XVI Incontri di Fisica delle Alte Energie
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Università degli Studi di Trieste

Plasma-based Experiments at the SPARC_LAB Test Facility

Enrica Chiadroni (INFN-LNF)
on behalf of the SPARC_LAB collaboration

Outline

- Motivation and goals
  - **Energy frontier accelerators**
  - Preservation of beam quality
- Principle of plasma acceleration
- SPARC_LAB Test Facility
  - **High brightness photo-injector**
- Preparation to plasma-based acceleration experiments
  - **External injection of high brightness electron bunches** (HBEBs) in both laser-driven and particle driven plasma wakefield (LWFA and PWFA, respectively)
  - **Active plasma lenses for final focusing**
    - Preliminary results
- Conclusions

Advanced Accelerator Concepts

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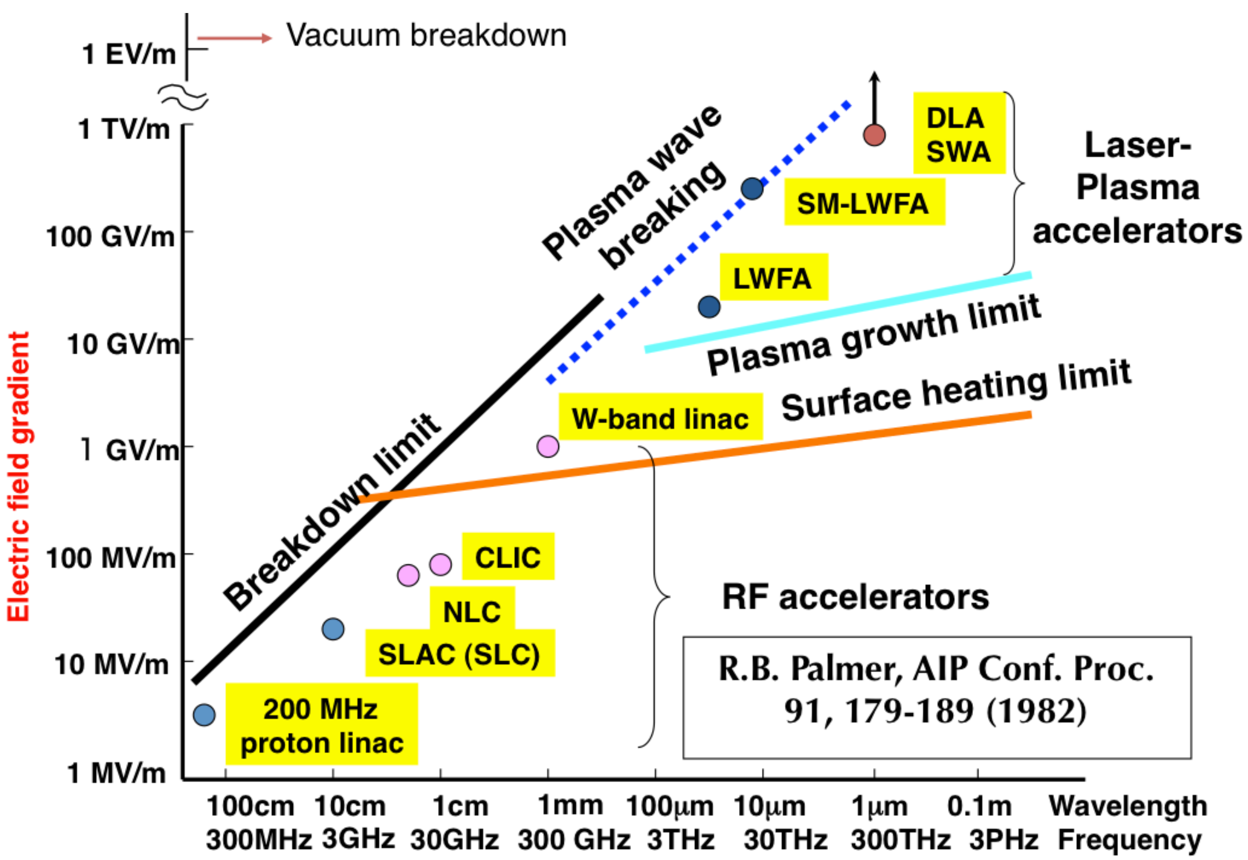
- **Conventional RF structures** reached a **practical limit**
  - they cannot sustain accelerating gradients larger than ~100 MV/m (X-band structures) due to **breakdown** on the wall surfaces
- **Ultra-high gradients** require structures to sustain high fields
  - **Plasma-filled structures**
    - Maximum accelerating field a plasma can sustain: **Wave breaking field**



$$E_{Max}[V/m] = \frac{m_e c \omega_p}{e} \approx 100\sqrt{n_0[cm^{-3}]}$$

Scale length of the plasma wake

$$\lambda_p[\mu m] \approx \frac{3.3\ 10^4}{\sqrt{n_0[cm^{-3}]}}$$

$$n_0 = 10^{16} \div 10^{18} cm^{-3}$$

The **frontier** in modern accelerator physics is based on R&D towards **compacts accelerators**.

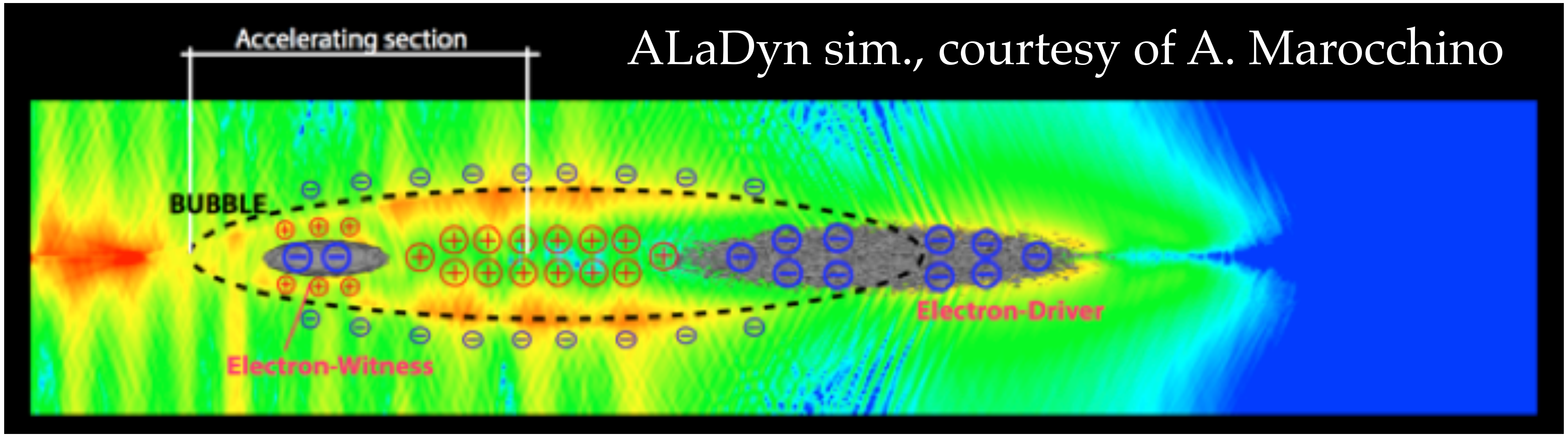
Goals

- Plasma-based acceleration has already proved the **ability to reach ultra-high, ~GV/m, accelerating gradients**
  - J. Rosenzweig et al., Phys. Rev. Lett. **61**, 98 (1988): *First experimental demonstration of PWFA*
  - Mangles, Geddes, Faure et al., Nature **431**, (2004): *The dream beam*
  - W. P. Leemans, Nature Physics vol. **2**, p.696-699 (2006): *GeV electron beams from a centimetre-scale accelerator*
  - I. Blumenfeld et al., Nature **445**, p. 741 (2007): *Doubling energy in a plasma wake*
  - P. Muggli et al, in Proc. of PAC 2011, TUOBN3: *Driving wakefields with multiple bunches*
- The **next step** is the extraction and transport of the beam, preserving its quality, i.e. 6D high brightness, stability and reliability to **drive a plasma-based user facility** (the EuPRAXIA Design Study* has been funded from EU)
  - M. Litos et al., Nature **515**, 92 (2014): *High efficiency acceleration in the driver-trailing bunches*
  - S. Steinke et al., Nature **000** (2016) doi:10.1038/nature16525: *Multi-stage coupling*

*http://www.eupraxia-project.eu

Plasma Wakefield Acceleration

PWFA

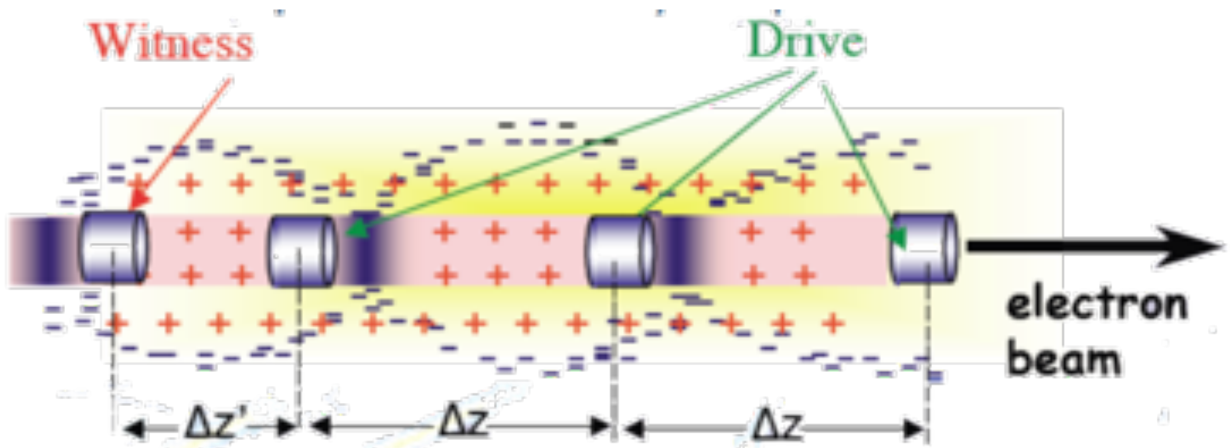


- An **intense, high-energy charged particle beam** (**driver**) drives a **high-gradient wakefield** as it passes through the plasma
- The **space-charge** of the electron bunch **blows out plasma electrons**
- **Plasma electrons rush back in and overshoot** setting up a plasma density oscillation

$$\omega = \omega_p = \sqrt{\frac{4\pi n_0 e^2}{m_e}}$$

- A second beam (**witness**), injected at the accelerating phase, is then accelerated by the wake

Resonant PWFA



- Bunch spacing depends on the plasma density

Driver $\Delta z = \lambda_p$

Witness $\Delta z' \approx \frac{\lambda_p}{2}$

$\lambda_p(\mu m) \approx 3.3 \cdot 10^4 \; n_e^{-1/2}(cm^{-3})$ = 330 μm @ $n_e = 10^{16}$ cm^{-3}

$$E_z \propto \left(\frac{N}{\sigma_z}\right)^2 N_T \gtrsim GV/m$$

- **Multi-bunch shaping is one of the most promising candidates**
  - Increase in energy of a trailing particle
  - Better control of the energy spread

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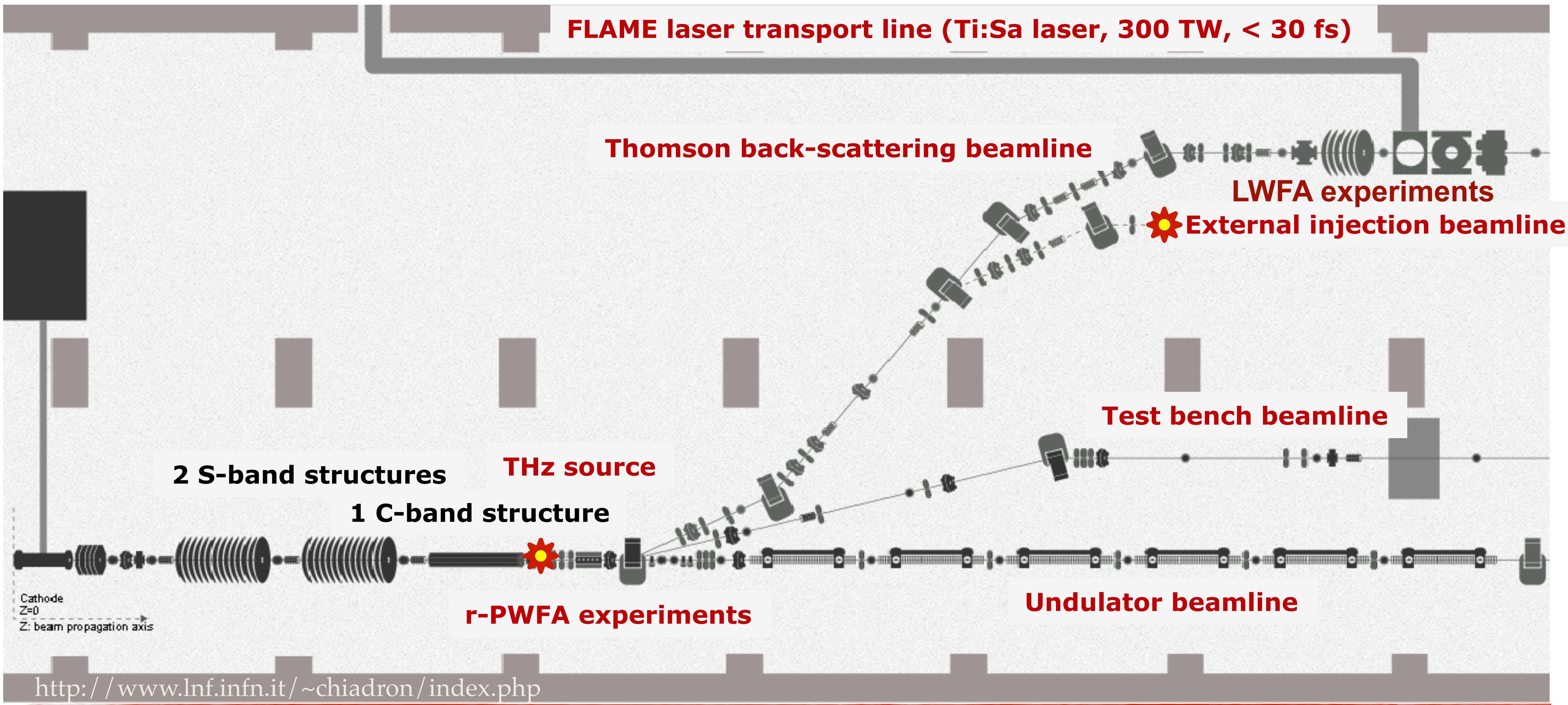
The SPARC_LAB Test Facility

Sources for Plasma Accelerators and Radiation Compton with Lasers And Beams



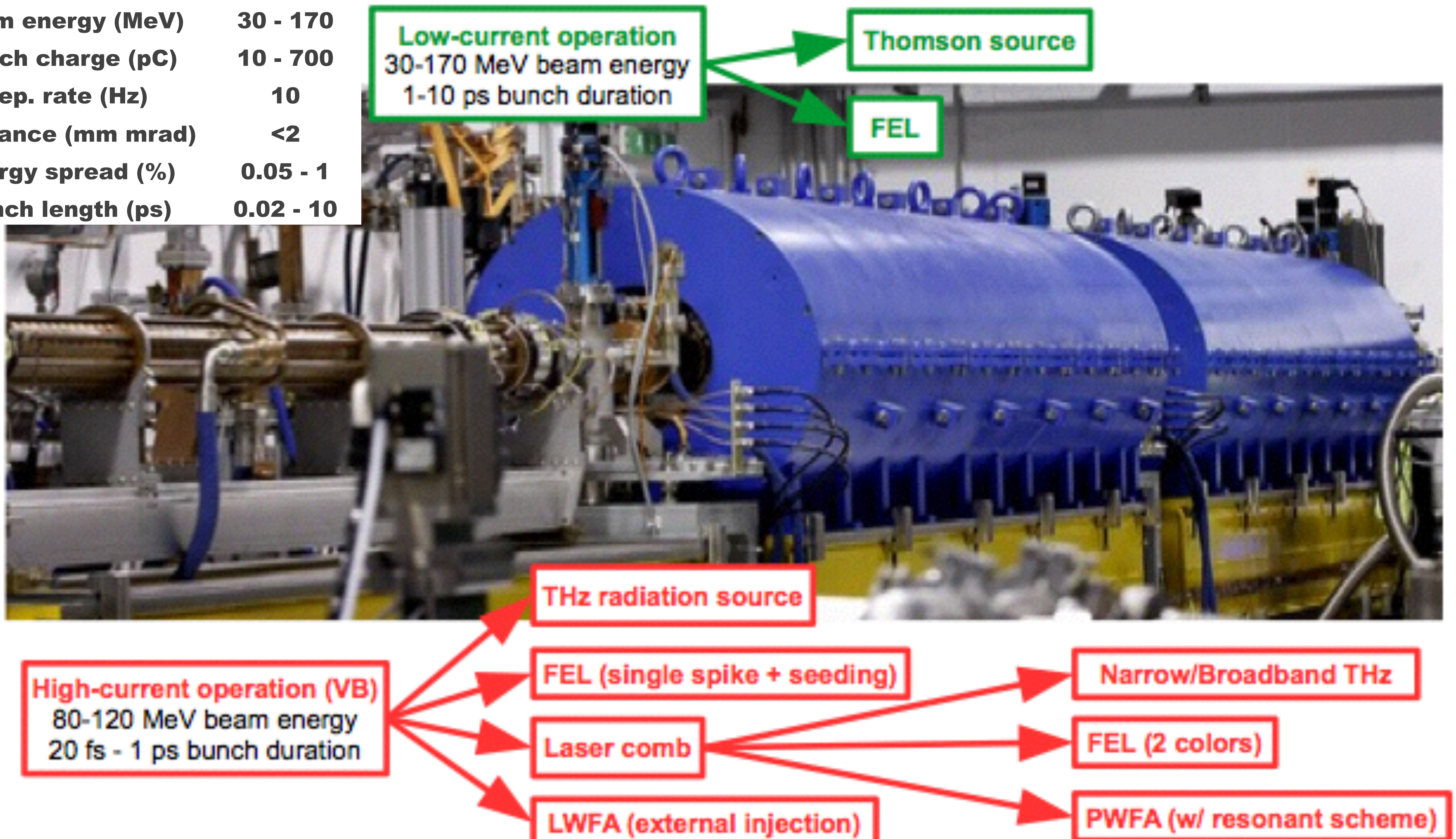
https://www.google.it/maps/@41.8231995,12.6743967,3a,69.7y,130.68h,76.68t/data=!3m6!1e1!3m4!1sYyB35yaBMxJgQ92-wp3oYQ!2e0!7i13312!8i6656?hl=en

High Brightness Photo-Injector

SPARC LAB

M. Ferrario et al., *SPARC_LAB present and future*, NIM B **309**, 183–188 (2013)

Beam energy (MeV)	**30 - 170**
Bunch charge (pC)	**10 - 700**
Rep. rate (Hz)	**10**
emittance (mm mrad)	**<2**
energy spread (%)	**0.05 - 1**
Bunch length (ps)	**0.02 - 10**



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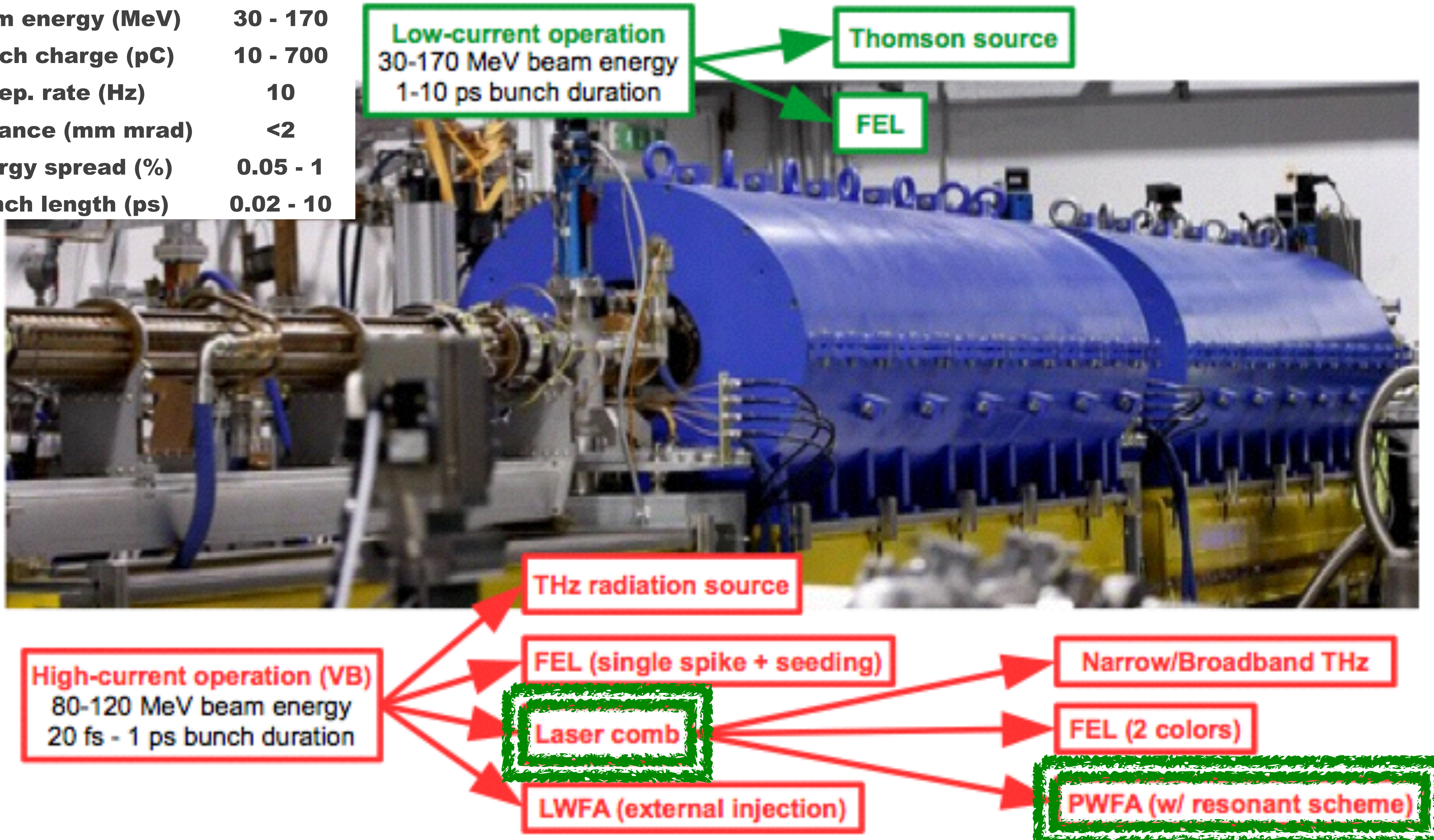
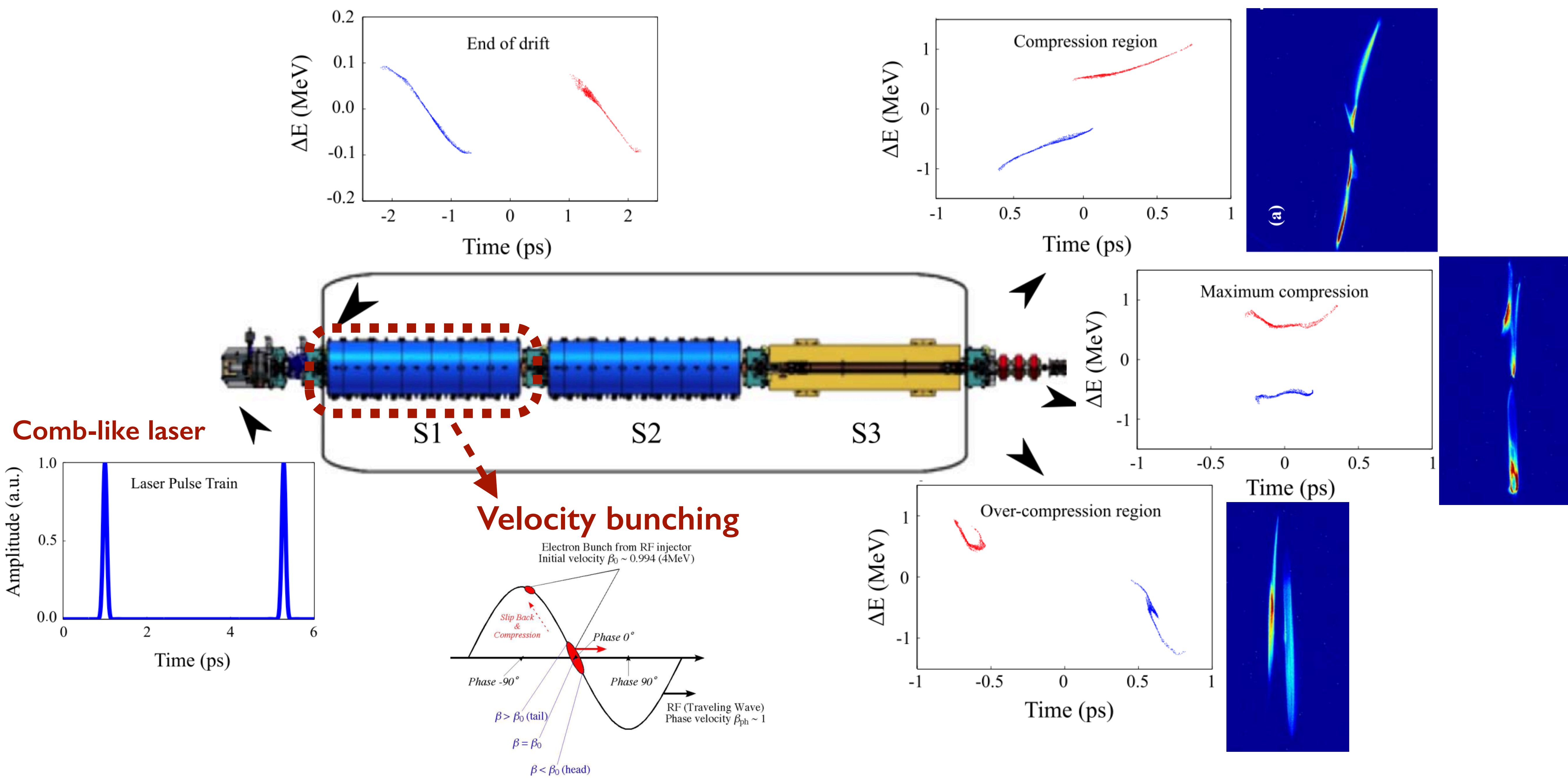


- **L. Serafini and M. Ferrario**, *Velocity Bunching in Photo-injectors*, Physics of, and Science with the X-Ray Free-Electron Laser, edited.by S. Chattopadhyay et al. © 2001 American Institute of Physics
- **M. Ferrario et al.**, *Experimental Demonstration of Emittance Compensation with Velocity Bunching*, Phys. Rev. Lett. **104**, 054801 (2010)
- **P. O. Shea et al.**, Proc. of 2001 IEEE PAC, Chicago, USA (2001) p.704.
- **M. Ferrario et al.**, Int. J. of Mod. Phys. B, 2006

Generation of multi-bunch trains

Sub-relativistic electrons ($\beta_c < 1$) injected into a traveling wave cavity at zero crossing move more slowly than the RF wave ($\beta_{RF} \sim 1$). The electron bunch slips back to an accelerating phase and becomes simultaneously accelerated and compressed.



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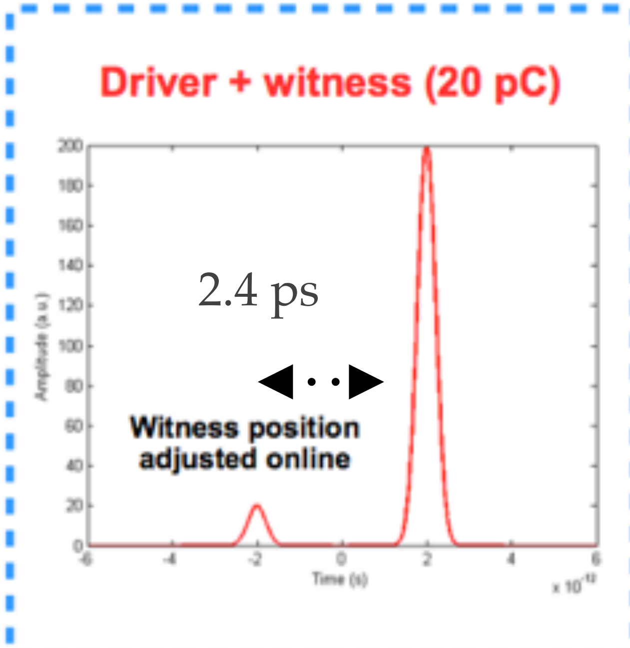
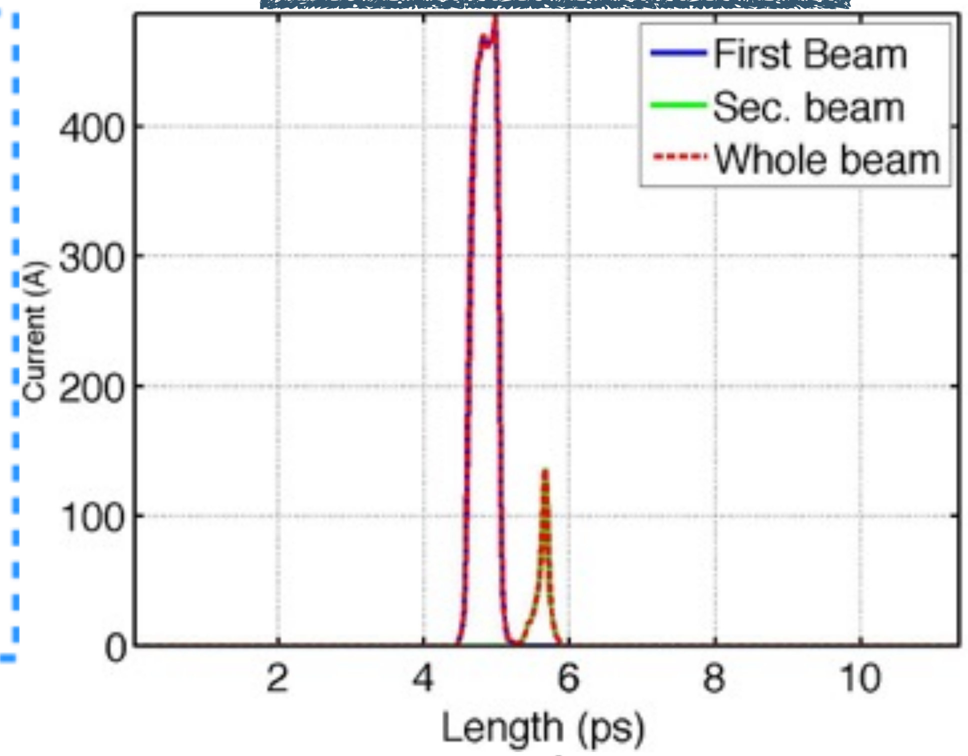
Driver and Witness Working Point

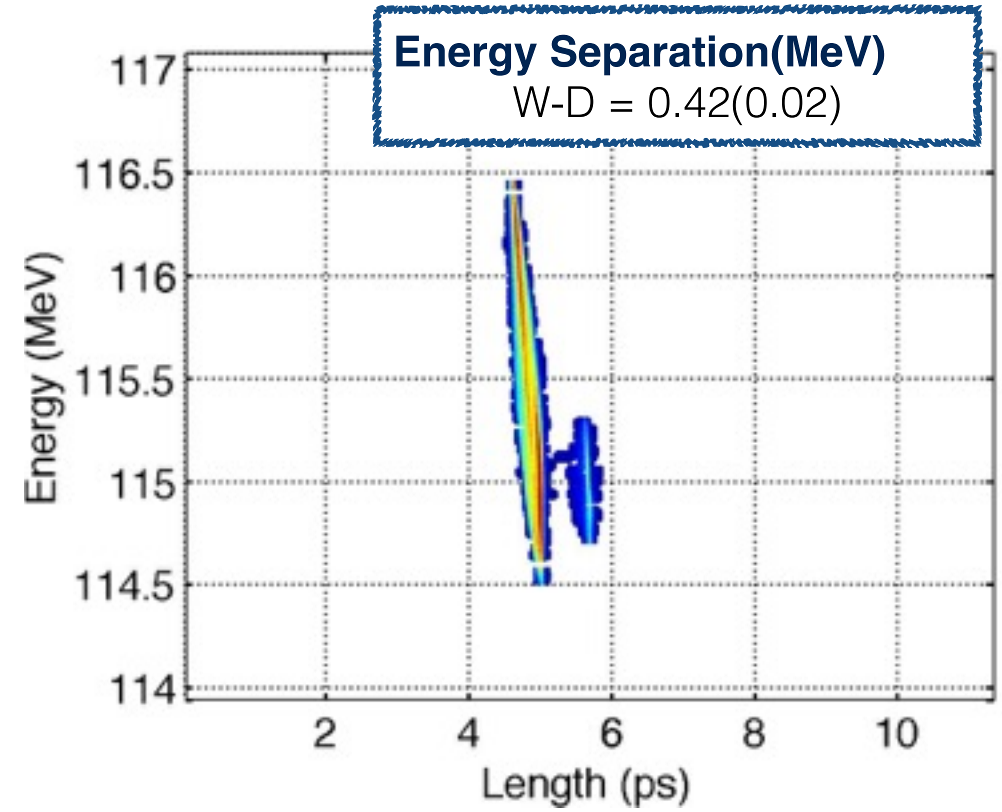
Experimental Data

Laser profile on photo-cathode

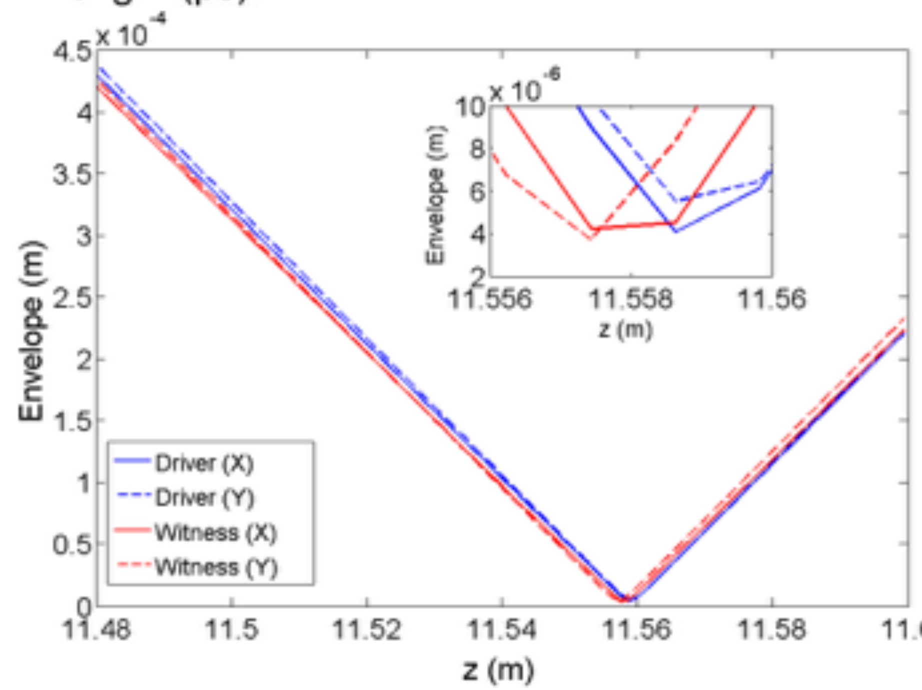


Time Separation ~ $\frac{\lambda_p}{2}$
0.77 (0.05) ps





	Driver	Witness
Charge (pC)	200	20
Energy (MeV)	115.4	114.9
Final focus (um)	5.5	3
Duration (fs)	80	35
e_n (mm mrad)	4.5	2.4



GPT simulation for the final focus with PMQ from experimental beam parameters

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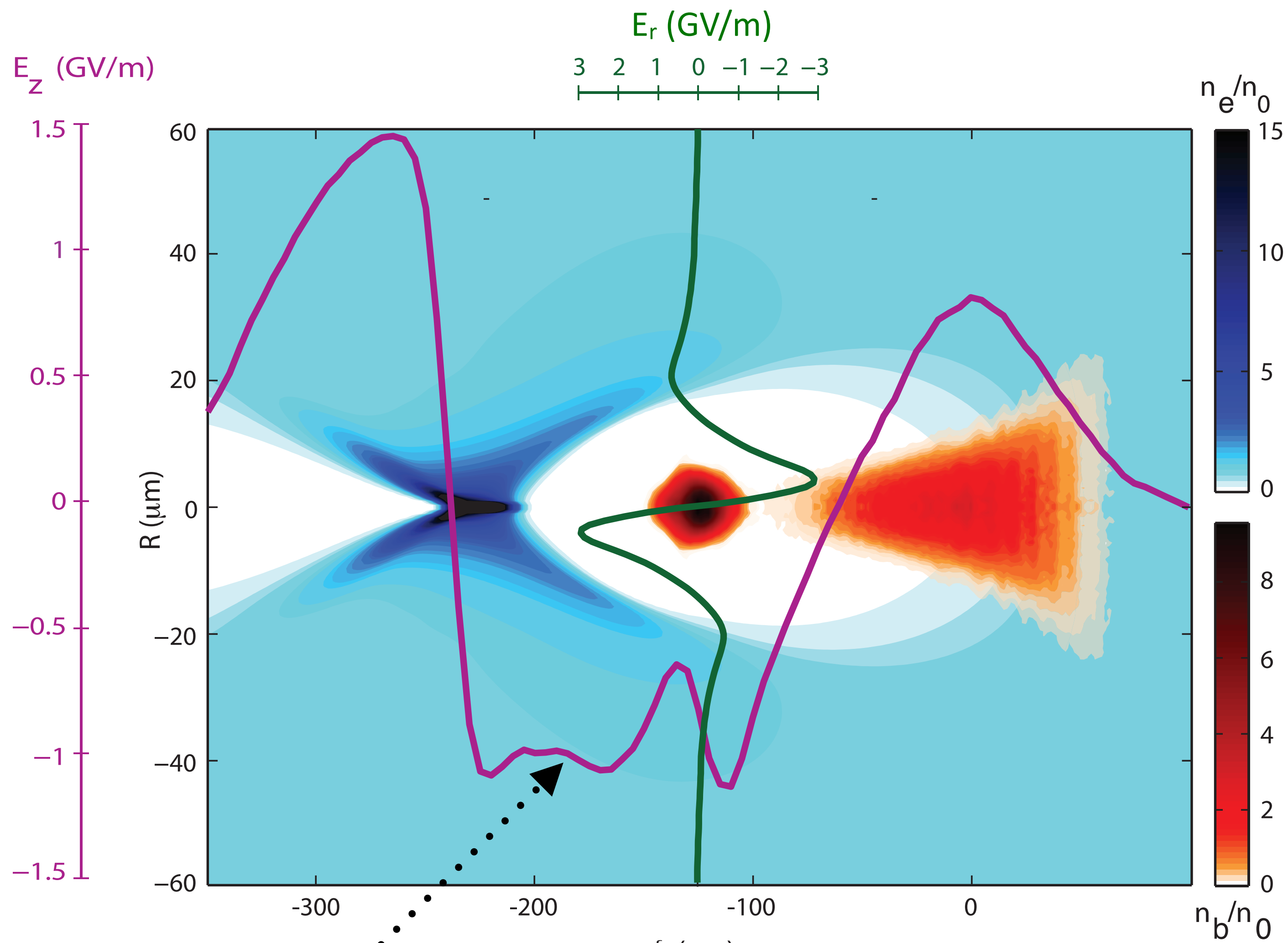
Start-to-End Simulation

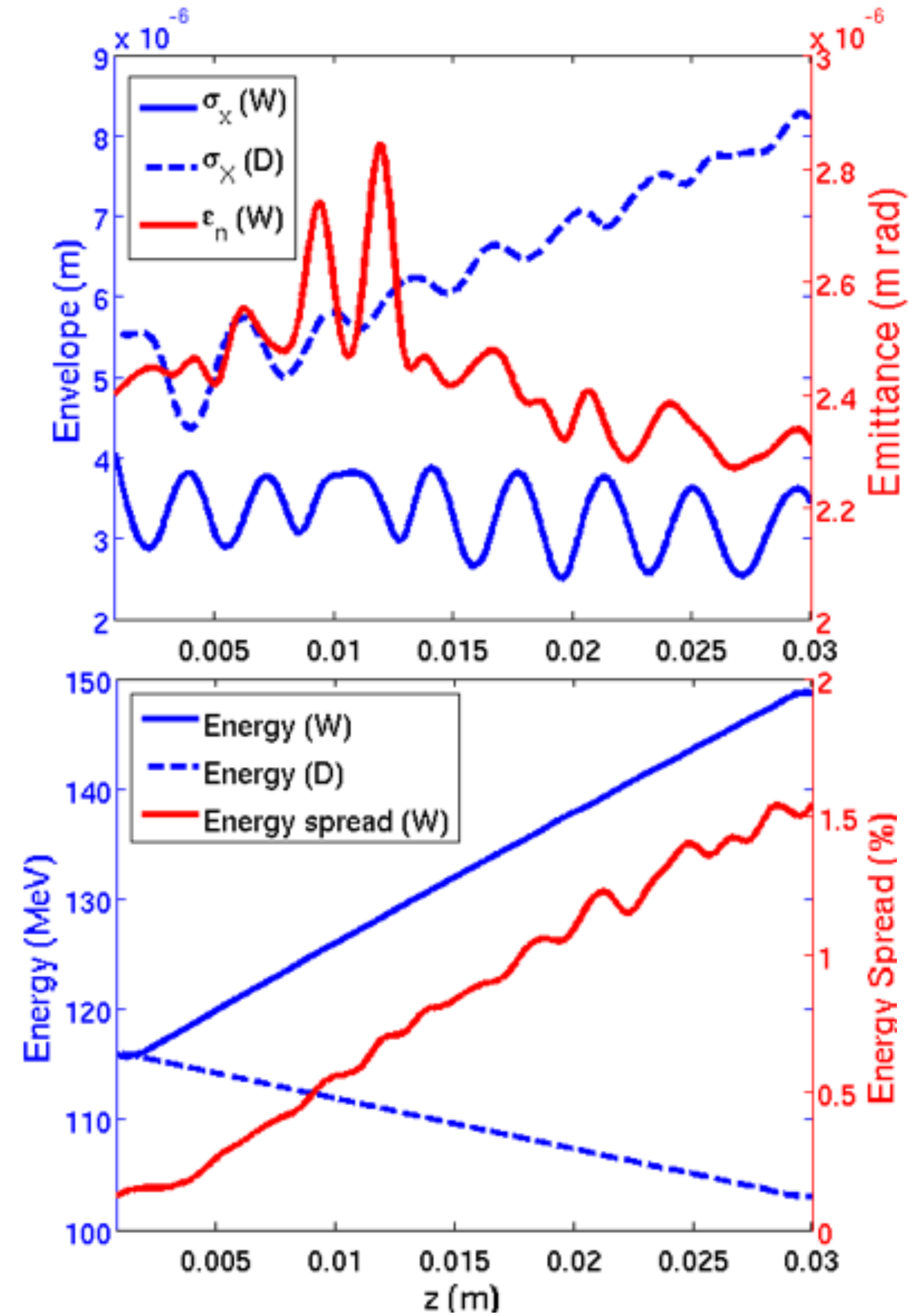
Hybrid kinetic-fluid simulation by Architect*

- **PIC** (bunch), **fluid** (plasma), 3-5 hours for 3 cm
- Cross-checked with full PIC codes (ALaDyn)



flattens wake, reduces energy spread

$n_p = 10^{16}\ cm^{-3}$
$E_z \sim 1.1\ GV/m$



F. Marocchino and F. Massimo, *Proc. of the 2nd EAAC (2015)*

Courtesy of A. Marocchino, A. R. Rossi

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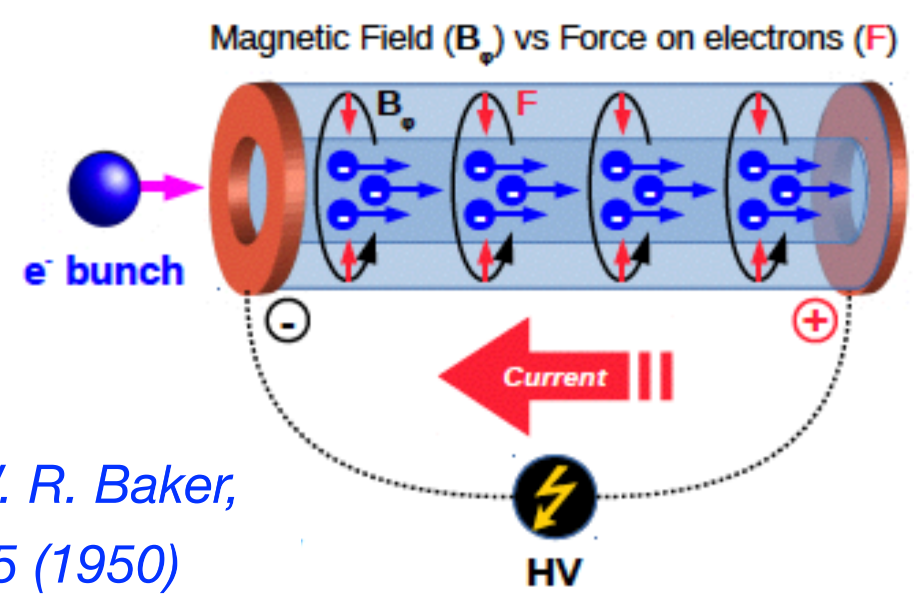
Active Plasma Lens

- **Matching is critical for preserving beam quality**, both when the bunch enters the plasma and when it leaves the interaction area
  - **Discharge current in a gas-filled capillary**



W. K. H. Panofsky and W. R. Baker, Rev. Sci. Instrum. ***21****, 445 (1950)*

Advantages

- **Radial focusing**
- **Weak chromaticity**

$$k \propto \frac{1}{\gamma}$$

- **Compactness**
  - Focusing gradient ~ kT/m

The bunch is focused by the azimuthal magnetic field generated by the discharge current, according to Ampere's law

$$B_\phi(r) = \frac{1}{2}\int_0^r \mu_0 J(r')dr'$$

J. Van Tilborg et al., Phys. Rev. Lett. **115**, 184802 (2015)
R. Pompili et al., Appl. Phys. Lett. **110**, 104101 (2017)

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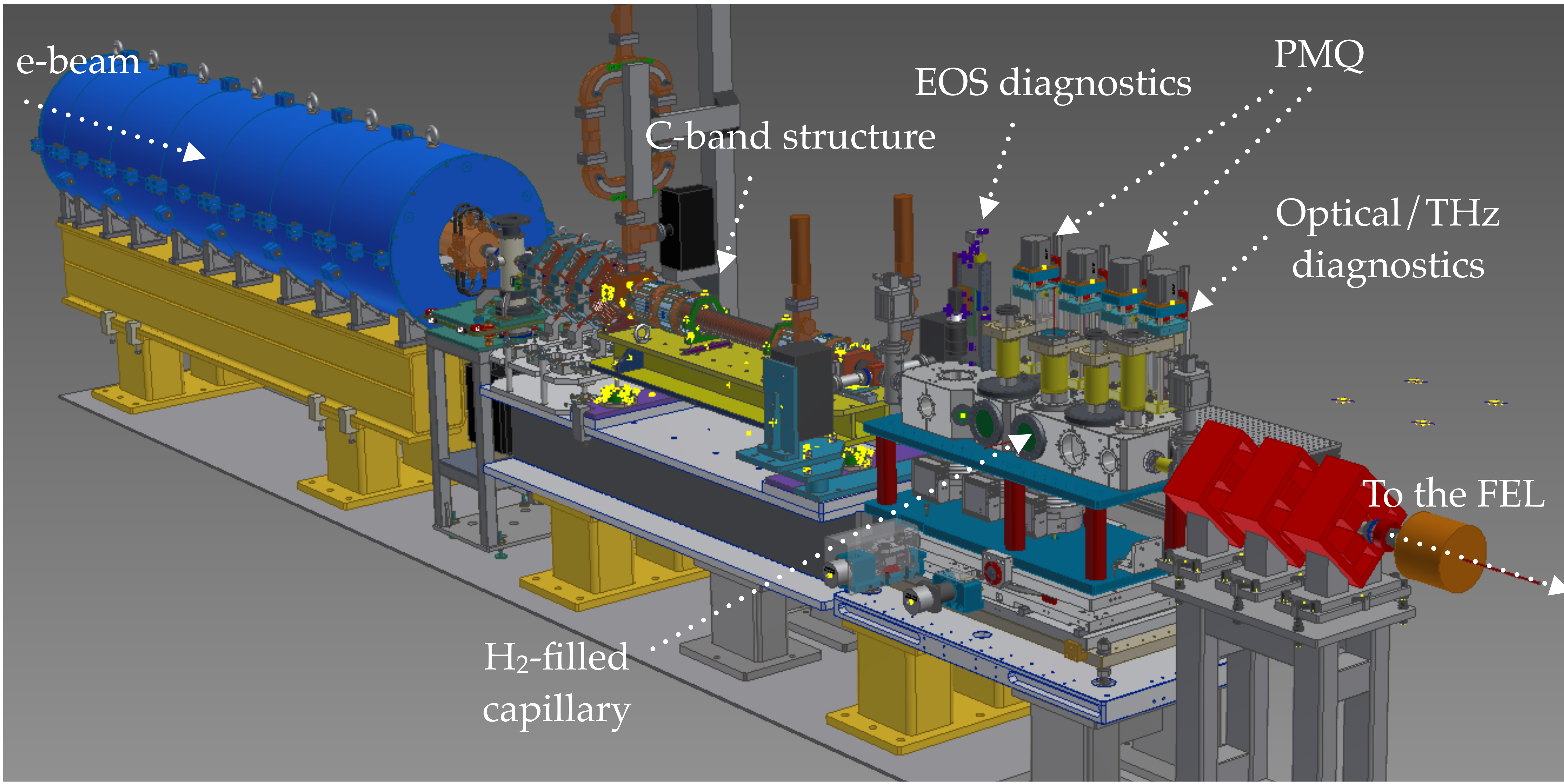
Experimental Layout



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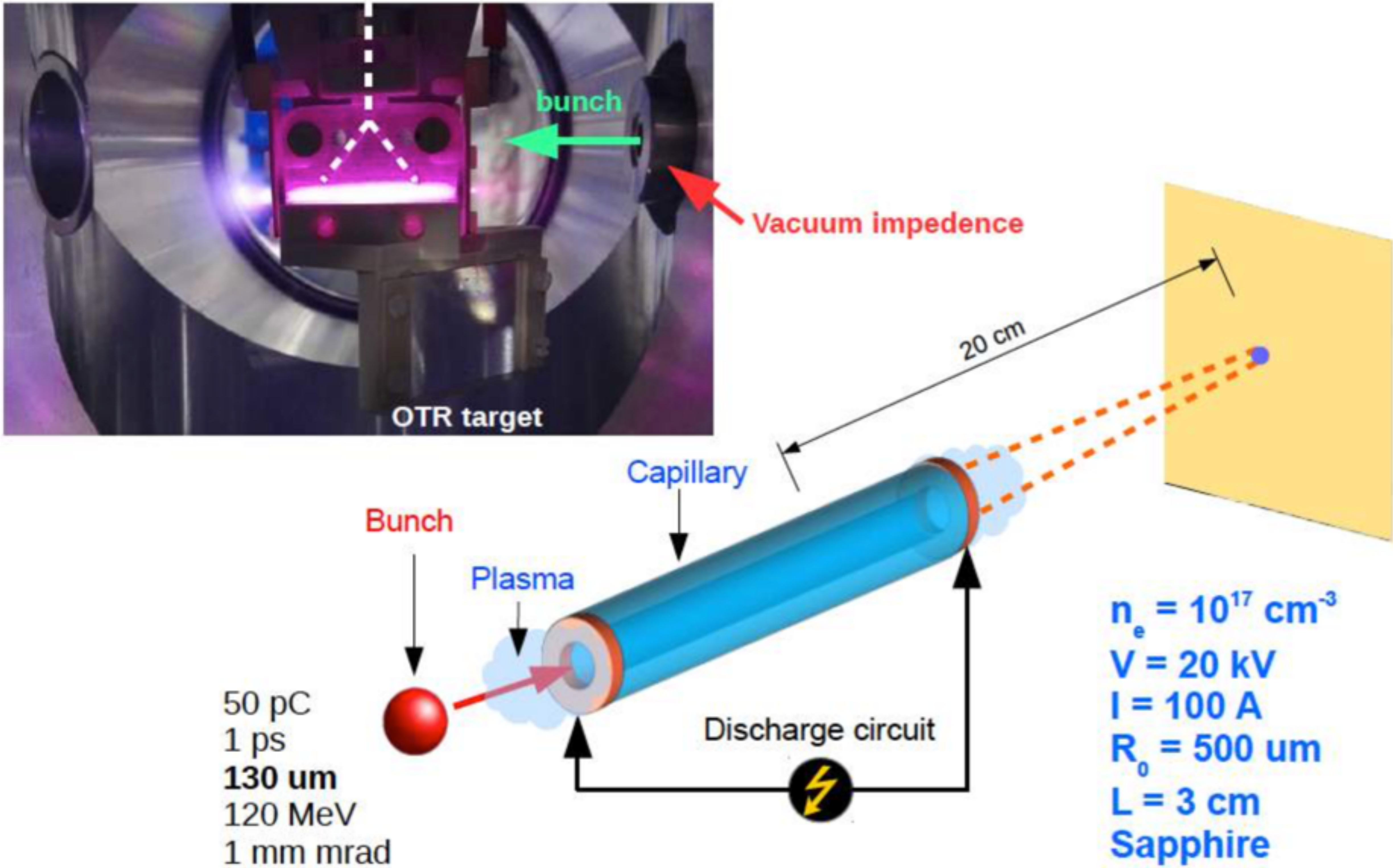
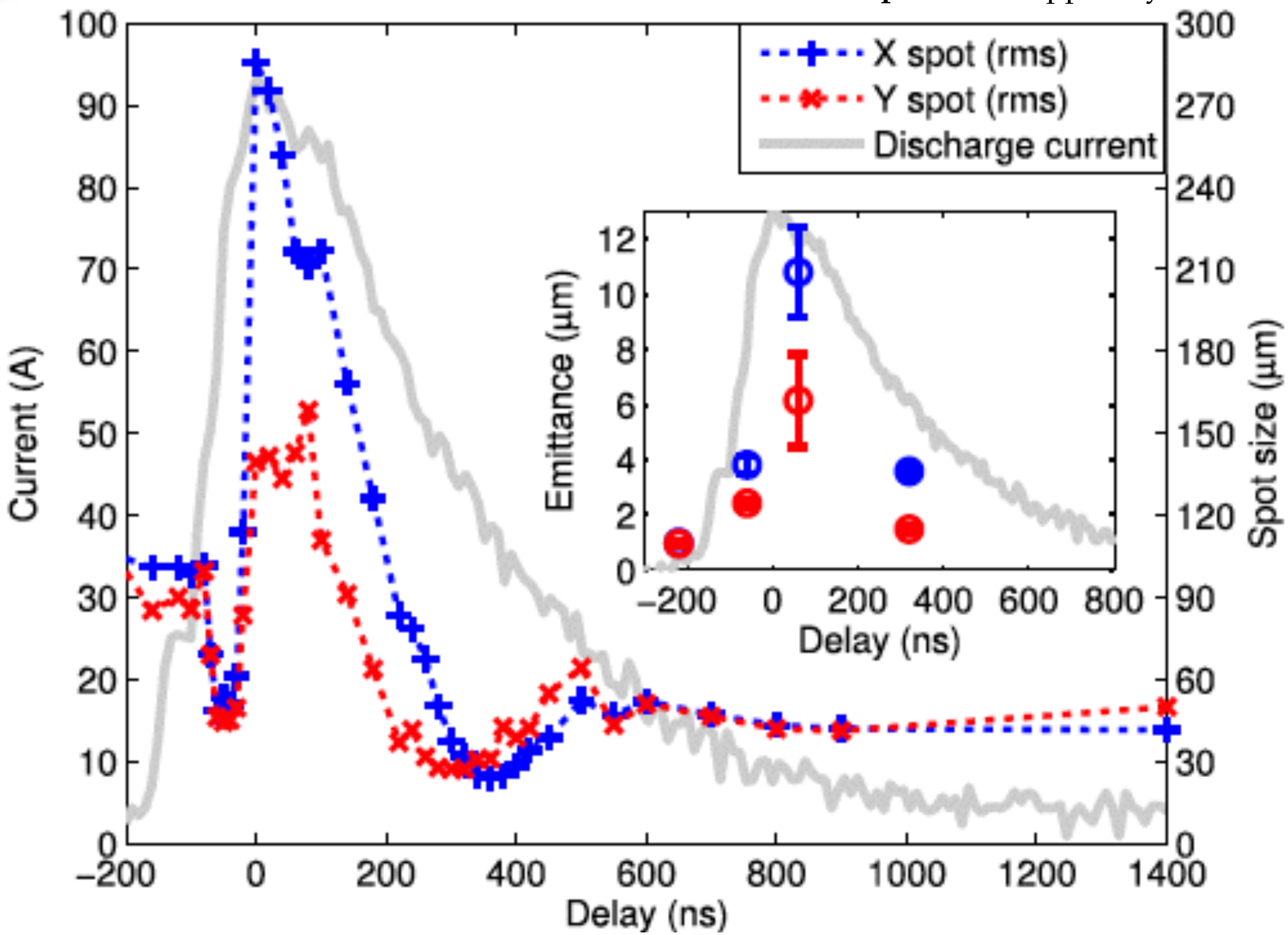
Active Plasma Lens Layout



Envelope scan

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



The arrival time of the electron beam is scanned with respect to the discharge pulse in order to change the active plasma lens focusing.

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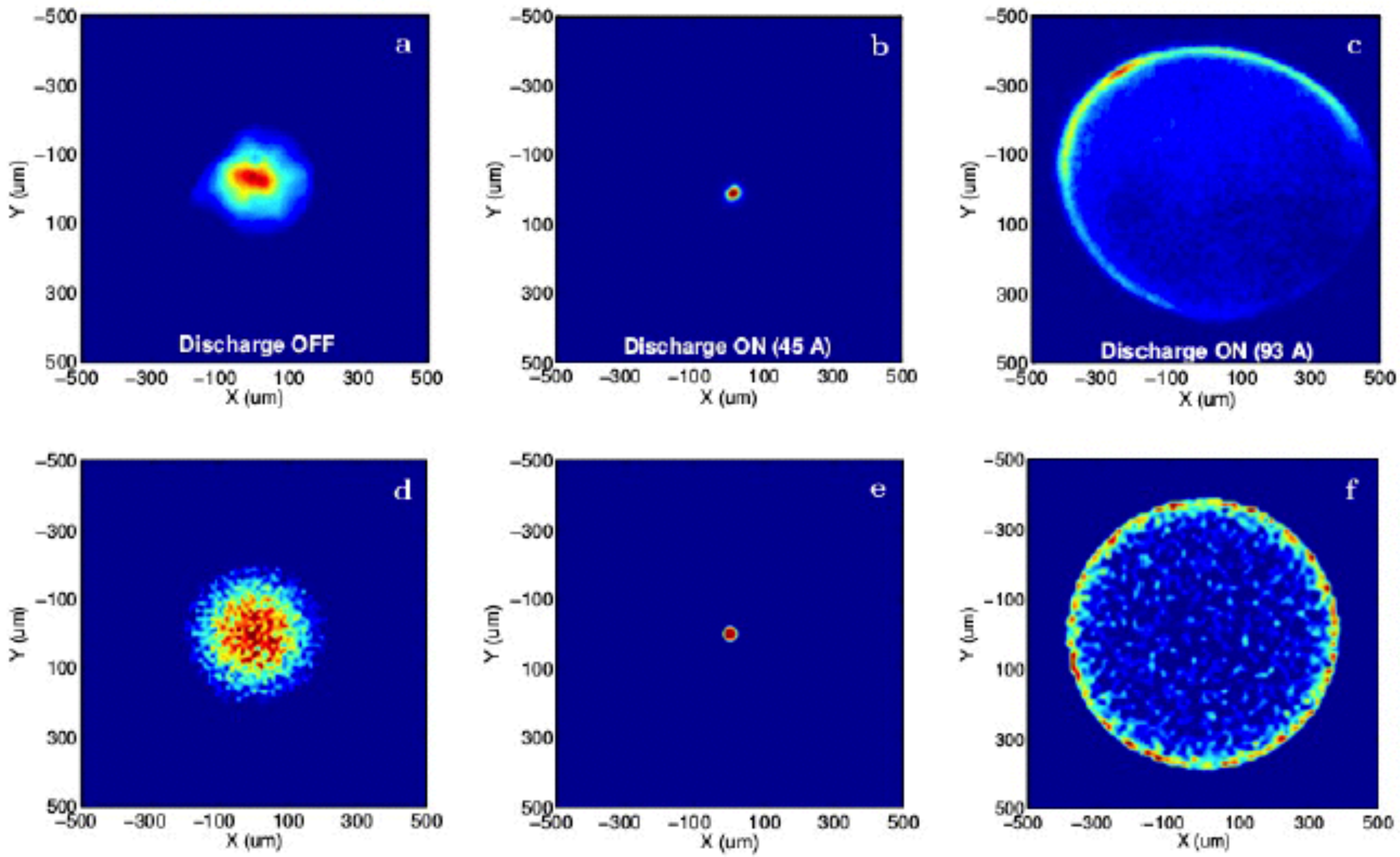
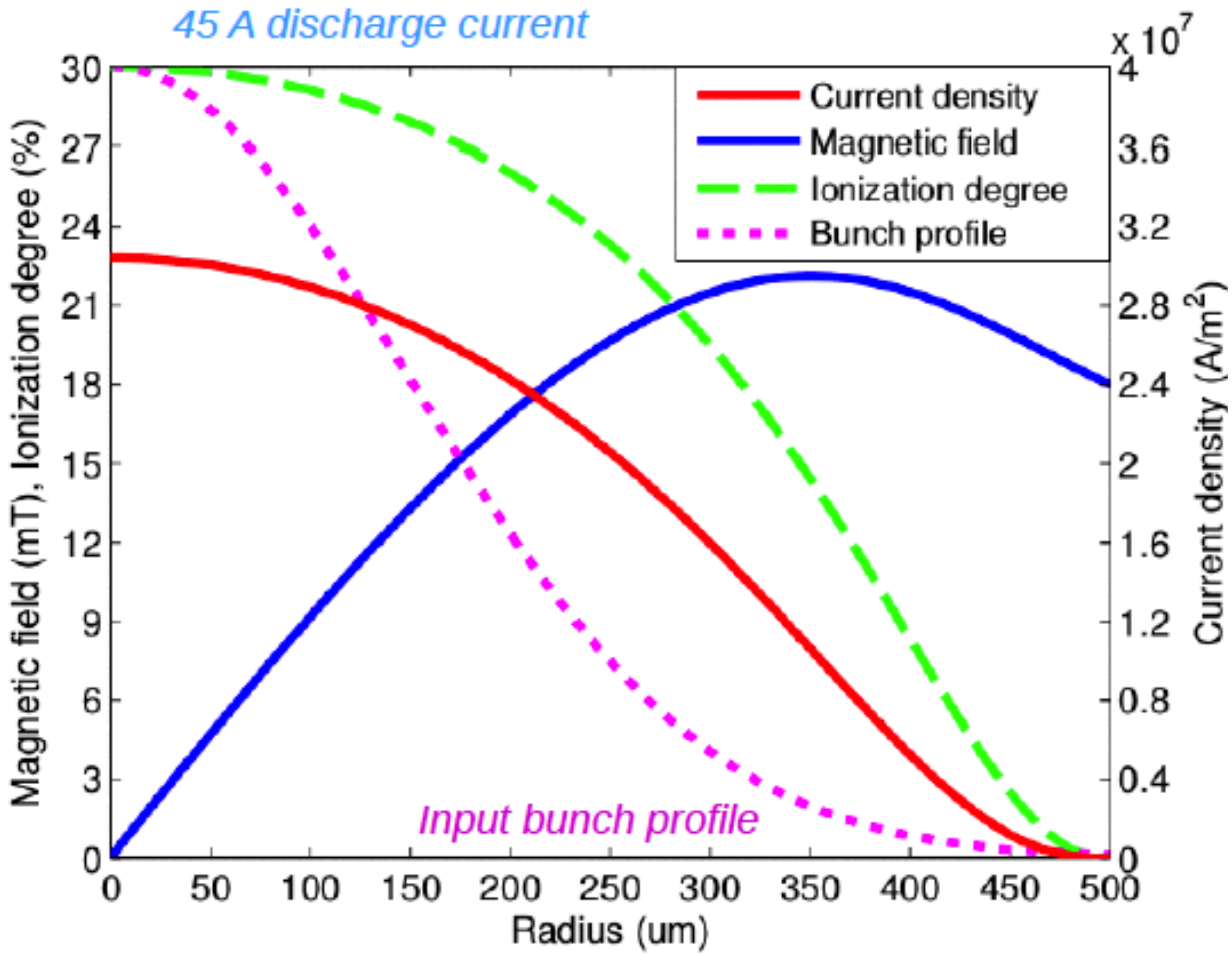
Measurements &Simulations



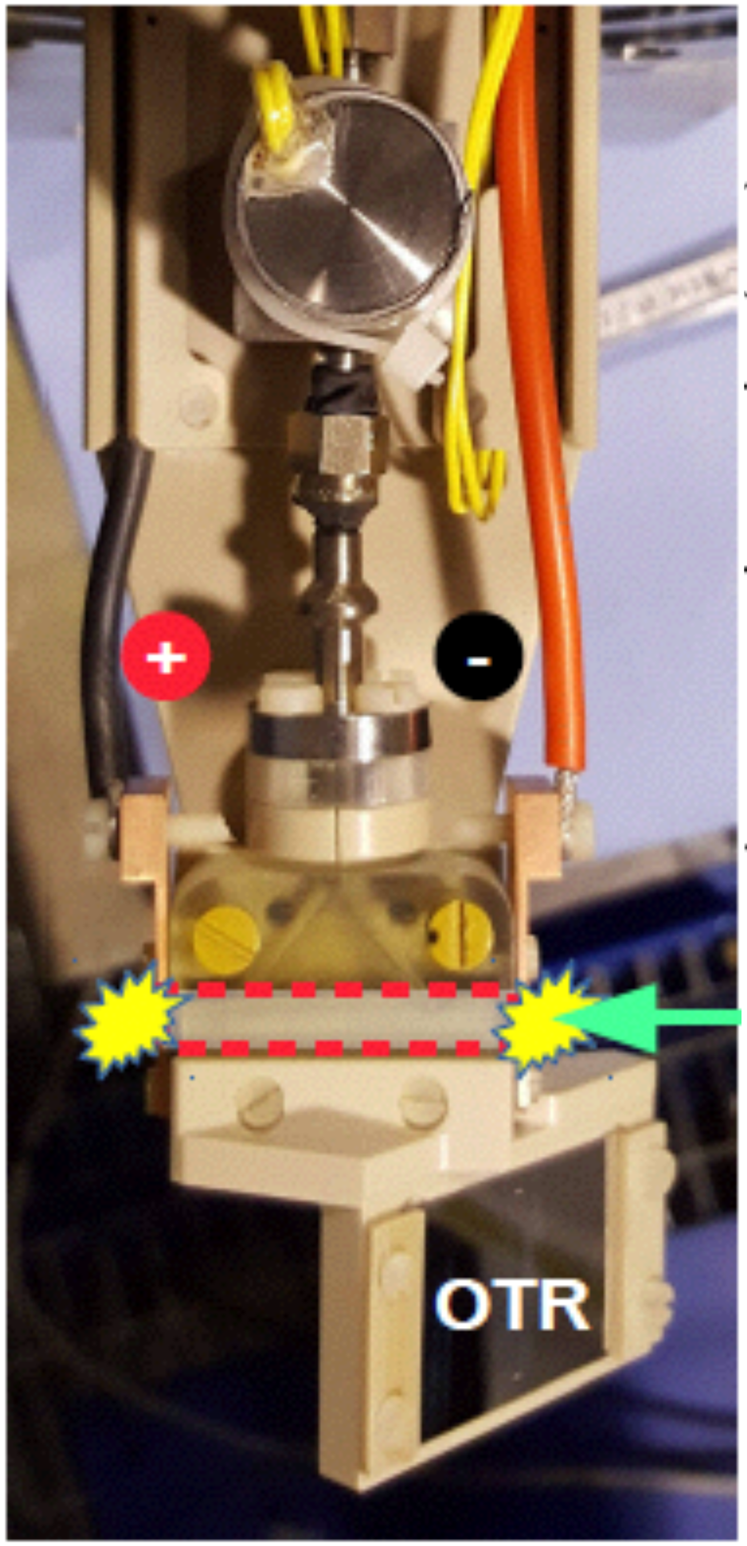
Images recorded on the screen downstream the capillary with the discharge turned off (σ ≈ 100 μm, a) and on, at ID ≈ 45 A (σ ≈ 24 μm, b) and ID ≈ 93 A (σ ≈ 280 μm, c). (d-f) Simulated transverse profiles obtained on the same screen with the combined use of the GPT and Architect codes.

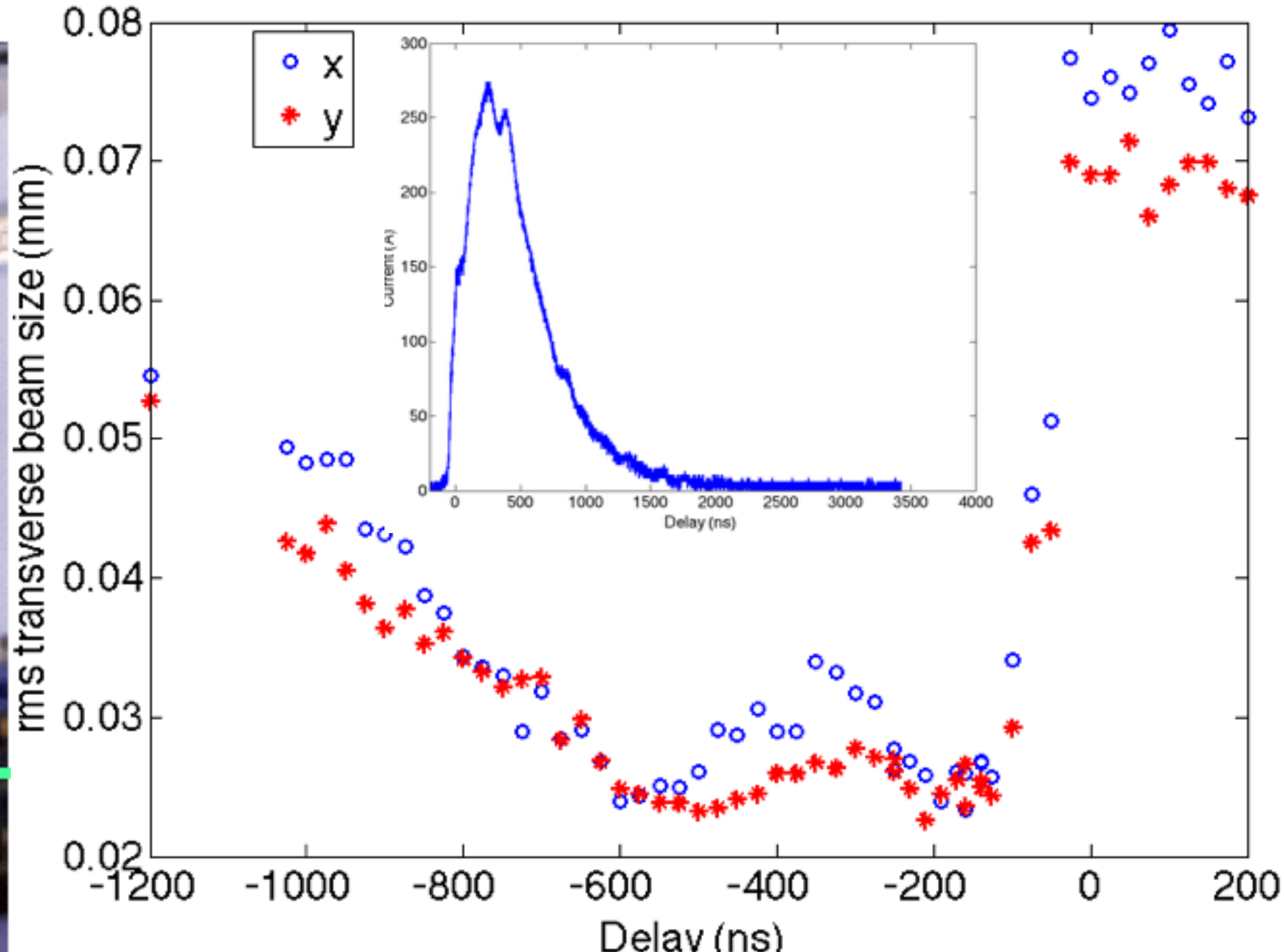
Non-linear focusing field

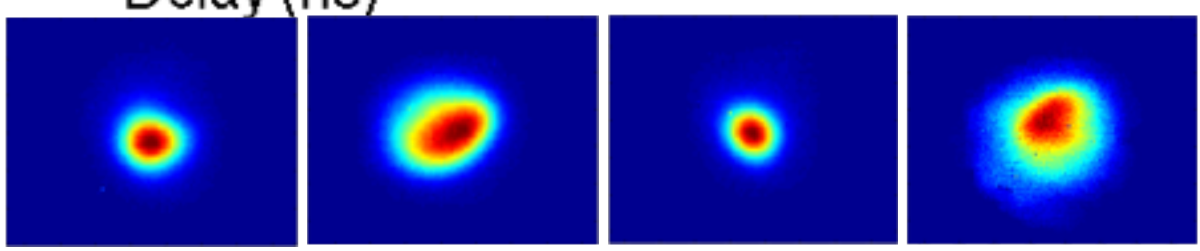


The current flows mainly on the axis and thus resulting in a radially nonlinear magnetic field

Envelope scan with 1 cm capillary







-600 ns   -350 ns   -160 ns   0 ns

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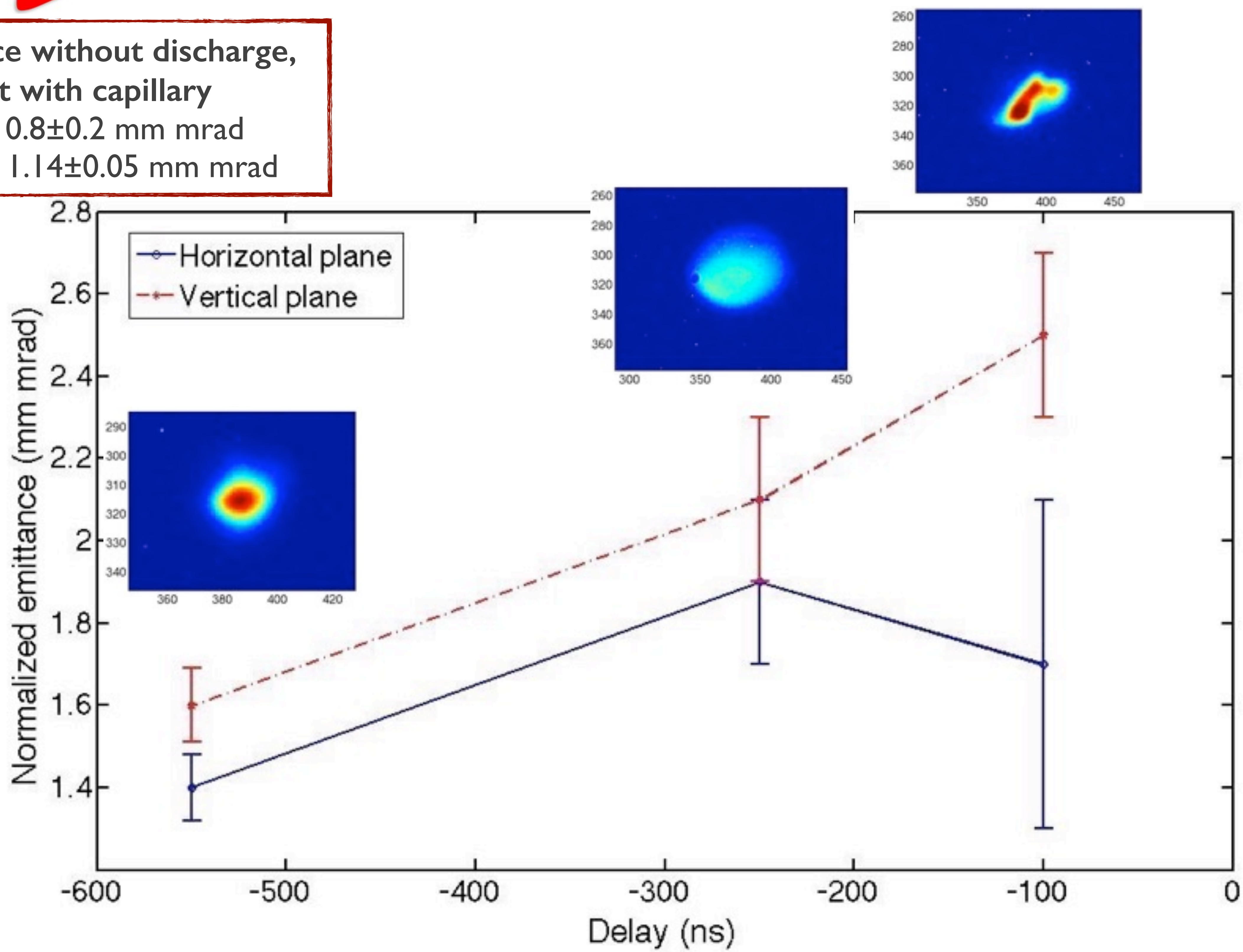
Control of emittance growth

emittance without discharge, but with capillary
e_{nx} = 0.8±0.2 mm mrad
e_{ny} = 1.14±0.05 mm mrad



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Conclusions

- Plasma-based ***acceleration provides*** ultra-high gradients
  - Plasma-based ***accelerators demand*** high brightness beams
    - Many potential applications possible for compact plasma-based accelerators, delivering ultra-short, high peak current electron beams (e.g. FEL, γ rays,…)
- **SPARC_LAB is currently preparing the beam-driven plasma acceleration experiment**
  - We started investigating the focusing properties of a 3 cm-long active plasma lens, “probed” with an high-brightness electron beam
    - **Full characterization of the bunch 6D phase space for the first time**
    - Further investigations are ongoing since **plasma-based focusing and extraction transport lines are mandatory for the proper matching** to “user” beam lines

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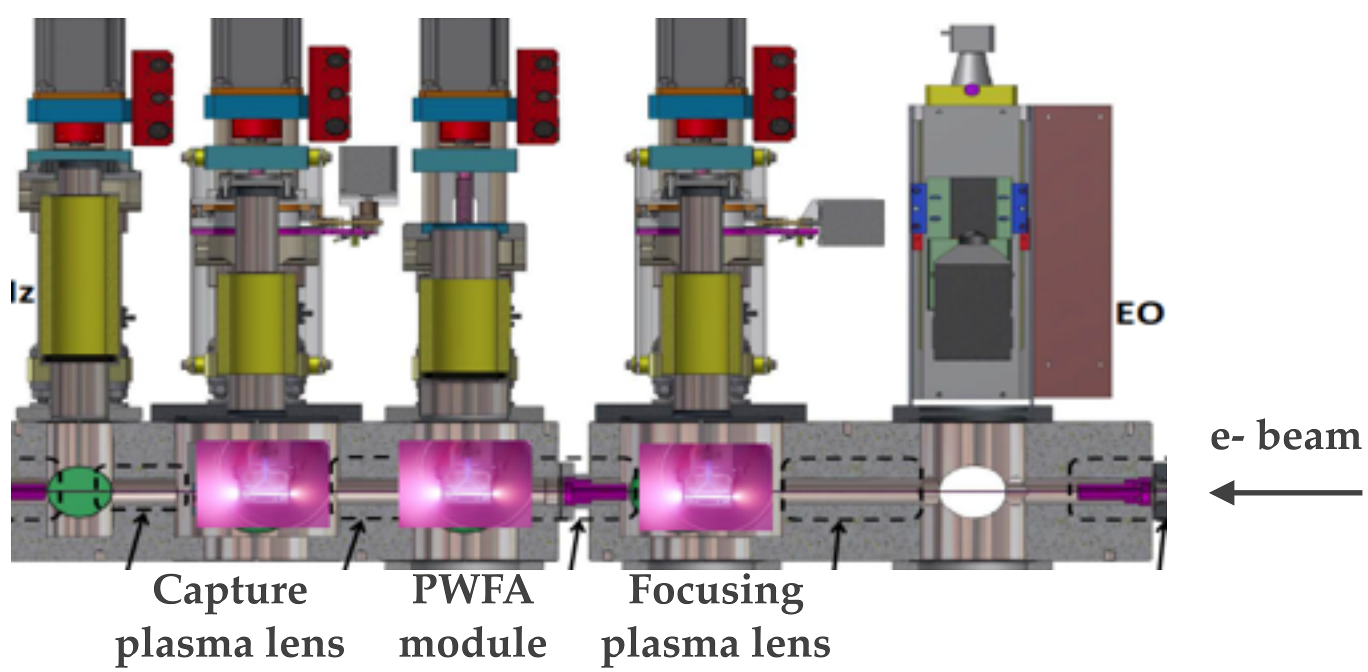
    - **The next step:**



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  - M.P. Anania, M. Bellaveglia, A. Biagioni, M. Croia, D. Di Giovenale, M. Ferrario, F. Filippi, V. Lollo, A. Marocchino, S. Pella, G. Di Pirro, R. Pompili, S. Romeo, J. Scifo, V. Shpakov, C. Vaccarezza, F. Villa (*INFN, Frascati*)
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