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

François Méot, BNL C-AD, Upton, New York, USA
David Kelliher, Shinji Machida, Ben Shepherd, STFC/RAL/ASTeC, Chilton, UK

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 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

Table 1: Parameters of EMMA FFAG

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

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

* Work supported by Brookhaven Science Associates, LLC under Contract No. DE-AC02-98CH10886 with the U.S. Department of Energy.

Novel Cyclotrons and FFAGs

No Sub Class

Copyright © 2013 CC-BY-3.0 and by the respective authors
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 $[-0.7, 0.7]$ $\text{kG}$ at the other end, geo-
metrical 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.](image)

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 partic-
ular 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 con-
junction 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 posi-
tioning and time-dependent field scaling factor.

**Acceleration** in EMMA is based on a method of “ser-
pentine” quasi-isochronous phase space configuration [10].
The number of turns, $N = \frac{T}{\tau}$, is controlled via the RF vol-
tage. Figure 4 displays a $N = 8$ turns regime obtained
for $V \approx 64$ kV per cavity. The earlier “$\frac{T}{\tau}$” 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 ‘REBELTE’.
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 ‘REBELTE’.

The extraction kicker pulse timing during EMMA exper-
iments allows specific turns to be extracted following ac-
celeration. 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 equip-
ment downstream of the extraction septum, see Section 3.

**VIRTUAL EMMA, END-TO-END**

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

![Figure 3: A zoom on the injection region in Figure 1, including the 10 MeV injected path and $14 - \frac{T}{\tau}$ subsequent turns.](image)

![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.](image)

In the campaign of measurements reported in refer-
ence [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 mea-
surement 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 cen-
troid position for each passage of the beam, allowing mea-
surement of closed orbit distortion and betatron oscilla-
tions. 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 AL-
ICE, optics matching for reference can be taken from two
YAG screens in the ring during the injection set-up.
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].

<table>
<thead>
<tr>
<th>EMMA ring in Zgoubi</th>
<th>start of 3rd cell follows, includes first RF cavity</th>
</tr>
</thead>
<tbody>
<tr>
<td>'MARKER' septExtr extraction septum</td>
<td>extraction kickers are at cells #26 and 27</td>
</tr>
<tr>
<td>'MARKER' EndRing extraction kickers are at cells #26 and 27</td>
<td></td>
</tr>
<tr>
<td>'MARKER' septInj injection septum</td>
<td>extraction septum entrance extraction septum</td>
</tr>
<tr>
<td>'MARKER' E-measurement energy measurement location</td>
<td></td>
</tr>
<tr>
<td>'MARKER' #measurement END</td>
<td></td>
</tr>
</tbody>
</table>

REFERENCES


