

END-TO-END 6-D TRACKING USING EMMA ON-LINE MODEL*

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Abstract

Simulation of end-to-end 6-D acceleration over a complete cycle in the prototype linear FFAG EMMA is described. It uses the on-line model code, Zgoubi, and a specific input data file developed in that aim. The optical sequence starts at the entrance of the injection septum, followed by EMMA ring, and ends at the exit of the extraction septum. It includes the injection and extraction kicker pairs and accounts for the time dependence of the septum and kicker fields. This software tool aims at allowing data analysis, following experimental data taking at EMMA.

INTRODUCTION

The Electron Model for Many Applications, EMMA, a 10–20 MeV fixed field alternating gradient ring built at the Daresbury Laboratory, UK, has achieved experimental demonstration of the linear non-scaling FFAG principle and of the serpentine acceleration [1].

EMMA lattice [2] consists of 42 quadrupole-doublet cells. The focusing and defocusing quadrupoles are offset horizontally with respect to the beam axis so to provide a net bending. They are mounted on sliders that allow radial motion, so providing independent setting of time of flight and tunes. The fixed field and absence of nonlinear elements cause the tune to vary from typically 0.3 down to 0.1 per cell, both planes, over the acceleration range.

EMMA FFAG ring parameters are summarized in Table 1, its representation in Zgoubi is displayed in Figure 1. RF cavities are located every two other cell except for two which house injection and extraction equipments. The RF voltage can be varied, to explore acceleration regimes. EMMA is injected at arbitrary momentum, with 40 pC about charge bunches, using DL's ALICE electron recirculator.

The end-to-end simulation tools discussed here use the ray-tracing code Zgoubi [3, 4], the engine for EMMA on-line model [5]. They aim at allowing data analysis, following experimental data taking at EMMA, which included beam position, closed orbit distortion, orbital period as a function of momentum, acceleration.

The lattice cell in Zgoubi can be simulated in various different ways, from the most realistic using field maps, to analytical models of the quadrupoles, possibly accounting for overlapping fringe fields. These have been described in detail and compared in earlier works [6, 7]. All necessary mispositioning effects (e.g., to simulate measured horizontal and vertical CODs) and other field defects can be accounted for. These various models of EMMA cell can

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Table 1: Parameters of EMMA FFAG

circumference	<i>m</i>	16.568
Momentum range	<i>MeV/c</i>	10.5 - 20.5
Tune shift	<i>/cell</i>	~ 0.3 - 0.1
Lattice		Quad doublet
No of cells		42
Acceptance	<i>mm.mrad</i>	3 π
<i>EMMA cell</i>		
cell length	<i>cm</i>	39.448
length of F/D quad	<i>cm</i>	5.878 / 7.570
Nominal int^d gradient	<i>T</i>	0.402 / -0.367
drifts, short/long	<i>cm</i>	5 / 21
<i>EMMA RF</i>		
No of RF cavities		19
RF frequency / range	<i>GHz / MHz</i>	1.301 / 5.6
RF voltage	<i>kV/cavity</i>	20 - 120

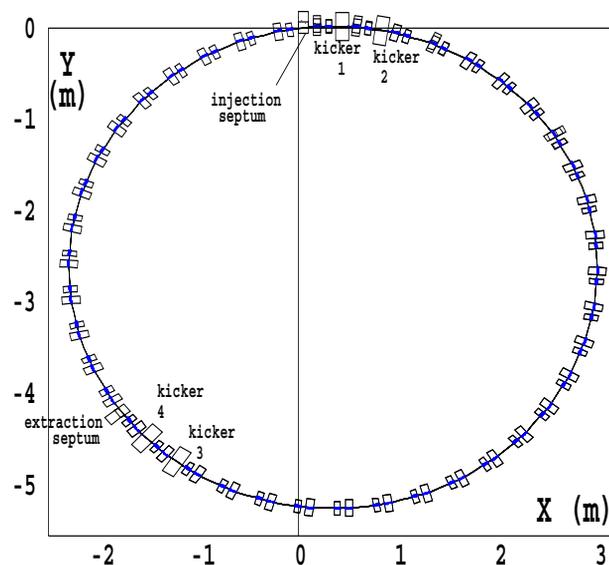


Figure 1: EMMA ring in Zgoubi using the interface software “zpop” [4]. The tracks of $14 - \frac{7}{19}$ accelerated turns are shown (blue), motion is clockwise.

easily be interchanged. For this reason and for the sake of simplicity, and in addition in order to allow possible direct comparison with matrix methods (using MADX for instance), a simple hard-edge model is used in the present discussion. However, for the analysis of EMMA experimental data, OPERA field maps of the quadrupole doublet will be used instead.

Injection and extraction sections have similar geometry, a series of three successive cells house respectively

the septum and two kickers. The injection is sketched in Figure 2. For all injected momenta, the appropriate range of values of these three variables is derived by matching with a series of constraints : closed orbit coordinates at one end, septum field limits $[-0.7, 0.7]$ kG at the other end, geometrical acceptance of the vacuum pipe. Figure 2-right sketches typical paths so obtained at injection [8, 9].

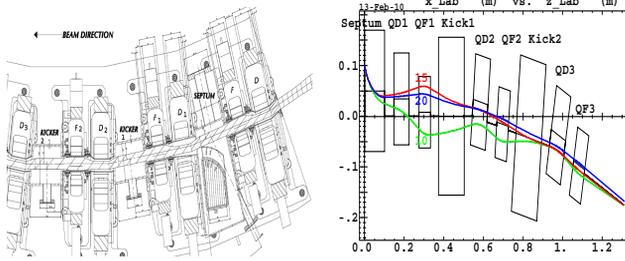


Figure 2: Injection section and 10, 15, 20 MeV orbits.

Time dependence of the septum and kicker fields are managed using the power supply command keyword ‘SCALING’ in Zgoubi, see Section 3. This allows in particular simulating stray fields from the injection and extraction septa, which have been identified as major sources of COD. OPERA field maps for these elements can be used, in conjunction with OPERA field maps of the quadrupoles, since the dedicated keyword in Zgoubi, ‘TOSCA’, allows linear superimposition of field maps with each one its own positioning and time-dependent field scaling factor.

Acceleration in EMMA is based on a method of “serpentine” quasi-isochronous phase space configuration [10]. The number of turns, $N = \frac{7}{19}$, is controlled via the RF voltage. Figure 4 displays a $N = 8$ turns regime obtained for $\hat{V} \approx 64$ kV per cavity. The earlier “ $\frac{7}{19}$ ” stands for the fact that the final path from injection point in the ring (‘RingInj’ label in Zgoubi optical stack, see Zgoubi data file template in Section 3) to extraction point (‘RingExtr’ label) only covers 12 of the 19 cavities in the ring.

For the sake of flexibility on N , a new argument has been developed in the multi-turn tracking keyword ‘REBELOTE’. It is thus possible to tell (i) where, in the optical sequence, the ring starts (‘RingInj’), (ii) where the multi-pass tracking ends in the ring (‘RingExtr’), by means of the regular labelling technique in Zgoubi [3], and (iii) the number of passes to accomplish. Thus, changing EMMA acceleration rate just requires changing the 19 cavities RF voltage and the value of N under ‘REBELOTE’.

The extraction kicker pulse timing during EMMA experiments allows specific turns to be extracted following acceleration. Beam energy is measured using two fluorescent screens either side of the first extraction line dipole, which acts as a spectrometer. This can be simulated in Zgoubi using ‘SCALING’ to pulse the kickers, and dedicated equipment downstream of the extraction septum, see Section 3.

VIRTUAL EMMA, END-TO-END

Figure 1 shows the full ring synopsis including injection and extraction sections. Figure 3 zooms on the injection region and displays an injected 10.5 MeV/c trajectory and subsequent $N = 14$ accelerated turns, 43 kVolts/cavity. Figure 4 shows serpentine motion in the longitudinal phase space, in the acceleration regime $N = 8$, 69 kVolts/cavity.

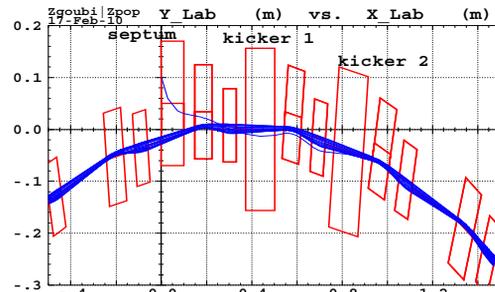


Figure 3: A zoom on the injection region in Figure 1, including the 10 MeV injected path and $14 - \frac{7}{19}$ subsequent turns.

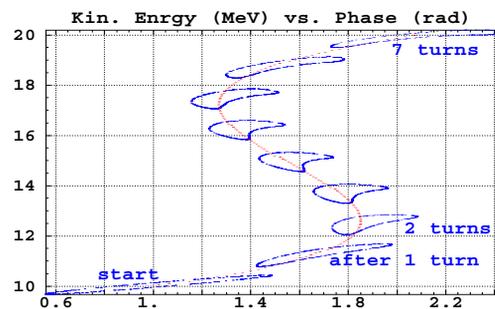


Figure 4: Serpentine motion of a hollow bunch in longitudinal phase-space, from 10 to 20 MeV, 145 cavities crossed (7 full turns and an additional 12 cavities). The serpentine curve represents the beam centroid Hamiltonian.

In the campaign of measurements reported in reference [1] the injector momentum was fixed at 12.5 MeV/c. To characterize EMMA with a range of different injection momenta, a change in momentum was faked by scaling the quadrupole strengths. This simulation method gives a measurement of the dynamics directly equivalent to changing the injected momentum in the whole range from 10.5 to 20.5 MeV/c. This is readily simulated by a mere change of scaling factors in the power supply command keyword ‘SCALING’ in Zgoubi, see next Section.

Beam position monitors in EMMA detect the beam centroid position for each passage of the beam, allowing measurement of closed orbit distortion and betatron oscillations. The orbital period is measured at a BPM electrode. EMMA BPMs are part of the optical stack in Zgoubi data file, next Section. Beam emittance for the simulations is available from measurements in the injection line from ALICE, optics matching for reference can be taken from two YAG screens in the ring during the injection set-up.

ZGOUBI DATA FILE

The multi-turn tracking input data file that yielded Figs. 1-4 is downloadable from the “exemples” on Zgoubi SourceForge development site [4]. It is operational with the “zgoubi-5.1.0” version of the code available there, and with any subsequent version on the author’s branch.

Excerpts of zgoubi.dat are commented in the input data list given here, to facilitate its use, and possible modifications. Details regarding the keywords, arguments, and usage, can be found in the Users’ Guide [3, 4]. Additional comments regarding EMMA sequence in zgoubi.dat can be found in reference [5].

```
EMMA ring in Zgoubi           from injection, to extraction
'MCOBJET'                     15.5 MeV/c reference
+51.7110386592                random coordinates
3                               100 particles
100                            6-D bunch density type
3 3 3 3 2 2                   orbit for 10.5 MeV/c starting momentum
0.0995 -1.134 0.0 -0.854 0.677214 'i' horizontal emittance
0.015390 0.063314 0e-6 2      vertical emittance
-3.074521 0.704221 0e-6 2     longitudinal emittance
-4 3 1E-5 -4 -40001          seeds
123456 234567 345678        time dependence of power supplies
'SCALING'
1 3
MULTIPOL kicker1 kicker2     injection kickers
3
1 0.0                         off after first pass
1 2 9999
MULTIPOL kicker3 kicker4     extraction kickers
3
0.0 1.
1 13 14                       off till last pass
MULTIPOL QF QD               quadrupole field
2
1.1.                          constant, matches momentum as defined by 'OBJET'
1 14
'MARKER' septum Injection     injection septum entrance
'MULTIPOL' septInj           injection septum
00 20
10. 10. -2.90 0.000000000
0.0 1.00 1.00 1.00 1.00 1.1. 1.1.
4.1455 2.2670 -6395 1.1558 0.0 0.0.
0.0 1.00 1.00 1.00 1.00 1.1. 1.1.
4.1455 2.2670 -6395 1.1558 0.0 0.0.
0.0 0.0 0.0 0.0 0.0 0.0 0.0.
0.1
2.0 5.0.
'DRIFT' dr 1 distance to septum exit
2.1011412
'DRIFT' dr 1 distance to septum vessel opening
2.7151711
'MARKER' End injection line
'MARKER' RingInj BegRing     start of ring. Injection point
'MULTIPOL' QD                start of first cell
00 20
7.56987 5.3 0. -2.493246 0 0 0 0 0 0 0
0.0 1.00 1.00 1.00 1.00 1.1. 1.1.
4.1455 2.2670 -6395 1.1558 0.0 0.0.
0.0 1.00 1.00 1.00 1.00 1.1. 1.1.
4.1455 2.2670 -6395 1.1558 0.0 0.0.
0.0 0.0 0.0 0.0 0.0 0.0 0.0.
0.1
2.0 3.404834122312866 0.
'MARKER' BPM2 off           BPM location
'DRIFT' sd
5.00
'MULTIPOL' QF
00 20
5.87824 3.7 0. 2.477081 0 0 0 0 0 0 0
0.0 1.00 1.00 1.00 1.00 1.1. 1.1.
4.1455 2.2670 -6395 1.1558 0.0 0.0.
0.0 1.00 1.00 1.00 1.00 1.1. 1.1.
4.1455 2.2670 -6395 1.1558 0.0 0.0.
0.0 0.0 0.0 0.0 0.0 0.0 0.0.
0.1
2.0 0.7513707181808552 0.
'DRIFT' ld
4.
'MULTIPOL' kicker1         first injection kicker
00 20
13. 10. -0.55891 0.000000000
0.0 1.00 1.00 1.00 1.00 1.1. 1.1.
4.1455 2.2670 -6395 1.1558 0.0 0.0.
0.0 1.00 1.00 1.00 1.00 1.1. 1.1.
4.1455 2.2670 -6395 1.1558 0.0 0.0.
0.0 0.0 0.0 0.0 0.0 0.0 0.0.
0.1
2.0 0.0.
'DRIFT' ld
4.
'MARKER' BPM1 off           BPM location
'CHANGREF'                 end of first cell
0.0 -8.571428571429        orientation of next cell
.....
kicker 2 cell stands here - not shown
3rd cell follows, includes first RF cavity
```

```
'MULTIPOL' QD                start of 3rd cell
00 20
7.5699 5.3 1.60161 -2.49312 0 0 0 0 0 0 0
0.0 1.00 1.00 1.00 1.00 1.1. 1.1.
4.1455 2.2670 -6395 1.1558 0.0 0.0.
0.0 1.00 1.00 1.00 1.00 1.1. 1.1.
4.1455 2.2670 -6395 1.1558 0.0 0.0.
0.0 0.0 0.0 0.0 0.0 0.0 0.0.
0.1
1.0 0.0.
'MARKER' BPM2 off           BPM location
'DRIFT' sd
5.00
'MULTIPOL' QF
00 20
5.8782 3.7 -0.50306 2.47715 0 0 0 0 0 0 0
0.0 1.00 1.00 1.00 1.00 1.1. 1.1.
4.1455 2.2670 -6395 1.1558 0.0 0.0.
0.0 1.00 1.00 1.00 1.00 1.1. 1.1.
4.1455 2.2670 -6395 1.1558 0.0 0.0.
0.0 0.0 0.0 0.0 0.0 0.0 0.0.
0.1
1.0 0.0.
'DRIFT' ld
10.5
'CAVITE' #cav                first RF cavity
7
0.00 1.51730e9              RF freq
38.61e3 0.                  RF voltage, relative phase of 1st cavity
'MARKER' #CAV
'DRIFT' ld
10.5
'CHANGREF'
0.0 -8.571428571429
.....
extraction kickers are at cells #26 and 27
extraction point 'RingExtr' at cell #28
14 additional cells close the ring - not shown
end of last cell, #42
extraction is at "RingExtr" label at pass # 14
14 0.1 99.2 RingInj RingExtr
'MARKER' Start Extraction line extraction line starts here
'DRIFT' sep2F                end of this drift is at septum entrance
6.129285847219867391
'MULTIPOL' septExtr         extraction septum
00 20 1 .plt
10. 10. -6.98057 0.000000000
0.0 1.00 1.00 1.00 1.00 1.1. 1.1.
4.1455 2.2670 -6395 1.1558 0.0 0.0.
0.0 1.00 1.00 1.00 1.00 1.1. 1.1.
4.1455 2.2670 -6395 1.1558 0.0 0.0.
0.0 0.0 0.0 0.0 0.0 0.0 0.0.
0.1
2.0 0.0.
'MARKER' E-measurmnt        energy measurement location
'END'
```

REFERENCES

- [1] S. Machida et al., *Acceleration in the linear non-scaling fixed-field alternating-gradient accelerator EMMA*, Nature Physics, 10 January 2012.
- [2] J.S. Berg, *The EMMA Main Ring Lattice*, Nucl. Instrum. Methods A 596 (2008) 276-284.
- [3] F. Méot, BNL CA/AP/470 (Oct. 2012), *Zgoubi Users’ Guide*, www.scienceaccelerator.gov/dsa/result-list/fullRecord:zgoubi/
- [4] Zgoubi source, Users’ Guide, interface zpop and examples including the present EMMA simulations, are down-loadable at <http://sourceforge.net/projects/zgoubi/>
- [5] J.S. Berg et al., *Recent Developments On The EMMA On-Line Commissioning Software*, Procs. IPAC 10 Conf., Kyoto, Japan.
- [6] Y. Giboudot et al., *BD Simulations Regarding The Experimental FFAG EMMA, Using The On-Line Code*, Procs. IPAC 10 Conf., Kyoto.
- [7] F. Méot, *Virtual EMMA using Zgoubi*, EMMA commissioning workshop, Daresbury, Dec. 2009.
- [8] F. Méot, *Injection into EMMA, septum and kicker tunings*, rep. LPSC-10-24 (2010).
- [9] F. Méot, *Simulation of injection into EMMA, injection section*, rep. LPSC-10-33 (2010).
- [10] E. Keil, *Electron model: Lattice and performance*, Nucl. Phys. B. Proc. Suppl. 155, 323324 (2006).