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

OR,

USING MODERN TOOLS TO DESIGN ACCELERATORS

F. Méot, S. Brook, D. Trbojevic, N. Tsoupas
Brookhaven National Laboratory
Collider-Accelerator Department
J. Crittenden
Cornell
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
  -9.6987160E-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 -1.887096 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
  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
  2
  .2
  2 0.00000000E+00 -.019 0.E+00 ! Y-offset -0.019cm = inward
  '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.

<table>
<thead>
<tr>
<th>E (MeV)</th>
<th>42</th>
<th>78</th>
<th>114</th>
<th>150</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single 3D map</td>
<td>44.4846</td>
<td>44.3298</td>
<td>44.3898</td>
<td>44.5806</td>
</tr>
<tr>
<td>Two 2D or 3D maps</td>
<td>44.4845</td>
<td>44.3291</td>
<td>44.3884</td>
<td>44.5797</td>
</tr>
</tbody>
</table>
• **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)
Maximum stable invariants and tunes, superimposed, case of (i) separate QF, BD 2-D maps, (ii) single QF-BD 3-D map

“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
  HEADER’8  ZroBXY
  451 83 27 15.3  1.  0.01  0.00001  ! 3 independent knobs

  3D-Cell-fieldMap.table
  FConDCoff-3D-fieldMap.table
  FCoeffDCon-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:

Orbits, from zgoubi.OPTICS.out

\[ x, y \text{ [m]} \]
\[ s \text{ [m]} \]

\[ x \text{ orbit} \]
\[ y \text{ orbit} \]

\[ \beta_{x,y}, \text{ from zgoubi.OPTICS.out} \]

\[ \beta_x \]
\[ \beta_y \]

\[ s \text{ [m]} \]

\[ \eta_{x,y}, \text{ from zgoubi.OPTICS.out} \]

\[ \eta_x \]
\[ \eta_y \]

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 1.0501
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 have large gap/width, gap/length,
- and in addition: they have fancy chamfers, shimming

The H1 dipole series:

(i) Hard-edge:

<table>
<thead>
<tr>
<th>s [cm]</th>
<th>B [kG]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.21700</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>0.9503</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

(ii) OPERA field map:

<table>
<thead>
<tr>
<th>s [cm]</th>
<th>B [kG]</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>0.9834</td>
</tr>
<tr>
<td>40</td>
<td>0.215709</td>
</tr>
<tr>
<td>50</td>
<td>0.983583</td>
</tr>
<tr>
<td>60</td>
<td>0</td>
</tr>
<tr>
<td>70</td>
<td>0</td>
</tr>
</tbody>
</table>
- 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, 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.

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