Work Project Report

Simulating the Beam-line at CERN's ISOLDE Experiment

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Abstract

Maximizing the optical matching along portions of the ISOLDE beam-line and automating this procedure will make it easier for scientists to determine what the strengths of the electrical fields of each beam-line element should be in order to reduce particle loss. Simulations are run using a program called MAD-X, however, certain issues were discovered that hindered an immediate success of the simulations. Specifically, the transfer matrices for electrostatic components like the switchyards, kickers, and electric quadrupoles were missing from the original coding. The primary aim of this project was to design these components using AutoCAD and then extract the transfer matrices using SIMION. Future work will then implement these transfer matrices into the MAD-X code to make the simulations of the beam-line more accurate.

Project Goal

The main goal of this project was to work on maximizing the optical matching along a portion of the beam-line at the ISOLDE facility by running simulations to help minimize the loss of ions as they travel along the beam-lines. Ideally, one would like all of the ions that are produced in the lab and transported through different sections to different experimental areas to make it to the end and hit their targets. However, due to the complex motion of particles along the beam-line this is hard to achieve. Spatial and momentum dispersion, in addition to Coulomb repulsion of the ions themselves, will cause the ions to deviate from their ideal paths. For this reason accelerators and beam-lines contain a number of different types of magnets, such as quadrupoles, to correct and control the motion of the particles as much as possible. However, even with these magnets, particles are likely to be lost as they travel long distances. The beam envelope changes dynamically, and if not controlled then particles that deviate too far from the center of the beam-line can come in contact with the walls and be lost.

However, because of the mathematical understanding of accelerator and beam physics, ion motion can be described and implemented into simulations. At ISOLDE, the positions of the electromagnets along the beam-line are fixed, however, the strengths of the electromagnetic fields can be controlled in the lab. This allows simulations to be carried out which aim at changing the electromagnetic field strengths along the beam-line in order to alter and contain the ions as they travel from the start of the beam-line to the end. Ultimately, it would be advantageous to have a program that can simulate any type of ion that is produced in the lab at ISOLDE and its motion along the beam-line. In this way, a scientist could specify the type of ion that they have produced and its initial conditions, and then run a simulation to determine what the ideal settings of the electromagnets should be, to ensure the maximum efficiency in the ion transportation from its source to its experiment.

In order to run these simulations our group chose to use a program called MAD-X [1], which was originally designed here at CERN for the creation and simulation of different accelerators and beam-lines. This program was used at the start of this project, until a few issues were discovered which needed to be assessed. At this point we decided that the problems needed to be addressed immediately, before truly accurate simulations could be continued with MAD-X. The focus of this report will begin with MAD-X and its problems, and describe the solution that was taken to solve these problems.

Creating the Simulations

MAD-X allows the user to specify the types and positions of magnets, the type and number of particles to be simulated, and the initial conditions of these particles (such as their initial energy and momentum dispersions). It can then run tracking procedures and iterations on the strengths of the electromagnetic fields until it has minimized the beam envelope and ensured the maximum number of particles have made it to their target. This is quite a convenient procedure, and ideal for what we are trying to achieve.

However, some fundamental problems in the approach that the MAD-X code takes to perform the simulations hindered an immediate achievement of our goal [1]. First, it is not completely reliable for electrostatic components, and ISOLDE uses electrostatic quadrupoles. Second, the transfer matrices for two of the components (the kicker and the switchyard) don't actually exist in the MAD-X coding. The first is an issue because there may be subtle differences in the quadrupoles that MAD-X simulates, and the ones at ISOLDE. The second, however, is more problematic, because the transfer matrices describe the motion of a particle (mathematically) through different components, and thus allow for the calculation of the particle's new position after it has passed through that component. This problem means that we can't actually insert a kicker or switchyard into our simulation using MAD-X at the moment, because they don't exist. The portion of the beam-line that we want to model is shown in Figure 1, which does contain these two elements. Therefore it is necessary to obtain the transfer matrices of these components in order to continue with the MAD-X simulations.

At this point we came up with the following solution to address these issues. First the components that we needed (the electric quadrupoles, the kicker, and a three- and five-way switchyard) would be modeled using AutoCAD (a 3D engineering program). Then, these files would be uploaded into another program called SIMION [2], which would calculate the transfer matrices for particles given the specific geometries provided. These transfer

[1]We acknowledge Daniel Barna from the Technology Department and Didier Voulot from the Beams Department at CERN for the discussions about the simulations.

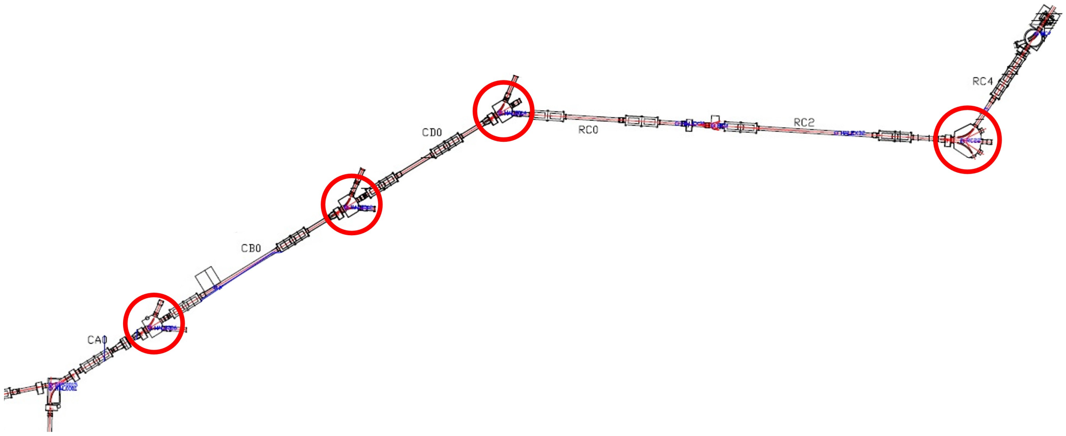


Figure 1: The red circles indicate the positions of the kickers and the switchyards. The purpose of these devices is to divert the ions along a different portion of the beam-line to other experimental areas.

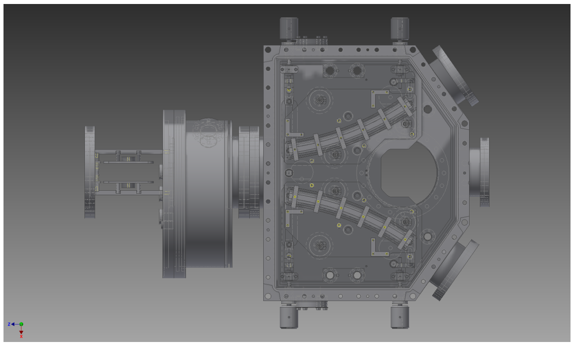
matrices could ultimately be introduced in the MAD-X simulations to make them run more accurately.

Creating the Models

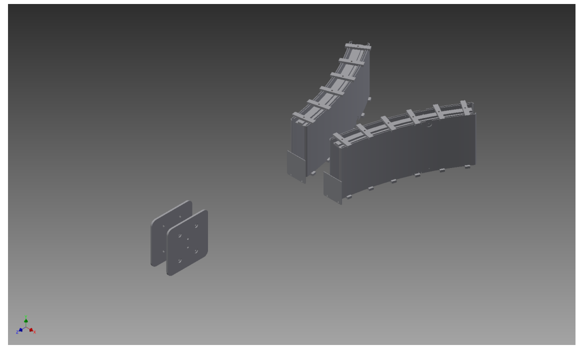
Originally it was going to be our task to design these components entirely, however, we discovered that a student from Politechnika Krakowska had already designed the ASPIC beam-line at ISOLDE [2]. This portion contained the quadrupoles and three-way switchyard that we needed, so we were able to acquire and use these files. There were some subtle differences, however, between the ASPIC components and the components that we were trying to model. Specifically, the ASPIC beam-line contains components of the Ultra-High Vacuum (UHV), and our beam-line does not contain any of these UHV components. As a result, when comparing measurements taken of the UHV three-way switchyard and our three-way switchyard, there were some differences. The most important pieces to consider were the distances and positions of the kicker plates relative to the deflector plates inside of the switchyard box, because this would affect the general geometry of the entire component. Once these were corrected the model was then simplified to just its most basic and fundamental constituents, in order to make the file sizes smaller and easier to upload into SIMION. Before and after comparisons of the device are shown in Figure 2.

In addition to the three-way switchyards there was a five-way switchyard. This component doesn't exist on the ASPIC beam-line, therefore we needed to design it on our own. However, at the moment there are no diagrams available of the inside of the five-way switchyard. Thus, it was not possible to determine with absolute certainty where the deflector plates and where the kicker plates were located. However, using the three-way switchyard as a starting point, we took measurements of the outside of the five-way switchyard at the ISOLDE facility and, given the deflection angles of the kicker and deflector plates (which we

[2]Credit goes to Tomasz Wlodarski.



(a) Complete design with inner components exposed.



(b) The only components uploaded to SIMION.

Figure 2: The AutoCAD model of the three-way switchyard.

did know), we constructed a simple five-way switchyard to serve as the model until actual measurements can be made of the inside in the future.

Finally, the quadrupole piece was also taken from the ASPIC beam-line, and it too was simplified down to its most basic parts to make it easier to upload to SIMION.

Results from SIMION

Once the geometry files in AutoCAD had been altered they were uploaded into SIMION. When the files are converted in SIMION they become very large in size, to the point where the computer can't run any simulations, and for this reason each of the components had to be simplified. However, once they were uploaded, we ran a script that was written to run SIMION and iterate on the voltages of the different electrostatic plates. To begin we defined an initial position and a final position of the particle, at the beginning of the kicker plate and at the end of the deflector plates, respectively. We then chose a particle and its initial energy. The script procedure then launched the particle through the detector, while iterating on the voltages applied to the deflector plates, shown in Figure 3. This is then continued until the particle reached the center of the start of the deflector plates. Once it reached this position the deflector plate voltages were held constant, and the iterative procedure then continued on the deflector plates until the particle had reached its final specified position (this is the final path in Figure 3).

This entire procedure then outputs what the respective kicker and deflector voltage values were. For Figure 3, the particle was a proton at 50 keV, and the values of the kicker plate voltages and the deflector plate voltages were $\pm 2067.69\ V$ and $\pm 2421.79\ V$, respectively. Most importantly, it also calculates the transfer matrix $\mathbf{R}$, which for this example was

$$\mathbf{R} = \begin{vmatrix} 0.928447 & 0.682261 & -0.025918 & -0.104912 \\ -0.546270 & 0.105721 & -0.054838 & -0.057641 \\ -0.026533 & -0.001919 & 0.999794 & 0.713014 \\ -0.083600 & -0.003370 & -0.004589 & 0.964268 \end{vmatrix} \tag{1}$$

(Note that this does not include the longitudinal nor the momentum deviation components

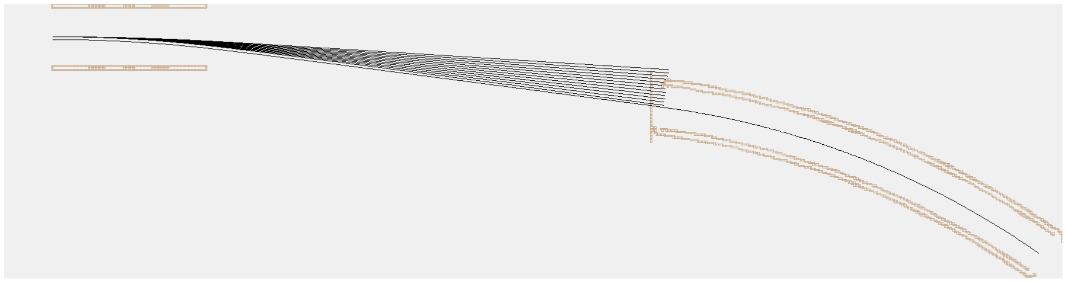


Figure 3: The kicker plates are located to the left, and one set of the deflector plates for the three-way switchyard is located to the right. The dark lines are ray traces of the particle's path.

in the calculated transfer matrix because the dispersion was set equal to zero - only the spatial and angular deviations are calculated).

Future Work

There are a number of steps still to be taken in the future on this project. At this point we have begun extracting the transfer matrices for the three-way switchyard, but they will need to be calculated from the electrostatic quadrupoles and the five-way switchyard. Moreover, the nature of the calculations performed in SIMION is stochastic - the initial conditions of the particles' positions and angles are taken randomly from a user-defined distribution and in order to initialize the pseudo-random number generator a non-repetitive seed state is used. Thus the transfer matrices will change slightly if run multiple times with the same settings. This means that representative values must be chosen for the transfer matrices that will ultimately be incorporated into MAD-X.

Then, once the MAD-X code has been updated, accurate simulations of the entire beam-line shown in Figure 1 can be performed. As mentioned before, the ultimate goal of this work will be to create a simulation that automates the entire optical matching procedure of the electrostatic quadrupoles along the beam-line so that scientists can determine what each electromagnetic field strength should be for all of the electromagnets, for their particular experiments.

References

[1] Frank Schmidt, *MAD-X User's Guide*. CERN (European Organisation for Nuclear Research), Geneva, Switzerland, 1990. <http://madx.web.cern.ch/madx/doc/madx_manual.pdf>.

[2] David Manura, David A. Dahl, *SIMION 8.0 User Manual*. Scientific Instrument Services Inc., 2003-2006.