Beam Tests of a Permanent Magnet Medical Accelerator Arc from 10-250MeV

S. Brooks, G. Mahler, D. Trbojevic, IPAC’26

Hadron Therapy Accelerator

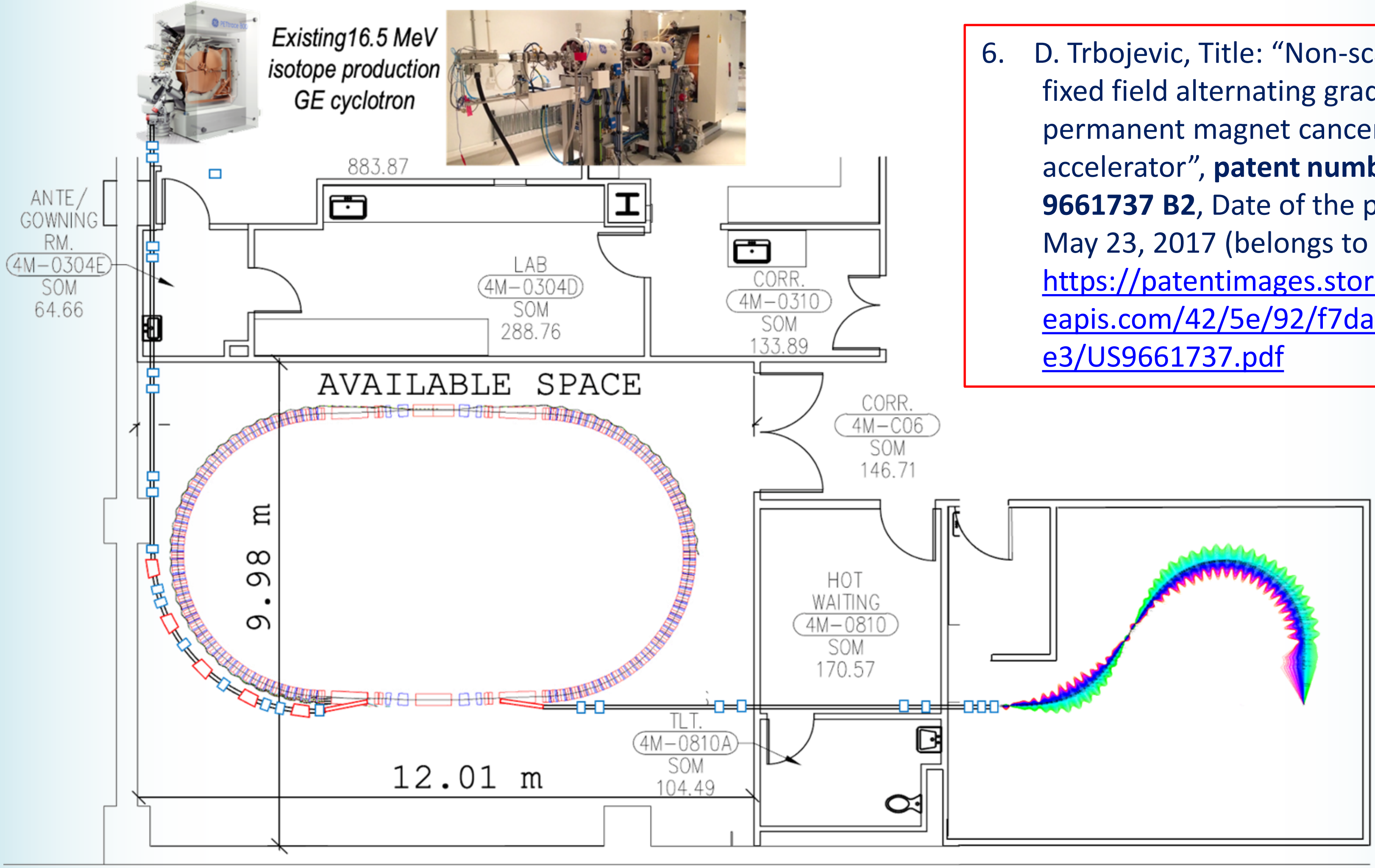
- Dejan Trbojevic proposes to accelerate protons in 10-250MeV range with a rapid cycle (500Hz+) for FLASH hadron therapy
  - Many cycles within ~100ms allow many energy (depth) slices to be irradiated as well as being quick enough to trigger the biological FLASH effect
- Need a fixed-field (FFA) ring with fixed tunes
  - But needs to fit in the hospital, so smaller than a scaling FFA → **nonlinear non-scaling FFA**

Nonlinear Non-Scaling FFAs

- Linear field non-scaling FFAs have cell tunes that vary with momentum
- This tune dependence can be flattened by adding non-linear components to the magnet fields (although not necessarily for an unlimited momentum range)
- Quadrupole affects tune level, sextupole affects dQ/dp, octupole affects d^2Q/dp^2, etc.

'FLASH' Proton Therapy facility:

Stony Brook University Hospital – Radiation Oncology

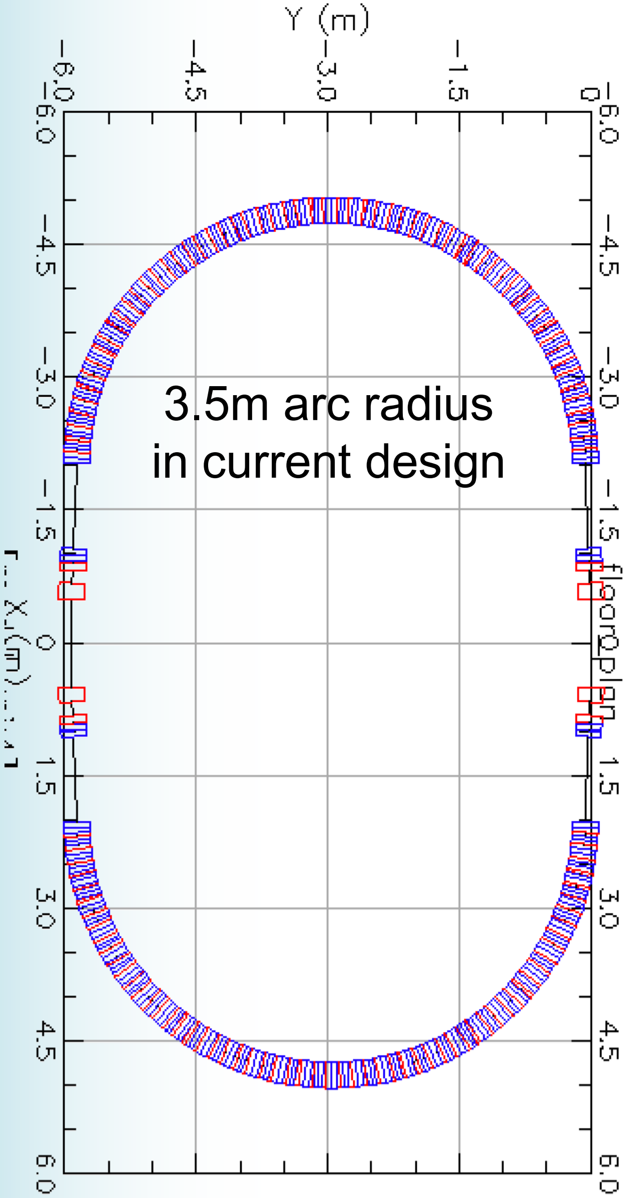


6. D. Trbojevic, Title: "Non-scaling fixed field alternating gradient permanent magnet cancer therapy accelerator", **patent number: US 9661737 B2**, Date of the patent: May 23, 2017 (belongs to the DOE). https://patentimages.storage.googleapis.com/42/5e/92/f7da1cf617d6e3/US9661737.pdf

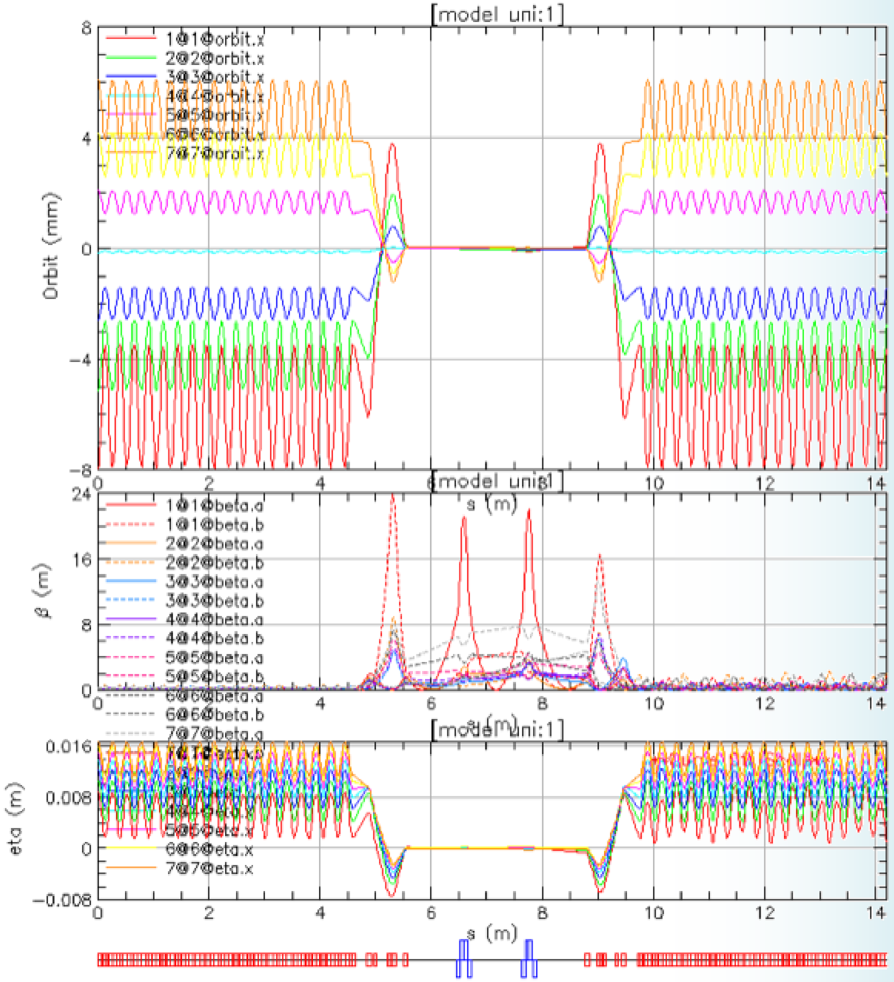
Facility Parameters

Parameter	Value	Unit
Injection E_k	10-30	MeV
Extraction E_k range	65-250	MeV
Arc radius	3.5	m
Machine cycle rate	500-800	Hz
Energy gain per turn	30-45	kV
Treatment charge	60	nC
Treatment time	75-250	ms

Matching of the Multiple Energy Orbits to the Straight Section

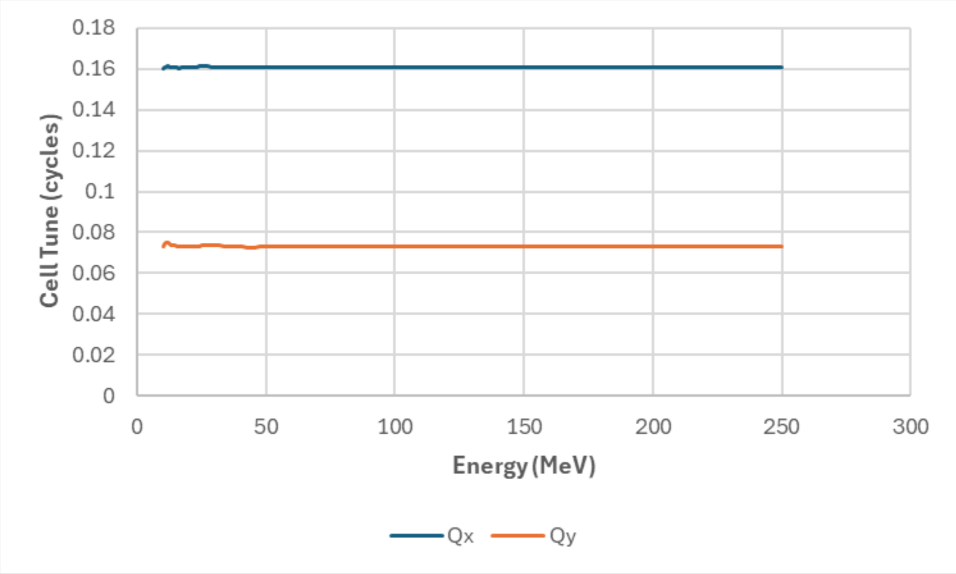


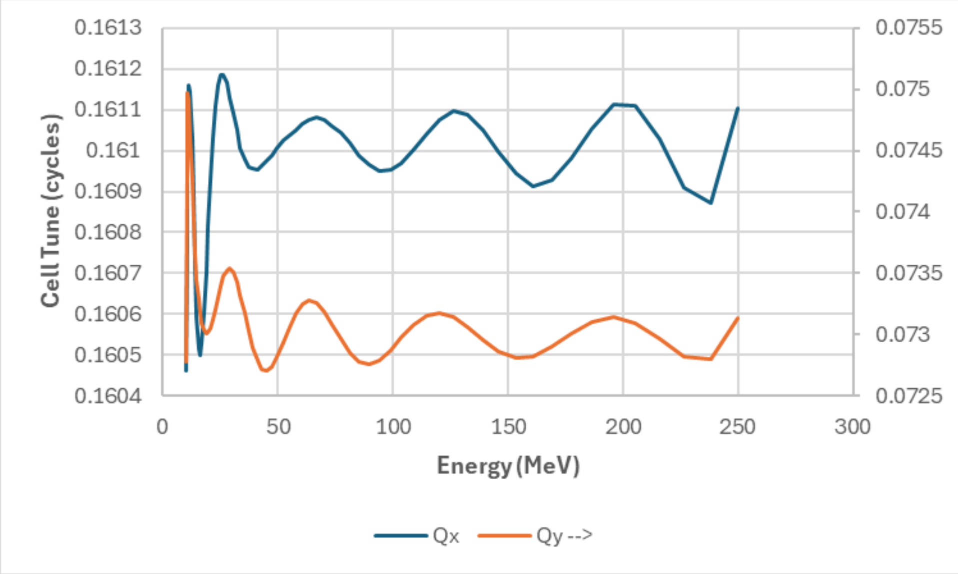
3.5m arc radius
in current design



FFA Arc Cell Tunes

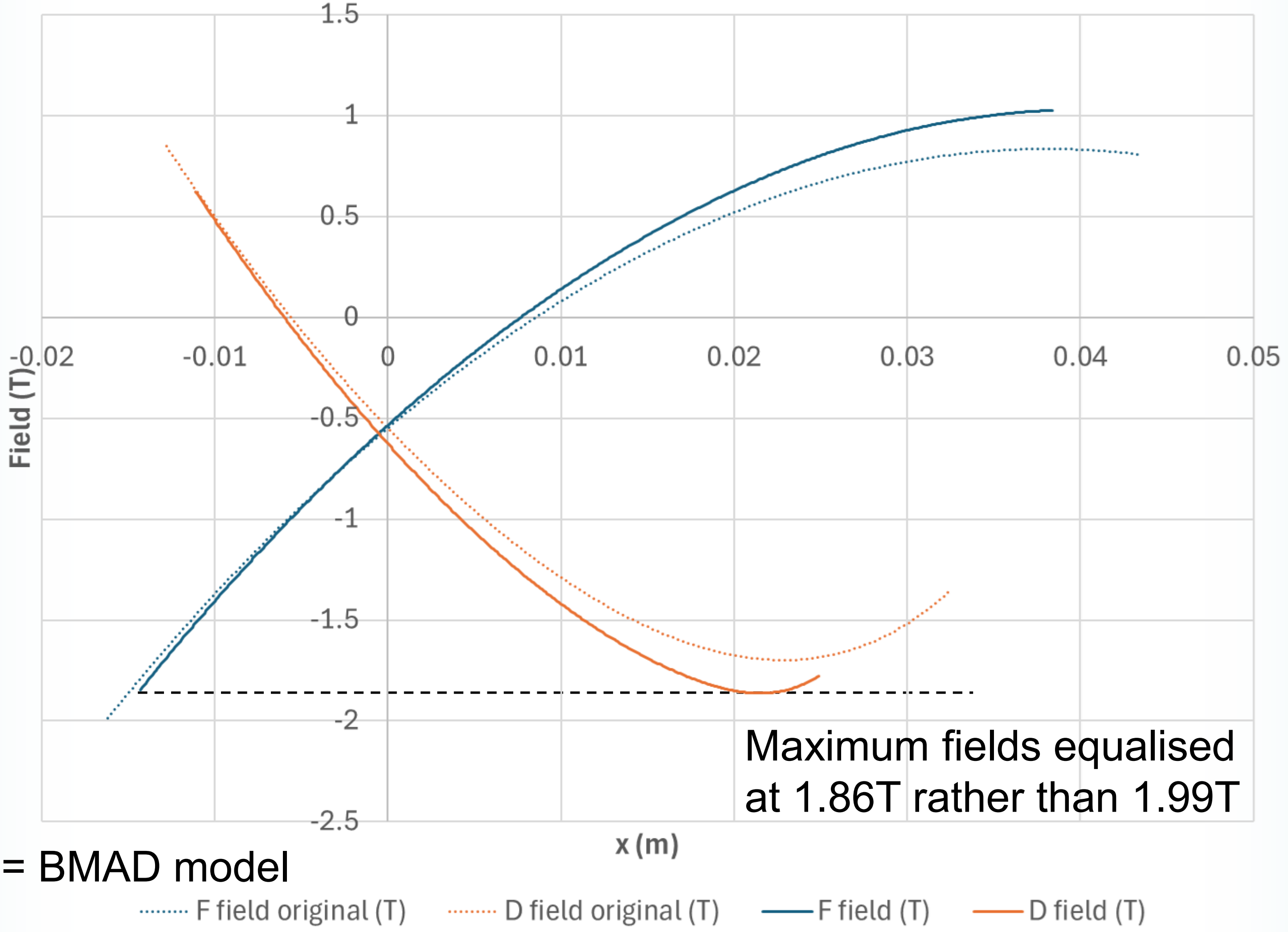
After iterative correction in Muon1, starting from an initial BMAD model, tunes are stable from 10MeV – 250MeV and nearly constant.
(Wiggly near low energy end because rigidity changes fast there).





Cell tune ranges:
Qx = 0.1608 ± 0.0004
Qy = 0.0738 ± 0.0011

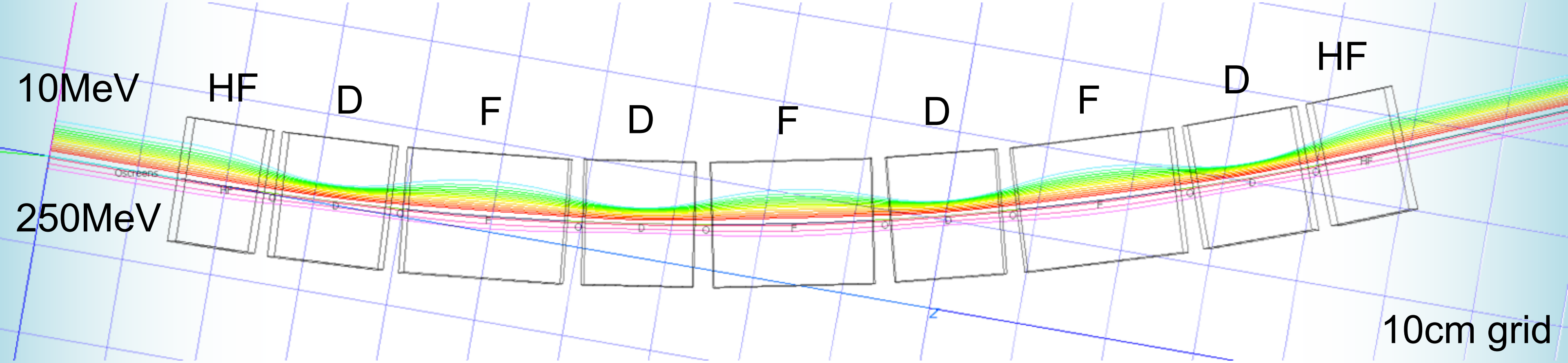
Nonlinear Magnet Field Profiles



Maximum fields equalised at 1.86T rather than 1.99T

“original” = BMAD model

Test Beamline Simulated Orbits



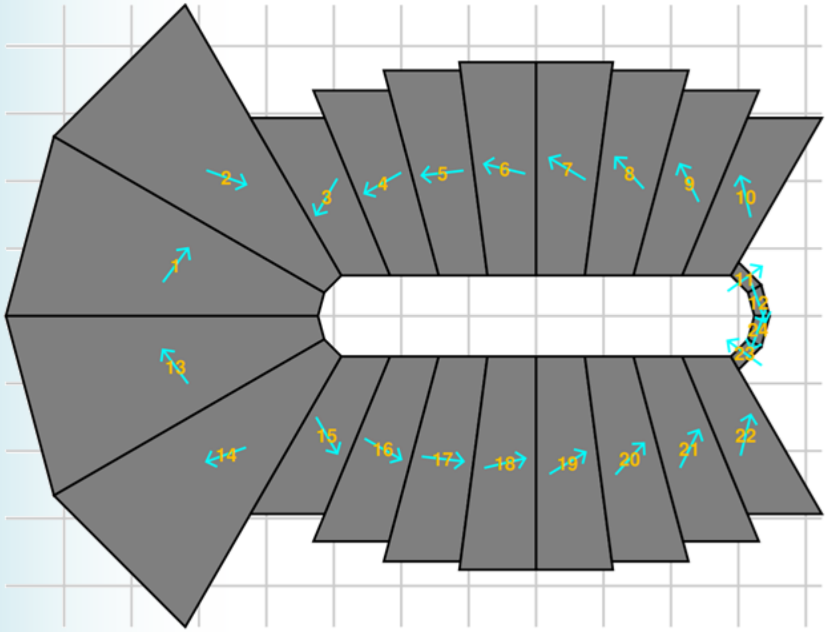
Angle 5.625° per cell, 4 cells total = 22.5° (1/8 of an 180° arc)

Half-F magnets on each end → parallel orbits

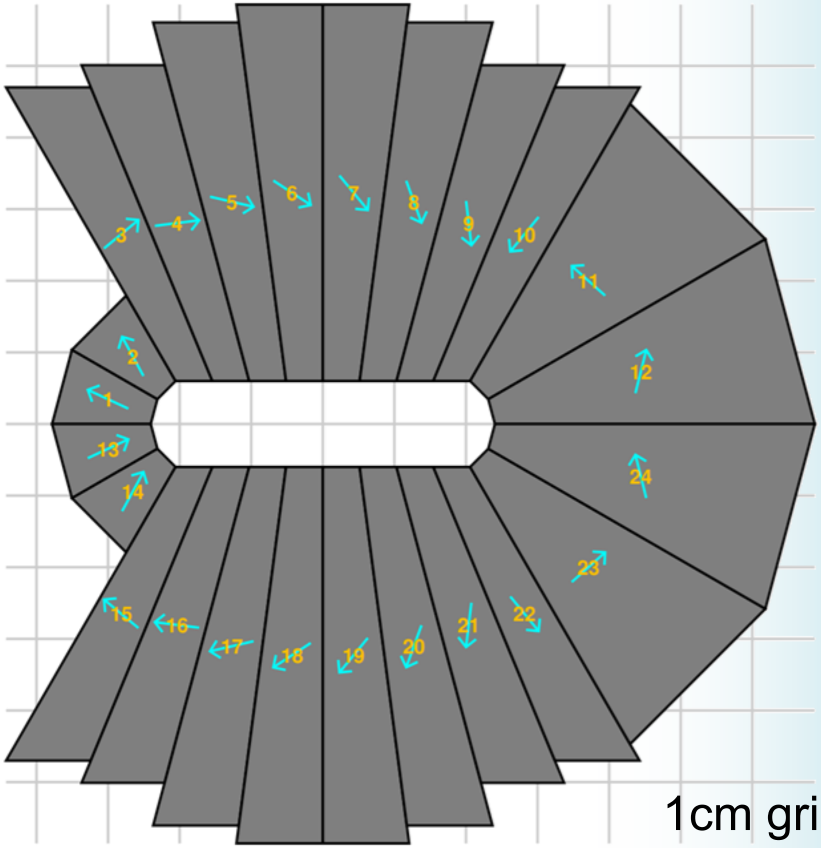
Cell length 34.4cm, 4 cells total = 1.374m

Permanent Magnet Cross-Sections

F



D

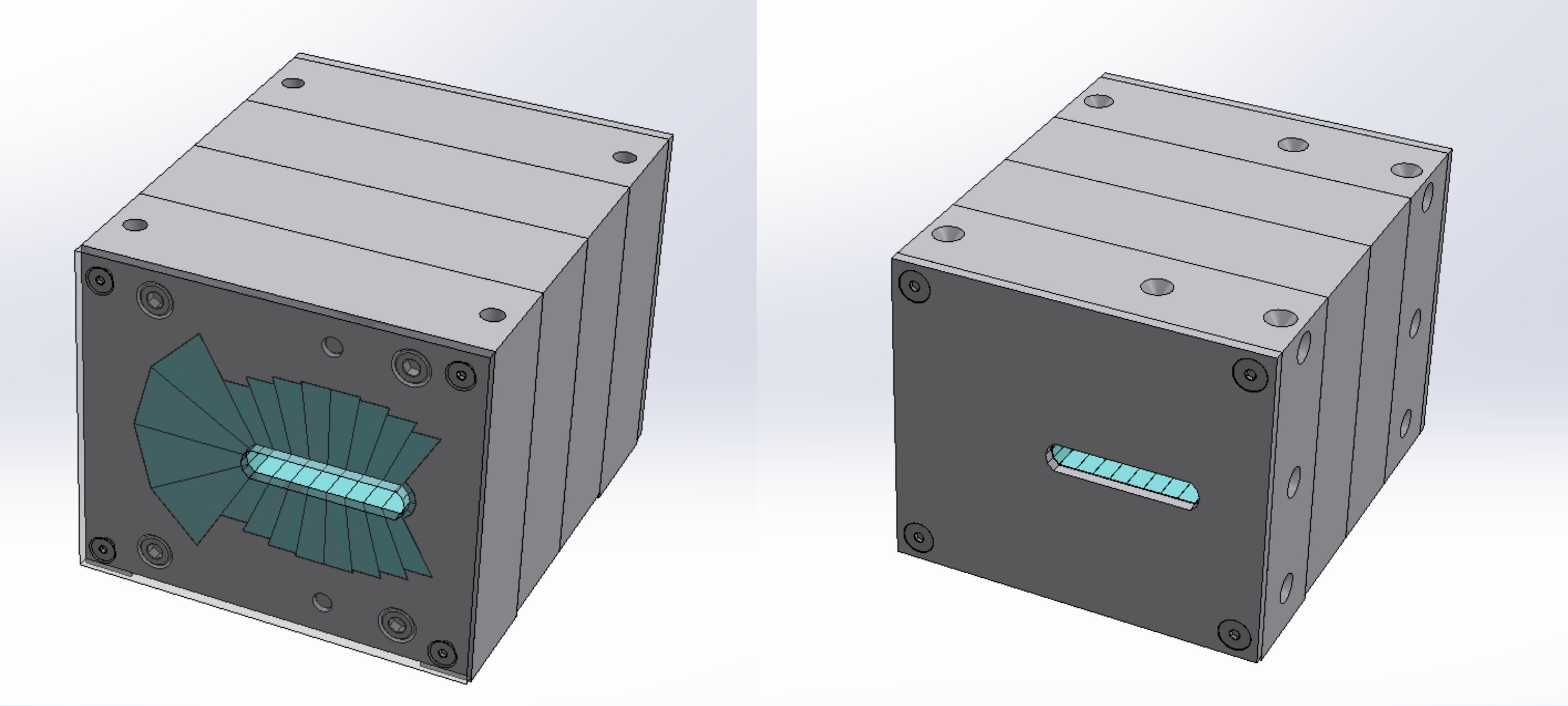


1cm grid

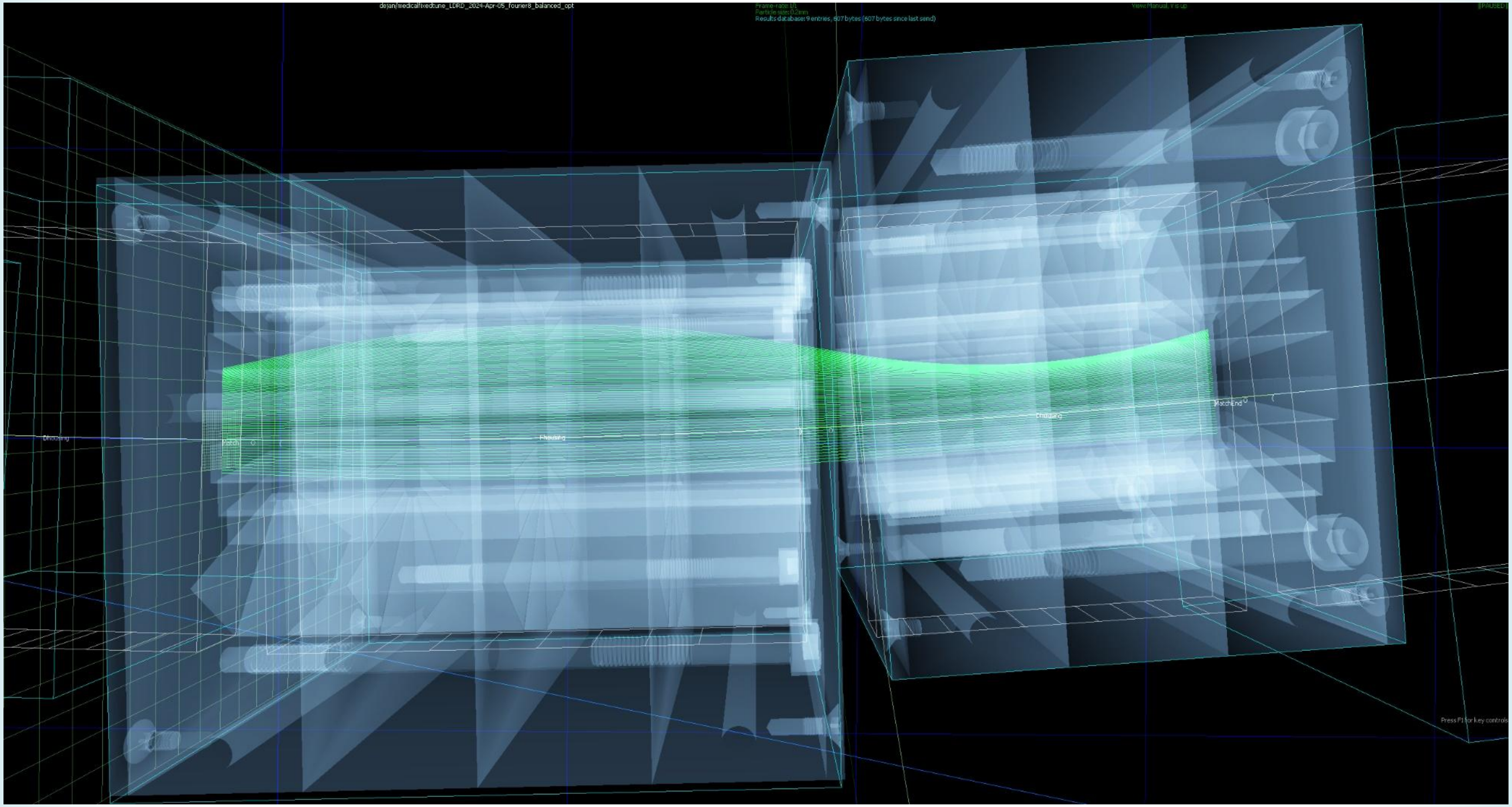
Permanent Magnet Parameters

Parameter	F magnet	D magnet	Unit
Material	NdFeB		
Grade	N42EH		
Remnant field B_r	1.30		T
Area	69.90	93.88	cm^2
Full aperture	64.7 × 12	48.1 × 12	mm
Good field region x	±26.3	±18.0	mm
Maximum field	1.85	1.86	T

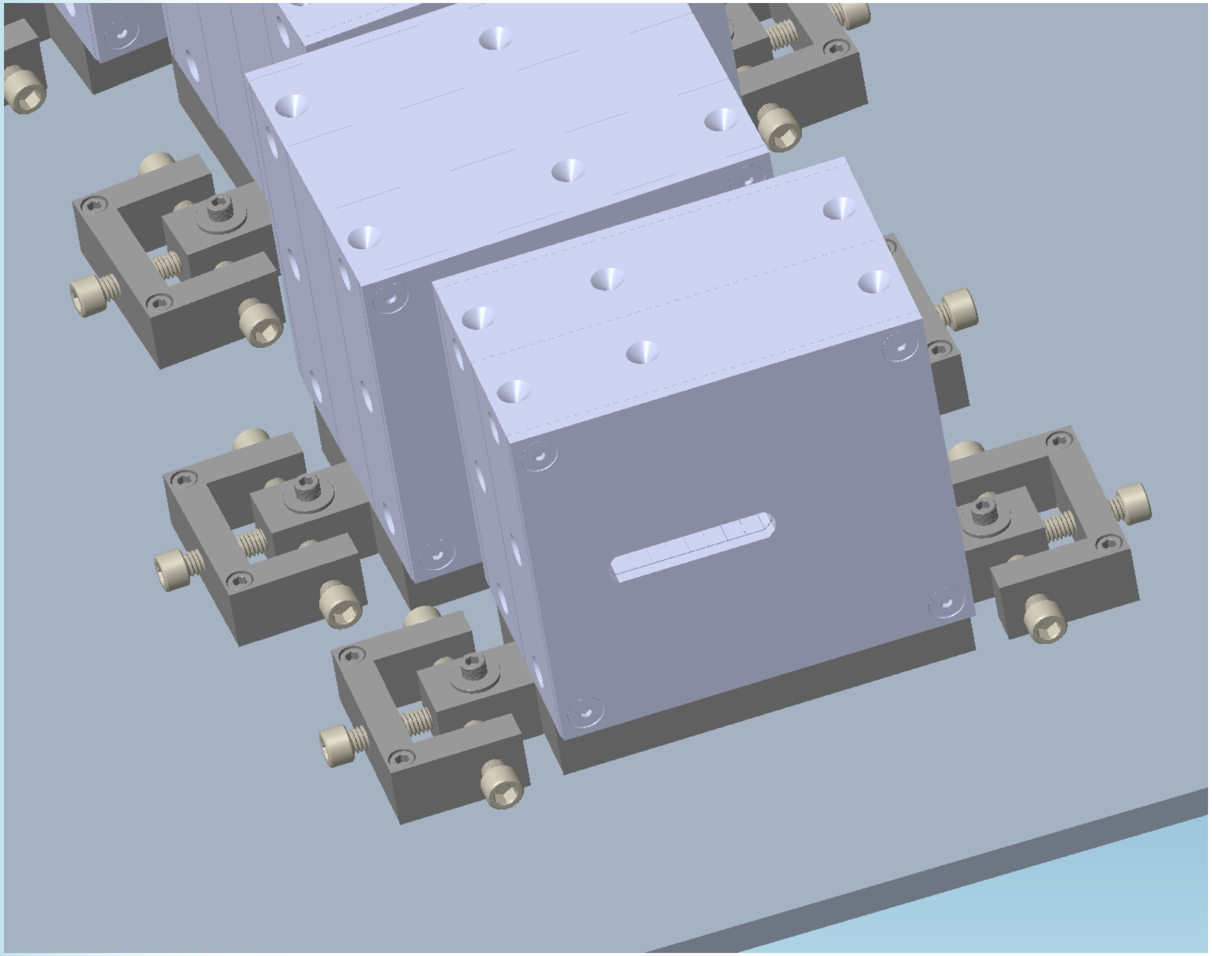
Magnets Ordered from SABR Enterprises, LLC.

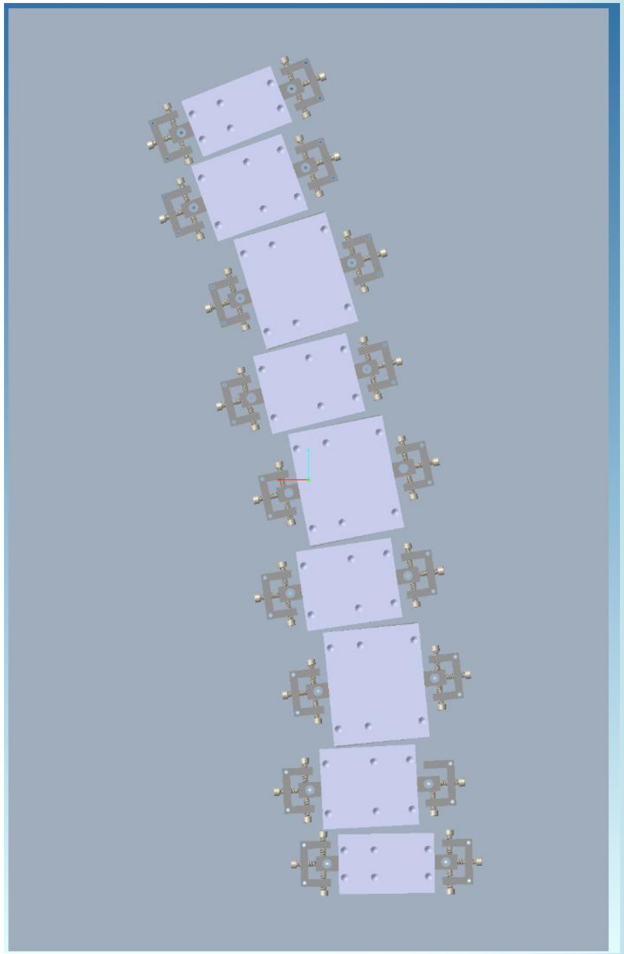


Orbits within Magnet Models



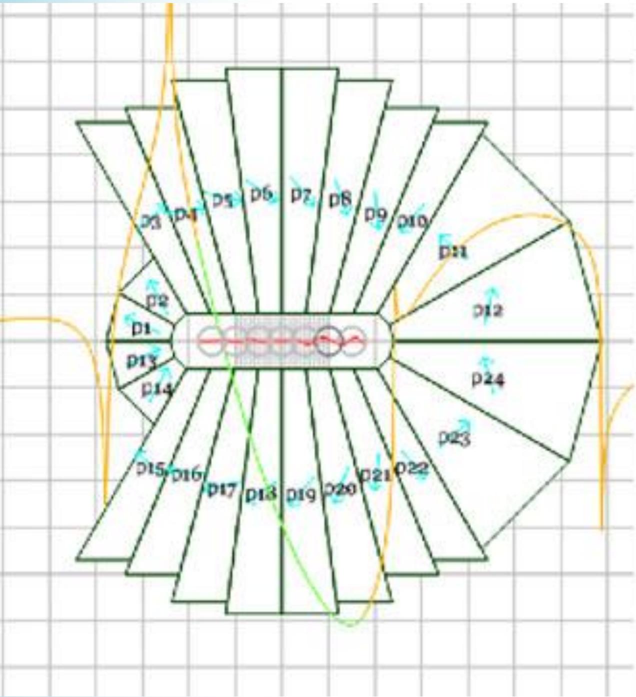
Test Beamline with Mounting

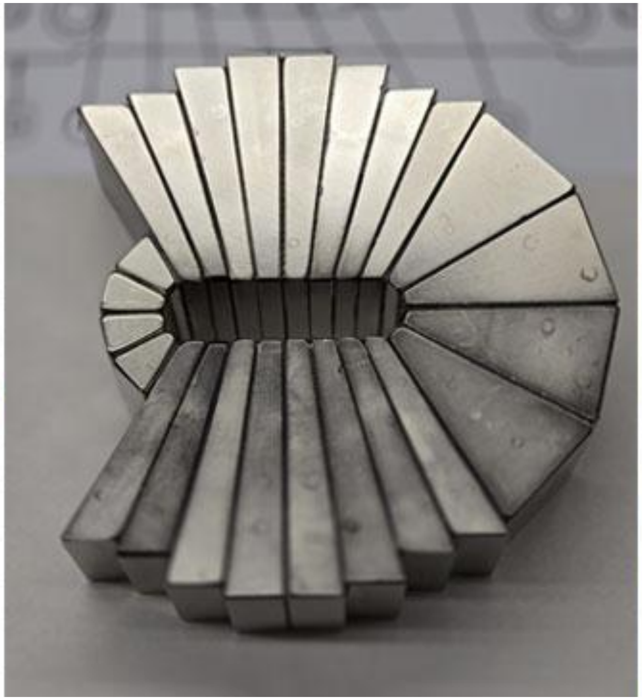


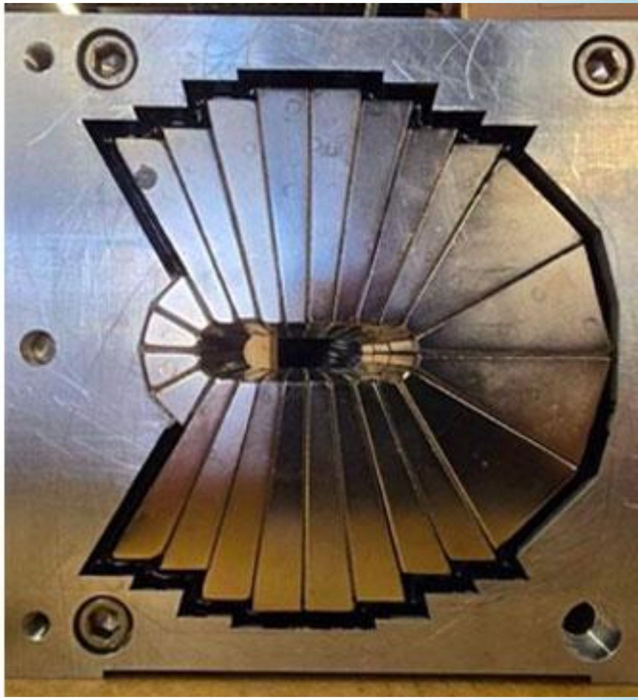


Magnet Construction by Vendor

SABR Enterprises, LLC. in Massachusetts

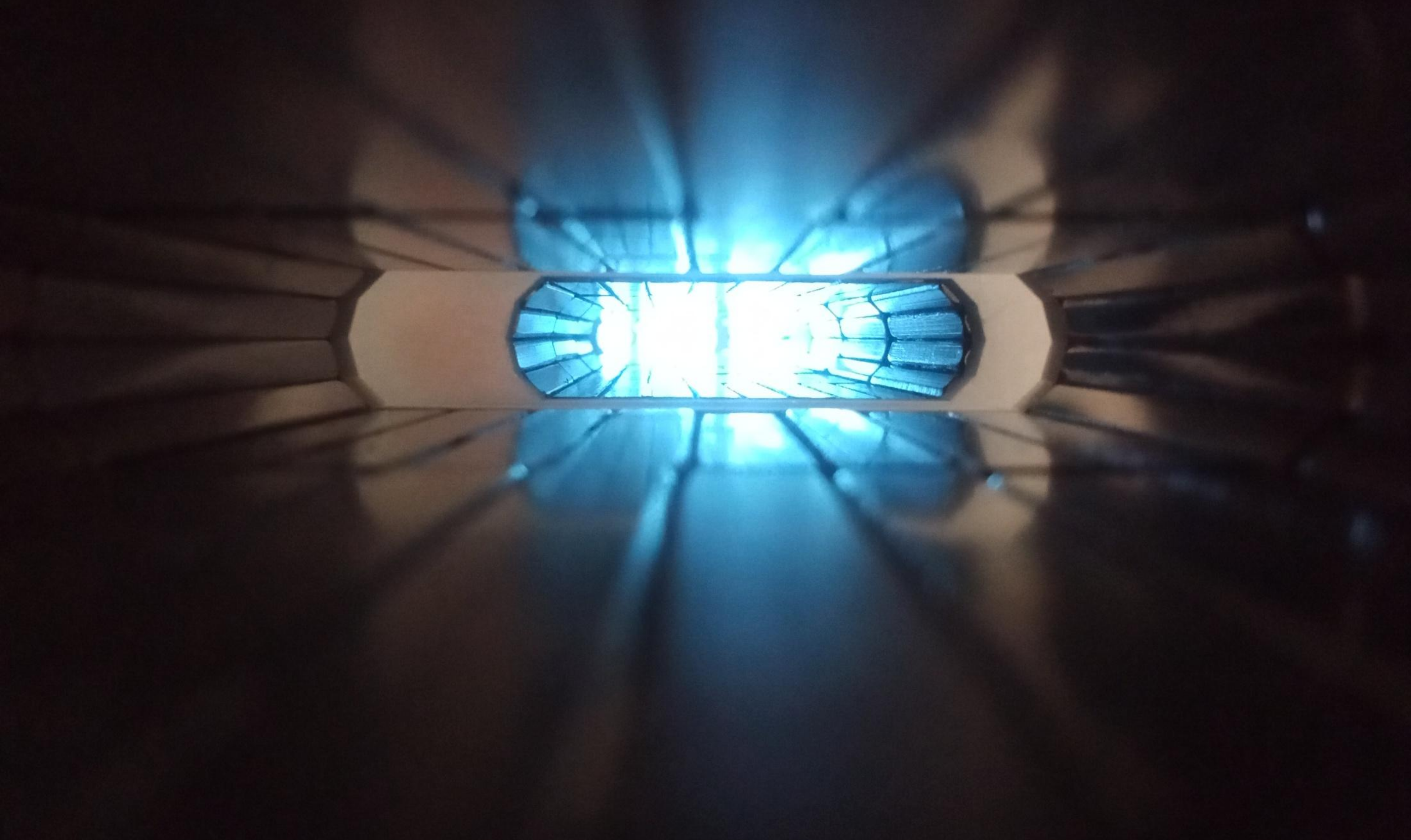




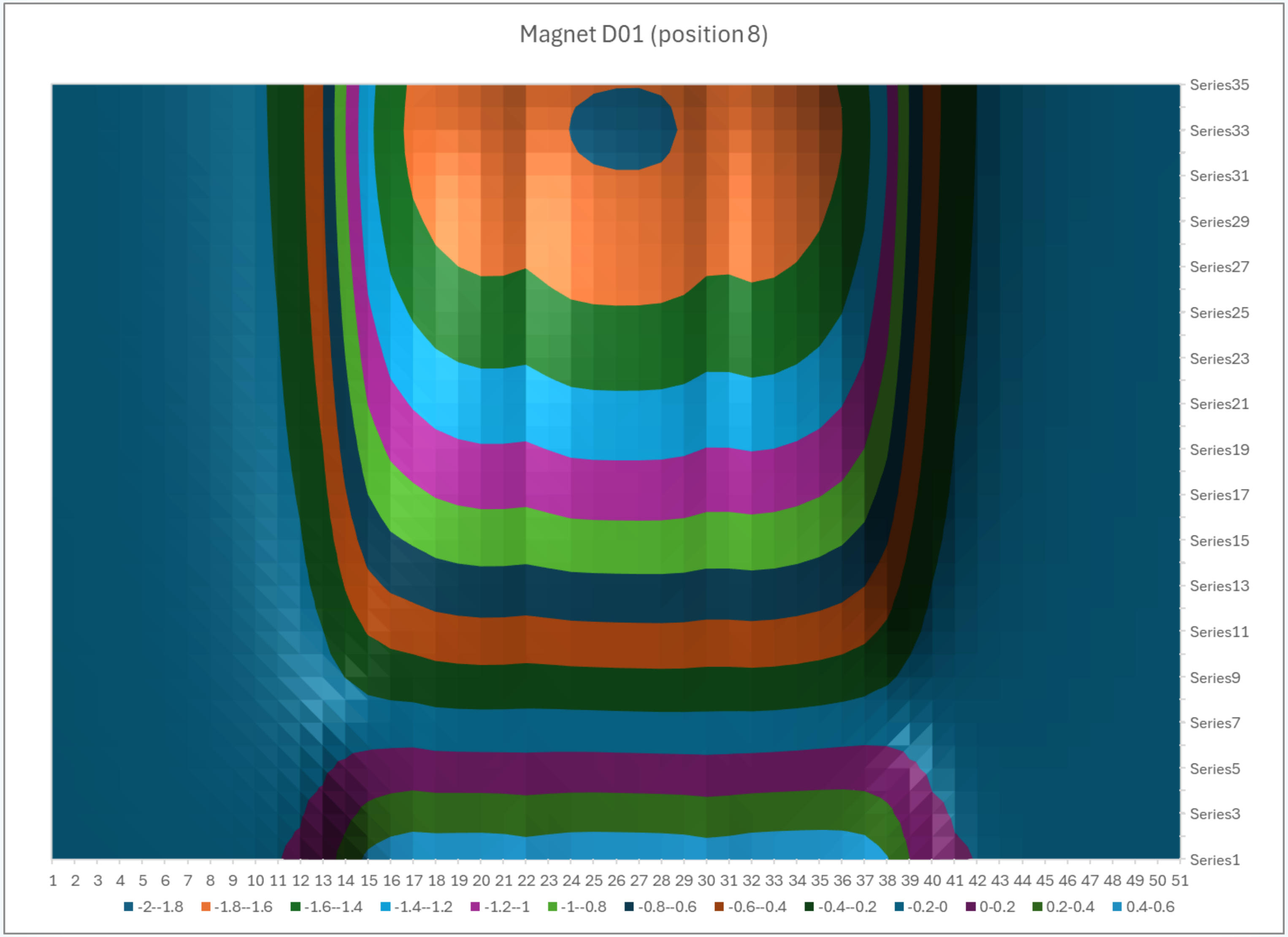


Beamline Assembly

Magnet Apertures

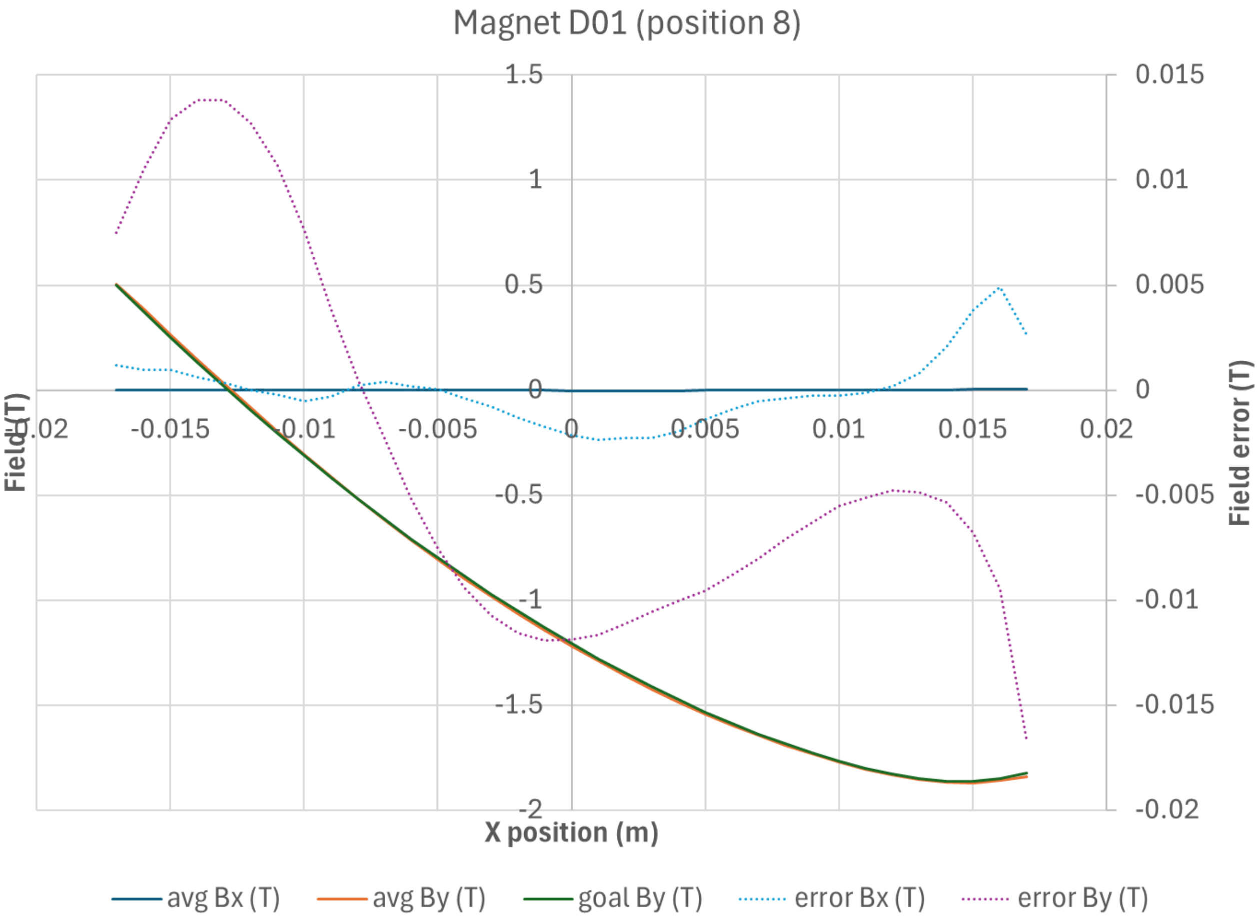


Fieldmap of one magnet



Measured Integrated Field

Corrected via fit for Hall probe displacements and tilt angles, <1% error



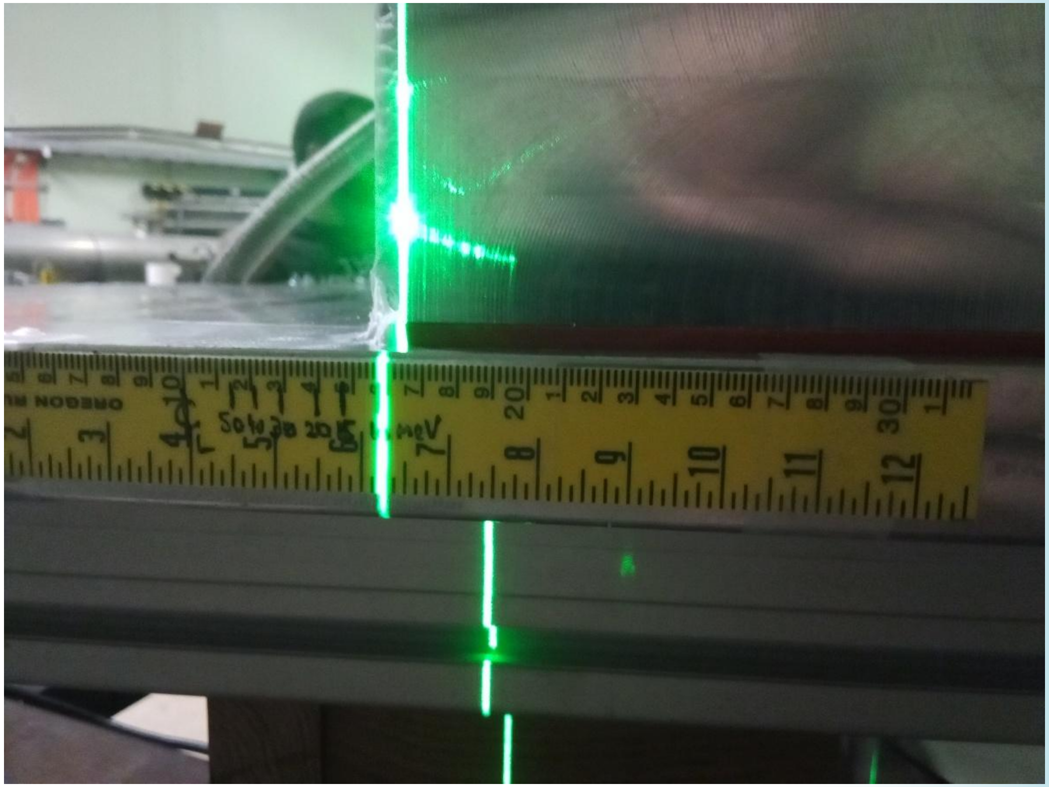
Camera and Beam Screen Plates

These were attached to both ends of the beamline.
4 cameras and 4 screens in total.

Experiment at BNL beamlines

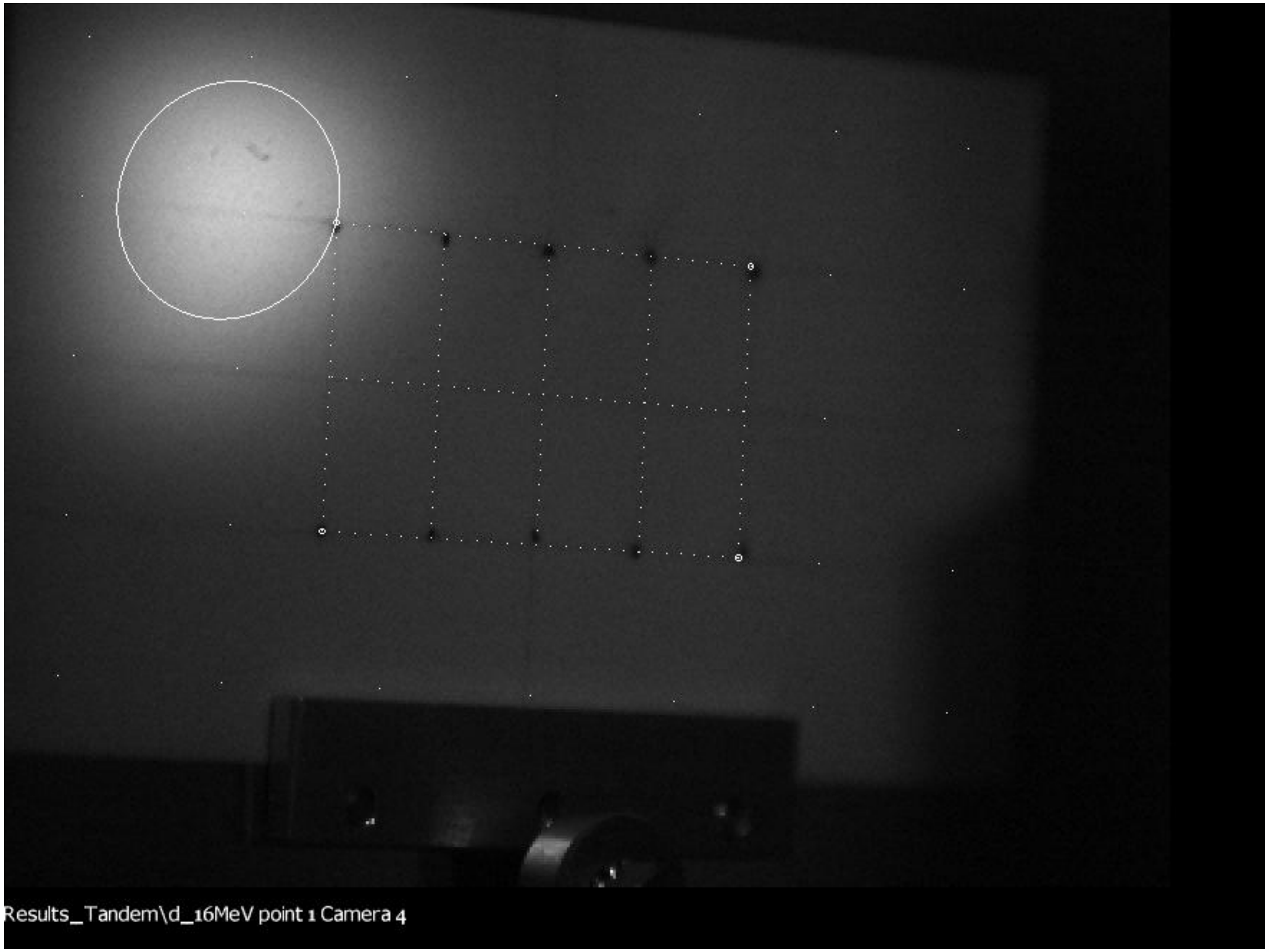
- NSRL
  - Protons 50-250MeV
  - 1 day 2 hours
- Tandem
  - Deuterons 12.9-28MeV
  - Equivalent to protons 10-50MeV
    - Via rigidity but also window/air energy loss calculation
    - Tandem proton max energy is 28.75MeV
  - 1 day

Installation (Tandem)

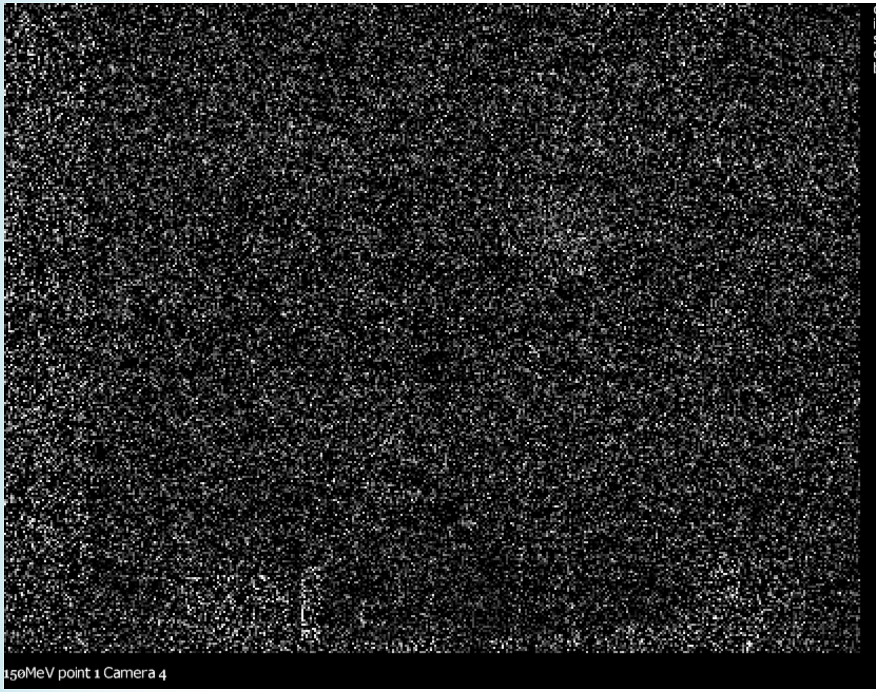


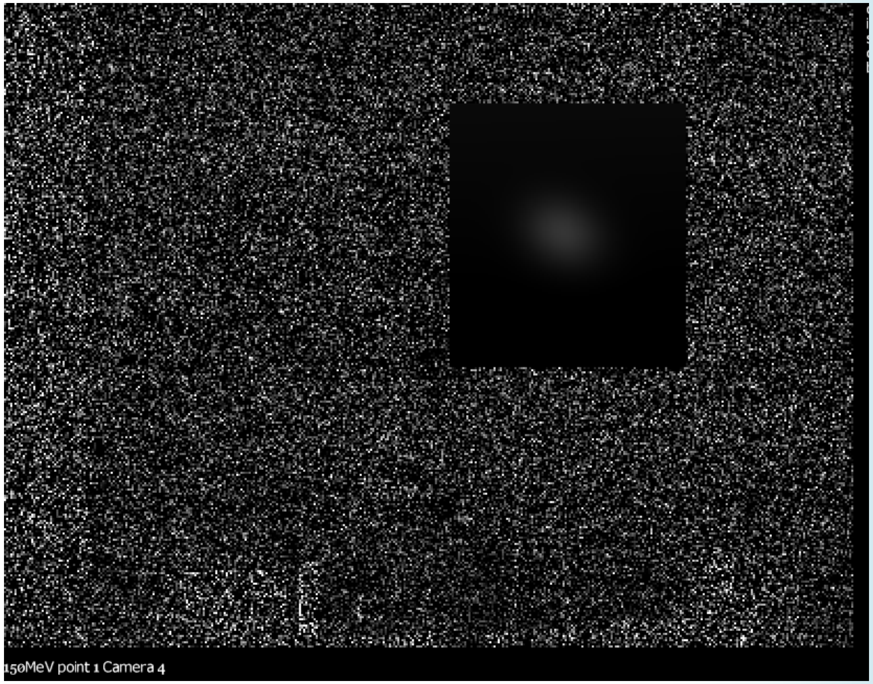
Different beam energies marked on a ruler for alignment.

Calibration and 1σ Ellipse Fit



Dimmest Beam Fit



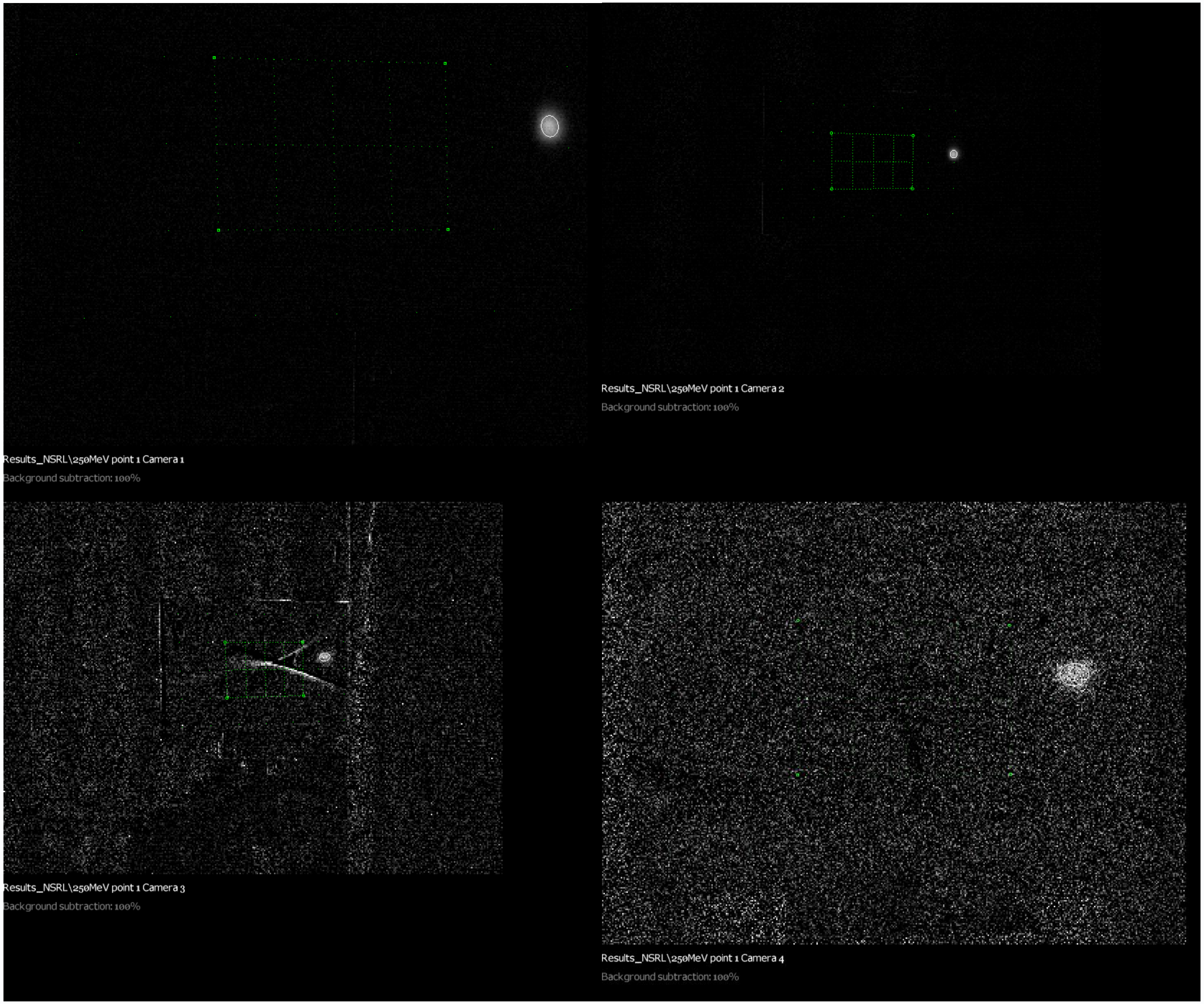


Also background frames were subtracted

NSRL 250MeV protons

Beam in

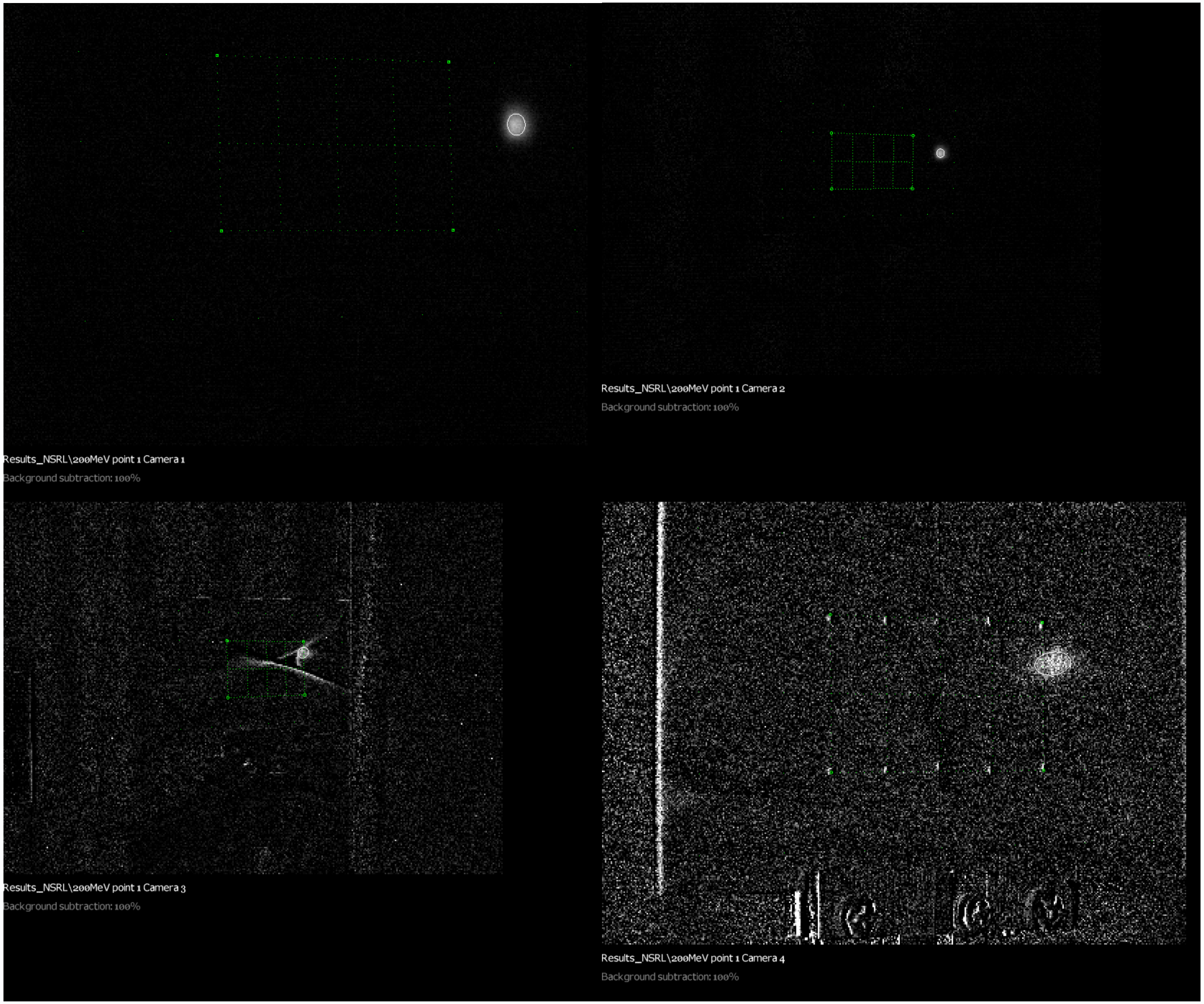
Beam out



NSRL 200MeV protons

Beam in

Beam out



Results_NSRL\200MeV point 1 Camera 1

Background subtraction: 100%

Results_NSRL\200MeV point 1 Camera 2

Background subtraction: 100%

Results_NSRL\200MeV point 1 Camera 3

Background subtraction: 100%

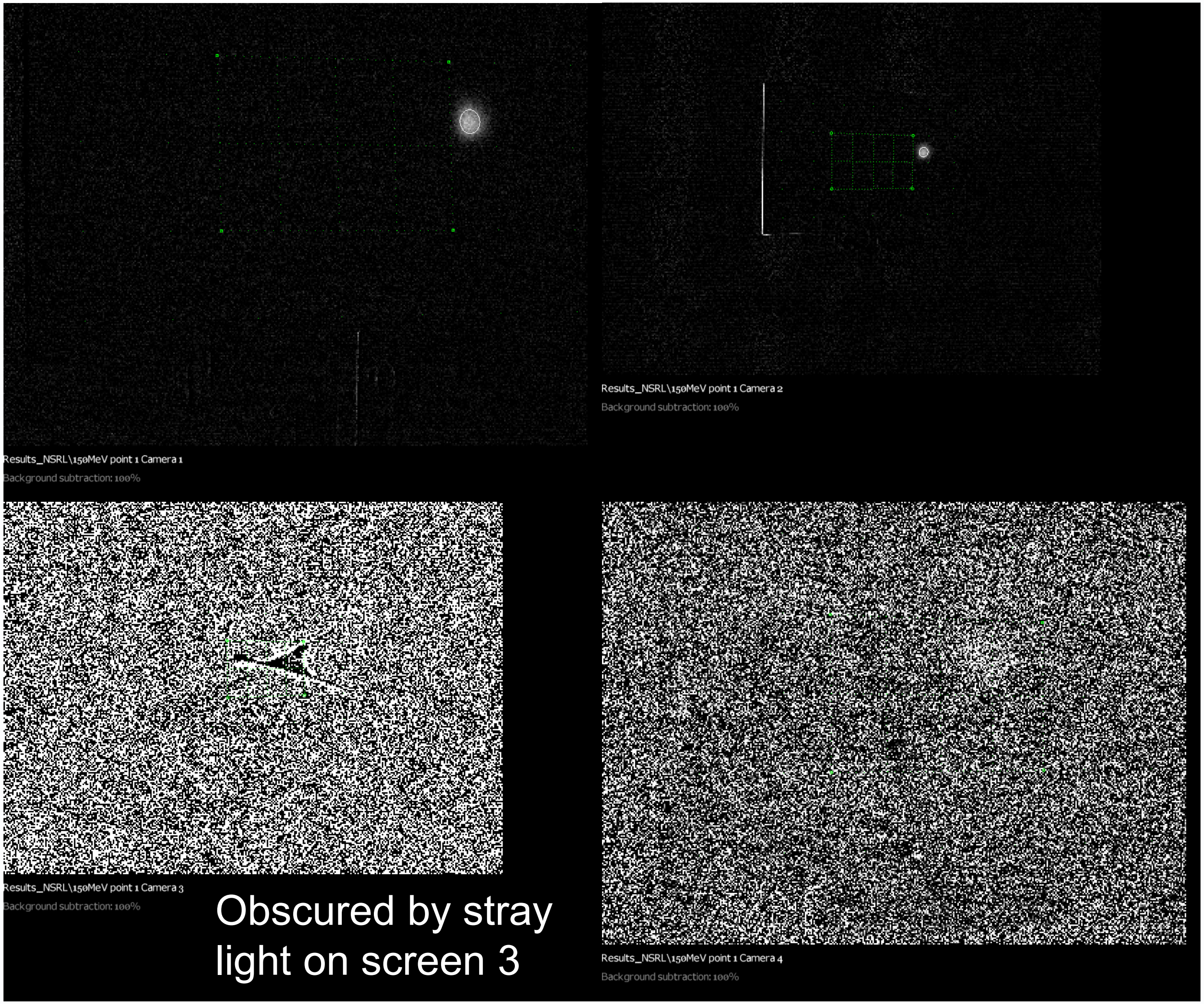
Results_NSRL\200MeV point 1 Camera 4

Background subtraction: 100%

NSRL 150MeV protons

Beam in

Beam out



Results_NSRL\150MeV point 1 Camera 1
Background subtraction: 100%

Results_NSRL\150MeV point 1 Camera 2
Background subtraction: 100%

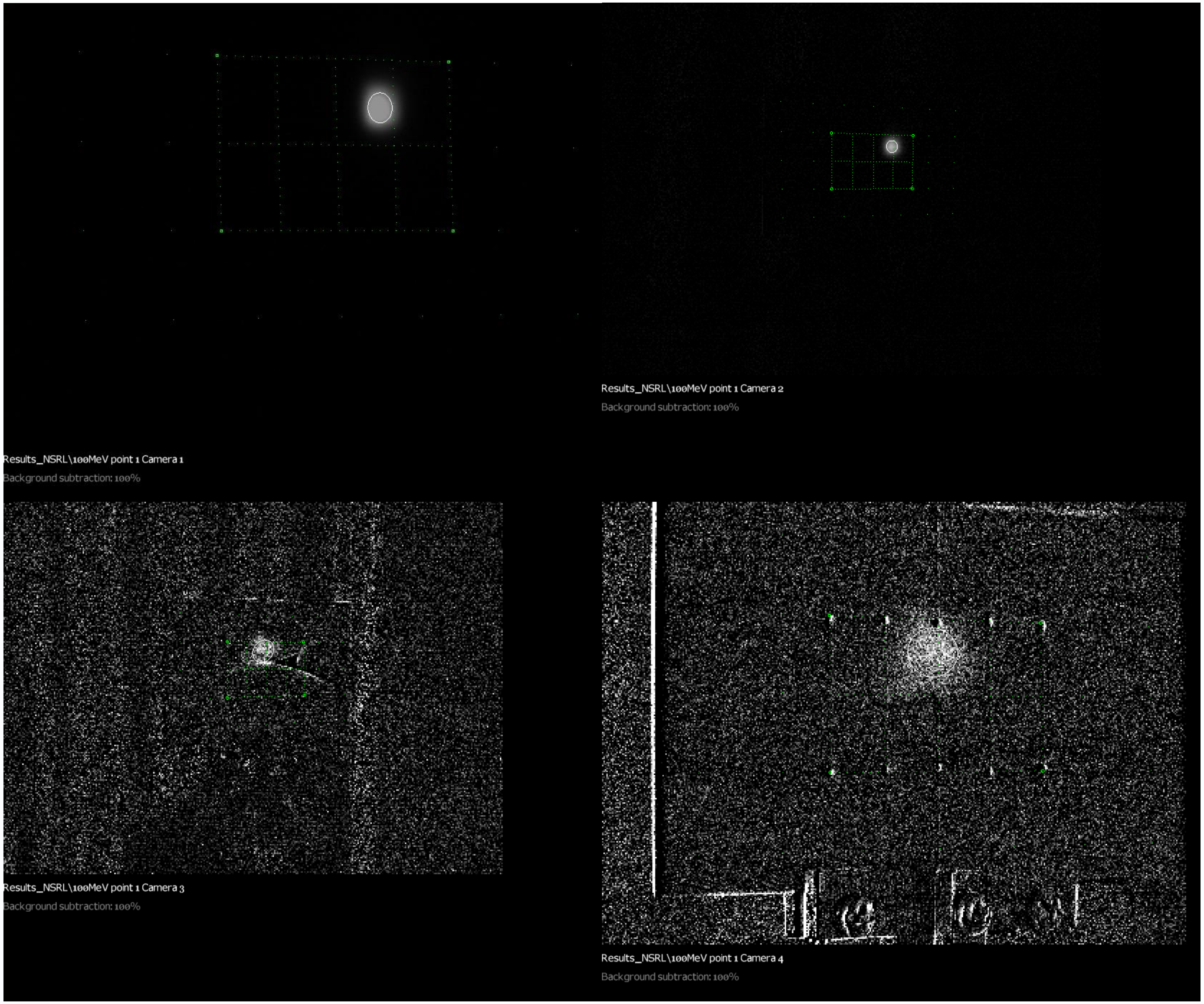
Results_NSRL\150MeV point 1 Camera 3
Background subtraction: 100%

Obscured by stray light on screen 3

Results_NSRL\150MeV point 1 Camera 4
Background subtraction: 100%

NSRL 100MeV protons

Beam in

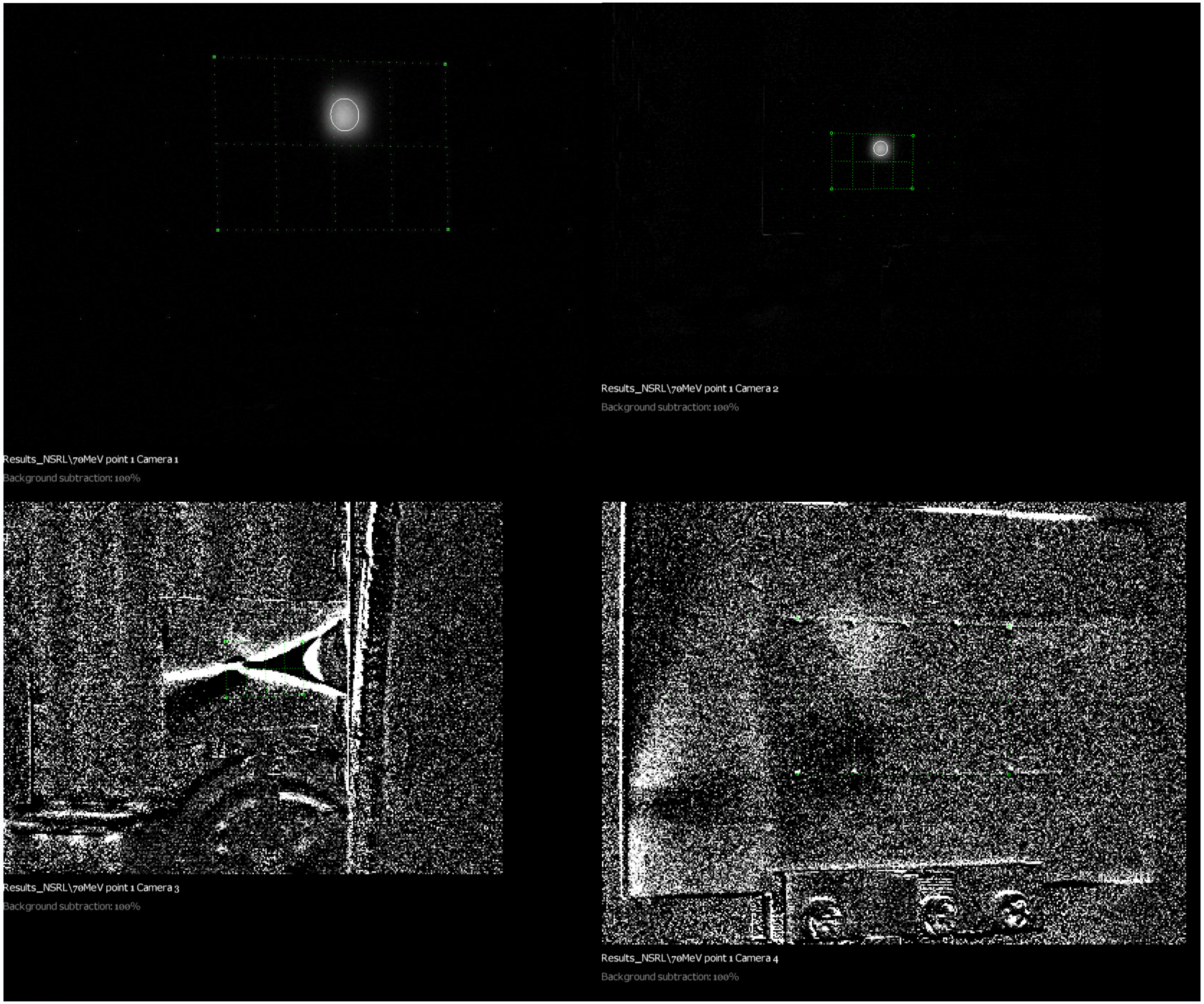


Beam out

NSRL 70MeV protons

Beam in

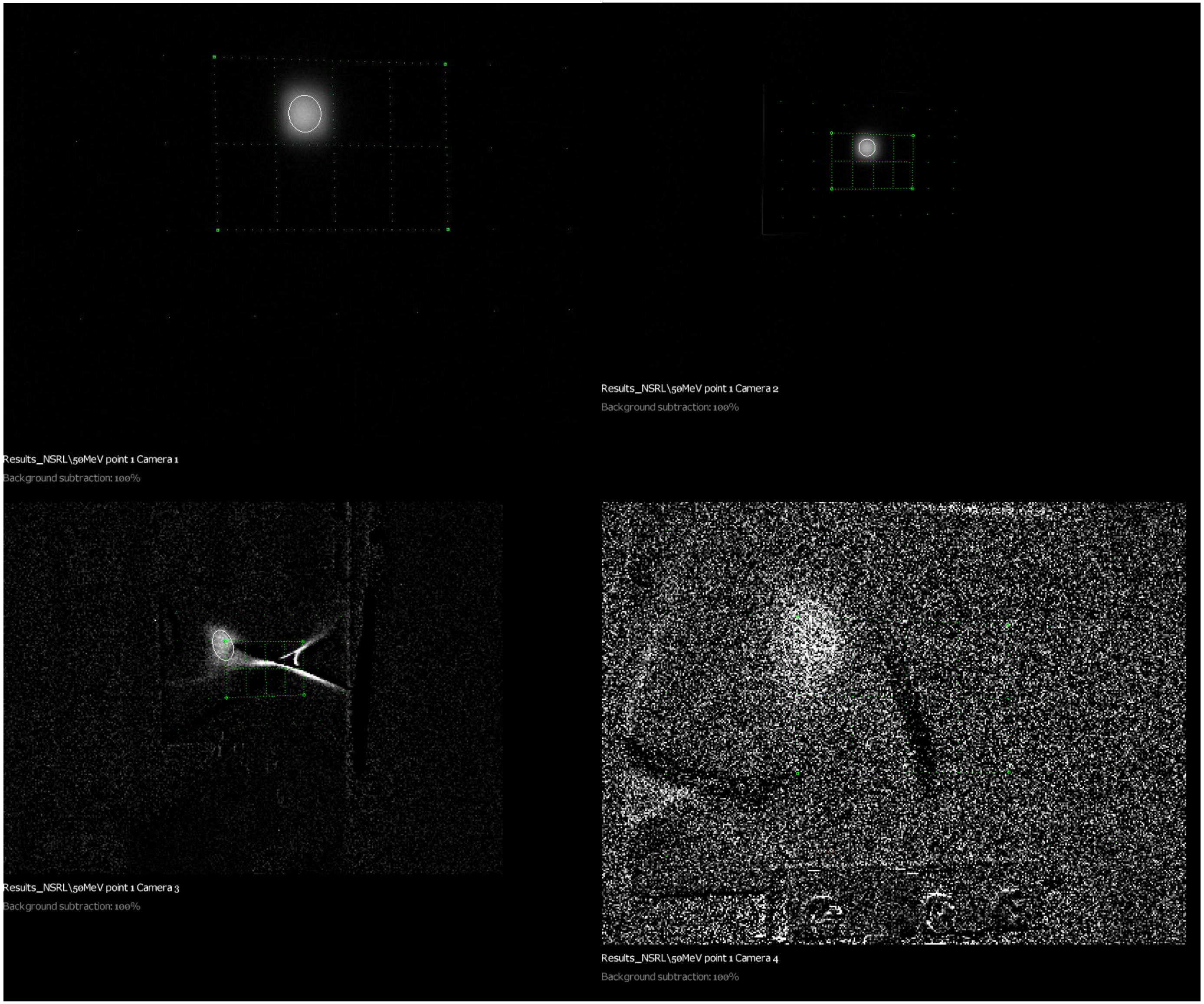
Beam out



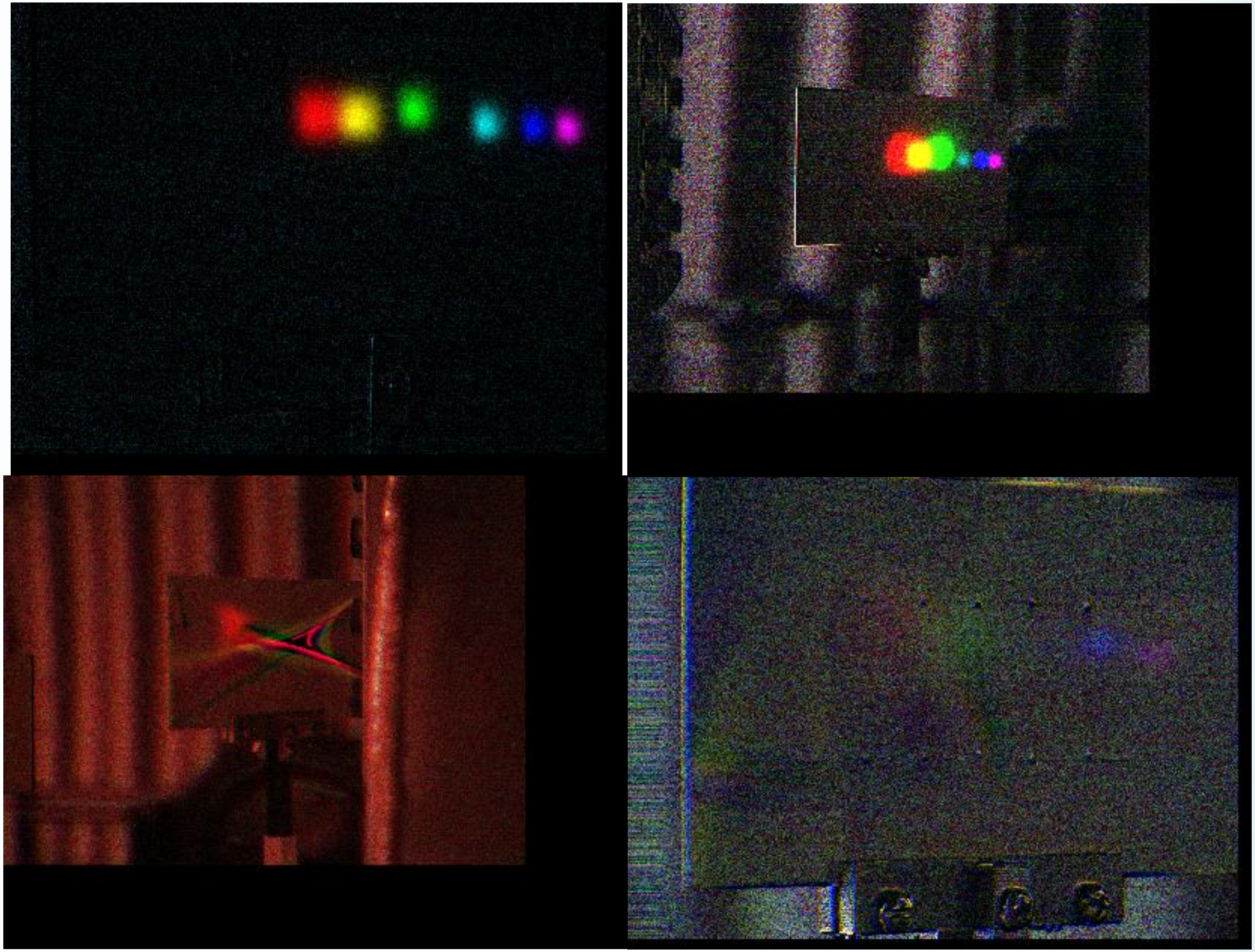
NSRL 50MeV protons

Beam in

Beam out



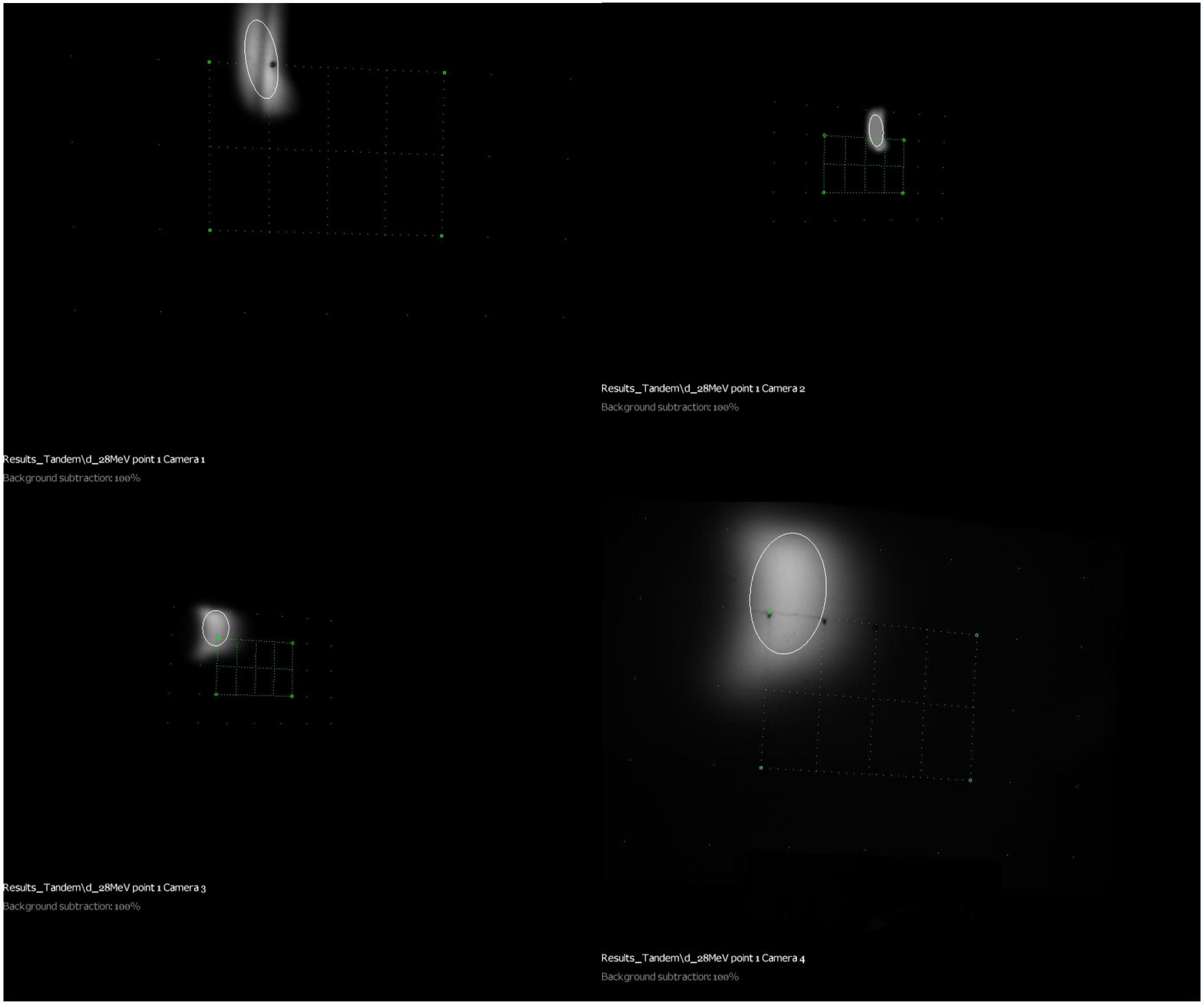
NSRL All Energies



Beam in

Beam out

Tandem 28MeV d ~ 50MeV p



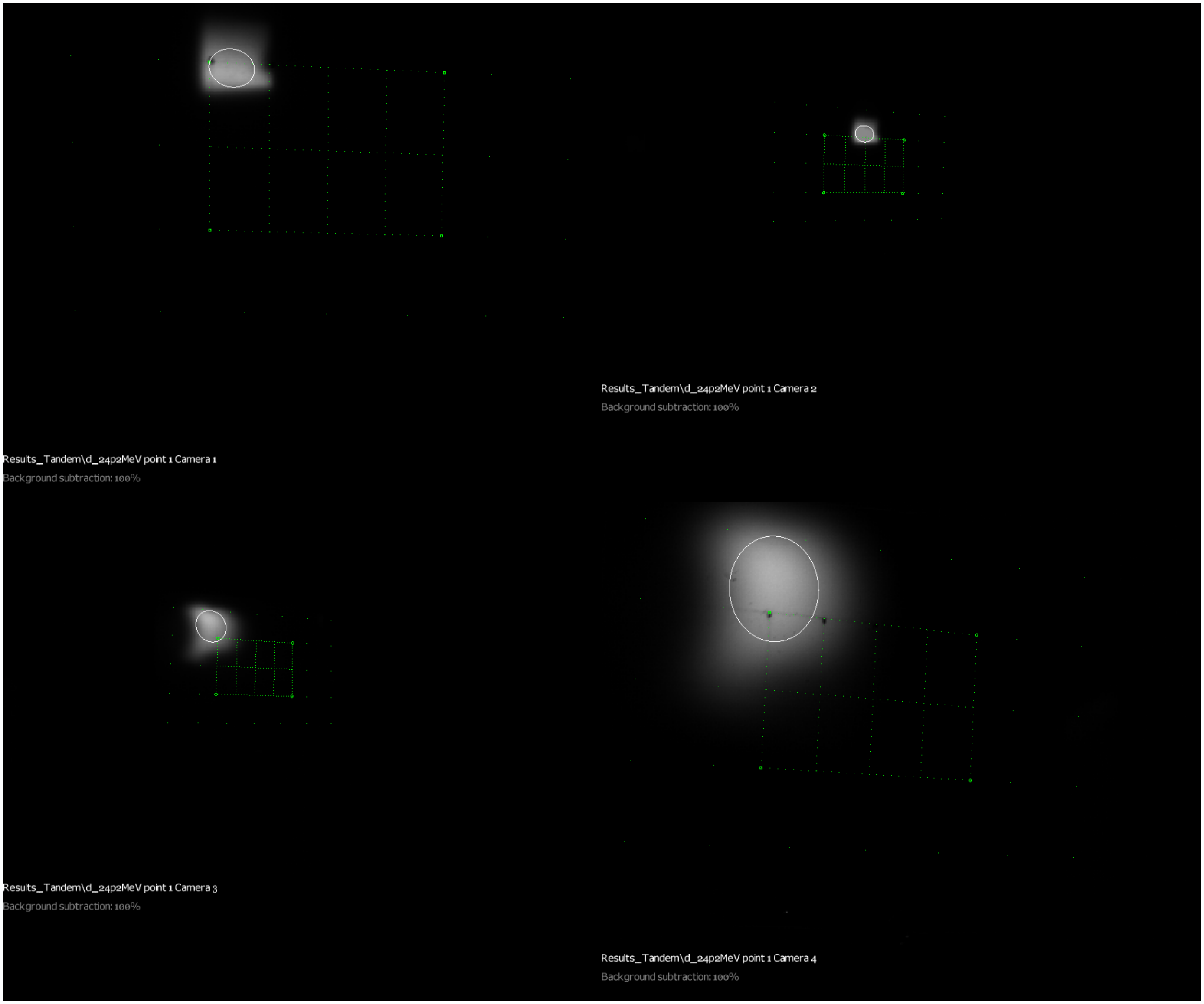
Beam in

Beam out

Tandem 24.2MeV d ~ 40MeV p

Beam in

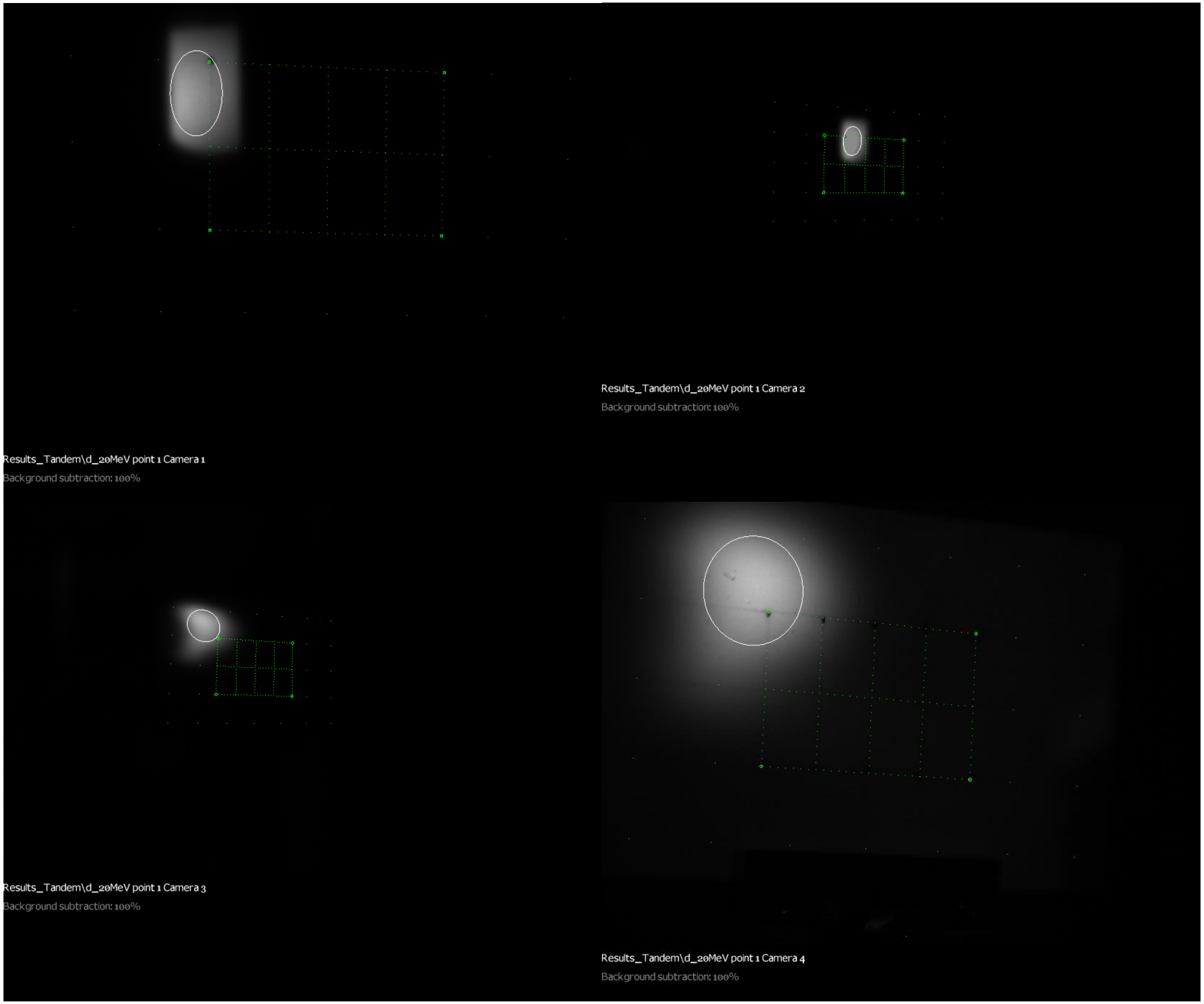
Beam out



Tandem 20MeV d ~ 30MeV p

Beam in

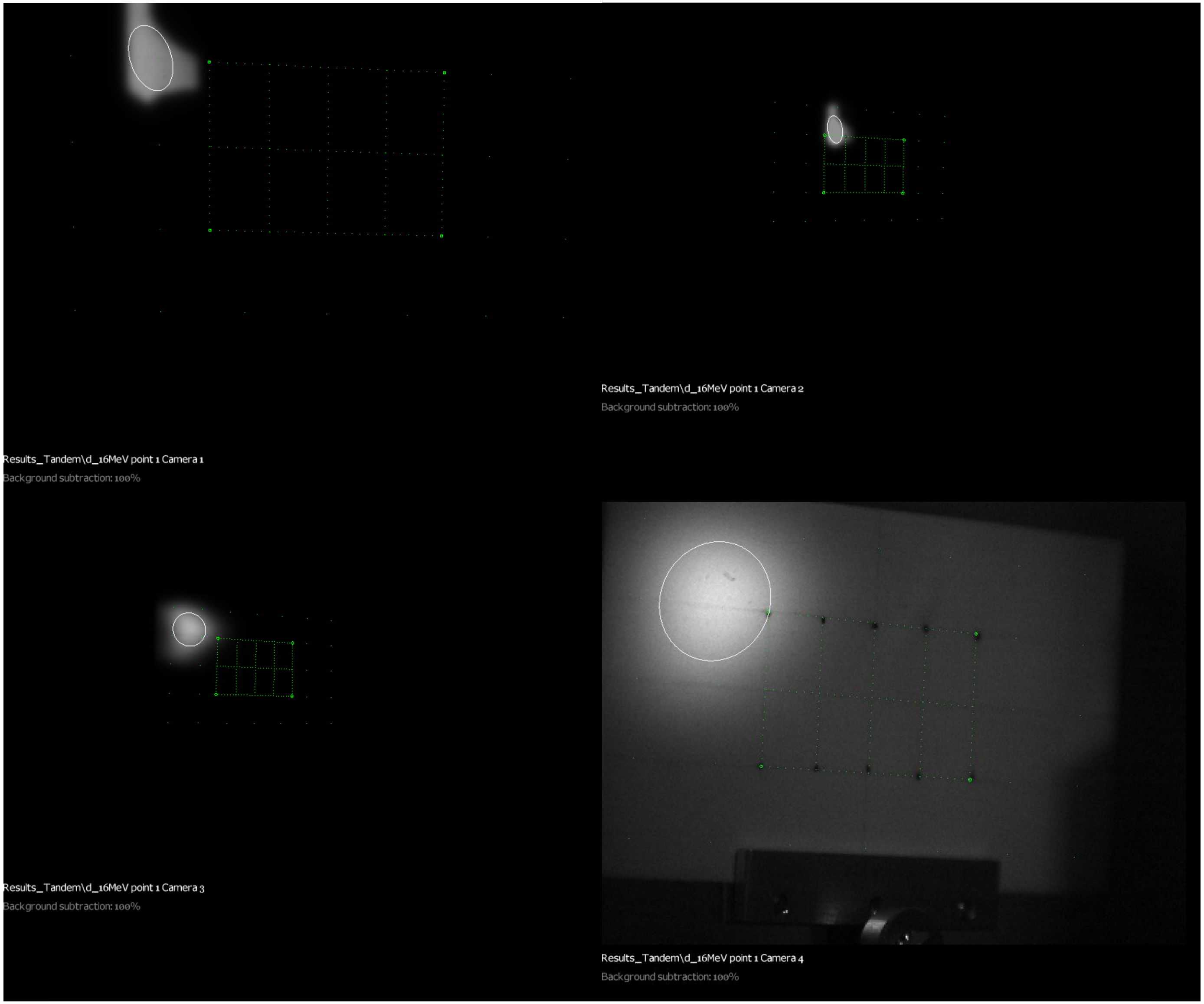
Beam out



Tandem 16MeV d ~ 20MeV p

Beam in

Beam out



Results_Tandem\d_16MeV point 1 Camera 1
Background subtraction: 100%

Results_Tandem\d_16MeV point 1 Camera 2
Background subtraction: 100%

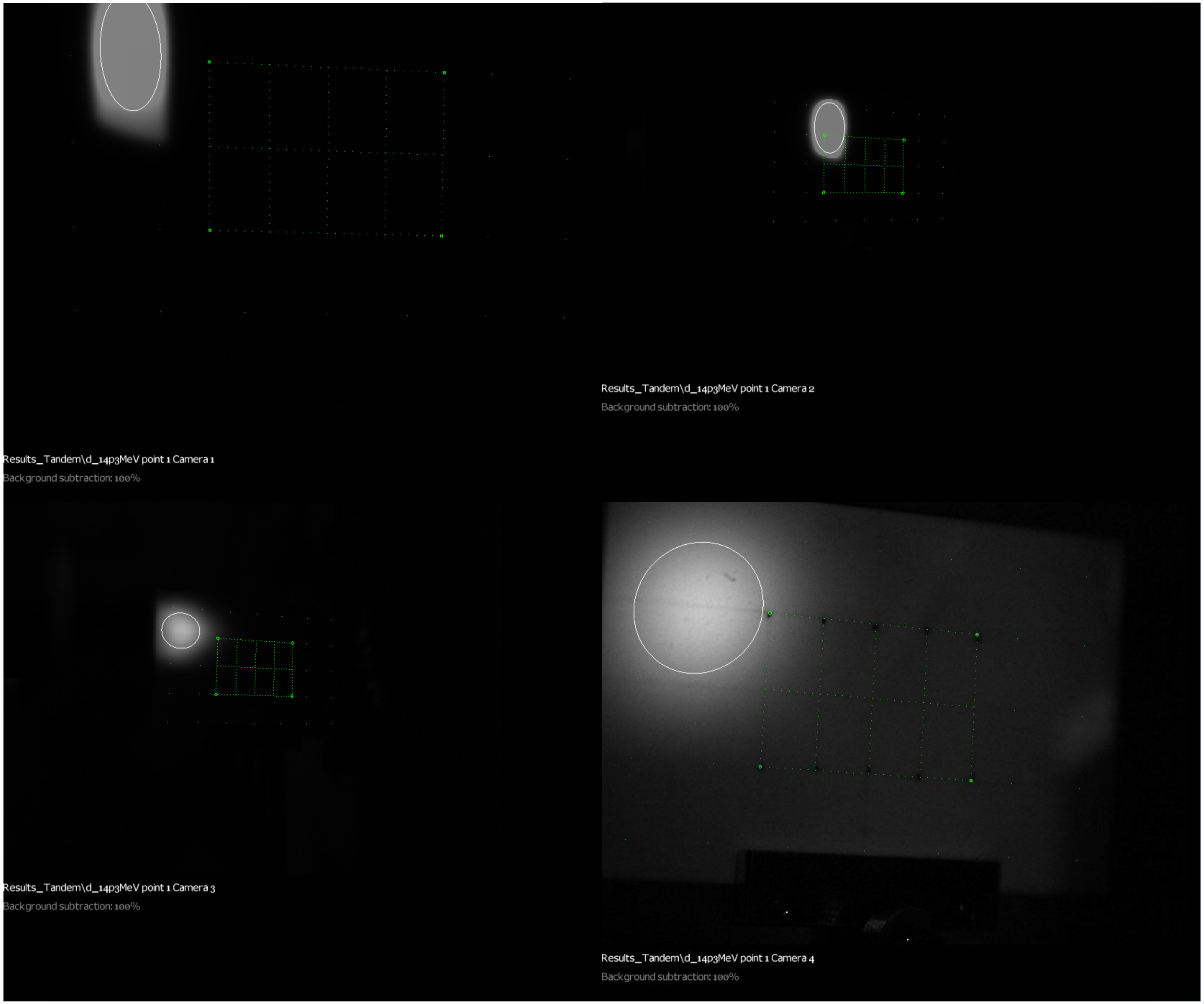
Results_Tandem\d_16MeV point 1 Camera 3
Background subtraction: 100%

Results_Tandem\d_16MeV point 1 Camera 4
Background subtraction: 100%

Tandem 14.3MeV d ~ 15MeV p

Beam in

Beam out



Tandem 12.9MeV d ~ 10MeV p

Beam in

Beam out

Results_Tandem\d_12p9MeV point 1 Camera 1
Background subtraction: 100%

Results_Tandem\d_12p9MeV point 1 Camera 2
Background subtraction: 100%

Results_Tandem\d_12p9MeV point 1 Camera 3
Background subtraction: 100%

Results_Tandem\d_12p9MeV point 1 Camera 4
Background subtraction: 100%

Beam may have stopped in air before screen 4

Tandem All Energies

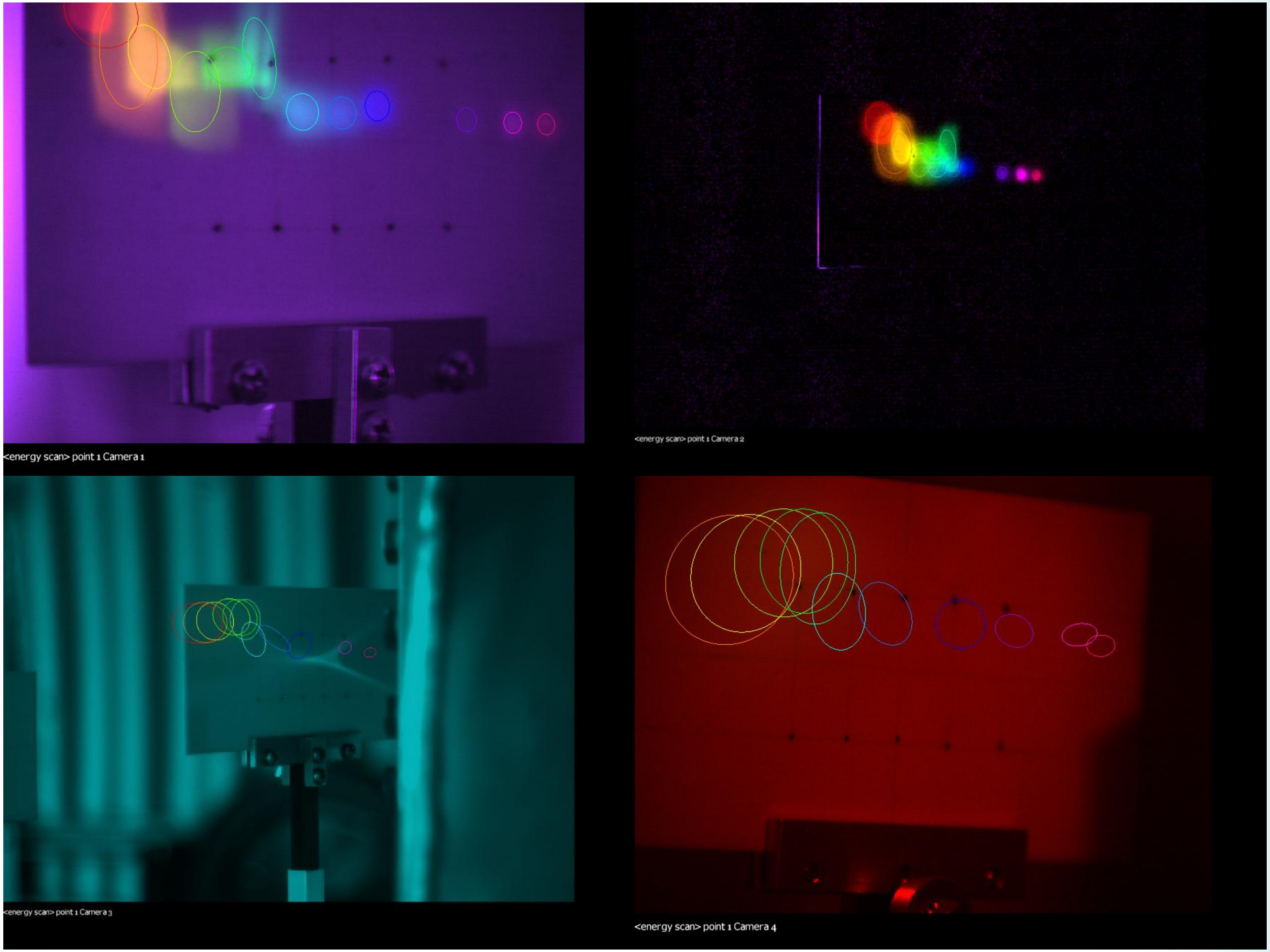
Beam in

Beam out

All 12 Ellipses

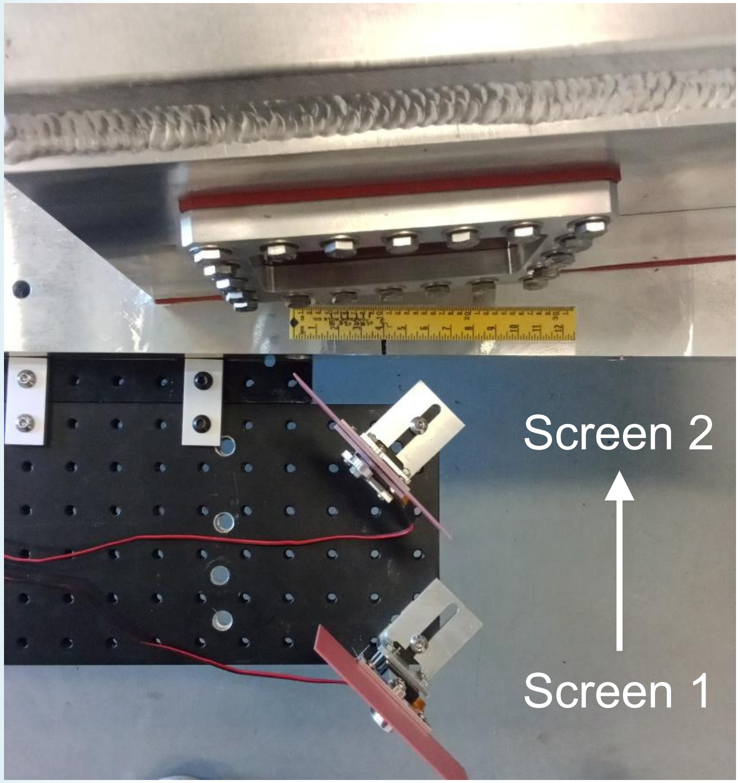
Beam in

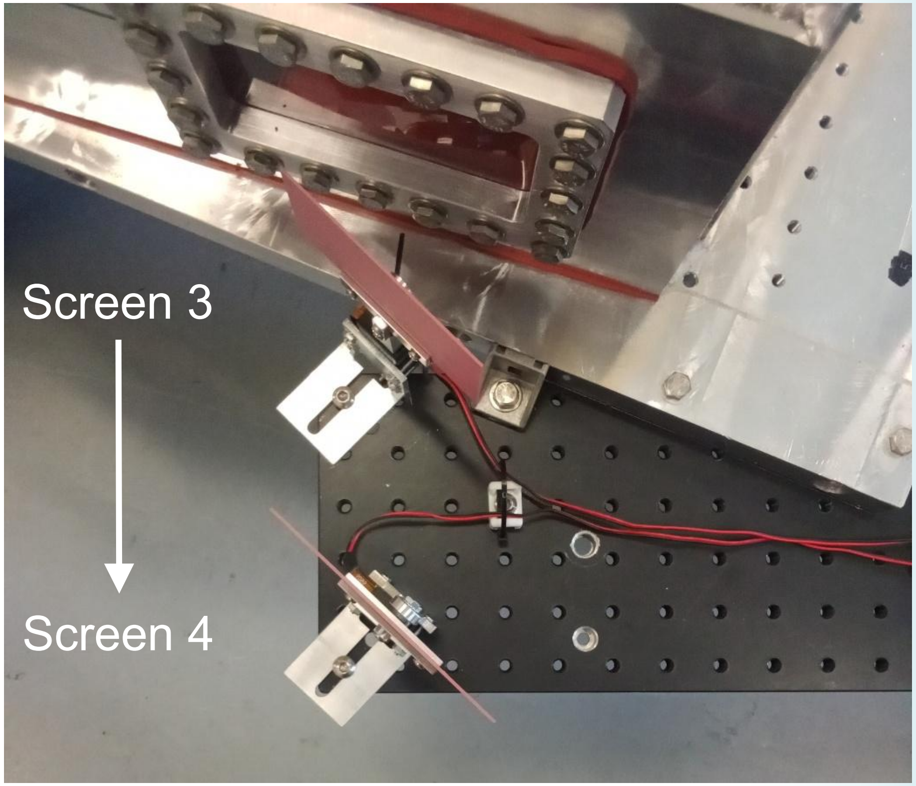
Beam out



Screen Alignment Errors

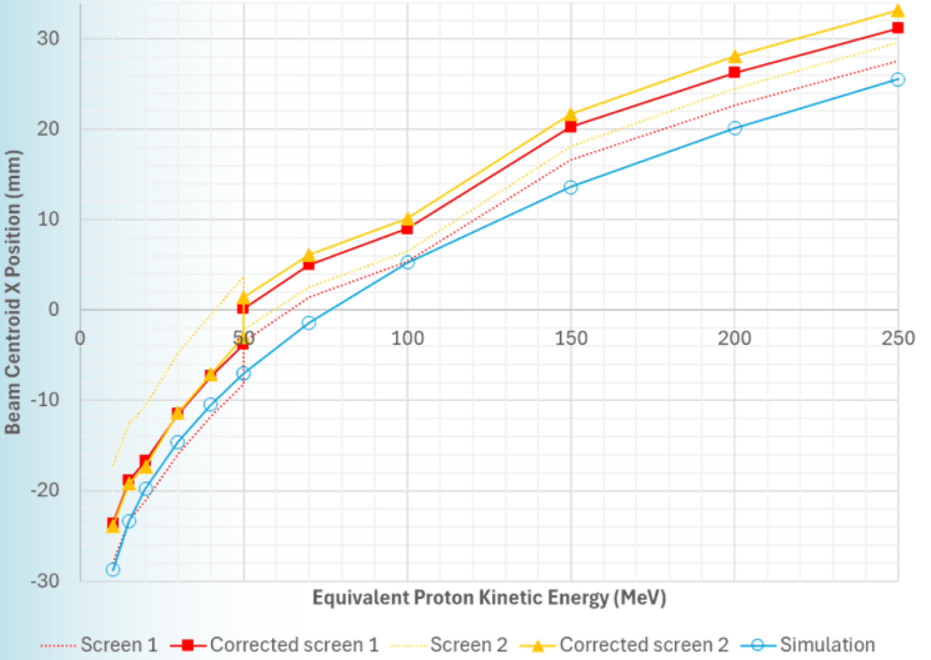
- This affected the Tandem run, so the screens were resurveyed and the offsets subtracted



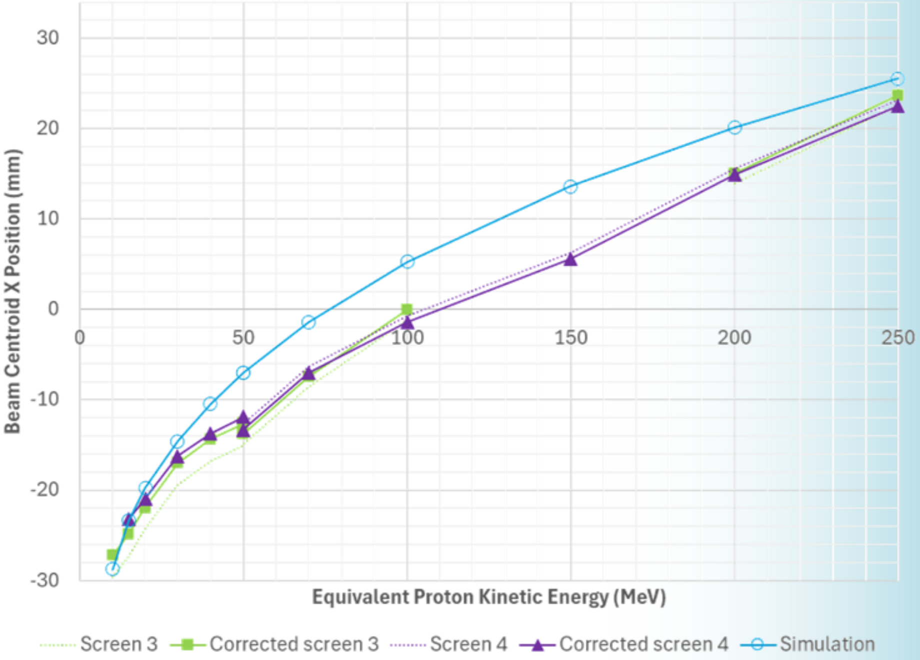


Corrected Centroid X Positions

Beam in



Beam out

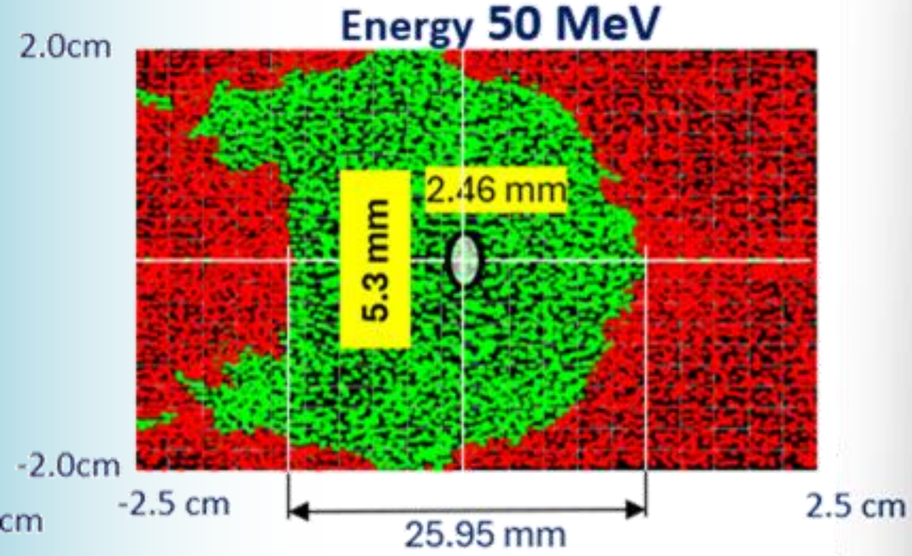


- Location tracks with energy as expected
- Alignment was “by hand”: 3-8mm input errors

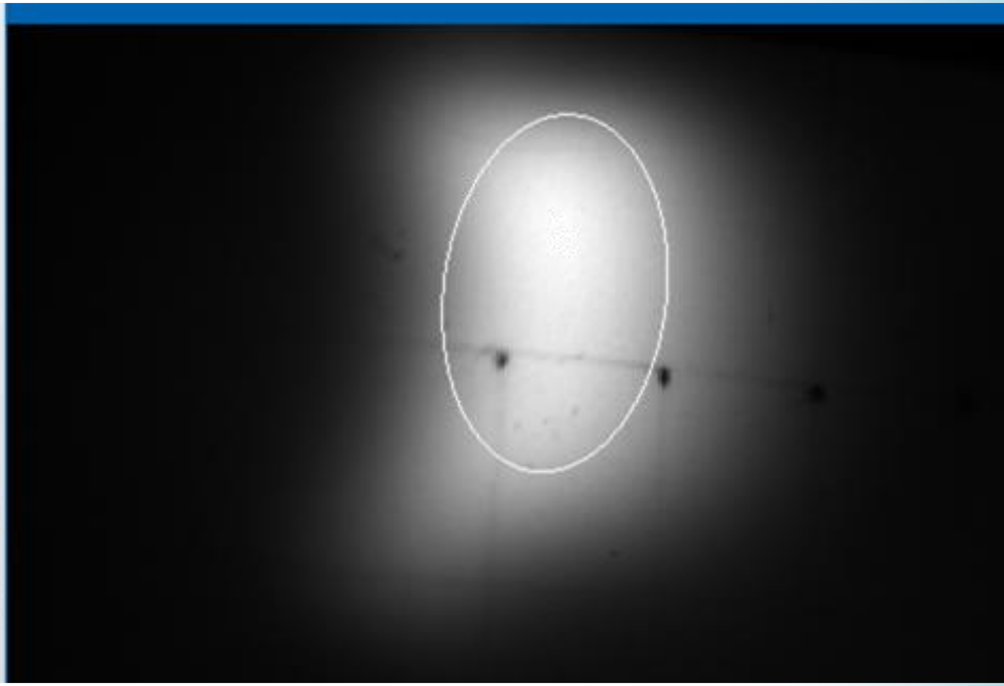
Filling the Dynamic Aperture?

- At lower energies, the output beam gets very large and starts to assume a crescent shape

Simulation



Experiment

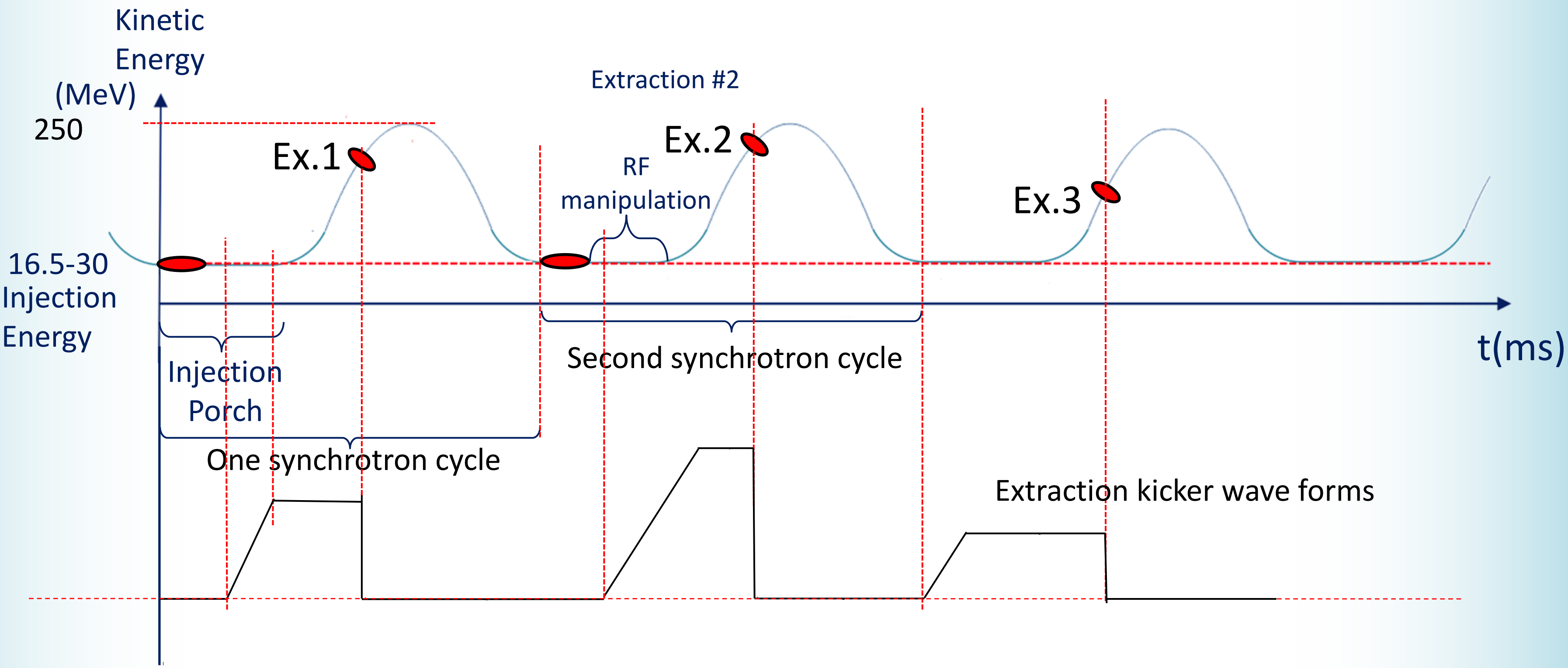


Experiment Conclusion

- Beams at all energies were transmitted through the 4-cell test girder (22.5° or 1/8 arc)
  - Protons at NSRL and deuterons at Tandem
- 10-250MeV is a factor of 5.3× in momentum
  - Very large for a non-scaling FFA, especially one with a flattened tune
  - 250MeV is highest ever energy in any NS-FFA line
- Beam ought to propagate several cells around a ring at the start of commissioning
  - (even without magnet shimming/correction here)

BACKUP

Fast Cycling Synchrotron Cycles



0.8ms < τ < 1.85ms
1.3kHz< f < 540 Hz

Time of bunch flight 405-550 ns
At the injection porch time of 926 μs there are 1680 turns. 15 turns for 15 Cyclotron bunches and 1650 turns for RF manipulations

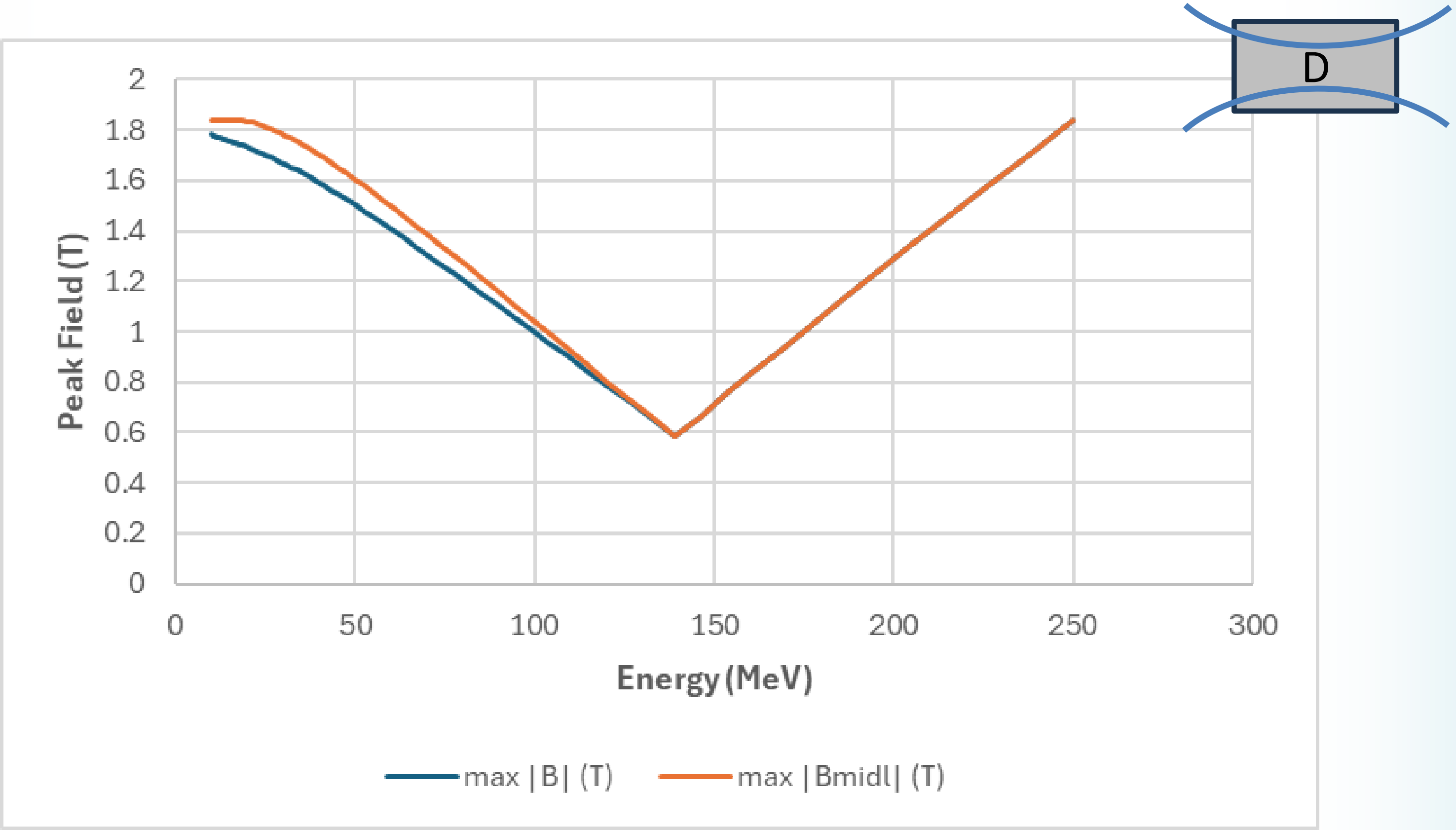
If the RF kicks are ±30 kV, during the slip-stacking merge a difference in the time of flight for two 2 energies is 773ps. If the batches are 15 m apart it would take 370 turns to get them aligned. Next step would be to merge into one bucket by snaping the new RF voltage on.

Fast Cycling Acceleration with Ferrite cavities

By Stephen Brooks

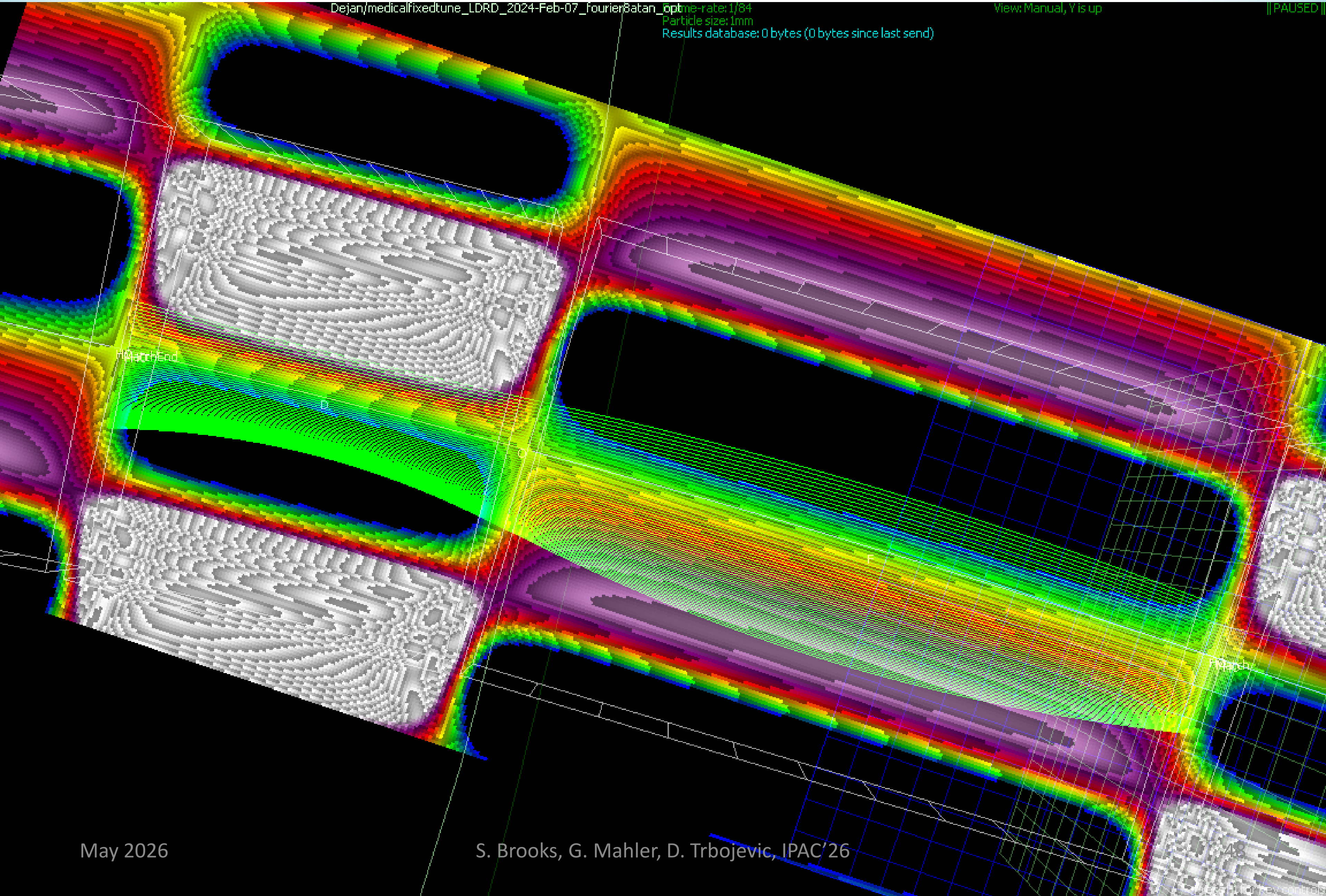
	Choices for injector cyclotron				Units
	ACSI	GE	TR-19	IBA	
Energy of Injector Cyclotron	14	16.5	19	30	MeV
Cyclotron current	400	200	400	1200	μA
Treatment charge	60	60	60	60	nC
Injection turns	4	4	4	2	#
RF acceleration per turn	29.70	29.70	29.70	44.55	kV
Calculation	Treatments Options				
Turn duration	585.74	540.6	504.8	405.1	ns
Charge per turn	0.234	0.108	0.151	0.486	nC
Charge per injection	0.937	0.432	0.606	0.972	nC
Machine cycles	65	139	100	62	#
Machine cycle rate	540	540	540	809.95	Hz
Outputs					
Treatment time	120	257	185	76.54	ms

Peak Fields vs. Energy



Orange line is field at magnet longitudinal centre, which is different than at exit (orbit in fringe area) for D magnet.

Orbits and Fields in Muon1



Lattice Converted from BMAD

Three cells for field wrap

Multipoles dipole…dodeca

Componer	Name	Length	AlignMode	Angle	FringeFunc	FringeFunc	FringeFunc	FringeLimi	func3	func3c0	func3c1	func3c2	func3c3	func3c4	func3c5	func3degr	HalfHeight	HalfWidth
Drift	HO	0.01																
Magnet3Re	F	0.18	Integral	0.058204	TwoAtan	0.008	0.04	0.5	Polynomia	-0.54862	72.3	-967.9	2250	-65000	570000	5	0.01	0.07
Drift	O	0.02																
Magnet3Re	D	0.123612	Integral	0.039971	TwoAtan	0.008	0.04	0.5	Polynomia	-0.54862	-89.31	1497	-870	312000	5500000	5	0.01	0.07
Drift	HO	0.01																
MatchScar	Match																	
Drift	HO	0.01																
Magnet3Re	F	0.18	Integral	0.058204	TwoAtan	0.008	0.04	0.5	Polynomia	-0.54862	72.3	-967.9	2250	-65000	570000	5	0.01	0.07
Drift	O	0.02																
Magnet3Re	D	0.123612	Integral	0.039971	TwoAtan	0.008	0.04	0.5	Polynomia	-0.54862	-89.31	1497	-870	312000	5500000	5	0.01	0.07
Drift	HO	0.01																
Match-Ape	MatchEnd																	
Drift	HO	0.01																
Magnet3Re	F	0.18	Integral	0.058204	TwoAtan	0.008	0.04	0.5	Polynomia	-0.54862	72.3	-967.9	2250	-65000	570000	5	0.01	0.07
Drift	O	0.02																
Magnet3Re	D	0.123612	Integral	0.039971	TwoAtan	0.008	0.04	0.5	Polynomia	-0.54862	-89.31	1497	-870	312000	5500000	5	0.01	0.07
Drift	HO	0.01																
Cell total		Length		Angle														
		0.343612	m	0.098175	rad													
		L_magnets		R_avg														
		0.303612	m	3.5	m													
		Packing factor																
		0.88359																

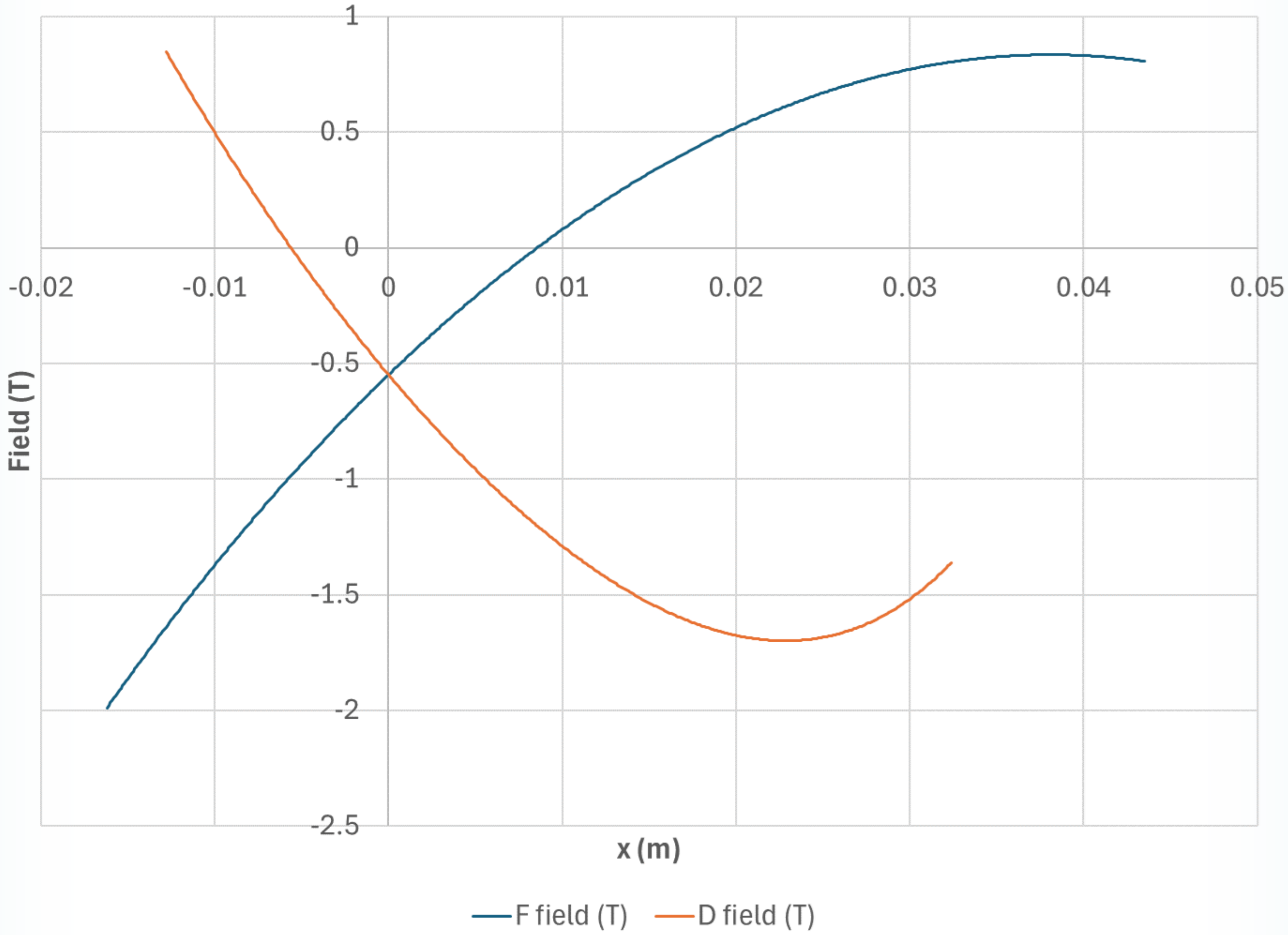
These slides look a lot like last year's, but Dejan's multipole numbers have changed!

Angle 5.625° per cell, 64 cells per turn. Cell length 34.4cm, R=3.5m.
This worked well in BMAD, fixed stable tunes from 10MeV – 250MeV

BMAD and Muon1 Magnet Models

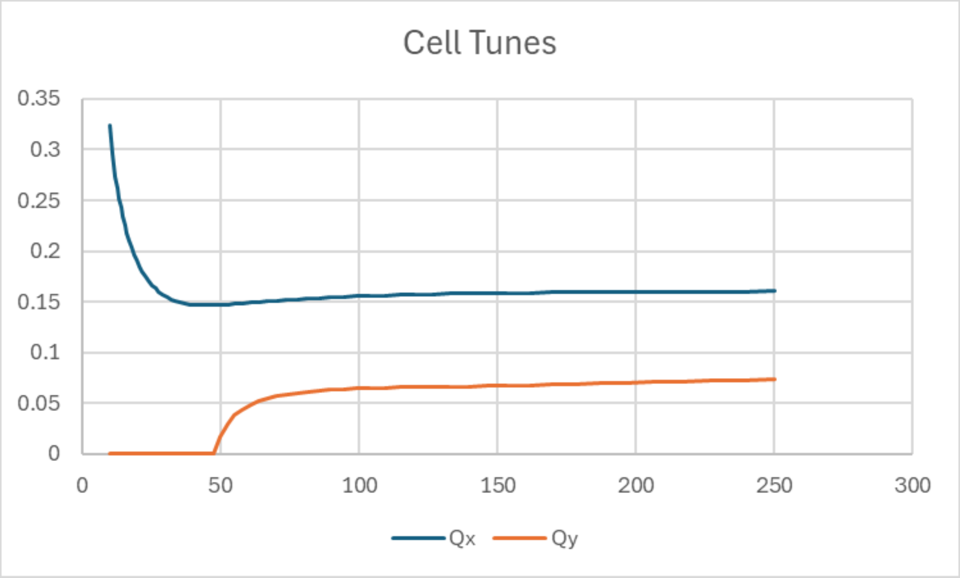
- BMAD has a zero-length end field model
- Muon1 has a Maxwellian fringe field model with finite length (bit more realistic)
  - But you have to choose the length yourself!
  - Only way to do this sort of field in BMAD is to generate fieldmaps, so there’s a difference
- We also changed from sectors to rectangles but that turned out to be a small effect

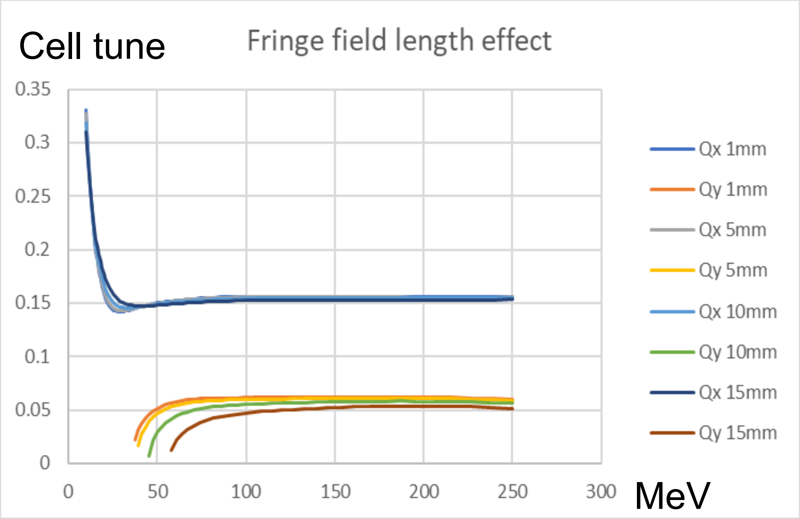
Field Profiles (BMAD)



BMAD Lattice in Muon1

- Vertical tune is unstable at low energies
  - On previous lattice version, this was true no matter what Muon1 fringe field length I chose





This cell can be "easily" fixed using the Algorithm I used before

- Runge-Kutta 4th order tracking step
- Loop to get trajectory in cell
- Finite difference to get transfer matrix
  - Also gives tunes if orbit is closed
- Iterate (Newton) to find closed orbit
- Loop over all FFA energies
- Finite difference parameters to get response matrix of tune functions to ~~multipole~~ Fourier coefficient changes
- Iterate (optimiser) to find fixed-tune lattice

Muon1

Muon1 cell optics mode

Muon1 FFA optics mode

Fixed-tune FFA optimiser (parallel)

Wait, Fourier coefficients?

- Representing the transverse midplane field dependence $B_y(x,0)$ as a Fourier series made optimisation work better than multipoles
  - Suspect this is because sin,cos(nx) are orthogonal whereas polynomials are highly correlated
- Used the form

$$B_y(x,0) = c_0 + \Sigma_{n=1..8}\, s_n \sin(nkx) + c_n \cos(nkx)$$

…where $2\pi/k$ is about twice the orbit excursion

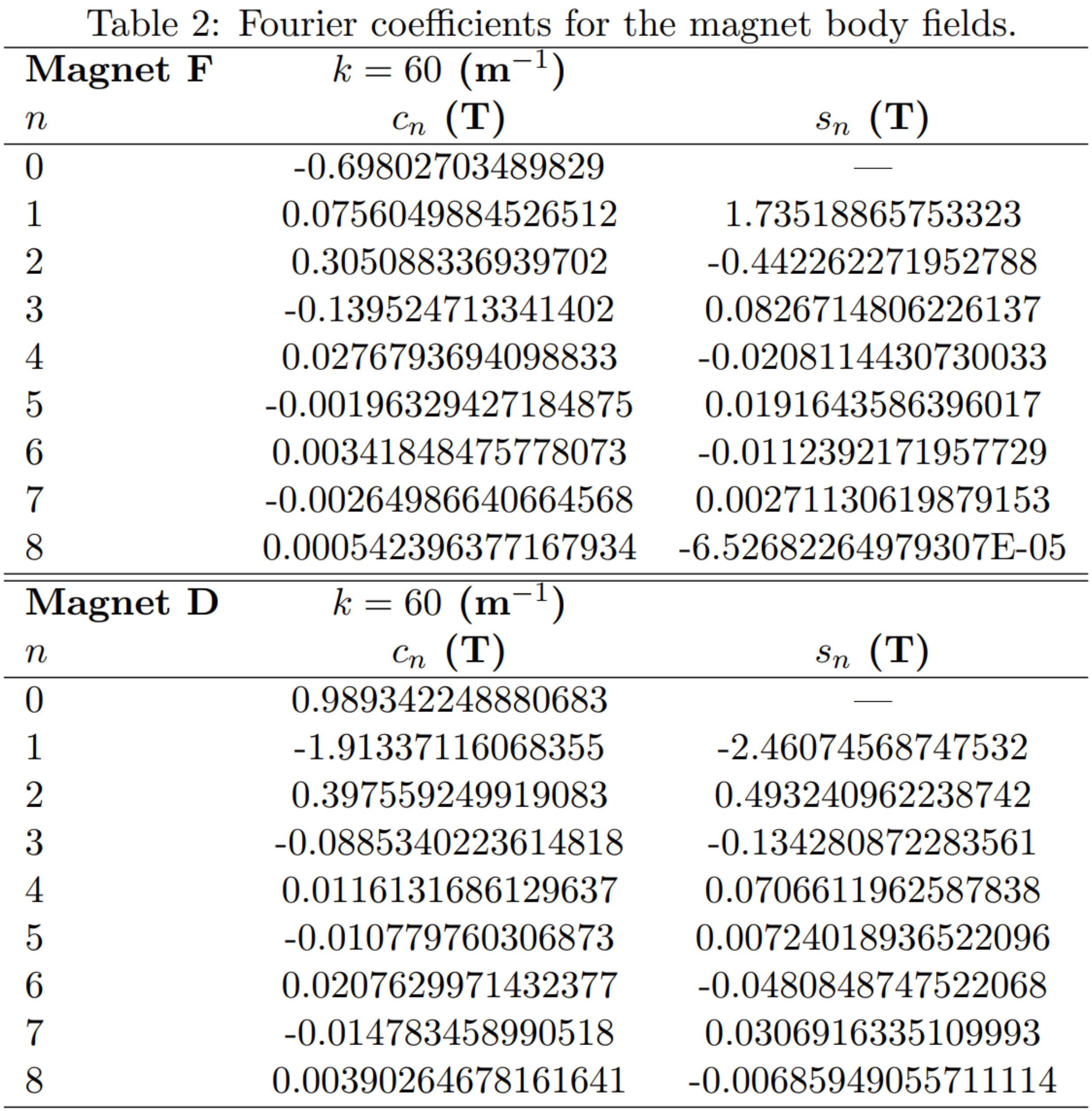
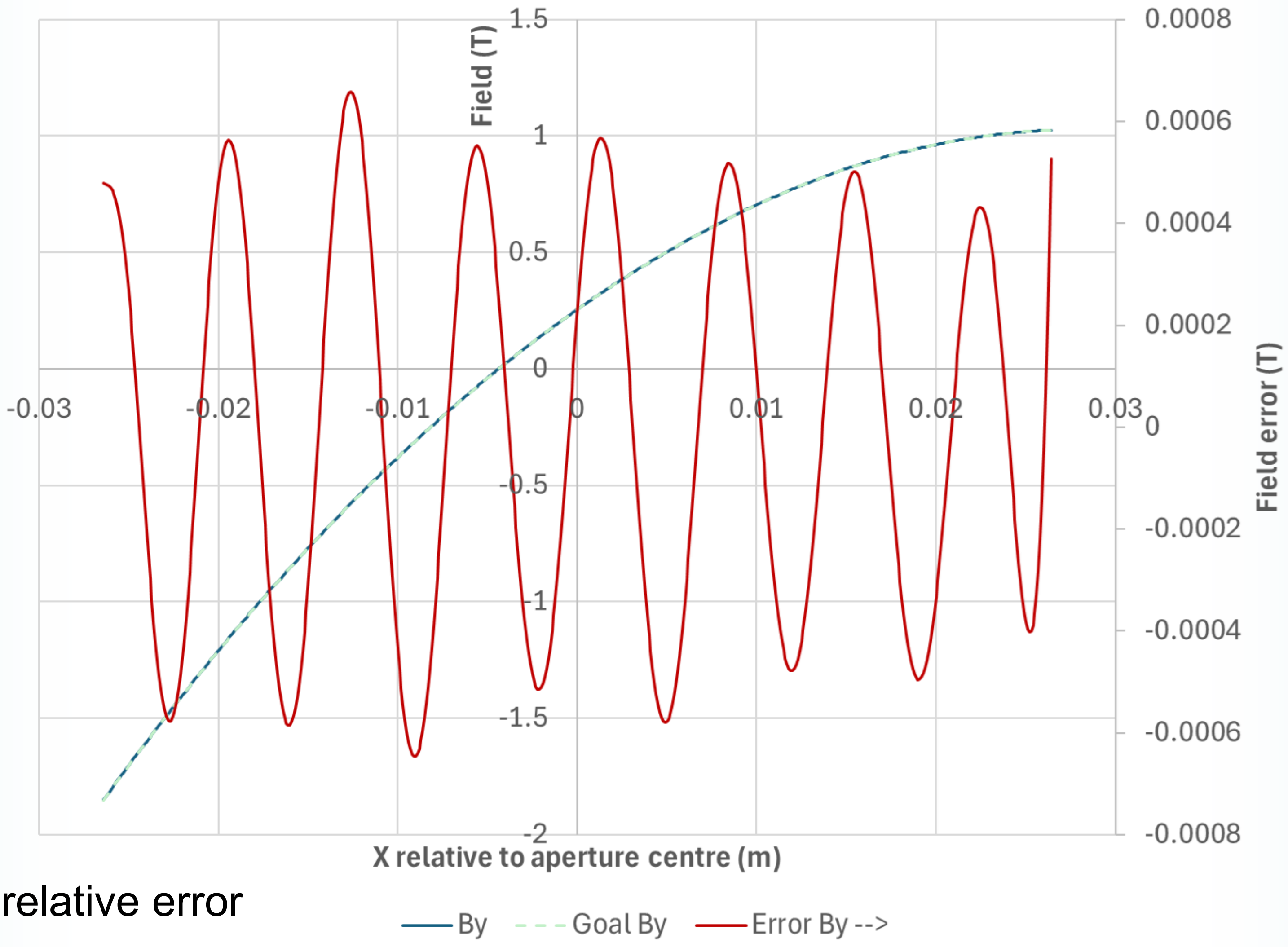


Table 2: Fourier coefficients for the magnet body fields.

Magnet F	$k = 60$ $(\mathbf{m}^{-1})$	
n	c_n **(T)**	s_n **(T)**
0	-0.69802703489829	—
1	0.0756049884526512	1.73518865753323
2	0.305088336939702	-0.442262271952788
3	-0.139524713341402	0.0826714806226137
4	0.0276793694098833	-0.0208114430730033
5	-0.00196329427184875	0.0191643586396017
6	0.00341848475778073	-0.0112392171957729
7	-0.00264986640664568	0.00271130619879153
8	0.000542396377167934	-6.52682264979307E-05

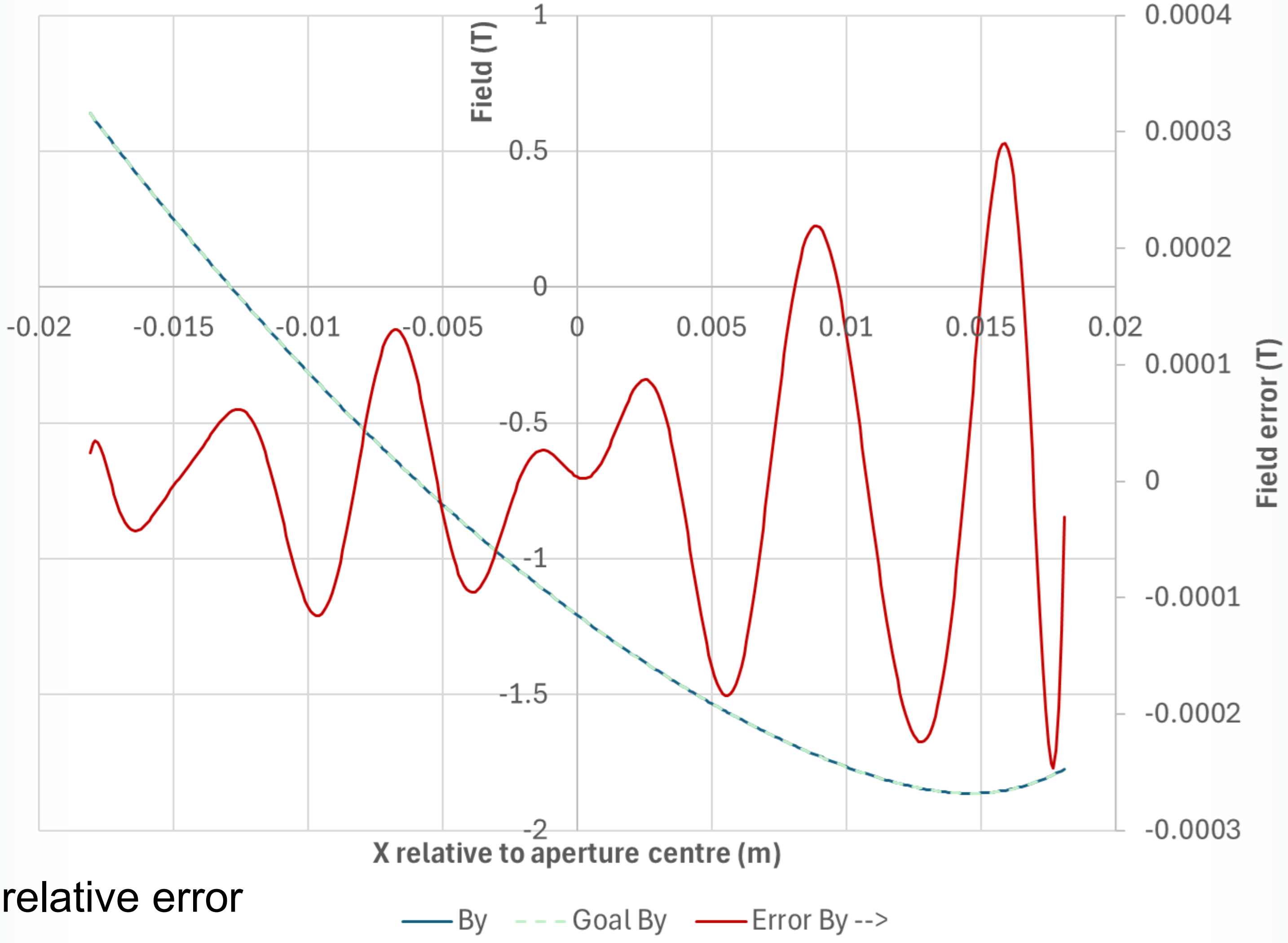
Magnet D	$k = 60$ $(\mathbf{m}^{-1})$	
n	c_n **(T)**	s_n **(T)**
0	0.989342248880683	—
1	-1.91337116068355	-2.46074568747532
2	0.397559249919083	0.493240962238742
3	-0.0885340223614818	-0.134280872283561
4	0.0116131686129637	0.0706611962587838
5	-0.010779760306873	0.00724018936522096
6	0.0207629971432377	-0.0480848747522068
7	-0.014783458990518	0.0306916335109993
8	0.00390264678161641	-0.00685949055711114

Magnet Sim. Field Error Graph (F)



3.6×10^{-4} relative error

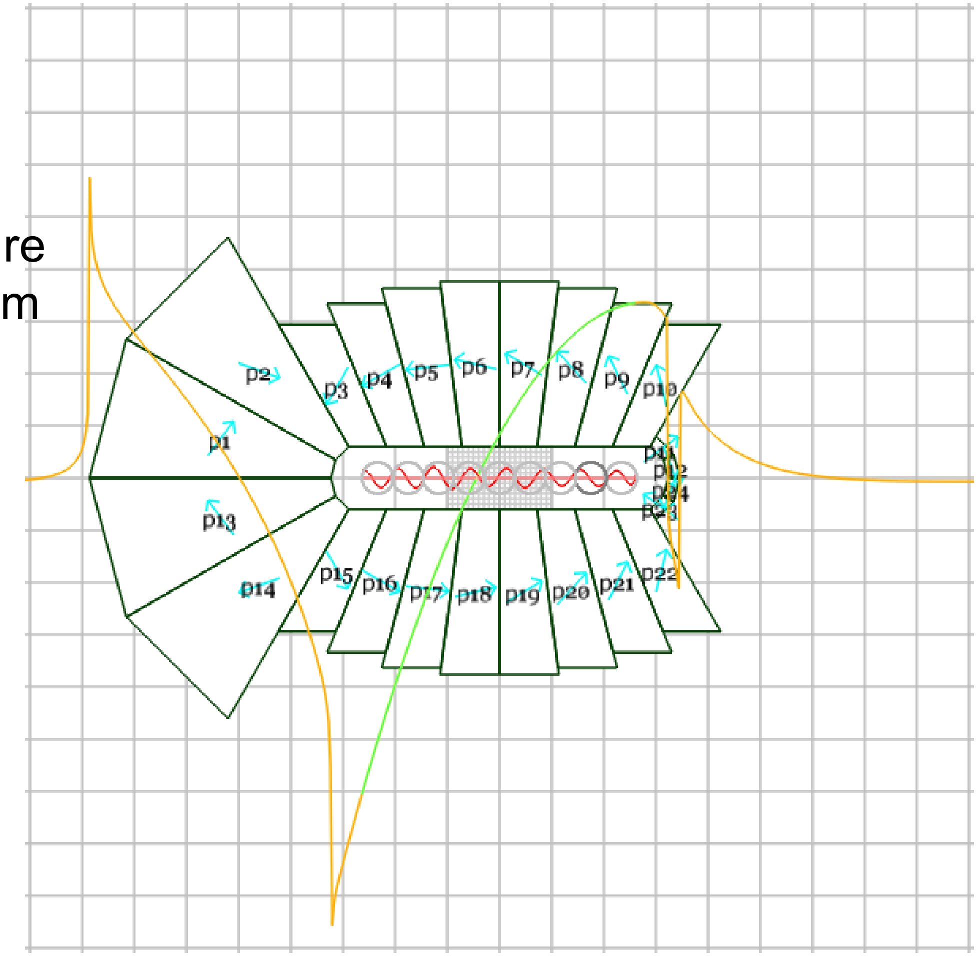
Magnet Sim. Field Error Graph (D)



1.6×10^{-4} relative error

Permanent Magnet Designs (F)

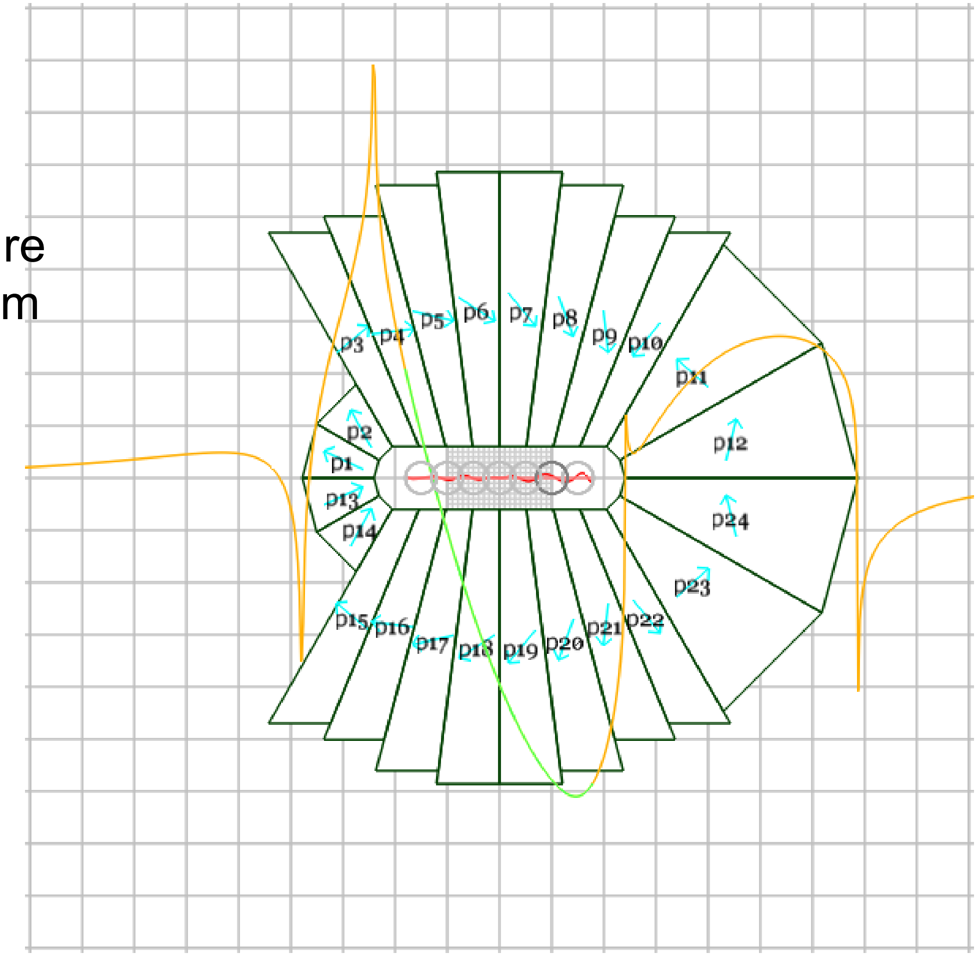
NdFeB material
N42EH grade
B_r=1.3T
69.90cm^2 area
64.7 x 12mm aperture
Good field X±26.3mm
1.85T max field



cm grid

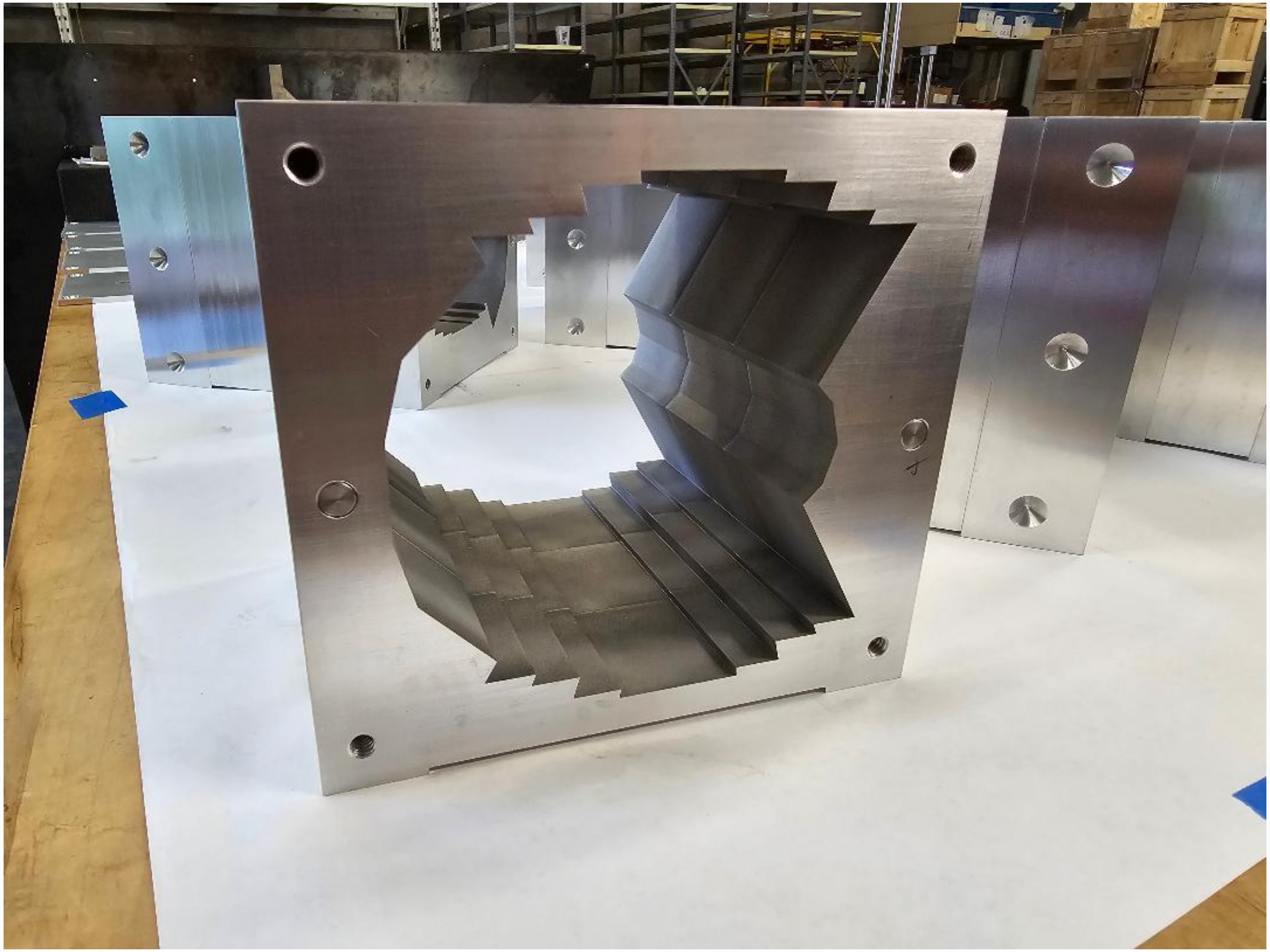
Permanent Magnet Designs (D)

NdFeB material
N42EH grade
B_r=1.3T
93.88cm^2 area
48.1 x 12mm aperture
Good field X±18.0mm
1.86T max field

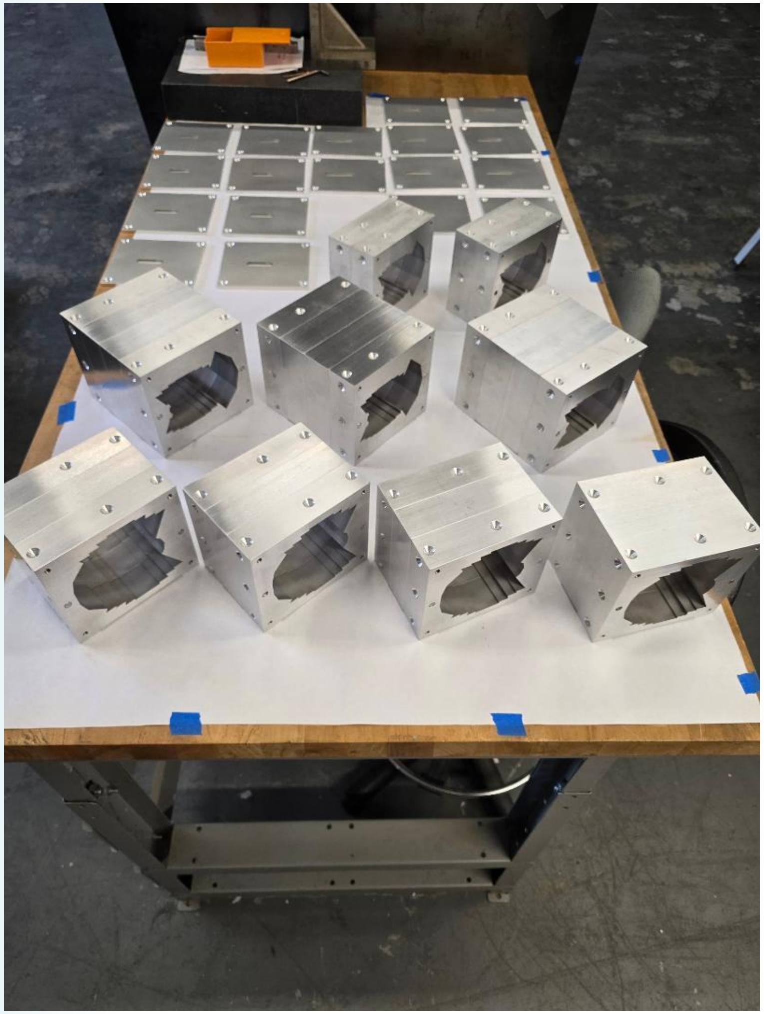


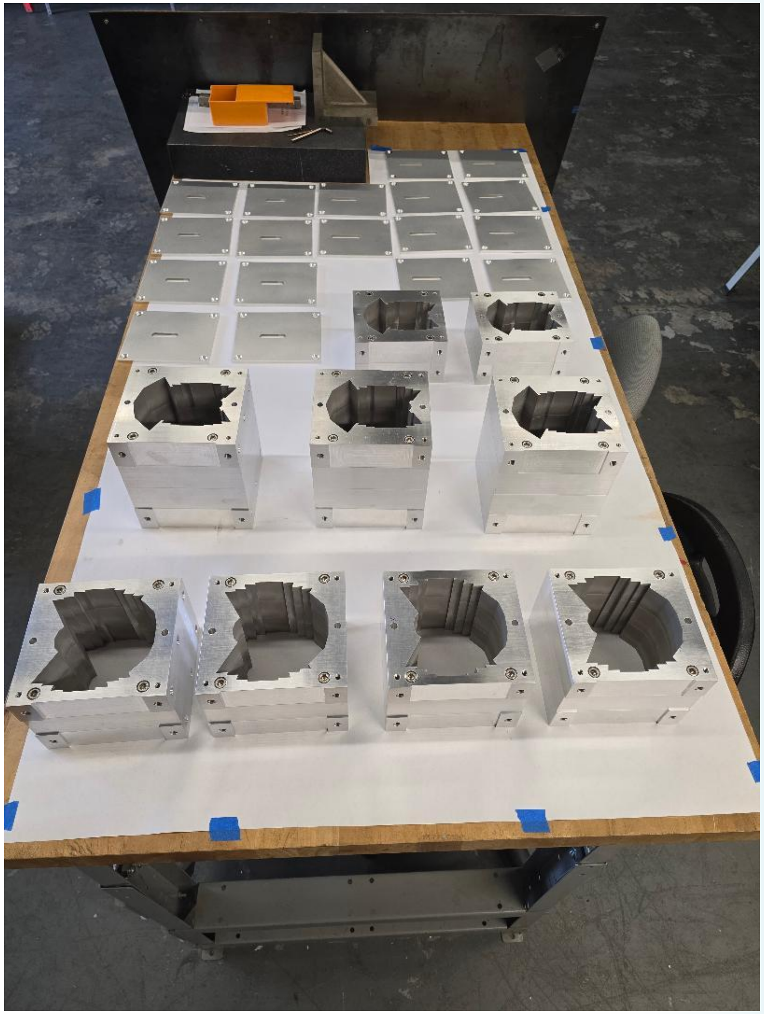
cm grid

Magnet Holders Machined

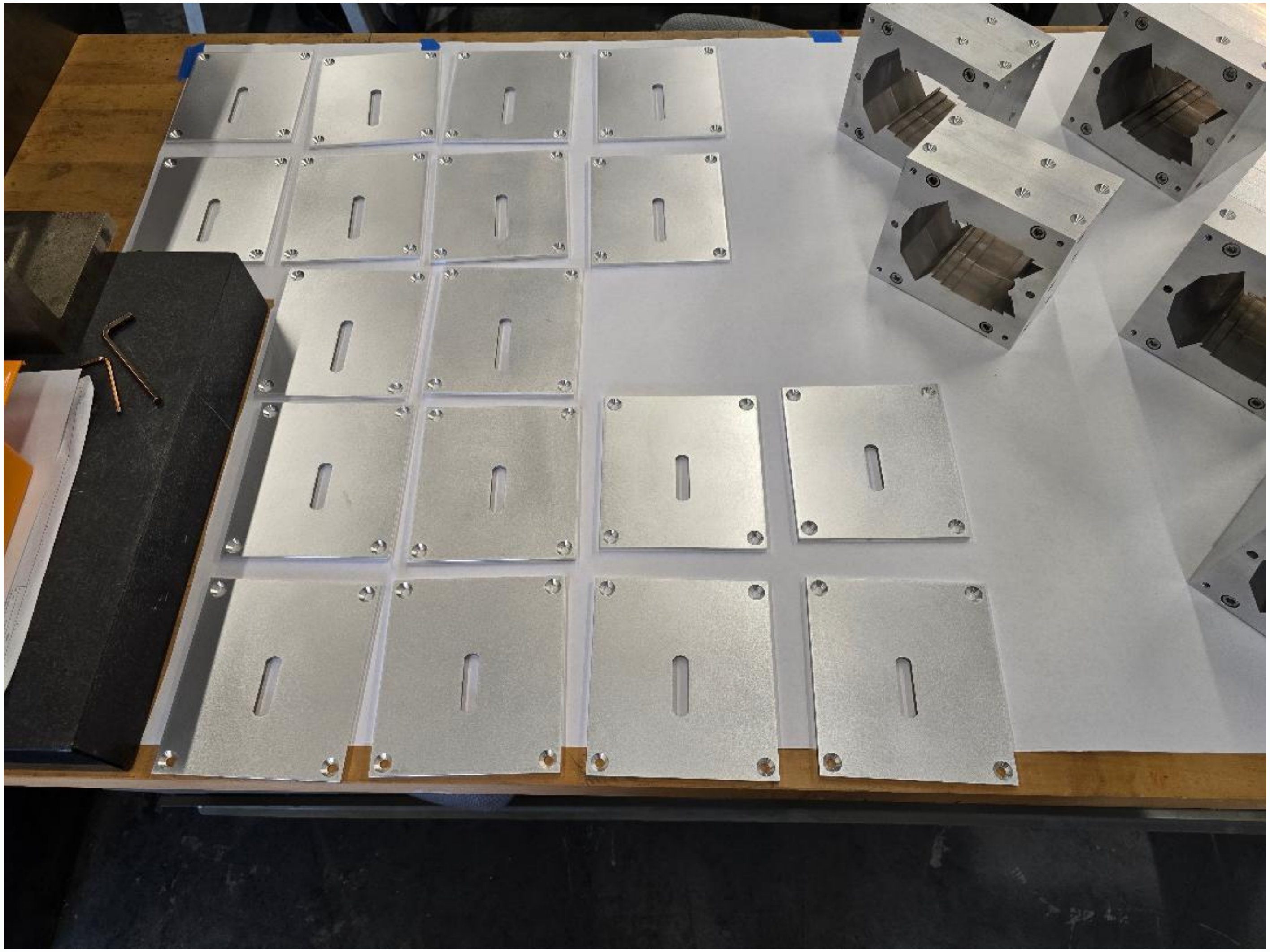


Magnet Holders Machined

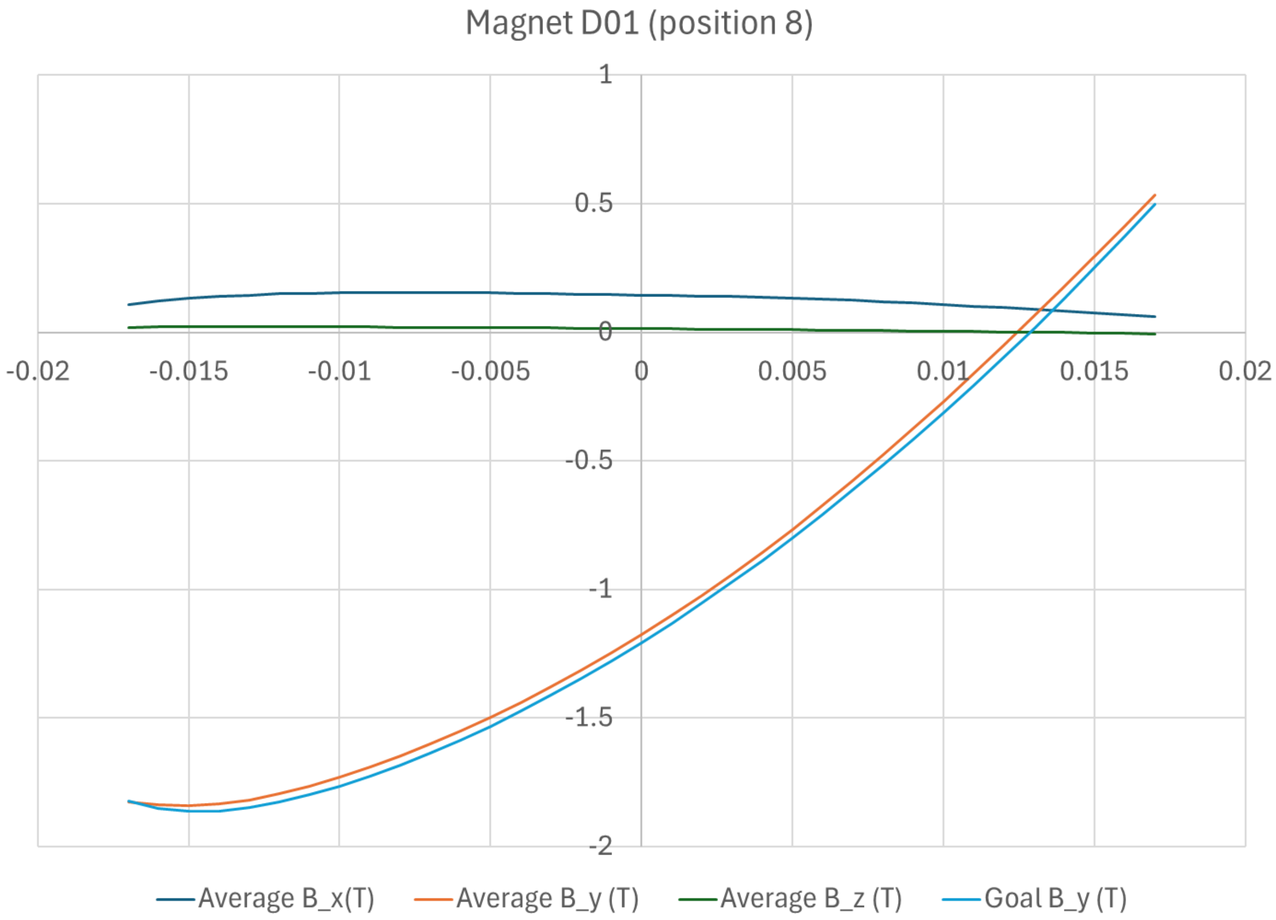




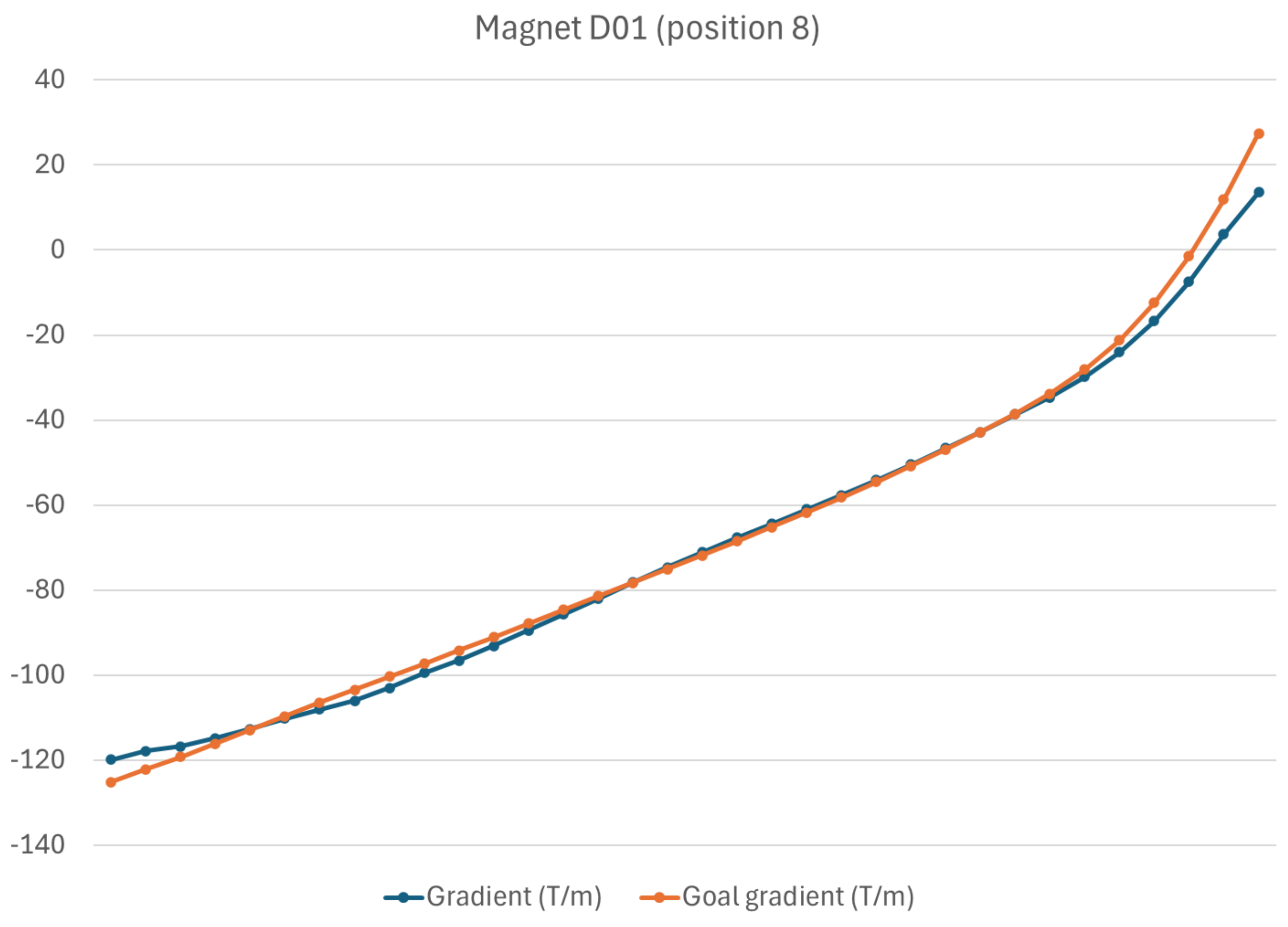
End Plates Machined



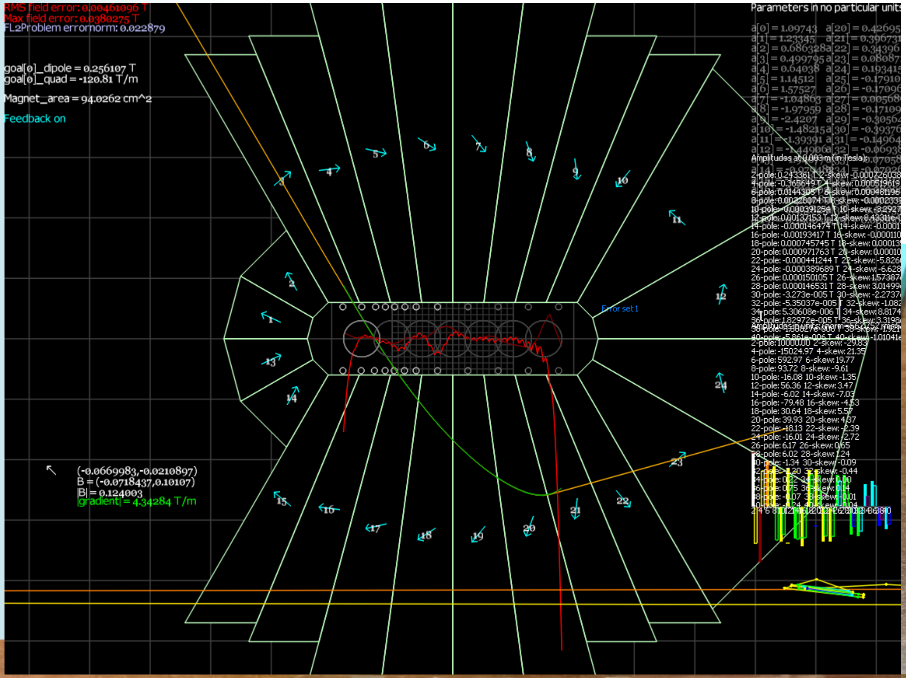
Raw Integrated Field Data



Measured Gradients



Attempt at Shimming



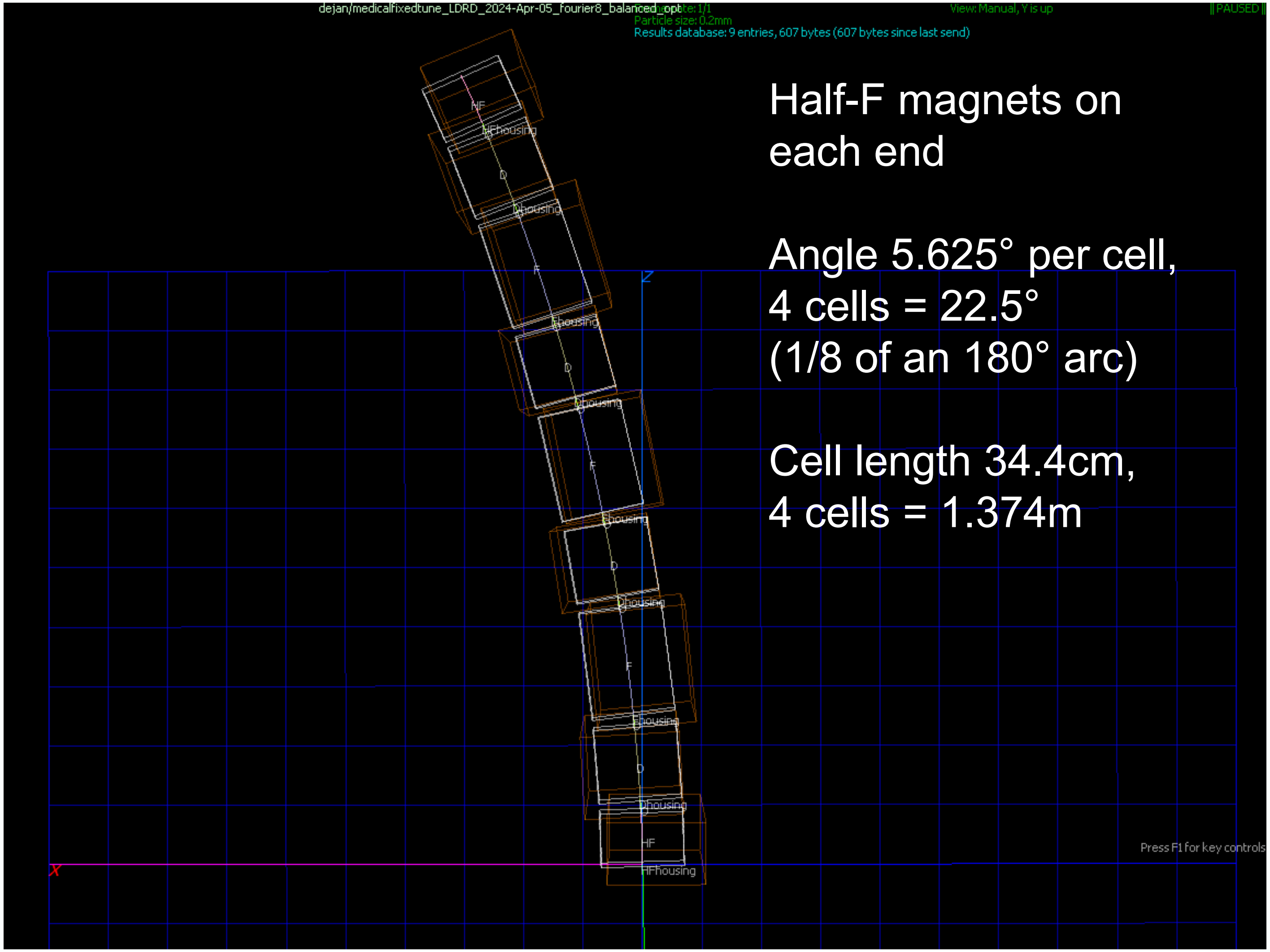
```
RMS field error: 0.00461096 T
Max field error: 0.0380275 T
FL2Problem errornorm: 0.022879

goal[0]_dipole = 0.256107 T
goal[0]_quad = -120.81 T/m

Magnet_area = 94.0262 cm^2

Feedback on
```

```
Parameters in no particular units

a[0] = 1.09743
a[1] = 1.23345
a[2] = 0.686328
a[3] = 0.499795
a[4] = 0.64038
a[5] = 1.14512
a[6] = 1.57527
a[7] = -1.04863
a[8] = -1.97959
a[9] = -2.4207
a[10] = -1.48215
a[11] = -1.39391
a[12] = -1.44906

Amplitudes at 0.003 m (in Tesla):
2-pole: 0.243361 T
4-pole: -0.365649 T
6-pole: 0.0144305 T
8-pole: 0.00228074 T
10-pole: -0.000391254 T
12-pole: 0.00137153 T
14-pole: -0.000146474 T
16-pole: -0.00193417 T
```

```
(-0.0669983,-0.0210897)
B = (-0.0718437,0.10107)
|B| = 0.124003
|gradient| = 4.34284 T/m
```

Shimming is possible in theory but more engineering is needed to keep wires securely in place in aperture, so magnets were not shimmed for this experiment.

Test Beamline, 4 cells



dejan/medicalfixedtune_LDRD_2024-Apr-05_fourier8_balanced_opt

Particle size: 0.2mm

Results database: 9 entries, 607 bytes (607 bytes since last send)

View: Manual, Y is up

|| PAUSED ||

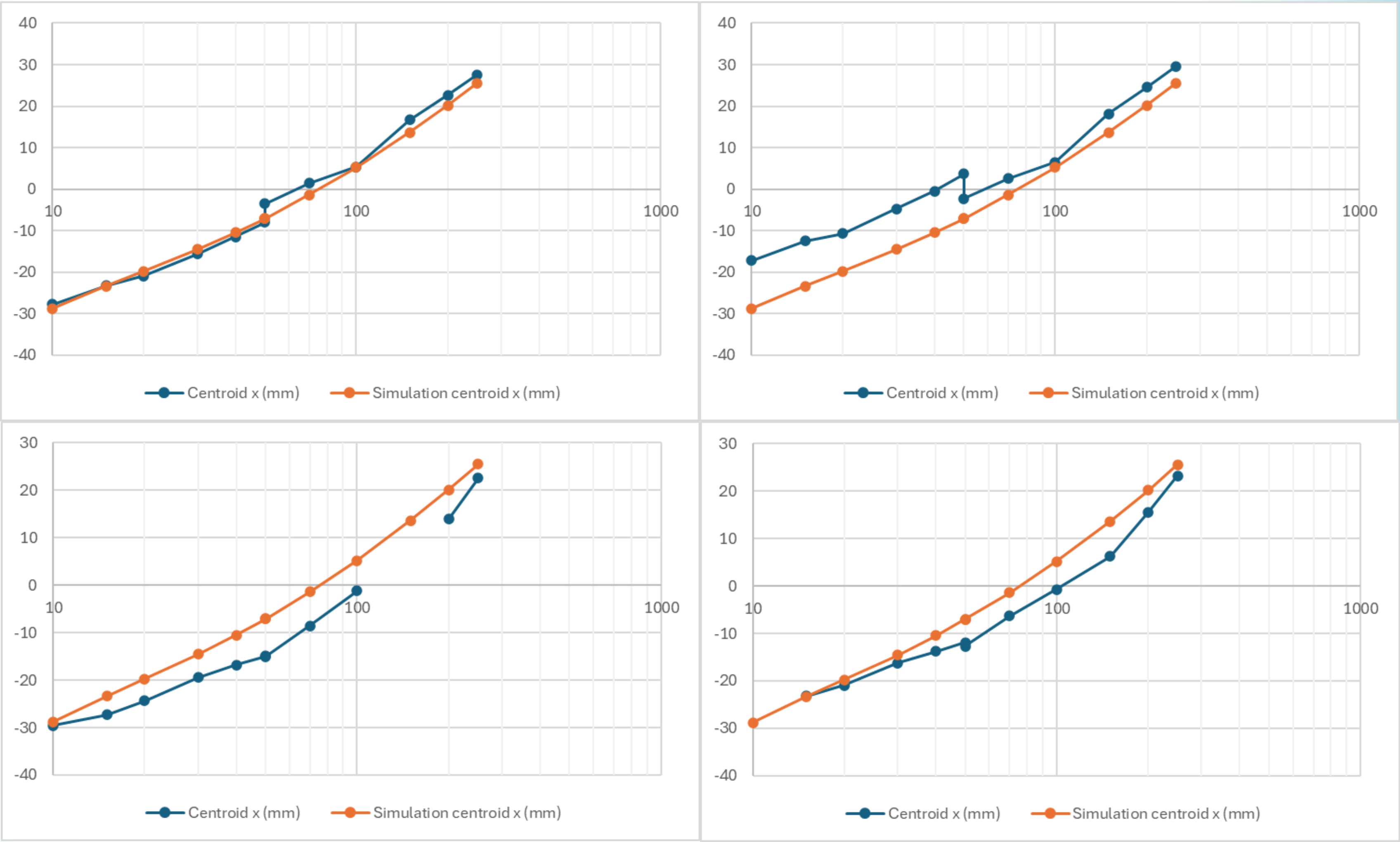
Press F1 for key controls

Half-F magnets on each end

Angle 5.625° per cell,
4 cells = 22.5°
(1/8 of an 180° arc)

Cell length 34.4cm,
4 cells = 1.374m

Centroid X Positions



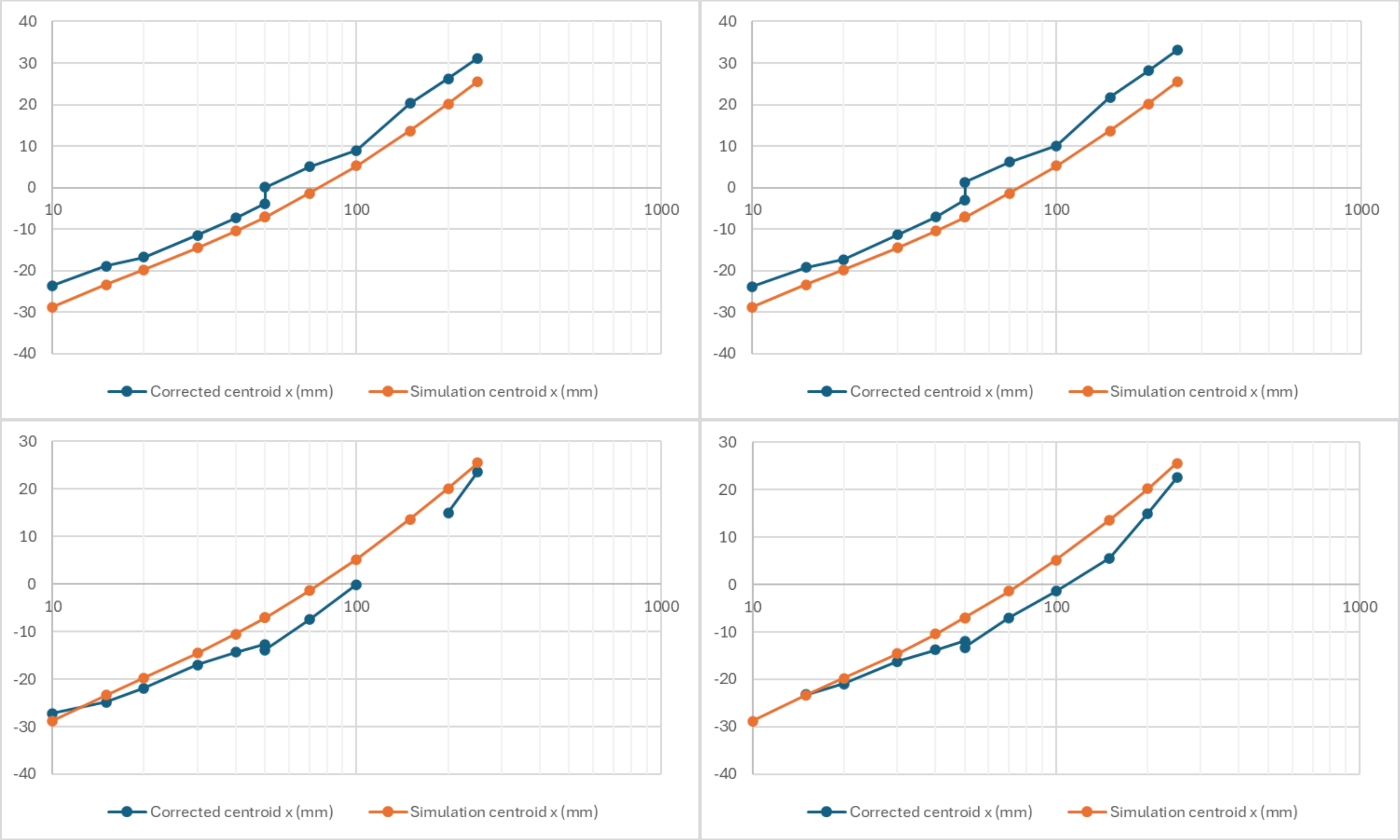
Beam in

Beam out

Corrected Centroid X Positions

Beam in

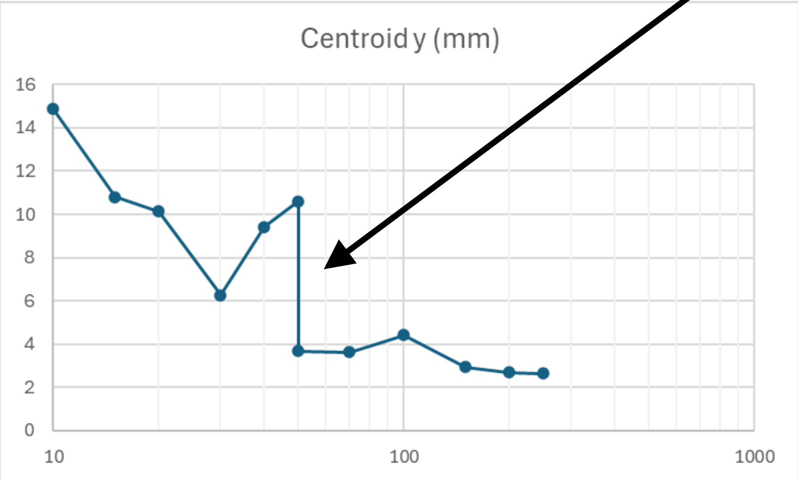
Beam out

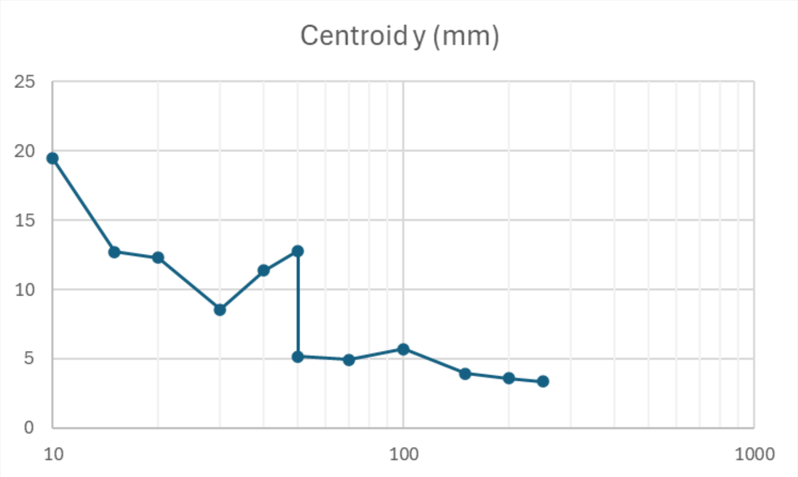


Centroid Y Positions

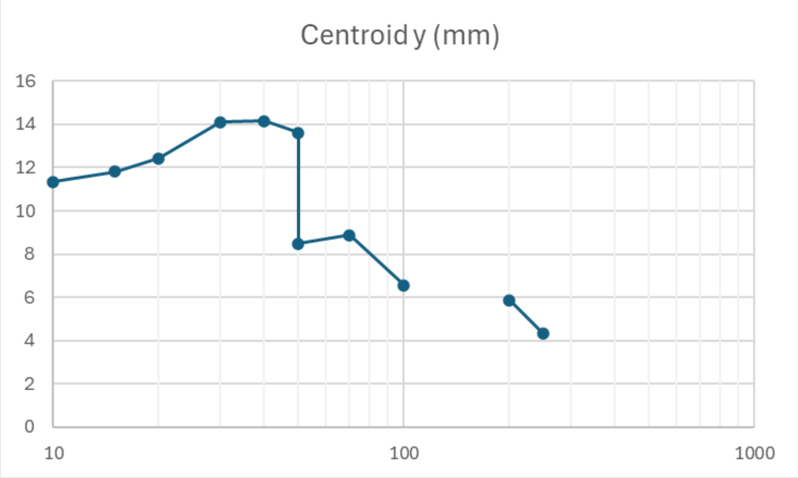
Known Y shift from reassembly of camera screens between NSRL and Tandem

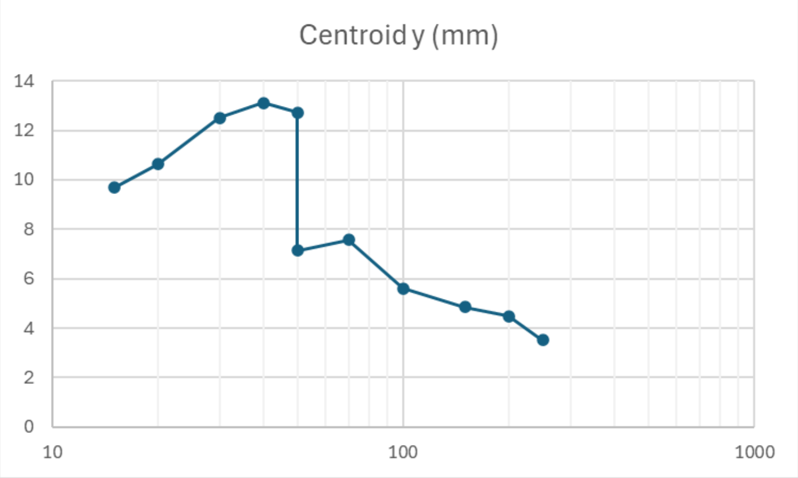
Beam in





Beam out





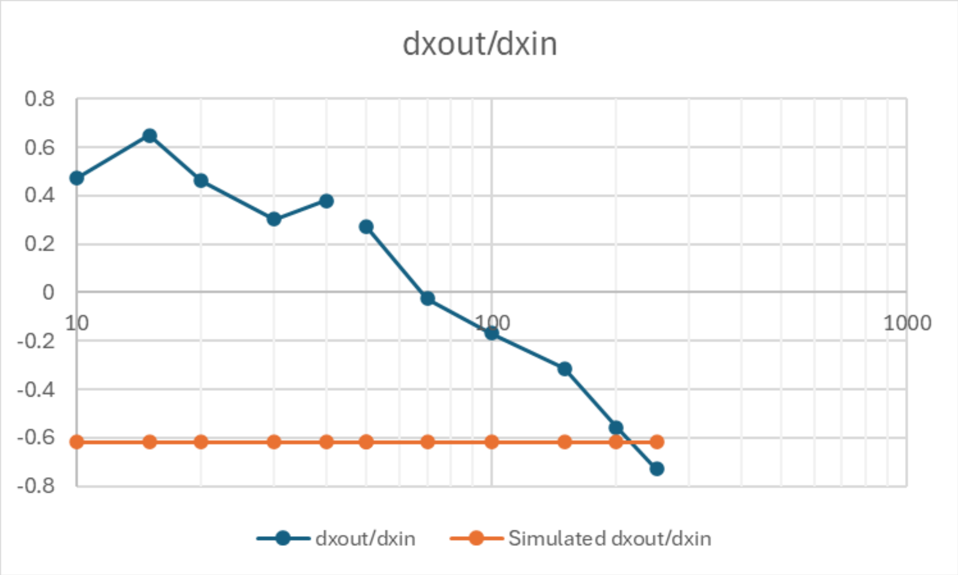
Attempt at Transfer Matrix Element

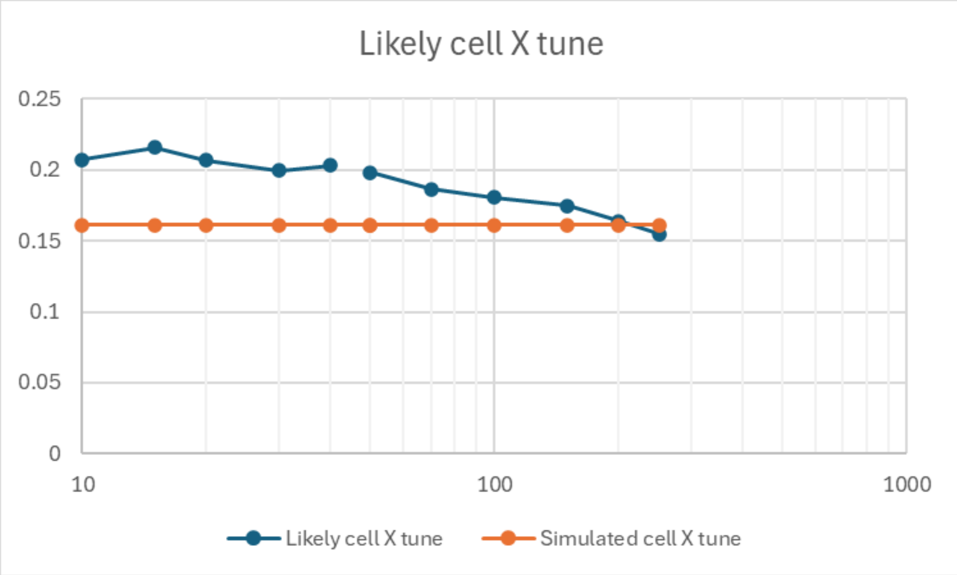
- Not much time, but some energies were tried offset horizontally from the nominal entrance position by a few mm
  - Often the entrance position of the previous energy was used with the next energy
- dx_{out}/dx_{in} ~= (change in average X centroid position on output screens)/(change in average X centroid on input screens)

Transfer Matrix M_{xx} Element

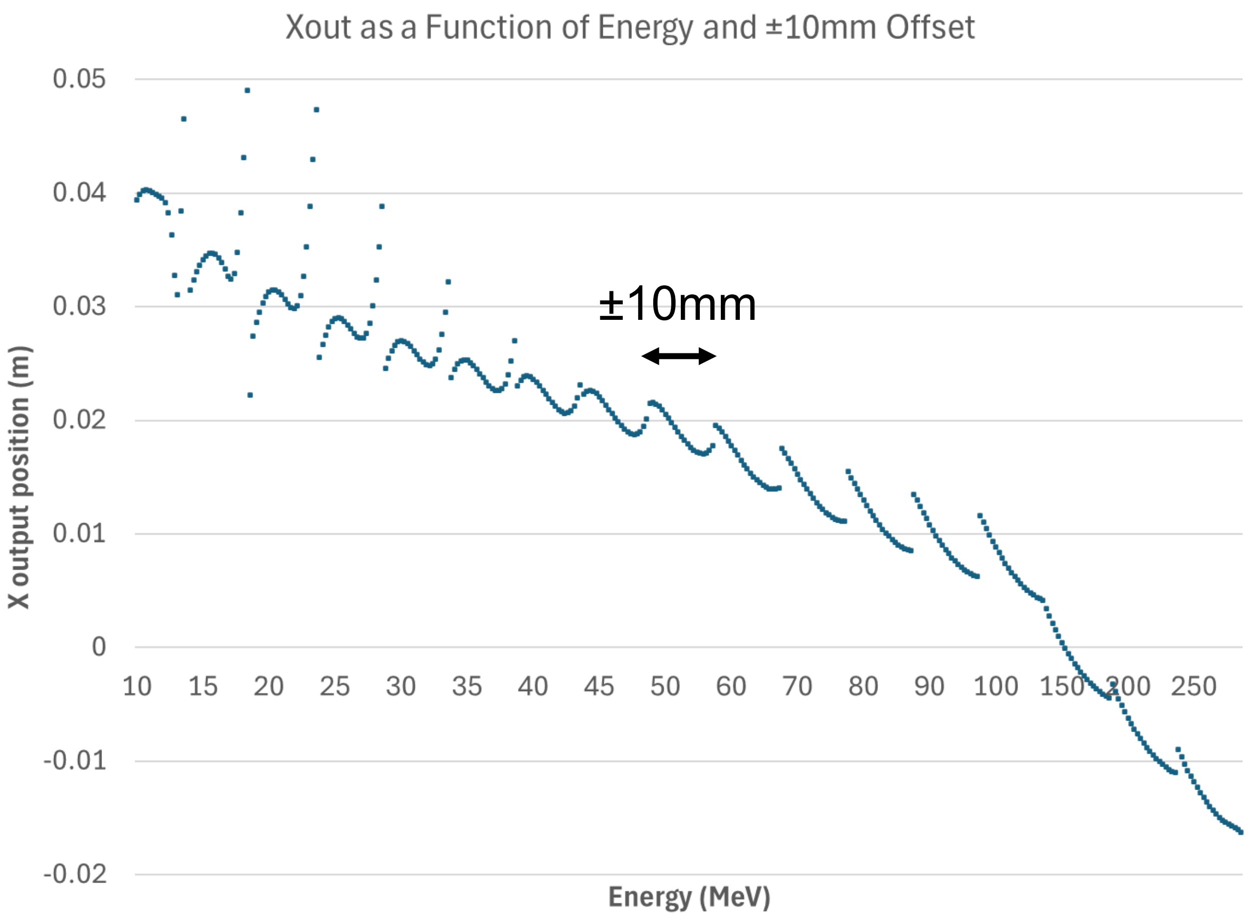
(Kind of surprised we got any valid data for this at all)

- $4Q_{x,\text{cell}} = 0.644 \rightarrow \cos(\phi_x) = -0.618$
- Agrees at high energy, changes at low energy
  - – Could be injecting off the closed orbit → sextupole feed down



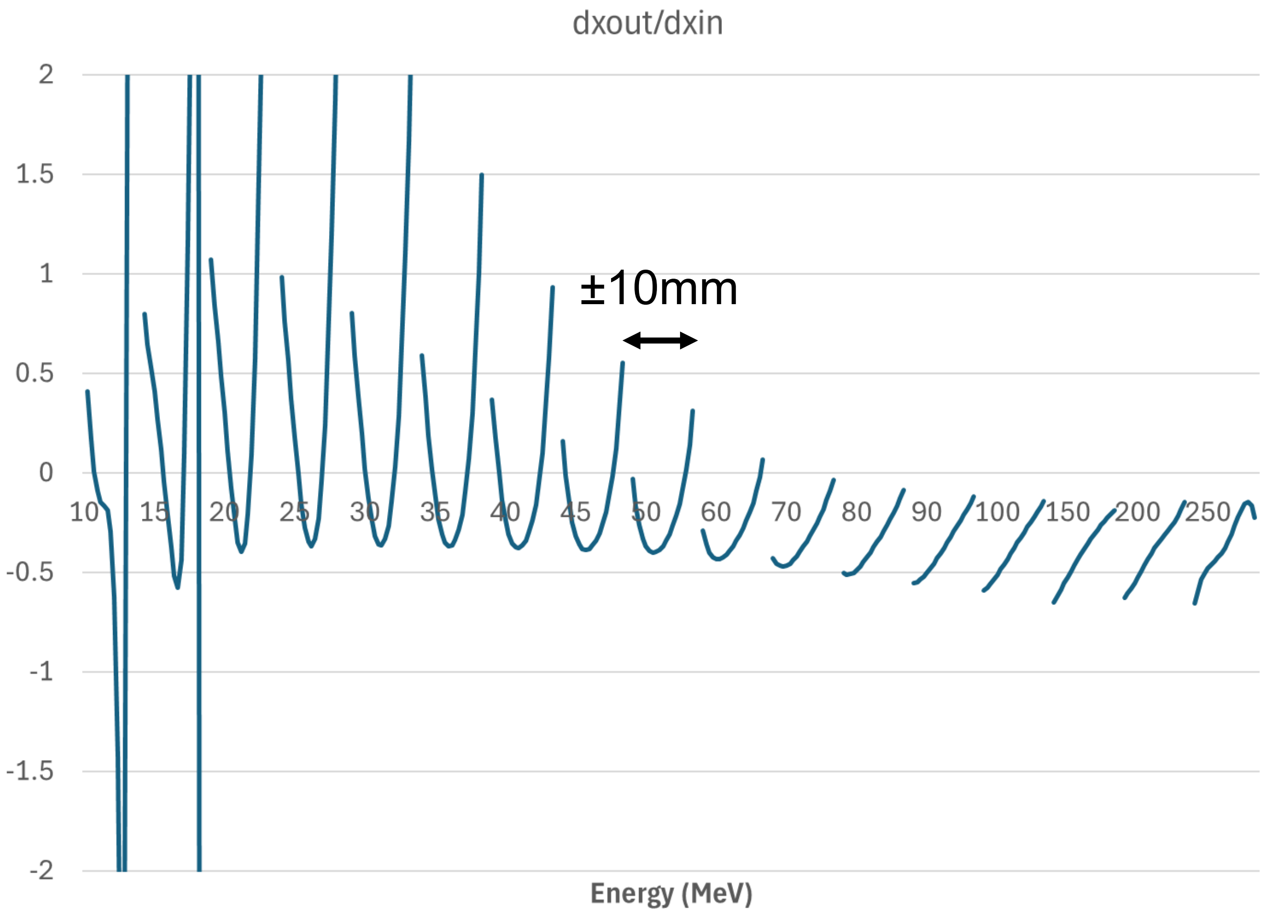


Tracking Offset Trajectories



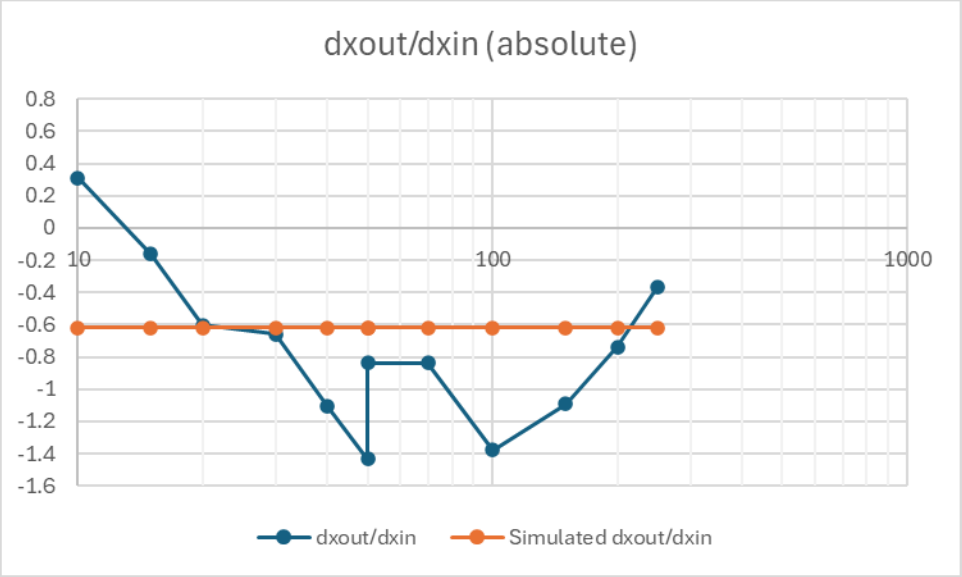
Matrix Element from Tracking

Looks sensitive to injection position especially at low energy



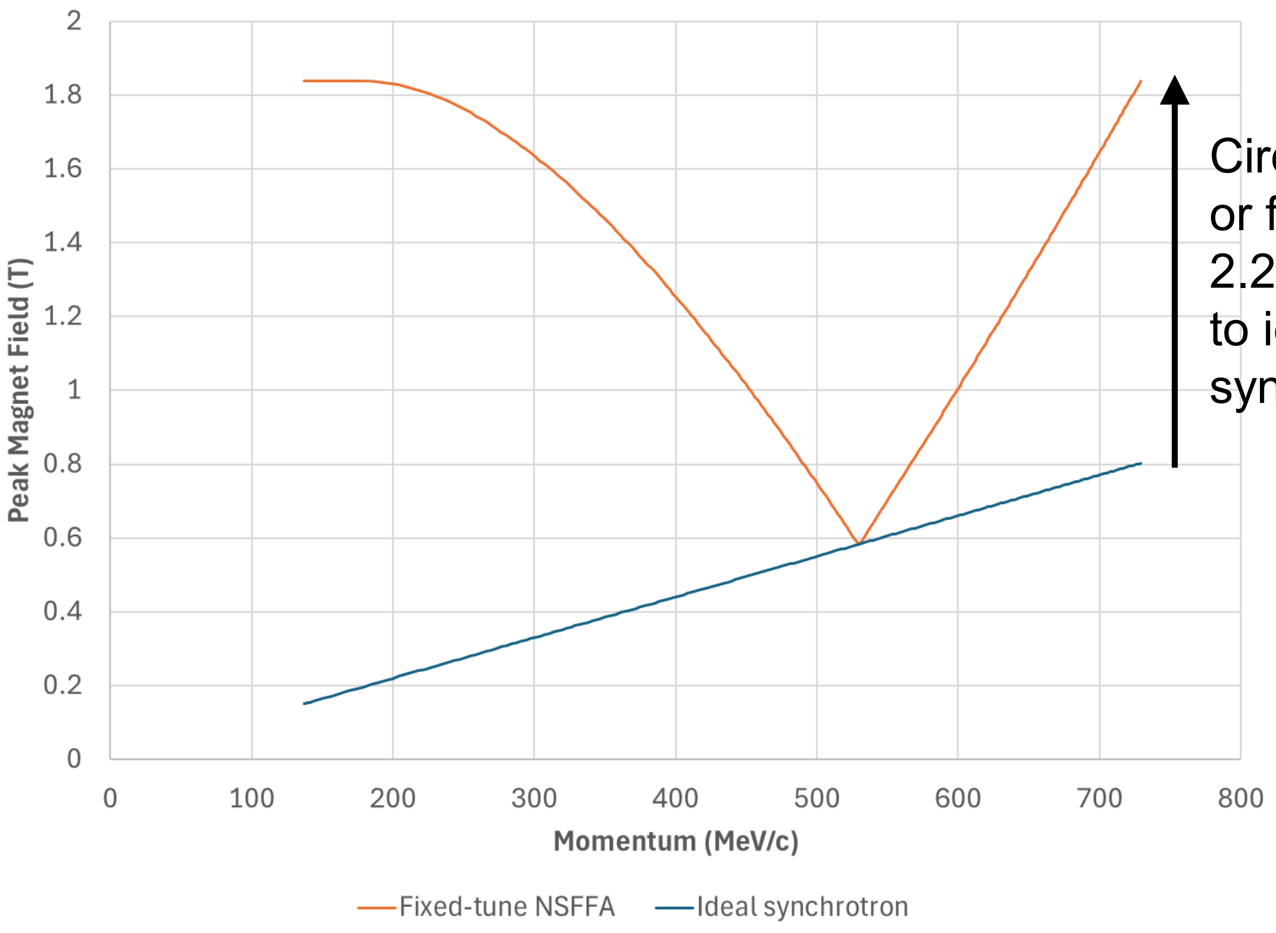
Transfer Matrix M_{xx} Element Again

- With the corrected centroids, use the difference of the beam position to the central orbit (according to survey) to derive a matrix element between input and output



  - No longer calculated around an offset orbit!
  - Looks more reliably negative, but noisier
  - 1mm centroid errors make large error bars on this

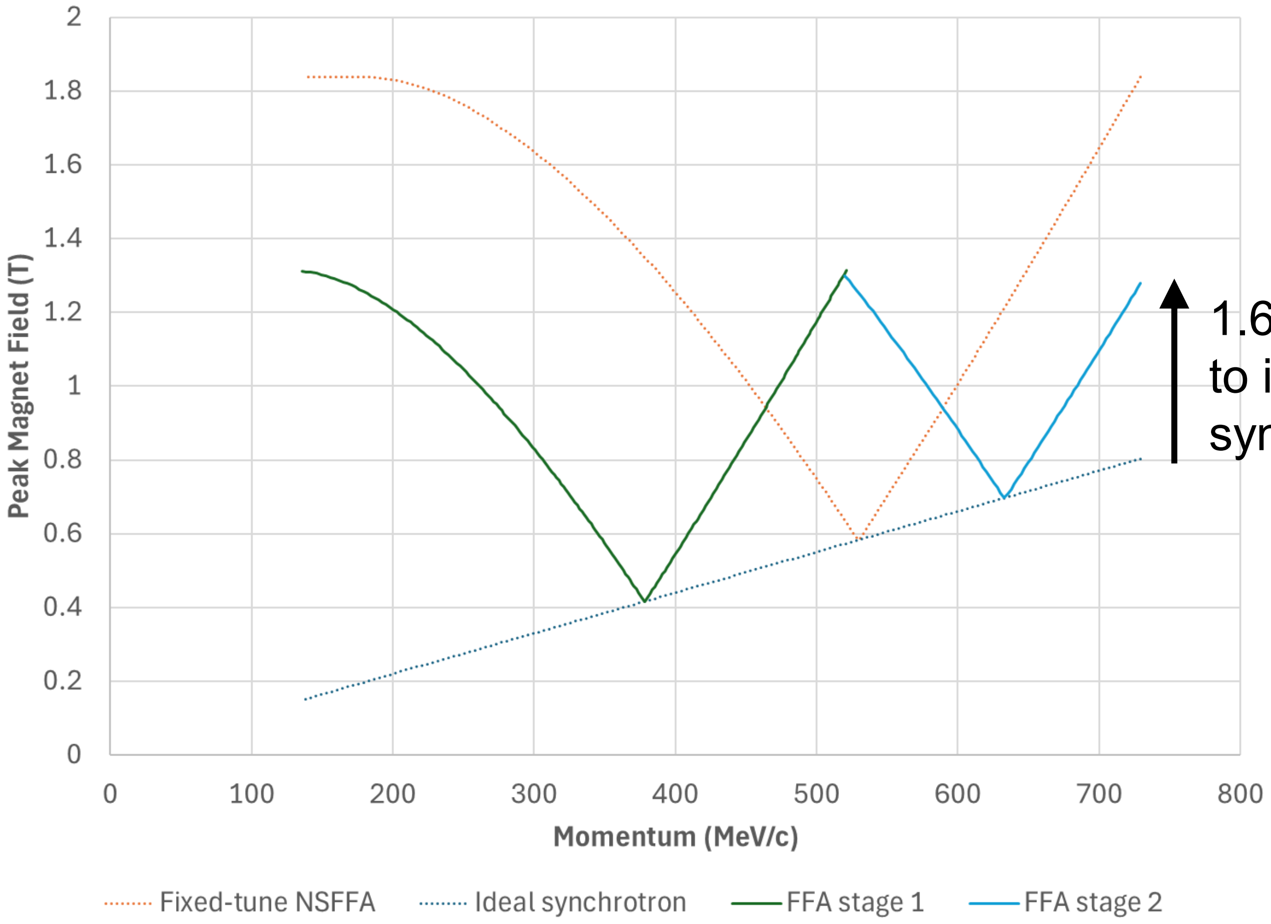
Magnetic Efficiency



Circumference or field factor of 2.29× relative to ideal synchrotron

Two Stage Machine

Momentum ratio 5.31=3.54*1.40, split at 135MeV k.e.



1.63× relative to ideal synchrotron

Two Stage Machine Conclusion

- The two stage machine reduces fields by a factor of 1.4, or same field at lower radius
  - One stage FFA: 3.5m radius (7m diameter)
  - Two stage FFA: 2.5m radius (5m diameter)
  - Ideal synchrotron: 1.53m radius (3.06m diameter)
    - But difficult to ramp the magnets at 100s of Hz
- Quick design: just cut out pieces of the original machine’s momentum range and scale them!