISS module within MAD-X a TFS table file can be produced, which contains for all elements in the beamline a number of requested properties. Although many different data points can be returned from this module, of key importance is the nominal integrated field strength which contains the focusing strength of each optical element in the beamline.

In order to build the G4Beamline simulation, a number of python scripts act as the interplay between the TFS file output and the G4Beamline input. Each object in the line is associated with a python class which the user may modify. Each object inherently has definitions from within its class that hold key information, such as aperture radius, object length and material. In this manner it is not just quadrupoles that are able to be simulated, but any object present within G4Beamline providing enough care is taken in constructing the python class correctly.

To facilitate in the extraction of objects from the TFS table and to aid in the evaluation of optical parameters, PyMADX [7] is utilised in conjunction with custom python scripts. By iterating through each object extracted from PyMADX and passing it to the class parser, a database of all objects is stored within python, ready to be manipulated and inserted into G4Beamline.

Construction

As each element extracted has an associated position along a curvilinear axis, when placing elements they are placed sequentially along the direction of travel. Because of this nature, the rotation of placed elements after a bend is handled automatically by the beamline, allowing for a much simpler user experience. As each element is stored in memory as an object, any element can be accessed and changed before construction of the beamline, which allows for the user to quickly evaluate errors within the beamline, for example a miscalculated optic strength can be inherently included.

Figure 2 visualises the result of automatic simulation and construction. Bends are present but iron yokes have been deliberately left clear to allow the user to see any effects resulting from horizontal bending. Defocusing quadrupoles are highlighted in red, focusing in blue, corrector magnets in pink and beam position monitors in green. Each beam position monitor returns a text file for that specific monitor, allowing for constant monitoring of the beam along its travel, these do not interfere with the beam, however, so can be included without any destructive effects.

Impact Of Fringe Fields

Fringe fields are not inherently included within MAD-X, meaning each quadrupole has a sharp edge fall off at the end of its iron length. In reality field strength slowly decays some distance after the end of the object's edge, this can be modelled in G4Beamline and is included in the simulations presented here.

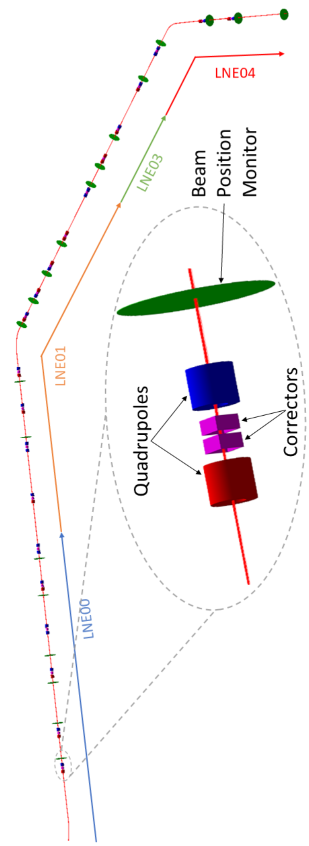

Figure 2: Simulated transfer line automatically constructed from MAD-X simulations.

Figure 3 shows the resulting Twiss parameters β_x, β_y from both MAD-X and G4Beamline from the initial simulations, i.e those without any error minimisation performed and with quadrupole strengths taken as those directly calculated from MAD-X. Although reasonably well matched at the beginning of the line, fringe fields cause large discrepancies towards later stages.

It is possible to manually adjust the quadrupole strengths to improve matching, however for many quadrupoles this takes the user significant time. G4Beamline is capable of tuning approximately 3 quadrupoles in a triplet on its own, however for the 42 quadrupoles used in the beamline under discussion, it falls short and an alternative method has been developed to go someway towards solving this.

Quadrupole Strength Optimisation

To minimise all 42 quadrupoles in the line, an error minimisation problem is constructed to improve agreement between the models. The minimisation function used takes an ordinary least squares minimisation approach between MAD-X and G4Beamline [Eq. (1)]. β_x^{G4} refers to the G4Beamline Twiss parameter β_x, whilst β_x^{MAD} refers to

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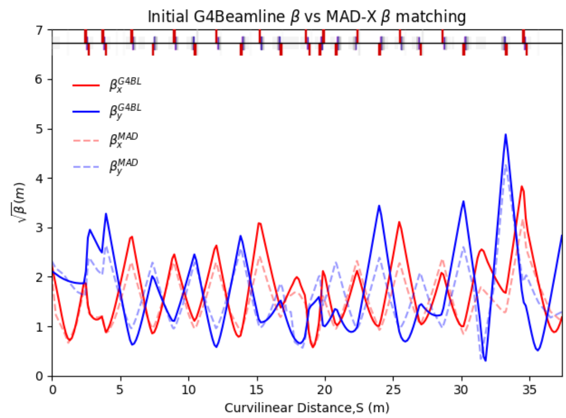

Figure 3: Beta Matching from initial simulations. $\sqrt{\beta}$ represents the Twiss beta function, whilst CurviLinear distance represents the distance travelled along the beam line, including any bends present. Solid lines are indicative of G4Beamline β values, and fainter dashed lines represent those from MAD-X. Red lines in both instances refer to β_x and blue β_y. Included at the top of the image is a schematic beamline showing each quadrupole location, those above the line represent focusing quadrupoles, whilst those below defocusing.

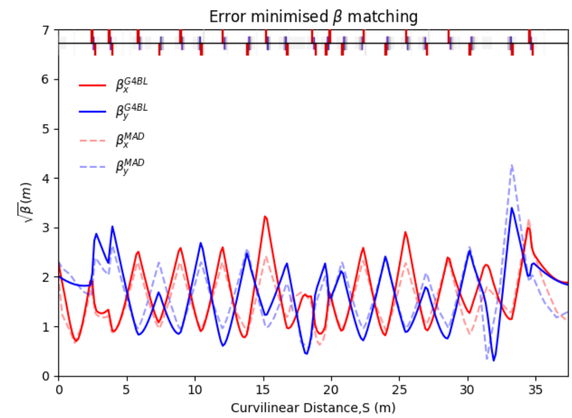

Figure 4: Beta matching after MCMC adjustments. All definitions remain the same as those in Figure 3. After 7500 iterations, matching is greatly improved along the entire beam length, providing improved agreement between MAD-X models and G4Beamline models in the presence of fringe fields.

its MAD-X counterpart. A similar nomenclature is used for β_y. The root mean square error is computed using both β_x and β_y.

$$RMSE = min(\sqrt{(\beta_x^{G4} - \beta_x^{MAD})^2 + (\beta_y^{G4} - \beta_y^{MAD})^2}) \quad (1)$$

This is not the only function that could be used, for example the user could specify reducing handover spot size or overall beta functions within G4Beamline itself without reference to MAD-X.

By utilising the MAD-X returned values as initial starting quadrupole strengths in combination with EMCEE, an MCMC (Markov Chain Monte Carlo) ensemble sampler [8], each of the quadrupoles in the line has an appropriate starting value and is subsequently adjusted to its optimised strength to reduce the minimisation function Eq. (1). An 7500 adjustment run is shown in Fig. 4 showing improved matching across the entire line. One advantage of using MCMC methods as opposed to more traditional methods involving beta function minimisation is the extensibility of MCMC minimisation functions.

For the ALPHA beamline, a stretch move based approach [9] of updating walker values was found to have the fastest convergence time, although the possibility of other walker moves is inherently included within EMCEE.

Figure 5 shows the relative change in quadrupole strength for each quadrupole along the line after 7500 iterations. Relative here implies that a positive change (shown in red) is an increase in focusing or defocusing strength, dependant on its initial starting value. Using the minimisation function 1, the initial root mean square error value of 208.42 is reduced to 142.56 showing 30% improvement in the beamline agreements without any manual adjustments.

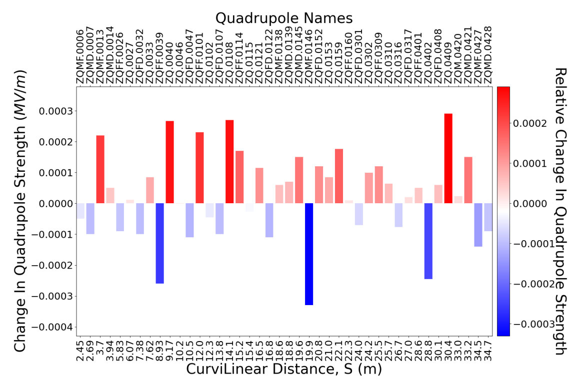

Figure 5: Relative change of each quadruple strength in the line, note a positive increase here means a positive increase in its relative focusing strength, not the field strength itself.

CONCLUSION

A new approach to rapidly modelling accelerator beamlines has been demonstrated to be quick and effective at prototyping MAD-X simulations into simulations in which particle movement is determined by electromagnetic fields. This allows for the inclusion of fringe fields as well as any stray magnetic fields. The effects of fringe fields has been accounted for by the development of a beta matching minimisation algorithm resulting in an improvement between the two simulations of approximately 30%.

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