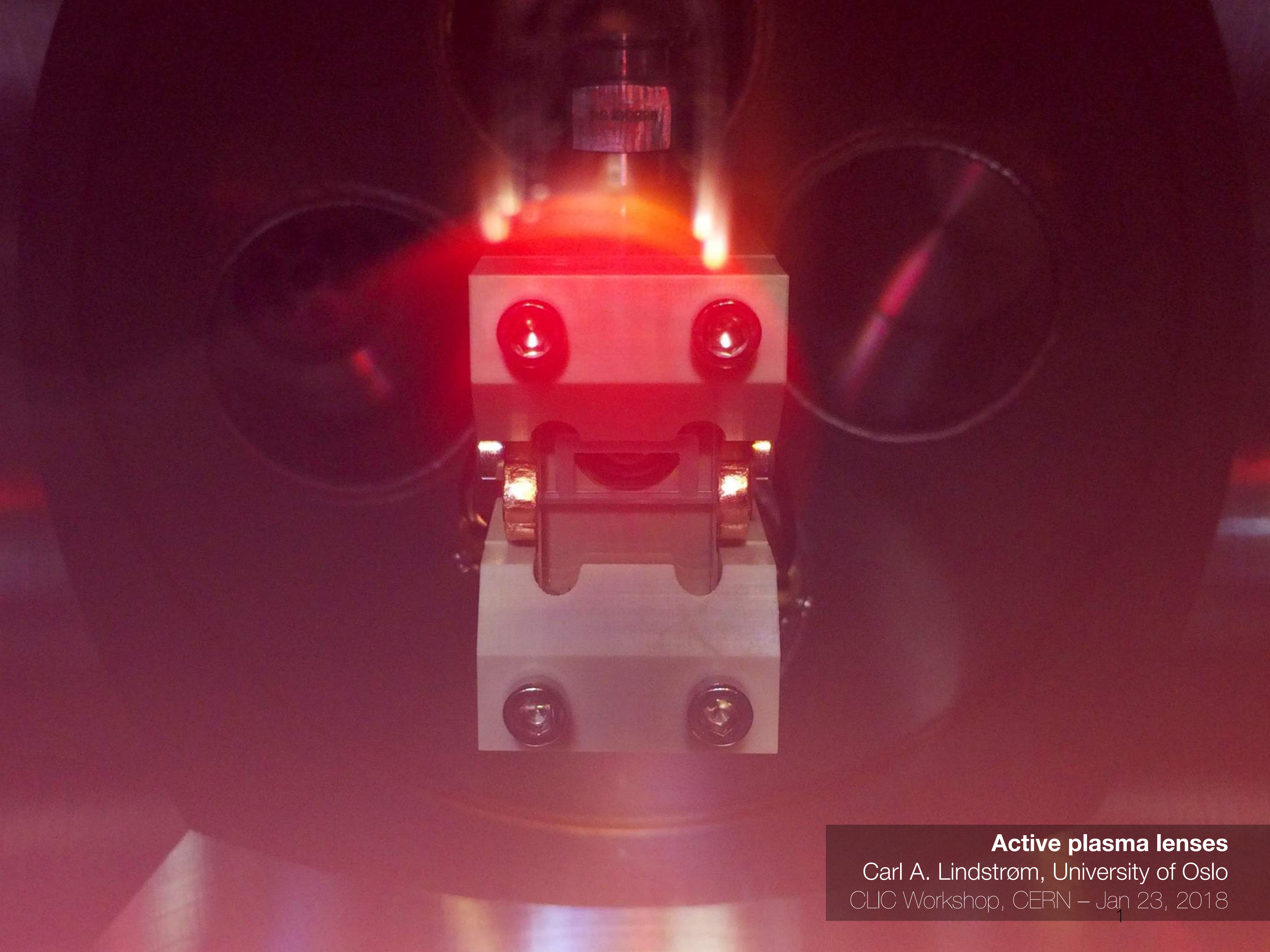


Active plasma lenses

Carl A. Lindstrøm, University of Oslo

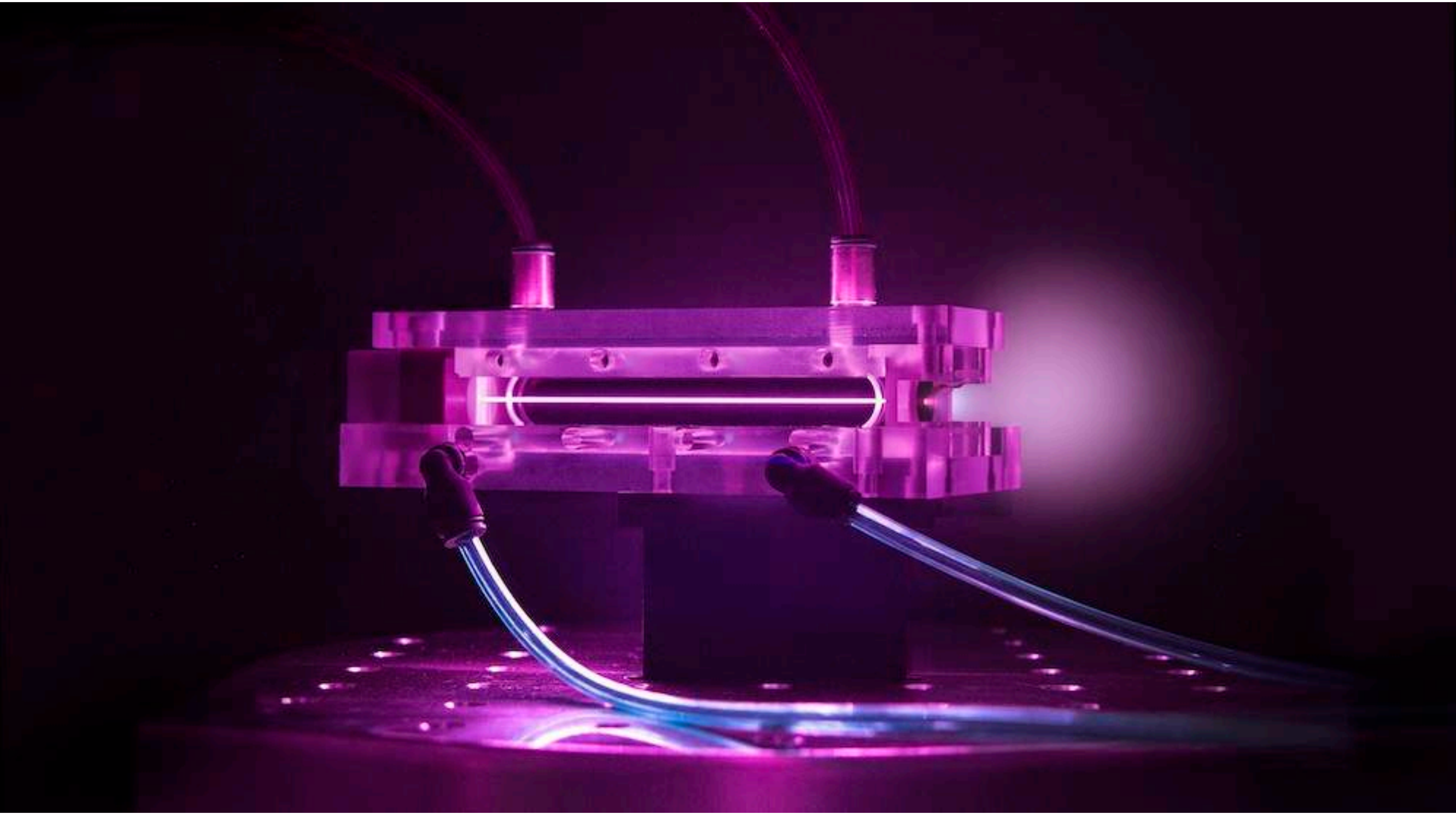
CLIC Workshop, CERN – Jan 23, 2018

Active plasma lenses

CLIC Workshop – Jan 23, 2018

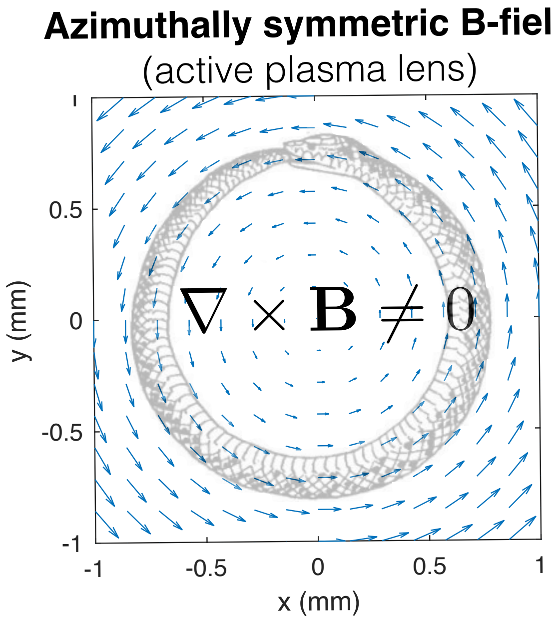
Carl A. Lindstrøm
PhD Student
University of Oslo, Department of Physics

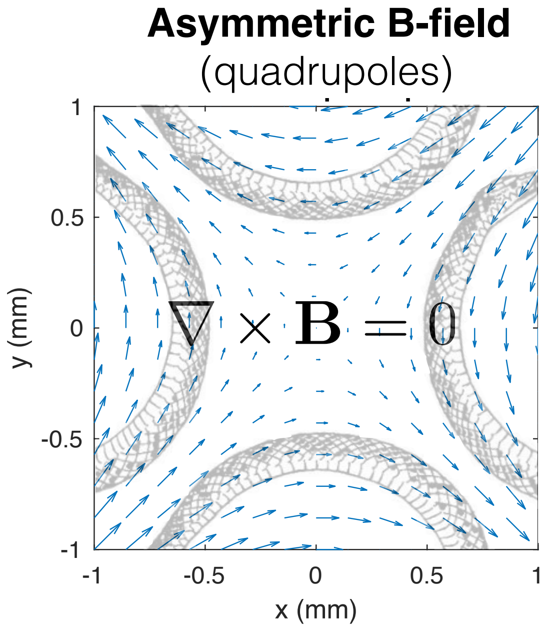
What is an active plasma lens?



Active plasma lensing – Focusing in both planes

- Maxwell equations require a **longitudinal current density** to have azimuthal focusing.
- We can use a plasma to conduct a large current parallel to the beam as it passes.
  => **Uniform current density** = an ideal/linear lens
- Can be up to 100 times stronger than conventional quadrupoles!
  (3500 T/m vs ~30 T/m)


Azimuthally symmetric B-field
(active plasma lens)


Asymmetric B-field
(quadrupoles)

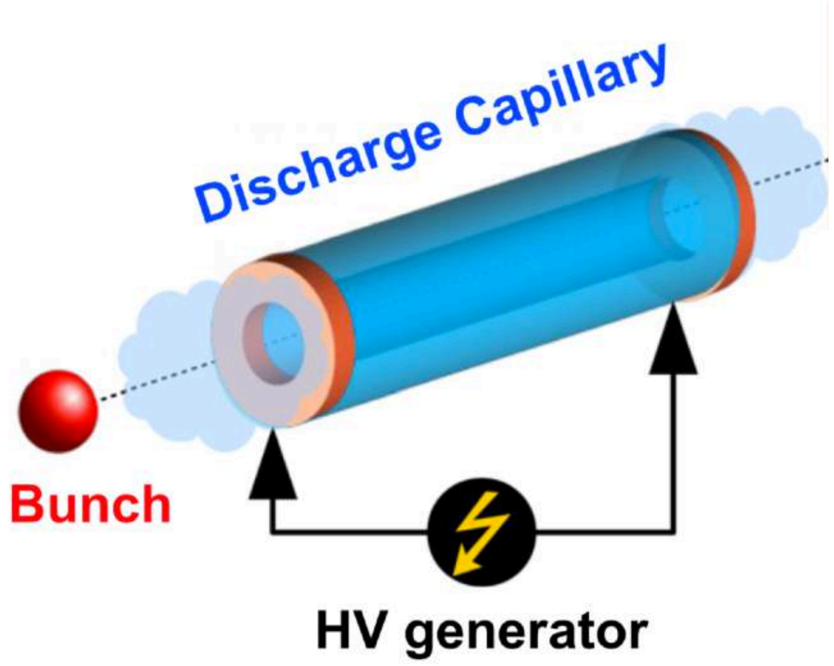


Image source: R. Pompili et al., **Appl. Phys. Lett. 110, 104101 (2017)**

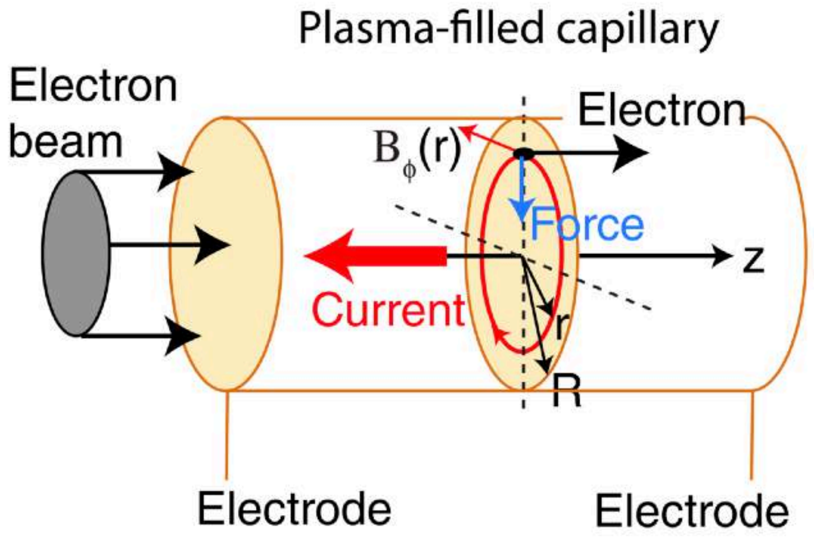
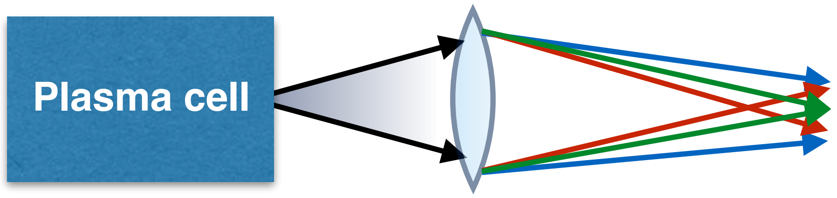


Image source: J. van Tilborg et al., **Phys. Rev. Lett. 115, 184802 (2015)**

Motivation

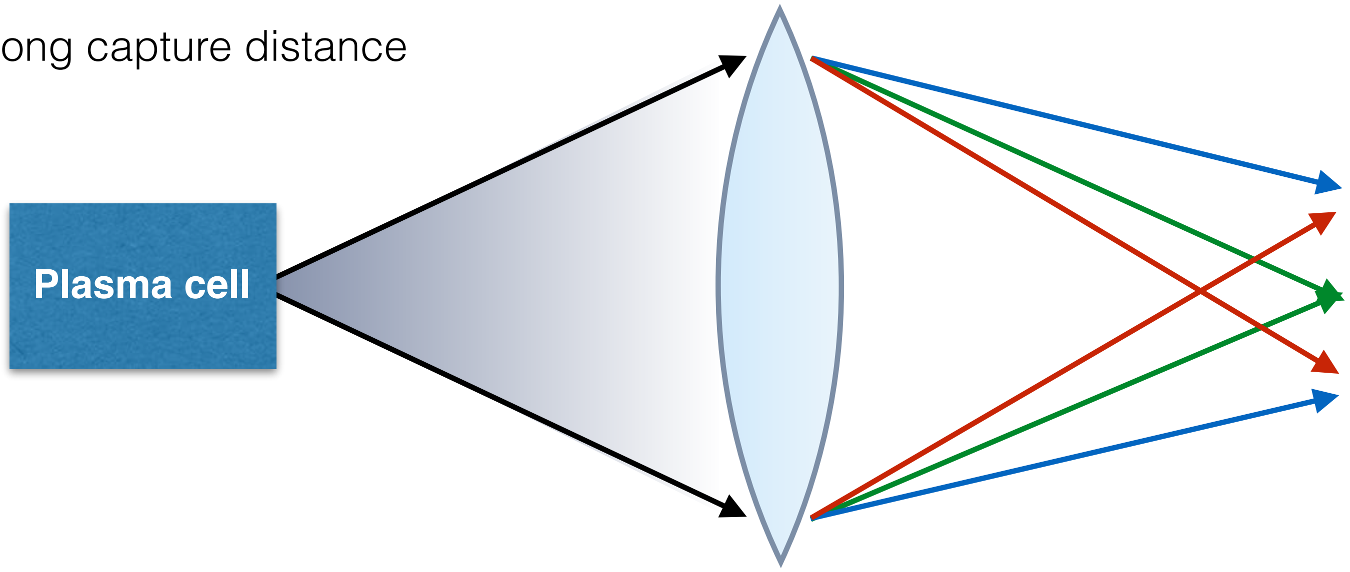
- Production and capture of highly divergent beams will benefit from azimuthally symmetric focusing.
- This is especially important when dealing with large energy spreads, e.g. in plasma wakefield accelerators.
- Azimuthally symmetric focusing already exists: solenoids. However, these scale unfavourably with higher energy ($1/\gamma^2$ instead of $1/\gamma$)

Short capture distance



Relative focusing error is SMALL

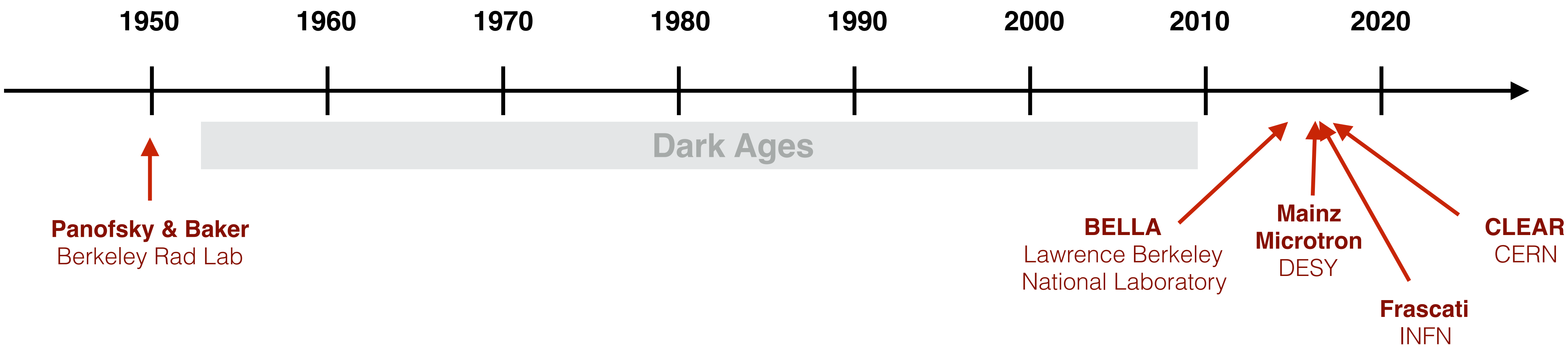
Long capture distance



Relative focusing error is LARGE

A bit of history

Timeline – then and now



Panofsky & Baker
Berkeley Rad Lab

BELLA
Lawrence Berkeley
National Laboratory

Mainz Microtron
DESY

Frascati
INFN

CLEAR
CERN

- First prototype was made by Panofsky and Baker at the Berkeley Rad Lab in 1950:
  – large lens (7.5 cm diameter, 1.2 m long)
  – protons

- Novel accelerator research sparked a recent renaissance of interest.
  – smaller (~1 mm diameter, 10-30 mm long)
  – electrons

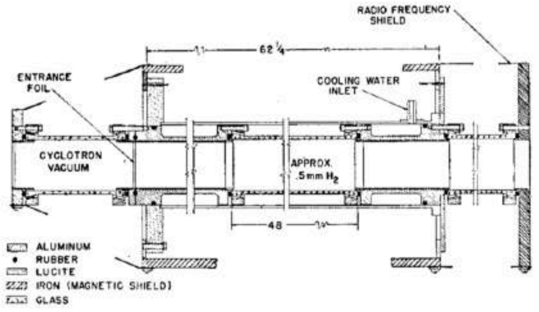
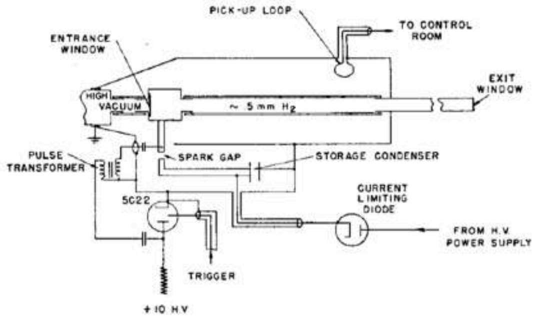


FIG. 2. Cross section of magnetic arc lens.



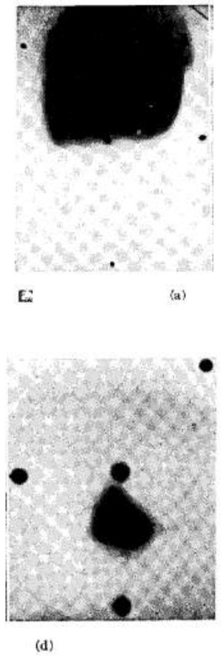


Image source: ***Baker and Panofsky, Rev. Sci. Instrum. 21, 445 (1950)***

A new revival – BELLA at LBNL and other labs worldwide

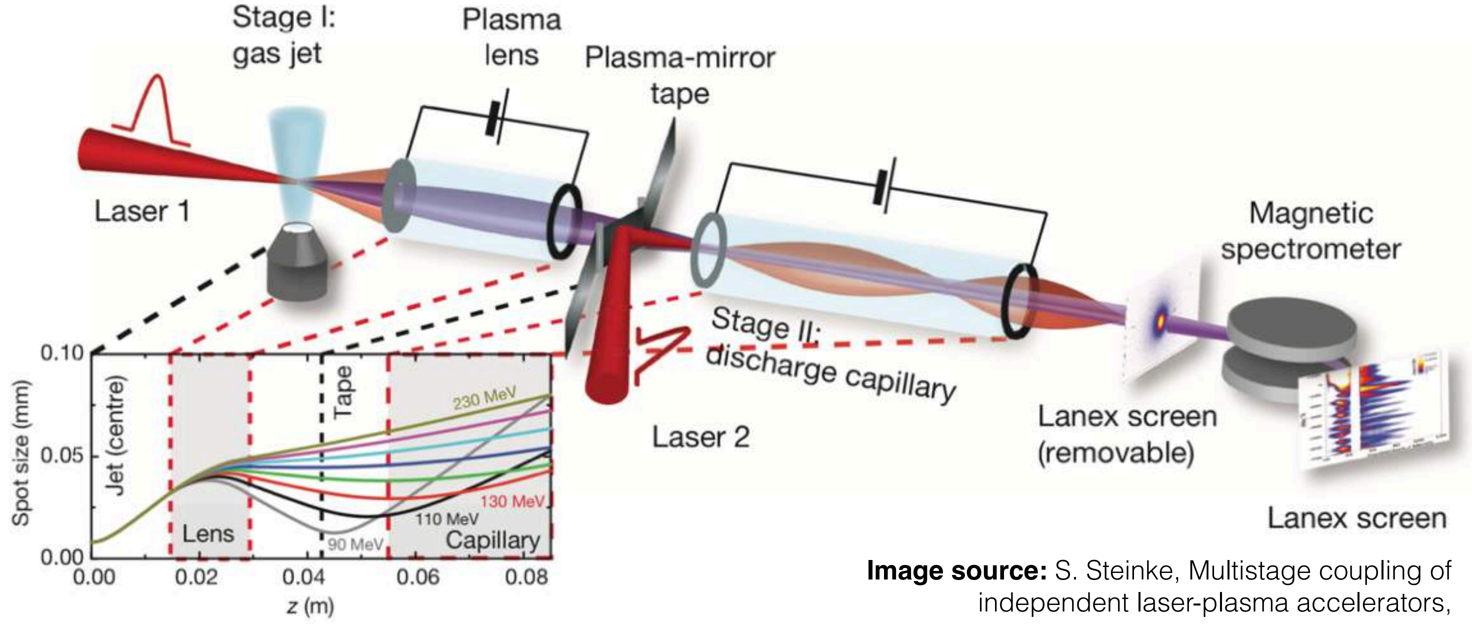
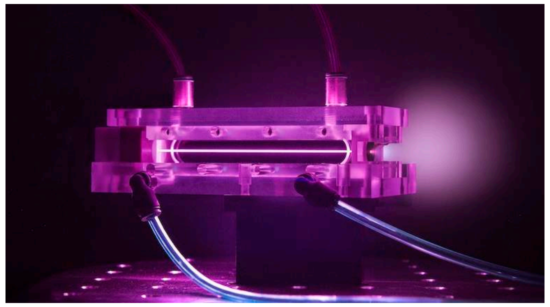


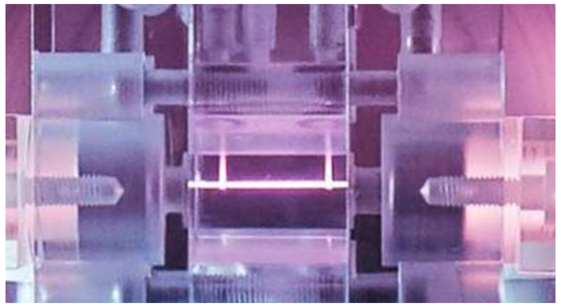
Image source: S. Steinke, Multistage coupling of independent laser-plasma accelerators, **Nature 530, 190–193 (2016)**

- Used for staging of laser plasma accelerators (BELLA lab at LBNL).
- Currently 4 labs are studying the active plasma lens:

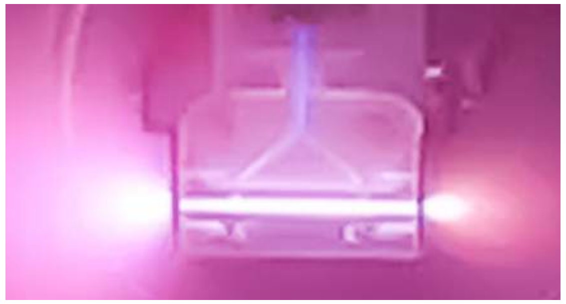
LBNL



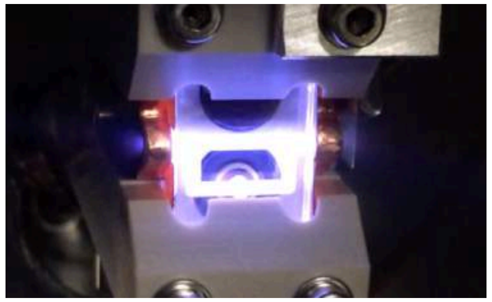
DESY



INFN

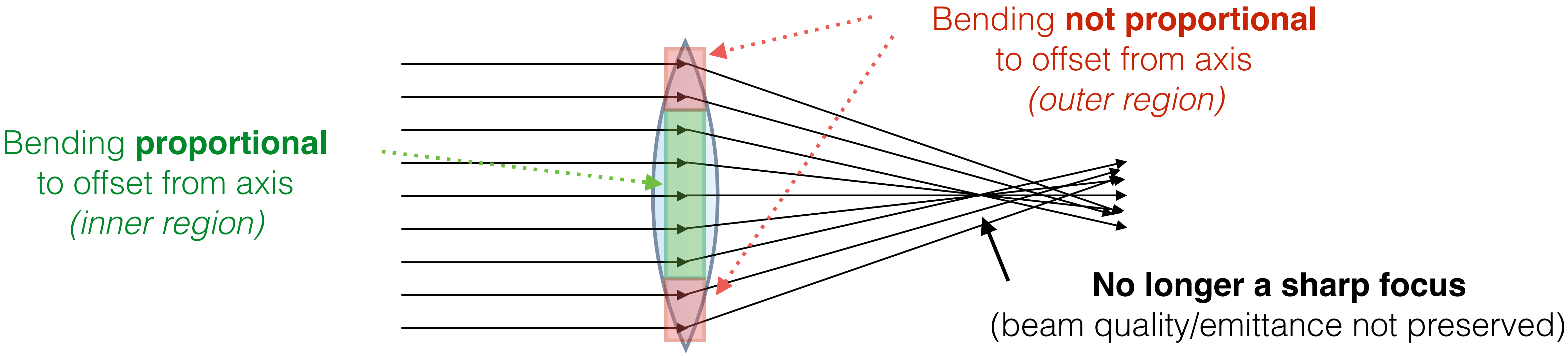


CERN



Spherical aberrations and emittance growth

Emittance growth and spherical aberrations



Bending **proportional**
to offset from axis
(inner region)

Bending **not proportional**
to offset from axis
(outer region)

No longer a sharp focus
(beam quality/emittance not preserved)

- Spherical aberration: Different focusing strength at different radii.
- Nonlinear focusing will in general lead to emittance growth and non-Gaussian beam profiles.

Uneven plasma heating

- Large currents heat the plasma, but unevenly.
- Plasma cooling close to the walls.
- High temperature plasma conducts current better
  ⇒ more current in the center.
- Theoretical model developed by LBNL.
- Likely sets an upper limit to current density.

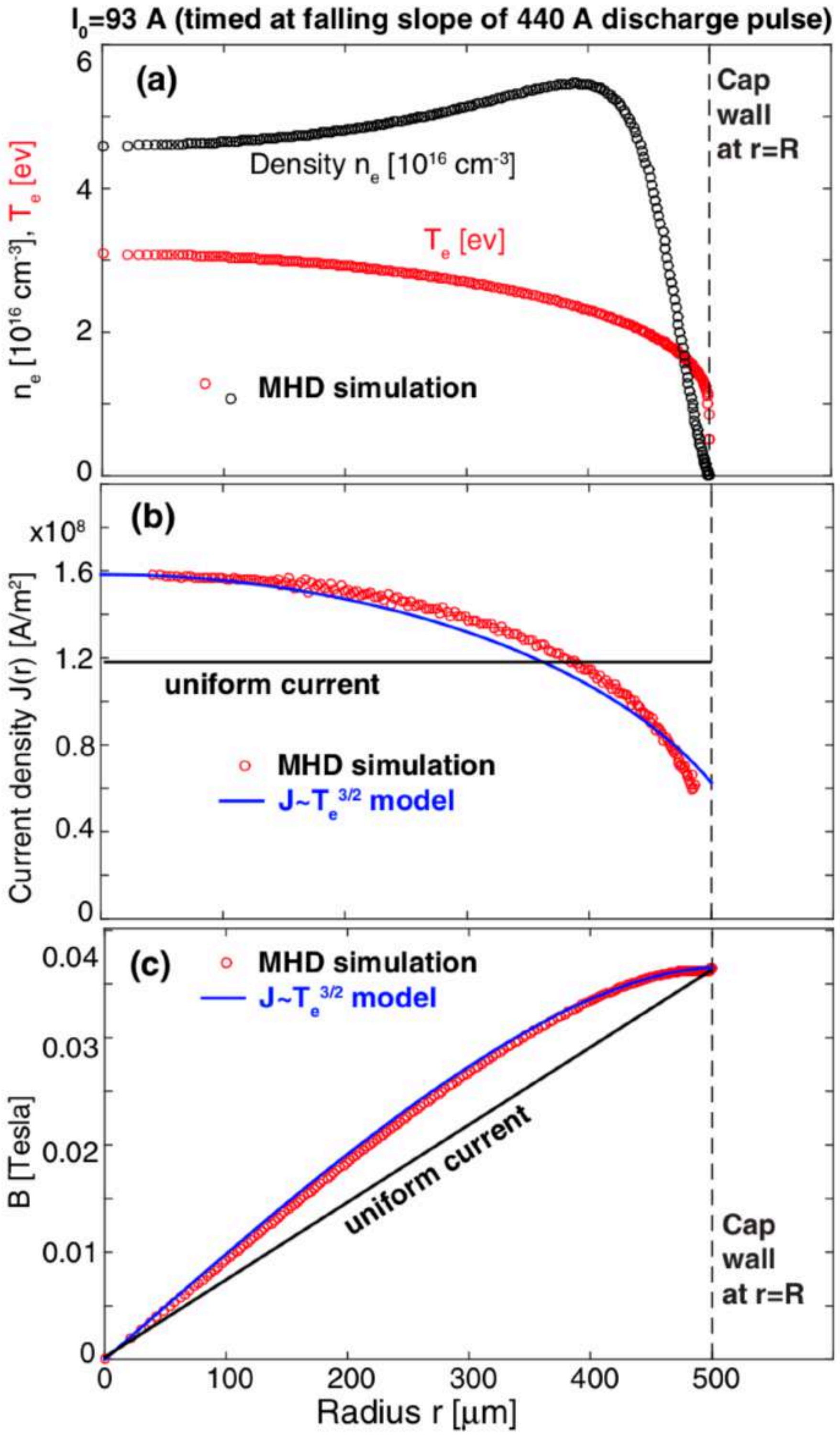


Image source: J. van Tilborg et al., **PRAB 20, 032803 (2017)**

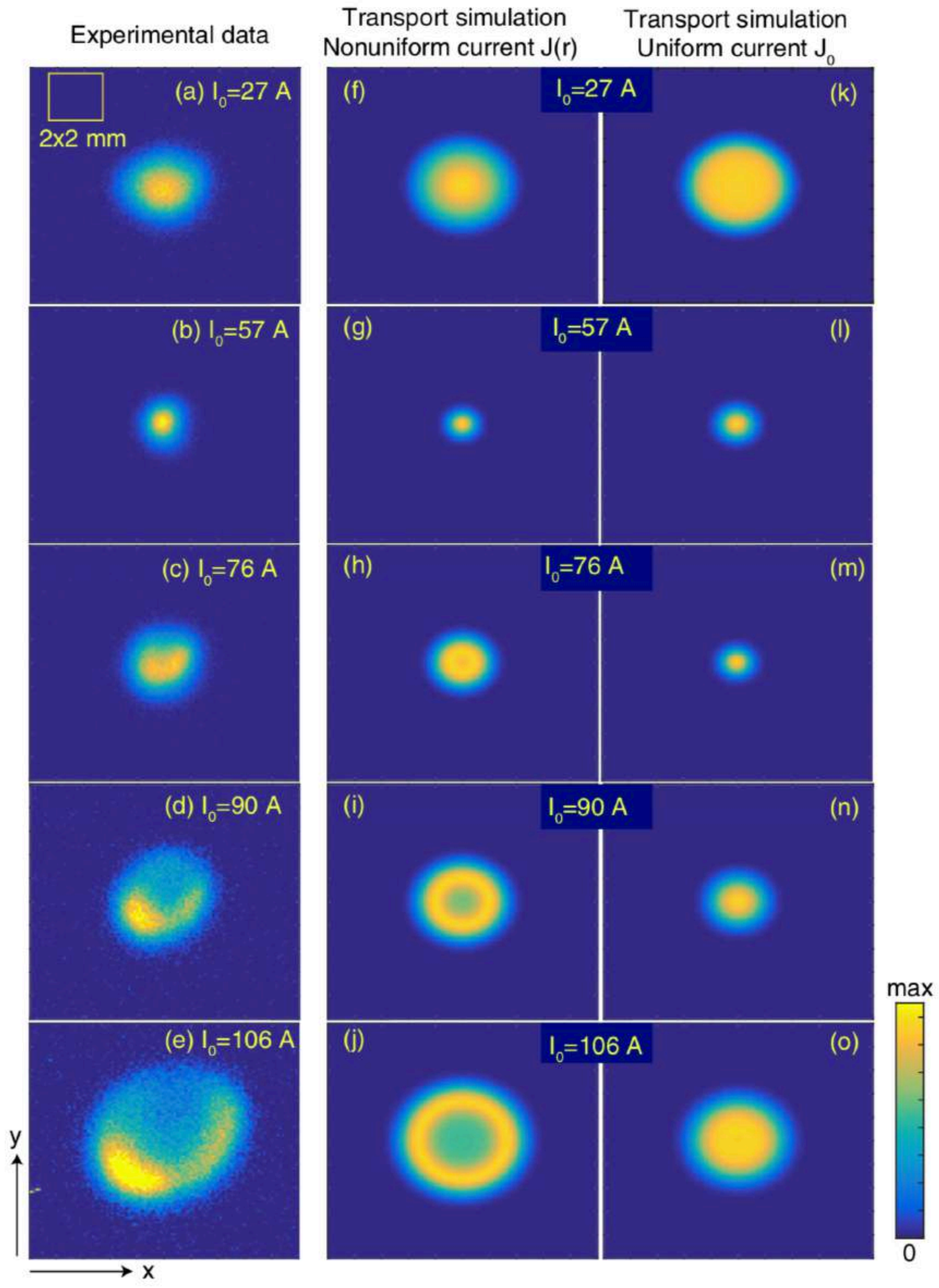
Indirect evidence of plasma heating

(Halo formation)

Experimental result from the BELLA experiment at the Lawrence Berkeley National Lab

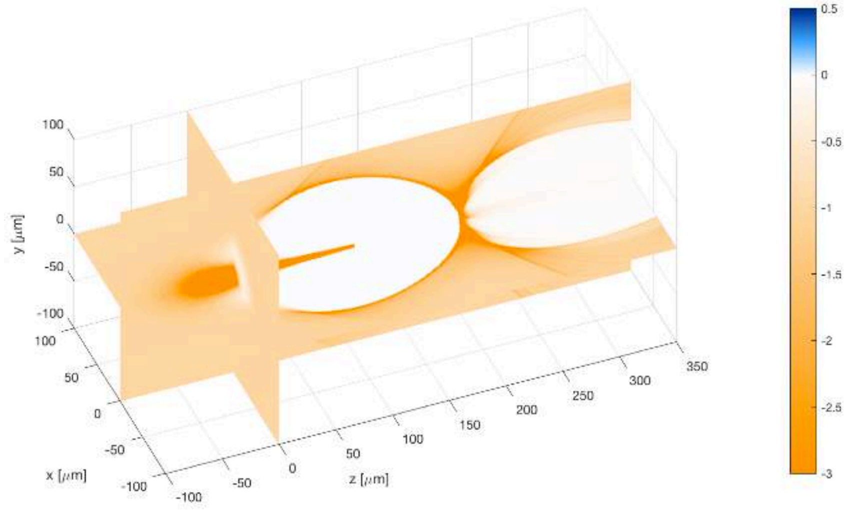
Indirect measurement (expected effect on the beam).

Not verified to be caused by uneven plasma heating.



Beam-driven plasma wakefields

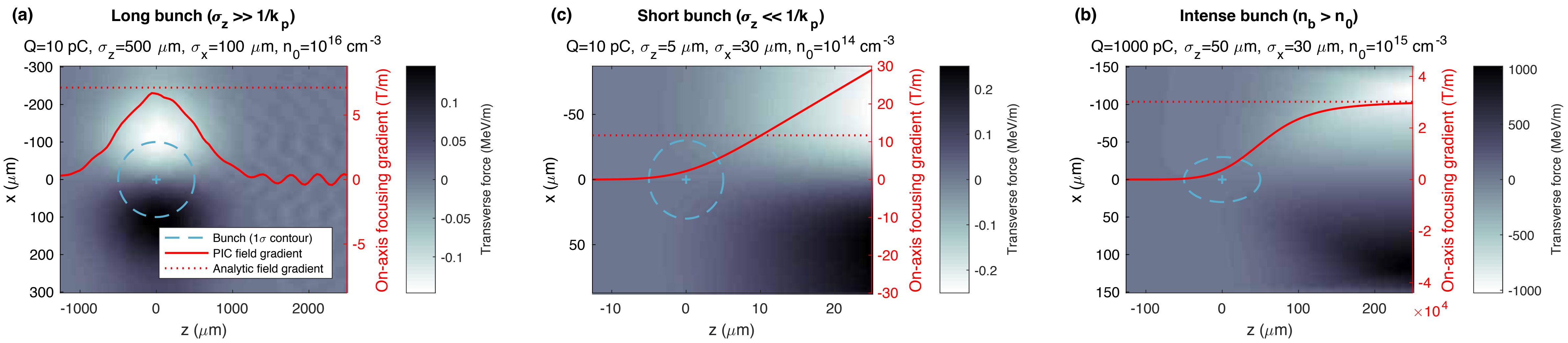
- Typically the beam transverse size is much larger in the lens than in the PWFA cell.
- However, if the electron beam is too intense, there will be a strong plasma wakefield.
- Analytical model of the maximum wakefield focusing gradient within a single bunch:



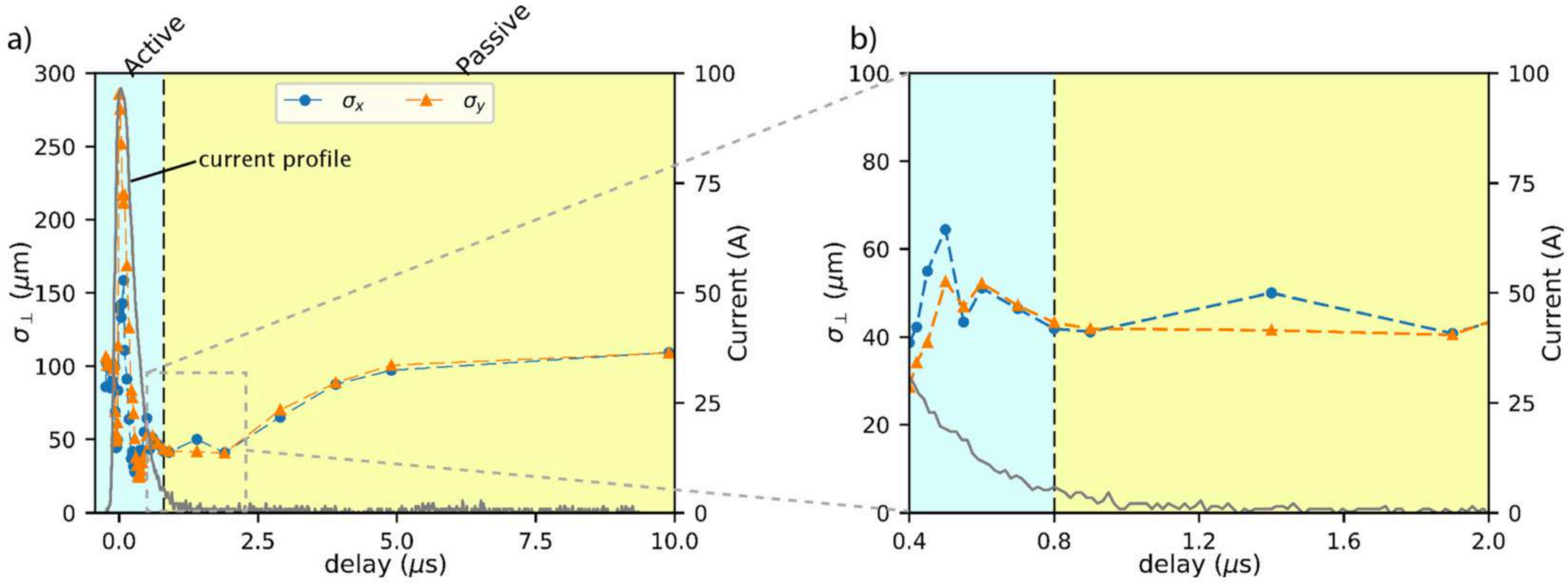
QuickPIC simulation of an intense electron beam in a plasma (nonlinear blowout regime)

$$g_{\max} \approx -\frac{e\mu_0 c}{2} \min\left(n_0, \frac{N k_p^2 \sigma_z}{\pi \sigma_r^2 \left(1 + \frac{k_p^2 \sigma_r^2}{2}\right) \left(1 + \sqrt{8\pi} k_p^2 \sigma_z^2\right)} \right)$$

New result! (will be published soon)

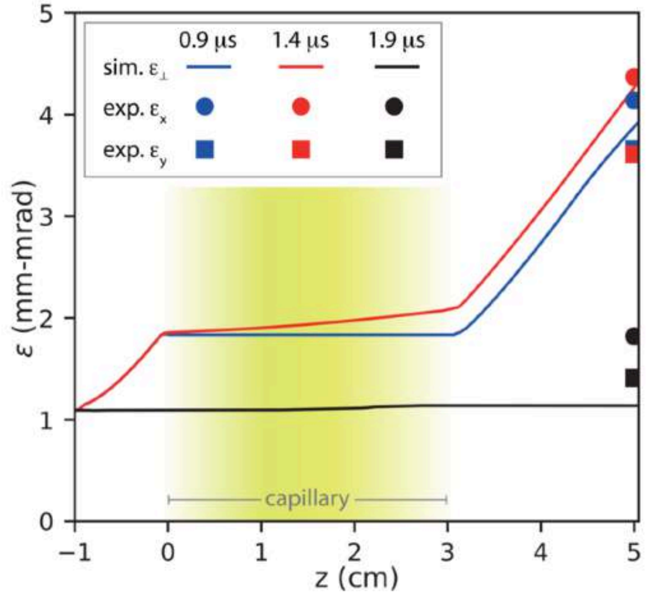


Evidence for passive plasma lensing (in an active plasma lens)



Experimental result from the
INFN Frascati plasma lens experiment

Image credit: ***A. Marocchino et al.***
Experimental characterization of the effects induced by passive plasma lens on high brightness electron bunches,
Appl. Phys. Lett. 111, 184101 (2017)



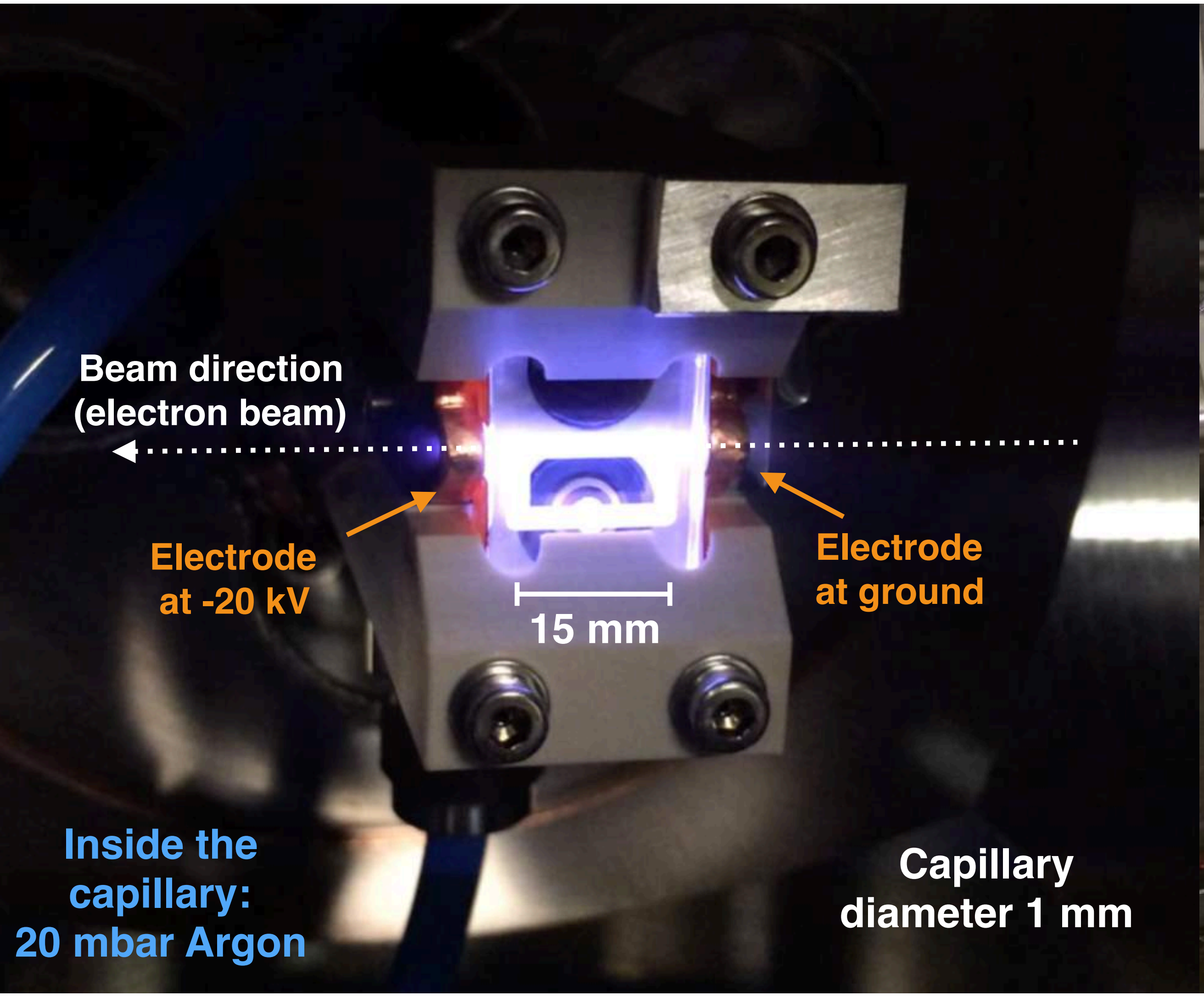
CLIC Workshop talk Wed, 11:20
Detailed description of the CLEAR plasma lens experiment
(also by Carl A. Lindstrøm)

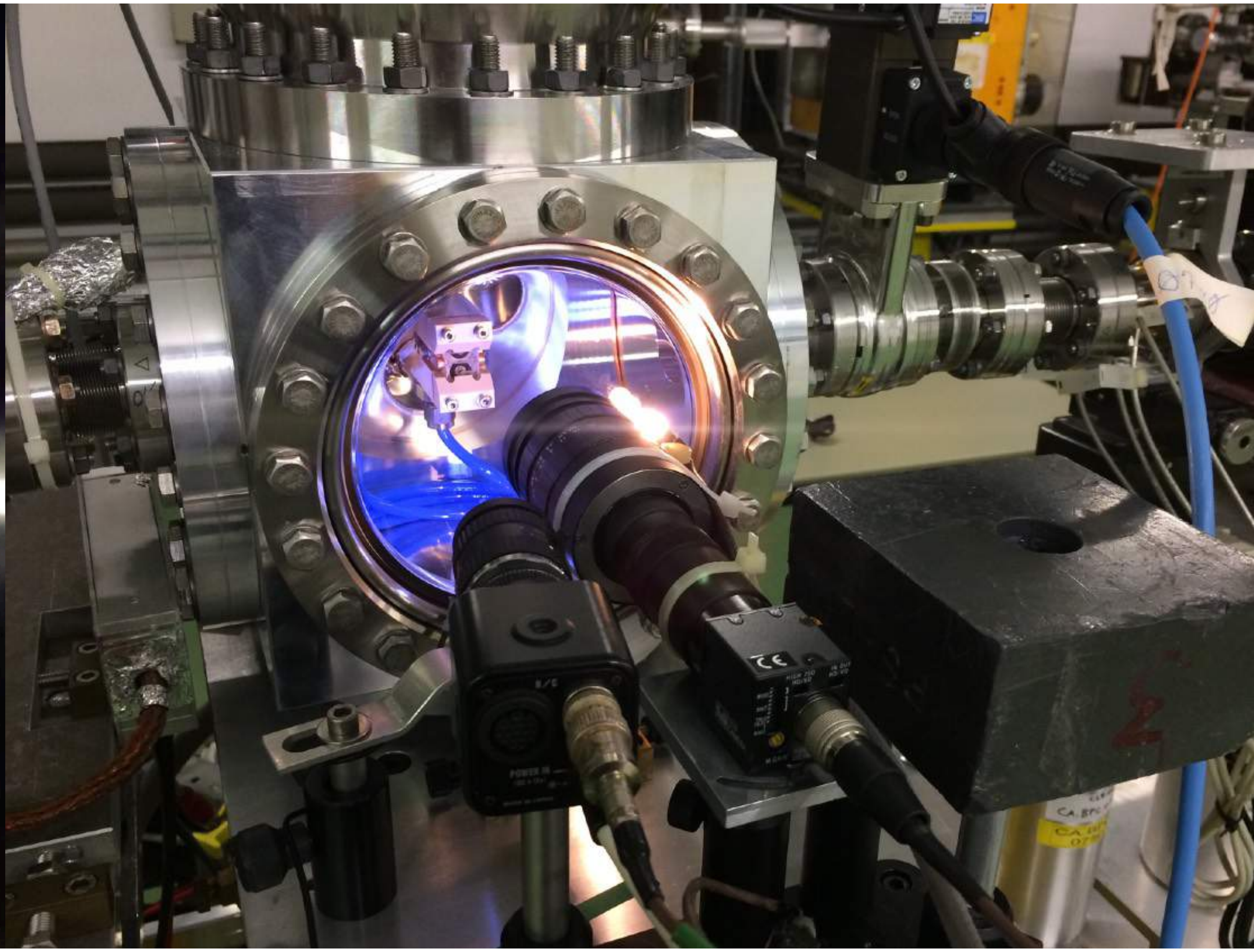
The CLEAR* Plasma Lens Experiment†

* *CERN Linear Electron Accelerator for Research*

† *C. A. Lindstrøm, K. N. Sjøbæk, E. Adli (PI) from the University of Oslo and CERN (W. Farabolini, D. Gamba, R. Corsini), with collaborators from DESY (J.-H. Röckemann, L. Schaper, J. Osterhoff) and Uni Oxford (A. Dyson, S. Hooker)*

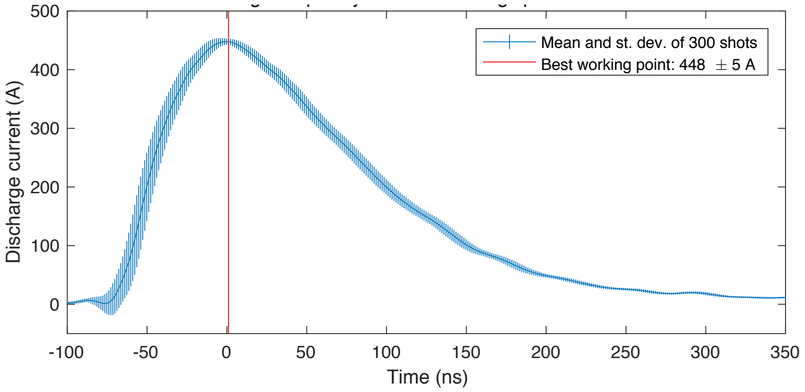
Experimental setup





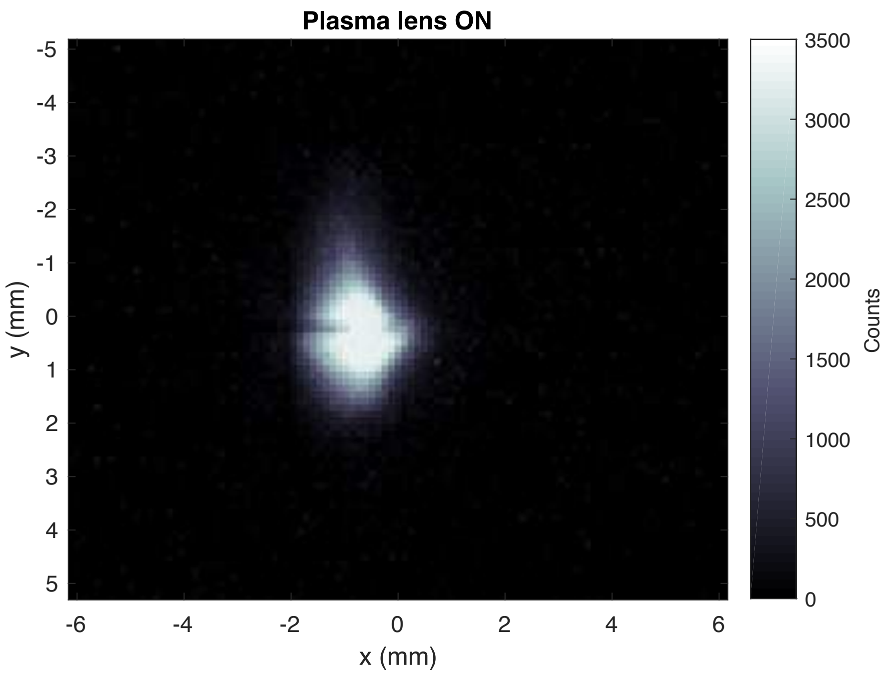
- An experiment to test the operation and characteristics of an active plasma lens.

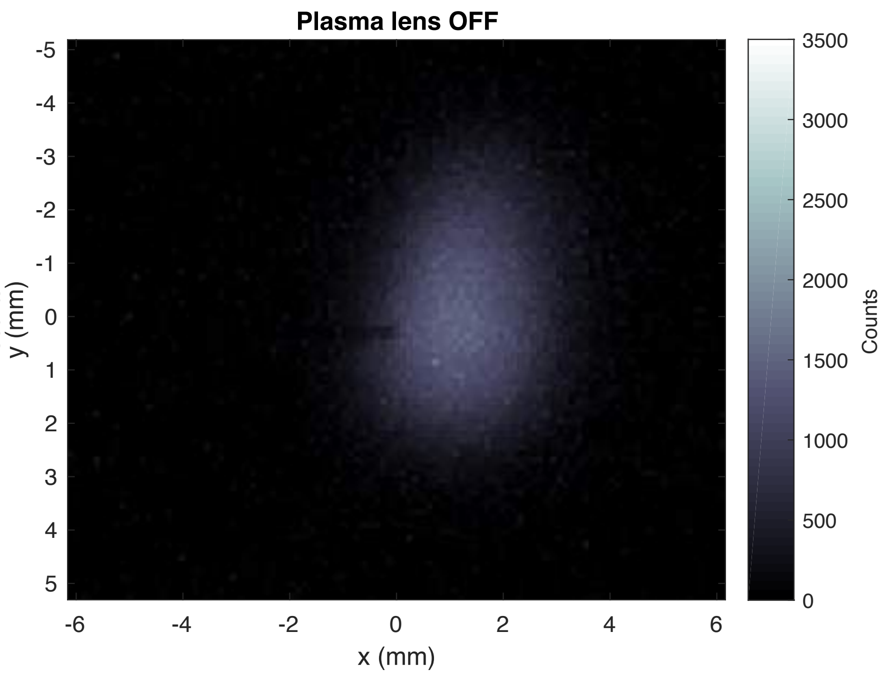
- Consists of many subsystems:
  - Sapphire capillary
  - Vacuum system (turbo pump and polymer windows)
  - Marx Generator: a high current (500 A), high voltage (20 kV) source.
  - Beam diagnostics for measuring the effect on the electron beam



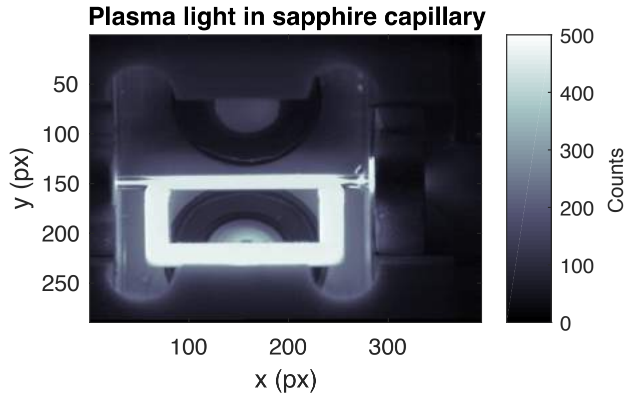
Successful lensing

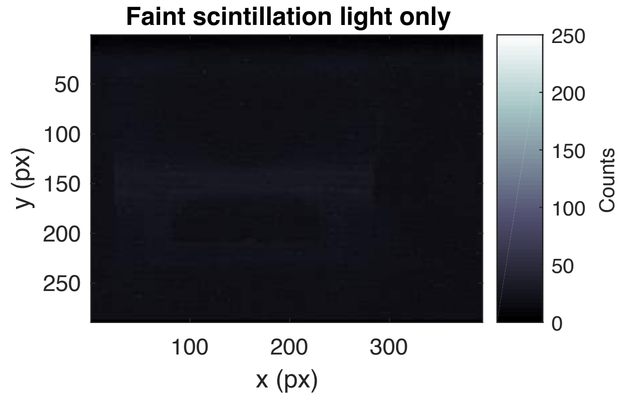
Camera 1

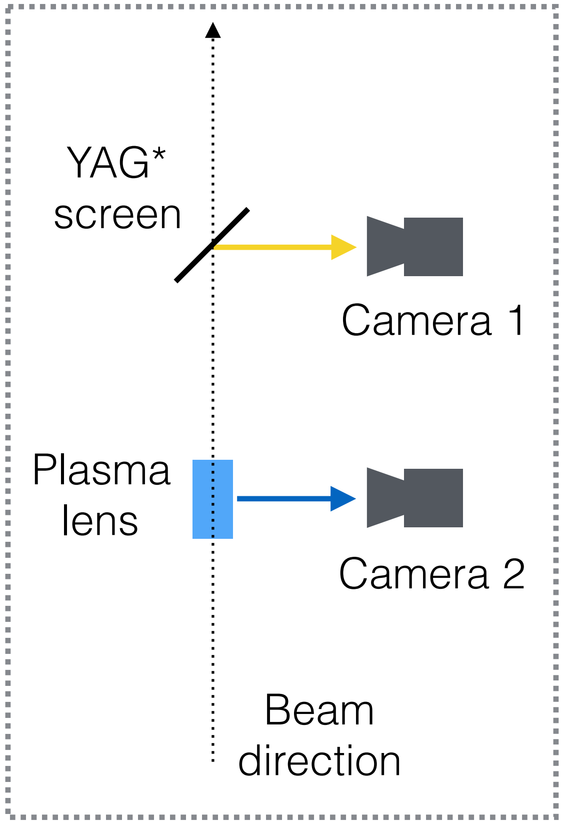




Camera 2

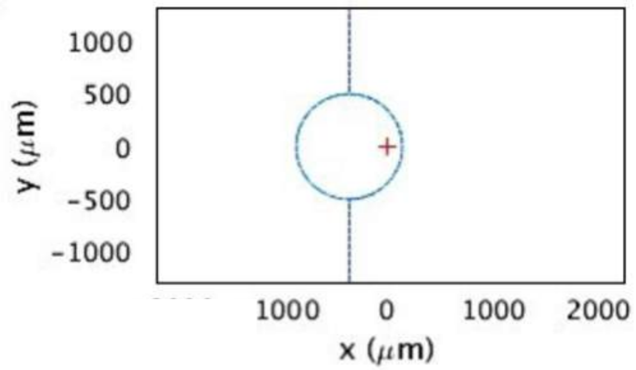






** yttrium aluminium garnet (crystal)*

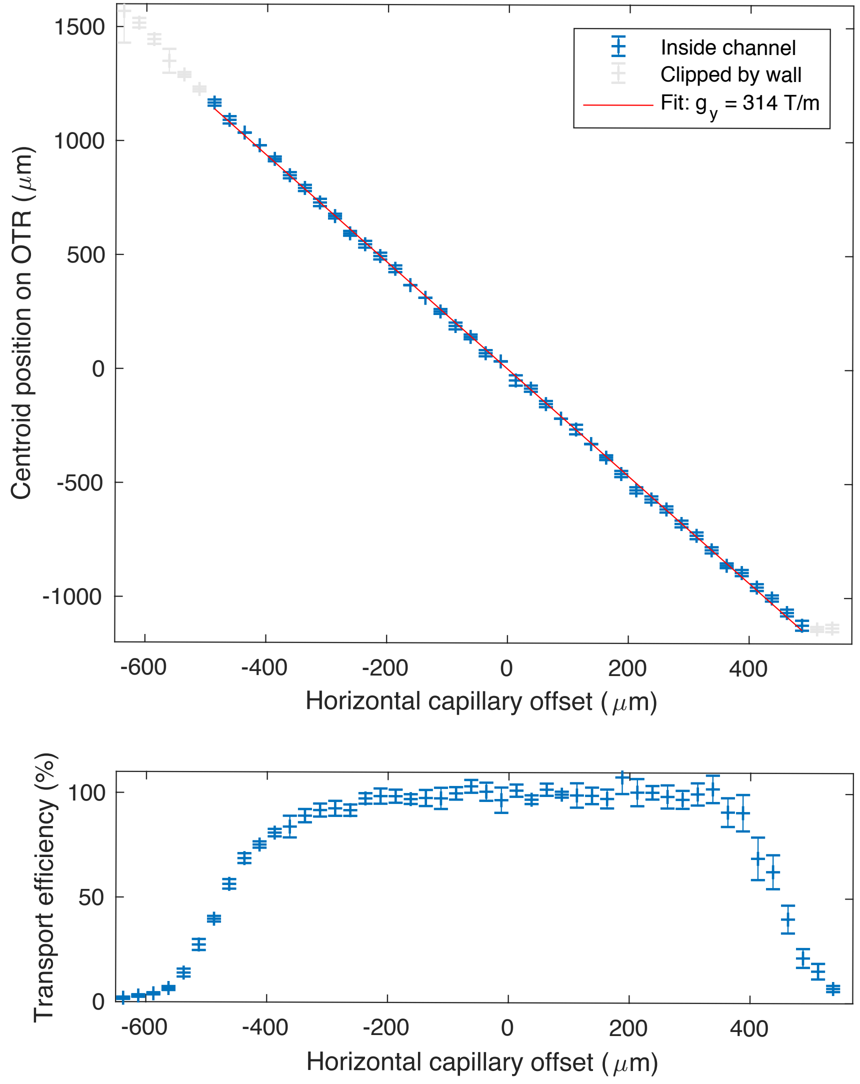
Spherical aberrations due from plasma heatir



No evidence for spherical aberration from uneven plasma heating!

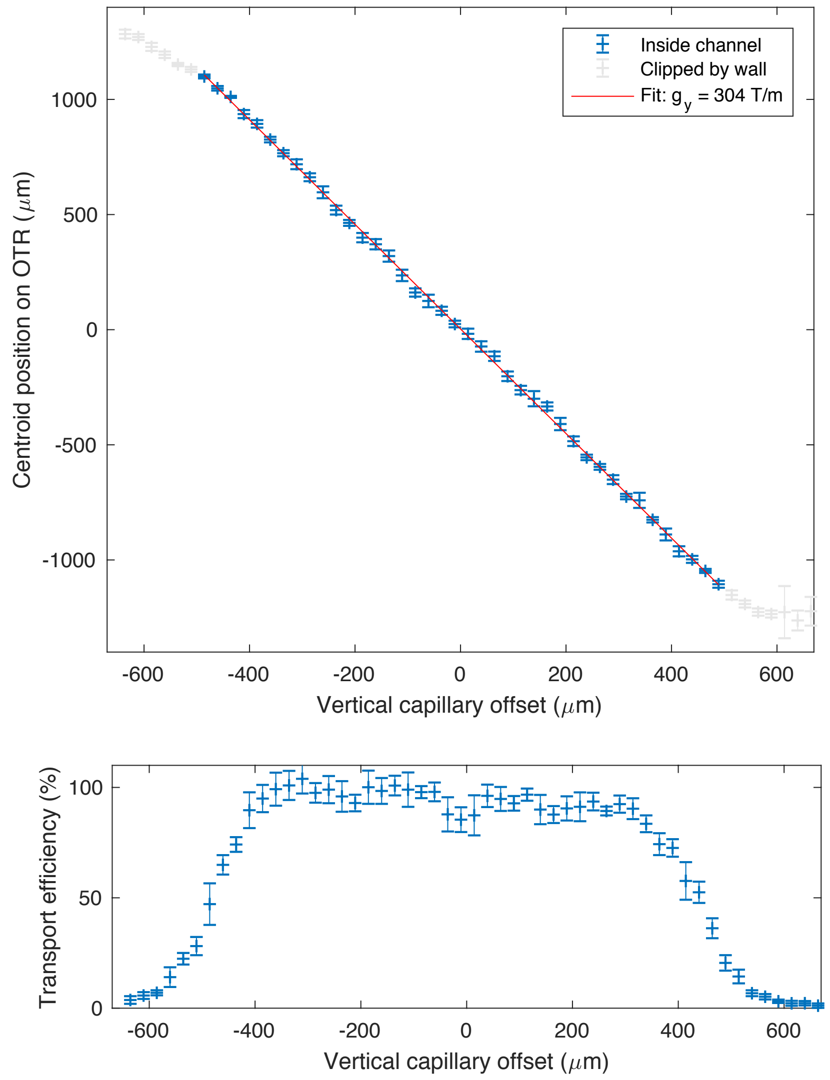
Horizontal offset scan

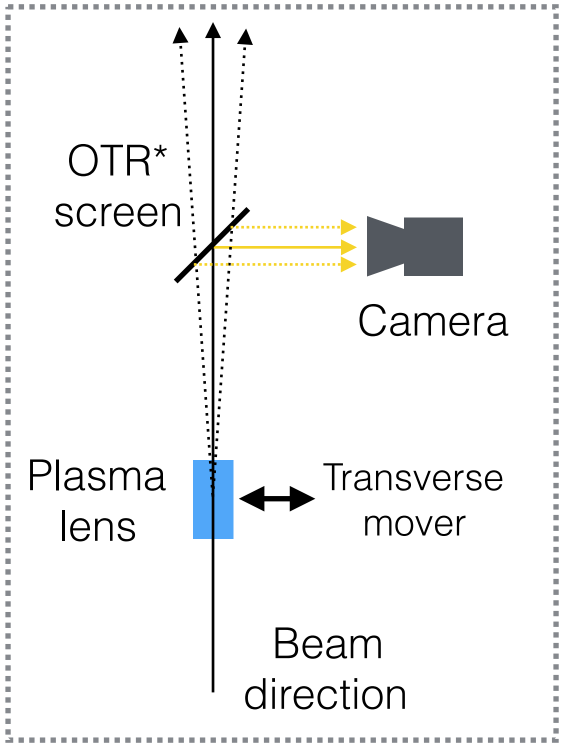
405 ± 33 A discharge current, 7 bunches, 20 pC total



Vertical offset scan

397 ± 14 A discharge current, 7 bunches, 20 pC total





* *optical transition radiation*

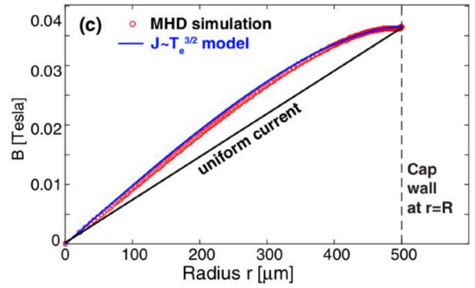


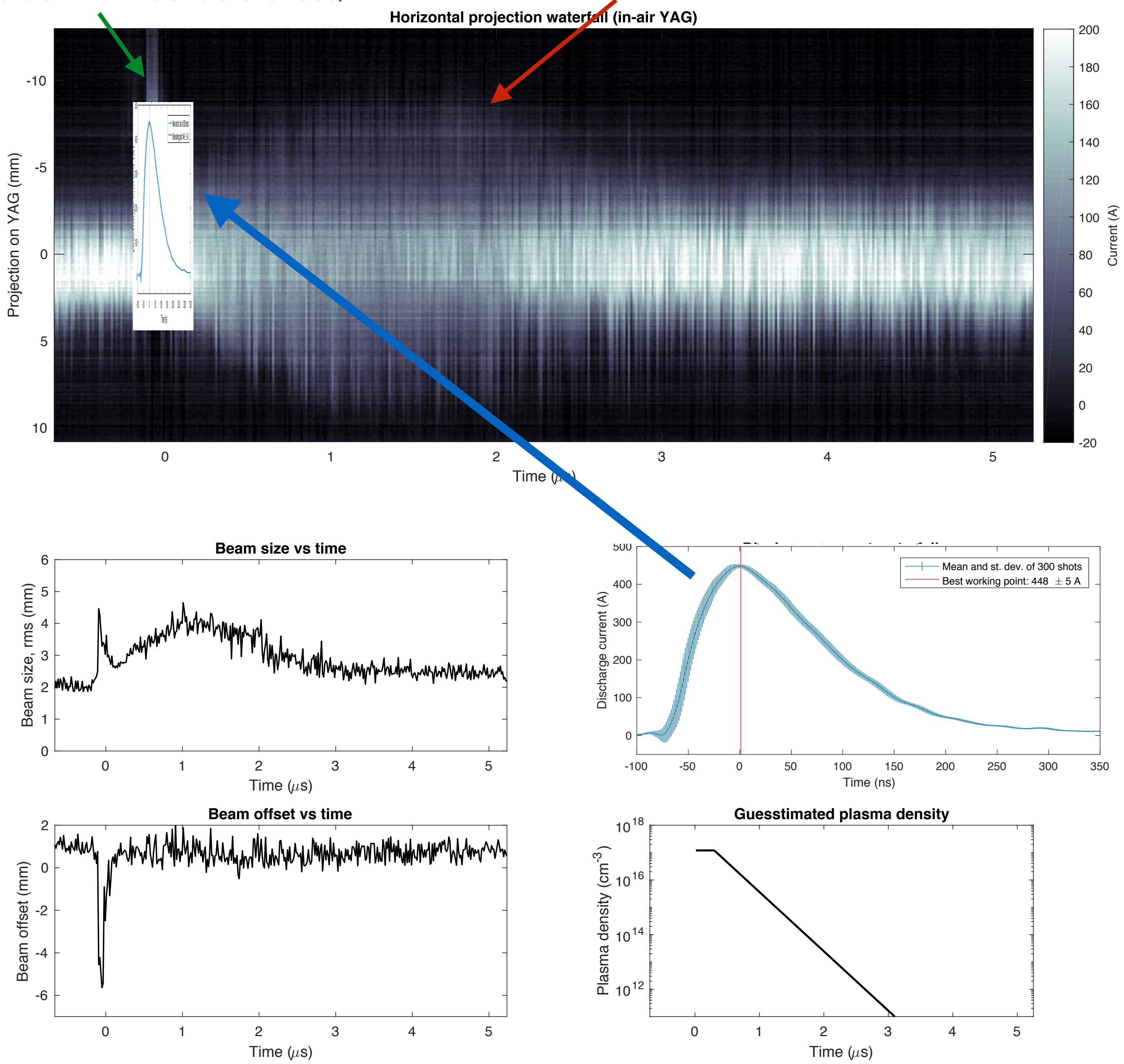
Image source: J. van Tilborg et al., **PRAB 20, 032803 (2017)**

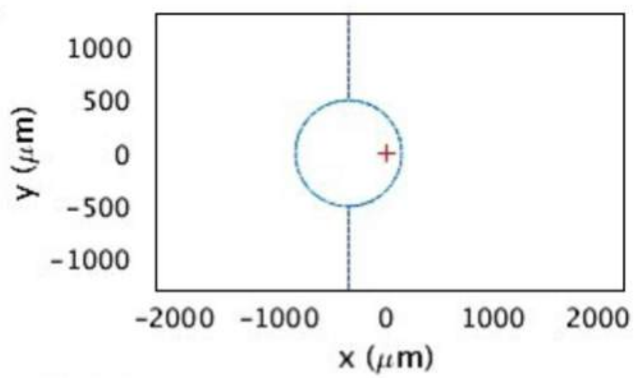
(preliminary data analysis)

Spherical aberrations due from plasma wakefields

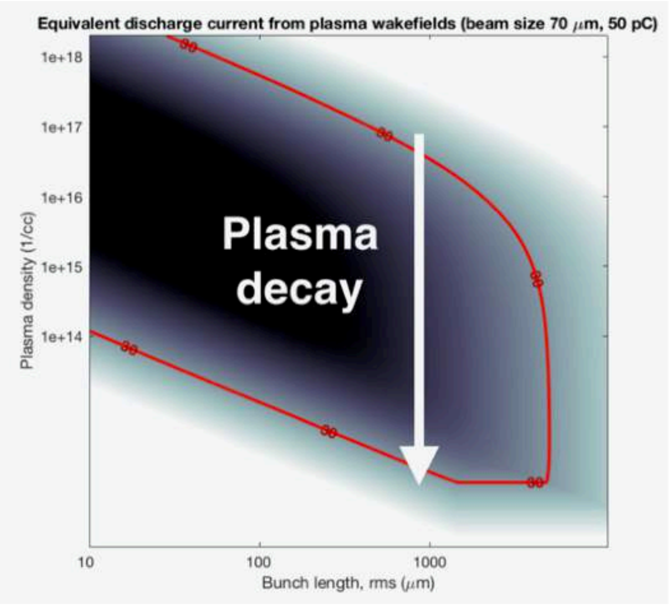
Normal active plasma lensing
(distortion AND centroid offset)

Beam-plasma self-focusing
(distortion, BUT NO centroid offset)





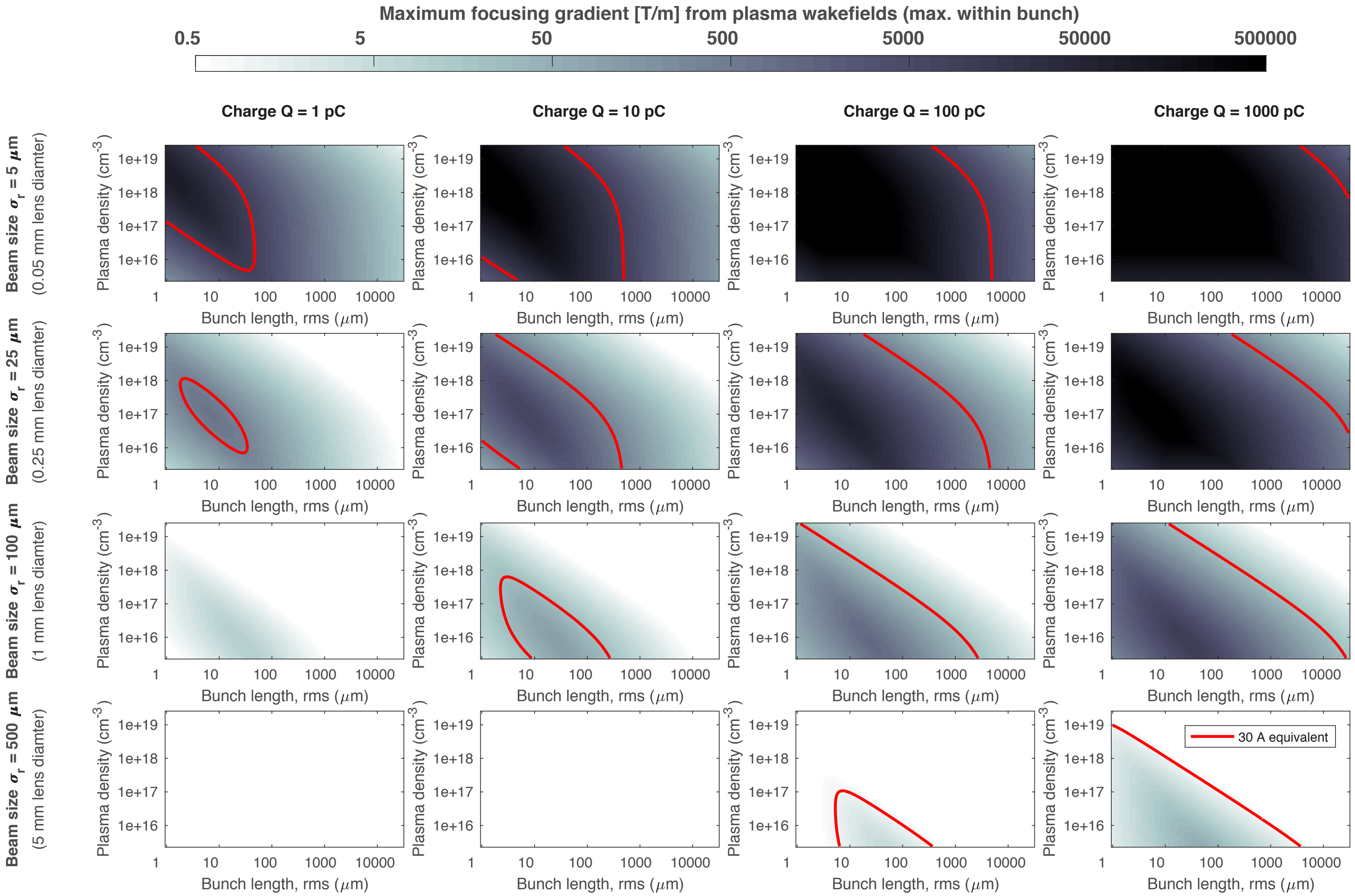
Used an offset beam in the lens to decouple passive and active plasma lensing



(preliminary data analysis)

Ongoing experiments at CLEAR (2018)

- Goal #1: verify negligible emittance growth with quad scans
- Goal #2: scan large parts of the beam/plasma parameter space for wakefield distortion



4D parameter space:

(outer)
Beam size,
bunch charge

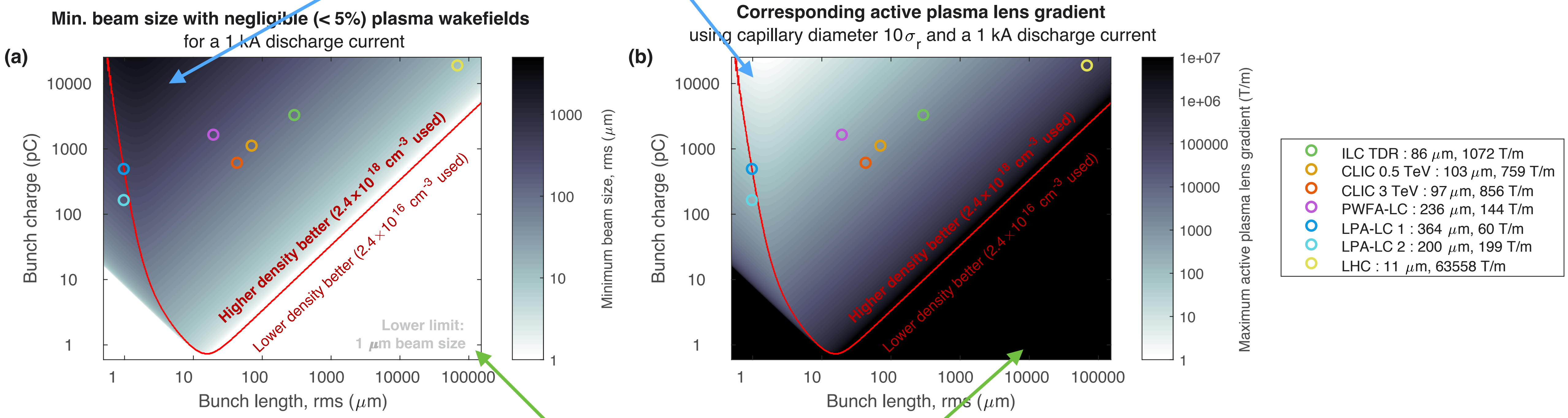
(inner)
Plasma density,
bunch length

Outlook for active plasma lenses

Possibilities and limitations

- Good news: Less spherical aberration from plasma heating than feared.

Intense beams: large spherical aberration



Weak beams: no spherical aberration

- Bad news: Plasma wakefields will distort intense beams.

- However, OK if beam size is large enough (but low emittance implies huge beta functions)
  ⇒ May (?) be used as an alternative for the final doublet with focusing in both planes, low chromaticity

In summary

- Interesting “new” technology – many labs investigating potential.
- Spherical aberrations and emittance growth caused by uneven plasma heating and plasma wakefields – sets limits on use.
- Experiments ongoing at the CLEAR user facility at CERN – preliminary results indicate presence of plasma wakefields, but possibility to control heating.
- CLEAR experiments will continue throughout 2018.

Thanks for listening!

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