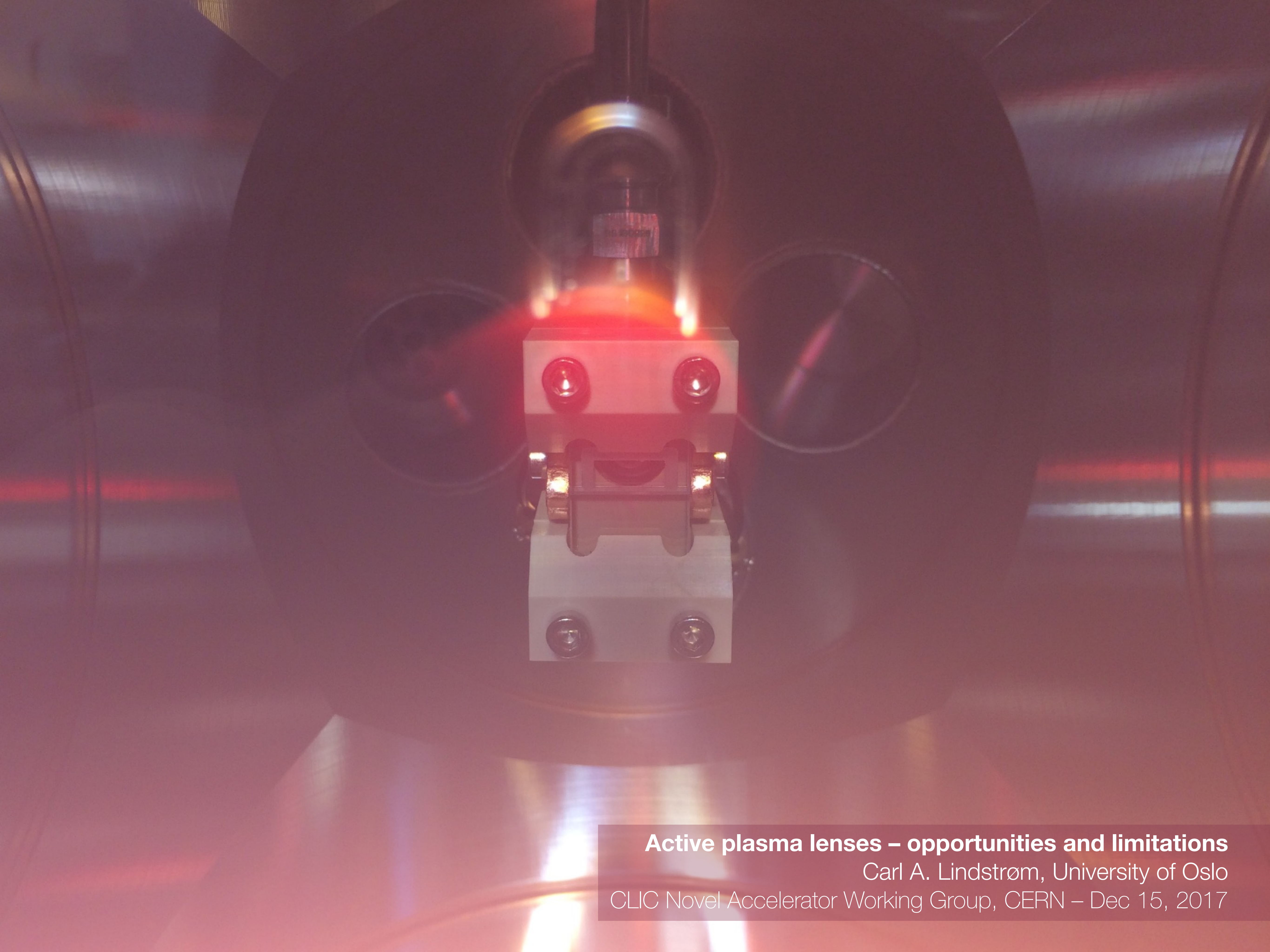

Active plasma lenses – opportunities and limitations

Carl A. Lindstrøm, University of Oslo

CLIC Novel Accelerator Working Group, CERN – Dec 15, 2017

Active plasma lenses
– opportunities and limitations

CLIC Novel Accelerator Working Group

CERN – Dec 15, 2017

Carl A. Lindstrøm

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Motivations

Miniaturization of accelerators

- Much like transistors in computers, the future success and degree of implementation of particle accelerators rely on miniaturization.
  - for higher energy/luminosity within an international budget
  - for economic viability in use cases beyond those used today

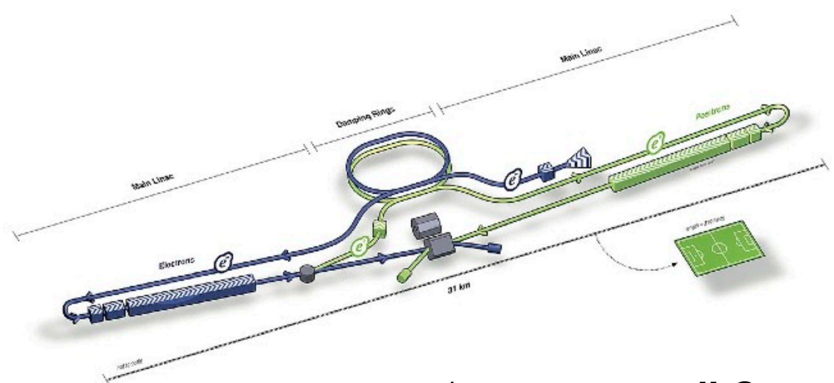


Image source: ***ILC***

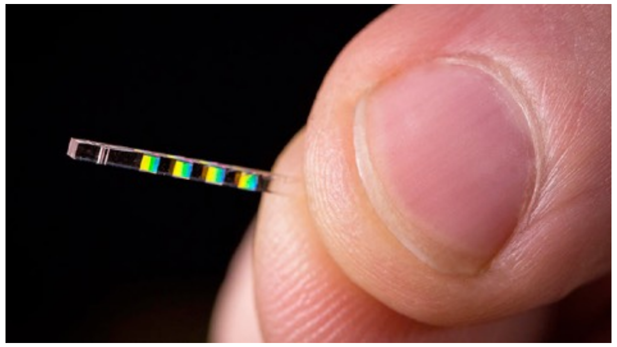
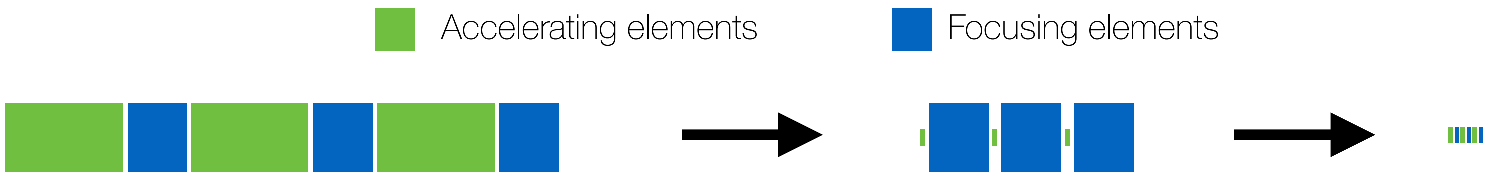


Image source: ***A-CHIP***

- Much emphasis is placed on miniaturizing the accelerating structures: a good first step.

- To truly gain orders of magnitude in compactness, all components must be made small: including focusing elements.



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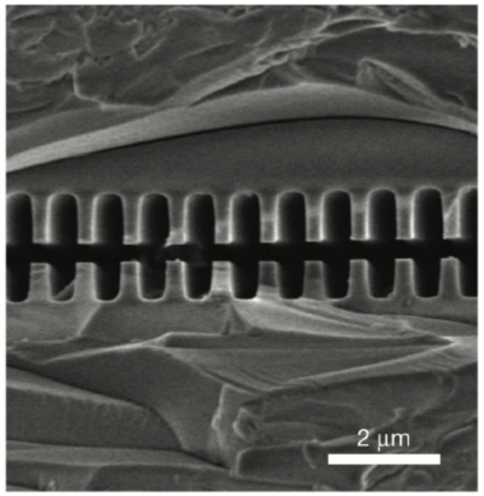
Short focal lengths for high energy beams

- Small accelerating structures require small beam sizes:
  – e.g. direct laser accelerators (DLA)

  ⇒ Strong focusing

  ⇒ or small emittances



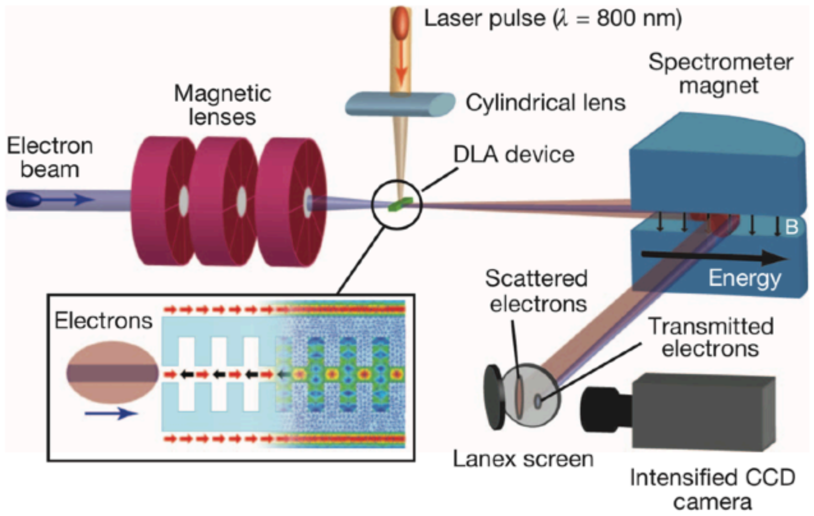


*Image source: E. A. Peralta, Nature **503**, 91–94*

- However, many novel accelerating methods also require small beta functions: highly diverging beams.
  – e.g. laser and plasma wakefield accelerators (LWFA and PWFA)

  ⇒ Strong focusing

  ⇒ must be close to avoid strong chromaticity

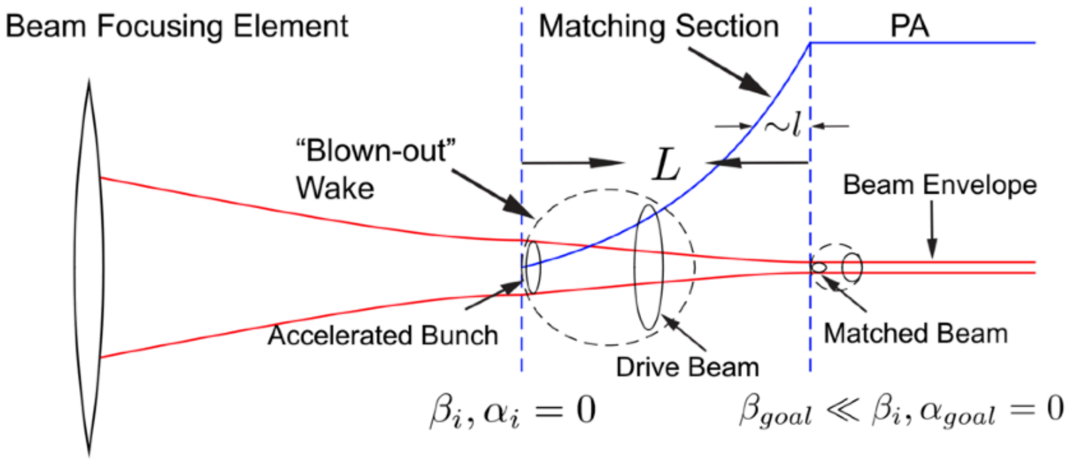
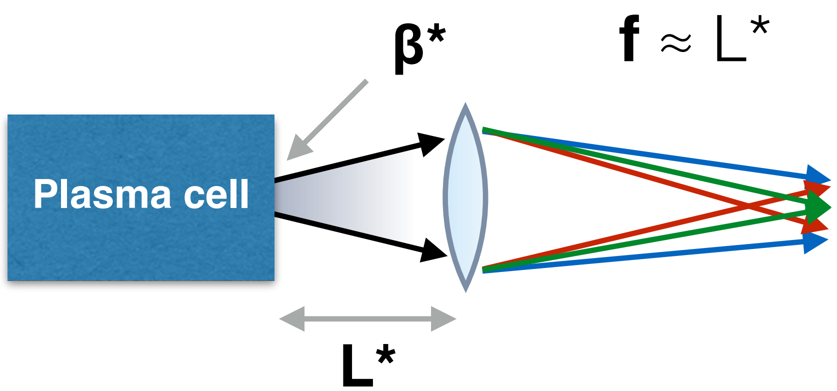


*Image source: X. Xu, Phys. Rev. Lett. **116**, 124801*

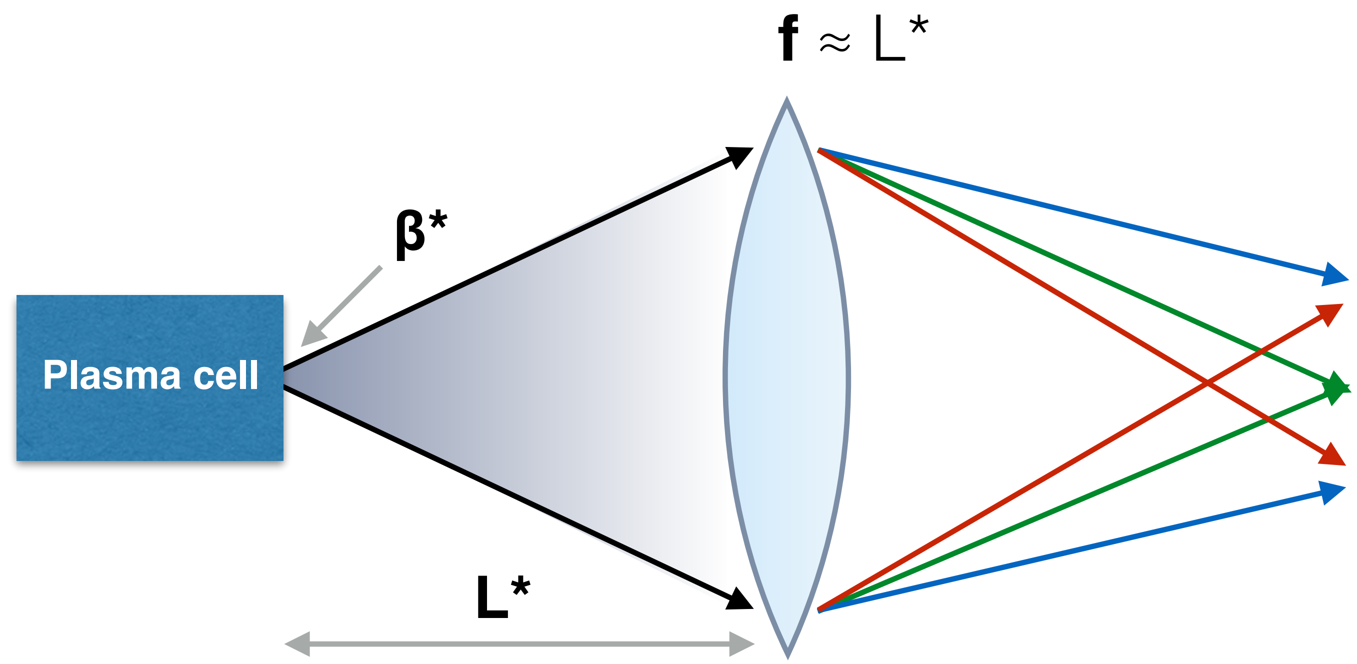
$$\beta_{match} = \frac{\sqrt{2\gamma}}{k_p}$$

Tight focusing and chromaticity

Example: *Exiting a PWFA cell*



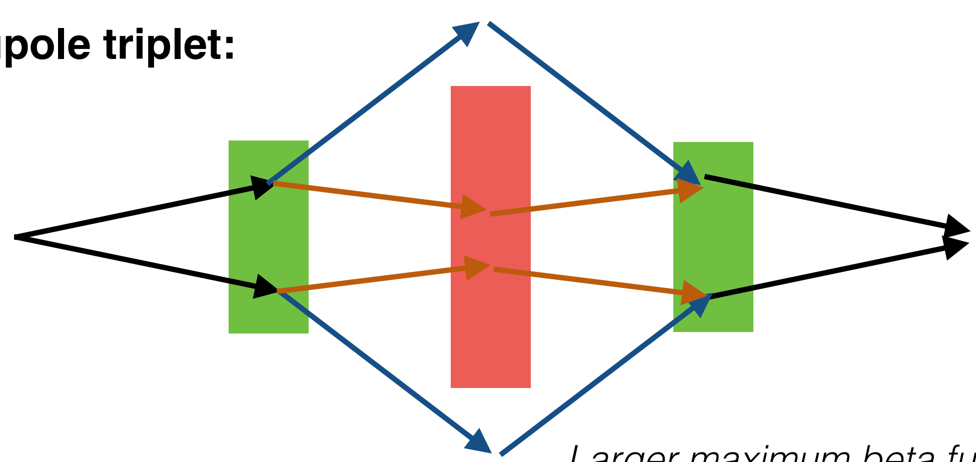
Relative focusing error $\frac{\left(\frac{\Delta\beta}{\Delta\delta}\right)}{\beta}$ **is SMALL**



Relative focusing error $\frac{\left(\frac{\Delta\beta}{\Delta\delta}\right)}{\beta}$ **is LARGE**

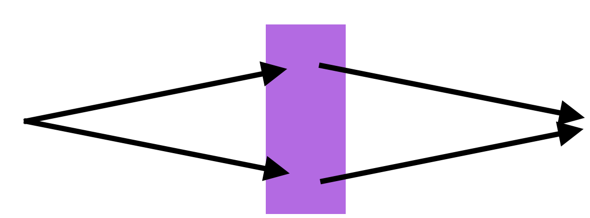
- A radial lens will always give a significantly lower chromaticity.

Quadrupole triplet:



Larger maximum beta functions

Azimuthally symmetric lens:



Making an azimuthally symmetric magnetic lens

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The Holy Grail: Azimuthally symmetric focusing

- To get azimuthally symmetric focusing, we need an azimuthally symmetric magnetic field.

  ⇒ Magnetic field lines form rings (curl)

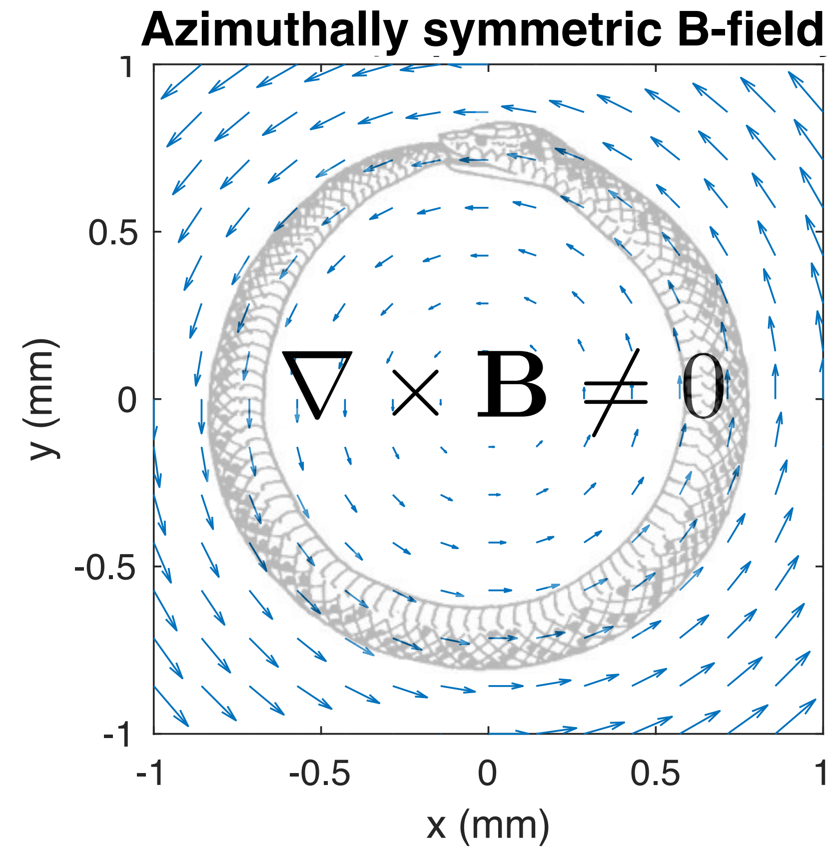
  ⇒ Ampere's law: **we need a longitudinal current density**

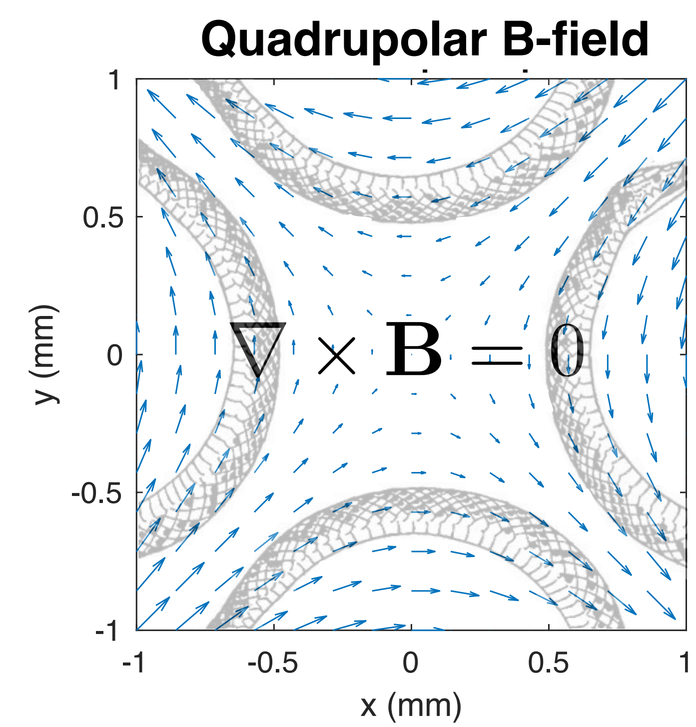
$$\nabla \times \mathbf{B} = \mu_0 \mathbf{J}$$

- A linear focusing field requires a **transversely uniform current density**.

- In a cylinder-symmetric coordinate system, Ampere's law is simply the magnetic field gradient [T/m]:

$$g = \frac{\partial B_\phi}{\partial r} = \frac{\mu_0 I_z}{2\pi R^2}$$





Need for an on-axis conductor

- A current on-axis requires a good electrical conductor.
- Several options:

1. **A low-density metal** (e.g. lithium lenses)
   ⇒ Metals can conduct short pulses up to mega-amperes
   ⇒ Scatters the beam
   ⇒ Good for high-emittance or high energy beams
   ⇒ Was used for 80 GeV antiproton beams at Fermilab
   (1 cm diameter, 10 cm long, 200 kA)

2. **A plasma** (active plasma lenses)
   ⇒ Virtually no scattering due to ion collisions
   ⇒ First conceptual design by Panofsky/Baker in 1950.
   ⇒ Currently gradients up to 3500 T/m (in experiments)

(3. A counter-propagating charged particle beam [no conductor])

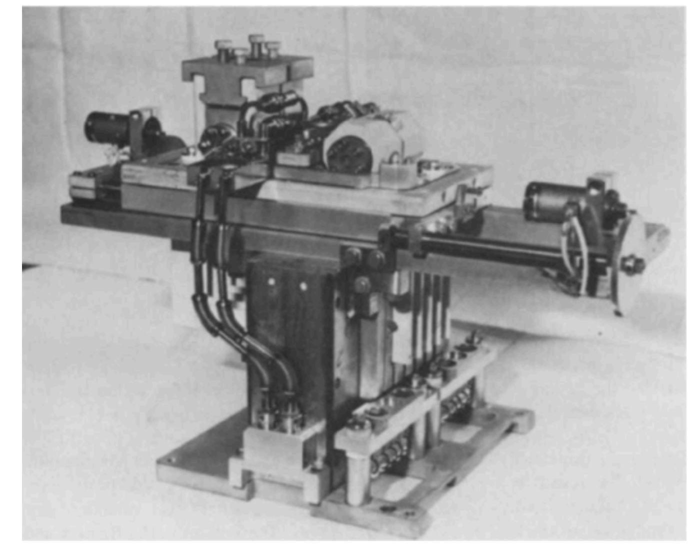


Image source: ***B. F. Bayanov, NIM 190, 9-14 (1981)***

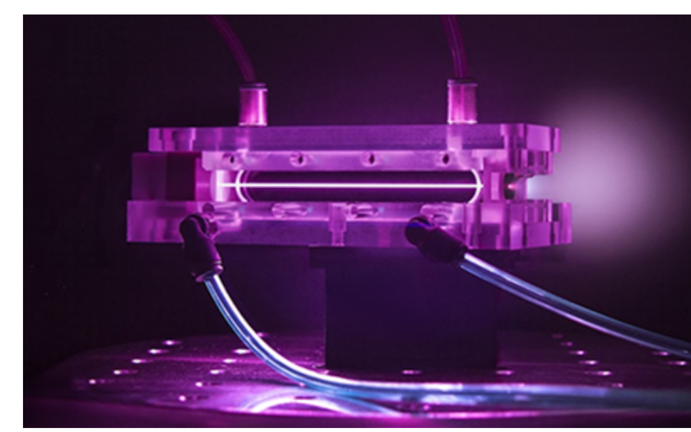


Image source: ***Lawrence Berkeley National Lab.***

Active plasma lenses

- Active plasma lenses consist of three main parts:
  - A **hollow capillary**, typically made from sapphire for durability
  - **Gas inlets** to fill the capillary with a low density gas (~mbar)
  - **Electrodes** on either side (upstream/downstream) to break down the gas and provide current.
- Works equally well for electrons and positrons

$$g = \frac{\partial B_\phi}{\partial r} = \frac{\mu_0 I_z}{2\pi R^2}$$

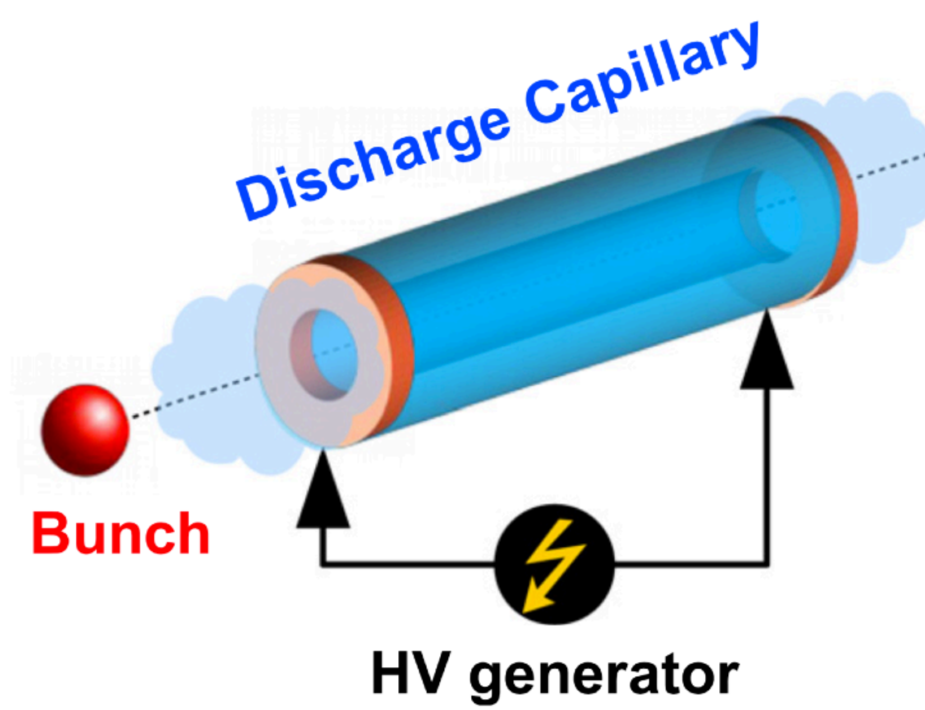


Image source: ***R. Pompili, Appl. Phys. Lett. 100 104101 (2017)***

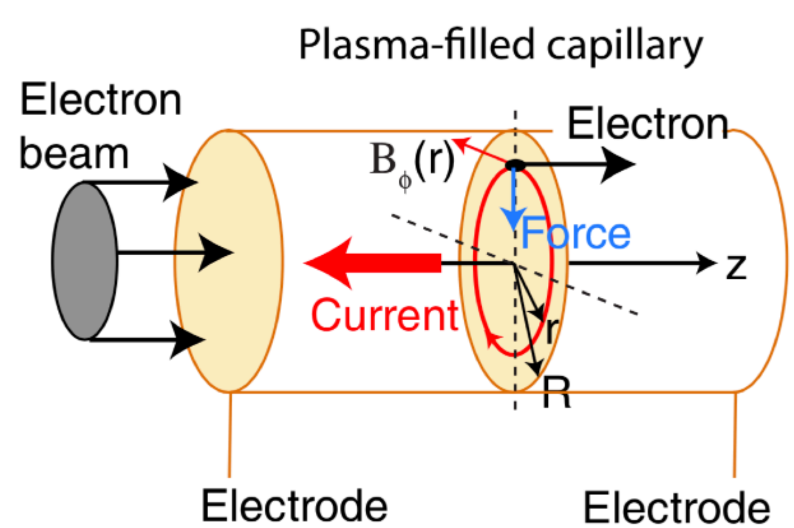


Image source: ***J. van Tilborg, Phys. Rev. Lett 115, 184802 (2015)***

Comparison to solenoids

- Solenoids are another conventional azimuthally symmetric focusing magnet.

- However, they are very different from active plasma lenses:

  – Solenoids scale as $1/\gamma^2$ instead of as $1/\gamma$ for plasma lenses (just like quads) ⇒ hence only used for low energy beams

  – Solenoids do not have linear focusing fields: do not conserve emittance

  – Solenoids couple the *x* and *y* planes.

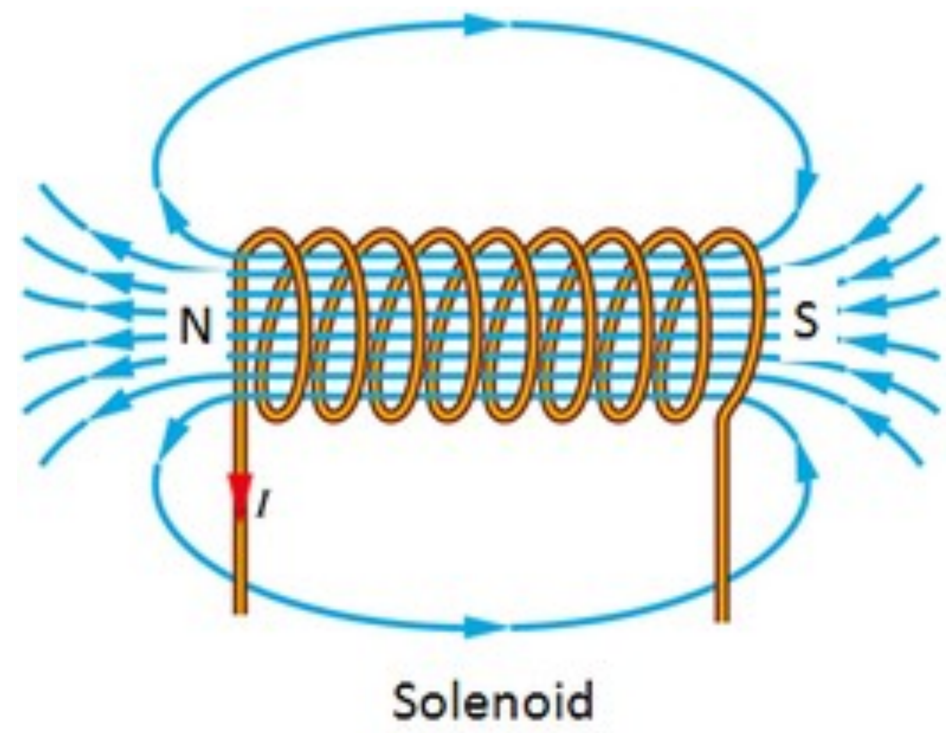


Image source: **excelatphysics.com**

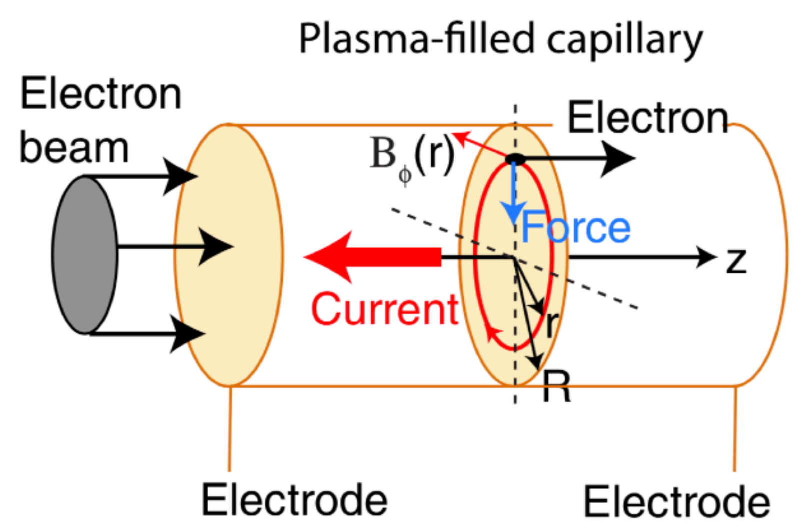


Image source: **J. van Tilborg, Phys. Rev. Lett 115, 184802 (2015)**

Active vs. passive plasma lenses

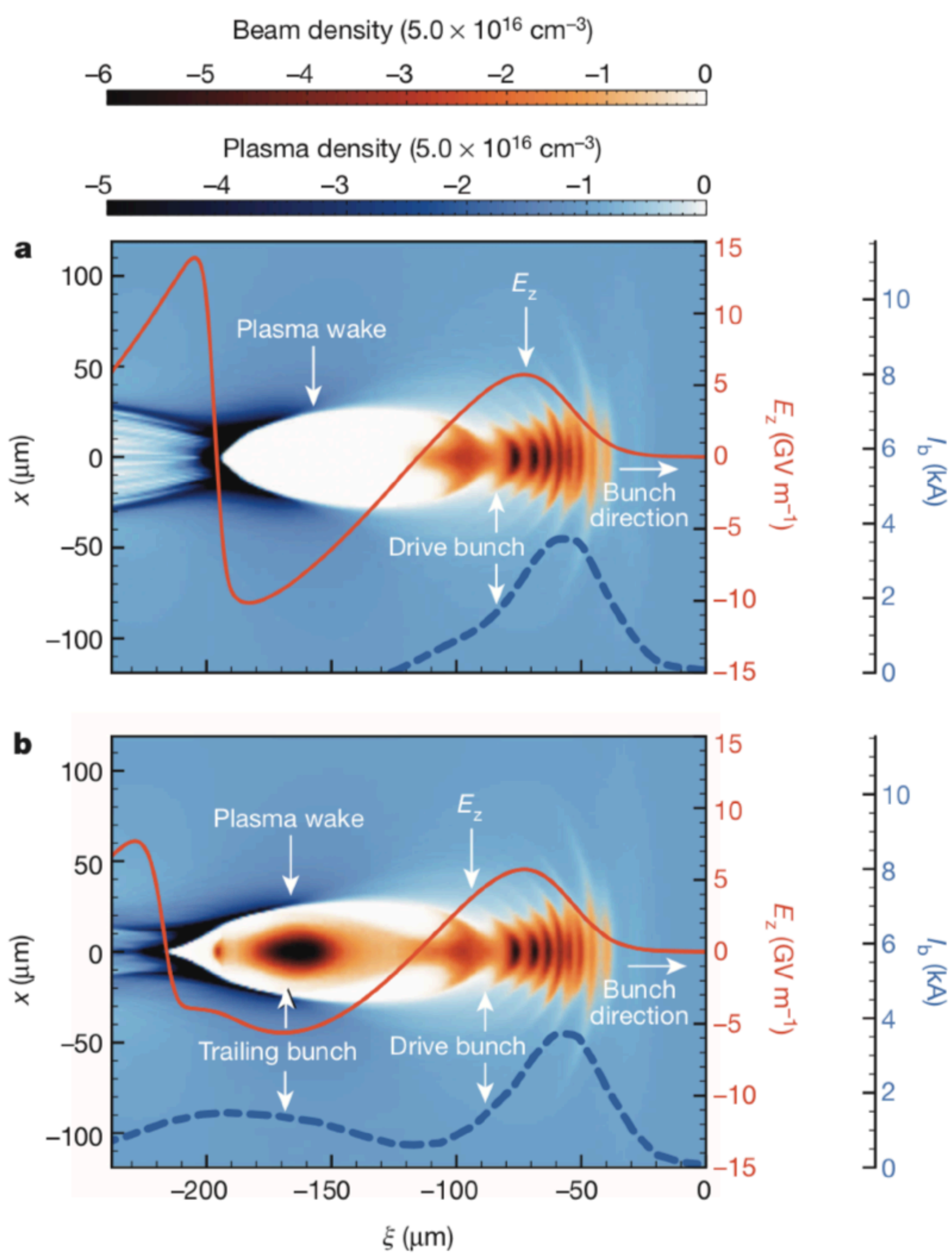


Image source: ***M. Litos et al., Nature 515, 92- 95 (2014)***

- In **active plasma lenses** require an *external current* to focus the beam
- In **passive plasma lenses**, no external current is required: rather the beam interacts with the plasma and *focuses itself*.
- Passive plasma lenses are **inherently much stronger** (easily MT/m in passive compared to kT/m in active).
- Unless a drive beam is used to provide a blowout (very expensive), the focusing fields are **non-linear** transversely and longitudinally
- Works for electrons, but **not for positrons.**

Recent experiments and results

A deep dive in the history books: Panofsky and Baker, 1950

- Back in 1950 (before quadrupoles were conventional), W. K. H. Panofsky and W. R. Baker from the Rad Lab at Berkeley needed to focus the 350 MeV proton beam from their 184-inch cyclotron.

- They used a big glass tube
  - 7.5 cm diameter
  - 1.2 m long

  filled with ~1 mbar of hydrogen

- This was arced using a powerful high voltage supply:
  - 4000 A
  - 70 kV

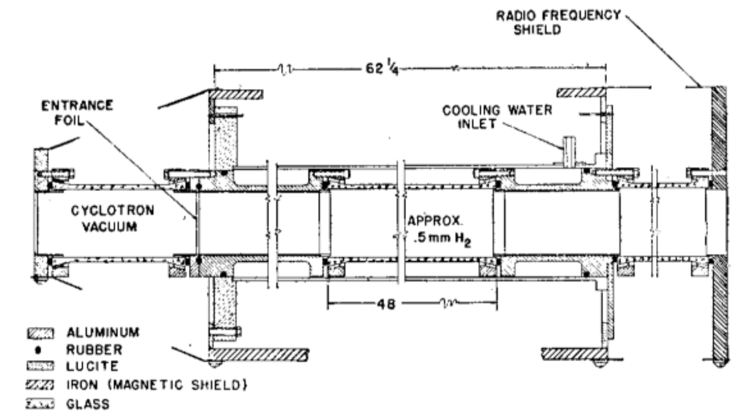
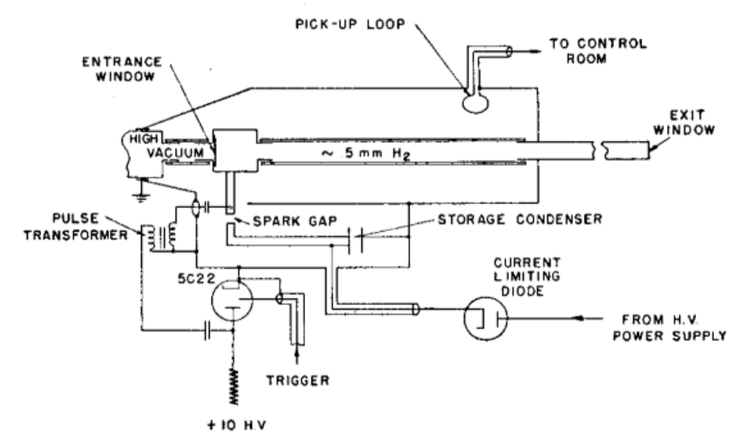
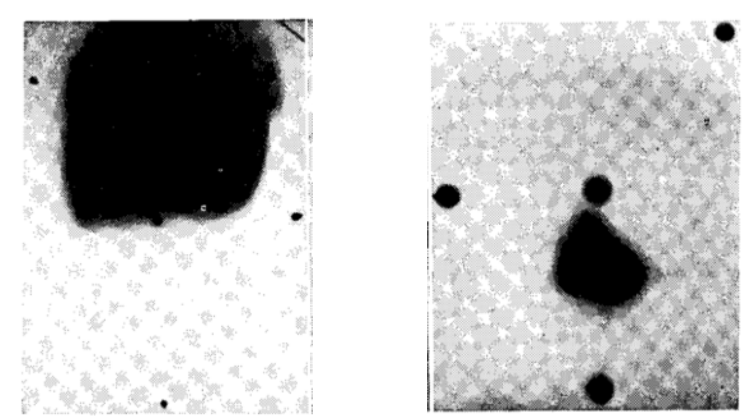


FIG. 2. Cross section of magnetic arc lens.





(a) (d)

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

BELLA at Lawrence Berkeley National Lab, USA

- In 2015, BELLA at LBNL used a similar plasma lens (serendipitously rediscovered) to connect two laser wakefield accelerator stages.
- Holds the current record for highest gradient:
  3500 T/m in a 33 mm long, 250 μm diameter capillary
- The BELLA group is continuing to push the technology.

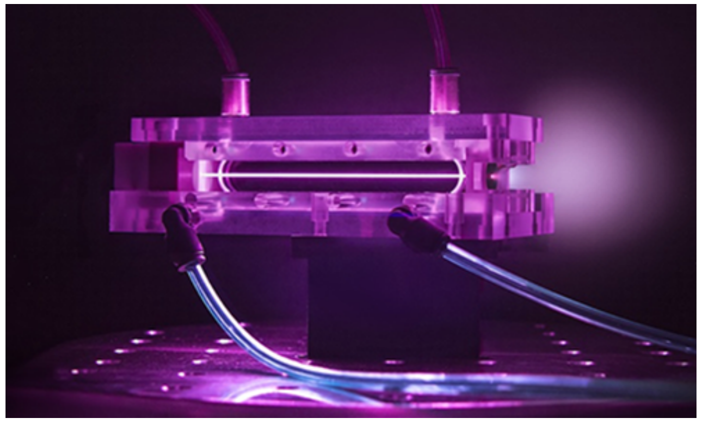


Image source: ***Lawrence Berkeley National Lab.***

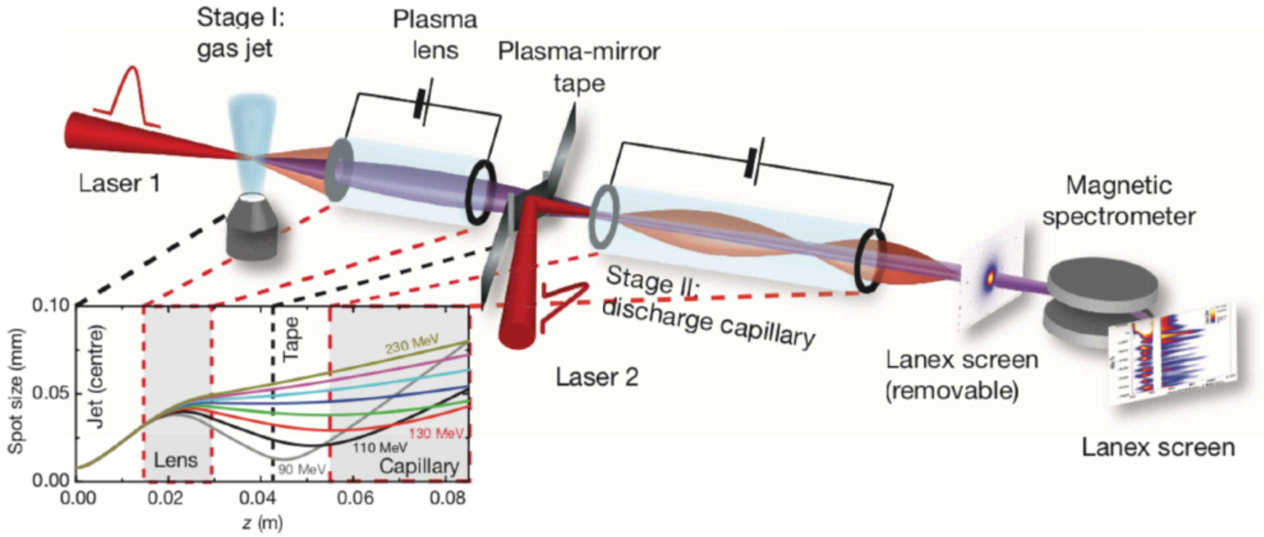


Image source: ***S. Steinke et al., Nature 530, 190–193 (2016)***

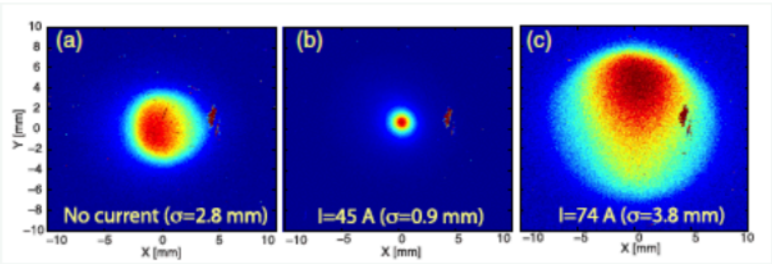


Image source: ***J. van Tilborg, PRL 115, 184802 (2015)***

INFN Frascati

- SPARC_LAB at INFN Frascati is currently running a plasma lens experiment.
- They have reported emittance growth due to spherical aberrations.

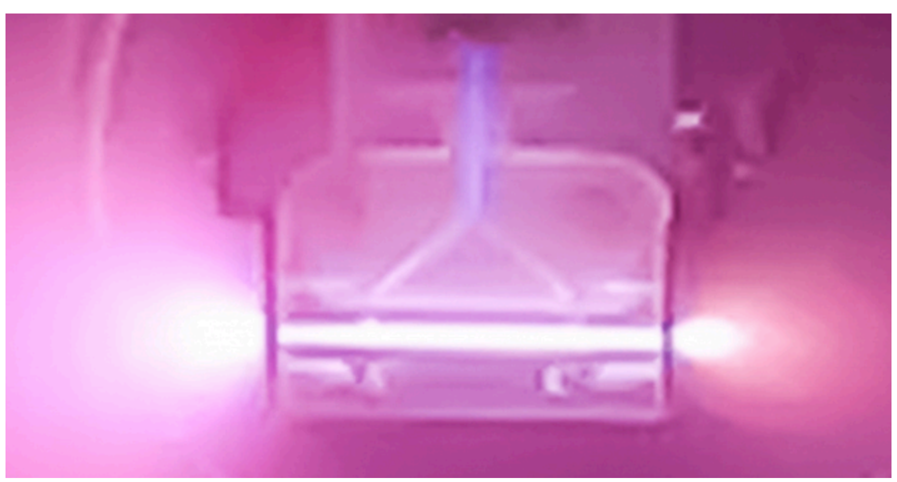
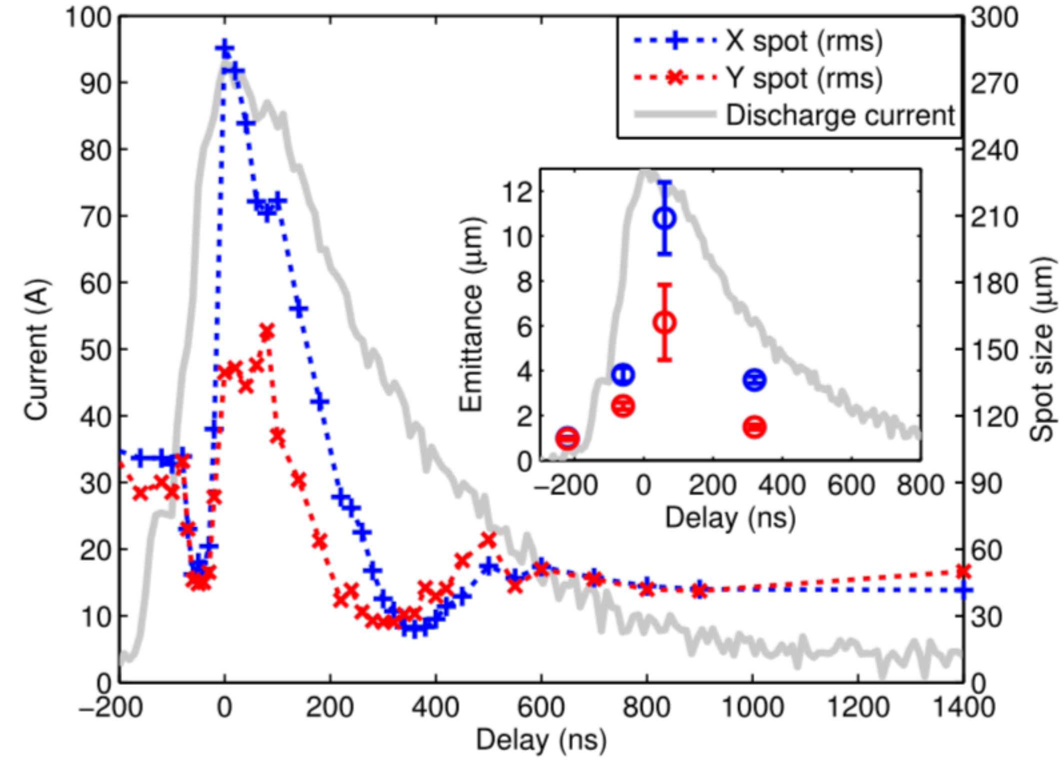


Image source: ***E. Chiadroni, Overview of Plasma Lens Experiments and Recent Results, EAAC 2017***



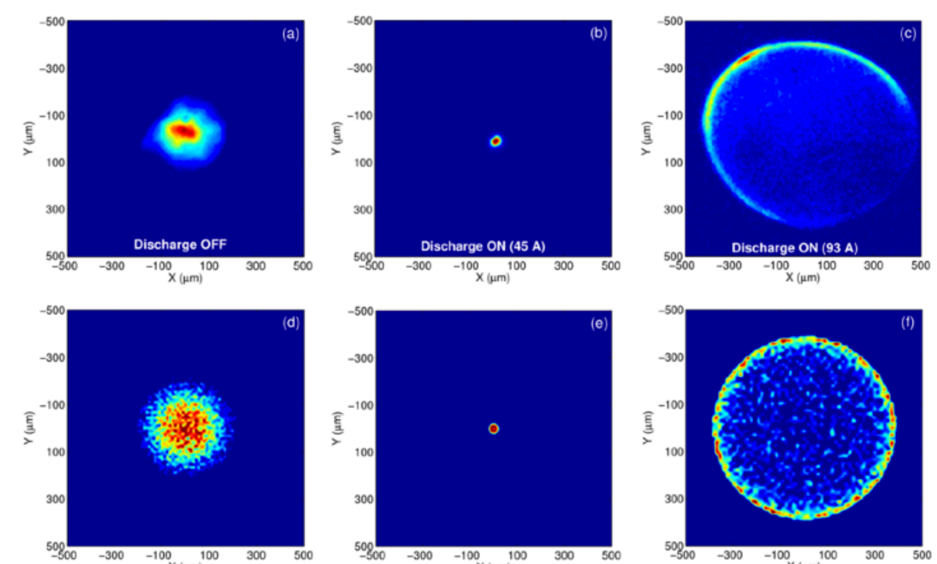


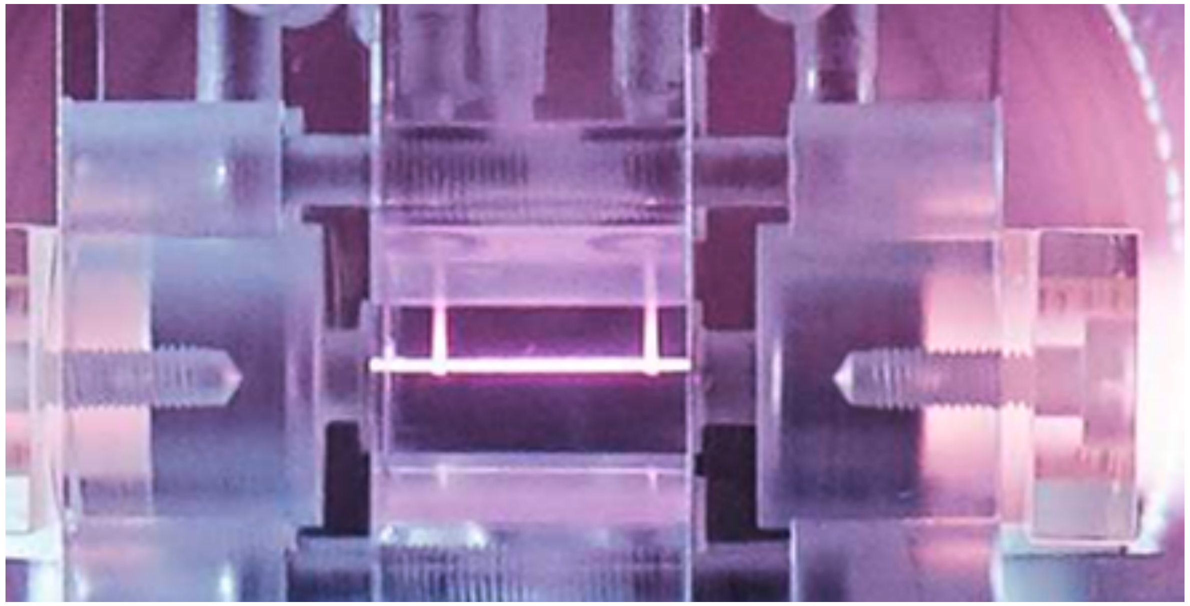
Image source: ***R. Pompili, Appl. Phys. Lett. 100 104101 (2017)***

DESY Mainz Microtron

- A DESY-led experiment at the Mainz Microtron (Germany) has used a 1 mm diameter sapphire capillary of lengths 7 mm, 15 mm, 33 mm.

- A thyrotron and a pulse forming network was used to form the current pulse.

- Results have not yet been published, but are believed to show some emittance growth.



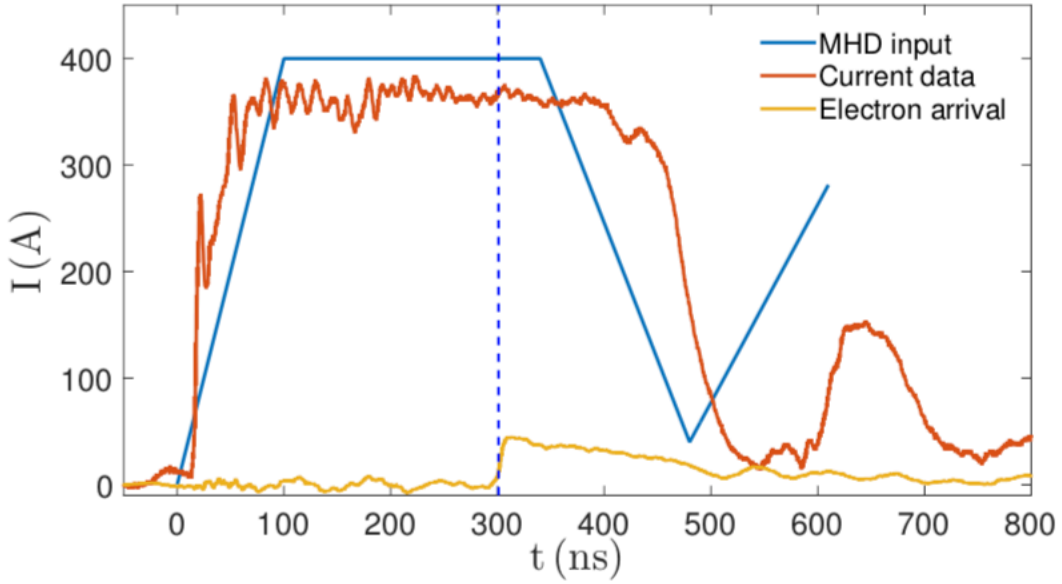
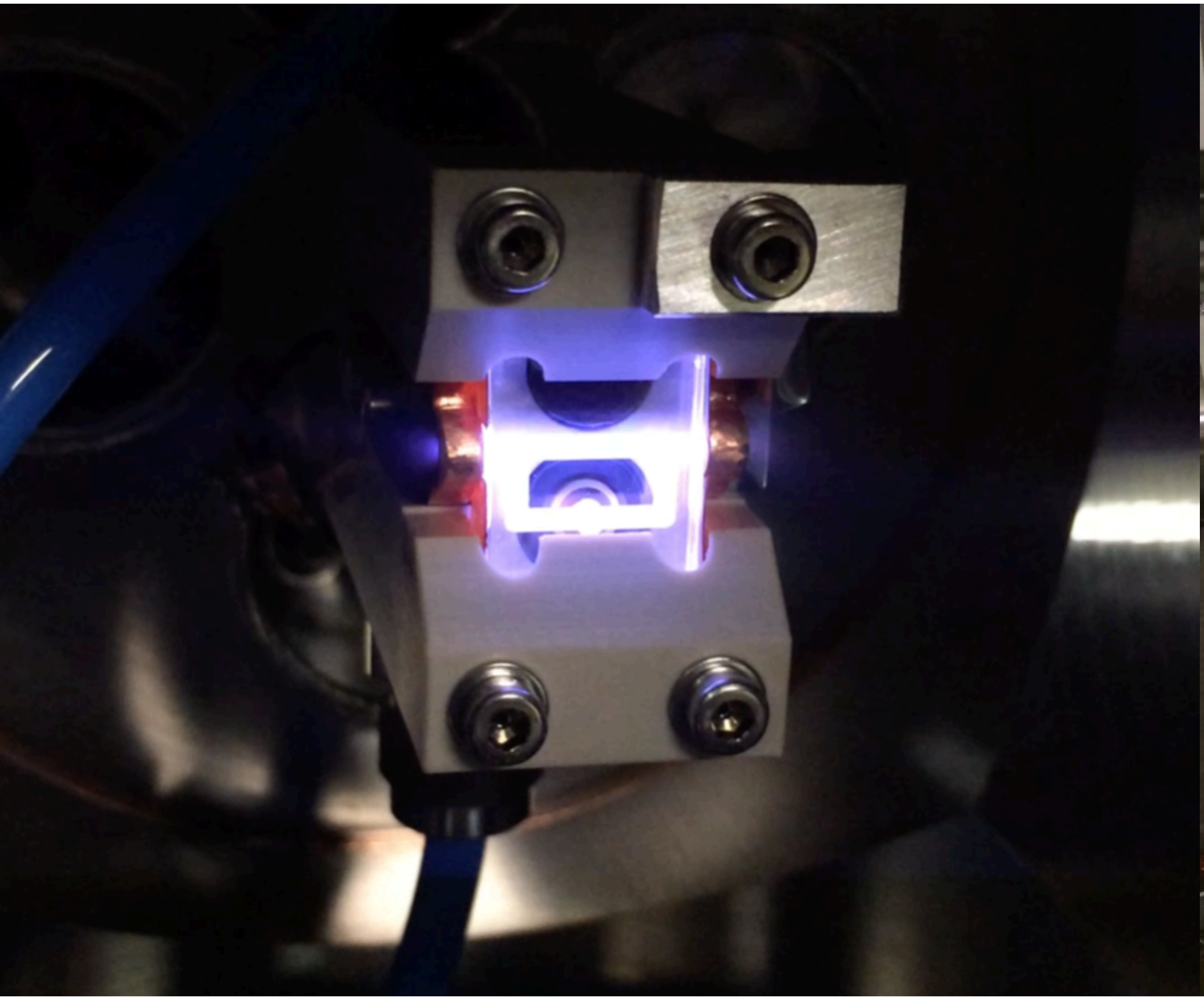
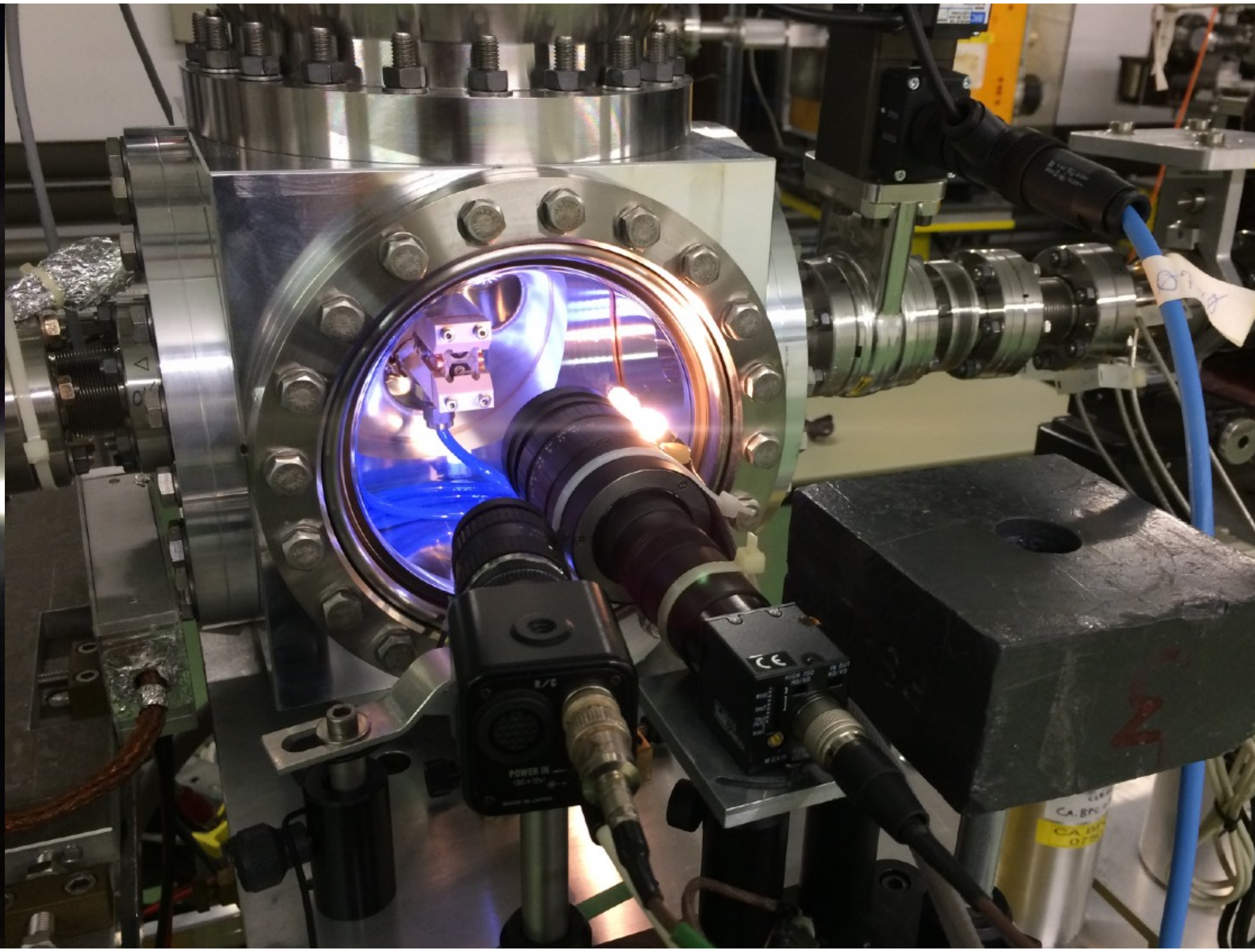


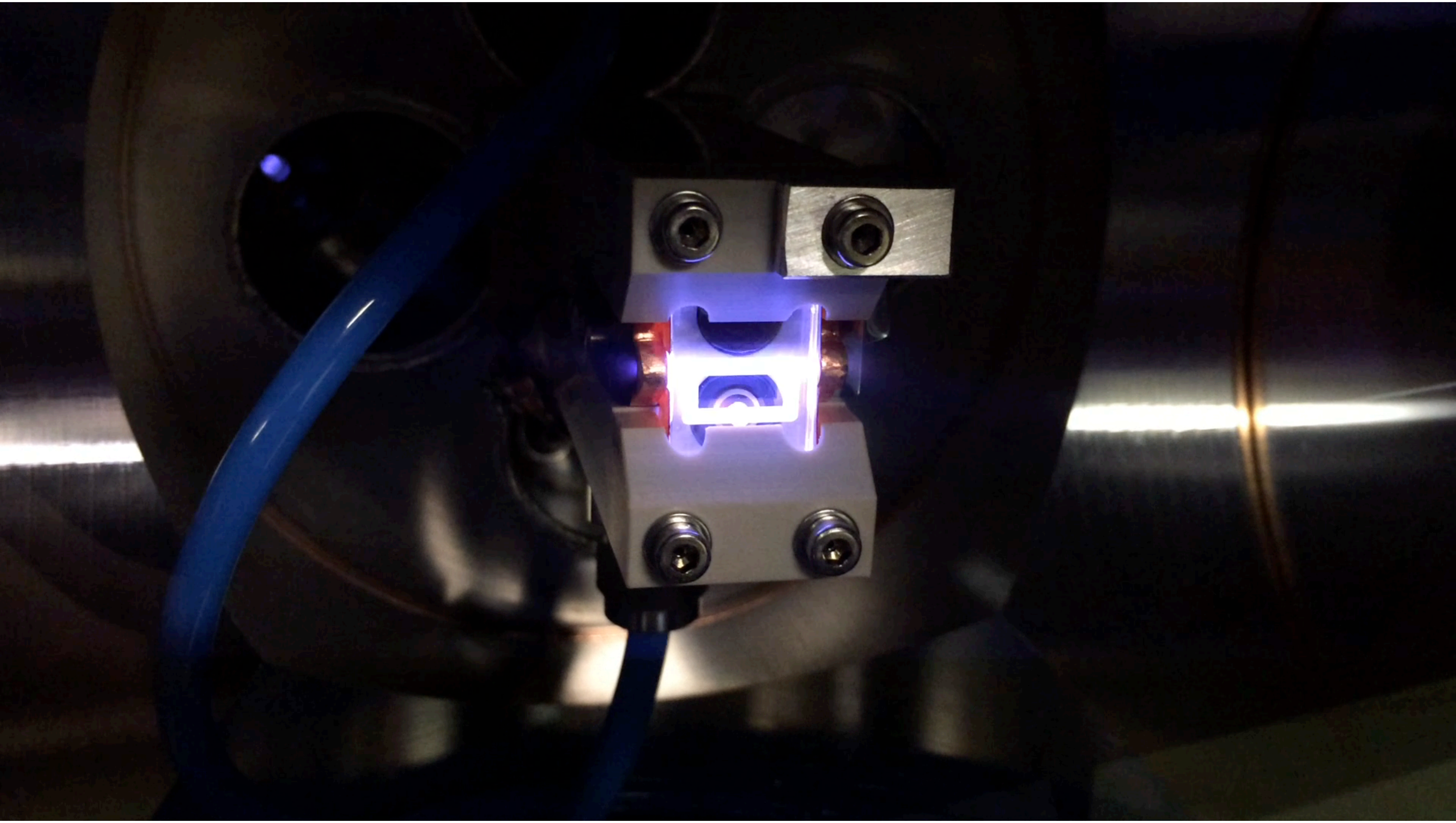
Image source: ***DESY***

CLEAR at CERN

- An experiment to test plasma lenses at the new CLEAR User Facility.
- A collaboration between Uni Oslo, CERN, DESY and Uni Oxford.

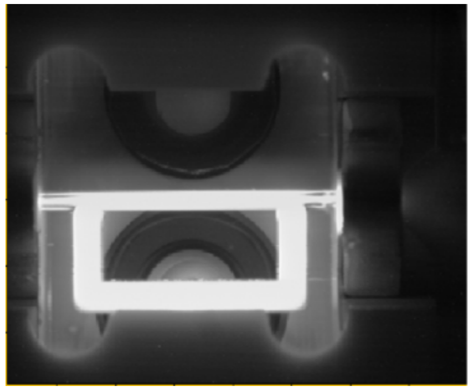




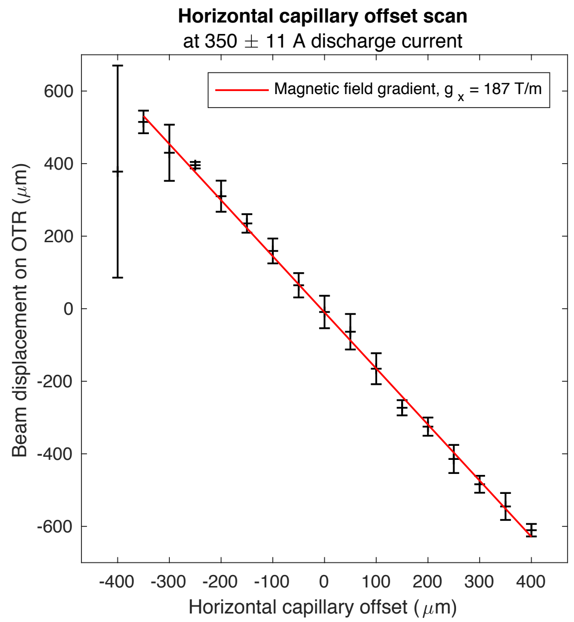


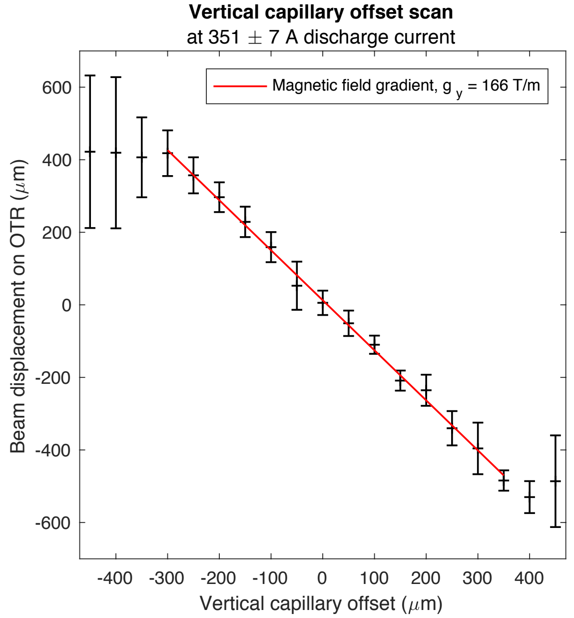
Recent results from the CLEAR Plasma Lens Exp.

- First results obtained Dec 1, 2017.

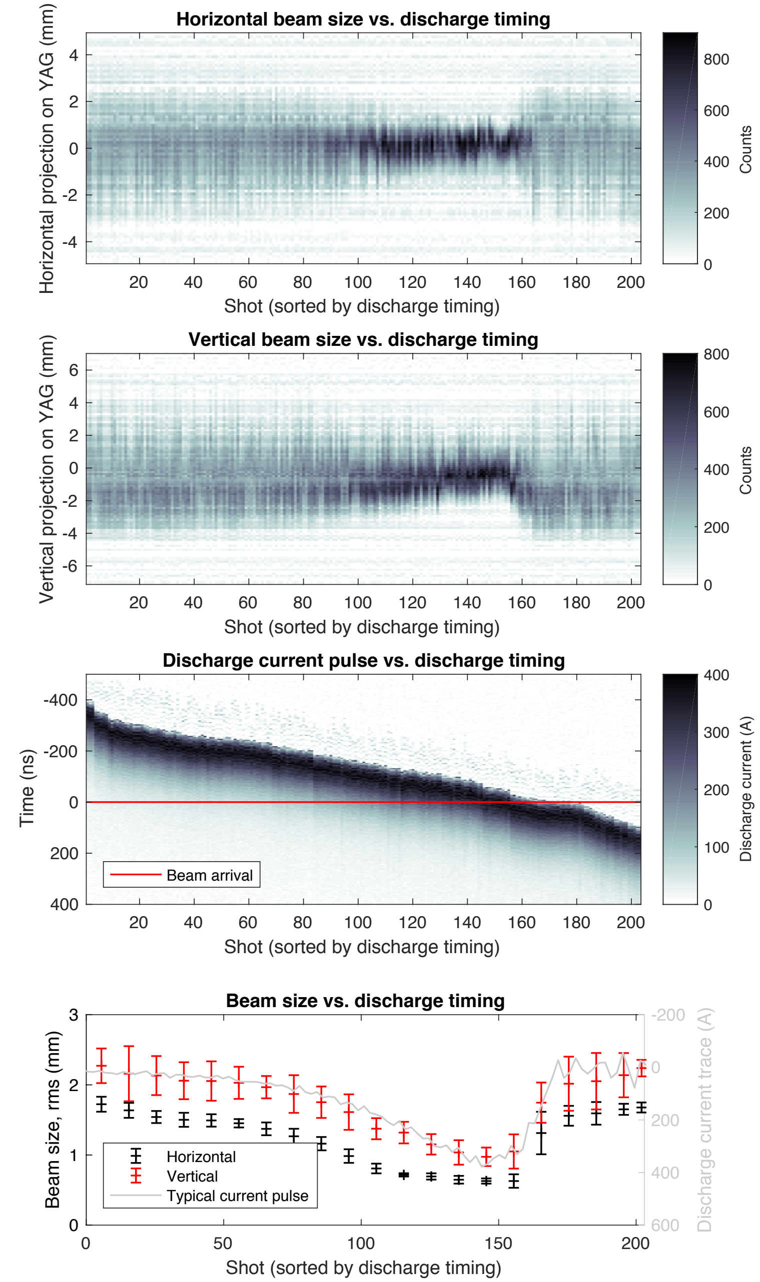


Offset scan

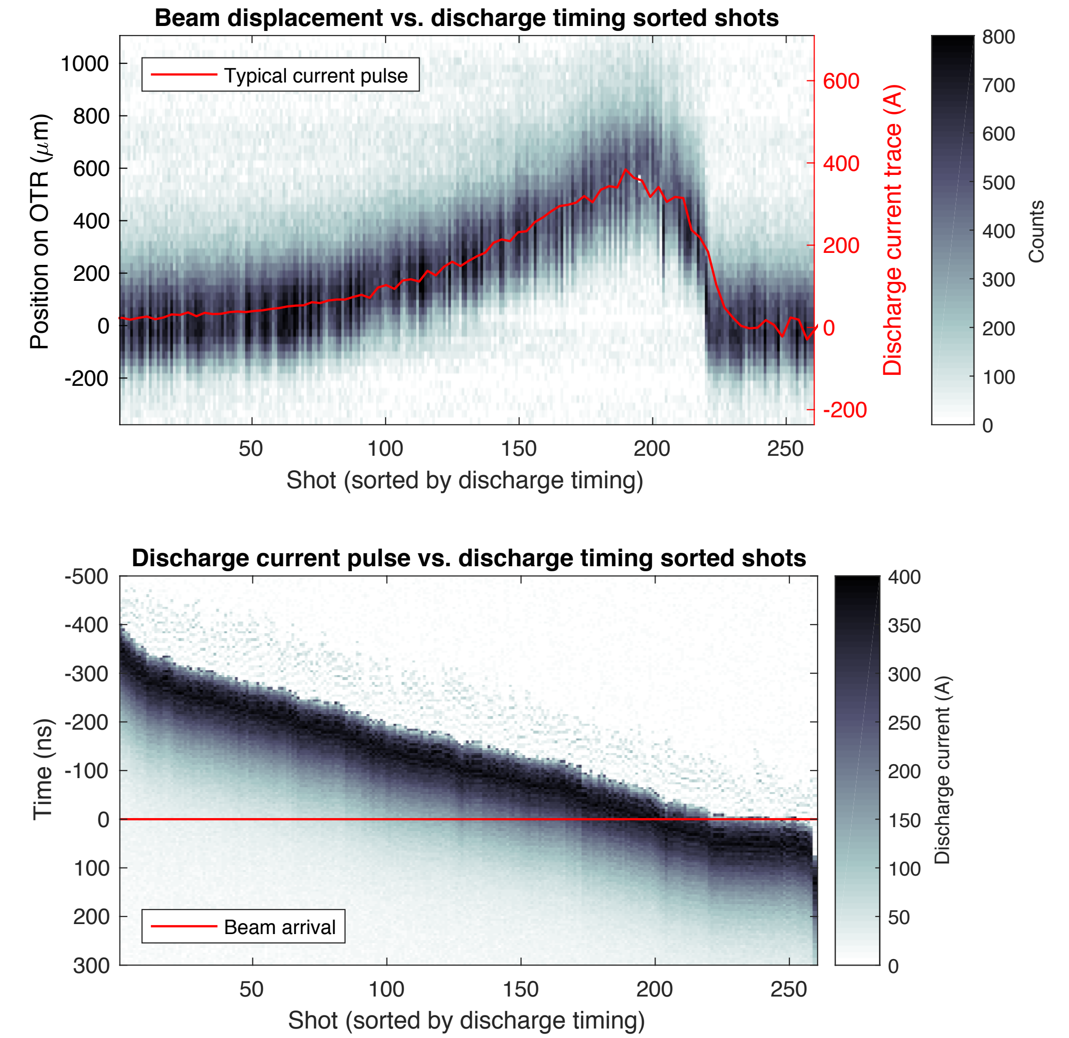




Timing scan – focusing



Timing scan – dipole kicks



Opportunities

Summary of what active plasma lenses can offer

Provides **azimuthally symmetric focusing**
– important for miniaturizing particle accelerators.

Provides **strong focusing**
– up to kT/m

Relatively **cheap and compact devices**
– simple and made from cheap materials

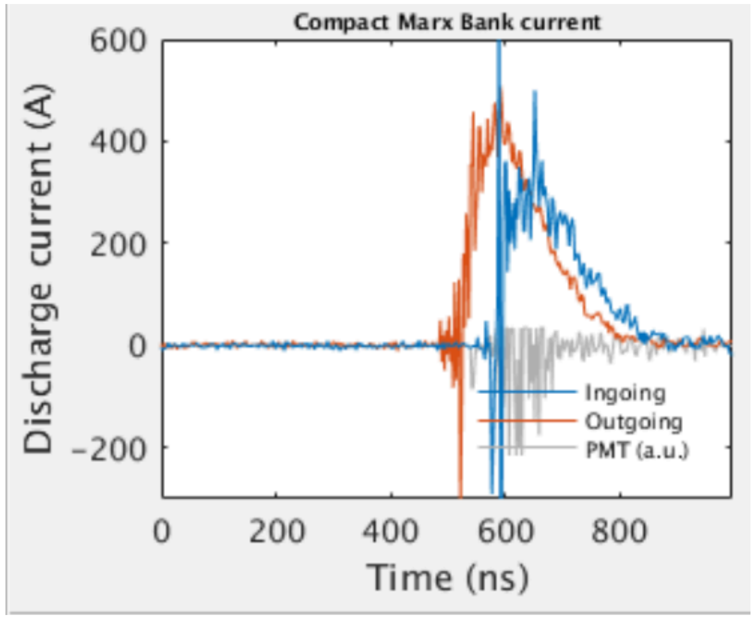
Limitations – technical and fundamental

Technical limitations (can probably overcome by clever engineering)

- **Vacuum levels**
  – Requires gas in the accelerator
  – Currently solved with differential pumping or beam windows (e.g. polymers)
  – Limits use of large capillaries (too much flow).

- **Repetition rate**
  – In principle nothing in the way of running at kHz-MHz
  – Difficult to provide enough current pulses (~MW peak power over 100 ns)
  – Heating of the system

- **Electromagnetic pulse (EMP) noise**
  – The large current pulse easily creates noise for sensitive equipment nearby.



Field gradient non-uniformity – limits the current

- Heating of the plasma electrons can be uneven: this leads to nonuniform magnetic field gradients.
- Close to the capillary wall, the plasma cools (compared to on-axis).
- All experiments so far have found emittance growth and nonuniform focusing.
- An approximate enhancement factor 1.35 of the central field gradient was found at BELLA.
- An analytic model of nonuniformities has been developed, matching MHD simulations:

$$B(r) = \left(\frac{\mu_0 I_0}{2\pi R^2}\right) \frac{u(0)^{3/7}}{2m_I} x \left[1 - \frac{3x^2}{56u(0)^{4/7}}\right]$$

- Overall, this limits the current to ~1 kA.

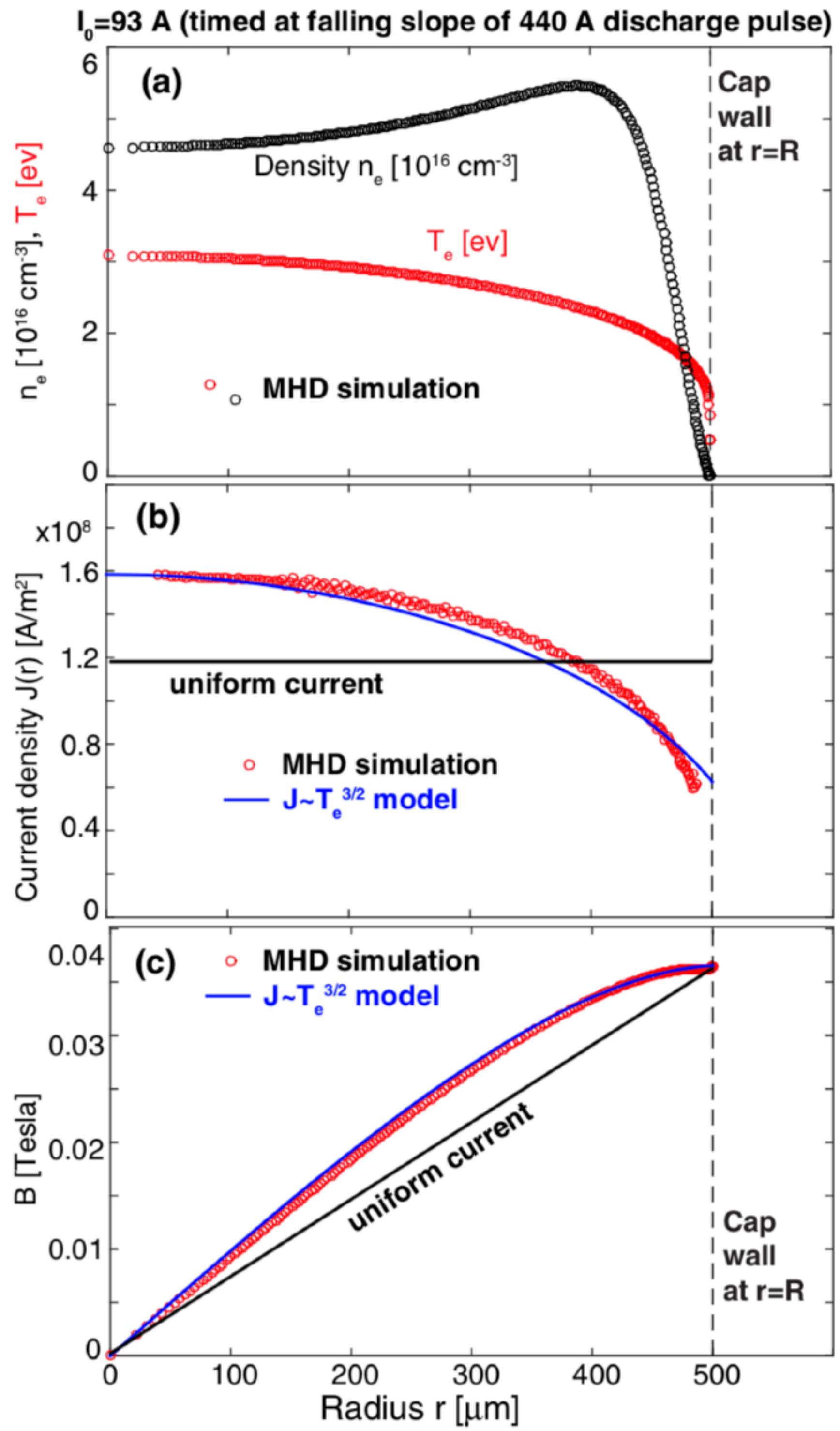
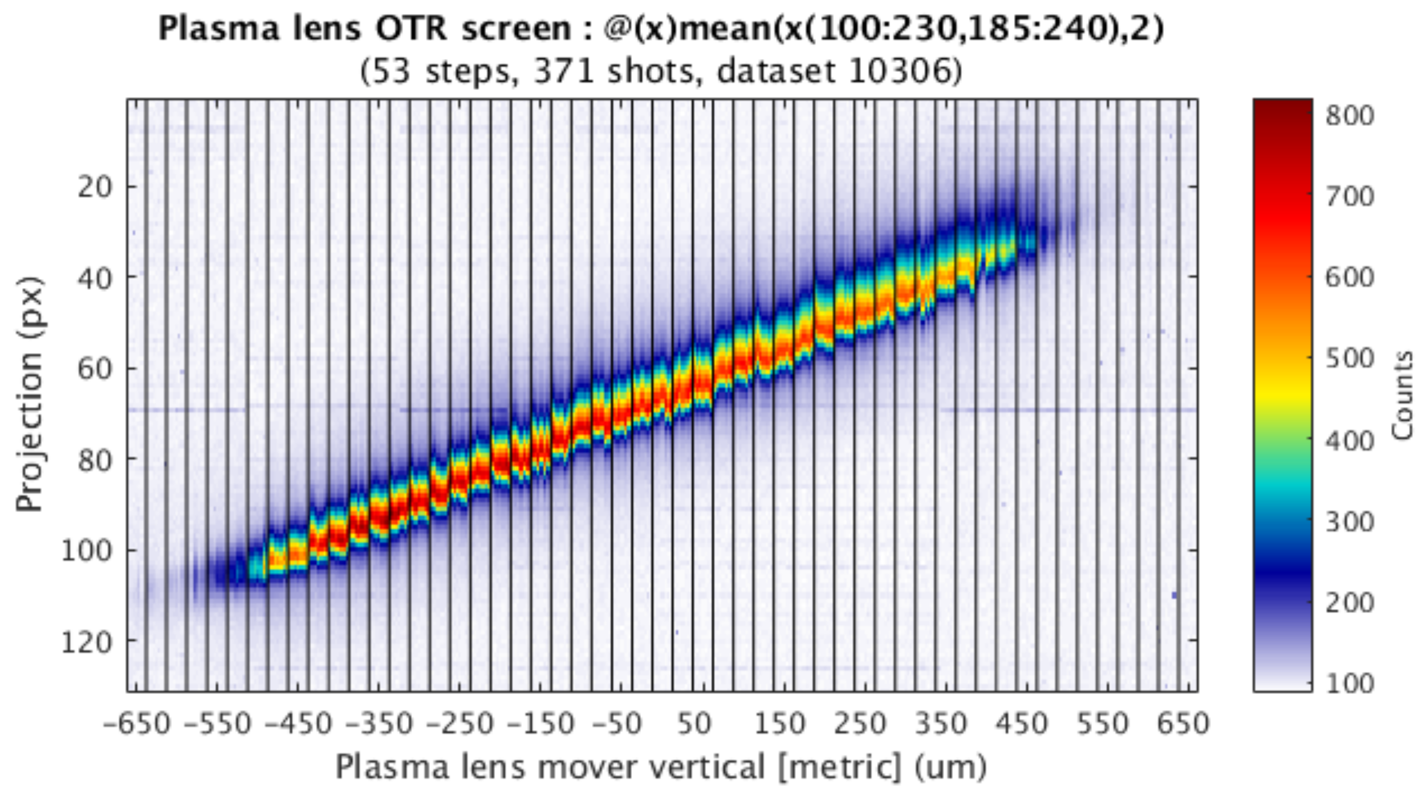
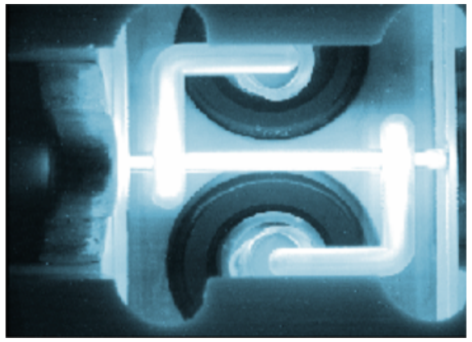


Image source: ***J. van Tilborg et al., Phys. Rev. Accel. Beans 20, 032803 (2017)***

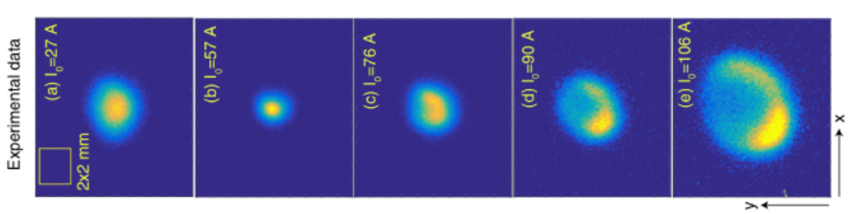
Recent result from the CLEAR Plasma Lens Exp. – Obtained Dec 12, 2017



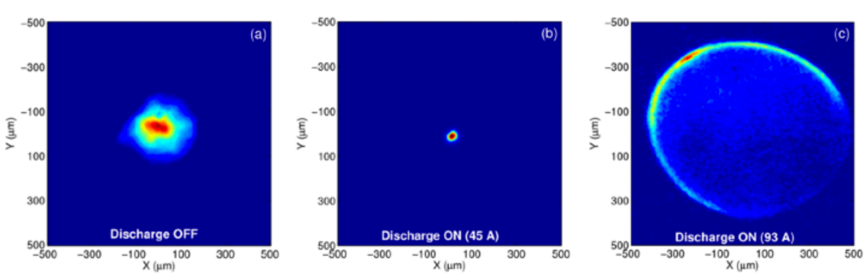


Vertical offset of the plasma lens using a pencil beam.
Dipole kicks measured as offset downstream.

BELLA results:



INFN results:



- **No evidence of nonuniform focusing** in the first direct measurement of the field.
- Measurements thus far were only indirect measurements showing spherical aberrations.

Plasma wakefields – limits use for intense beams

- When the beam density approaches that of the plasma, wakefields form in the plasma
- Even moderate perturbations of the plasma sets up very strong focusing fields.
- The wakefields fall into two regimes:
  - Linear plasma wakefields (described analytically) $n_b \ll n_p$
  - Nonlinear/blowout plasma wakefields (limited model + particle-in-cell simulations) $n_b \approx n_p$
- We are interested in the maximum focusing field for any set of beam/plasma parameters
- **Problem: PIC simulations are very slow!**

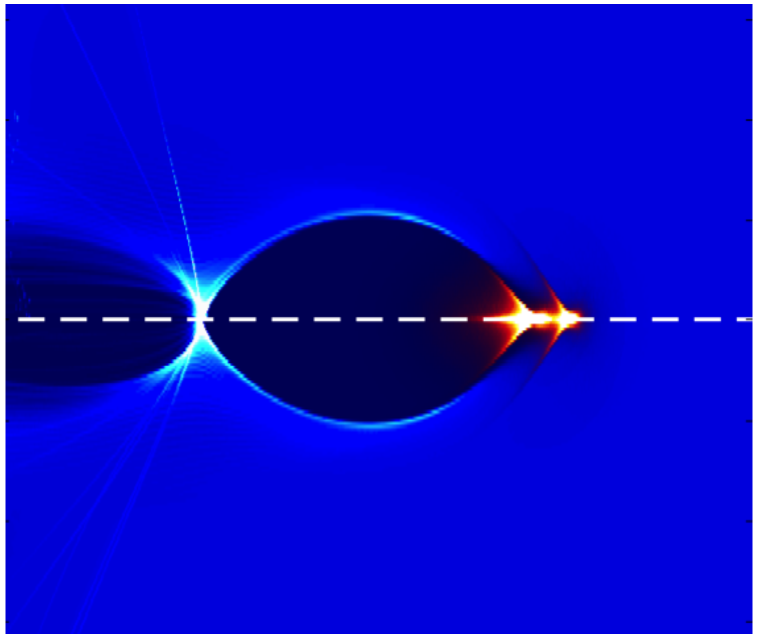
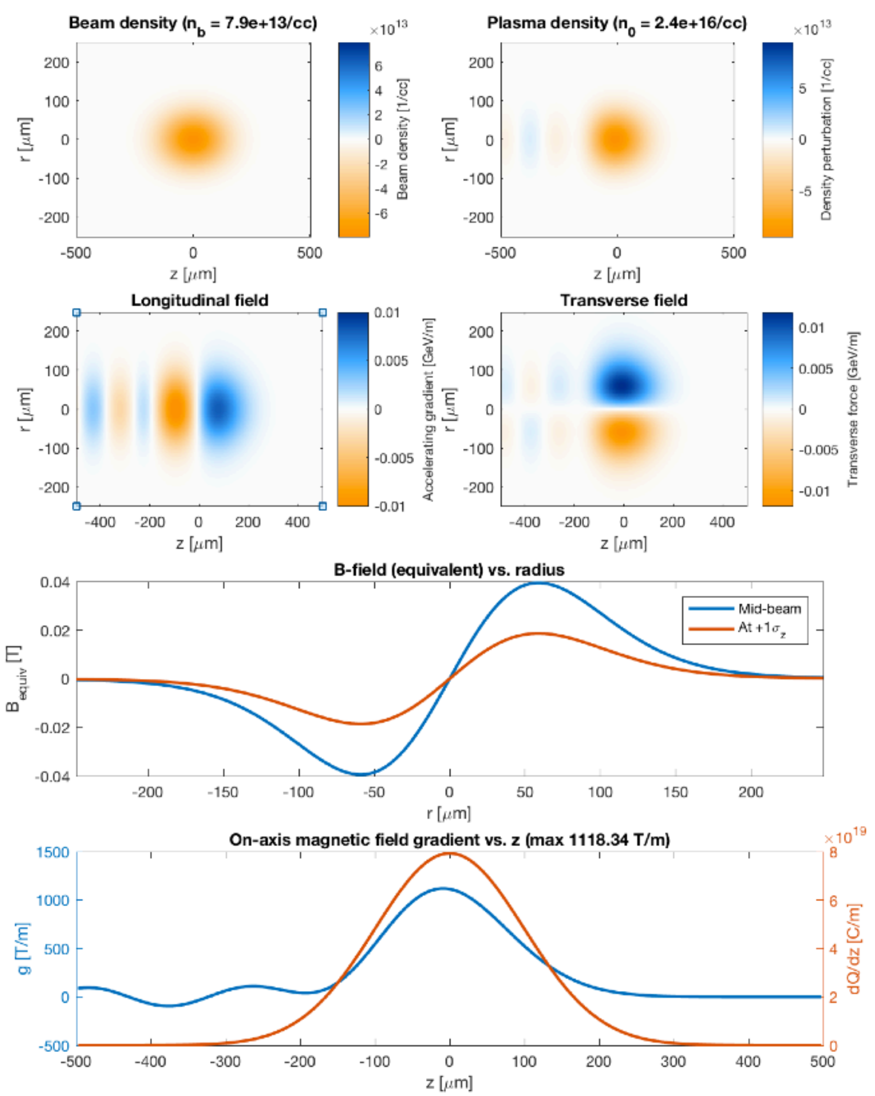


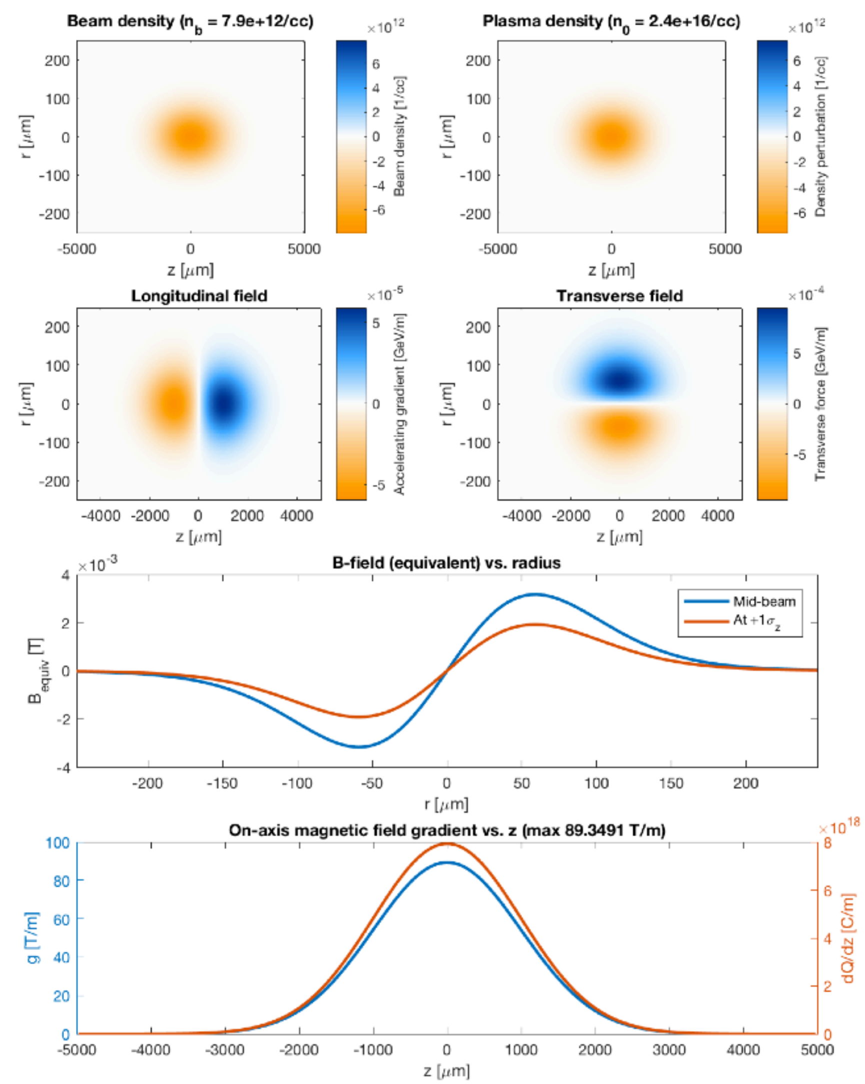
Image source: **DESY**

Three regimes: long, short and intense

Long beams
(linear theory)



Short beams
(linear theory)



Intense beams
(nonlinear theory)

Requires PIC simulation

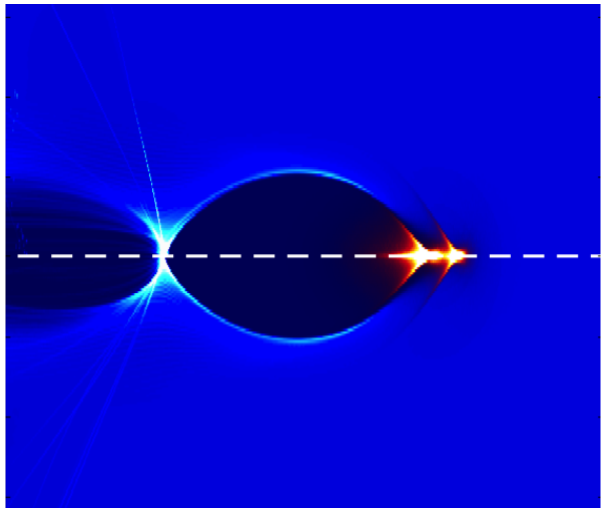


Image source: **DESY**

However: the maximum focusing gradient is given by the ion column!

Analytic expressions for the maximum focusing gradient

Expressions for a Gaussian beam:

Long bunches
(linear theory)

$$g_{\text{long}}^{\text{max}} = -\frac{eNc\mu_0}{2\sqrt{2\pi}^3 \sigma_r^2 \sigma_z} \left(1 + \frac{k_p^2 \sigma_r^2}{2} e^{\frac{k_p^2 \sigma_r^2}{2}} \text{Ei}\left(-\frac{k_p^2 \sigma_r^2}{2}\right)\right)$$

Short bunches
(linear theory)

$$g_{\text{short}}^{\text{max}} = -\frac{eNc\mu_0 k_p^2 \sigma_z}{2\pi \sigma_r^2} \left(1 + \frac{k_p^2 \sigma_r^2}{2} e^{\frac{k_p^2 \sigma_r^2}{2}} \text{Ei}\left(-\frac{k_p^2 \sigma_r^2}{2}\right)\right)$$

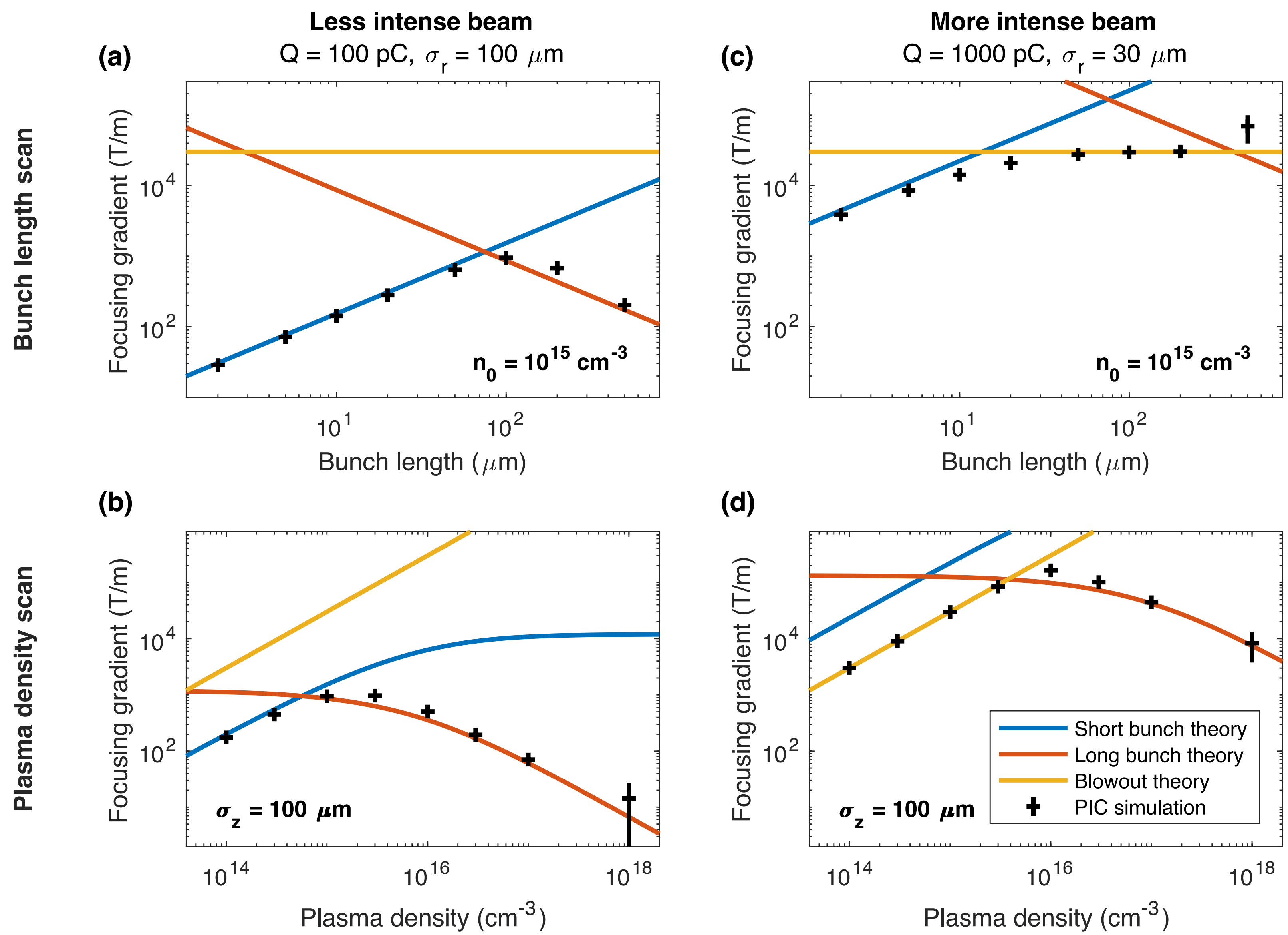
Intense bunches
(just an ion column)

$$g_{\text{intense}}^{\text{max}} = \frac{en_0}{2c\epsilon_0}$$

Combined expression:

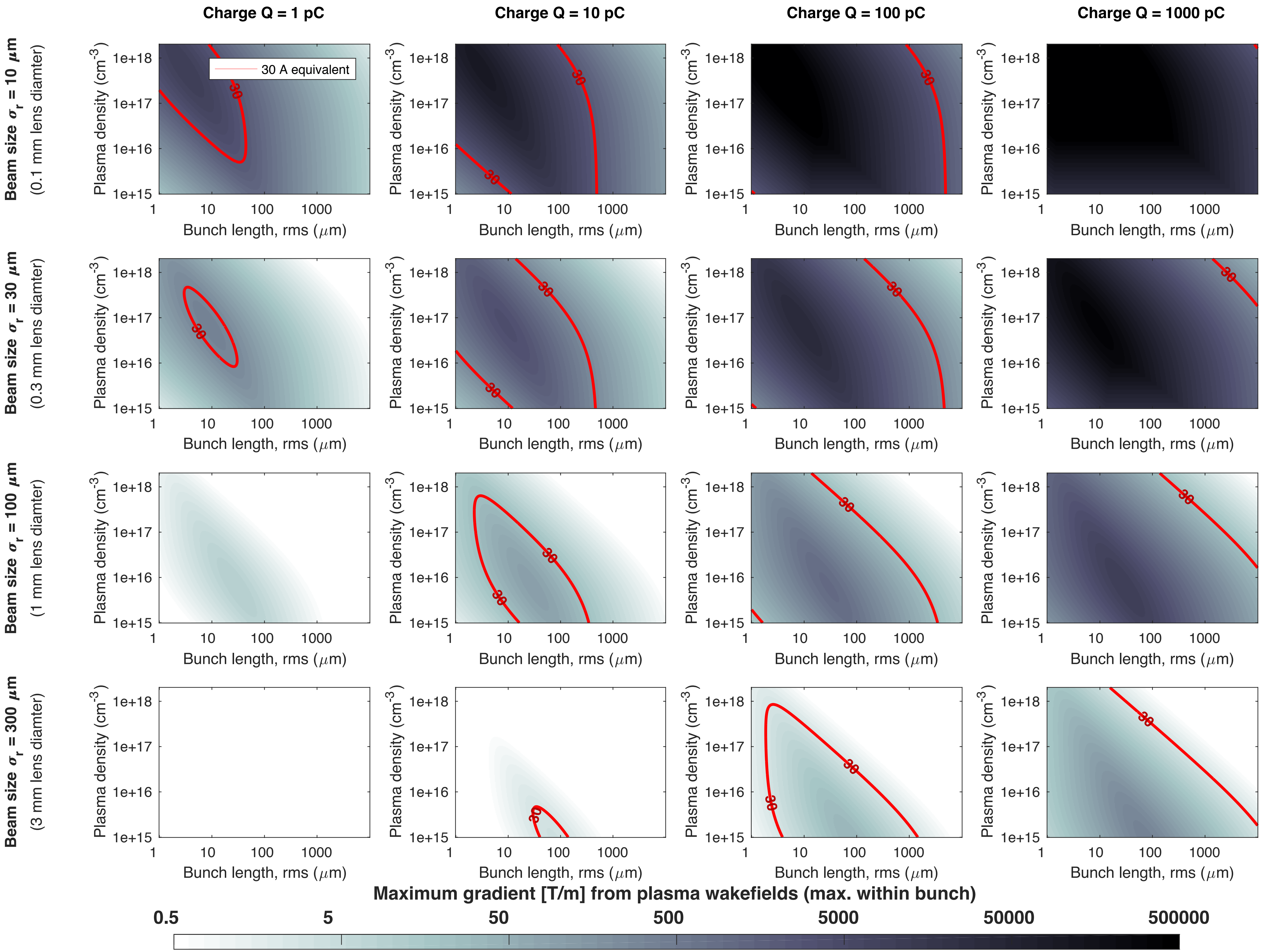
$$g_{\text{max}} = \min(g_{\text{long}}^{\text{max}}, g_{\text{short}}^{\text{max}}, g_{\text{intense}}^{\text{max}})$$

Comparison of analytic model to PIC simulations



- **Very good fit to PIC simulations**, but many orders of magnitudes faster.
- Method and expressions to be published shortly.

Plasma wakefield limits: Full 4D parameter space for active plasma lenses



Linear colliders?

Application to current experiments

- No experiments have had plasma wakefields in an active plasma yet, as of yet.

	LBNL BELLA	**INFN Frascati**	**DESY Mainz**	**CERN CLEAR (current)**
Energy / MeV	100	126	855	200
Charge / pC	30	50	1	1-1000
Beam size rms / µm	100	130	150	30 (50 pC) or 70 (1 nC) - 200
Bunch length / µm	2	330	> 100000	300-1200
Capillary radius / µm	125	500	500	500
Capillary length / mm	33	30	7 - 10 - 15	15
Max current / A	330	100	740	500
Pressure / mbar	150	40	4	1-30
Plasma density / cm-3	7×10^{18}	9×10^{16}	$\sim 10^{17}$	2×10^{16} - 7×10^{17}
Maximum plasma wakefield within bunch /	**14**	**3.5**	**1.2 x 10-4**	**0.0005 - 2260**

- Should be possible at CLEAR!

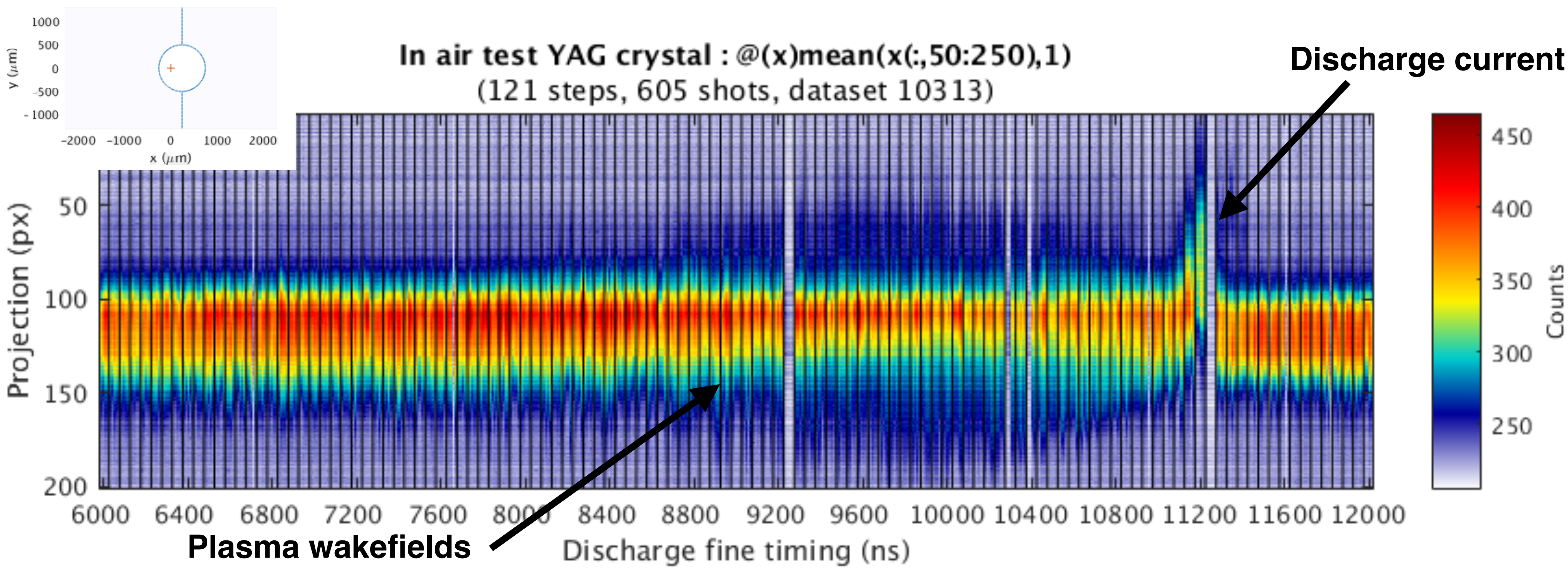
Application to a linear collider

- Consider the beams in CLIC and ILC:

	ILC	CLIC	PWFA LC (Adli et al.)
Energy / MeV	500 000	1 500 000	1 000 000 (final stage)
Charge / pC	3200	660	1600
Beam size rms / µm	$\sqrt{(28 \times 1.7)} \approx 7$	$\sqrt{(5 \times 0.5)} \approx 1.6$	~2
Bunch length / µm	300	44	20
Plasma density / cm-3	1×10^{16}	1×10^{16}	1×10^{16}
Maximum plasma wakefield within bunch / T/m	**3×10^5 (blowout)**	**3×10^5 (blowout)**	**3×10^5 (blowout)**

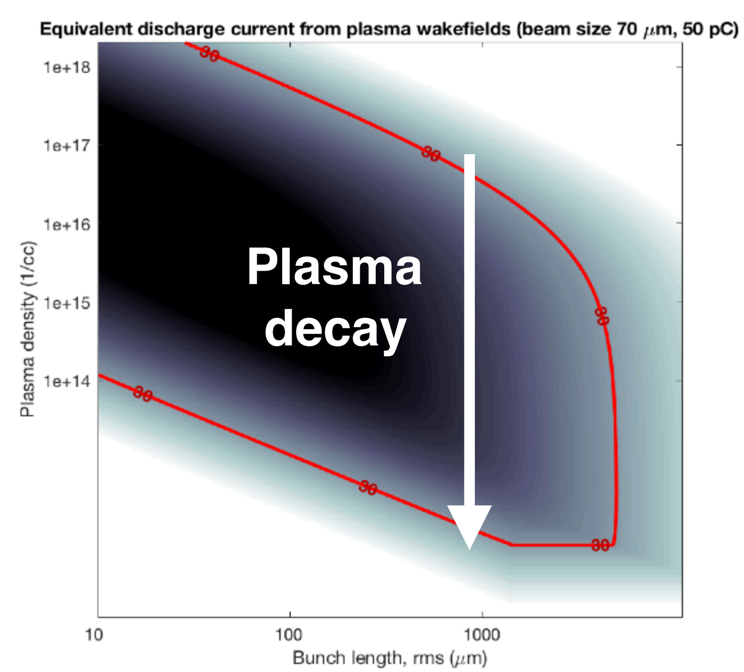
- The repetition rate of these linear colliders also represent a significant challenge, but is not as fundamental.
- Clearly, active plasma lenses are **not suitable for intense collider-style beams**.
- This runs counter to the hope that active plasma lenses can be used in conjunction with e.g. plasma wakefield accelerators.
- However: a collider with a **different time structure** could make use of active plasma lenses.

Recent result from the CLEAR Plasma Lens Exp. – Obtained Dec 14, 2017

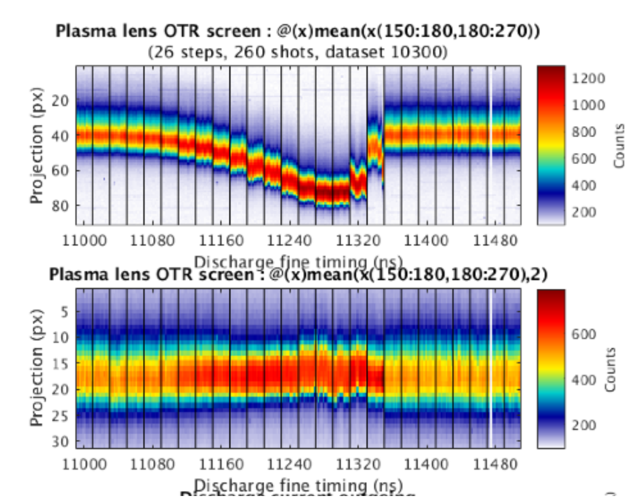


- Dipole kicks during current: only focusing during wakefields.

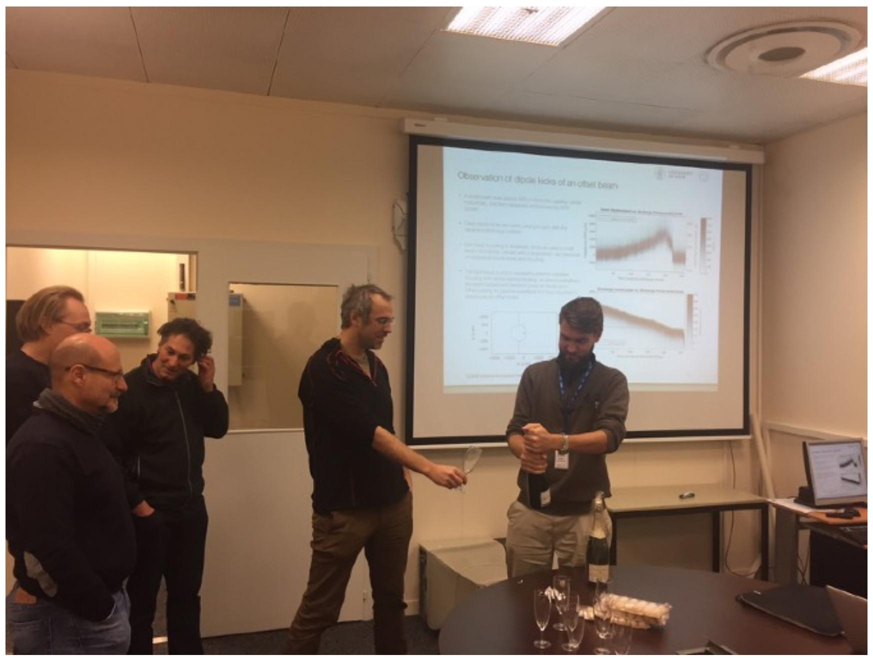
- **First result showing plasma wakefield focusing in a plasma lens!**



Reference:
only from discharge



Last Monday



Today!

Conclusions

Conclusions

- Active plasma lenses represent an intriguing path toward strong, compact focusing.
- There is a large recent experimental activity on the subject, including at CERN.
- However, both technical and fundamental limits exist.
- Non-linearities may cause emittance growth if not mitigated.
- Importantly: plasma wakefields set stringent limits on usability for intense beams
- Still: very suitable for accelerators with less intense bunches.

Thanks!