Non-Scaling FFAG Arc test at ATF

Thanks to:

George Mahler – engineering

John Cintorino, Animesh Jain – magnet measurement

Stephen Brooks, sbrooks@bnl.gov,

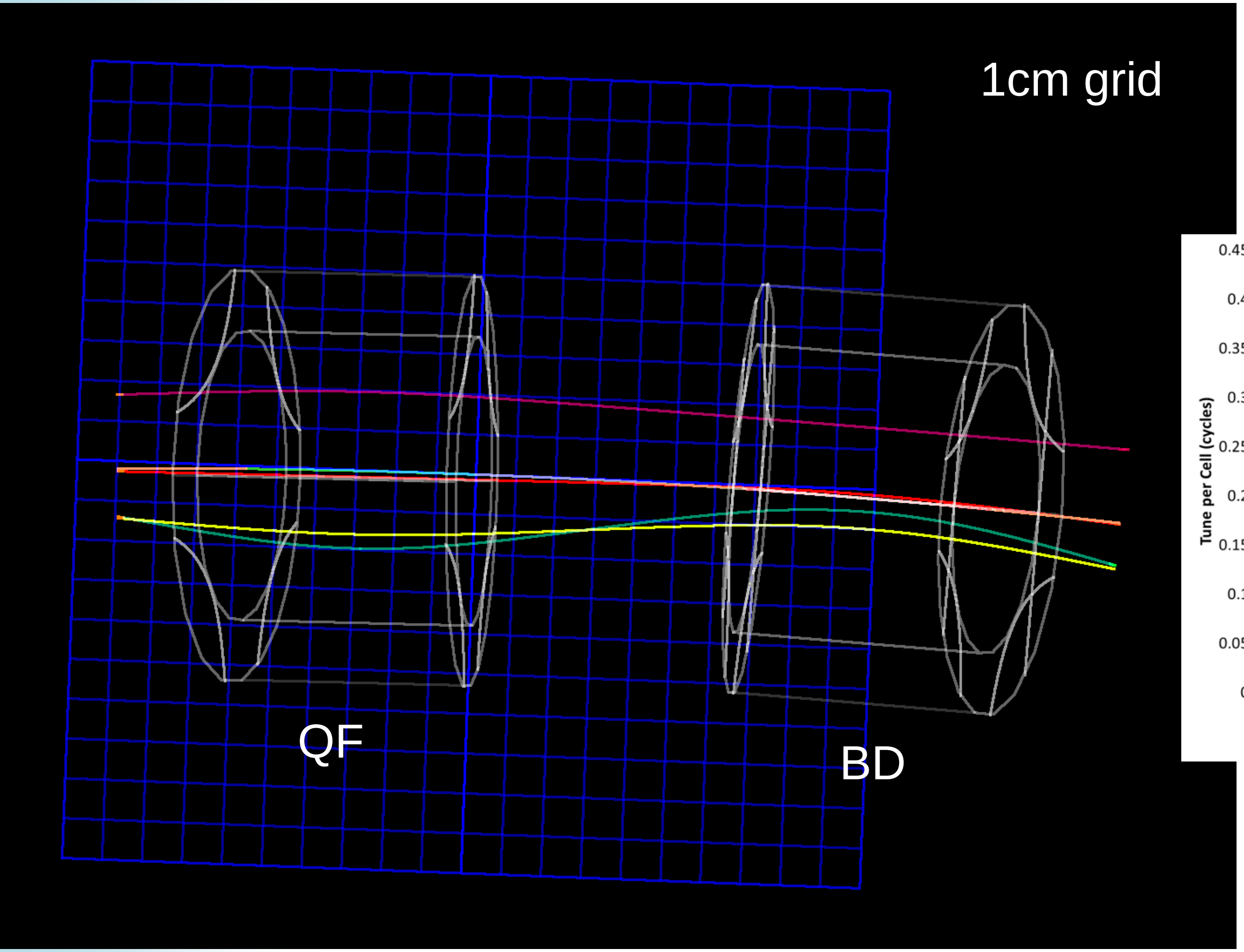
Motivation

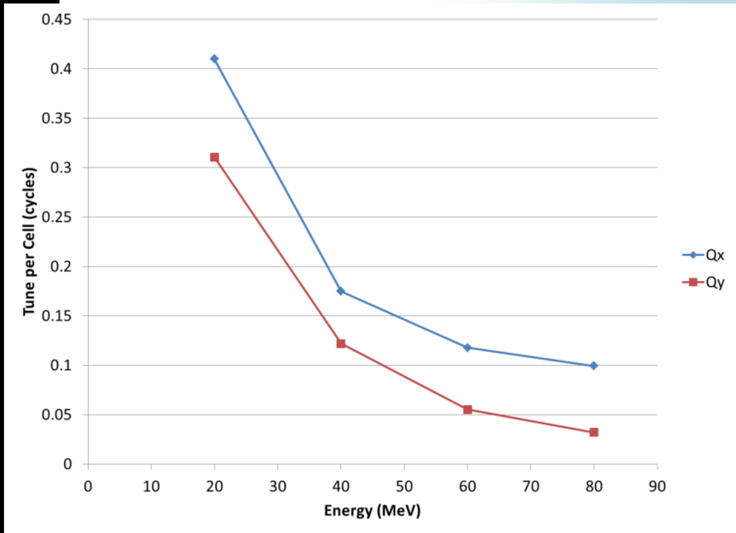
- An FFAG transmits multiple energies (on different paths) within a single fixed-field magnet lattice
- eRHIC is a multi-pass ERL and this reduces the cost of return lines around the RHIC tunnel
- Not many FFAGs have been built
- Only non-scaling (linear field) one so far was EMMA and that achieved ~1.7x energy range

New Technology

- Halbach-derived permanent magnets
  - Developed at BNL, novel geometry, generalised shimming method, use of 3D printing, cheap
- Beamline resembles segment "FFAG gantry" for hadron therapy (work by Dejan Trbojevic)
  - Allows rapid energy scanning (depth in tissue)
  - Permanent magnets can't reach the highest energies but are far lighter than superconducting or iron magnets (~1 ton gantry vs. ~50 tons)

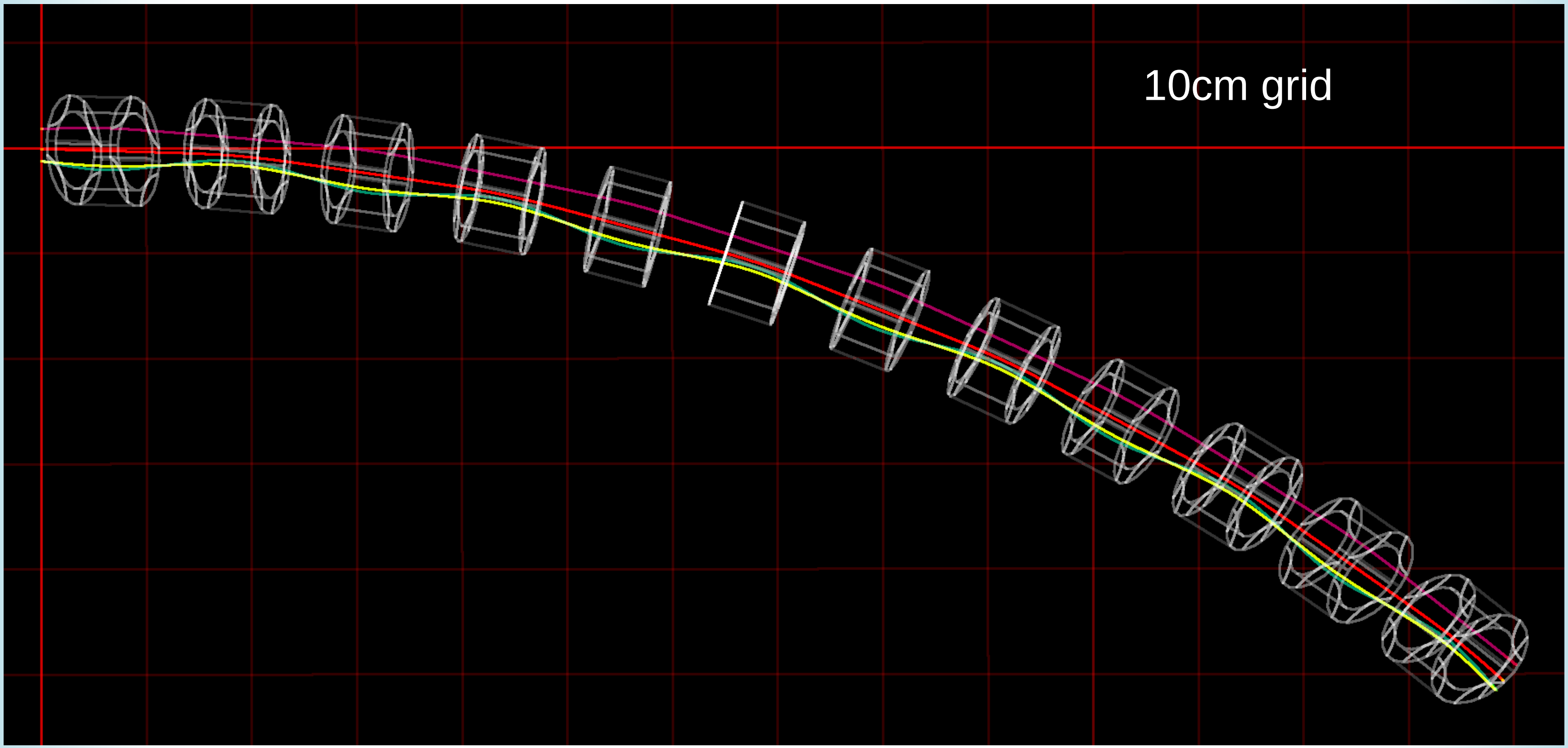
20-80MeV Orbits in a NS-FFAG Cell





Stephen Brooks, sbrooks@bnl.gov,
ATF users' meeting 2016

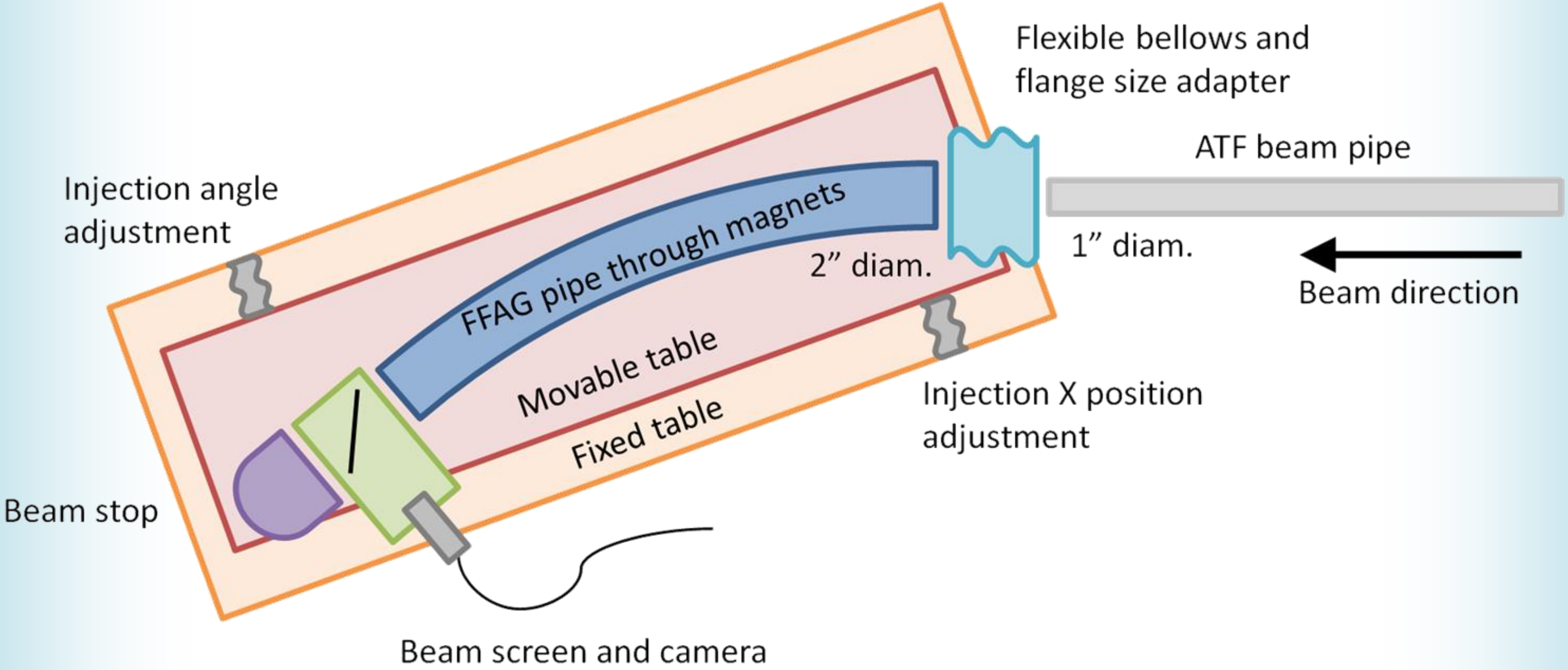
Orbits in Proposed ATF Beamline



Experiment

- Goal: achieve wide energy range ≥2x and potentially up to 4x in a NS-FFAG for first time
- Tune ATF to different energies in the 20-80MeV range and for each:
  - Transmit beam to beam screen at end of line
  - Change input (x,x') and watch output x response
  - Response should be linear → 2 matrix entries
  - Gives phase advance as function of energy
  - Maybe kick in y axis too

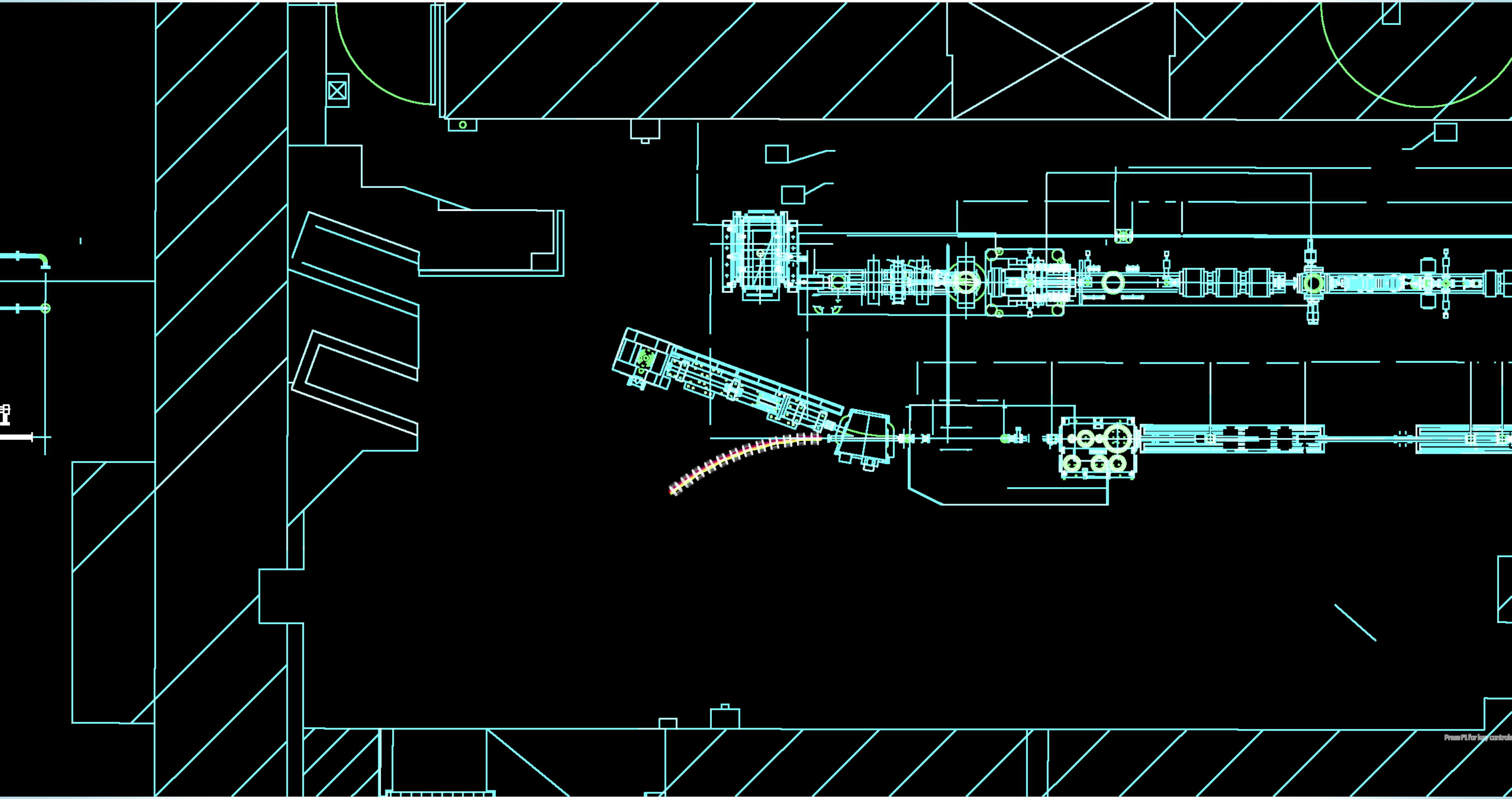
Outline of Main Components

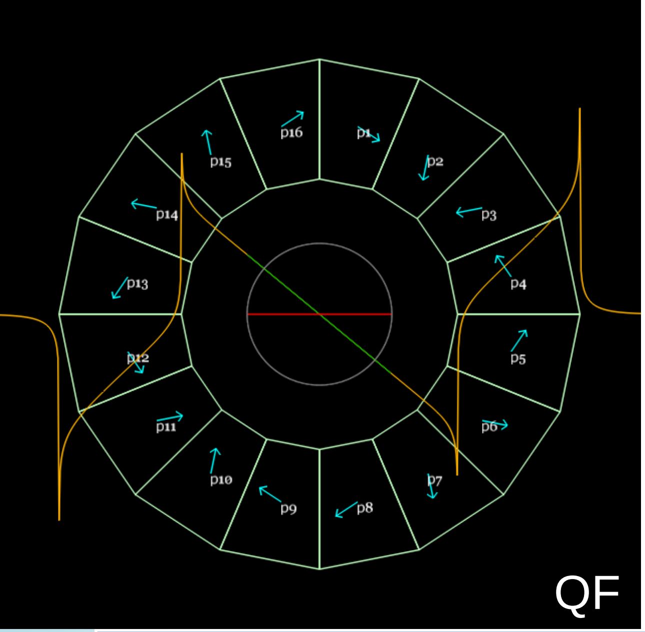


NS-FFAG Beamline Parameters

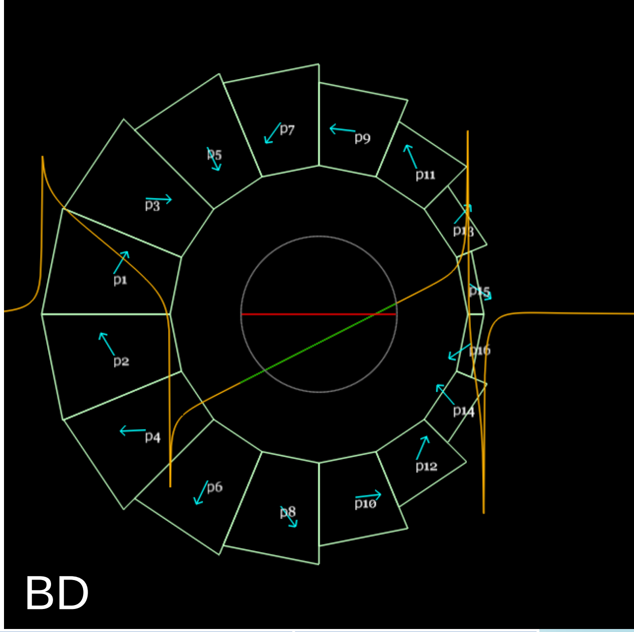
Parameter	Value	Units
Particle species	Electron	
Energy range	20-80	MeV
Cell Length	0.251751	m
Cell Angle	6.666…	degrees (54 per turn)
R = avg. radius of curvature	2.16364	m
Max orbit excursion	19.83	mm (from circle radius R)
Tune range per cell	$Q_{y,80} = 0.032$, $Q_{x,20} = 0.410$	cycles
Cell lattice	halfD2, QF, D1, BD, halfD2	
Drift lengths	D1 = 67.55, D2 = 64.90	mm
Number of cells	6	
Total length	1.51051	m
Total angle	40	degrees

One Possible Location at ATF





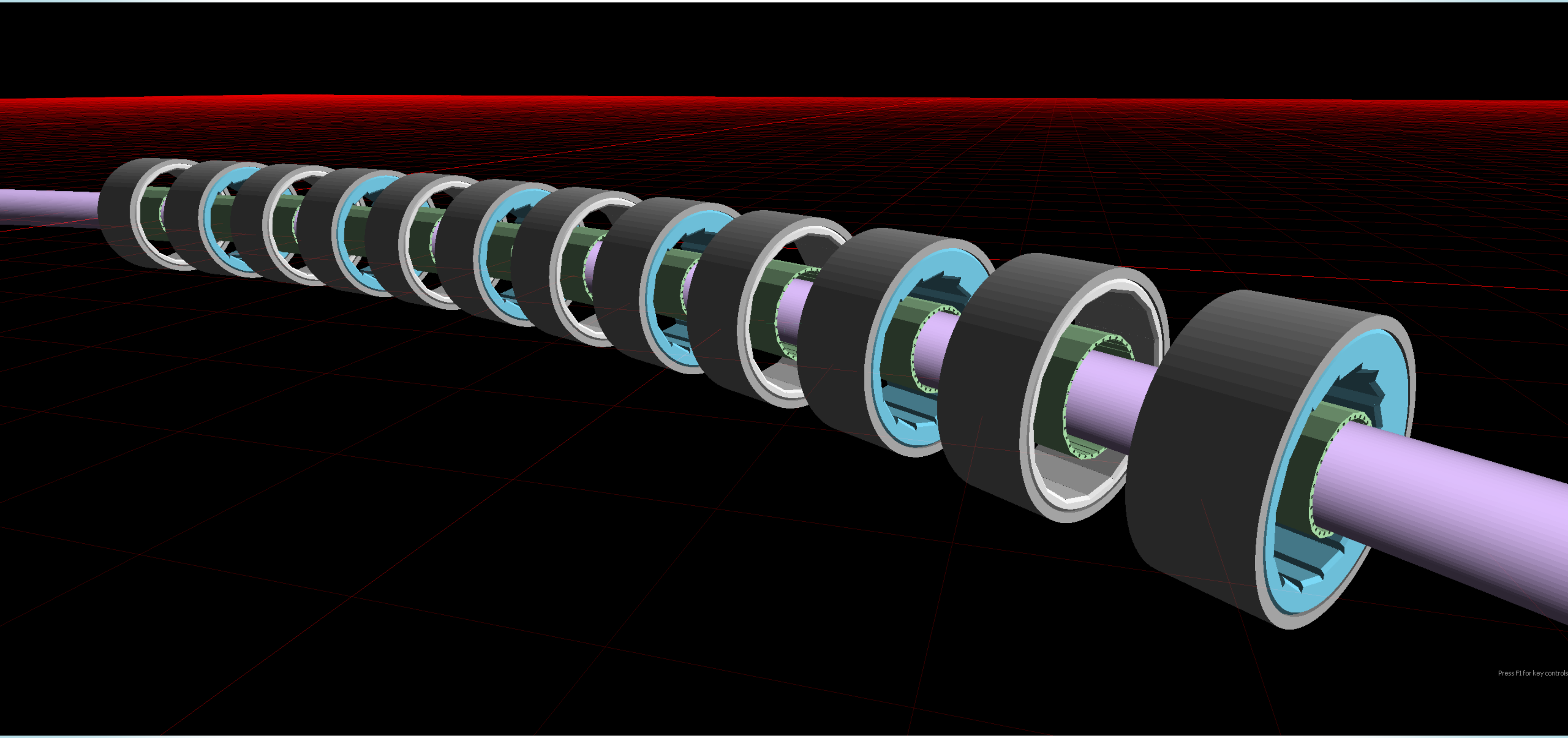
Magnet Design and Parameters



Parameter	"QF" magnet	"BD" magnet	Units
Length	57.44	61.86	mm
Dipole $B_y(x=0)$	0	-0.37679	T
Quadrupole dB_y/dx	-23.624	19.119	T/m
Inner radius (magnet pieces)	37.20	30.70	mm
(shim holder)	34.70	27.60	mm
"Pole-tip" field (magnet pieces)	0.879	(-)0.964	T
Outer radius (magnet pieces)	62.45	59.43	mm
(tubular support)	76.2	76.2	mm

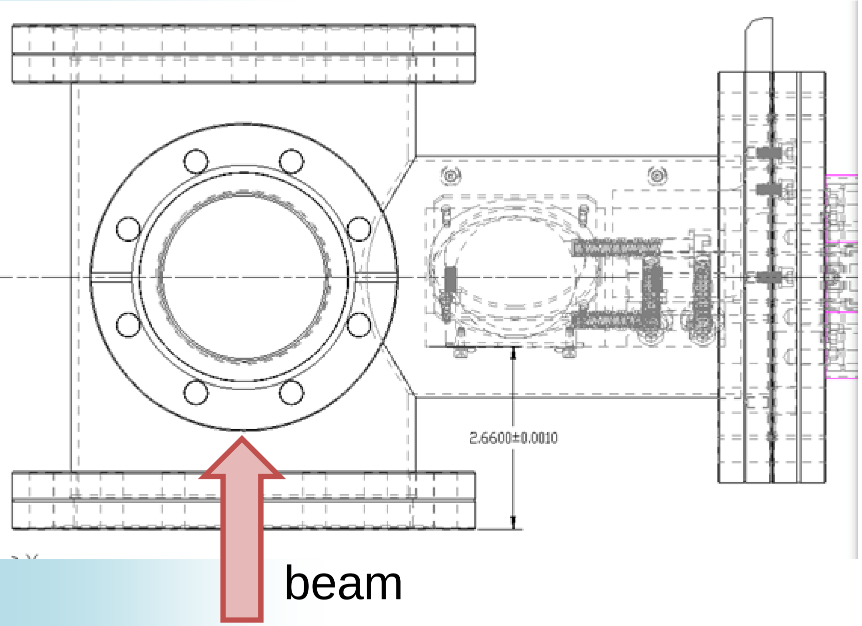
All the magnets have already been built as part of CBETA R&D. Shimming (left) has been done on 5 out of 12 with good results.

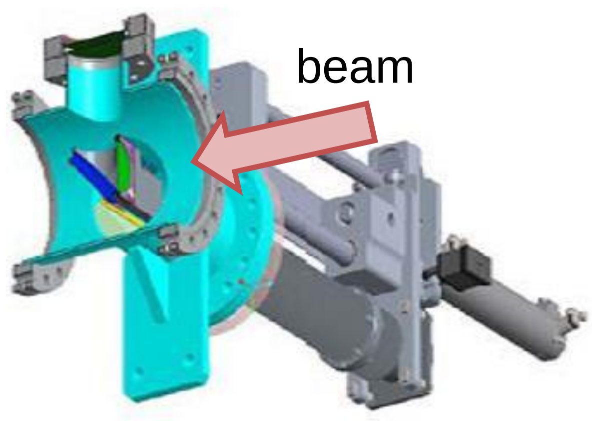
3D Geometry of Beamline

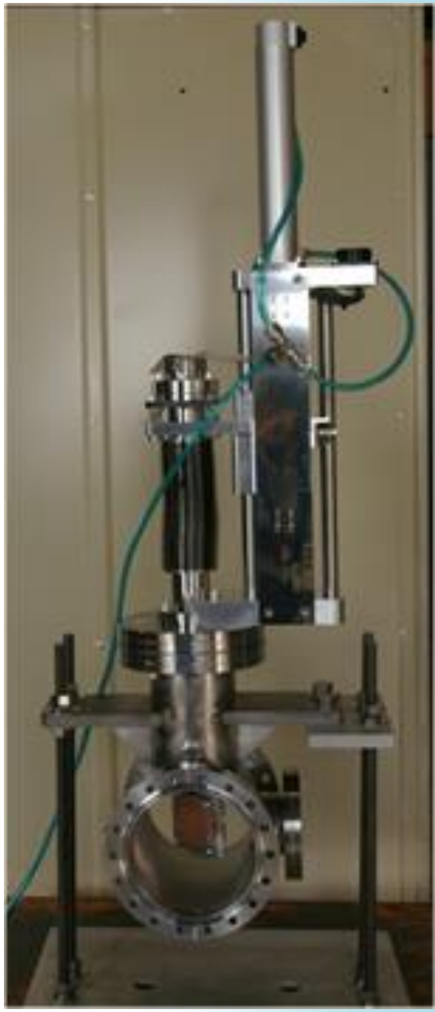


Diagnostic Borrowed from LEReC

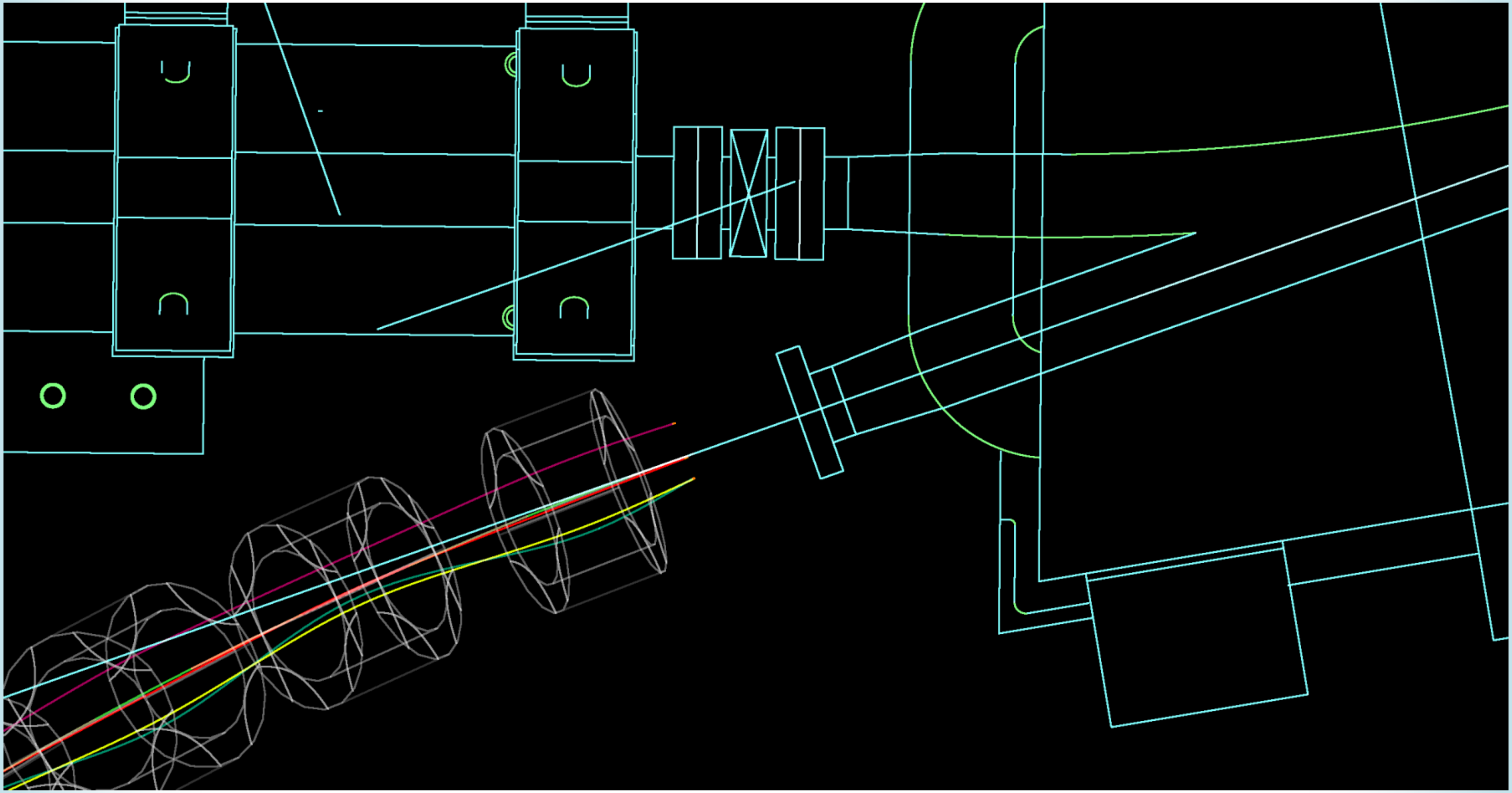
- Need 40-50mm diameter screen
  - Larger than ATF “pop-ins” (10mm)
- They want this back summer 2017





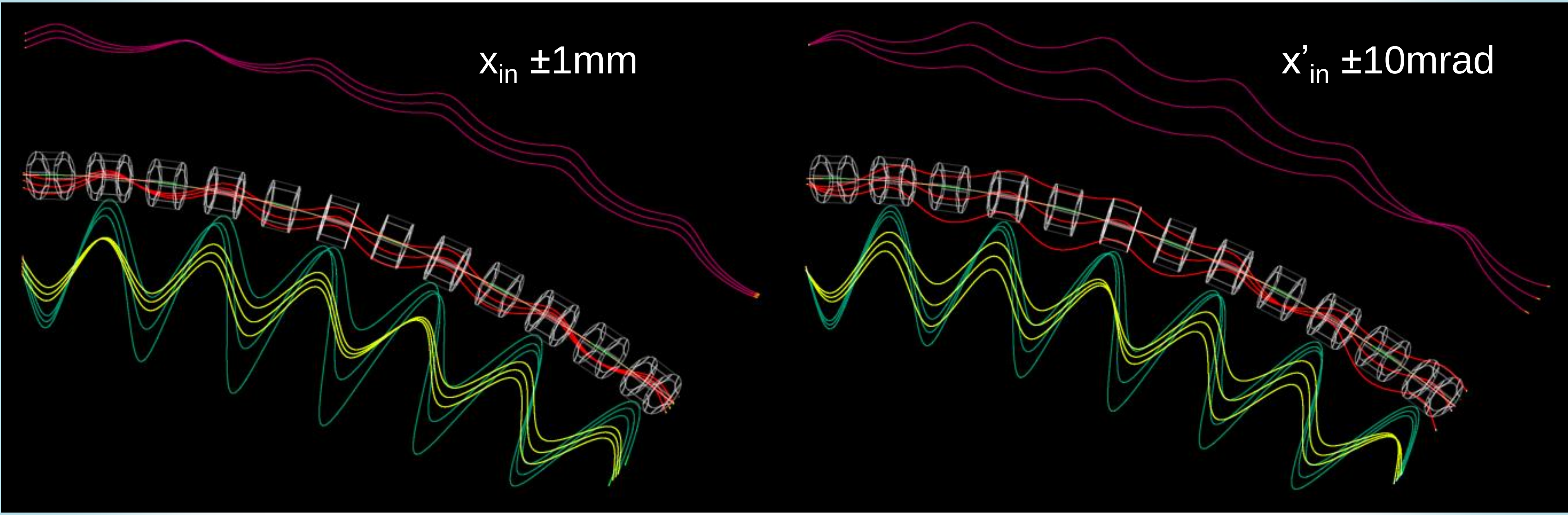


Injection: Moving Table Required



Effect of (x,x’) Offsets

- Trajectories have been magnified transversely by 16x for visibility

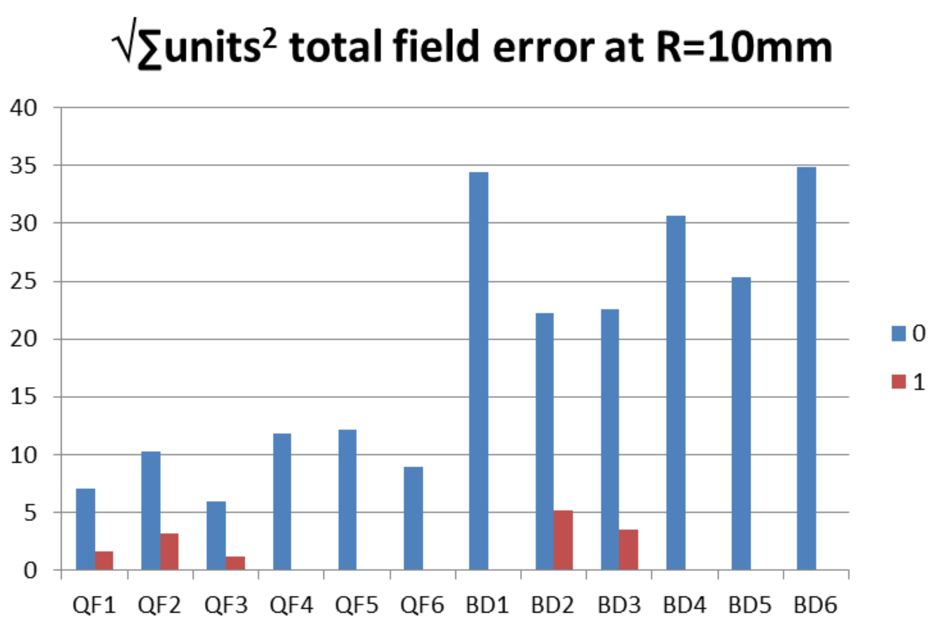


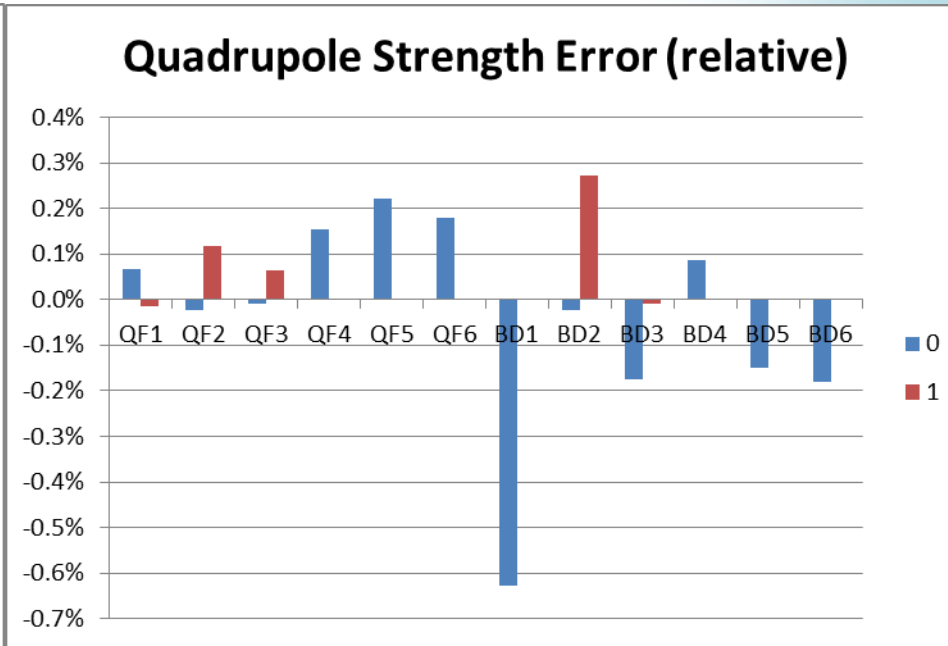
Time Request

- Asked for 3 weeks (120 hours) total
- Probably split into 2-3 sessions
  - Start by getting beam through at middle energy
  - Perform phase space scans
  - Progress towards ends of energy range (harder)
  - Experimenters at BNL so schedule can be flexible
- Will try to install during ATF shutdown (winter)
- ATF's existing cameras, software can be used

Backup Material

Magnet Field Quality Results

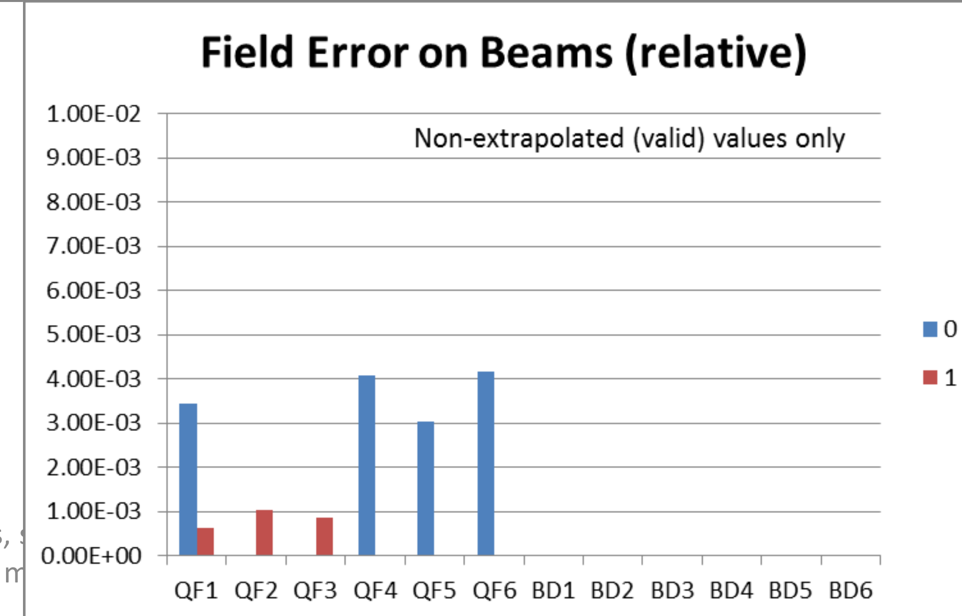




Measured on BNL magnet division's rotating coil in Bldg. 902

"units" are 10^{-4} of main field

"0" is before shimming and "1" is after one iteration of shimming; extra iterations are possible



Radii Stacking and Clearances

Object	Radius relative to magnet axis (mm)	Relative to vacuum pipe toroid (mm)	Difference (mm)
Beam centroids (widest spread in QF)	21.70	19.83	(NB: QF is displaced relative to pipe)
Vaccum pipe inner surface		23.75	3.92 outermost beam centroid to pipe
Vacuum pipe outer surface		25.40	1.65 pipe thickness
Shim holder inner surface (smallest in BD)	27.60	27.45	2.05 vacuum pipe to shim holder
Permanent magnet inner surface (smallest in BD)	30.70	30.55	3.10 thickest shim holder (BD)
Aluminium support inside	69.85		
Aluminium support outside	76.20		

Varying Curvature and Clearance

Total bend (6 cells) (deg)	Bend per cell (deg)	Max beam radius (mm)	Radius inside 2" OD pipe (mm)	Clearance (mm)
30	5	13.44263	23.749	10.30637
35	5.833333	16.64794	23.749	7.101057
40	6.666667	19.82601	23.749	3.922993
45	7.5	22.94169	23.749	0.807306

- Current design is highlighted in green
- Different curvatures attainable with the same magnets placed differently
  - Can increase clearance to pipe if needed

Injection Trajectories and Optics

Beam Energy	Entrance x (mm)	Entrance x' (rad)	Periodic x (mm)	Periodic x' (rad)	Exit x (mm)	Exit x' (rad)
20MeV	-11.99	-0.19425	-12.09	-0.18617	-12.13	-0.18914
40MeV	-12.41	-0.09679	-12.46	-0.09285	-12.48	-0.09450
60MeV	-0.74	-0.02802	-0.77	-0.02616	-0.77	-0.02614
80MeV	18.48	0.02436	18.48	0.02440	18.50	0.02559

Beam Energy	β_x (m)	α_x	β_y (m)	α_y
20MeV	0.2583	-3.9992	0.1905	2.3516
40MeV	0.2429	-1.2540	0.3409	1.6601
60MeV	0.3489	-1.1027	0.7365	2.2325
80MeV	0.4122	-0.9987	1.2793	2.8975

Gantry Parameters Comparison

Parameter	ATF FFAG	Gantry	Units
Particle species	Electron	Proton	
Kinetic energy range	20–80	50–250	MeV
Momentum range	20.5–80.5	310.4–729.1	MeV/c
Cell Length	0.251751	0.537588	m
Cell Angle	6.666…	6.16030	degrees
R = avg. radius of curvature	2.16364	5	m
Max orbit excursion (in QF)	19.83	17.01	mm (from circle radius R)
Magnet bore radius (QF, BD)	37.20, 30.70	27.61, 27.61	mm (without shims)
Tune range per cell	0.032–0.410	0.031–0.379	cycles
Drift lengths	67.55, 64.90	50, 50	mm
Magnet lengths (QF, BD)	57.44, 61.86	223.42, 214.16	mm
Magnet material grade	N35SH	N48H	
Effective B_r	1.194	1.4	T
Magnet max radius	62.45	78.58	mm
Magnet cross-section (QF, BD)	75.35, 46.71	100.91, 96.83	cm^2
Magnet mass per cell	5.486	32.89	kg
Magnet mass per 180°	148.1	961.1	kg

Position Error Study

- 0.1mm RMS Gaussian position errors in X, Y, Z
- Positions logged at beamline output

k.e. (MeV)	count	Ideal x	avg x	sigma x	Ideal y	avg y	sigma y
20	6417	0.012126	0.012063	0.001516	0	1.64E-05	0.000927
40	6417	0.012485	0.012472	0.000582	0	1.39E-05	0.000768
60	6417	0.000766	0.000762	0.000543	0	-1.4E-06	0.001254
80	6417	-0.0185	-0.01849	0.000463	0	-4.7E-06	0.00124

- Amplification factors 4.6x – 15.2x
  - 20MeV in X plane is trickiest
  - Followed by 60, 80MeV in Y plane

Quad Strength Error Study

- Use the observed 0.202% RMS strength error

k.e. (MeV)	count	Ideal x	avg x	sigma x	Ideal y	avg y	sigma y
20	8541	0.012126	0.012127	0.00047	0	0	0
40	8541	0.012485	0.012485	0.000147	0	0	0
60	8541	0.000766	0.000766	2.5E-06	0	0	0
80	8541	-0.0185	-0.0185	0.000187	0	0	0

- Worst case sigma X (20MeV) = 0.47mm