E-320: Probing Strong-field QED at FACET-II

ExHILP 2021

September 15, 2021

Elias Gerstmayr

(for the E-320 collaboration)

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Additional support: *Cindy Patty, Doug McCormick, Juan Cruz, Nadya Smith, the PULSE Team (in particular Ritu Khurana)*, B40 Laserlab*: Shambhu Ghimire, and many more*

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E-320 Collaboration (SLAC/FACET-II)

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E-320: observing nonperturbative photon emission

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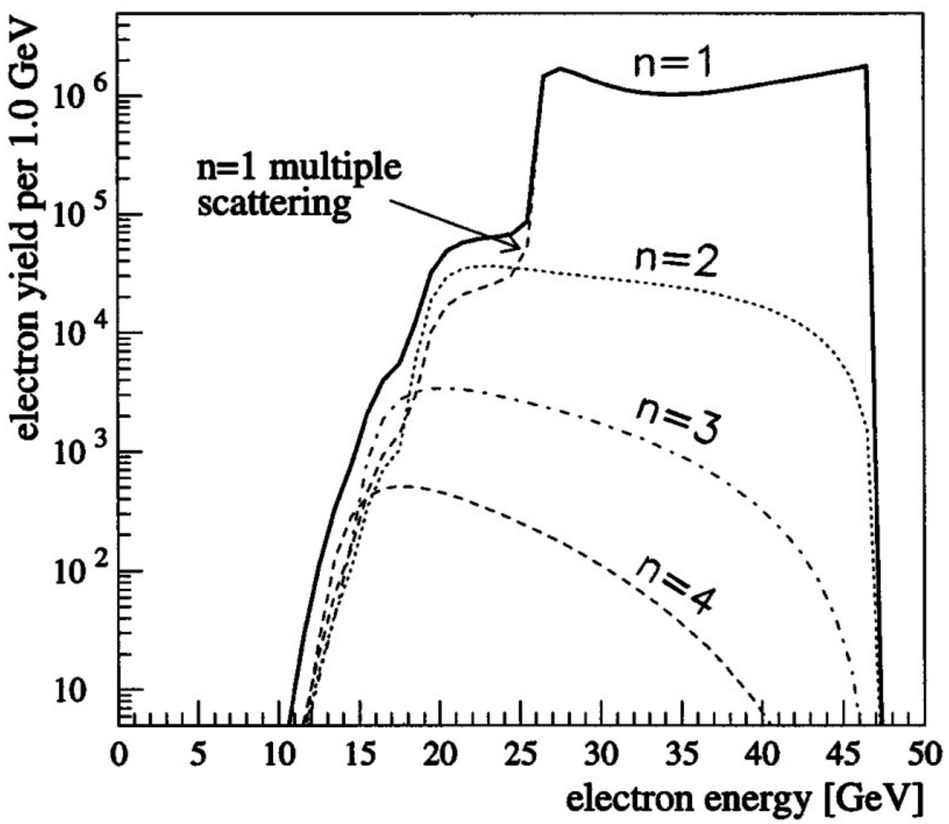
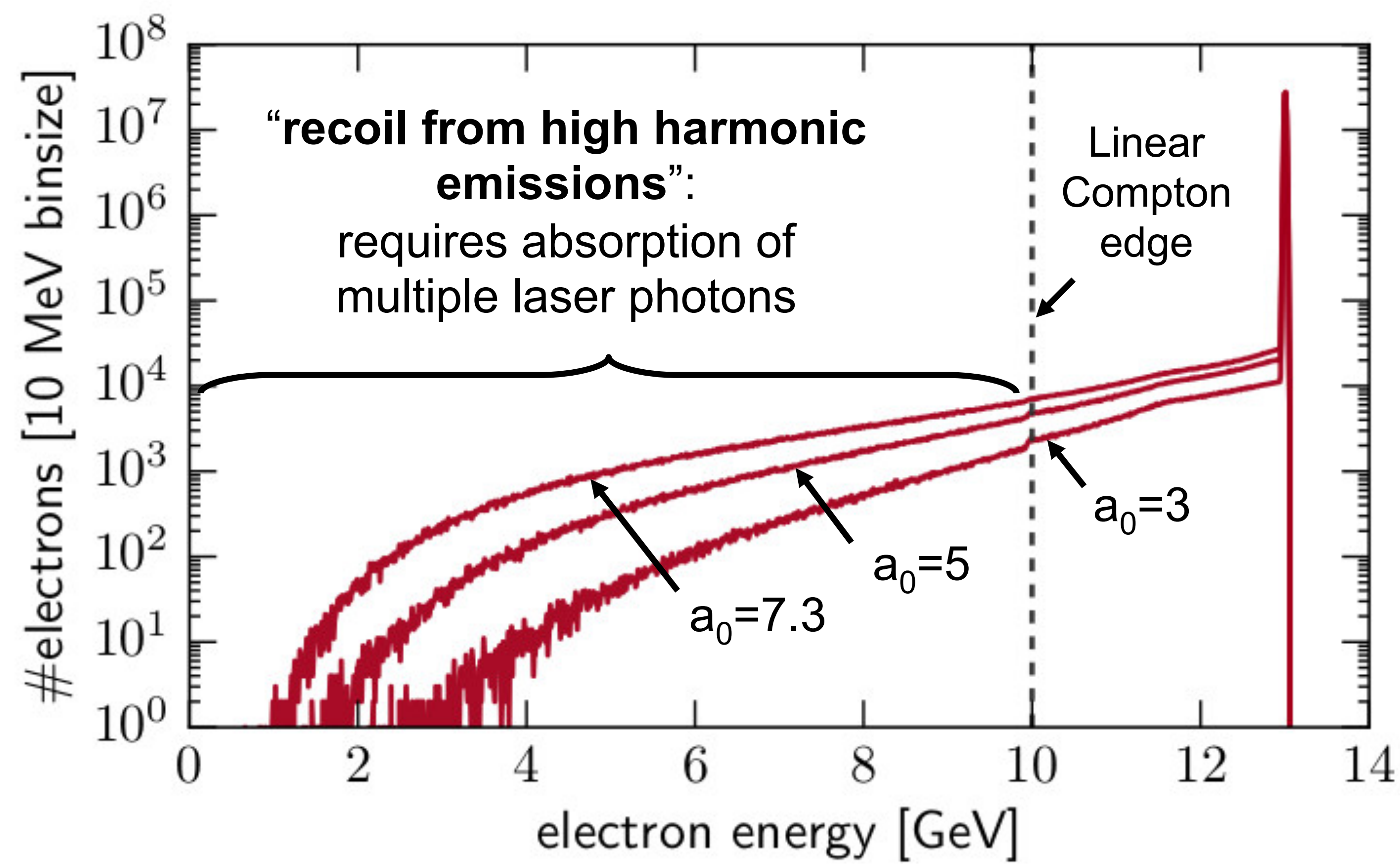
E-144: perturbative multi-photon regime
($a_0 \lesssim 1$, $\chi \lesssim 1$:1990s)



E-144 PRL 76, 3116 (1996)
perturbative scaling: $\sim a_0^{2n}$

E-320: nonperturbative quantum regime
($a_0 \gg 1$, $\chi \gtrsim 1$: 2021)



Interaction with n~100 laser photons

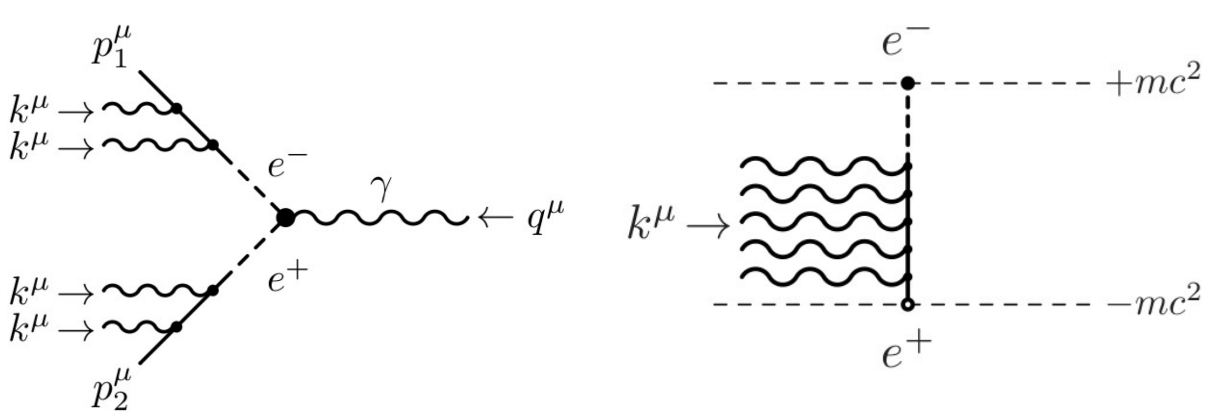
Simulations: Nielsen, Tamburini, Vranic

$$a_0 = \frac{|e|E}{mc\omega} \approx 0.75\,\frac{\mathrm{eV}}{\hbar\omega}\sqrt{\frac{I}{10^{18}\,\mathrm{W/cm^2}}}$$

$$\chi = \frac{2\gamma a_0 \hbar\omega}{mc^2} = \frac{2\gamma E_L}{E_{crit}} \approx 0.057\,\frac{\epsilon}{\mathrm{GeV}}\sqrt{\frac{2I_0}{10^{20}\,\mathrm{W/cm^2}}}$$

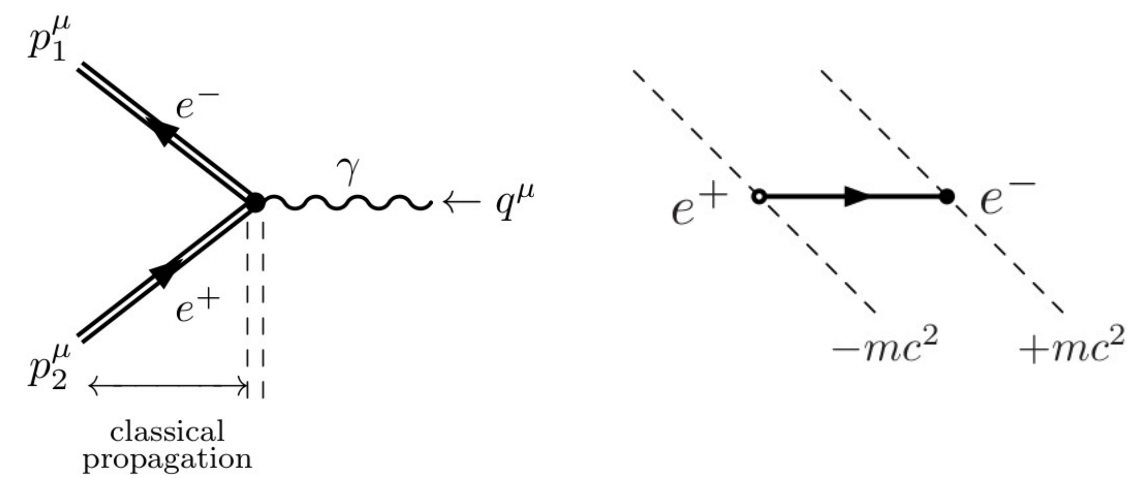
E-320: observing photo-induced vacuum decay

E-144: multi-photon pair production



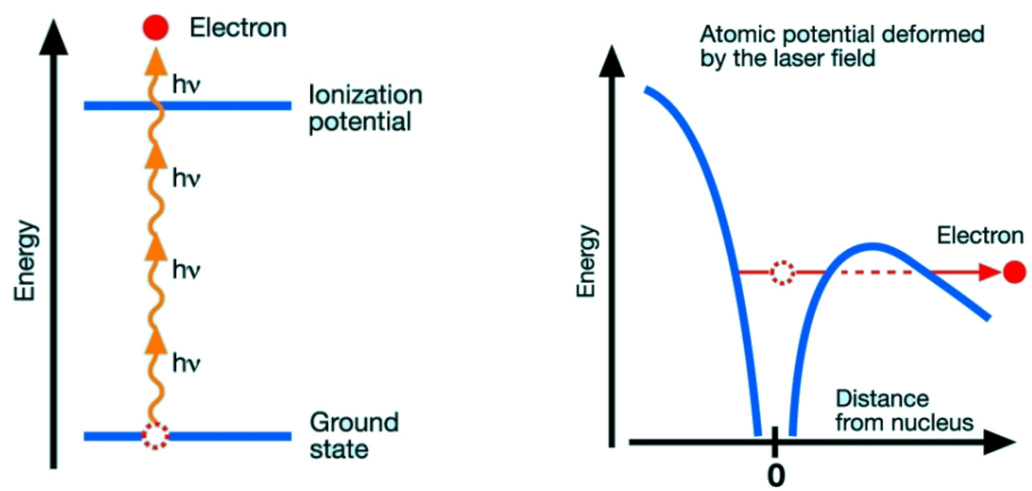
"Positron Production in Multiphoton Light-by-Light Scattering" E-144 PRL 79, 1626 (1997)

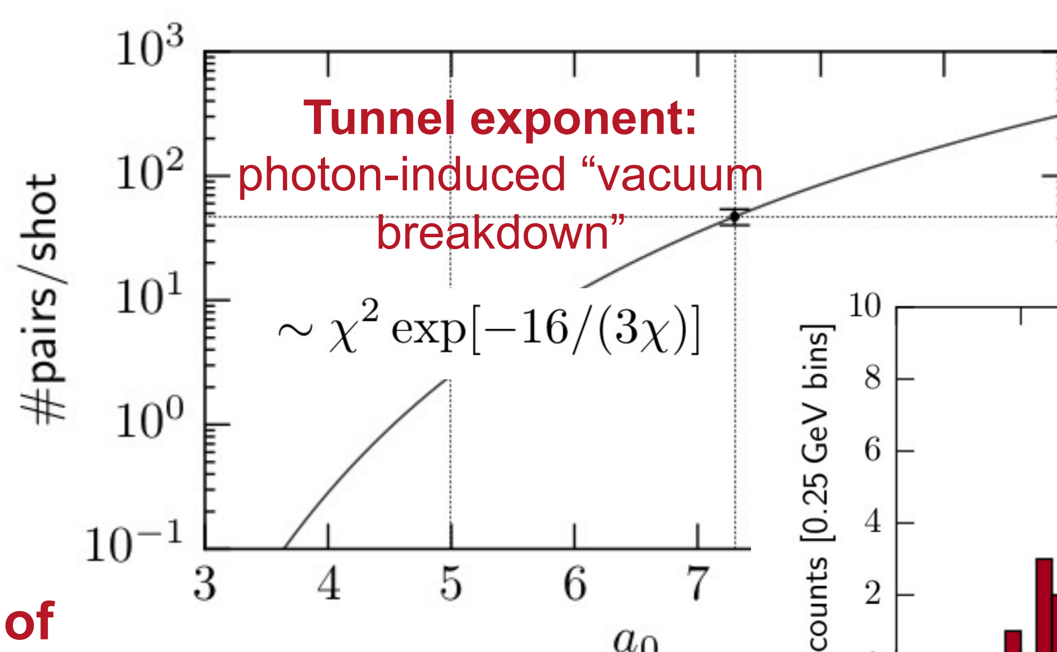
E-320: tunneling pair production



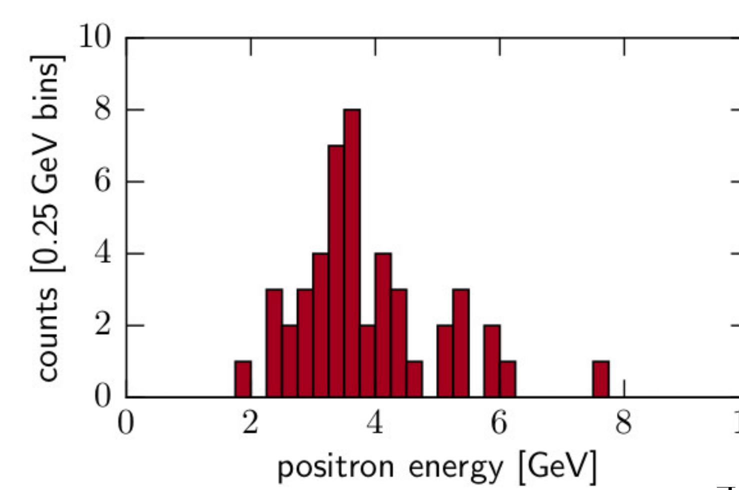
Photon → virtual pair → tunneling →real pair (local constant field approximation)

Analogous to tunnel ionization





Positron spectrum



E-320 will probe a qualitatively new regime of light-matter interaction

E-320 parameters and perspectives at FACET-II (SLAC)

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TABLE V. Single-bunch, high-quality mode parameters.

Parameter (units)	Value
Final beam energy E_f (GeV)	13.0
Bunch charge Q_b (nC)	2.0
rms bunch length σ_z (mm)	0.1
β^* (m)	10
Final rms energy spread, dE/E (%)	0.05

FACET-II: Yakimenko et al., PRAB 22, 101301 (2019)

Energy[a] [J]	Duration[b] [fs]	Power [TW]	Spot[d] [μm]	Strehl	Intensity [W/cm²]	a_0	χ
0.30	50	5.6		0.4	4.7×10^{19}	4.7	0.68
0.44	40	10	2.00 (1.67)	0.6	1.3×10^{20}	7.8	1.1
0.60	35	16		0.7	2.3×10^{20}	10	1.5
1.28	35	34	1.85 (1.48)	0.6	5.0×10^{20}	15	2.2
4.0	35	107	1.94 (1.55)	0.7	1.7×10^{21}	28	4.0

[a] Total energy after compressor
[b] Gaussian temporal profile, intensity FWHM
[c] Flattop, diameter before OAP
[d] intensity FWHM (limit given by Airy disk)

Existing laser

Potential upgrade

E-320 parameters and perspectives at FACET-II (SLAC)

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FACET-II: Yakimenko et al., PRAB 22, 101301 (2019)

- KPPs have been exceeded (June 2021)
- First experiment beam time (August 2021)

Key performance Parameter	Threshold KPP	Achieved
Particle Energy	> 9 GeV	9.3 GeV
Bunch Charge	> 0.1 nC	0.4 nC
Normalized Emittance in Sector 19	50 mm-mrad	25 mm-mrad
Bunch Length	< 100 µm	70 µm

M. Hogan

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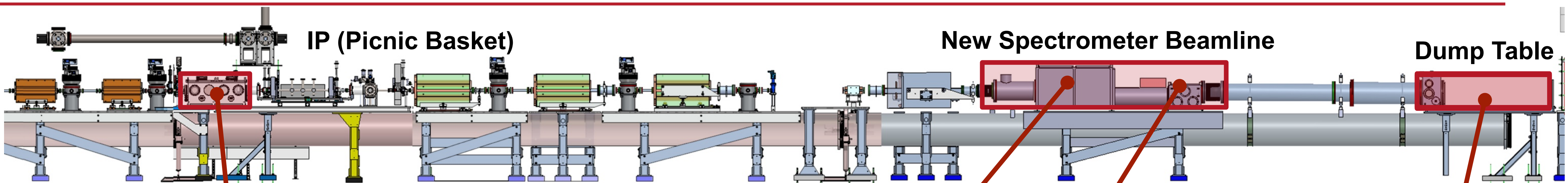
Existing laser

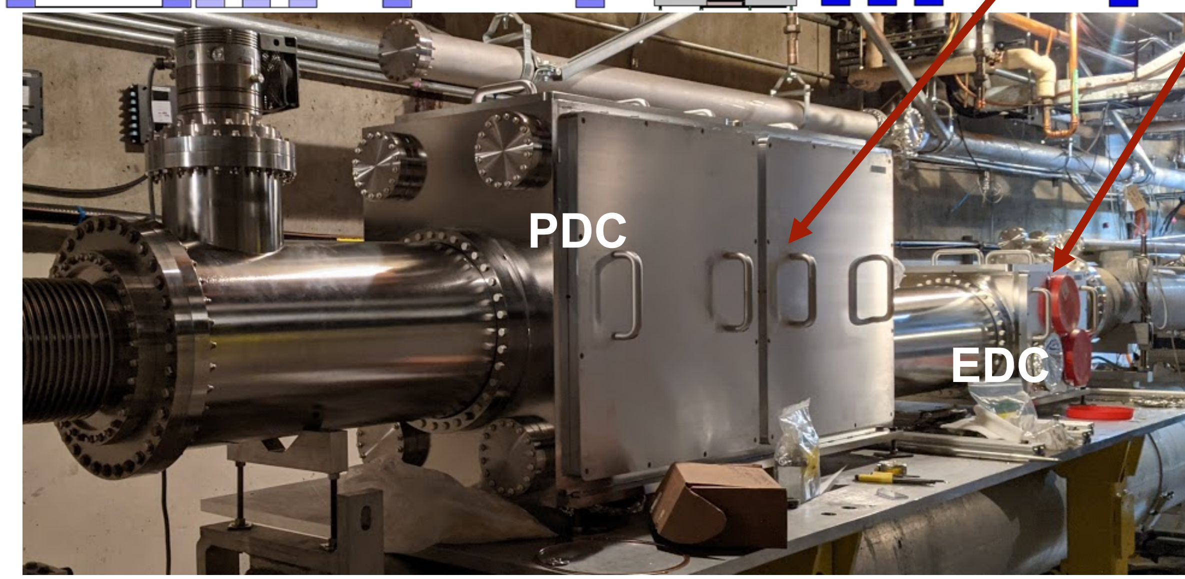
Potential upgrade

Achieved laser parameters (July 2021):

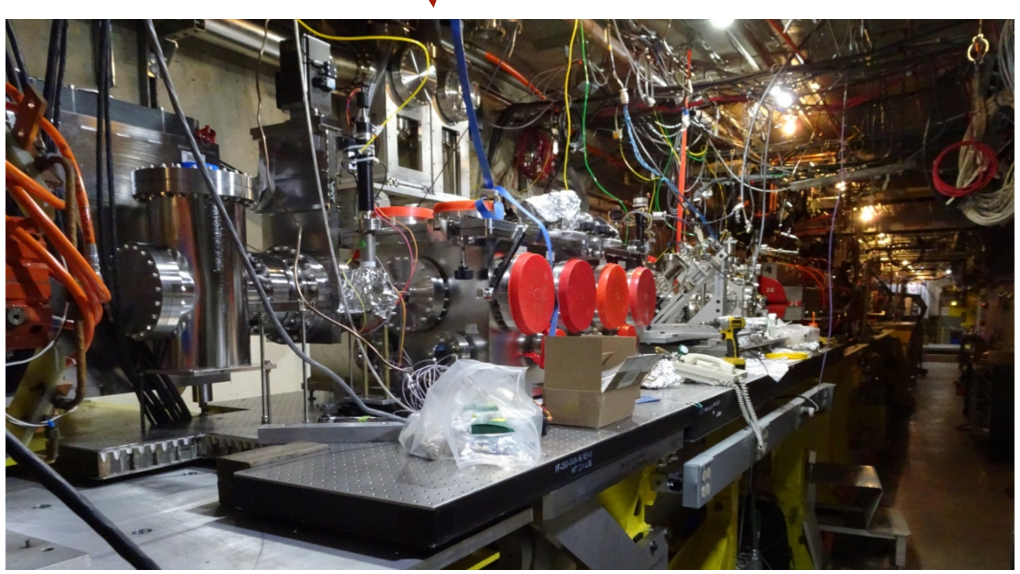
- Compressed pulse duration: 45 fs FWHM (not amplified)
- Amplified laser energy: 750 mJ (before losses)
- Energy on target: ~ 475 mJ (estimated)

Interaction region and detectors are spatially separated

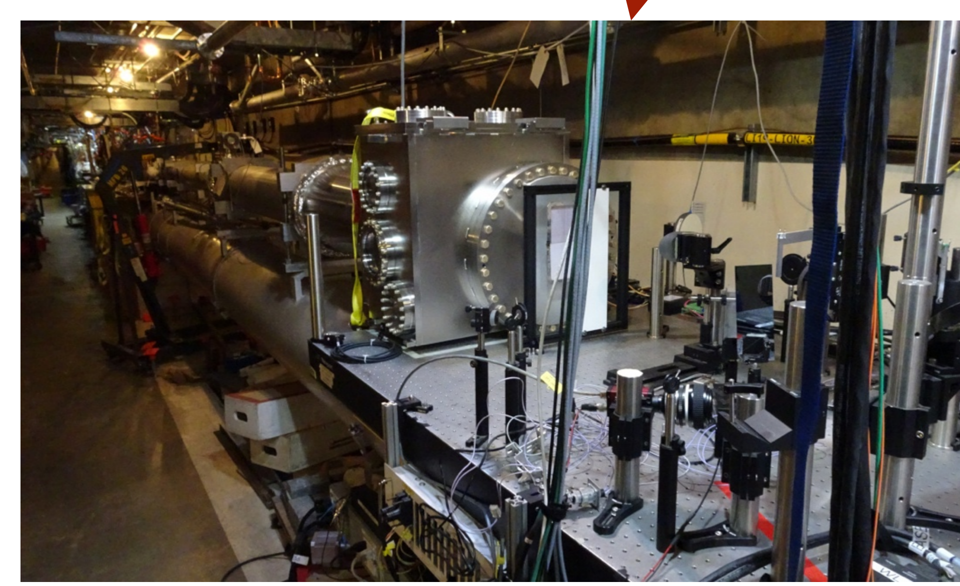




New spectrometer beamline (Storey):
positron/low-energy electron diagnostics



E-320 Interaction Point (IP) in the "Picnic Basket"



Dump table:
Electron/gamma diagnostics

Interaction geometry and laser diagnostics

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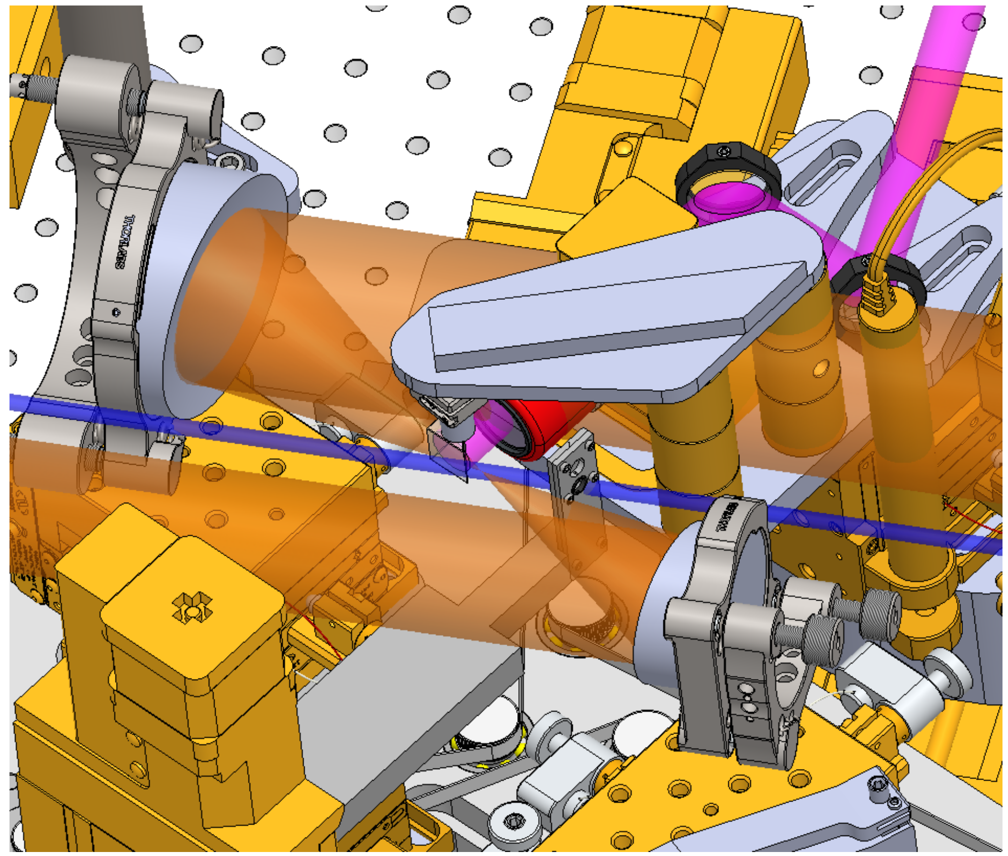
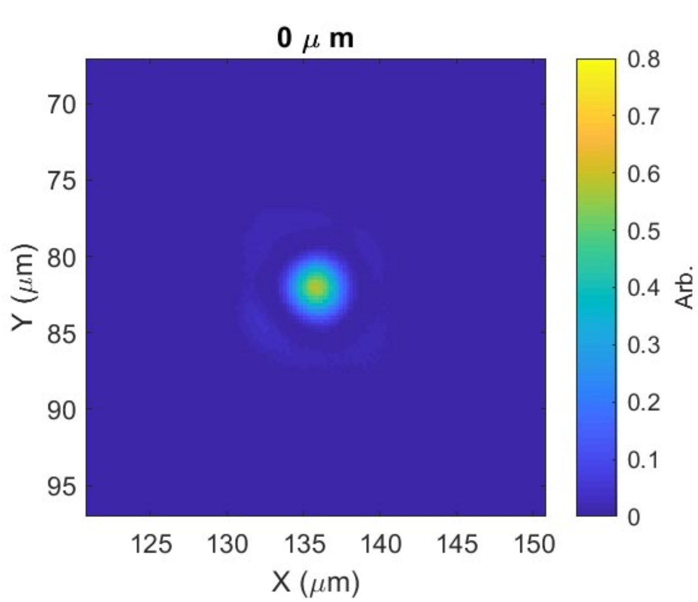


Interaction geometry

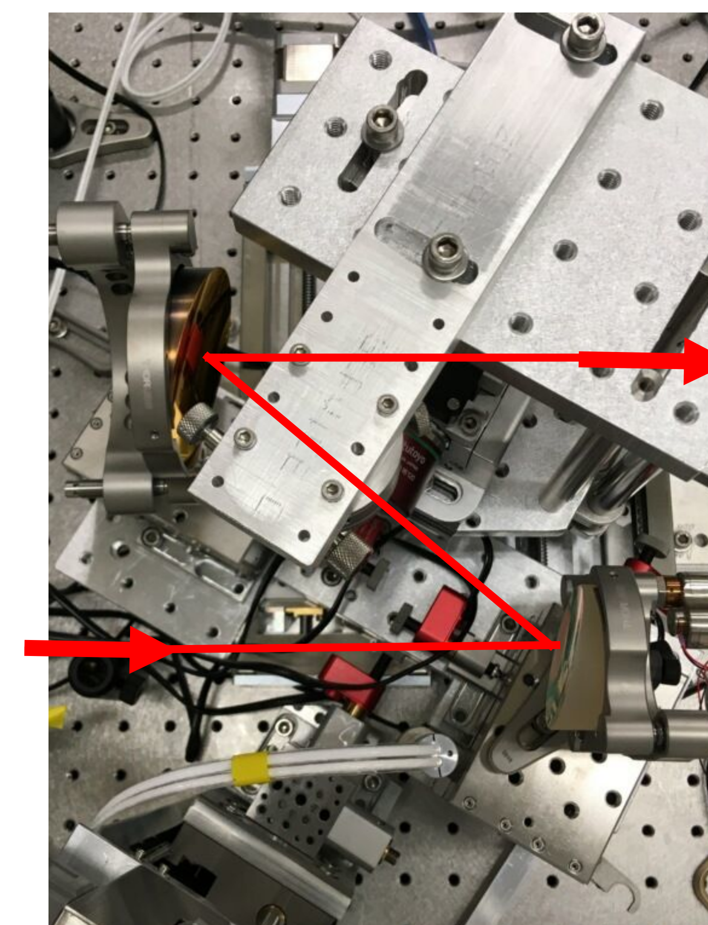
- 1st OAP focuses laser pulse (f/d = 1.91)
- e-beam/laser collision at 28.07°
- 2nd OAP re-collimates laser pulse

FWHM (ideal)	2.665 um (1.65 um)
Enclosed Energy	37.70%



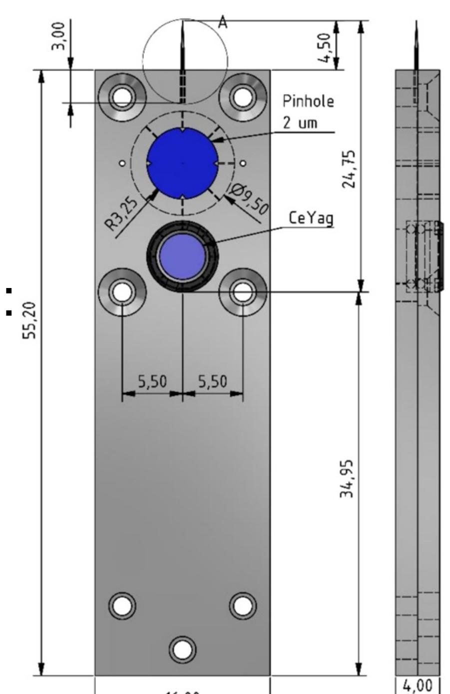
Laser diagnostics/control

- NF/FF diagnostics before/after IP
- Focal spot diagnostic
- Wavefront sensor
- Deformable mirror
- Interferometer for OAP alignment

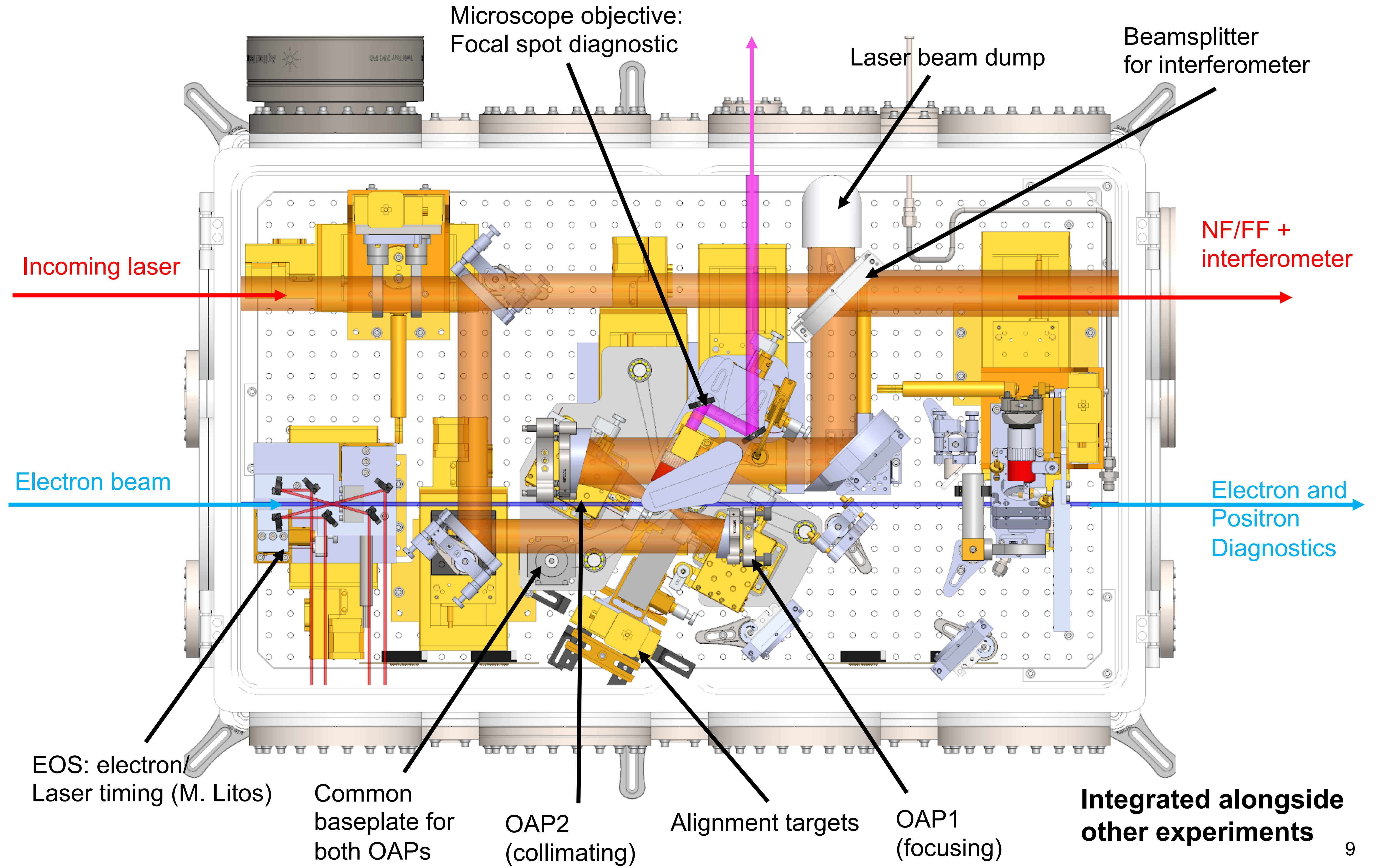


Alignment Targets

- Beam/laser spatial overlap: Ce:YAG screen/needle
- Pinhole for alternative OAP alignment



E-320 interaction point in the picnic basket



Integrated alongside other experiments

Fitting test in the picnic basket (May 2021)

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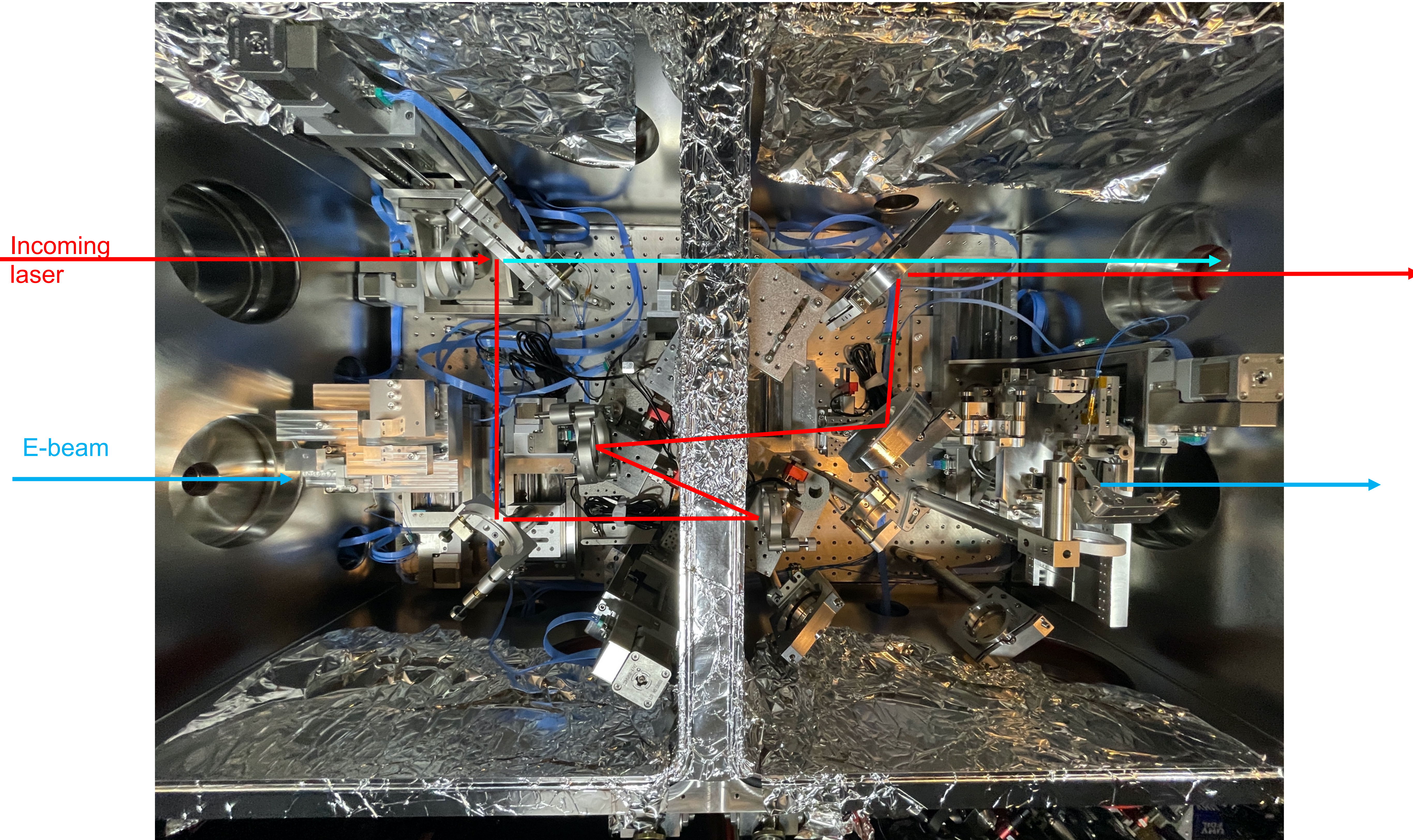

Interferometric alignment enables post-IP laser diagnostic

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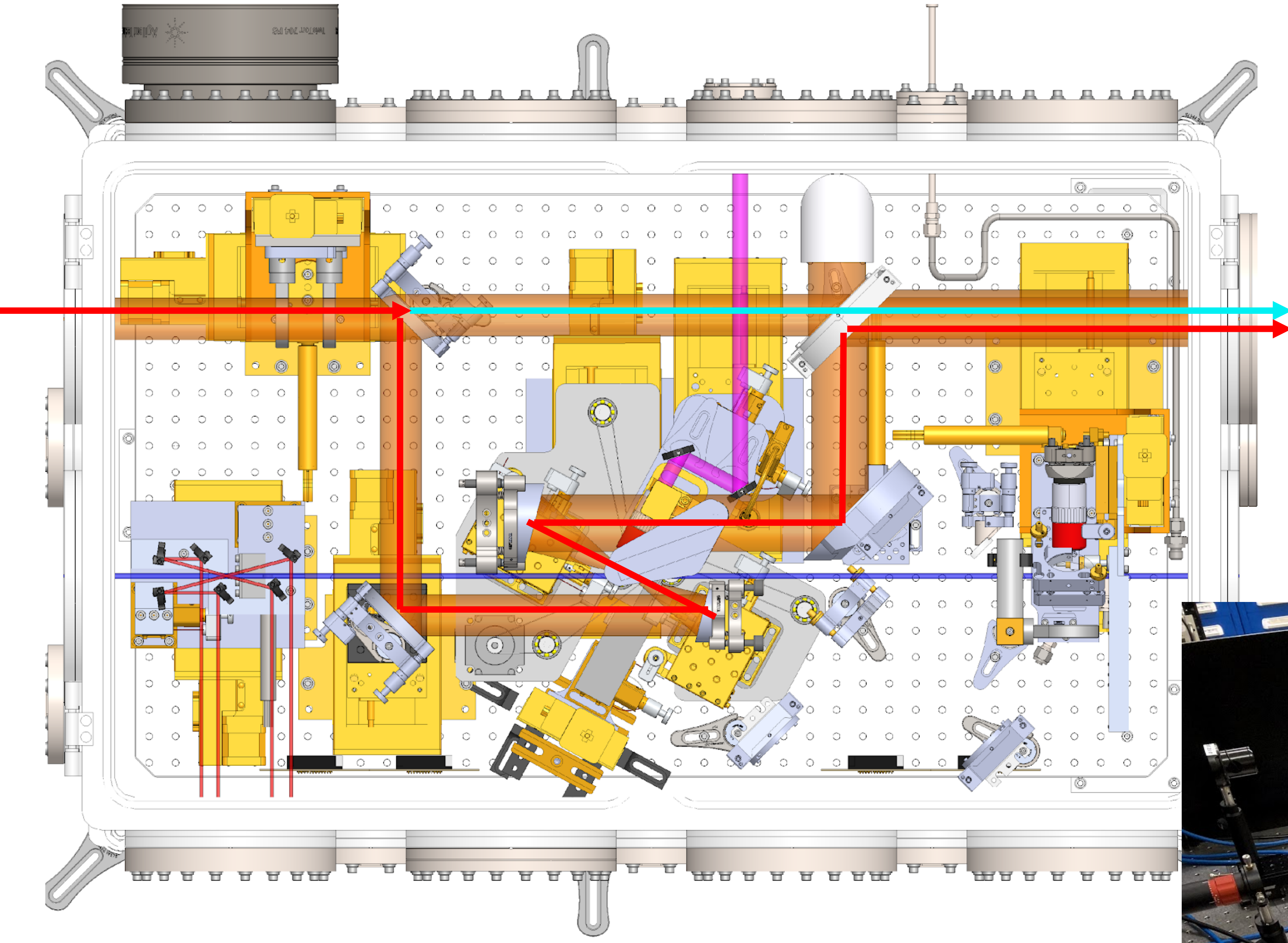
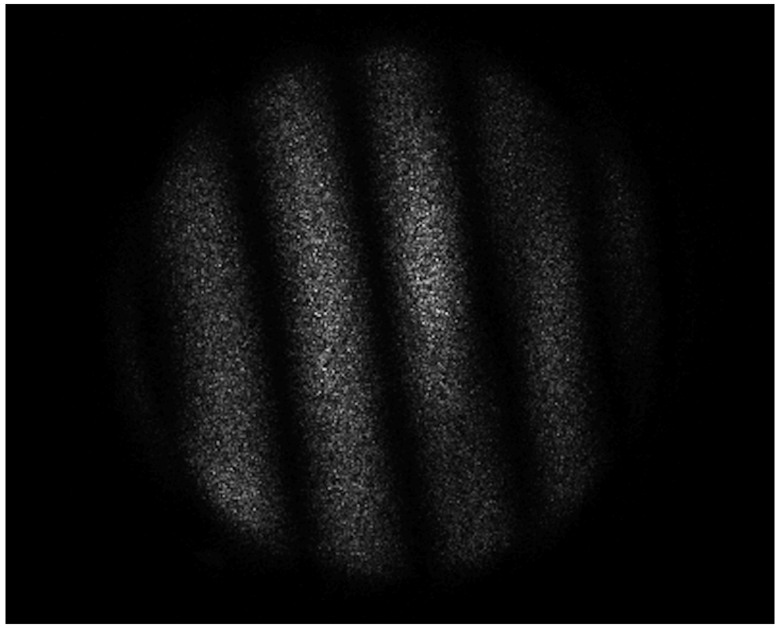
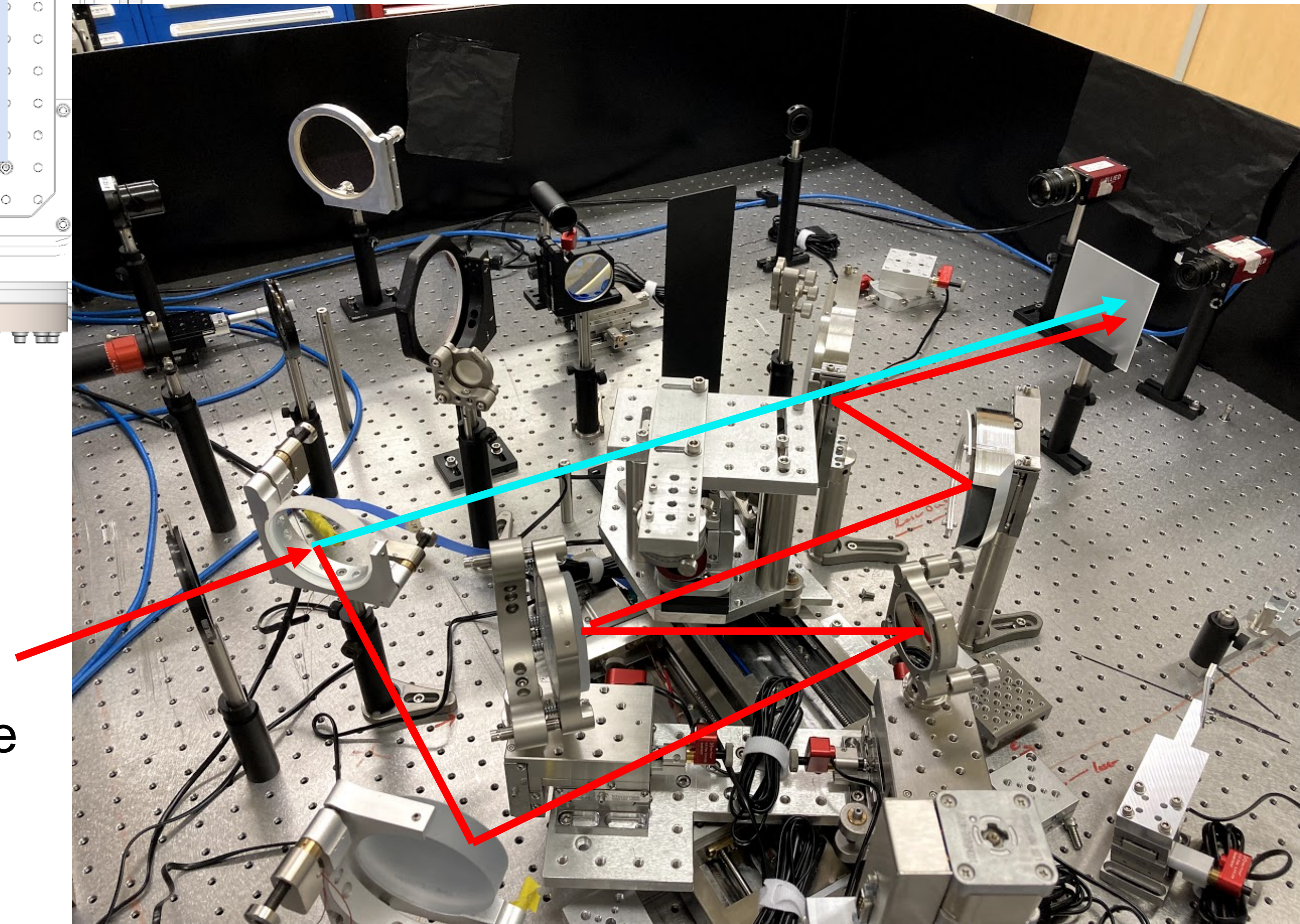


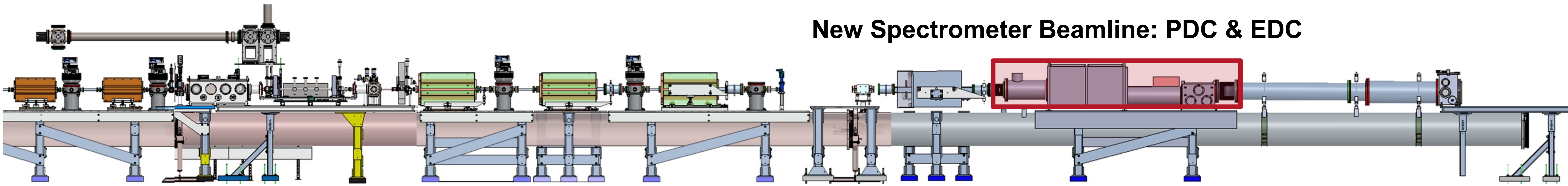


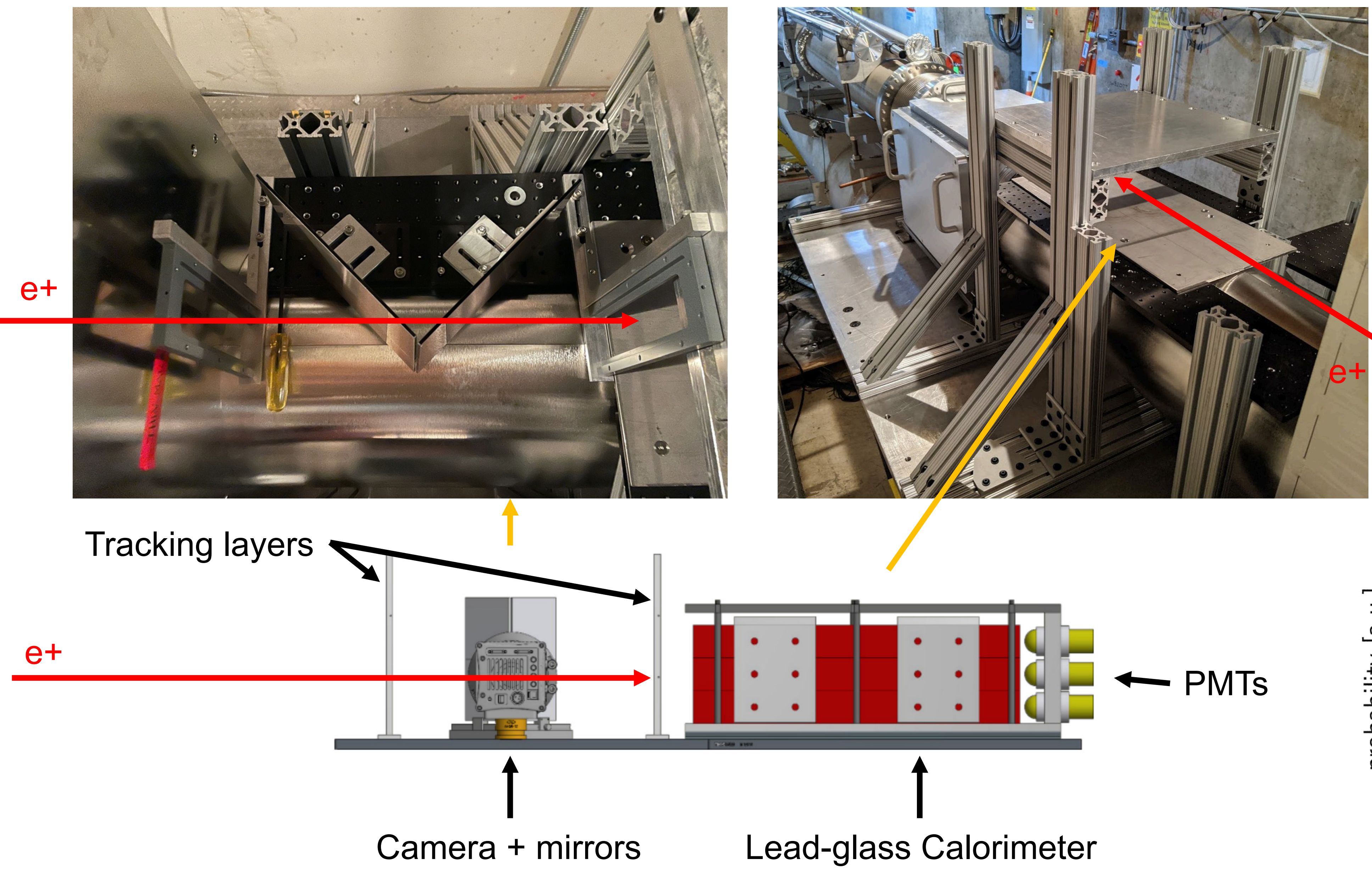
Interference pattern using CW laser and flat optics



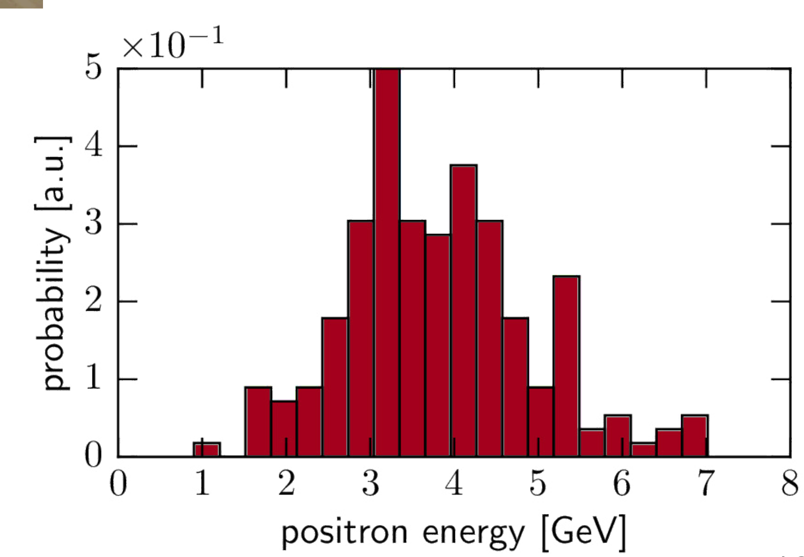
- Interferometer for precise relative OAP alignment
  - Tested with flat optics (July 2021)
  - Currently using OAPs to test alignment procedure

New beamline for positron and electron detection





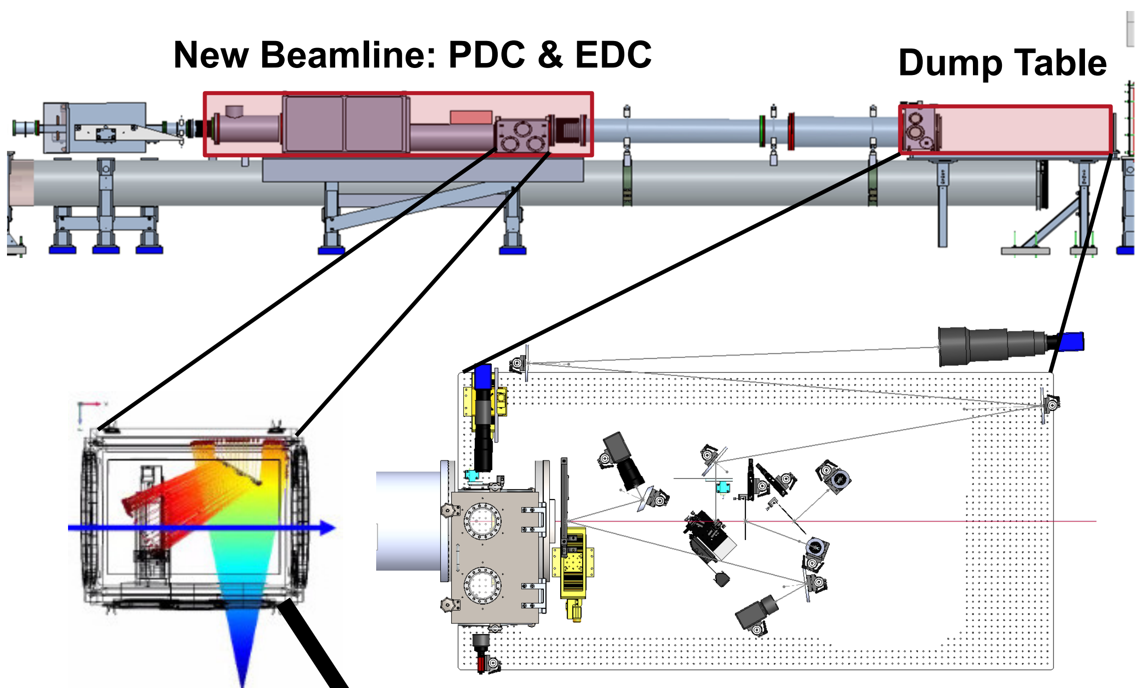
- New spectrometer beamline away from beam dump to reduce noise
- Combine calorimeter & tracking: background rejection
- Energy range 2.5-5.7 GeV (at nominal dipole setting)

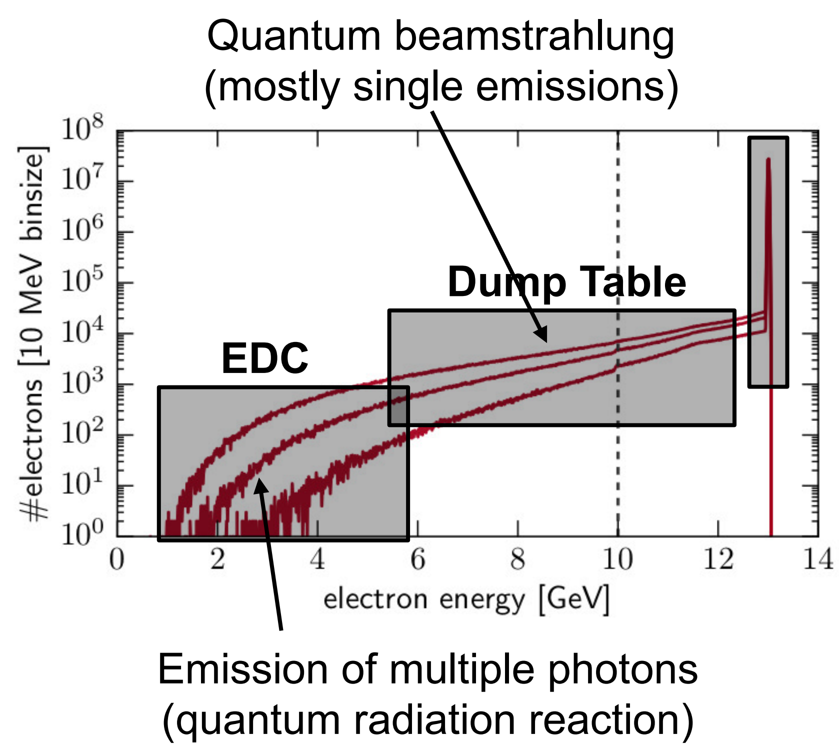


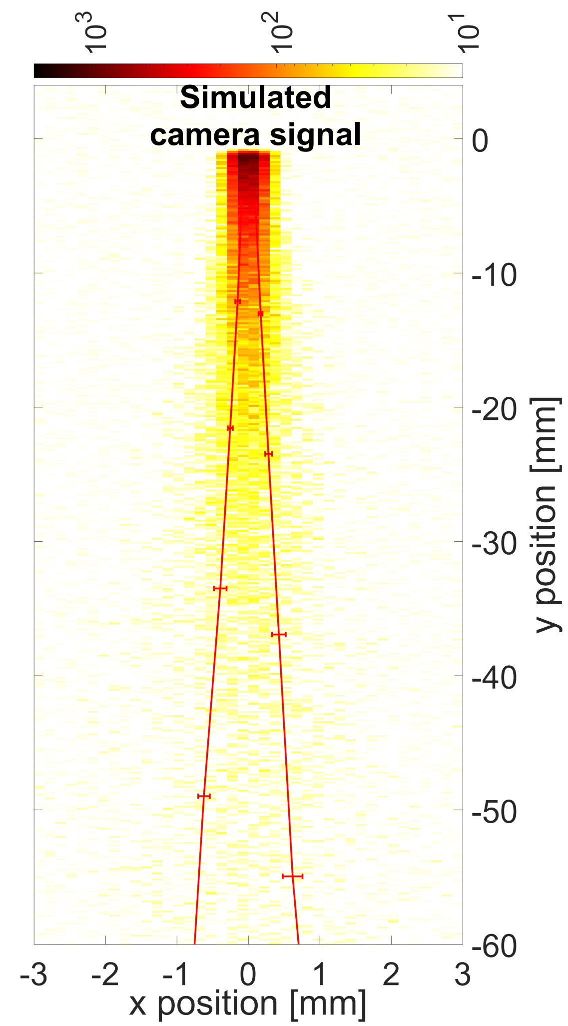
Simulation: M. Tamburini

More details in F. Salgado et al., *arXiv:2107.03697*

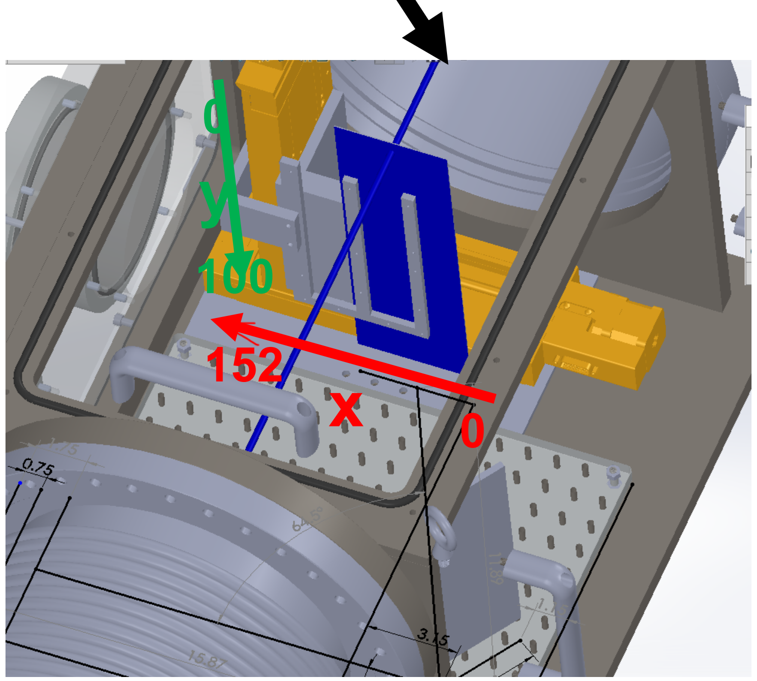
Two spectrometer screens for electron detection



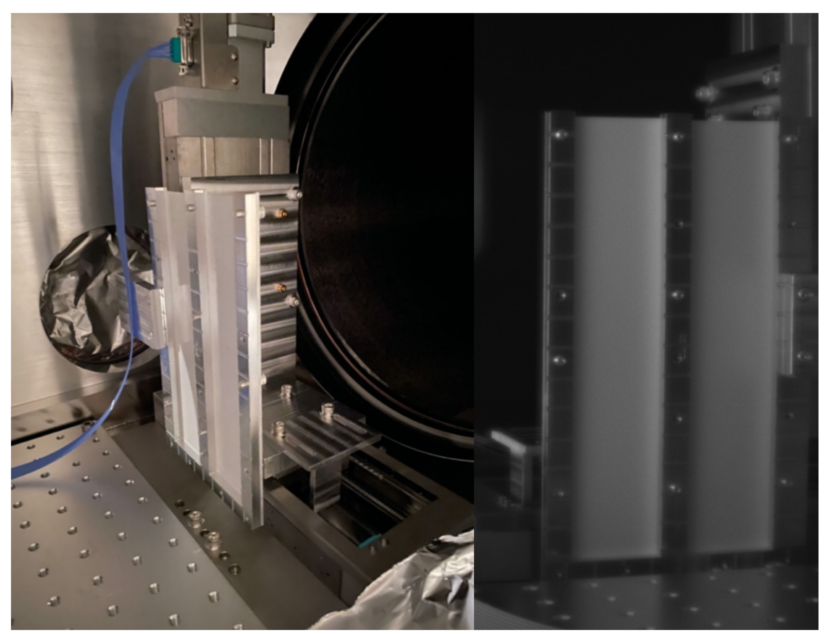




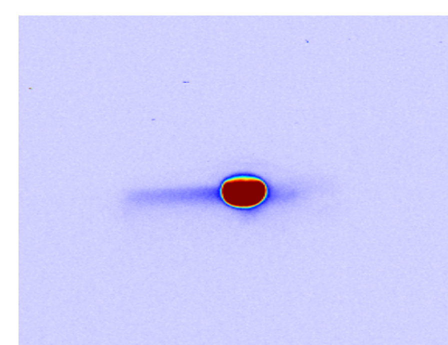
Mir-Ali Hessami & Storey



CAD design



Installation and imaging completed (July 2021)

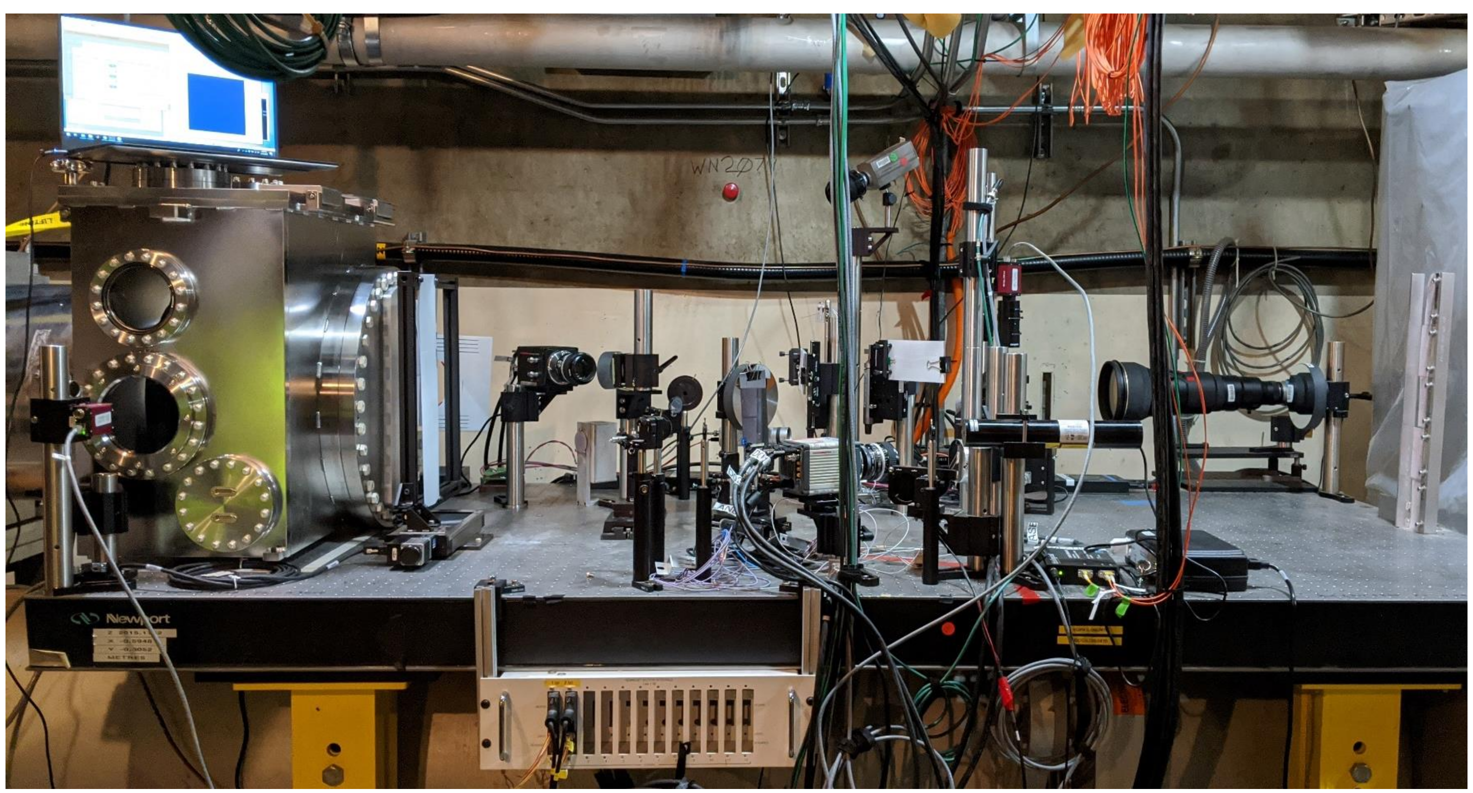


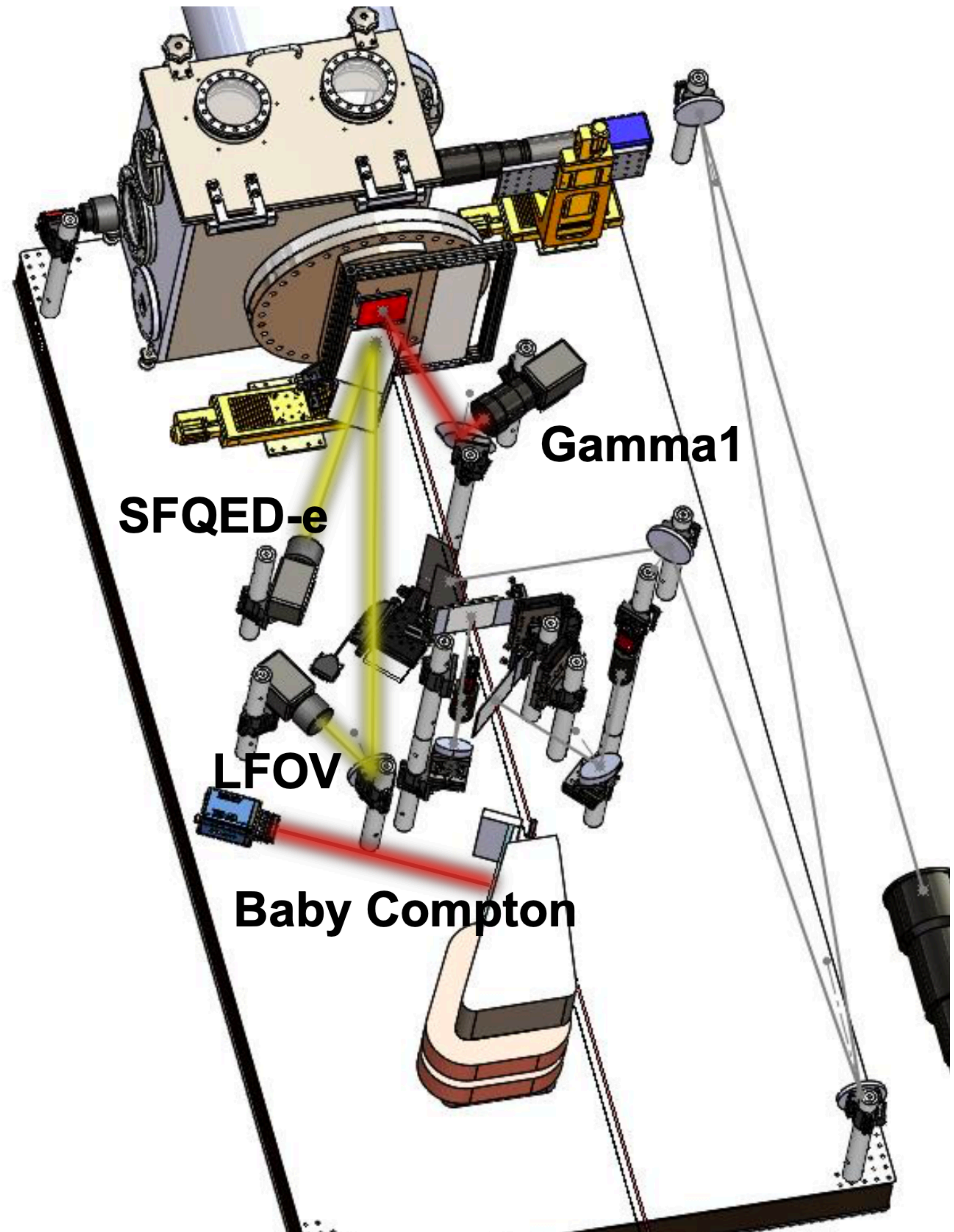
First beam on screen (August 2021)

- EDC for low-energy electrons at low numbers
- Dump for high-energy electrons at high numbers

FACET-II dump table diagnostics

- **Gamma1** (CsI array with 0.5mm x 0.5mm pixels)
  → photon intensity/angular profile
- **LFOV** (large FOV e^- profile monitor)
- **SFQED-e** (higher resolution, brighter e^- profile)
  → DRZ/CsI scintillator screens
- **Electron spectrometer screen** (DRZ)





Storey

Breakdown of the LCFA at small photon energies

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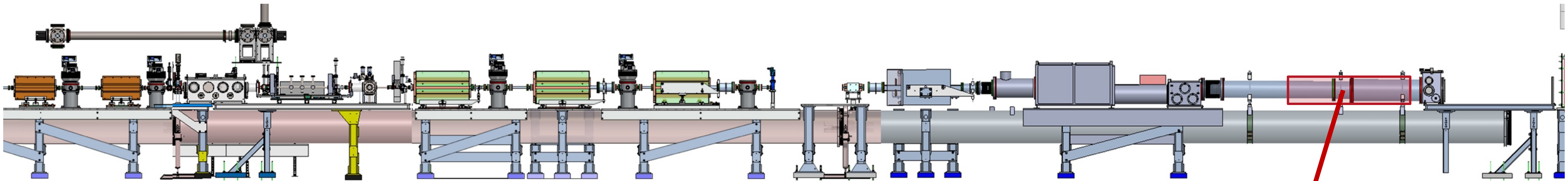
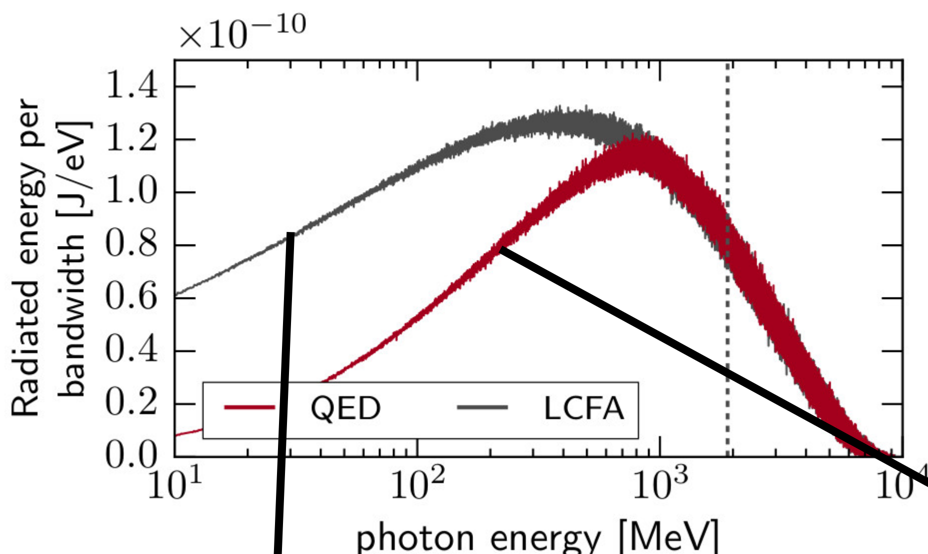
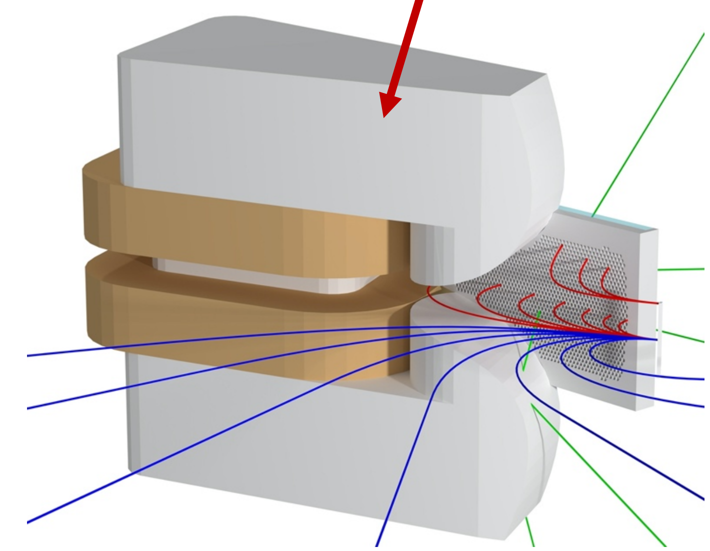


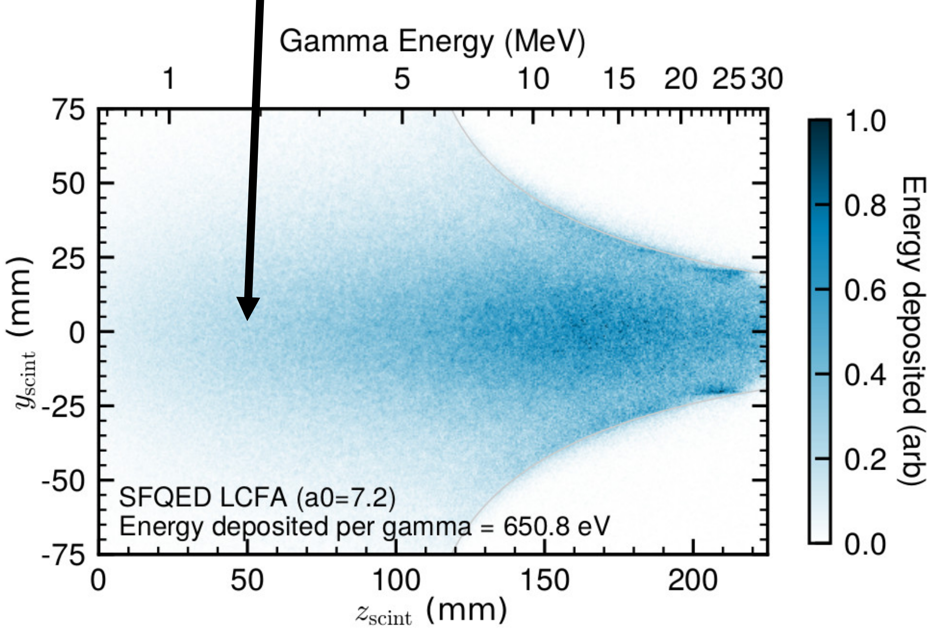
Tamburini

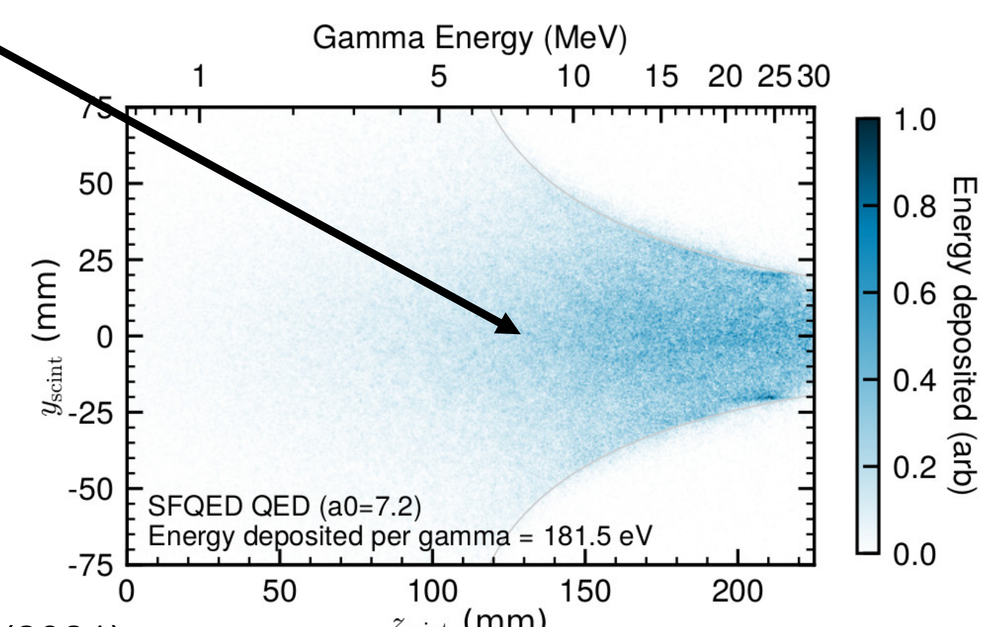


- Spectrum: 160 keV – 23 MeV
- 1% energy resolution ≳ 1 MeV



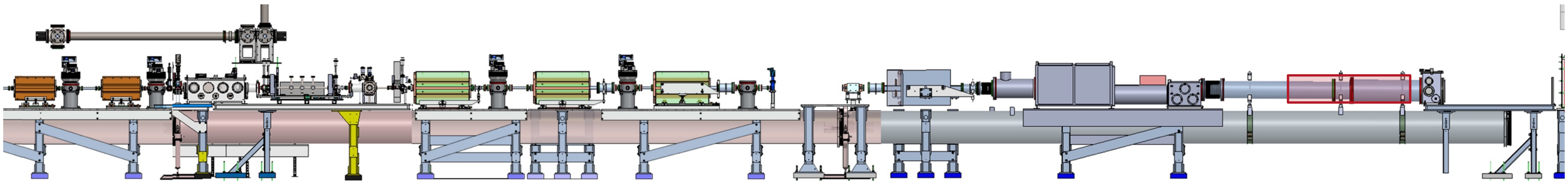
Naranjo/Rosenzweig

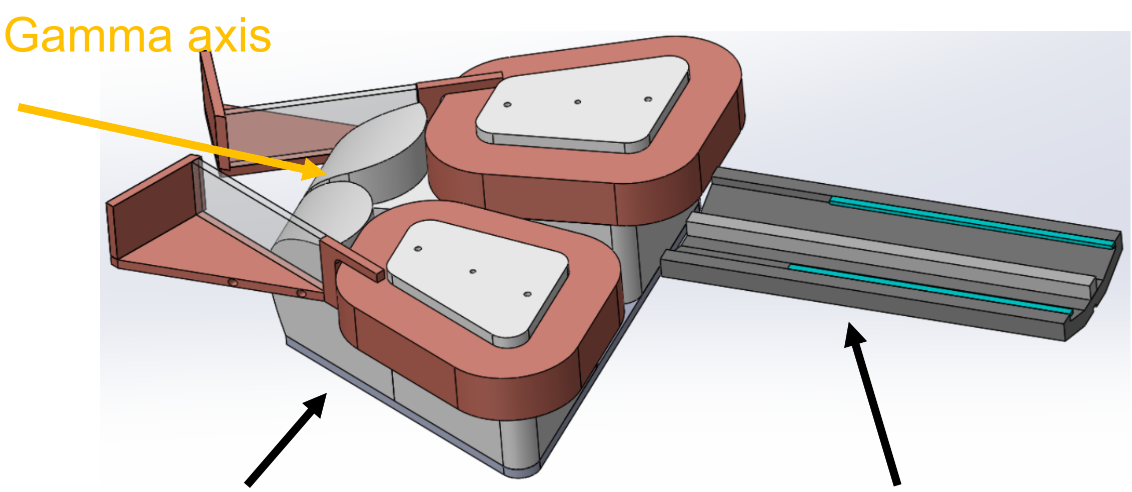


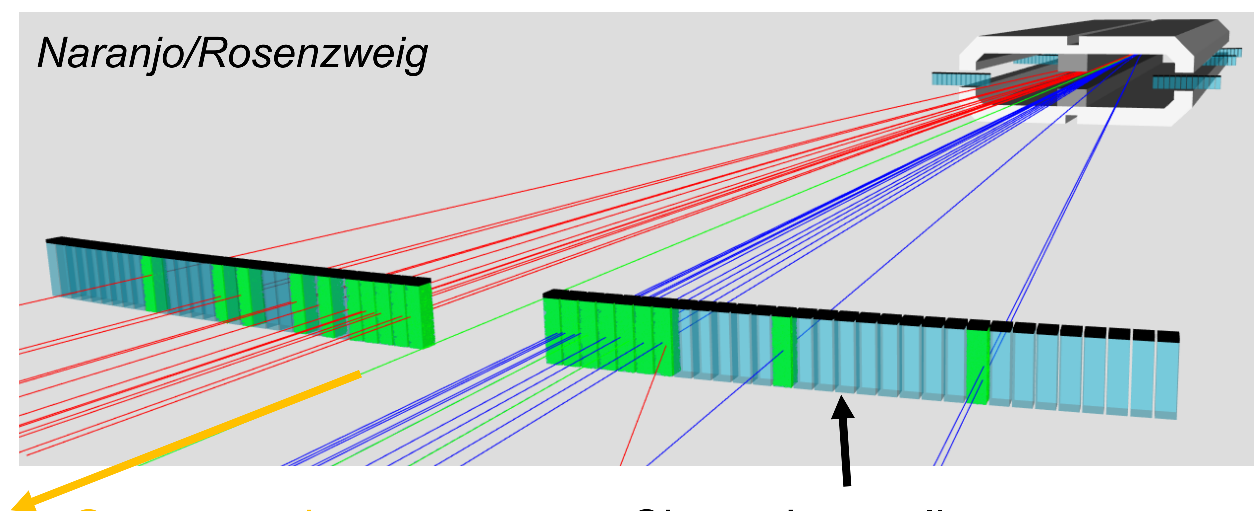


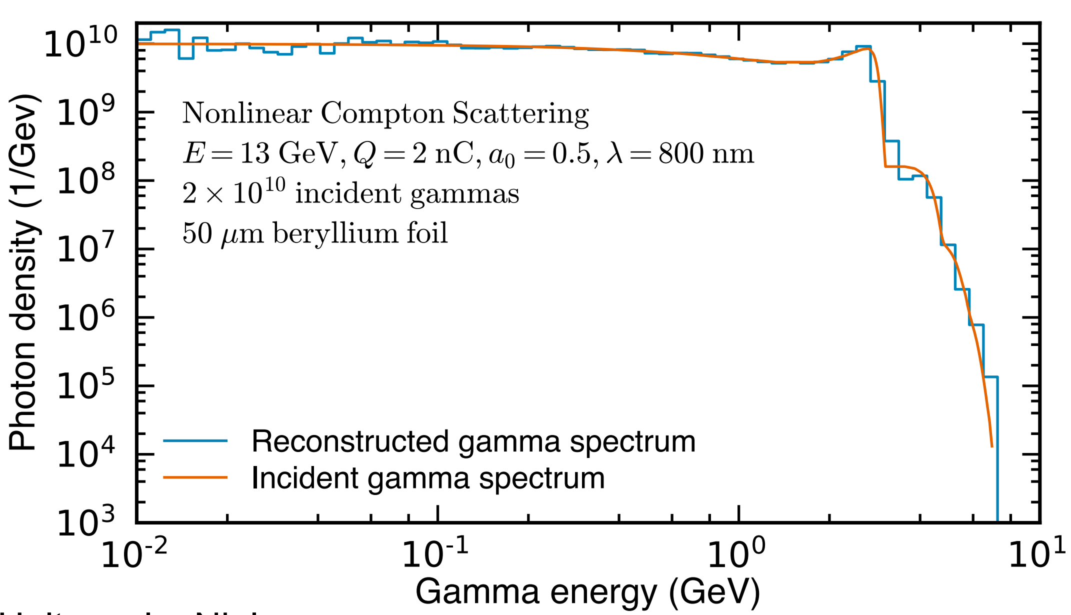
Naranjo et al., *in preparation* (2021)

Pair spectrometer to resolve full gamma spectrum

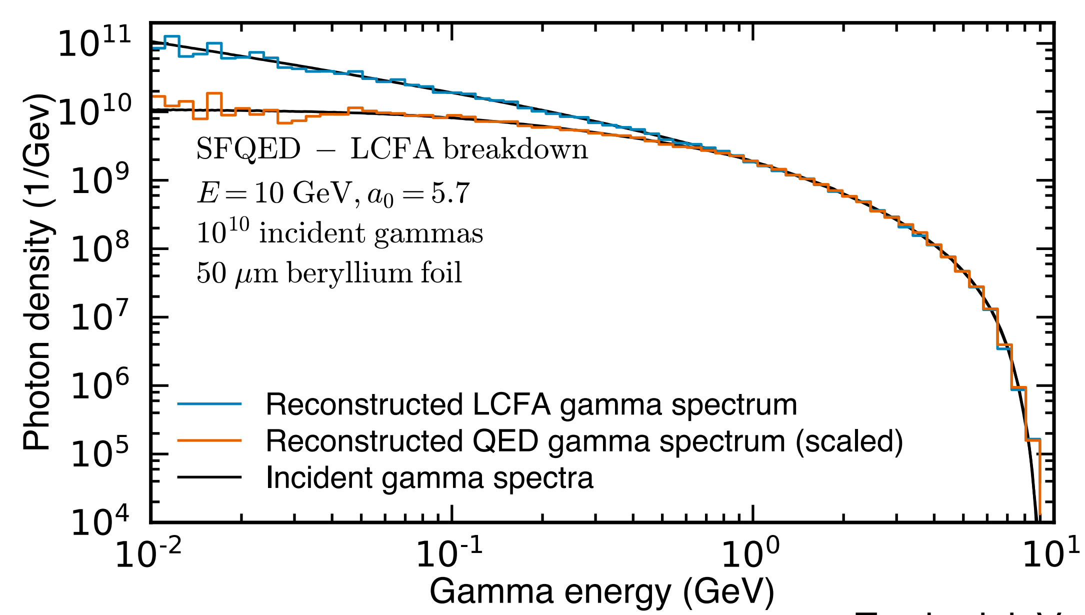








Holtzapple, Nielsen



Tamburini, Vranic

Naranjo et al., *in preparation* (2021)

First measurements expected later this year

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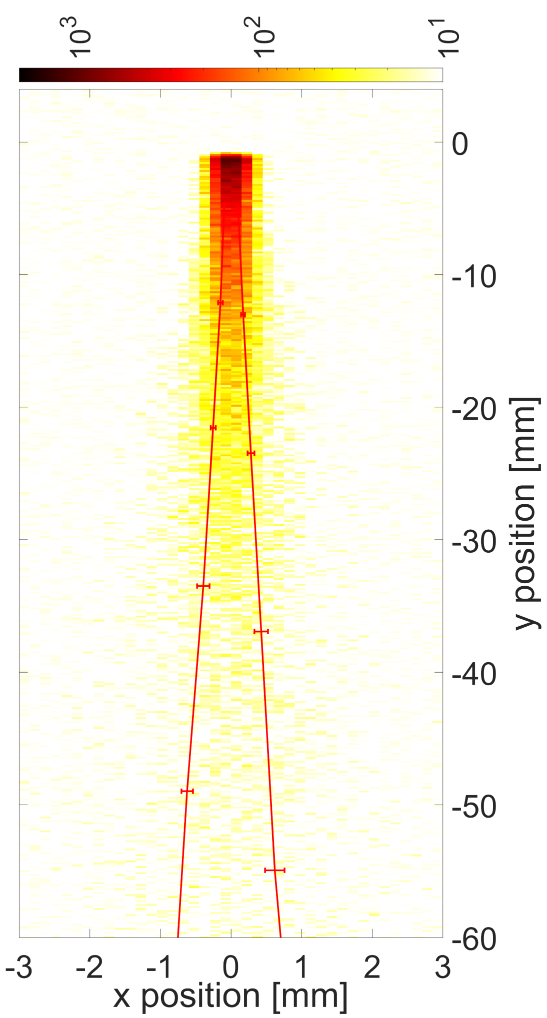
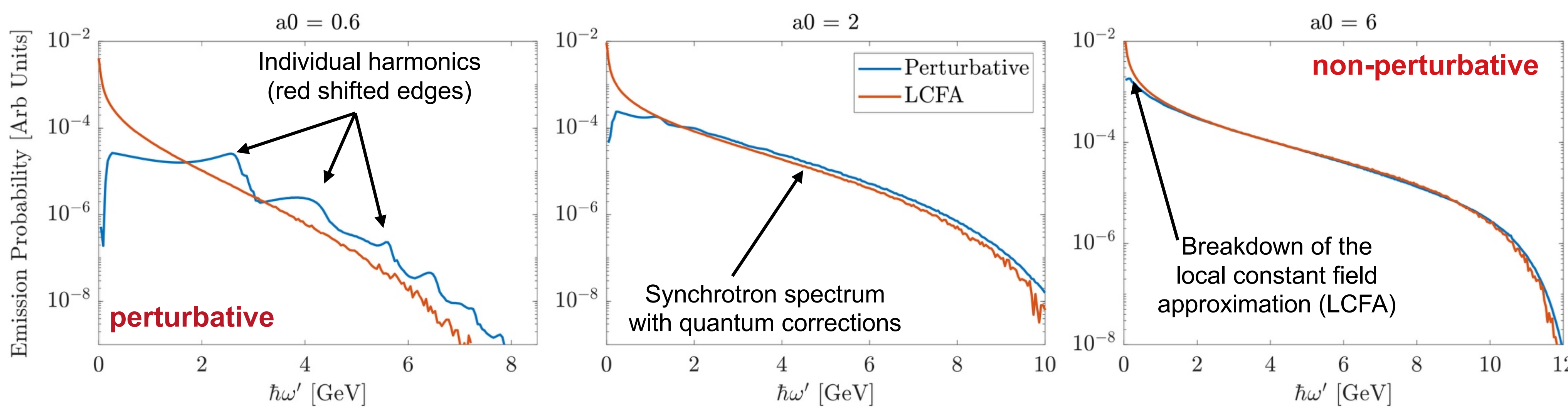
- **2021 (fall)**: calibrate detectors, measure backgrounds, access perturbative regime: $a_0 \lesssim 1$ (~10^{18} W/cm^2)
- **2021 (winter)**: observe the transition to nonperturbative laser-electron interactions: $a_0 \gtrsim 5$ ($\gtrsim 10^{19}$ W/cm^2)

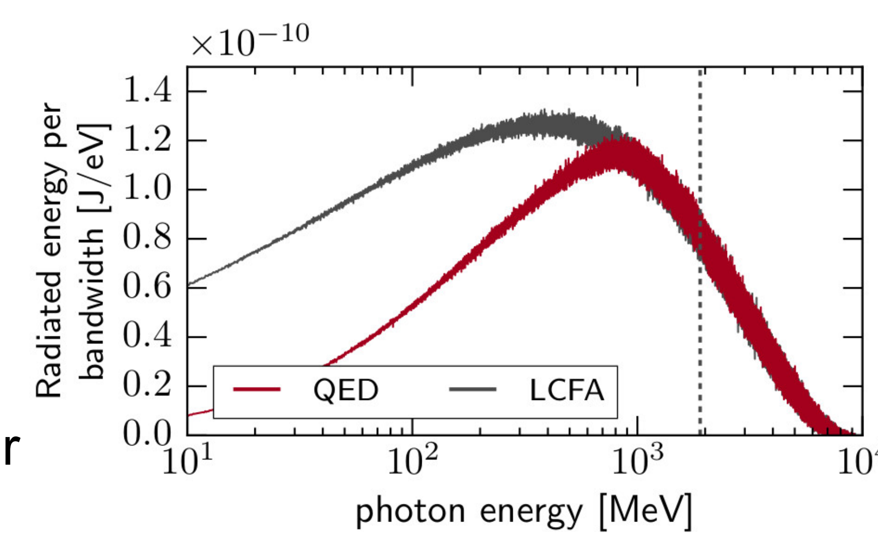


Mir-Ali Hessami & Storey

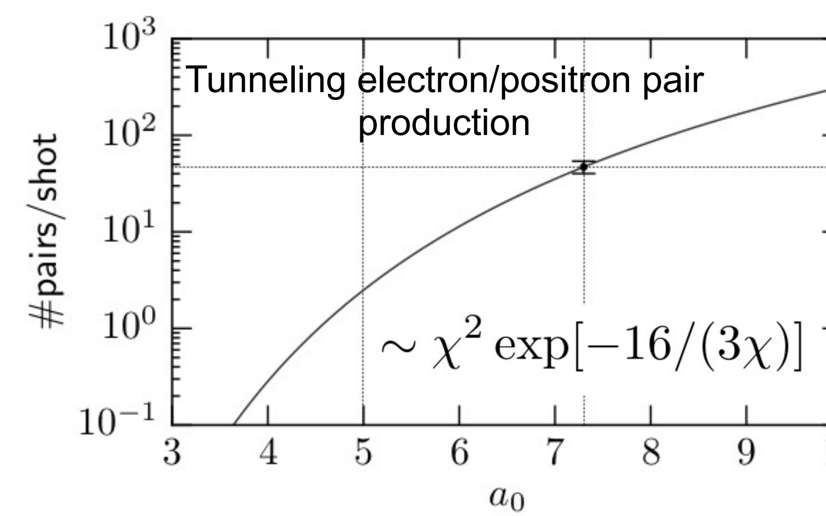


Nielsen

- **2021 (winter)**: quantum radiation reaction (electrons emitting $n \gtrsim 5$ photons)
- **2021 (winter)**: QED vacuum breakdown: $a_0 \gtrsim 10$ ($\gtrsim 2\text{x}10^{20}$ W/cm^2)



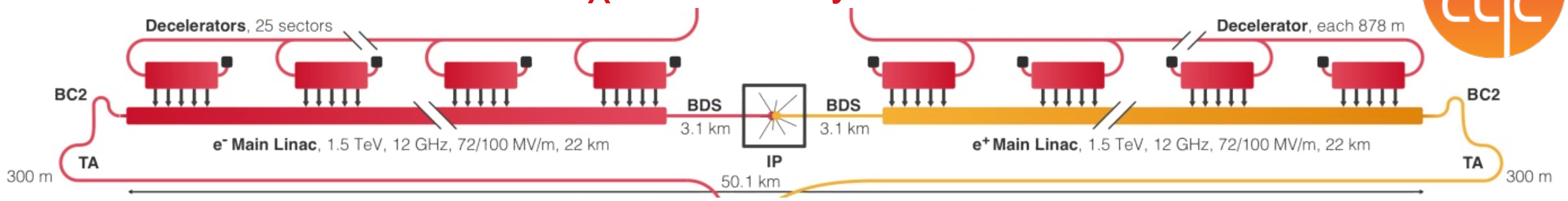
Tamburini



- **2022 (spring)**: LCFA breakdown requires Compton / pair spectrometer (*Naranjo & Rosenzweig*)

Future science program

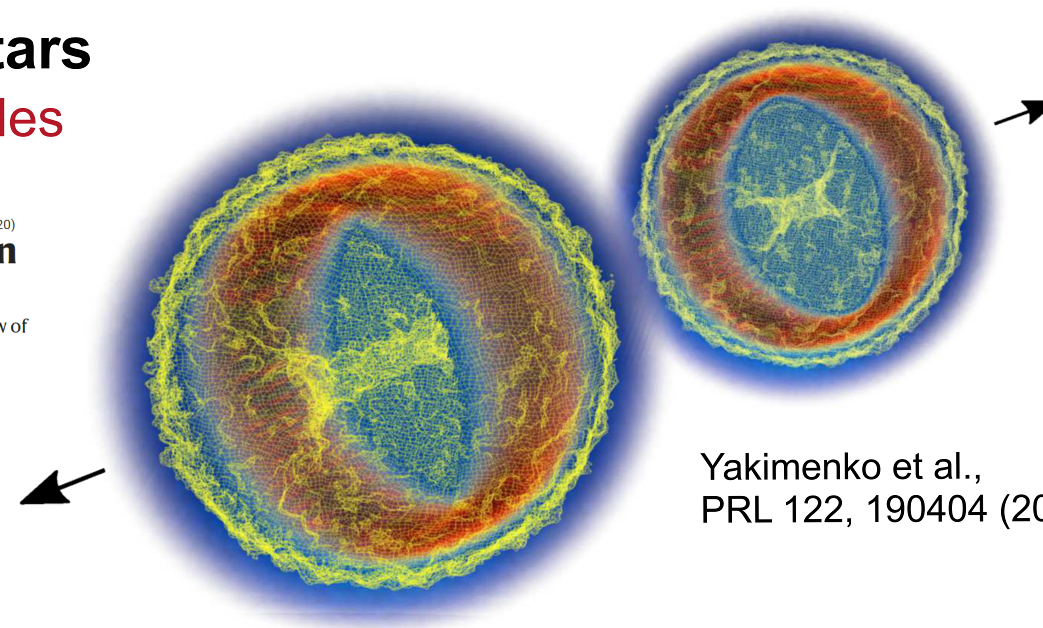
Beam-Beam Collisions: χ≳10 already for 3 TeV CLIC



Esberg et al., PRSTAB 17, 051003 (2014)

Beamstrahlung Mitigation: Short-Bunch Paradigm

- plasma lens: transverse size ≲ μm
- 90° collisions: interaction time ≲6 fs



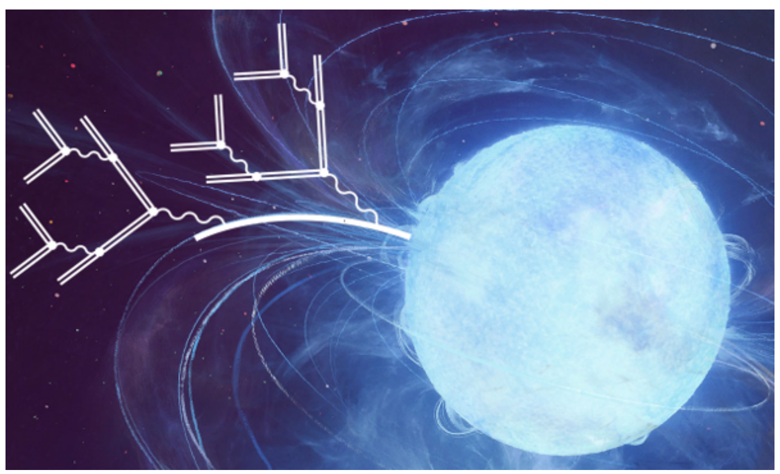
Laboratory Astrophysics: Understanding Magnetars

χ≳2: onset of QED cascades

NEWS · 09 JUNE 2020 — Nature 582, 322-323 (2020)

Astronomers spot first fast radio burst in the Milky Way

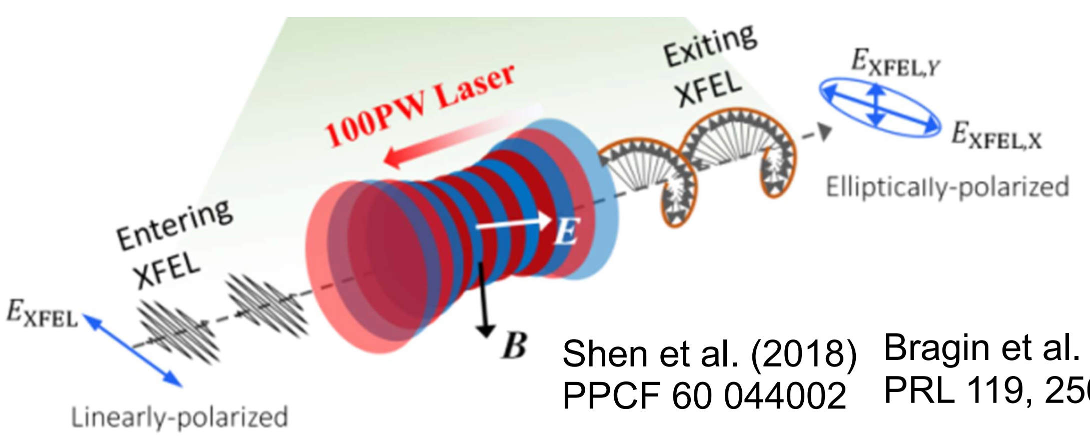
The nearby burst came from a magnetized star – and provides a close-up view of one of astronomy's biggest puzzles.



Yakimenko et al., PRL 122, 190404 (2019)

Photon-Photon Collider (gamma/optical): 2nd IP → Vacuum Birefringence

- 12.9 keV x-ray + 100 PW ↔ 6 GeV γ + 100 TW

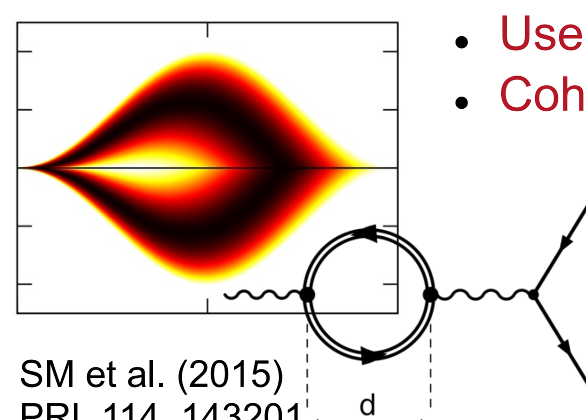


Shen et al. (2018) PPCF 60 044002

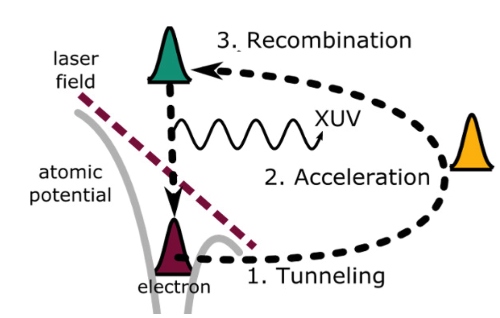
Bragin et al. (2017) PRL 119, 250403

Quantum Coherence in Extreme Conditions

- Use two-color laser with phase control
- Coherent e⁻e⁺ re-collisions



SM et al. (2015) PRL 114, 143201



Potential facility upgrades for E-320

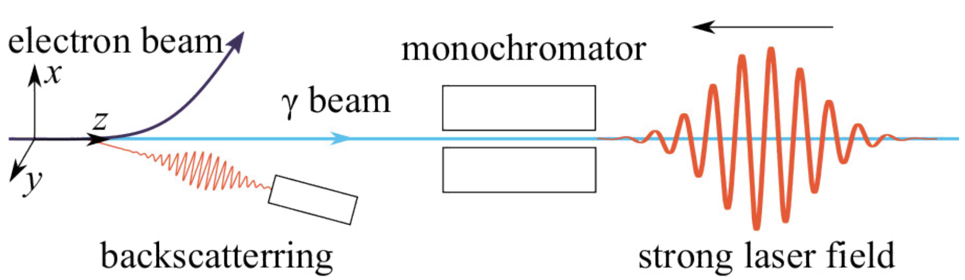
Laser upgrade: 100 TW scale to start probing χ ≫1

Energy[a] [J]	Duration[b] [fs]	Power [TW]	Diameter[c] [mm]	Optics	OAP $f_\#$	Spot[d] [µm]	Strehl	Intensity [W/cm²]	a_0	χ
0.30	50	5.6					0.4	4.7×10^{19}	4.7	0.68
0.44	40	10	40	3"	2.0	2.00 (1.67)	0.6	1.3×10^{20}	7.8	1.1
0.60	35	16					0.7	2.3×10^{20}	10	1.5
1.28	35	34	60	4"	1.8	1.85 (1.48)	0.6	5.0×10^{20}	15	2.2
4.0	35	107	100	6"	1.9	1.94 (1.55)	0.7	1.7×10^{21}	28	4.0

[a] Total energy after compressor
[b] Gaussian temporal profile, intensity FWHM
[c] Flattop, diameter before OAP
[d] intensity FWHM (limit given by Airy disk)

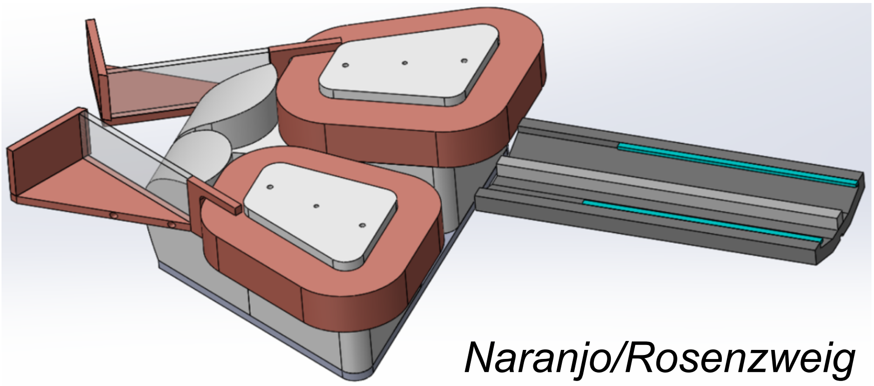
Beamline upgrade: introduce 2nd IP for photon-photon collider

- Compton backscattering: 13 GeV + 3rd harmonic
  → 6 GeV gamma photons, polarization control
- Requires a dogleg / chicane to deflect main beam
- Access to a new level of control, rich new physics program, e.g., vacuum dichroism/birefringence



Detector upgrades

- Pair spectrometer (access to full gamma spectrum)
- Silicon tracking detectors (positron energy spectrum)



Naranjo/Rosenzweig

Thank you for your attention