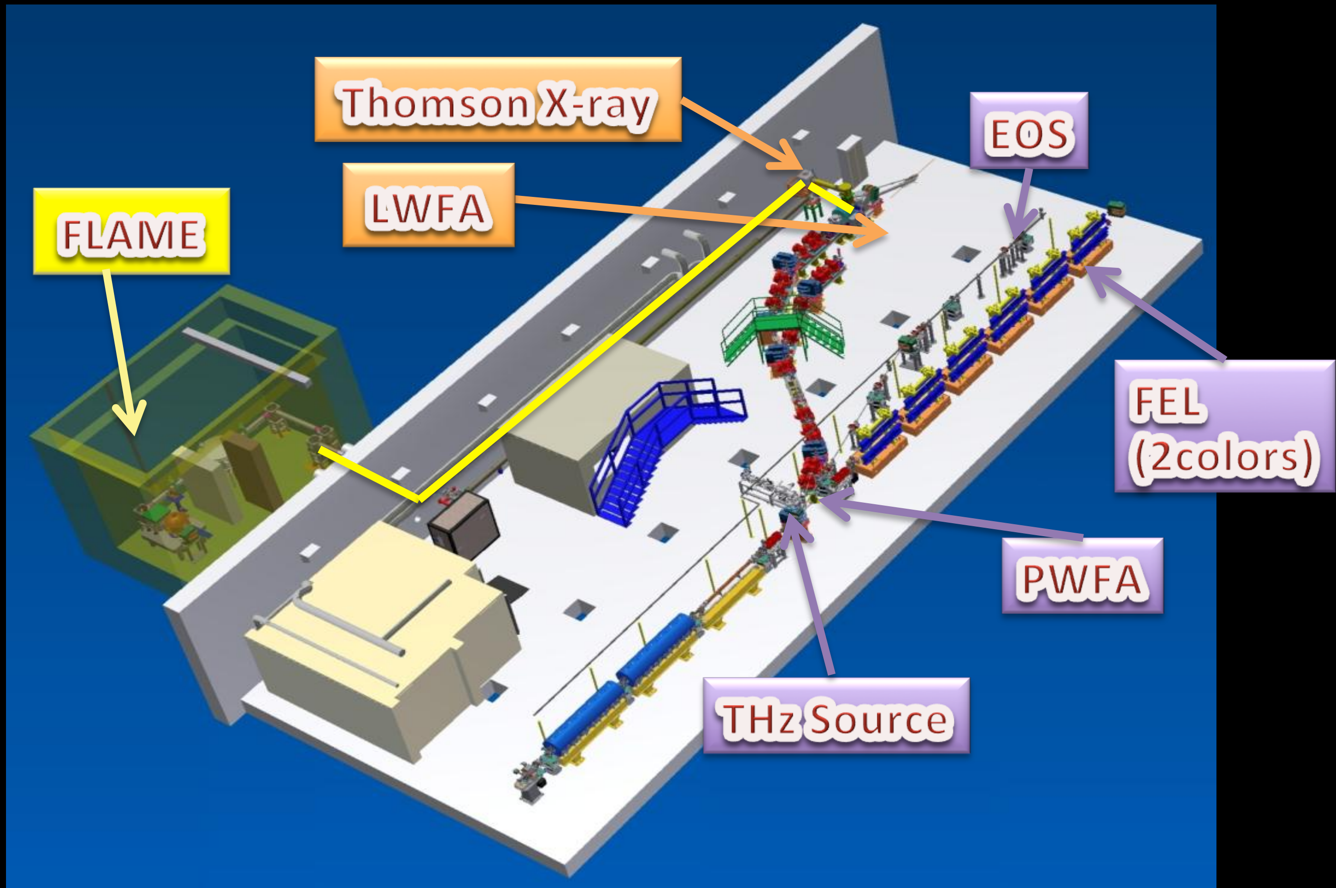
Plasma acceleration research at SPARC-LAB

Massimo.Ferrario@LNF.INFN.IT
On behalf of the SPARC_LAB collaboration

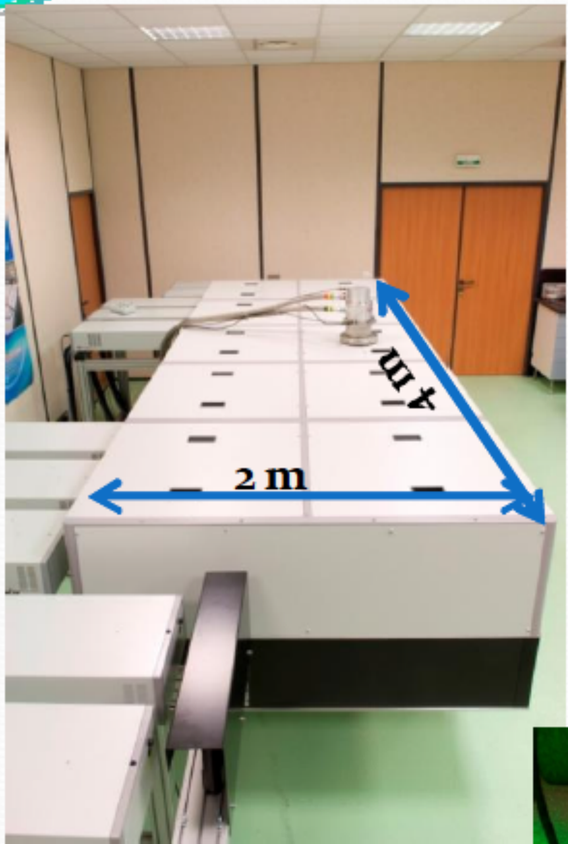


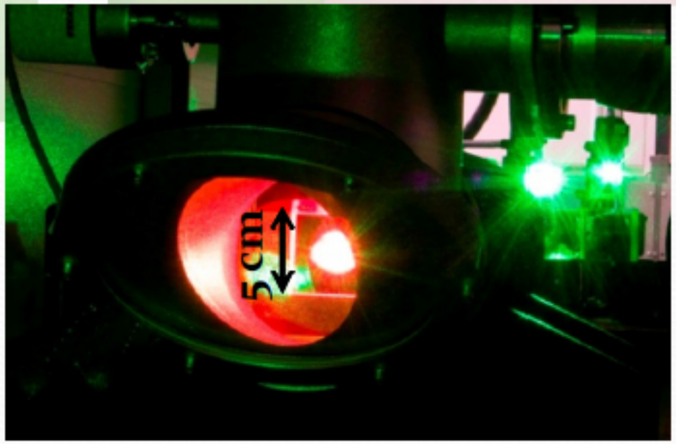
“Miniworkshop su Acceleratori” LNL- February 17, 2015

SPARC_LAB Welcomes:

- Prof. Arie Zigler (Hebrew University of Jerusalem) 1 year sabbatical
- Prof. Jamie Rosenzweig (UCLA) 7 months sabbatical
- Dr. Weiwei Li, PhD student from University of Science and Technology of China, 15 momths
- Dr. Alex Brynes, post doc from STFC, 3 months
- 3 new PhD students form University of Roma
- Dr. H. Fares, Physics Dep., Assiut Univ., Egypt. , 2 years

Il laser FLAME





Energia massima: 7J

Energia massima sul target: ~5J

Durata minima: 23 fs

Lunghezza d'onda: 800 nm

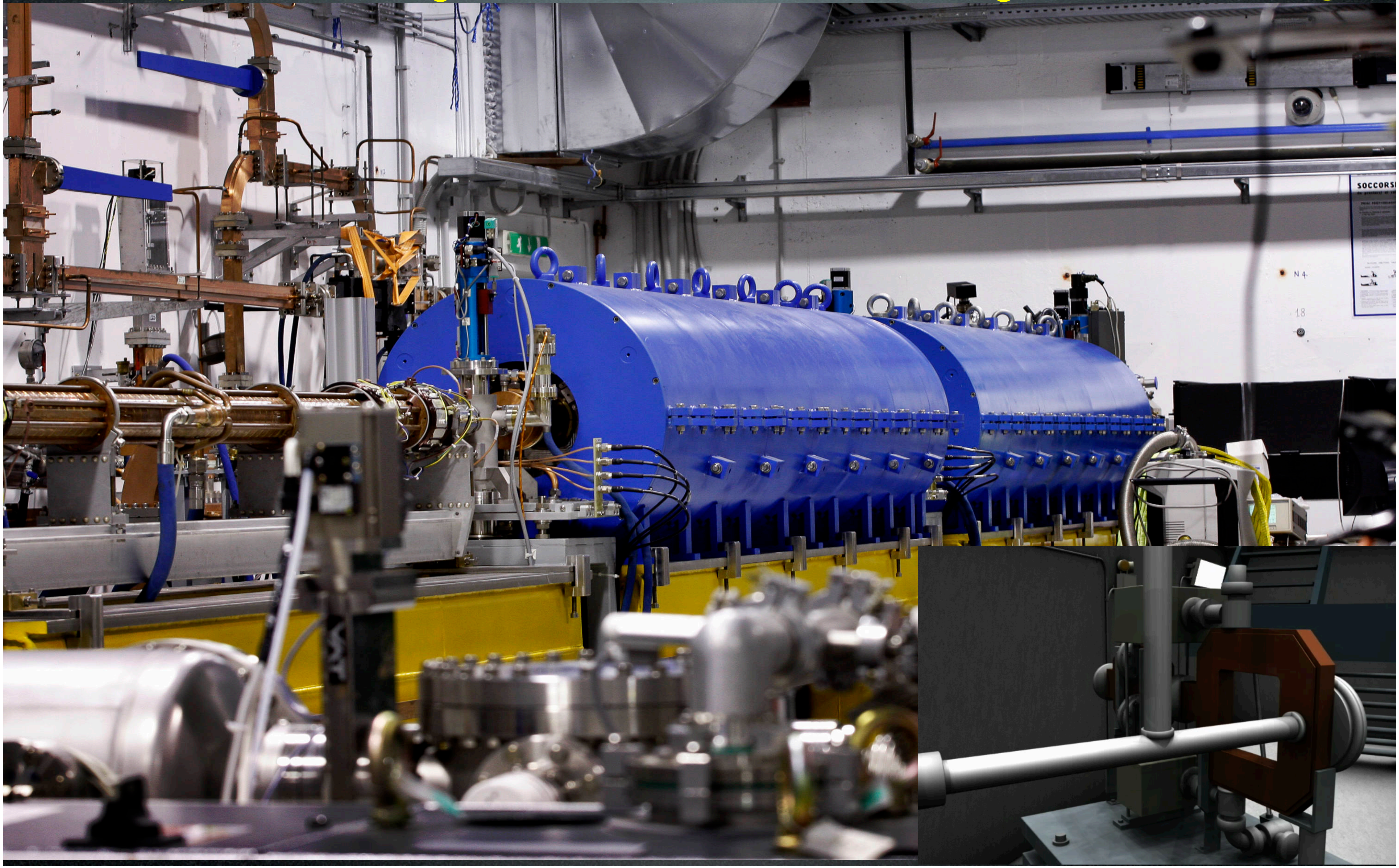
Larghezza di banda: 60/80 nm

Spot-size @ focus: 10 μm

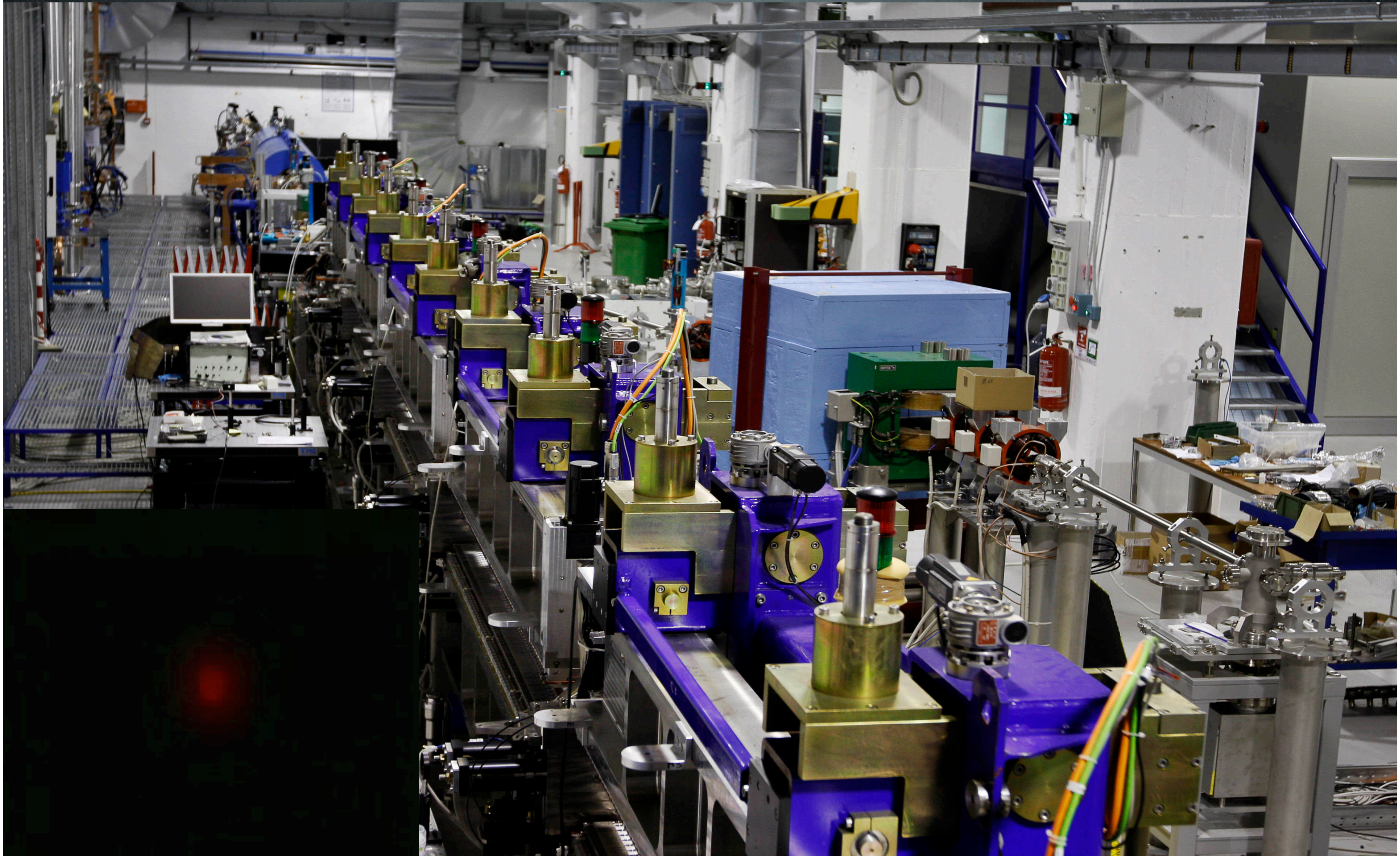
Potenza massima: ~300 TW

Contrasto: 10^{10}

HB photo- injector with Velocity Bunching

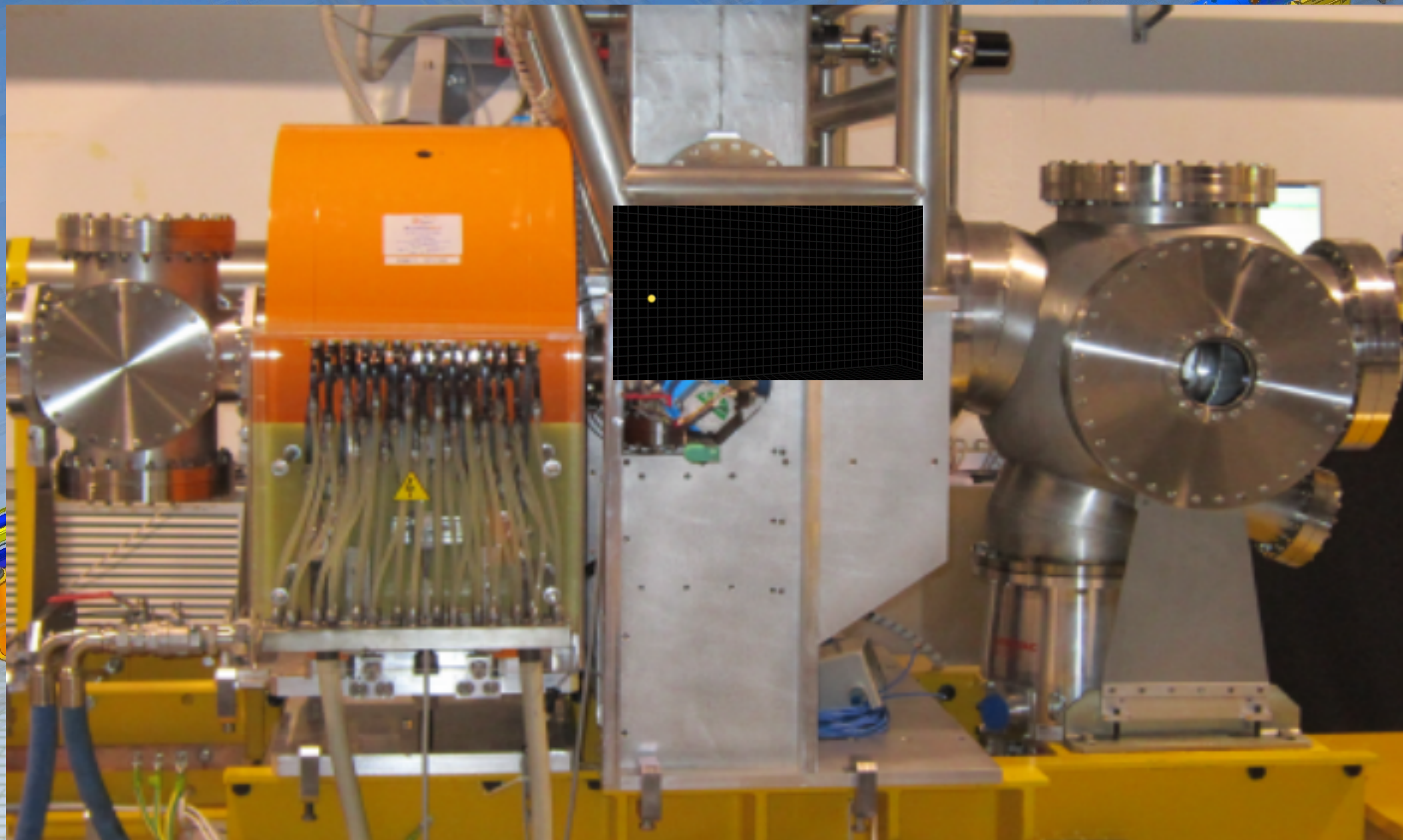


Free Electron Laser



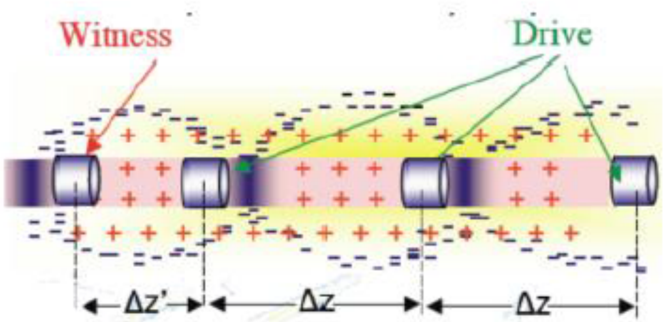
Thomson back-scattering source

carica (pC)	energia (MeV)	enx (mm mrad)	eny (mm mrad)	IP sigmax mm	IP sigmay (mm)
230	157	2.7	4.5	.50	.55
220 230	75 50	2.9 1.2	5 2.3	.28 .17	.36 .18



Plasma-based acceleration techniques

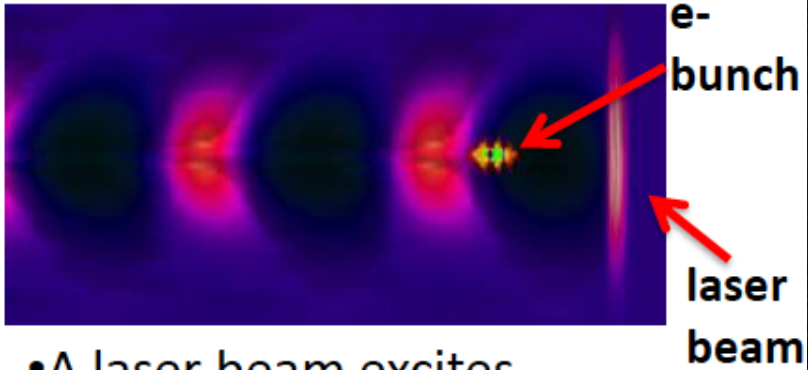
resonant-PWFA



•A train of three electron bunches (driver bunches) is sent through a capillary discharge
•A resonant plasma wave is then excited in plasma
•A fourth electron beam (witness beam) uses this wave to be accelerated

$n_e = 2x10^{16}$ cm^{-3}
$\lambda_p = 300\mu m$
Capillary 1mm
Hydrogen

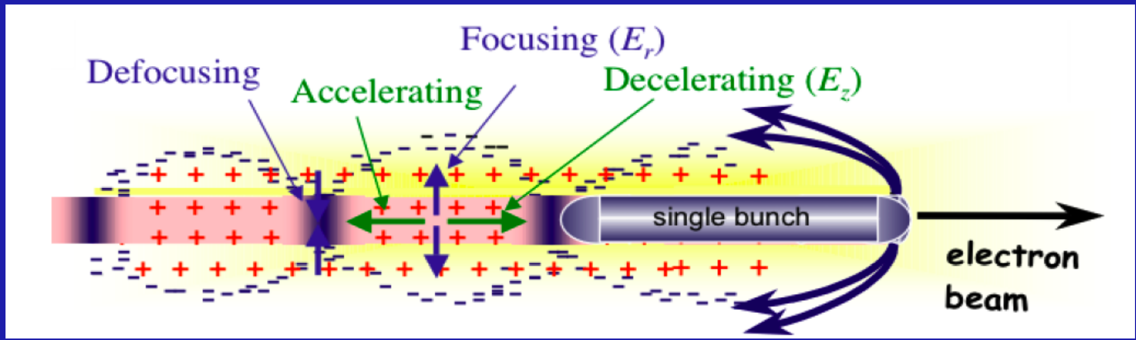
external injection LWFA

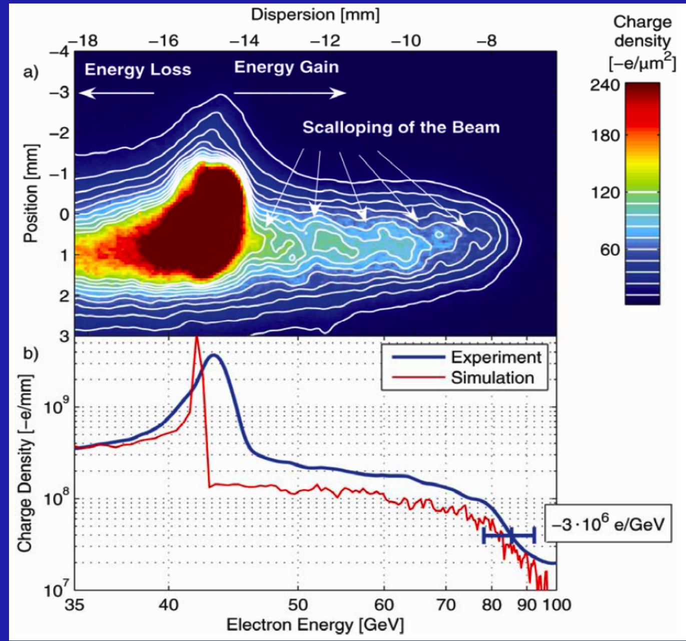


•A laser beam excites plasma waves in a capillary filled with gas
•A high brightness electron beam uses this wave to be accelerated

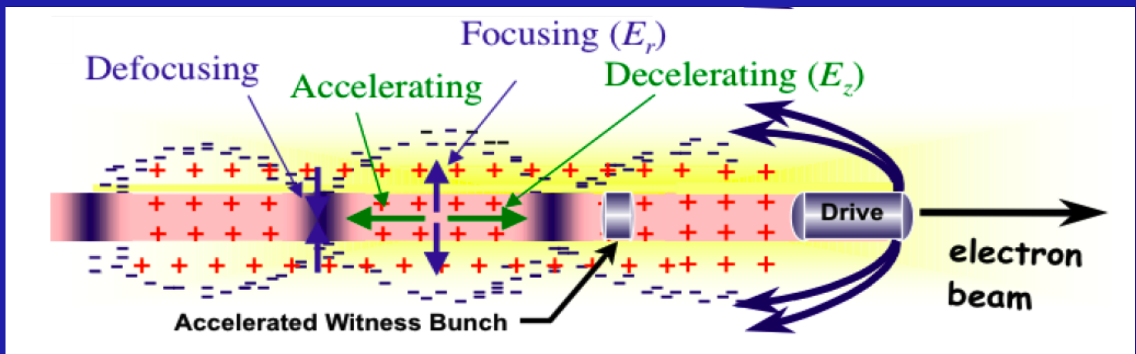
$n_e = 1x10^{17}$ cm^{-3}
$\lambda_p = 100\mu m$
Capillary 100 µm
Hydrogen

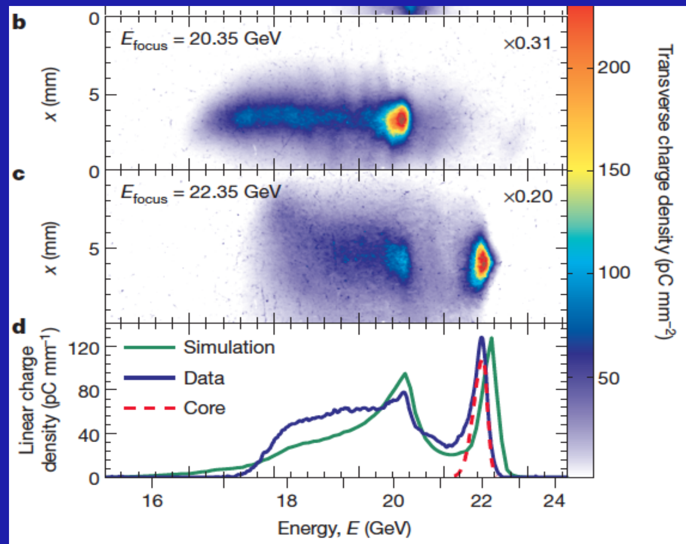
Recent exciting results at FACET & BELLA





Blumenfeld, I. et al. *Energy doubling of 42 GeV electrons in a metre-scale plasma wakefield accelerator*. **Nature** 445, 741–744 (2007).





Litos, M. et al. *High-efficiency acceleration of an electron beamin a plasma wakefield accelerator*. **Nature** 515, 92–95 (2014).

CONCEPTUAL DESIGN OF THE DRIVE BEAM FOR A PWFA-LC*

S. Pei#, M. J. Hogan, T. O. Raubenheimer, A. Seryi, SLAC, CA 94025, U.S.A.
H. H. Braun, R. Corsini, J. P. Delahaye, CERN, Geneva

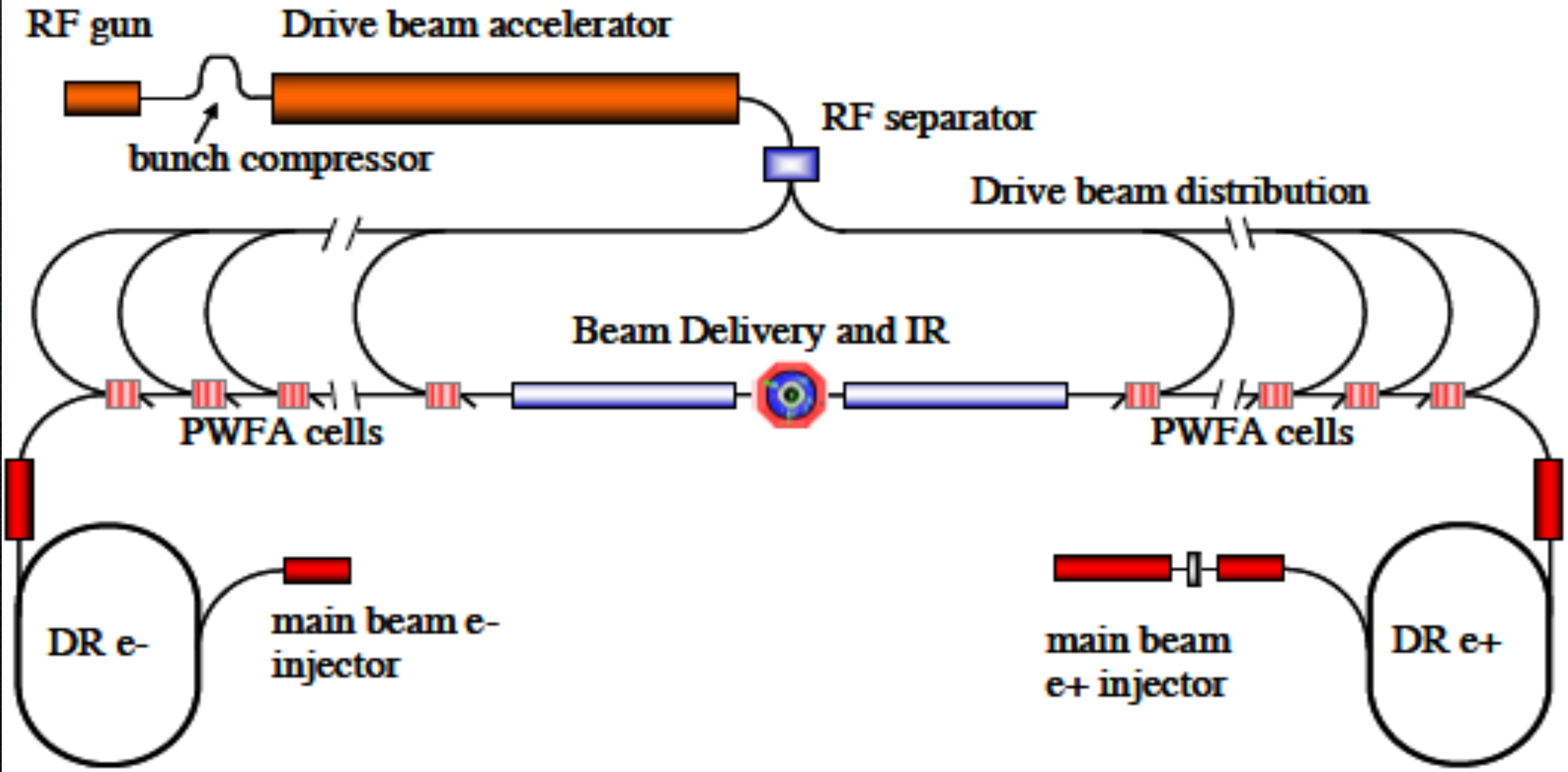


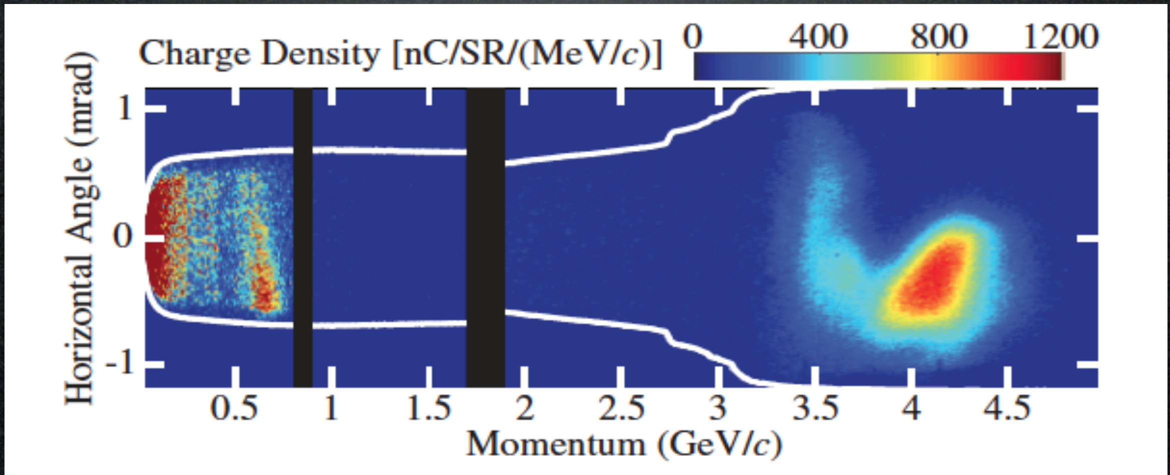
Fig. 1: Concept for a multi-stage PWFA Linear Collider.

Selected for a Viewpoint in *Physics*
PRL **113**, 245002 (2014) PHYSICAL REVIEW LETTERS week ending 12 DECEMBER 2014

Multi-GeV Electron Beams from Capillary-Discharge-Guided Subpetawatt Laser Pulses in the Self-Trapping Regime

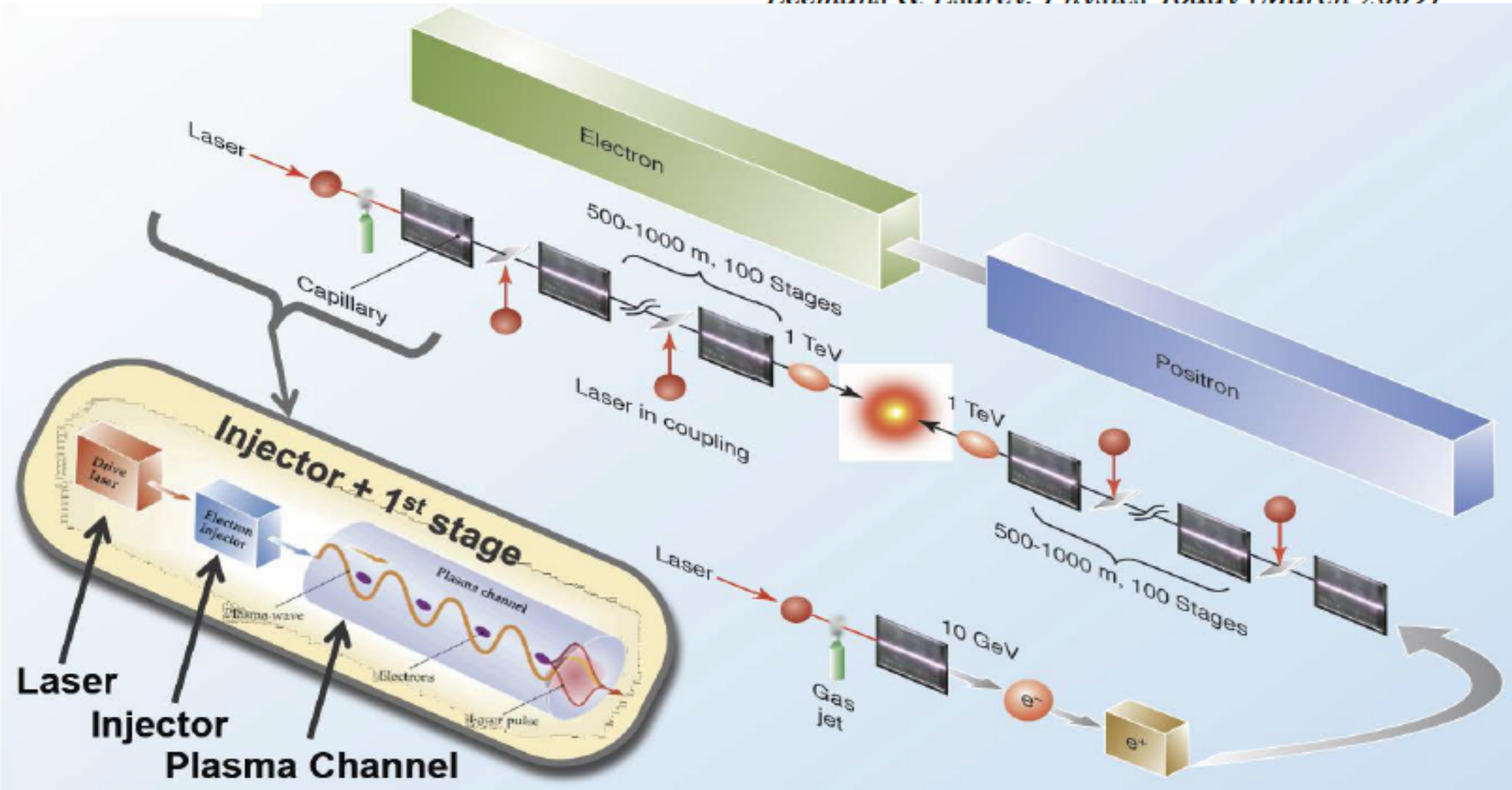
W. P. Leemans,[1,2,*] A. J. Gonsalves,[1] H.-S. Mao,[1] K. Nakamura,[1] C. Benedetti,[1] C. B. Schroeder,[1] Cs. Tóth,[1] J. Daniels,[1] D. E. Mittelberger,[2,1] S. S. Bulanov,[2,1] J.-L. Vay,[1] C. G. R. Geddes,[1] and E. Esarey[1]
[1]*Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA*
[2]*Department of Physics, University of California, Berkeley, California 94720, USA*
(Received 3 July 2014; revised manuscript received 11 September 2014; published 8 December 2014)

Multi-GeV electron beams with energy up to 4.2 GeV, 6% rms energy spread, 6 pC charge, and 0.3 mrad rms divergence have been produced from a 9-cm-long capillary discharge waveguide with a plasma density of $\approx 7 \times 10^{17}$ cm^{-3}, powered by laser pulses with peak power up to 0.3 PW. Preformed plasma waveguides allow the use of lower laser power compared to unguided plasma structures to achieve the same electron beam energy. A detailed comparison between experiment and simulation indicates the sensitivity in this regime of the guiding and acceleration in the plasma structure to input intensity, density, and near-field laser mode profile.

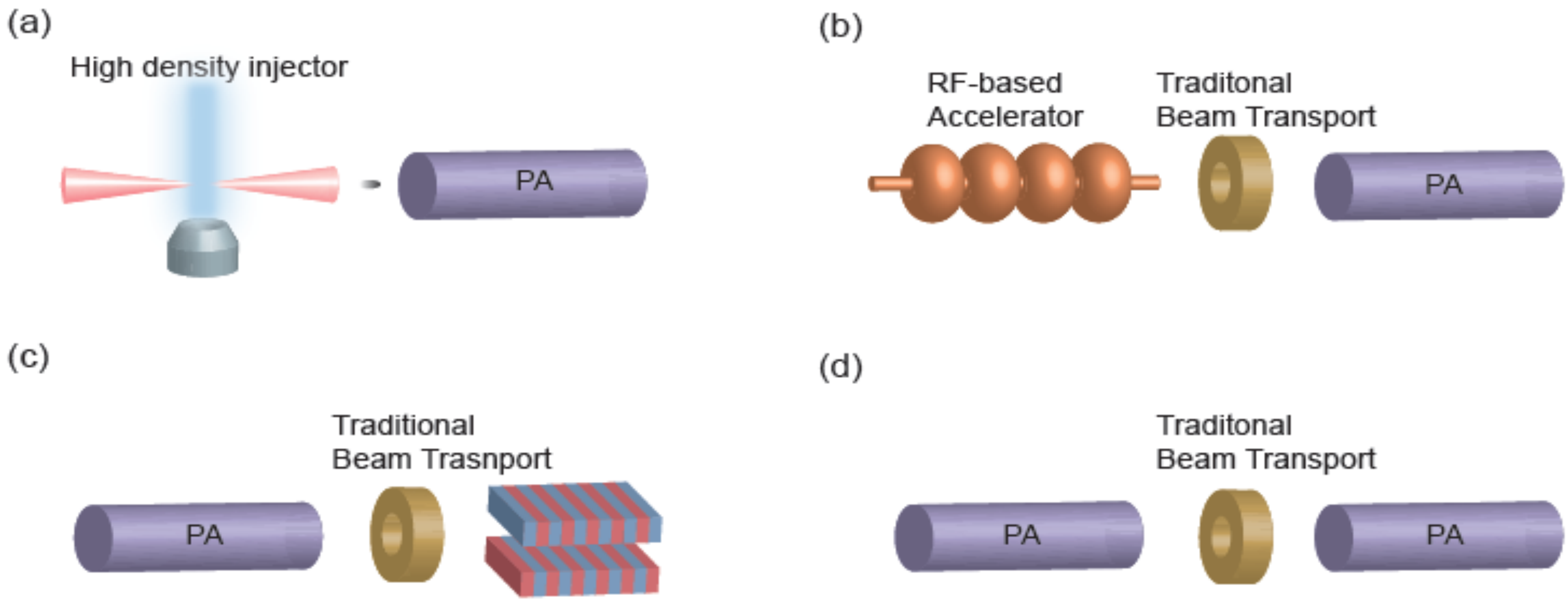


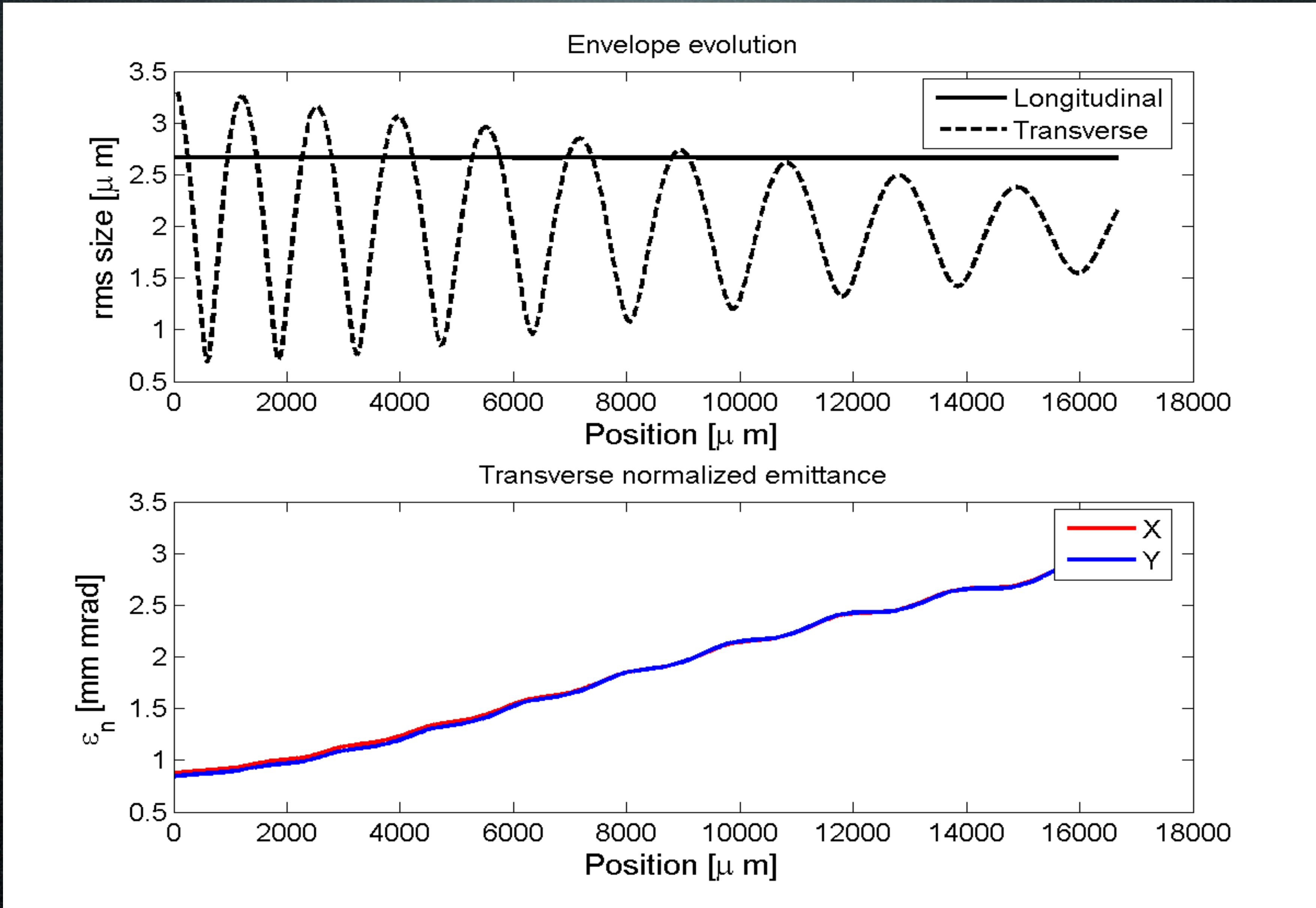
Laser-Plasma-Accelerator LC

Leemans & Esarey, Physics Today (March 2009)



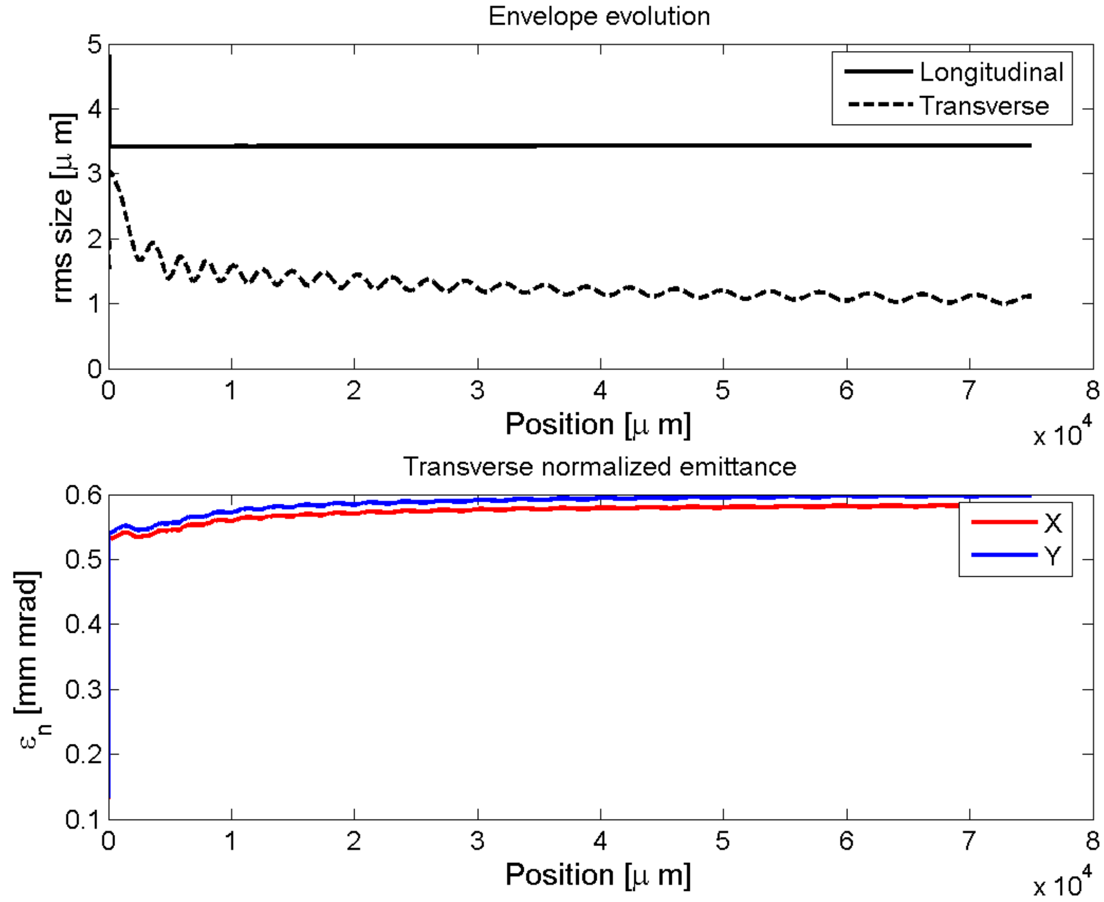
Injection, Extraction & Matching



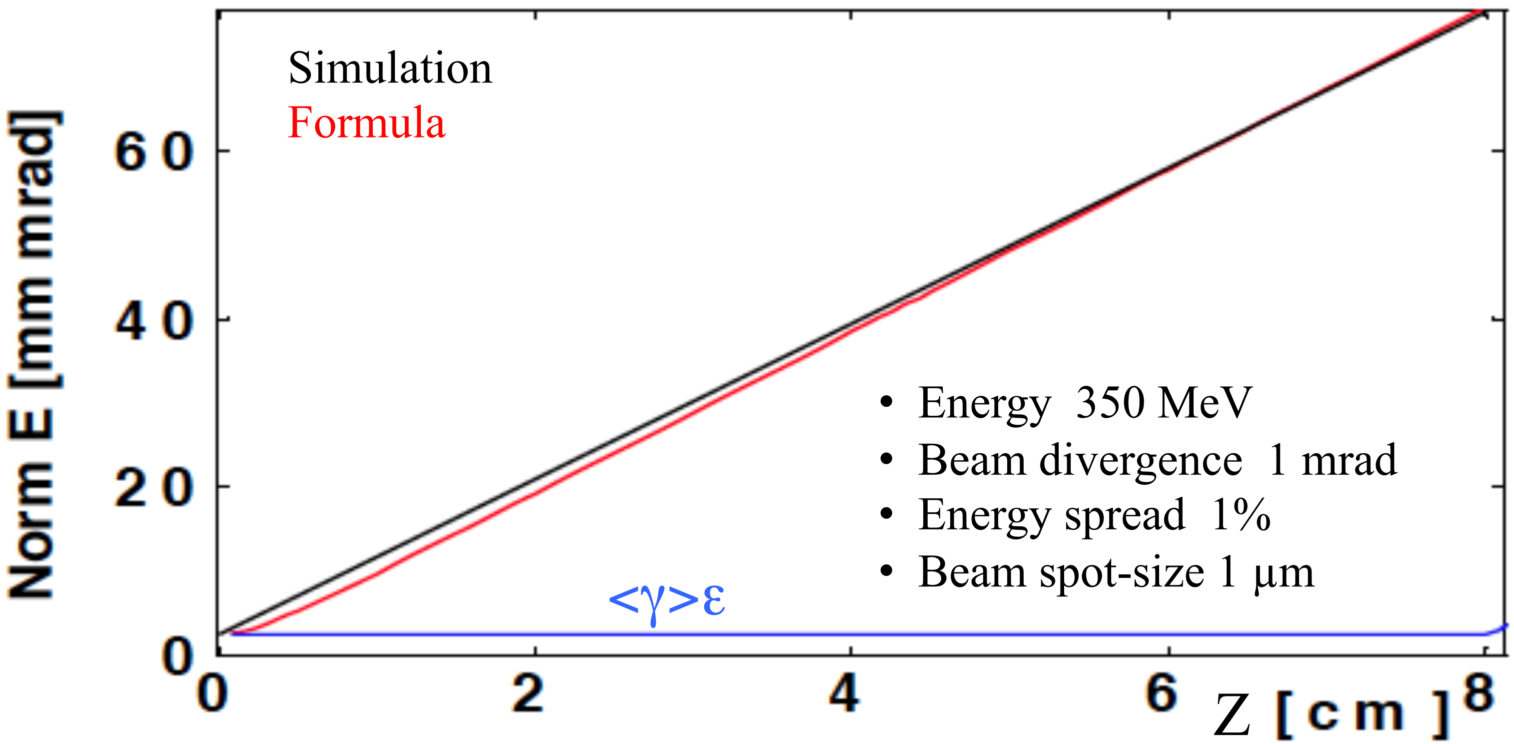


Courtesy P. Tomassini

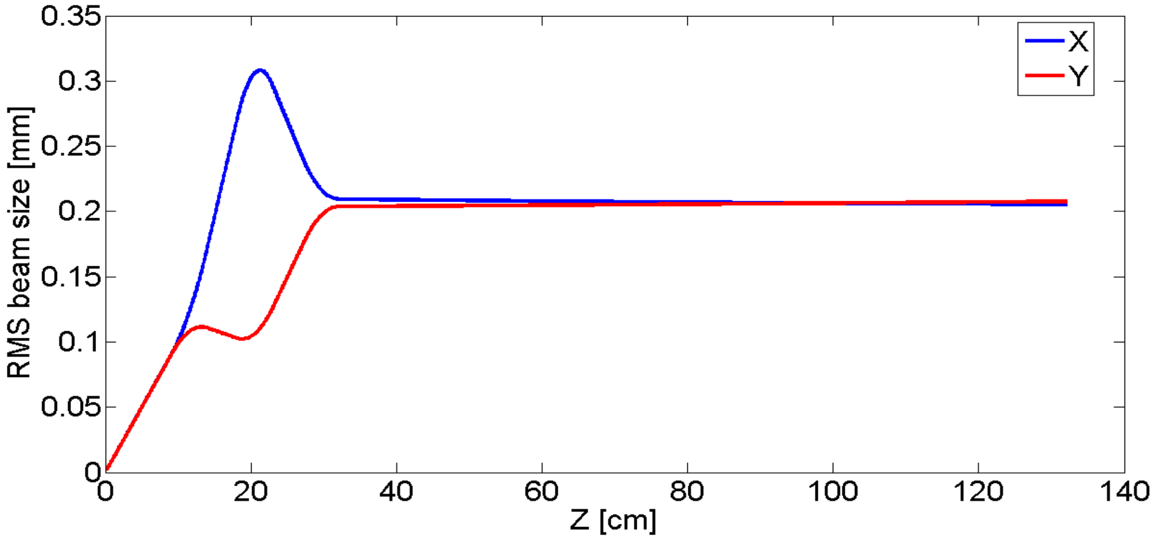
$$\sigma_\varepsilon = \sqrt[4]{\frac{3}{\gamma}}\sqrt{\frac{\varepsilon_n}{k_p}}$$



$$\varepsilon_n^2 = \langle\gamma\rangle^2(s^2\sigma_E^2\sigma_{x'}^4 + \varepsilon^2)$$



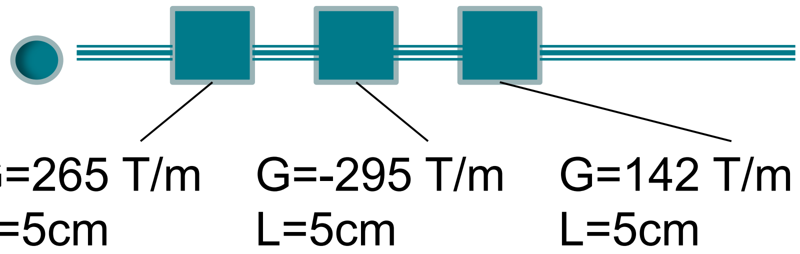
Beam transport line simulated with TSTEP

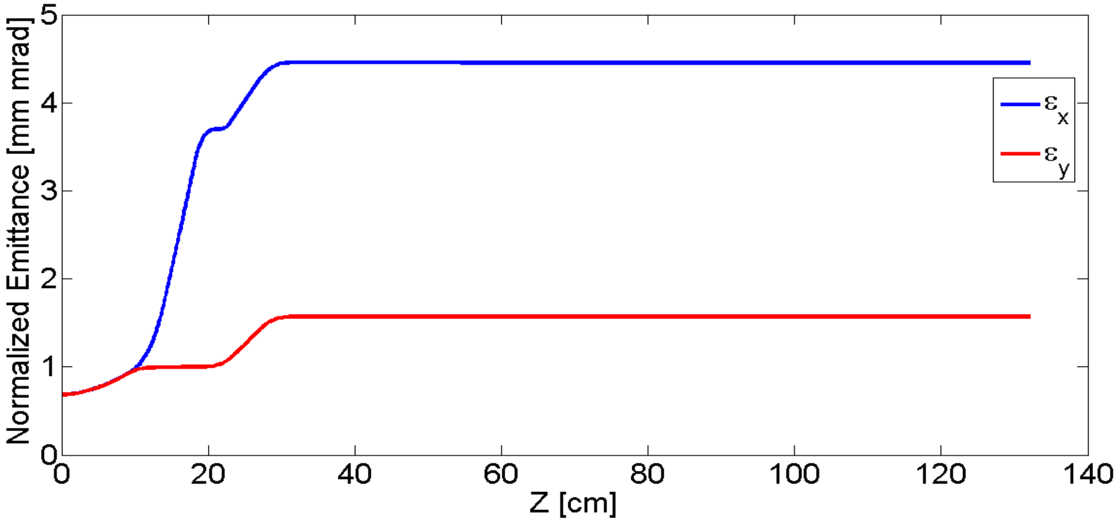


Beam transport line based on a triplet-lattice.

Beam parameters are:

- Energy 350 MeV
- Beam divergence 1 mrad
- Energy spread 1%
- Beam spot-size 1 μm





Keeping the **beam size under control** is possible, **but normalized emittance grows** throughout the beamline.

$$\Delta\varepsilon_{n,rms} = \langle\gamma\rangle\left|\left(\sigma_{\gamma}k_{q}l_{q} + \sigma'_{o}\right)\sigma_{o}^{2} + \sigma_{o}\sigma'_{o}\right|$$

Demonstration of electron beam focusing by a laser-plasma lens

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J.-P. Goddet,[1] A. Tafzi,[1] A. Flacco,[1] F. Tissandier,[1] S. Sebban,[1] A. Rousse,[1] and V. Malka[1]

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[2] *Centro de Laseres Pulsados, Parque Cientfico, 37185 Villamayor, Salamanca, Spain*

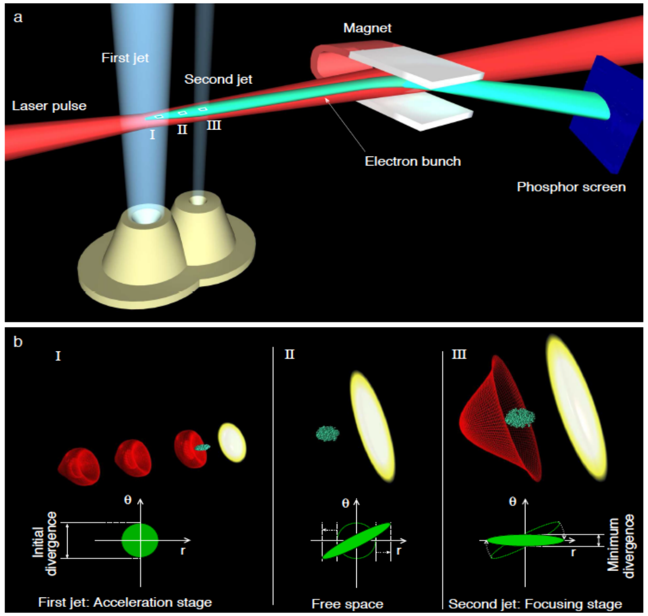
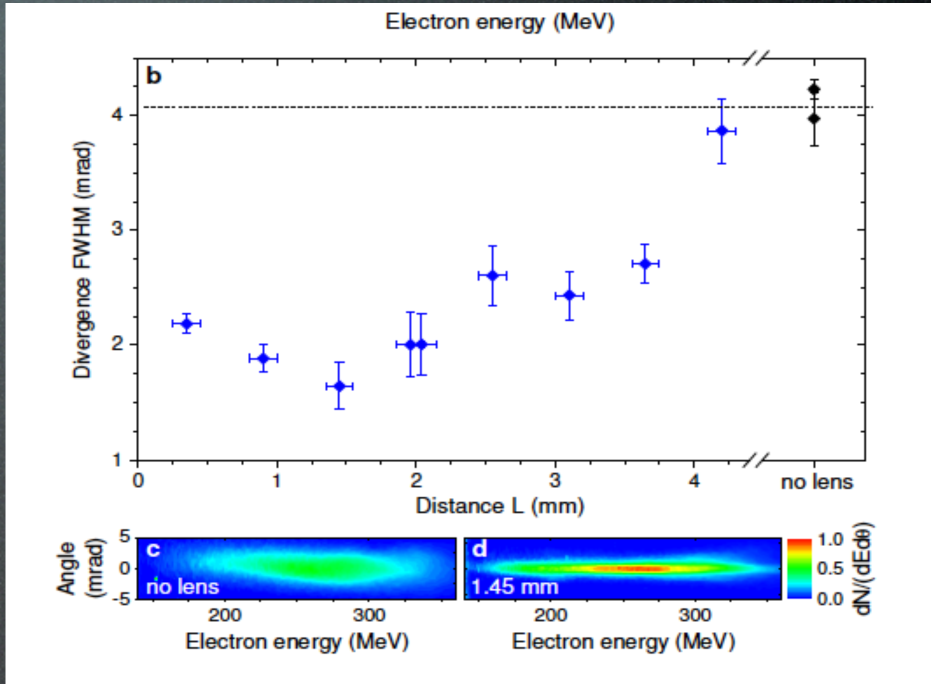
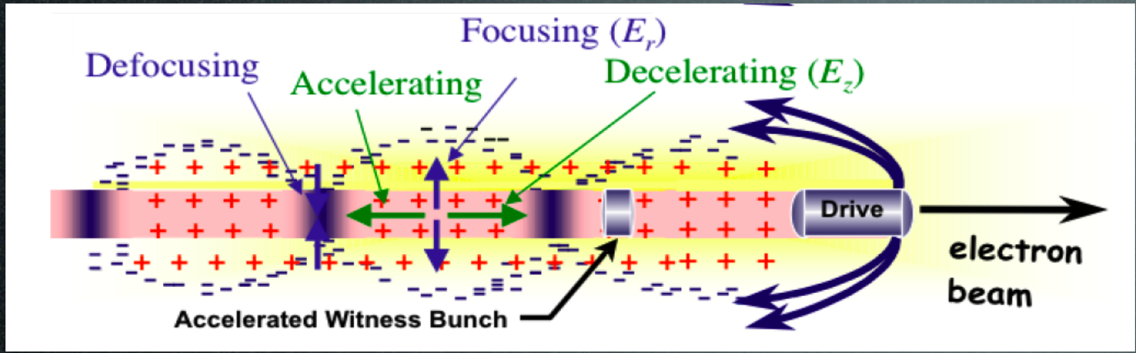
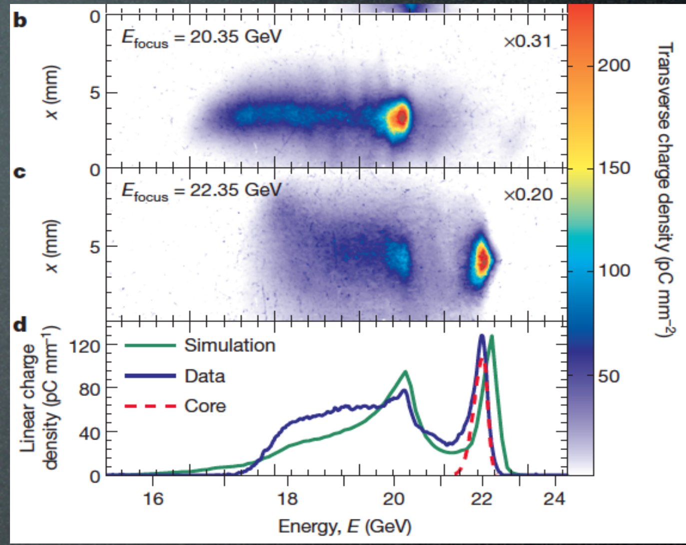


FIG. 1. Principle scheme of the laser-plasma lens. (a) An electron beam is accelerated in the first gas jet (accelerator), then it enters free space where it diverges, and is eventually focused in the second gas jet (lens). The same laser triggers a wakefield in both gas jets. Electron spectra are measured using an electron spectrometer consisting of a dipole magnet and a phosphor screen, imaged by a CCD camera. (b) Phase spaces at the end of the acceleration (I), drift (II) and focalization (III) stages.



Beam Driven Plasma Wake Field Acceleration





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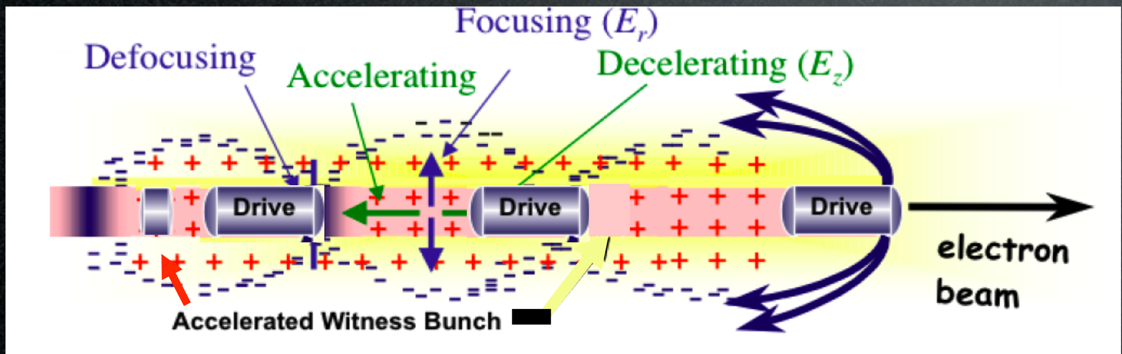
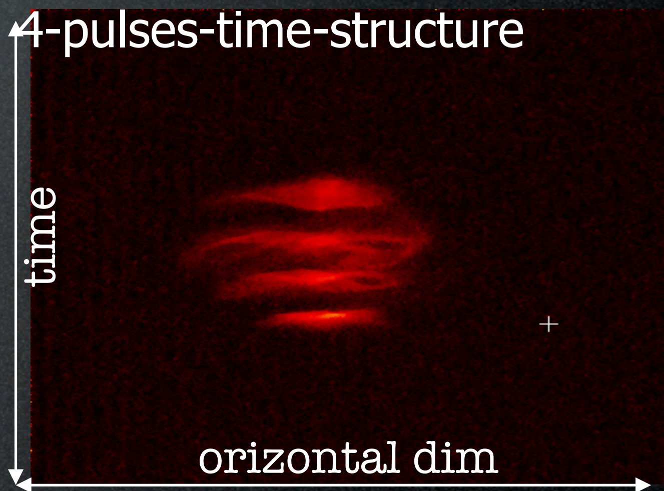




In progress at SPARC_LAB

Submitted to HORIZON 2020 FET, (ELBA, M. Ferrario, E. Chiadroni, A. Cianchi)

Quasi-nonlinear regime of PWFA

Condition for blowout: $\frac{n_b}{n_p} > 1$

A measure of nonlinearity is the normalized charge:

$$\tilde{Q} \equiv \frac{N_b k_p^3}{n_p} = 4\pi k_p r_e N_b \begin{cases} << 1, & \text{linear regime} \\ > 1, & \text{nonlinear "blowout".} \end{cases}$$

Using *low emittance, high brightness* beams, can achieve:

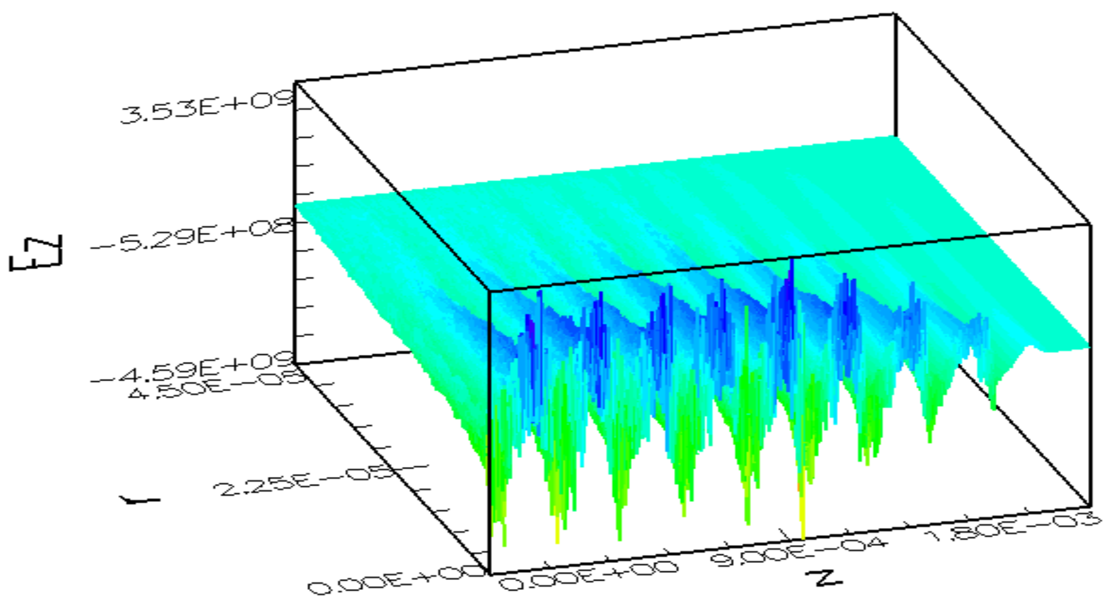
$$\tilde{Q} < 1 \qquad \frac{n_b}{n_p} > 1$$

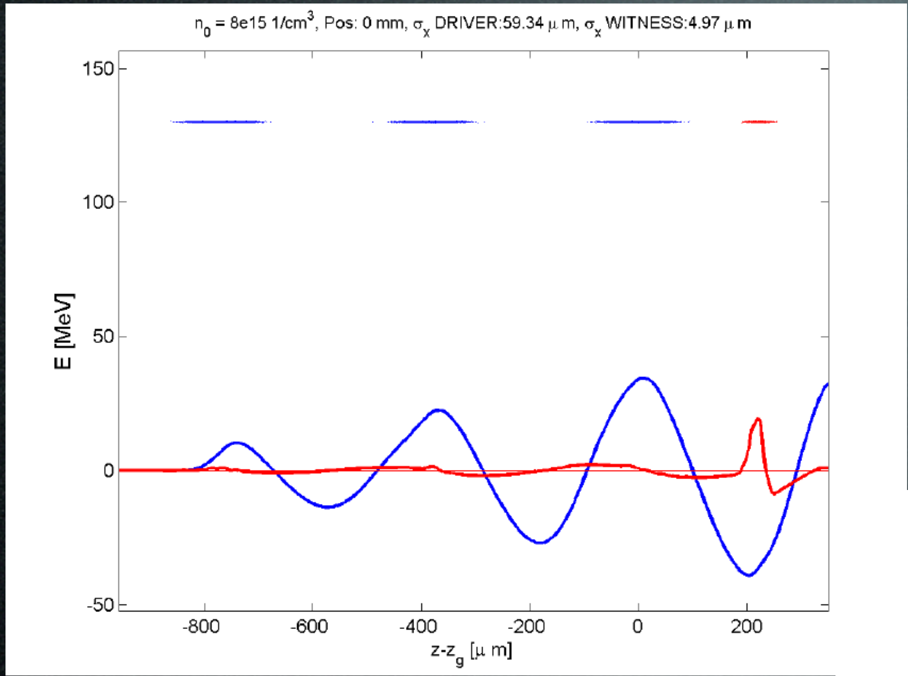
These conditions define the *quasi-nonlinear* regime

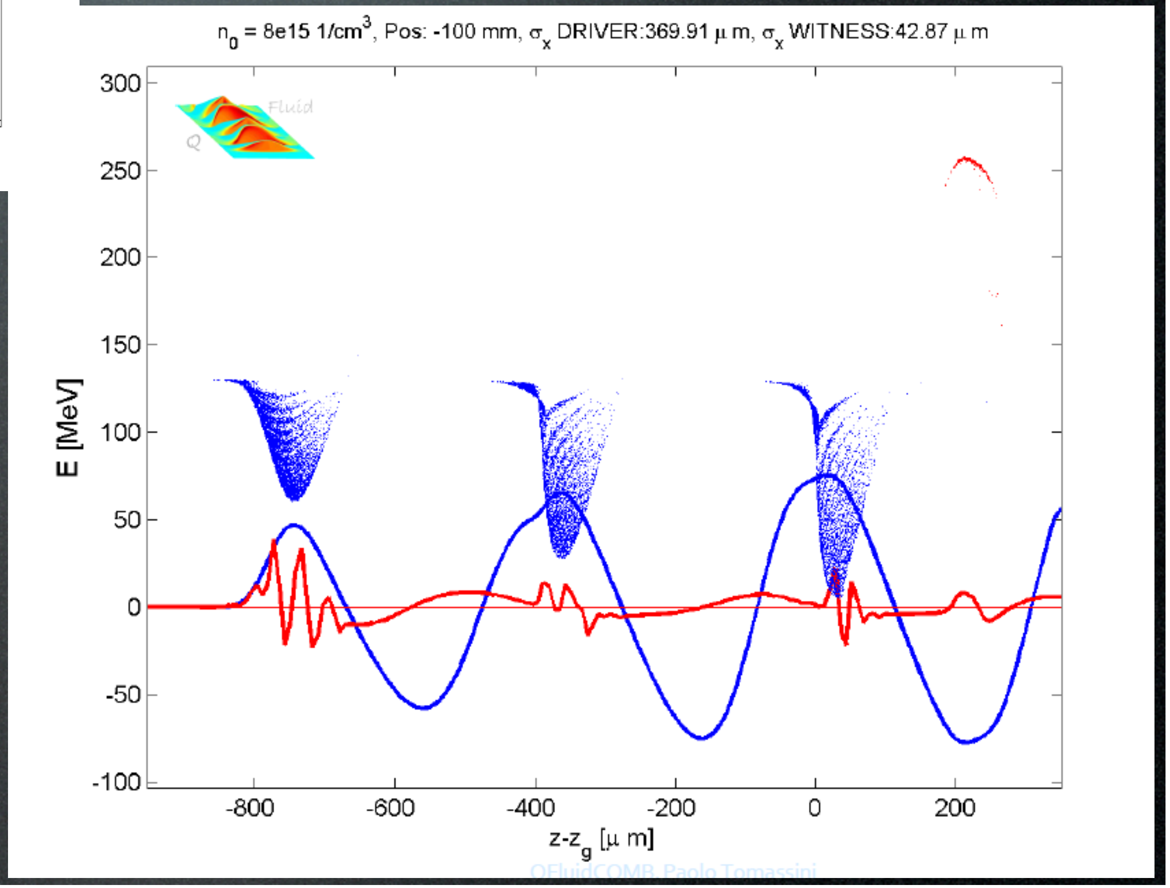
Multipulse PWFA operation in quasi-nonlinear regime

- Resonance works well (at λ_p!)
- SPARC (INFN-LNF) example gives 3 GV/m
  - Original example!

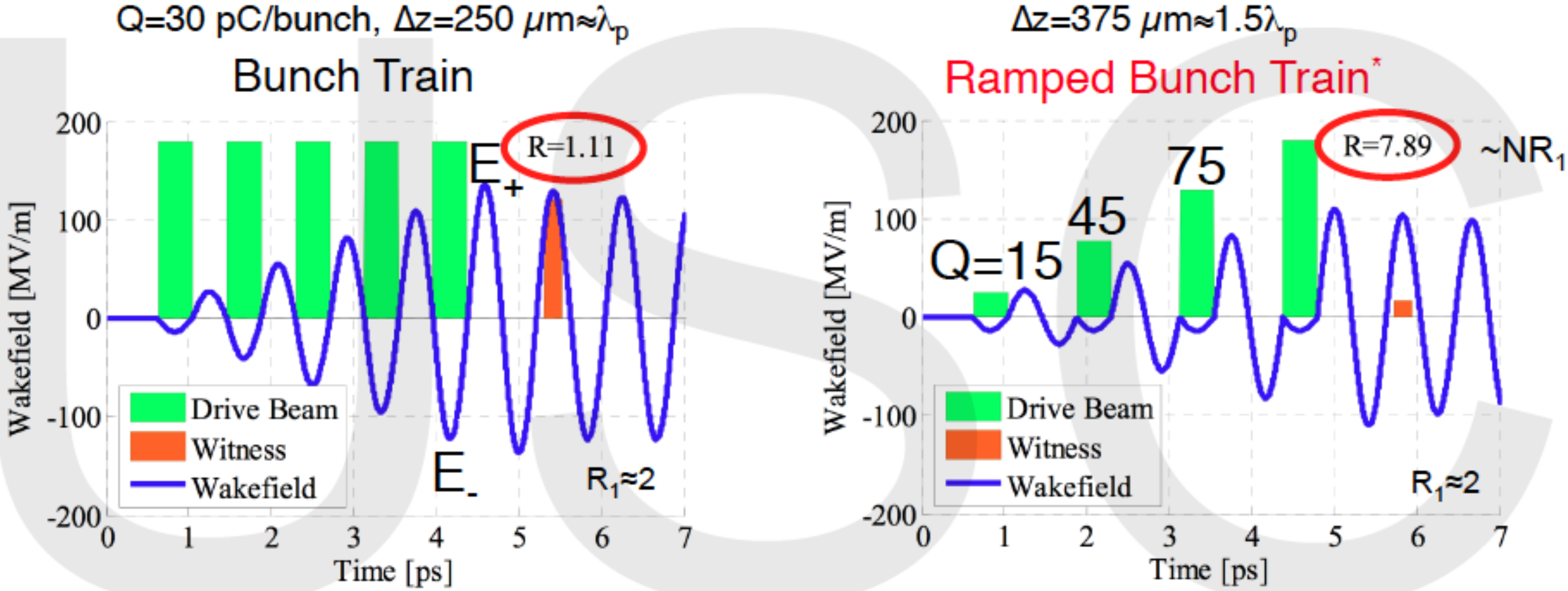
Example:
pulses=4
N_b=1E8
n_e=3E16 cm^{-3}
λ_p=190 μm
$\tilde{Q}_1$=0.117




n0 = 8e15 1/cm3, Pos: 0 mm, σx DRIVER:59.34 μ m, σx WITNESS:4.97 μ m
E [MeV]
z-zg [μ m]


n0 = 8e15 1/cm3, Pos: -100 mm, σx DRIVER:369.91 μ m, σx WITNESS:42.87 μ m
E [MeV]
z-zg [μ m]

Ramped Bunch Train → longer active length



Kallos, PAC'07 Proceedings

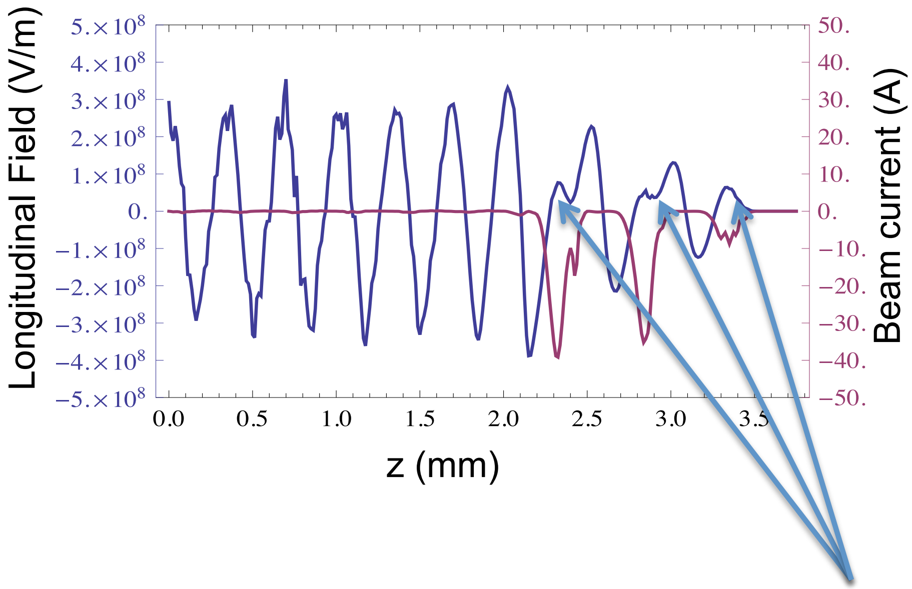
*Tsakanov, NIMA, 1999

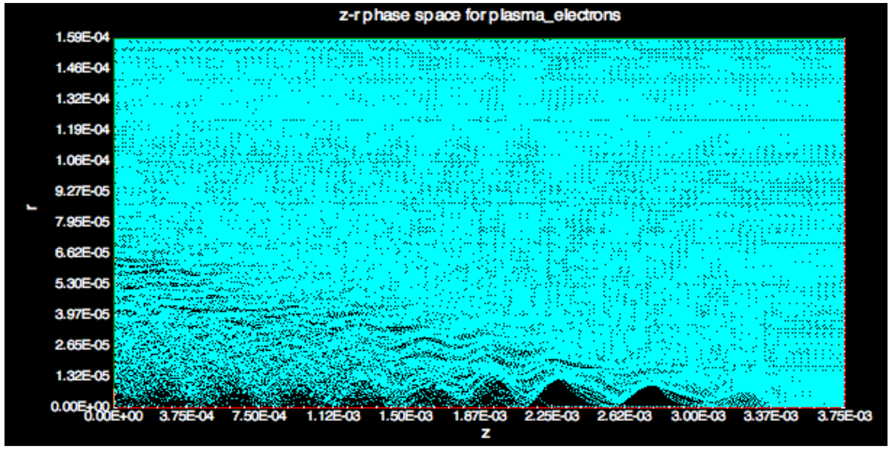
Resonant approach: ramped *bunch train*

Using same ATF pulse train format as before, we can change n_0 such that the $\lambda = 1.5\,\lambda_p$ i.e. $n_0 = 1.0 \times 10^{16}\, cm^{-3}$

To simulate ramp, total charge is kept fixed but redistributed:

$$Q_1 = \frac{1}{3} Q_0 \qquad Q_2 = Q_0 \qquad Q_3 = \frac{5}{3} Q_0 \qquad \text{with} \qquad Q_0 = 30\, pC$$





Decelerating field the same inside each bunch

Transformer ratio increased to ~4 for three pulse train

Laser Comb technique: generation of a train of short bunches

(Parmela code)

Charge vs. Time

Energy vs. Time

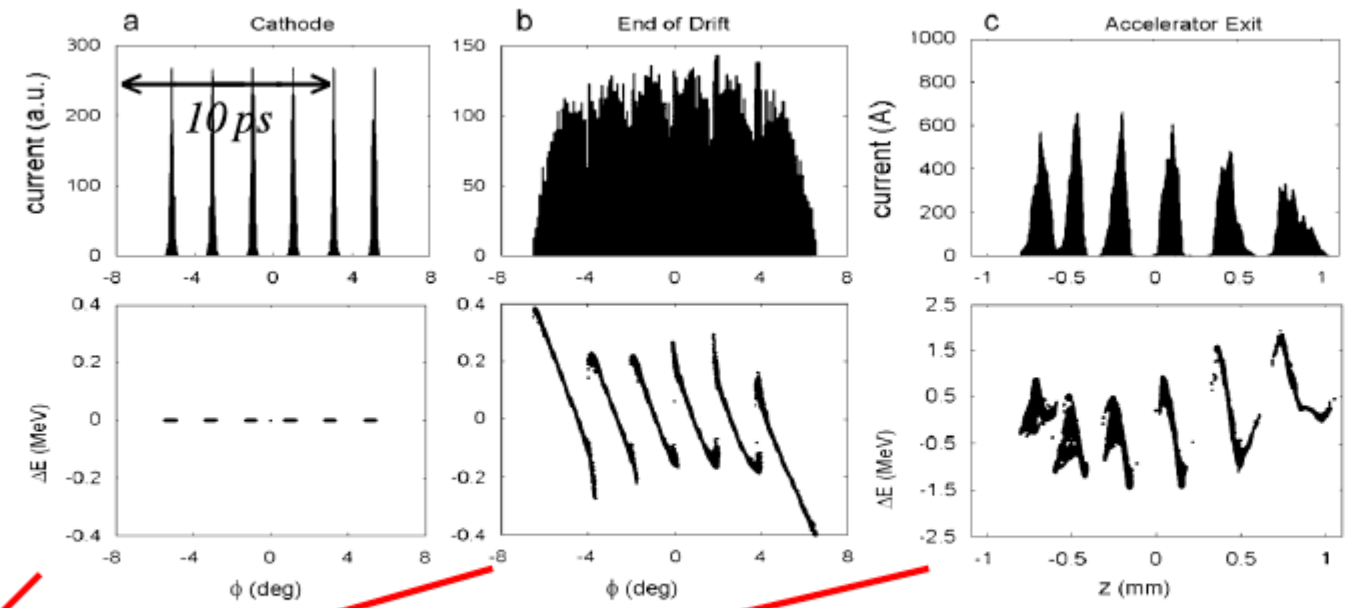
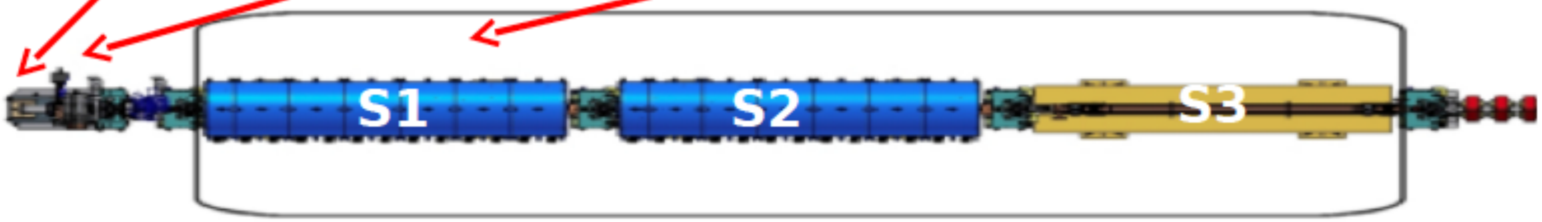
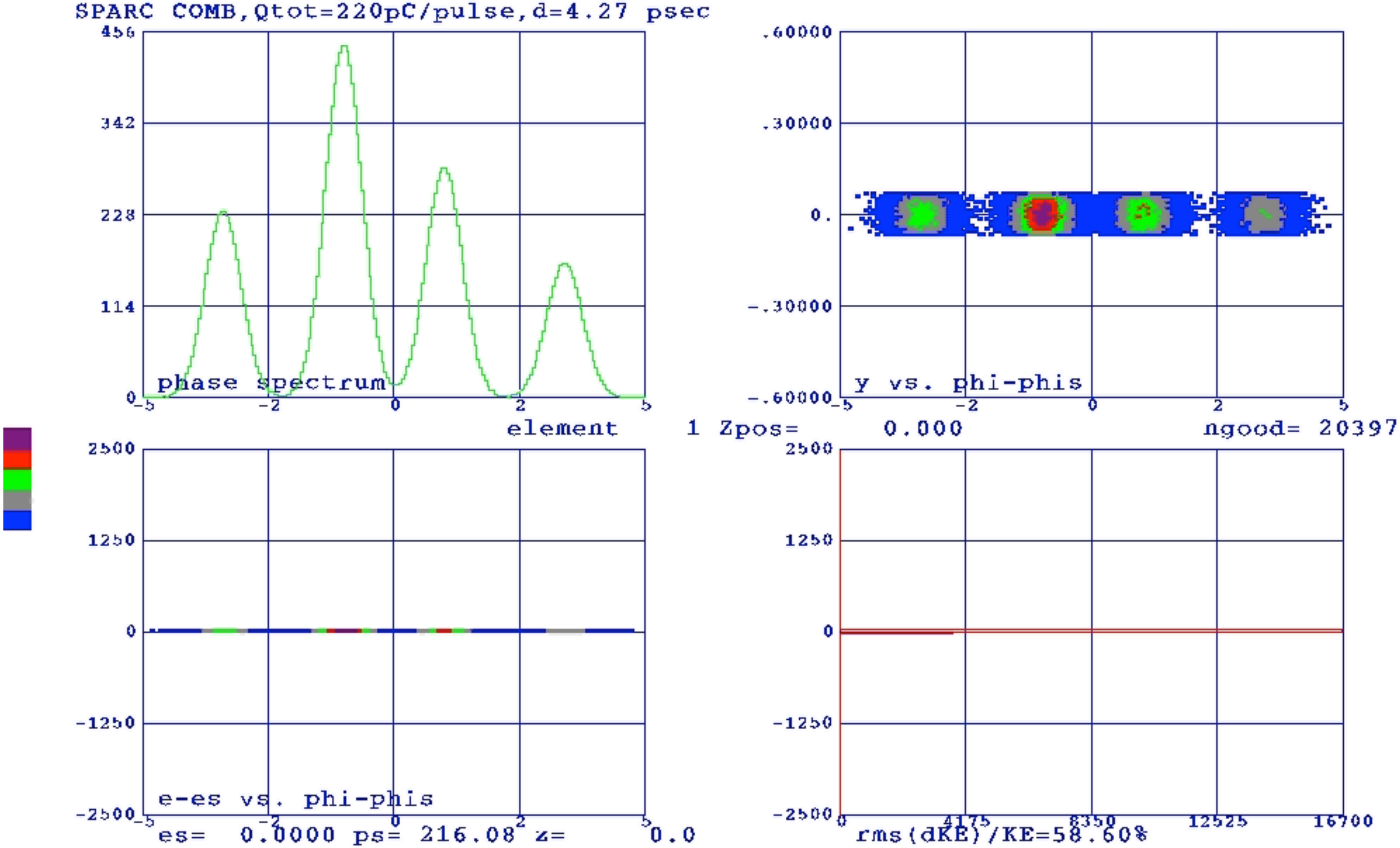


Fig. 1. Evolution of a six bunches electron beam train: the columns from left refer, respectively, to (a) the cathode, (b) the end of the drift at 150 cm and (c) the end of linac at 12 m far from cathode. The rows from top refer, respectively, to longitudinal profile and to energy modulation ΔE (MeV).

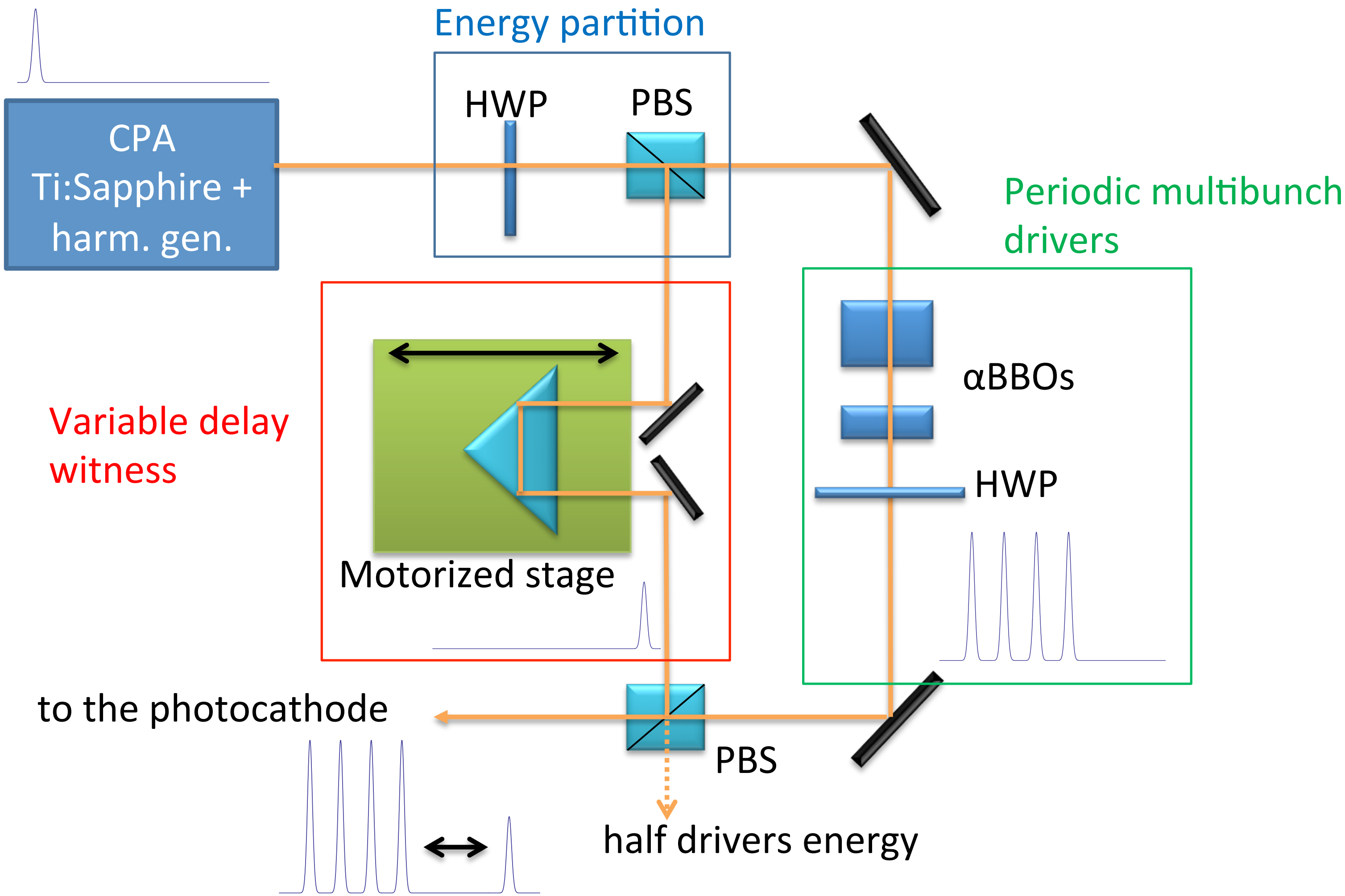


- P.O.Shea et al., Proc. of 2001 IEEE PAC, Chicago, USA (2001) p.704. (Low charge regime only)
- M. Ferrario. M. Boscolo et al., Int. J. of Mod. Phys. B, 2006 (High charge, Beam Echo)

Overcompression

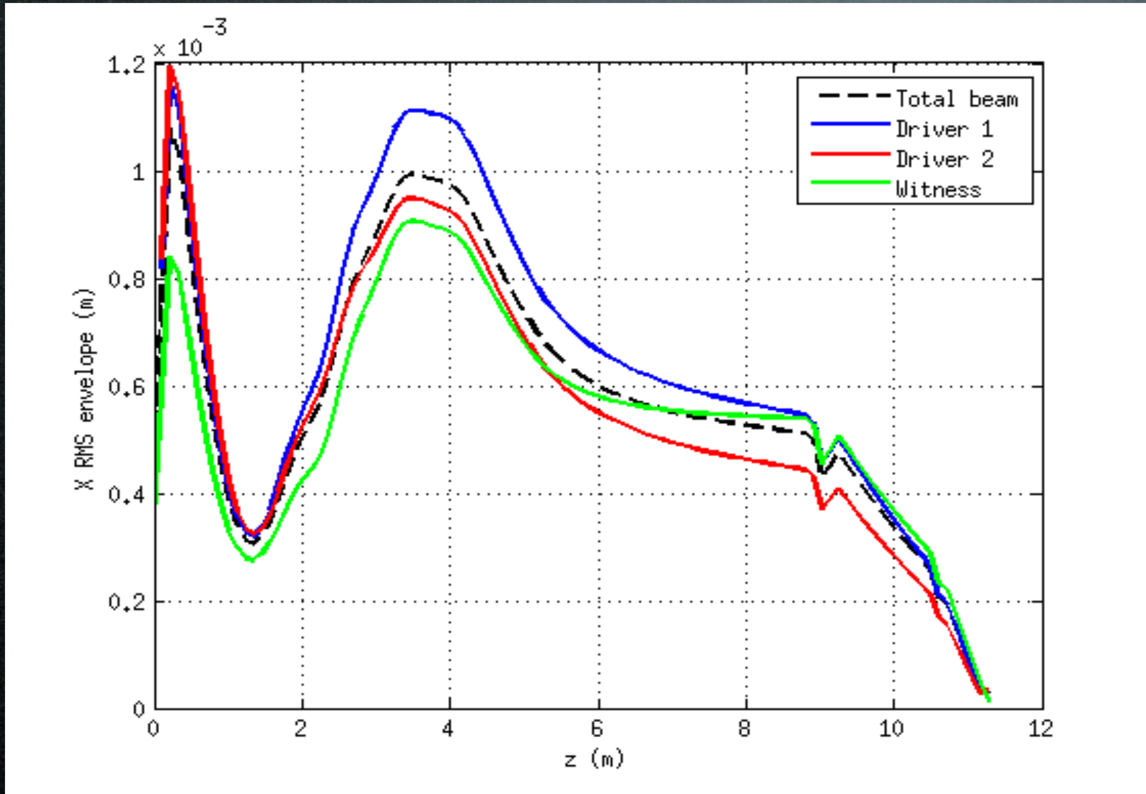


Driving and witness bunches generation

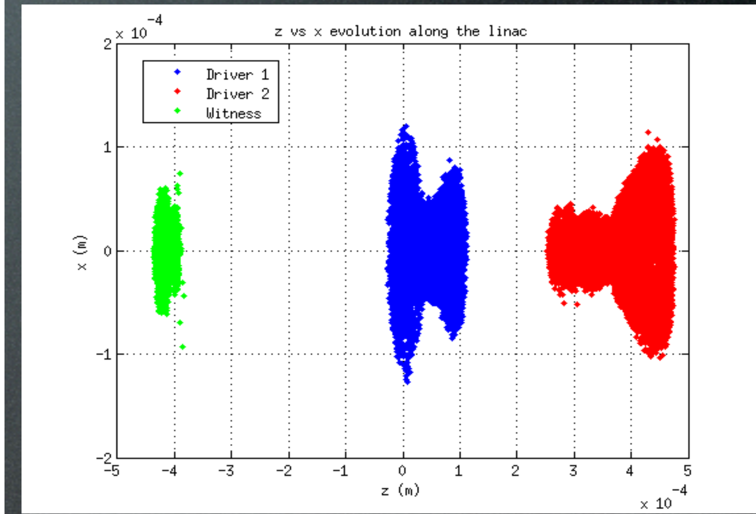


Courtesy F. Villa

•2x50 pc +1x25pC



•Plasma input beam



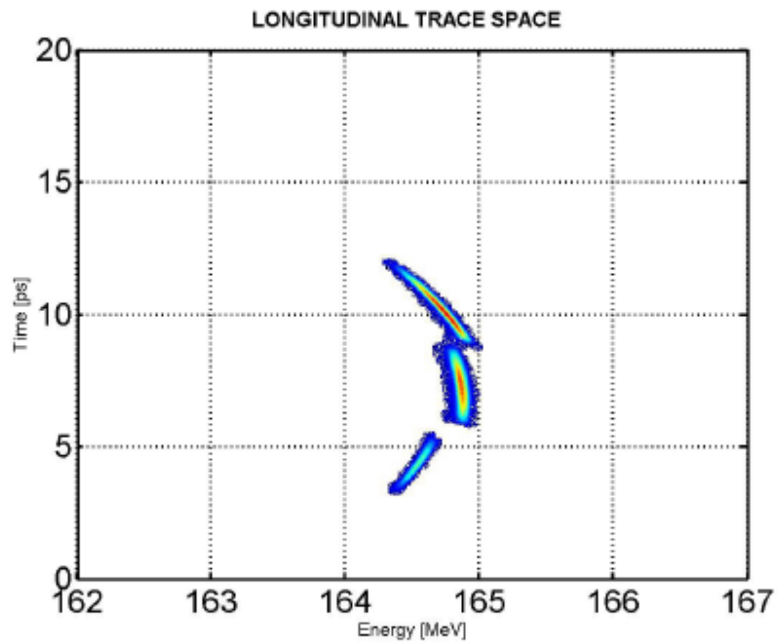
•rms spot: 33 um (driver 1 and driver 2), 13 um (witness)

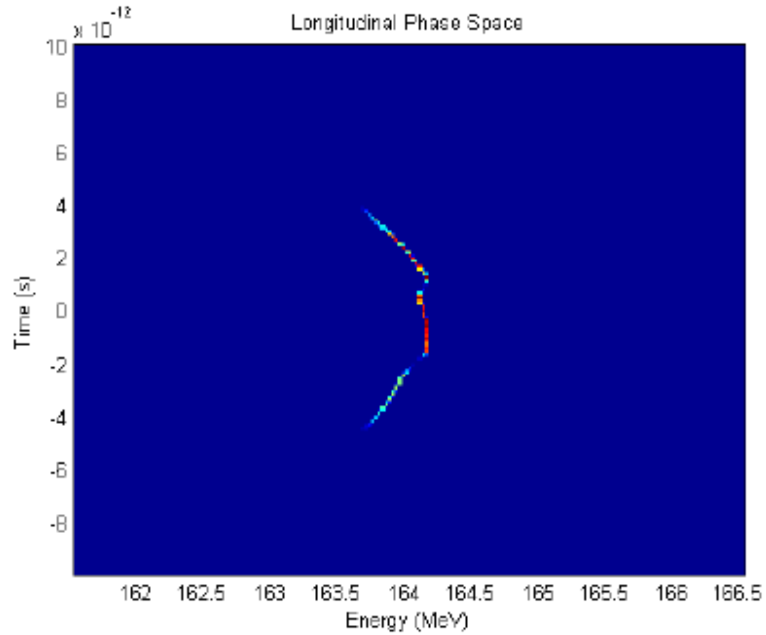
•rms emittance: 2 um (driver 1), 1.6 um (driver 2), 1.2 um (witness)

•rms length: 31 um (driver 1), 55 um (driver 2), 7.4 um (witness)

Courtesy R. Pompili

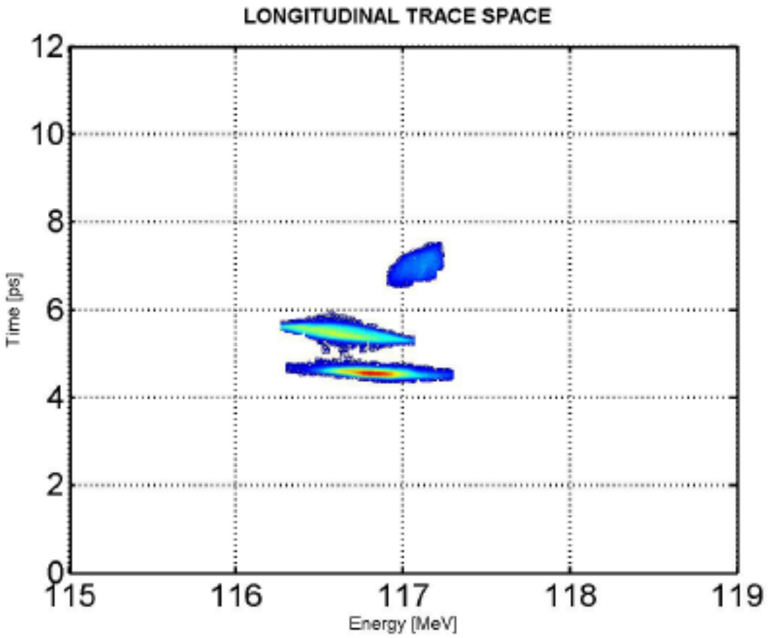
"On Crest" configuration

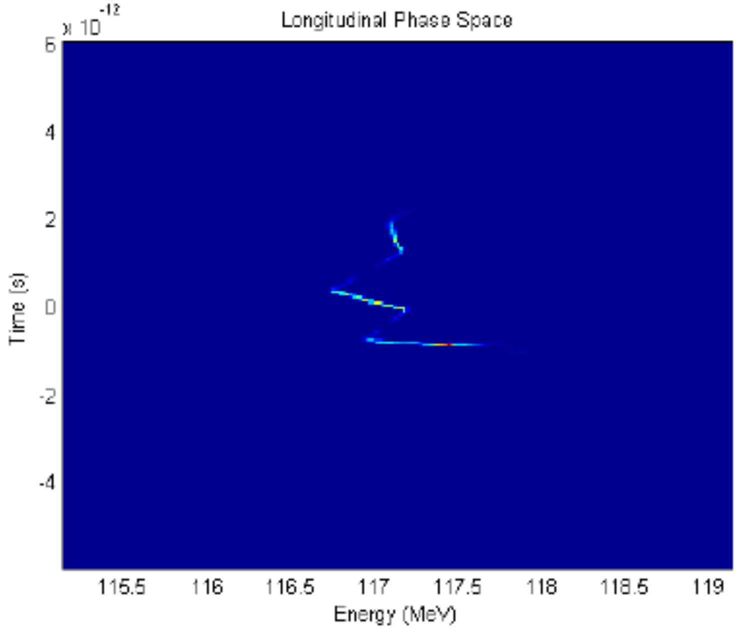




- Experimental Data
  - Charge: 40-40-20
  - Energy (Gun): 5.2 MeV
  - Energy (Linac): 164 MeV
  - Energy Spread: 150 keV
  - Duration: 2.2 ps
  - Emittance: 1.04(1.05) um X(Y)
- GPT simulation
  - Charge: 40-40-20
  - Energy (Gun): 5.22 MeV
  - Energy (Linac): 164 MeV
  - Energy Spread: 130 keV
  - Duration: 2.16 ps
  - Emittance: 0.5 mm mrad

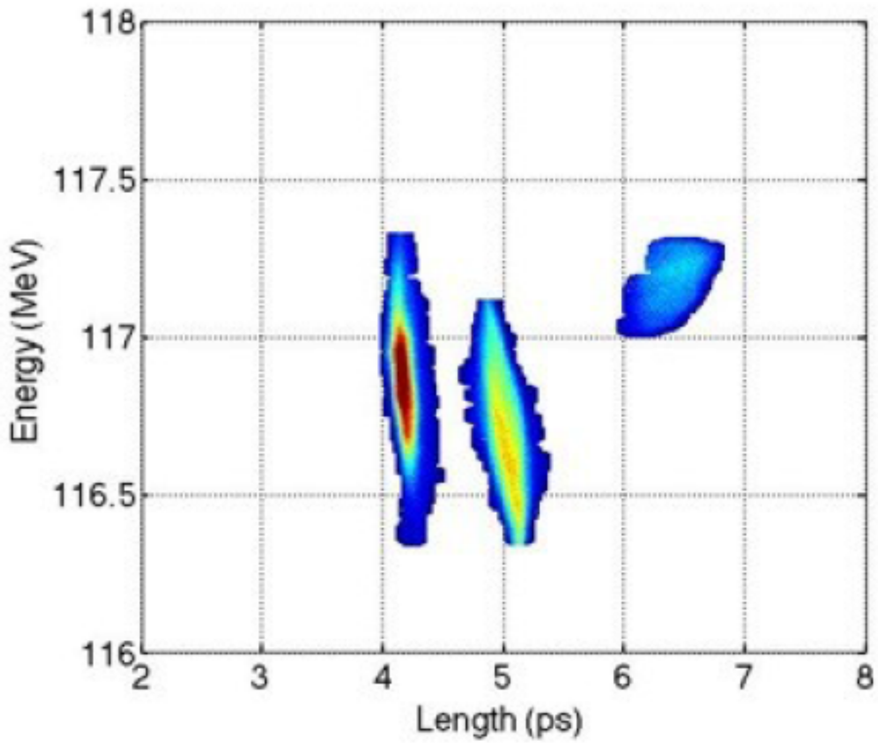
Velocity Bunching configuration

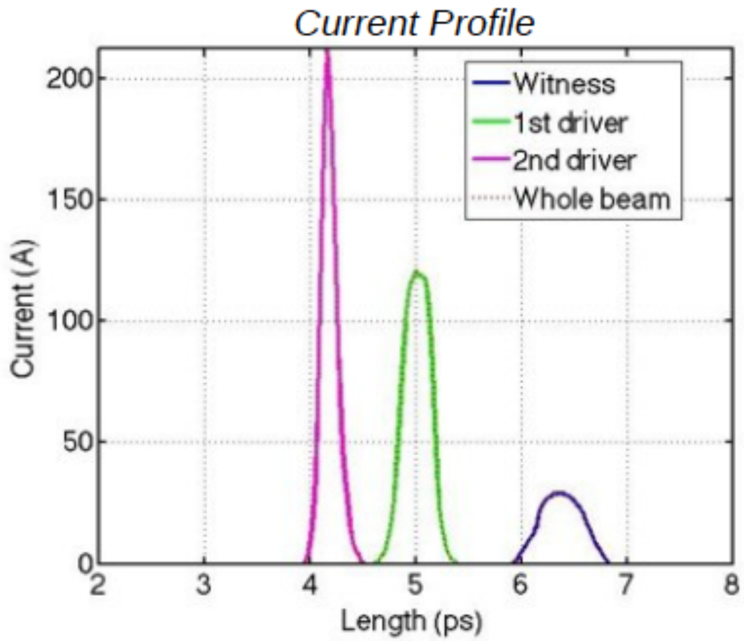


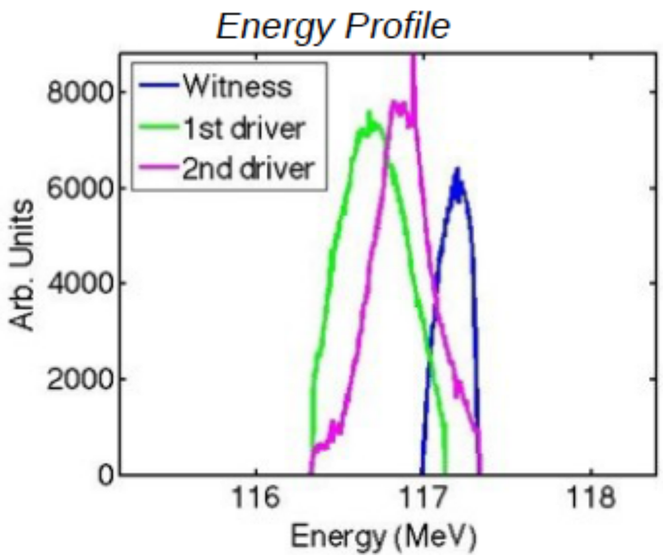


- Experimental Data
  - Energy (Linac): 116 MeV
  - Energy Spread: 250 keV
  - Duration: 730 fs
  - Emittance: 2.7 (4.8) um X (Y)
  - Driver Distance: 0.88 ps
  - Witness Distance: 1.49 ps
- GPT simulation
  - Energy (Linac): 117 MeV
  - Energy Spread: 220 keV
  - Duration: 886 fs
  - Emittance: 6 um
  - Driver Distance: 0.97 ps
  - Witness Distance: 1.4 ps

COMB beam for PWFA: first results



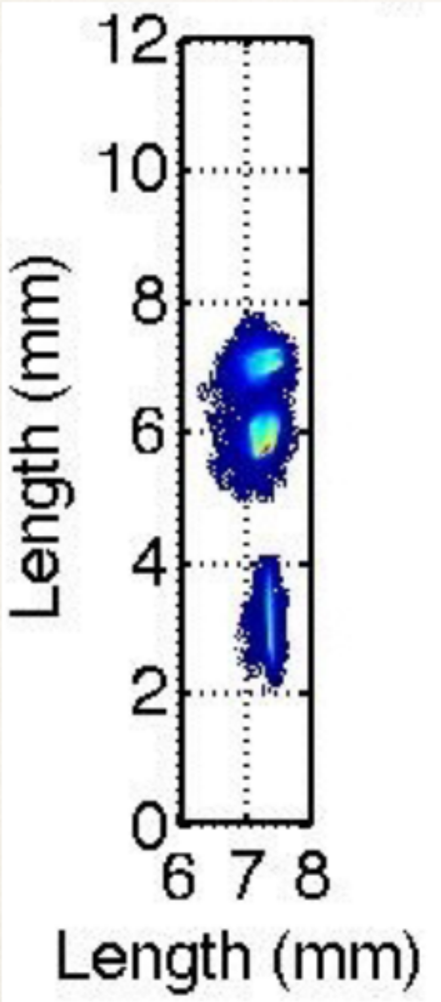




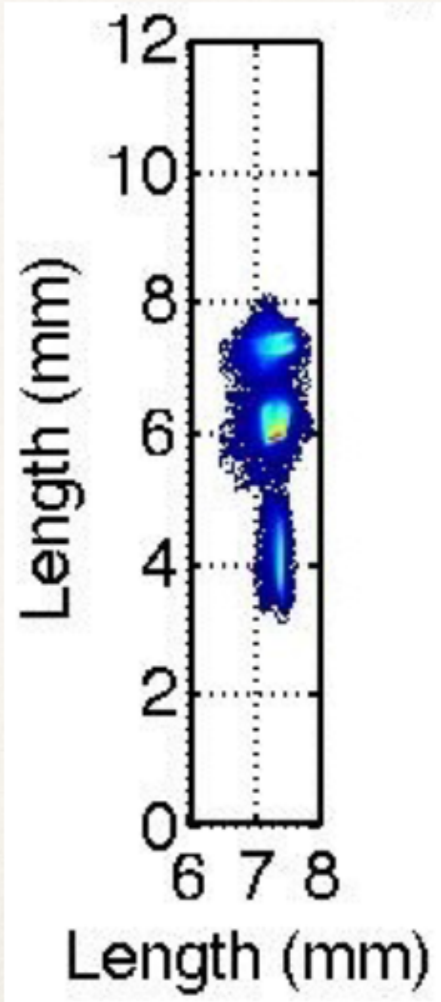
Distance between drivers:	0.82 ps
Driver – Witness distance:	1.37 ps
Driver 1 length:	81 fs (Q 43%)
Driver 2 length:	124 fs (Q 40%)
Witness length:	190 fs (Q 17%)

Delayed Witness Bunch

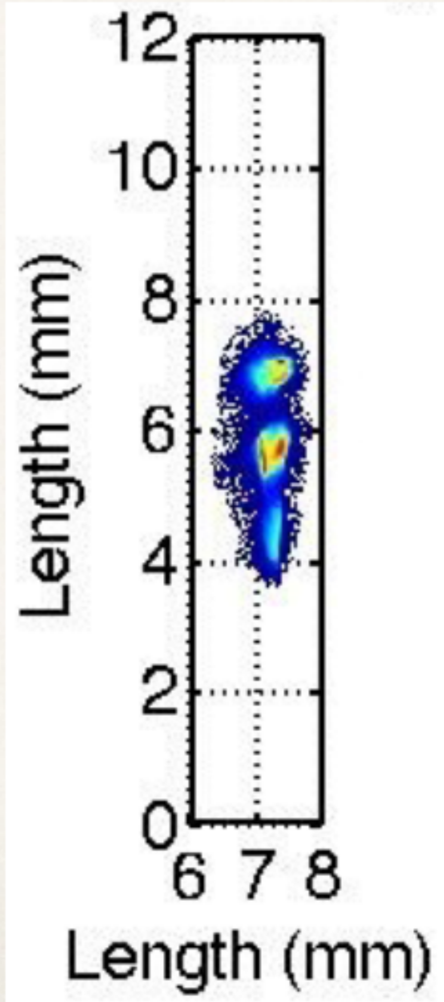
-100 steps <=> 1.67 ps



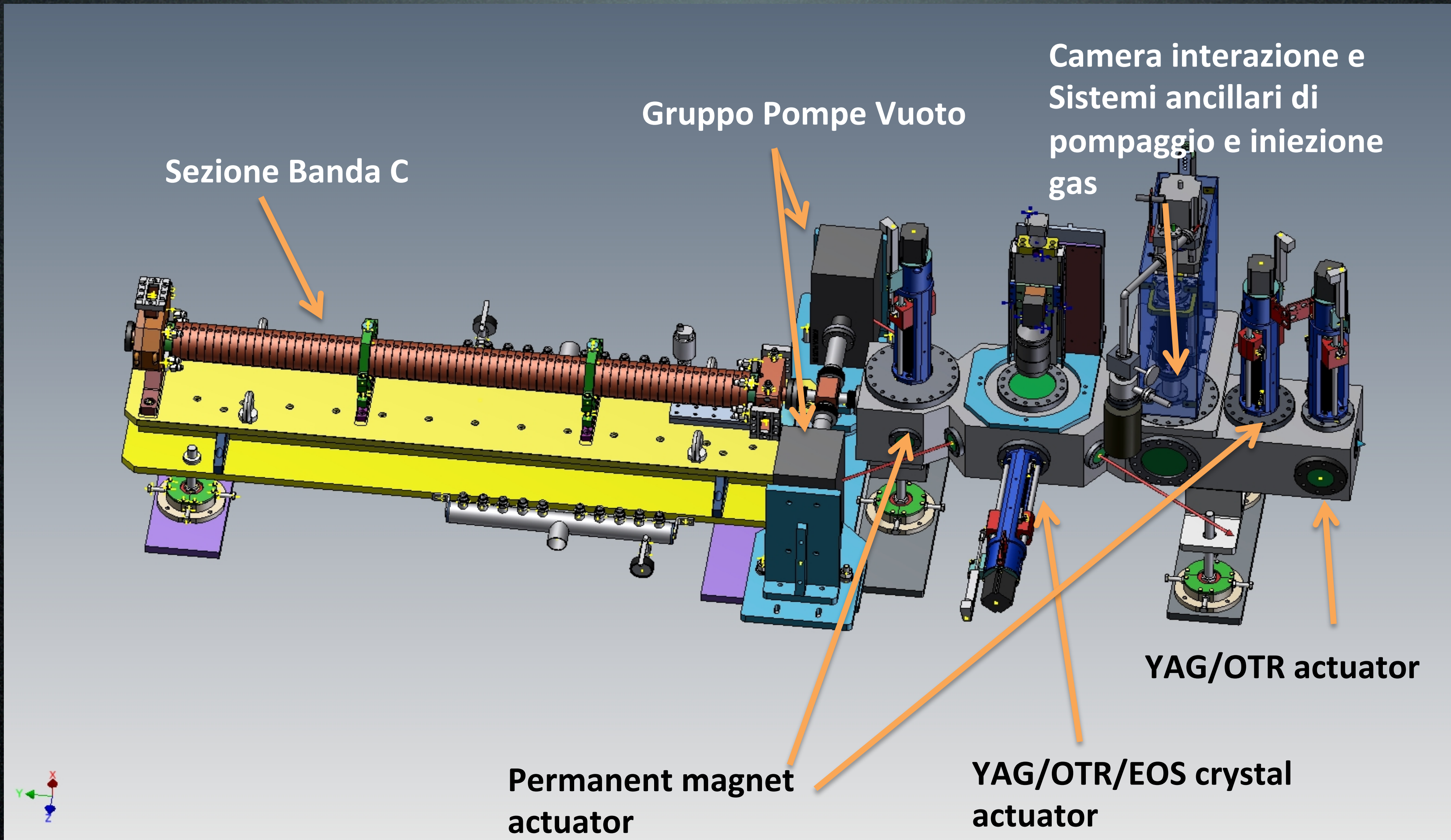
Reference position



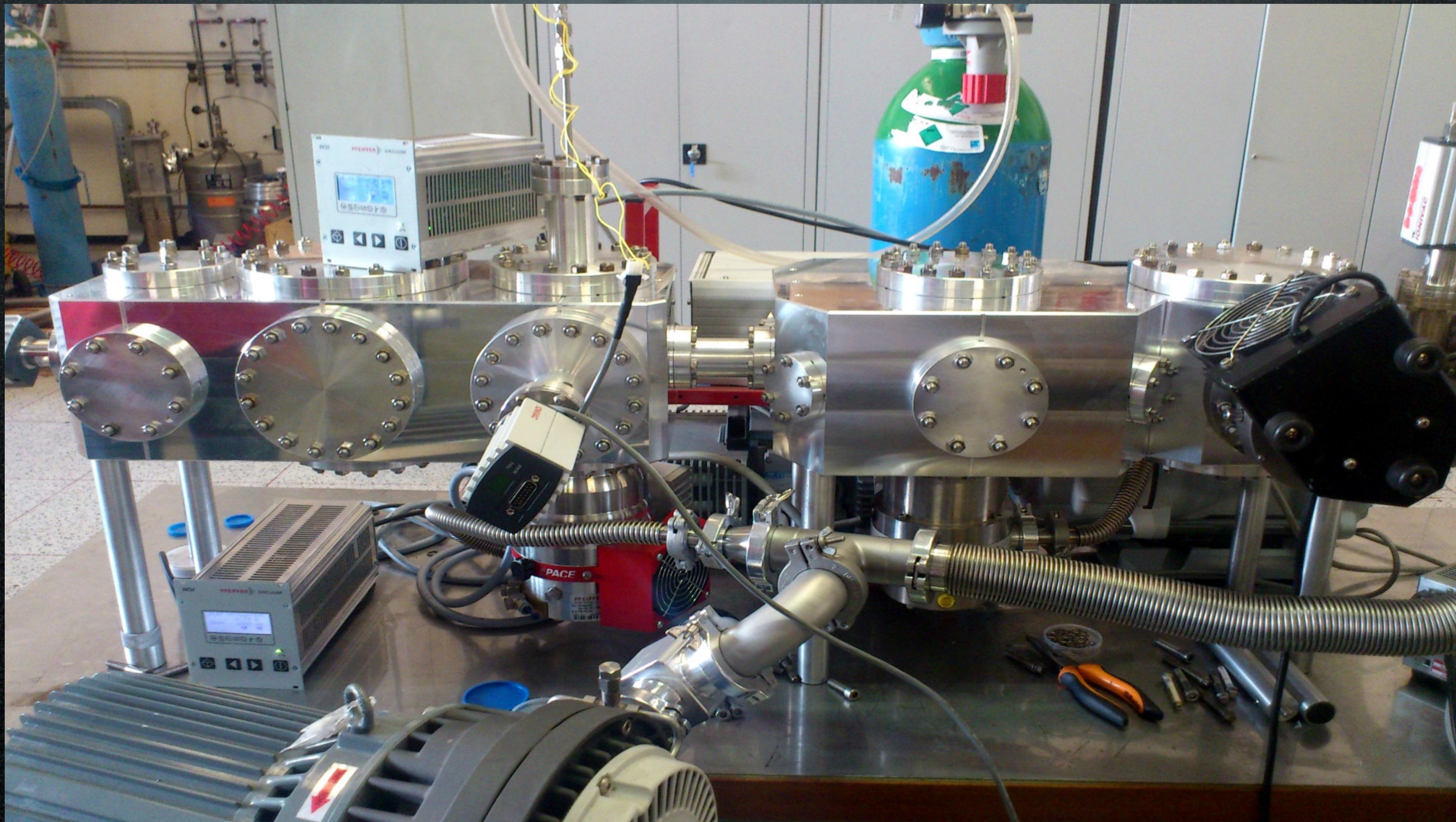
100 steps <=> 1.67 ps



COMB plasma interaction chamber

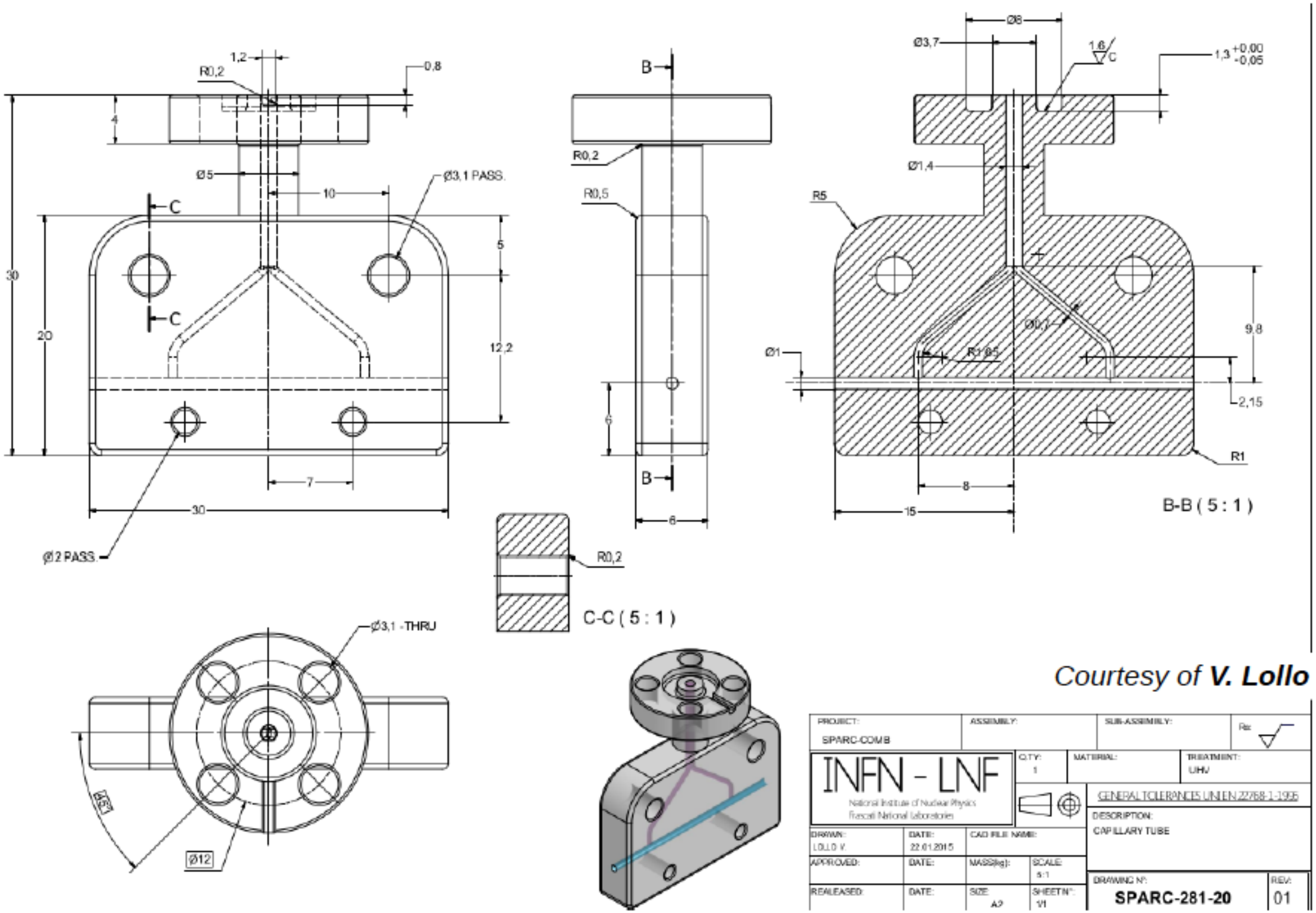


COMB interaction chamber delivered in July 2014
Dedicated plasma lab needed



Courtesy M. P. Anania

Plasma capillary



Courtesy of ***V. Lollo***

Laser Driven Plasma Wake Field Acceleration

Preliminary studies

Position	1	2	3	4
Charge (pC)	20	20	20	14
σ_x (μm)	120	450	13	3.5
σ_z (μm)	90	21	8.7	8.7
Energy (MeV)		78	78	630
Energy spread (% uncorr.)		0.1	0.2	1
ε_{xn} (mm mrad)		0.23	2.7	3.5

Capillary
10 cm length
Quasi-nonlinear regime
~5 GV/m
R_c=60μm
$n_0=1\times10^{17}\ cm^{-3}$

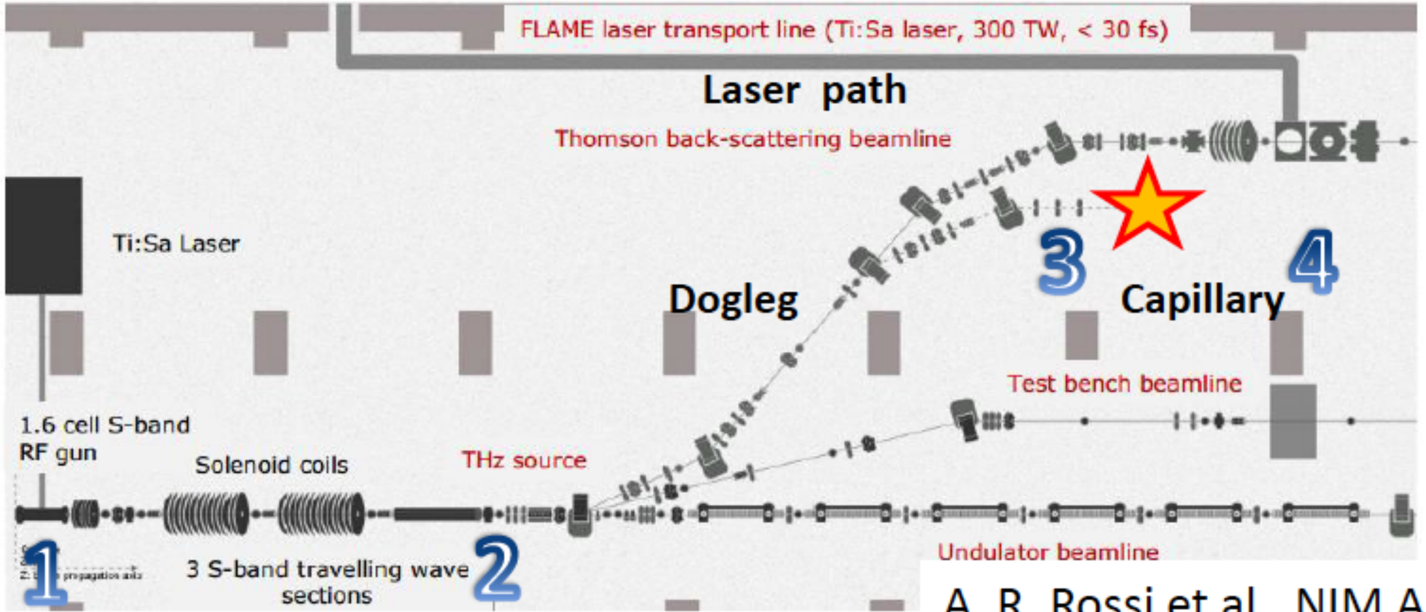
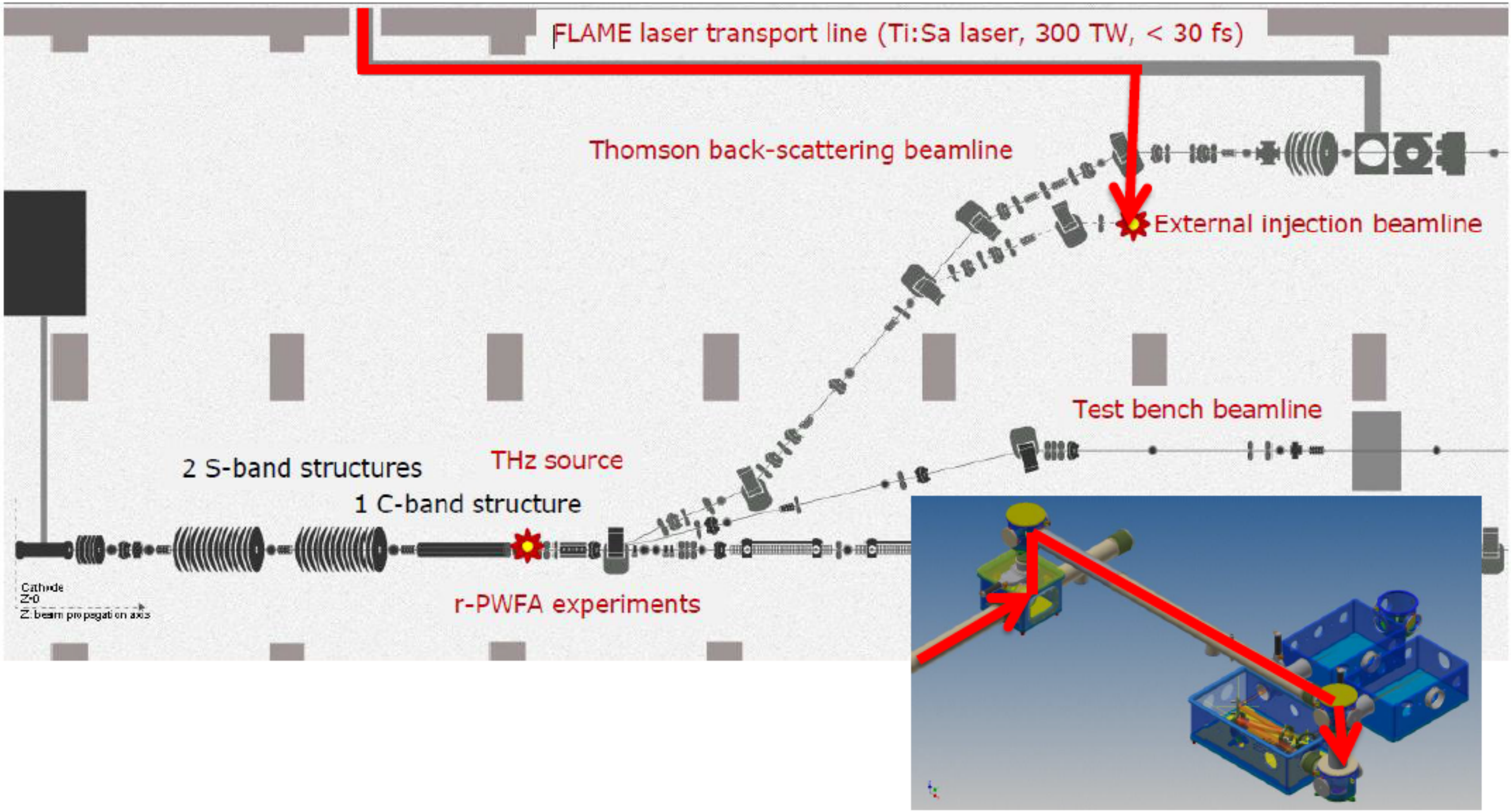


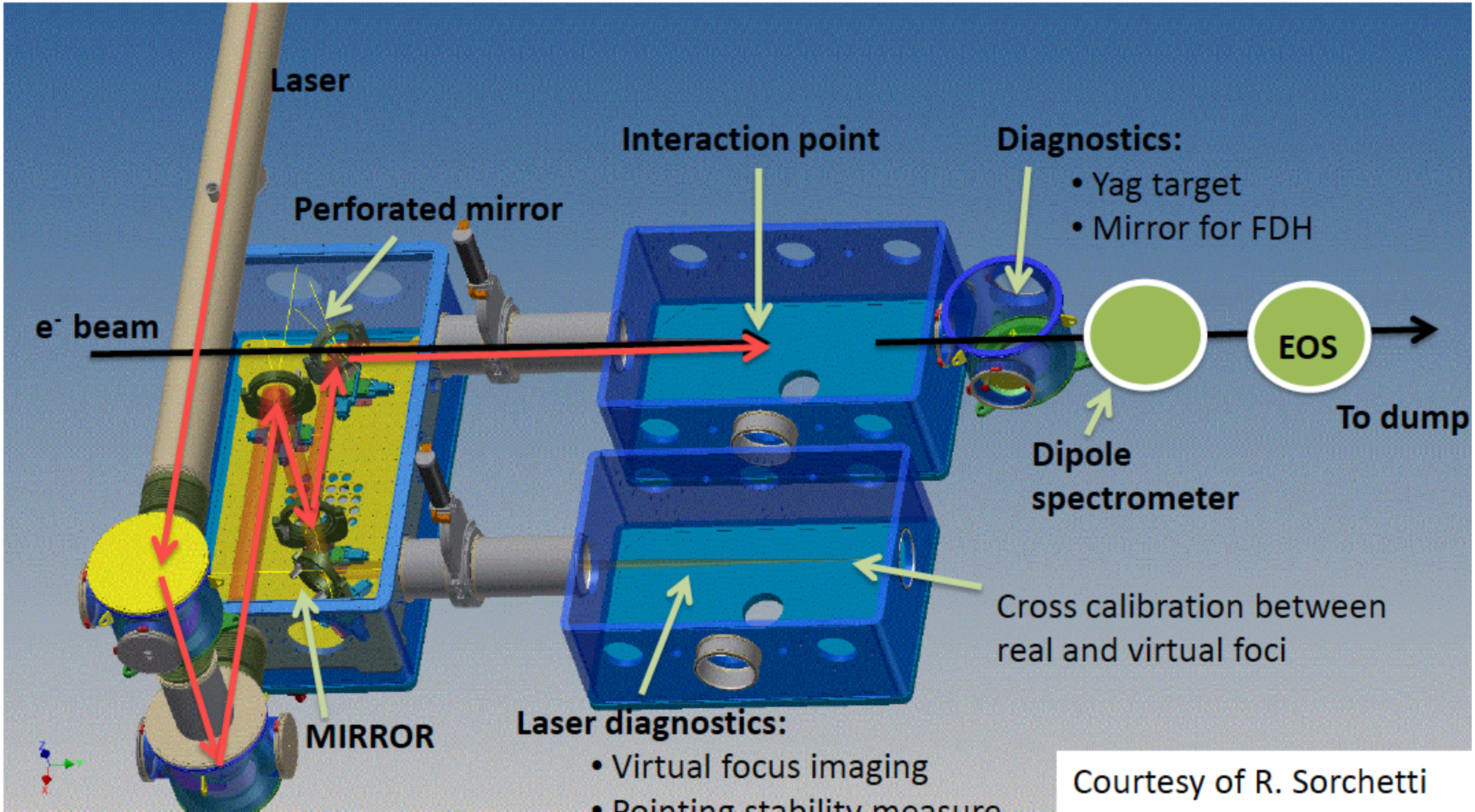
Photo-cathode

A. R. Rossi et al., NIM A **740, 60-66 (2014)**

Experimental setup

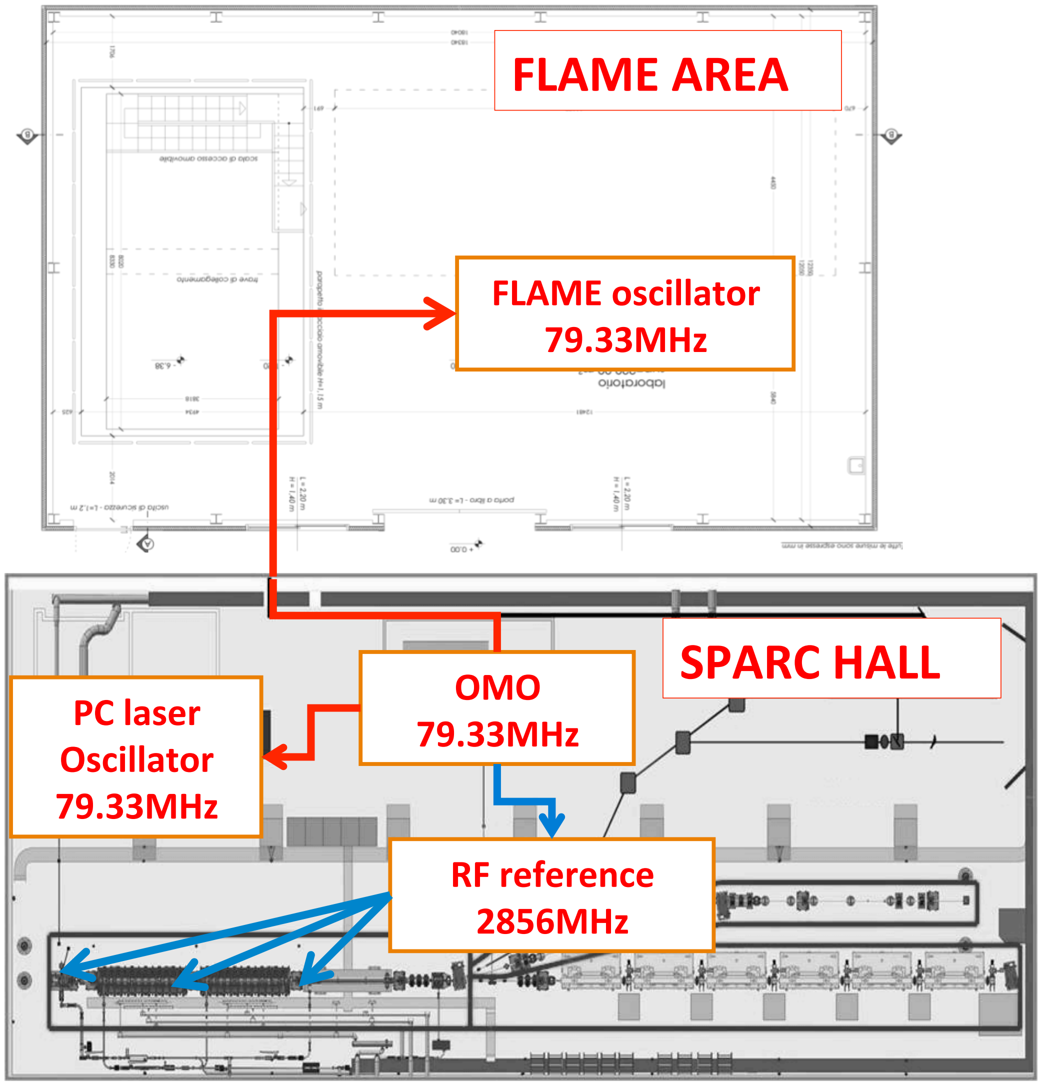


Experimental setup



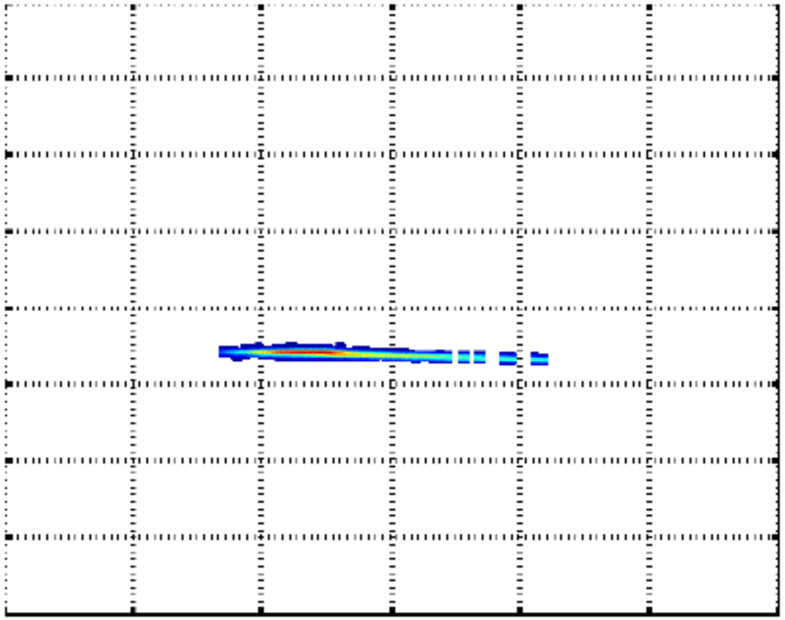
Courtesy of R. Sorchetti

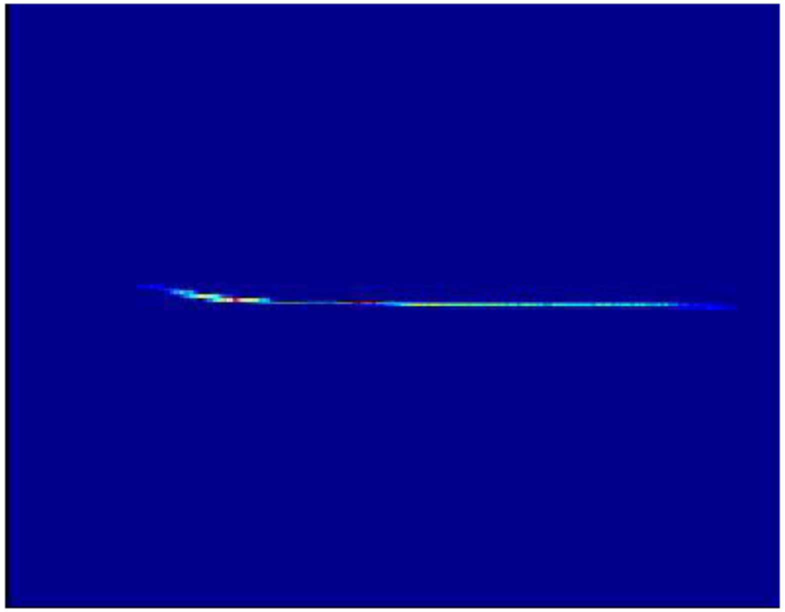
System upgrade



- <u>Optical reference</u>
  - RF reference will be substituted by fiber optical oscillator
  - Fiber laser OMO (Optical Master Oscillator) installed and tested
  - Systems locked through high resolution optical phase monitors (cross-correlators in house and ready to be tested)
  - Fiber link stabilization is ongoing (order placed) to distribute the reference signal
  - **FLAME laser VS electrons estimated time jitter <50fs$_{RMS}$**

SPARC-LAB Brightness record et al.

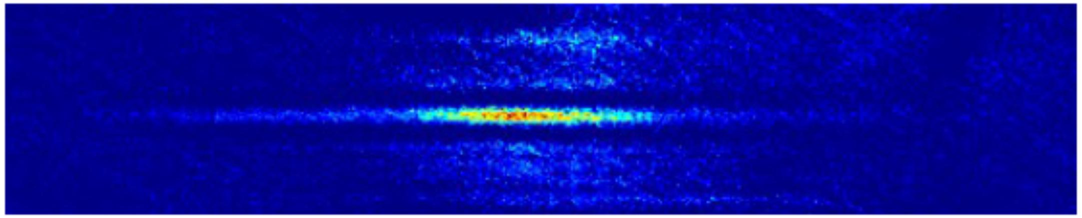


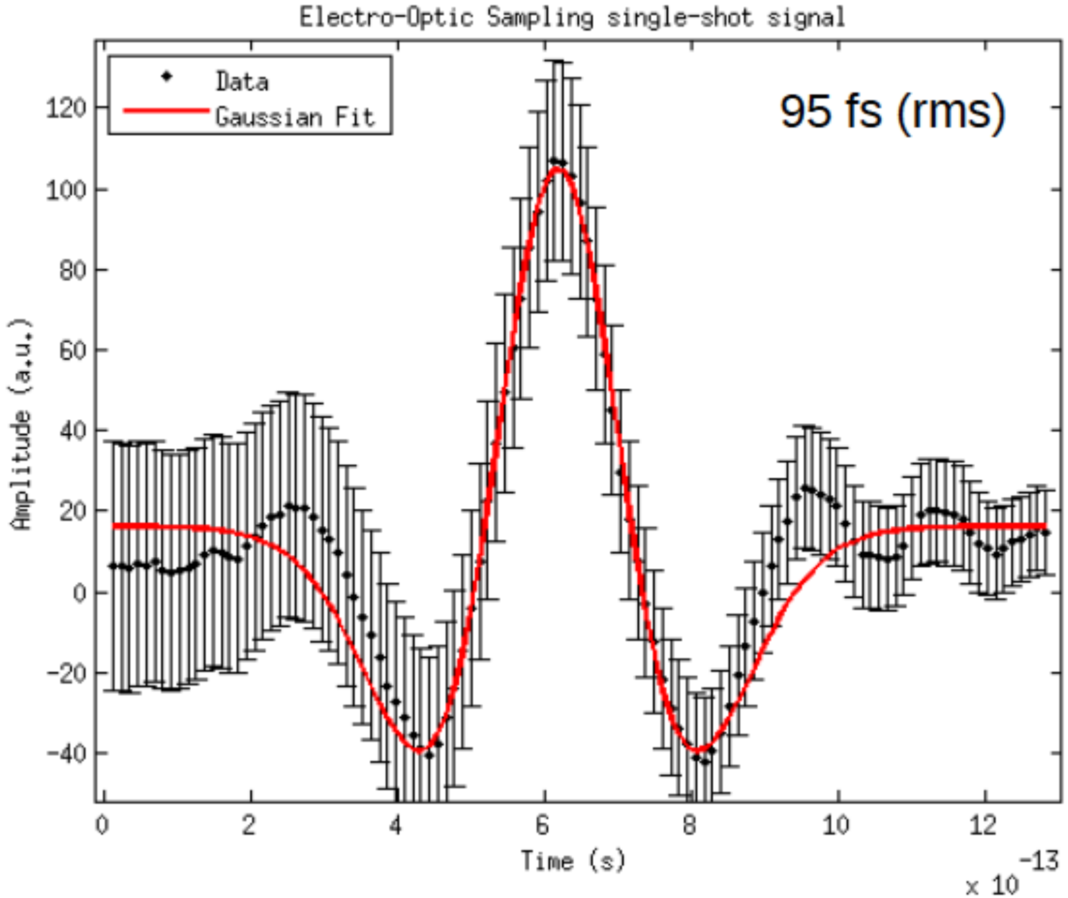


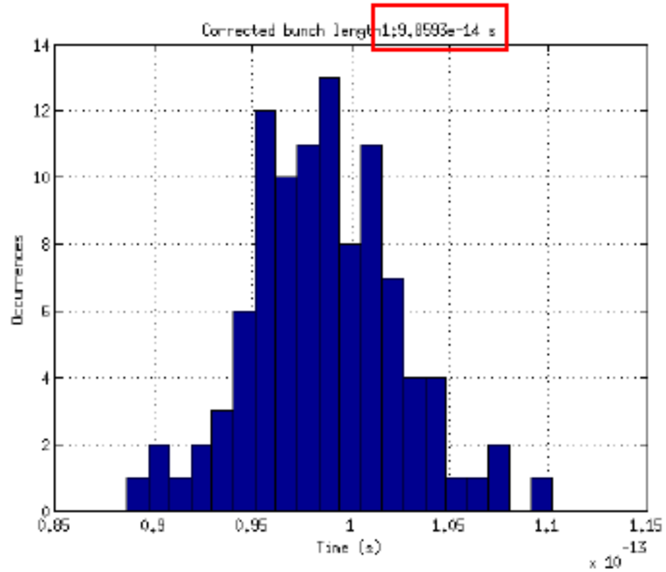
- Experimental Data
  - Charge: 55-60 pC
  - Energy (Linac): 81.12
  - Energy Spread: 0.44 MeV
  - Duration: 51 fs
  - Emittance: 0.87(1.48) x(y)
- GPT simulation
  - Charge: 55 pC
  - Energy (Linac): 80.93 MeV
  - Energy Spread: 0.51 MeV
  - Duration: 54 fs
  - Emittance: 1.3 mm mrad

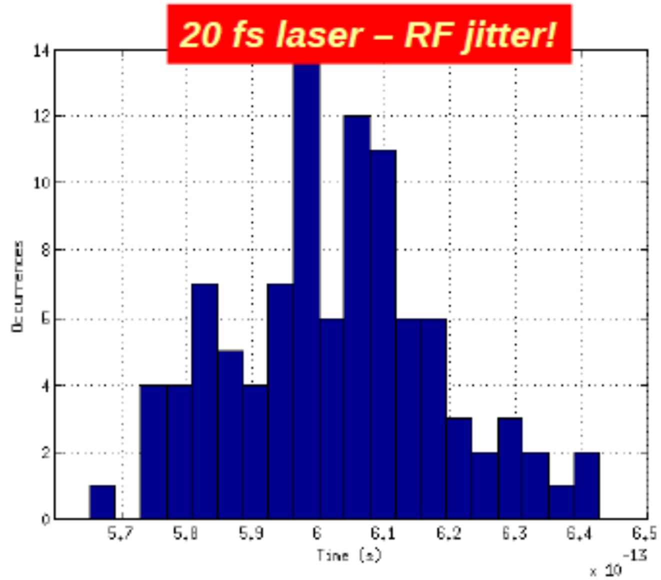
Latest results

GaP crystal *(100 um thickness)*









Laser Driven planning

- e^- beam 1st phase diagnostics (EOS, betatron rad.) is under test
- Upstream electron beam line components acquired
- Exapod for gas cell (and capillary) support ordered
- Development of fsec synchronization system ongoing
- Start installation of beam lines and inter. chamber in June 2015
- Start commissioning beams (e^- and laser) in October 2015
- Start gas cell commissioning in January 2016: acceleration tests

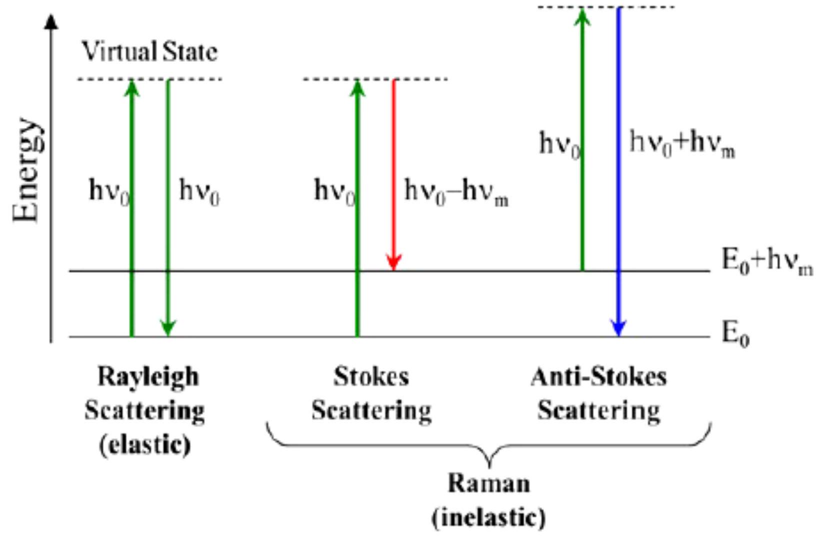
REQUESTS ON SPARC-LAB BEAMS:

A) 3.5 *J* on target from FLAME @ 20-40 *fs* and $\sigma_x > 10\ \mu m$

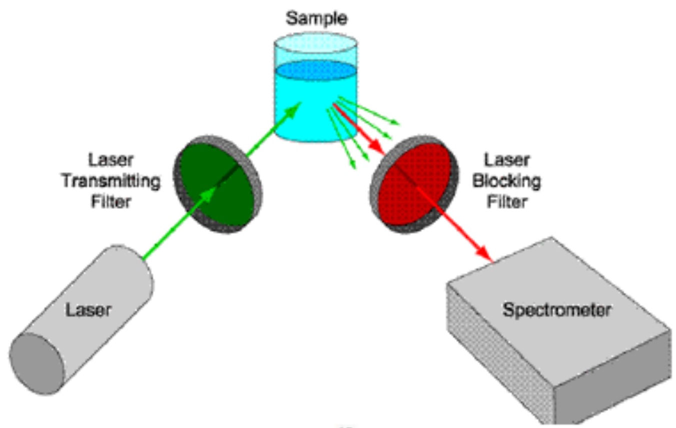
B) 5-30 *pC* e^- bunches at 10-60 *fs* length @ $\varepsilon_x < 2\ \mu m$

Advanced Diagnostics

Raman Spectroscopy



Longitudinal density profile has to be determined in order to check the plasma uniformity along the whole capillary.

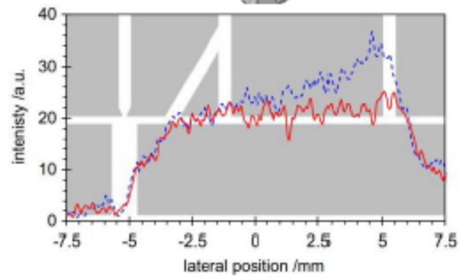


The **Raman scattering** is the scattering between laser and gas molecule. If the scattering is inelastic the emitted radiation is spectrally separated by the laser

$$I_{emission} \propto I_{laser} \frac{n_0}{\lambda_{laser}^4}$$

λ incident (nm)	λ scattered (nm)
355	416
532	683

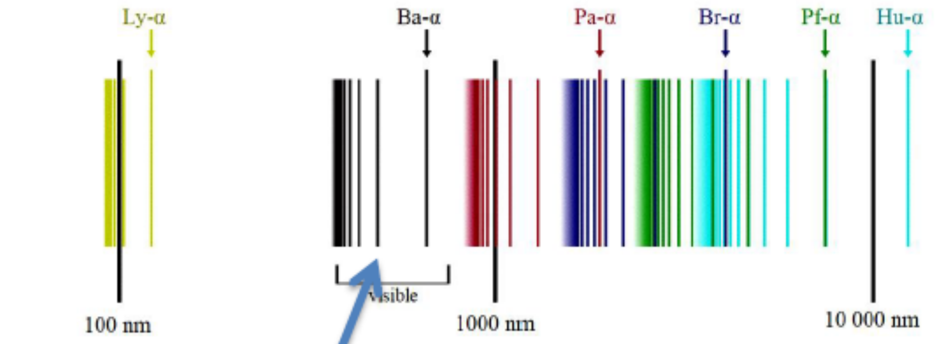
H2 scattered light



Schaper, L., **NIM A**, 740 (2014): 208-211

Stark broadening

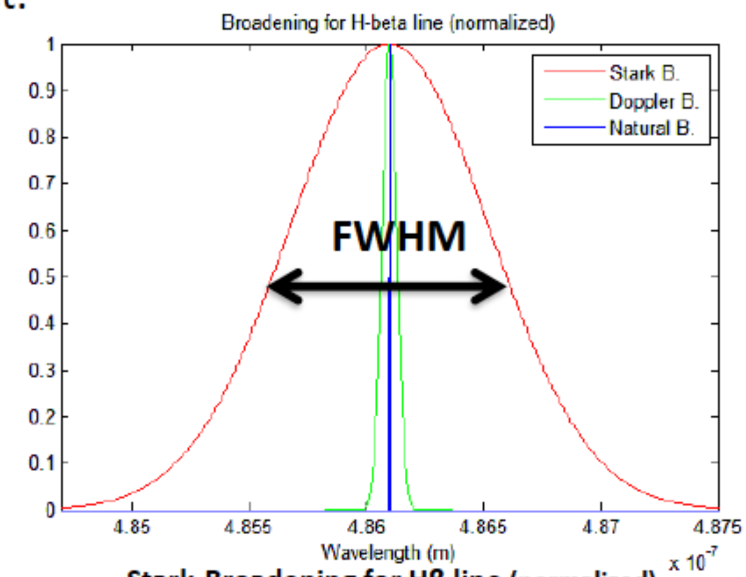
Ligth emitted by plasma allows to reconstruct the electron density from spectroscopy on emission line broadening due to Stark-Lo Surdo effect.



Hydrogen spectral series

Hβ, λ=486.1 nm

Less sensitive to temperature **Δλ FWHM**



Stark-Broadening for Hβ line (normalized)

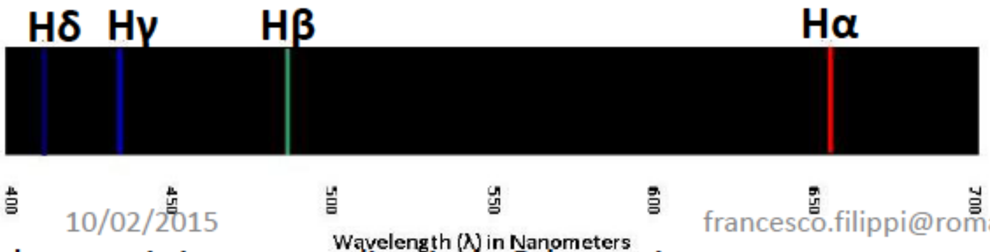
@n_e=10^{16}cm^{-3}
@4eV

STARK BROADENING	**1.002 nm**
DOPPLER BROADENING	**0.0747 nm**

The line-width is directly related to the plasma density

$$\Delta\lambda \propto \alpha(T)\, n_0^{2/3}$$

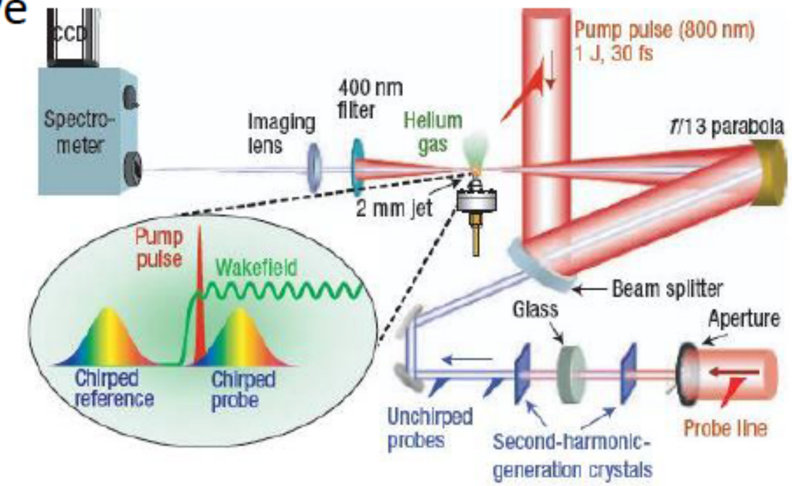
Spectral lines are broadened as a result of the emitter interaction with the electric field produced by nearby ions.



Hydrogen emission spectrum lines in the Balmer series

Frequency Domain Holography

2D visualization of the propagating plasma wave

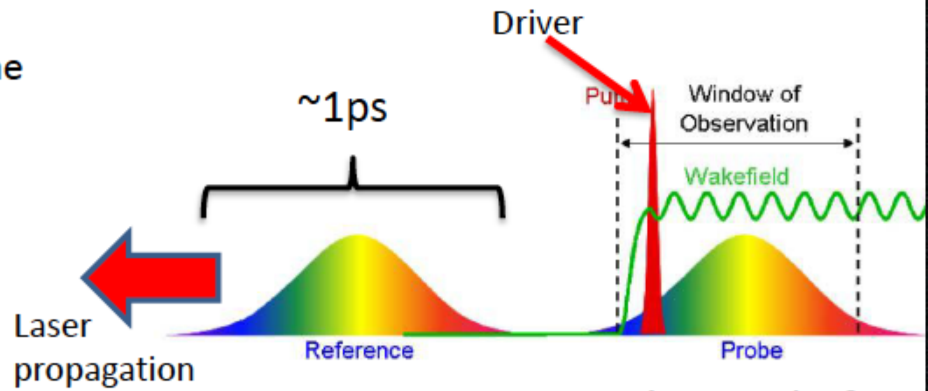


Two co-propagating linearly-chirped pulses separated in time (few ps) propagate through the plasma
The probe laser accumulates dephasing in the plasma due to refractive index variation

PLASMA REFRACTIVE INDEX

$$\eta = \sqrt{1 - \frac{n_e}{n_c}}$$

Plasma refractive index varies with the plasma density



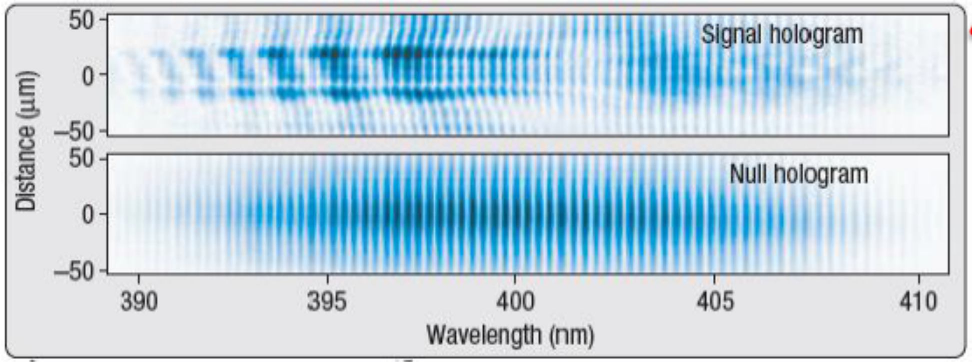
Before the driver

During and after the driver

Phase shifts are recorded in Frequency Domain fringes of period *2π/Δt*

Δφ = (2π/λpr) [1-η(r,ζ)] L

Frequency Domain Holography



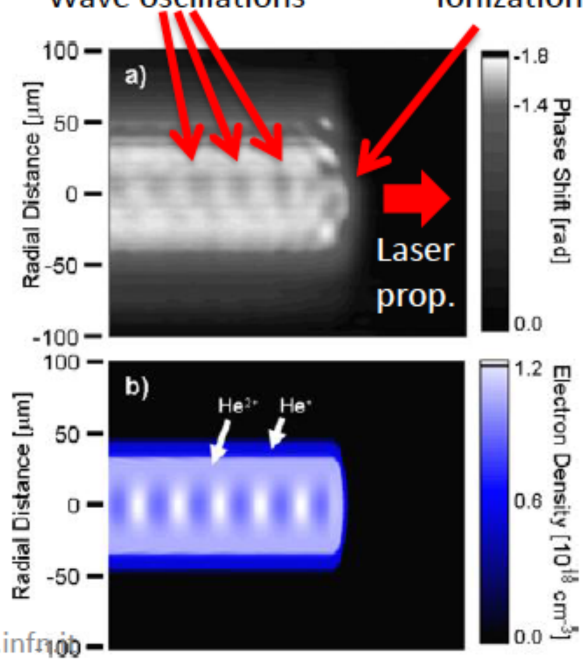
Transverse spatial variation

Temporal variation

The interferogram captures the evolution of multiple wake periods

Wake morphology is reconstructed in real-time, providing experimental feedback and optimization.

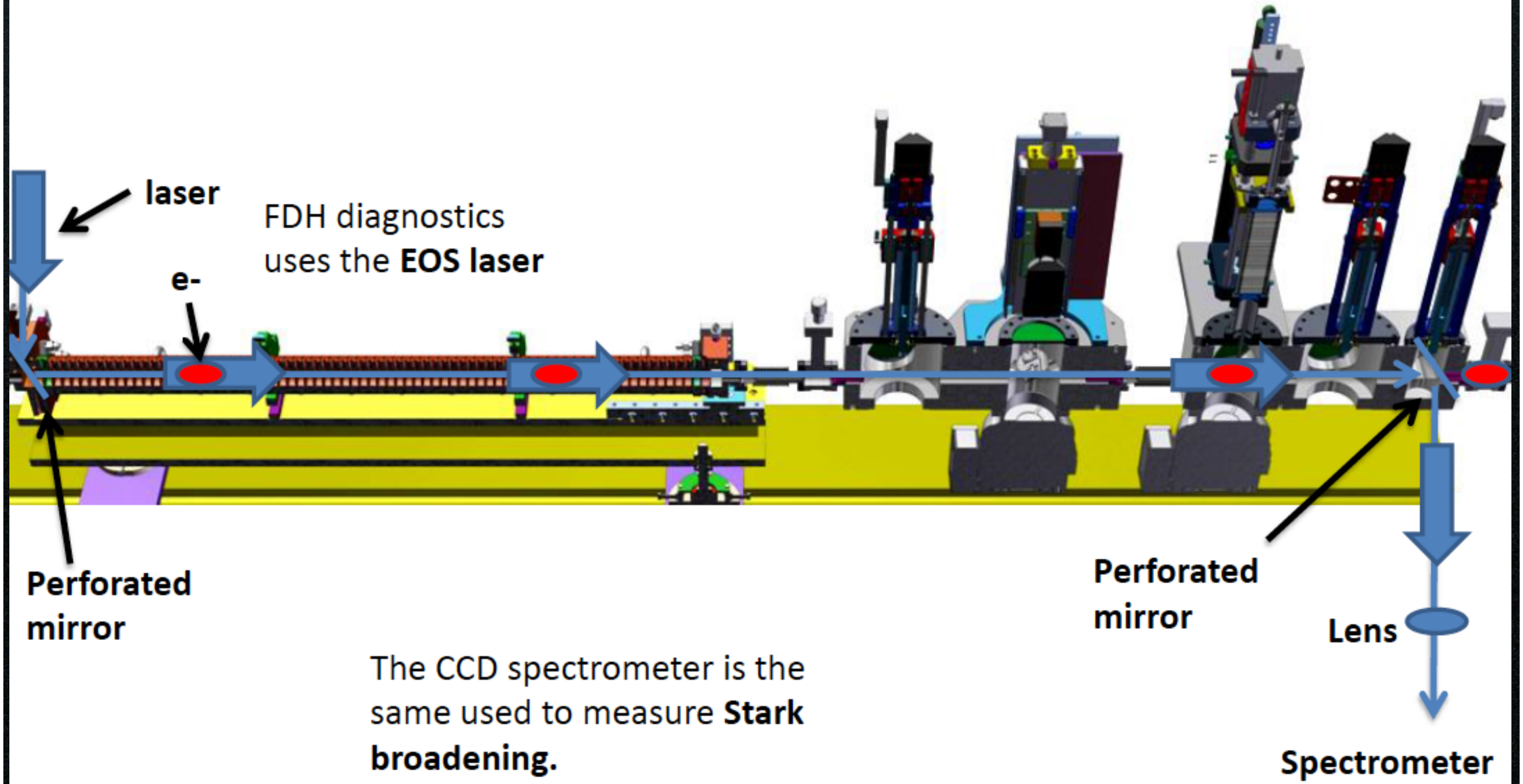
Matlis, Nicholas H.,Nature Physics 2.11 (2006): 749-753.



Measured

Simulated

Frequency Domain Holography

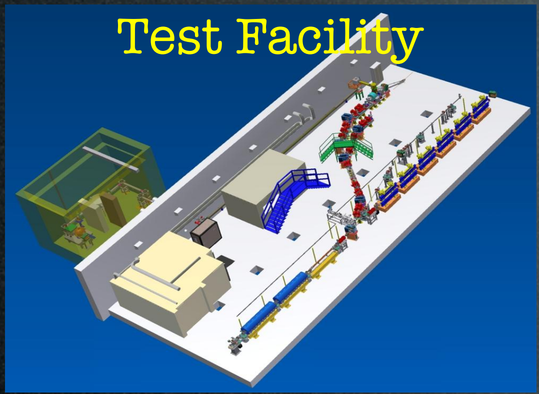


FDH diagnostics uses the **EOS laser**

The CCD spectrometer is the same used to measure **Stark broadening.**

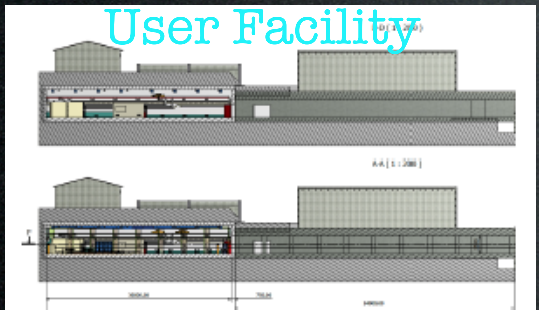
The SPARC_LAB future?

Future scenarios



Consolidation: on going, ~3 years,~ 4 M€ allocated

- FLAME maintenance
- Injector upgrade (C-band, X-band)
- THz user beam line upgrade
- Thomson and Plasma beam lines final commissioning
- FEL new undulator



Upgrade: proposed, ~5 years

- Infrastructure extension 4 M€
- Linac upgrade ~1 GeV (C-X-band, multibunch) 9 M€
- THz, X-ray Compton and FEL user facility) 11 M€
- Advanced FEL schemes (oscillator?) 7 M€
- FLAME upgrade towards 1 PW 10 M€
- Positron production and plasma acceleration 2 M€
- AND RELIABILITY !!!!

European Facility, ~10 years, ~200 M€

- Plasma based FEL Pilot User Facility
- Plasma based HEP beam line
- (Photon-Photon Collider?)

SPARC_EU_LAB?

Excellent Science
Developing new world-class research infrastructures
H2020-INFRADEV-1-2014-1
Deadlines: 02/09/2014
Opening Date: 11/12/2013

ESFRI
European Strategy Forum on Research Infrastructures

~200 M€

- Design Studies with at least 3 Countries,
- Cost. Schedule, Siting?
- What is the governance model?
- What is the intended user community?
- Will it be open access?
- Apply for H2020 preparatory phase (PP)?

- Support will be provided by Horizon2020 and MIUR for the implementation (PP) and operation of the research infrastructures listed on the ESFRI Roadmap and ERIC.

Design Study on the "European Plasma Research Accelerator with eXcellence In Applications" (EuPRAXIA)

Submitted to HORIZON 2020 INFRADEV, 4 years, 3 M€