FFAG 2019 WORKSHOP - 19-22 November 2019
PSI, Villigen, Confédération des Helvètes

USING FIELD MAPS TO VALIDATE THE FFAG CELL. BEYOND: ALL MAPS OUT TO TRACK CBETA ERL!

OR,

USING MODERN TOOLS TO DESIGN ACCELERATORS

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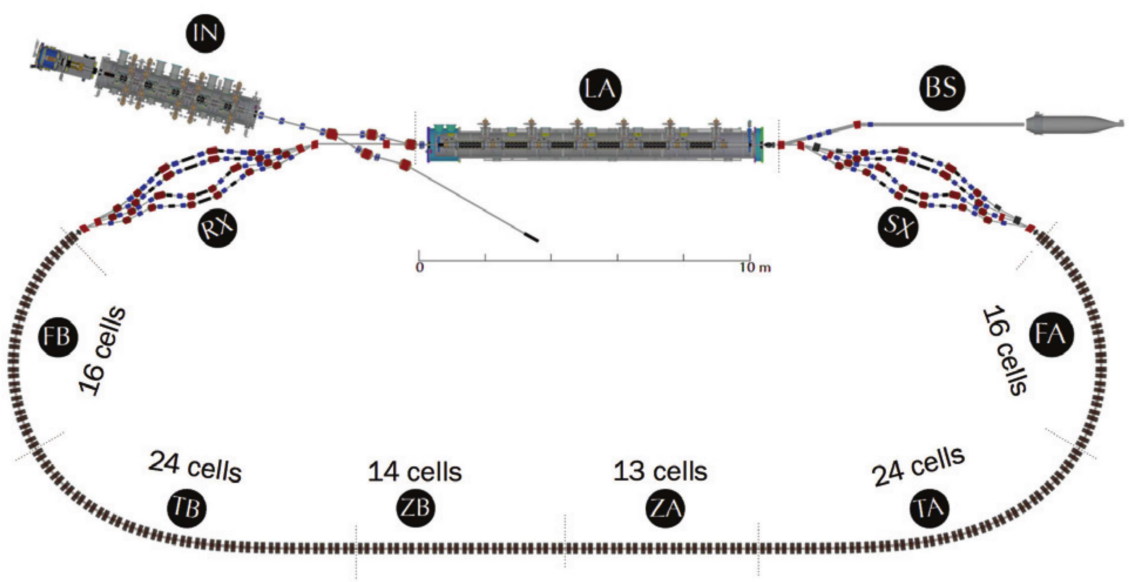
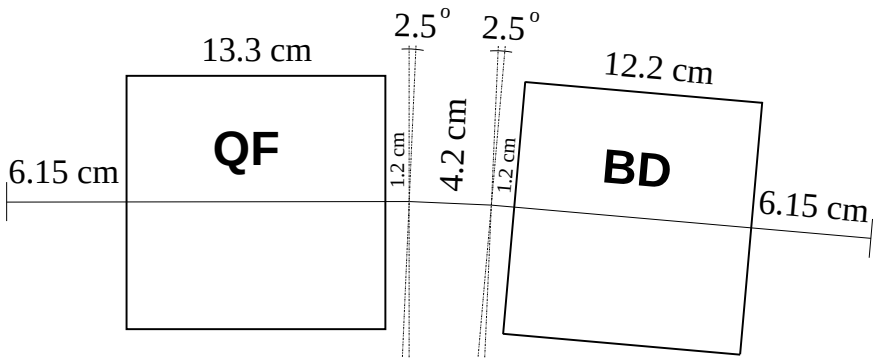
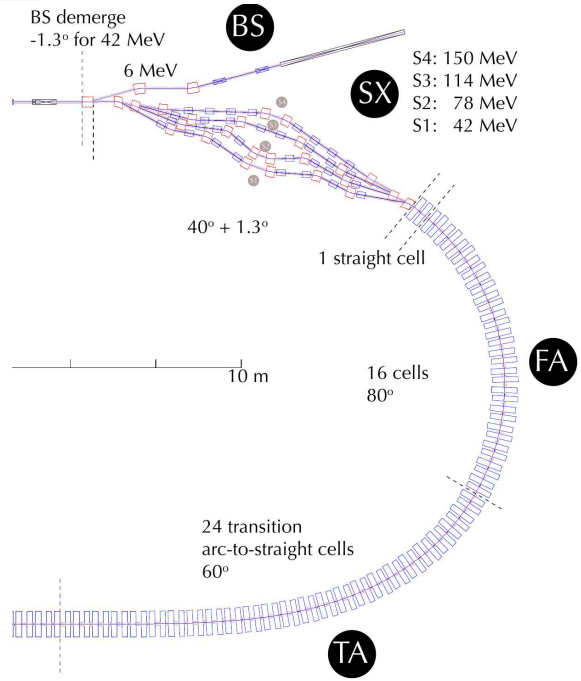


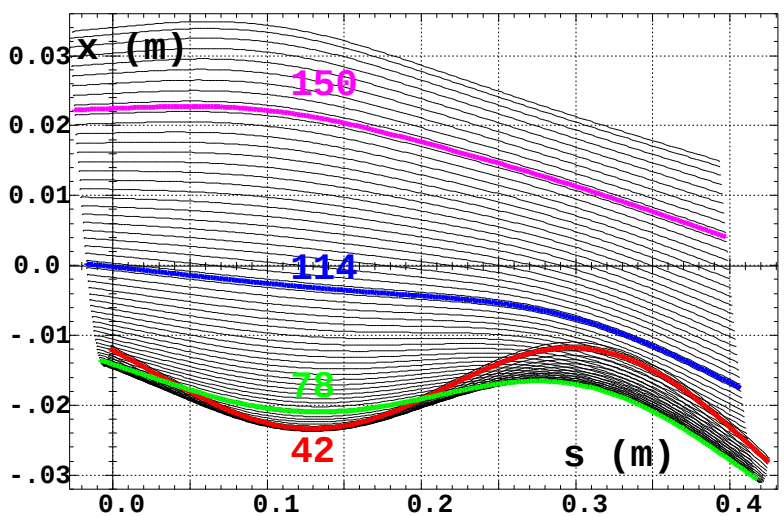
CBETA FFAG ARC Cell

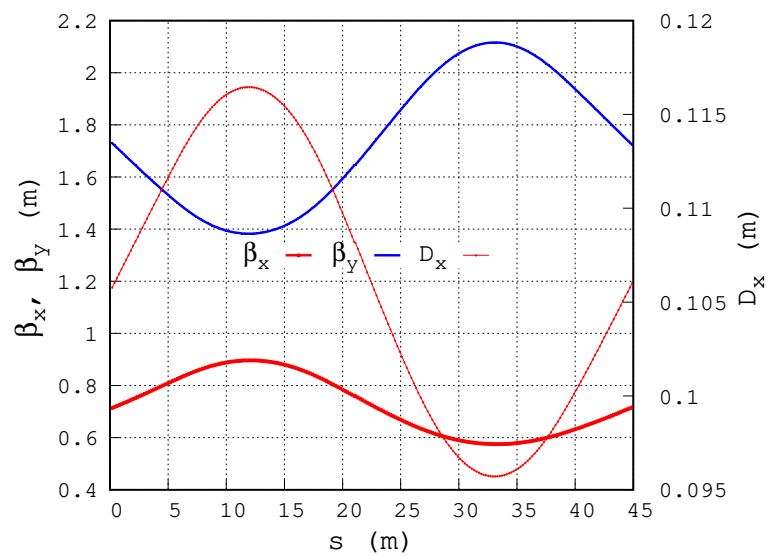
107 cells
in CBETA return loop





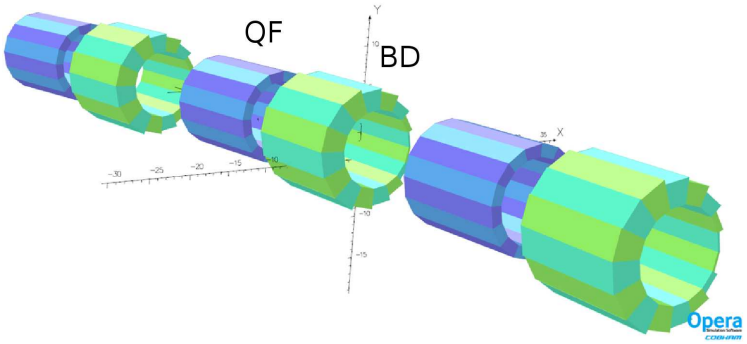
Orbits and optical functions, from OPERA field maps:

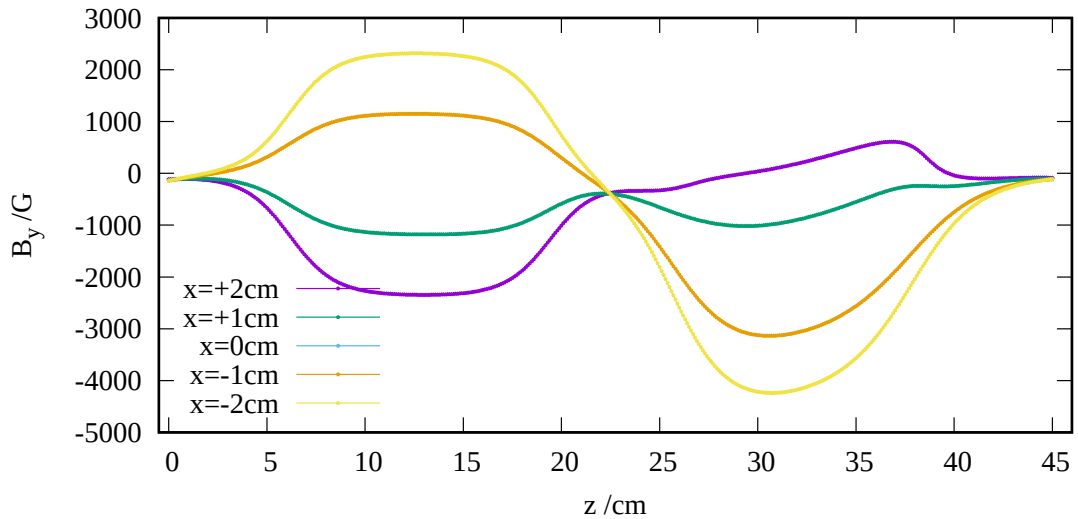




OPERA simulation of CBETA return loop FFAG cell

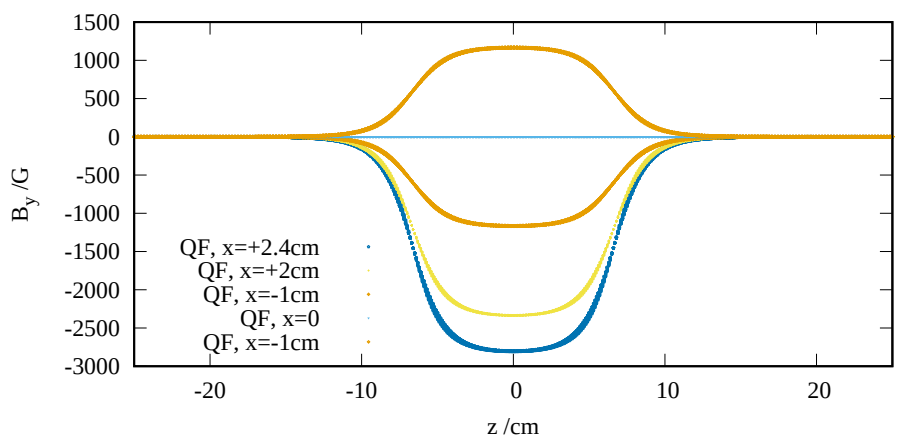
- **Either a single full-cell field map:**



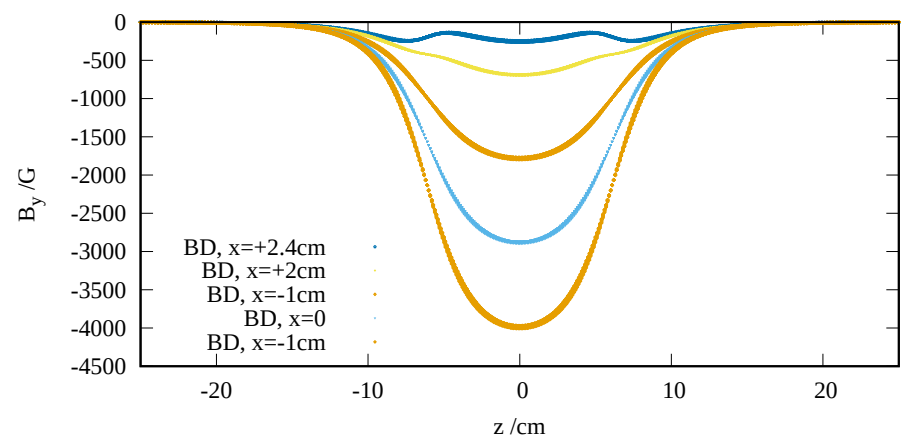


- **Far more flexible if it proves to work: two separate maps**

QF magnet



BD magnet



What the code sequence looks like, for an FFAG loop cell

- **Full-cell 3D field map:**

```
'TOSCA'   QF+BD
0  0
-9.69871600E-04  1.000  1.000  1.000
HEADER_8  ZroBXY
451 83 27 15.1  1.
3cellFieldMap.table
1 -508.5 44.49 2.2E4 ! MOTION BOUNDARY
2
.2
2   0.000  0.000  0.000
  'CHANGREF'
XS -0.678391 YS -1.8870962 ZR  -5.0
```

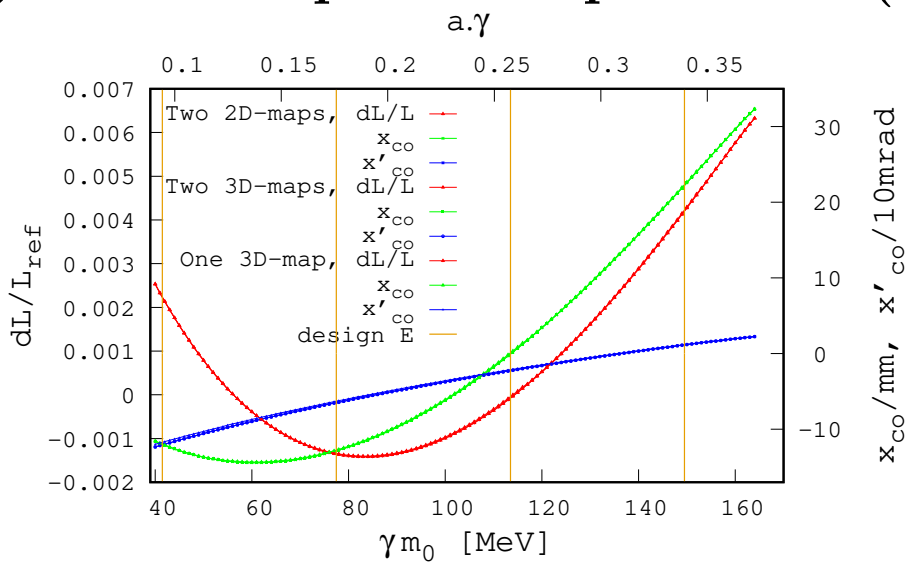
- **Separate QF, BD maps:**

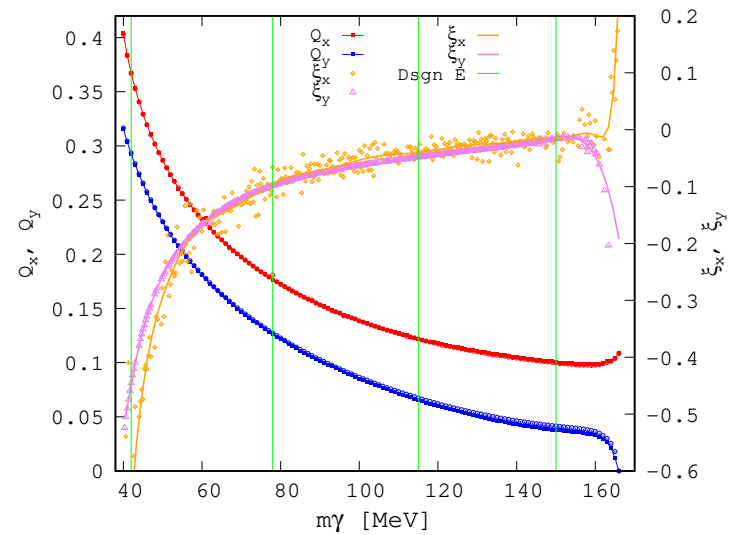
```
  'DRIFT'  HD2
6.15
  'DRIFT'
-18.35  ! = (50cm - 13.3cm)/2  (50cm is field map extent)
'TOSCA'  QF
0 0
-9.76E-04  1.  1.  1.
HEADER_8  ZroBXY
501 83 1 15.1  1.
 QF-3D-fieldMap.table
0 0 0 0
2
.2
2   0.00000000E+00  0.00000000E+00  0.00000000E+00
  'DRIFT'
-18.35  ! = (50cm - 13.3cm)/2   (50cm is field map extent)
  'DRIFT'   ED1
1.2
  'CHANGREF'   CORNER
ZR  -2.50000000
  'DRIFT'   BPM
4.2
  'CHANGREF'   CORNER
ZR  -2.50000000
  'DRIFT'   ED1
1.2
  'DRIFT'
-18.9   ! = (50cm - 12.2cm)/2   (50cm is field map extent)
 'TOSCA'   BD
0  0
-9.76E-04  1.00000000E+00  1.00000000E+00  1.00000000E+00
HEADER_8  ZroBXY
501 83 1  15.1  1.0
 BD-3D-fieldMap.table
0 0 0 0
2
.2
2   0.00000000E+00   -.019  0.E+00    ! Y-offset -0.019cm = inwar
  'DRIFT'
-18.9   ! = (50cm - 12.2cm)/2   (50cm is field map extent)
  'DRIFT'  HD2
6.15
```

Case of two independent maps: optics validation

• FIRST ORDER PARAMETERS OF THE ARC CELL

◇ separate field maps of QF and BD, or 3-D full-cell single map, yield same paraxial quantities (orbits, tunes, chromaticities, etc.)





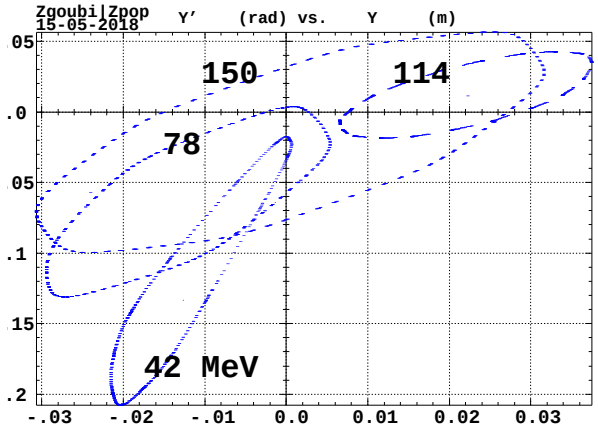
Path length across cell (cm) Difference is at few ppm level.				
E (MeV)	42	78	114	150
Single 3D map	44.4846	44.3298	44.3898	44.5806
Two 2D or 3D maps	44.4845	44.3291	44.3884	44.5797

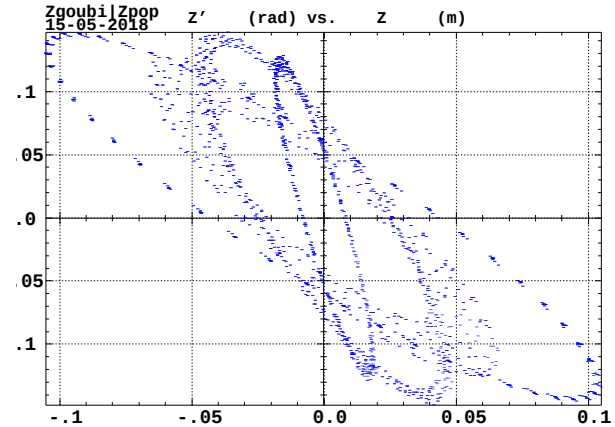
• DYNAMICAL ADMITTANCE, 400-CELL

◇ Maximum stable invariants are ∼meter normalized, far beyond μm CBETA beam emittance

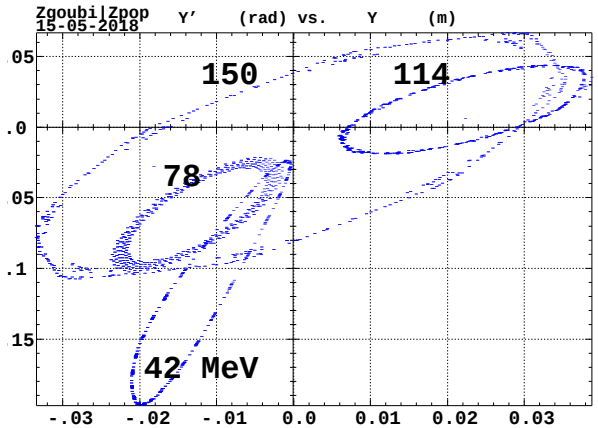
H **V**

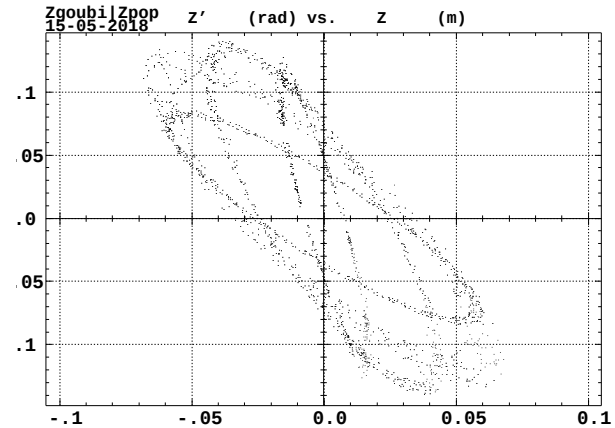
case of separate 2D field maps:



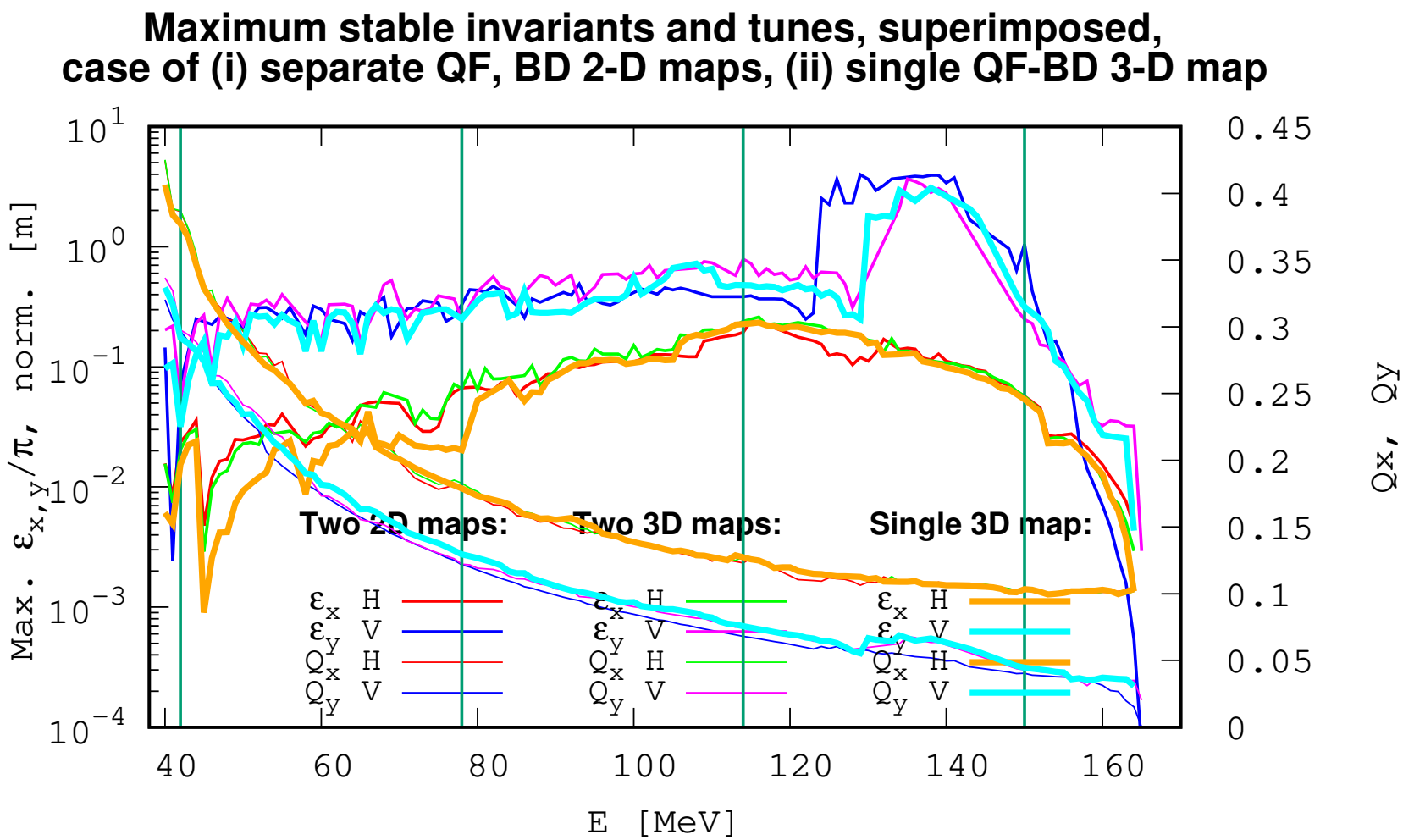


case of single 3D field map (same scales)





• DYNAMICAL ADMITTANCE, ENERGY SCAN



"H": horizontal motion (initial V invariant is taken very small).

"V": vertical motion (initial H invariant is taken very small).

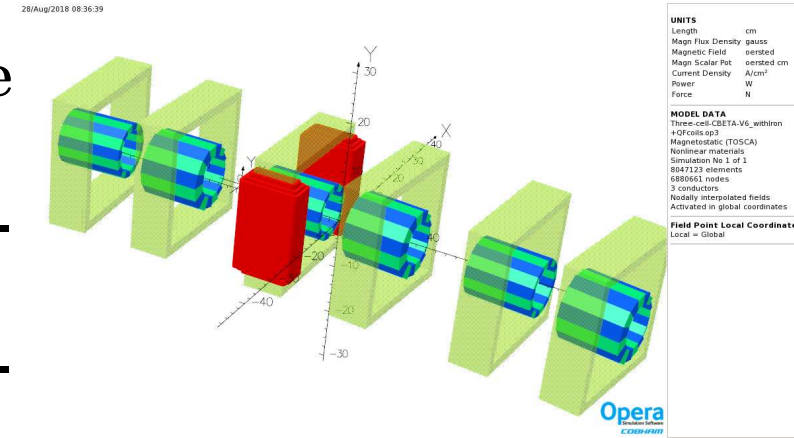
We can make the FFAG cell model even fancier...

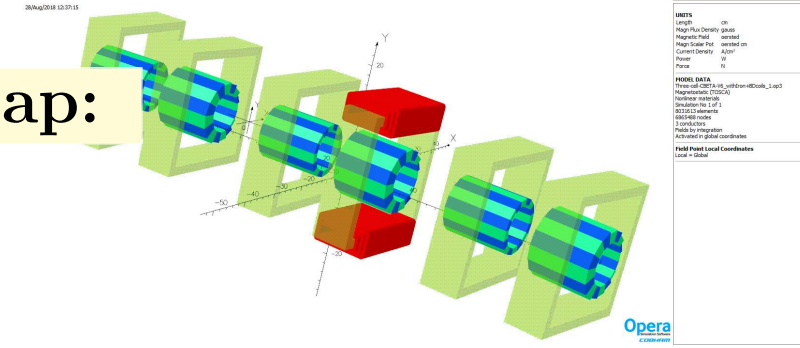
- **Include iron core steerers, with independent control**

  ◇ Two corrector field maps, and as we did for EMMA:

  - one has F-corrector on and D-corrector off

  - one has F-corrector off and D-corrector on





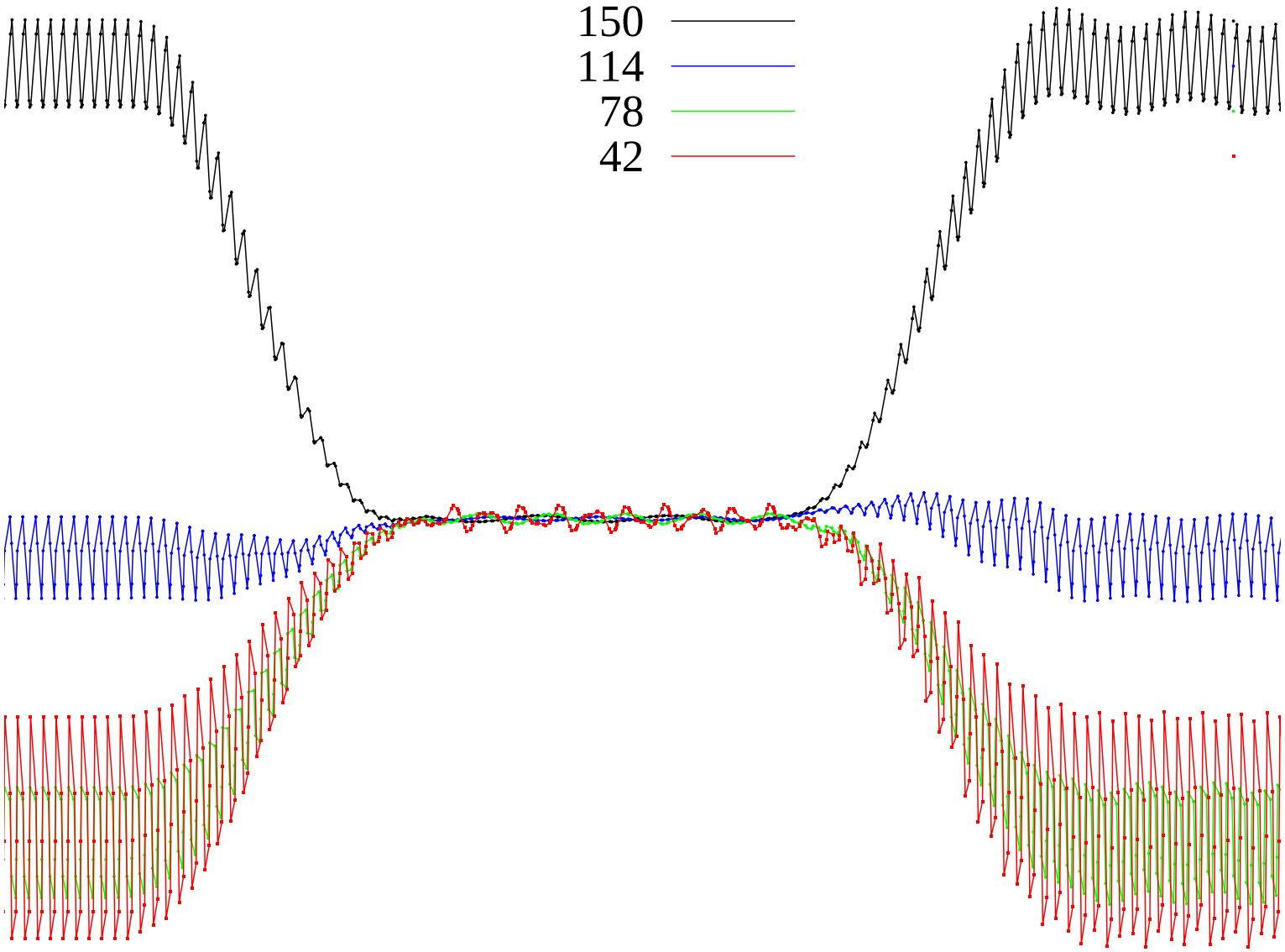
- **Code sequence, case of single full-map:**

```
'TOSCA'   QF+BD map + corrector maps
 0  0
  -9.69871600E-04  1.  1.  1.
  HEADER˙8  ZroBXY
451 83 27 15.3  1.  0.01  0.00001   ! 3 independent knobs
 3D-Cell-fieldMap.table
 FConDCoff-3D-fieldMap.table
 FCoffDCon-3D-fieldMap.table
  1  482.028 42.172 -20328          ! integration boundary
  2
  .2                                ! integration step size
  2   0.0  0.0  0.0                  ! magnet positioning
   'CHANGREF'
 XS -0.6586  YS -3.2061  ZR -5.0  YS 1.2047      ! magnet positioning
```

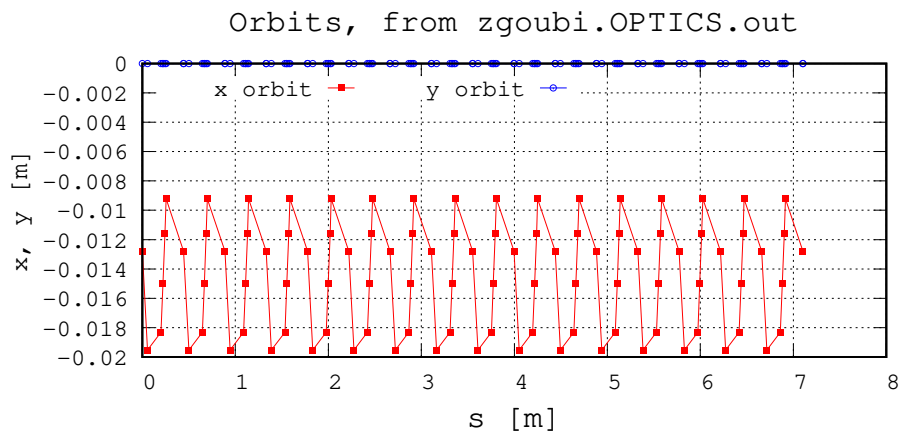
ALL FIELD MAPS OUT !

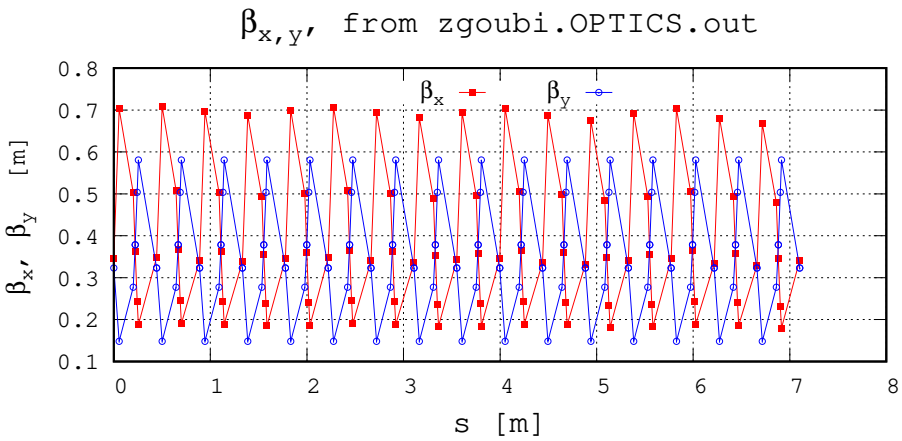
FFAG loop orbits:

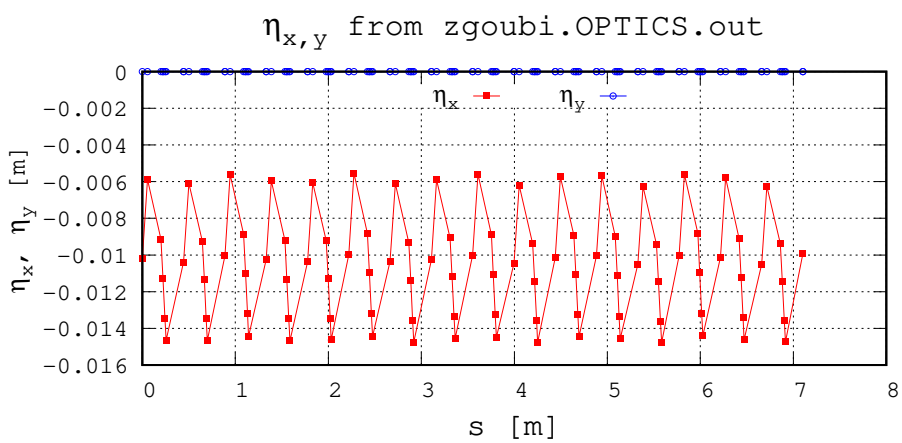
just one beam line, encompasses all 4 energies



• FA (FB) arc optics:

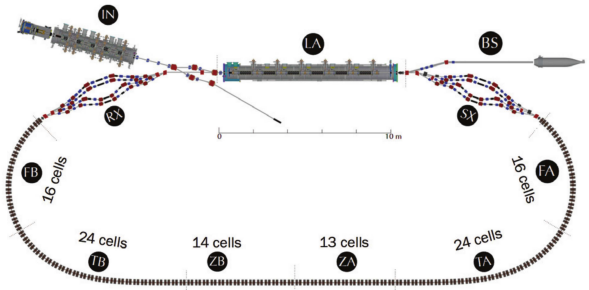






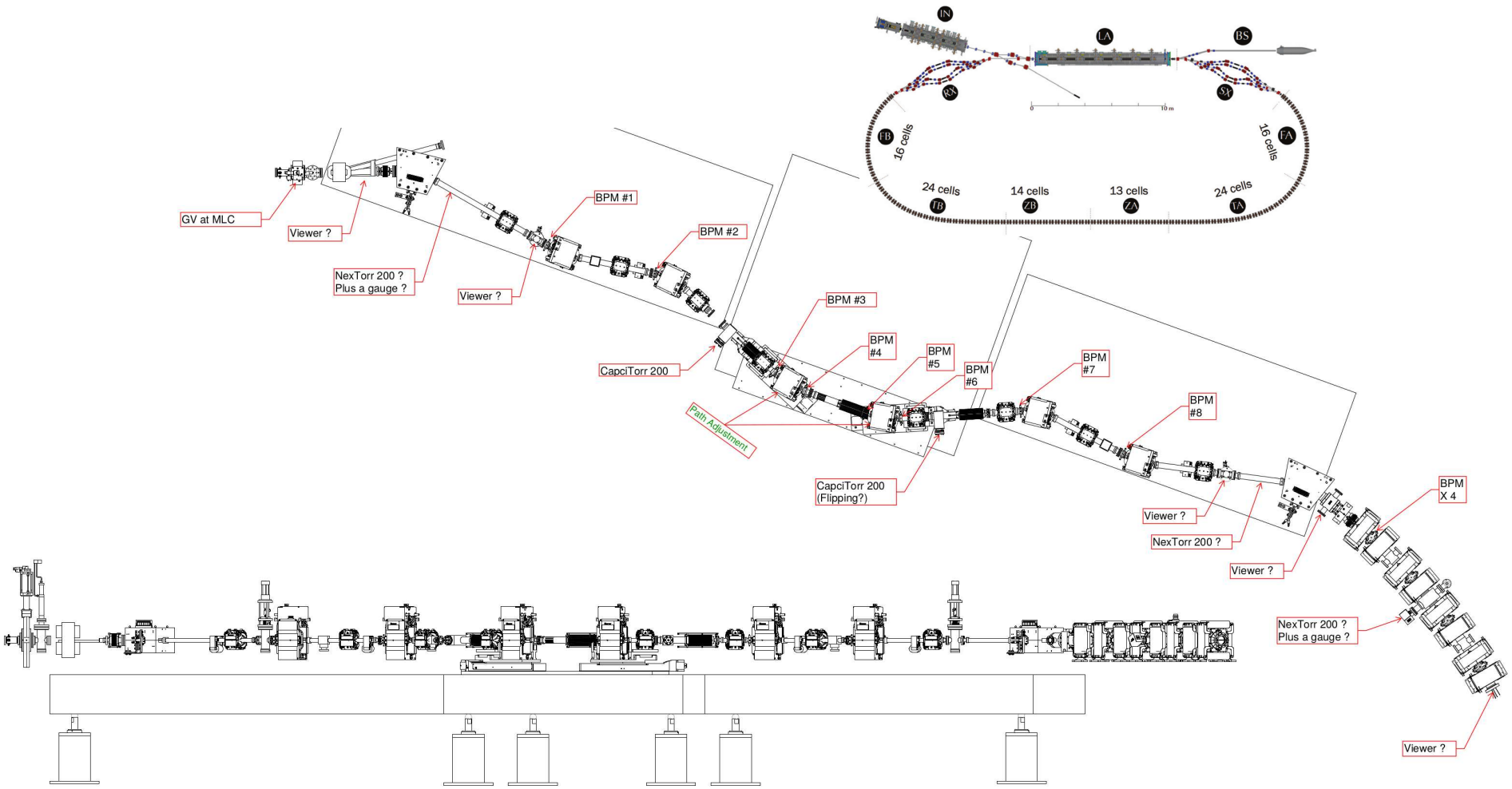
Two-map cell sequence:

```
'DRIFT'
5.6
'DRIFT'
-18.35
'TOSCA'   QF
0 0
 -9.69871600E-04  1.00E+00  1.00E+00  1.00E+00
HEADER_8  ZroBXY
501 83 1 15.2  1. 0.
  QF-2D-fieldMap.table
  FCorr-2D-fieldMap.table
0 0 0 0
2
.1
2   0.00E+00  0.00E+00  0.00E+00
'DRIFT'
-18.35
'DRIFT'
1.2
'CHANGREF'    CORNER
ZR  -2.50
'DRIFT'
4.2
'CHANGREF'    CORNER
ZR  -2.50
'DRIFT'
1.2
'DRIFT'
-18.9
'TOSCA'
0  0
 -9.69871600E-04  1.00E+00  1.00E+00  1.00E+00
HEADER_8  ZroBXY
501 83 1  15.1  1.0
501 83 1 15.2  1. 0.
  BD-2D-fieldMap.table
  DCorr-2D-fieldMap.table
0 0 0 0
2
.1
2   0.00E+00  3.60319403E-04  0.00E+00
'DRIFT'
-18.9
'DRIFT'
6.7
```



SX and RX still under construction

- **The 42 MeV spreader line + start of FFAG arc:**

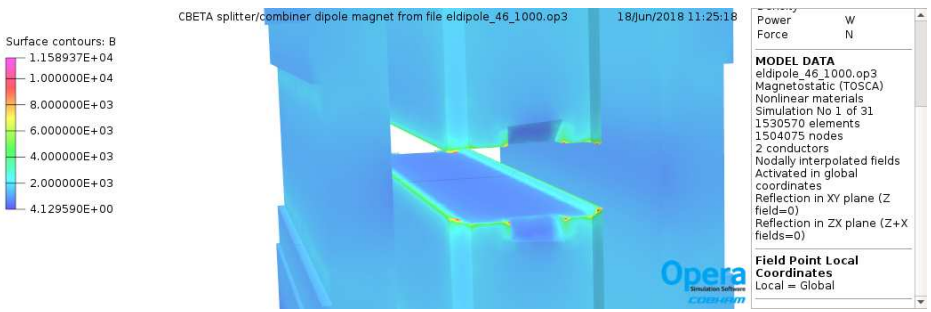


- **In the code sequence, step by step, replace the analytical models of the quadrupoles and bends by their OPERA field maps**

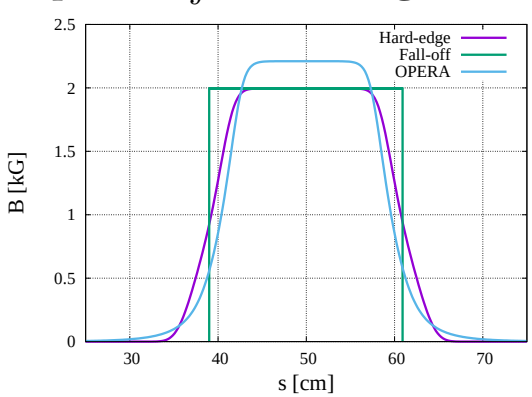
WHY FIELD MAPS FOR CONVENTIONAL OPTICS?

- **Spreader line magnets are short:**
  they large gap/width, gap/length,
- **and in addition:**
  they have fancy chamfers, shimming

The H1 dipole series :



Shims and chamfers equalize $\int \mathrm{B}\,\mathrm{ds}$ along arcs.



(i) Hard-edge:

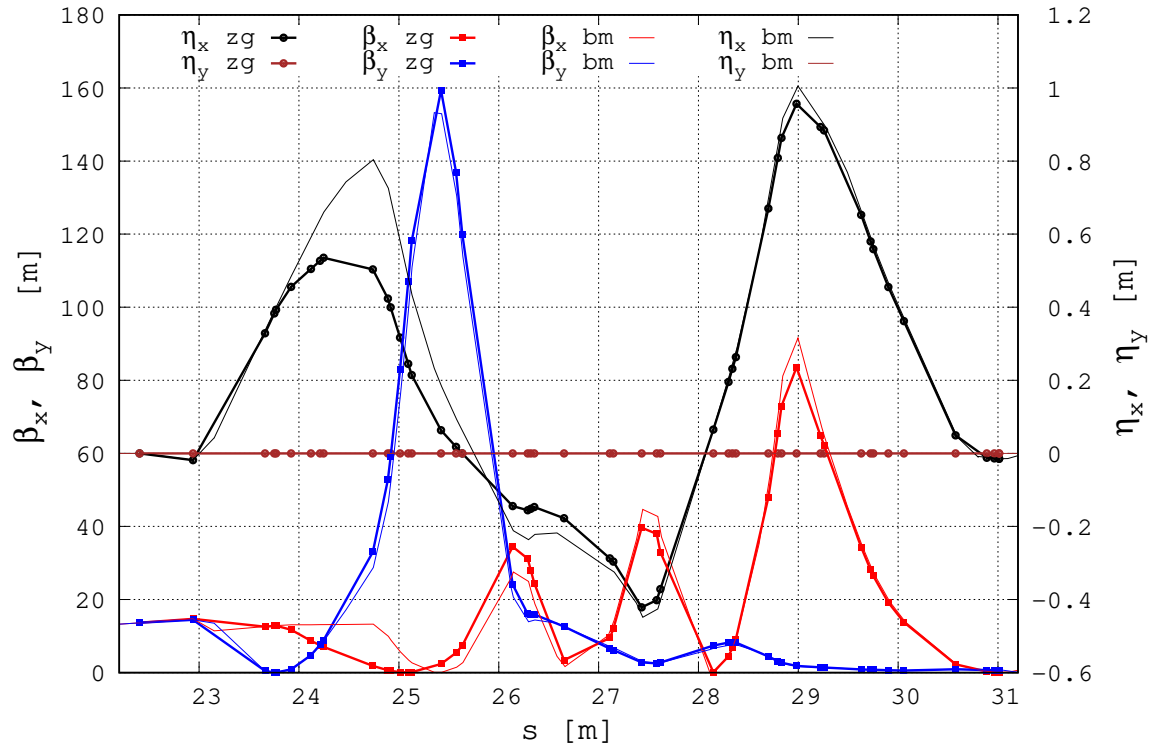
1	0.21700	0	0	-3.44E-2
0	1	0	0	-0.31666
0	0	0.9503	0.220605	0
0	0	-0.4396	0.950276	0
-0.31666	-0.0343	0	0	3.61E-3

(iii) OPERA field map:

0.9834	0.215709	0	0	-3.415E-2
-0.1520	0.983583	0	0	-0.31409
0	0	0.9696	0.2188	0
0	0	-0.2736	0.9696	0
-0.3141	-0.0341572	0	0	3.6048E-3

- **The 42 MeV spreader line S1 from linac exit to start of arc FA:**

  (former FFAG arc test optics, early 2018)



THANK YOU FOR YOUR ATTENTION

BIBLIOGRAPHY

- **BNL-Cornell collaboration and documents**
- **CBETA CDR**
- **F. Méot, et als., Beam dynamics validation of the Halbach Technology FFAG Cell for Cornell-BNL Energy Recovery Linac, NIM A 896 60-67 (2018)**
- **F. Méot, N. Tsoupas, Using field maps to track CBETA, FFAG'18 Workshop, Kyoto University (10-14 Sept. 2018). https://indico.rcnp.osaka-u.ac.jp/event/1143/contributions/1178/**

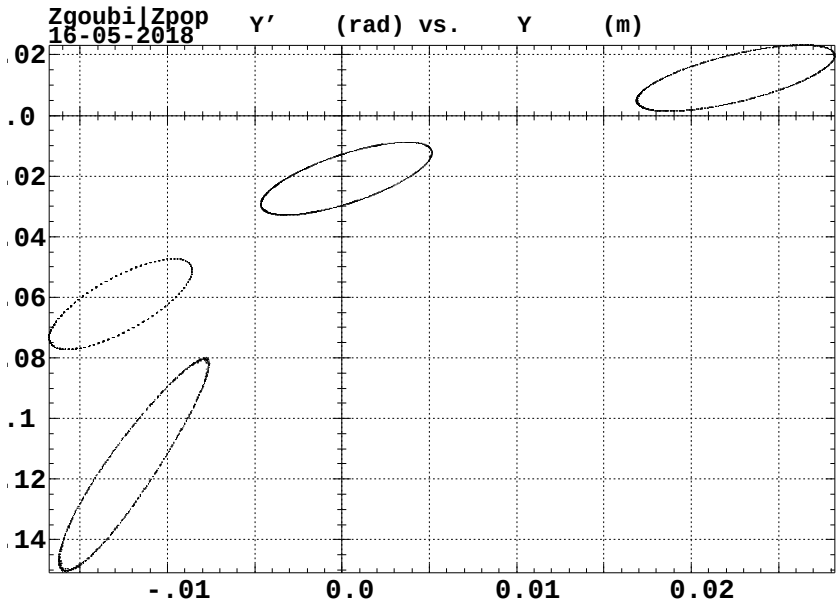
BACKUP SLIDES

Table 1.2.1: Primary parameters of the Cornell-BNL ERL Test Accelerator.

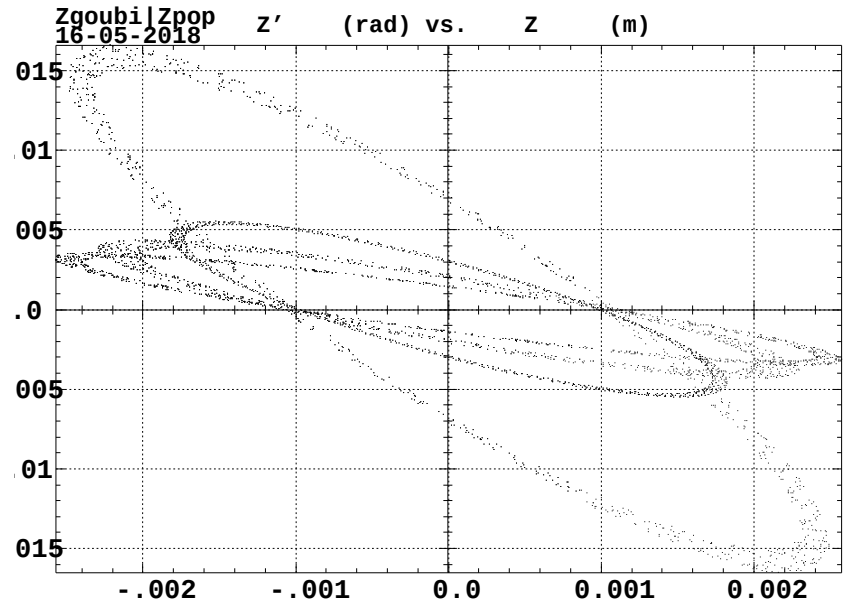
Parameter	Value	Unit
Largest energy	150	MeV
Injection energy	6	MeV
Linac energy gain	36	MeV
Injector current (max)	40	mA
Linac passes	8	4 accel. + 4 decel.
Energy sequence in the arc	$42 \rightarrow 78 \rightarrow 114 \rightarrow 150 \rightarrow 114 \rightarrow 78 \rightarrow 42$	MeV
RF frequency	1300.	MHz
Bunch frequency (high-current mode)	325.	MHz
Circumference harmonic	343	
Circumference length	79.0997	m
Circumference time (pass 1)	0.263848164	μs
Circumference time (pass 2)	0.263845098	μs
Circumference time (pass 3)	0.263844646	μs
Circumference time (pass 4)	0.265003298	μs
Normalized transverse rms emittances	1	μm
Bunch length	4	ps
Typical arc beta functions	0.4	m
Typical splitter beta functions	50	m
Transverse rms bunch size (max)	1800	μm
Transverse rms bunch size (min)	52	μm
Bunch charge (min)	1	pC
Bunch charge (max)	123	pC

- **Accuracy of step-wise tracking ? A non-issue**

10^5-turn phase spaces, case of single full-cell 2D field map



Horizontal phase space observed in long drift.
Excursions are in 10 mm range.



Vertical phase space observed in long drift.
Excursions are in mm range.