Plasma-afterglow-based feedback and laser-ionized plasma lenses

A. Knetsch on behalf of collaborators

CLARA User Meeting 05.07.2022

Plasma afterglow metrology experiment – The team

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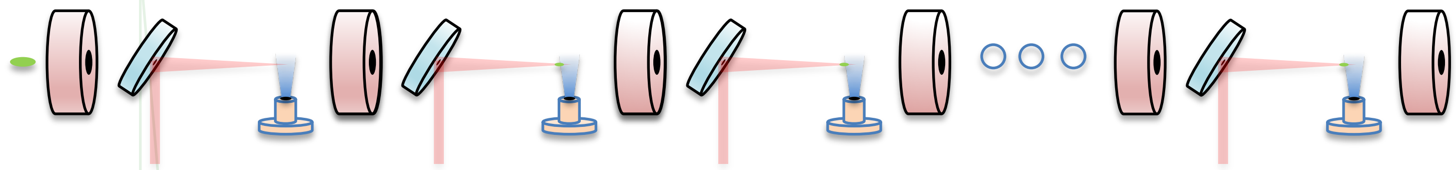
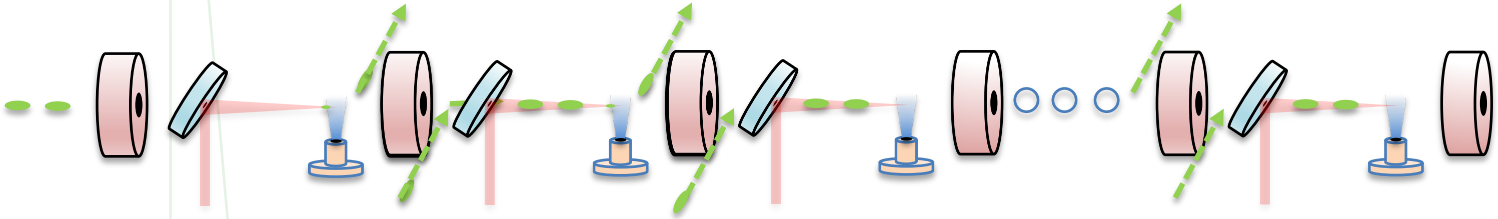
Complexity-driven need for simple diagnostics and synchronization



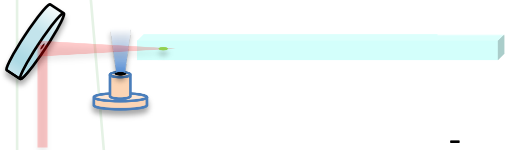
Multi-stage LWFA

- Record single-stage energy gain so far: 8 GeV
- 125 stages required for 1 TeV
- What if one of them fails ?



Multi-stage PWFA

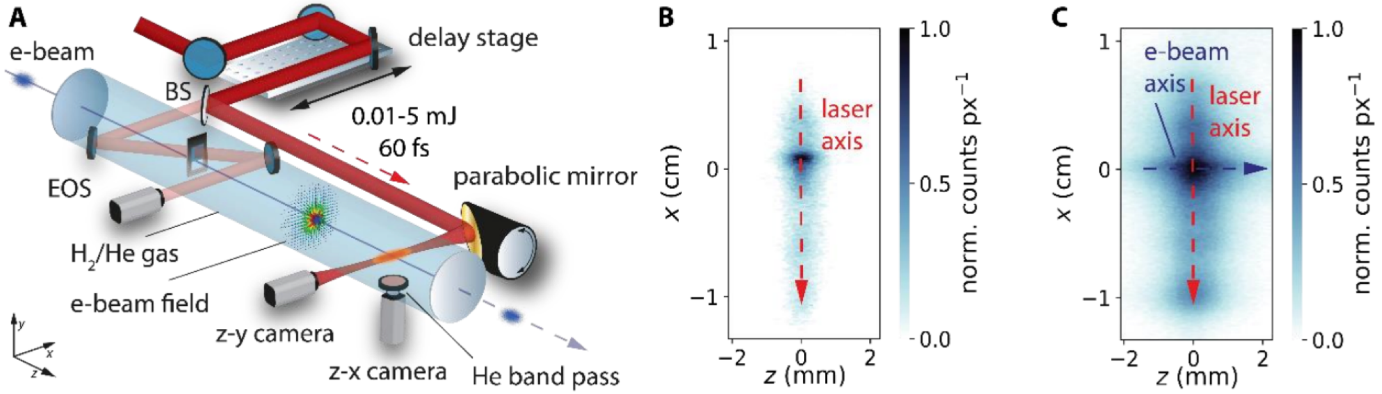
- Laser as ionizer needs to be well timed



Singe-stage PWFA (AWAKE2,FACET-II)

- Plasma lenses to match witness beam into PWFA
- Plasma afterglow gas jet to synchronize seed-laser with witness beam

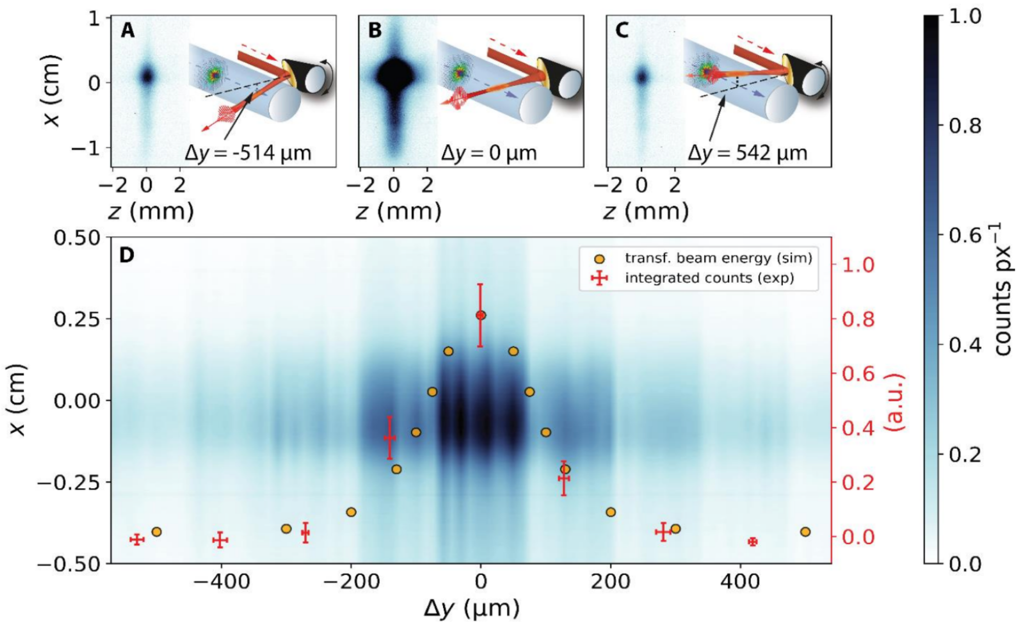
First observation

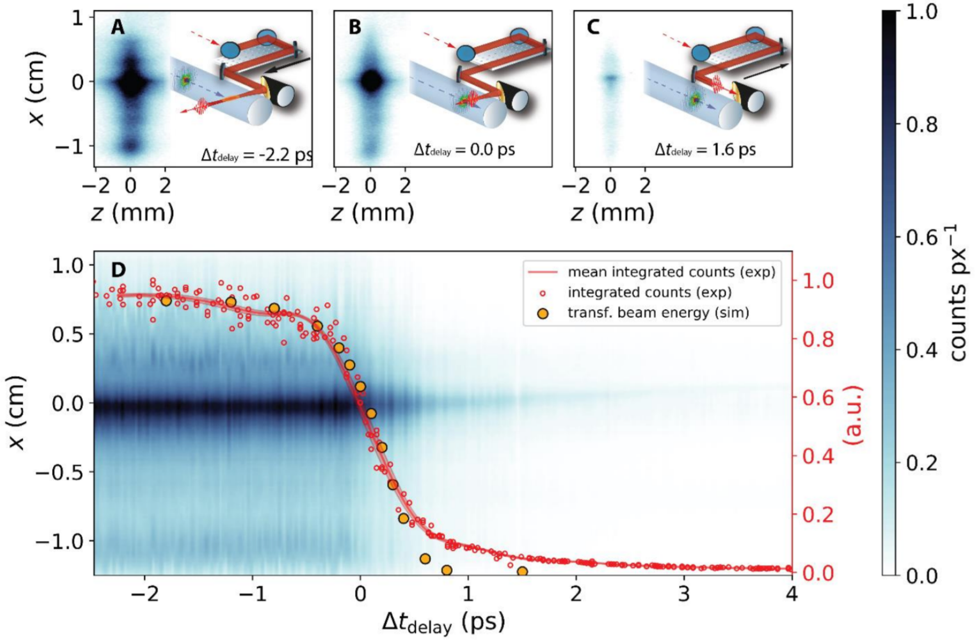


- Effect first demonstrated as part of E210 ‘Trojan Horse’ experiment at FACET
- Afterglow light yield found to vary as a function of overlap between the drive electron beam and the plasma-photocathode laser

A. Deng, et al. Nature Physics (2019)

First observation



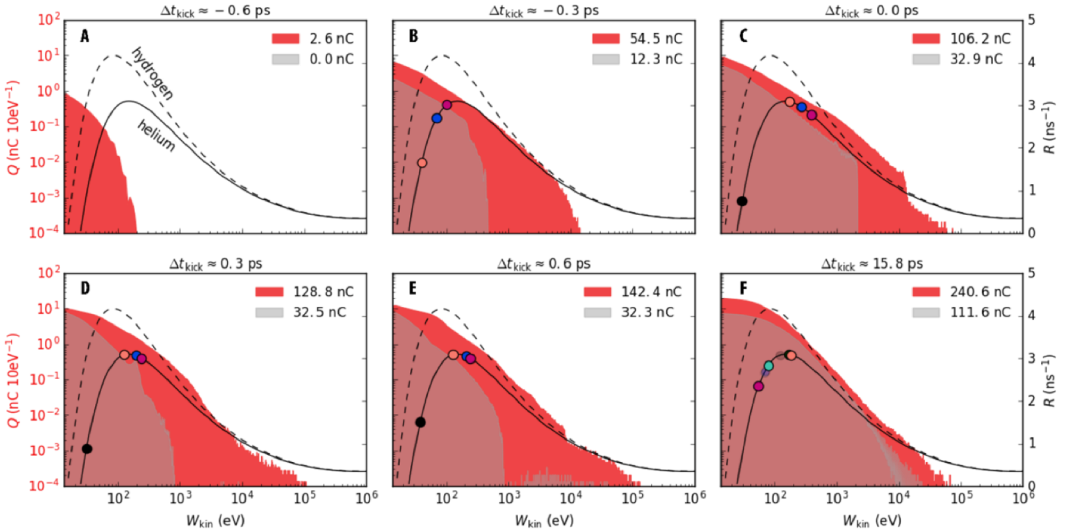


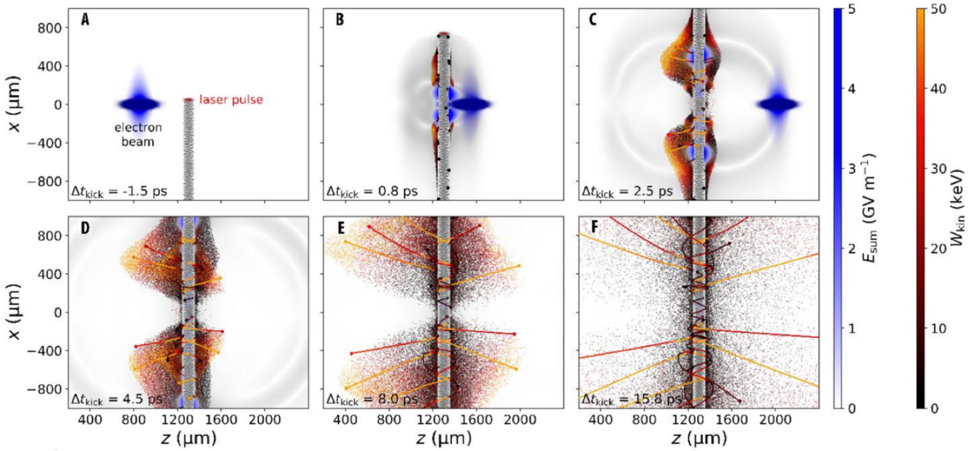
- Synchronization and spatial alignment of injection laser to electron beam
- Linear response to simulated energy loss identified as best model

P. Scherkl, et al. PRAB (2019)

Numerical studies – how does it work ?

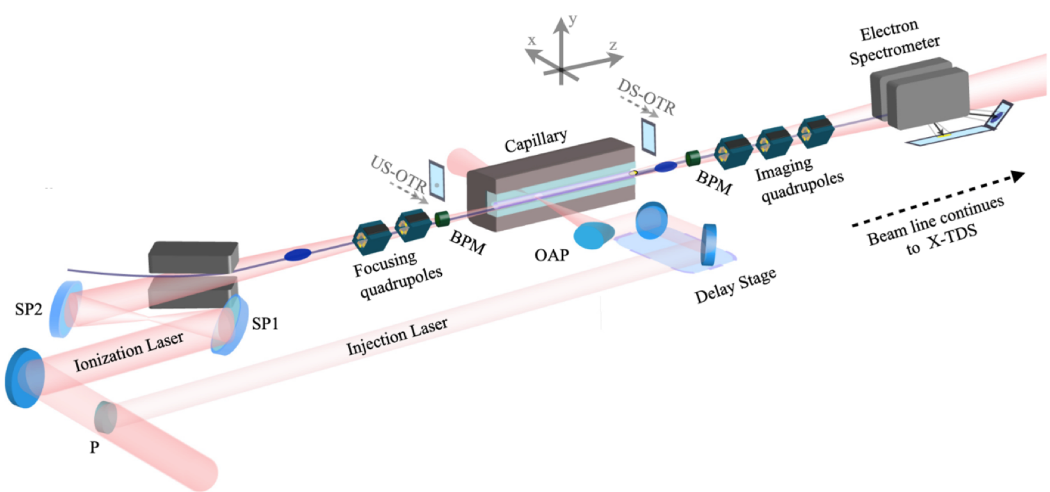
- Beam interacts with a laser-generated seed-plasma
  → Energy deposition into plasma
- Collisional ionization from oscillating plasma electrons
- Beam energies too high for collision ionization

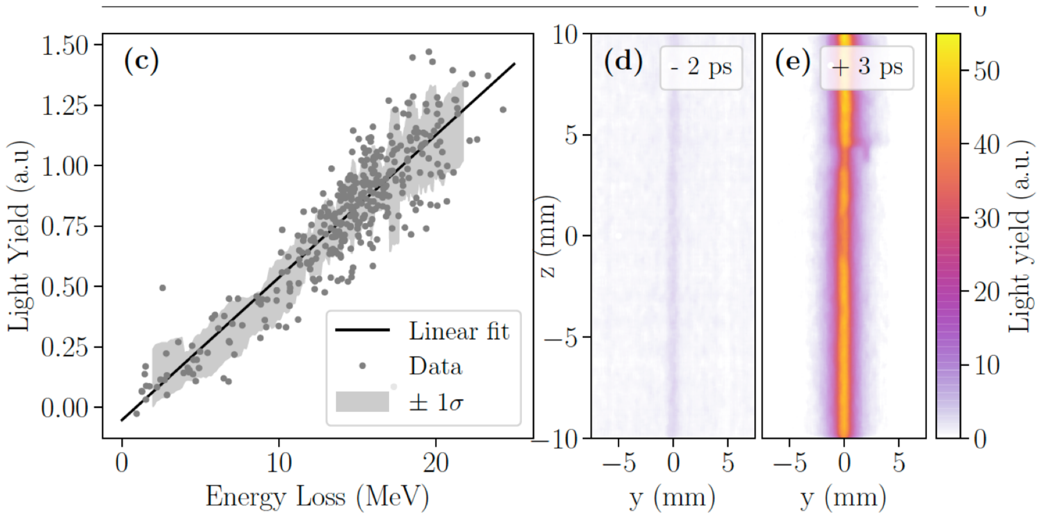


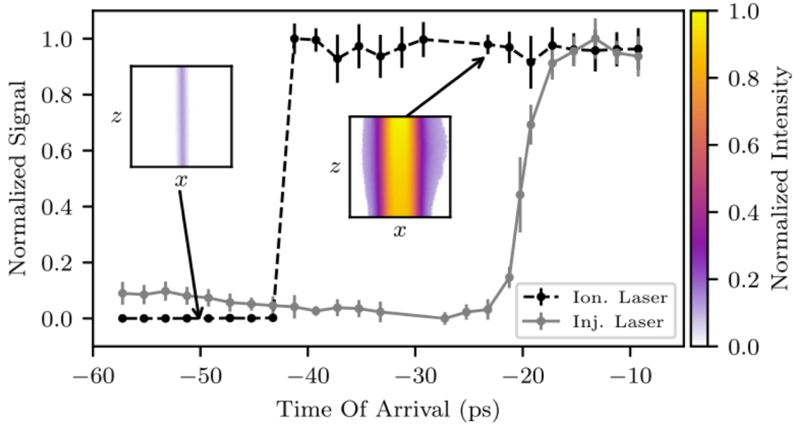


- Heated plasma constituents interact with each other and neutral gas- more light is produced when plasma decays
- Light after decay – Plasma Afterglow – is therefore a simple observable depending on overlap of e-beam and laser

Application at FLASHForward







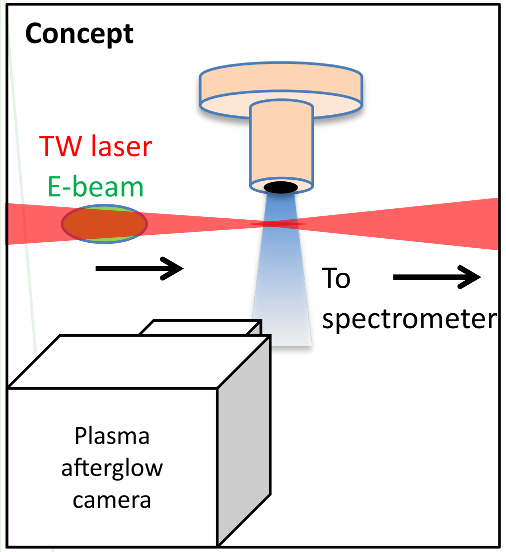
- Convenient synchronization method for ionizing and injection laser to electron beam

- Linear relation between light-yield and energy loss confirmed at FFWD

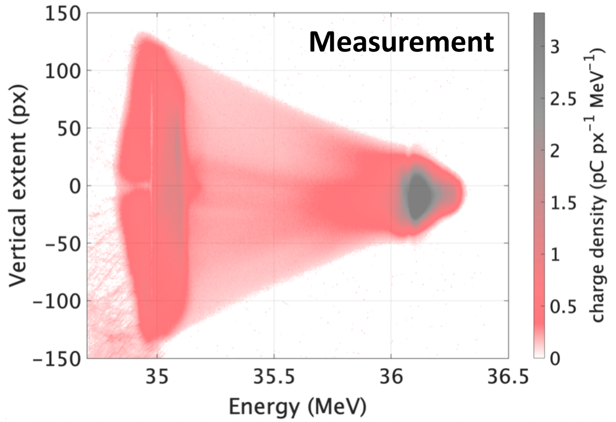
A. Knetsch, et al. Physical Review Accelerators and Beams (2021)

Bridget Sheeran, PhD thesis

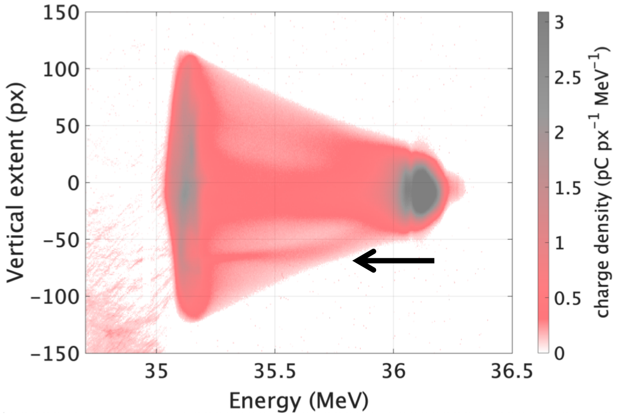
• Application at FLASHForward



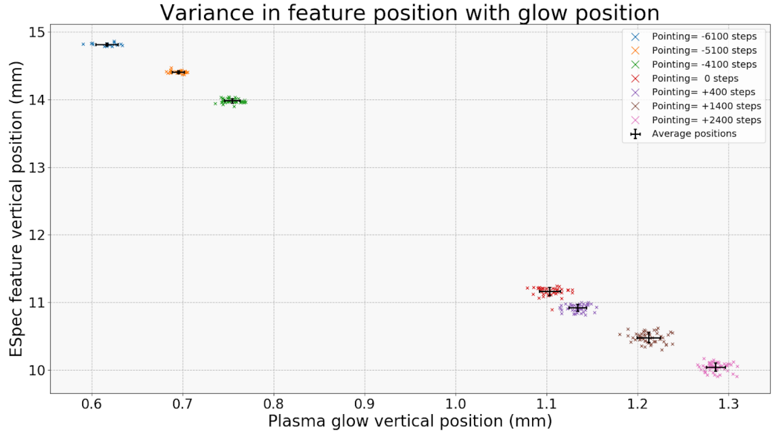
- Lensing effect on part of the beam
- No enhancement of plasma afterglow observed

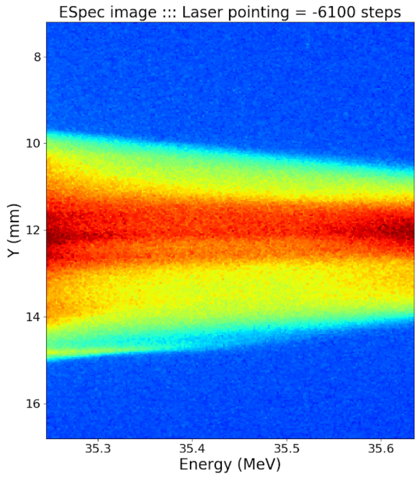


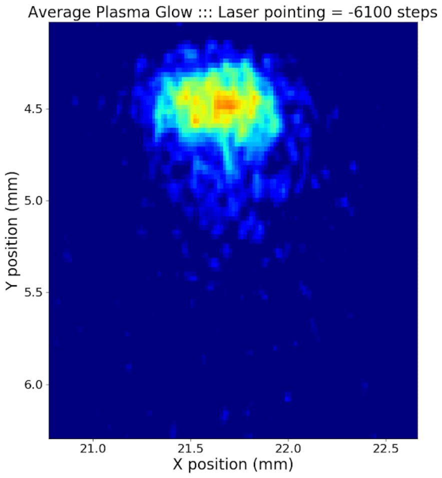
Electron-beam spectrum without plasma-interaction



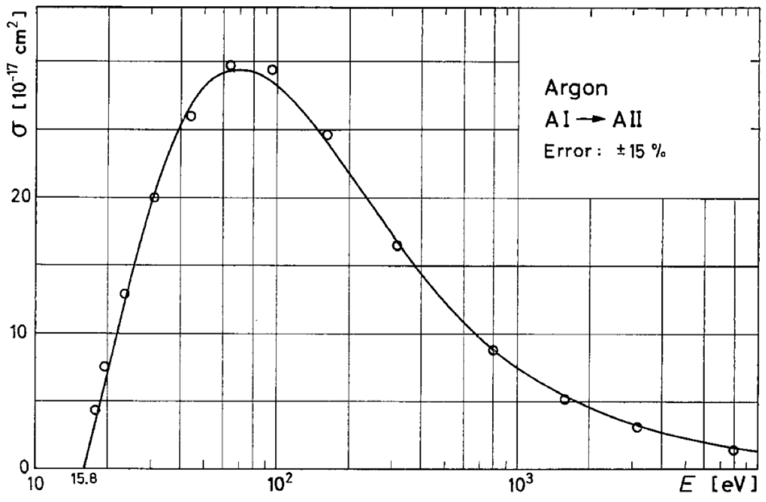
Partial beam-focusing due to plasma-interaction



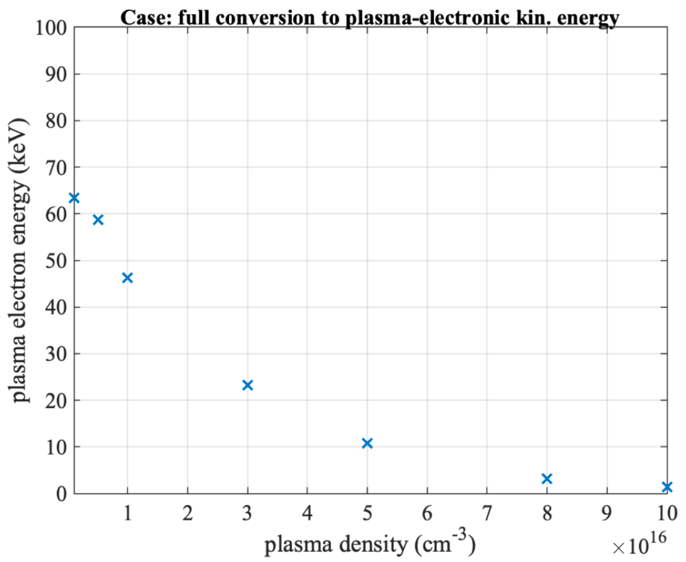


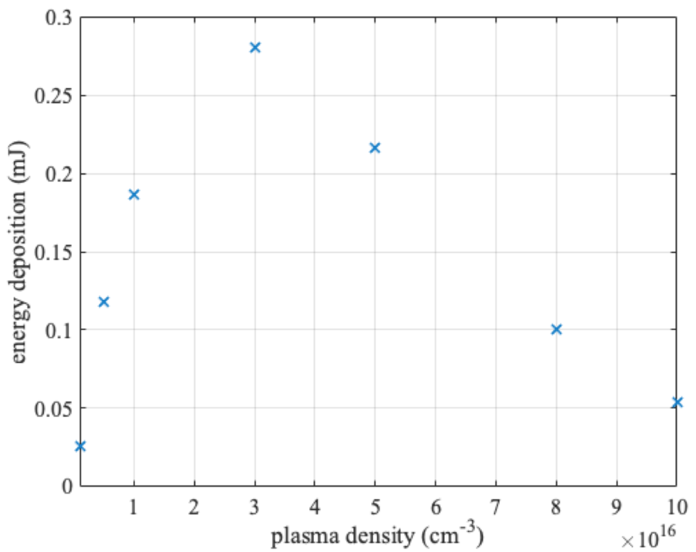


PIC simulations: Energy deposition



Electronic Collision ionization cross-section [1]



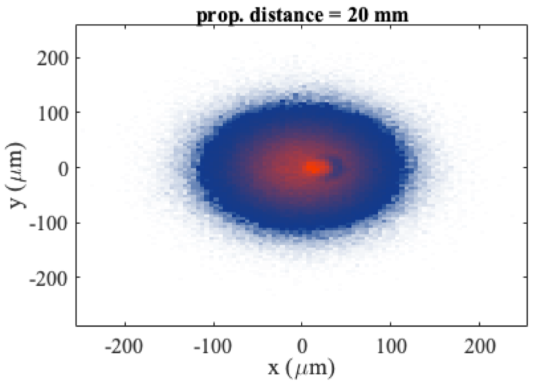


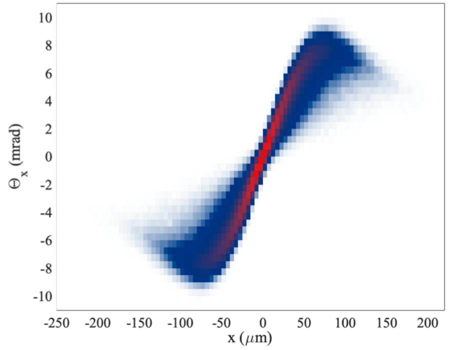
- Assumed electron beam:
  - Spotsize on target 50 um
  - Charge 100 pC
  - Bunch length 120 um
  - Norm. emittance 2 um
- Kinetic energies > 16 eV are necessary to ionize Ar with a peak at ca. 0.1 keV
- Ideal conditions at plasma densities 10-100 times the beam density

Wolfgang Lotz. An empirical formula for the electron-impact ionization cross-section.Zeitschrift_ für Physik, 206(2):205–211, 1967

Studies of tiny plasma lenses

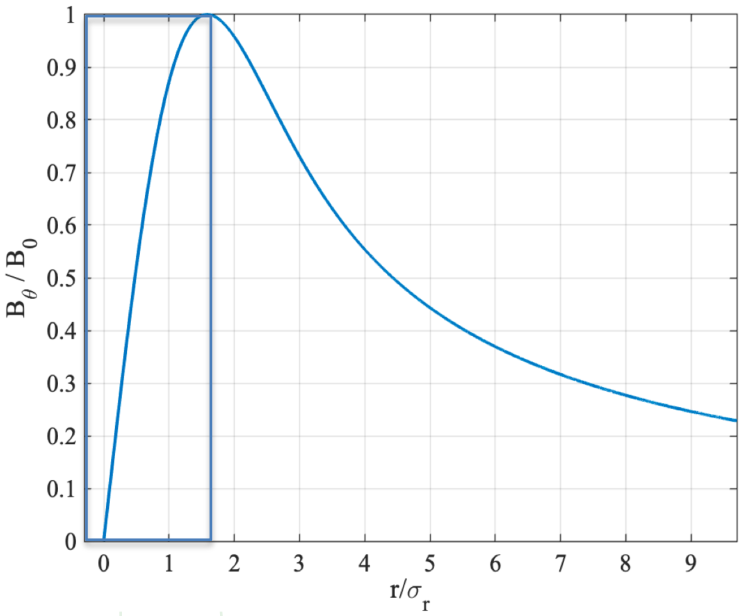
- Electric self-field is much more strongly shielded than the magnetic field → Net focusing
- Linear focusing only expected in central region up 1.6 sigma (includes 72.25 % of charge)
- < 2 mrad divergence of sub-beam

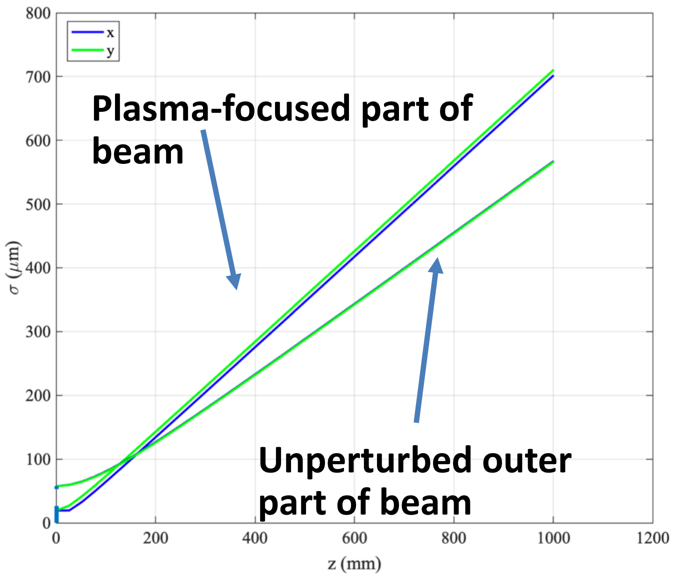


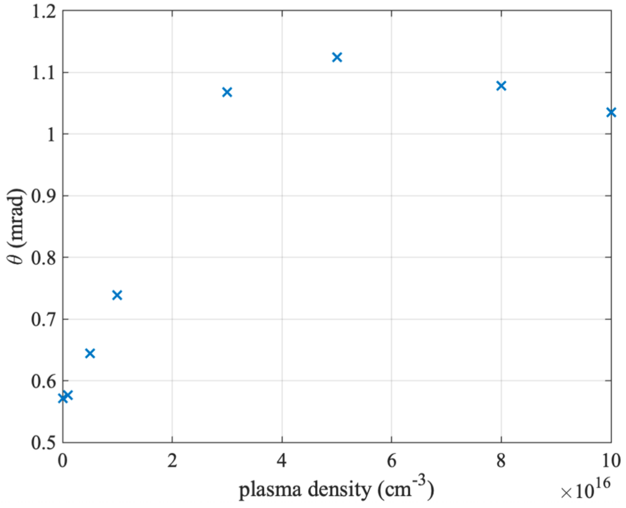


$$E_r^b(r,\xi) = \frac{qN}{(2\pi)^{3/2}\sigma_\parallel \epsilon_0 r}\left(1 - e^{-r^2/(2\sigma_\perp^2)}\right) e^{-\frac{\xi^2}{2\sigma_\parallel^2}}$$

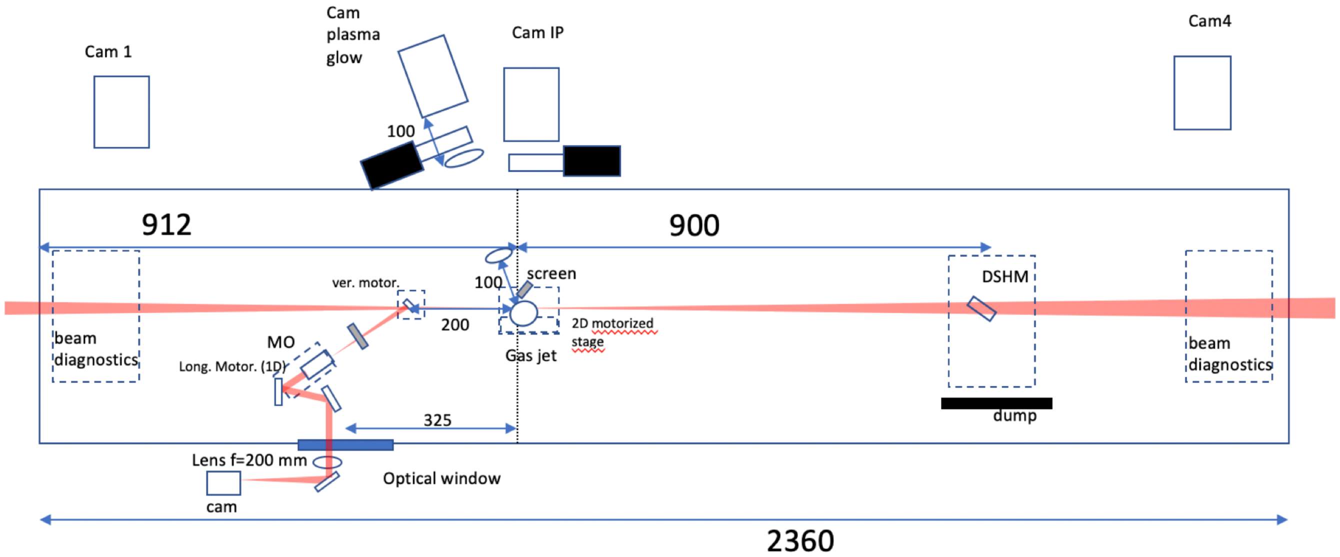
$$B_\theta^b(r,\xi) = \frac{qN}{(2\pi)^{3/2}\sigma_\parallel c\epsilon_0 r}\left(1 - e^{-r^2/(2\sigma_\perp^2)}\right) e^{-\frac{\xi^2}{2\sigma_\parallel^2}}$$

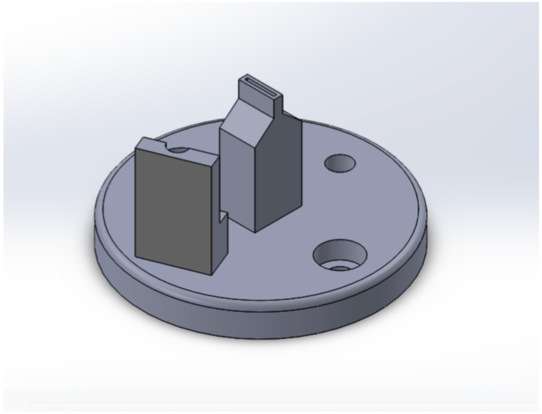


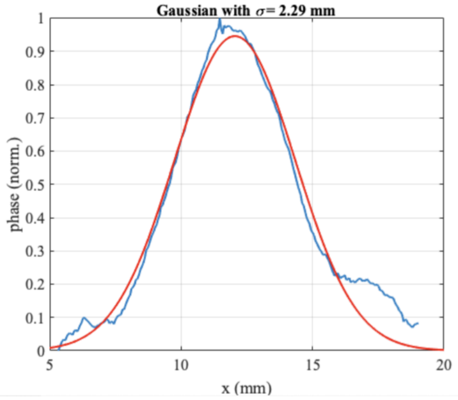




The plan





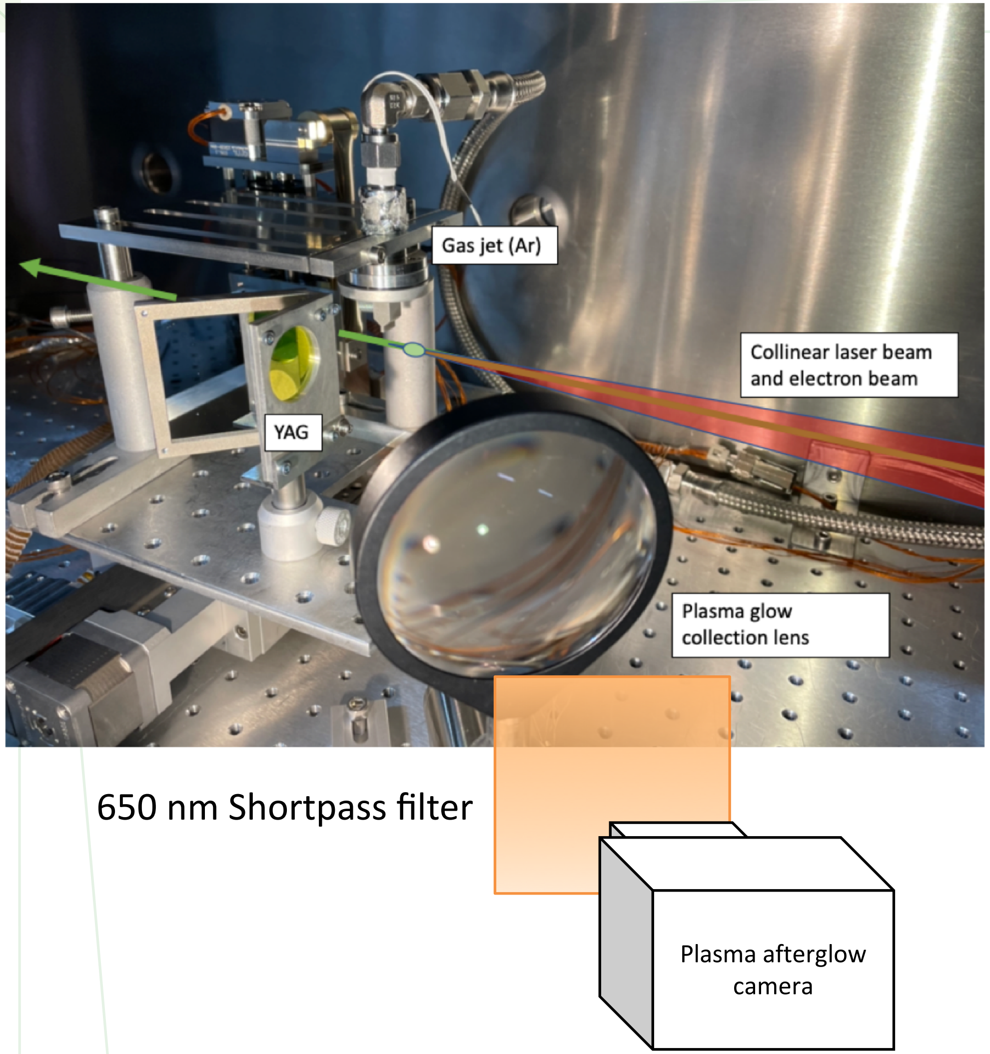


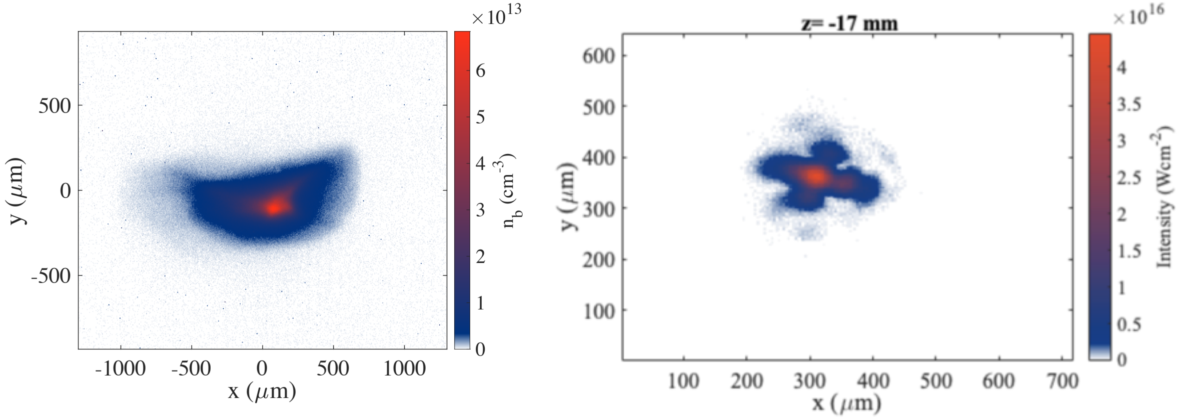
- **Co-linear geometry**

- **Short sub-sonic gas jet (slit geometry facilitates alignment and reduces gas load)**

- **Holed DSHM limits transportable divergence to electron spectrometer**

The setup in BA1



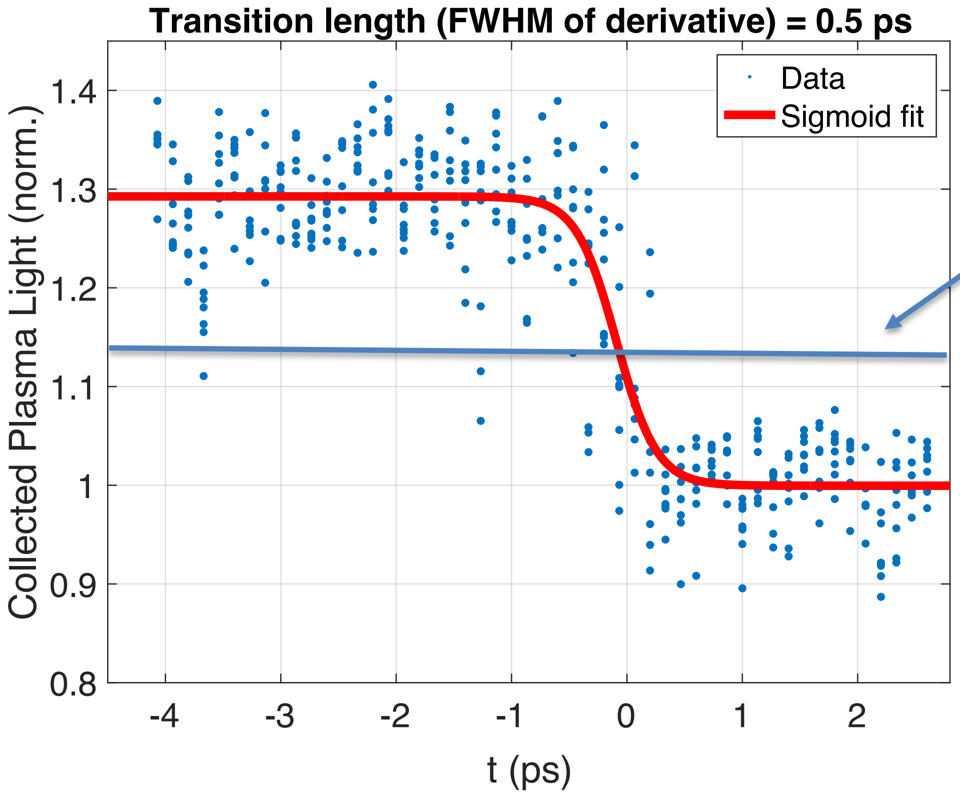


- Moderately dense electron beam
- TW laser system with LWFA capability

Energy	35.5 MeV
Charge	80 pC
Waist spot size (rms)	87 um x 38 um
Bunch length (rms)	300 fs
Laser spot size (rms)	35 um x 48 um

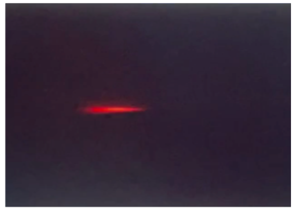
Plasma afterglow metrology experiment

Laser arrives first

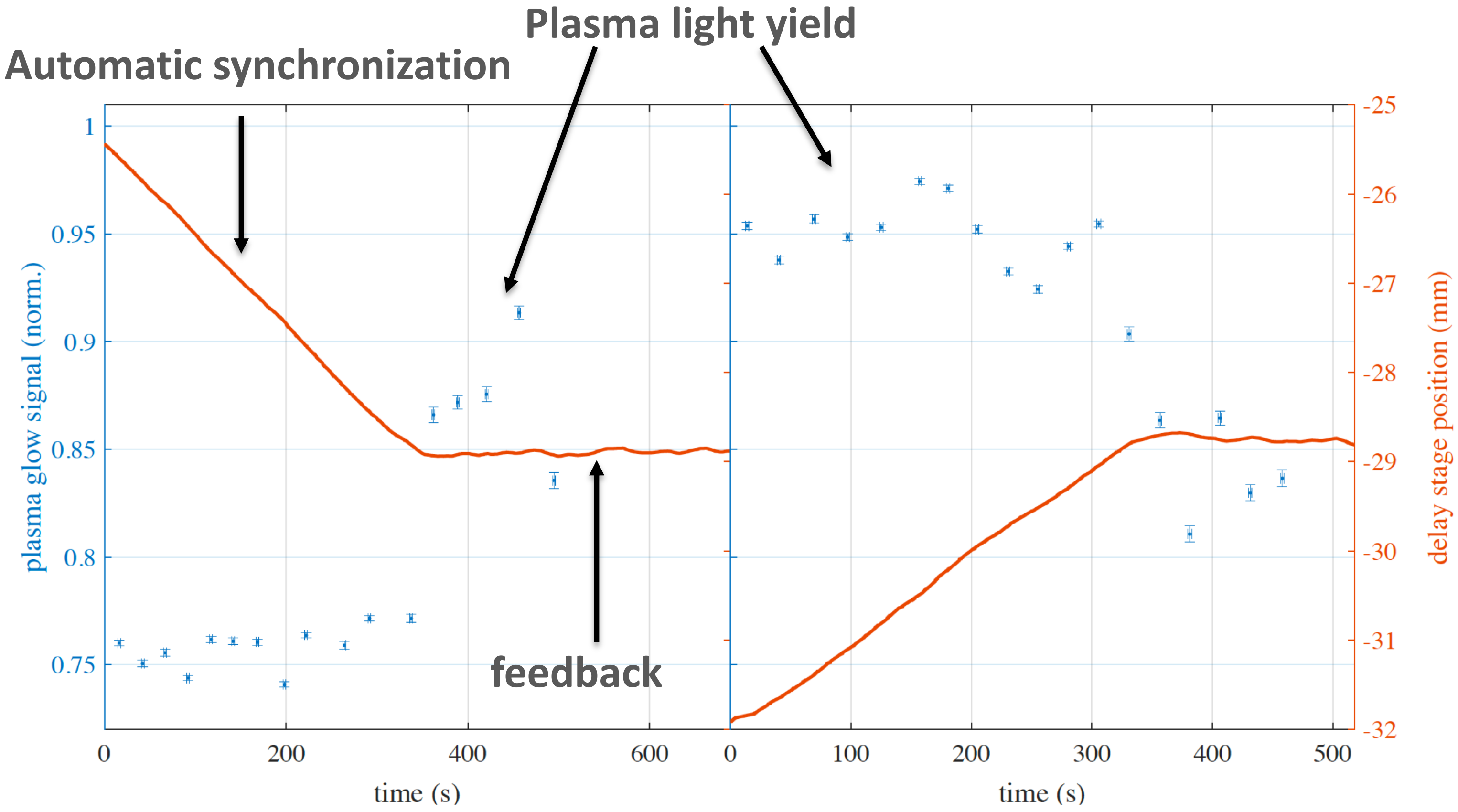


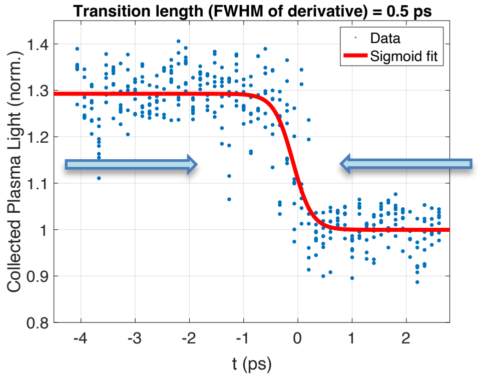
Threshold value

Electron beam arrives first



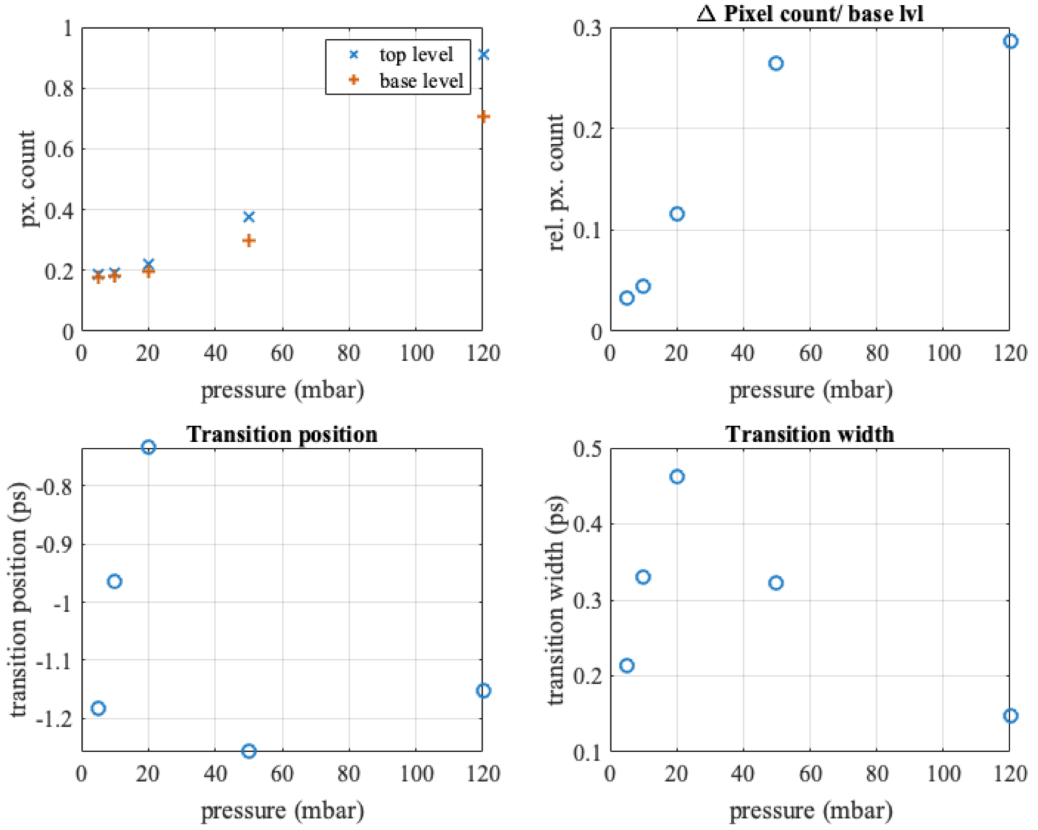
Feedback systems for plasma accelerators

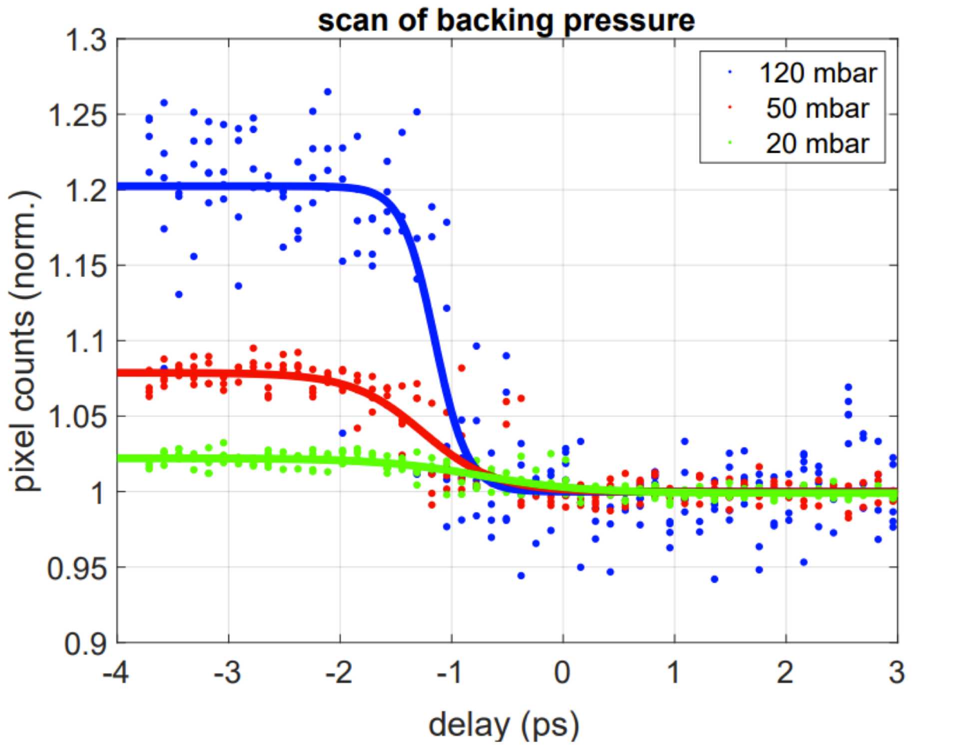




- Delay stage to control relative delay between electron beam and laser
- Plasma afterglow controlled laser delay to overlap with electron beam

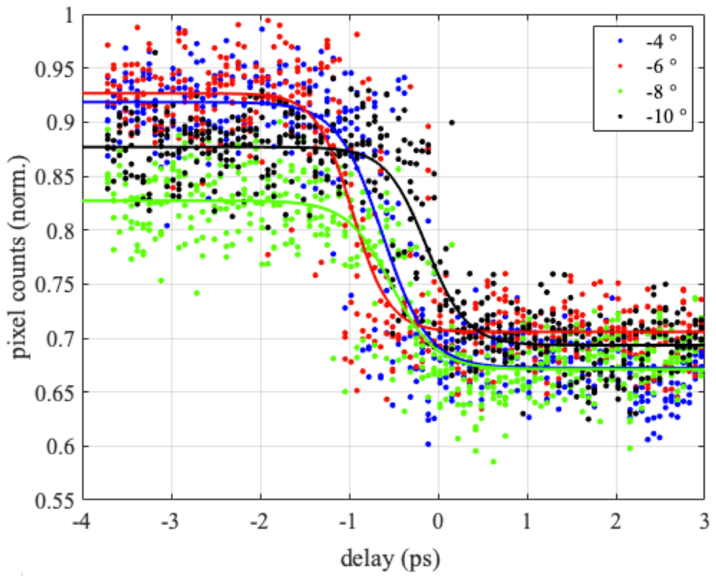
Influence of backing pressure

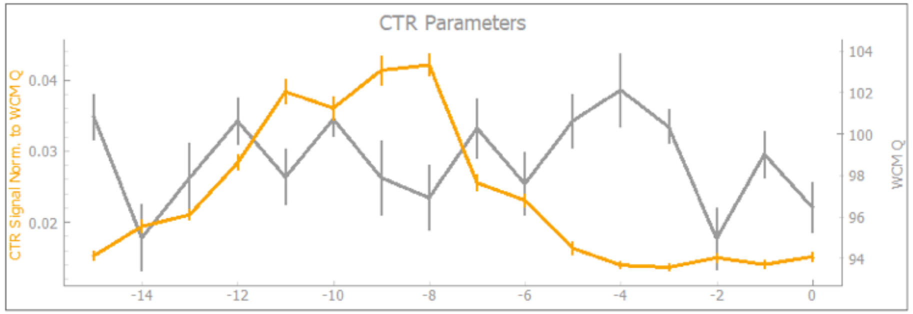


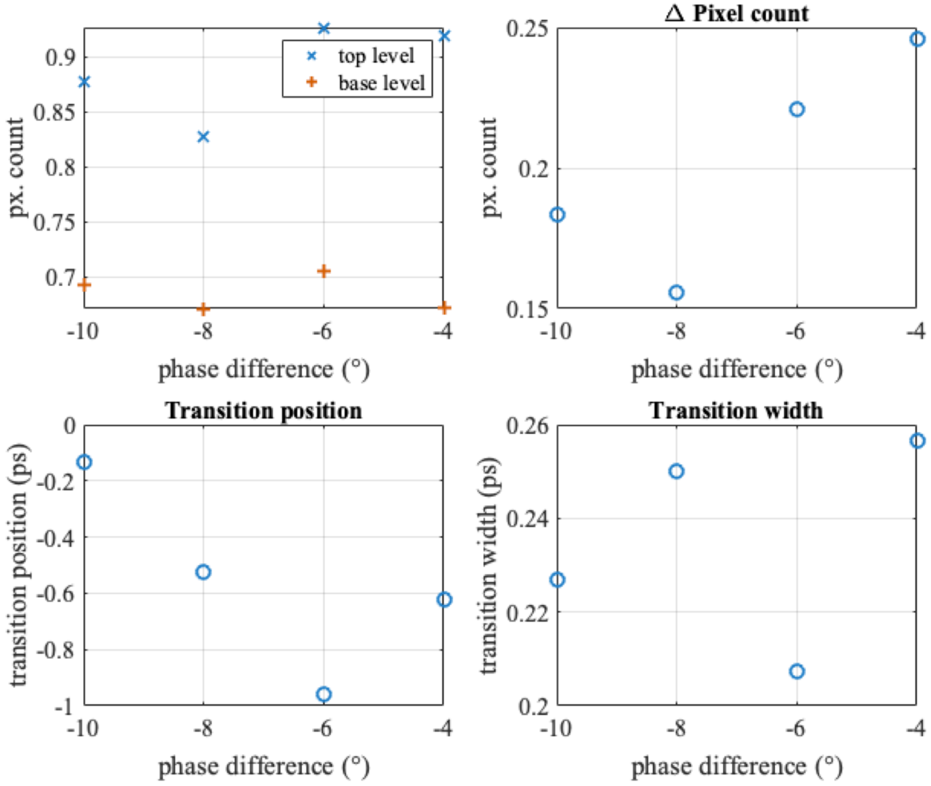


- Short transition for a large range of gas pressure / plasma densities
- Saturation for larger pressures with eventual drop to 0 at p > 1 bar
- **But:** Curve needs to be calibrated for every pressure to set threshold

Dependency on LINAC phase



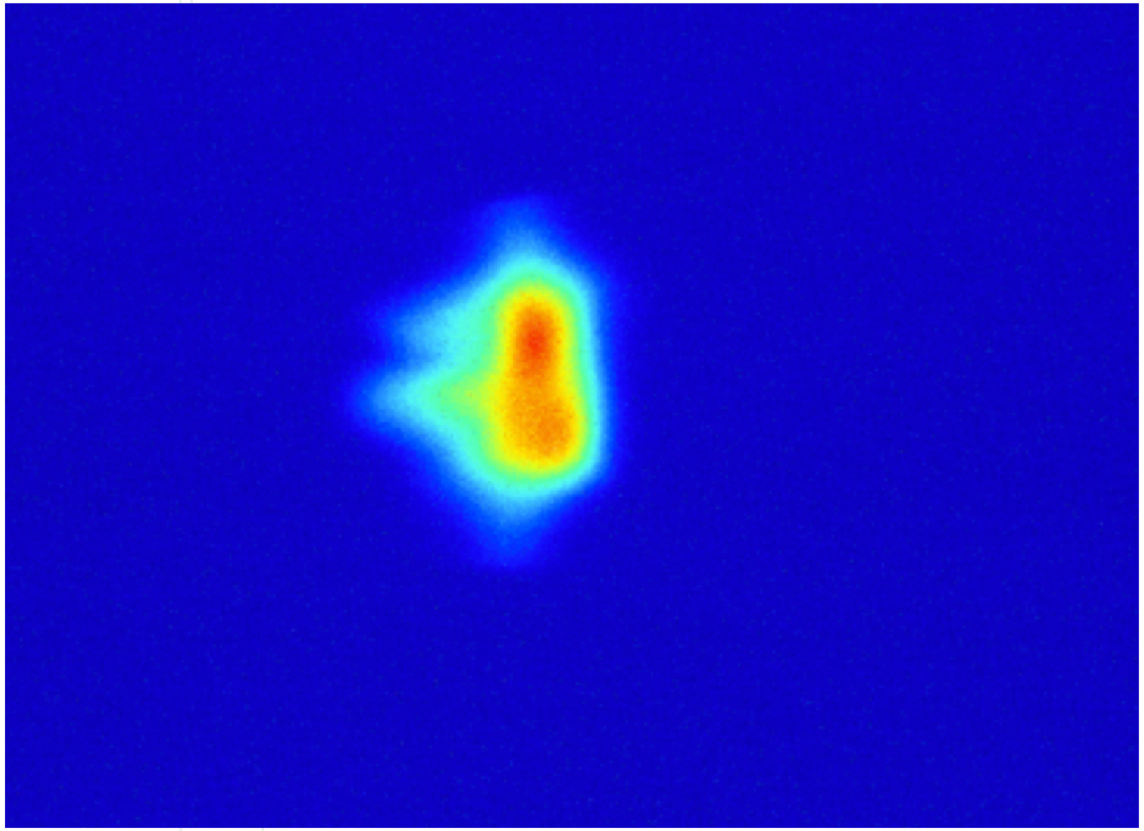




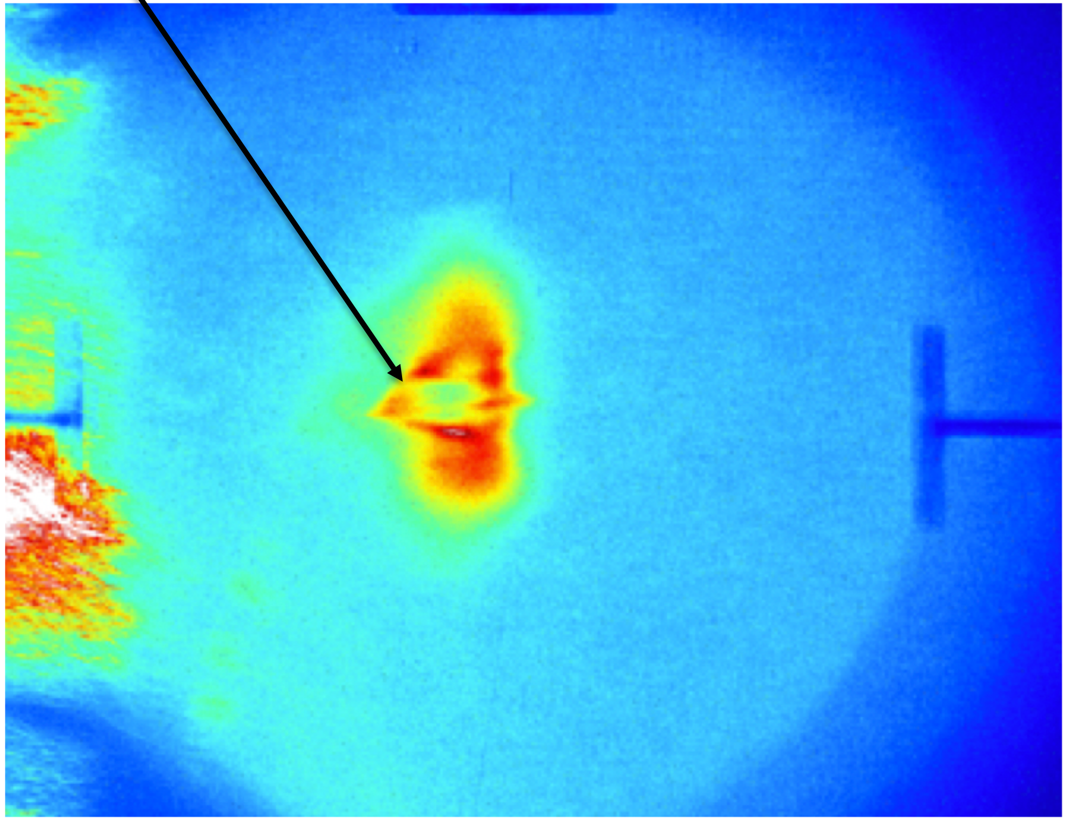
- Transition curves remain comparable in a RF phase range from -4 to -10 degree
- Plasma afterglow feedback remained stable without RF feedback

Plasma micro lens: 2D Imaging mode of plasma lens

Lensed sub-beam movable in x and y

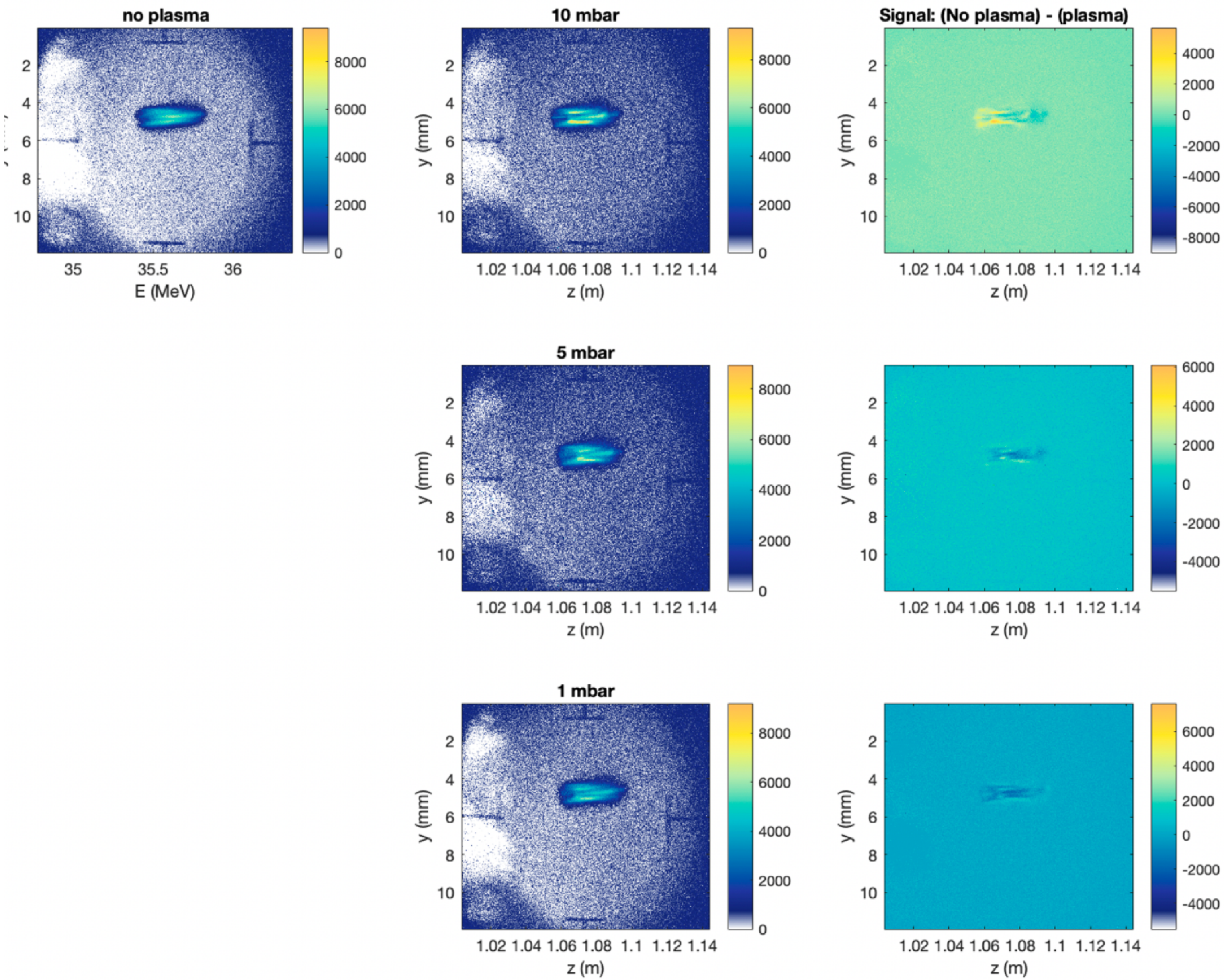


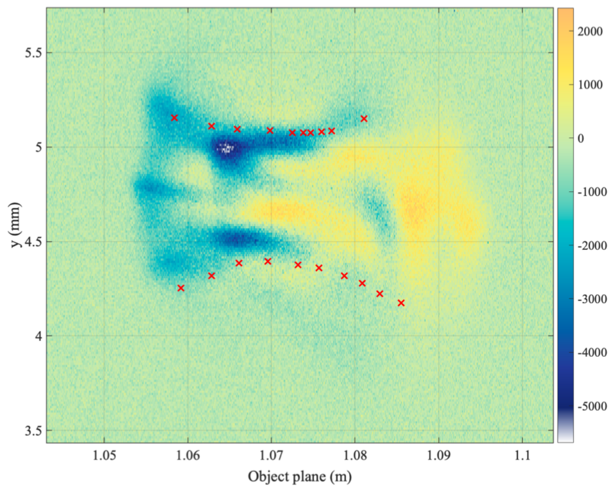
Laser off



Laser on

Evaluation of the perturbed beam part



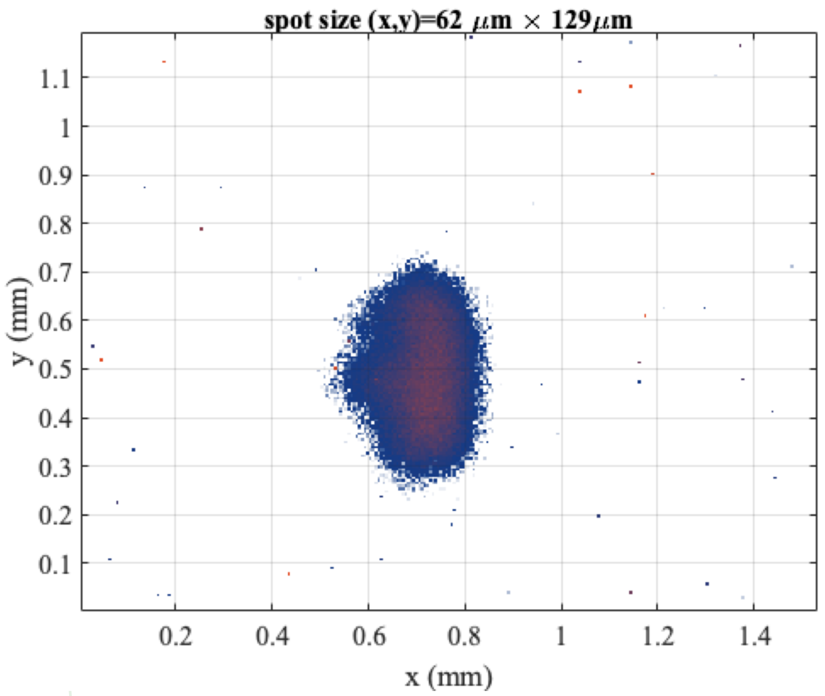


- Butterfly gives information of sub-beam focusing

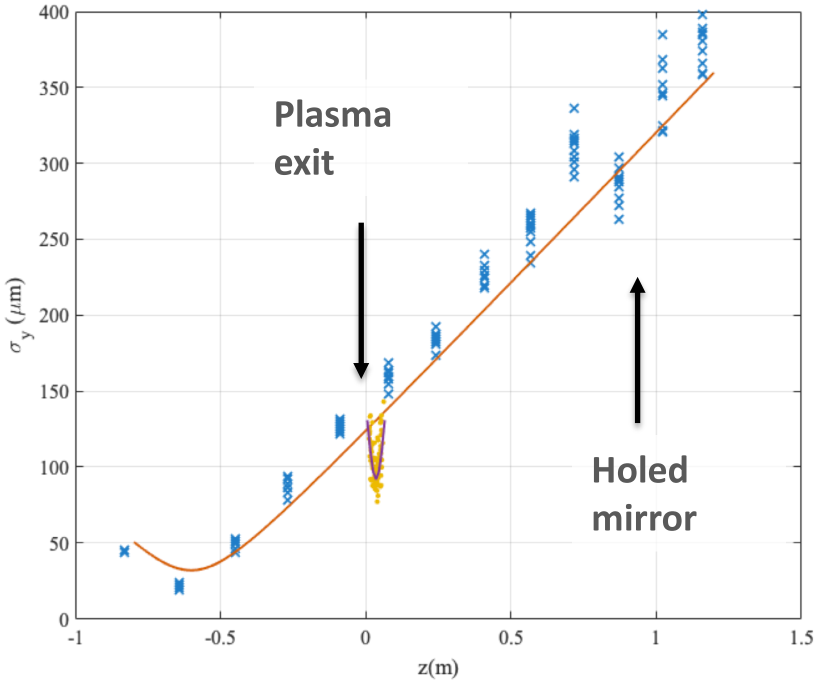
- High-divergent particles likely got absorbed in the holed mirror so appear as a ‘hole’ in the signal.

Plasma lens results

YAG image

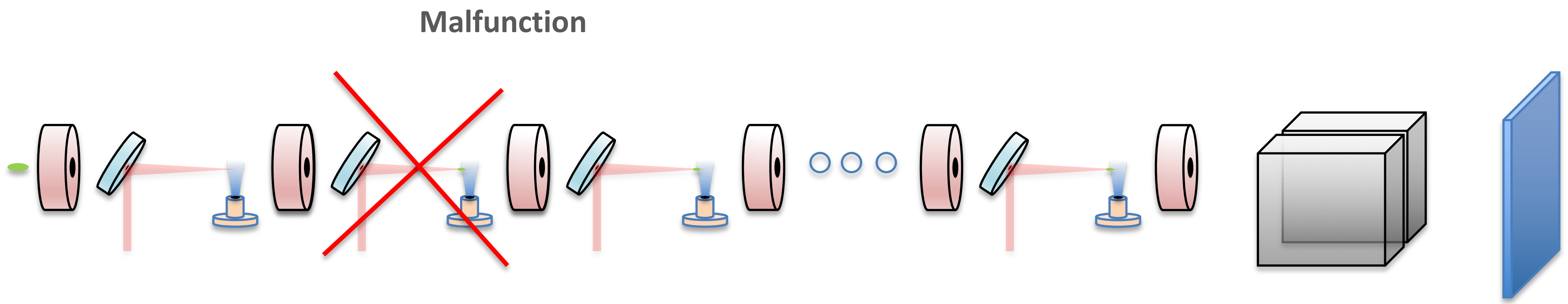


Object-plane scan

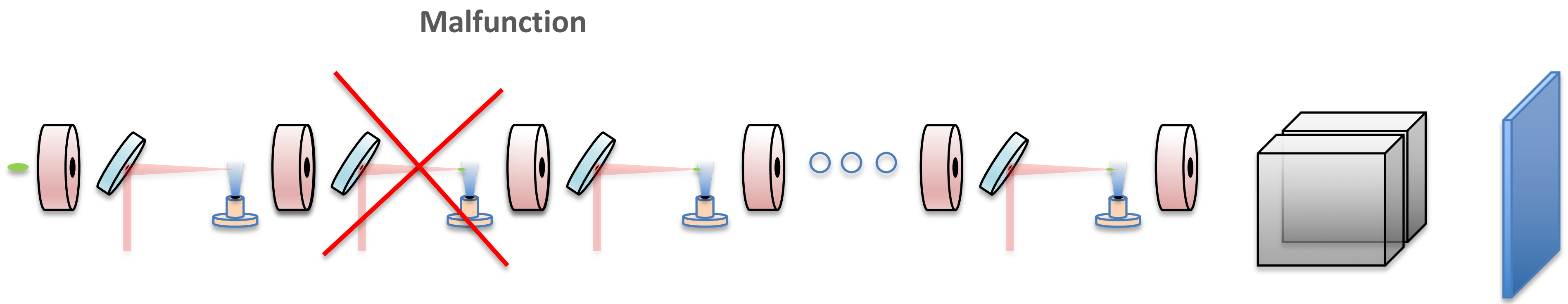


- Use electron spectrometer to image different planes
- Combined single-shot and multi-shot measurements
- Demonstration and measurement of tiny plasma-lens focusing

Outlook – potential application



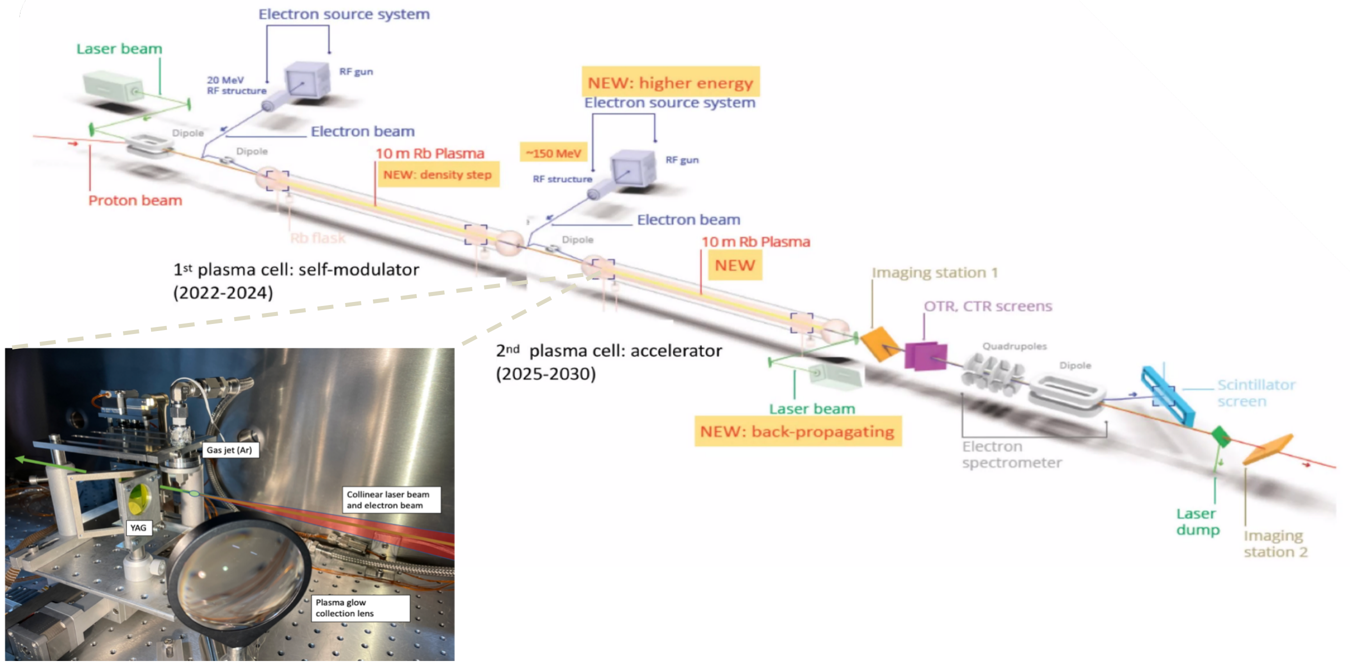
Outlook – potential application



Automated maintenance

1. Lower gas pressure of any gas jet and lower laser energy to ionize → LWFA stage becomes plasma lens to remain transport
2. Scan transverse alignment of laser to electron beam for centering
3. Scan timing of particular stage, set timing close to transition
4. Increase laser energy and gas pressure again
5. Go to next stage

Outlook – AWAKE 2



- Beam density AWAKE 2 of new electron source E15 cm^{-3}
- This is 1 order of magnitude higher than presented experiment
- Potential for a similar feedback system to ensure phase-stable seeding of self modulation.
- Great synergies also between FEBE beams and AWAKE 2 electron beams

Thank you for your attention