Magnetic sextupole spectrometers

B. Naranjo, G. Andonian, A. Fukasawa, Y. Kang, P. Manwani, J. Phillips, J. Rozells, O. Williams, J. Rosenzweig

UCLA Dept. of Physics & Astronomy

M. Yadav

Old Dominion University School of Data Science

P. Alva Rosa

Augsburg University

C. Hast, I. Rajkovic, D. Storey

SLAC National Accelerator Laboratory

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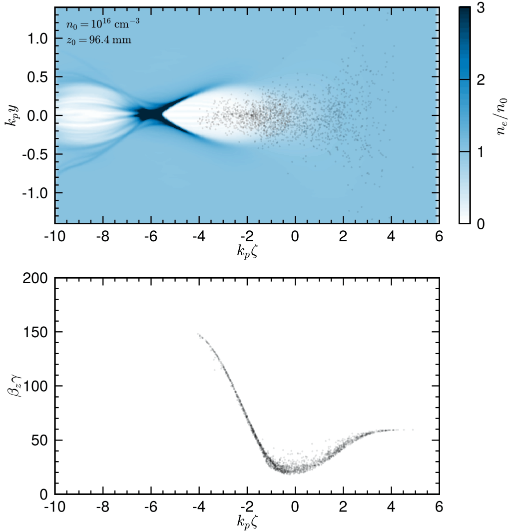
Motivation for broadband electron spectrometer



- Long 30 MeV driver beam run to nearly full depletion in PWFA at MITHRA.
- Want to record 1-100 MeV in a single shot to fully capture depleted head and accelerated tail.
- Repurpose FACET-II CPT sextupole design.

Multipole field

For magnetostatic current-free quasi-2D regions,

$$\left.\begin{array}{l}\nabla \cdot \mathbf{B} = 0 \\ \nabla \times \mathbf{B} = 0\end{array}\right\} \implies \left.\begin{array}{l}\mathbf{B} = \nabla \times \mathbf{A} \\ \mathbf{B} = -\nabla\phi\end{array}\right\} \implies \begin{array}{ll} B_x = -\dfrac{\partial\phi}{\partial x} & = \dfrac{\partial A}{\partial y} \\ B_y = -\dfrac{\partial\phi}{\partial y} & = -\dfrac{\partial A}{\partial x}\end{array}$$

With $z = x + iy$, we may write the complex potential as

$$w(z) = -A(z) - i\phi(z).$$

Then, the Cauchy-Riemann equations give the fields

$$\frac{dw}{dz} = B_y + iB_x.$$

For a multipole of order k, the complex potential is a **homogeneous function** of degree k,

$$w(z) = \frac{b_k z^k}{k} \implies \phi = -\frac{b_k}{k} r^k \cos(k\theta), \text{ etc.}$$

Mechanical similarity

A relativistic particle of charge q and mass m obeys Lorentz force law

$$\frac{d^2x^\mu}{d\tau^2} = \frac{q}{m}F^{\mu\nu}\frac{dx_\nu}{d\tau}$$

which follows from a Lagrangian of the form

$$L = -\frac{1}{2}mu^\mu u_\mu - qu^\mu A_\mu.$$

Consider a 4-potential that, for some choice of gauge, is a homogeneous function of degree k,

$$A^\nu(\alpha x) = \alpha^k A^\nu(x).$$

Given a worldline solution $x^\mu(\tau)$, propose a new solution $\tilde{x}^\mu(\tilde{\tau})$ obtained by scaling

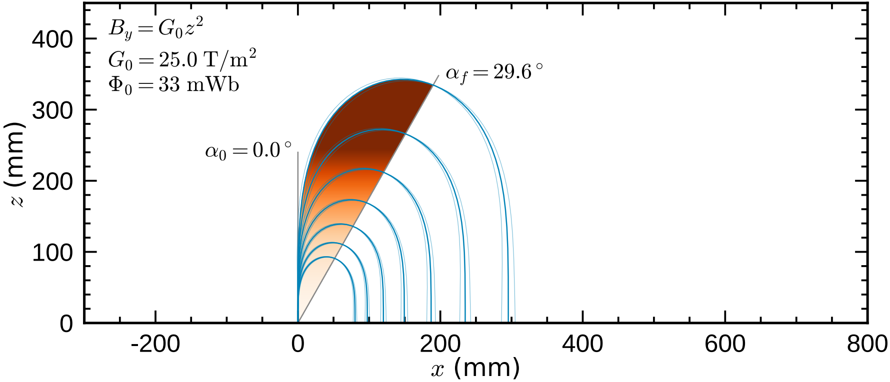
$$\tilde{x}^\mu = \alpha x^\mu \quad \text{and} \quad \tilde{\tau} = \alpha^{1-k}\tau.$$

Under this coordinate transformation, the overall Lagrangian scales as α^{2k}. Because multiplying the Lagrangian by an overall constant does not affect the equations of motion, we conclude that $\tilde{x}^\mu(\tilde{\tau})$ is a solution to the original equations of motion.

We thus find **mechanically similar** solutions with

$$\boxed{\text{length} \propto \text{momentum}^{1/k}}$$

Taking a 2D sextupole ($k = 3$) potential gives similar trajectories whose lengths scale with their cube roots of momenta. In other words, scaling a trajectory's momentum by a factor of eight only scales its path length by a factor of 2.



- Trajectory energies: $[100, 50, 25, 12.5, 6.25, 3.125, 1.5625]$ MeV
- Gap field strength is 1 Tesla at z = 200 mm
- Magnetic design constraints: 1) Flux budget and 2) Peak field strength
- By mechanical similarity, the focal point of each trajectory family lies in the same plane, where we then locate the scintillator.

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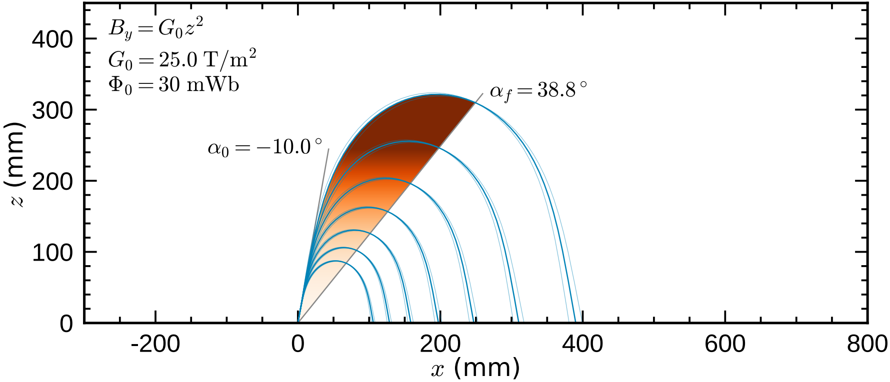

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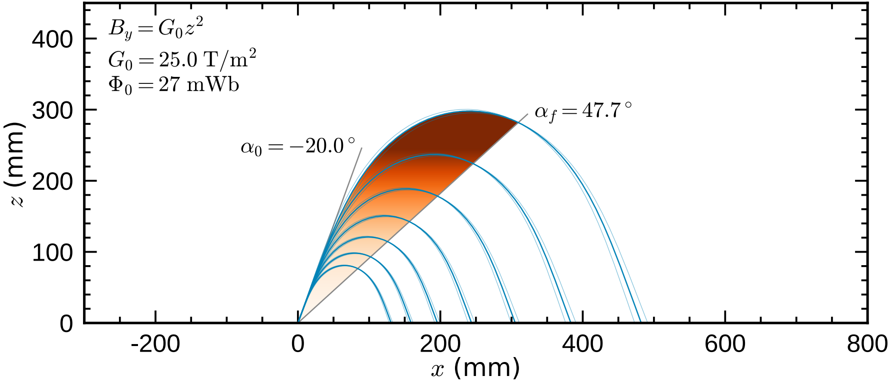

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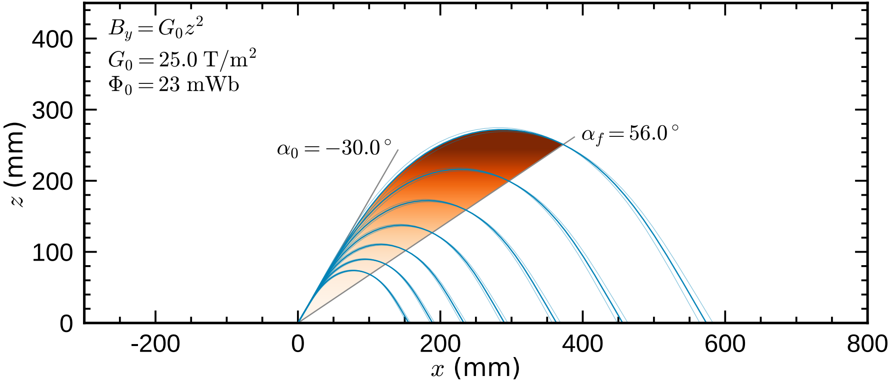

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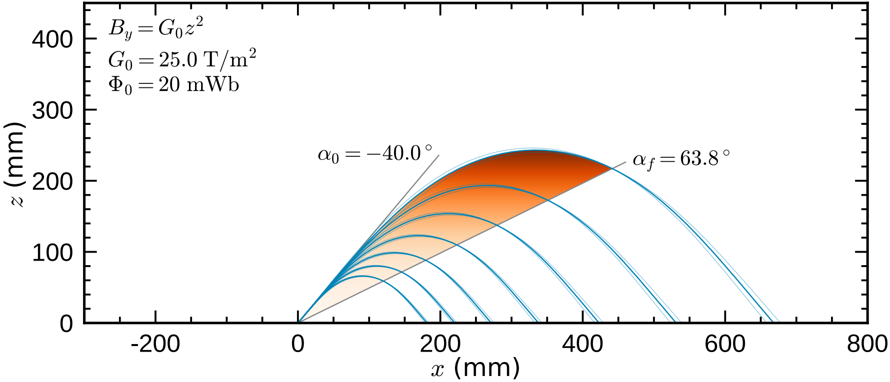

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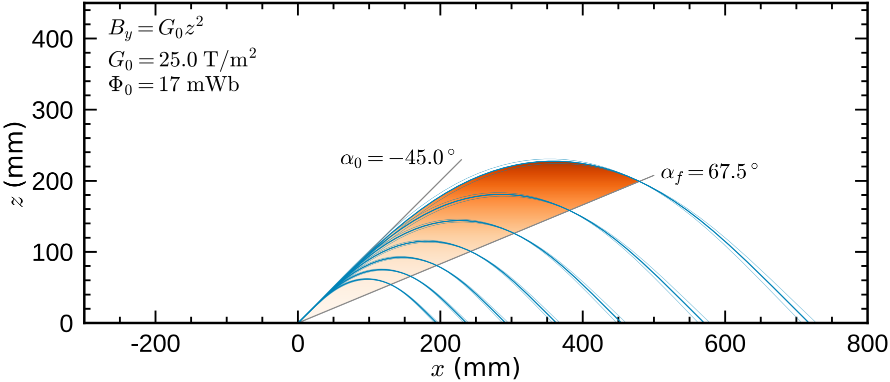

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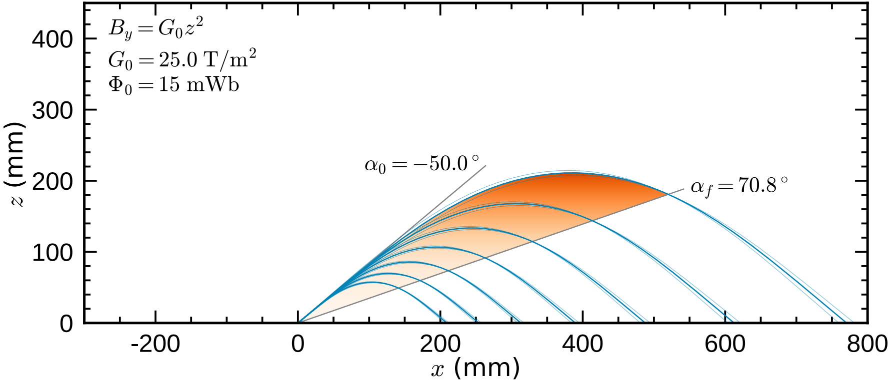

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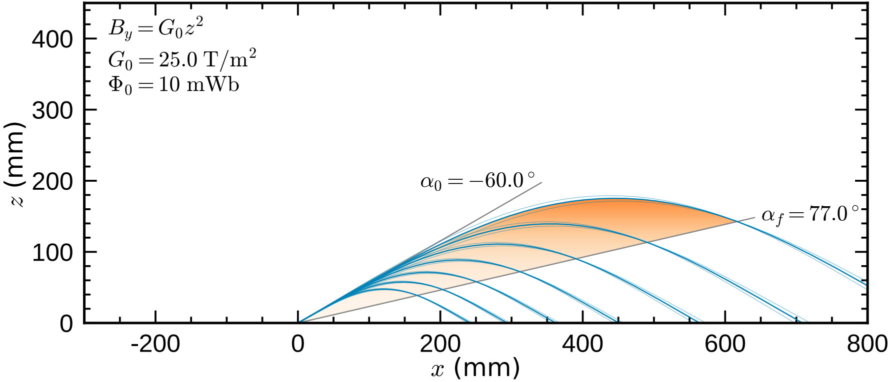

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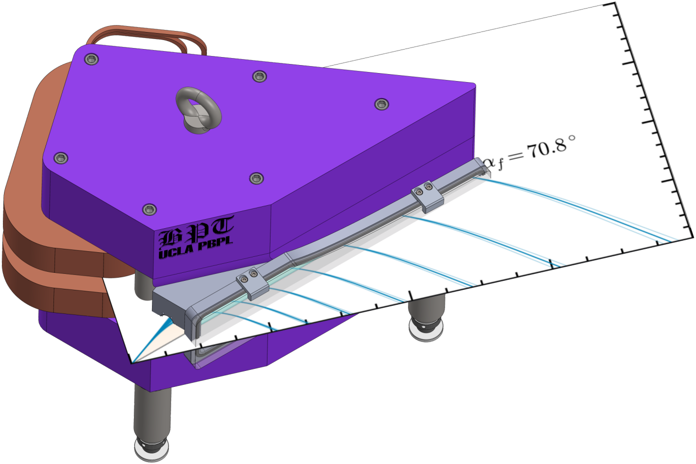
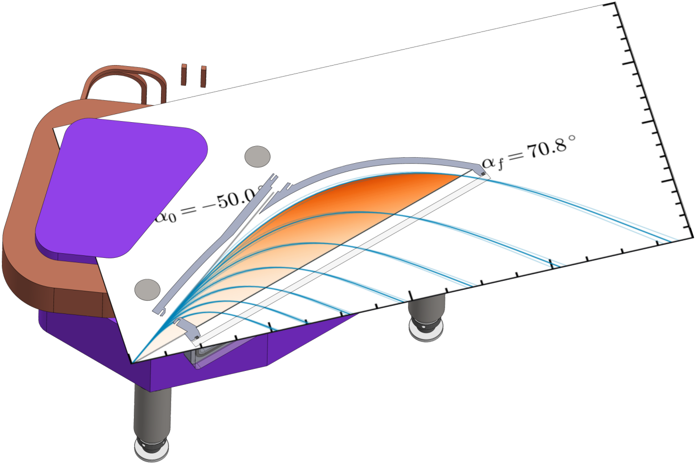


- Choose $\alpha_0 = 50^\circ$ as a good compromise among several factors, including peak magnetic field, magnetic flux consumed, size and mass of spectrometer, and spectrometer energy resolution.
- Coil shape and size constrained to match that of CPT to keep down cost.



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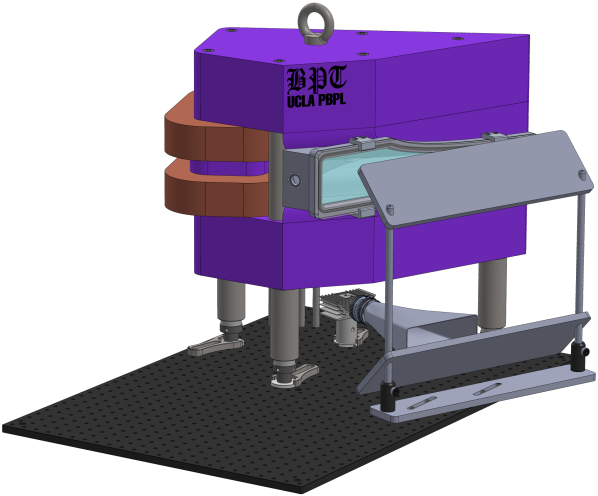
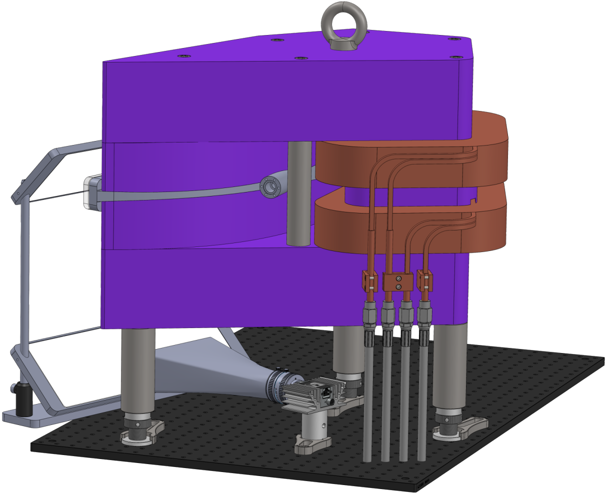


- Scintillator readout via camera and folded mirror arrangement.
- Total weight of spectrometer is 800 pounds.
- At maximum field, each pole surface pulls into the gap with over 2000 pounds net force, braced by two stainless support columns.



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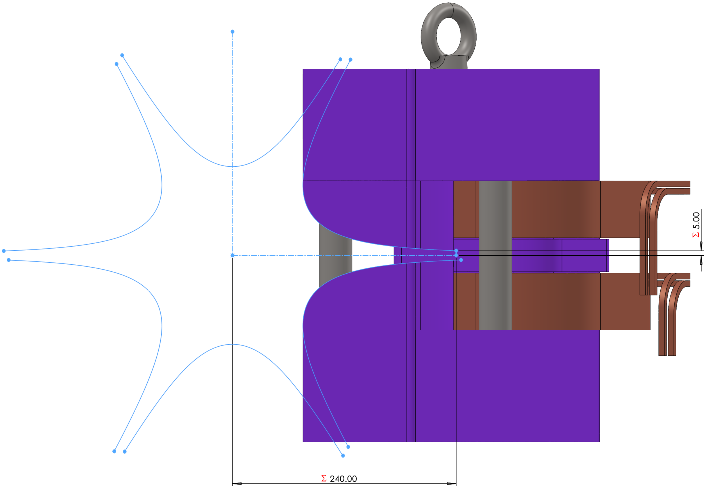
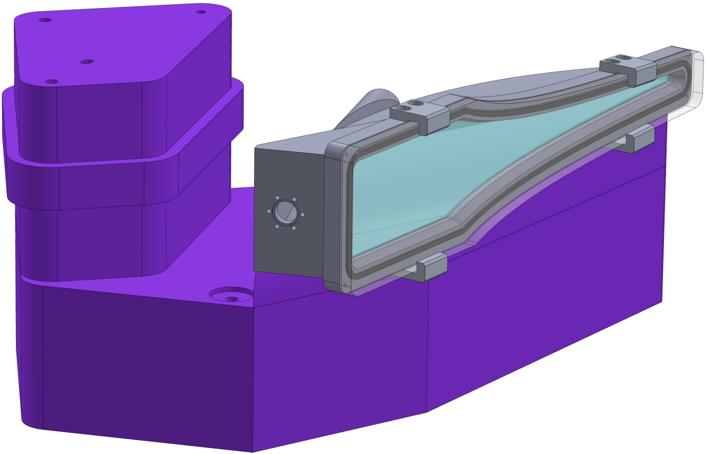


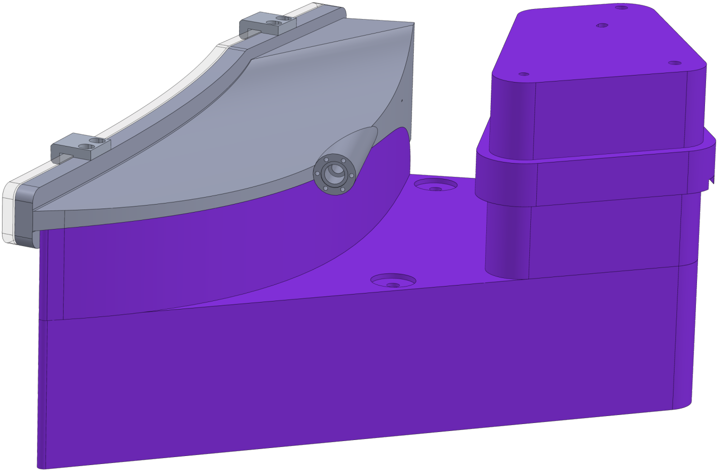
- Just two of the six poles are included. To compensate for excess fringe field, the inlet beam tube is magnetically shielded.

BPT: Vacuum chamber



- Beamline vacuum is maintained throughout the spectrometer. Integrated vacuum chamber with viewport and upstream/downstream beamline ports.
- Chamber is milled from a single block of aluminum.

BPT: Vacuum chamber



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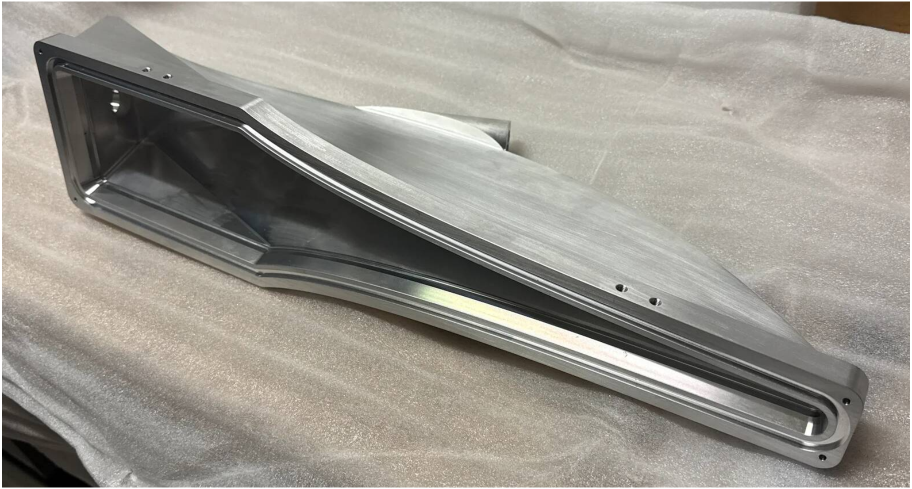

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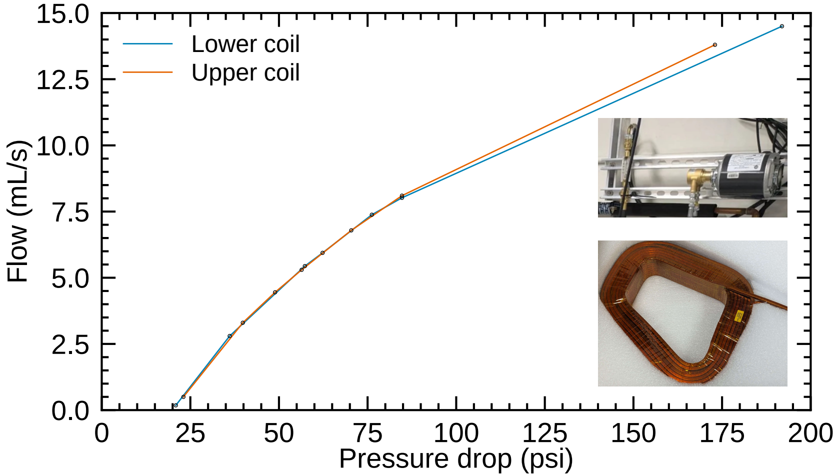
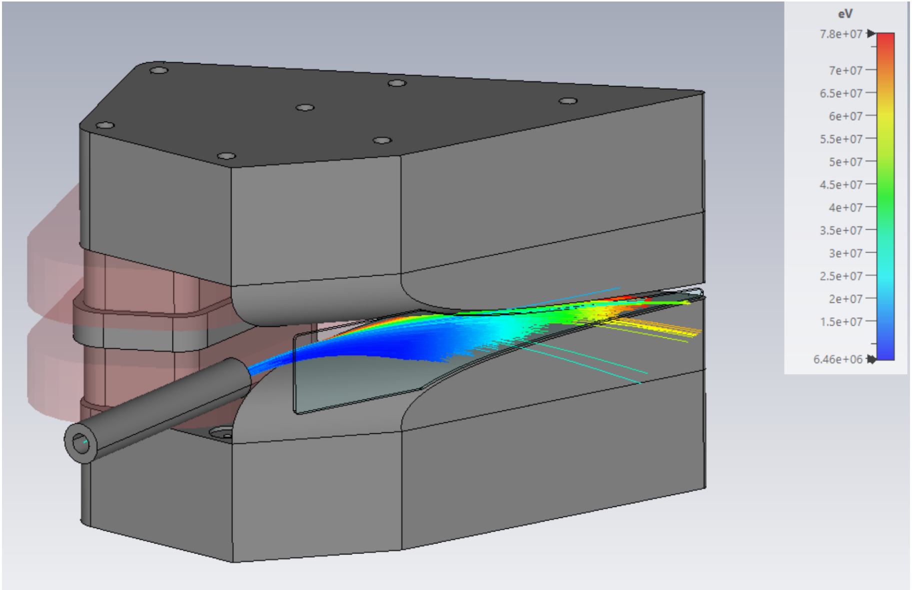
BPT: Water-cooled coils

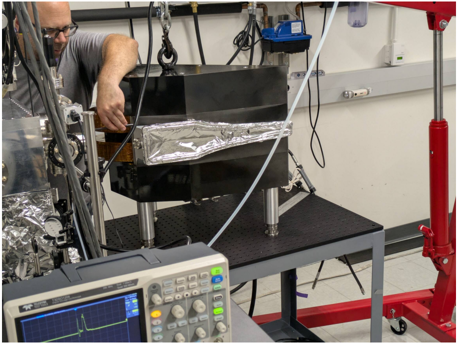


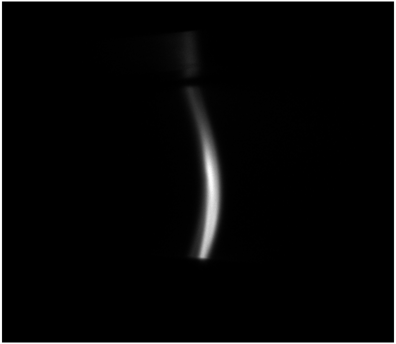
- At an operating current of 120 amps, each coil has 500 watts of heat production. Need water cooling.
- Each coil has an inner diameter of 1/8 inch and a length of approximately 70 meters.
- Booster pump provides 170 psi pressure drop and sufficient flow.



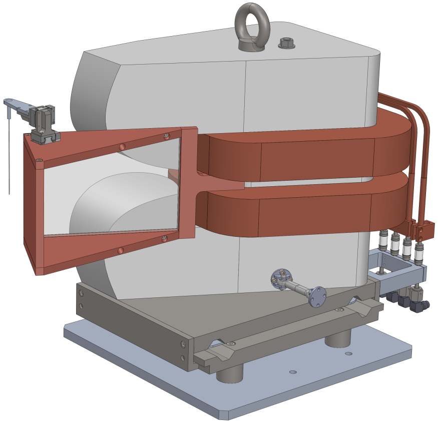
- MITHRA PWFA electron spectrum simulated in CST.

BPT: Installation at MITHRA

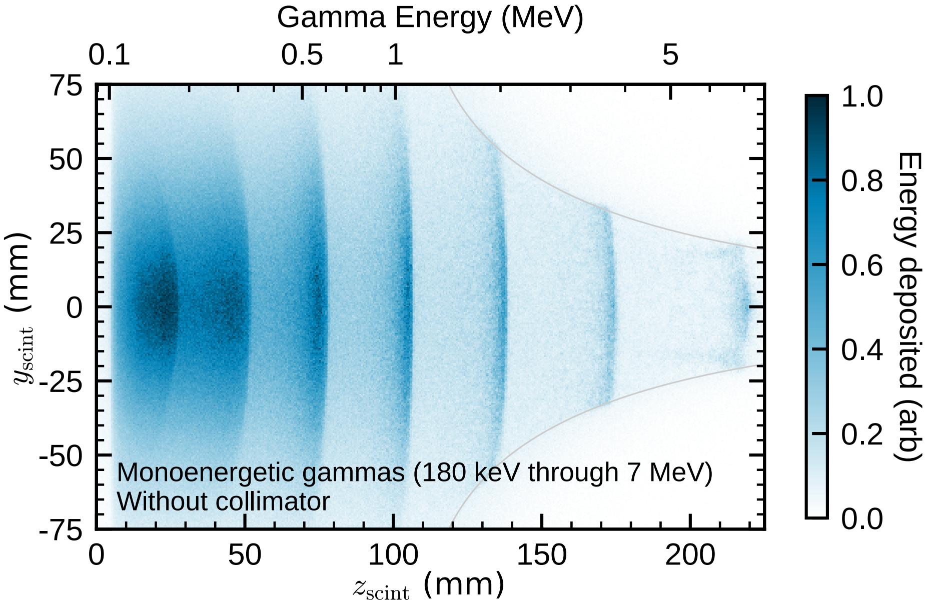


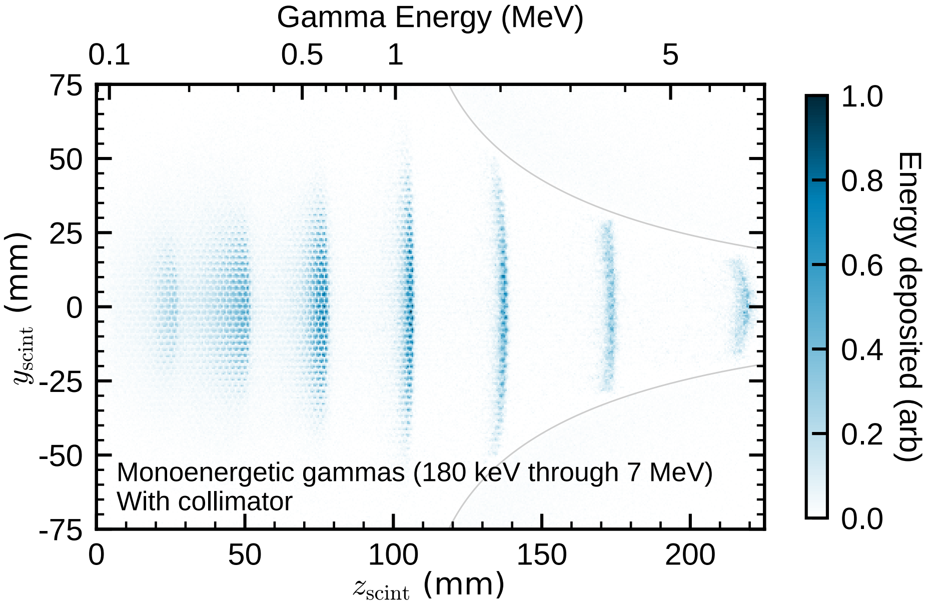


- Transported spectrometer from main campus to STRB last week.
- Reassembled and installed on beamline.
- First light with 30 MeV electron beam!



- 0.2-10 MeV single-shot Compton gamma spectrometer for FACET-II
- Gammas passing through beryllium converter rod Compton-scatter electrons forward for subsequent magnetic analysis.
- Spectrometer rolls on 1 inch diameter ceramic bearings so that it can move off beam when not in use. Total amount of in-vacuum translation is 75mm.
- Coils are water cooled in vacuum.
- Total weight of magnet plus stage = 650 pounds.


Gamma Energy (MeV)
0.1
0.5
1
5
75
50
25
0
-25
-50
-75
0
50
100
150
200
y_{scint} (mm)
z_{scint} (mm)
Monoenergetic gammas (180 keV through 7 MeV)
Without collimator
1.0
0.8
0.6
0.4
0.2
0.0
Energy deposited (arb)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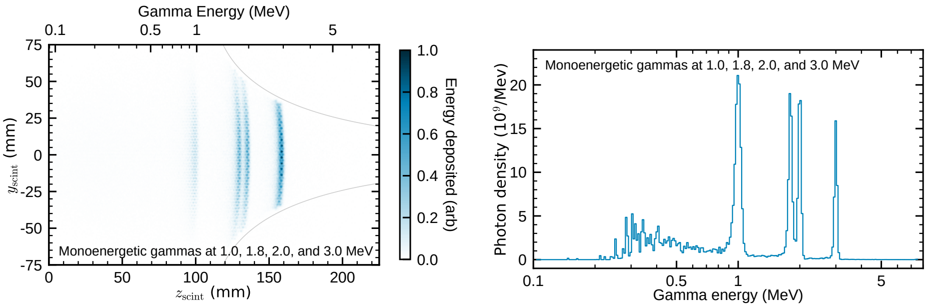
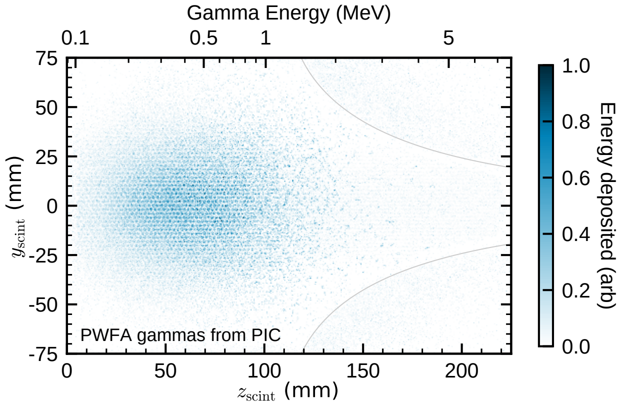
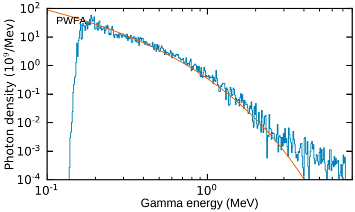


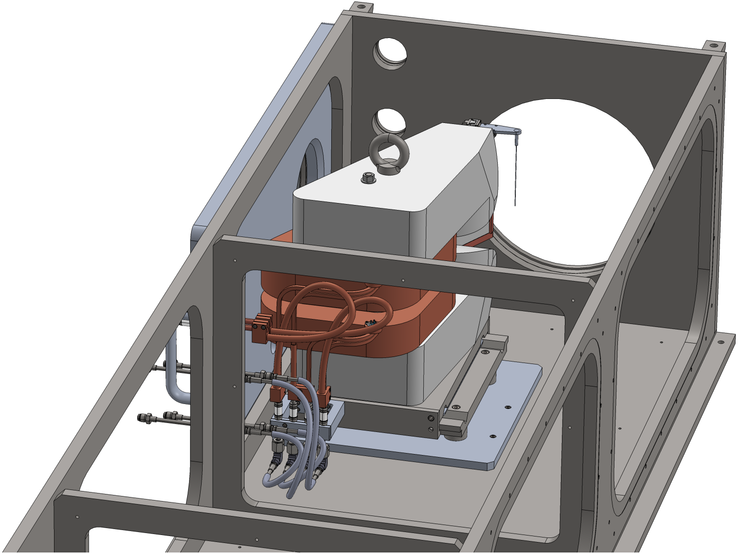
- ML-EM[1] is used as baseline for spectral reconstruction.
- Recovers gamma lines with energy resolution on the order of 1%.

[1] Shepp and Vardi, *IEEE Trans. Med. Imaging* **1**, 113 (1982)

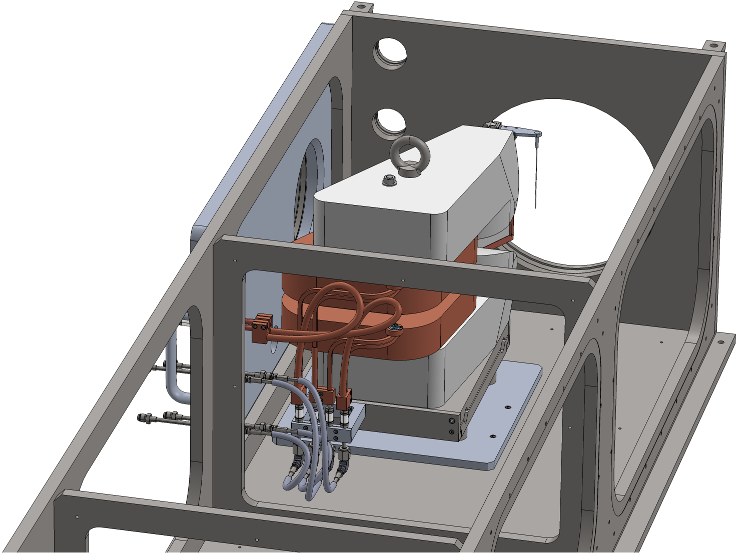
CPT: PWFA - Maximum likelihood reconstruction



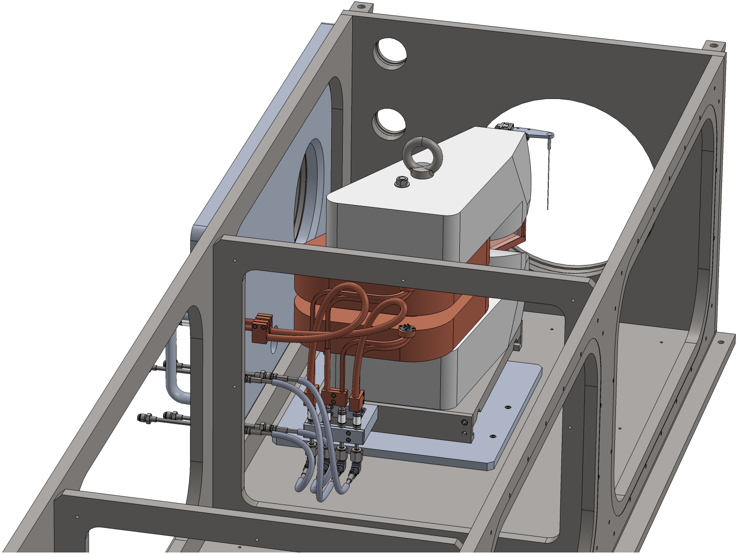




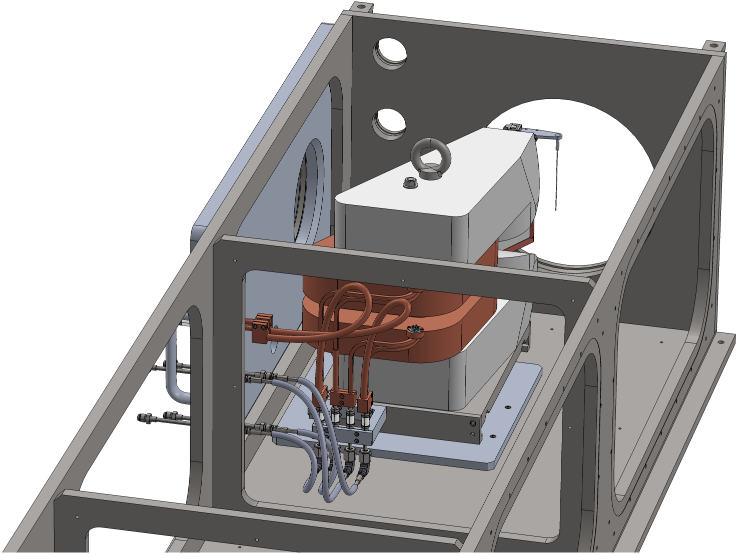
Fully retracted



Neutral position

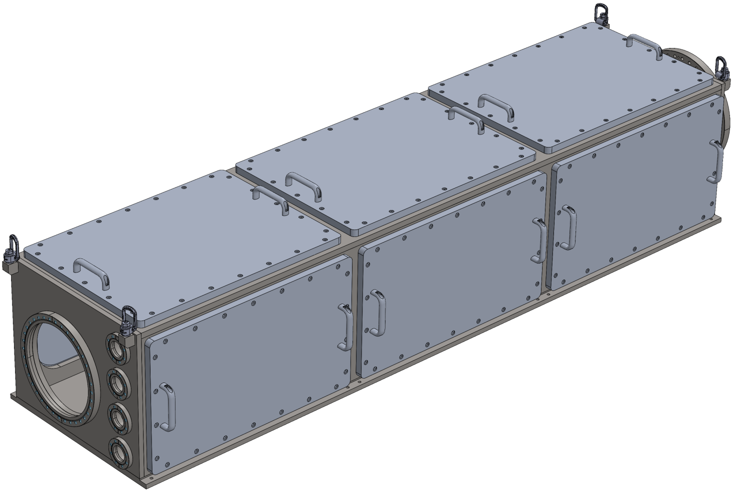


On beam



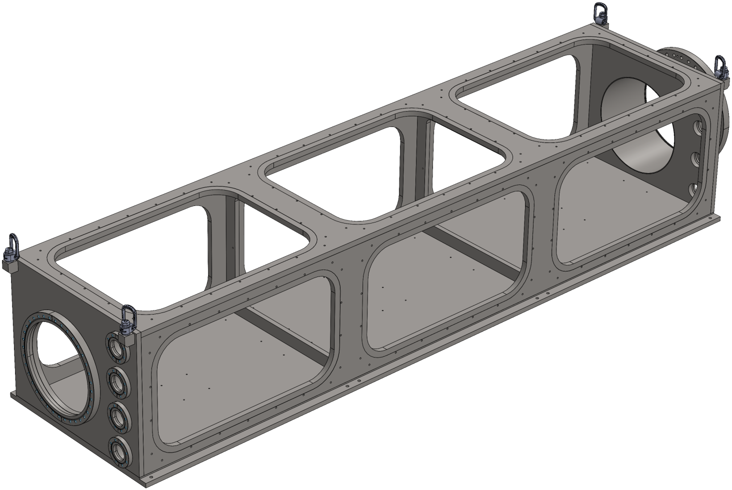
Fully inserted

GDC: Paneled design

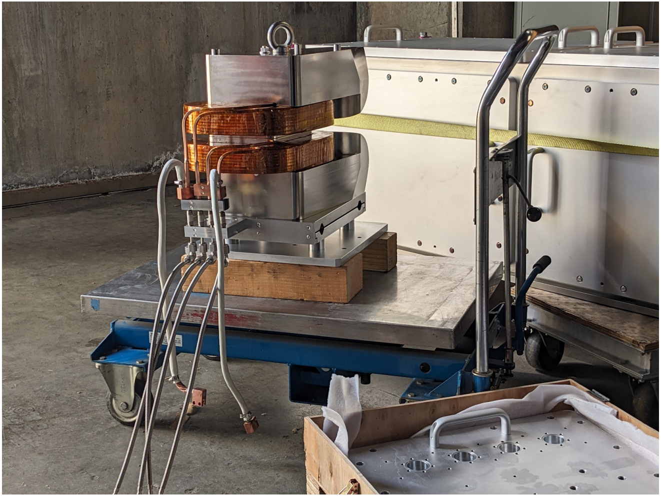


- GDC = Gamma Detection Chamber
- Stainless frame with nine O-ring sealed aluminum panels (similar to EDC/PDC).

GDC: Paneled design



- Interior stiffening ribs
- Upstream 16” Conflat flange and downstream 19” Wireseal flange
- Eight auxiliary CF450s



- Both CPT and the GDC shown here at End Station B.

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CPT: Delivery to SLAC

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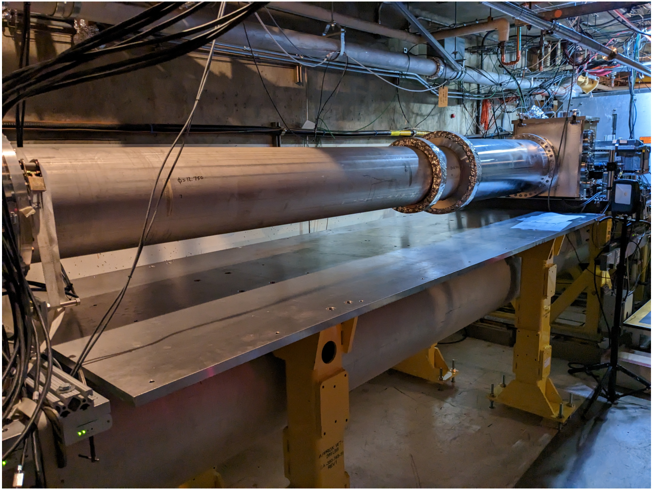
CPT: Installation location



- To be installed here, between the EDC and the Butterfly Chamber.
- Support table is new. Same design as the PDC/EDC support table.
- Chamber and spectrometer installation in July.