END-TO-END

FROM EMMA TO eRHIC

François Méot

Brookhaven National Laboratory
Collider-Accelerator Department
Upton, LI, NY, USA

FFAG'13, TRIUMF, Vancouver, BC, Canada, 21-24 Sept. 2013

Contents

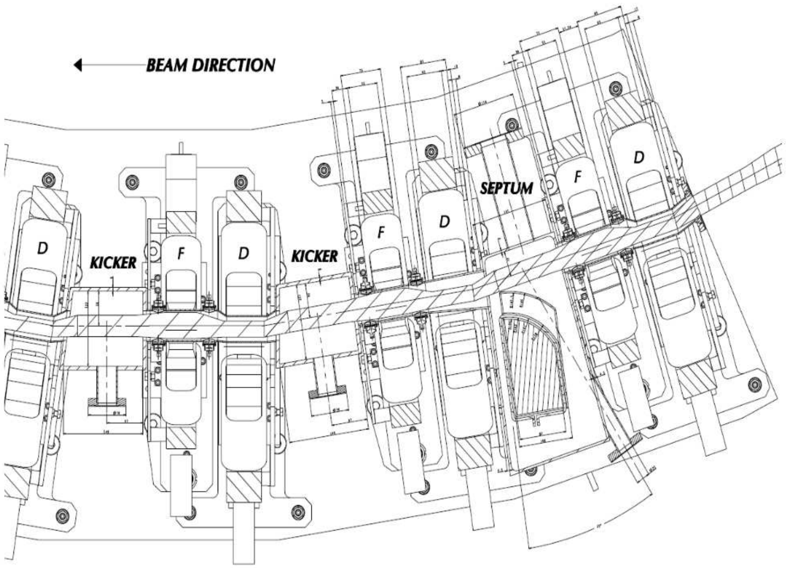
- The optical sequence of EMMA in this end-to-end simulation
  - starts at the entrance of the injection septum,
  - followed by EMMA ring,
  - and ends at the exit of the extraction septum.

- It includes the injection and extraction kicker pairs and accounts for the time dependence of the septum and kicker fields.

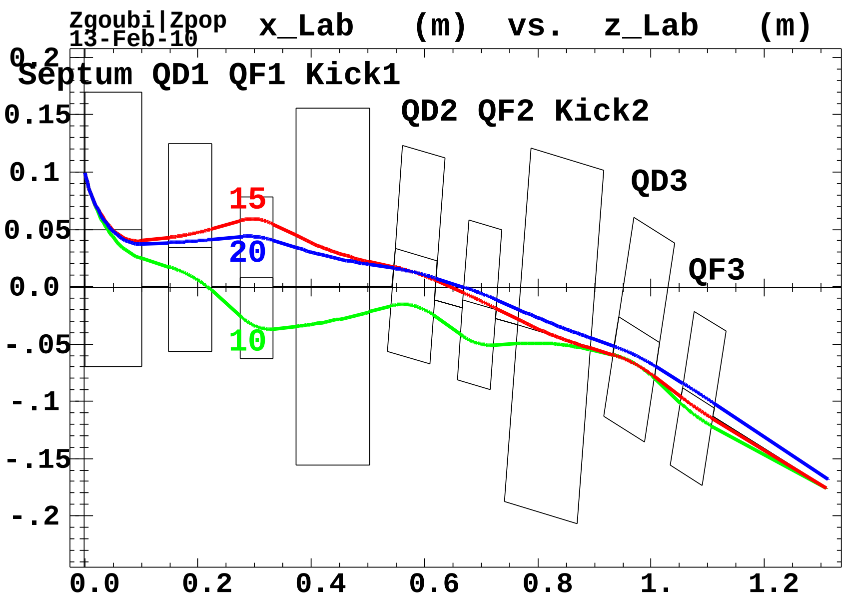
- The aim in developing this material was to allow data analysis, following experimental data taking at EMMA.

- A particular interest of the method :
  - any acceleration regime is allowed, by changing just two data : number of turns and RF voltage.
  - Yoel did it, however he was using a sequence comprised of N rings, for a N-turn simulation : lacks flexibility.

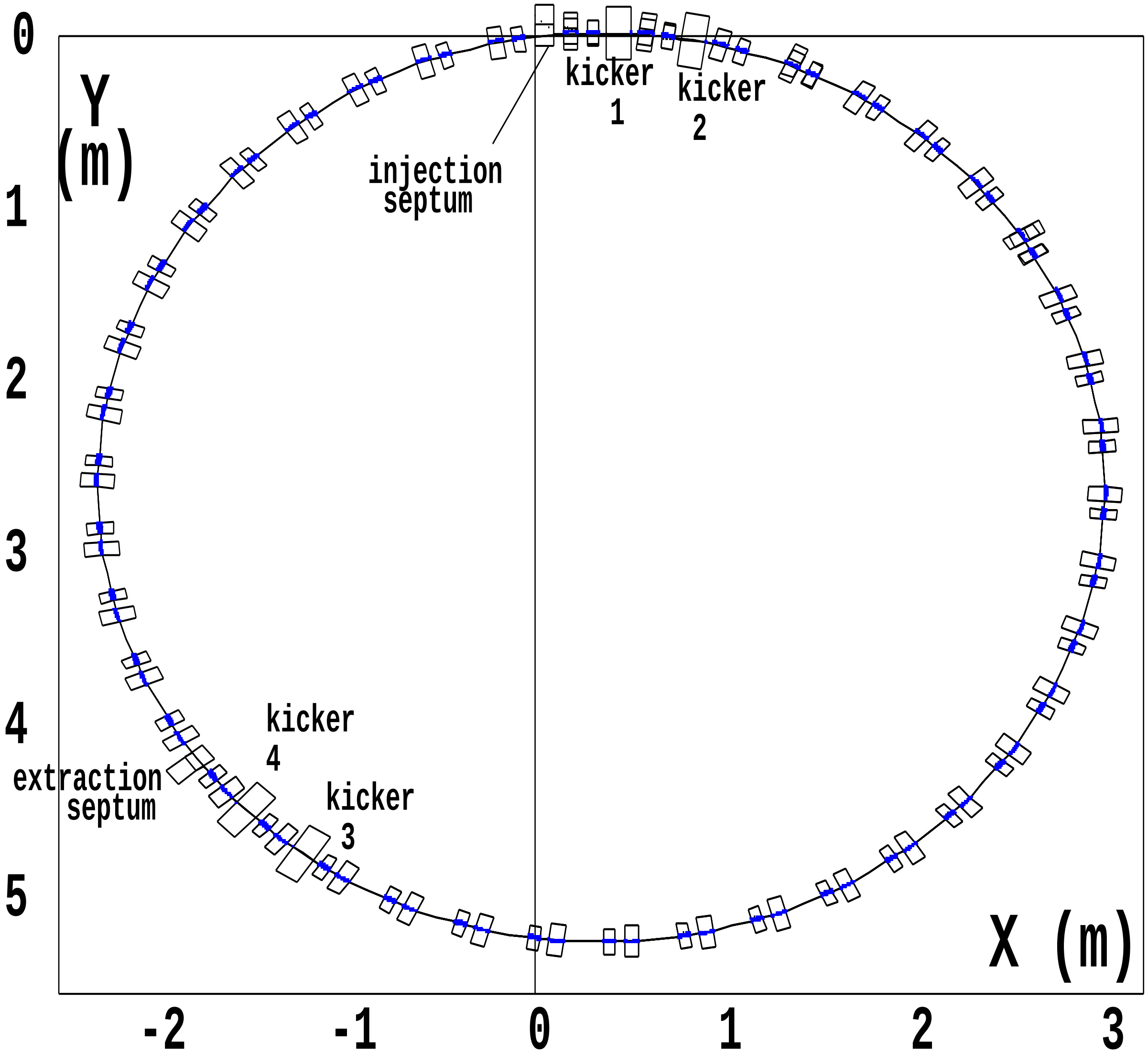
INJECTION



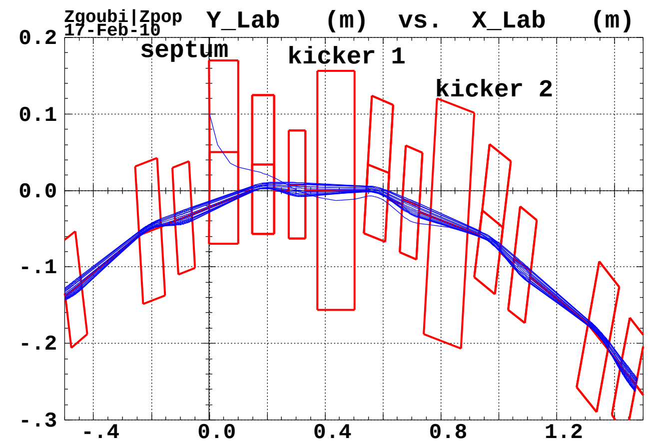
EMMA injection region in the end-to-end simulation.



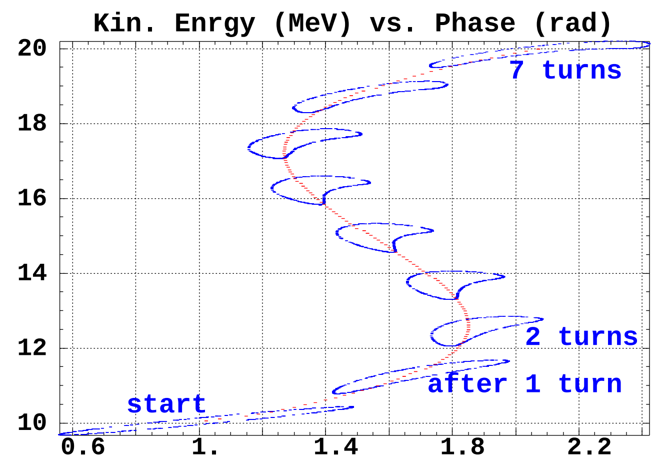
Injection paths.



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



A zoom on the injection region.



Serpentine motion from 10 to 20 MeV, 145 cavities crossed (7 full turns and an additional 12 cavities).

FFAG’13, TRIUMF, Vancouver, BC, Canada, 21-24 Sept. 2013

EMMA ring in Zgoubi	from injection, to extraction
'MCOBJET'	
+51.7110386592	15.5 MeV/c reference
3	random coordinates
100	100 particles
3 3 3 3 2 2	6-D bunch density type
0.1 -1.134 0. 0. -0.854 0.6772 'i'	orbit for starting 10.5 MeV/c
0.015390 0.063314 0e-6 2	horizontal emittance
-3.074521 0.704221 0e-6 2	vertical emittance
-4 3 1E-5 -.4 .40001	longitudinal emittance
123456 234567 345678	seeds
'SCALING'	power supplies
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.	
1 14	
'MARKER' septum Injection	injection septum entrance
'MULTIPOL' septInj	injection septum
00 20	
10. 10. -2.9 0. 0 0 0 0 0 0 0 0	
0. 0. 1.00 1.00 1.00 1.00 1.00 1. 1. 1. 1.	
4 .1455 2.2670 -.6395 1.1558 0. 0. 0.	
0. 0. 1.00 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.	
0.1	
2 0. 5. 0.	
'DRIFT' dr	distance to septum exit
2.1011412	
'DRIFT' dr	distance to septum vessel
2.7151711	
'MARKER'	End injection line

'MARKER' RingInj BegRing	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. 0. 1.00 1.00 1.00 1.00 1.00 1. 1. 1. 1.	
4 .1455 2.2670 -.6395 1.1558 0. 0. 0.	
0. 0. 1.00 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.	
0.1	
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. 0. 1.00 1.00 1.00 1.00 1.00 1. 1. 1. 1.	
4 .1455 2.2670 -.6395 1.1558 0. 0. 0.	
0. 0. 1.00 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.	
0.1	
2 0. 0.7513707181808552 0.	
'DRIFT' ld	
4.	
'MULTIPOL' kicker1	first injection kicker
00 20	
13. 10. -0.55891 0. 0 0 0 0 0 0 0 0	
0. 0. 1.00 1.00 1.00 1.00 1.00 1. 1. 1. 1.	
4 .1455 2.2670 -.6395 1.1558 0. 0. 0.	
0. 0. 1.00 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.	
0.1	
2 0. 0. 0.	
'DRIFT' ld	
4.	
'MARKER' BPM1 off	BPM location
'CHANGREF'	end of first cell
0. 0. -8.571428571429	angle to next cell

```
........................                                  kicker 2 cell here
........................                                  3rd cell follows, RF
'MULTIPOL' QD                                             start of 3rd cell
00 20 0
7.5699 5.3 1.60161 -2.49312 0 0 0 0 0 0 0 0
0. 0. 1.00 1.00 1.00 1.00 1.00 1. 1. 1. 1.
4 .1455 2.2670 -.6395 1.1558 0. 0. 0.
0. 0. 1.00 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.
0.1
1 0. 0. 0.
'MARKER' BPM2 off                                         BPM location
'DRIFT' sd
5.00
'MULTIPOL' QF
00 20 0
5.8782 3.7 -0.5 2.47715 0 0 0 0 0 0 0 0
0. 0. 1.00 1.00 1.00 1.00 1.00 1. 1. 1. 1.
4 .1455 2.2670 -.6395 1.1558 0. 0. 0.
0. 0. 1.00 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.
0.1
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, phase
'MARKER' #CAV
'DRIFT' ld
10.5
'CHANGREF'
0. 0. -8.571428571429
```

```
........................                                  extraction kickers at cells 26, 27
........................                                  extraction 'RingExtr' at cell 28
........................                                  14 additional cells
'MARKER' EndRing                                          end of last cell, 42

'REBELOTE'                                                extraction at "RingExtr"
14   0.1   99.2   RingInj   RingExtr

'MARKER' Start Extraction line                            extraction line starts here
'DRIFT' sep2F                                             septum entrance
6.129285847219867391
'MULTIPOL' septExtr                                       extraction septum
00 20 ! .plt
10. 10. -6.98 0. 0 0 0 0 0 0 0 0
0. 0. 1.00 1.00 1.00 1.00 1.00 1. 1. 1. 1.
4 .1455 2.2670 -.6395 1.1558 0. 0. 0.
0. 0. 1.00 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.
0.1
2 0. 0. 0.
'MARKER' E-measuremnt                                     energy measurement location
'END'
```

2 eRHIC, pieces of the puzzle

- **eRHIC arc optics compares with EMMA : linear, FDF triplet.**

- **In the present state of the design : 6-arc eRHIC structure, 1.2 GeV linac in one of the straights,**

- **6 orbits with 6 different energies in the ring.**

$$\mathbf{2.8} \xrightarrow{1.2\ GeV} \mathbf{4} \xrightarrow{1.2\ GeV} \mathbf{5.2} \xrightarrow{1.2\ GeV} \mathbf{6.4} \xrightarrow{1.2\ GeV} \mathbf{7.6} \xrightarrow{1.2\ GeV} \mathbf{8.8} \xrightarrow{1.2\ GeV} \mathbf{10}$$

```
 Generated by MADX -> Zgoubi translator
 'MCOBJET'
9.34027191586d3
3
2000
2 2 2 2 2 2
 -7.2E-04 0.  0.0  0.0  0.0  3.5714285 'X'
0. 1. 0.e-6 4
0. 1. 0.e-6 4
0. 1.       0. 1
123456 234567 345678

 'PARTICUL'
0.51099892 1.60217653e-19  1.8  0. 0.

 'SCALING'
1 1
MULTIPOL
-1
33.3581139852
1

 'SRLOSS'
1
MULTIPOL
1  123456

'SPNTRK'
4.1
0. 0.  1.

 'FAISTORE'
b_zgoubi.fai   CSTART
1

 'MARKER'   CSTART  .plt
 'DRIFT'    DRIF      O
14.462288
 'MULTIPOL' RBEN      QF
0  .Dip
50.000005  10.00   0.003139422   0.709632718   0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0
0. 0. 10.00  4.0  0.800 0.00 0.00 0.00 0.00 0. 0. 0. 0.
4  .1455   2.2670  -.6395  1.1558  0. 0.  0.
0. 0. 10.00  4.0  0.800 0.00 0.00 0.00 0.00 0. 0. 0. 0.
4  .1455   2.2670  -.6395  1.1558  0. 0.  0.
0. 0. 0. 0. 0. 0. 0. 0. 0. 0.
#30|50|30    Dip  QF
3   0. 0.    7.848557575E-004
 'DRIFT'    DRIF      DL3
8.000000
 'MULTIPOL' RBEN      BD
0  .Dip
125.000080  10.00   0.003139419  -0.536581572   0. 0.0 0.0 0.0 0.0 0.0 0.0 0.0
0. 0. 10.00  4.0  0.800 0.00 0.00 0.00 0.00 0. 0. 0. 0.
4  .1455   2.2670  -.6395  1.1558  0. 0.  0.
0. 0. 10.00  4.0  0.800 0.00 0.00 0.00 0.00 0. 0. 0. 0.
4  .1455   2.2670  -.6395  1.1558  0. 0.  0.
0. 0. 0. 0. 0. 0. 0. 0. 0. 0.
#30|125|30    Dip  BD
3   0.  0.      -1.962139394E-003
 'DRIFT'    DRIF      DL3
8.000000
 'MULTIPOL' RBEN      QF
0  .Dip
50.000005  10.00   0.003139422   0.709632718   0. 0.0 0.0 0.0 0.0 0.0 0.0 0.0
0. 0. 10.00  4.0  0.800 0.00 0.00 0.00 0.00 0. 0. 0. 0.
4  .1455   2.2670  -.6395  1.1558  0. 0.  0.
0. 0. 10.00  4.0  0.800 0.00 0.00 0.00 0.00 0. 0. 0. 0.
4  .1455   2.2670  -.6395  1.1558  0. 0.  0.
0. 0. 0. 0. 0. 0. 0. 0. 0. 0.
#30|50|30    Dip  QF
3   0.      0.    7.848557575E-004
 'DRIFT'    DRIF      O
14.462288
 'MARKER'   CELLH$END   .plt

'REBELOTE'
 147 0.1 99

 'FAISTORE'
b_zgoubi.fai   CSTART
1

 'SRPRNT'
 'SPNPRT'
 'FAISCEAU'

 'END'
```

Synchrotron radiation

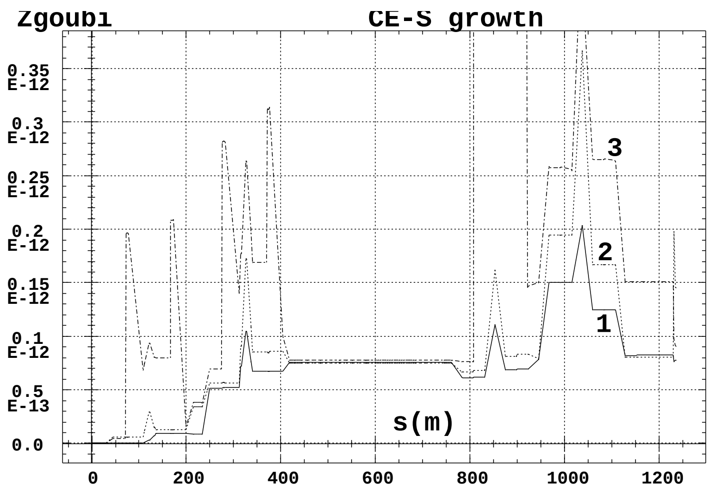
• **SR statistics in uniform field converges towards the following averages :**

- **energy loss, namely, per particle over an arc $\Delta\theta$:** $\Delta E(eV) = 2r_0 E_0 \gamma^4 \Delta\theta \ / \ 3\rho$

- **induced beam energy spread,** $\sigma_E/E = \frac{\sqrt{110\sqrt{3}\hbar c \ / \ \pi\epsilon_0}}{576 E_0^2} \ \gamma^{5/2}\sqrt{\Delta\theta} \ / \ \rho = 3.794 \ 10^{-14} \ \gamma^{5/2}\sqrt{\Delta\theta}/\rho$

- **scattering, due to SR emitted at an angle with respect to particle velocity. This induces vertical emittance increase.**

• **Expected in eRHIC arcs :**
- **beam emittance increase with distance**
- **average energy loss $\rightarrow$ rigidity decreases with distance / requires scaling of magnet strengths.**



Emittance increase in TESLA BDS.

Emittance increase with distance in one eRHIC arc, 10 GeV pass.

Emittance increase with distance in one eRHIC arc, 10 GeV pass.

Spin

- **Assuming 6 arcs, 148 cells per arc, same bend angle in all three quadrupoles :**

Number of spin rotations is $G\gamma \approx 1.1\,10^{-3} \times 20000 = 22$ **rotations per turn,**

spin rotation in a dipole is $G\gamma\alpha/N \approx 1.1\,10^{-3} \times 20000 \times 360/148/6 \approx 8$ **degrees/dipole**