EuroNNAc and EuPRAXIA Workshop on a European Plasma Accelerator
June 29th - July 1st, CNR - Pisa
EUSPARC Meeting
July 12th, LNF - Frascati

WP5: Electron Beam Design and Optimization

INFN (enrica.chiadroni@lnf.infn.it),
CEA (antoine.chance@cea.fr),
UROM, DESY, ULIV, USTRATH, SOLEIL, UHH

INFN People

- **<u>Enrica Chiadroni</u>: WP5 Leader**
  - Accelerator physicist, expert in high brightness photo-injectors and electron beam diagnostics, both transverse and longitudinal
    - **Responsible for the machine operation at SPARC_LAB** (Laboratori Nazionali di Frascati, INFN)
  - **Principal Investigator** of the "FIRB 2012" grant, funded by the Italian Minister of Research, for the development of experiments to be performed at SPARC_LAB on the **acceleration of high brightness electron beams in a plasma-based accelerator**
- **INFN Team**: Massimo Ferrario (WP9), Enrica Chiadroni, Alberto Marocchino (WP5 and WP2)

CEA/IRFU People

- **<u>Antoine Chance</u>: WP5 co-Leader**
  - Accelerator physicist, expert in beam dynamics, storage rings and colliders (design)
  - Transfer line @200 MeV between both acceleration stages for CILEX WP2 leader (« arc design ») for EuroCirCol
  - Interests: beam dynamics and simulations for plasma acceleration of electrons
- **CEA/Irfu Team:** Olivier Delferrière, Claire Simon, Antoine Chance, Phi Nghiem (WP2), Alban Mosnier (WP2), Xiangkun Li (post-doc, WP2 & WP5) + PhD student (WP2,not yet selected)

WP5 Description

- In **external injection schemes**, the optimum performance of a plasma accelerator is set by the **quality of the injected electron beam**
- **High brightness bunches** have to be generated directly at the cathode and transported without losses and with minimum quality degradation down to the plasma entrance
  - **Mitigation of sources of emittance degradation**
    - Proper choice of the electron injector
    - Emittance compensation schemes to assure an optimized matching to the plasma
  - **Longitudinal compression techniques** to provide bunch lengths << plasma wavelength
- **Optimization of**
  - <u>witness bunch</u> parameters
    - at the *entrance of the plasma* accelerating structure
      - matching studies both for the LWFA and PWFA performances
    - at the *plasma exit* to fit user needs
  - <u>driver bunch</u> parameters
    - at the *entrance of the plasma* accelerating structure
      - matching tolerance studies for alternative electron beam driven plasma structures
- Design of **electron beam diagnostics** before and after the plasma channel, taking profit from both standard and novel techniques

- **Task 5.1**: Coordination and Communication (INFN, CEA)
- **Task 5.2**: Electron Beam for *external* injection (RF injector) (UROM, DESY, ULIV, USTRATH)
- **Task 5.3**: Electron Beam Manipulation (INFN, CEA,UROM, DESY, ULIV, USTRATH, SOLEIL)
- **Task 5.4**: Electron Beam Diagnostics and Practical Issue (INFN, CEA,UROM, DESY, ULIV, USTRATH, UHH)

Milestones and Deliverables

- **M 5.1**: Personell recruitment [M12]
  - ✓ INFN-LNF Post-doc assigned
    - Alberto Marocchino: 50% to WP5, 50% to WP9
  - ✓ CEA Post-doc assigned
    - Xiangkun Li: WP5 and WP2
- **M 5.2**: Preliminary RF accelerator specifications [M12]
  - Project report (WPs involved: 5,2,3,6,7,9,12,14)
    - *Charge, average and peak current, energy, both for laser and particle driven plasma acceleration* to drive the choice of the most suitable injector
- **M 5.3**: Specification of the transfer line from the RF injector to the plasma [M24]
  - Project report
- **M 5.4**: Definition of diagnostics before and after the plasma channel [M40]
  - Project report

- **D 5.1**: Design report photo injector recruitment [M30]
  - Definition of laser, photocathode, cavities, emittance compensation schemes and tools for the diagnostics of the required electron beam parameters for both laser and particle driven schemes
- **D 5.2**: Report on optimal beam handling [M42]
  - Beam matching to the plasma and transport beam lines to users
- **D 5.3**: Full design report EuPRAXIA, WP5 contribution [M48]
  - Section 12 of the Conceptual Design Report (CDR)

Task 5.2

- **Task 5.2**: Electron Beam for *external* injection (RF injector) (UROM, DESY, ULIV, USTRATH)
  - External RF Injector consists of laser, cathode, gun and first acceleration stage
    - Tolerance and reliability
    - **LWFA**
      - **Ultra-short** (fs scale) electron bunch
        - Define main parameters to drive injector choice
    - **PWFA**
      - **Multi-bunch train** (i.e. *comb*-like), *ramped charge bunches*
        - Define main parameters to drive injector choice

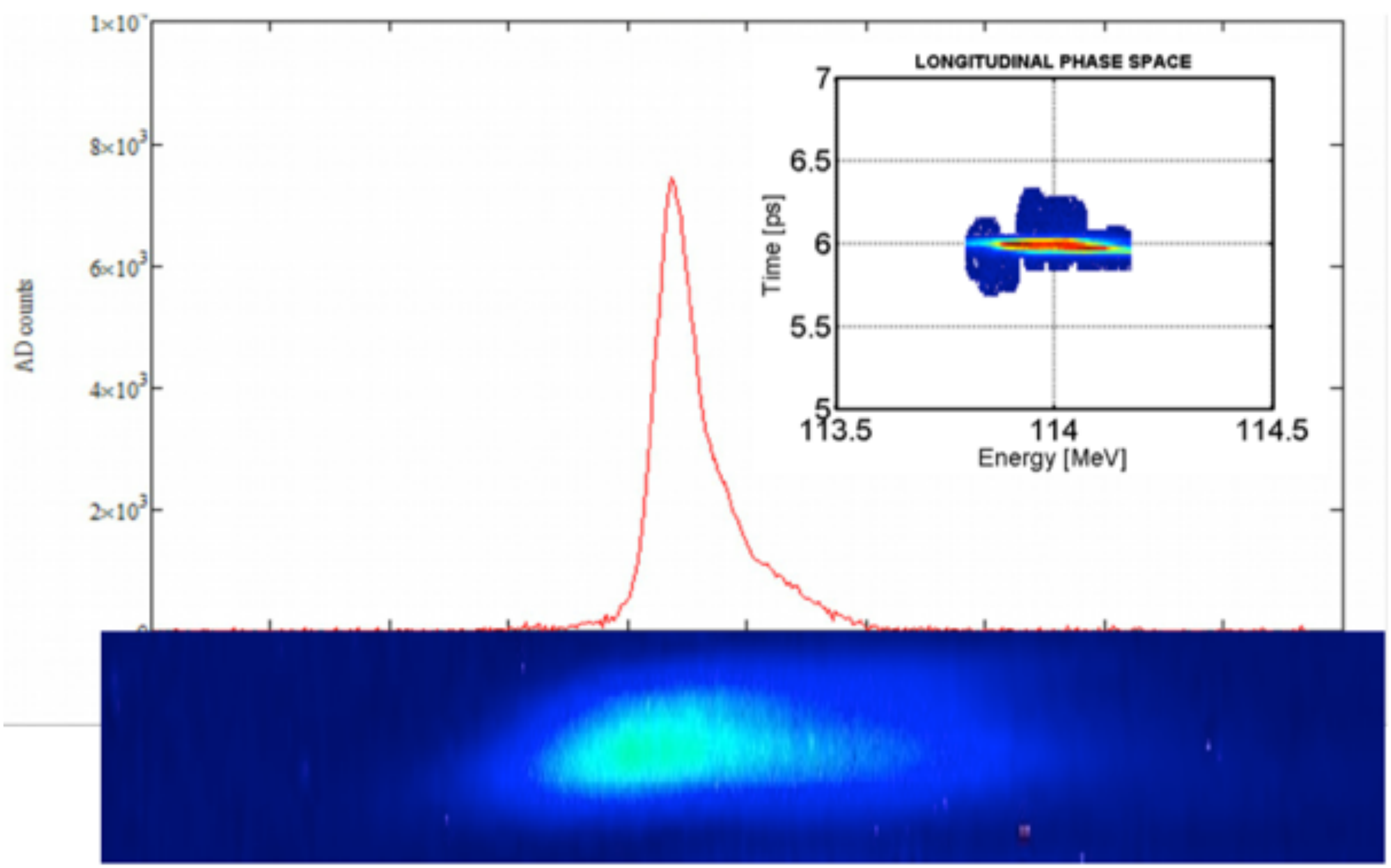
Task 5.2: SPARC LAB Experience

◉ **LWFA**

- **Ultra-short** (fs scale) electron bunch for single spike SASE FEL operation

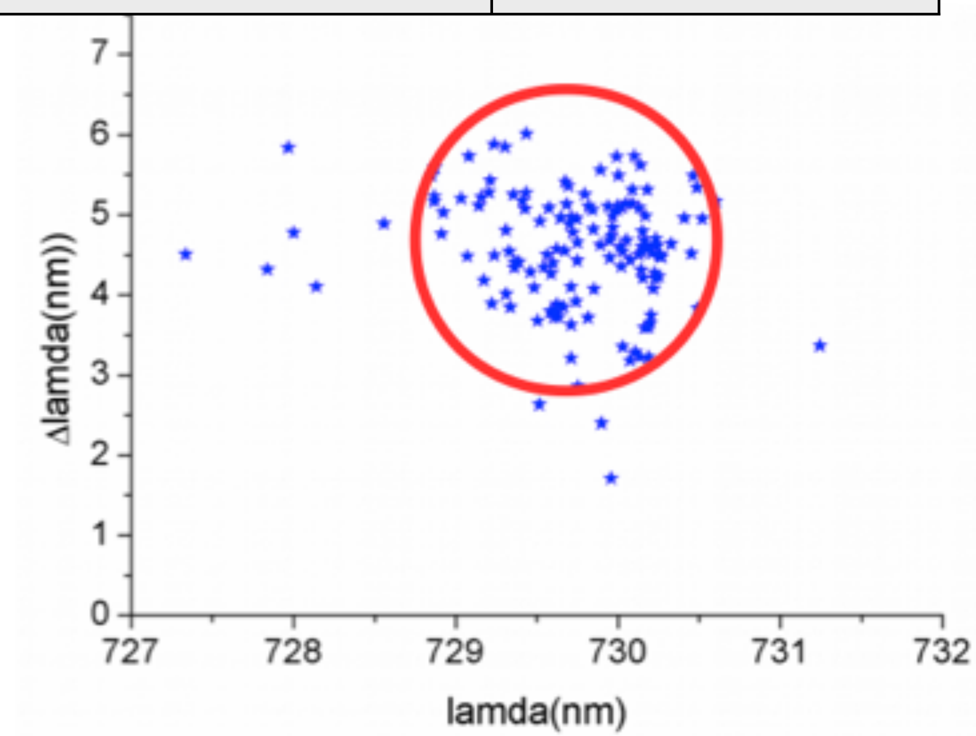
Charge (pC)	Energy (MeV)	Energy spread (%)	Duration (fs)	Emittance (mm mrad)	Peak current (A)
20	114	0.1	26	1.2	400

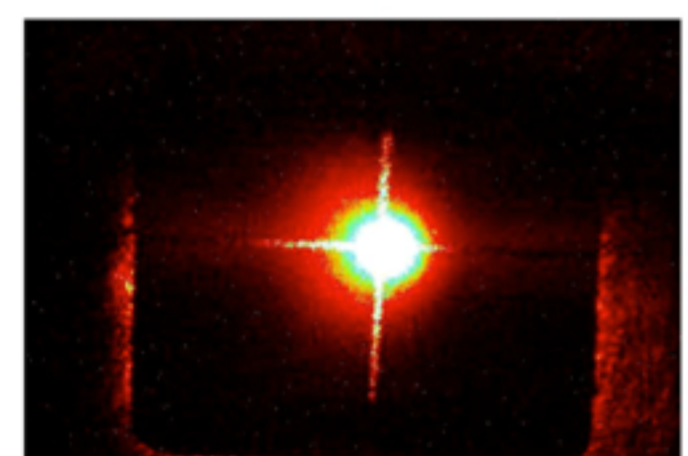
Single-spike FEL means high quality ultra-short beam!



Collected FEL light, 100 fs (rms), 40 μJ

F. Villa, V. Petrillo et al., submitted to Proc. of HBB 2016

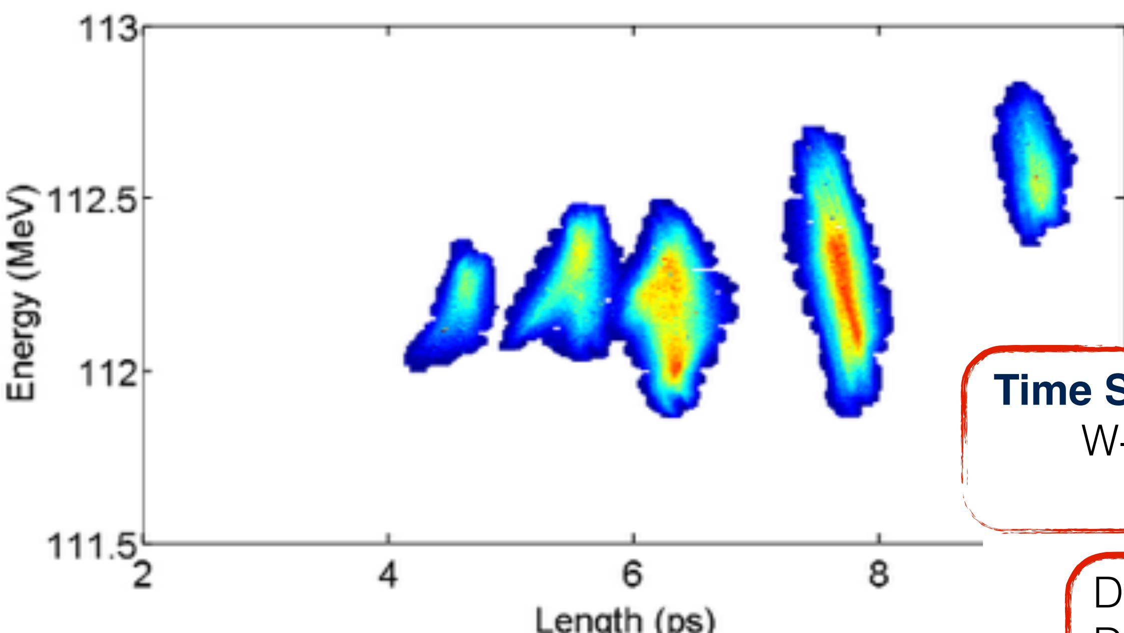


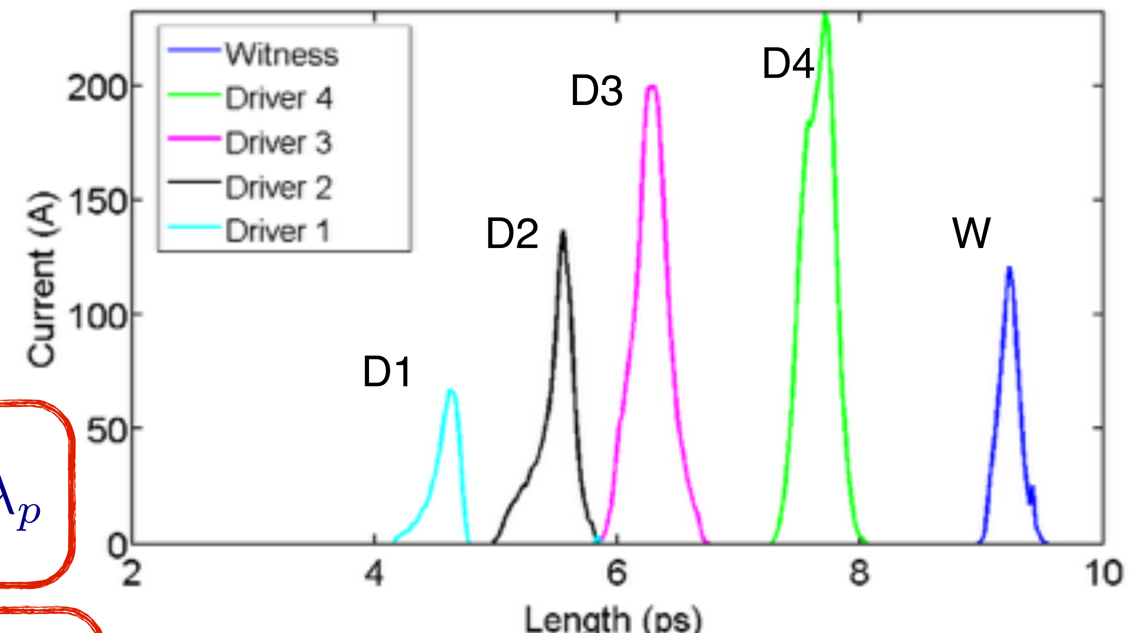


Task 5.2: SPARC_LAB Experience

- **PWFA**
  - **Multi-bunch train** (i.e. *comb*-like), *ramped charge bunches: laser comb profile and Velocity Bunching regime*

Measured Longitudinal Phase Space





Time Separation(ps)
W-D4 =1.58 (0.02) ~ $\frac{3}{2}\lambda_p$

D4-D3 =1.38 (0.03)
D3-D2 =0.80 (0.03)
D2-D1 =0.91 (0.05)
$\approx \lambda_p$

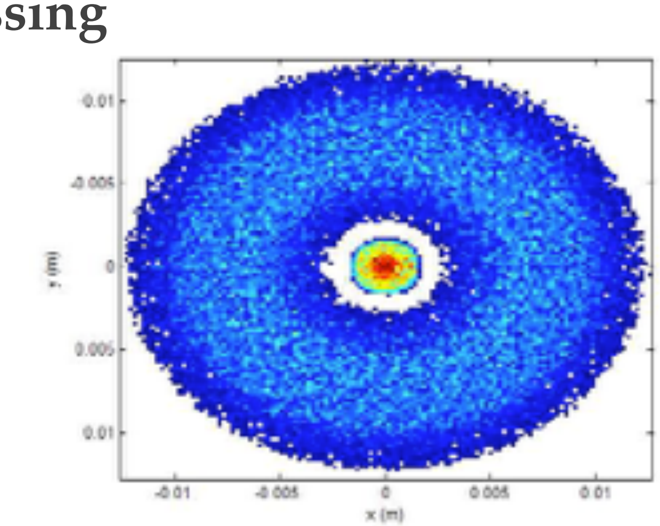
	Beam Energy (MeV)	Energy spread (%)	Bunch duration (ps)	Charge (pC)
Witness Beam	112.58(0.03)	0.084(0.003)	**<0.088(0.001)**	24.04(0.28)
Driver 4	112.28(0.03)	0.159(0.003)	**0.042(0.001)**	74.91(0.46)
Driver 3	112.17(0.03)	0.112(0.003)	**0.092(0.001)**	69.39(0.36)
Driver 2	112.26(0.02)	0.087(0.003)	**0.113(0.001)**	36.34(0.20)
Driver 1	112.20(0.02)	0.045(0.004)	**<0.100(0.024)**	36.34(0.20)
Whole Beam	112.27(0.03)	0.162(0.003)	1.275(0.003)	220.00(0.78)

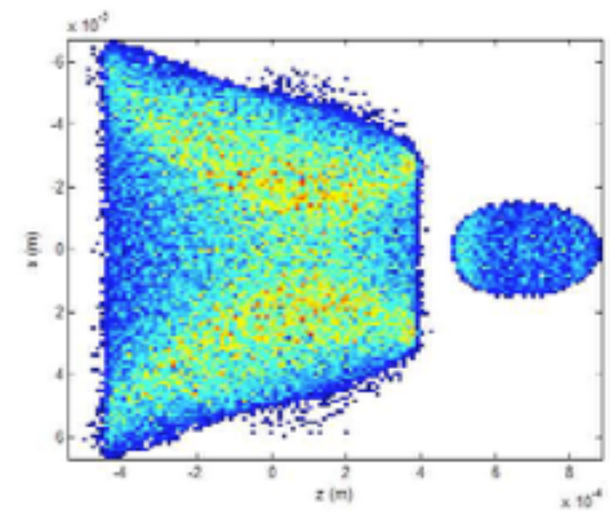
PWFA

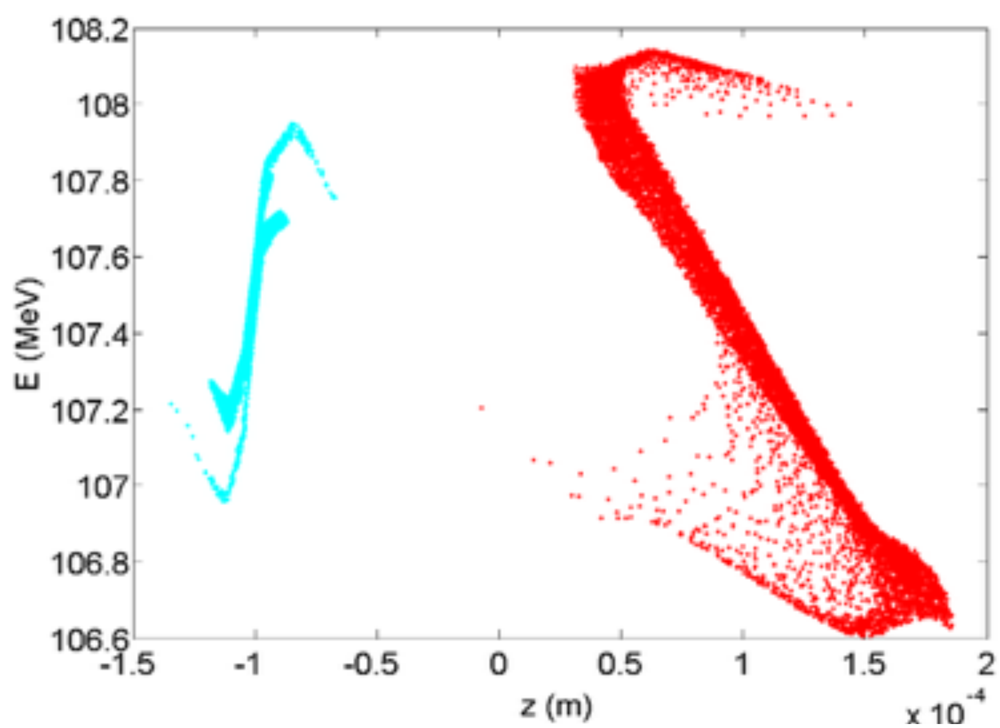
- **Multi-bunch train** (i.e. *comb*-like) and transverse shape: *hollow comb beam*

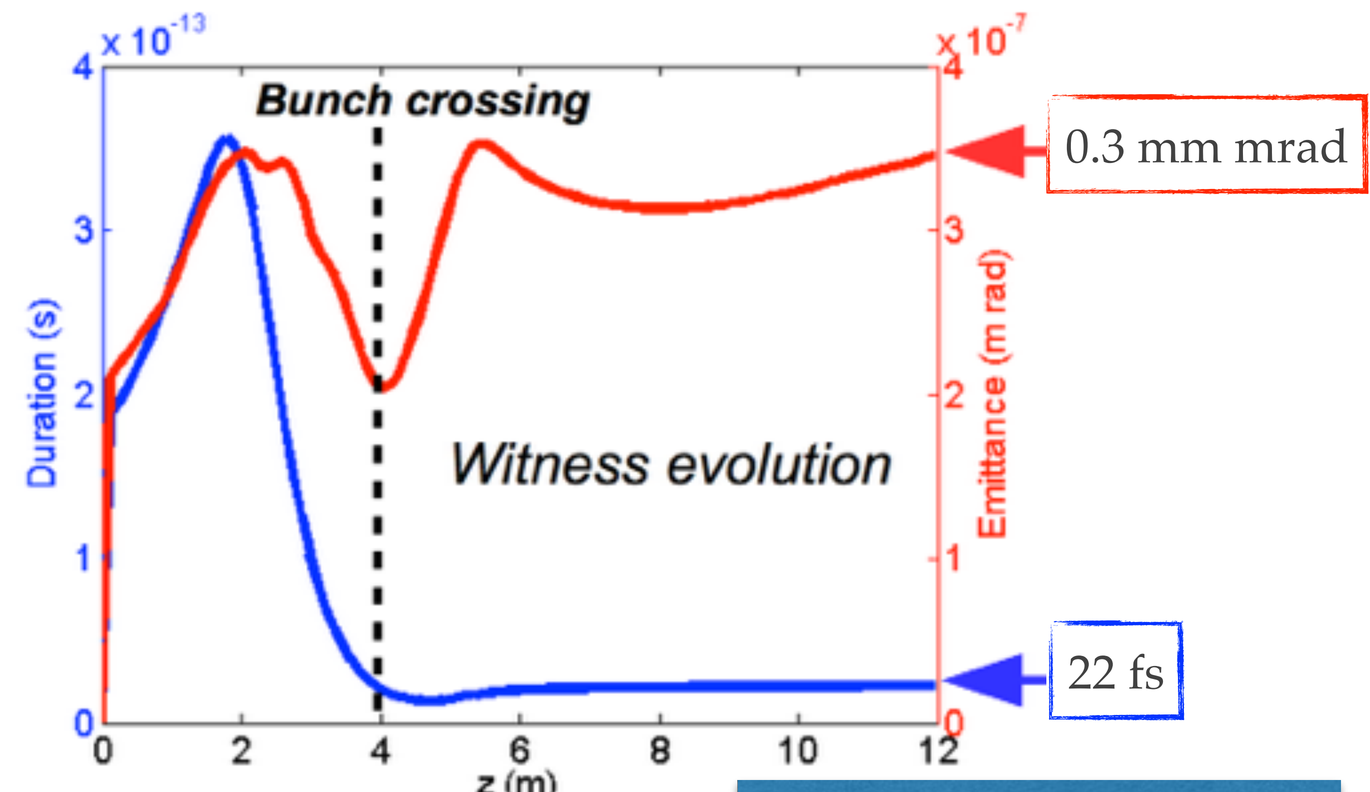
Witness degradation occurs during bunch crossing
- Driver acts as nonlinear lens
  - emittance growth
- Driver field is opposed to RF
  - lower compression

Hollow driver beam
- No beam-beam effects
  - unperturbed witness
- Higher driver emittance (larger spot on cathode)





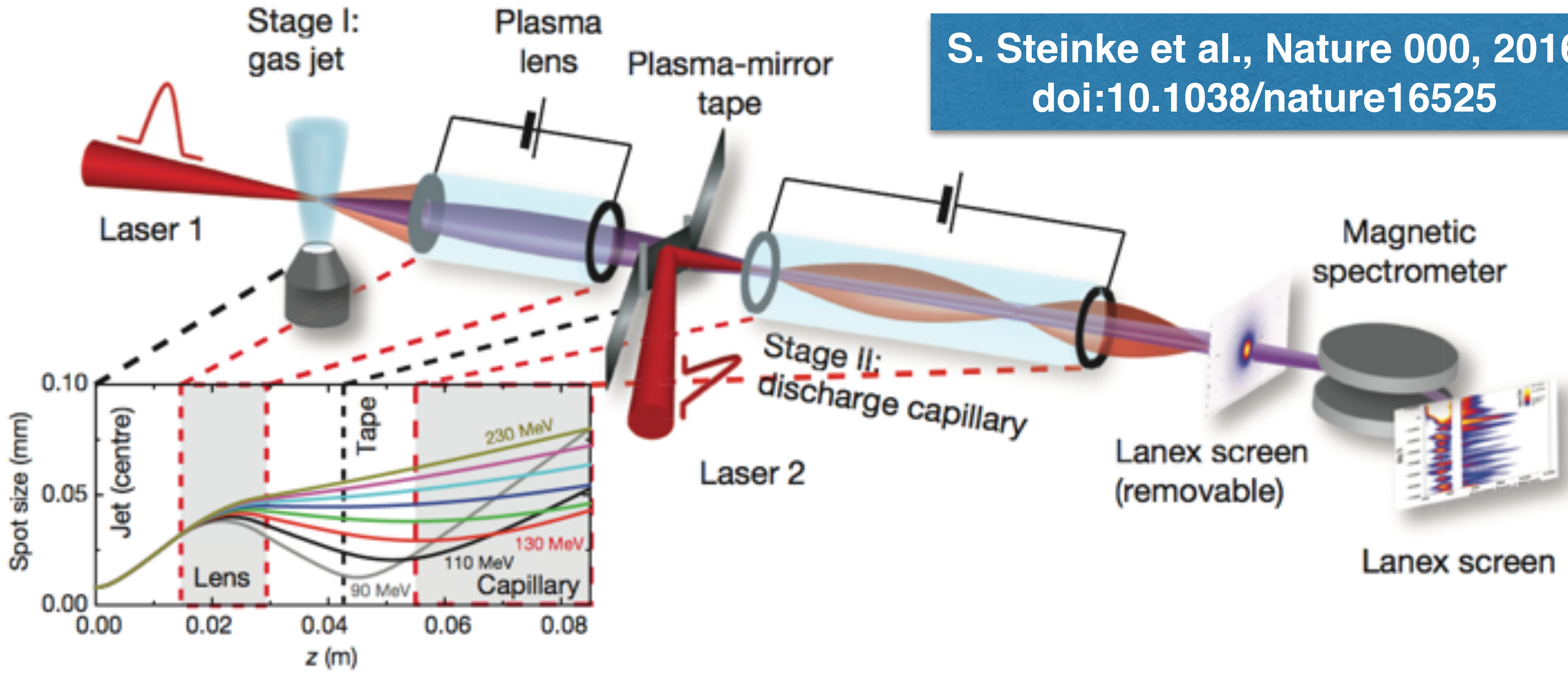




Courtesy of R. Pompili (LNF)

Task 5.3

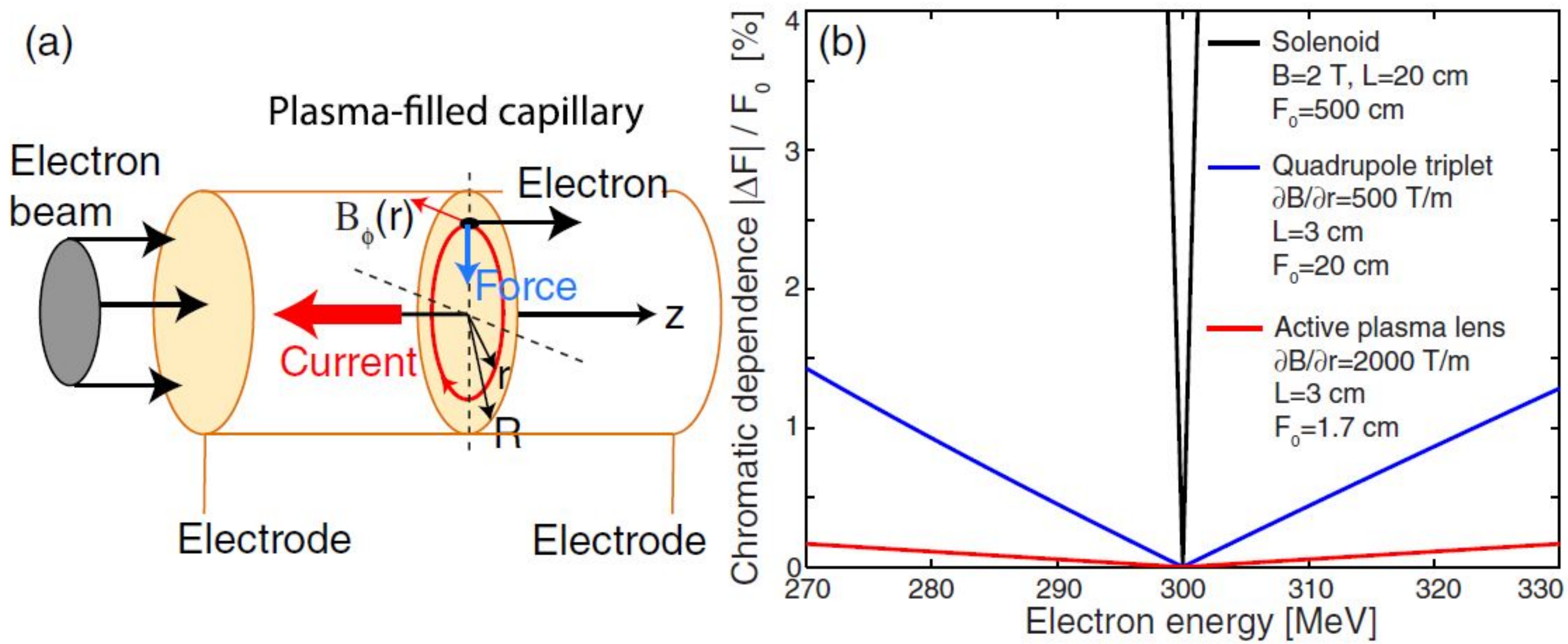
- **Task 5.3**: Electron Beam Manipulation (INFN, CEA,UROM, DESY, ULIV, USTRATH, SOLEIL)
  - Beam transport from the source
    - either external RF injector or plasma injector (**WP3**) to the plasma
  - Transfer line from the plasma accelerating structure to Pilot Application beam line
  - **Plasma lens** for injection and extraction

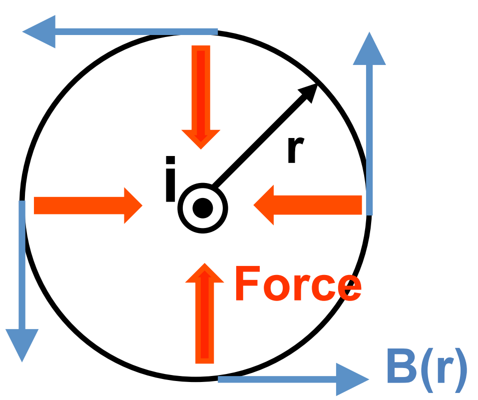


S. Steinke et al., Nature 000, 2016
doi:10.1038/nature16525

Task 5.3: SPARC LAB Experience

- **Plasma lens** for injection
  - Active plasma lens (Panofsky & Baker, 1950)



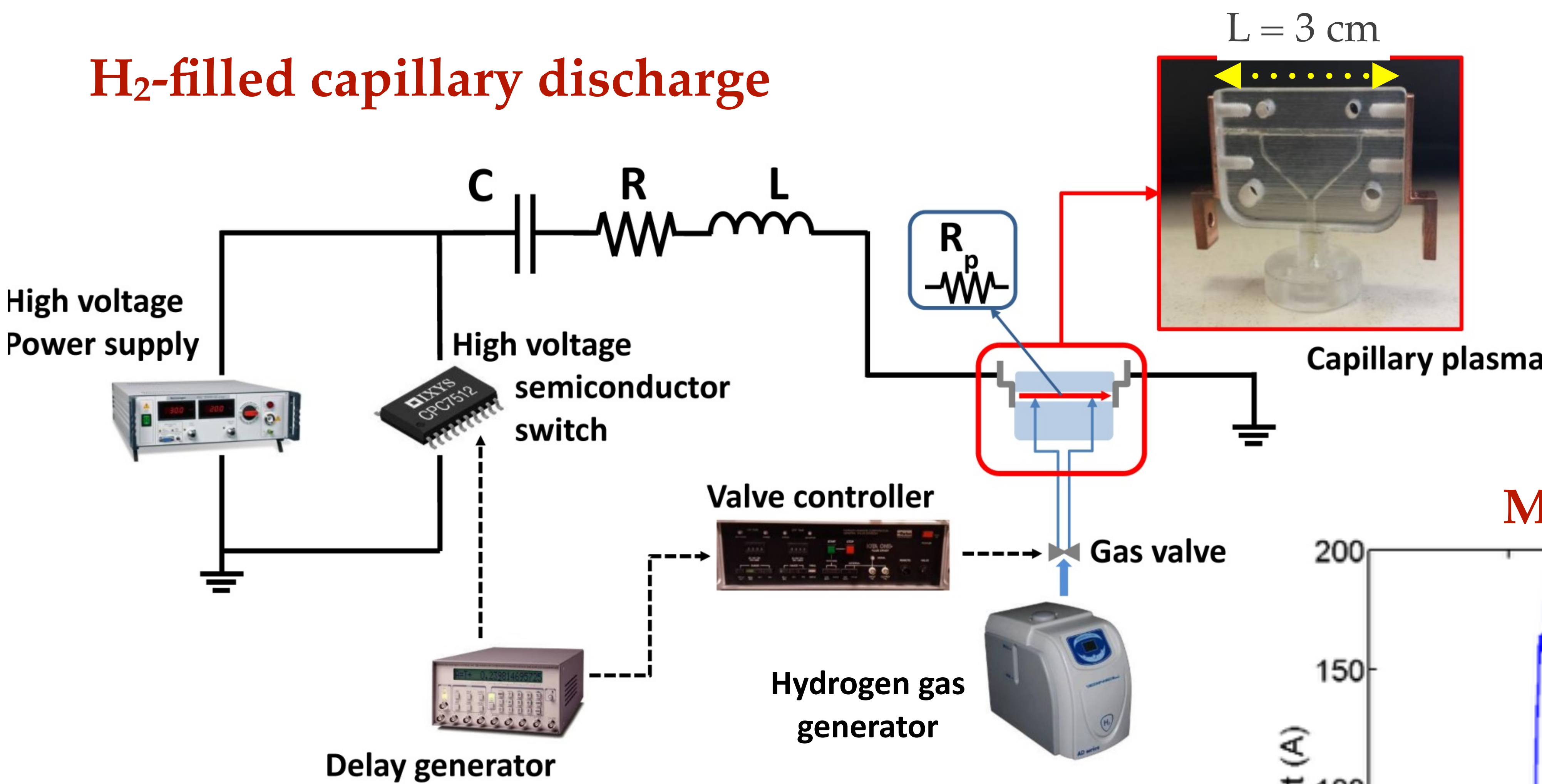


Red arrow: focusing force received by the electron beam within an active plasma lens is represented by the red arrow

$$f = \frac{1}{kL}; \quad k = \frac{eg}{p}; \quad g_{flat1} = \frac{\partial B_y}{\partial x} = \frac{\partial}{\partial x}\left[\frac{4\mu_0 ir}{6\pi R^2}\right] = \frac{4\mu_0 i}{6\pi R^2}$$

Task 5.3: SPARC LAB Experience

H_2-filled capillary discharge



P_{H2} = 10 mbar

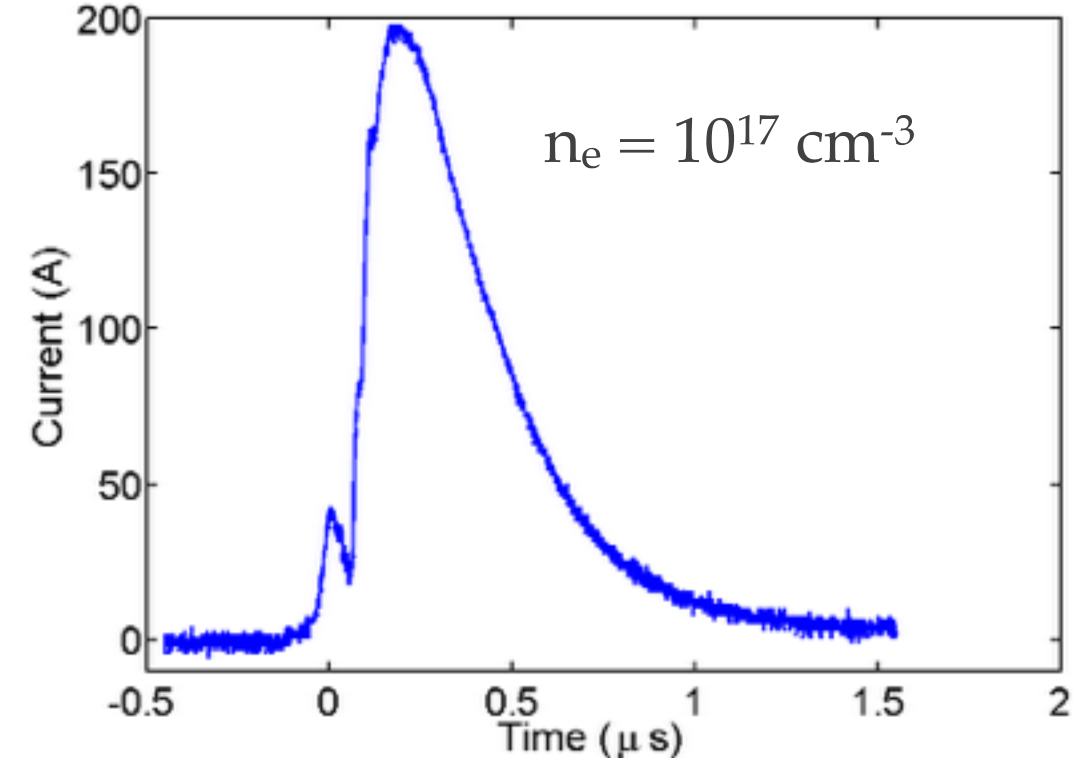
Total discharge duration :800 ns

Voltage : 20 kV

Peak current : 100 A

Capacitor : 6 nF

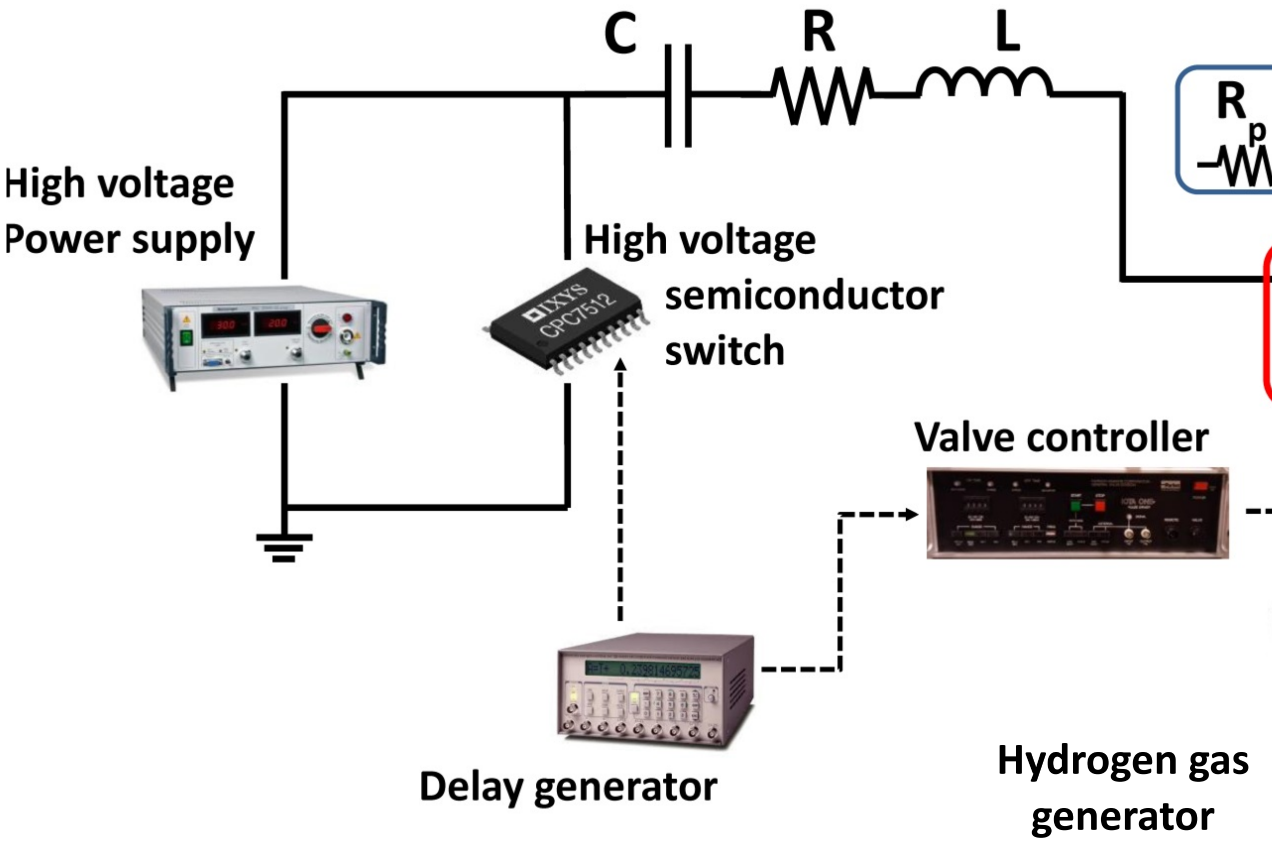
Measured current

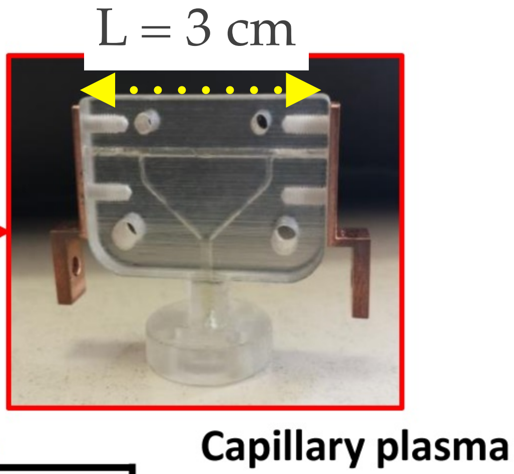


Courtesy of M. P. Anania, A. Biagioni, D. Di Giovenale, F. Filippi, S. Pella

Task 5.3: SPARC_LAB Experience

H_2-filled capillary discharge





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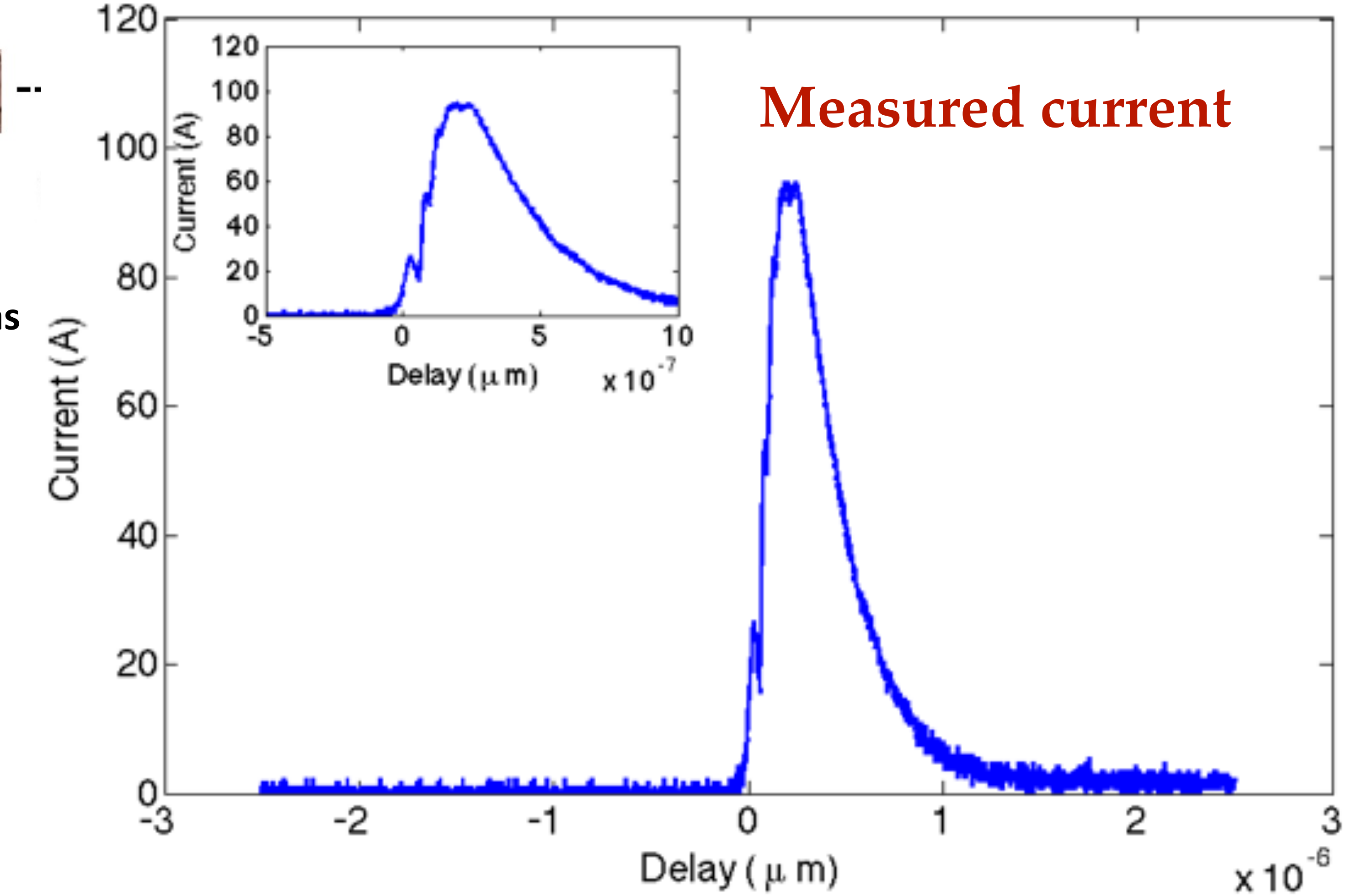
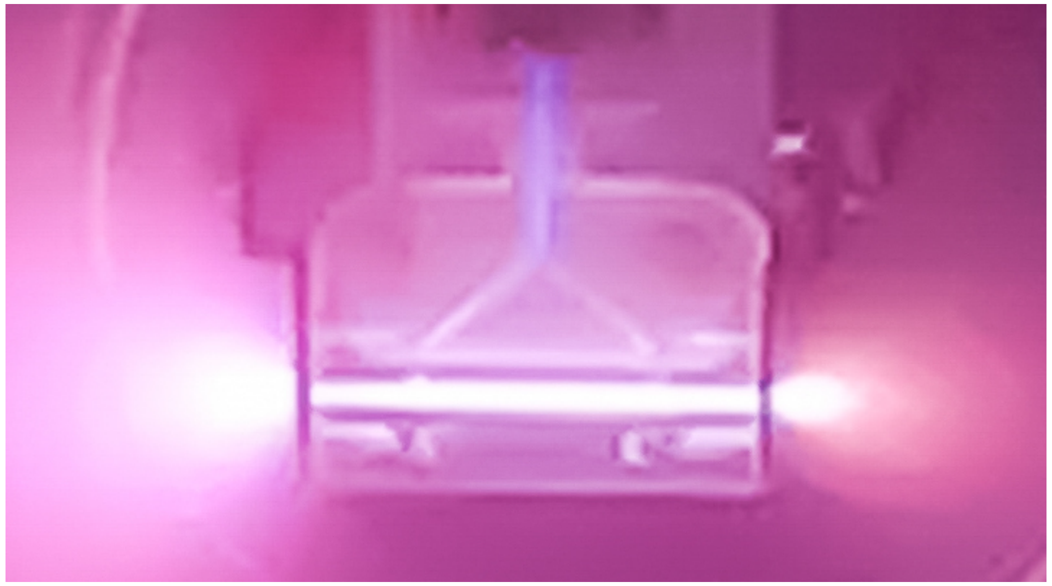
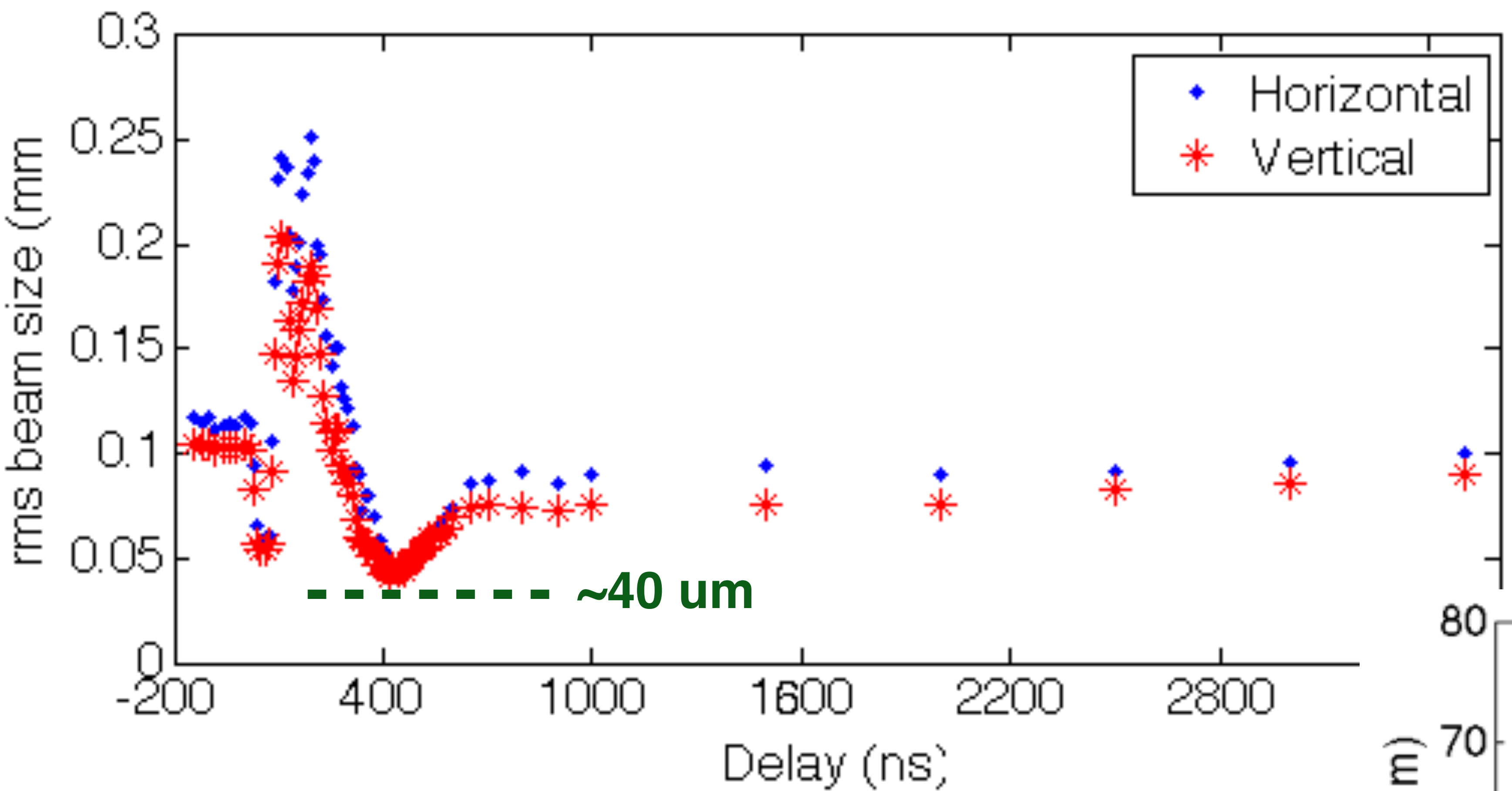


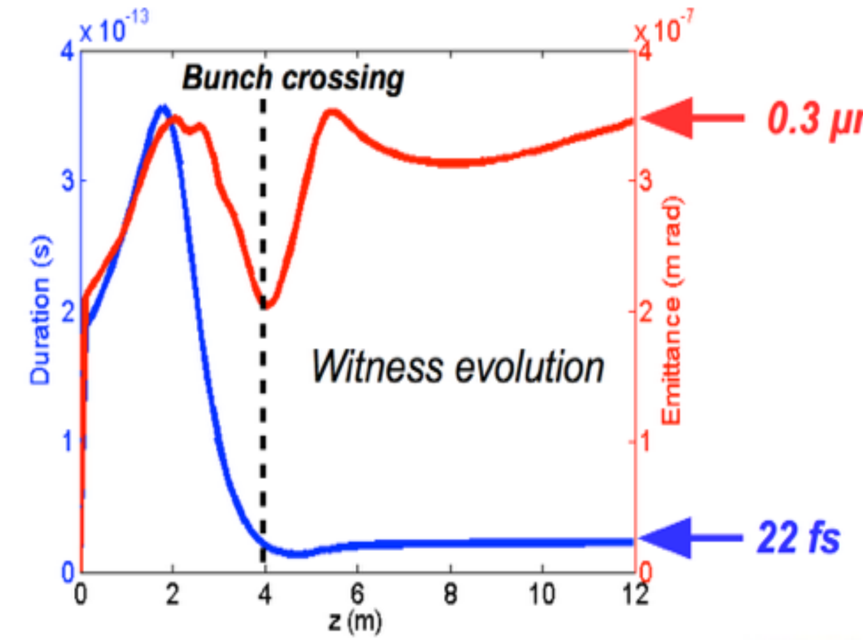


Courtesy of M. P. Anania, A. Biagioni, D. Di Giovenale, F. Filippi, S. Pella

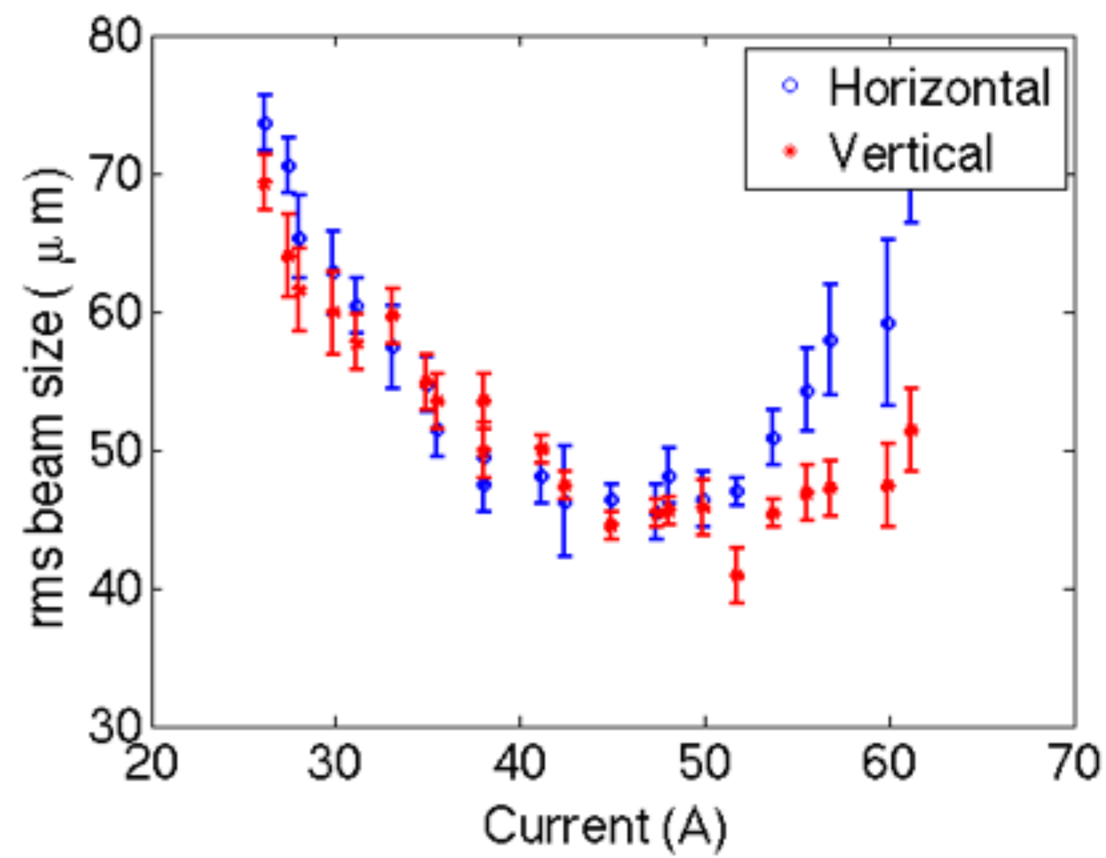
Task 5.3: SPARC_LAB Experience

- **Plasma lens** for injection
  - Active plasma lens



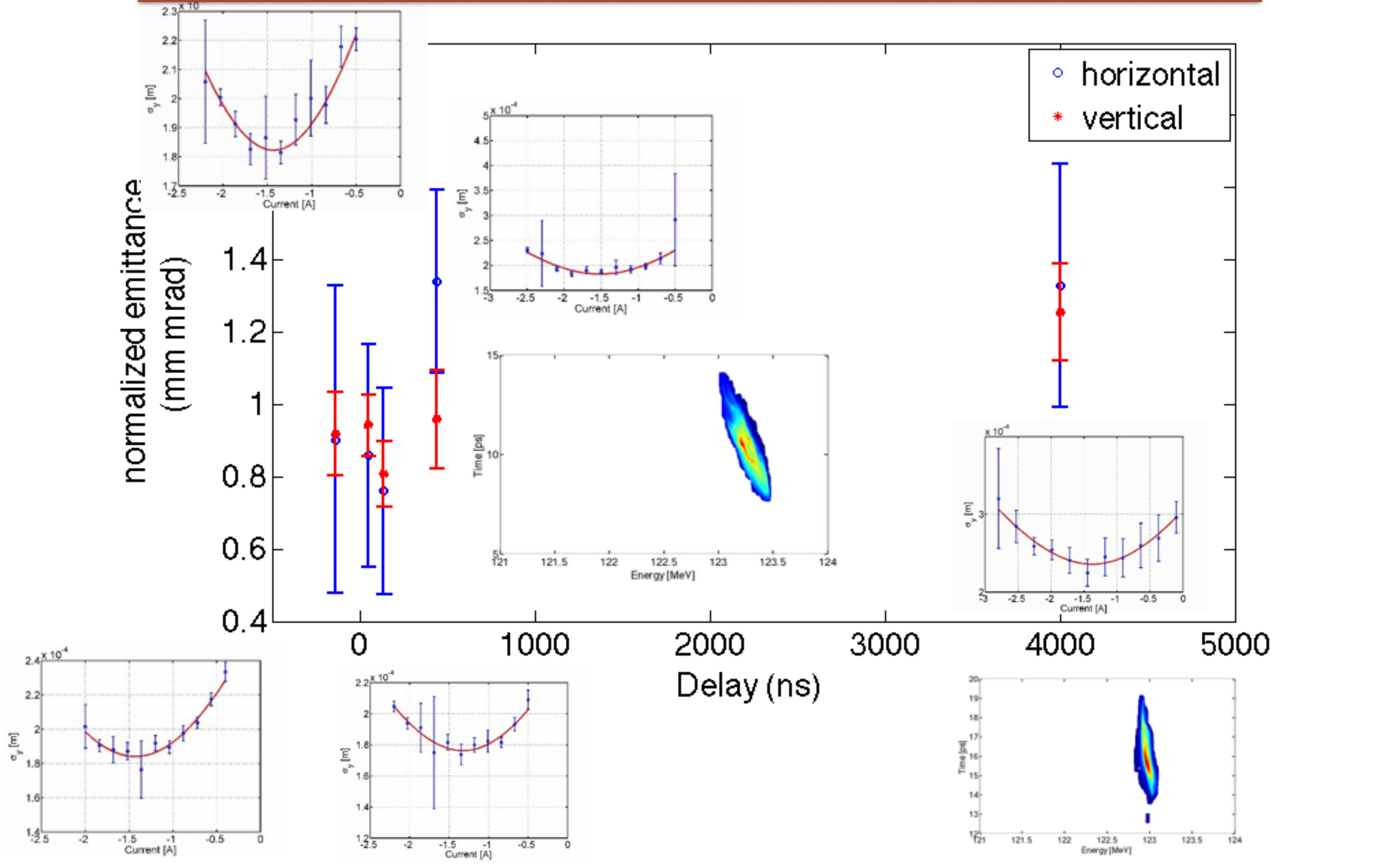


Measured spot size VS discharge current
Plasma lens scan for retrieving emittance



Task 5.3: SPARC_LAB Experience

Emittance scan VS delay to study emittance degradation due to plasma

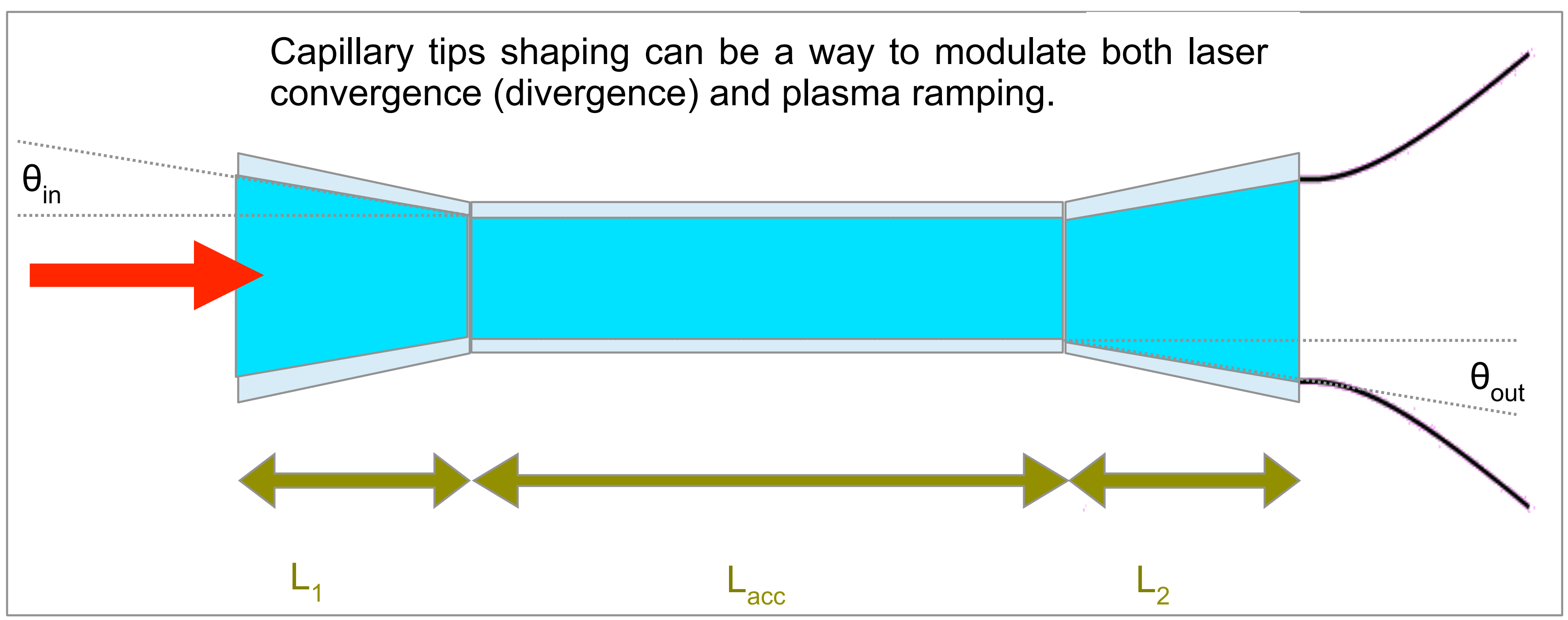


Task 5.3: SPARC LAB Experience

- **Plasma lens** for extraction
    - Adiabatic plasma lens
        - tapering plasma density

Linear tapering: The incoming bunch is deal with double Gaussian profiles, 17 fs long (FWHM), < 30 fs timing jitter, 5.5 um wide (rms), 10 pC charge, 80 MeV and 1 mm mrad normalized emittance

Laser Parameters	
Energy (J)	3.5
Duration (fs)	35
Bandwidth (nm)	60/80



Courtesy of A. R. Rossi

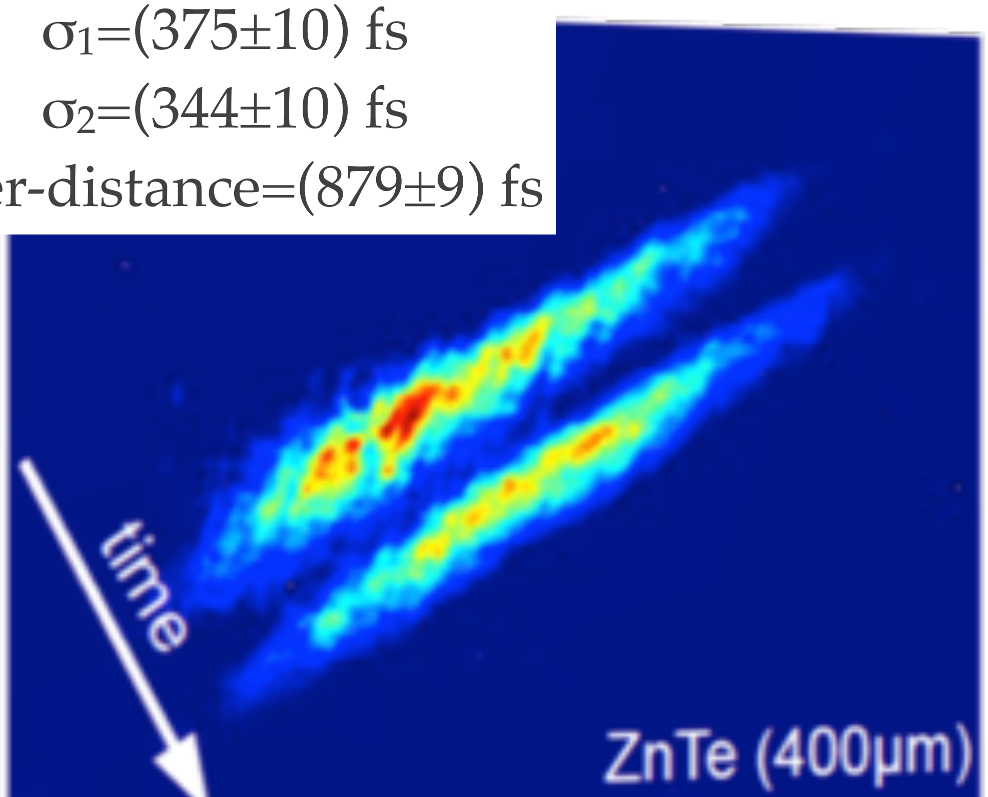
Task 5.4

- **Task 5.4**: Electron Beam Diagnostics and Practical Issue (INFN, CEA,UROM, DESY, ULIV, USTRATH, UHH)
  - **Before injection**
    - Beam transverse and longitudinal size
    - The relative time of arrival jitter of the two beams, i.e. laser and electron in LWFA,
      - timing system between the electron beam and the laser pulse
  - **After acceleration in plasma**
    - Energy, energy spread, emittance => single shot diagnostics

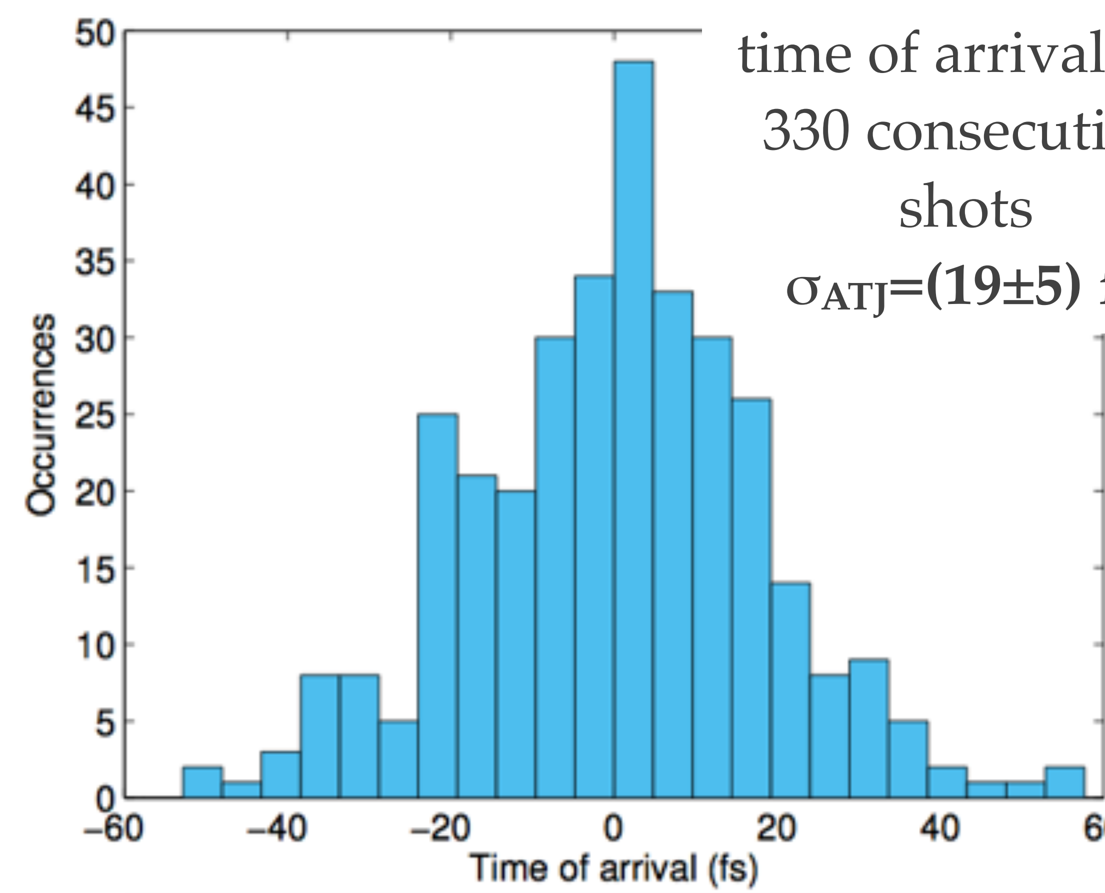
EuPRAXIA Task 5.4: SPARC LAB Experience

- **Before injection**
  - Beam *longitudinal* diagnostics
    - ***Electro-Optical Sampling***
      - Single shot, non-intercepting diagnostics to monitor multi-bunch train injection in plasma: ***temporal spacing*** (to check the resonance condition in resonant-PWFA) ***and duration***
      - Measurement of the relative time of arrival jitter of the two beams, i.e. laser and electron in LWFA
        - The position of signal, where laser crosses with crystal, indicates the time of arrival of beam, the width of signal is related to longitudinal profile of beam

σ_1=(375±10) fs
σ_2=(344±10) fs
inter-distance=(879±9) fs



R. Pompili et al., NIM A: Accelerators. 740, 216 (2014)



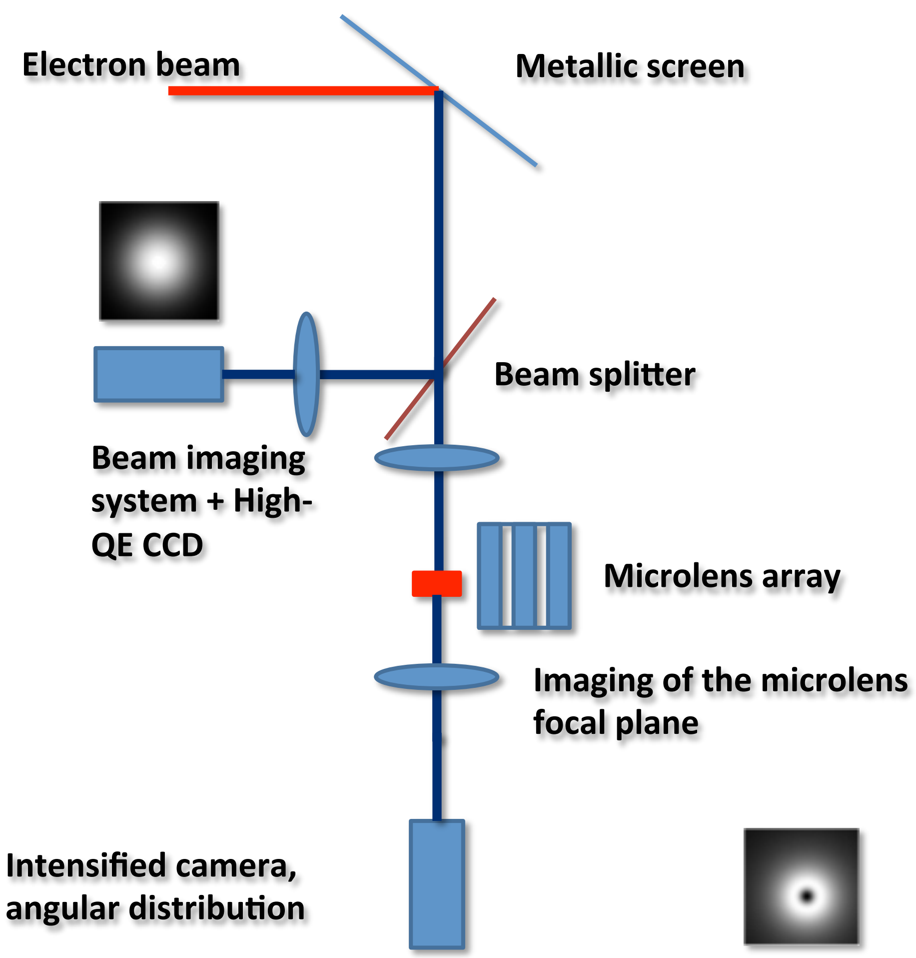
time of arrival for 330 consecutive shots

σ_{ATJ}=(19±5) fs

R. Pompili et al., submitted to NJP

Task 5.4: SPARC LAB Experience

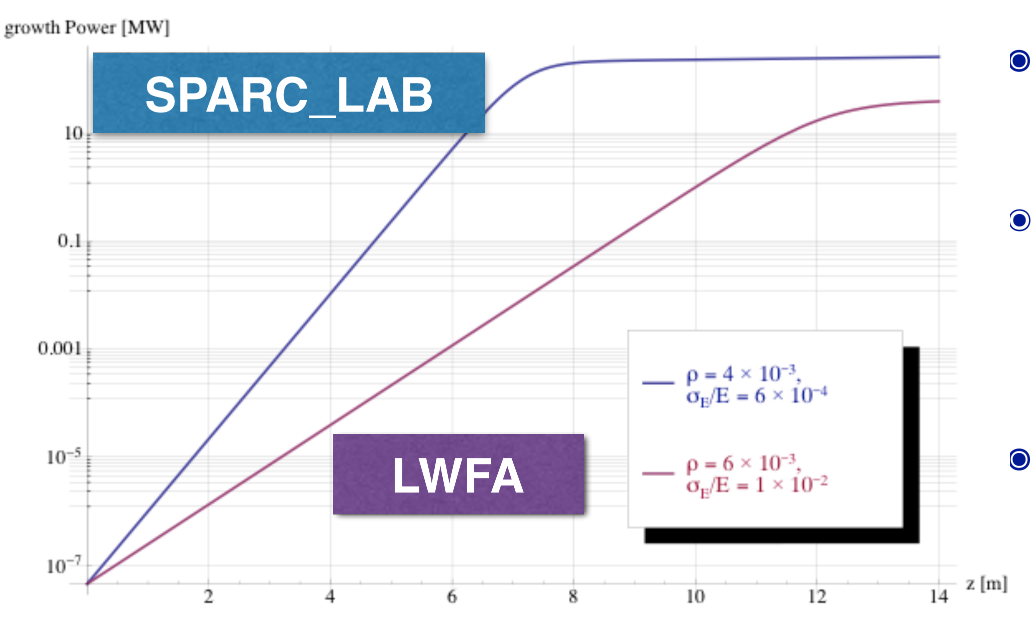
- **Before injection**
  - Beam *transverse* size
    - **um scale** resolution diagnostics
- **After acceleration in plasma**
  - Beam *transverse* size
    - Energy, energy spread, *emittance => single shot diagnostics*
- ***Optical Transition Radiation Imaging and Angular Distribution***
  - ***One Shot Emittance (OSE)***



Courtesy by A. Cianchi

Interaction with other WPs

- **WP2: Physics and Simulations (A. Mosnier, L. Oliveira Silva)**
  - Both plasma dynamics and RF injectors
- **WP3: High Gradient Laser Plasma Accelerating Structure (B. Cross, Z. Najmudin)**
  - beam handling from plasma injector => ***Input****: beam parameters*
  - plasma lens design
- **WP6: FEL Pilot Application (M.-E. Couprie, G. Dattoli)**
  - Design transfer line => ***Input****: Matching conditions at the undulator*
    - Accelerated witness beam parameters: **1 - 5 GeV, 1 mm mrad, 0.1% energy spread**



Courtesy of G. Dattoli and F. Nguyen

- **WP7: High Energy Physics and other Pilot Applications**
  - Design transfer line => ***Input****: Matching conditions at the interaction point*
- **WP9: Alternative e-Beam Driven Plasma Structure**
  - RF injector requirements for PWFA
    - *Multi-bunch train for increasing transformer ratio*
- **WP10: Use of Other Novel Technologies**
  - Study other novel injector concepts
    - *Cryogenic injector*
- **WP12: Accelerator Prototyping and Experiments at Test Facilities**
  - Experimental tests
- **WP14: Hybrid Laser-Electron-Beam Driven Acceleration**
  - Timing and synchronization issues
    - *femtosecond scale*

RF Injector preliminary parameters

- **Charge: 10 pC - 100 pC**
  - Cathodes
    - robustness, fast response (to allow pulse shaping), high QE, low intrinsic emittance
- **Injector energy: 100-200 MeV**
- energy spread: ~0.1‰
- Rep. rate: ??
- **Normalized emittance: ~< 1 mm mrad**
- **Peak current: ~kA**
  - Preferably two compression stages: hybrid compression
    - Low energy RF compression
      - rectilinear trajectories (no CSR which dilutes emittance), integrated in emittance compensation scheme
    - High energy magnetic compression
      - Jitter (e-beam to external laser): ~10 fs

Preliminary Working Point

The wish parameter list strongly depends on the beam parameters for the given application.

For a FEL pilot experiment lasing at *10 nm,* **“1 cube”** working point, plasma accelerator should provide

- Charge: from few pC to hundreds pC level
- **Peak current: 1 kA**
- **Energy: 1 GeV**
- energy spread: ~ 0.1%
- **Normalized slice emittance: 1 mm mrad**

Conceptual Design Report

Section 12 of the CDR

- Electron Beam Design and Optimization (WP5)
  - 1.1 Introduction
    - *State-of-the-art electron injectors*
  - 1.2 Design of the photo-injector
    - *Photo-cathode laser*
    - *Cathode*
    - *RF gun*
  - 1.3 Beam handling
    - *Beam manipulation for high brightness preservation*
    - *Includes measurement, correction, feedback?* *It should include diagnostics*
    - *Up- and downstream of plasma?* *Yes*
      - *Beam transfer lines to user experiments*
  - 1.4 Collimation and **beam shaping**
    - *3rd harmonic accelerator cavity for longitudinal phase-space linearization*
    - *Longitudinal beam shaping, e.g. triangularly ramped current profiles*
    - *Done by WP or done by DESY*

Contribution to EUSPARC

Working group 1: Injector and Linac

- Survey of the **state-of-the-art electron injectors** for high brightness beams
  - Photo-injectors allowed for both transverse and longitudinal pulse shaping
    - e.g. Hollow comb beam

- Next Generation High Brightness Electron Beams From Ultra-High Field Cryogenic RF Photocathode Sources
  - Extreme low emittance scenarios obtained at low operating charge
  - Cryogenic operation to reduce intrinsic cathode temperature, therefore intrinsic emittance
  - Cathode cooling to suppress dark current despite the large fields employed