
# *Overview* of Plasma Lens Experiments and Recent Results

Enrica Chiadroni (INFN - LNF)

***Abstract***

***Beam injection and extraction*** *from a plasma module is* ***still one of the crucial aspects*** *to solve in order to produce high quality electron beams with a plasma accelerator. Proper matching conditions require to focus the incoming high brightness beam down to few microns size and to capture a high divergent beam at the exit without loss of beam quality.*

***Plasma-based lenses*** *have proven to provide focusing gradients of the order of kT/m with* ***radially symmetric focusing*** *thus promising* ***compact and affordable*** *alternative to permanent magnets in the design of transport lines.*

*In this talk an overview of recent experiments and future perspectives of plasma lenses is reported.*

INFN
LNF
Istituto Nazionale di Fisica Nucleare

# Motivation

✓ ***Multi GeV*** acceleration ***in cm scale*** plasma structures

➡ Acceleration of high brightness electron beams and their transport up to the final application, preserving the high quality of the 6D phase space


- Injection and matching to plasma accelerating module
  - the beam has to be focused to the matching spot to prevent envelope oscillations that may cause emittance growth
    - **Blow-out regime**

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

$$\alpha_{matching} = 0$$

**Matching condition**

$$\sigma_{matching} = \sqrt{\frac{\beta_{matching}\varepsilon_n}{\gamma}} \approx \mu m$$

**Typical numbers**

$$k_p = \frac{2\pi}{\lambda_p}$$

$$\lambda_p(\mu m) \approx 3.3\ 10^4 n_p^{-1/2}(cm^{-3})$$

$$\gamma = 1000$$

$$n_p = 10^{16}\ cm^{-3}$$

$$\varepsilon_n = 1\ mm\ mrad$$

# Motivation

- Extraction from plasma accelerating module
  - plasma fields are stronger than in conventional accelerators

$$\boxed{G[MT/m] \equiv \frac{F_r}{ecr} \approx 3n_p[10^{17}cm^{-3}]}$$

$F_r$ : transverse focusing force

    - beams experience huge transverse size variation when propagating from the plasma outer surface to the conventional focusing optics

$$\boxed{\sigma_x \sim \mu m} \qquad \boxed{\sigma_{x'} \sim mrad}$$

    - the particle transverse motion becomes extremely sensitive to energy spread
  - the beam angular divergence has to be reduced and the transverse spot size increased to limit the chromatic induced emittance degradation in vacuum

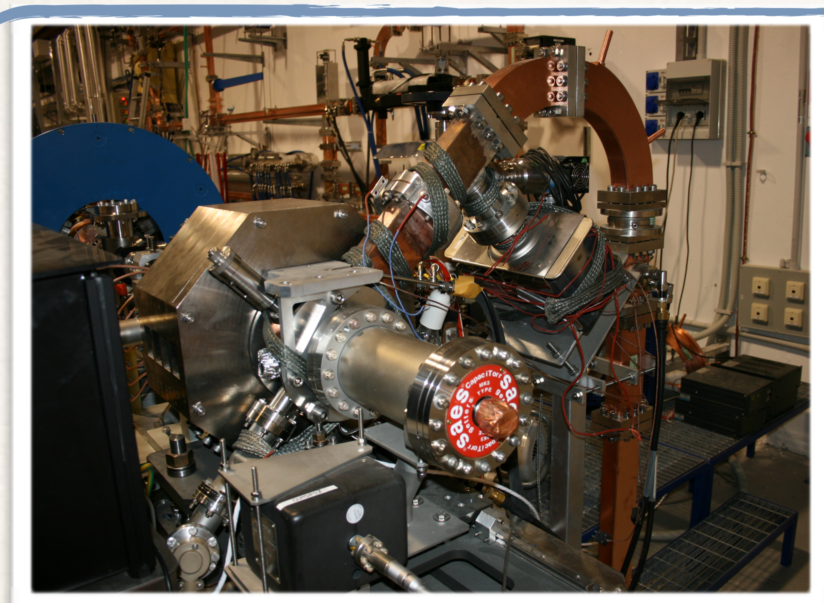
$$\boxed{\varepsilon_n^2 = <\gamma>^2 (\sigma_E^2 \sigma_x^2 \sigma_{x'}^2 + \varepsilon^2) \approx <\gamma>^2 (\sigma_E^2 \sigma_{x'}^4 s^2 + \varepsilon^2)}$$

*M. Migliorati et al., PRST AB* ***16****, 011302 (2013)*

# What would we like?

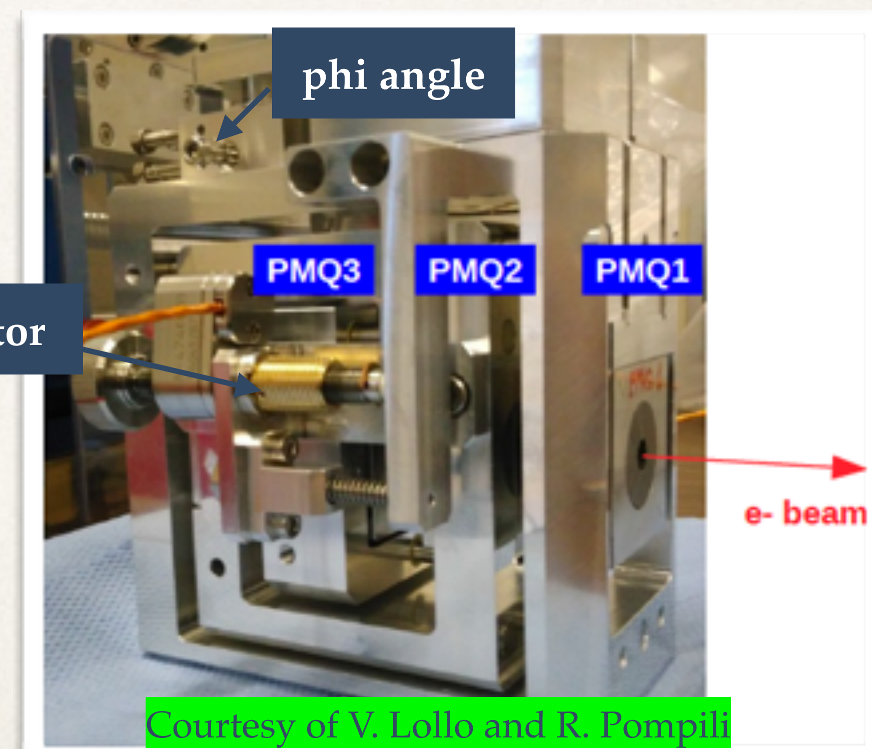
- Radially symmetric focusing gradient ~ kT/m and eventually up to MT/m
  - mitigation of beam expansion at the plasma-vacuum interface
- focusing strength: $K \propto \frac{1}{\gamma}$
  - highly relativistic particles
- focusing field varying linearly with the radius
  - no geometric aberrations
  - emittance preservation
- focusing field independent on beam distribution
- tunability
  - adjustable focal length

# Conventional magnets focusing systems



- **Solenoid Magnet**
  - radial focusing
  - focusing strength: $K_{sol} = \left(\frac{e_0 B_z}{2m_0 c}\right)^2 \frac{1}{\gamma^2}$
    - weak focusing for relativistic electrons
  - focal length ~ m
    - higher chromatic dependence
    - tunable

- **Permanent Magnet Quadrupole (PMQ)**
  - symmetric focusing is achieved with a triplet system
  - focusing strength: $K_q = \frac{e_0 g}{\beta m_0 c} \frac{1}{\gamma}$
  - focal length ~ 10 cm
  - not easily tunable focal length
    - a single system covers only a narrow range of energy
    - non-trivial adjustable holder are needed to remotely control the focal length



# Plasma lenses: *An Historical View*

- **Early 1922**: electrostatic focusing of a continuous low energy electron beam by beam-ionized gas within a cathode ray tube
  - J.B. Johnson, J. Opt. Soc. Am. **6**, 701 (1922)
- **Early 1930s**: Passive plasma lens
  - an electron stream can magnetically self-focus if it has sufficient current and its space charge is neutralized by positive ions
    - W.H. Bennett, Phys. Rev. **45**, 890 (1934)
- **1950**: Active plasma lens
  - first idea of using externally driven plasma axial current to focus a proton beam by the azimuthal magnetic field
    - W.K.H. Panofsky and W.R. Baker, Rev. Sci. Instr. 21, 445 (1950)
- **Mid-1980s:** Possible use of passive plasma lenses for the final focus in linear colliders
  - P. Chen, Part. Accel. **20**, 171 (1987)
- **Early 1990s**: Final focus experiments at SLAC
  - B. Barletta et al., Part. Accel. **20**, 171 (1987)

J. Opt. Soc. Am. 6, 701 (1922)

A LOW VOLTAGE CATHODE RAY OSCILLOGRAPH

By J. B. Johnson

ABSTRACT

A sensitive cathode ray oscillograph tube is described which operates at a low voltage. The electron stream comes from a thermionic cathode, and is focused by the action of the ionized gas in the tube. Illustrations show examples of the use of the tube.

Magnetically Self-Focussing Streams

Willard H. Bennett, *Ohio State University*
(Received January 13, 1933)

Streams of fast electrons which can accumulate positive ions in sufficient quantity to have a linear density of positives about equal to the linear density of electrons, along the stream, become magnetically self-focussing when the current exceeds a value which can be calculated from the initial stream conditions. Focussing conditions obtain when breakdown occurs in cold emission. The characteristic features of breakdown are explained by the theory. Failure of high voltage tubes is also discussed.

Introduction ... moving, i.e., the familiar Coulomb force. The

THE REVIEW OF SCIENTIFIC INSTRUMENTS VOLUME 21, NUMBER 5 MAY, 1950

A Focusing Device for the External 350-Mev Proton Beam of the 184-Inch Cyclotron at Berkeley

W. K. H. Panofsky and W. R. Baker
*Department of Physics, Radiation Laboratory, University of California, Berkeley, California*
(Received January 11, 1950)

A device has been constructed to focus the external beam of the 184-in. cyclotron at Berkeley. The device consists of a cylindrical tube 4 ft. in length and 3 in. in diameter, which contains a longitudinal arc of nearly uniform current density. Such a device will focus any beam of cylindrical symmetry. Owing to the large power requirements of such a device it is applicable only to very short pulsed beams.

A POSSIBLE FINAL FOCUSING MECHANISM FOR LINEAR COLLIDERS†

PISIN CHEN

*Stanford Linear Accelerator Center, Stanford University, Stanford, CA 94305, and*

© 1993 IEEE. Personal use of this material is permitted. However, permission to reprint/republish this material for advertising or promotional purposes or for creating new collective works for resale or redistribution to servers or lists, or to reuse any copyrighted component of this work in other works must be obtained from the IEEE.

Plasma Lens Experiments at the Final Focus Test Beam*

B. Barletta[2,4], S. Chattopadhyay[4], P. Chen[12], D. Cline[2], W. Craddock[12], W. Gabella[2], I. Hsu[9], T. Katsouleas[11], P. Kwok[2], P. Lai[11], W. Leemans[4], R. Liou[11], D. D. Meyerhofer[10], K. Nakajima[8], H. Nakanishi[8], C. K. Ng[12], Y. Nishida[13], J. Norem[1], A. Ogata[8], S. Rajagopalan[2], J. Rosenzweig[2], A. Sessler[4], J. Spencer[12], J. J. Su[7], G. Westenskow[5], D. Whittum[8], R. Williams[3], J. Wurtele[6].

*Abstract*

We intend to carry out a series of plasma lens experiments at the Final Focus Test Beam facility at SLAC. These experiments will be the first to study the focusing of particle beams by plasma focusing devices in the parameter regime of experiments were 6 to 7 orders of magnitude lower than the nominal colliding beam density at the SLC and the next generation linear colliders, so that the experience is insufficient to design or evaluate a plasma lens in a high energy collider detector. A beam such as the FFTB offers a

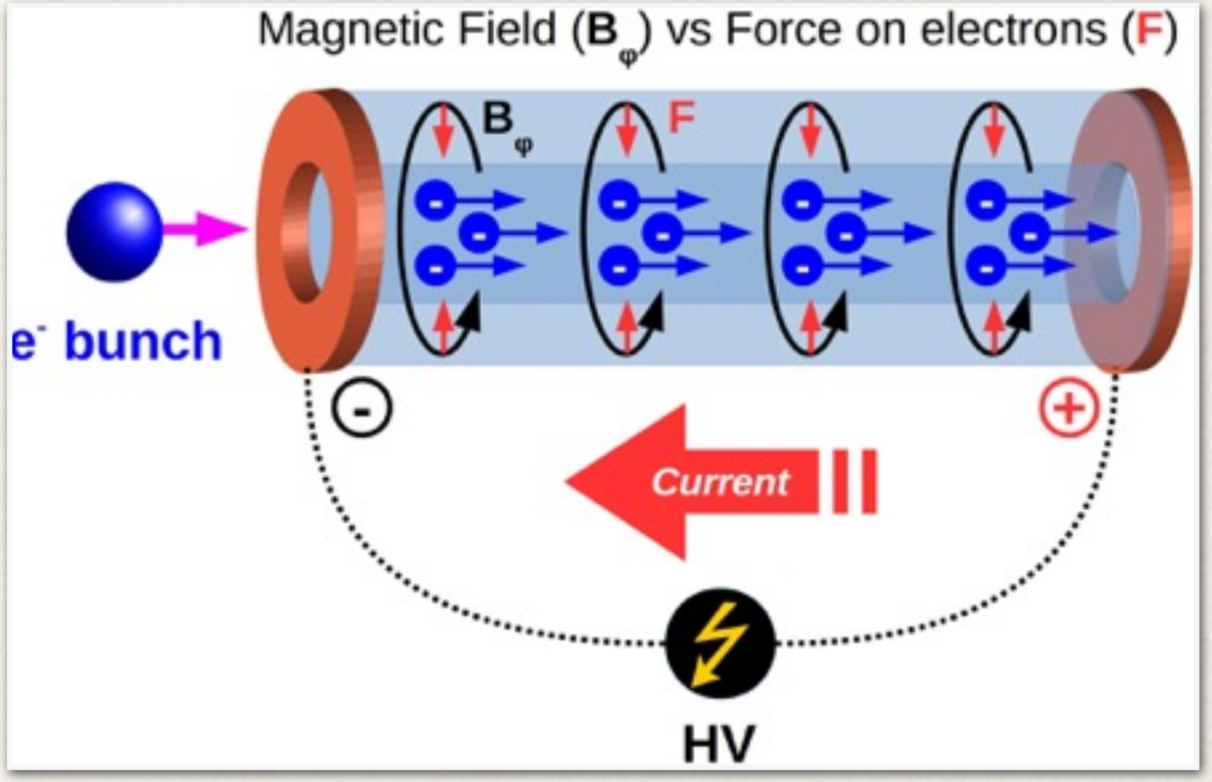
# Active Plasma Lens

- Discharge current in gas-filled capillary
  - the bunch is focused by the azimuthal magnetic field generated by the discharge current density, according to Ampère's law

$$B_\phi(r) = \frac{\mu_0}{r}\int_0^r J(r')r'dr'$$

**Advantages**

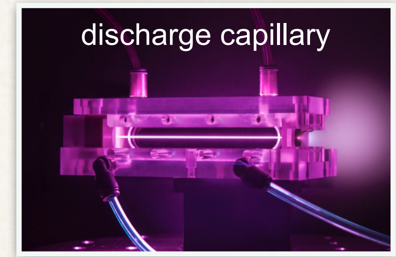
- Cylindrical symmetry
  - purely radial focusing effect
- Tunability
- Focusing strength $k \propto \frac{1}{\gamma}$
- High focusing gradient ~ kT/m
  - short focal length
    - weak chromaticity

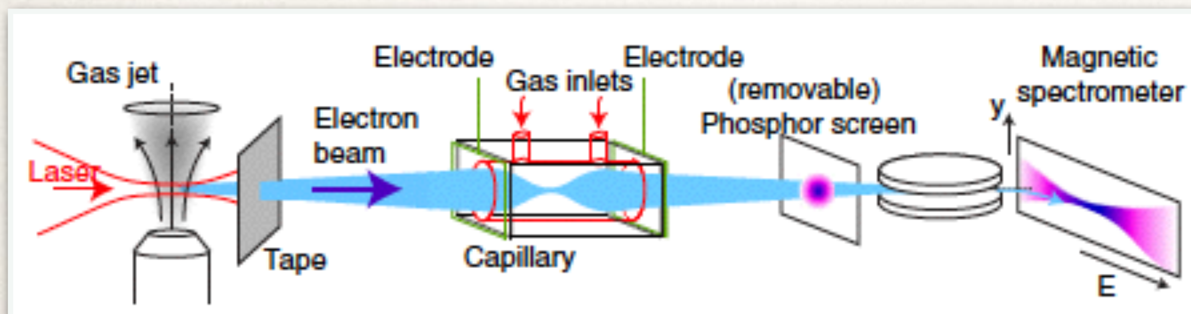


# Experimental Results at BELLA, LBNL

**2015: APL for relativistic LPA electron beams** => J. van Tilborg *et al*. PRL **115**, 184802 (2015)

- Radial-symmetric
- Tunable with discharge current
- Strong **multi-kT/m gradients =>** 10 cm-scale foci for GeV e-

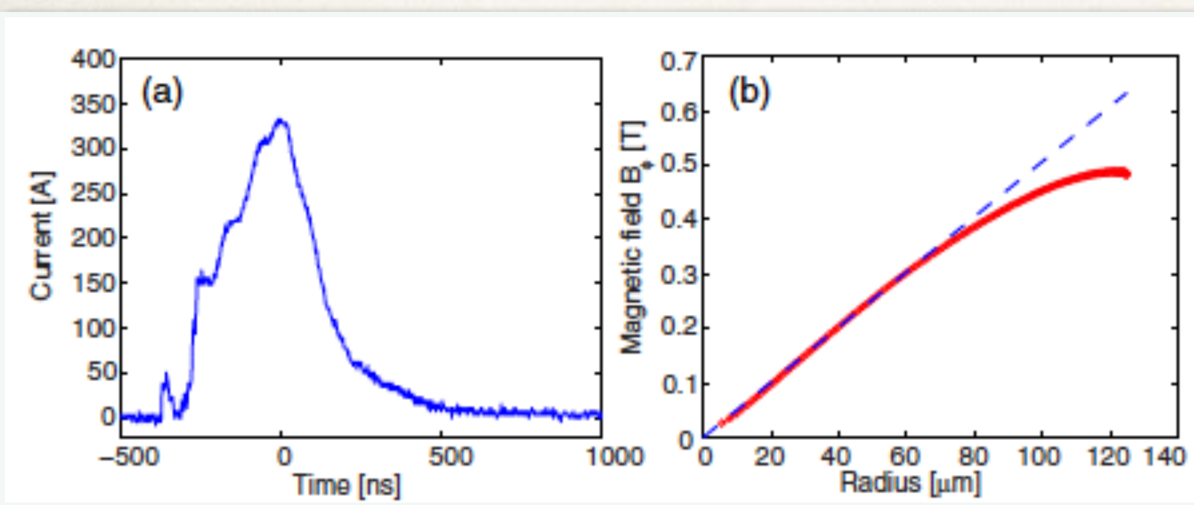


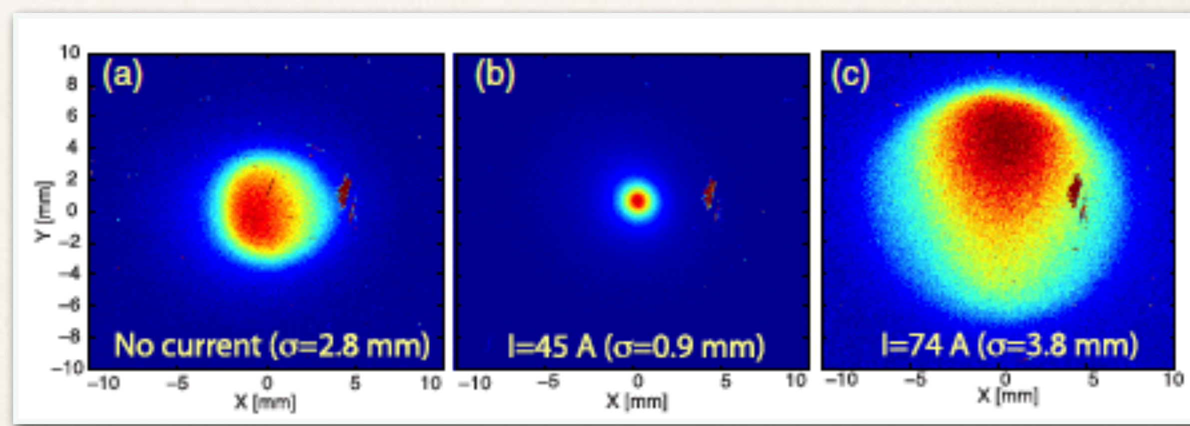




**Beam parameters**

$Q = 30$ pC
$E = 100$ MeV
$\Delta E/E = 30\%$
$\sigma_t \sim 7$ fs
$\sigma_x = 100\ \mu m$

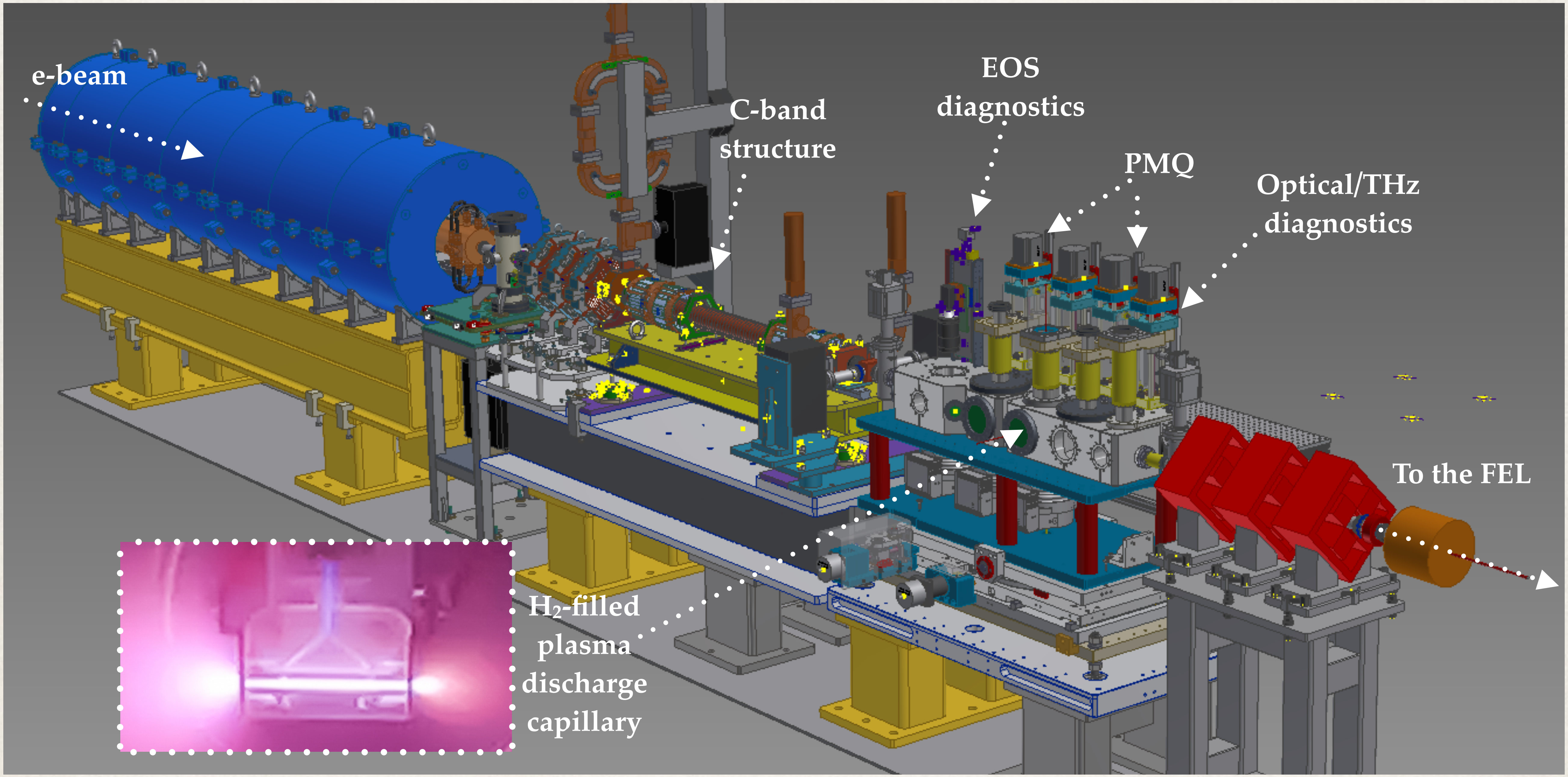
$n_e = 7\ 10^{18}$ cm$^{-3}$
$I = 330$ A
$R_0 = 125\ \mu m$
$L = 3.3$ cm
Sapphire capillary




(a) Current trace for the sapphire-based capillary discharge.
(b) Scaling of the magnetic field with radius as obtained from MHD simulations at $I_0$=330 A (solid curve). Linear field gradients (dashed curve) are observed to be linear up to R/2, with R the capillary radius.

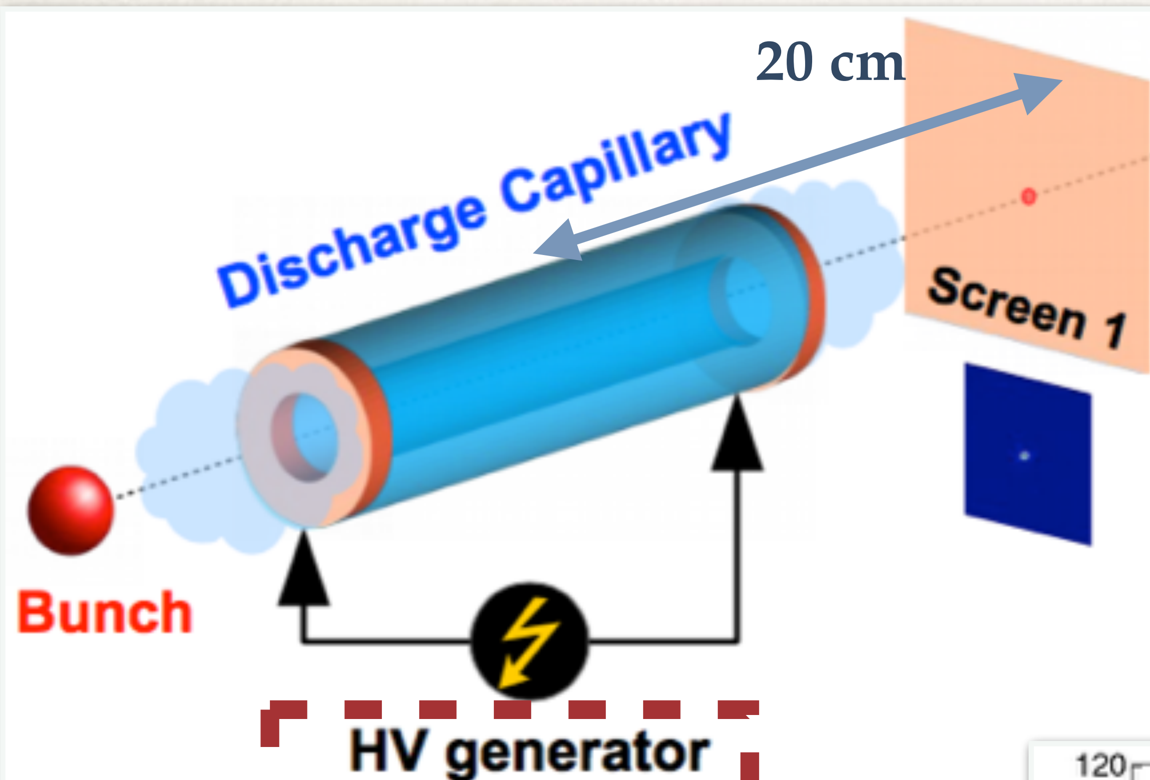
# Experimental Results at SPARC_LAB

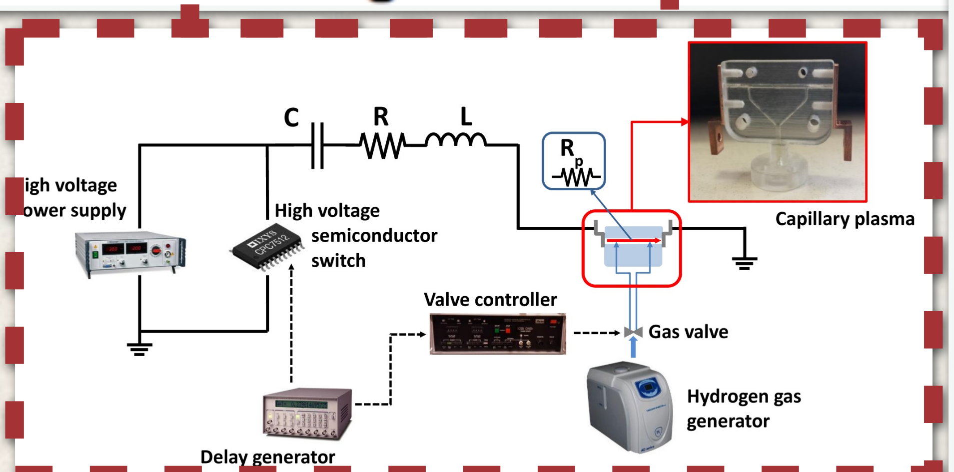


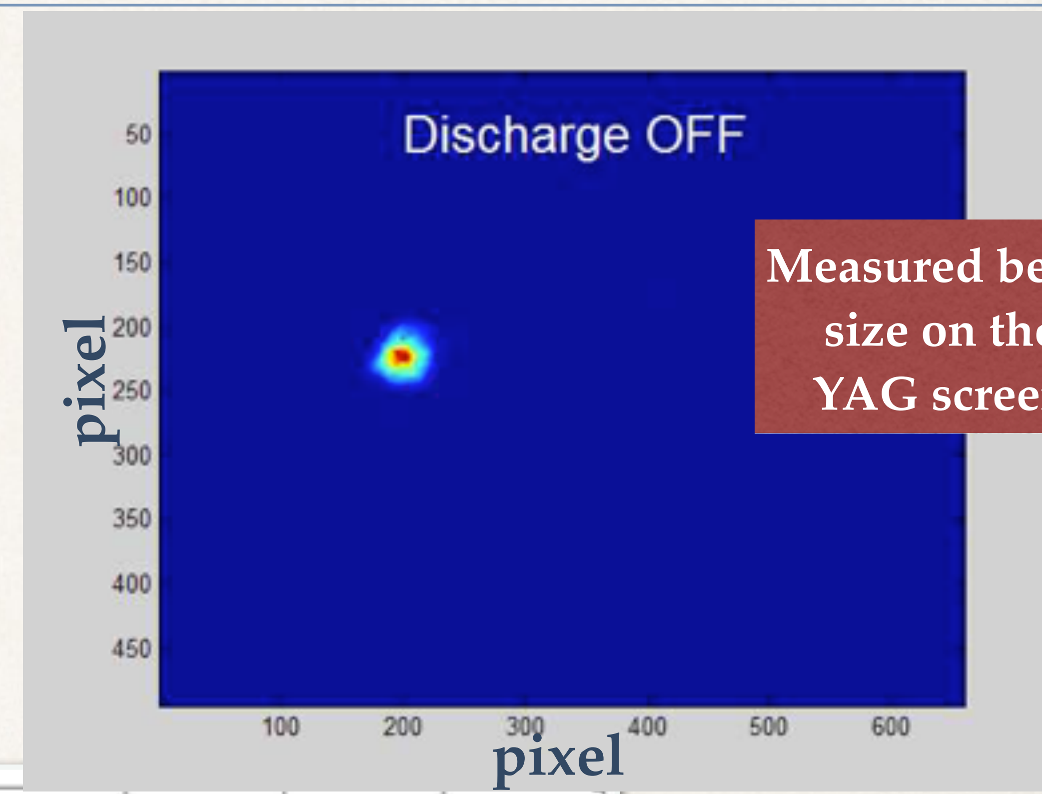

3 cm(1 cm)-long capillary made by sapphire or 3D printed

- 1 mm hole diameter
- 2 symmetric inlets for gas flow at 1/4 and 3/4 of capillary

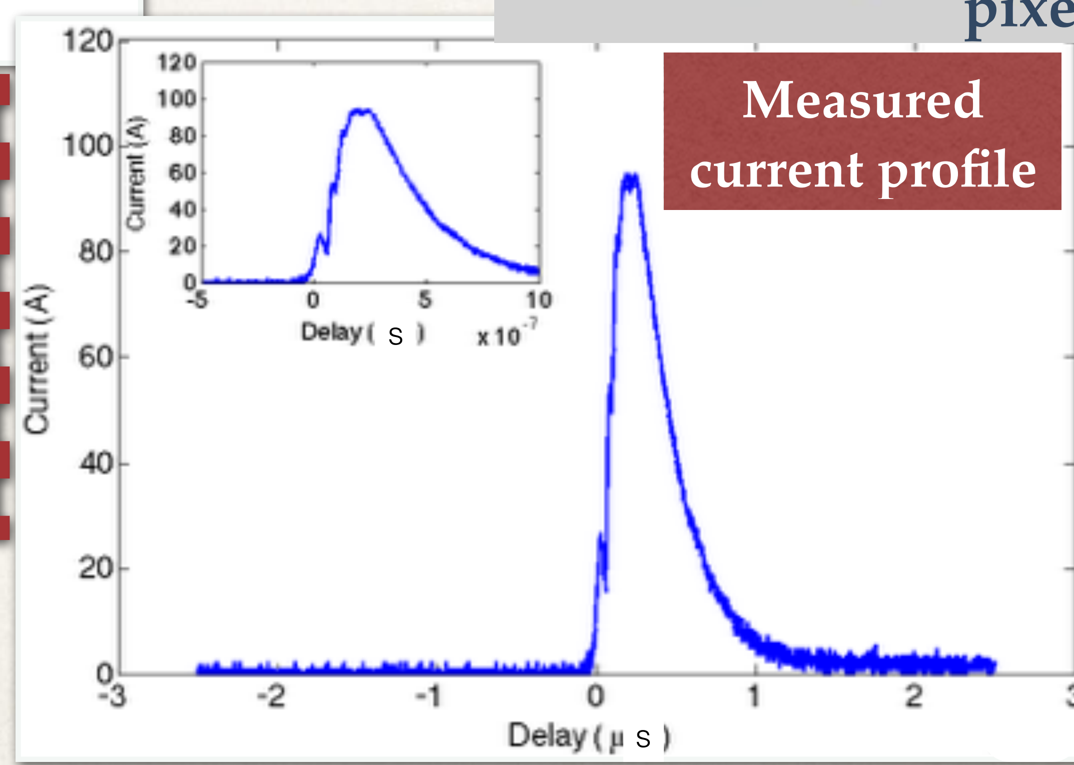
# Experimental setup




Measured beam size on the YAG screen




Measured current profile

**A. Biagioni**, Wake fields effects in dielectric capillary, **WG3: Poster session I**



*enrica.chiadroni@lnf.infn.it*

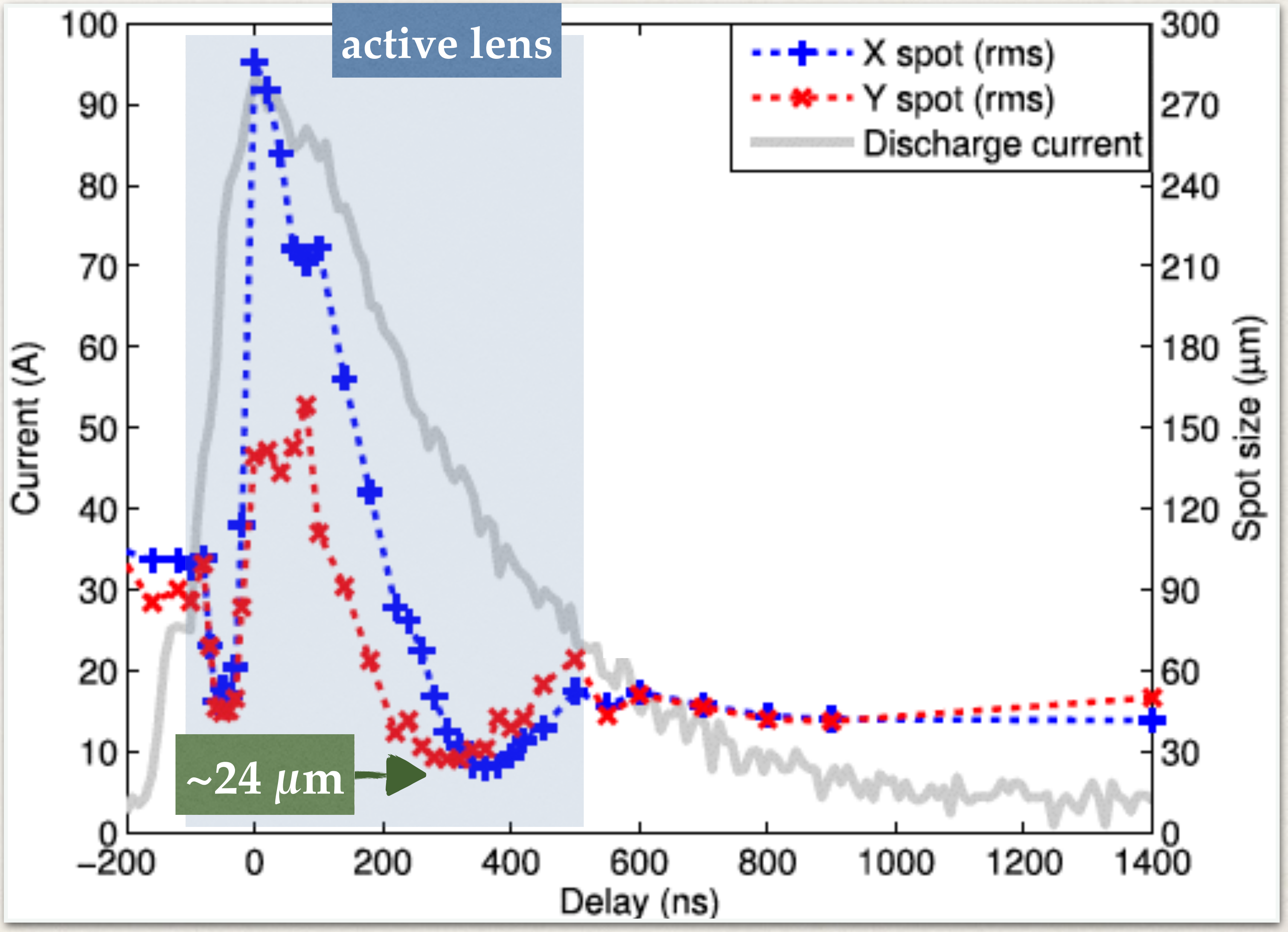
# Envelope scan

**Beam parameters**

- $Q = 50$ pC
- $E = 120$ MeV
- $\Delta E/E = 0.1\%$
- $\varepsilon_n = 1$ mm mrad
- $\sigma_t = 1$ ps
- $\sigma_x = 110\ \mu m$

**Plasma discharge parameters**

- $n_e = 9\ 10^{16}\ cm^{-3}$
- $V = 20$ kV
- $I = 100$ A
- $R_0 = 500\ \mu m$
- **L = 3 cm**
- **Sapphire capillary**




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

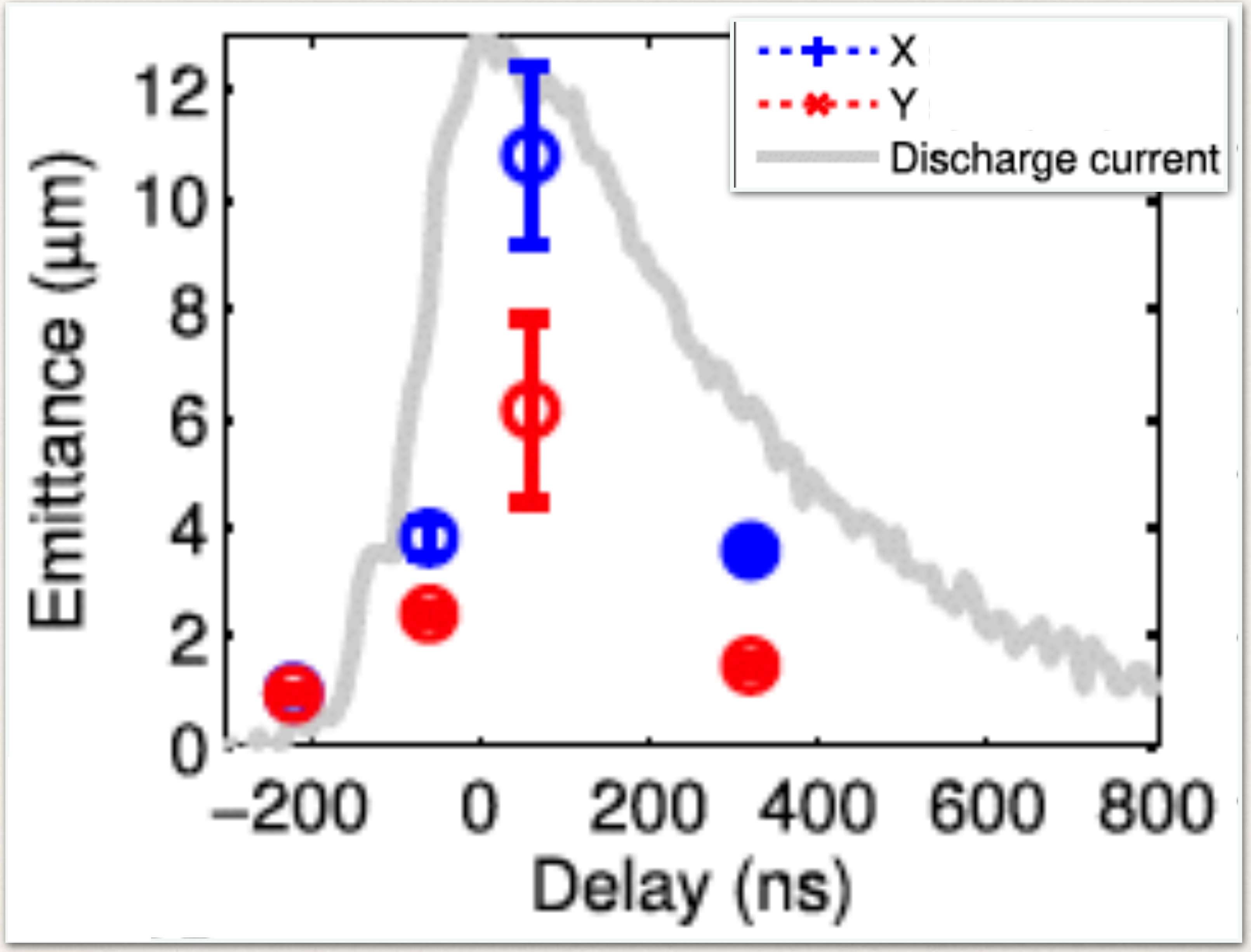
# Emittance characterization

**Beam parameters**

$Q = 50$ pC
$E = 120$ MeV
$\Delta E/E = 0.1\%$
$\varepsilon_n = 1$ mm mrad
$\sigma_t = 1$ ps
$\sigma_x = 110\ \mu m$

**Plasma discharge parameters**

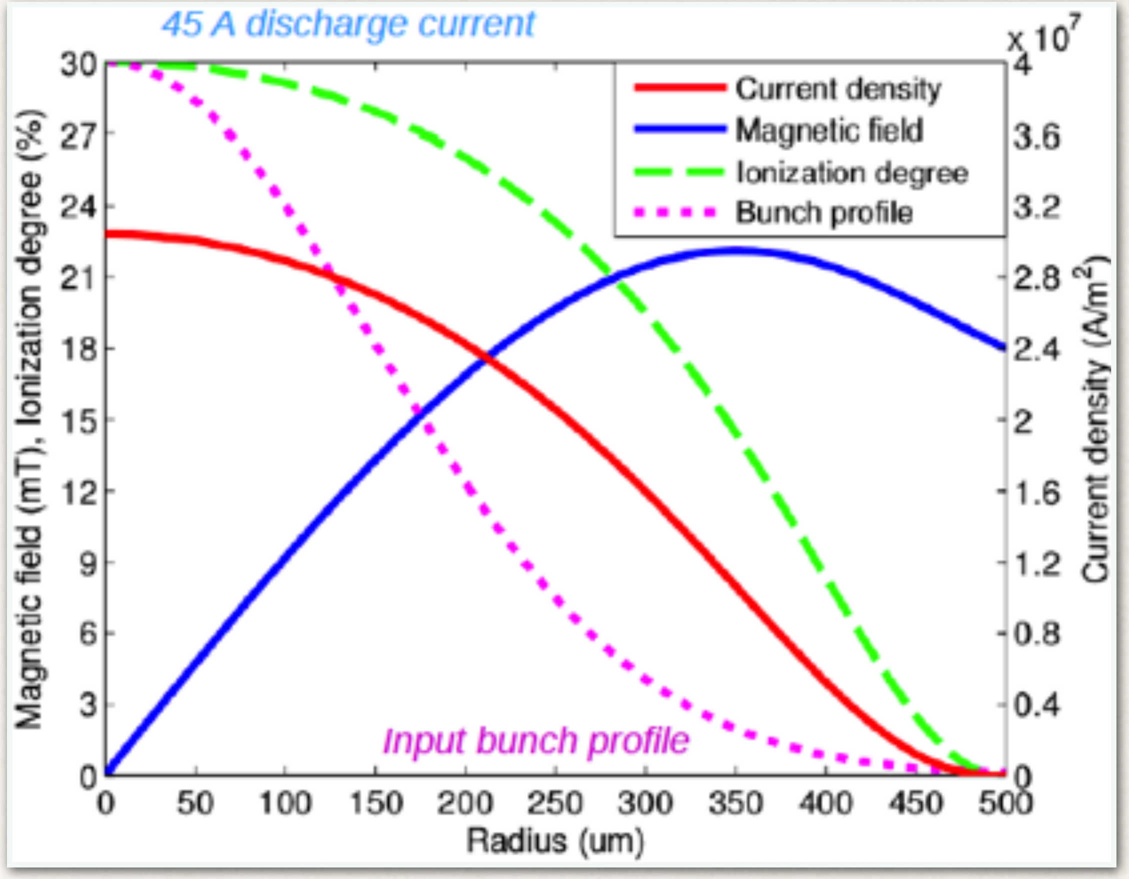
$n_e = 9\ 10^{16}\ cm^{-3}$
V = 20 kV
I = 100 A
$R_0 = 500\ \mu m$
**L = 3 cm**
**Sapphire capillary**




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

# Non-linear focusing field

The magnetic field profile assumes that the equilibrium is determined only by the balance between Ohmic heating and cooling due to the electron heat conduction.




N. Bobrova et al., Phys. Rev. E **65**, 016407 (2001)

Partial ionization of the gas produced at low discharge currents.
The radial temperature profile *T(r)* is computed, allowing the retrieval of the current density as

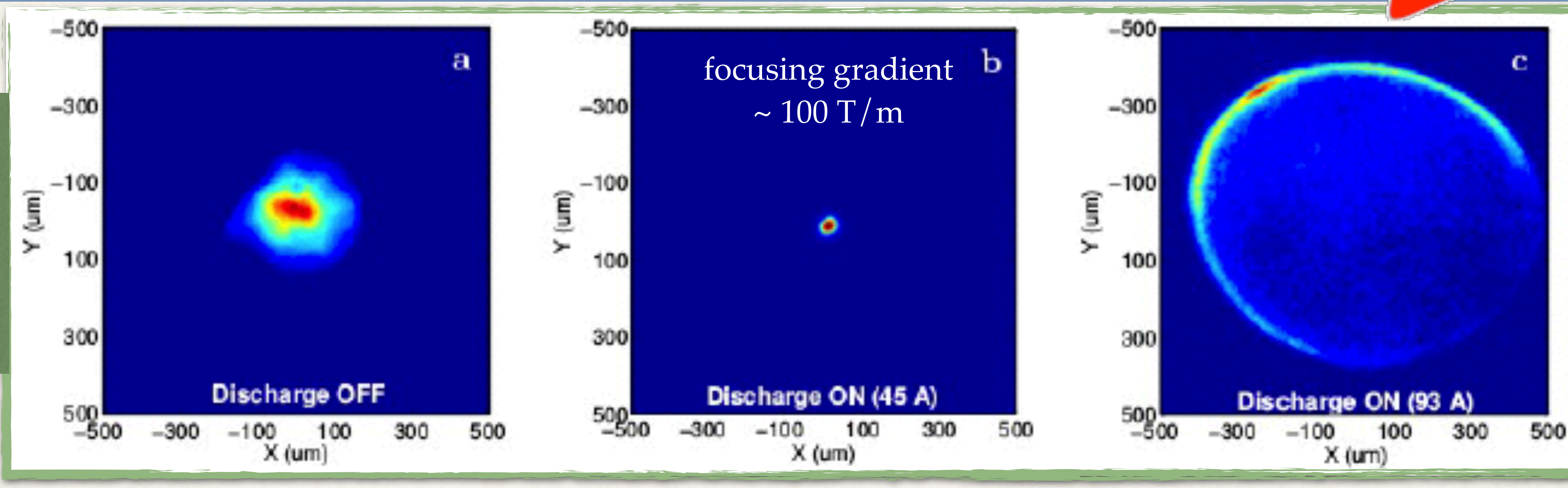
$$J(r) = \sigma_e(r) E \propto T(r)^{3/2} E$$

The current flows mainly on the axis and thus resulting in a radially nonlinear magnetic field

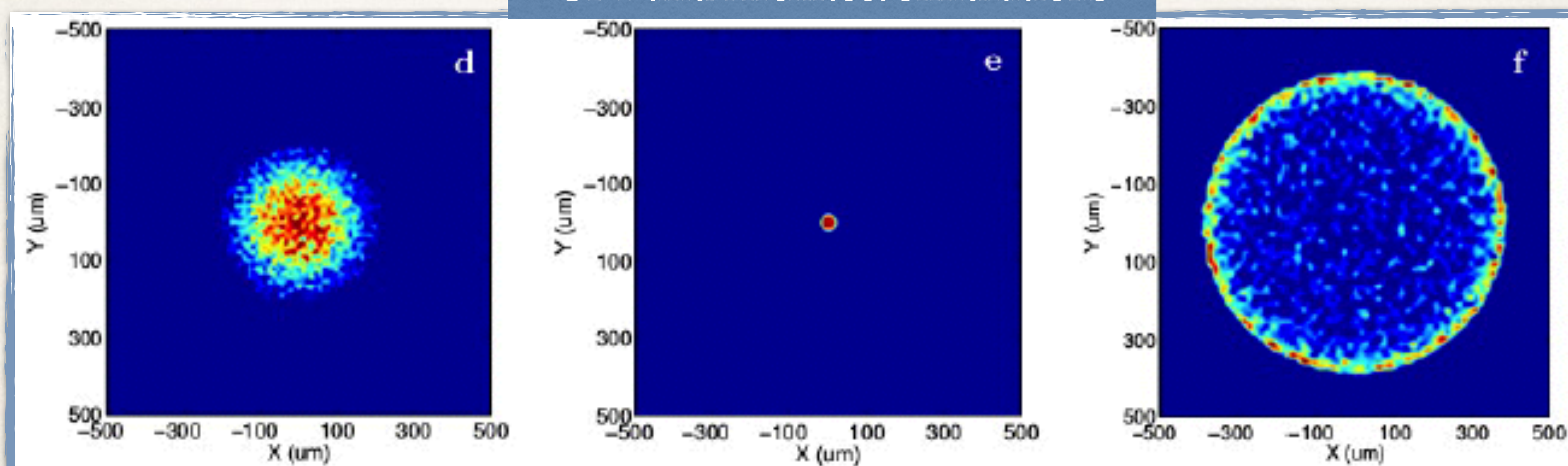
**E. Brentegani**, Numerical studies on capillary discharges as focusing elements for electron beams, **WG6: Poster session II**

# Beam transverse distribution

Measurements




GPT and Architect simulations



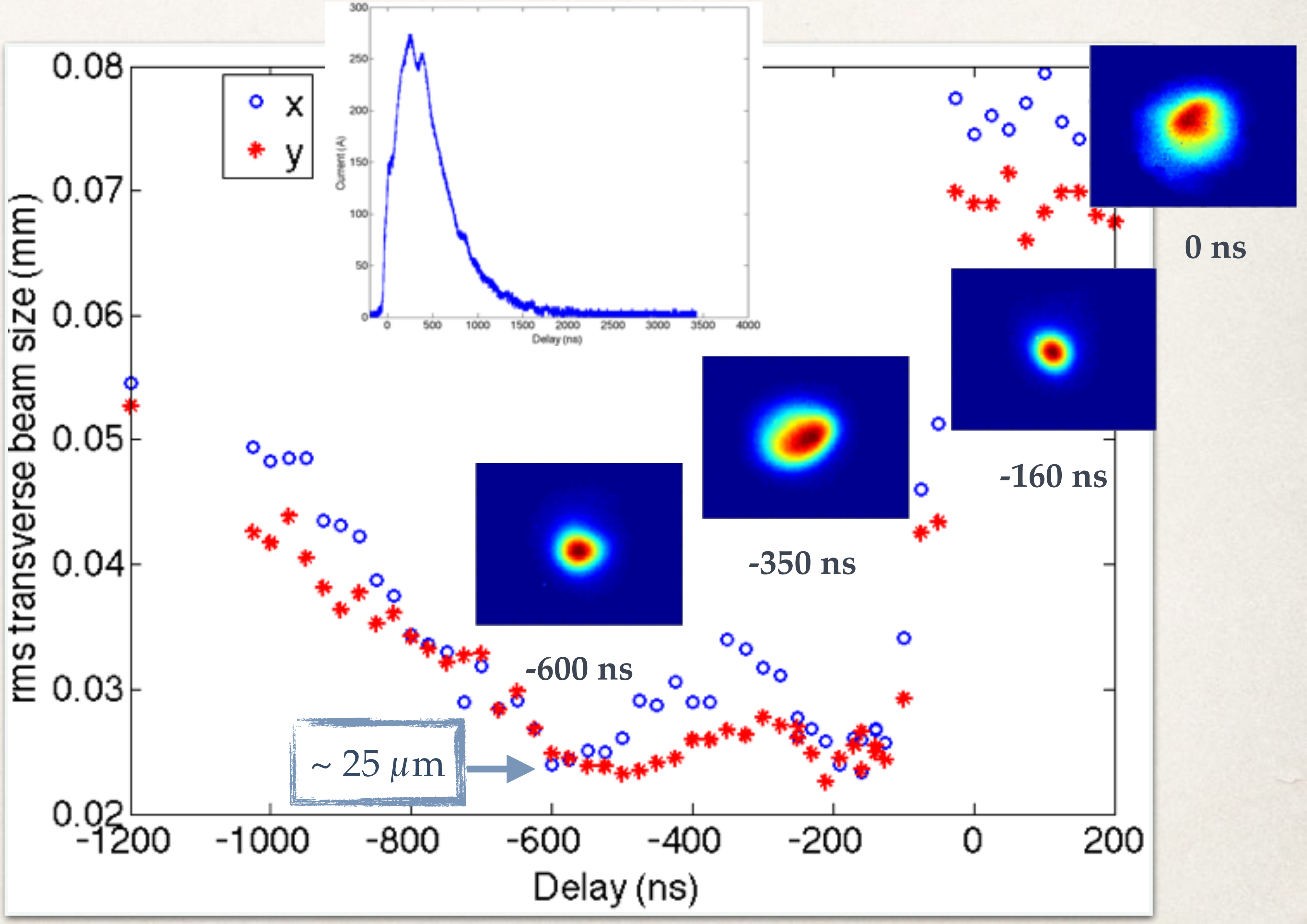
# Envelope scan with 1 cm capillary

**Beam parameters**

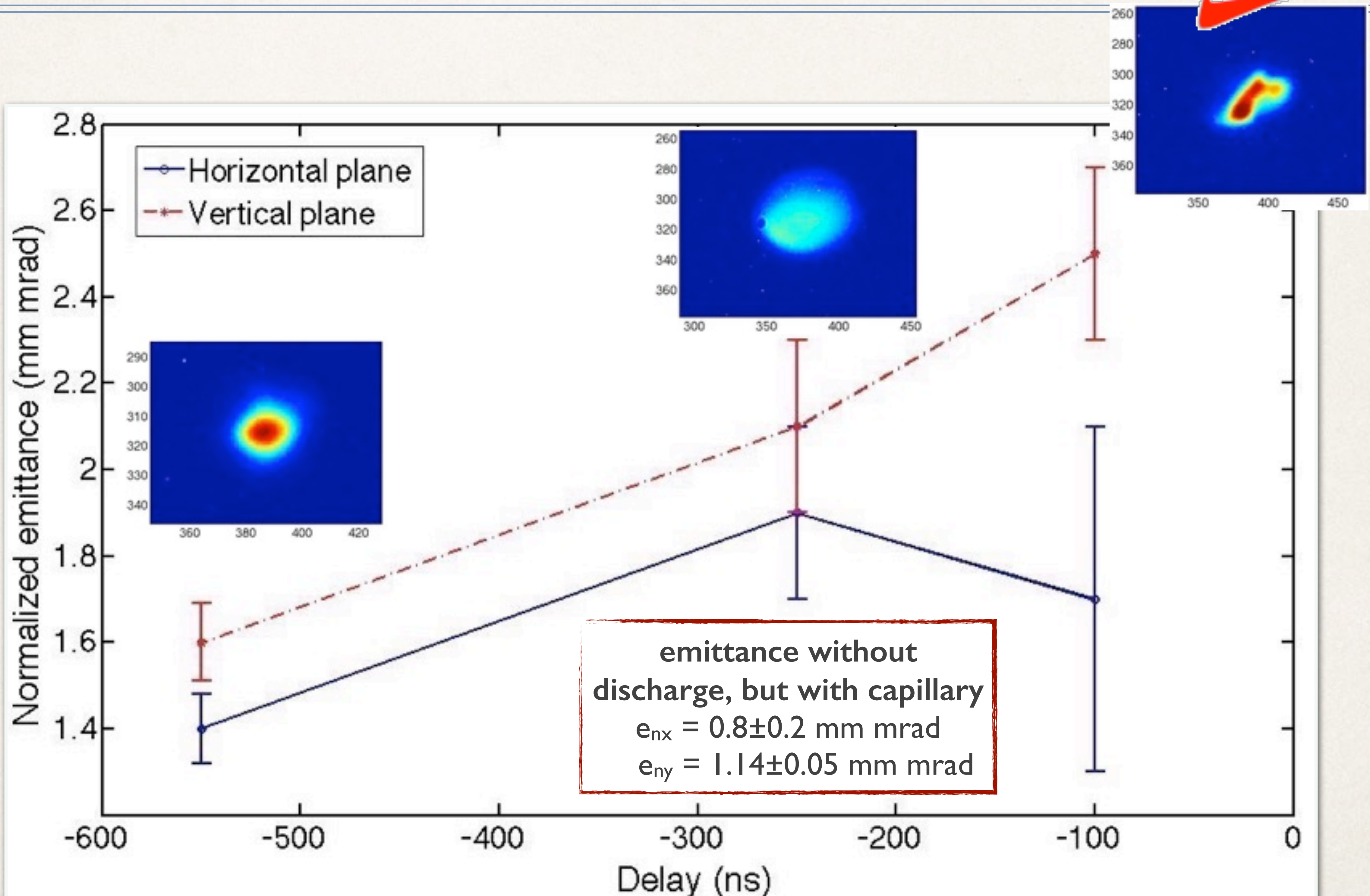
Q = 50 pC
E = 120 MeV
$\Delta E/E = 0.1\%$
$\varepsilon_n$ ~ 1 mm mrad
$\sigma_t = 1$ ps
$\sigma_x$ ~ 75 $\mu$m

**Plasma discharge parameters**

$n_e \sim 10^{17}$ cm$^{-3}$
V = 14 kV
I = 240 A
$R_0 = 500$ $\mu$m
**L = 1 cm**
**fully 3D printed** plastic capillary



# Control of emittance growth





enrica.chiadroni@lnf.infn.it

# Experimental Results at FLASHForward

Collaboration by DESY, UHH, JGU, Berkeley Lab — part of FF▸▸

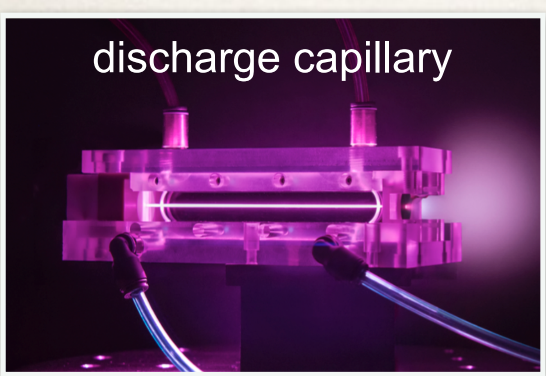
Publication in preparation

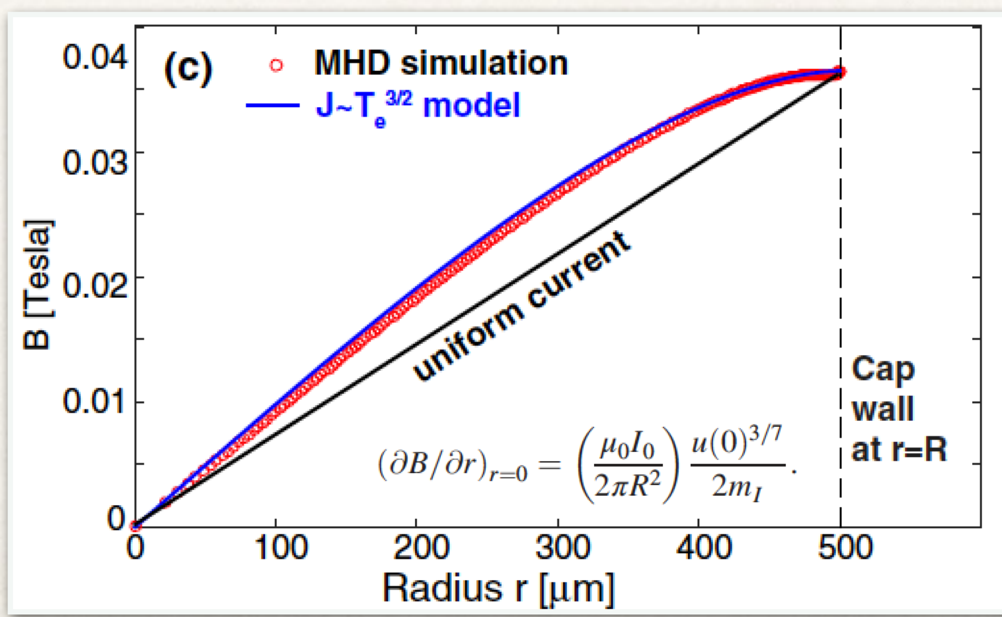
Courtesy of Jan-Hendrik Röckemann (DESY) *et al.*
*publication in preparation*

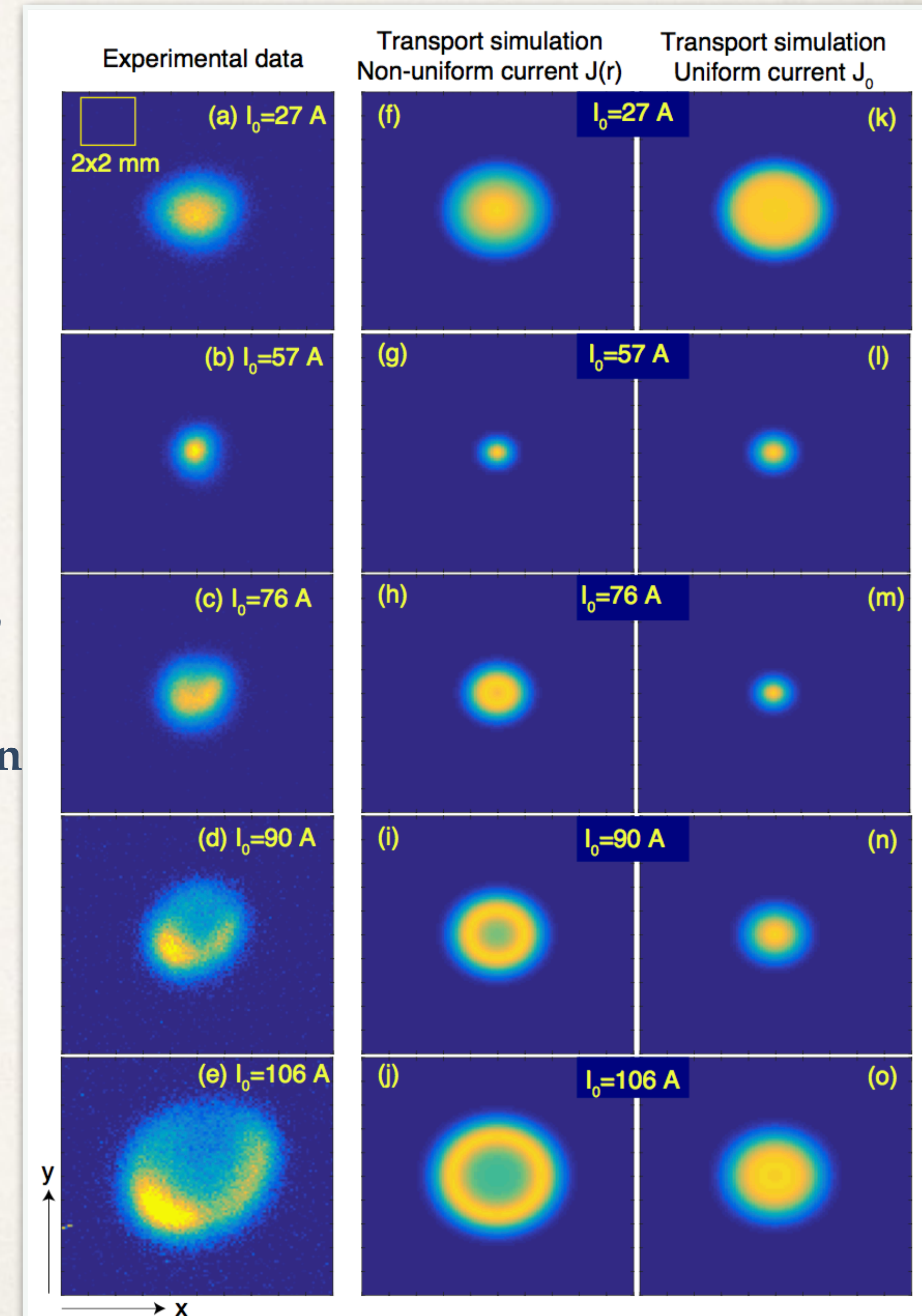
# Experimental Results at BELLA, LBNL

**2017: Non-uniform discharge current in APL** => J. van Tilborg *et al.* PR-AB **20**, 032803 (2017)

- **Near-axis focusing gradient enhancement**
  - Plasma temperature model agrees with experiments
- **Emittance degradation**
  - Reveals itself as ring beams for over-focusing current
  - Degradation minimal for beams < capillary radius
  - Degradation factor depends on definition (*i.e.* all particles versus 95% core)
  - **Partial ionization (weak discharge current) can enhance degradation**



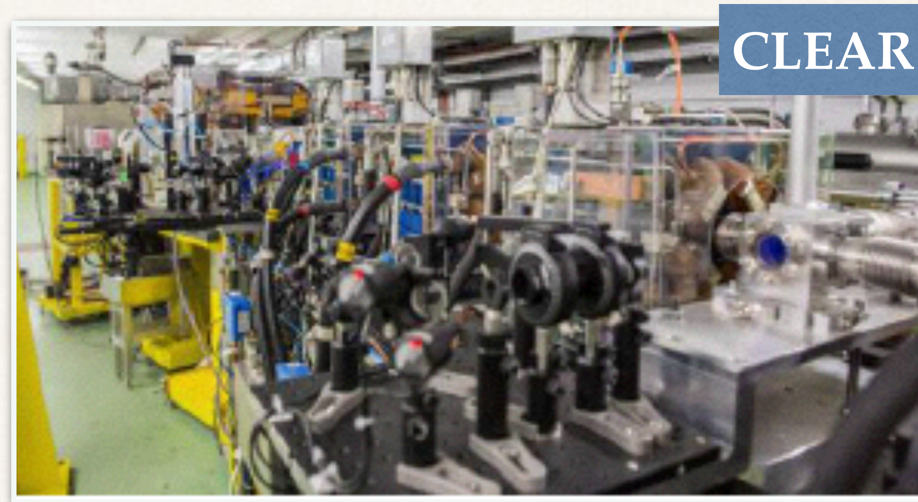



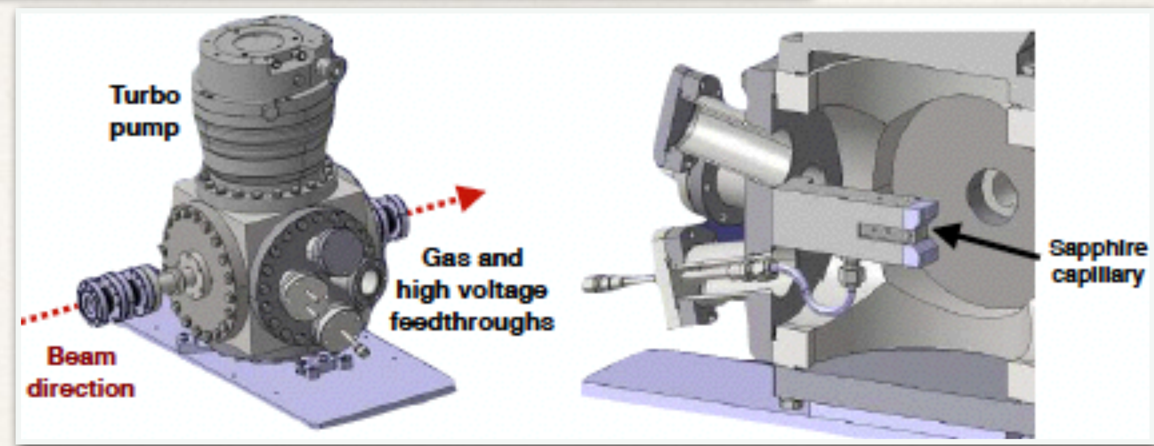

Courtesy of J. van Tilborg *et al.* (LBNL)

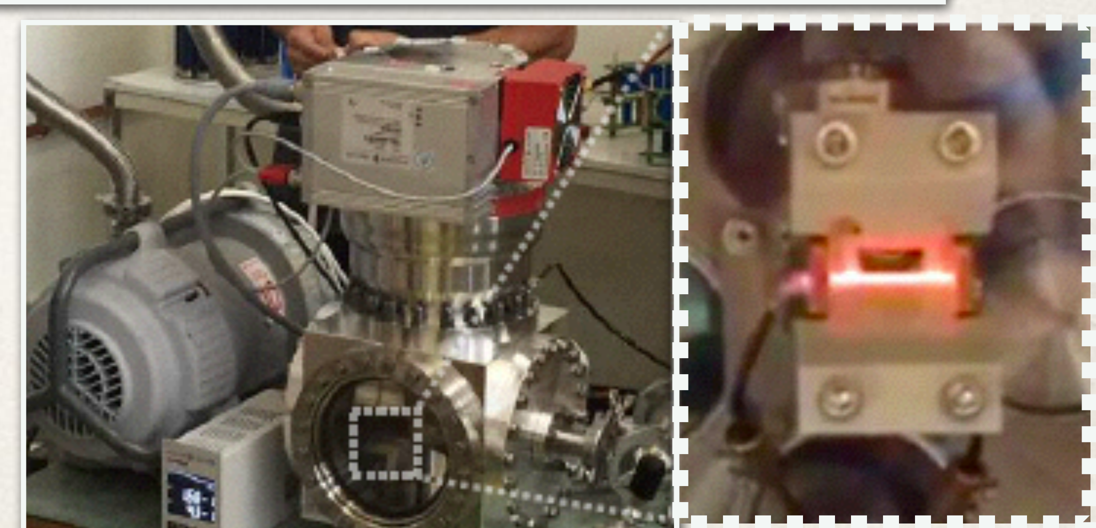
# CLEAR Plasma Lens Experiment

- CERN-based experiment, a collaboration between
  - University of Oslo (E. Adli, C. Lindstrøm)
  - DESY (J. Röckemann, J. Osterhoff)
  - University of Oxford (A. Dyson, S. Hooker)
  - CERN (W. Farabolini, D. Gamba, R. Corsini)
- Goals
  - **Characterizing radial non-linearities** of a capillary discharge plasma lens
  - **Investigating limits from beam-induced plasma wakefields**
- Characteristics
  - Compact Marx Bank discharge source (500 A, ~150 ns)
  - 15 mm long, 500-1000 μm diameter sapphire capillary
  - **Multiple gases (He, Ar, ++)**
  - High current, tightly focused beam (sufficient to drive a wake)
- **Achievements**
  - CERN, August 2017: **Bench test (without beam) completed successfully**
  - Currently being installed into the CLEAR Test Facility
    - **Autumn 2017-2018: First experiments**

CLEAR Test Facility



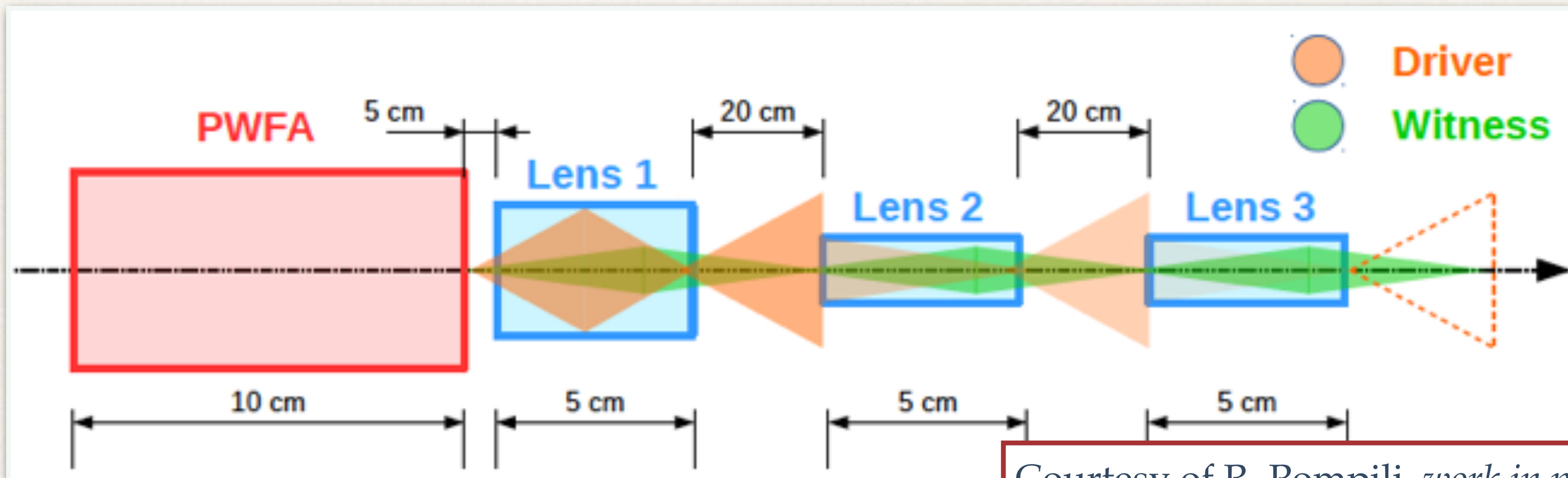


Courtesy of Carl Lindstrøm (Univ. of Oslo) *et al.*

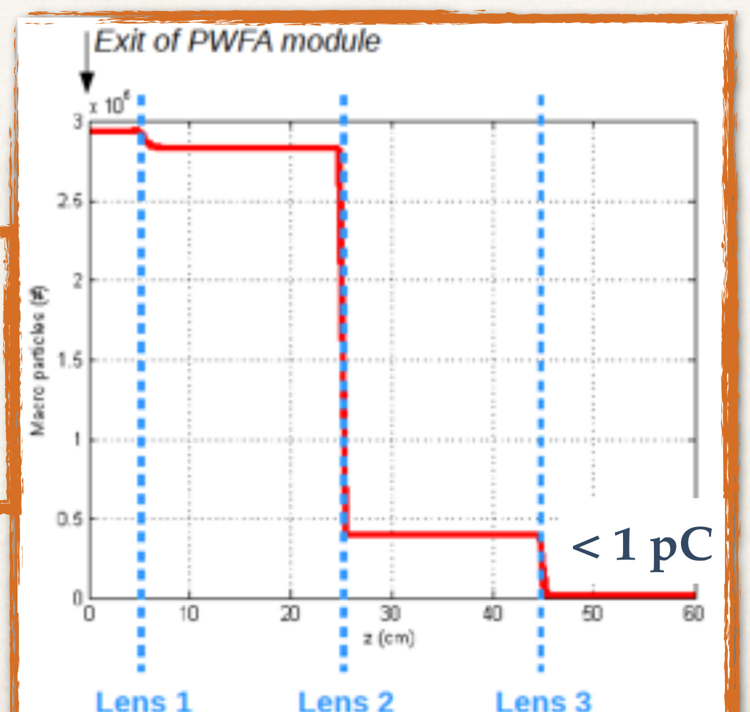
# Examples of extraction systems

In PWFA, active plasma lenses may serve also as driver removal

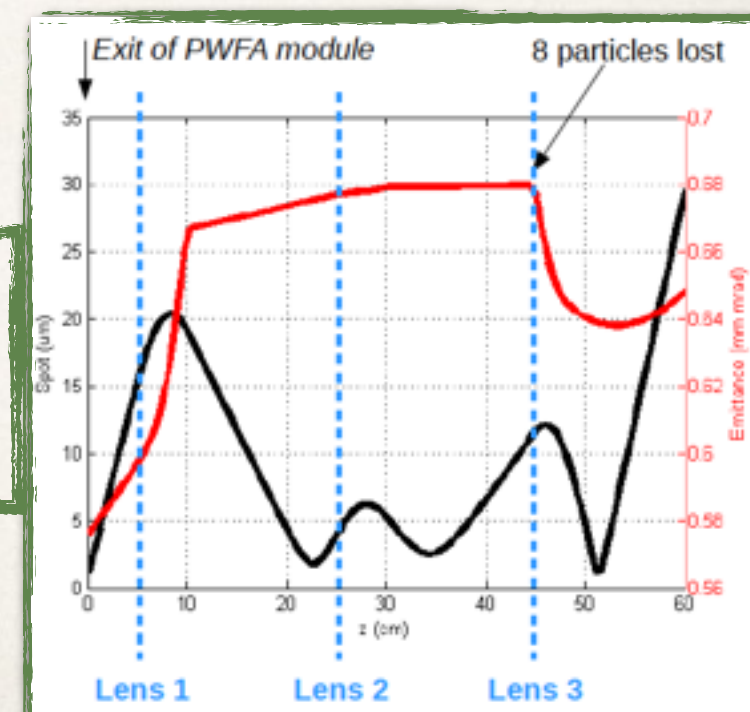



Courtesy of R. Pompili, *work in progress*

Q = 200 pC
Energy ~ 1 GeV
$t_{FWHM}$ = 156 fs

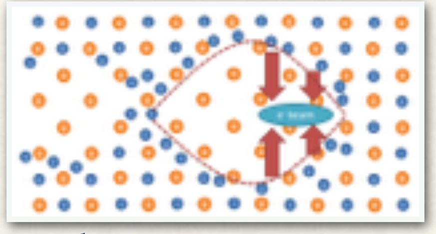



Q = 30 pC
Energy ~ 1 GeV
$t_{FWHM}$ = 6 fs



# Passive Plasma Lenses

- Self-focusing effect arises because the electrons in the plasma are expelled (in case of interacting with an electron bunch) by the leading particle in the bunch; on this time scale, the ions in the plasma can be considered stationary
  - **over-dense regime** $\boxed{n_b \ll n_p}$ the bunch's self-field creates only a small perturbation of the plasma density, $n_p$
    - the plasma electrons respond to the excess of charge by shifting away from the beam particles
    - the remaining plasma ions neutralize the space charge force within the beam
    - the beam experiences the effect of its self-generated azimuthal magnetic field
    - the focusing strength depends on the beam density $\boxed{K \approx \frac{2\pi r_e n_b}{\gamma}}$
  - **under-dense regime** $\boxed{n_b > n_p}$ the bunch drives a strong plasma wave in the background plasma
    - the plasma electrons are completely rarefied by the electron beam



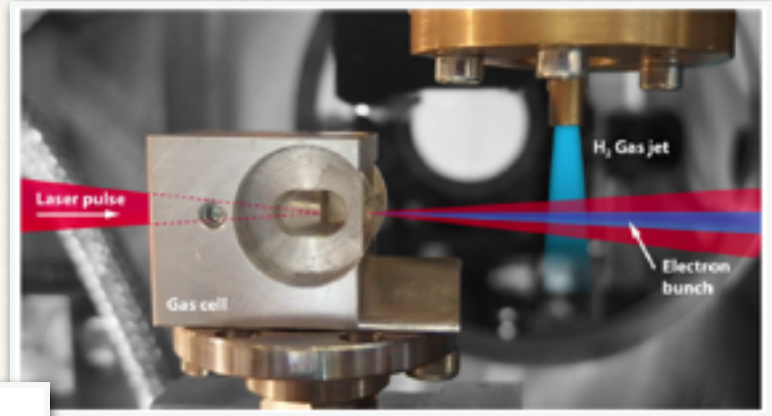
      - uniform charge density of the ions
        - linear focusing, nearly aberration-free, due to the transverse electric fields of the plasma wave
        - the focusing strength depends only on the plasma density $\boxed{K \equiv -\frac{W_r}{r p_z c} = \frac{2\pi r_e n_p}{\gamma}}$

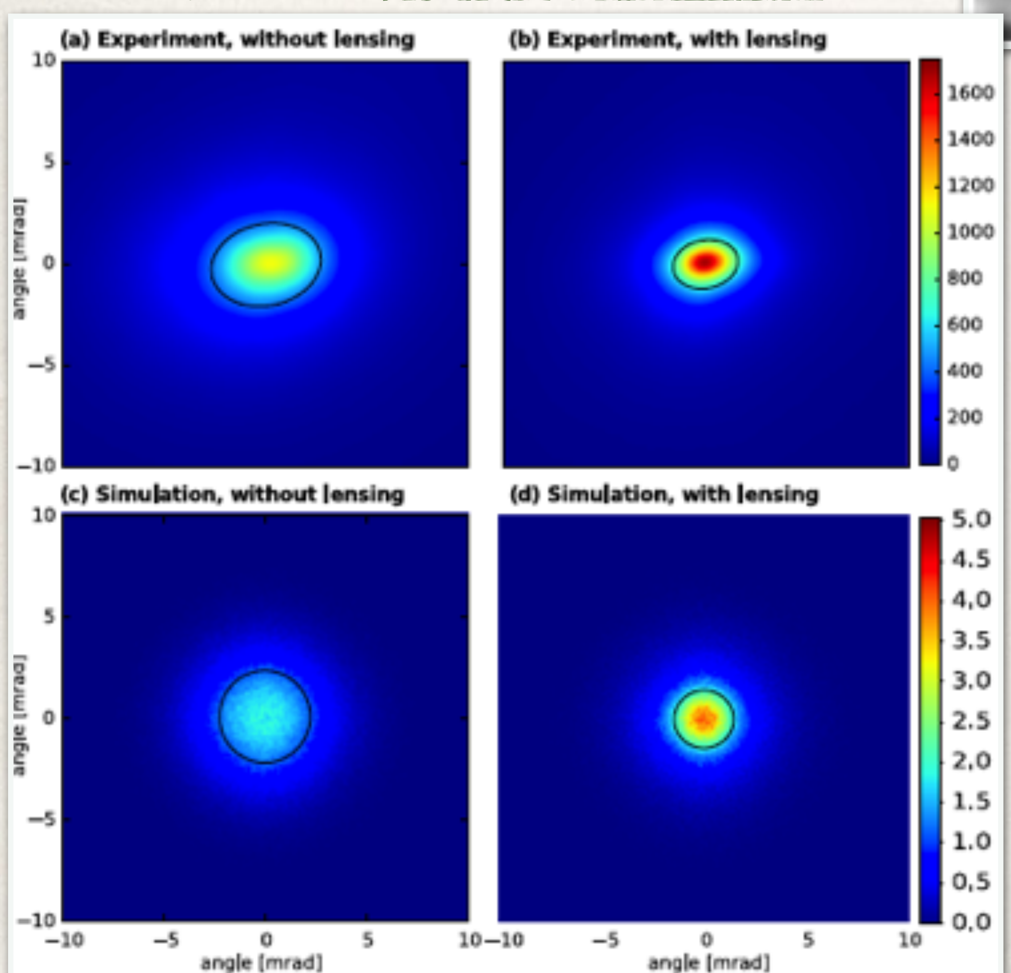
# Passive plasma lens for LWFA electrons

## Experimental results at Jena

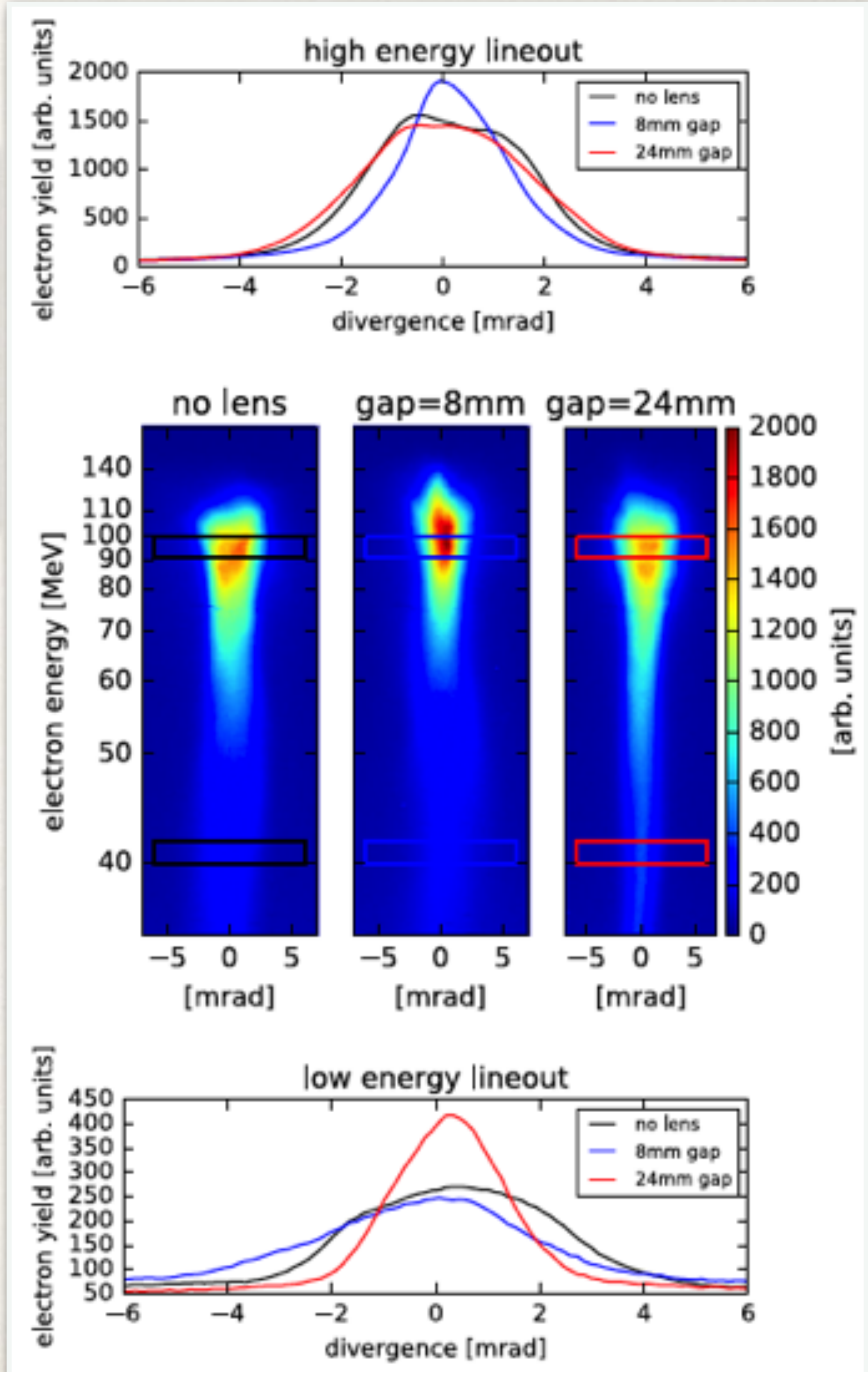
**First demonstration** of a passive plasma lens in case of **ultra-short, ~6 fs, electron bunches, from LWFA** with high energy spread, ~ 10%, in the **over-dense regime**

Beam energy = 100 - 150 MeV
Energy spread < 20MeV
Q ~ 5 pC
$n_b \sim 2\ 10^{15}\ cm^{-3}$
$n_p \sim 10^{19}\ cm^{-3}$




- Lensing stage: supersonic gas jet of 2.5 mm length
- The laser does not trigger any wakefield in the lensing stage
- Achievements
  - ✓ Divergence reduction of ~ 40%
  - ✓ Measurements varying the gap between the accelerating and focusing stages
- ➡ No emittance measurement, only a guess




S. Kuschel et al., Phys. Rev. Accel. and Beams **19**, 071301 (2016)

# Passive plasma lenses

## Experimental results: SPARC_LAB

- **Over-dense regime**

Under submission

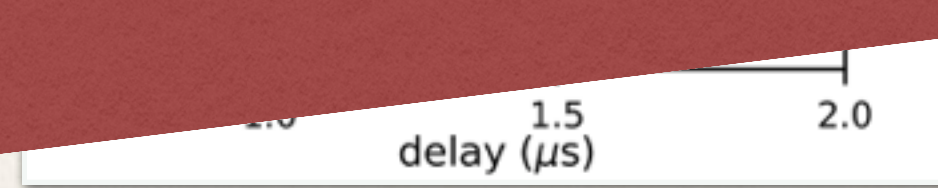
A. Marocchino et al., submitted to APL

# Passive plasma lenses

**Experimental results: SPARC_LAB**

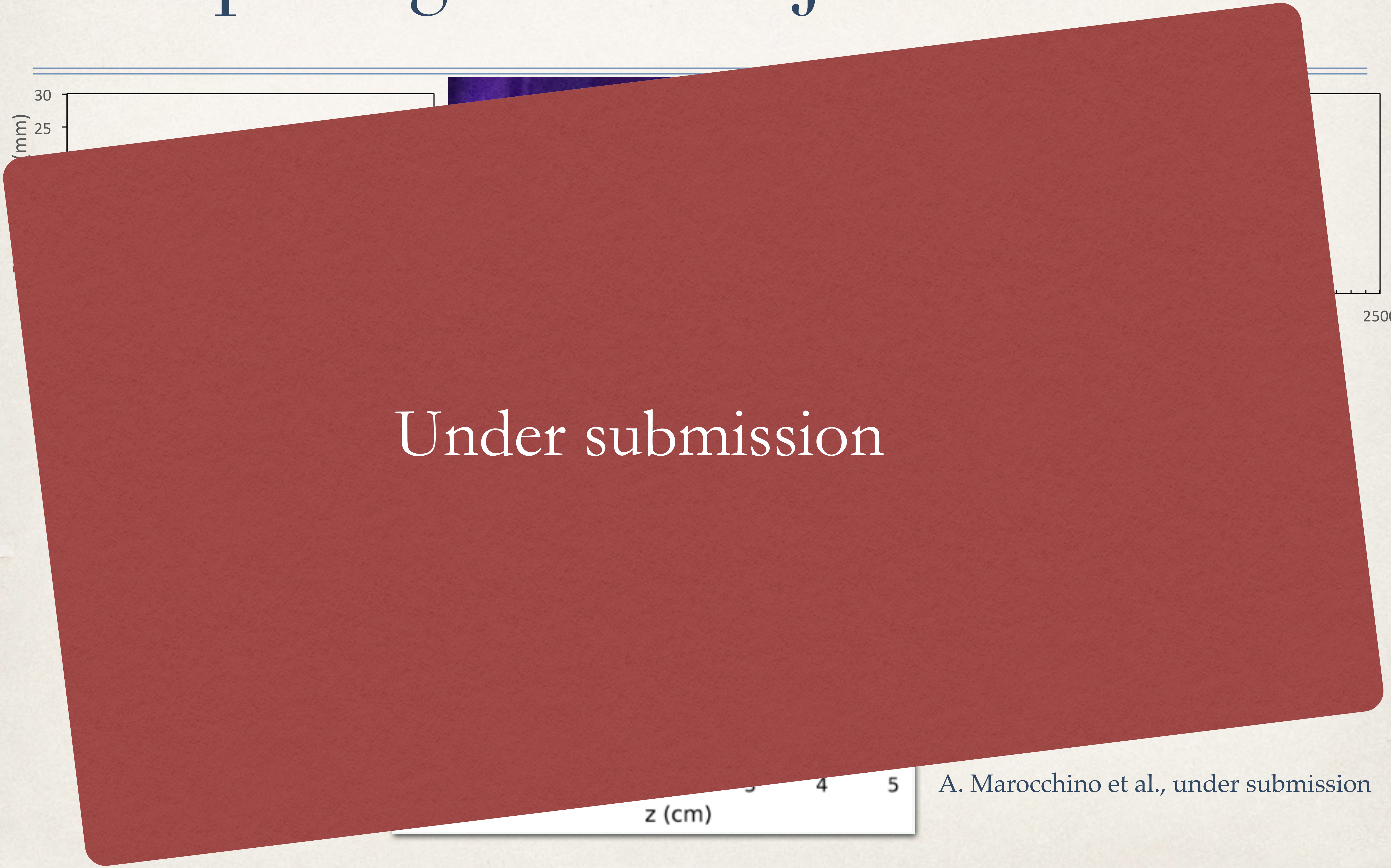
- **Over-dense regime**

Under submission




A. Marocchino et al., under submission

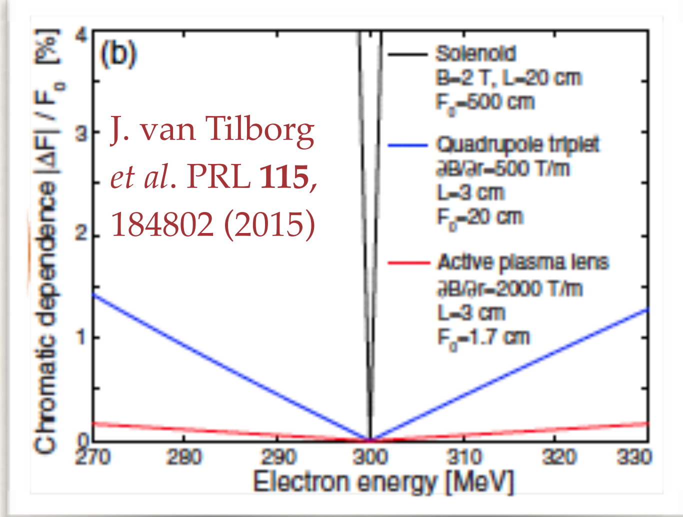
# Ramp length of the jets




A. Marocchino et al., under submission

# Conclusions

- ✓ Plasma lenses allows radial focusing with gradient ~ kT/m (active) and up to MT/m (passive)
  - compactness
  - cm-scale focal length
    - lower chromaticity
- ✓ focusing strength: $K \propto \frac{1}{\gamma}$
- ✓ focusing field independent on beam distribution
  - active and under-dense passive lens
- ✓ full tunability for active plasma lenses
  - adjustable focal length
- ➡ emittance preservation is under studying




# Acknowledgement

- **You for the kind attention**
- W. Leemans, J. van Tilborg and BELLA team
- E. Adli, C. Lindstrøm and CLEAR team
- J. Osterhoff, J. H. Röckemann and FLASHForward collaboration
- J. Rosenzweig and A. Ziegler
- S. Kuschel and collaborators
- My colleagues at SPARC_LAB
- I apologize with those I've forgotten

*This work has been partially supported by the EU Commission in the framework of H2020 research and innovation program under grant agreement (GA) n. 653782 (EuPRAXIA), via ARIES under GA 730871, and by the Commissione Scientifica Nazionale V of the INFN as SL_COMB.*