ICAP'18 - 13th ICAP - Key West, Florida

USING FIELD MAPS TO TRACK CBETA FFAG ERL

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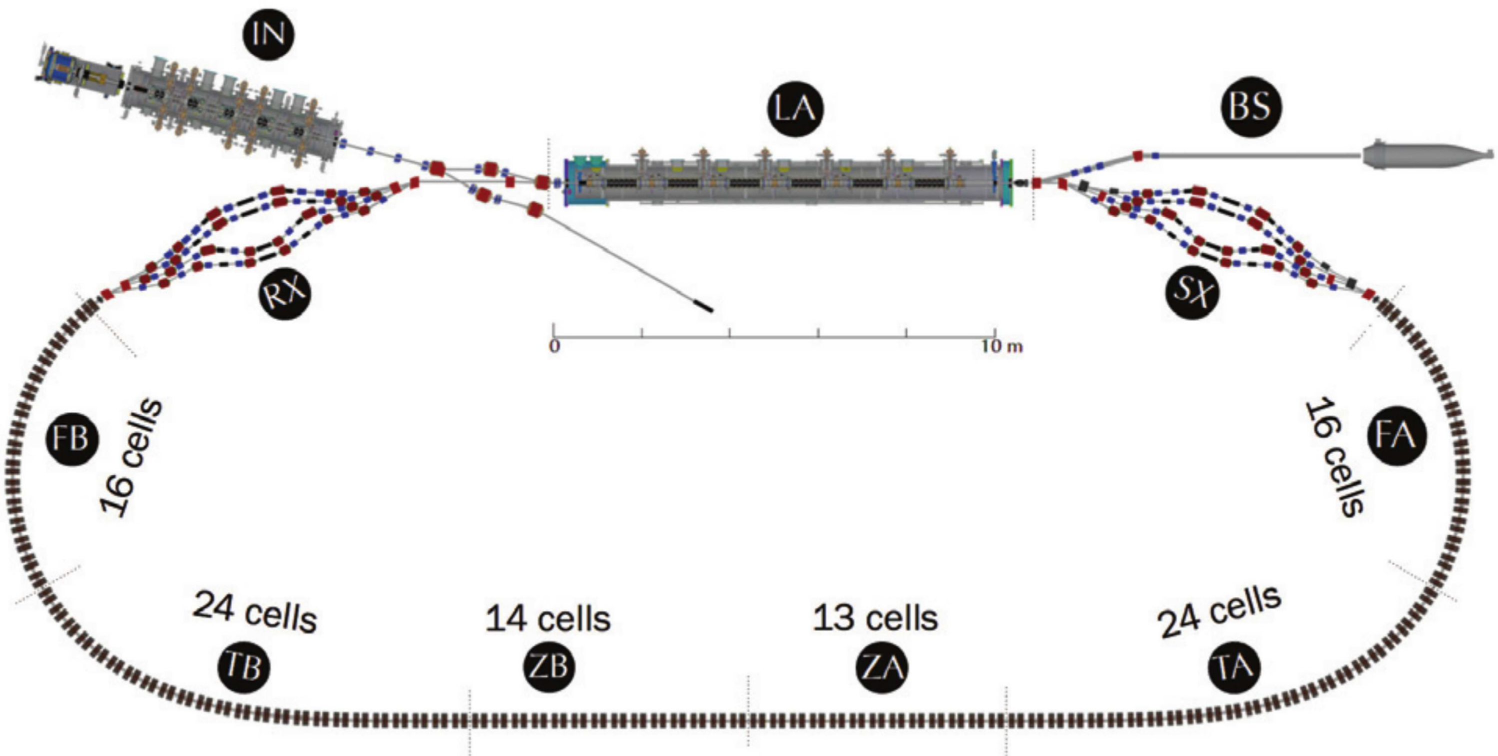
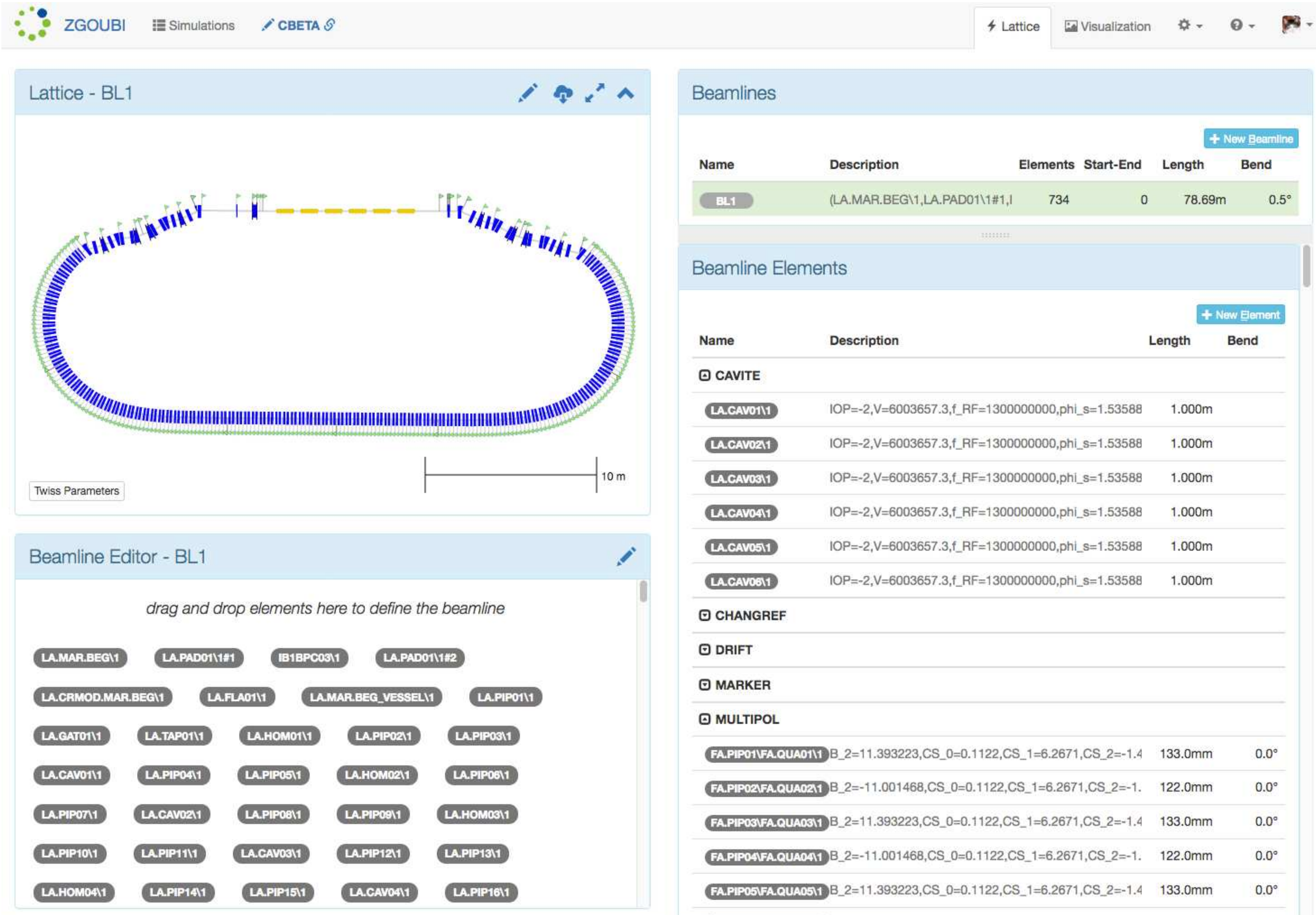


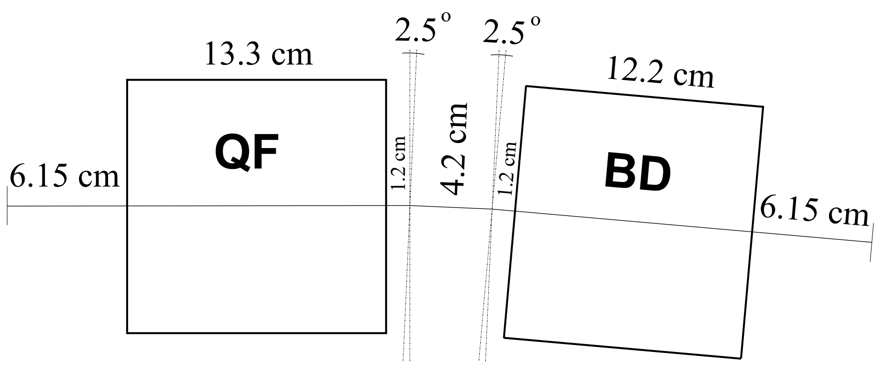
Commissioning will commence in March 2019

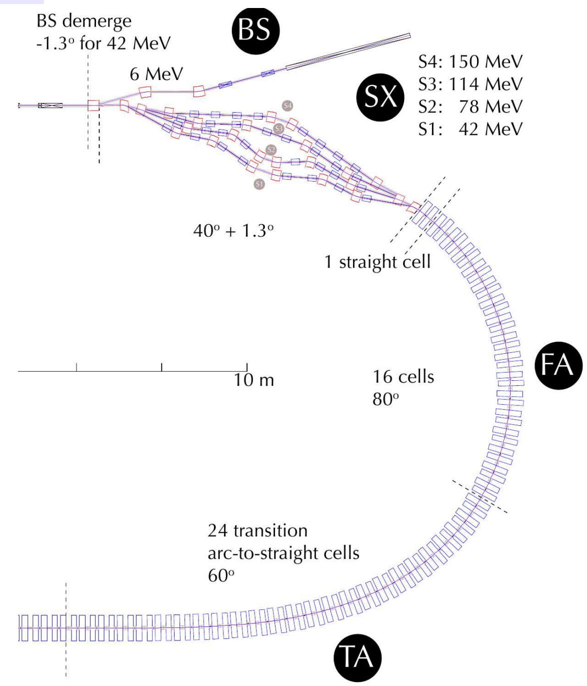
Dan Abell, "Zgoubi: Recent Developments and Future Plans", Tue. 9:45.
SIREPO sample here by Paul Moeller/Radiasoft.
An interface to accelerator codes - https://beta.SIREPO.com/#/accel



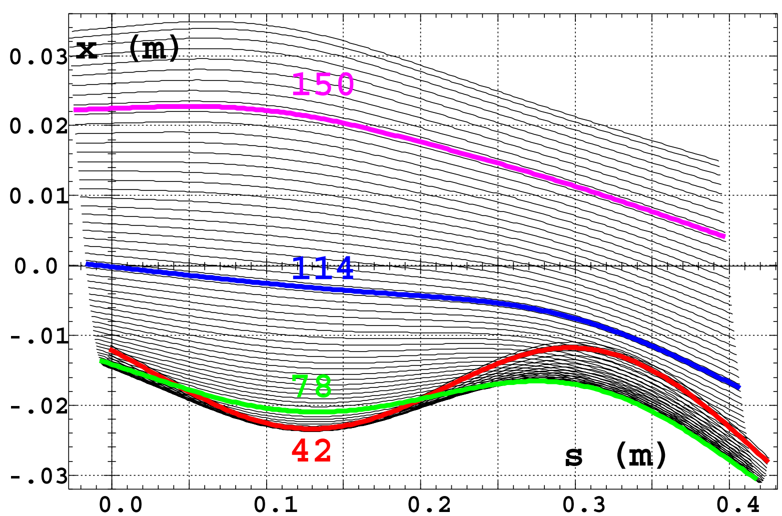
CBETA FFAG ARC Cell

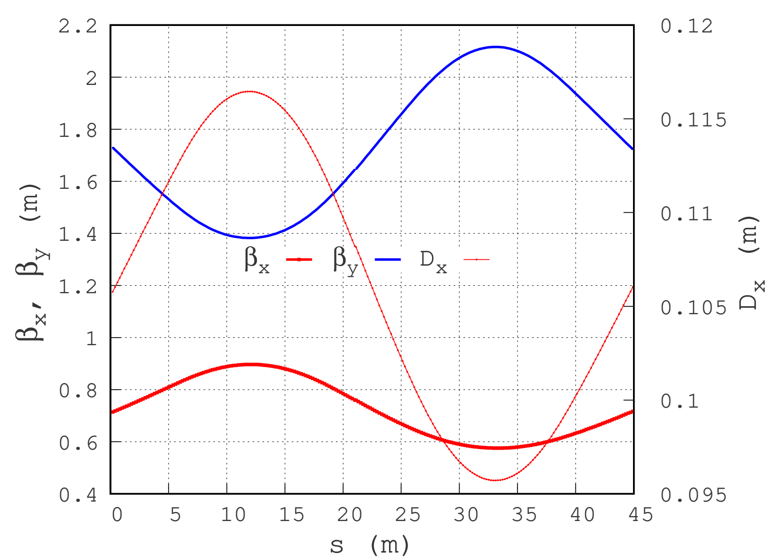
107 cells in CBETA return loop





Orbits and optical functions, from OPERA field maps:





Why use field maps ?

- All necessary material is available, so, why not just do it? (and, in passing... forget about questionable mapping approximations)

- FFAG experience dictates to do so... as Frank Coles wrote regarding Runge-Kutta tracking in MURA FFAGs - 1950s, via KEK and KURRI 150 MeV rings, RACCAM spiral magnet, the EMMA linear FFAG ring at Daresbury (CBETA arc cell is similar)

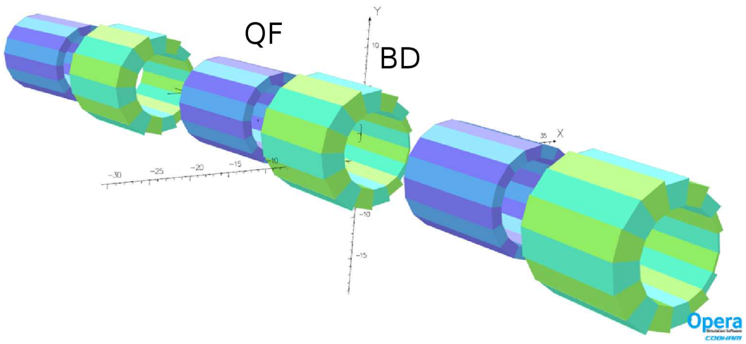
- Have closest-to-real-life simulation of the Halbach doublets return loop, over the all 8 passes (4 accelerated, 4 decelerated)

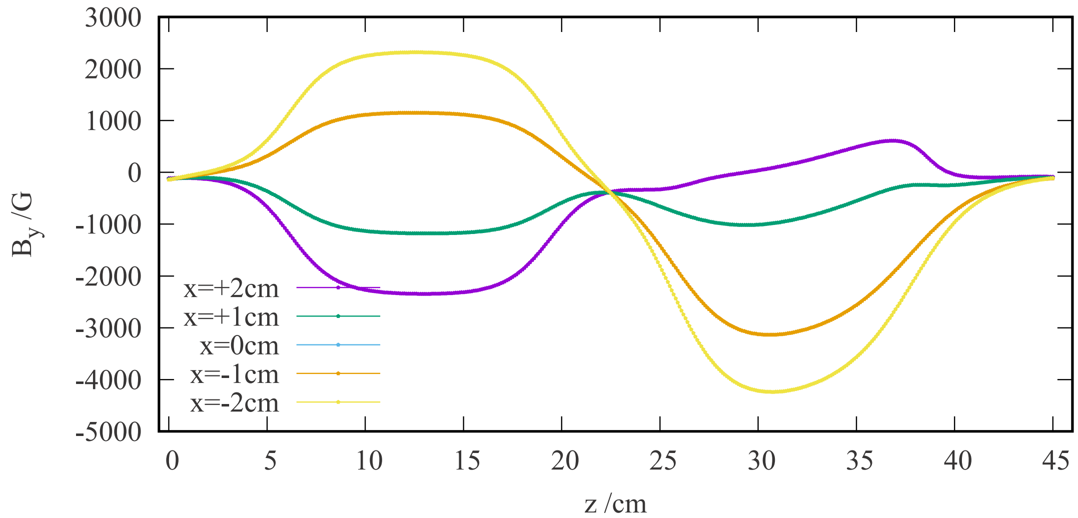
- Validation of the method includes the feasibility of:
  - using separate/overlapping QF and BD/QD field maps
  - including the effect of corrector yokes

- Interest of using separate field maps: flexibility in the modeling
  - independent fine-tuning of QF or BD Halbach magnet strengths
  - independent "PS" knob for each corrector field map
  - possibility of independent field & positioning errors/compensation
  - easier connection between sectors (FA, TA, ZA, ...)

OPERA simulation of CBETA cell

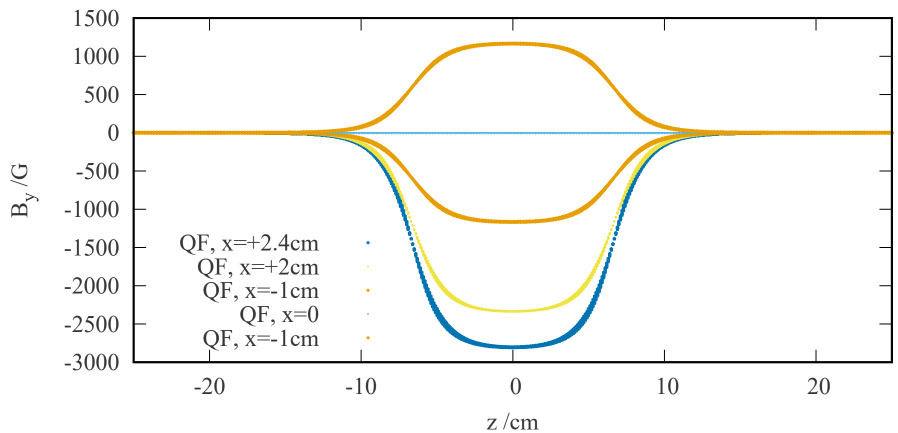
- Either a single full-cell field map:



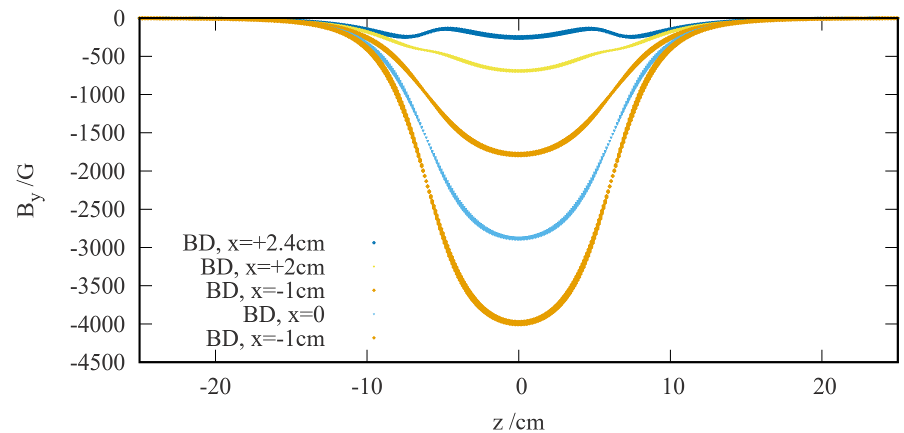


- Or, two separate field maps:

QF magnet



BD magnet



Code sequence for a 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
```

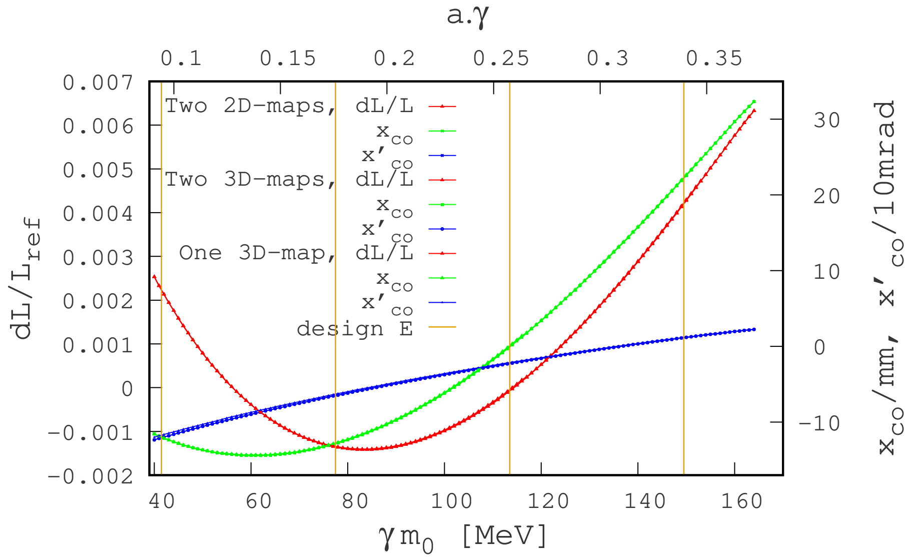
- **Separate QF, BD maps:**

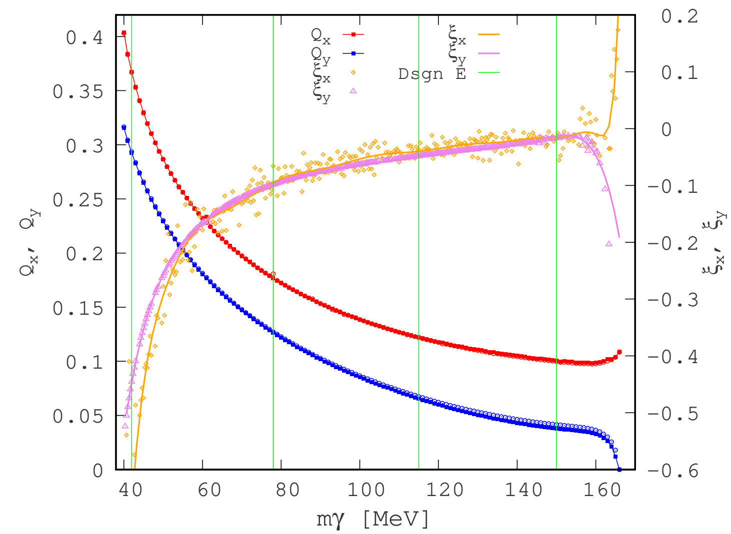
```
  'DRIFT'   HD2
6.15
  'DRIFT'
-18.35   ! = (50cm - 13.3cm)/2  (50cm is field map extent)
'TOSCA'   QF
0 0
-9.76E-04  1.  1.  1.
HEADER_8  ZroBXY
501 83 1 15.1  1.
 QF-3D-fieldMap.table
0 0 0 0
2
.2
2   0.00000000E+00  0.00000000E+00  0.00000000E+00
  'DRIFT'
-18.35   ! = (50cm - 13.3cm)/2   (50cm 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
```

Beam optics validations

• 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.)





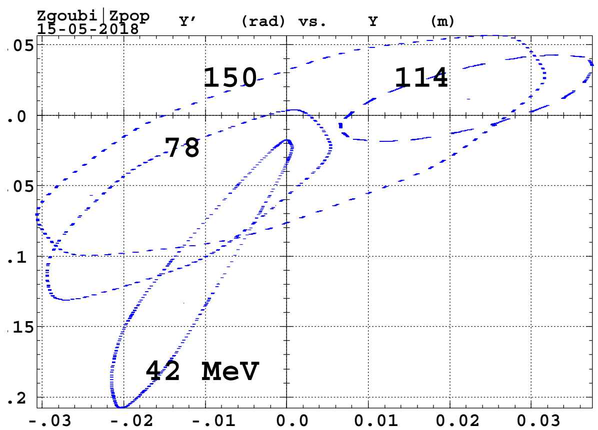
Path length across cell (cm)				
Difference is at few ppm level.				
E (MeV)	42	78	114	150
Single 3D map	44.4846	44.3298	44.3898	44.5806
Two 2D or 3D maps	44.4845	44.3291	44.3884	44.5797

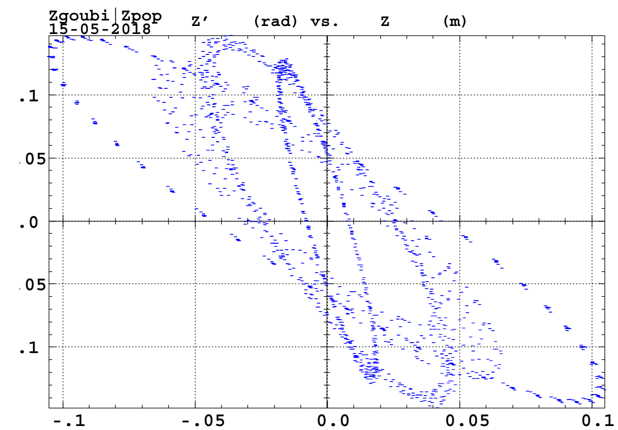
• DYNAMICAL ADMITTANCE, 400-CELL

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

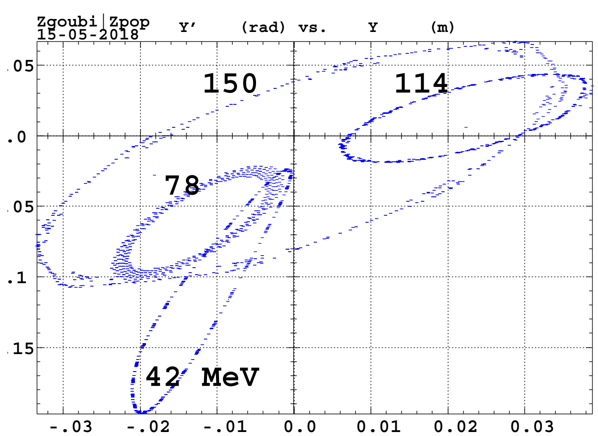
H **V**

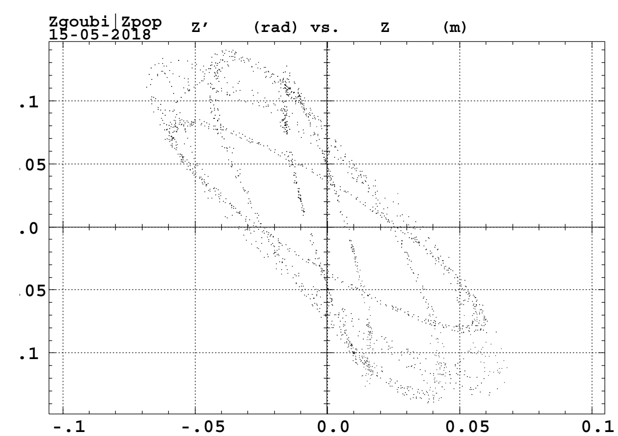
case of separate 2D field maps:





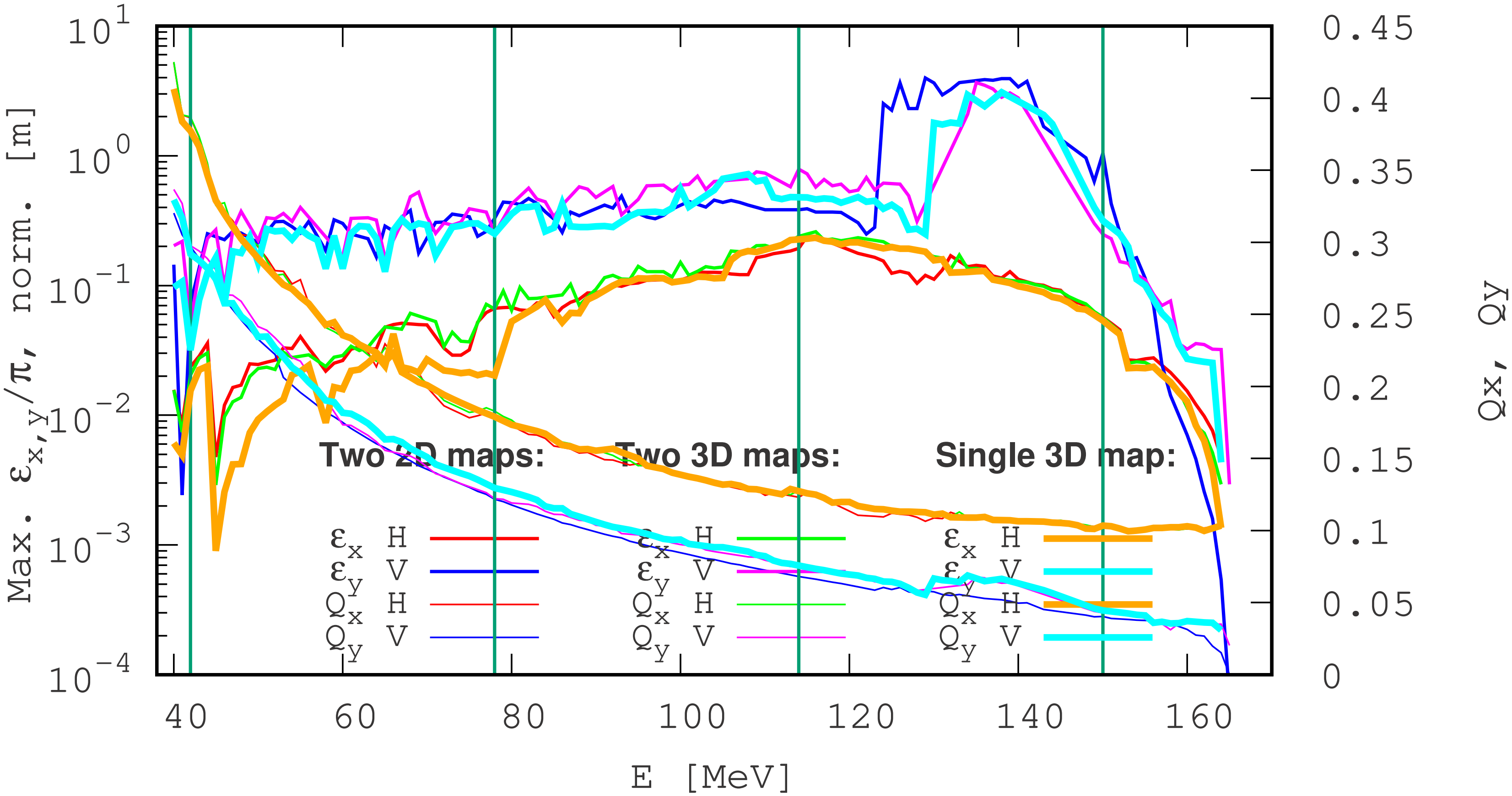
case of single 3D field map (same scales)





• DYNAMICAL ADMITTANCE, ENERGY SCAN

Maximum stable invariants and tunes, superimposed. Case of (i) separate QF, BD 2-D maps, (ii) single QF-BD 2-D, (iii) 3-D map



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

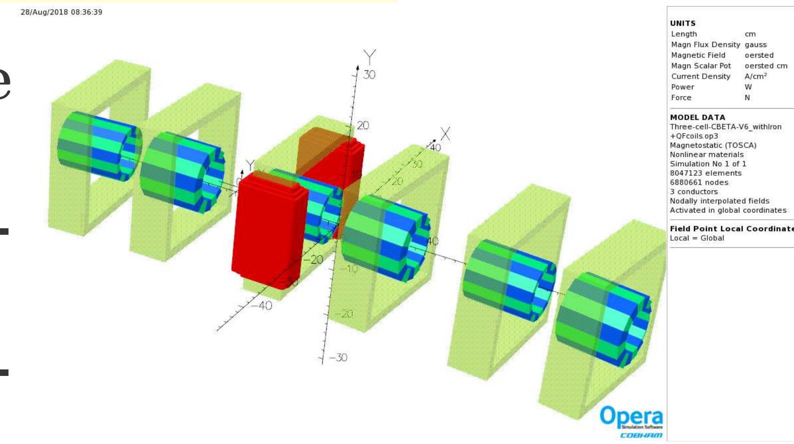
We want the cell model even fancier...

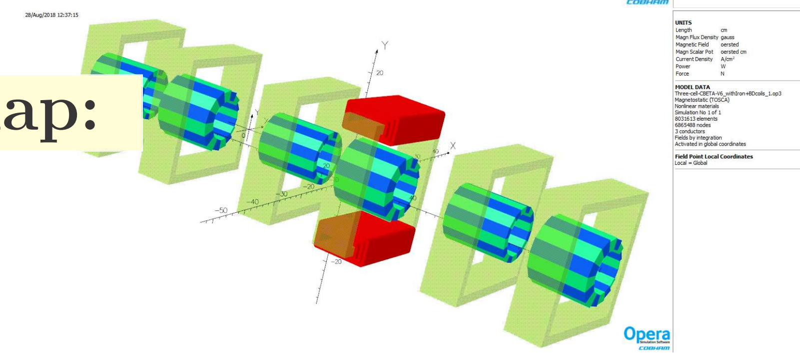
- Include iron steerers, with independent control

◇ 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



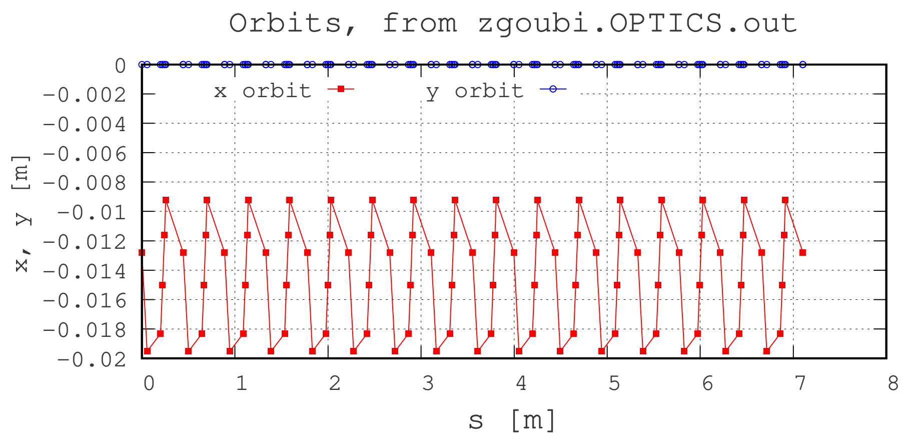


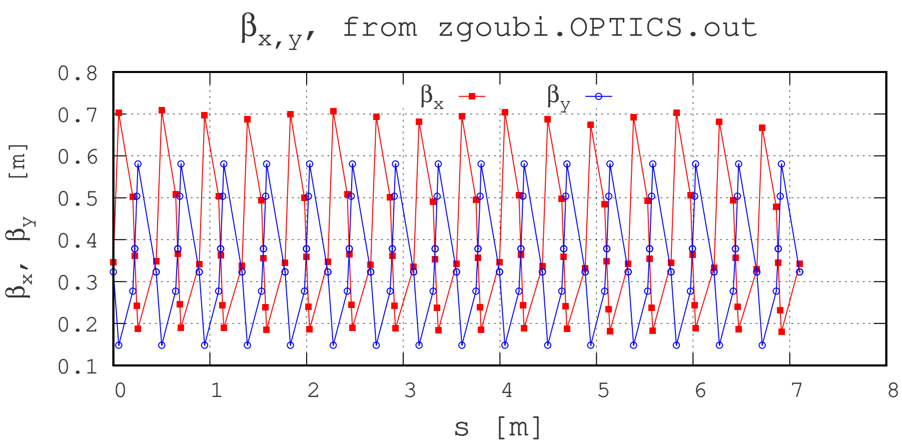
- Code sequence, case of single full-map:

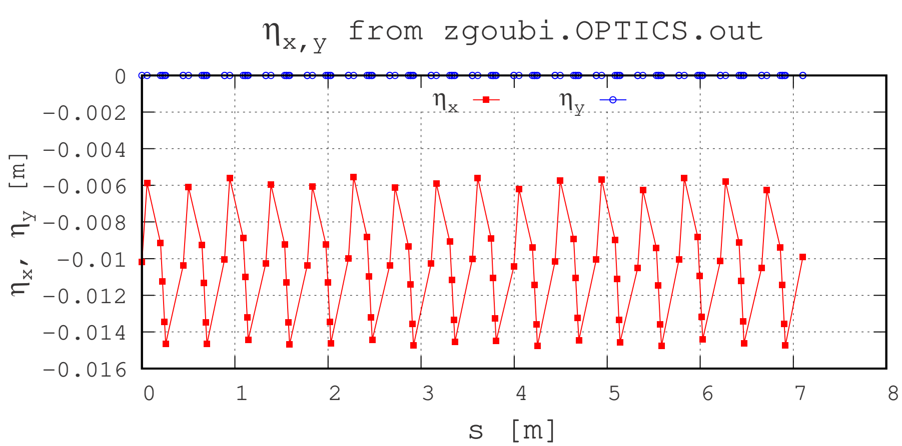
```
'TOSCA'   QF+BD map + corrector maps
0  0
-9.69871600E-04  1.  1.  1.
HEADER_8  ZroBXY
451 83 27 15.3  1.   0.01   0.00001   ! 3 independent knobs
3D-Cell-fieldMap.table
FConDCoff-3D-fieldMap.table
FCoffDCon-3D-fieldMap.table
1  482.028 42.172 -20328            ! integration boundary
2
.2                                  ! 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
```

The complete return loop is operational. Full field-map.

• FA (FB) arc optics:

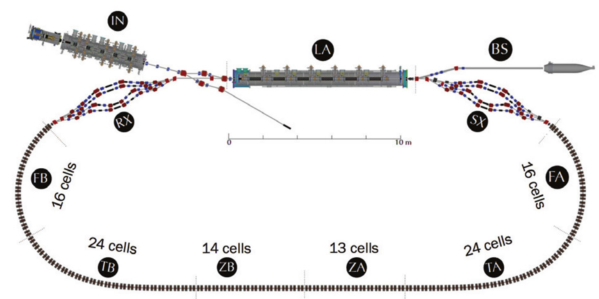






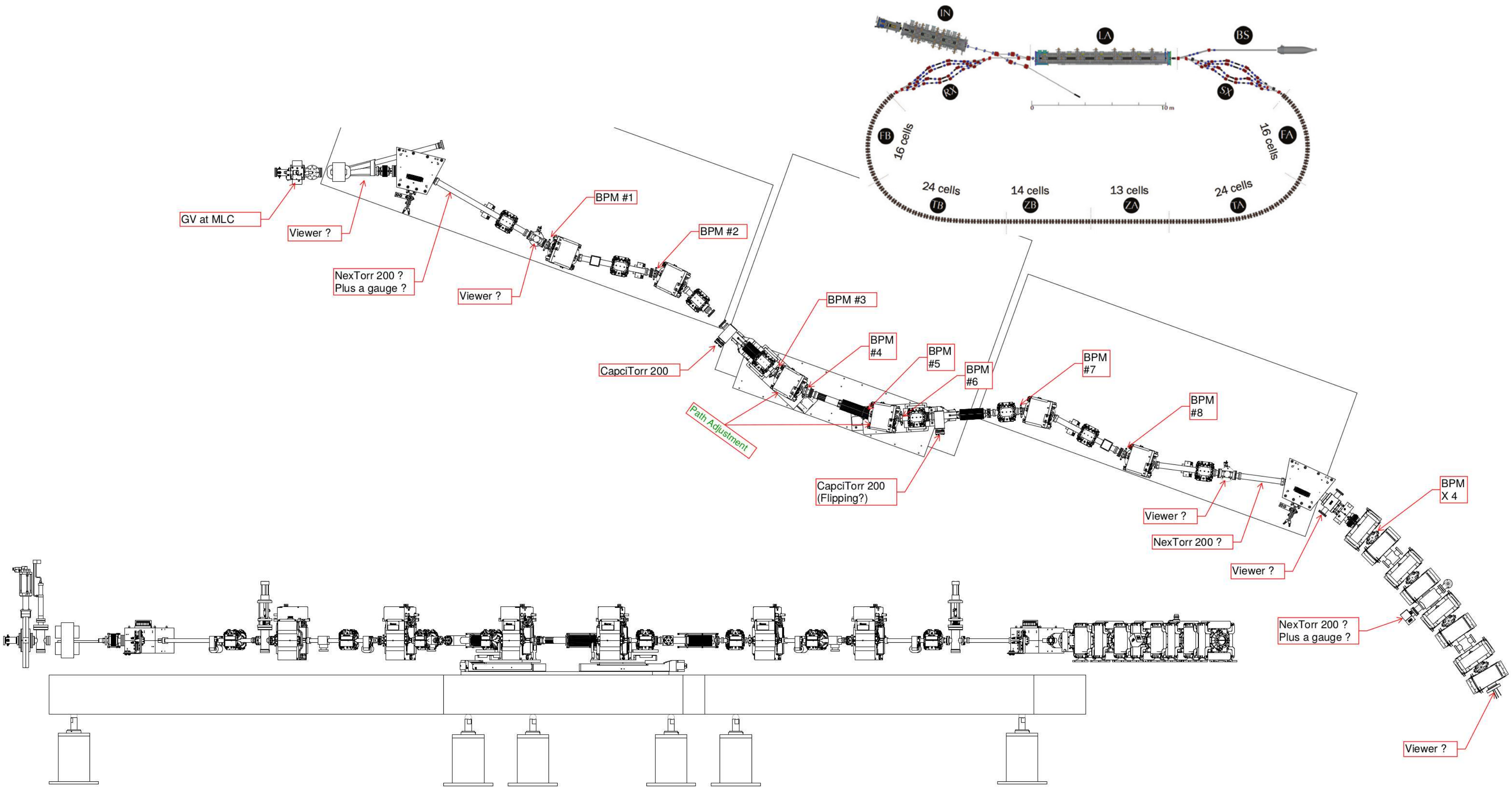
Two-map cell sequence:

```
'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 are under construction

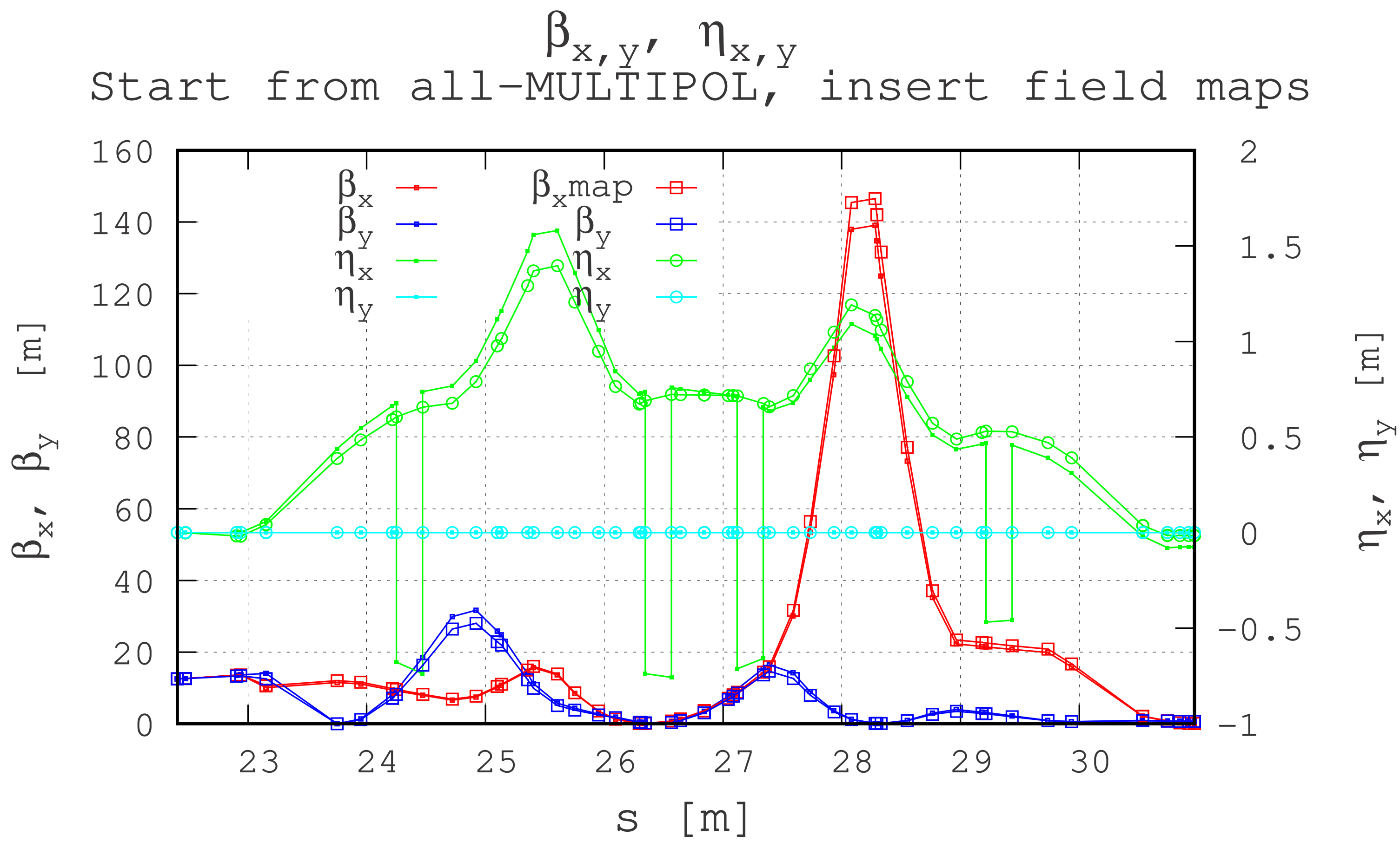
- The 42 MeV spreader line + start of FFAG arc:



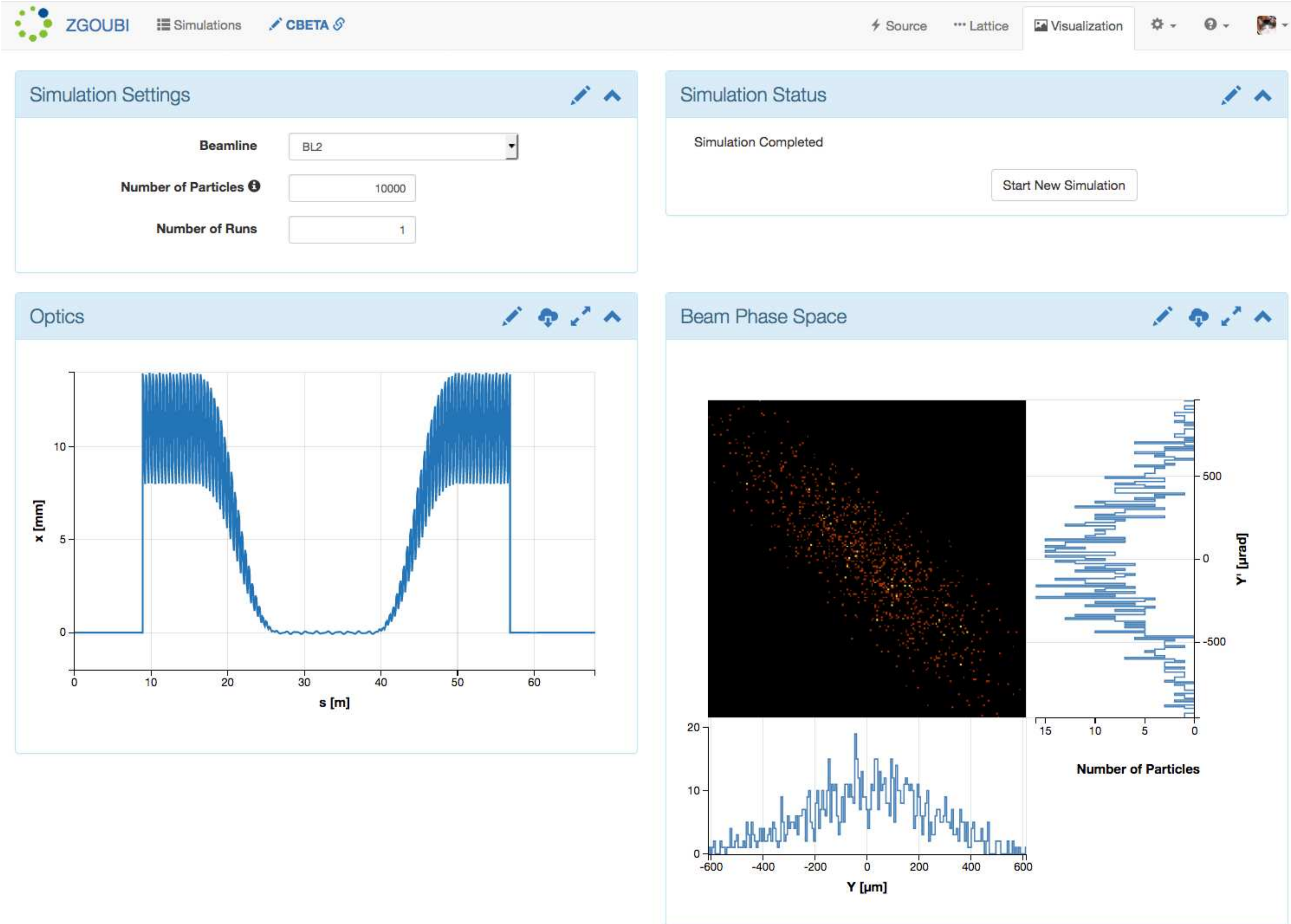
- In the code sequence, step by step, replace the analytical models of the quadrupoles and bends by their OPERA field maps

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

(former FFAG arc test optics, early 2018)



- **Working on the first turn in SIREPO environment**



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/

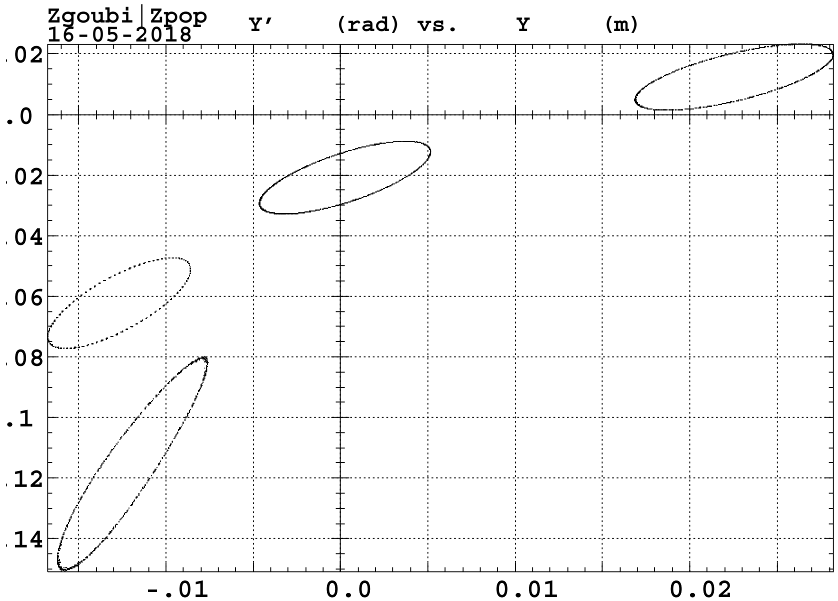
BACKUP SLIDES

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

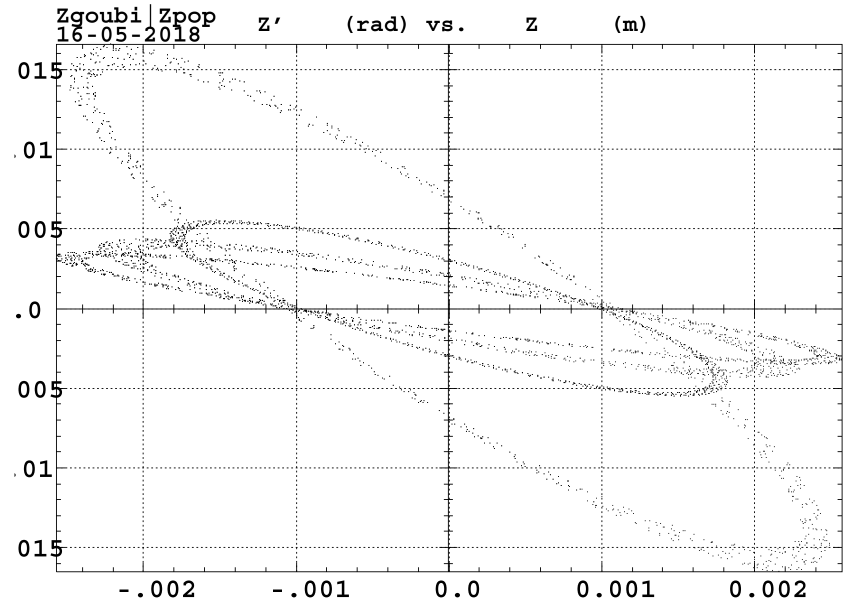
Parameter	Value	Unit
Largest energy	150	MeV
Injection energy	6	MeV
Linac energy gain	36	MeV
Injector current (max)	40	mA
Linac passes	8	4 accel. + 4 decel.
Energy sequence in the arc	$42 \to 78 \to 114 \to 150 \to 114 \to 78 \to 42$	MeV
RF frequency	1300.	MHz
Bunch frequency (high-current mode)	325.	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

- Tracking accuracy ?   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.