INSTITUT POLYTECHNIQUE DE PARIS

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E-305 and E-332: from beam filamentation, bright gamma rays to strong-field QED

LOA

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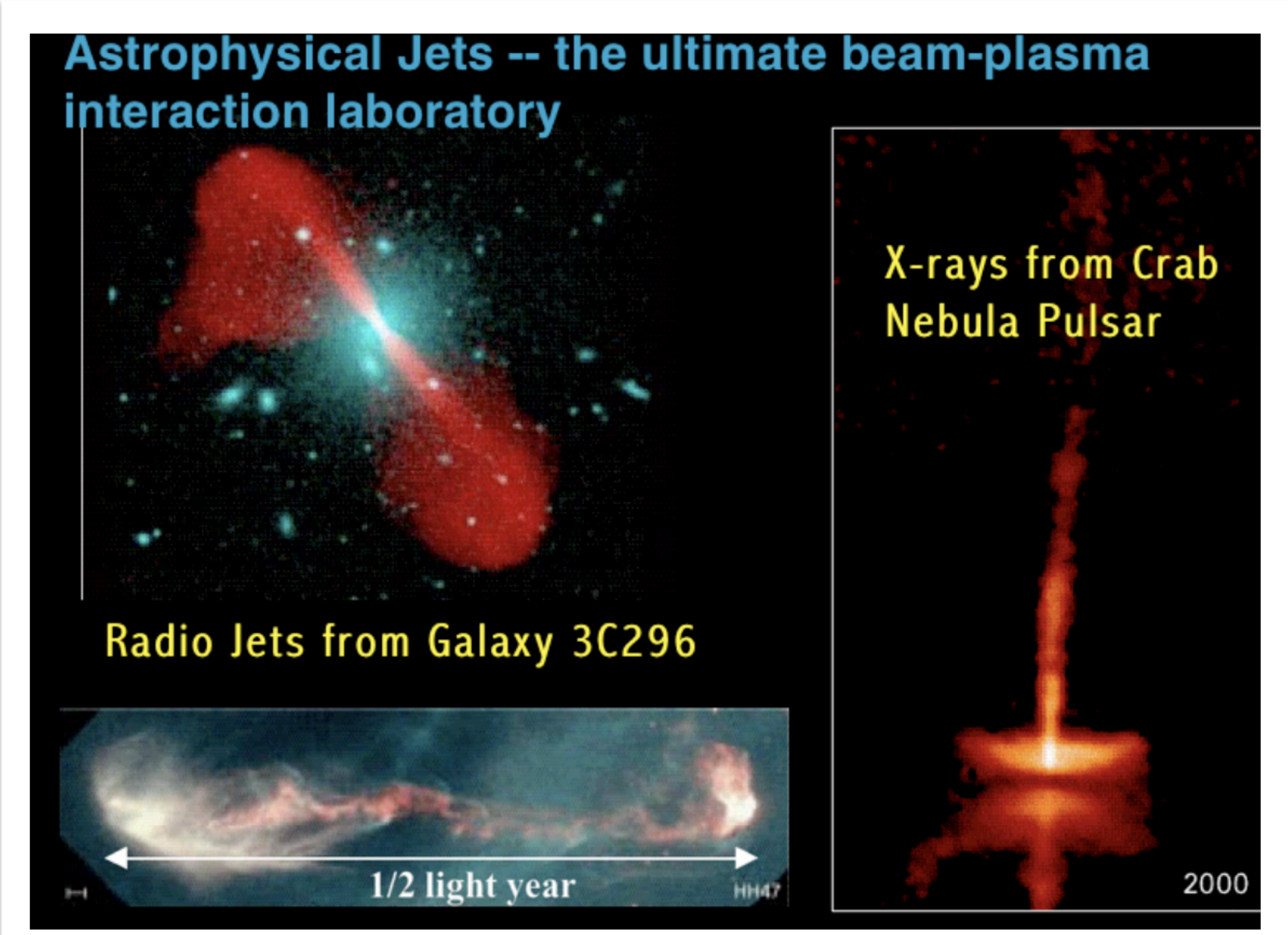
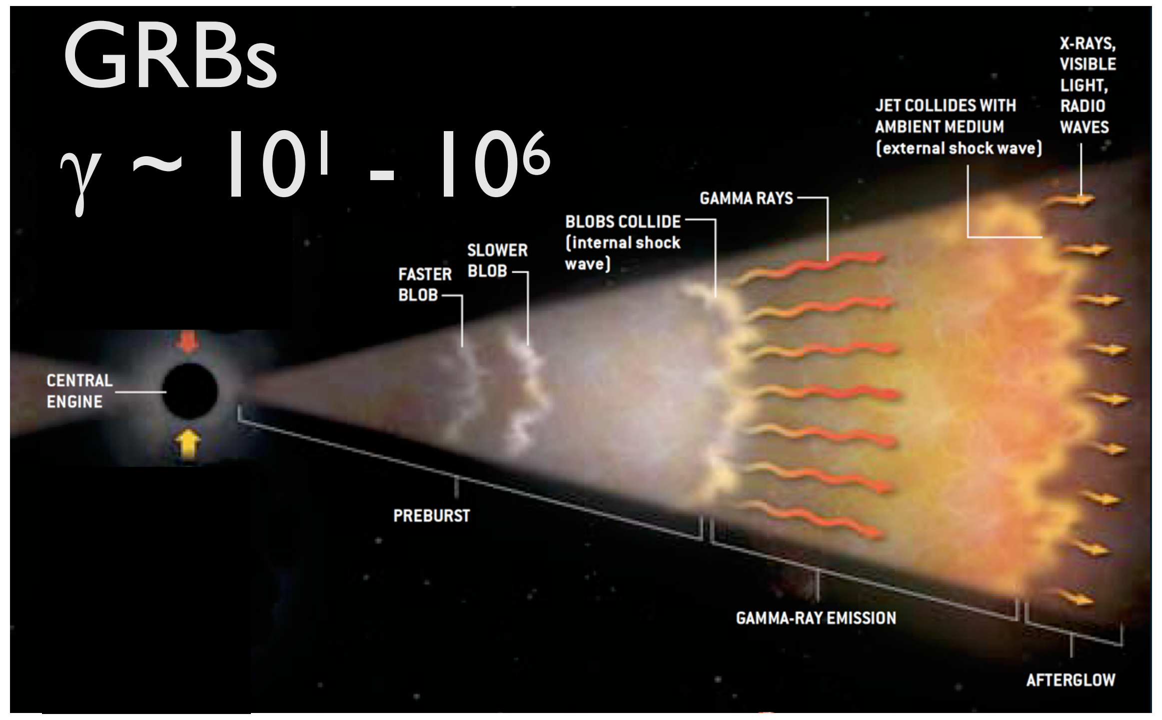
E305 & 332 motivations and concepts

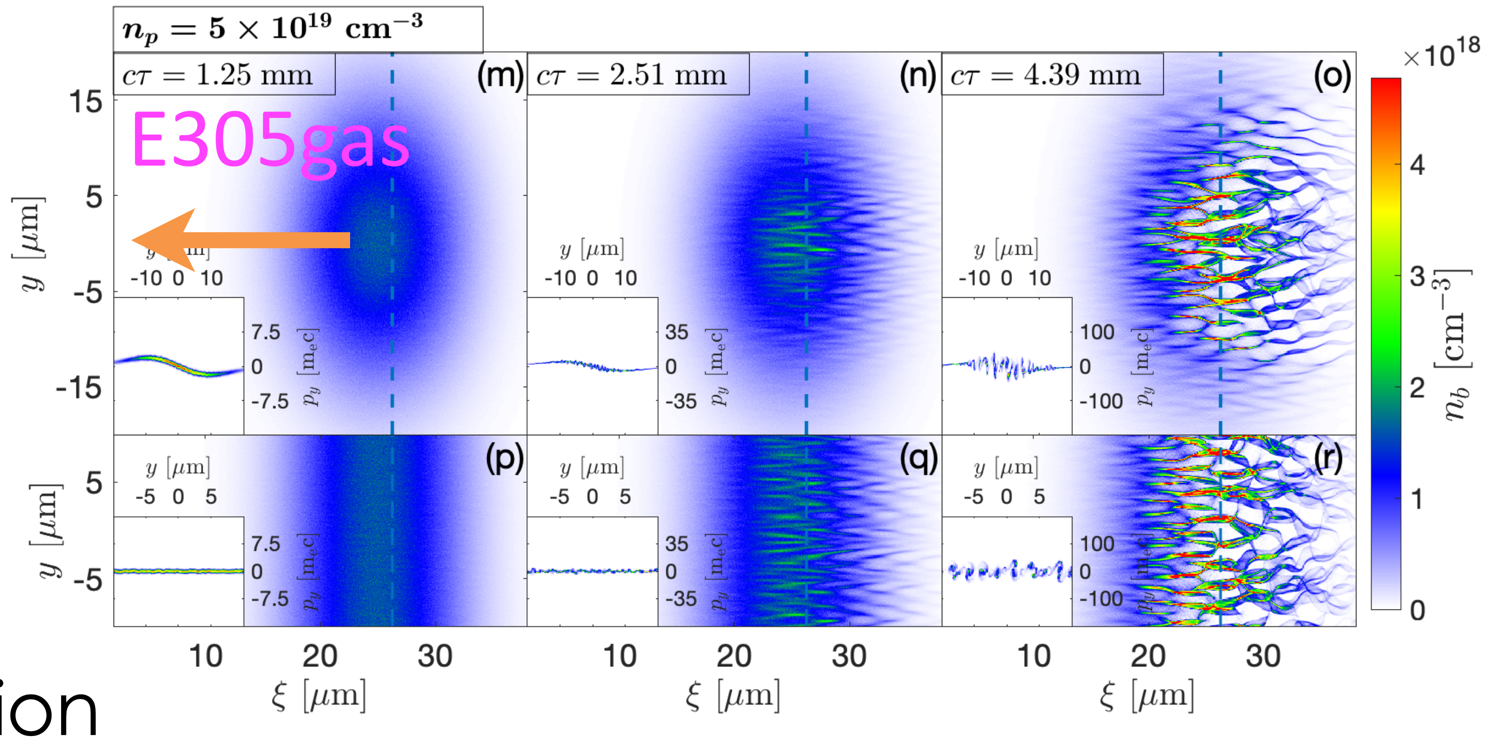
Motivations for filamentation physics and bright gamma rays

Relativistic streaming instabilities are pervasive in astrophysics



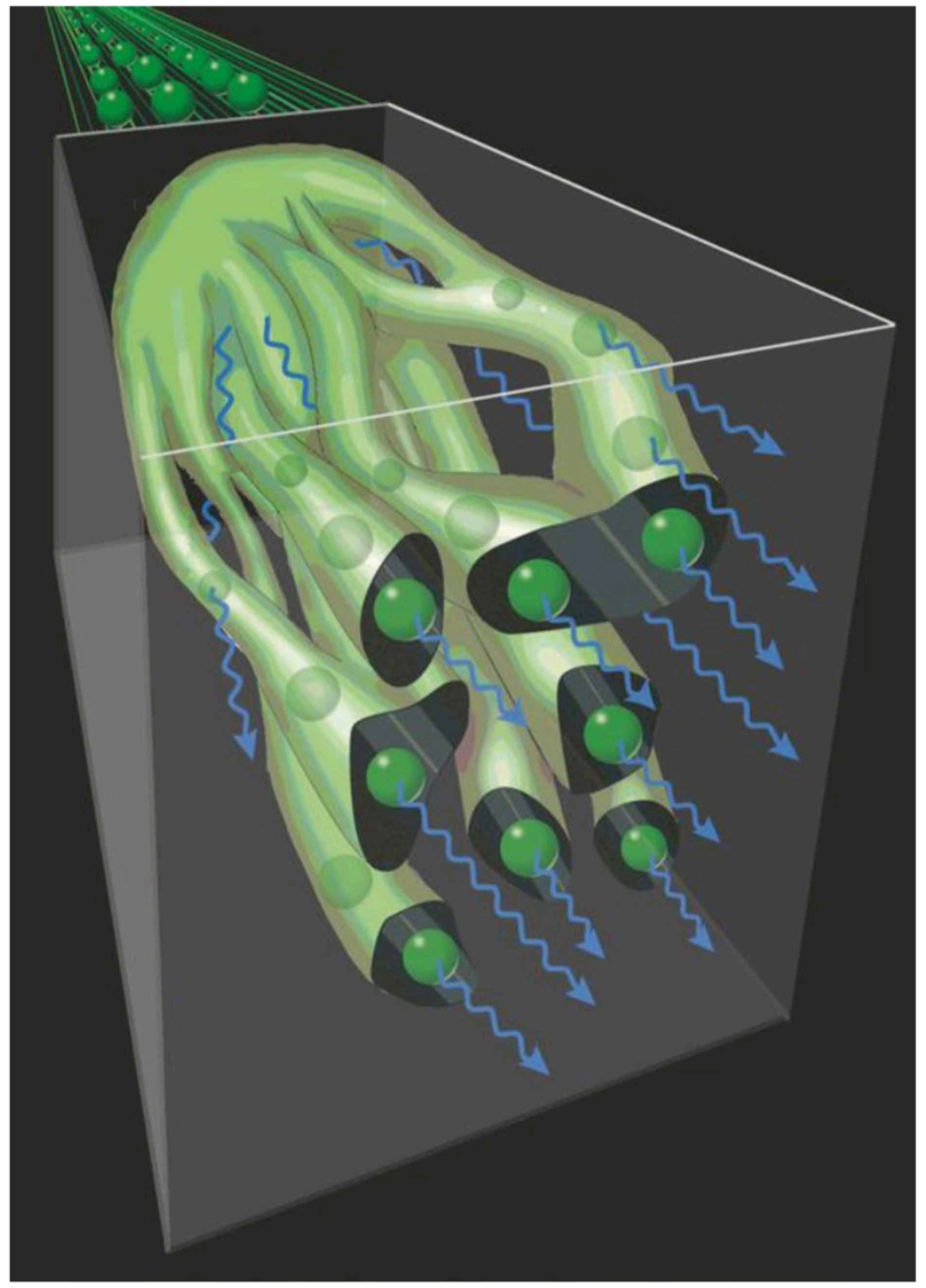
T. Katsouleas, role of Weibel instability in astrophysics and cosmic jets





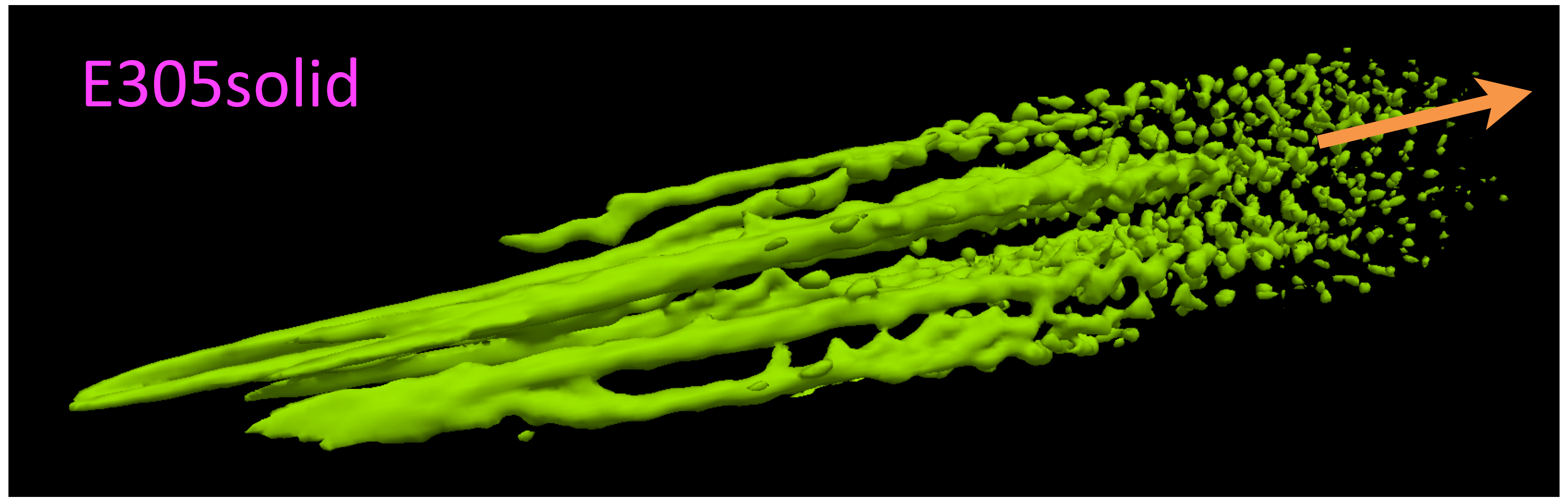
Current filamentation instability and oblique instabilities are believed to:

- mediate slow down of energetic flows (e.g. in GRBs and blazars)
- mediate shock formation and cosmic-ray acceleration
- determine radiation signatures of energetic environments



Nature Photon. 12, 314 (2018), Nature Photon. 12, 319 (2018)

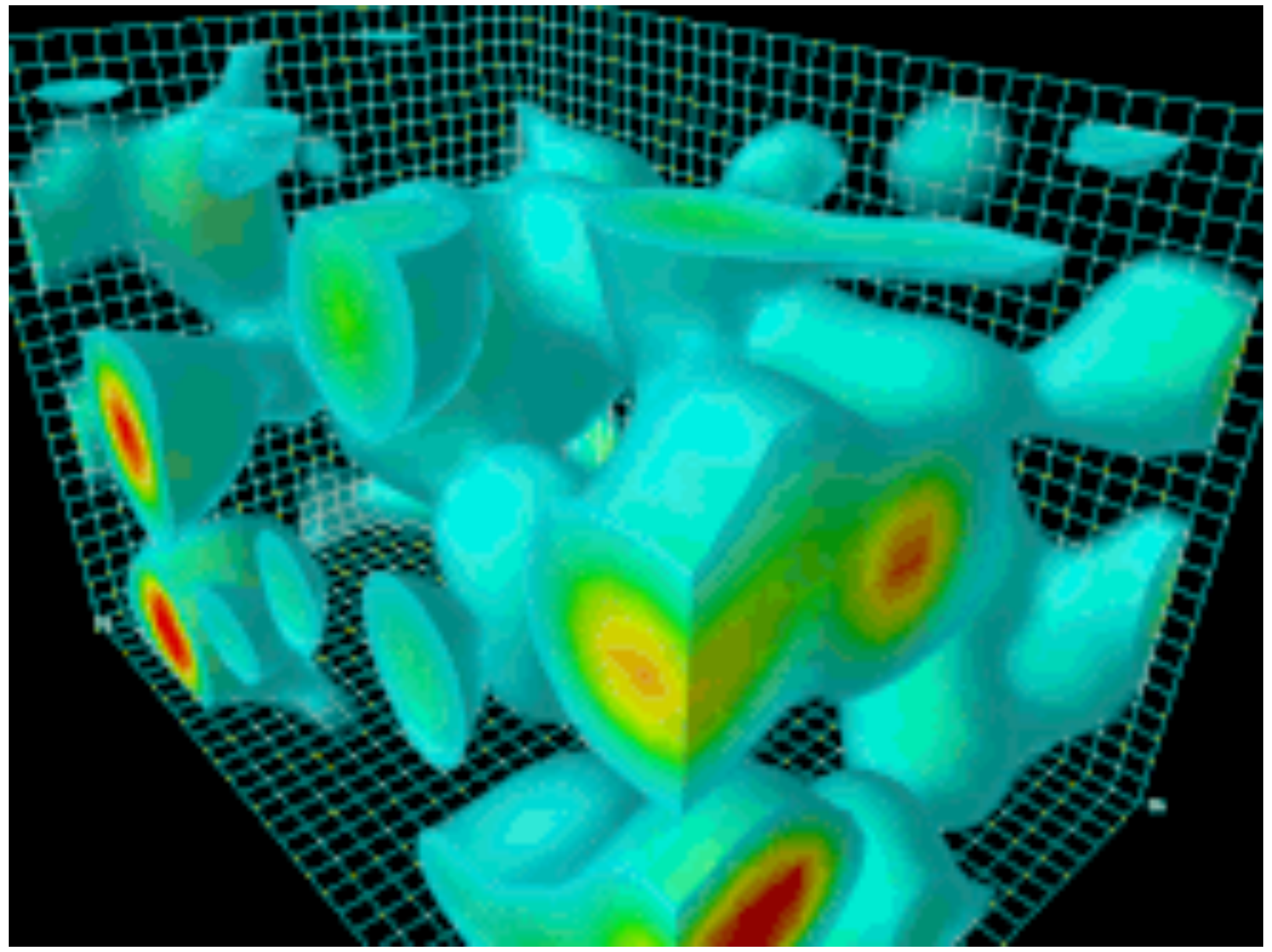
- in solids, it has implications for ultrafast condensed matter physics
- in addition to its fundamental importance for astrophysics, it provides a mechanism for energy conversion from particles to EM fields, and to gamma-ray radiation: measurements of gamma rays provide a signature of beam-plasma instabilities
- gamma-ray source with applications to defence, industry, medicine, scientific research



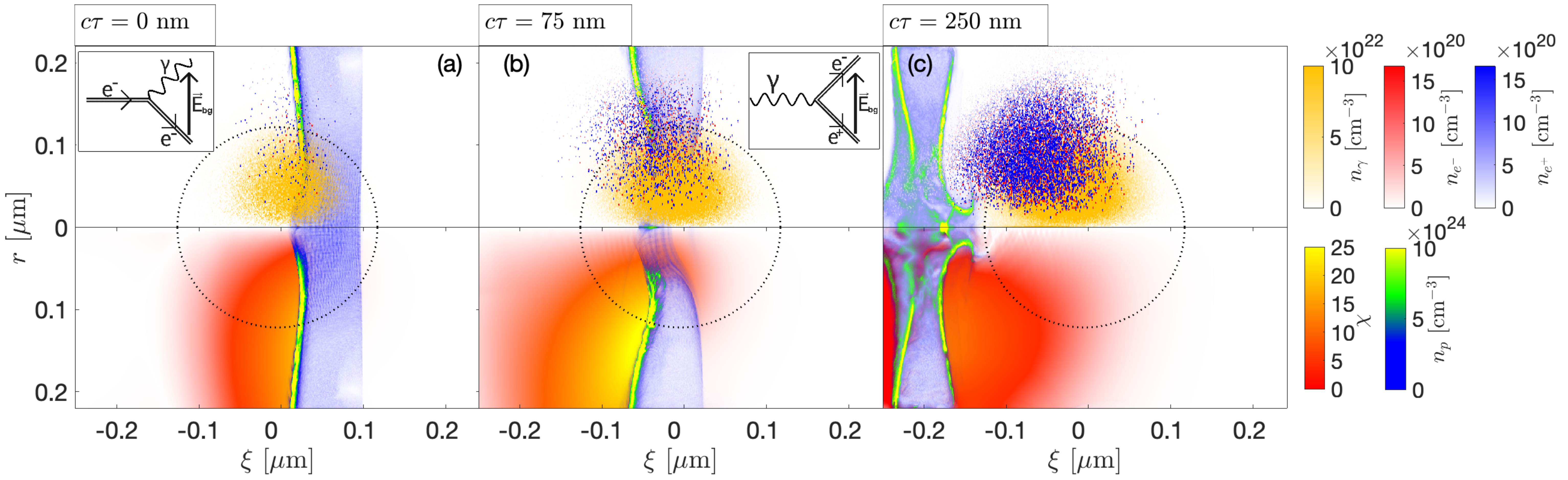
Motivations for solid-density e^-/γ beams and laserless SFQED

Dense gamma-ray beams open new opportunities for materials science, nuclear photonics, photo-fission, quark-gluon plasma, investigation of nuclear excited states, laboratory astrophysics, probing the quantum vacuum and photon-photon physics ($\gamma+\gamma \rightarrow \gamma+\gamma$, $\gamma+\gamma \rightarrow e^- + e^+$, $\gamma+\gamma \rightarrow X+\bar{X}$)

Solid-density electron beams open new opportunities in nonlinear material studies such as investigations of the relativistic plasma electron response at the surface and in the bulk, plasma channeling and generation of plasma wakefields in solid-density plasmas, probing SFQED without lasers in electron beam-solid-density plasma (quantum parameter $\chi = \gamma E/E_{cr} > 1$)



https://en.wikipedia.org/wiki/Quantum_fluctuation

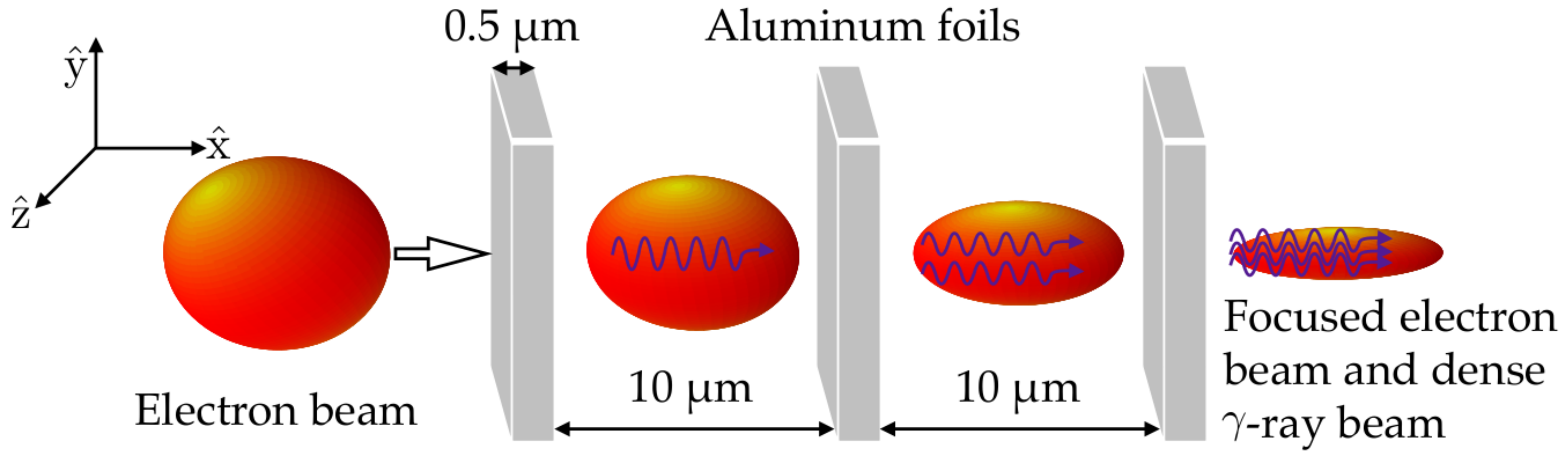


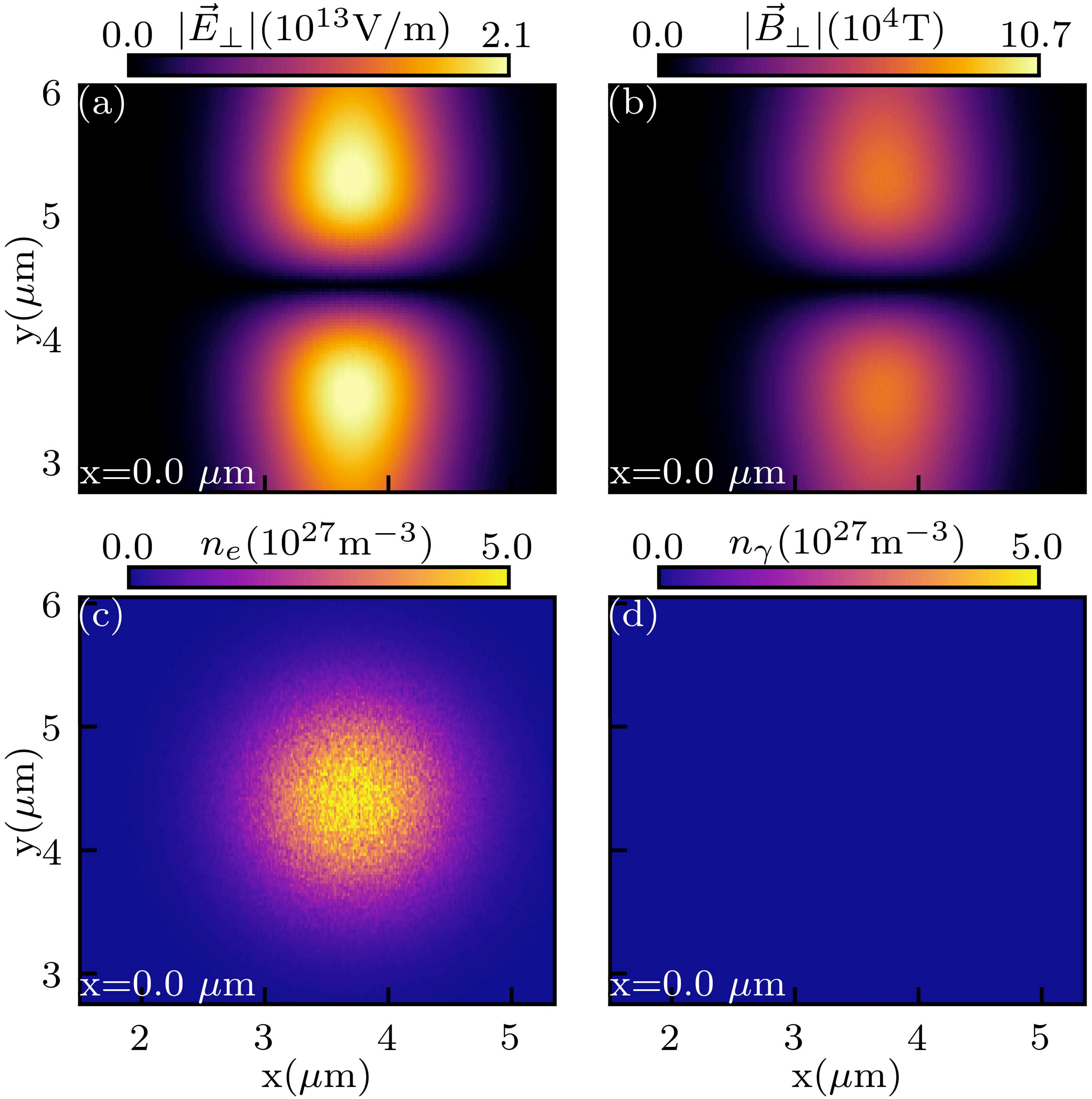
CALDER 3D PIC simulation (Aimé Matheron)

e- beam-gold foil collision with $n_b = 0.7 n_p$

A. Matheron et al., Communications Physics 6, 141 (2023)

E332 concept: near-field CTR





Smilei 3D PIC simulation, 2 nC beam, Gaussian spatial and momentum distribution with $\sigma_\parallel = \sigma_\perp = 0.55\ \mu m$, 10 GeV mean energy, 212 MeV FWHM energy spread, 3 mm-mrad normalized emittance.

The beam collides with 20 consecutive aluminum foils with 0.5 μm thickness, and 10 μm interfoil distance.

Physics included in the simulation:
initial self-consistent beam fields, field and collisional ionization, binary Coulomb collisions, synchrotron and bremsstrahlung emission, multiphoton Breit-Wheeler and Bethe-Heitler pair production.

A. Sampath et al., Phys. Rev. Lett. 126, 064801 (2021)

E305 & 332 progress

E305 progress

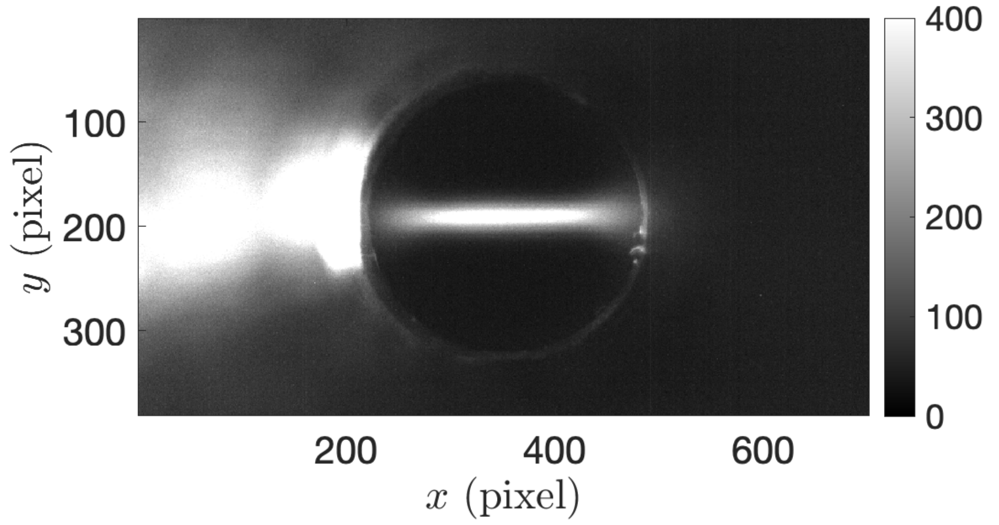
- Commissioning of gas jet operation with He and H_2 and of PB pumping:
  - Numerous tests performed to evaluate the residual background pressure for different gas jet opening time, repetition rate, backing pressure and type of gas
  - Successfully operated gas jet at 5 Hz for backing pressure up to 200 psi
  - At high backing pressure of up to 1200 psi, gas jet operation limited to 1 Hz (with beam at 10 Hz); required DAQ development and tests
  - 5-mm round nozzle and 2-cm slit nozzle tested successfully

He Pressures in Torr in Picnic basket, US4 and DS2

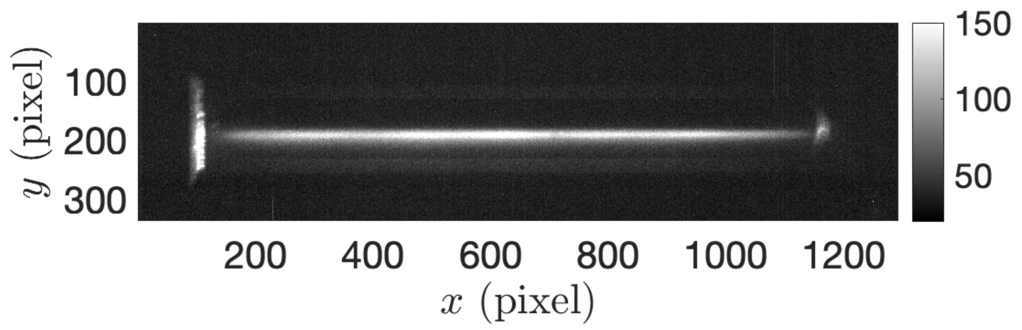
- 1ms width

Gas pressure		0.2 Hz	0.5 Hz	1 Hz	5 Hz	10 Hz
30 psi	TM					4.2e-5
	PB					under
	US4					2.1e-10
	DS2					3.7e-9
60 psi	TM					8e-5
	PB					2.3e-4
	US4					2.1e-10
	DS2					4.2e-9
100 psi	TM	4e-6	9e-6	2e-5	8e-5	1.7e-4
	PB	under	under	under	3e-4	2e-3
	US4	2.1e-10	2.1e-10	2.1e-10	2.1e-10	2.1e-10
	DS2	3.7e-9	3.6e-9	3.9e-9	4.4e-9	9.3e-9
200 psi	TM	6e-6	1.5e-5	2.8e-5	1.3e-4	3.e-4
	PB	under	under	under	1e-3	8.6e-3
	US4	2.1e-10	2.1e-10	2.1e-10	2.1e-10	2.2e-10
	DS2	4e-9	4e-9	4.3e-9	8.3e-8	1.7e-8
400 psi	TM	1.3e-5	3e-5	4.7e-5	2.9e-4	6.8e-3
	PB	under	under	under	6.5e-3	3.8e2
	US4	2.1e-10	2.1e-10	2.1e-10	2.2e-10	2.3e-10
	DS2	4e-9	4e-9	4e-9	1.4e-8	3e-8
800 psi	TM	2e-5	4e-5	8.3e-5	2e-3	1e-2
	PB	under	under	5e-4	2.2e-2	6e-2
	US4	2.1e-10	2.1e-10	2.1e-10	2.2e-10	2.3e-10
	DS2	4.5e-9	4.7e-9	5e-9	2e-8	4e-8
1200 psi	TM	3e-5	6.5e-5	1.3e-4	9e-3	6e-2
	PB	2e-3?	?	2e-3	6e-2	over
	US4	2.1e-10	2.1e-10	2.1e-10	2.3e-10	2.6e-10
	DS2	4e-9	4e-9	8e-9	4e-8	9e-7

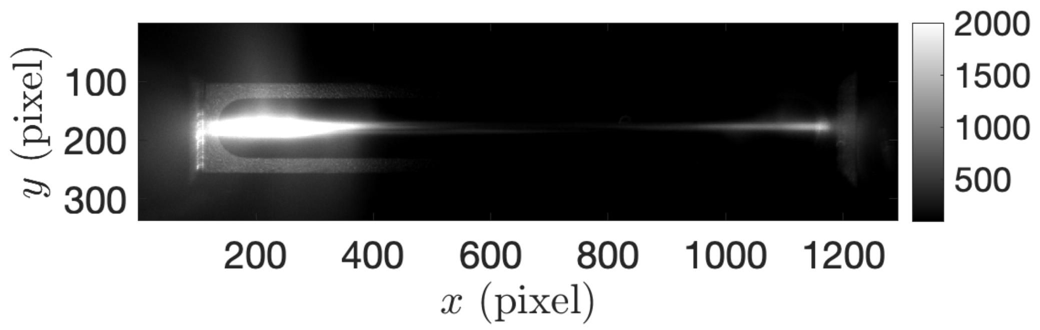
- Laser ionization:
  - Specific focusing optics for E305: diffractive axilens with 1-cm line focus for monochromatic light, stretched to 3-4 cm line focus by chromatic focusing with the real FACET-II laser
  - Successfully generated plasma in 5-mm nozzle, and in 2-cm slit nozzle up to 200 psi
  - Need to understand what's limiting the plasma length at higher backing pressure



5-mm nozzle, H_2 at 110 psi



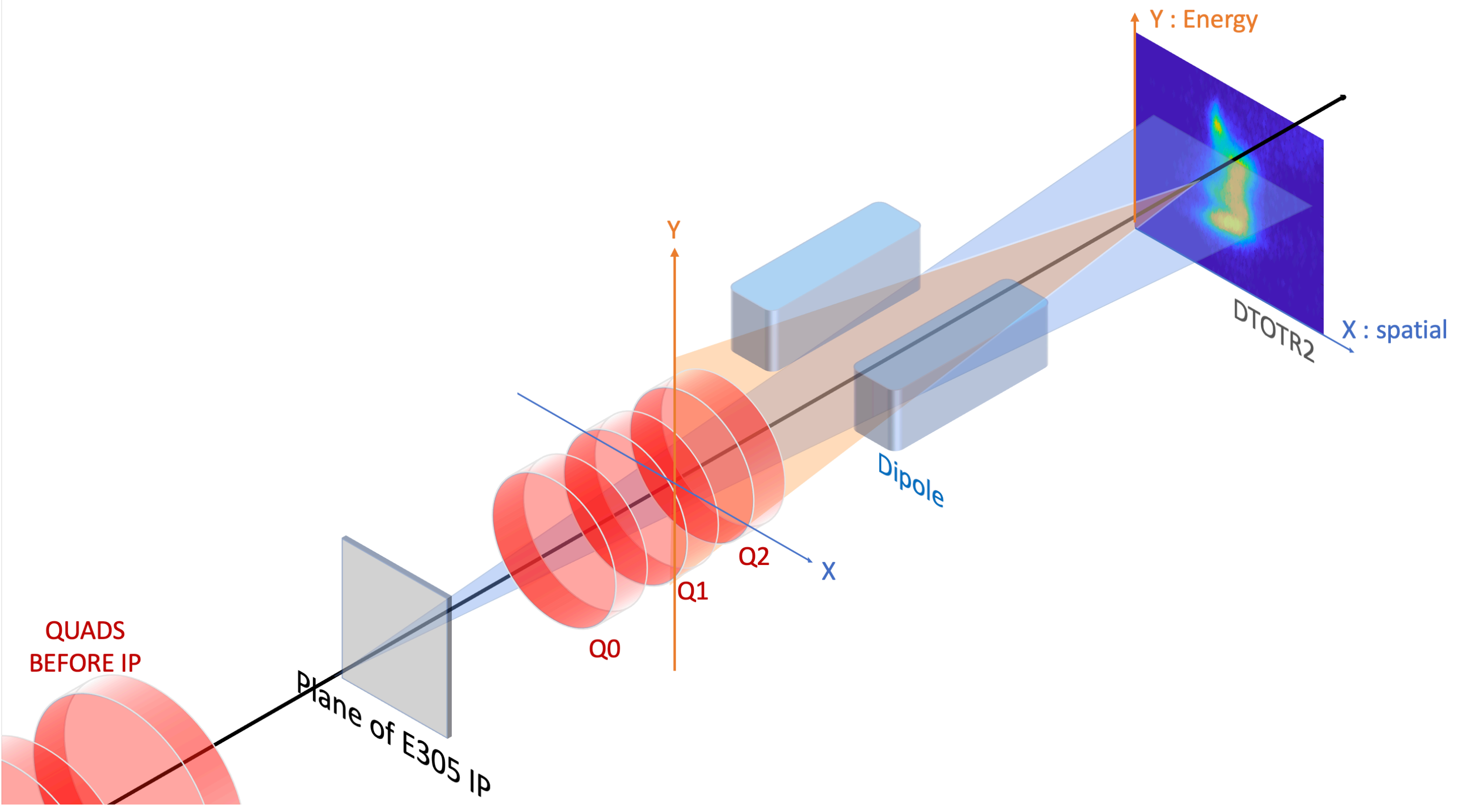
2-cm nozzle, H_2 at 150 psi



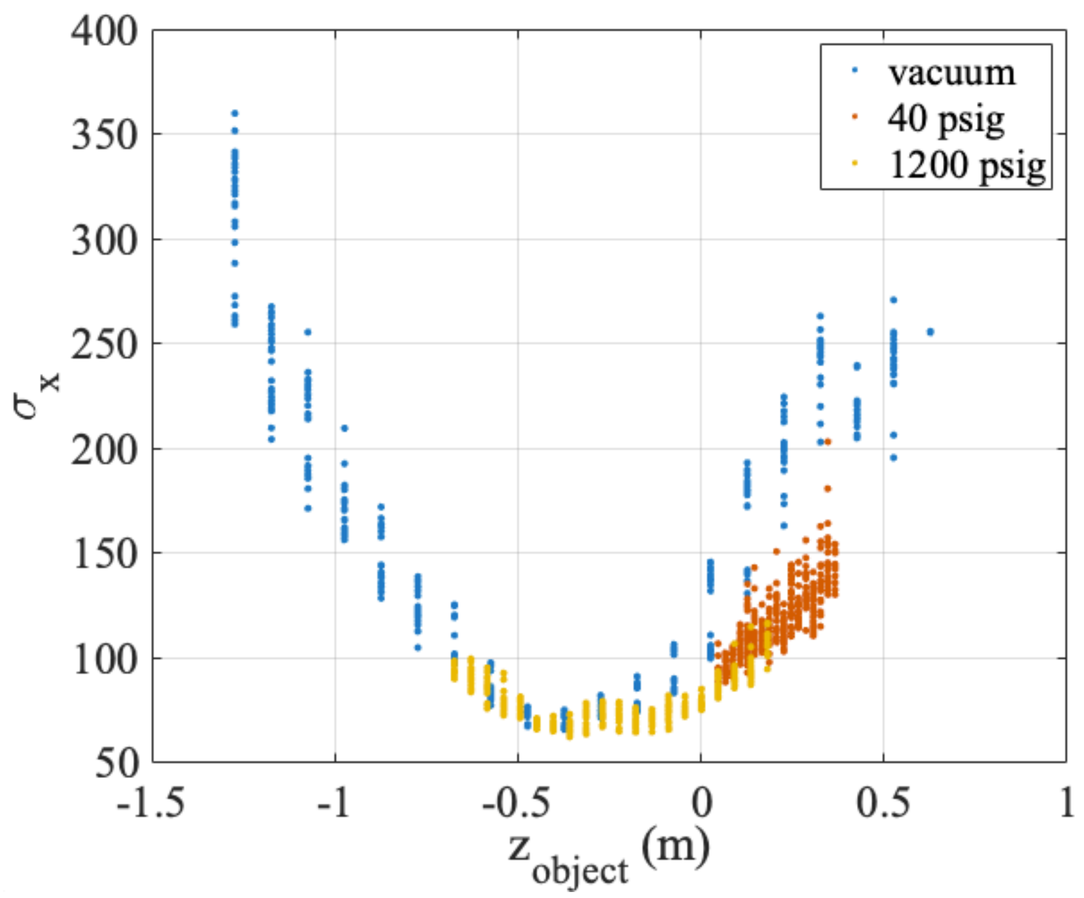
2-cm nozzle, H_2 at 614 psi

E305 progress

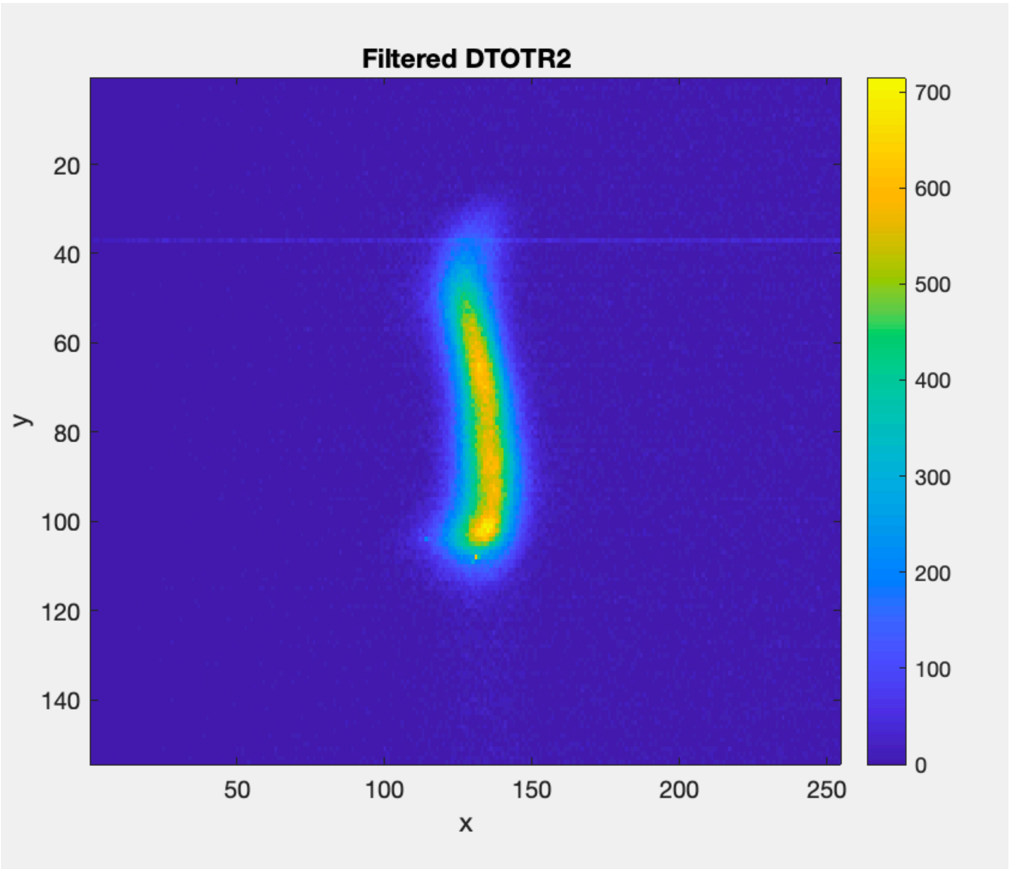
- Electron and gamma diagnostics:
  - Instead of using a profile monitor downstream of IP for a measurement of the beam angular profile (compromised by coherent OTR light), we rely on DTOTR electron spectrometer at the dump table:



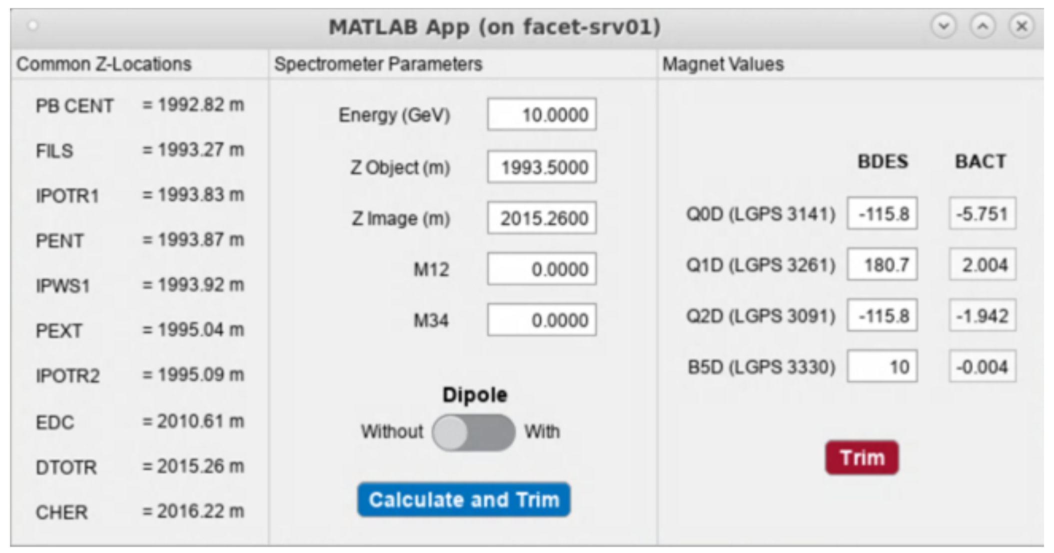
Large M_{12} and M_{34} = 0 to measure horizontal momentum p_x



Object plane scan

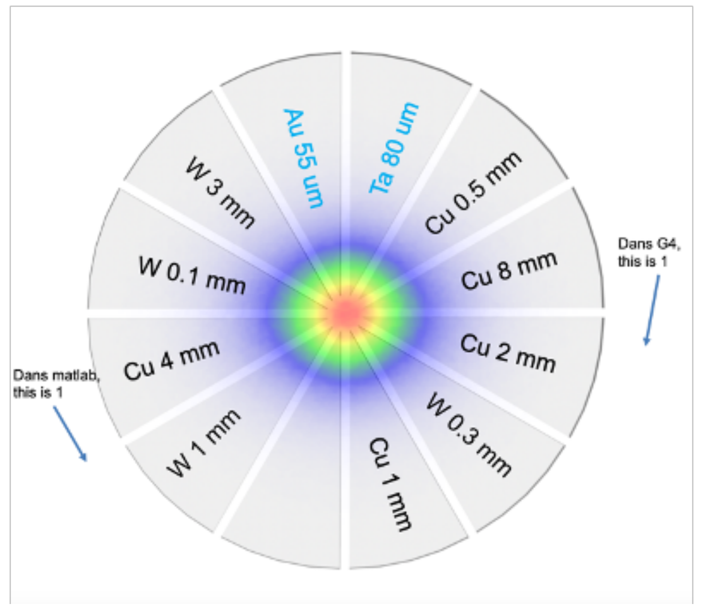


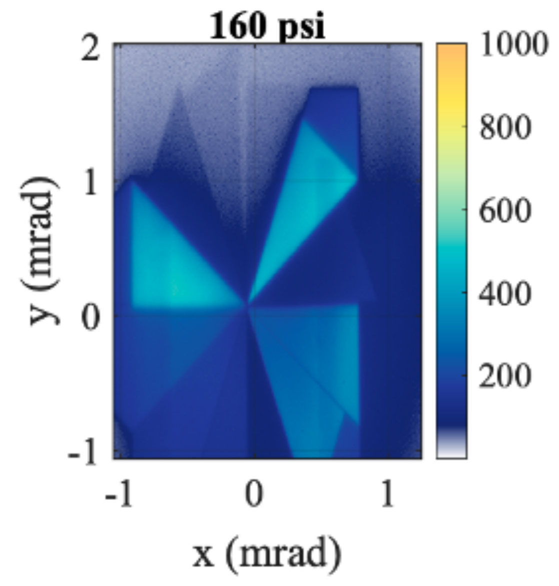
M_{12} = M_{34} = 0 for best energy measurement

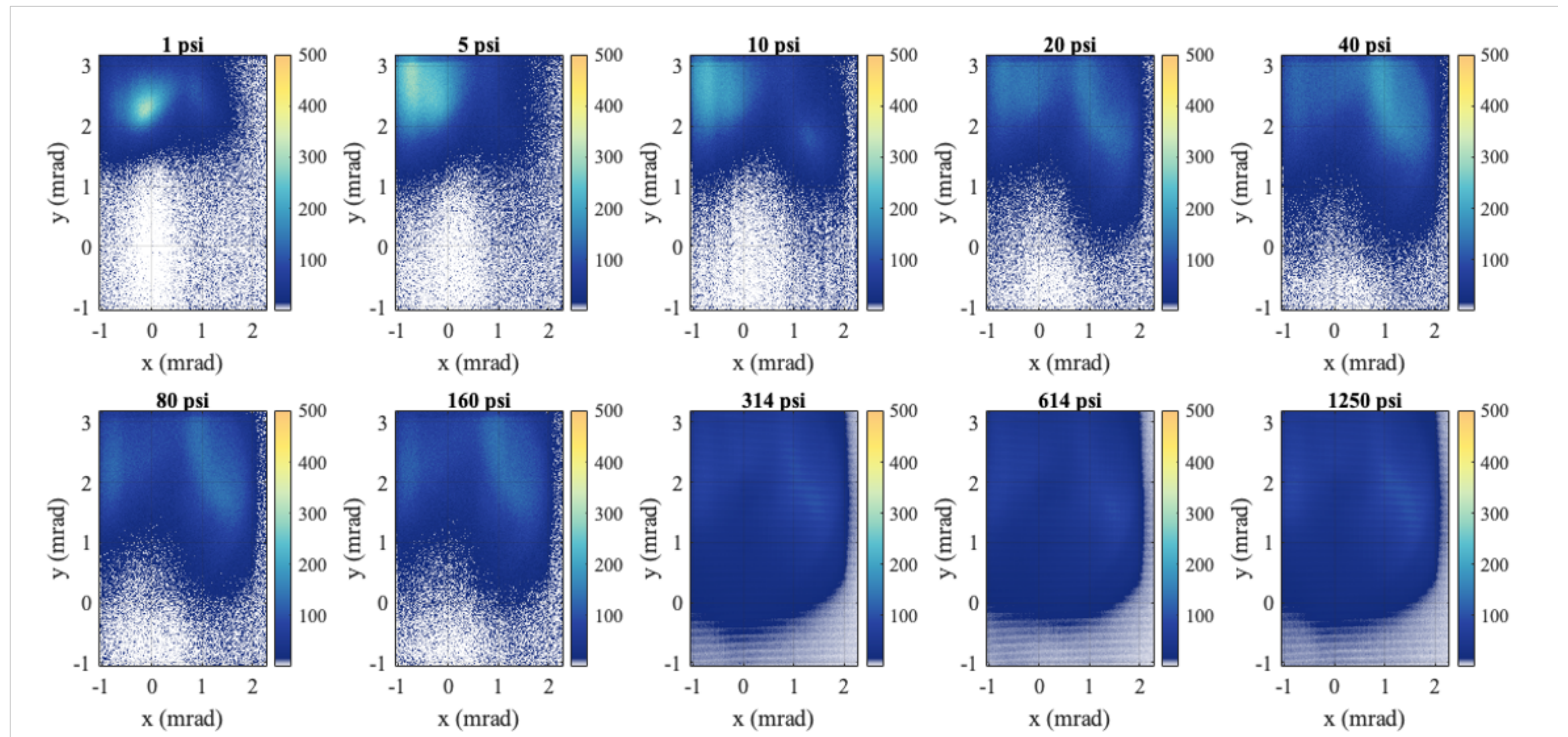


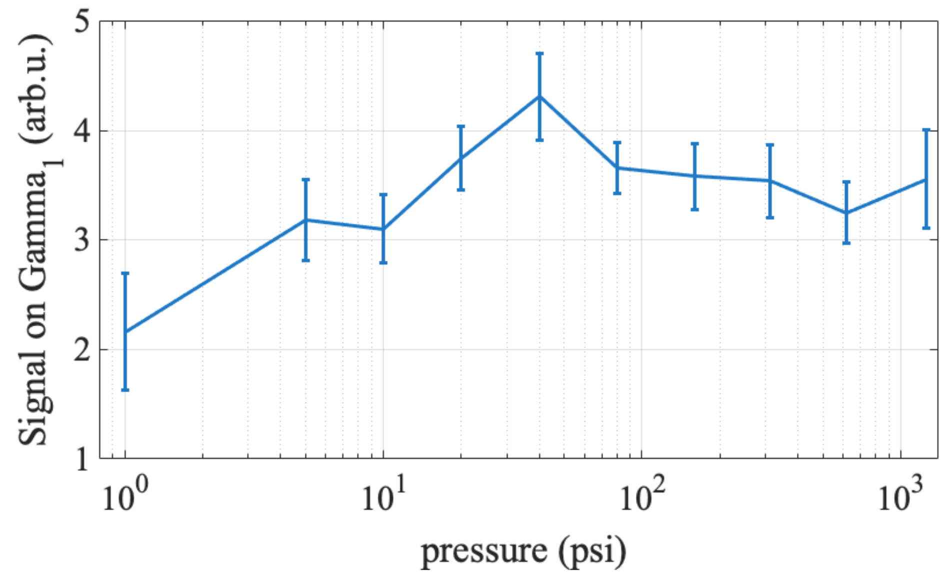
GUI +
DAQ functions

  - Gamma screens commissioned for E305





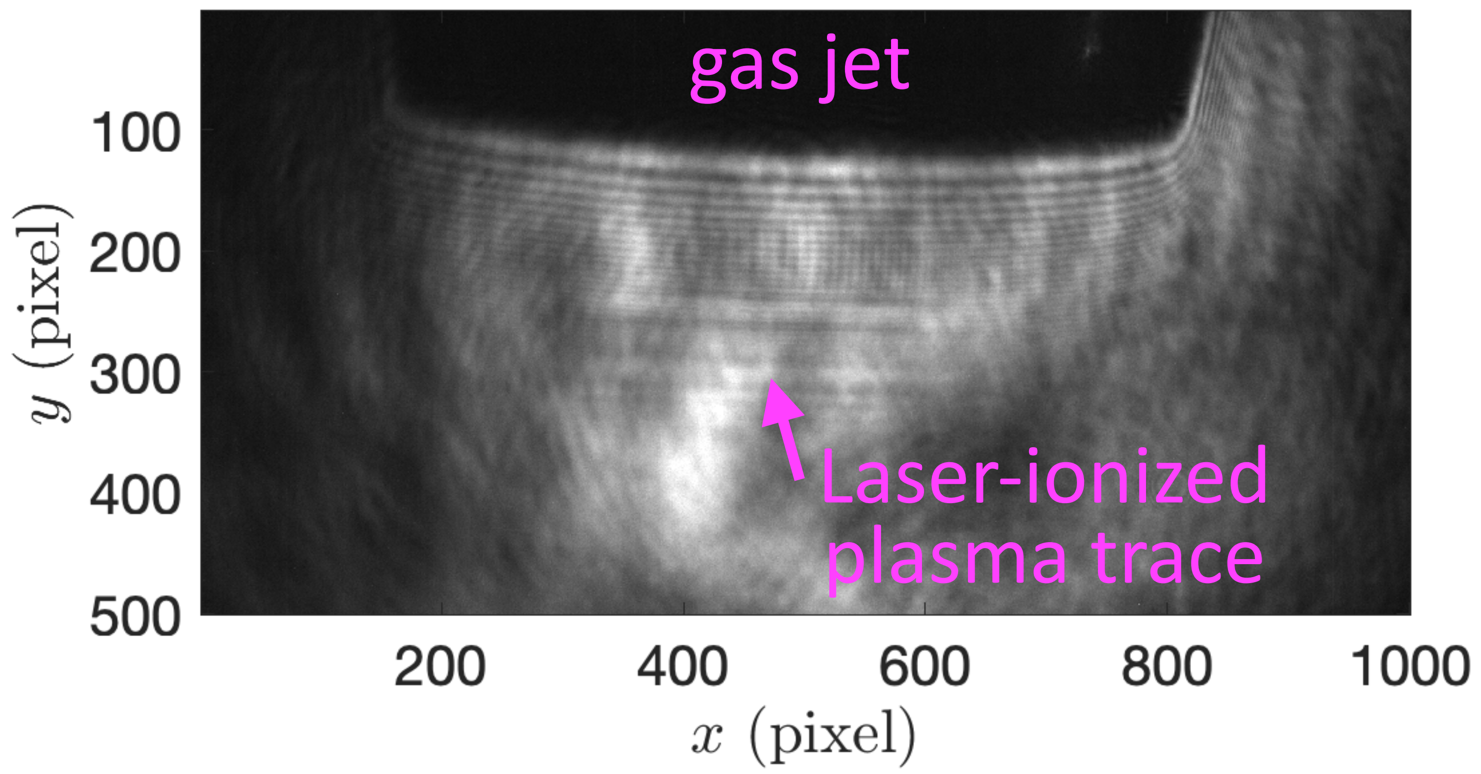




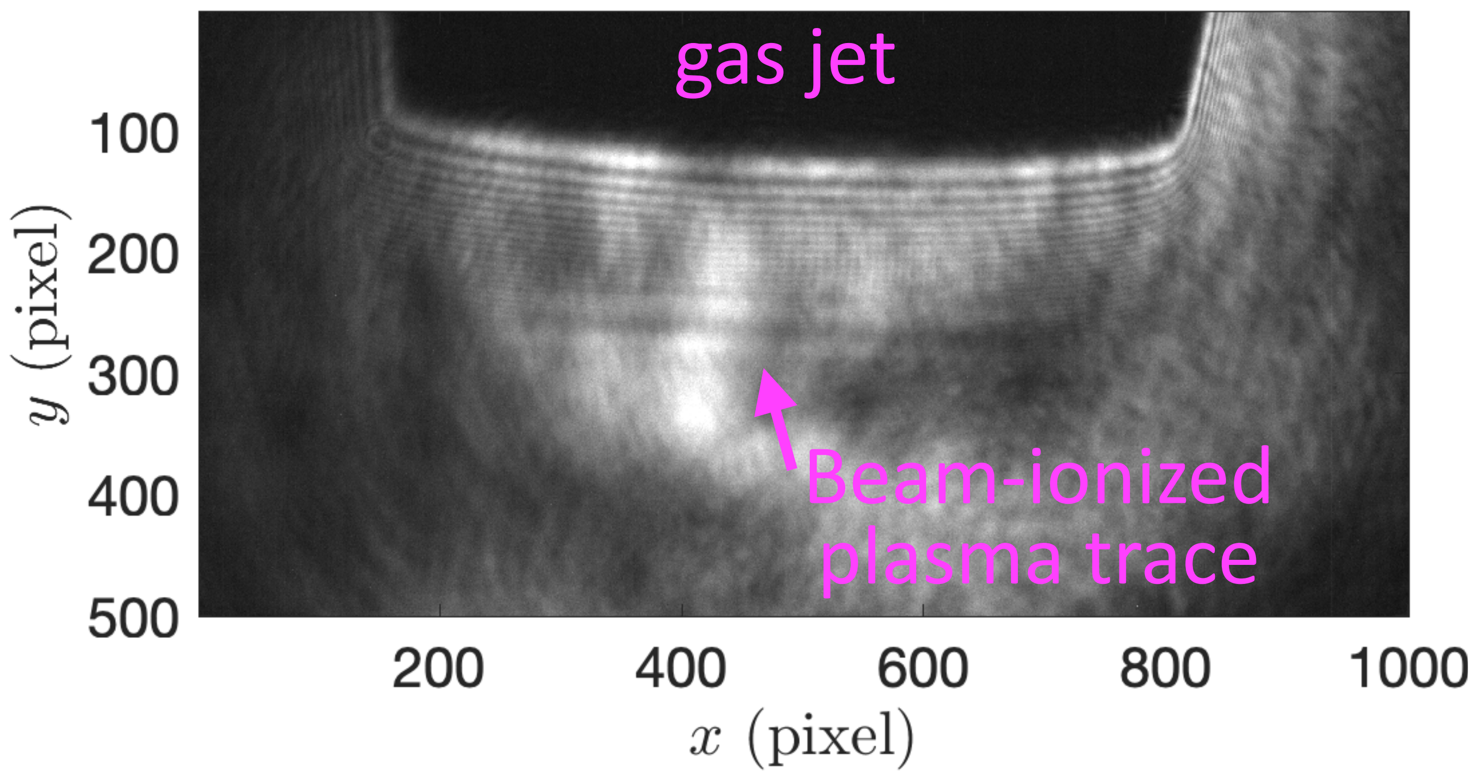
E305 progress

- Shadowgraphy:
  - Low resolution fully commissioned:

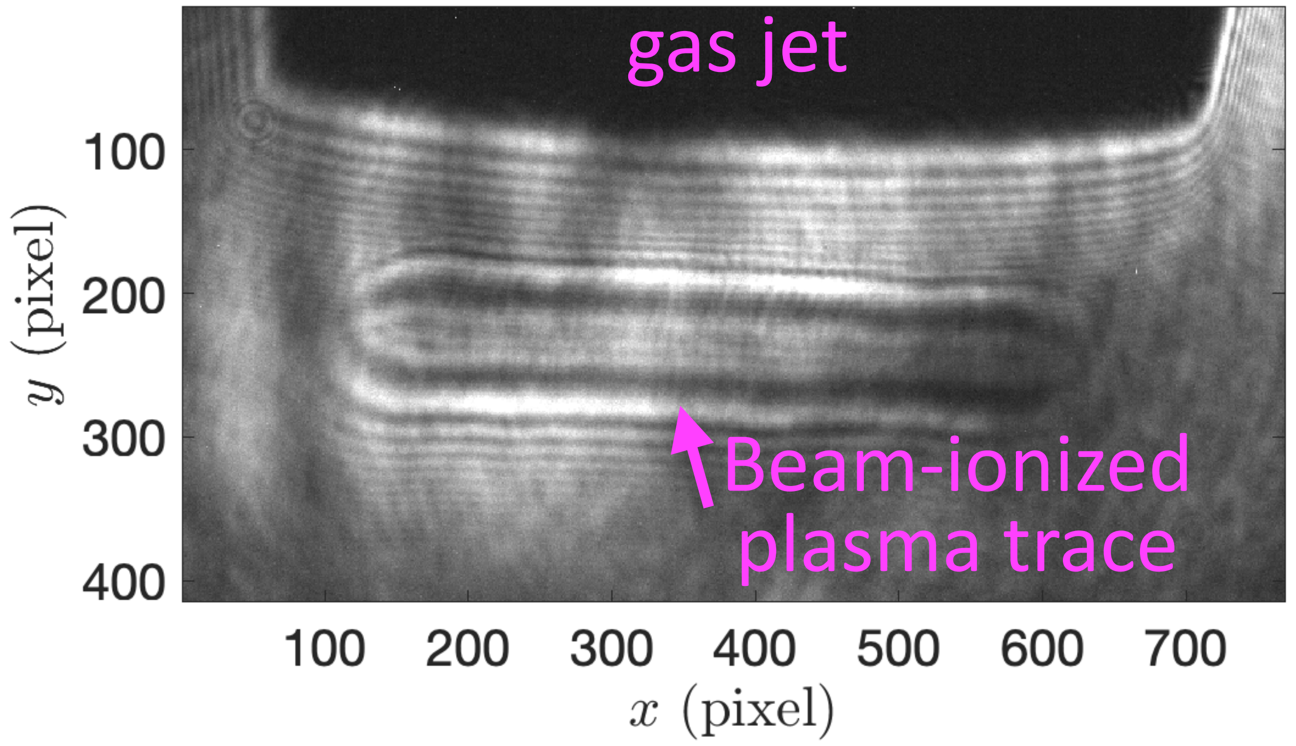
Conditions:
H_2, 110 psi



Conditions:
H_2, 1010 psi and 1 Hz

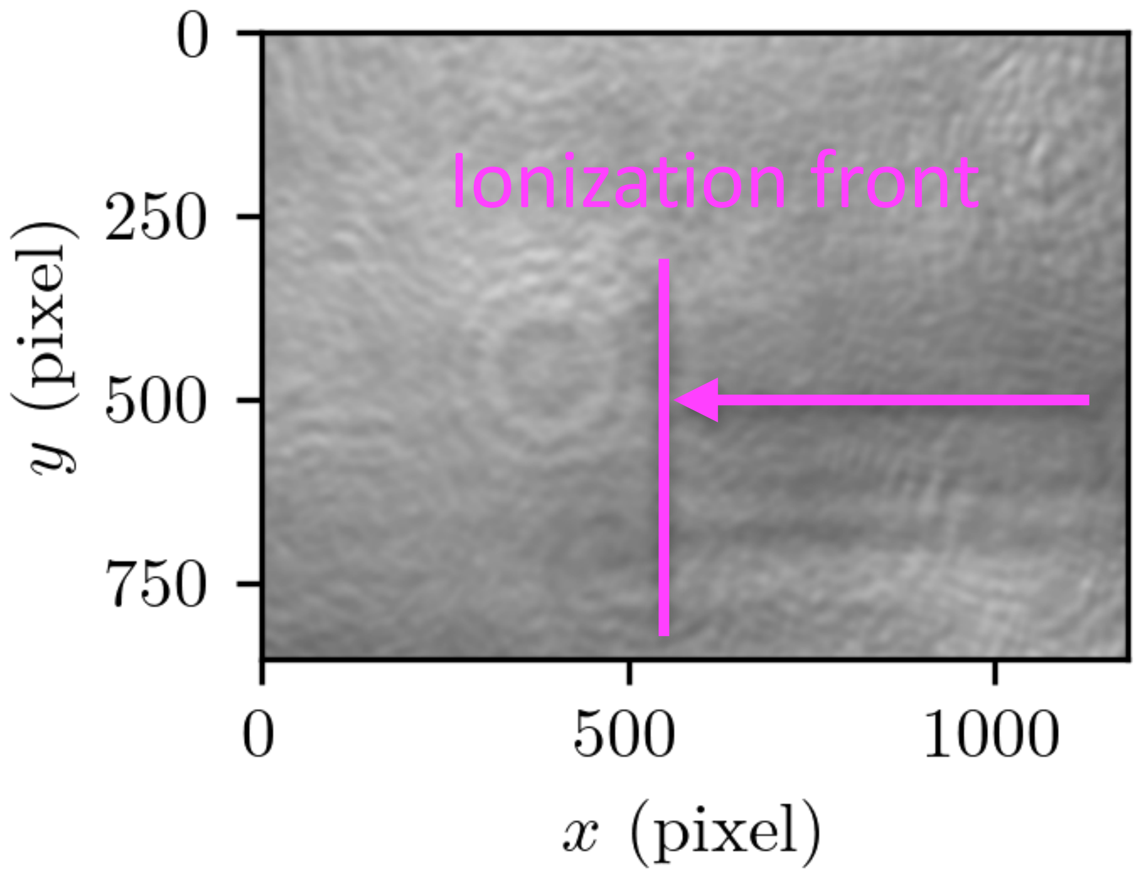


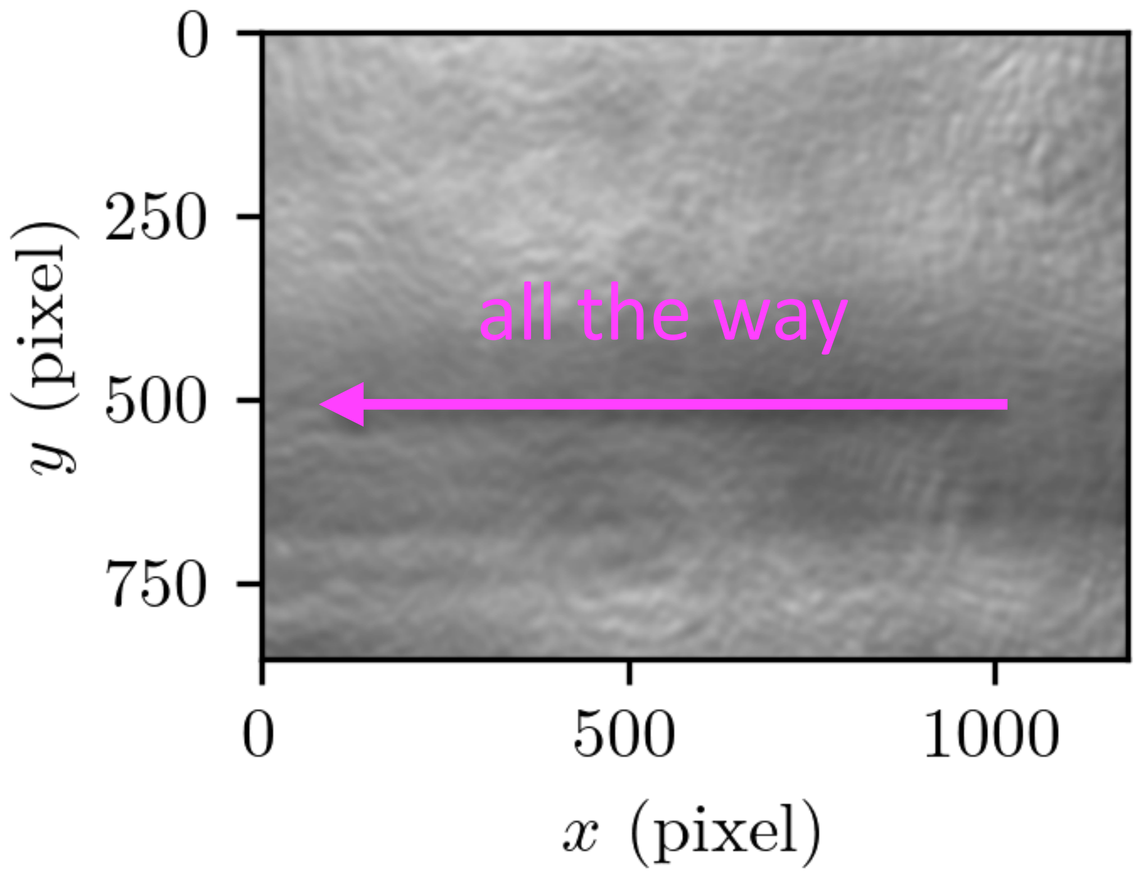
Conditions:
H_2, 1010 psi and 5 Hz



—> residual background pressure in PB (~0.1 Torr)
—> self-focused electron beam entering the gas jet

  - First tests of high resolution, with microscope objective inserted and with laser ionization front identified:

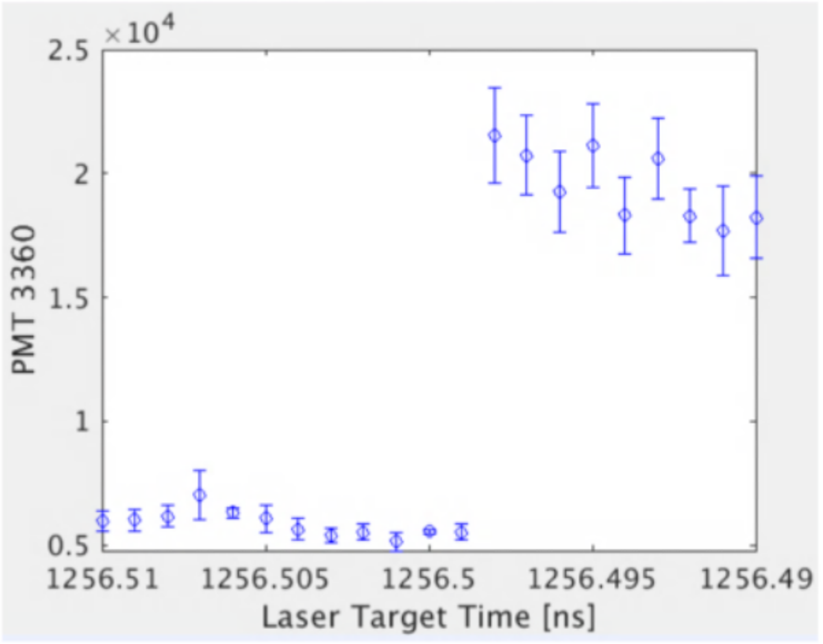


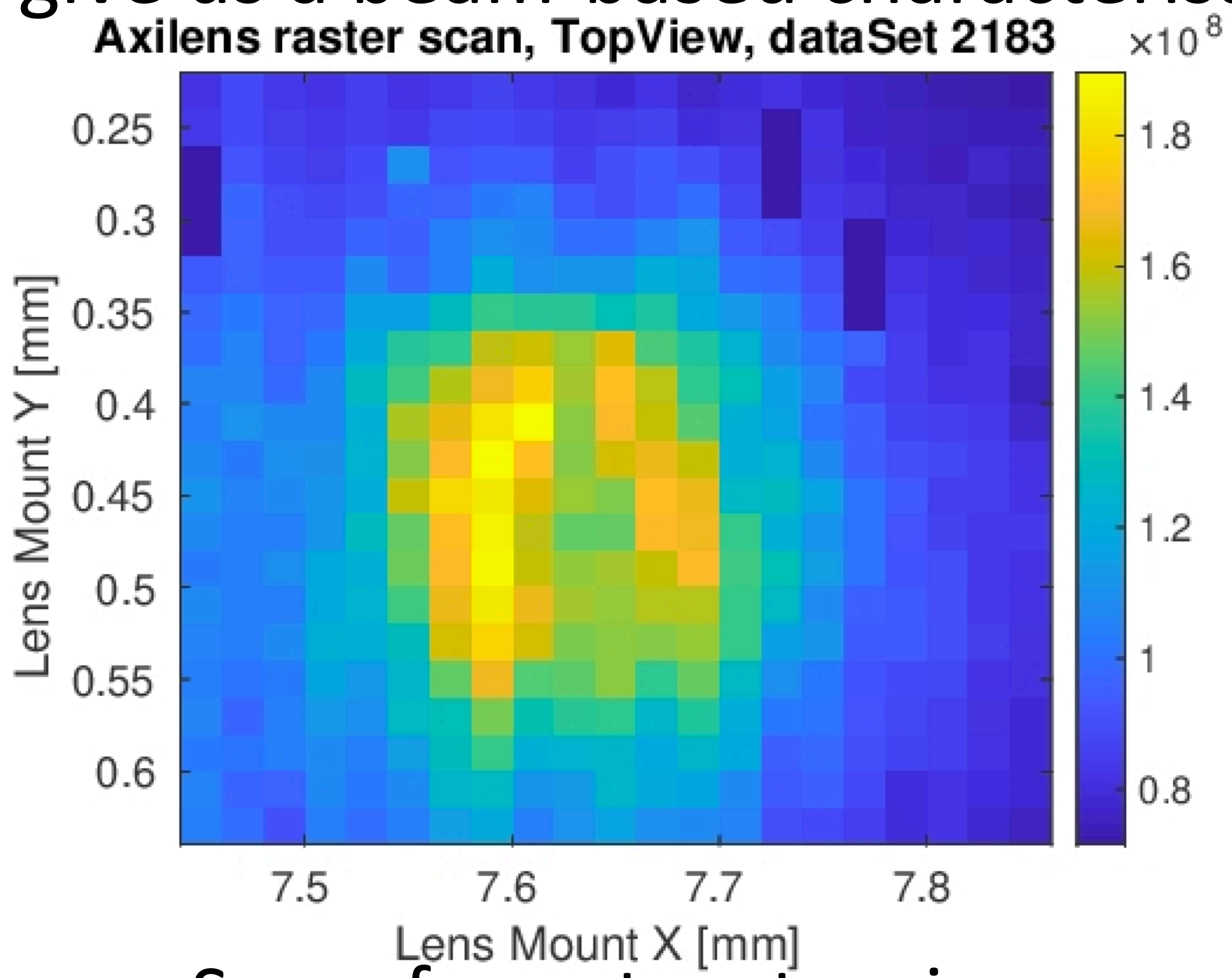


Conditions:
H_2, 500 psi

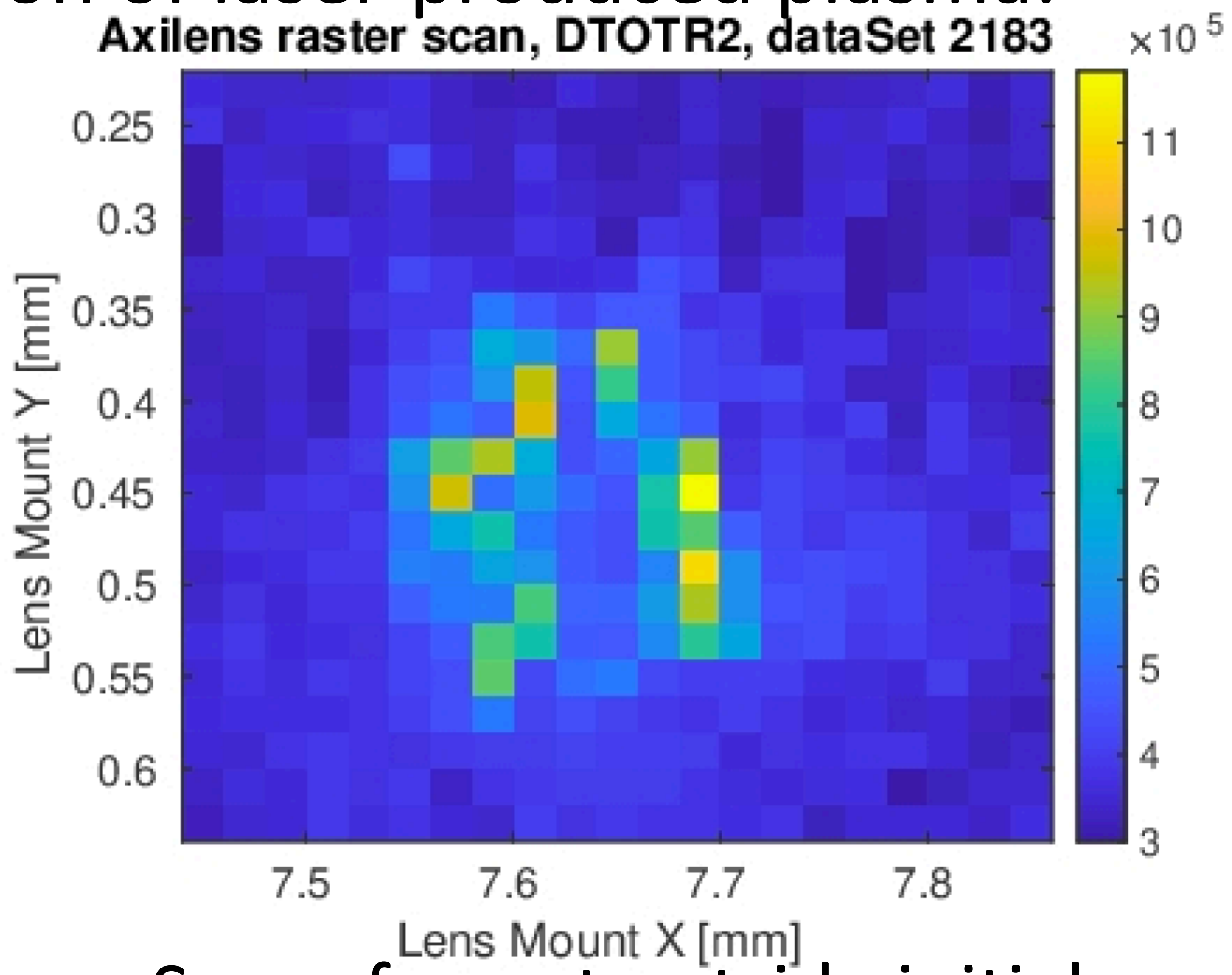
E305 progress

- Laser-ebeam overlap and beam-based characterisation of laser-produced plasma:
  - Timing: clear transition identified on most diags (shadowgraphy can be used for very high accuracy)
  - Approximate spatial overlap done on front view
  - More precise spatial overlap can be achieved from plasma traces on topview and shadow
  - Afterglow signal was found to be very powerful to quickly fine tune the laser-ebeam overlap
  - Laser raster scans give us a beam-based characterisation of laser-produced plasma:





Sum of count on topview Afterglow signal

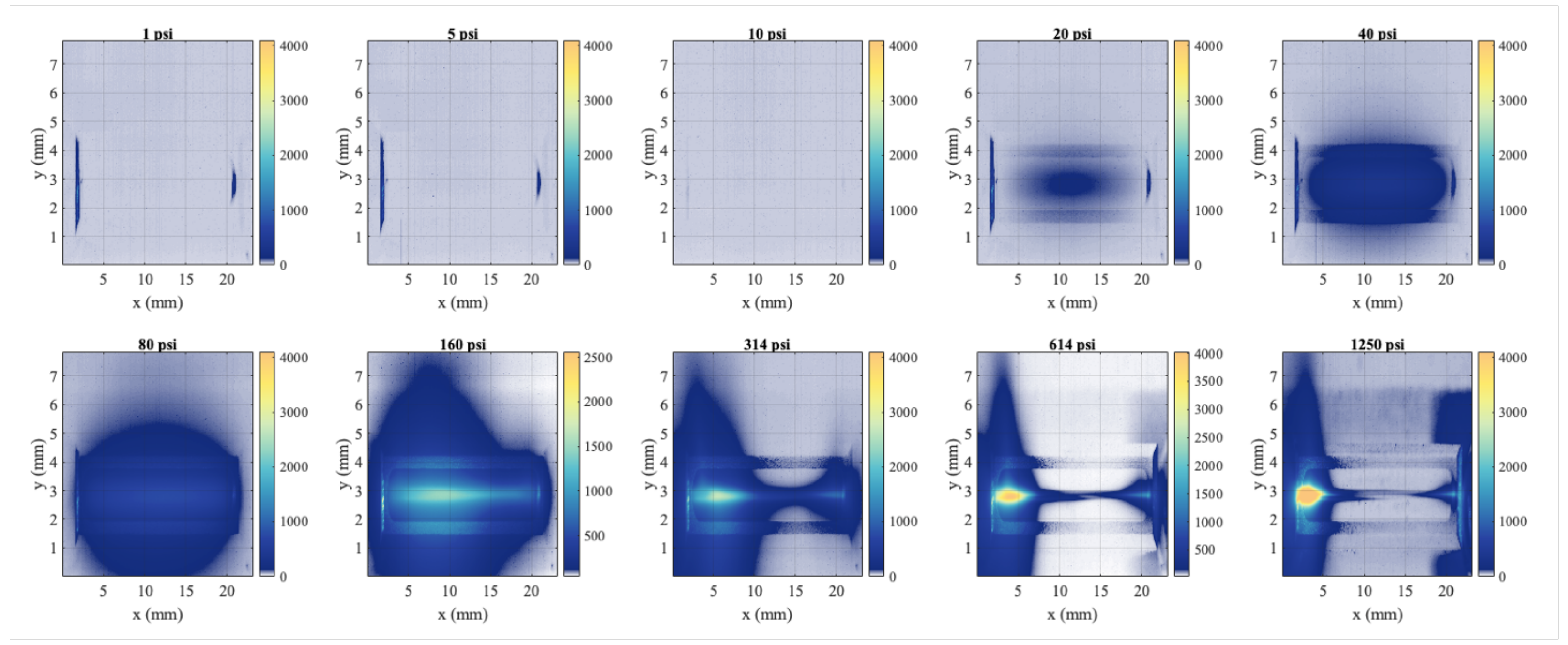


Sum of count outside initial beam location on DTOTR2

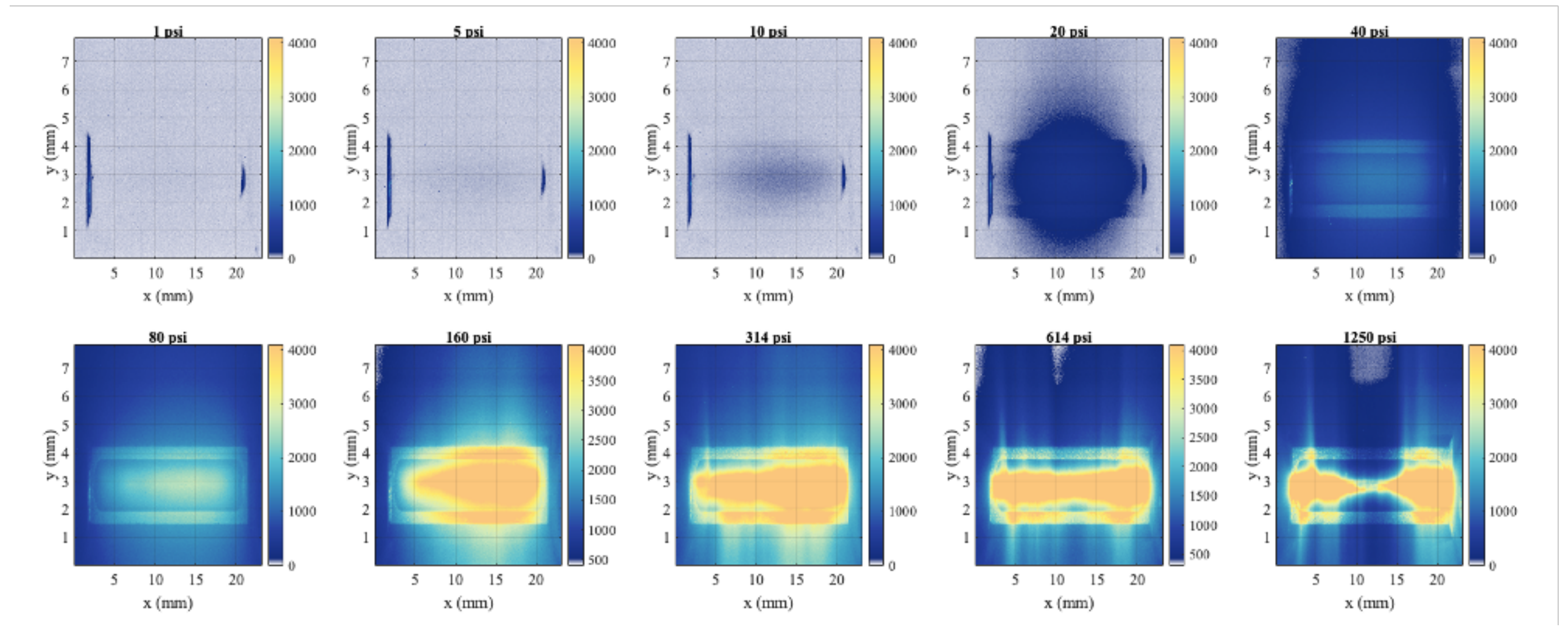
E305 progress

- First beam-plasma interactions in 2-cm H_2 gas jet:
  - Expected from simulations: spanning regimes going from plasma lensing, PWFA, to beam filamentation when the pressure is increased from 1 to 1000 psi.
  - Experimental observations: complex outcome that can be understood by a beam larger than the plasma along the horizontal axis, affecting only the central part of the beam.

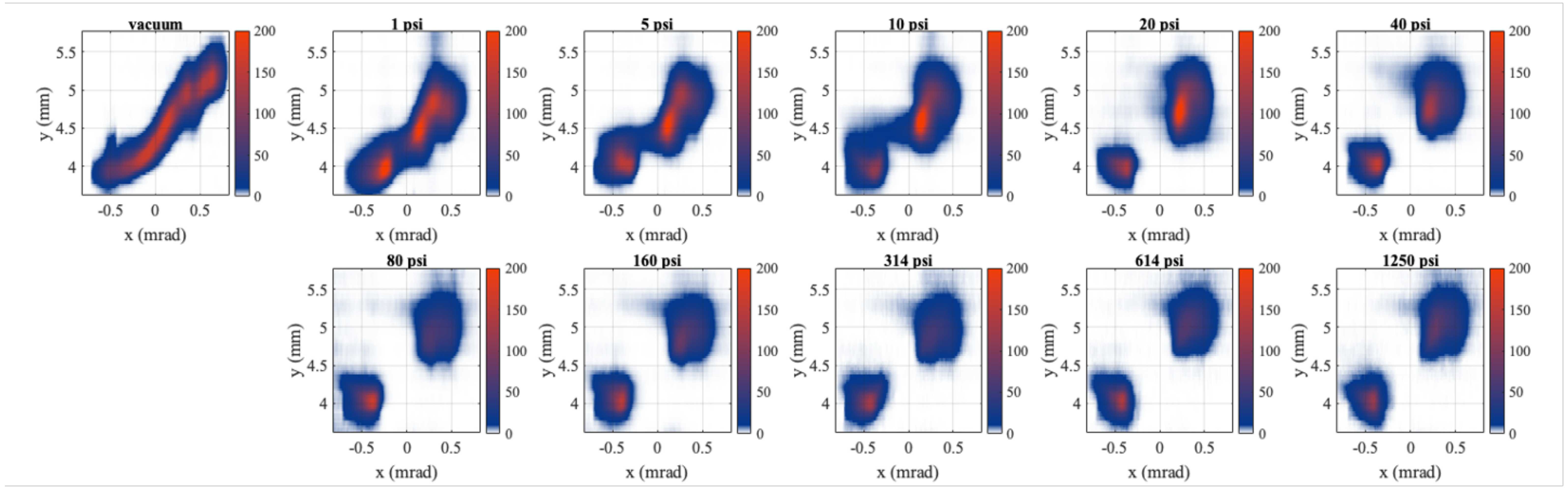
Laser only



Laser + ebeam



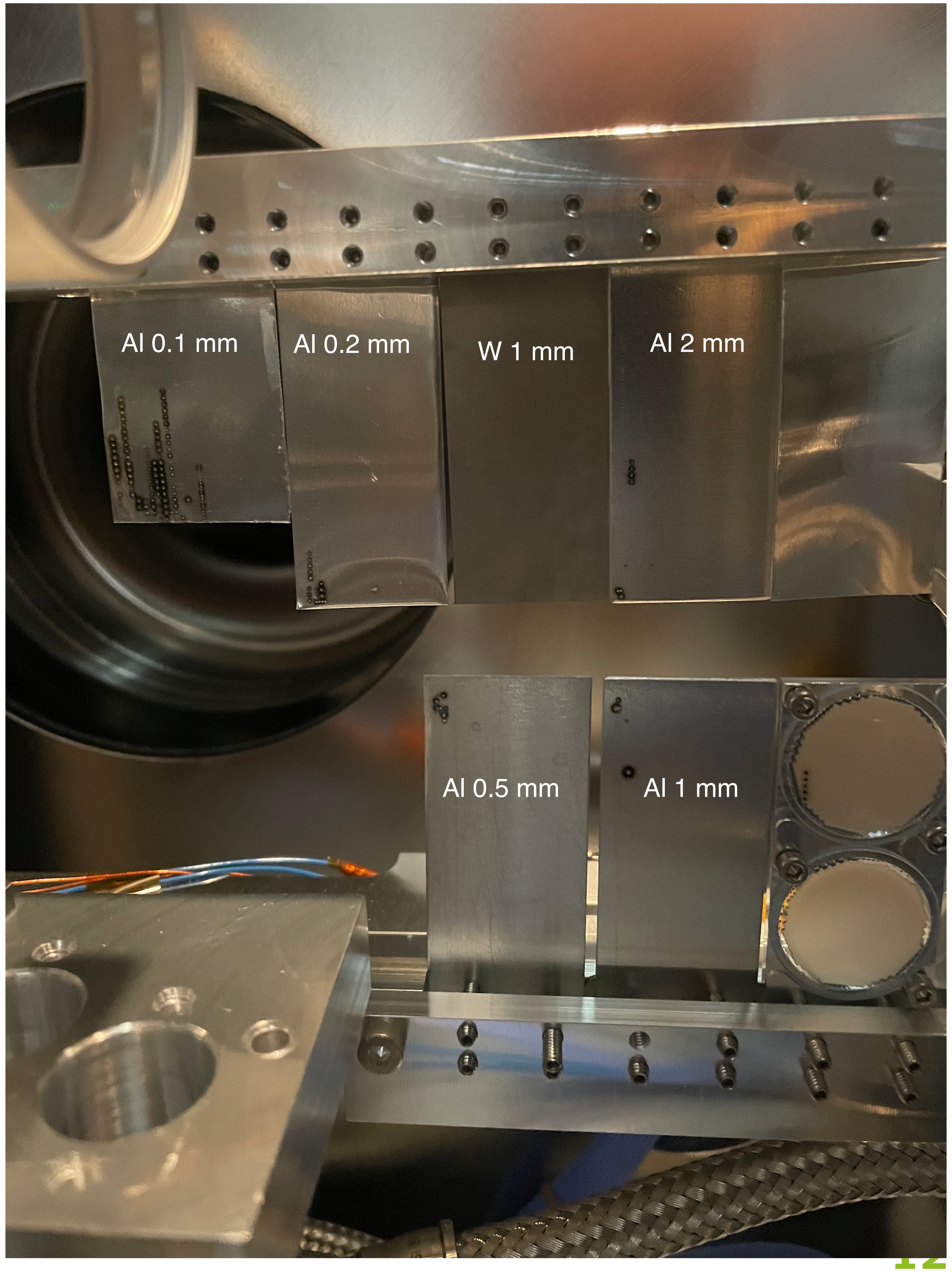
DTOTR2



E332 progress

- May 11 (σ_x = ?? µm , σ_y = ?? µm):
- Operating the machine at 1Hz, DAQ commissioning.
- June 13 (σ_x = ?? µm , σ_y = ?? µm):
- Measuring beam on DTOTR/GAMMA1 cameras with and without Al 0.1 mm.
- Quad-scans performed to assess beam waist position
- July 18 (σ_x = 46 µm , σ_y = 48 µm): First holes
- First evidence of holes being drilled in foils (holes completely drilled in 2 minutes with Al 0.1 mm).
- Data of GAMMA1 signal decreasing with time while shooting at a fixed foil position
- July 25 (σ_x = 47 µm , σ_y = 33 µm):
- We were able to use the new Quad-Scan functions of the DAQ and take comprehensive data.
- Quad-scans of M_{12} performed and very clear data has been taken.
- August 1 (σ_x = 49 µm , σ_y = 39 µm): **Compression optimisation**
- Holes were drilled in the foils and an optimization of bunch compression was made using L2 phase (chirp scan).
- Data of GAMMA1 signal for different foil thicknesses as a function of time.
- August 4 (σ_x = 40 µm , σ_y = 46 µm): **First test of NF-CTR**
- Data was taken for different compressions to search for a NFCTR effect.
- Scans with and without foil were taken.
- August 12 (σ_x = 41 µm , σ_y = 46 µm):
- Object plane scan of the beam interacting with the Al 0.1 mm foil.
- Data taken for different foil thicknesses.
- Compare foil damage for different thicknesses with different repetition rates.
- August 20 (σ_x = 30 µm , σ_y = 51 µm): Small β function
- Scan of β function from 50 cm to 5 cm : beam drilled holes faster at 5 cm.
- Raster scan on the 0.1mm Al foil with β = 5 cm.
- Foil damage analysis by looking at GAMMA cameras for different β

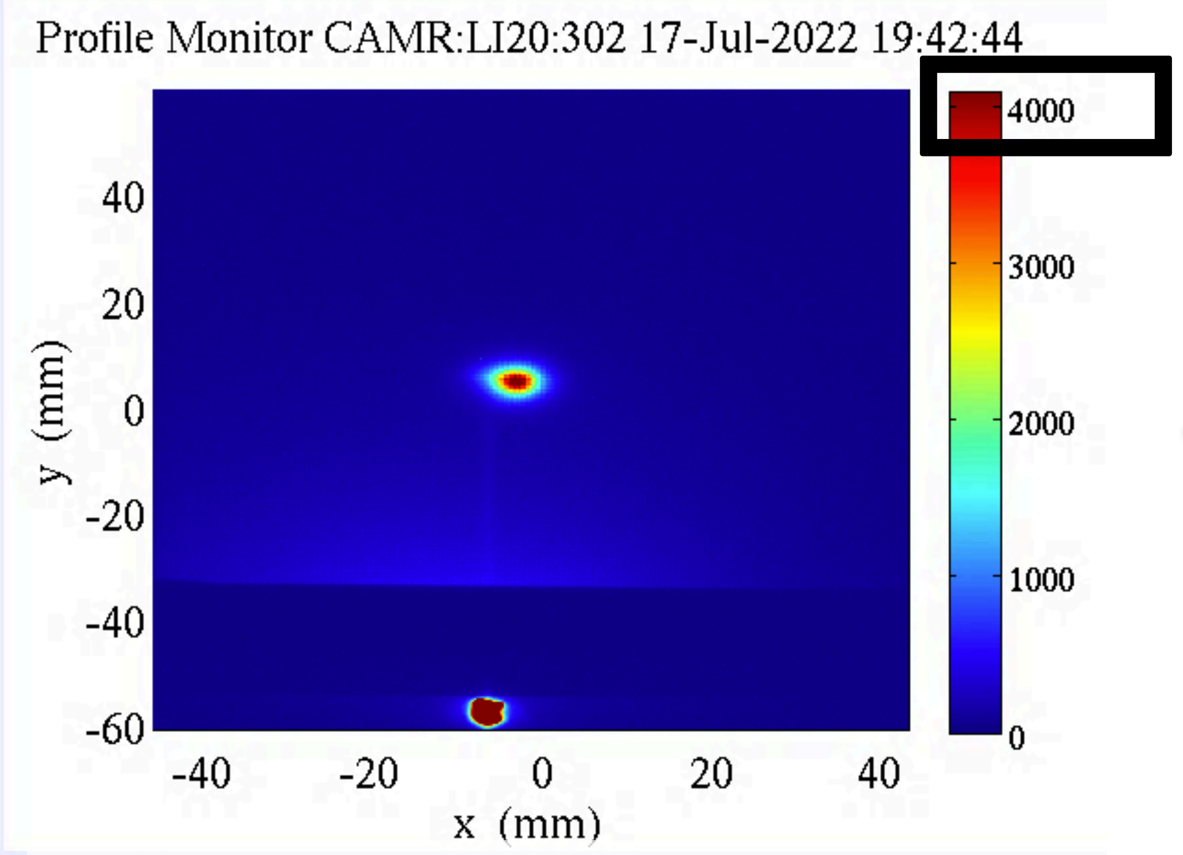
July 18, 2022
First holes!



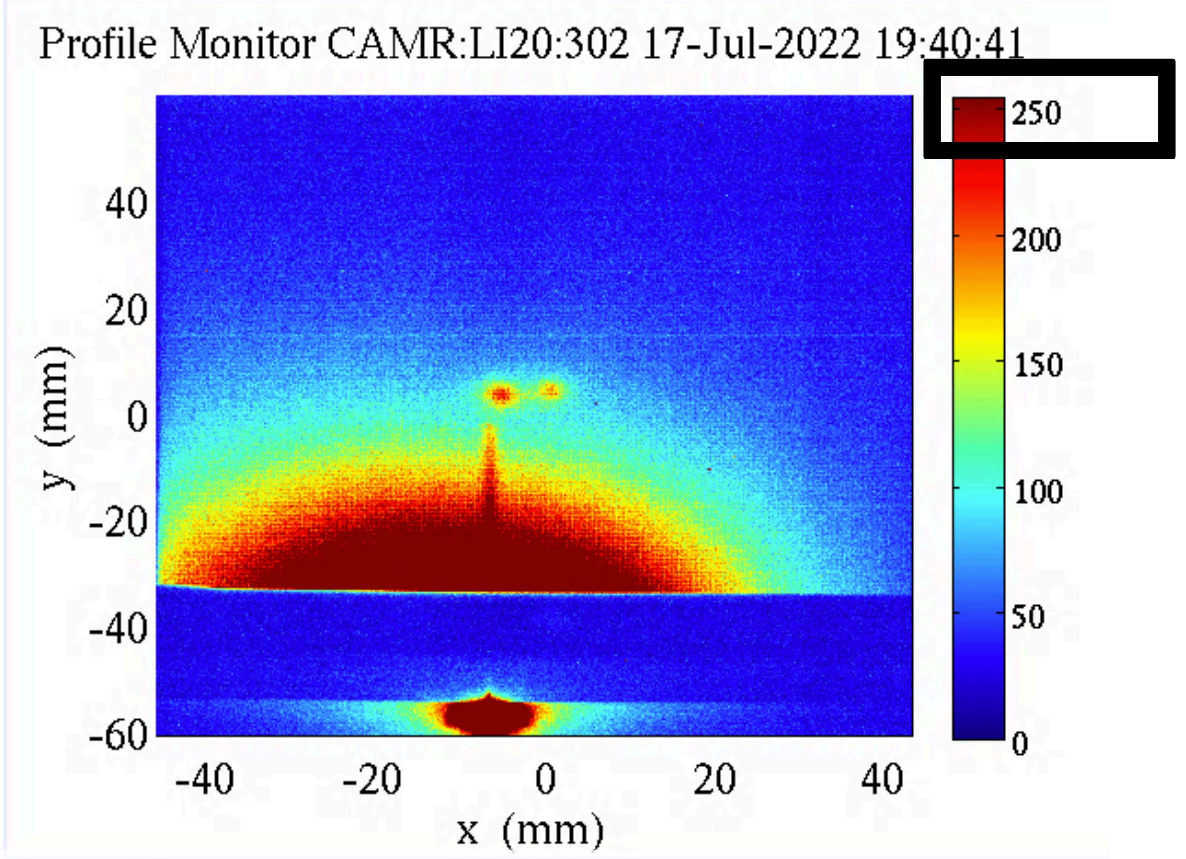
(σ_x , σ_y) : from wirescanner before/after the shift.

E332 progress

i. First evidence of holes being drilled in foils (holes completely drilled in 2 minutes with Al 0.1 mm).
ii. Data of GAMMA1 signal decreasing with time while shooting at a fixed foil position
iii. Foil damage is **proxy for strong near-field CTR (Ohmic heating by surface currents)**

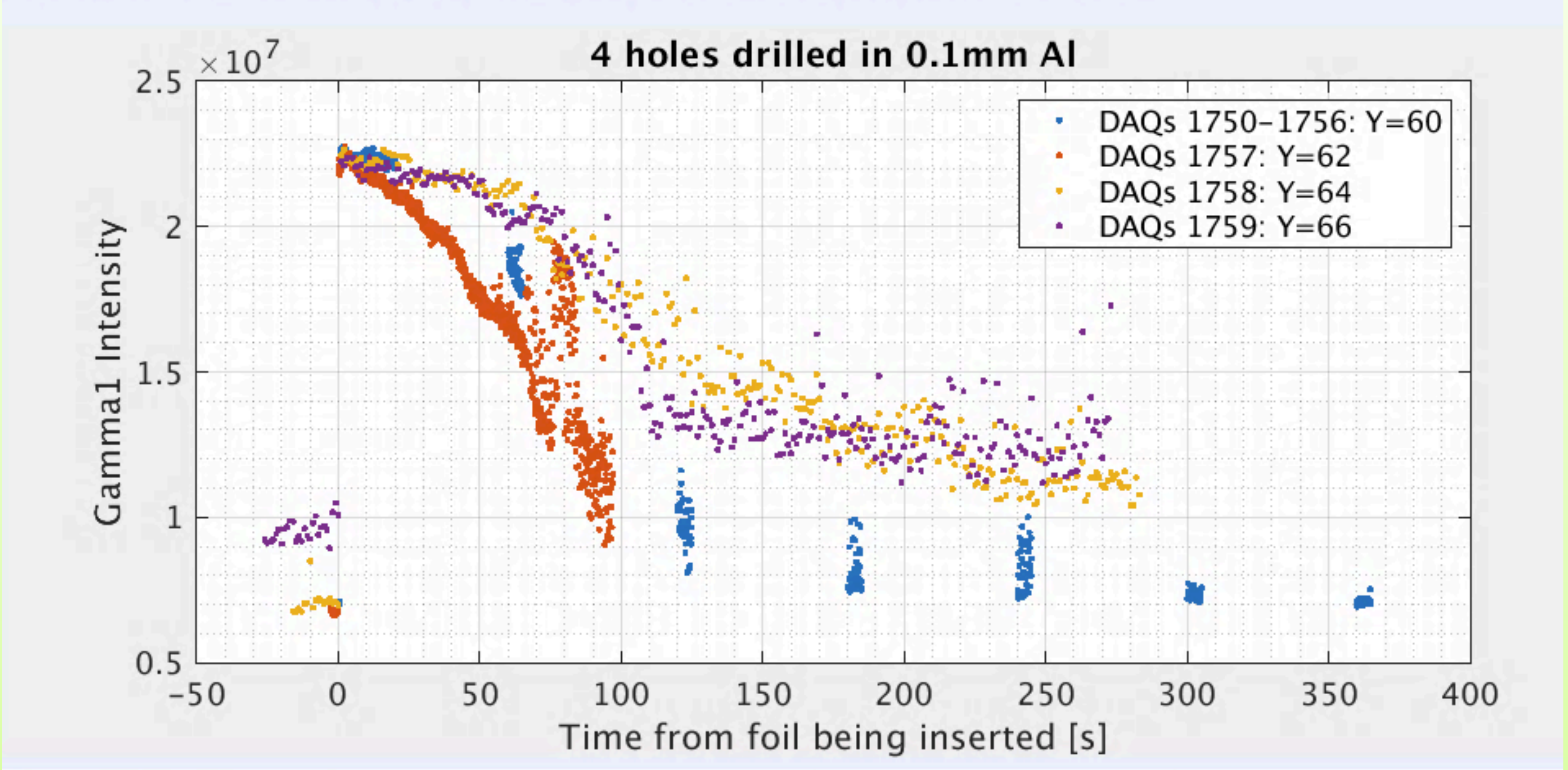


After 10 min



Gamma signal after 0 min at 10Hz (Al 0.1 mm)

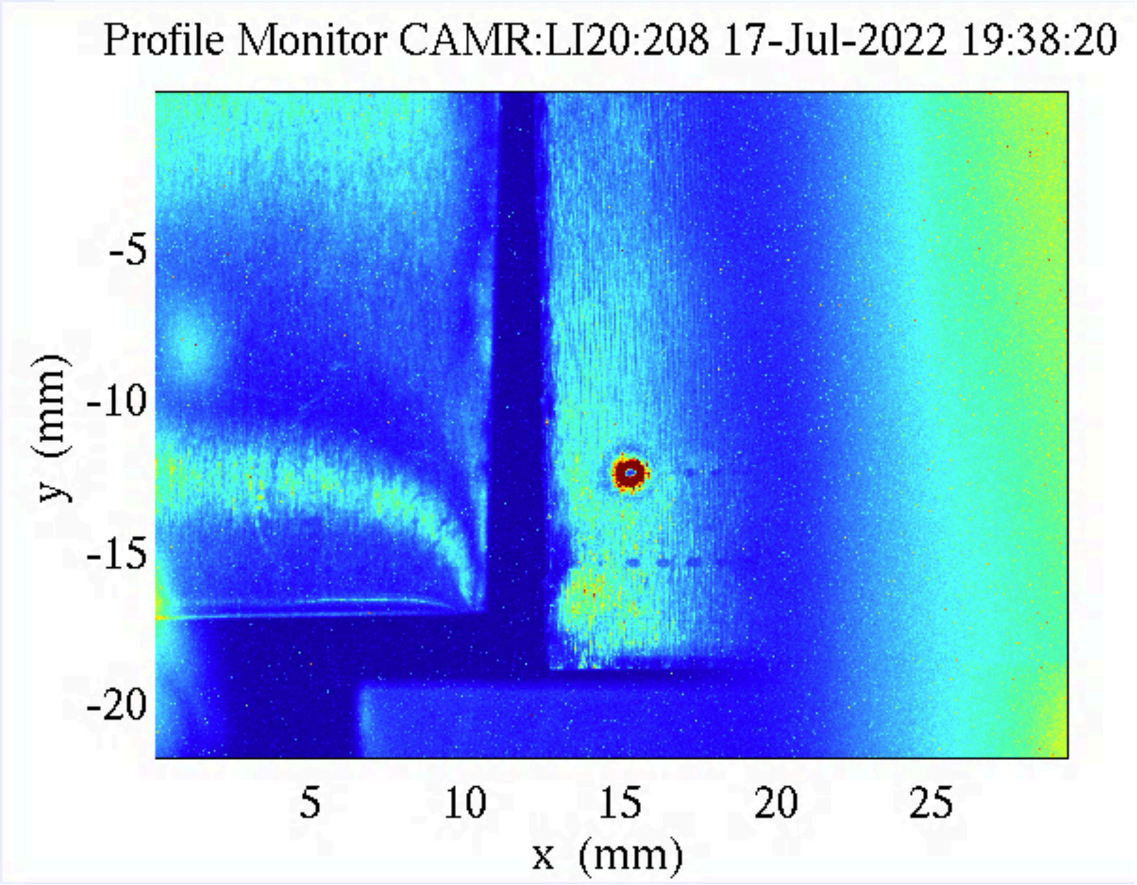
Gamma signal after 10 min at 10Hz (Al 0.1 mm)

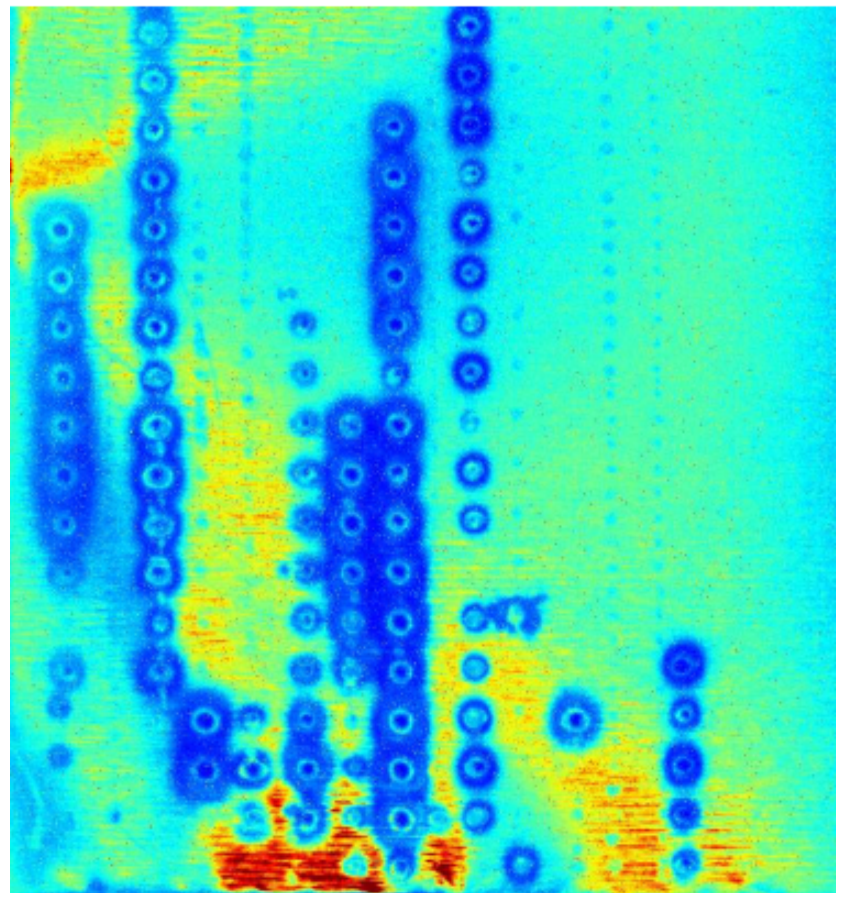


- GAMMA1 signal decreasing gradually after inserting the foil due to the hole being drilled.

- Drilled through Al 0.1mm with the e-beam over 1000 shots.

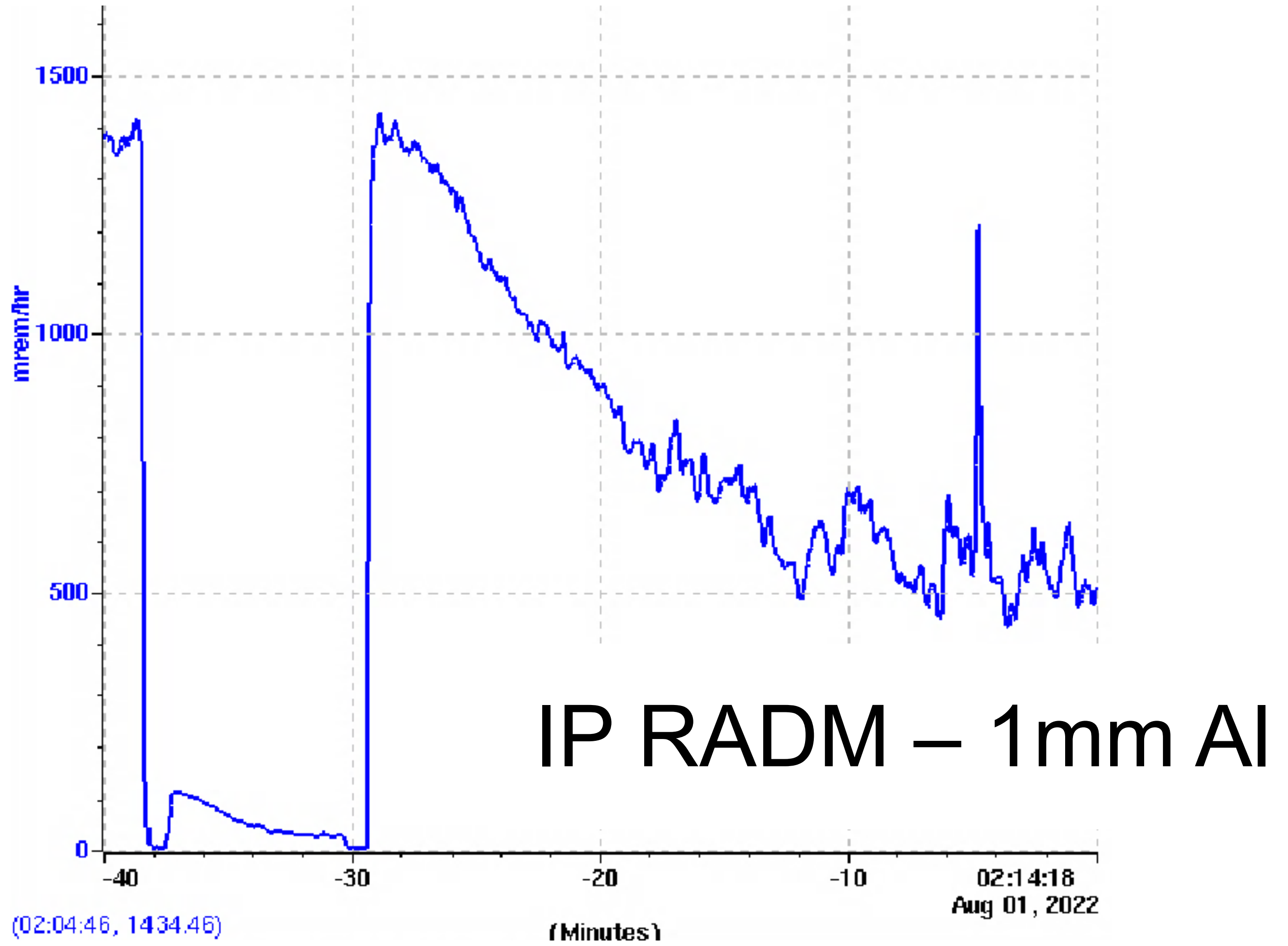
i. Damage is visible on Frontview camera
ii. Very clear signal on IP RADM that decreases by about 80% when hole is all the way through





First time drilling a hole

Many holes



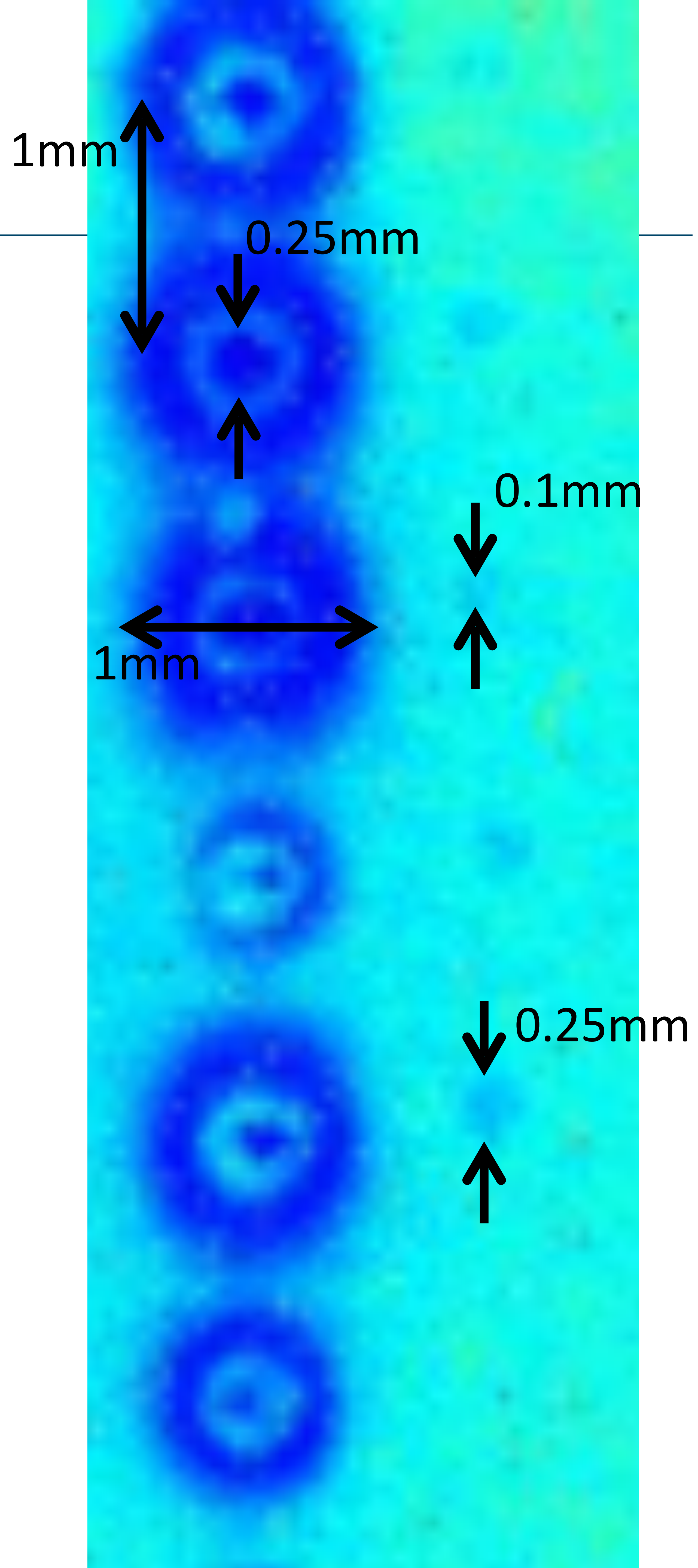
E332 progress

Size of damaged area

- Multi-shot burn through hole:
  - Max hole diameter ~250 µm Ø
  - Visible thermal damage ~1 mm Ø

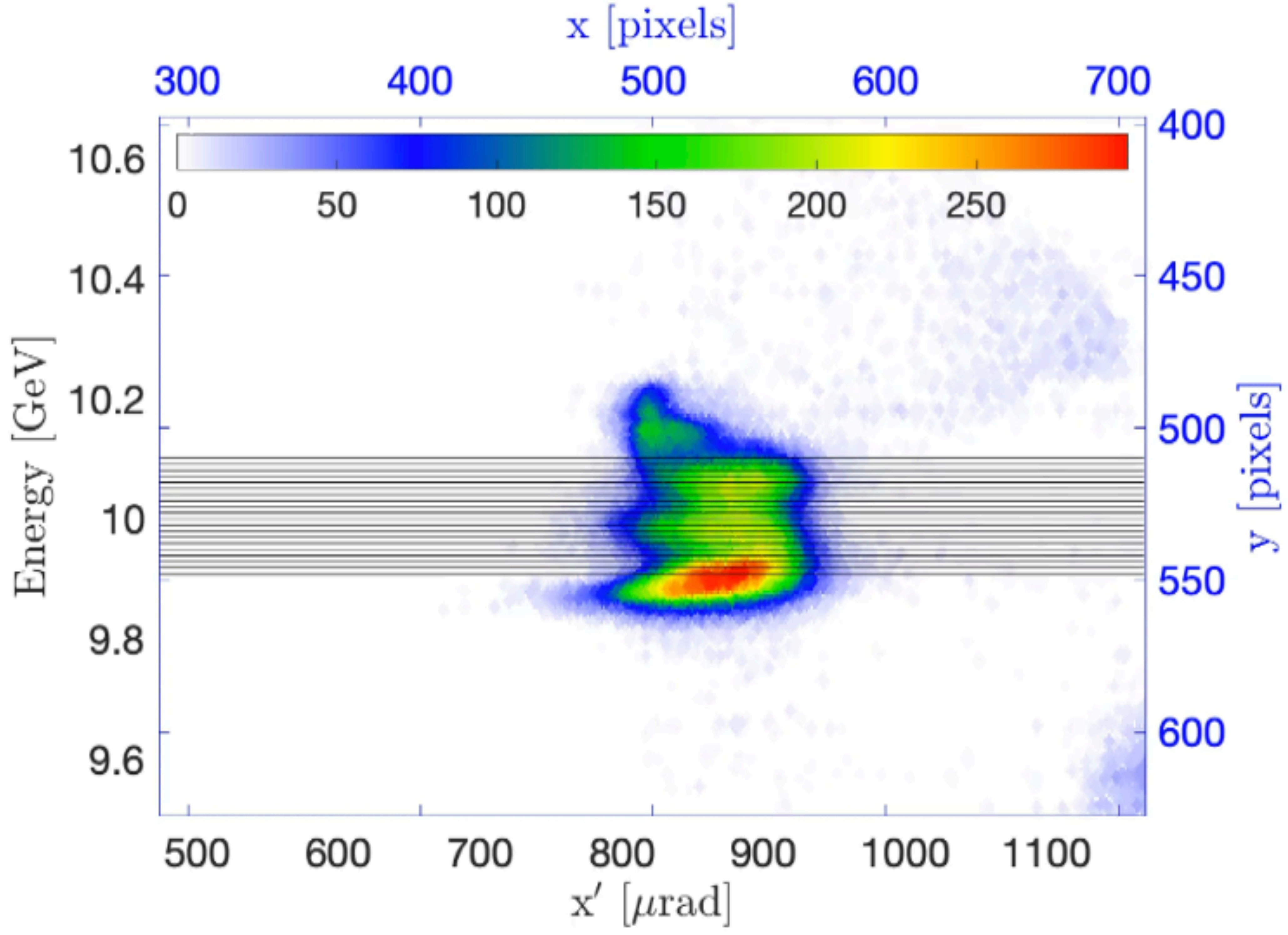
- Single shot damage:
  - Diameter: 100 - 250 µm Ø

- Moving ~0.5mm/step is enough to move to a fresh spot
  - This may change with smaller spot sizes

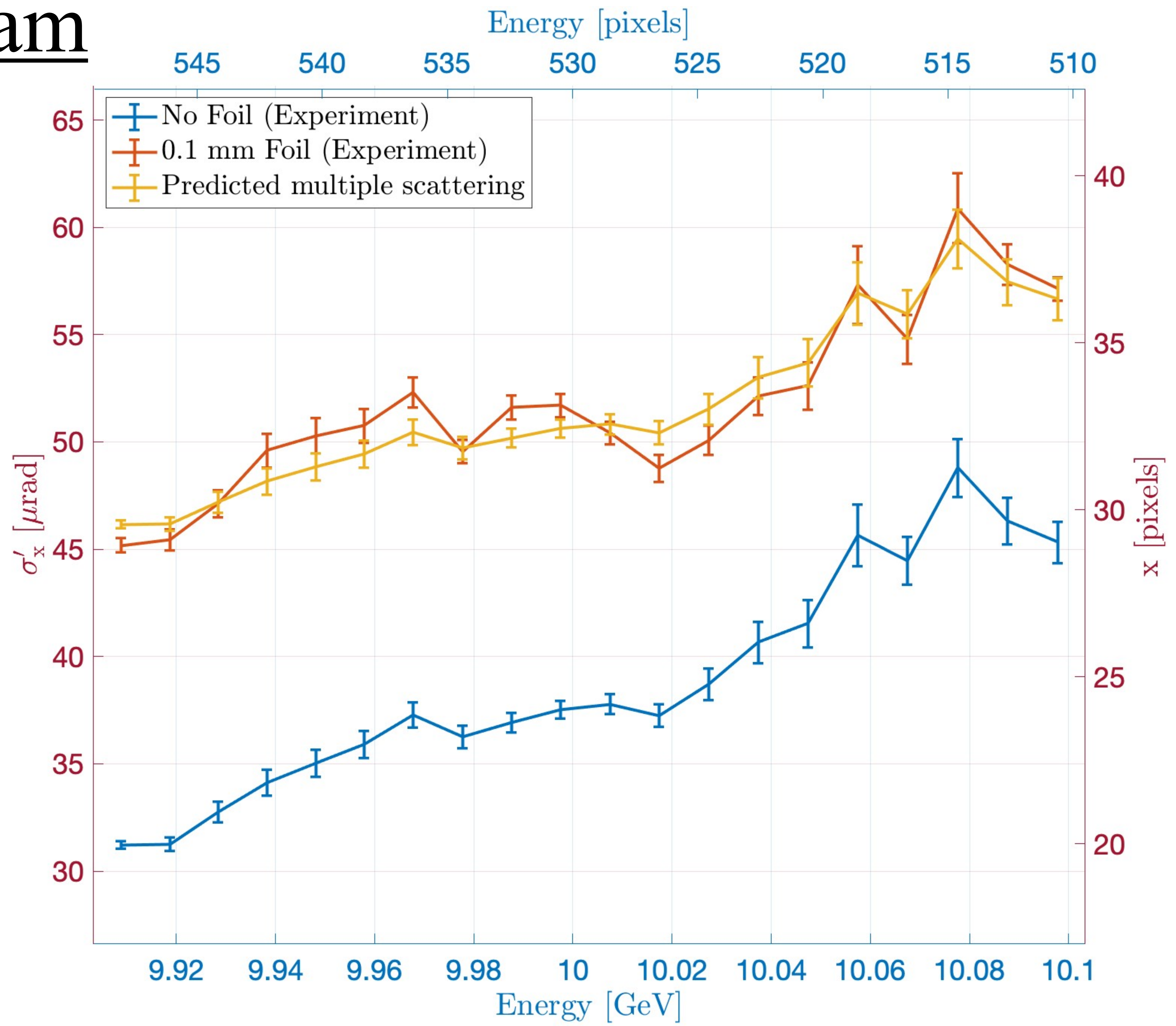


E332 progress

Effect of single foil (Al 0.1 mm) on the beam



M_{12} = -20 m ("large") to measure divergence at DTOTR2

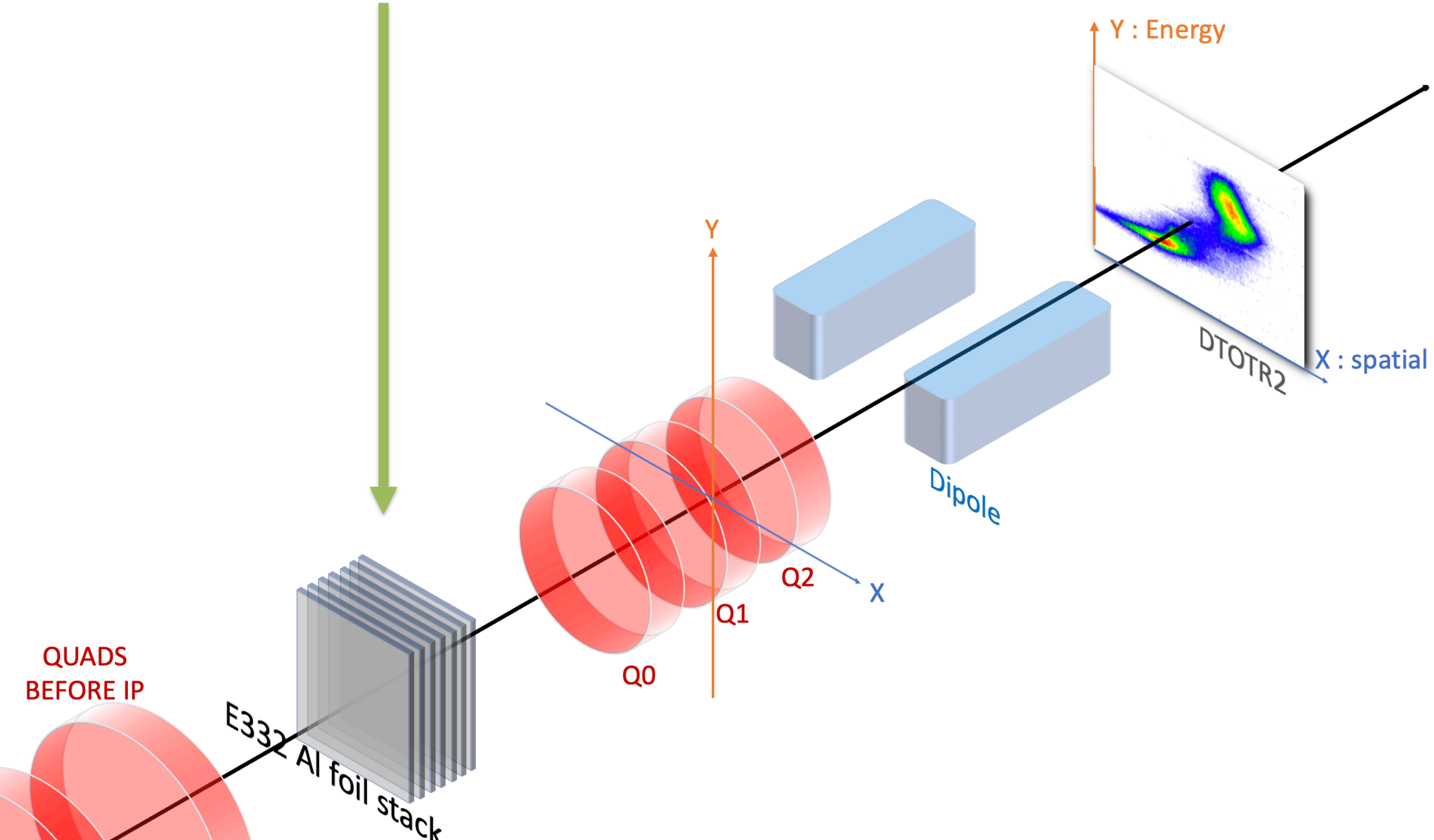


Observed effect compatible with multiple scattering, no evidence of near-field CTR focusing

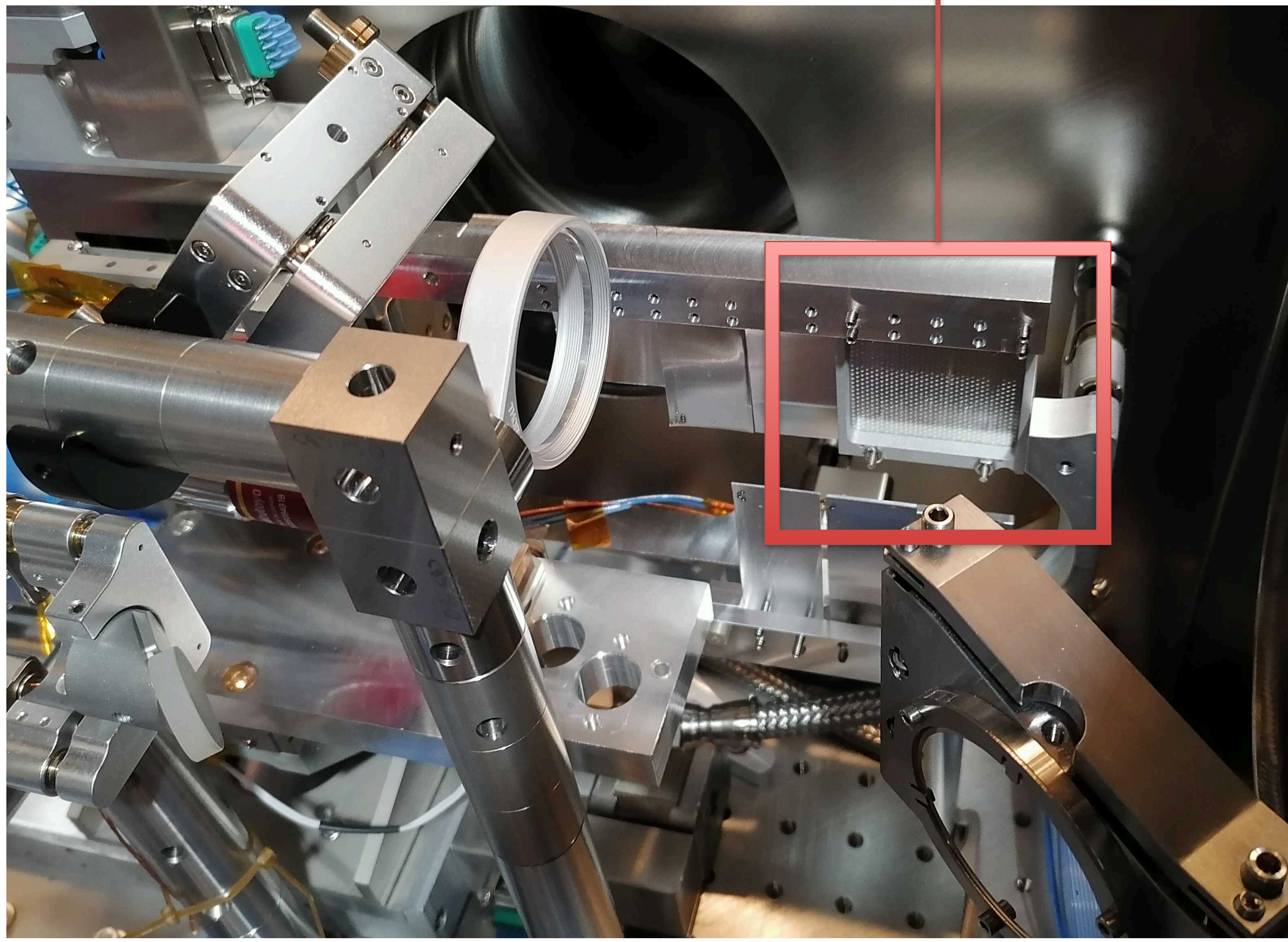
E332 progress

Multifoil installation (40 times Al 0.9 um, 100 um distance between foils)

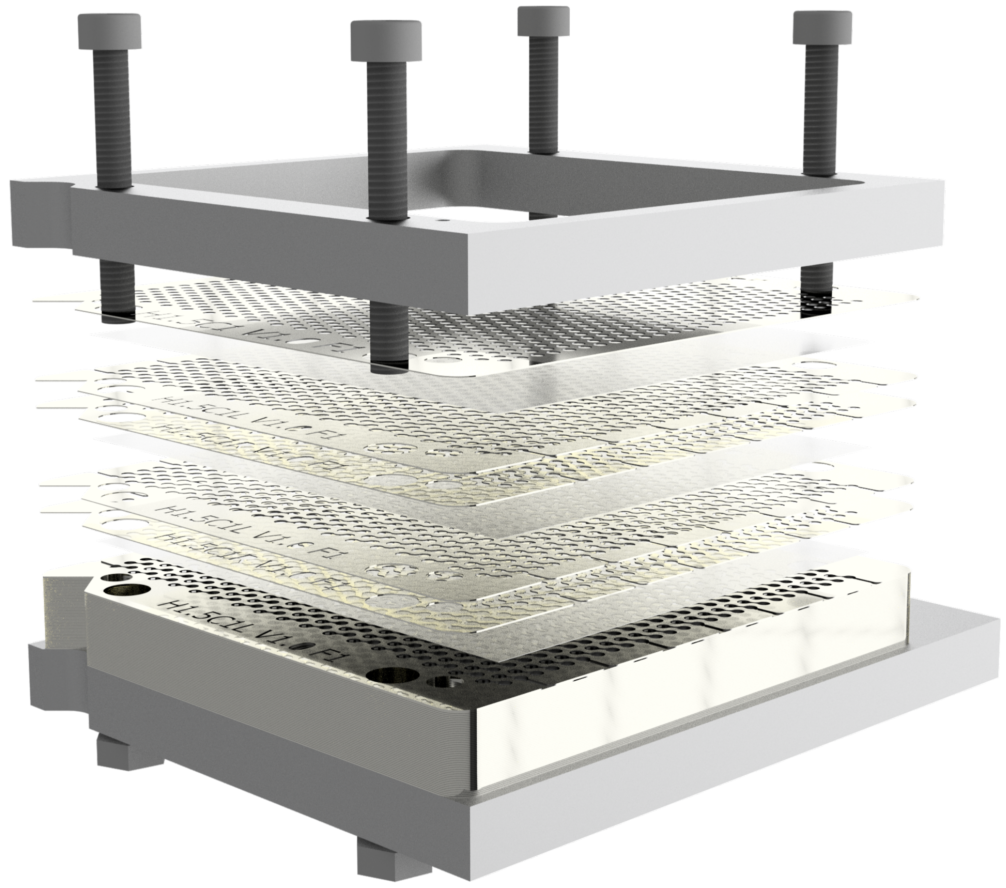
We replaced the single foil by a 40 foils stack

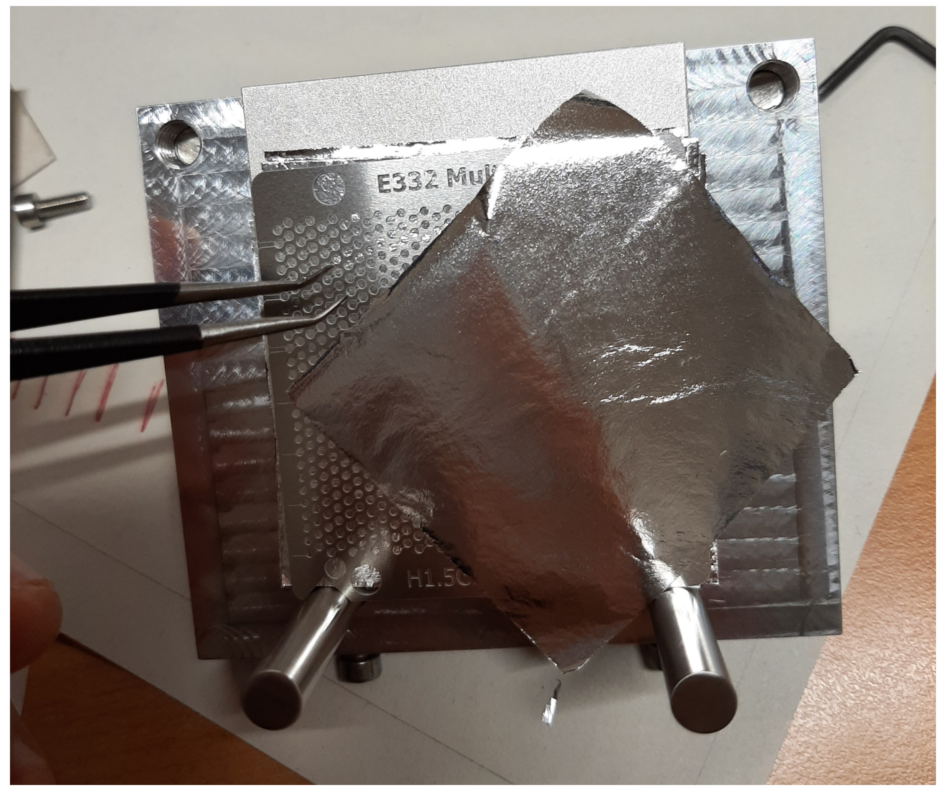


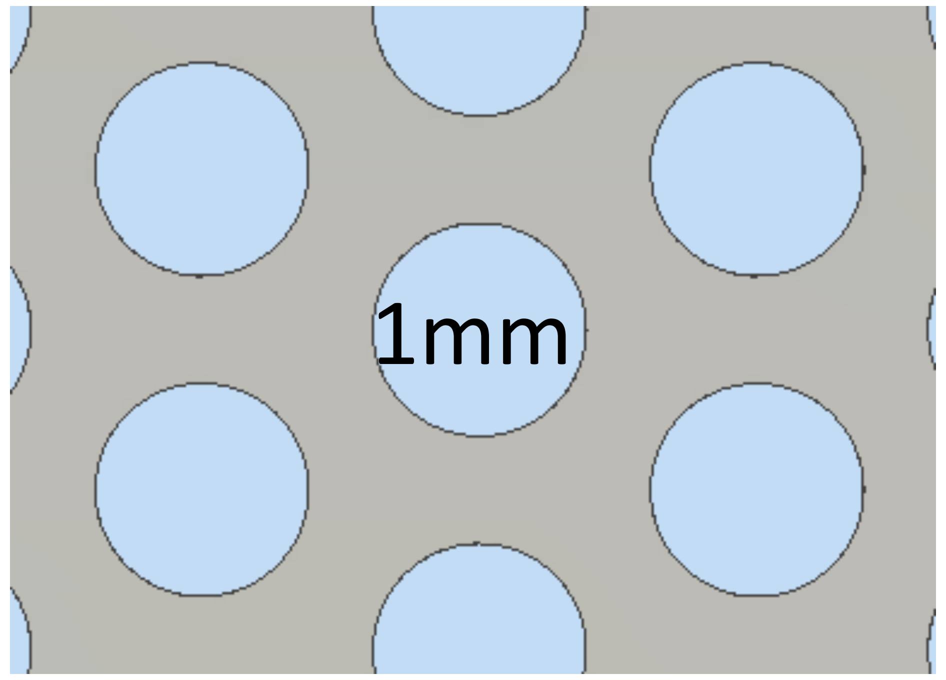
multifoil

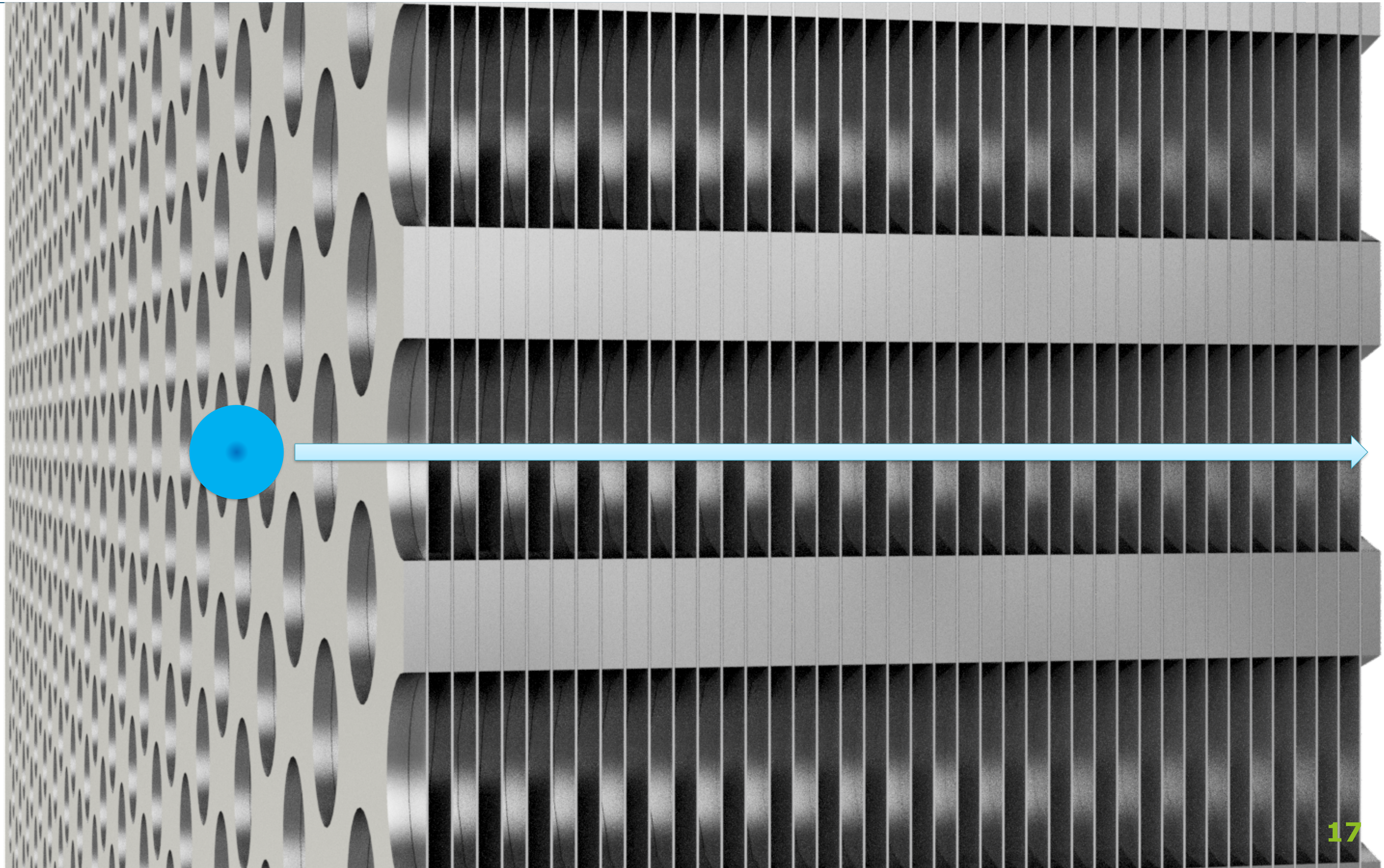


E332 progress





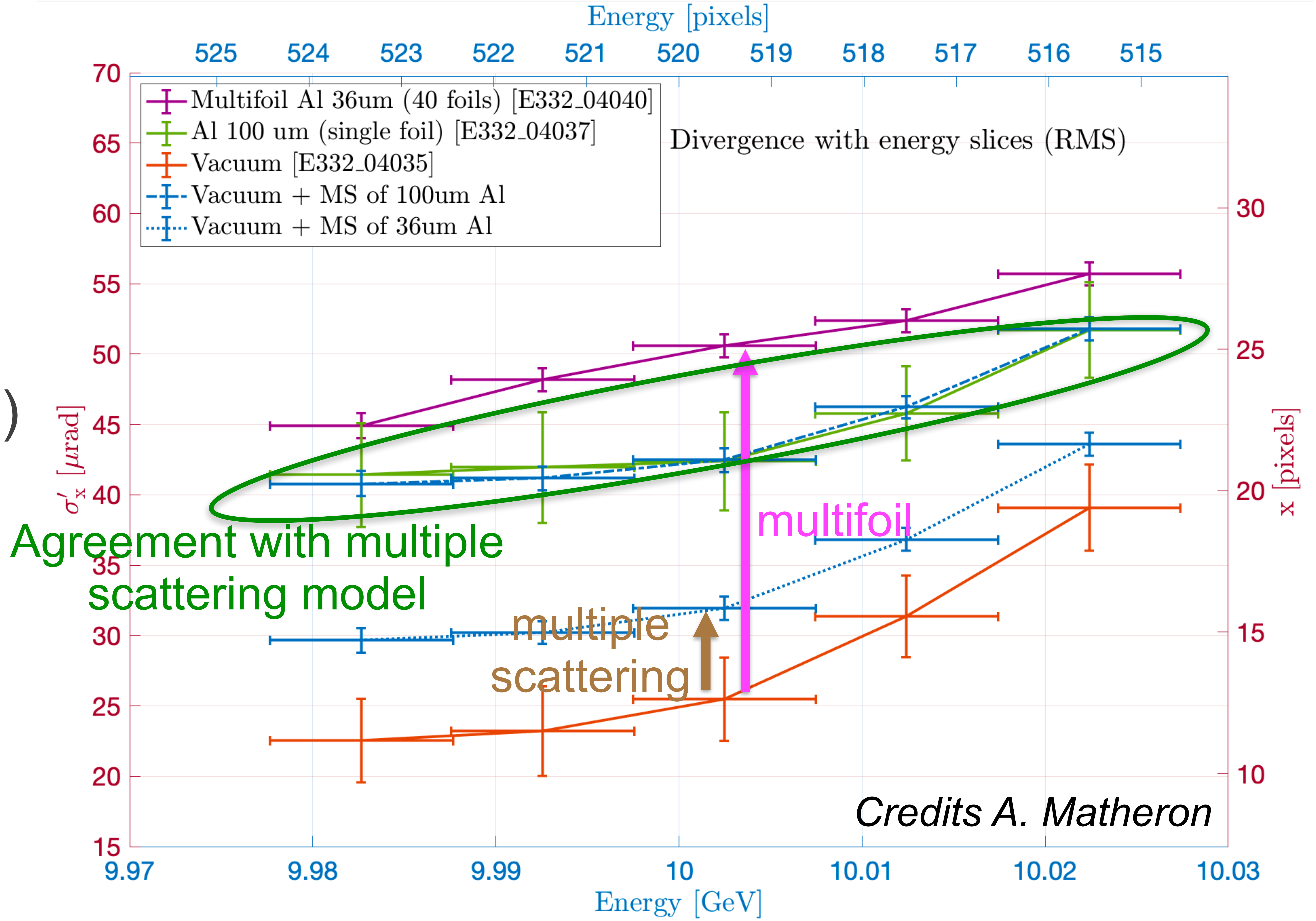




E332 progress

Evidence of near-field CTR focusing in multifoil:

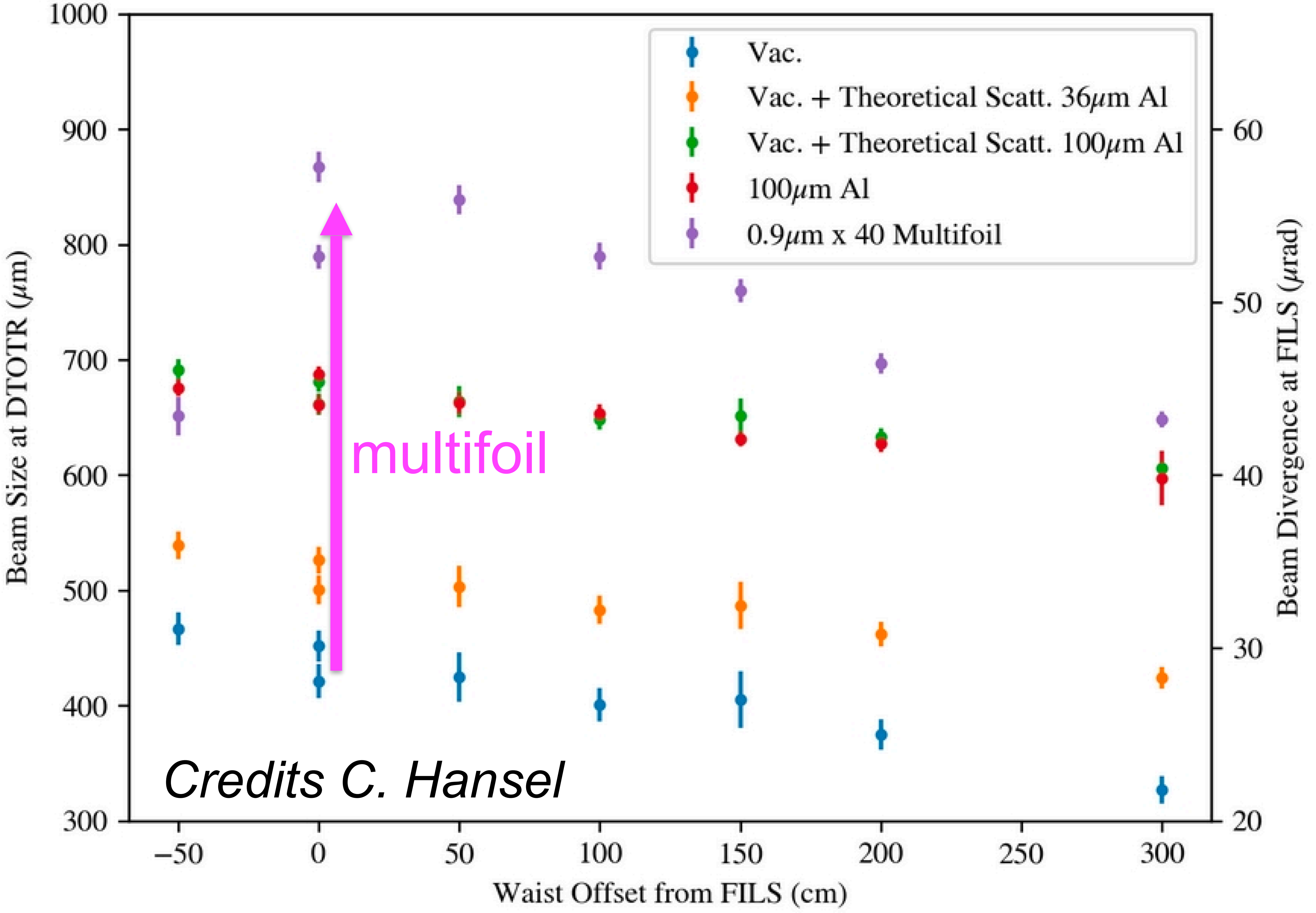
- Divergence doubles in multifoil (40x0.9 = 36 um of Al)
- Multiple scattering: well reproduced for Al 100 um
- Multiple scattering for Al 36 um: can only explain +20%



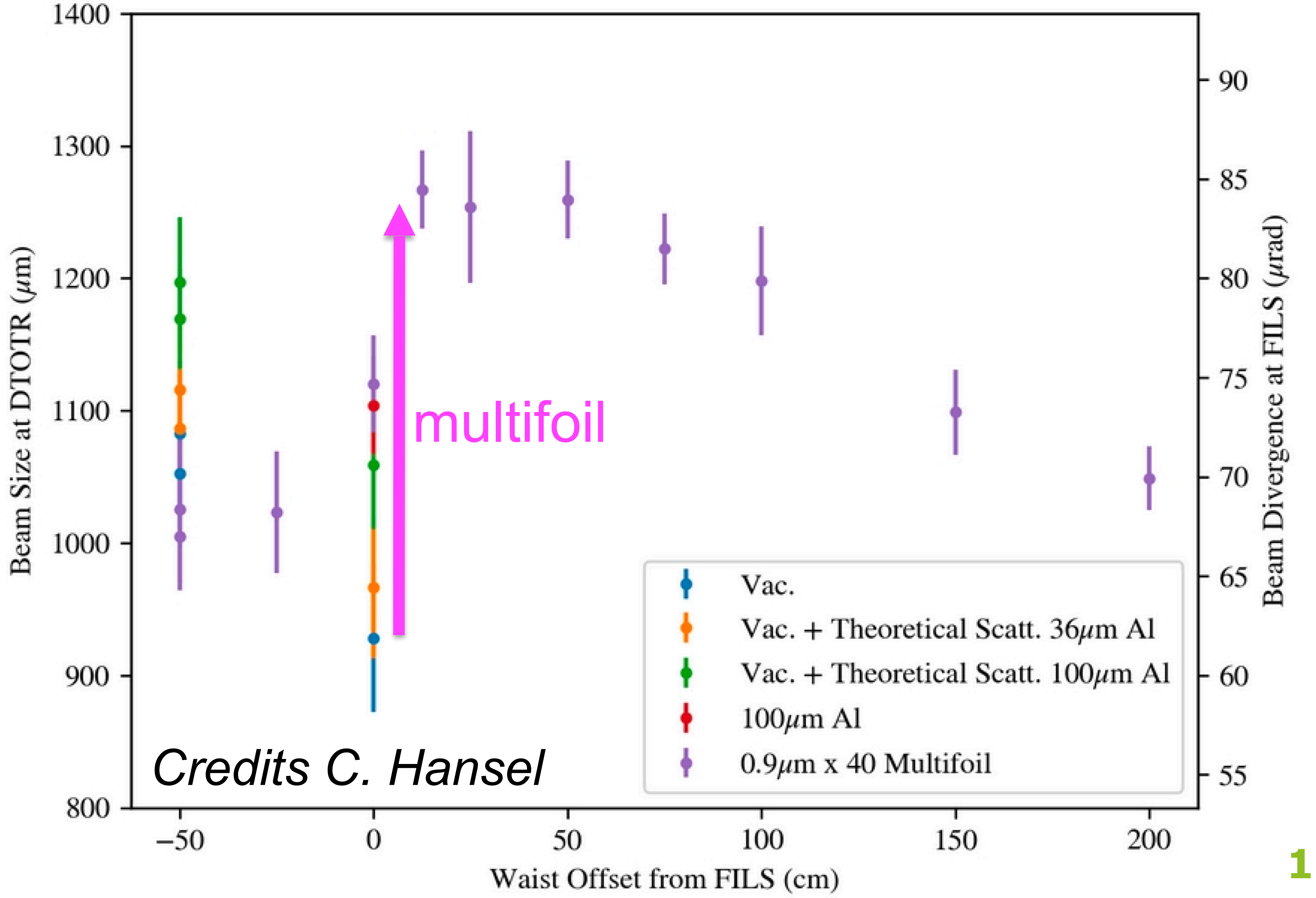
M_{12} = +15 m and M_{11} = 0 (parallel-to-point optics) for perfect measurement of divergence at DTOTR2

Waist dependence of near-field CTR focusing in multifoil:

β = 50 cm



β = 10 cm



E305 & 332 plans

E305 plans for FY24

- Plans for E305 experimental set-up:
  - Plasma generation at high pressure for length greater than 5 mm. Improved laser, leverage spatiotemporal couplings with a chirped laser.
  - Produce clean and transversely-uniform plasma, larger than the beam
  - Afterglow: dynamic range, consider using a lens to increase light collection, + filters on a flipper
  - Shadowgraphy:
    - frequency-double shadowgraphy probe (designed and hardware ready)
    - assess the need to change pico by stepper motor for shadowgraphy MO
    - commission dark-field mode with mask for Fourier filtering (high-k shadowgraphy)

- Plans for E305 shifts:
  - Repeat beam-plasma interaction with improved beam and plasma
  - Carry out the experiment with a chirped beam (undercompressed with 100 um bunch length)

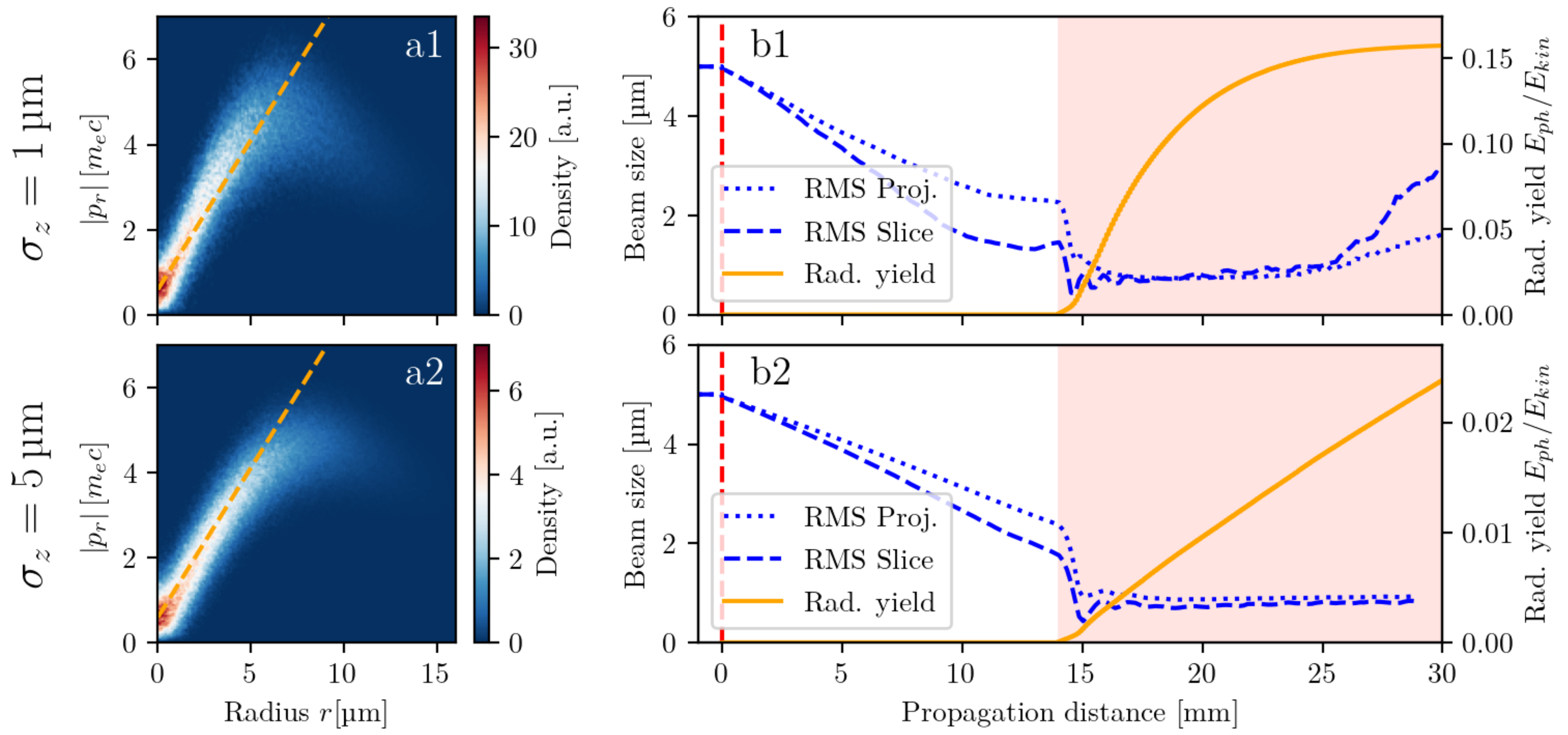
E332 plans for FY24

- Plans for E332 experimental set-up:
  - Change multifoil for 111 foils of Al 0.9 um: maximise near-field CTR focusing and provide clean comparison to single Al 100 um foil
- Plans for E332 shifts:
  - Take data with compressed beam and with bunch length characterised, to allow comparison to models and simulations
  - Demonstrate fully-resolved DTOTR1 beam size measurement
  - M_{12}/object plan scans to evidence the focused beam size and waist shift with respect to foil (can use 2 mm Al to calibrate “waist at foil” in M_{12} scans)
  - Clean waist scan data showing both increased divergence and decreased divergence

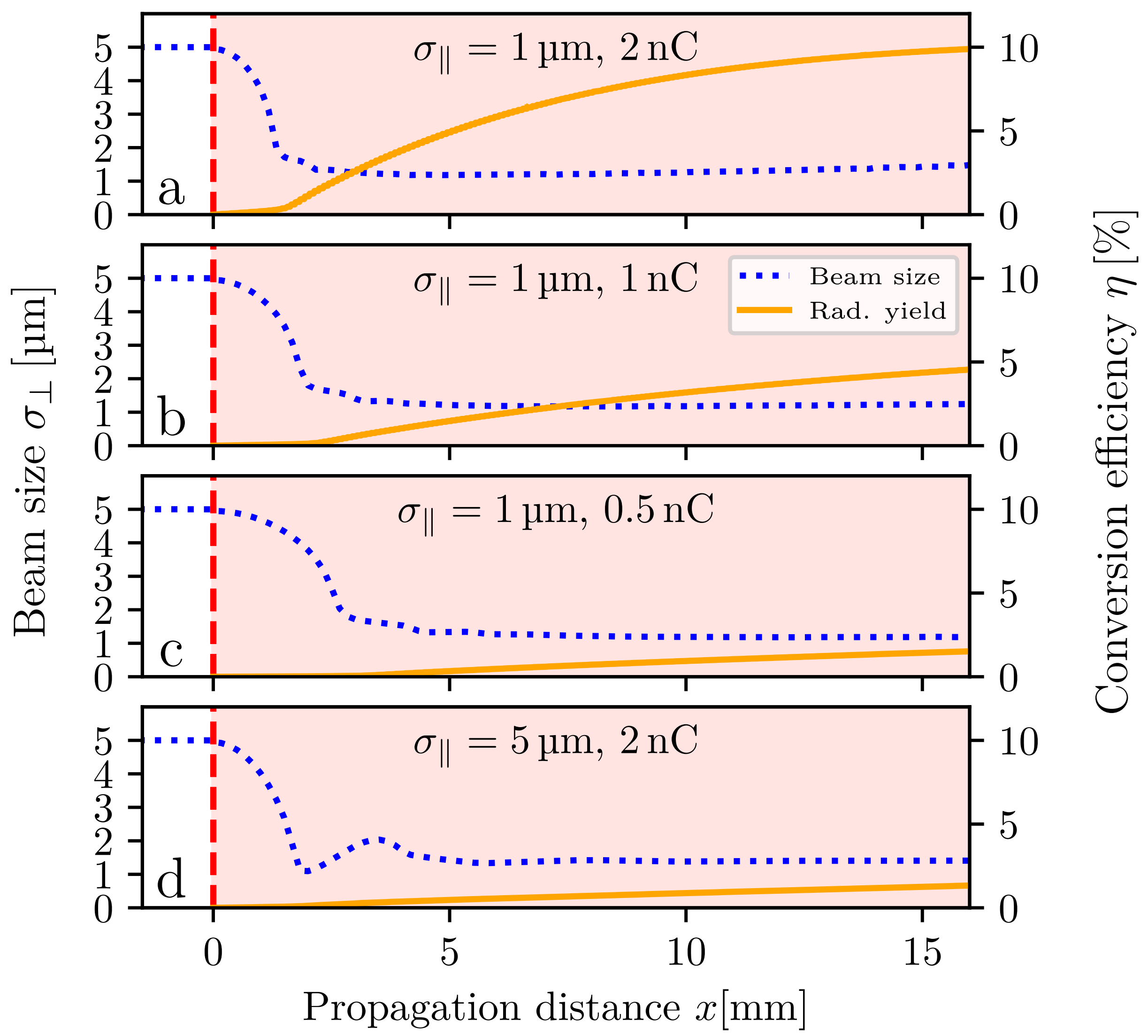
E332 plans in the long run

- Longer term:
  - With beam size of 5 um or less, current of 50 kA or more: bright gamma-ray source

1 foil + 1 stack



1 stack



Beam focusing by near-field transition radiation

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S. Corde et al., hal-02937777 (2020)

  - With 100 kA or more, couple plasma lens (E308) and multifoil (E332) for laserless SFQED.

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Thank you for your attention