Status of 6-D beam dynamics simulations in FFAGs using Zgoubi

F. Méot, **CEA DAPNIA**
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1 Introduction

Fixed Field Alternating Gradient (FFAG) accelerators are envisaged in various types of applications, such as the acceleration of muon beams in the Neutrino Factory, medical machines, proton drivers [1].

Considering the difficulty of modelling FFAG optics using regular matrix or algebra methods, stepwise ray-tracing has, from the very beginning, been considered a convenient, as well as accurate, way of simulating 6-D beam dynamics in these machines [2].

For that reason, the ray-tracing code Zgoubi [3] has been recently abundantly used in several FFAG studies [4] . This paper reports on the present status of 6-D transmission simulation methods and results, regarding that code.

2 Code developments

Optics. Dedicated procedures, "`FFAG`" and "`DIPOLES`", have been developed in the ray-tracing code Zgoubi ; details concerning the numerical methods used can be found in Ref. [5] ; various applications are described in the following.

They allow simulating particle trajectories in sector (Fig. 1) or spiral scaling FFAG dipoles with magnetic field of form $B_z(r,\theta) = B_{z0}\,\mathcal{F}(r,\theta)\,\mathcal{R}(r)$, and including fringe fields and their overlapping, as well as variable gap size $g = g_0(R_0/r)^K$.

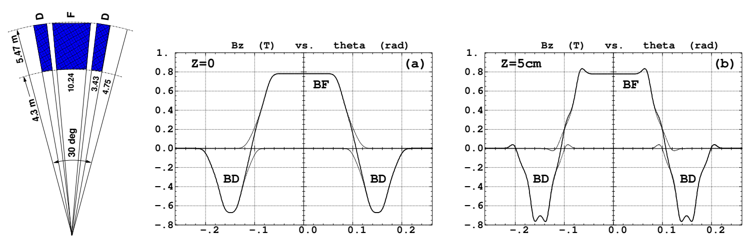


Figure 1: Field experienced across the DFD dipole triplet shown on the left, along the $r_0 = 4.87$ m orbit [5].

The radial dependence of the field can take the form ("`FFAG`" procedure) $R_i(r) = (r/R_{0,i})^{K_i}$ for the simulation of normal conducting magnets, or the form ("`DIPOLES`") $\mathcal{R}_i(r) = b_{0_i} + b_{1_i}(r - R_{0,i})/R_{0,i} + b_{2_i}(r - R_{0,i})^2/R_{0,i}^2 + ...$ for that of SC magnets [6].

Non-scaling FFAGs also, can be simulated by using the already existing "`MULTIPOLE`" procedure [3], as well as isochronous types of FFAGs by means of "`MULTIPOLE`" and/or "`DIPOLES`".

Acceleration in these FFAG simulations uses the already available procedure "CAVITE" [3]. The question of time of flight (TOF), either in terms of a reference particle or absolute, is handled in a manner compatible with FFAG needs and did not need special developments.

Fitting means are indispensable tools for preliminary adjustments (tunes, etc.) prior to 6-D simulations, and useful for further assessment and optimization of higher order behavior, DA, transmission, etc. Various types of constraints, including closed orbits, tunes, chromaticities, anharmonicities, have been added to fulfill the needs of FFAG and periodic structures studies.

3 Scaling FFAG

Fig. 2 shows the horizontal and the vertical motion of a particle accelerated from 12 to 125 MeV in a 12-period ring based on the triplet described above. The numerical integration method used is based on Taylor series and features high accuracy, allowing rather large integration step size, as large as 0.5 cm here for instance in spite of the strong field non-linearities (see Fig. 1). Fig. 3 shows sample horizontal and vertical phase space plots. The quality of the latter proves the accuracy of the integration method.

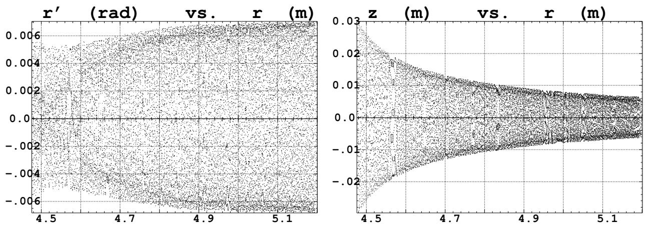


Figure 2: $2\,10^4$ turns horizontal and vertical motion over 12→150 MeV acceleration in a radial sector FFAG.

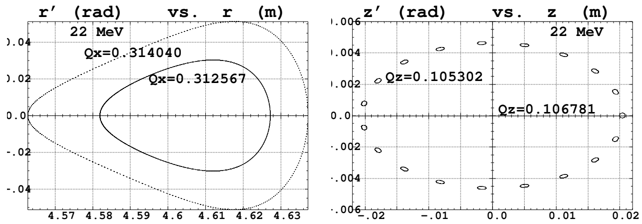


Figure 3: Horizontal and vertical phase space motions, and corresponding tunes, near transverse stability limits.

3-D field maps can also been used [7], and yield similar multiturn results and ensuing quantities as tunes, acceptance, with very good symplecticity (yet, needing much smaller step size). For illustration Fig. 4 shows horizontal stability limits as derived using both methods, analytical model [5] and field maps [7]. Fig. 5 below shows a simulation involving the use of the RF procedure ("CAVITE"), namely the gymnastic of fast bunch rotation, and the ensuing radial damping, in the PRISM 10-period radial triplet scaling FFAG [8].

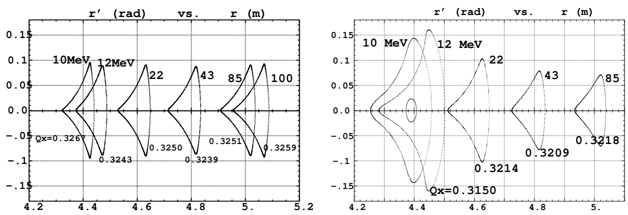


Figure 4: Horizontal transverse stability limits, using analytical model (left) or field maps (right).

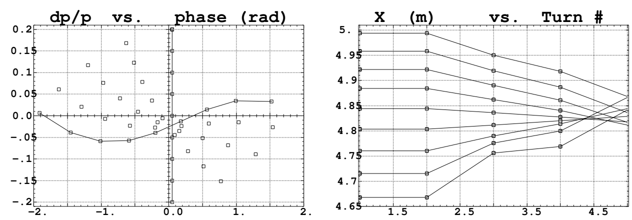
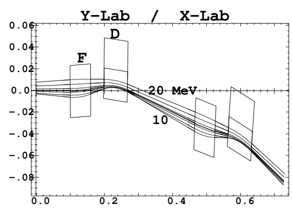


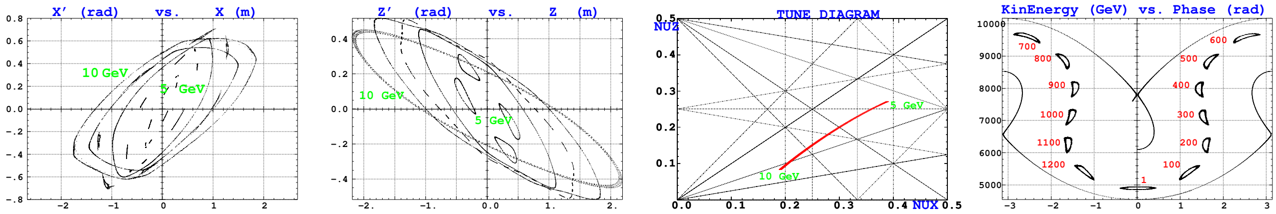
Figure 5: Momentum and transverse beam compression in PRISM.

4 Linear ("non-scaling") FFAG

Being based on the regular "MULTIPOLE" Zgoubi procedure, 6-D tracking in linear FFAGs could be successfully undertaken in early designs [9]. The more recent NuFact 5-10 GeV muon FFAG case with ISS parameters [10] is detailed here : the 285 m circumference muon ring is comprised of 64 quadrupole doublet (FD) cells, a pair of which, including closed orbits, looking as shown aside.



One cavity per cell (200 MHz) is assumed in these simulations, acceleration is performed in 9 turns.



The motion stability limits have been tracked and are shown in the Fig. above, they well contain the injected beam (3πcm/0.05 eV.s). They are well defined and correspond to particle tunes that neighbor harmful systematic resonance lines. Transmission in the 5 $\rightarrow$ 10 GeV ring with 3 cm / 0.05 eV.s injected beam, 6-D, has been obtained in that manner [11].

6-D transmission simulations in the electron model "EMMA" have also been performed [12]. Fig. 6 show show various typical aspects of the electron beam behavior during acceleration from 10 to 20 MeV.

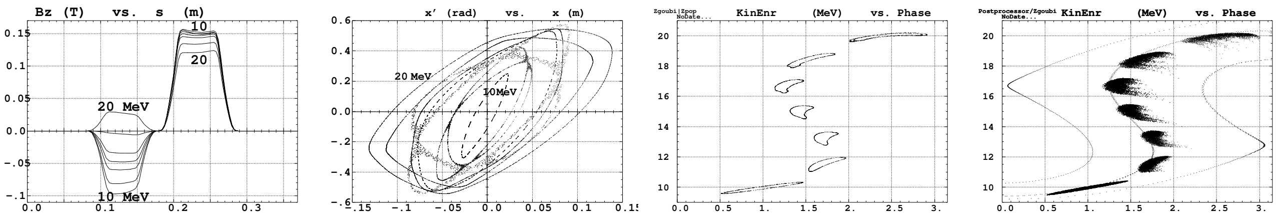


Figure 6: (i) field on closed orbits in EMMA (FD) lattice cell, at various energies. (ii) horizontal DA. (iii) the sensible effect of non-zero transverse size : left with $\epsilon_{x,z} = 0$, versus right with $\epsilon_x = 200\,\pi$ mm.mrad norm.

5 Isochronous FFAG

The isochronous FFAG allows on-crest (cyclotron-like) acceleration [13]. The lattice is based on a cell (Fig. 7) comprised of 5 strongly non-linear magnets, including multipoles up to dodecapole and featuring positive chromaticity and $\gamma_{tr} = \gamma$ at all γ.

This optics, based on high order multipole magnets, is simulated, on the one hand by means of the "`MULTIPOLE`" procedure as to the central and the two end rectangular multipoles, on the other hand by means of the "`DIPOLES`" procedure as to the second and fourth sector shape multipoles [14].

An electron model of an isochronous FFAG has been tracked [14]. The ring comprises 45 cells, acceleration from 11 to 20 MeV is performed in 15 turss at a rate of 40 kV/cell using 3 GHz RF.

The transverse acceptance at injection is obtained by tracking of a beam with excessively large initial 4-D emittance. It results in about $\epsilon_{x/z} = 97/33\,\pi$ mm.mrad normalized X/Z acceptances.

A muon ring of this isochronous type is currently being designed. It accelerates the muons from 8 to 20 GeV in 16 turns, using 200 MHz, 18 MV/cavity RF. The ring comprises 123, 10.2 m long cells. Preliminary 6-D tracking results show strong beam loss in the 17 GeV region, correlated to the beam straddling a resonance node in tune diagram (Fig. 7-right). A insertion type of lattice is under study, featuring very low chromaticity and limited resonance line traversal liable to improve acceptance.

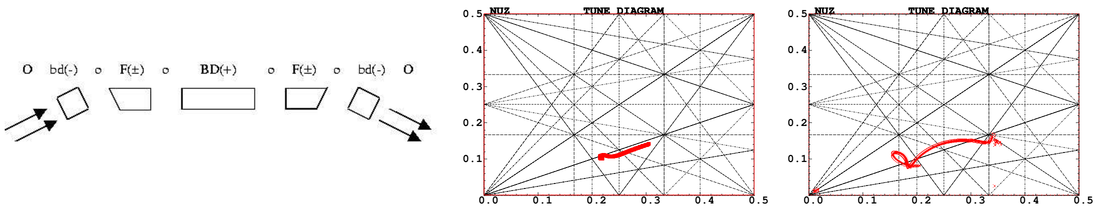


Figure 7: Isochronous cell. Beam path in tune diagram : left : eModel, right : muon ring.

6 Conclusions

A powerful tool for 6-D tracking in all types of FFAG lattices is available, based on the ray-tracing code Zgoubi.

• The optical elements developed for 6-D transmission simulations are operational, functioning well, and allow high speed tracking
• RF needs / TOF handling needs, are well satisfied : synchronous acceleration, stationary bucket, gutter
• Ray-tracing is routinely used to assess DA in the three types of lattices, linear, isochronous, scaling
• Preliminary 6-D transmission simulations yield results that show good agreement with low order behavior drawn from analytical and matrix methods (tunes, detunings, etc.).

It is planed in a near future to,

• Produce detailed transmission studies concerning lattices presently under investigation (NuFact muon accelerators, low-energy proton FFAG rings)
• Stick to the evolution of lattice studies (muon, electron model)
• Launch error studies - field and positioning, tolerances, effects of resonances
• Develop further ray-tracing based optimisation methods.

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