Benchmarking and Simulating the CBETA FFAG Arc Cell

Lattice Design	Scott Berg
Muon1 Simulations	Stephen Brooks
JSBFMD Simulations	Scott Berg
BMAD Simulations	Chris Mayes

Tracking Codes for CBETA

- BMAD

Used for end-to-end lattice, layout, tracking, some collective effects.
Needed some tweaking to track fieldmaps.

- PTC

Used for Cornell injector, good space charge model.

- Muon1

FFAG optimisation with fieldmap tracking or soft-edged magnet models.

- JSBFMD

FFAG design with fieldmaps, optimisation of fieldmap placement.

- JSBISD

FFAG design with hard-edged equivalent optics.

- Zgoubi (work in progress)

Will do nonlinear fieldmap tracking, spin tracking, end-to-end.

Code Comparison

Muon1 (by Stephen Brooks)

- Uses Cartesian global-frame coordinates
- Tracks in t
- Runge-Kutta 4th order
- Fixed timestep of 10ps (I sometimes lower this to 5ps for CBETA, very little difference)
- Fieldmaps are interpolated trilinearly (occasionally leads to rough edges when finding tunes)

JSBFMD (developed recently for CBETA by Scott Berg)

- Uses cylindrical polar coordinates (r,theta,y)
- Tracks in theta
- Also Runge-Kutta 4th order
- Fieldmaps are fitted with smooth splines and particles are tracked through the spline fit

BMAD

- Hard-edged fit to CBETA cell

NB: previous work for eRHIC got good agreement on an FFAG lattice between Muon1, Zgoubi, MAD-X+PTC and SYNCH

CBETA FFAG Arc Cell Lattice

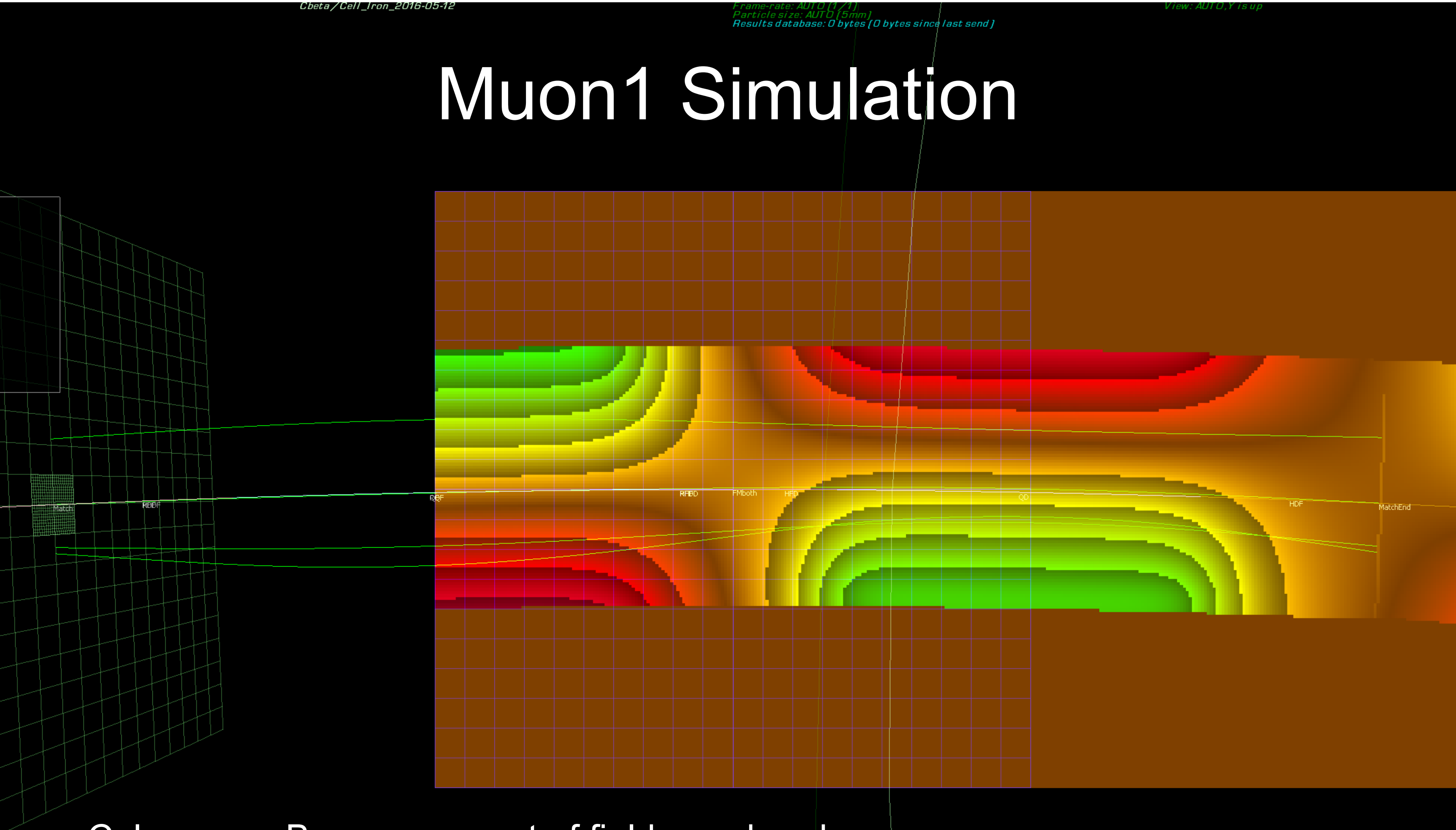
Table 2.6.1: Hard edge arc cell design parameters.

Injection Total Energy (MeV)	6	
Maximum Total Energy (MeV)	150	
Linac Passes	4	
Reference Radius (m)	5.099439	
L_{DF} (mm)	120	
L_{FD} (mm)	70	
α	F	D
$L_{Q\alpha}$ (mm)	133	122
x_{α} (mm)	−7.182	+20.132
Gradient (T/m)	+10.621	−10.017

Table 2.6.2: Horizontal displacements for the real magnets, determined using field maps.

x_F (mm)	−4.089
x_D (mm)	+17.313

Muon1 Simulation



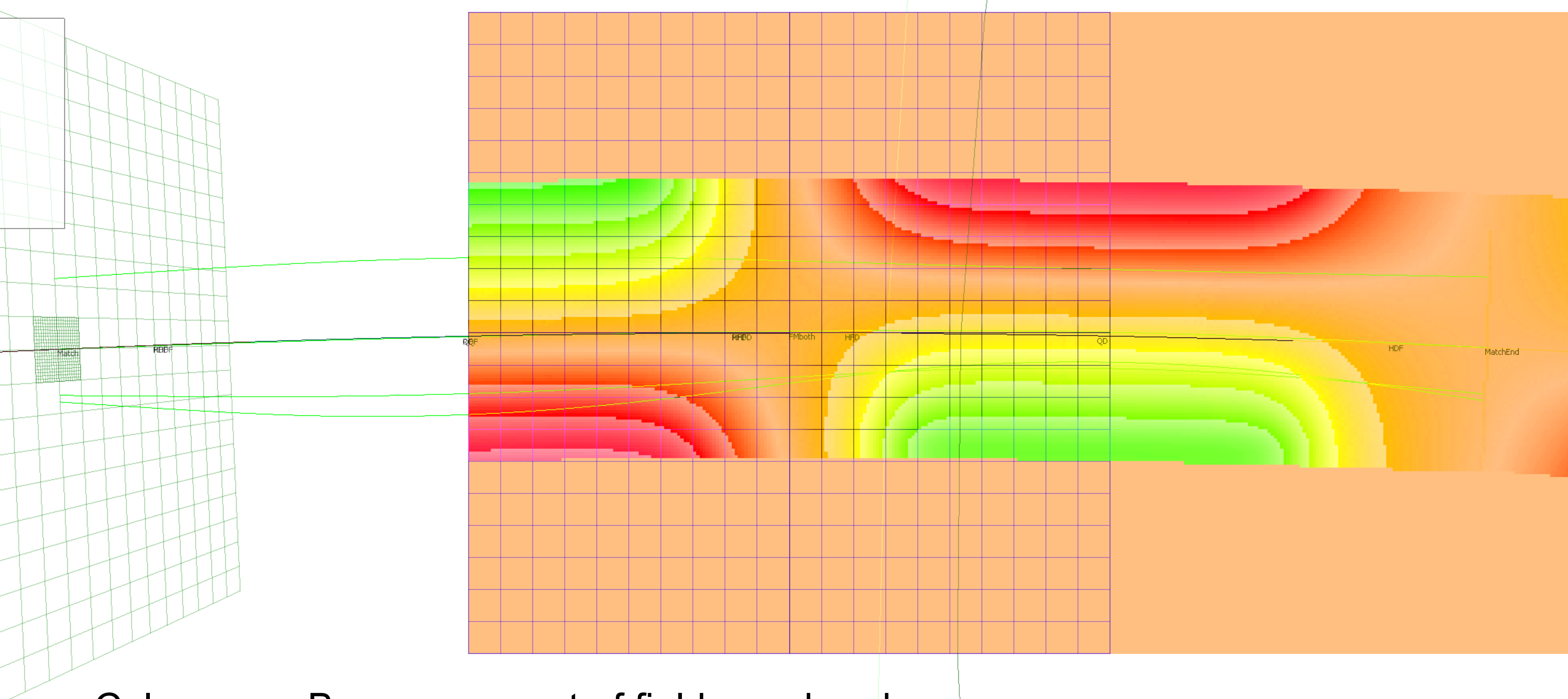
Colours are B_y component of fieldmap, bands are 0.1T intervals, dark orange band = 0

Cbeta/Cell_Iron_2016-05-12

Frame-rate: AUTO (1/1)
Particle size: AUTO (5mm)
Results database: 0 bytes (0 bytes since last send)

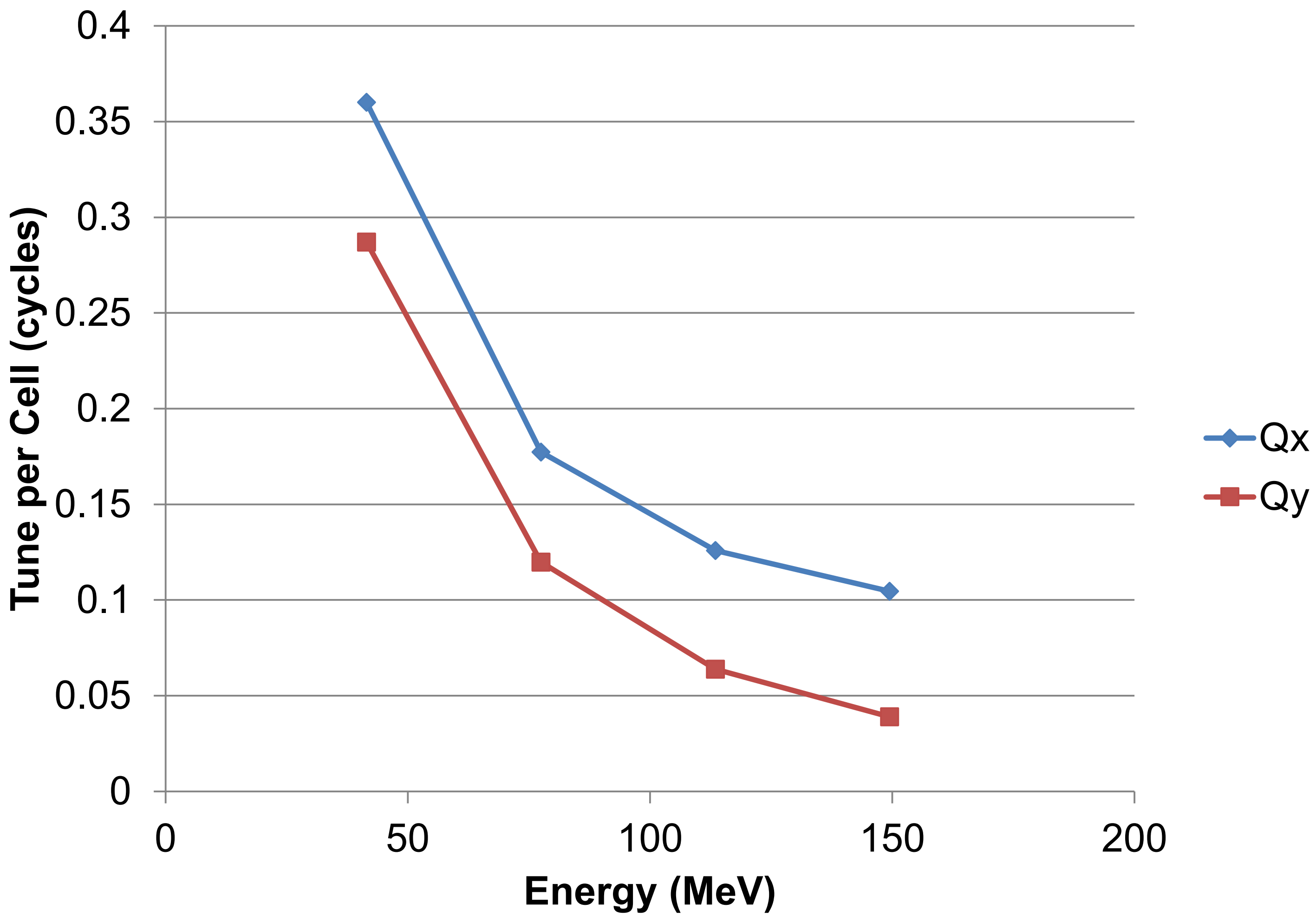
View: AUTO,Y is up

Muon1 Simulation

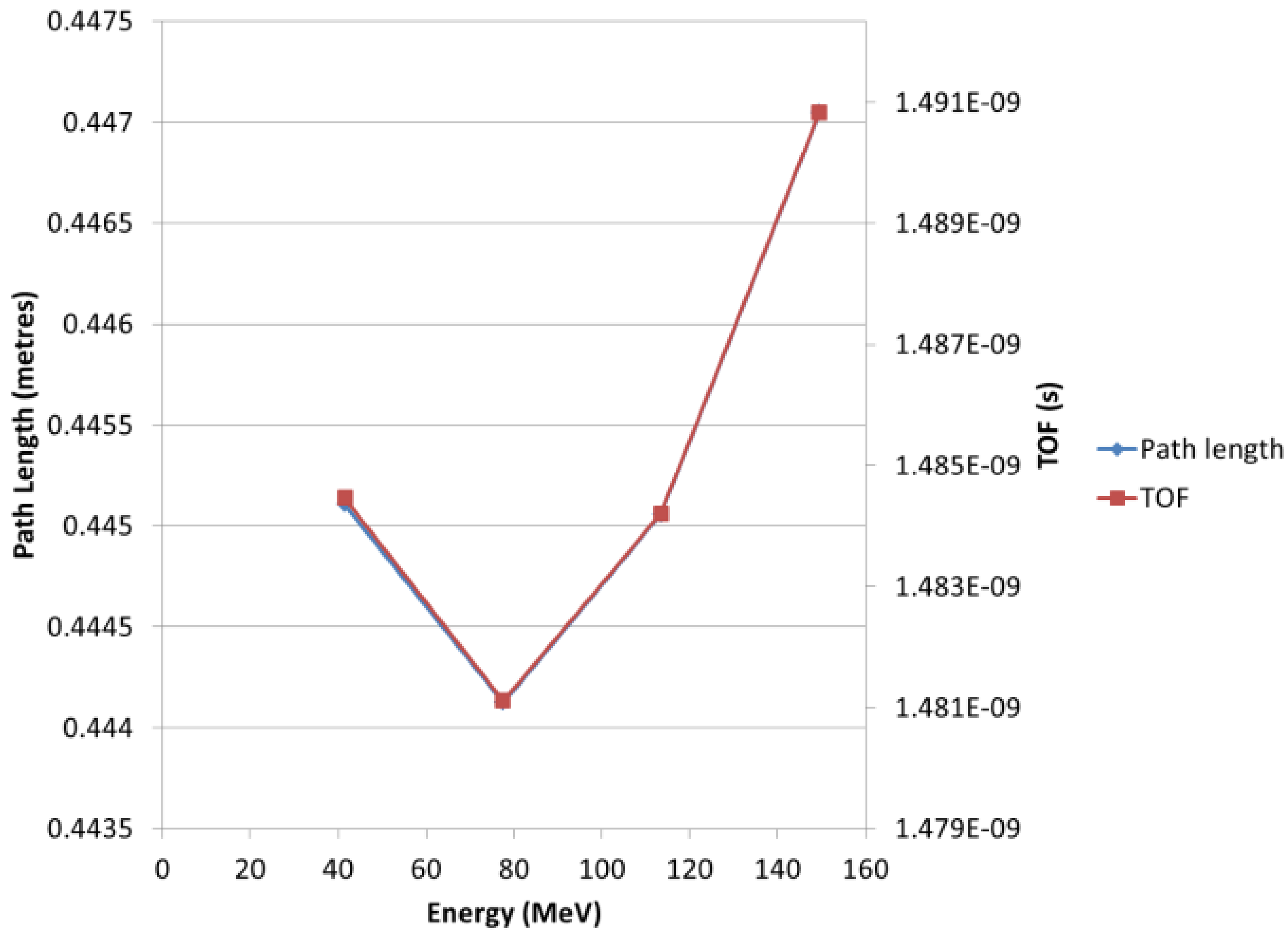


Colours are B_y component of fieldmap, bands are 0.1T intervals, dark orange band = 0

Cell Tunes from Muon1



Cell Path Length and TOF



Cell Tunes from Both Codes

Total Energy (MeV)	Muon1 Cell Tune X	JSBFMD Cell Tune X	BMAD Cell Tune X	Muon1 Cell Tune Y	JSBFMD Cell Tune Y	BMAD Cell Tune Y
42	0.360041	0.363443	0.361953	0.286975	0.289387	0.290147
78	0.177298	0.178187	0.177897	0.119886	0.120718	0.121138
114	0.125858	0.126546	0.124989	0.063870	0.064455	0.063132
150	0.104551	0.105049	0.103141	0.039038	0.039960	0.039837

Only the first turn (42MeV) is in the region susceptible to strong resonances. The rest of the turns are in the pseudo-continuous phase advance regime.

The low tune is always the Y tune at the highest energy. Going higher makes it difficult to find a lattice with practical field strengths. Going lower makes optics sensitive to focussing errors and not enough phase advance for “adiabatic” transition from FFAG arc to straight.

CBETA FFAG Arc Cell (and Holger's Fieldmaps) Imported Into Muon1

File "Cbeta/Cell_Iron_2016-05-12"

```
{Scott's 150MeV lattice from "160507-JSBerg" folder, using Holger's
fieldmaps from "160512-FieldMap" subfolder}

#h   = +1.9610000439244032e-01;
#R=1.0/h;

#lqf  = +1.3300000000000001e-01;
#lqd  = +1.2200000000000000e-01;
#lfd  = +7.0000000000000007e-02;
#ldf  = +1.2000000000000000e-01;

#thqf=2*asin(0.5*lqf/R);
#thqd=2*asin(0.5*lqd/R);
#thfd=2*asin(0.5*lfd/R);
#thdf=2*asin(0.5*ldf/R);

{Drift Length Angle}
DF #R*thdf# #thdf*-1#
QF #R*thqf# #thqf*-1#
FD #R*thfd# #thfd*-1#
QD #R*thqd# #thqd*-1#
HDF #DF.Length/2# #DF.Angle/2#
HFD #FD.Length/2# #FD.Angle/2#
```

Scott's parameters
h is inverse radius

Convert chord lengths to arc lengths

Define empty circular arc elements (radius R) for layout reference

Half-elements

```
#scalboth = 1; dispboth = 0;
#scalF = 1; scalD = 1;
#dispF = 0; dispD = 0;

{TrilinearFieldMap File Strength Xrel MirrorY=1}
FMboth Cbeta\Iron_2016-05-12\160308a-38-
48_5deg150MeVCombQdOnQfOn_polar.txt #scalboth*-1# #dispboth-
R#
FMF Cbeta\Iron_2016-05-12\160308a-38-
48_5deg150MeVSepQfOn_polar.txt #scalF*-1# #dispF-R#
FMD Cbeta\Iron_2016-05-12\160308a-38-
48_5deg150MeVSepQdOn_polar.txt #scalD*-1# #dispD-R#

CellFM: HDF,QF,HFD,FMboth,HFD,QD,HDF;
CellFMsep: HDF,QF,HFD,FMF,FMD,HFD,QD,HDF;

#Emin = +4.2000000000000000e+07;
#Emax = +1.5000000000000000e+08;
#n    = 4;

#EmasseV=510998.928;
{MatchScan Estart Egoal Estep Species=Electron AllowUnstable=1}
Match #Emax-EmasseV#eV #Emin-EmasseV#eV #(Emax-Emin)/(n-
1)#eV
MatchFine #Match.Estart# #Match.Egoal# 1MeV

{Match-Aperture}
MatchEnd

CellFM,Match,CellFM,MatchEnd,CellFM;
```

No scaling or displacement for final fieldmap version

Fieldmaps

Cell definitions

Scott's energy range
Number of passes
Units, total E. -> k.e.

Place 3 cells to allow fringe field overlaps

Focus: Aligning the Fieldmaps

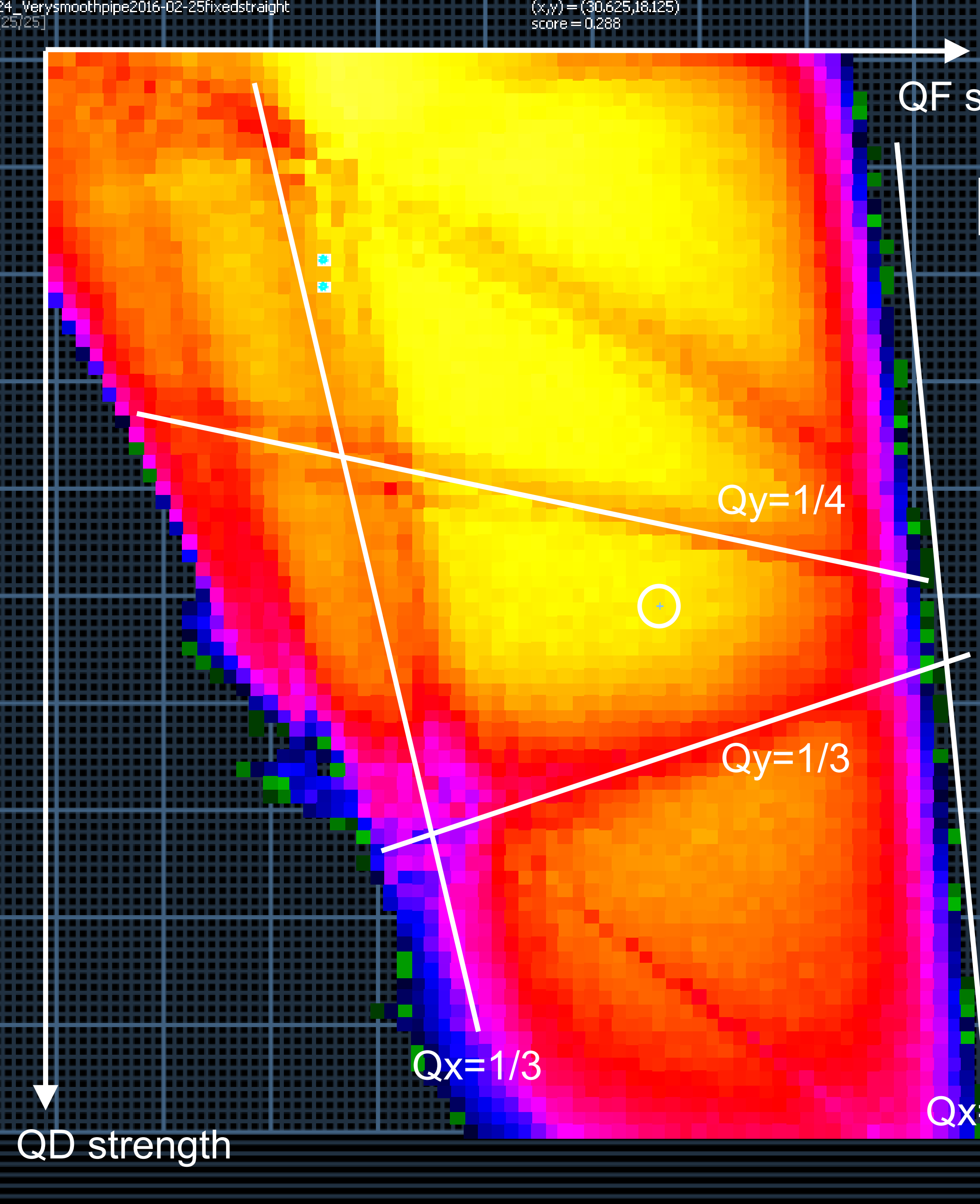
```
{TrilinearFieldMap File Strength Xrel MirrorY=1}
FMboth Cbeta\Iron_2016-05-12\160308a-38-48_5deg150MeVCombQdOnQfOn_polar.txt #scalboth*-1# #dispboth-R#
FMF Cbeta\Iron_2016-05-12\160308a-38-48_5deg150MeVSepQfOn_polar.txt #scalF*-1# #dispF-R#
FMD Cbeta\Iron_2016-05-12\160308a-38-48_5deg150MeVSepQdOn_polar.txt #scalD*-1# #dispD-R#
```

3 fieldmaps with long file names
Field magnitude is inverted due to difference in curvature direction (JSBFMD vs. reality)
Relative position in local X is "-R", i.e. origin is centre of radius R circle
Mirrored in Y to give both positive and negative Y

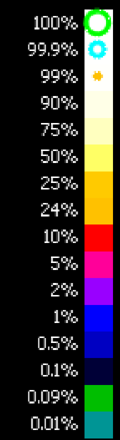
```
CellFM: HDF,QF,HFD,FMboth,HFD,QD,HDF;
CellFMsep: HDF,QF,HFD,FMF,FMD,HFD,QD,HDF;
```

For each version of the cell (combined or separate fieldmaps), the maps are placed at the centre of the F-to-D (short) drift
The cell entrance/exit is the centre of the D-to-F (long) drift

Resonance Plot



Plot of aperture (transmission of v.large 1cm-radius beam) as a function of two focussing strengths

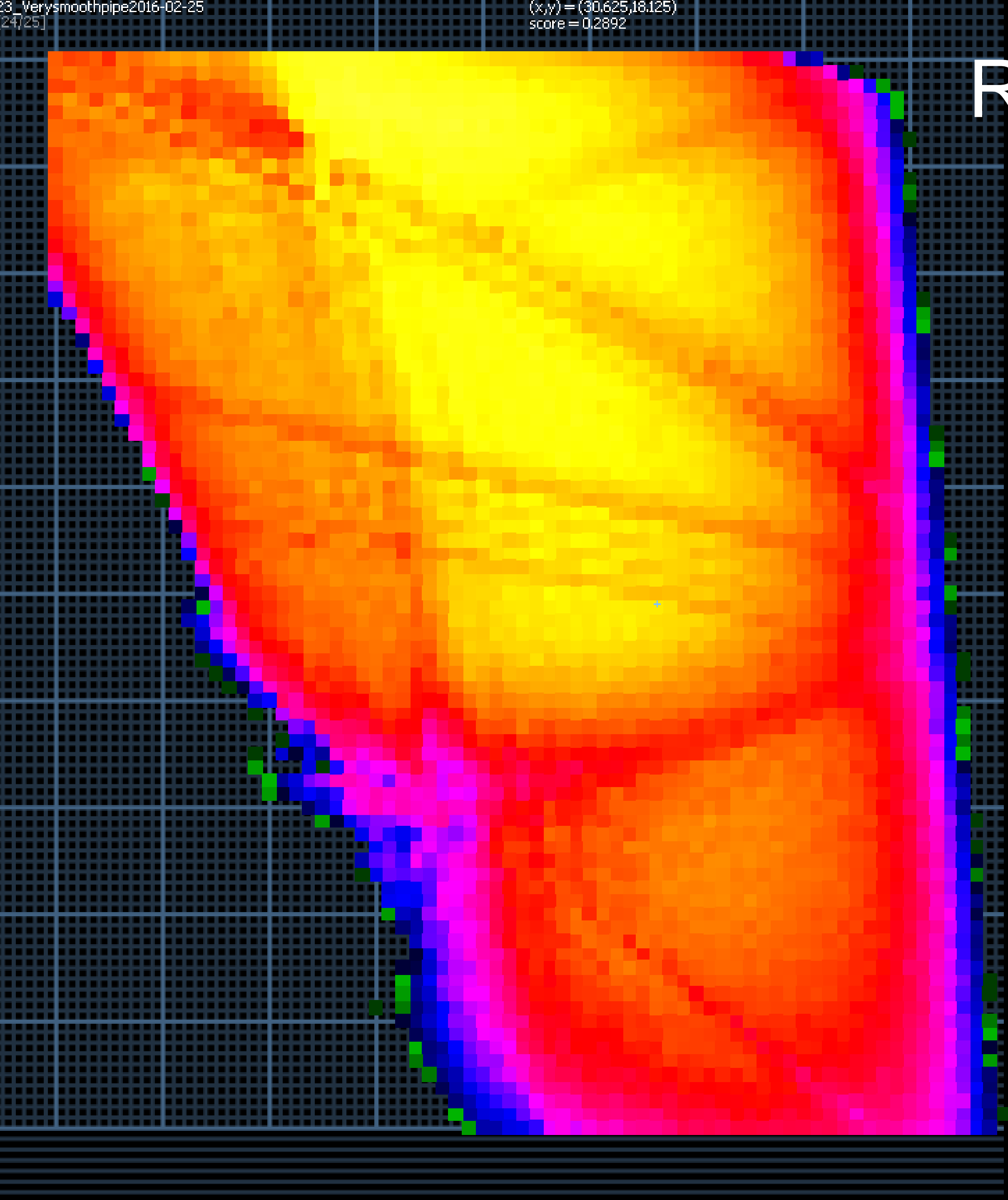


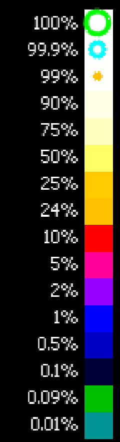
For lowest-energy pass, highest tunes.

Working point circled:
(Qx,Qy) = (0.360,0.287)

Resonance Plot

before adjustment to straight drift lengths





Resonance band features broadened because straight section has different tunes to arcs. Can fix by adjusting straight section drift lengths.

Conclusions

- The CBETA FFAG has been simulated in JSBFMD, Muon1 and BMAD
- These codes have very different internal operation yet we get consistent results
- Arc-to-straight match has been optimised for an old lattice, currently being optimised for the newest version