OPTICAL MATCHING OF EMMA CELL PARAMETERS USING FIELD MAP SETS*

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Abstract

The Non Scaling FFAG EMMA lattice allows a important displacement of the magnets in the radial direction. From this peculiarity, interesting studies of beam dynamics can be performed comparing simulation and experimental results. Being able to study specific resonances choosing a certain set of parameters for the lattice is really challenging. Simulations have been done integrating particle trajectories with Zgoubi through Magnetic Field Map created from OPERA. From a chosen tune evolution, one can find the corresponding Magnetic Field Map required by interpolating between a various set of Field Map. Relative position and strength of the magnets are degrees of freedom. However, summing field map requires a special care since the real magnetic field created by two magnets is not obviously linearly dependent on each single magnet. For this reason, frequently used hard edge and fringe field models may not be accurate enough. This linearity of the magnetic field has been studied directly through OPERA finite element method solutions and further on with zgoubi tracking results.

INTRODUCTION

In this section, we outline the key features of EMMA. In the following section, we describe the goal of the present study, which is to produce a tool to determine the appropriate machine configuration for specified dynamical behaviour. Then, we describe the magnet modelling work we have performed, paying particular attention to the issue of superposition of the fields from the magnets within a cell, and making comparison with magnetic measurements. Finally, we describe the results of some tracking simulations.

The EMMA prototype aims to study the Non Scaling FFAG acceleration scheme. Dynamical behavior of a beam in such a structure is still unknown and especially its response to resonance crossing. In order to cover a wide area of Dymanics, the EMMA lattice has been kept adjustable; magnets positions and currents are degrees of freedom. Hence, it will be possible to link a certain tune and time of flight evolution with energy with these parameters. Firstly, this is done by simulation before the comisionning of the real machine due this year. To do so, one has to model the magnetic field created by a certain configuration of magnet and track particle in this map.

The EMMA ring is composed of 42 cells. Within a cell, elements are positioned with respect to a straight line (see Fig. 1). The ring can then be seen as a 42-sided polygon. Corners are situated at the entrance of the defocussing magnet (D magnet) since bending of the electrons mainly occurs in this magnet. The rotation angle between two following sides is $\theta = 2 * \pi/42 = 0.14959\,\mathrm{rad}$. Since (without acceleration) the EMMA ring is periodic, only one pair of magnets (out of 42 pairs) has to be modeled, and tracking can be done iteratively in one cell.

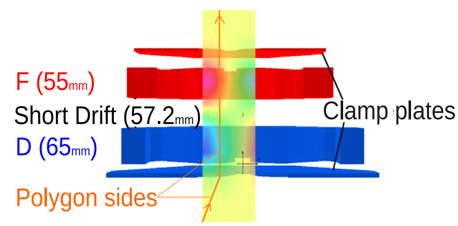

Figure 1: EMMA cell (394.481 mm long) and consists in long drift (here cut in two parts), D magnet ,short drift,F magnet.

Tune and of the time of flight (TOF) evolutions with energy, characterise the beam dynamics in EMMA. In the present study, acceleration is not taken into account; Closed orbits are found for different energies (10 to 20 MeV) and the tune and TOF are computed in each case.

PHILOSOPHY OF THE SIMULATIONS

For tuning, the EMMA lattice has four degrees of freedom: transverse positions x_d and x_f of the magnets, and currents I_d and I_f in the coils. Longitudinally, the lattice is fixed. The goal is to determine the appropriate set of parameters (magnet positions and coil currents) corresponding to a specified dynamics, e.g. tune variation (resonance crossing) with energy. A modelling tool that could find the appropriate machine parameters for any given dynamics would be extremely useful.

We have written a routine in Zgoubi, described in more detail below, to fit a desired tune evolution with energy, by adjusting the magnet positions and field strengths. By positioning the magnets and changing their gradient, a suitable magnetic configuration is found to fit the specified tune excursion.

Usually magnets are represented as hard edge magnets with fringe field. Such simulations have been done by J.S. Berg [2]. However, since the EMMA magnets have a short length and wide aperture, this model might not be sufficiently accurate. It is then interesting to run the Zgoubi fitting routine using magnetic field models computed in OPERA. Furthermore, the proximity of the magnets implies an overlapping of their magnet fields, and one has to

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check that the combined field generated by powering both magnets matches accurately the field obtained by superposition of the fields from each magnet individually. The ability to superpose the fields from the magnets is crucial for the freedom needed by the fitting routing in Zgoubi.

In the Zgoubi fitting routine, the gradient of a magnet is changed simply by multiplying globally the numerical value of the magnetic field by a parameter α. Hence, in a single map containing both magnets, the gradients of the two magnets cannot be adjusted seperately. To keep four degrees of freedom, the ratio between the two gradients could be added as a parameter; however, this would require solving many models with different ratios of the field gradients. An alternative solution is to compute a field map for each magnet individually, and then obtain the total field by superposition, with appropriate scaling parameters for each magnet. However, this depends on the accuracy with which the field produced by powering both magnets can be constructed by superposing the fields produced by each magnet individually; this accuracy could be limited, for example, if the iron in one magnet responds to the field from the other magnet.

OPERA MODEL

The final OPERA model file created in the magnet design process has been used as starting point of our resolution. Boundary conditions and meshing properties are the key features in a FEM code and are developped in more detail in this proceeding [3].

FEM Solver and Extraction of Data

From the OPERA post processor, one can extract the value of the vectorial magnetic field on a grid. The field from the FEM solution is linearly interpolated on this grid. When working with periodic condition for the boundaries, a polar grid (longitudinal step defined as a fraction of θ) is more appropriated since the cell is seen as a disk sector. If periodicity is not imposed, the edge of the model is far enough from the magnet and the magnetic field is then zero(middle of the long drift for example), a rectangular grid is more efficient (see Fig. 1).

Superposition of Fields

In a first approximation, one can compute a field map ("D+F") by superposing the field maps generated by powering each magnet separately ("D" and "F"). In reality the yoke of one magnet may influence the field created by the other magnet; so we also compute a field map for the case when both magnets are powered simultaneously ("D&F"), see Fig. 3.The field seen by the F yoke when only the D coils are "on" is up to 0.4 T on the pole. This can cause saturation when both magnets are on and then make superposition inaccurate. Hence a quantitative study is required.

The integrated gradient along particle trajectory in the cell have been used as criteria to design the magnets. Particles would see the same amount of gradient in the model used for initial particle tracking simulations and in the real magnets. Integrated gradients are then compared for "D&F" and "D+F" cases. In addition, the comparison will be done in terms of beam dynamics. The relevancy ,regarding accuracy, of the integrated gradient as criteria for magnets design in this case can then be discussed.

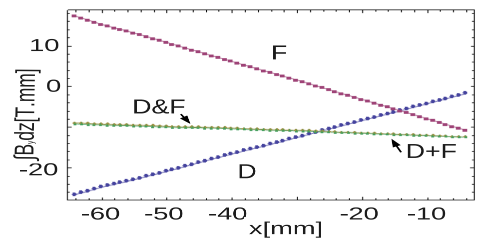

Figure 2: Longitudinal integrated gradient [T.mm] for various transverse (x[mm]) positions. x=0 on the axis of the D magnet

According to the OPERA model, there is an extremely small, less than 0.5% difference between the integrated gradient with both magnets on ("D&F") and the sum of the integrated gradients from each magnet powered individually ("D+F"). This suggests that the fields of the two magnets can indeed be computed independently, and the total field can be obtained by superposition.

Transverse Positions

The transverse position of the unpowered yoke has an influence on the field from the powered magnet. From previous work [2], a wide-ranging study of beam dynamics can be carried out if the magnets have a relative translation available of 38 mm. If the magnets are moved by step of 1 mm, it means that 38 maps have to be computed for each magnet on, which makes 76 maps in total. If we consider that the magnet yoke "off" does not influence the beam dynamics, then one can play with just two maps. This is being studied with Zgoubi and shortly presented in the next section.

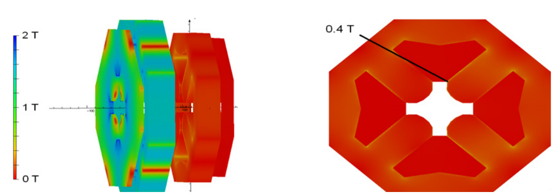

Figure 3: Field on magnet surface.F yoke (red) influenced by the field from the D magnet (blue). This effect may not be negligible

FITTING PROCEDURE IN ZGOUBI

In addition to the existing working mode in the raytracing code Zgoubi, namely,

(i) use of a single field map, describing the FD cell with frozen quadrupole arrangement and fields, of the "D&F" type addressed above (the "TOSCA" keyword does this job,

see [4]),
new software has been developed (including a new keyword, "EMMA") allowing the following additional two working modes :

(ii) the FD cell is described by a single pair of field maps, of the "D" type (D/on, F/off) and of the type "F" (F/on, D/off) mentioned above, with the F-D transverse distance, d_{FD}, frozen, and free field coefficients a_F, a_D,

(iii) the FD cell is described by an ensemble of pairs of field maps in arbitrary number, each pair like in (ii) with its d_{FD} value attached. Zgoubi will then interpolate in this set to get the field map corresponding to an arbitrary distance d_{FD} specified by the user. This working mode allows flexible use of the Zgoubi fitting procedure, with free and arbitrary variables a_F, a_D, d_{FD}.

In all three cases, the cell length plays the role of the fourth variable in that EMMA cell, and is a free parameter liable to fitting. Varying the cell length is somehow equivalent to a variation of the bending radius of the cell and thus corresponds to a transverse shift of the whole cell with respect to the fixed polygone.

A typical input file to the ray-tracing code Zgoubi in case (ii) is as follows.

```
'OBJET'
[...]                  Defines a set of closed orbits
'EMMA'
0  0
-1E-3 1. 1. 1.    Global normalization of map data
emma cell field map                         Comment
197 81 1  0            Number of nodes in Y,X,Z. Mode
1.  1.  0.                  a_F,  a_D,  distance d_FD
Dax265.Fon.cart.table          Name of F quad map
Dax265.Don.cart.table          Name of D quad map
0 0 0 0
2                                Interpolation method
.1                          Integration step size, cm
2 0 0 0                        Field map positionning
'CHANGREF'
0. 0. -8.57142857152              Cell positionning
'END'
```

a_F and a_D are the field amplitude coefficients addressed above. 'Mode=0' in this case, d_{FD} is inhibited.
In case (iii) the "EMMA" keyword data write

```
'EMMA'
0  0
-1E-3 1. 1. 1.    Global normalization of map data
emma cell field map                         Comment
197 81 1  24           Number of nodes in Y,X,Z. Mode
1.  1.  2.78                a_F,  a_D,  distance d_FD
Fon-Don_tables.file    A file containing filenames
0 0 0 0
2                                Interpolation method
.1                          Integration step size, cm
2 0 0 0                        Field map positionning
```

The file "Fon-Don_tables.file" contains the names of an arbitrary number of field map pairs, and the related transverse F-D distances d_{FD} for each pair. Zgoubi will interpolate in this set to get the field map corresponding to $d_{FD} = 2.78$ cm in this example.

(iv) the case discussed in the previous section, where a unique "D","F" pair would be used whatever d_{FD}, is under developement. Figure 4 shows preliminary results comparing "D&F" with "D+F", case $d_{FD} = 2.65$ cm. As stressed earlier, there are slight differences in tunes and in TOF, however possibly small enough that the method can be applied for getting a precise enough estimate of a_F, a_D and d_{FD} values.

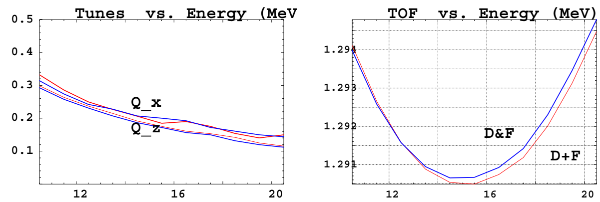

Figure 4: Tunes versus energy (left) and TOF parabola (right), case "D&F" (blue, thick lines) and case "D+F" (red, thin lines).

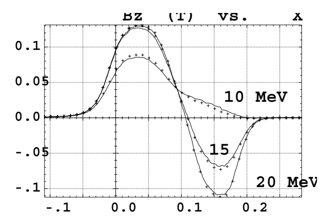

Figure 5: Field along closed orbits, case "D&F" (solid line) and case "D+F" (crosses). .

These procedures can be operated using either cartesian of cylindrical coordinate field maps. The change of frame from a cell to the next one is handled using the "CHANGREF" keyword.

FINAL REMARK

To conclude this paper, one point has to be underlined: comparing the integrated gradients of "D&F" and "D+F" in Opera leads to really small difference in the result. However, An non neglictable discrepancy is obtained when tracking particle in added map. This may mean that the comparison of integrated gradient is not a sufficient criteria for magnet design. An explanation could be that the individual influences of the "F" and the "D" magnets are not properly taken into account by simply computing the gradient integral along the whole cell; an infinite number of combinations of oppposite sign integral for D and F could lead to the overall integral. Positive and negative parts of this integral could be compared with individual magnet integrals. Magnetic lengths have then to be carefully considered.

REFERENCES

[1] Vector Field OPERA 3D. See http://www.vectorfield.com/

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[3] Giboudot Y., these proceedings , PAC 09 (2009).

[4] Zgoubi users' guide, F. Méot, S. Valero, CEA DAPNIA SEA-97-13 & FERMILAB-TM-2010 (1997).