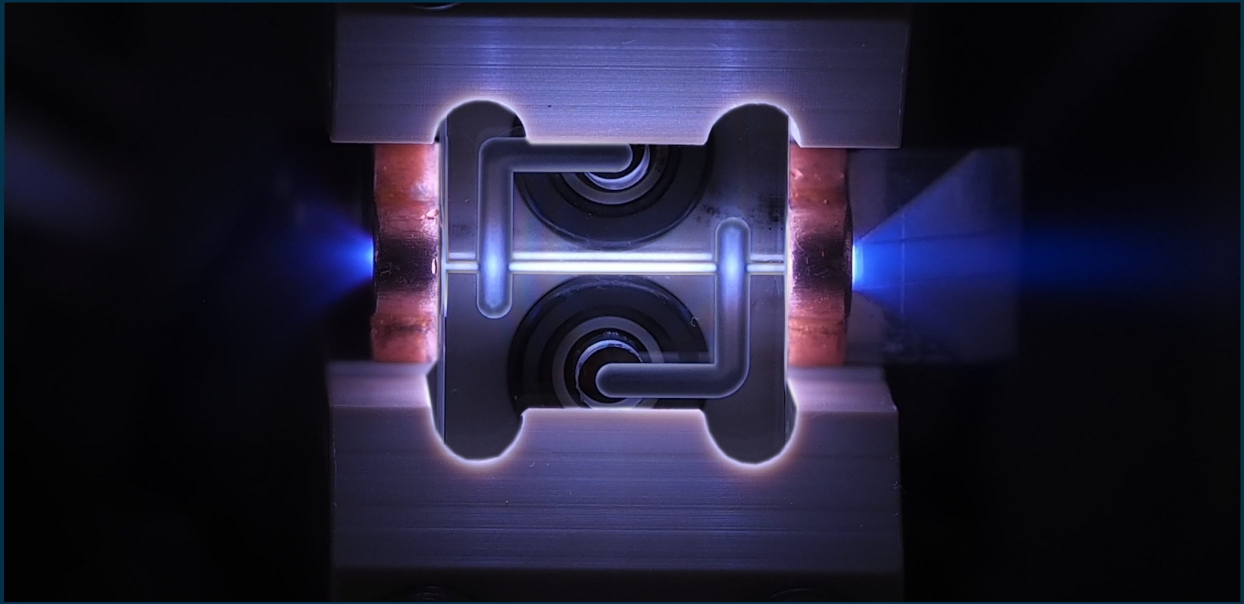
UiO plasma lenses research at CLEAR, with applications

NORCC



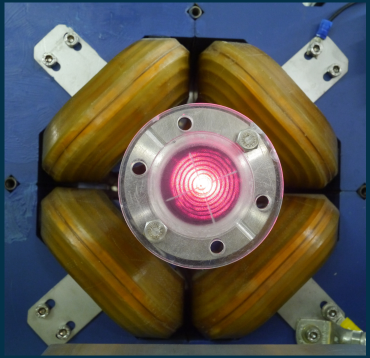
Kyrre Sjobak

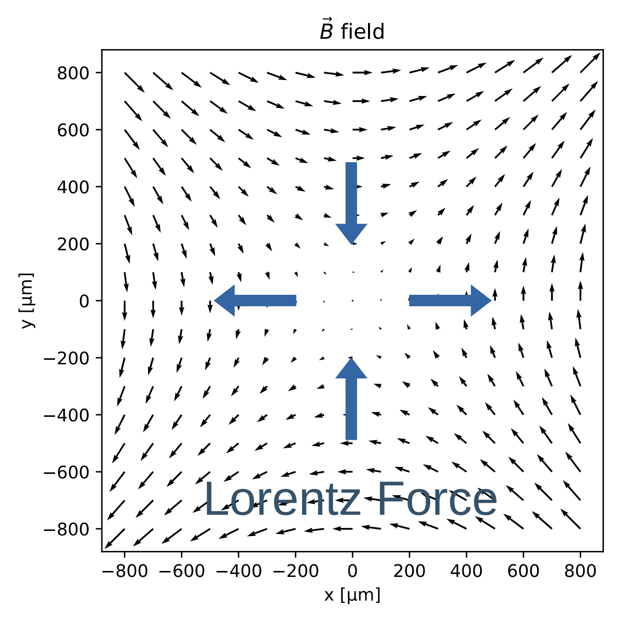
NorCC Workshop 2022, Sept. 14. – 15.

Session on Future Accelerators & Experiments

Plasma lenses: What are they?

- Charged particle beams must be controlled and focused, otherwise they diverge
- Standard method today is quadrupole magnets
  - Simultaneously focus and defocus the beam
  - Must be used in arrays for net focusing
- Alternative method:
  Active Plasma Lens
  - Same effect in horizontal and vertical planes
  - Works by passing a current through a plasma, generating a symmetric magnetic field, which focuses the beam





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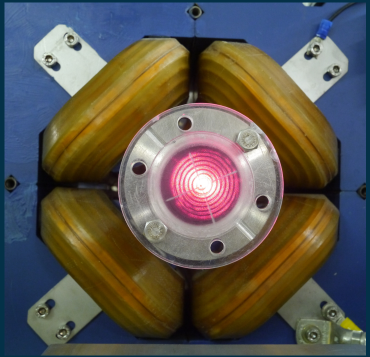

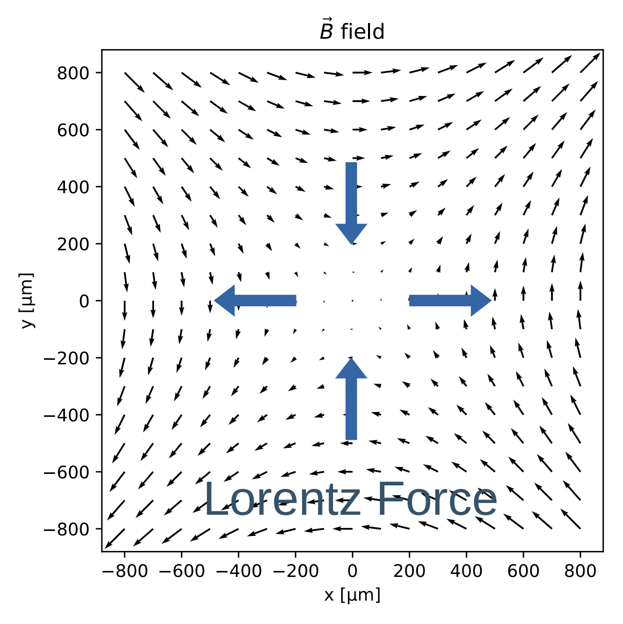

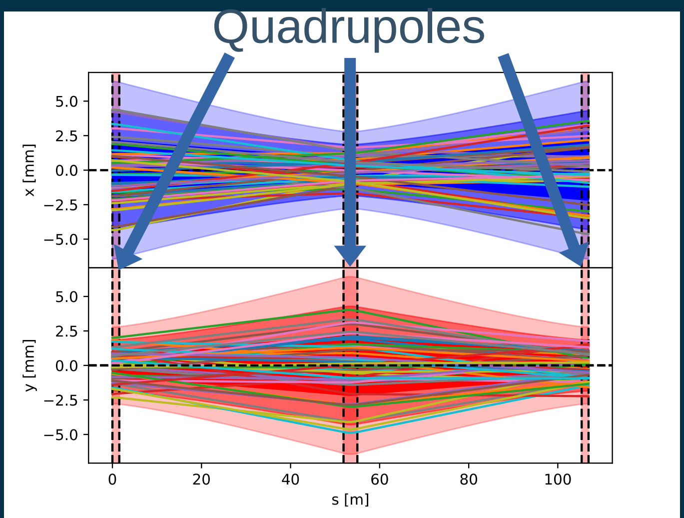

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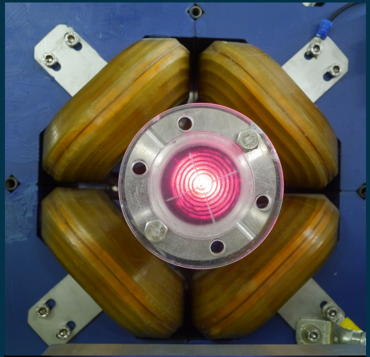

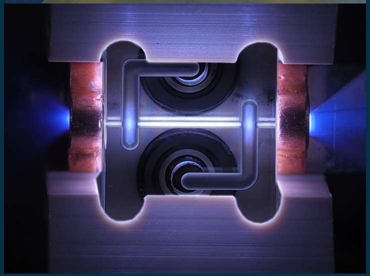

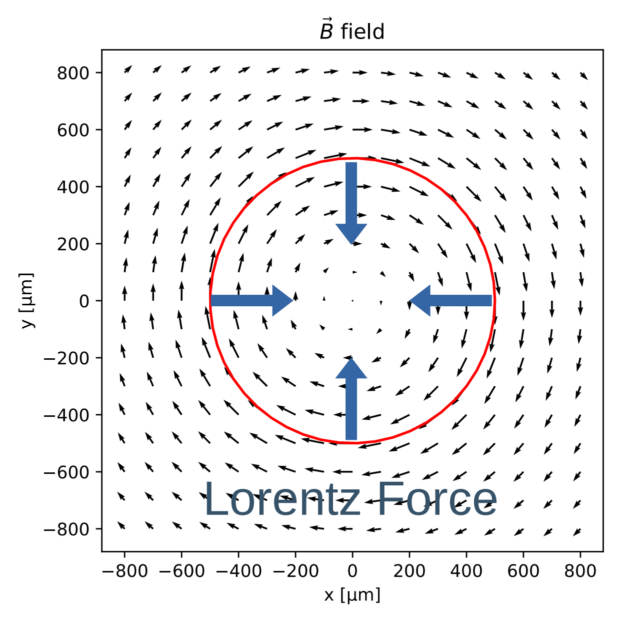

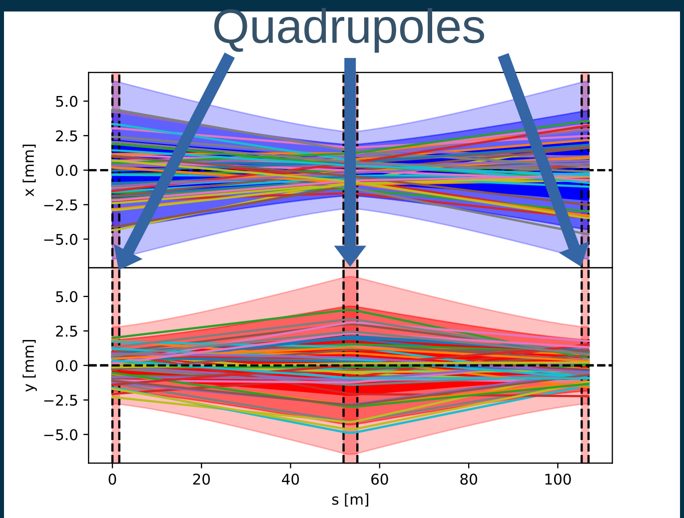

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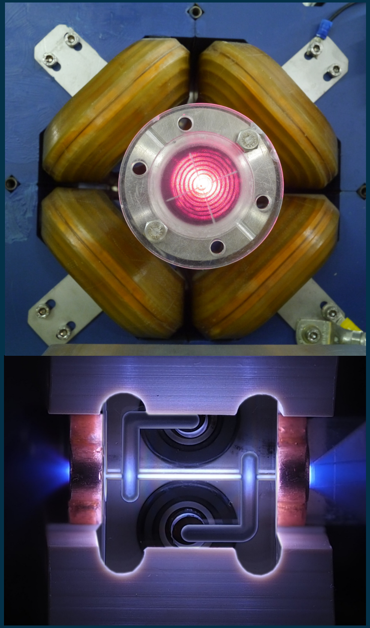
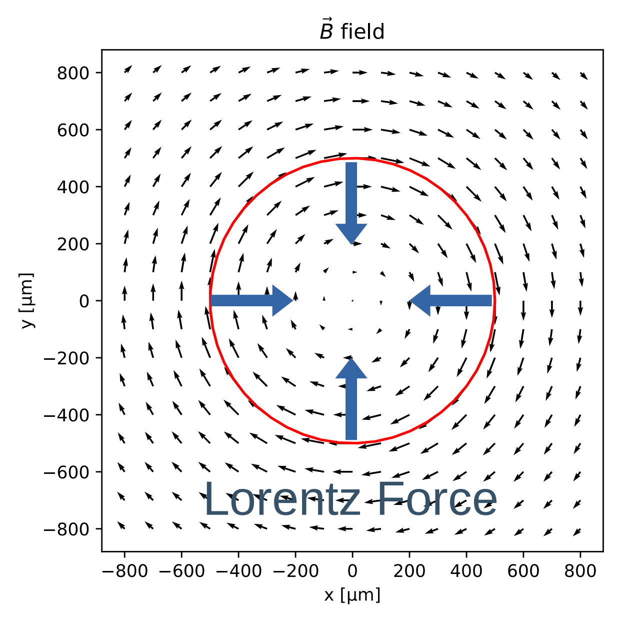
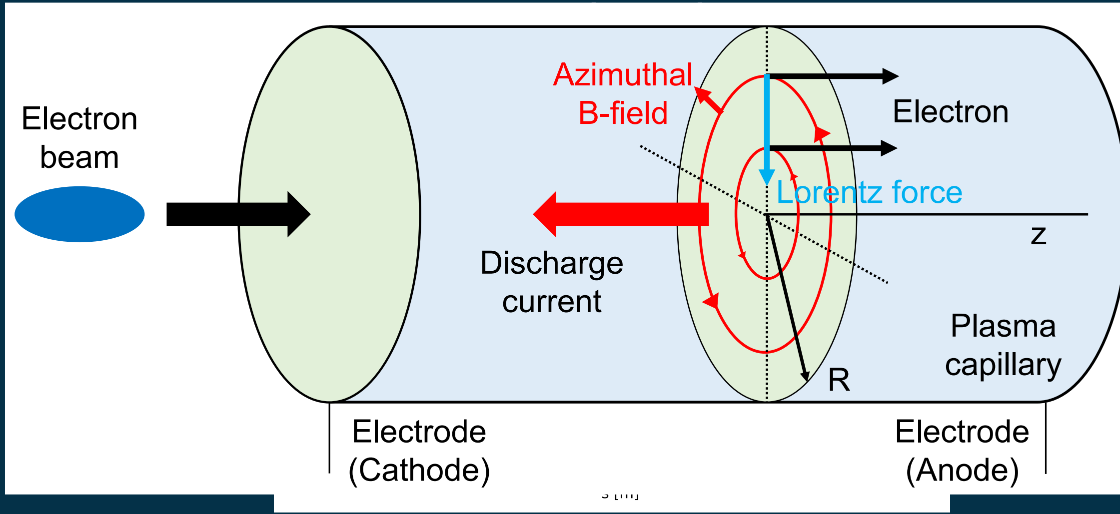
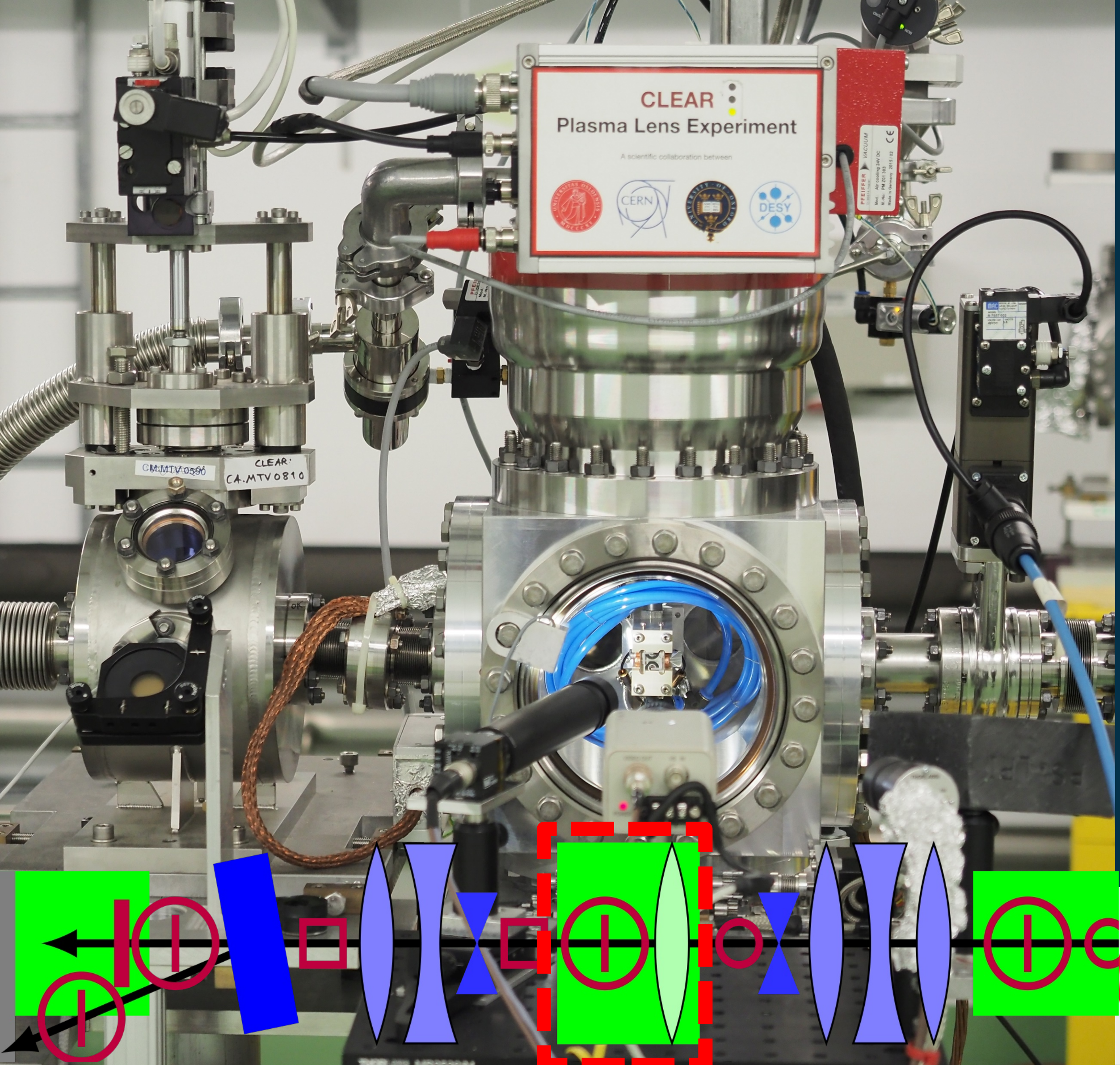






Plasma lenses: Why interesting?

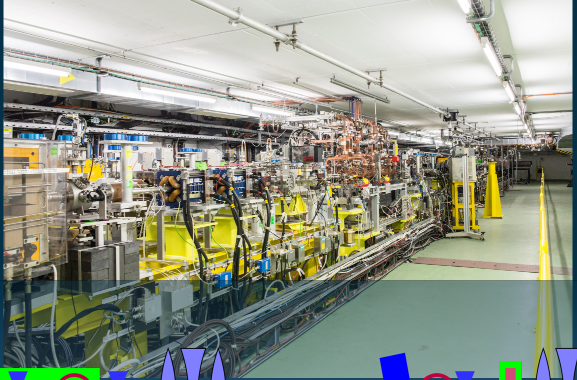
- Azimuthally symmetric focusing device
  - Can have constant gradient throughout the aperture
- Makes it possible to create simpler and more compact high-performance lens arrangements
- Interesting for several applications:
  - Staging of plasma wakefield accelerators to high energy (see Carl’s talk)
  - Fine focus of beam into experiments
  - Capture of strongly diverging beam from particle sources



The CLEAR Plasma Lens Experiment

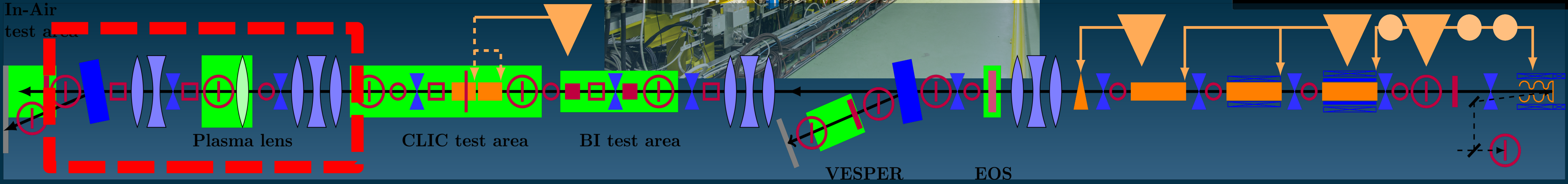
- Demonstrate plasma lenses for use in particle accelerators
- Characterize lens properties for different gasses, currents, capillary geometries, …
- Collaboration led by UiO, includes CERN, Oxford, and DESY
- Installed at CLEAR

clear



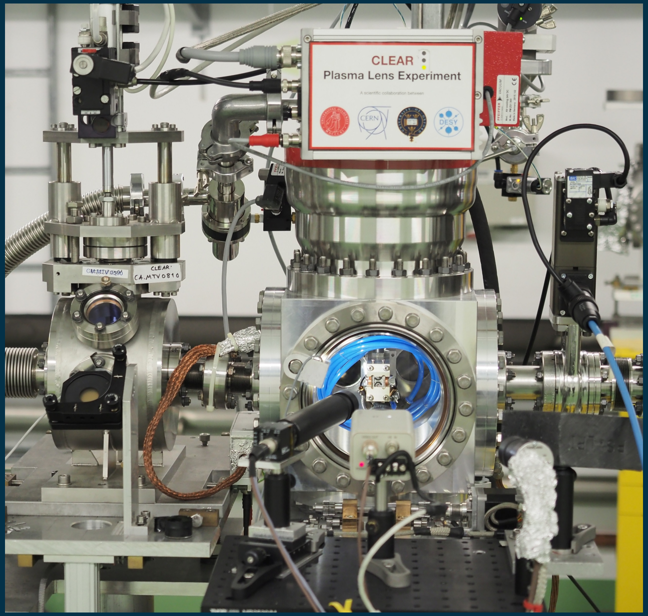
Beam parameters

- 60-200 MeV electrons
- 10 pC – 50 nC / pulse
- 1-10 pulses/second
- Pulse length 1 ps – 50 ns



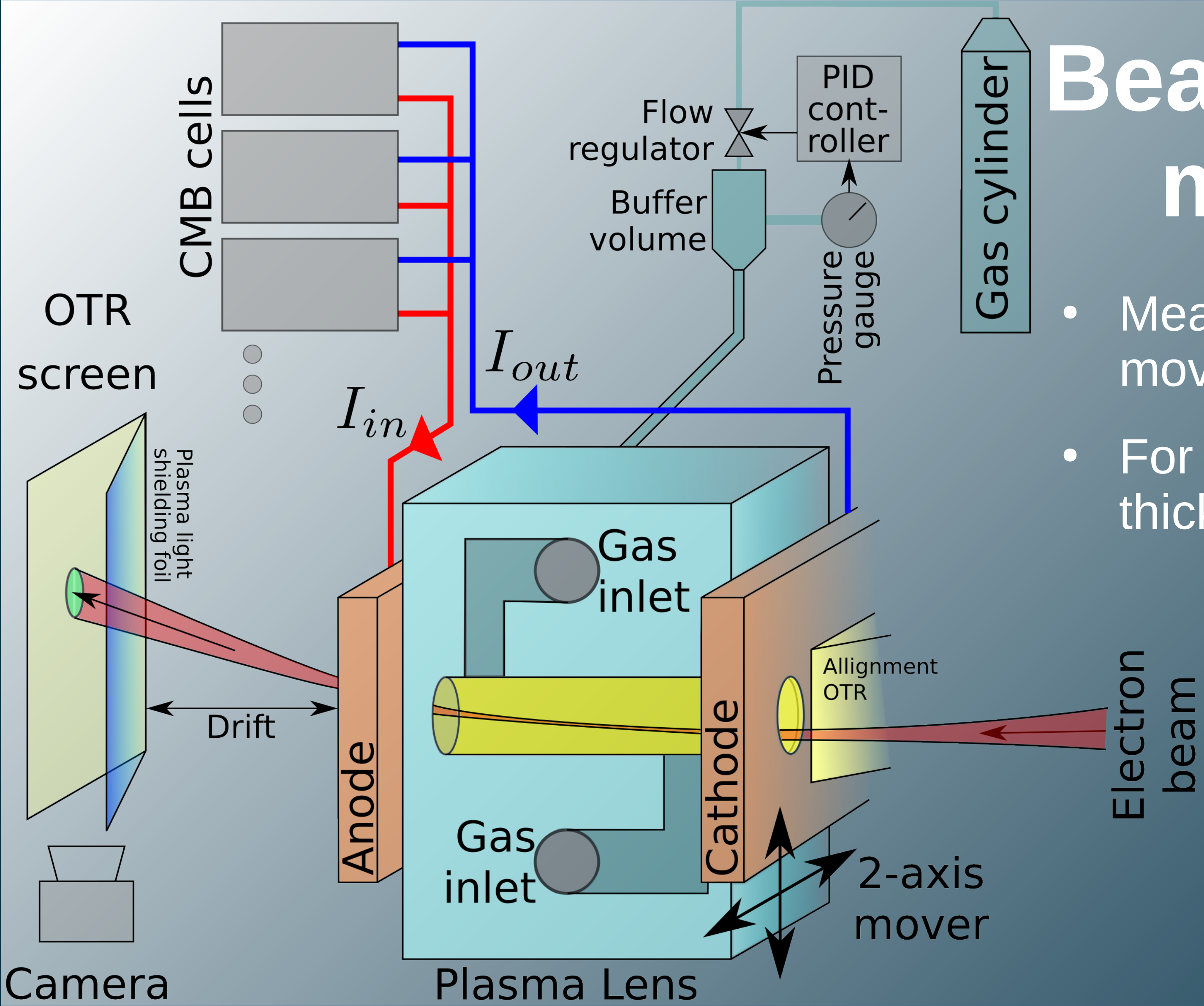
- CLEAR = CERN Linear Accelerator for Research
  - Based on the former CLIC test facility (CTF3)
- User facility:
  - Changing experiments on a ~weekly basis
  - Users from out- and inside CERN
- Diagnostics, data acquisition, and beam manipulation devices already installed
- Separated from rest of CERN accelerator complex → Ran through LS2
- Electrons → Clean radiation environment, little activation

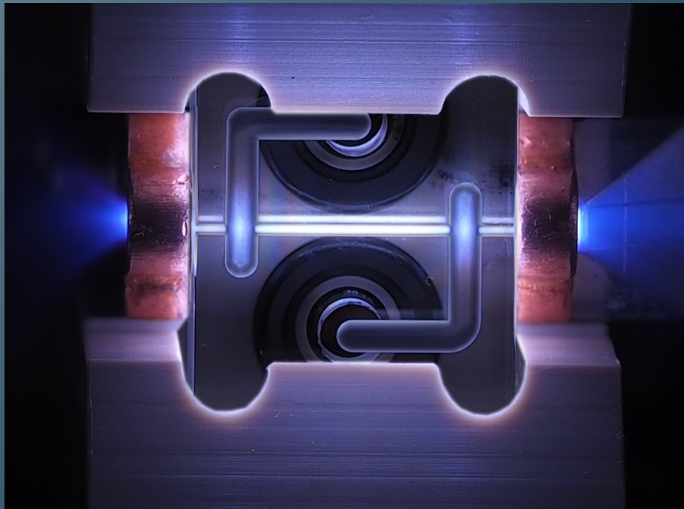
- Deep collaboration with accelerator group @UiO
- Examples of experiments:
  - Beam tests of accelerator devices: plasma lens,beam position monitors, bunch length meas.
  - Irradiation of electronics, functional tests for radiation environments
  - Tests of novel radiotherapy schemes (e.g. FLASH in collaboration with CHUV): Technology and effects



Beam deflection measurement

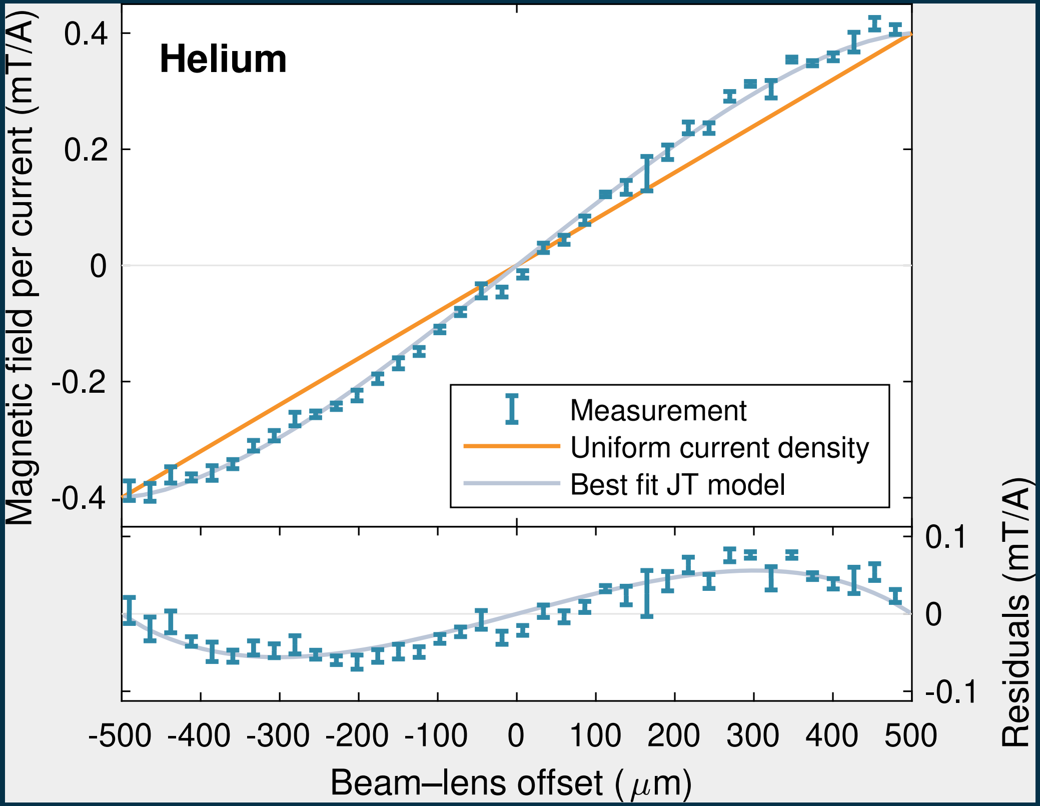
- Measure field profile by moving lens relative to beam
- For very strong fields, thick lens effect is important





Complications: Non-linearities

- With light gasses, the field is not linearly growing with radius
- This is caused by non-uniform electron temperature in the plasma, concentrating the current near the axis
- Non-linear field results in a growth of beam emittance
- Heavier gasses have a uniform electron temperature and a linear field
- This helps preserving beam emittance



C. Lindstrøm et al., “Emittance Preservation in an Aberration-Free Active Plasma Lens”, PRL 2018

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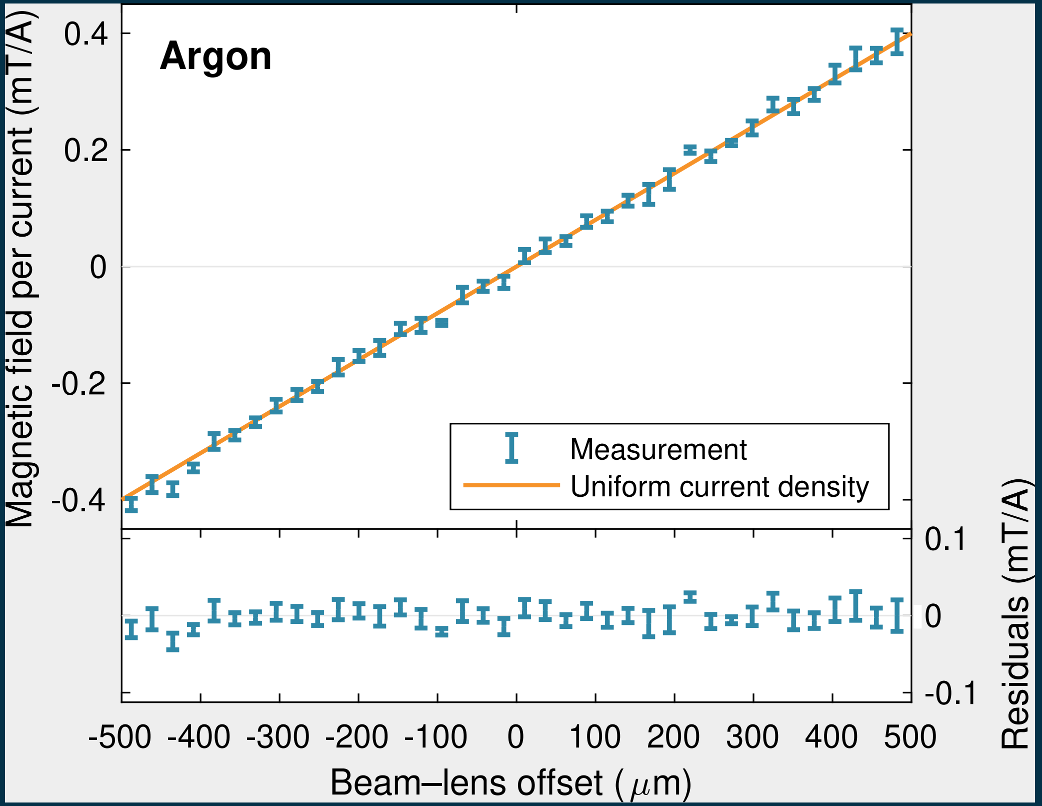

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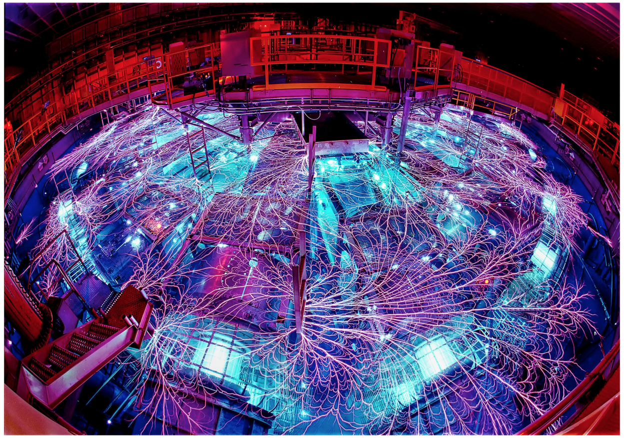


Randy Montoya/Sandia National Laboratory

Bert Hickman, Stoneridge Engineering

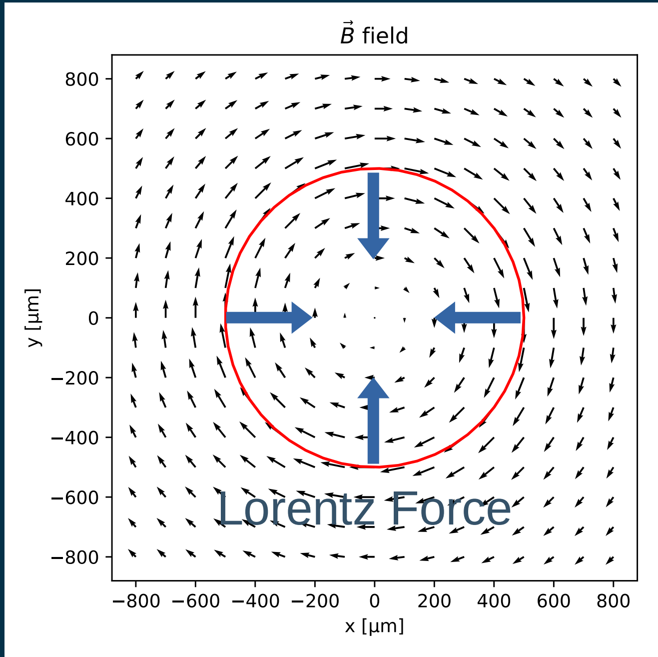
Complications: Magnetic z-pinch

Pinch!

$$\frac{B^2}{2\mu_0} = \frac{\mu_0 I^2}{8\pi^2 R^2} > n_0 k T_e \, ,$$

Lorentz force compression

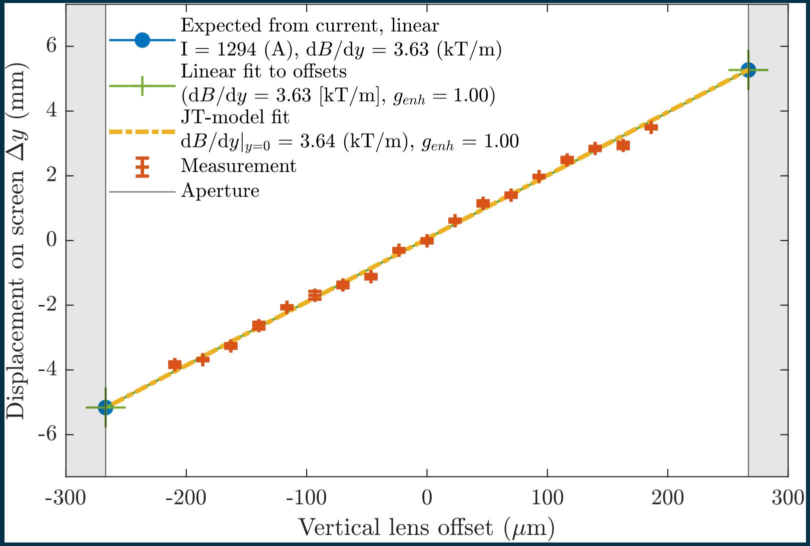
Plasma electron pressure

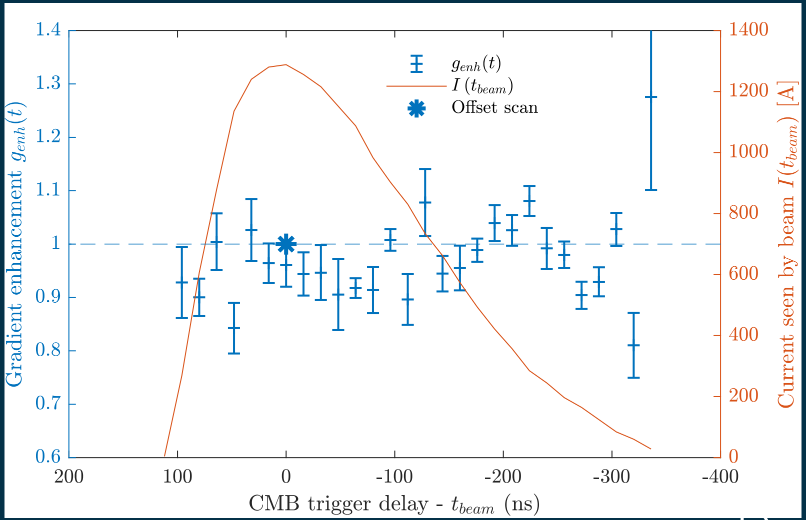


- Bennet Relation: Static balance of pressures
- If Lorentz force wins, current-carrying area contracts => Nonlinearity!
  - Gives a wire-like field, B $\propto$ 1/R
  - Has been tested for antiproton collection and heavy ion beams
  - Not ideal for preserving emittance from a small source
- Problem increases with surface magnetic field B = g*R
- Also depends on temperature, gas density and degree of ionization, …
- At what point do we hit the pinch limit?

Strong focusing in Active Plasma Lens

- Active plasma lens has been demonstrated to be linear up to at least 3.6 kT/m
  - Quadrupole magnets are limited to a few 100 T/m
- Lens stayed linear through ≈300 ns discharge
- No pinch even if Bennet was broken!
  - Not enough time?
  - High electron pressure
- Developed a technique to characterize extremely strong focusing (thick lens)
- Only 500 µm diameter capillary

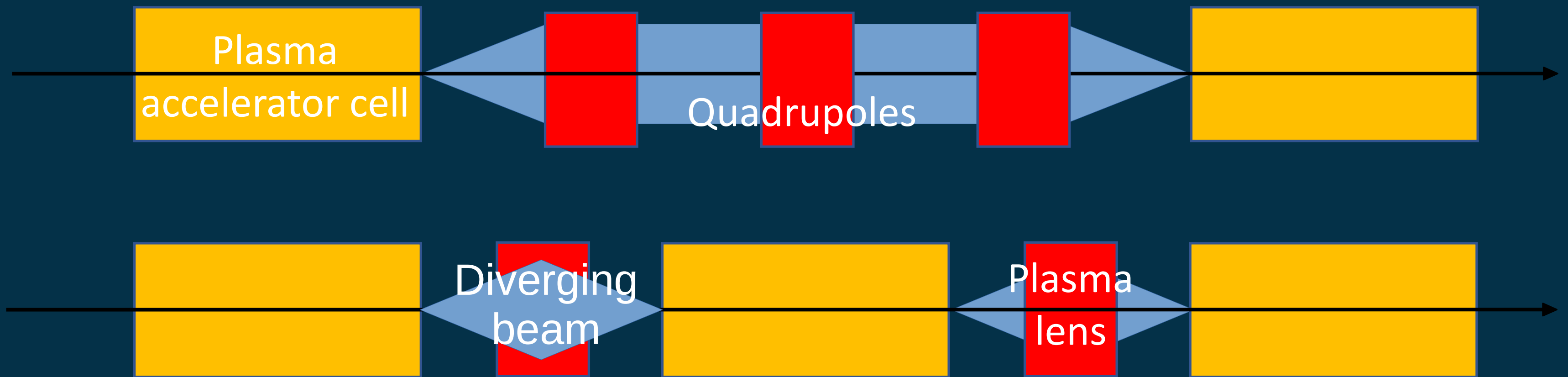




K. Sjobak et al., “Strong focusing gradient in a linear active plasma lens”, PRAB 2021

Staging of plasma accelerators

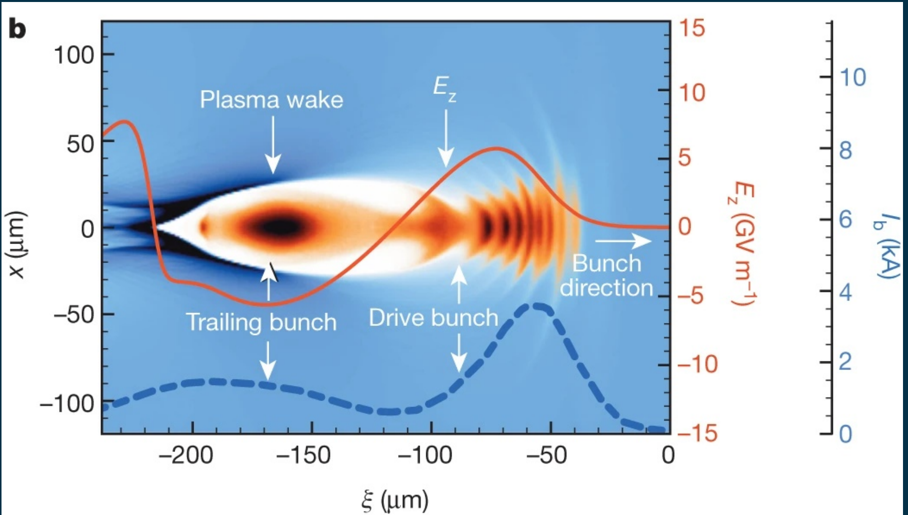
- Beam is small inside plasma accelerator stages
- Strong divergence at exit
  & strong focusing needed towards entrance
- Plasma lenses can potentially do this better and more compact than quadrupole arrays (see Carl's talk)



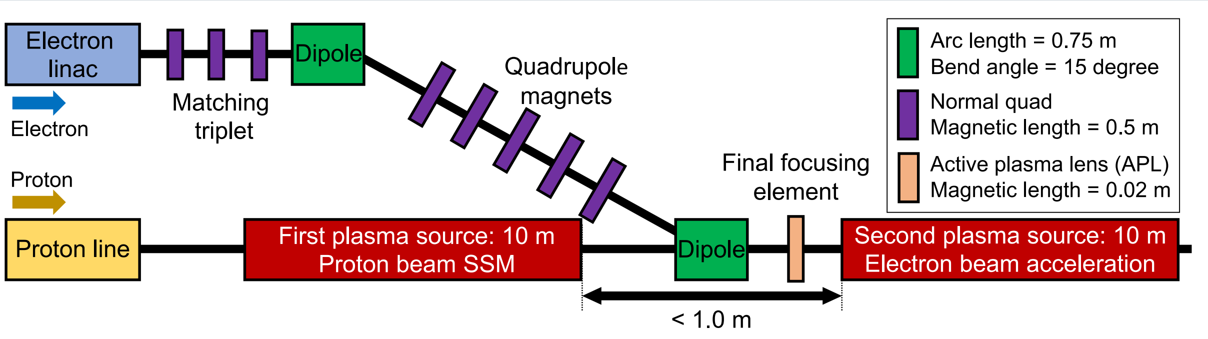
Injection of probe beam to AWAKE

- Need to focus electron beam down to ~10 μm to inject into plasma bubble created by proton driver
- Distance between plasma sources limited, or proton beam de-bunches
- Can be done with APL

M. Litos et al., “High-efficiency acceleration of an electron beam in a plasma wakefield accelerator”, Nature 2014

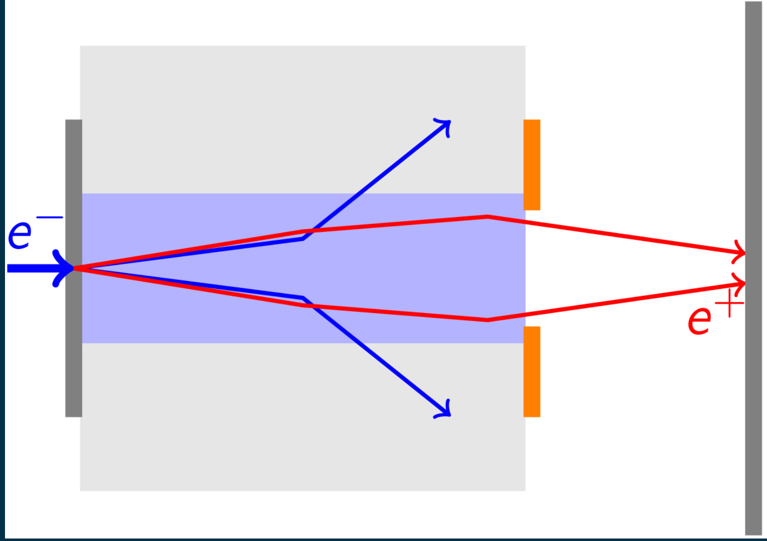


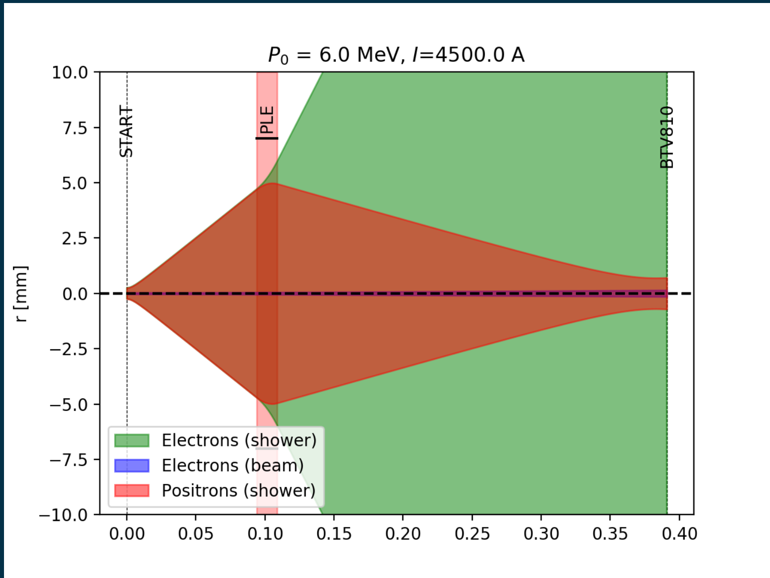
S.Y.-Kim et al., “Witness electron beam injection using an active plasma lens for a proton beam-driven plasma wakefield accelerator”, PRAB 2021



Positron sources

- Plasma lenses can efficiently collect secondary particles from a target
  - Positrons, antiprotons, …
- Rejects wrong-charge particles
- Less energy-dependent than solenoids





Some outstanding questions

- "Industrialization" of Active Plasma Lenses
- More possibilities with large (>1 mm diameter) lenses that have linear field and capable of high gradient
  - What is the margin to pinching? Trade-off vs. skin-depth?
  - Engineering: Gas handling and current sources
- Heavy gas preferable for linearity, but scatters more. Can we compromise? Is Argon *really* the best gas?
- How to best handle plasma wake-fields?
- Exotic lenses for specialized applications

Conclusions

- Plasma lenses are azimuthally symmetric magnetic focusing devices
- Can be linear, and can operate at very high magnetic gradients
- Very interesting device for controlling and creating strongly diverging/converging beams
- Possible applications to accelerator staging, experiment focusing, and secondary particle sources

Numbered references

1) D. Gamba et al., “The CLEAR user facility at CERN,” Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, Dec. 2017, doi: 10.1016/j.nima.2017.11.080.

2) K. Sjobak et al., “Status of the CLEAR Electron Beam User Facility at CERN,” 2019. doi: 10.18429/jacow-ipac2019-mopts054.