9th International Particle Accelerator Conference
April 30th - May 4th, 2018
Vancouver, BC - Canada

Status of Plasma-based Experiments at the SPARC_LAB Test Facility

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

Istituto Nazionale di Fisica Nucleare
LABORATORI NAZIONALI DI FRASCATI

Outline

- Motivation and goals
    - Preservation of beam quality
    - **Drive a plasma-based facility**
- Principle of plasma acceleration and focusing
- SPARC_LAB Test Facility
    - **High brightness photo-injector**
- Preparation to plasma-based acceleration experiments
    - **External injection of high brightness electron bunches**
    - **Active plasma lenses for final focusing**
        - Preliminary results
- Conclusions

enrica.chiadroni@lnf.infn.it

Motivation

✓ Multi-GeV in *cm scale* plasma structures

- 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*

➡ Acceleration, extraction and transport of stable and reliable high brightness electron beams

- 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*

➡ Plasma-based user facility

- H2020 EuPRAXIA Design Study => P. A. Walker, TUPML044

enrica.chiadroni@lnf.infn.it

Motivation

✓ Multi-GeV in *cm scale* plasma structures

- 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*

➡ Acceleration, extraction and transport of stable and reliable high brightness electron beams

- 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*

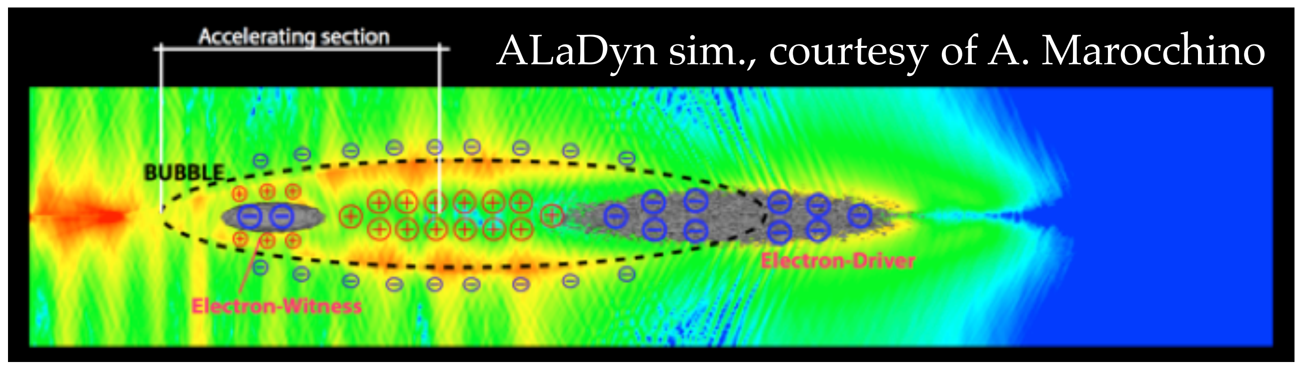
➡ Plasma-based user facility

- H2020 EuPRAXIA Design Study => P. A. Walker, TUPML044
- EuPRAXIA@SPARC_LAB => M. Diomede, THPMK058

enrica.chiadroni@lnf.infn.it

Towards a Plasma-based Facility

- **High quality** $\varepsilon_n \ll 1mm\ mrad, I_{peak} \sim kA, \frac{\Delta\gamma}{\gamma} \ll 1\%$
  - External injection of high brightness electron beams

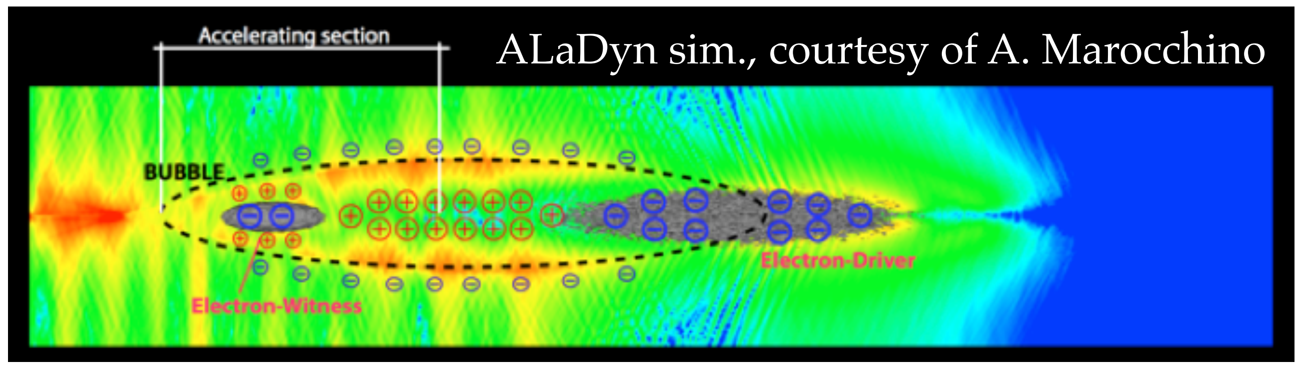


$\lambda_p(\mu m) \approx 3.3 \cdot 10^{10} n_p^{-1/2}(cm^{-3})$

$\boxed{\lambda_p \approx 330\mu m\ @\ n_p = 10^{16} cm^{-3}}$

Towards a Plasma-based Facility

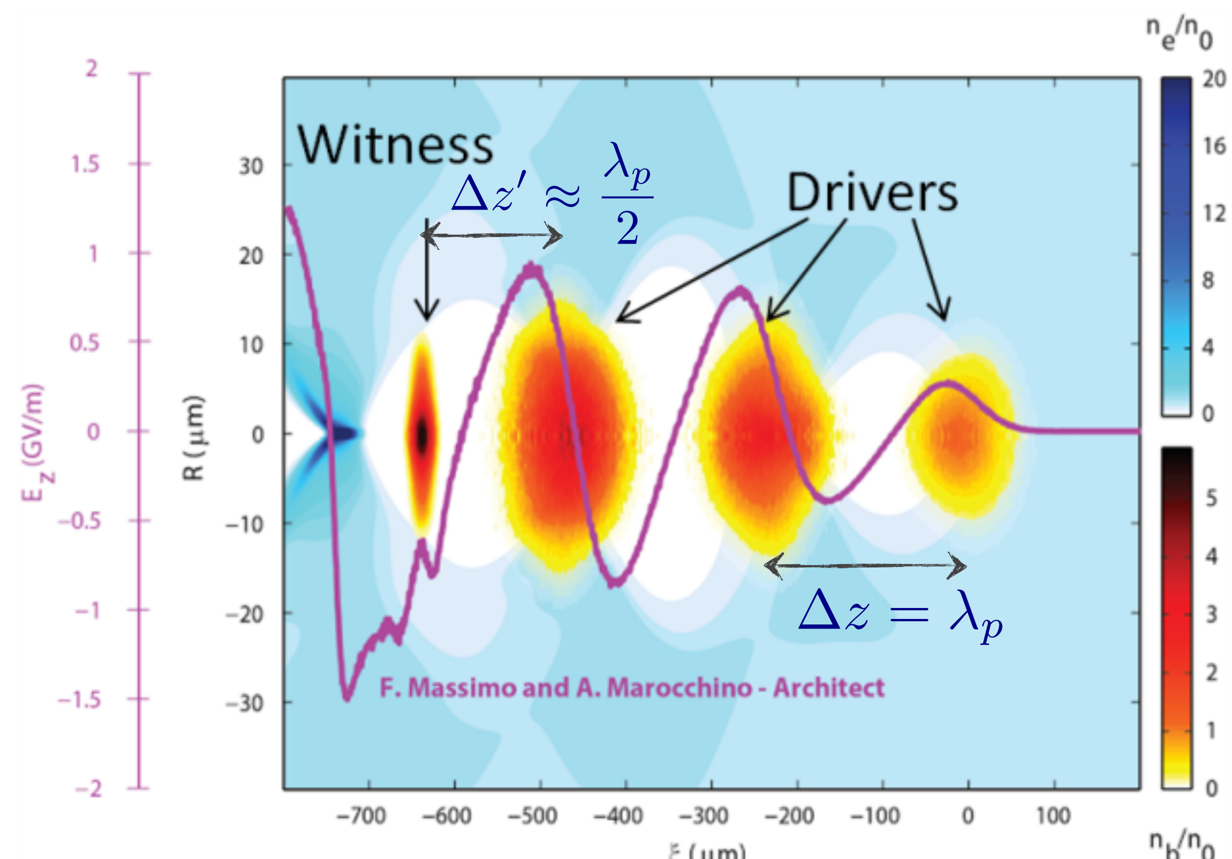
- **High quality** $\varepsilon_n \ll 1mm\ mrad, I_{peak} \sim kA, \frac{\Delta\gamma}{\gamma} \ll 1\%$
  - External injection of high brightness electron beams



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

$\boxed{\lambda_p \approx 330\mu m\ @\ n_p = 10^{16} cm^{-3}}$

- **High efficiency** $\boxed{\Delta\gamma \sim R\gamma_d}$
  - **Increase the transformer ratio** $\boxed{R = \frac{|E_{+,max}|}{|E_{-,max}|} > 2}$
    - Tailoring longitudinal current profile such that all longitudinal slices lose energy at the same rate
      - **Asymmetric drive bunch current profile,** i.e. triangular, double triangle, doorstep-like distributions, or **multiple ramped bunch trains,** overcome this limit

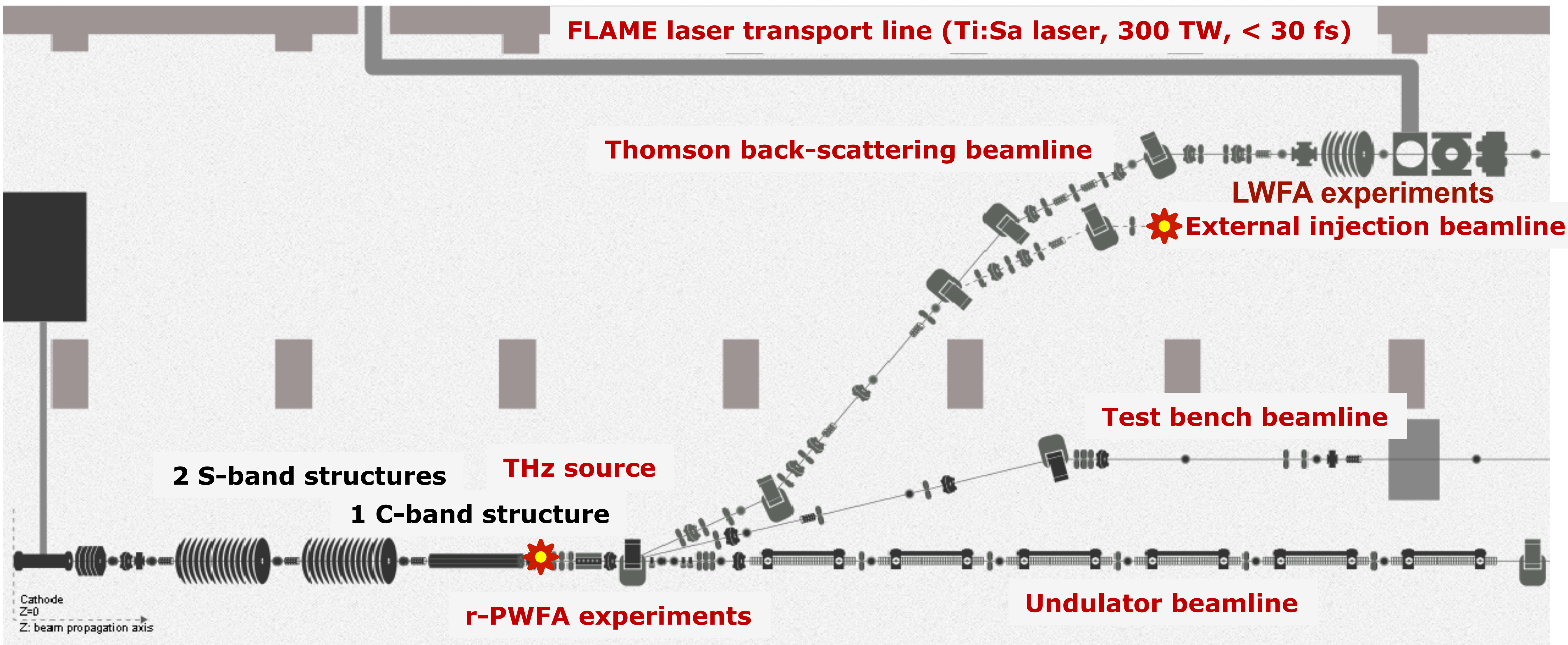


enrica.chiadroni@lnf.infn.it

The SPARC_LAB Test Facility

Sources for **P**lasma **A**ccelerators and **R**adiation **C**ompton with **L**asers **A**nd **B**eams

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



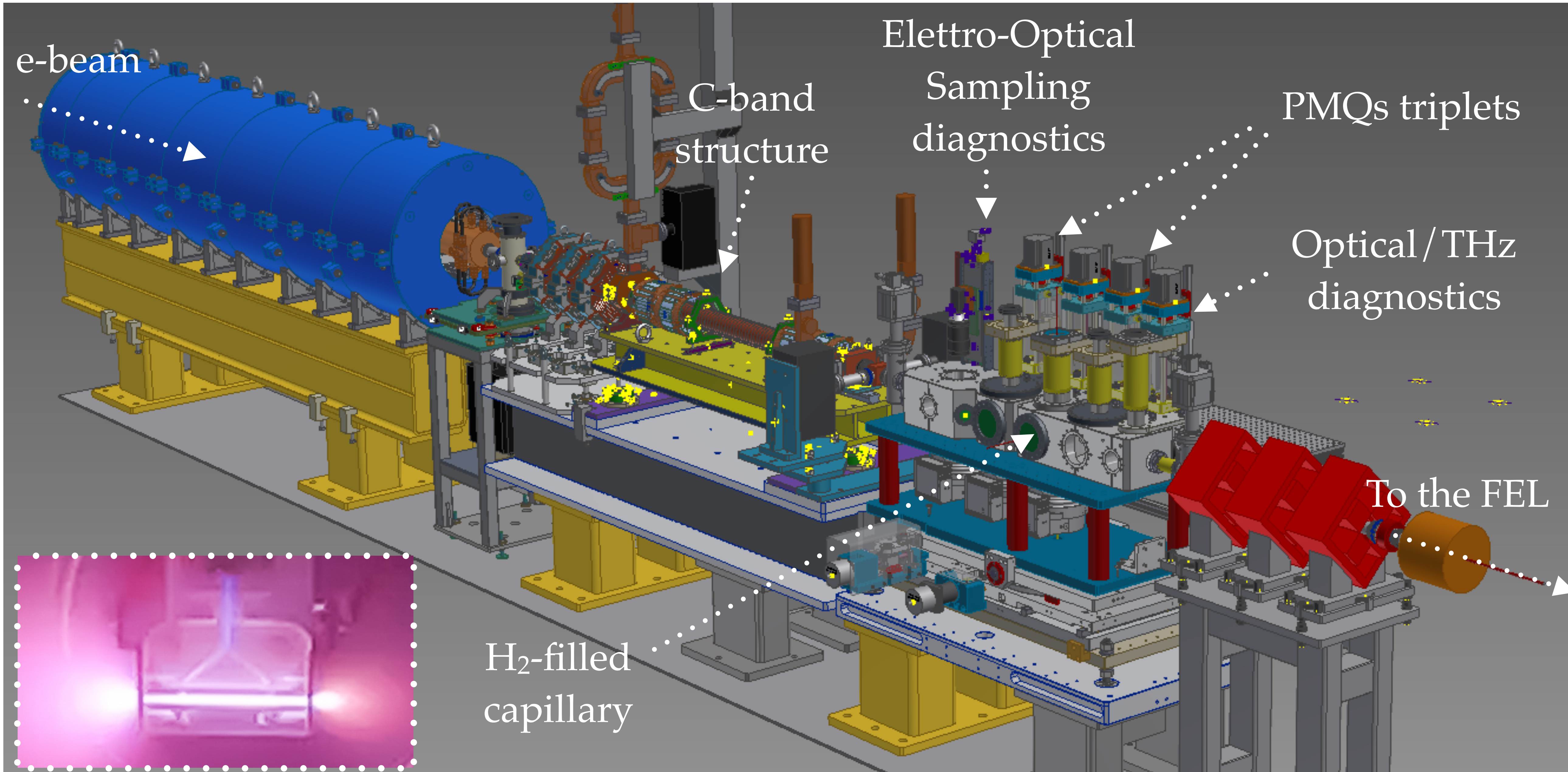
https://www.google.it/maps/@41.8231995,12.6743967,3a,69.7y,130.68h,76.68t/data=!3m6!1e1!3m4!1sYyB35yaBMxJgQ92-wp3oYQ!2e0!7i13312!8i6656?hl=en

enrica.chiadroni@lnf.infn.it

Plasma Interaction Chamber

H_2 generation and injection system

- Electrolytic generator (1 l of water → 1.4 m^3 Hydrogen)
- Pressure reduction system (300 mbar → 10 mbar in capillary)
- Electro-valve triggered by the HV discharge with tunable aperture (3 ms) and delay time (10 μs before discharge)

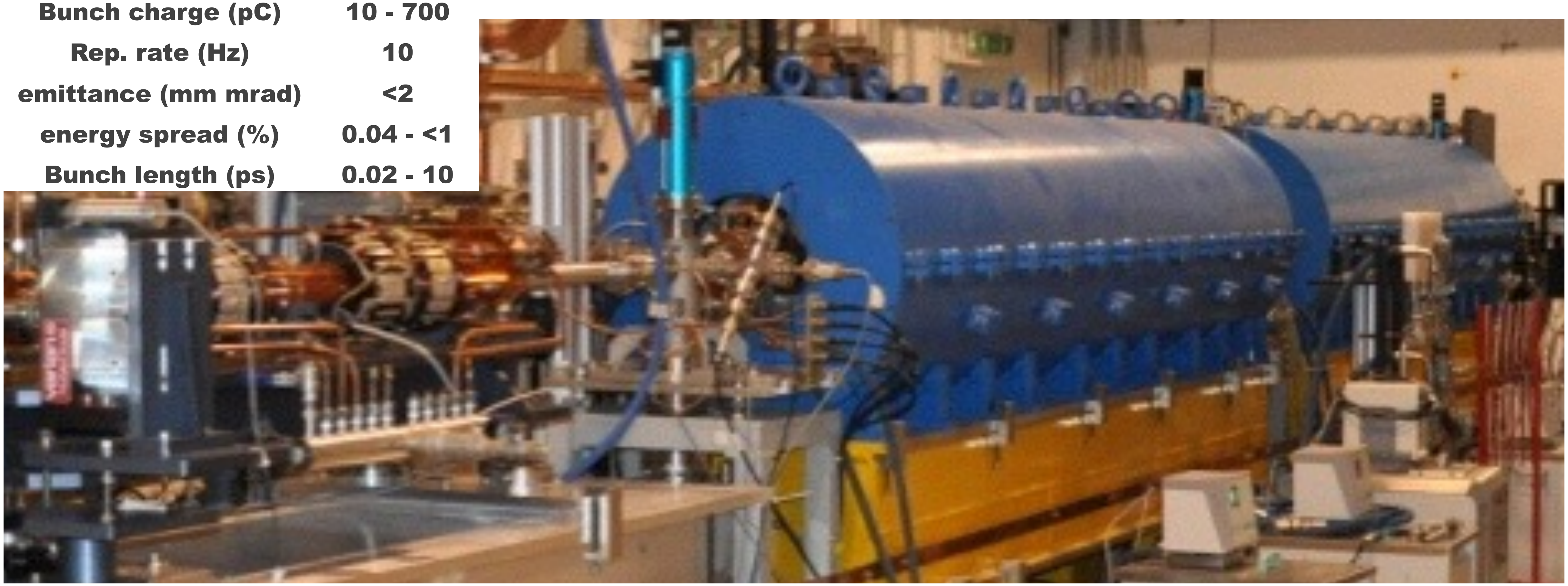


High Brightness Photo-Injector

High current operation (Velocity Bunching)
80 - 120 MeV beam energy
20 fs - 1 ps bunch duration

- **Broad-band THz radiation**
- **FEL (single spike + seeding)**
- **Laser comb**
  - **Narrow-band THz radiation**
  - **Two-color FEL**
  - **resonant PWFA**
- **LWFA (external injection**

Beam energy (MeV)	**30 - 170**
Bunch charge (pC)	**10 - 700**
Rep. rate (Hz)	**10**
emittance (mm mrad)	**<2**
energy spread (%)	**0.04 - <1**
Bunch length (ps)	**0.02 - 10**



- **L. Serafini and M. Ferrario**, 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.**, Phys. Rev. Lett. **104**, 054801 (2010)

enrica.chiadroni@lnf.infn.it

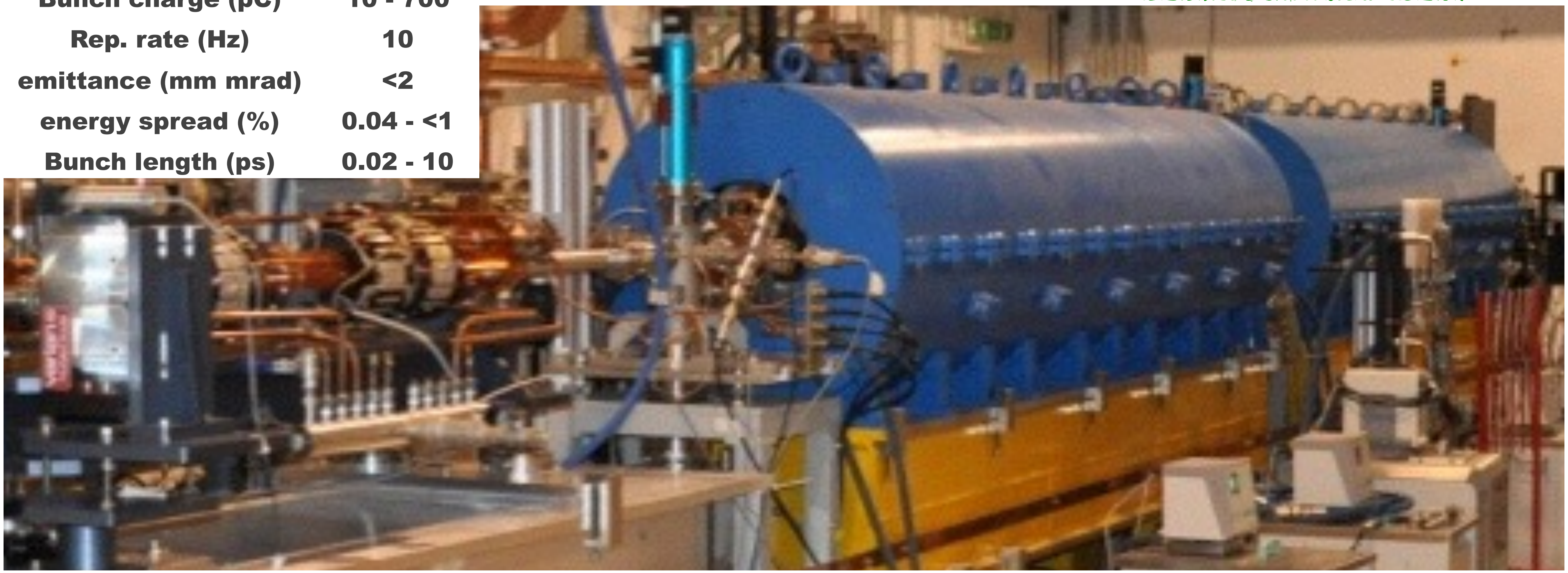
High Brightness Photo-Injector

High current operation (Velocity Bunching)
80 - 120 MeV beam energy
20 fs - 1 ps bunch duration

Broad-band THz radiation
FEL (single spike + seeding)
Laser comb
LWFA (external injection

Narrow-band THz radiation
Two-color FEL
resonant PWFA

Beam energy (MeV)	**30 - 170**
Bunch charge (pC)	**10 - 700**
Rep. rate (Hz)	**10**
emittance (mm mrad)	**<2**
energy spread (%)	**0.04 - <1**
Bunch length (ps)	**0.02 - 10**

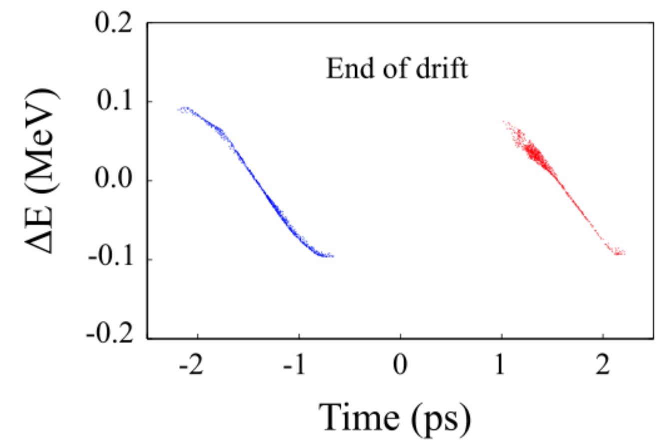


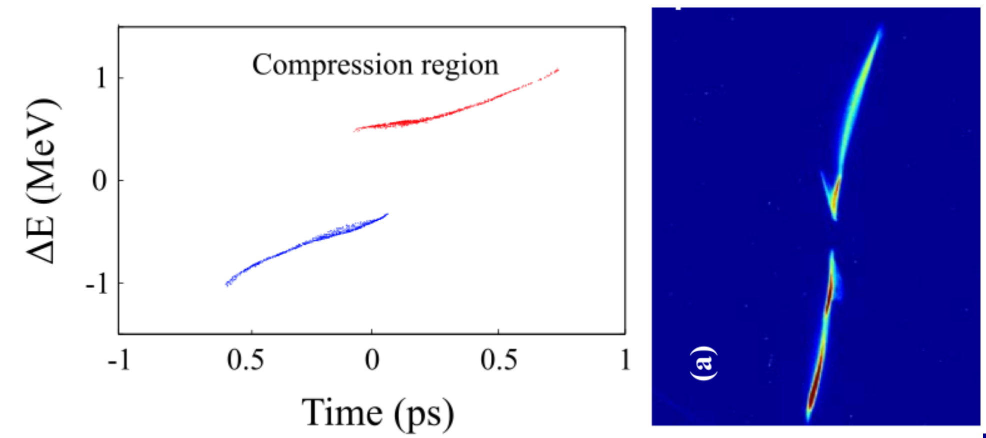
- **P. O. Shea et al.**, Proc. of 2001 IEEE PAC, Chicago, USA (2001) p.704.
- **M. Ferrario et al.**, Int. J. of Mod. Phys. B, 2006

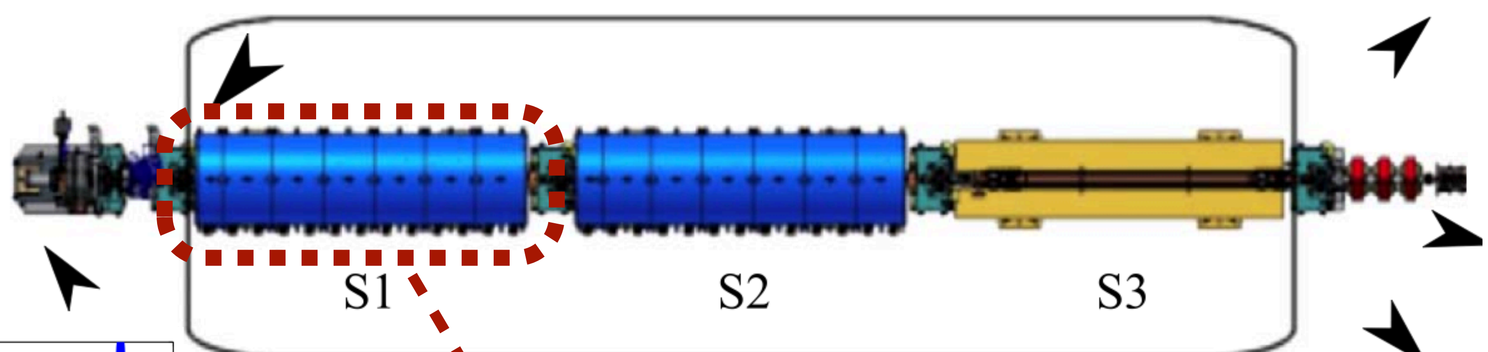
enrica.chiadroni@lnf.infn.it

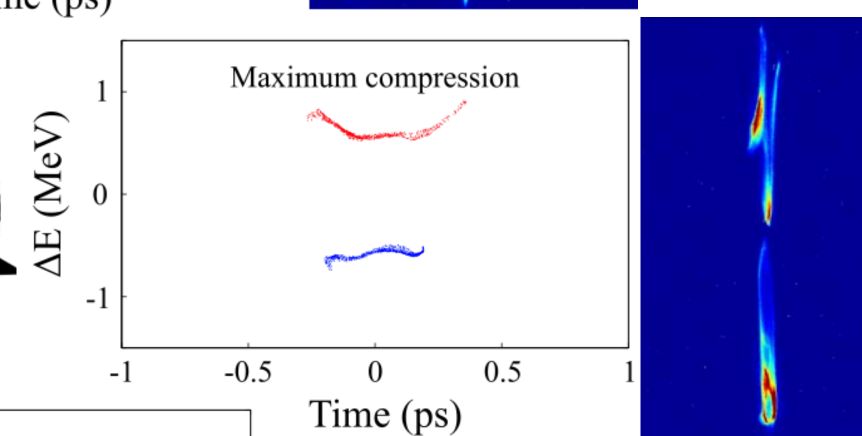
Generation of multi-bunch trains

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.

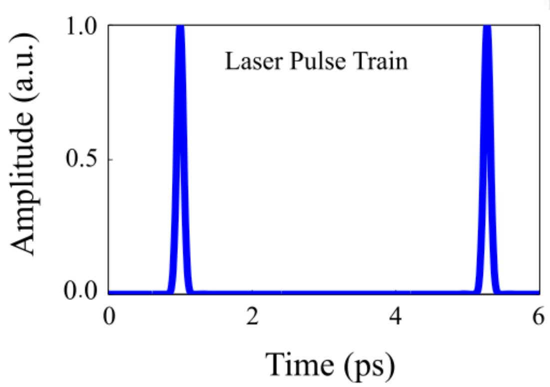




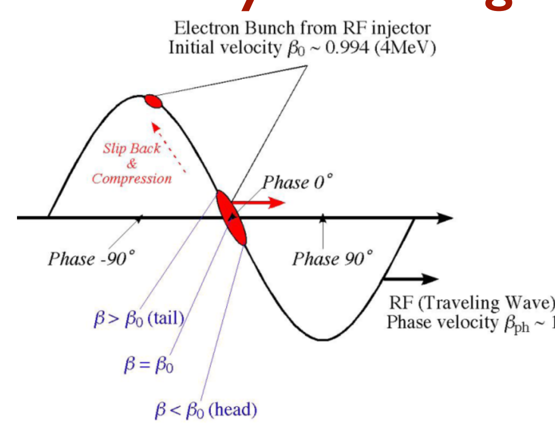


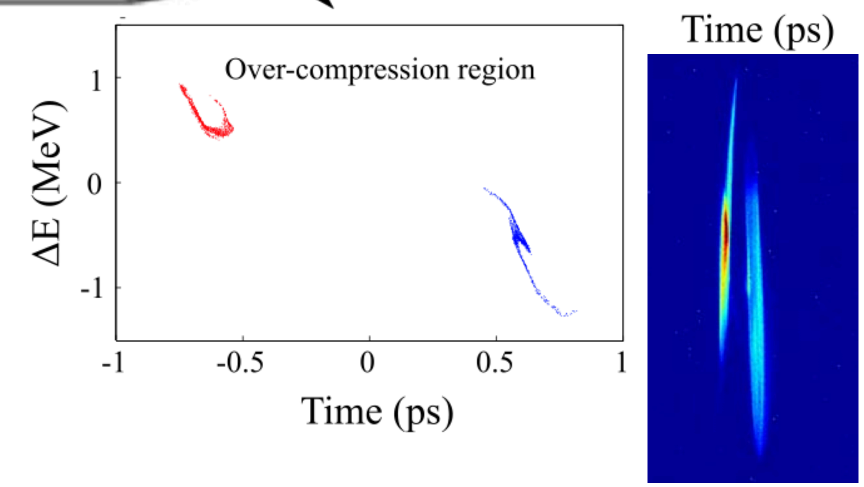


Comb-like laser



Velocity bunching

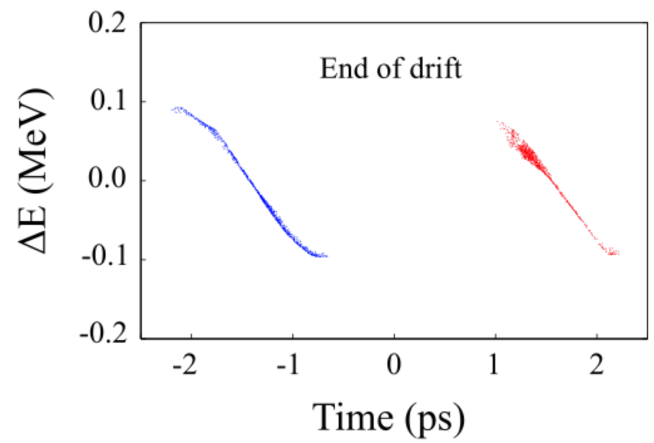


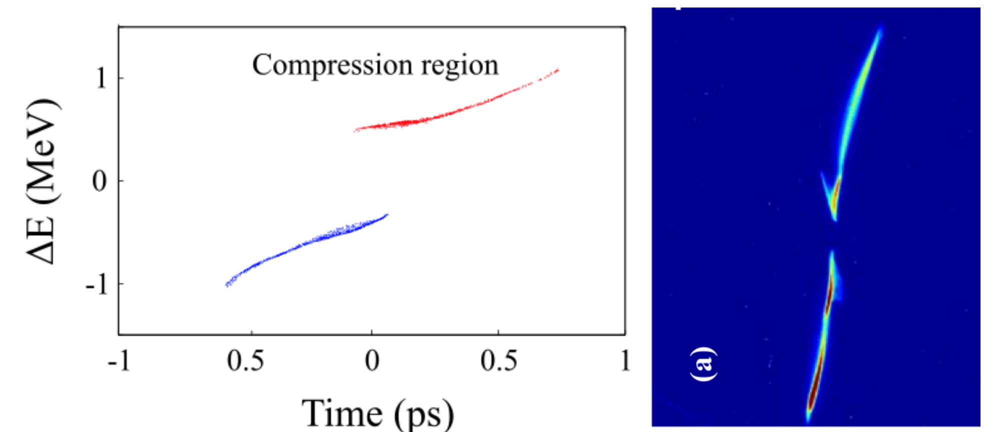


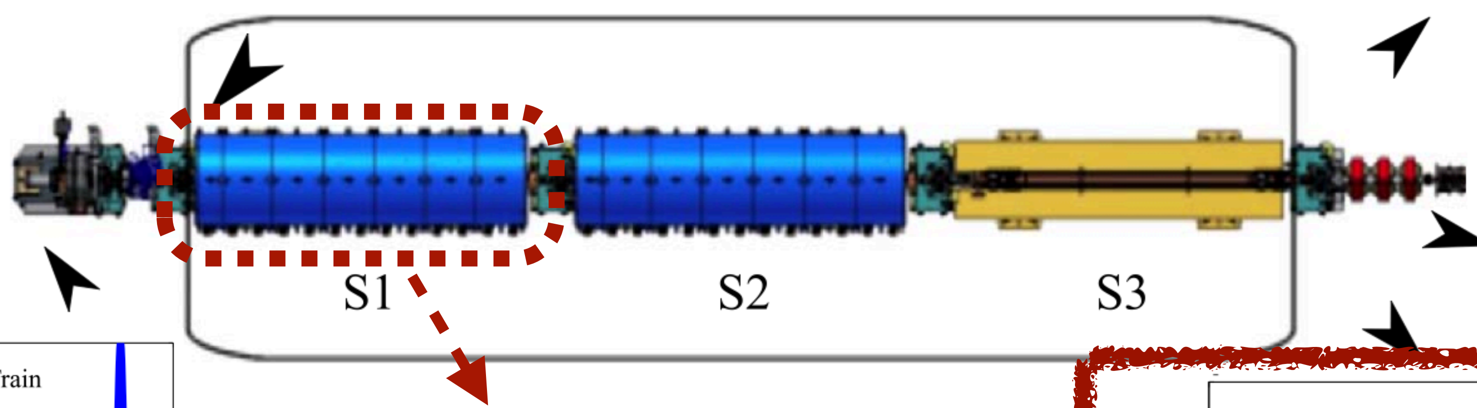
enrica.chiadroni@lnf.infn.it

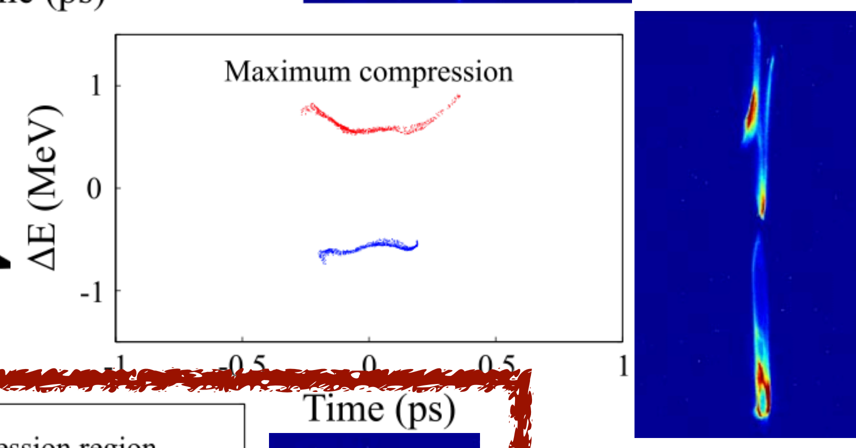
Generation of multi-bunch trains

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.

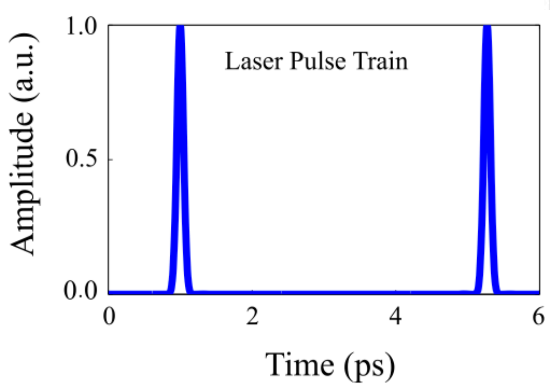




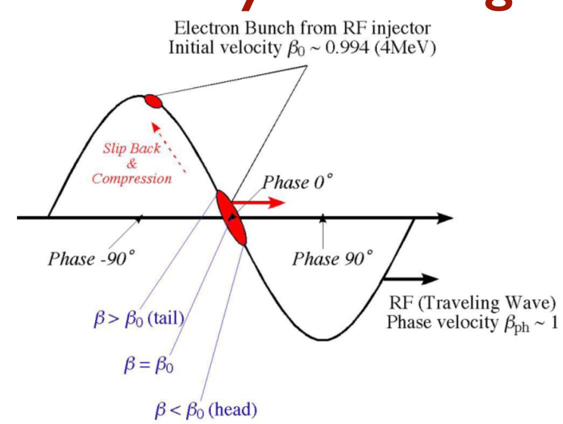


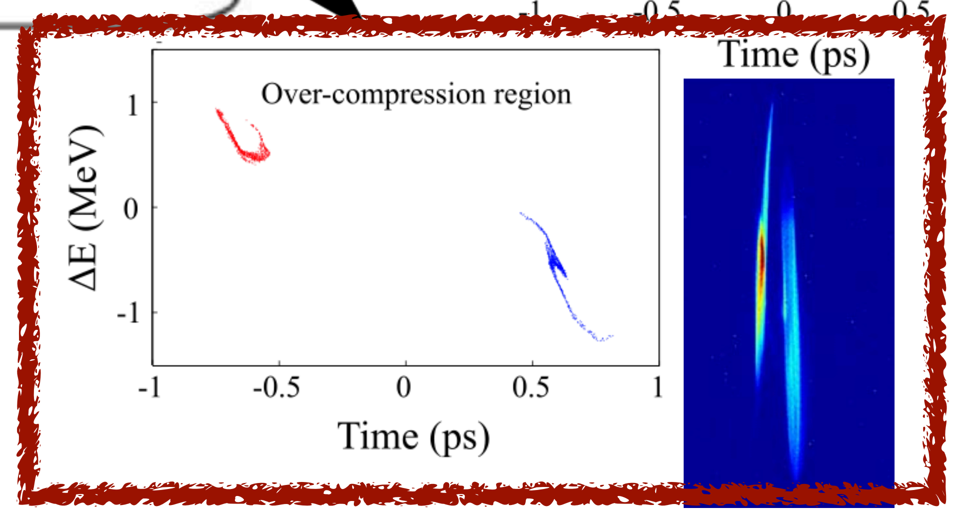


Comb-like laser



Velocity bunching

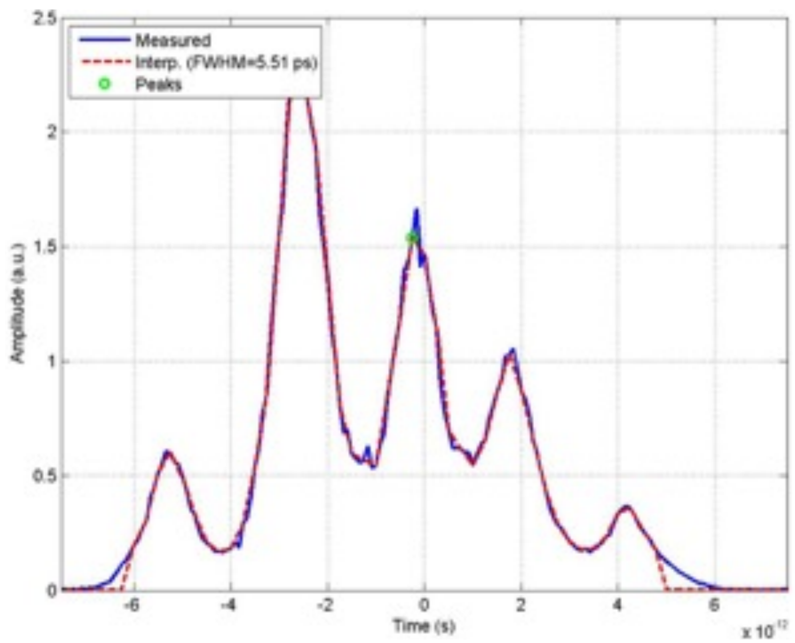


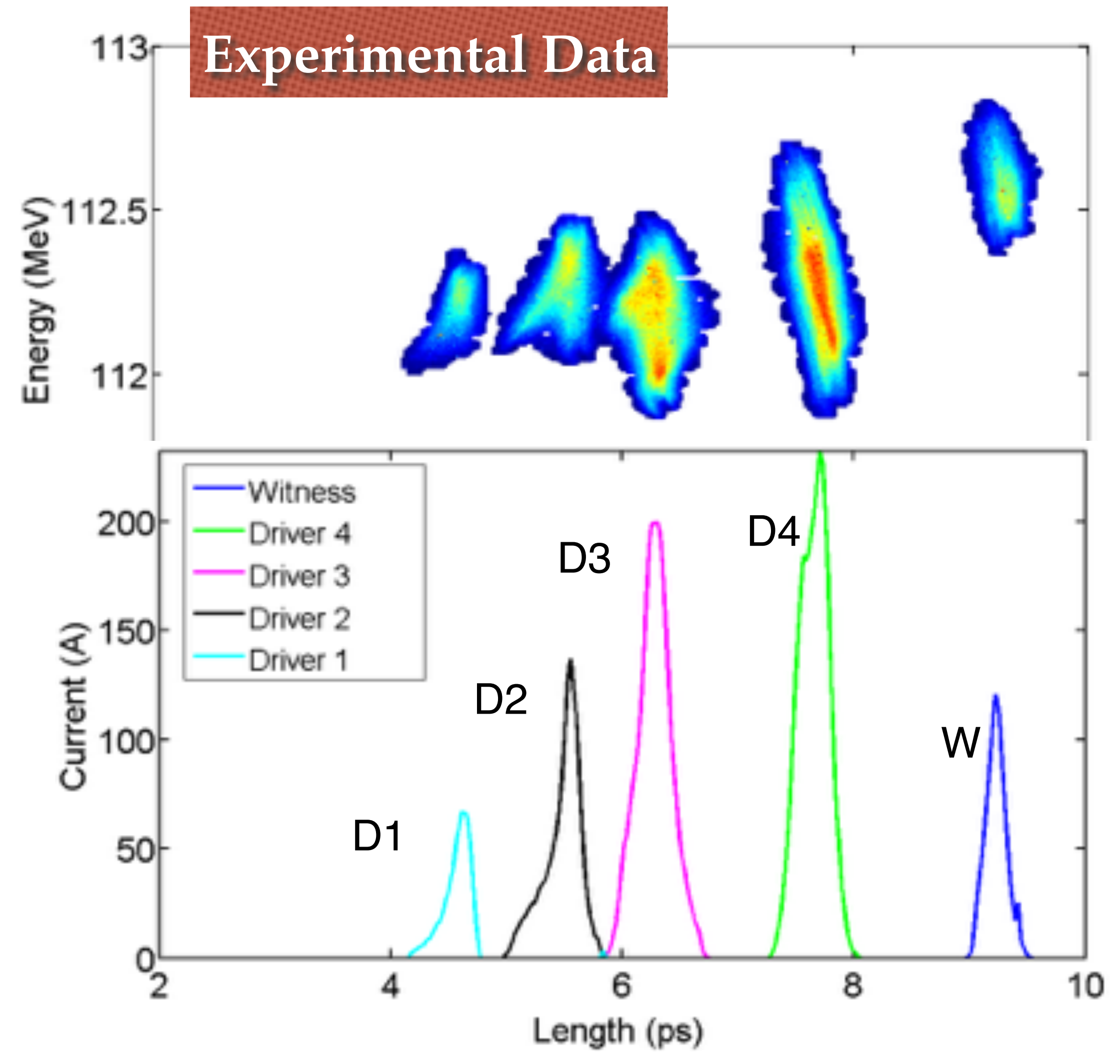


enrica.chiadroni@lnf.infn.it

Ramped Bunch Train

Laser profile on photo-cathode





	E (MeV)	$\Delta E/E$ (%)	σ_t (fs)	Q (pC)	ε_{nx} (mm mrad)
W	112.6	0.084	80	24	1(0.09)
D4	112.3	0.159	42	75	0.8(0.1)
D3	112.2	0.112	92	69	1.7(0.1)
D2	112.3	0.087	113	36	2.7(0.6)
D1	112.2	0.045	100	36	2.8(0.3)

Bunch Separation (μm)
W-D4 =470 (0.02) ~ $\frac{3}{2}\lambda_p$

D4-D3 =420 (0.03)
D3-D2 =240 (0.03)
D2-D1 =270 (0.05)
$\approx \lambda_p$

enrica.chiadroni@lnf.infn.it

Interaction with plasma

Hybrid kinetic-fluid simulation by Architect from measured drivers parameters

Beam parameters

- Q *witness* = 24 pC
- Q *drivers*(tot) ~ 200 pC
- E = 112 MeV
- ΔE/E = 0.1%
- ε_n ~ 1 mm mrad
- σ_t *drivers* < 100 fs
- σ_t *witness* ~80 fs

Weakly non-linear regime*

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

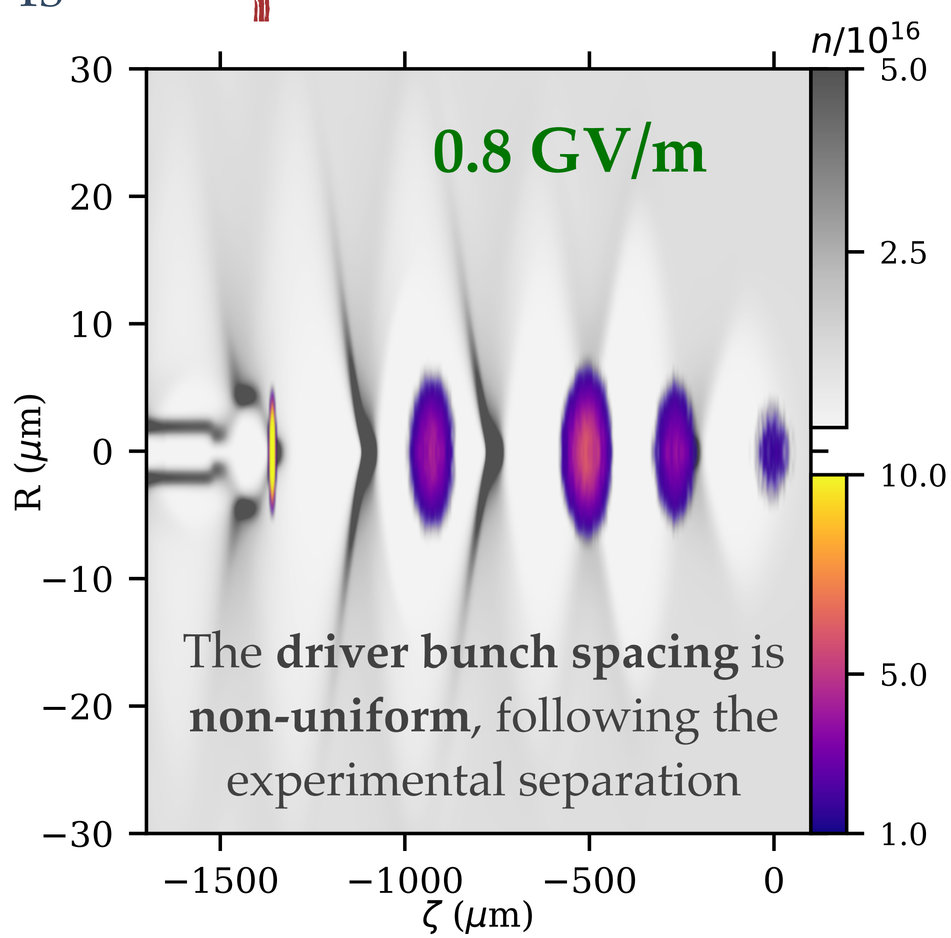
$\sigma_x = 2\ \mu\mathrm{m}$

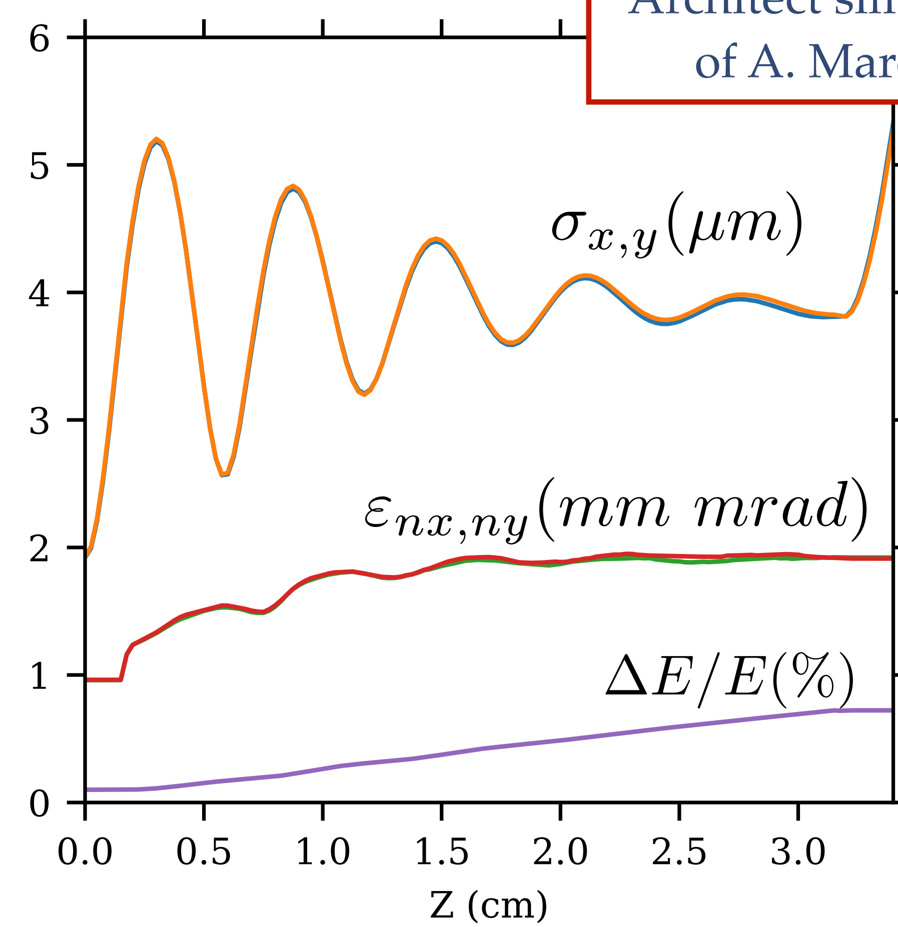
$$\alpha = \frac{n_b}{n_p} > 1$$

$$\tilde{Q} \equiv \frac{N_b k_p^3}{n_p} < 1$$

$n_b \sim 5 n_p$ and $\tilde{Q} \approx 0.8$

*J. B. Rosenzweig et al., in 14th AAC Workshop, AIP Conference Proceedings, 1299, pp. 500-504 (2010)
*P. Londrillo et al., NIM **740**, 236 (2014)





Architect sim., courtesy of A. Marocchino

enrica.chiadroni@lnf.infn.it

Plasma-based Focusing

Active Plasma Lenses

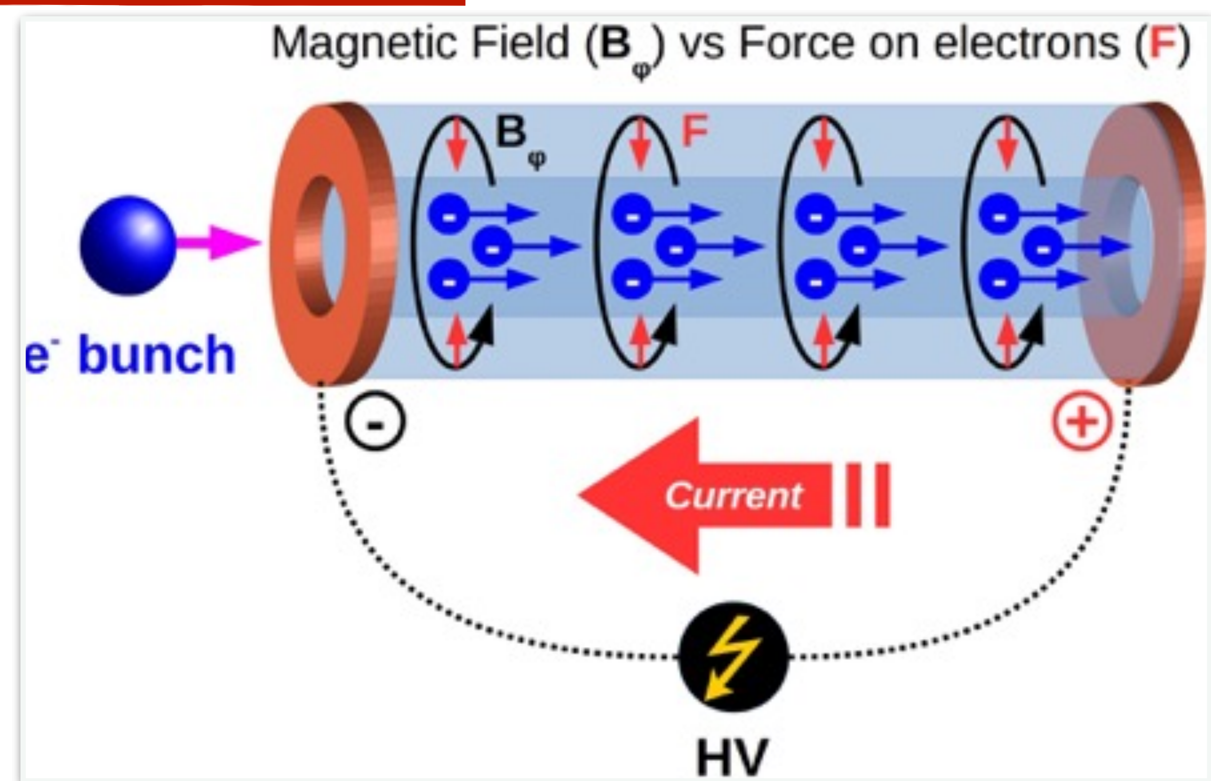
W.K.H. Panofsky and W.R. Baker, Rev. Sci. Instr. 21, 445 (1950)

- **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

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

Advantages

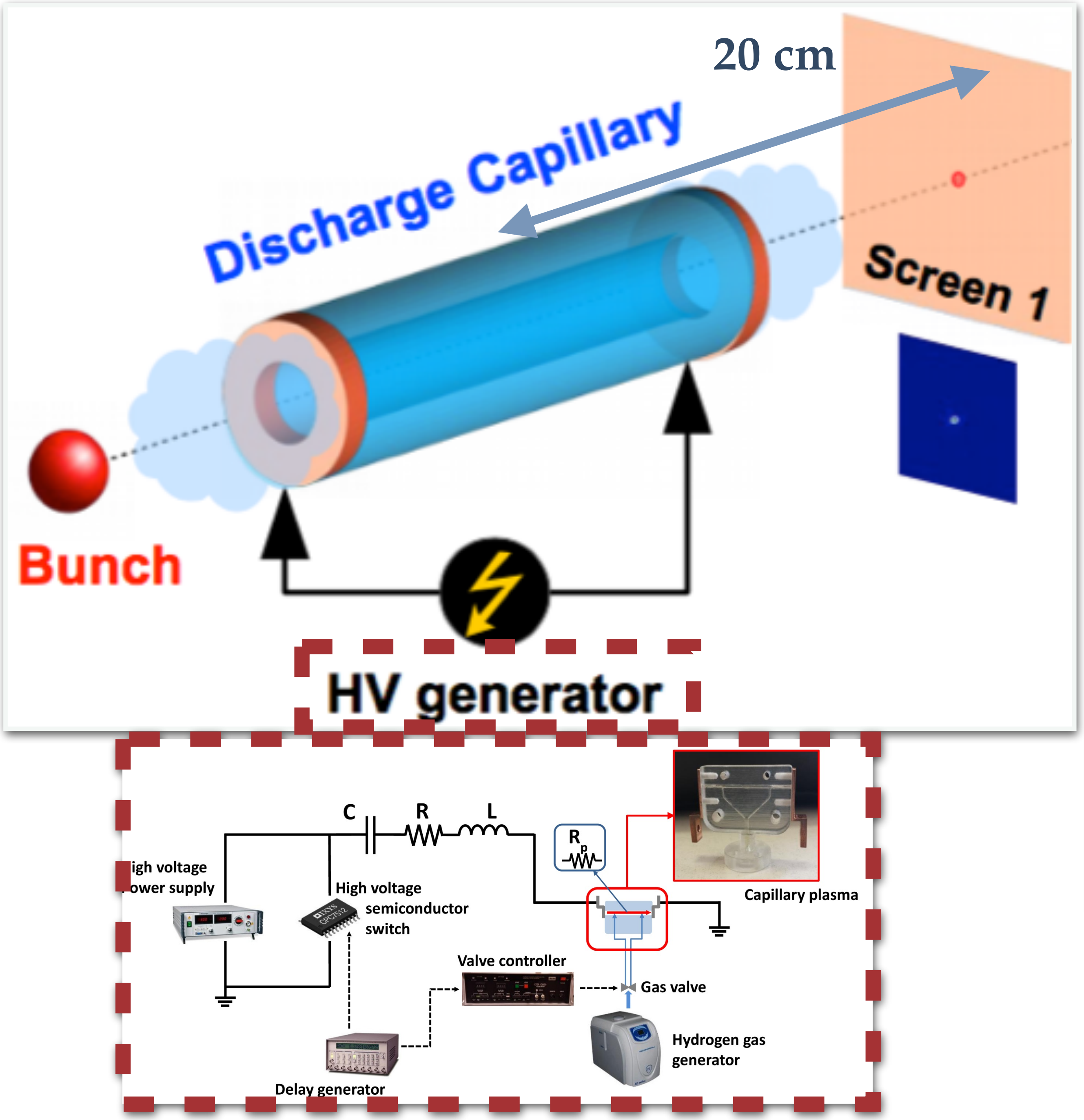
- Cylindrical symmetry
  - **purely radial focusing effect**
- **Tunability**
- Focusing strength $k \propto \dfrac{1}{\gamma}$
- High focusing gradient ~ **kT/m**
  - short focal length
    - **weak chromaticity**

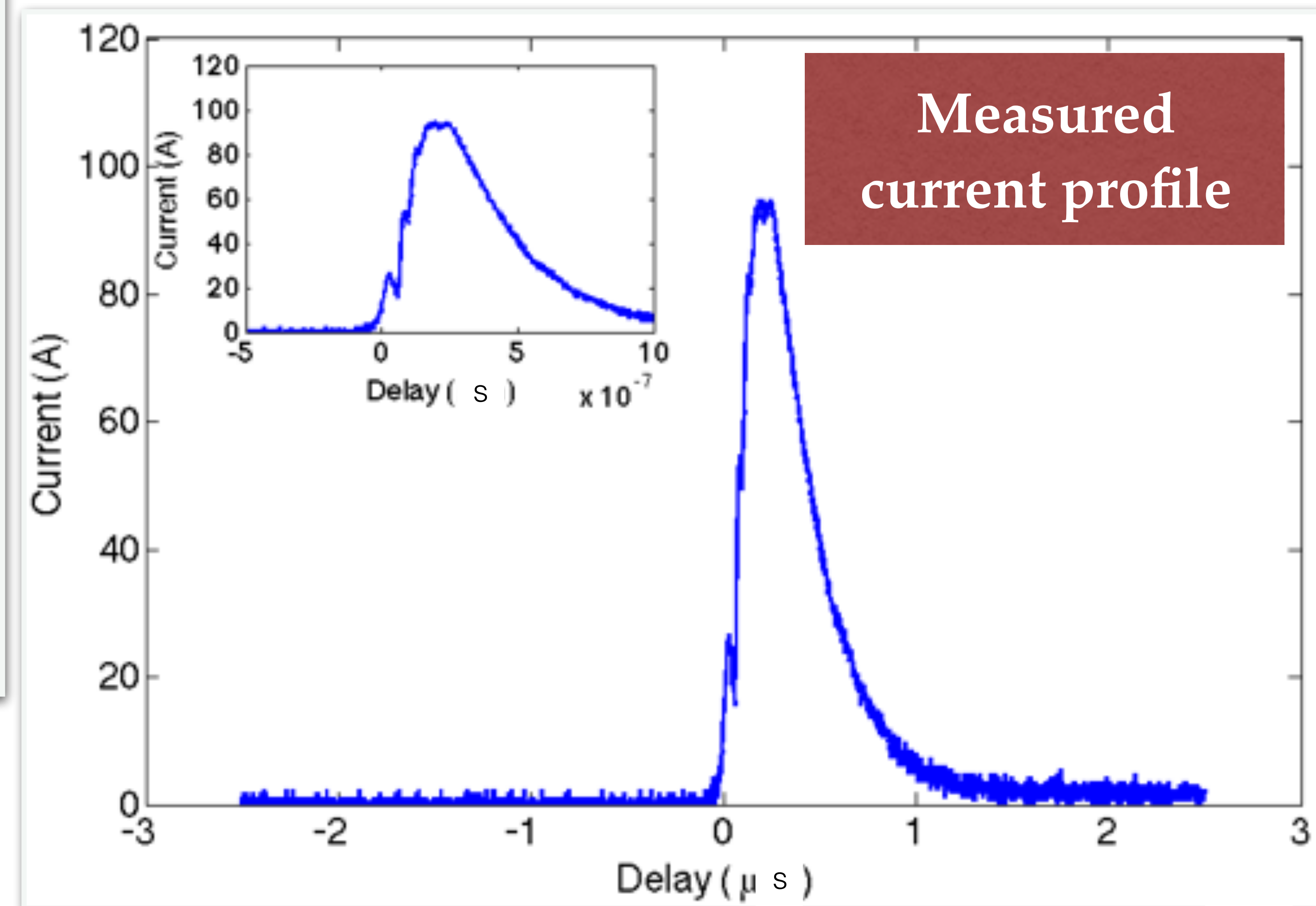


J. Van Tilborg et al., Phys. Rev. Lett. **115**, 184802 (2015)
R. Pompili et al., Appl. Phys. Lett. **110**, 104101 (2017)
J.-H. Röckemann et al., arXiv: 1803.06663v1

enrica.chiadroni@lnf.infn.it

Active Plasma Lens Experiments





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

enrica.chiadroni@lnf.infn.it

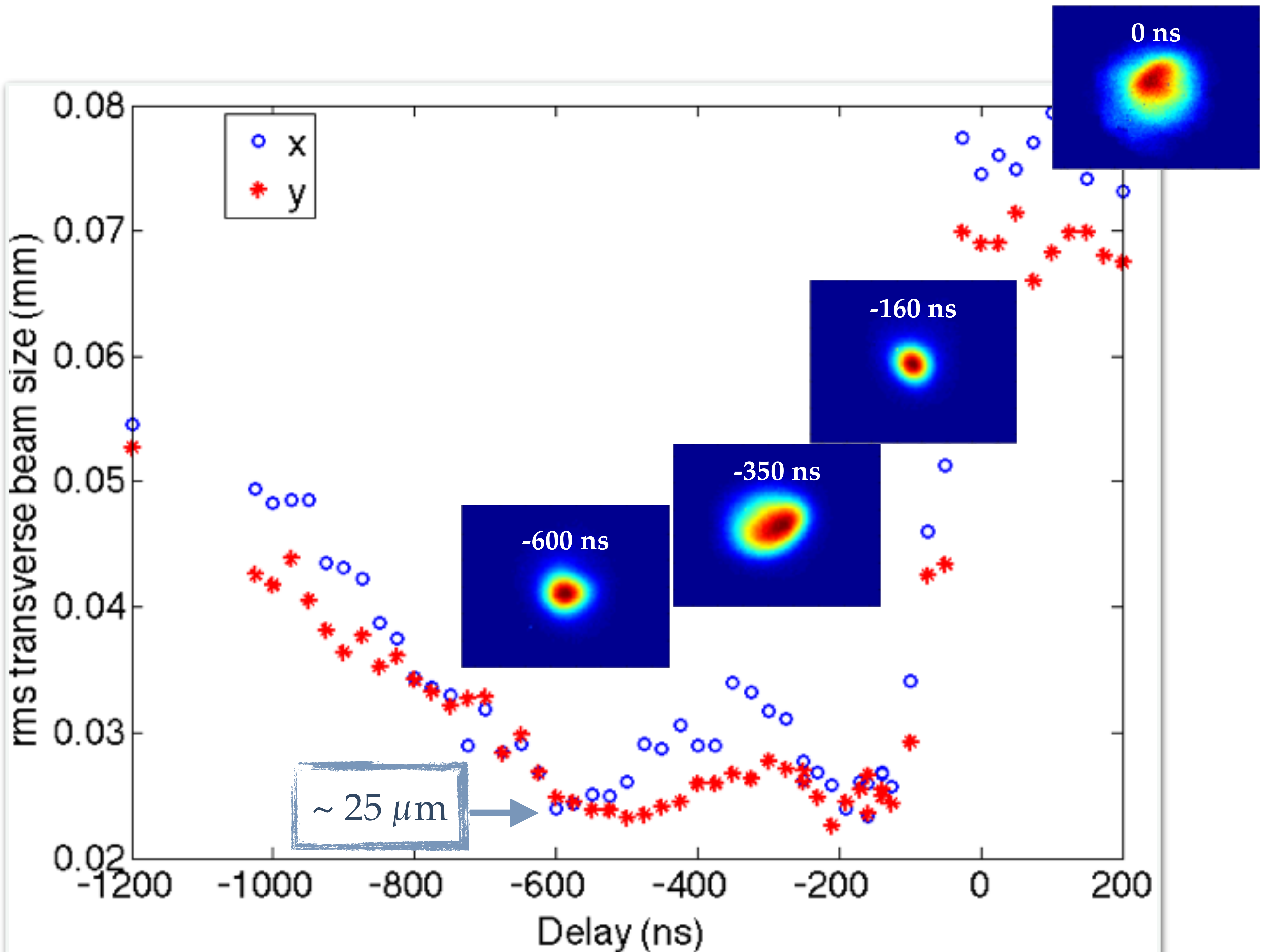
Active Plasma Lens Experiments

Beam parameters at the plasma entrance

Q (pC)	50 (5)
E (MeV)	126.5 (0.04)
$\Delta E/E$ (%)	0.06
ε_{nx} (mm mrad)	0.9 (0.1)
ε_{ny} (mm mrad)	1.15 (0.05)
σ_z (μm)	303 (6)
σ_x (μm)	79 (2)
σ_y (μm)	70 (2)

Plasma discharge parameters

$n_e \sim 10^{17}$ cm^{-3}
V = 14 kV
I_{peak} = 170 A
R_0 = 500 μm
L = 1 cm
fully 3D printed
plastic capillary



enrica.chiadroni@lnf.infn.it

Active Plasma Lens Experiments

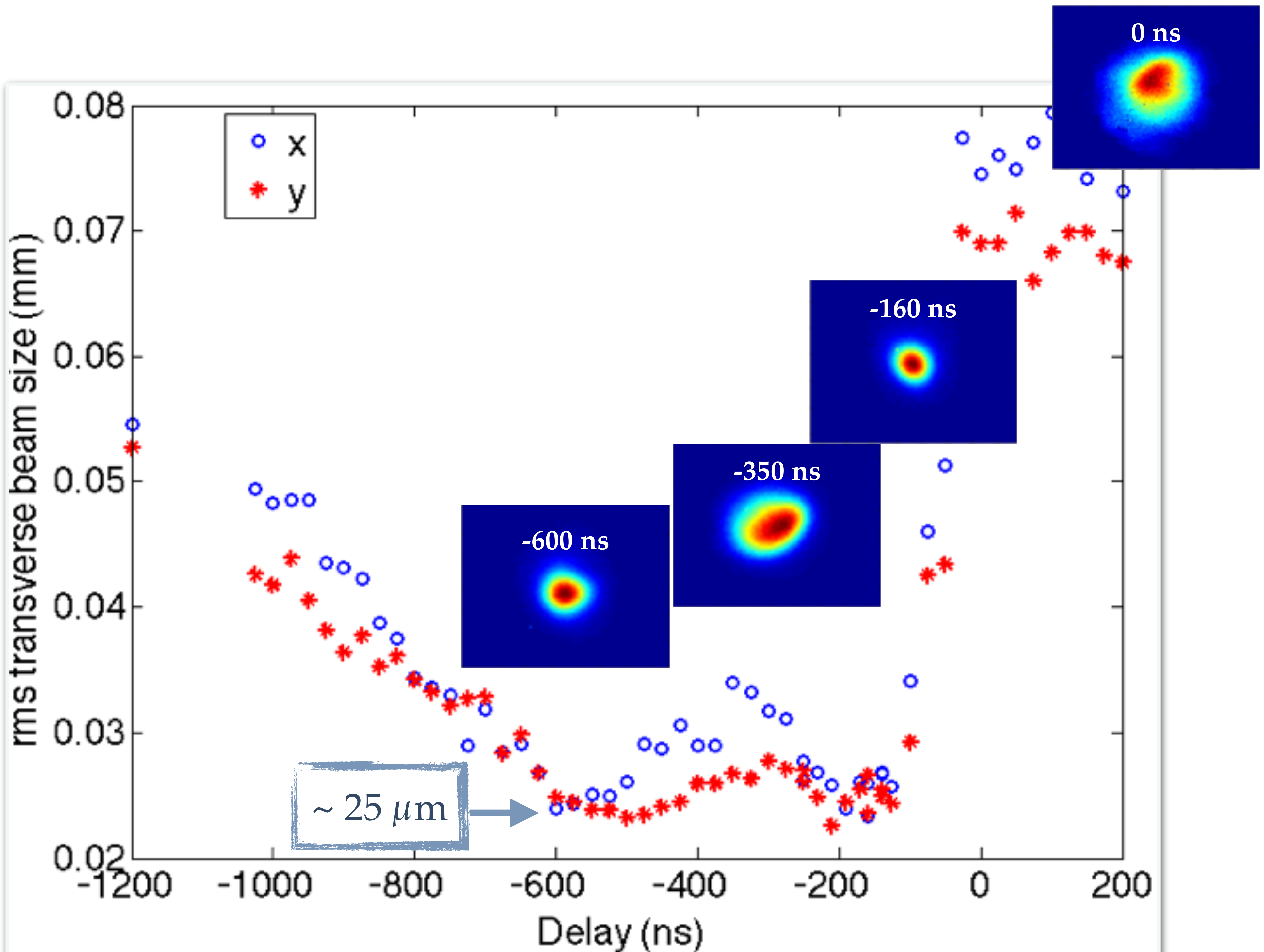
SPARC LAB

Beam parameters at the plasma entrance

Q (pC)	50 (5)
E (MeV)	126.5 (0.04)
$\Delta E/E$ (%)	0.06
ε_{nx} (mm mrad)	0.9 (0.1)
ε_{ny} (mm mrad)	1.15 (0.05)
σ_z (μm)	303 (6)
σ_x (μm)	79 (2)
σ_y (μm)	70 (2)

Plasma discharge parameters

$n_e \sim 10^{17}$ cm^{-3}
V = 14 kV
I_{peak} = 170 A
R_0 = 500 μm
L = 1 cm
fully 3D printed
plastic capillary

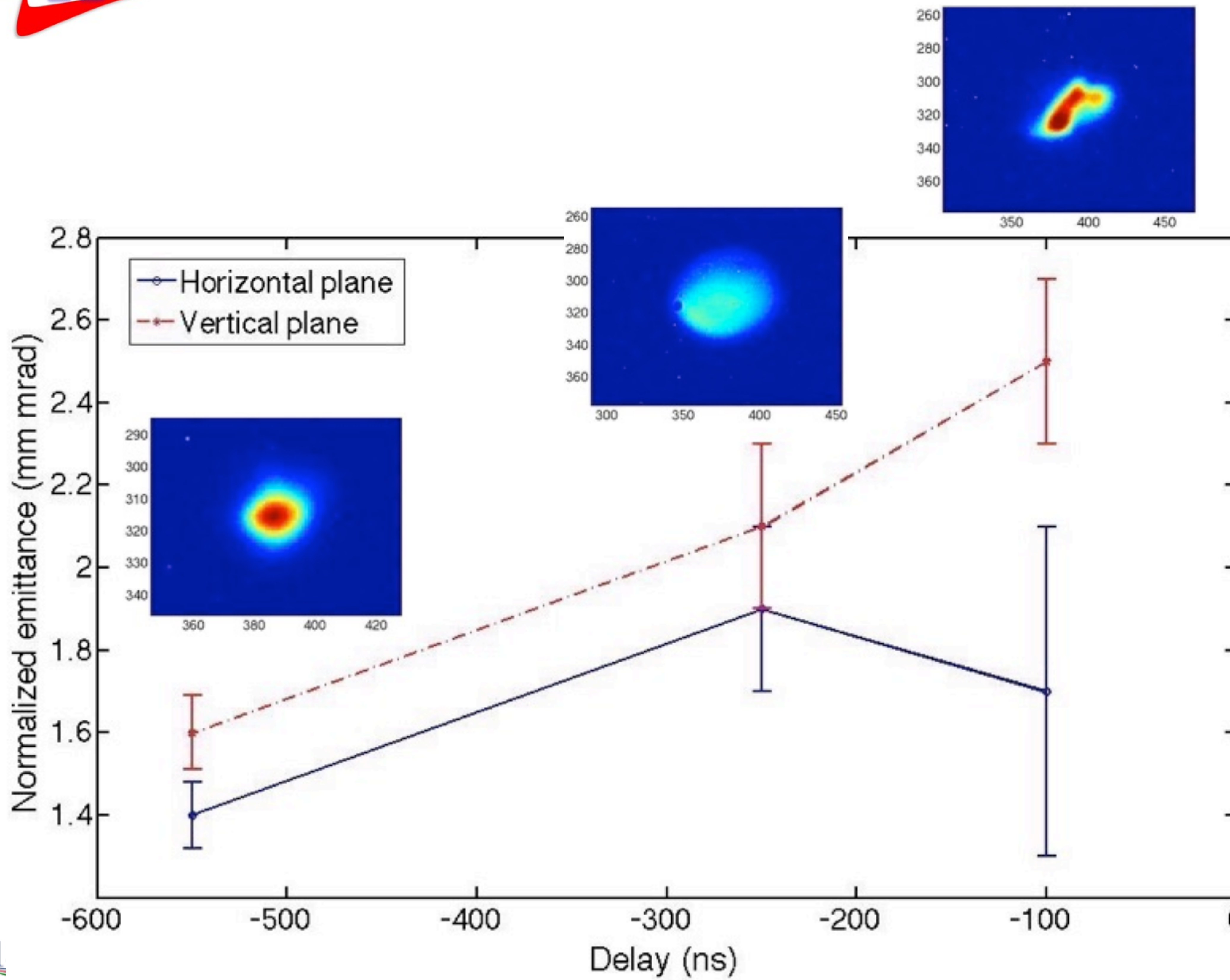


IPAC18

INFN LNF

enrica.chiadroni@lnf.infn.it

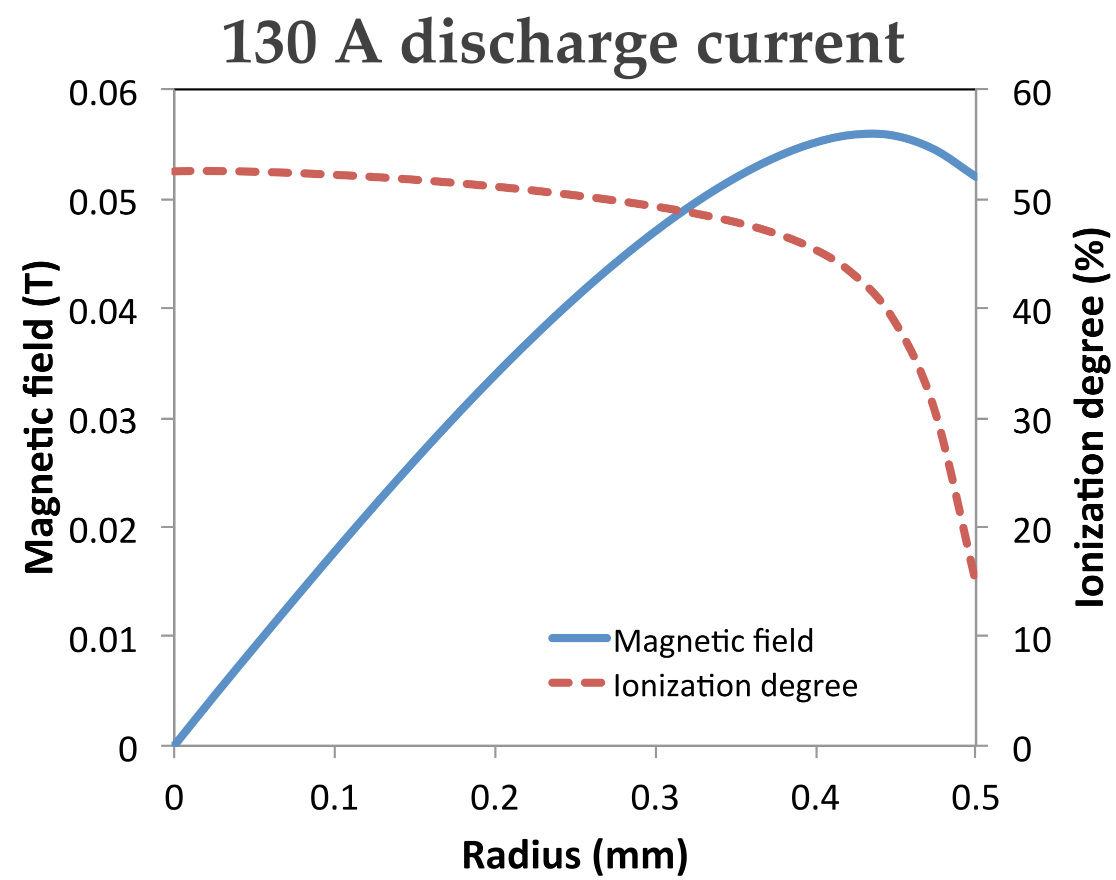
Control of emittance growth



enrica.chiadroni@lnf.infn.it

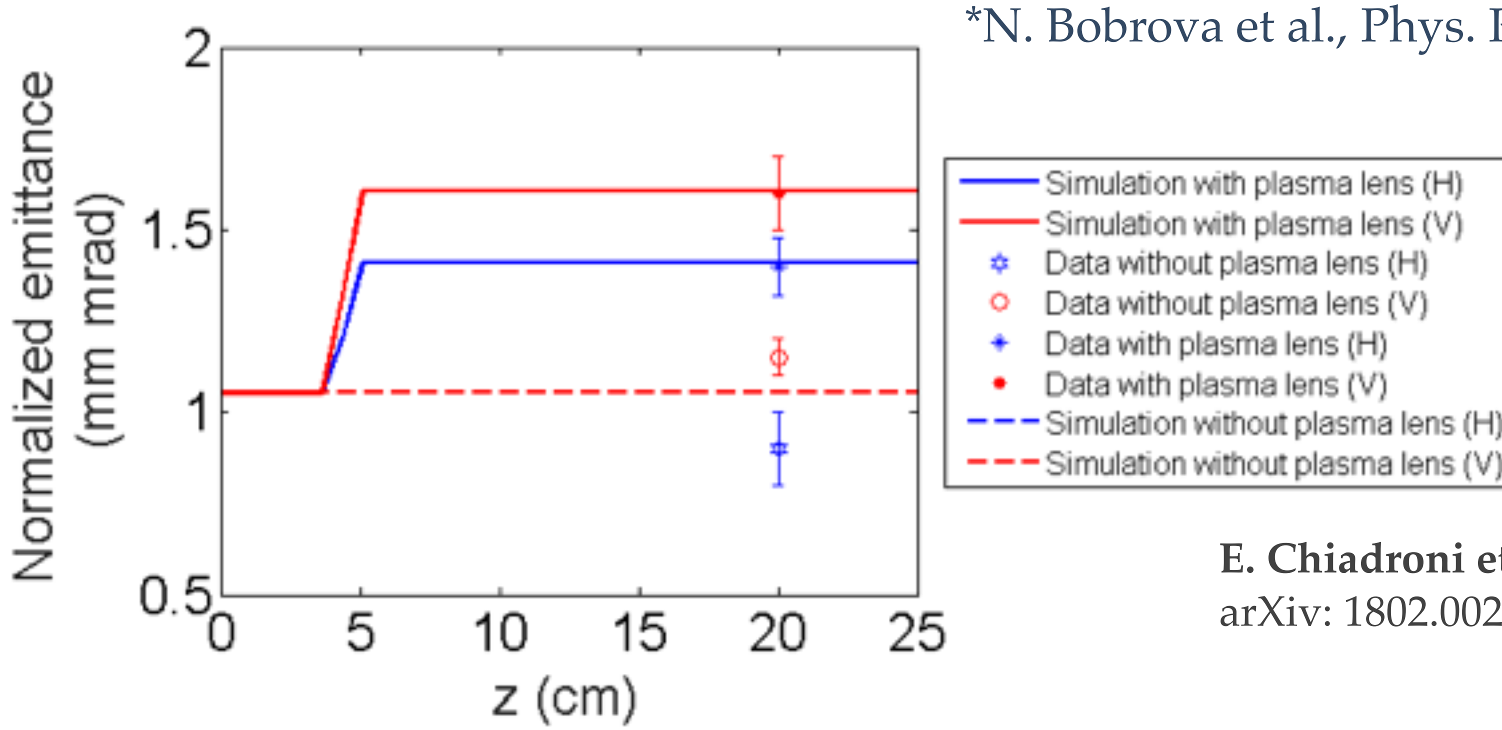
Effects of partial ionization

- **1D analytical model***: the distribution of plasma inside the capillary is at the equilibrium stage as soon as the discharge is initiated
  - **Equilibrium stage**: balance between Ohmic heating and cooling due to the electron heat conduction
- Even with a 1 cm long capillary and 170 A peak current, a **partial ionization of the gas** occurs
  - **non-linear magnetic field**, since the current is forced closer to the axes



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

GPT simulations, courtesy of R. Pompili



E. Chiadroni et al.,
arXiv: 1802.00279

enrica.chiadroni@lnf.infn.it

Conclusions

- ✓ Plasma-based ***acceleration provides*** ultra-high gradients
  - Plasma-based ***facilities demand*** high brightness beams, i.e.

$$\varepsilon_n \ll 1mm\ mrad, I_{peak} \sim kA, \frac{\Delta\gamma}{\gamma} \ll 1\%$$

    - Many potential applications possible for excellence in Science, e.g. FEL

- ✓ **SPARC_LAB is becoming a test bench facility for plasma-based experiments**
  - **External injection schemes** are under investigation, being **promising for** preserving the **high brightness**
  - **Plasma lenses** are promising **for final focus and extraction** from plasma accelerating module due to the kT/m up to MT/m plasma fields
    - **Minimization of emittance growth** is mandatory for the proper integration into conventional *user* beam lines

enrica.chiadroni@lnf.infn.it

Conclusions

- ✓ Plasma-based ***acceleration provides*** ultra-high gradients
  - Plasma-based ***facilities demand*** high brightness beams, i.e.

$$\varepsilon_n \ll 1mm\ mrad, I_{peak} \sim kA, \frac{\Delta\gamma}{\gamma} \ll 1\%$$

    - Many potential applications possible for excellence in Science, e.g. FEL

- ✓ **SPARC_LAB is becoming a test bench facility for plasma-based experiments**
  - **External injection schemes** are under investigation, being **promising for** preserving the **high brightness**
  - **Plasma lenses** are promising **for final focus and extraction** from plasma accelerating module due to the kT/m up to MT/m plasma fields
    - **Minimization of emittance growth** is mandatory for the proper integration into conventional *user* beam lines

Drive a plasma-based user facility!

enrica.chiadroni@lnf.infn.it

Acknowledgements

- ***Thanks to my SPARC_LAB colleagues and, in particular, to***
  - M.P. Anania, M. Bellaveglia, A. Biagioni, D. Di Giovenale, M. Ferrario, F. Filippi, A. Giribono, V. Lollo, A. Marocchino, S. Pella, G. Di Pirro, R. Pompili, V. Shpakov, C. Vaccarezza, F. Villa (*INFN, Frascati*)
  - A. Cianchi (*INFN and Tor Vergata University of Rome*)
  - A. Mostacci (*Sapienza University of Rome, SBAI*)
  - A. Bacci, A.R. Rossi (*INFN, Milano*)
  - J. B. Rosenzweig (*UCLA*)
  - A. Zigler (*Hebrew University of Jerusalem*)

This work has been partially supported by the EU Commission in the Seventh Framework Program, Grant Agreement 312453-EuCARD-2, H2020 research and innovation program under grant agreement n. 653782 (EuPRAXIA), the Italian Minister of Research in the framework of FIRB – Fondo per gli Investimenti della Ricerca di Base, Project n. RBFR12NK5K and the Commissione Scientifica Nazionale V of the INFN as SL_COMB and SL_EXIN.

enrica.chiadroni@lnf.infn.it

Thank You for the attention!

enrica.chiadroni@lnf.infn.it