Weak Blow-out Regime Driven Resonantly by a Train of Short Electron bunches at SPARC_LAB

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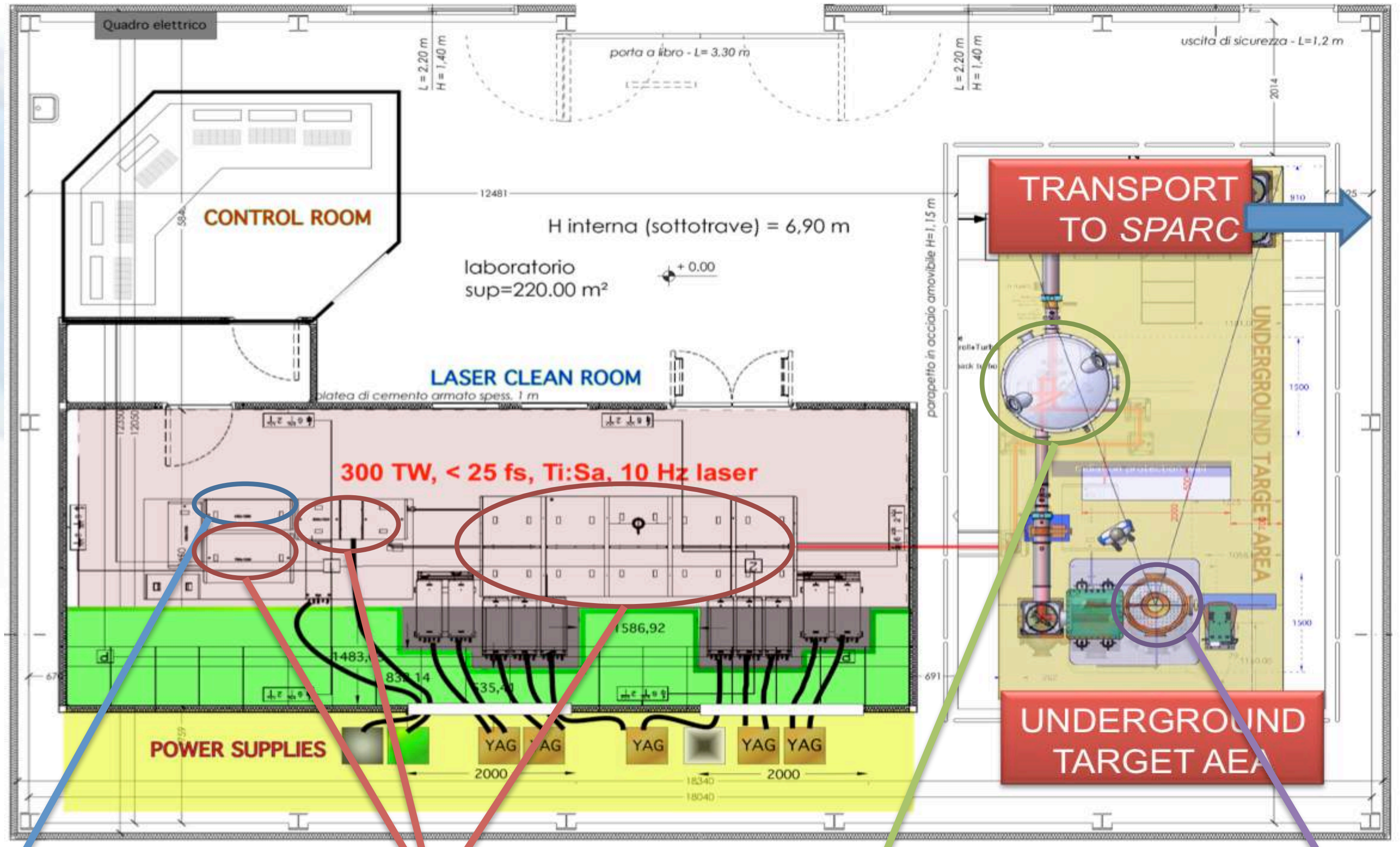
LA3NET – Novel Accelerator Workshop – Paris, 26 October 2016

Ti:Sa FLAME laser



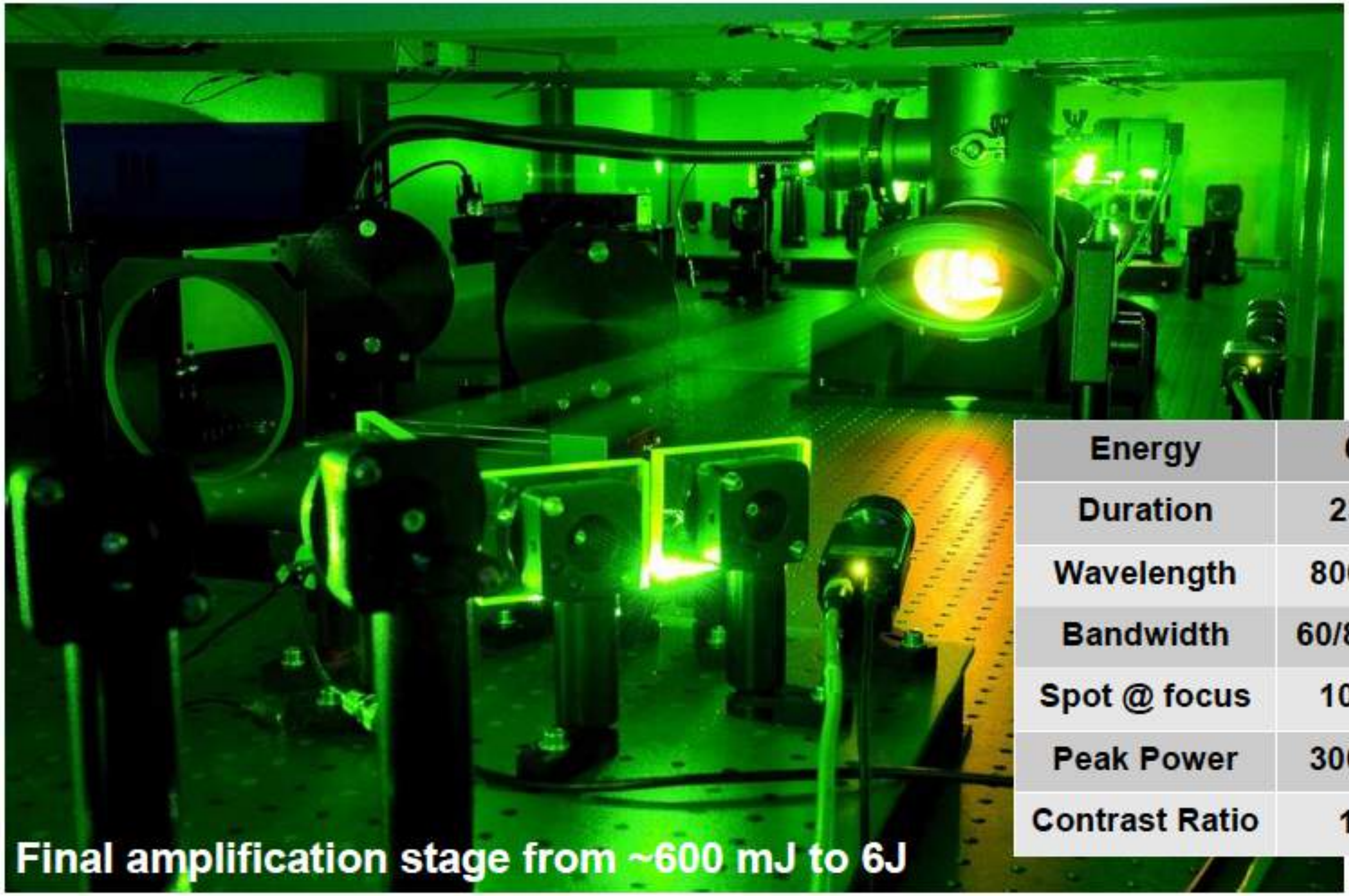
Stretcher

Amplifiers

Compressor

LWFA
Electron Self Injection
And
Protons

Ti:Sa FLAME laser

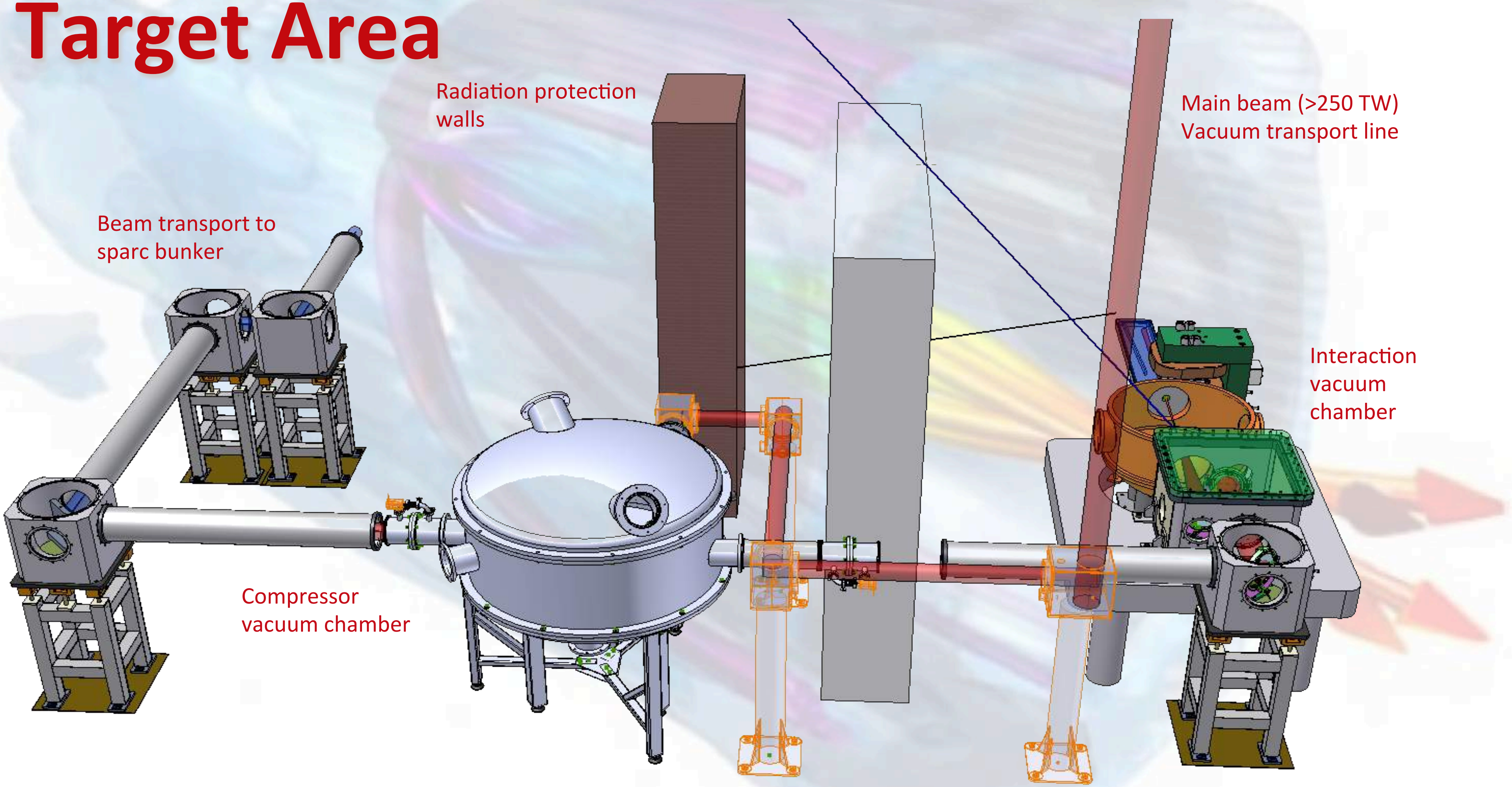


Final amplification stage from ~600 mJ to 6J

Energy	6 J
Duration	23 fs
Wavelength	800 nm
Bandwidth	60/80 nm
Spot @ focus	10 µm
Peak Power	300 TW
Contrast Ratio	10^{10}

Esperimenti di auto-iniezione

Target Area



Radiation protection walls

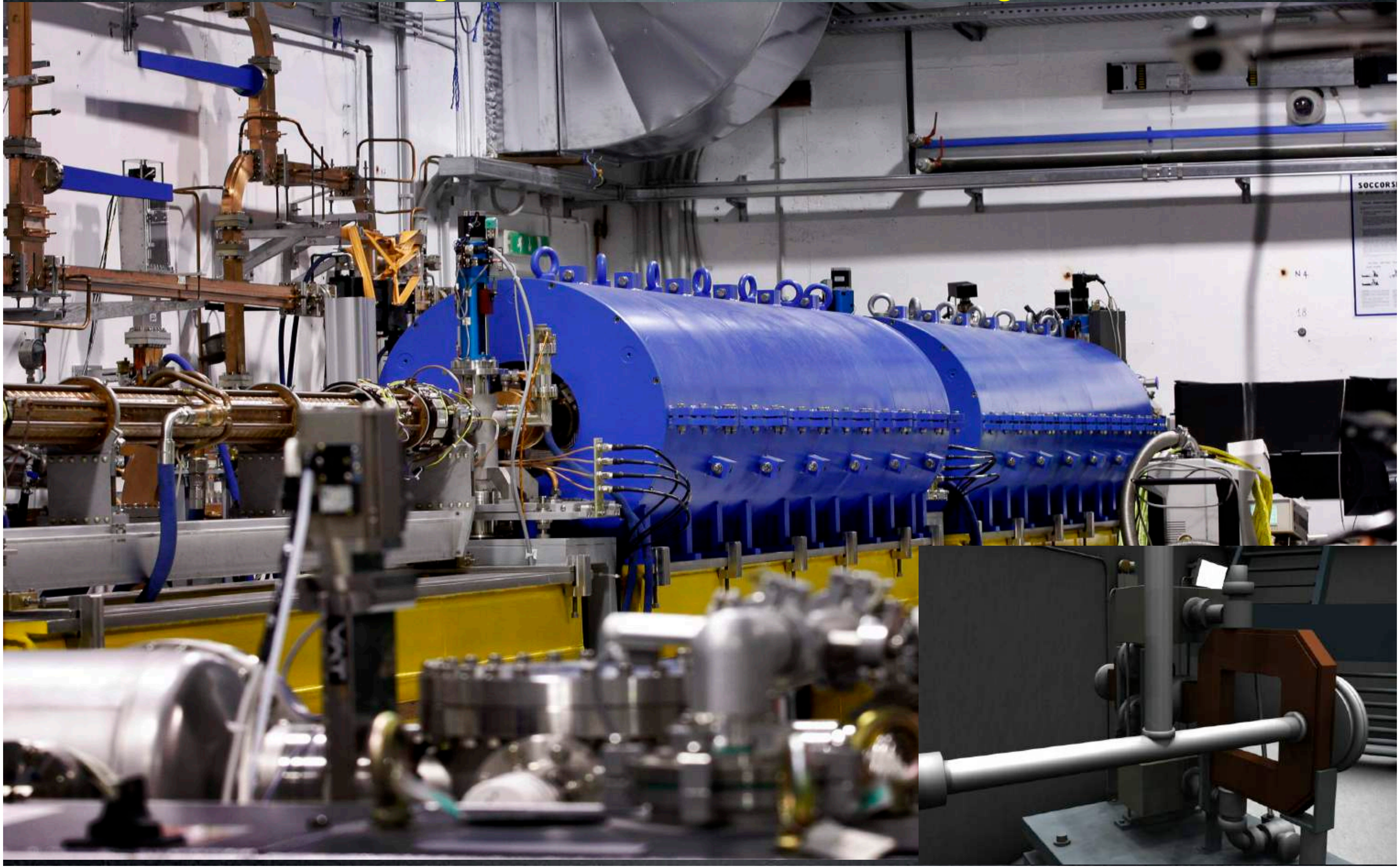
Main beam (>250 TW) Vacuum transport line

Beam transport to sparc bunker

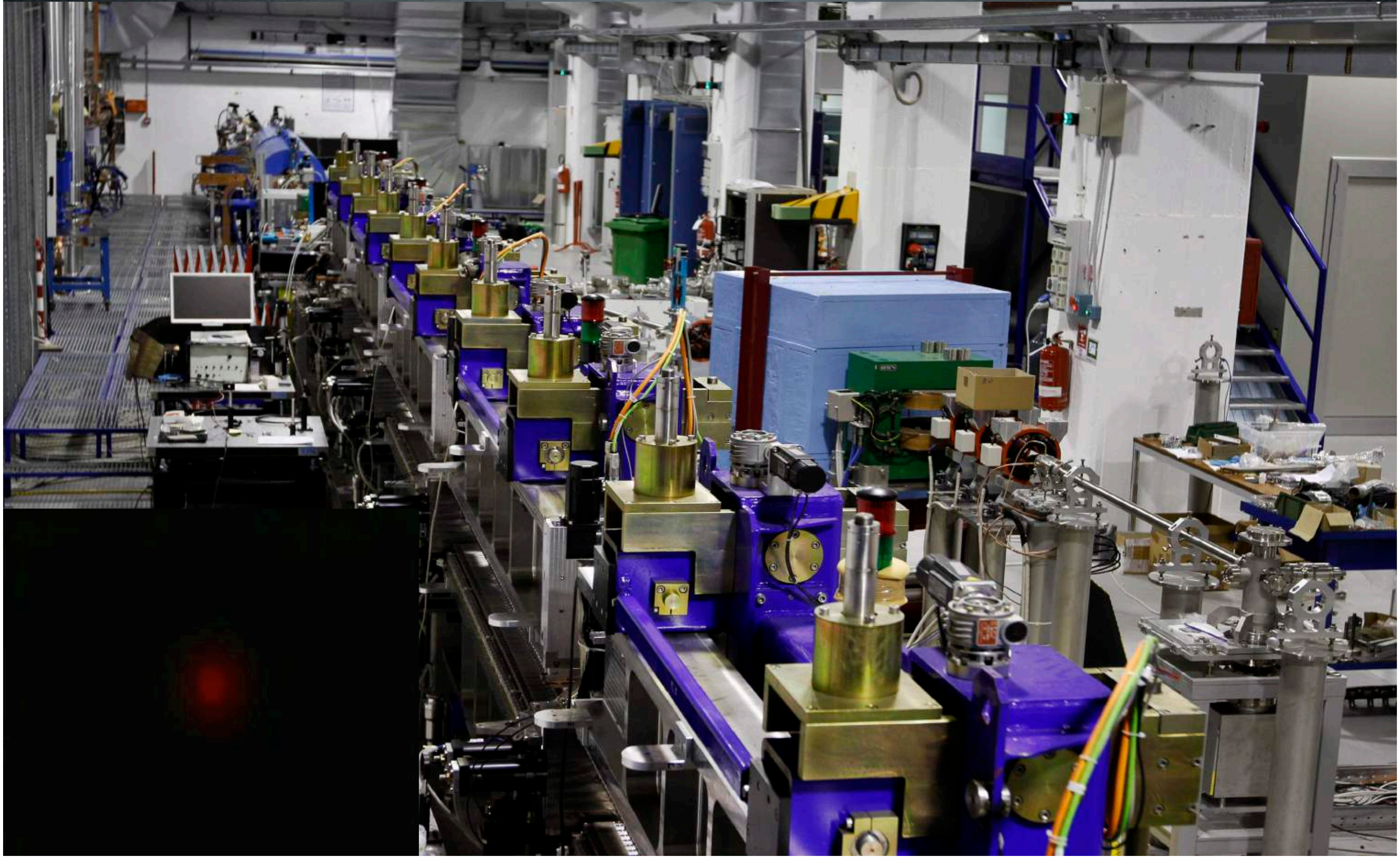
Interaction vacuum chamber

Compressor vacuum chamber

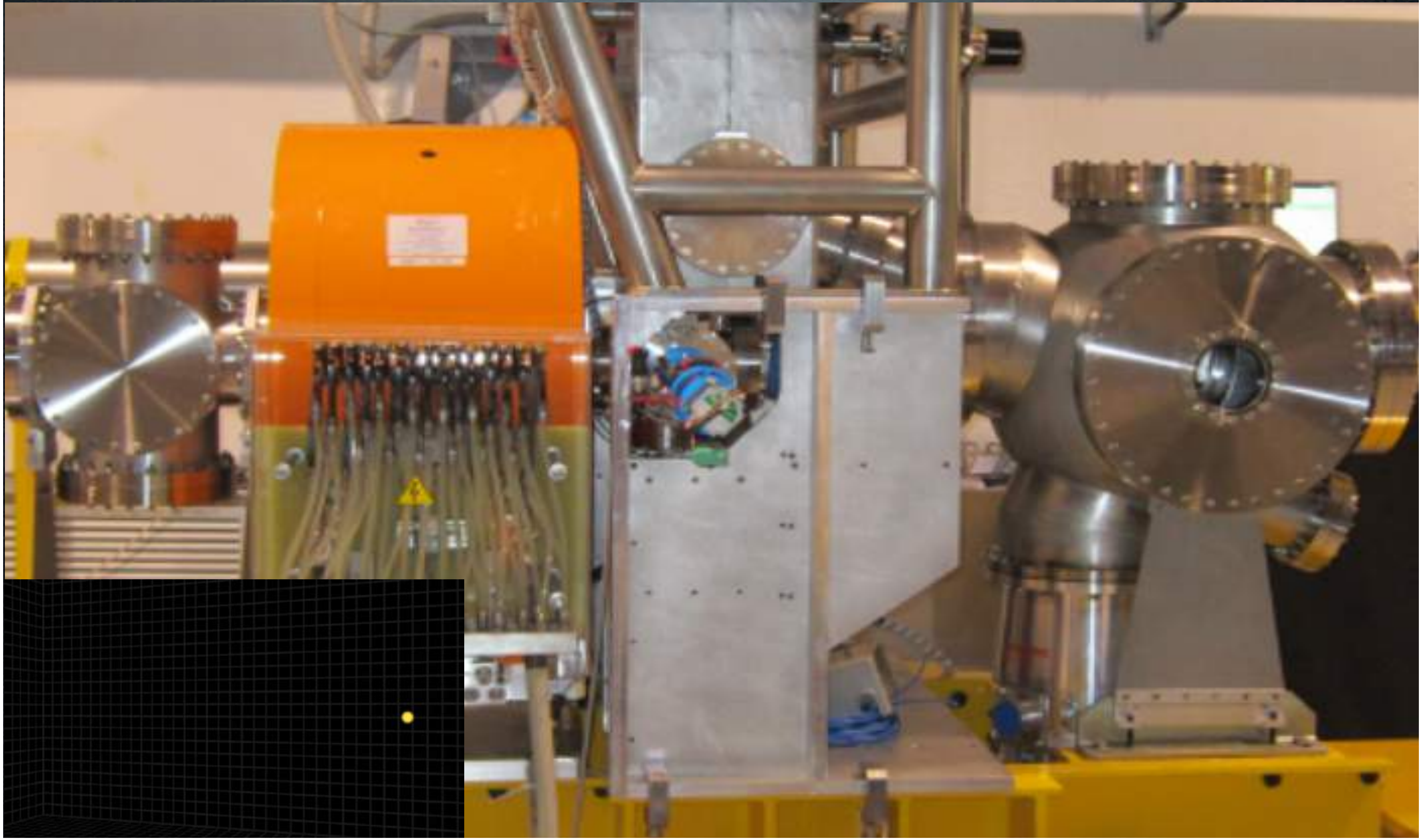
HB photo- injector with Velocity Bunching



Free Electron Laser

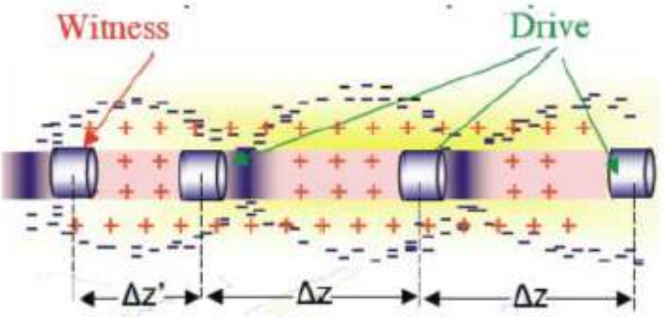


Thomson back-scattering source



Plasma-based acceleration techniques

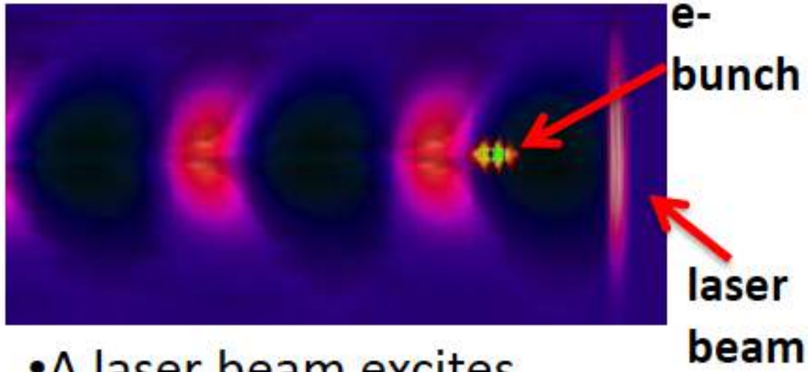
resonant-PWFA



- 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

$n_e = 2\mathrm{x}10^{16}\ \mathrm{cm}^{-3}$
$\lambda_p = 300\mu\mathrm{m}$
Capillary 1mm
Hydrogen

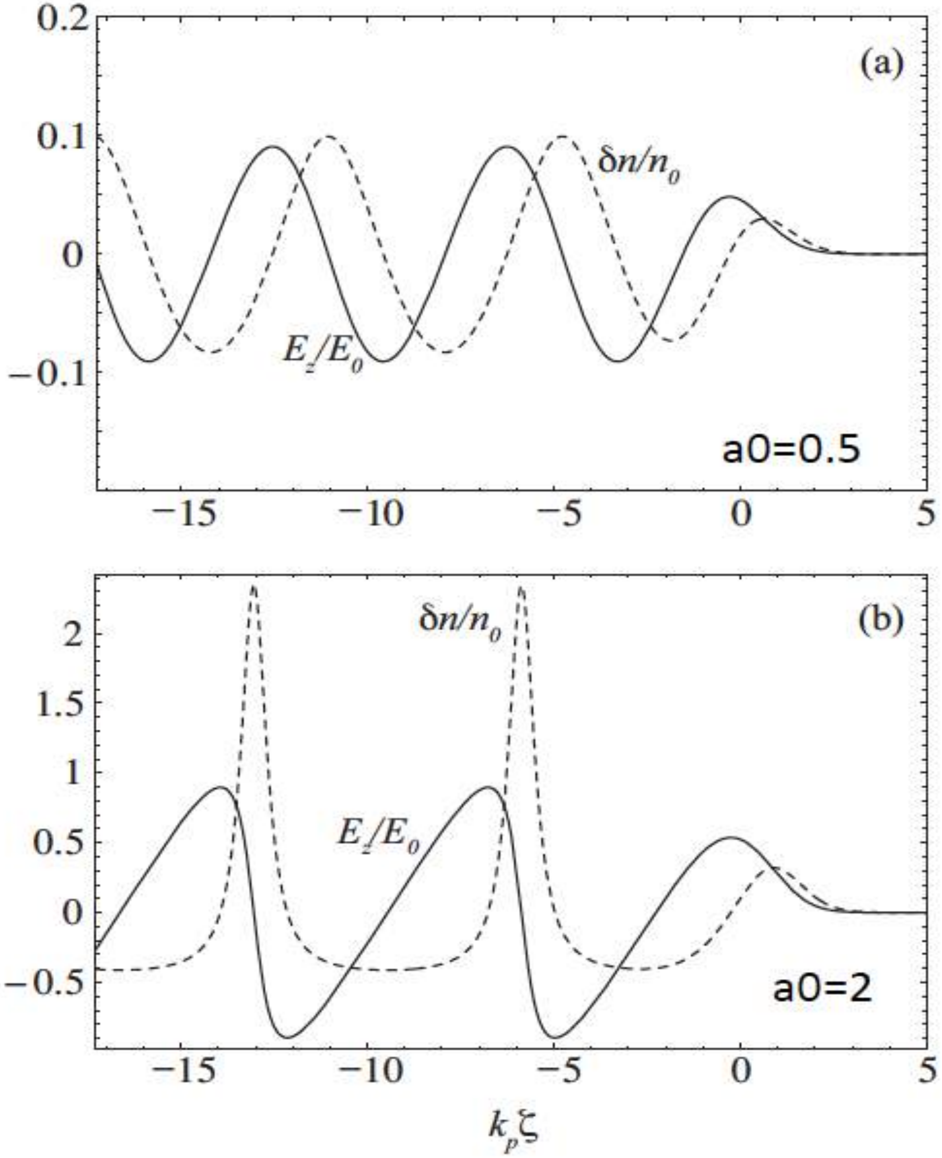
external injection LWFA



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

$n_e = 1\mathrm{x}10^{17}\ \mathrm{cm}^{-3}$
$\lambda_p = 100\mu\mathrm{m}$
Capillary 100 μm
Hydrogen

Regimes: Linear & Non-Linear



Linear

FIG. 8. Time-averaged density variation $\delta n/n_0$ (dashed curve) and axial electric field E_z/E_0 (solid curve) in an LWFA driven by a Gaussian laser pulse (pulse is moving to the right, centered at $k_p\zeta=0$ with rms intensity length $L_{\mathrm{rms}}=k_p^{-1}$) for (a) $a_0=0.5$ and (b) $a_0=2.0$.

Non-Linear

PWFA – Quasi-nonlinear regime

- Condition for blowout:

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

  - *Bubble formation w/o wave-breaking, λ_p is constant → **resonant scheme in blowout***
  - *Linear focusing force → emittance preserved*

- A measure of nonlinearity is the *normalized charge*

$$\tilde{Q} \equiv \frac{N_b k_p^3}{n_p} = 4\pi k_p r_e N_b \rightarrow \begin{cases} \ll 1 & \textit{linear regime} \\ > 1 & \textit{blowout regime} \end{cases}$$

- Using low emittance, high brightness beams we have

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

- These conditions define the quasi-nonlinear (QNL) regime
  - ***$n_p = 10^{16}$ cm^{-3}, Q_D = 200 pC, σ_t=180 fs, σ_x=5.5 um → n_b~5n_p** and* $\tilde{Q} = N_b k_p^3 / n_p \approx 0.8$

Rosenzweig, J. B., et al. "Plasma Wakefields in the Quasi□Nonlinear Regime." (2010): 500-504.
Londrillo, P., et al. "Numerical investigation of beam-driven PWFA in quasi-nonlinear regime." NIM 740 (2014): 236

Laser Comb Technique

Laser Comb technique: generation of a train of short bunches

(Parmela code)

Charge vs. Time

Energy vs. Time

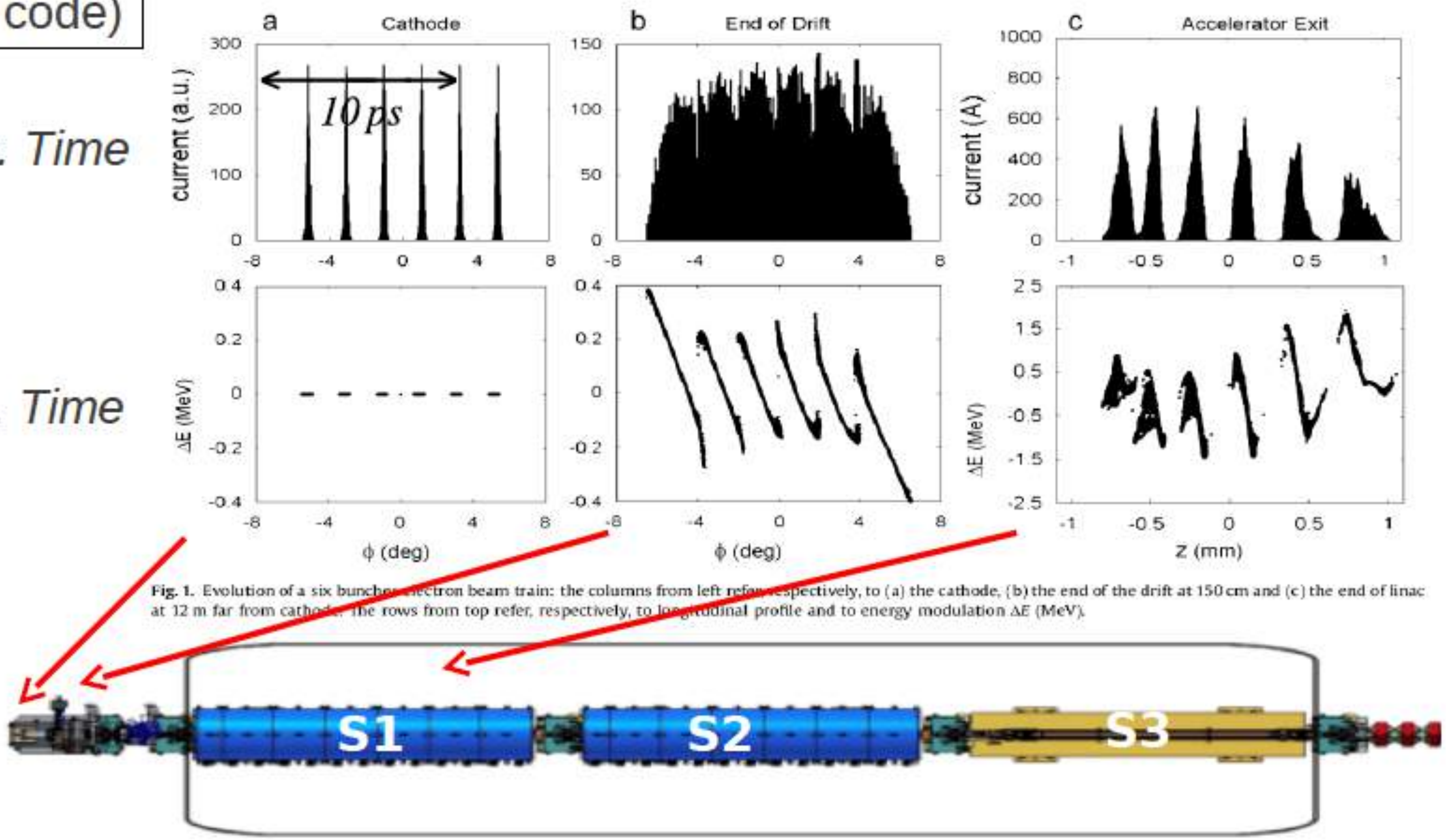
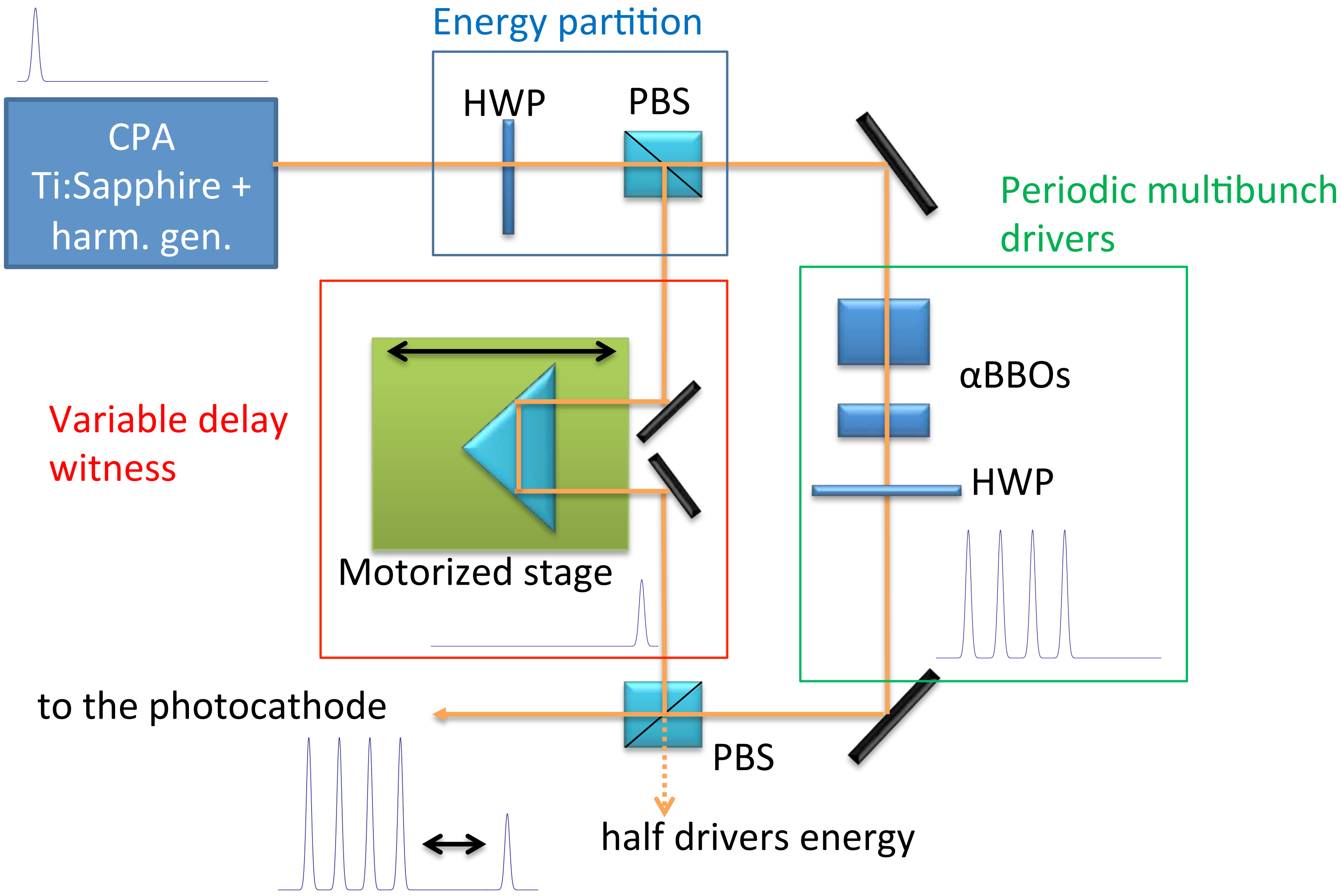


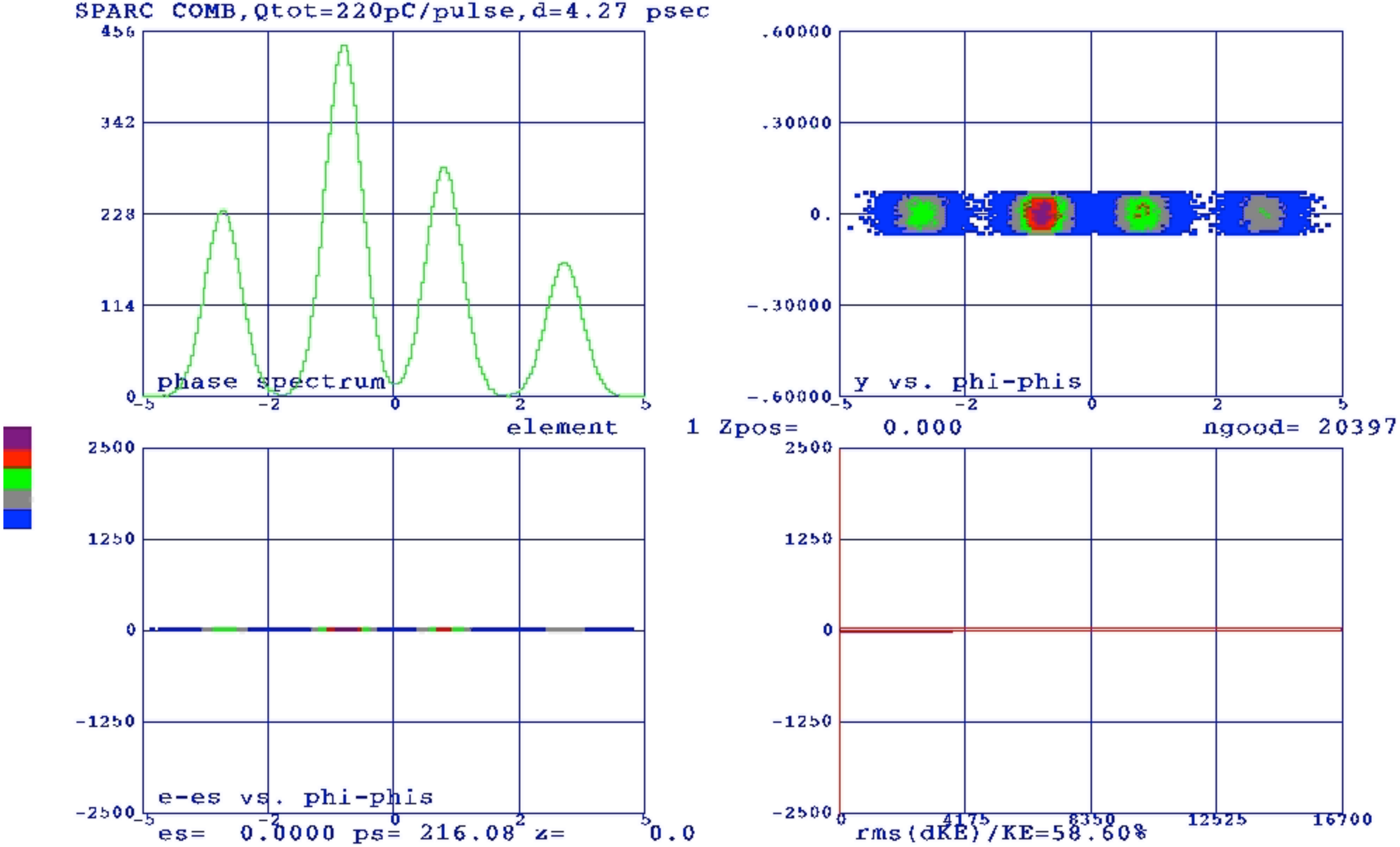
Fig. 1. Evolution of a six bunches electron beam train: the columns from left refer, respectively, to (a) the cathode, (b) the end of the drift at 150 cm and (c) the end of linac at 12 m far from cathode. The rows from top refer, respectively, to longitudinal profile and to energy modulation ΔE (MeV).

- 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)

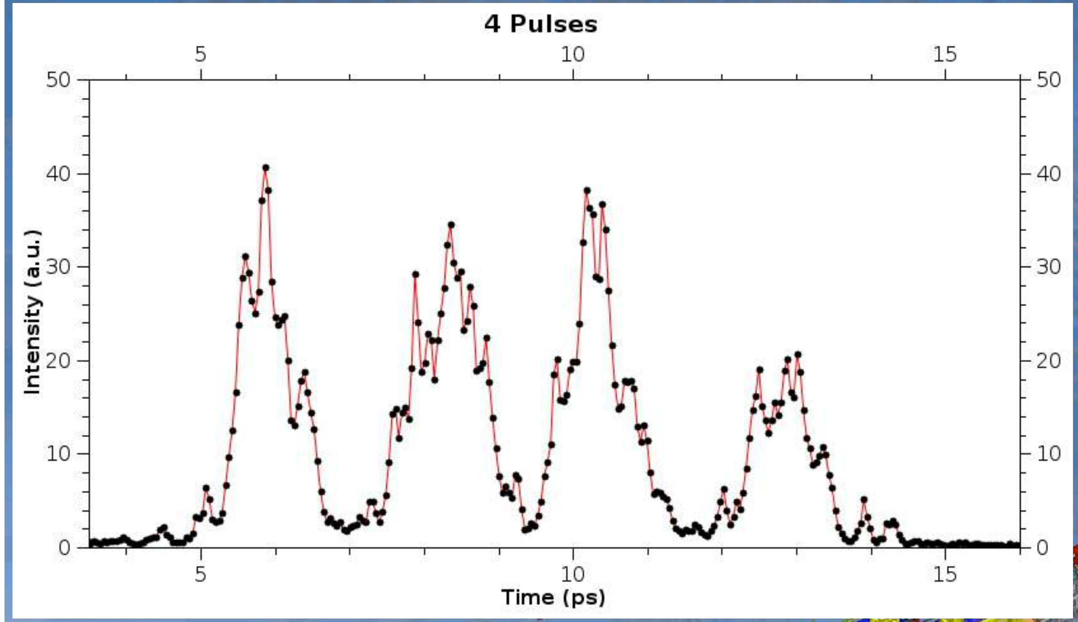
Driving and witness bunches generation

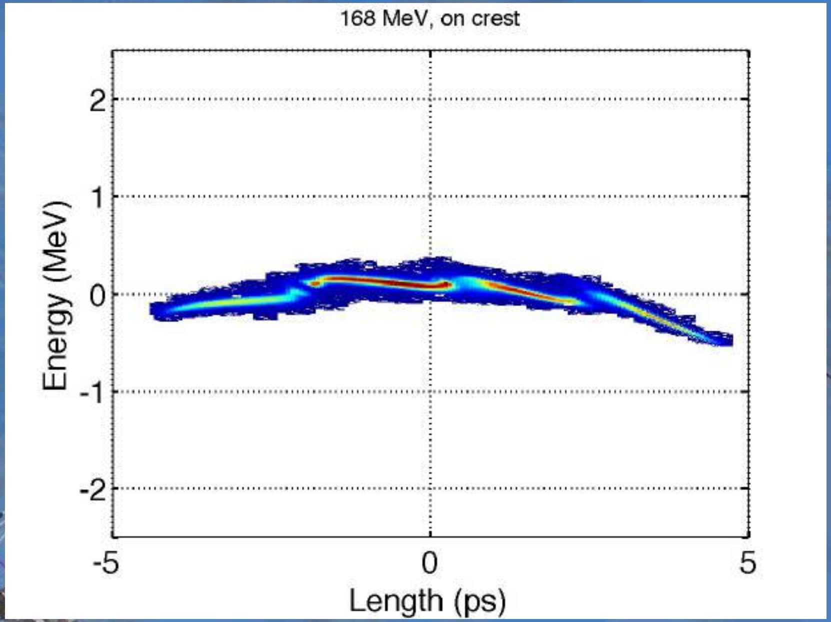


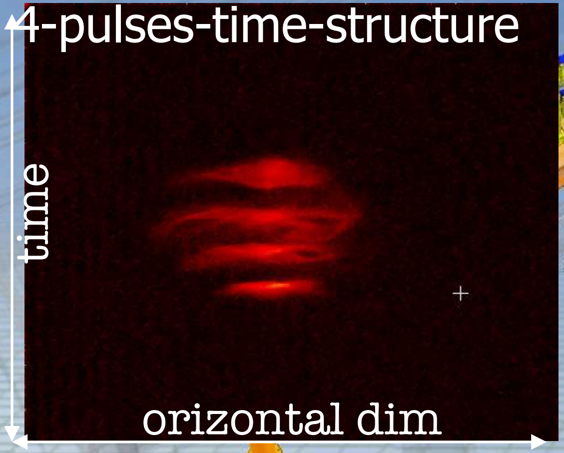
Overcompression

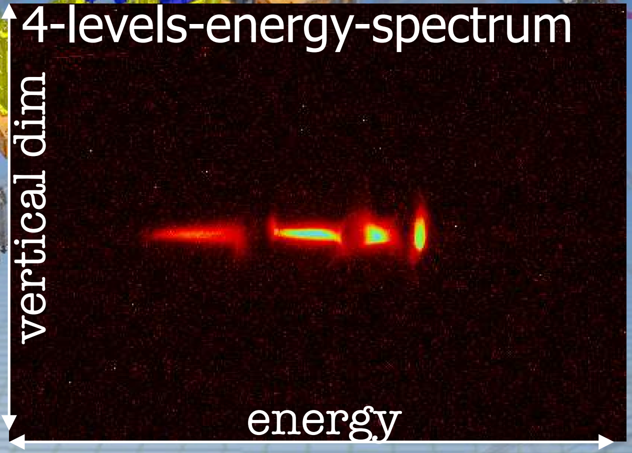


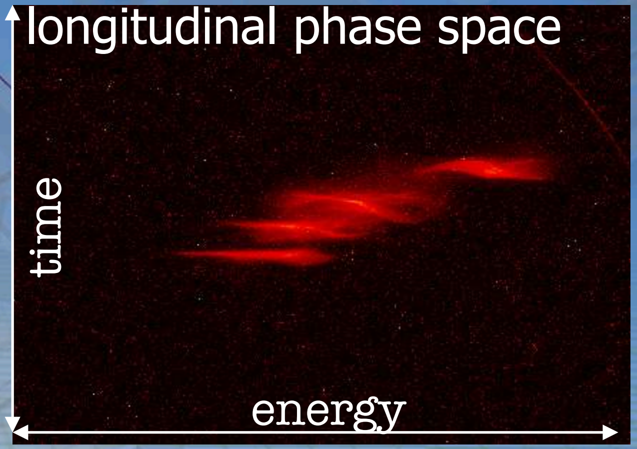
Laser COMB: experimental results









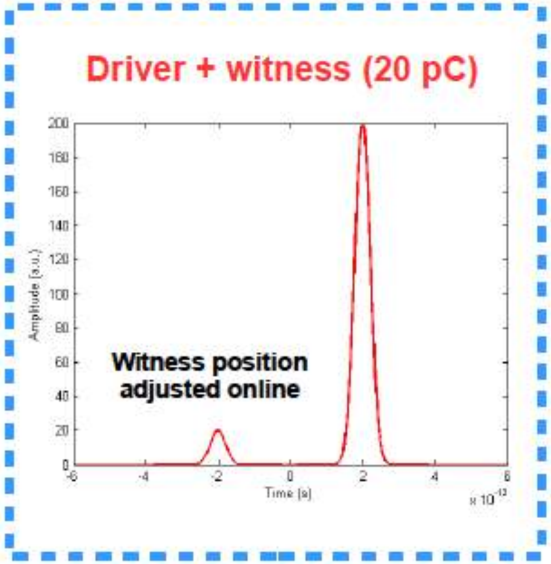


- M. Ferrario et al., Nucl. Inst. and Meth, A 637 (2011)
- A. Mostacci et al., Proc. of IPAC 2011, Spain

VB dynamics: 1 driver + witness

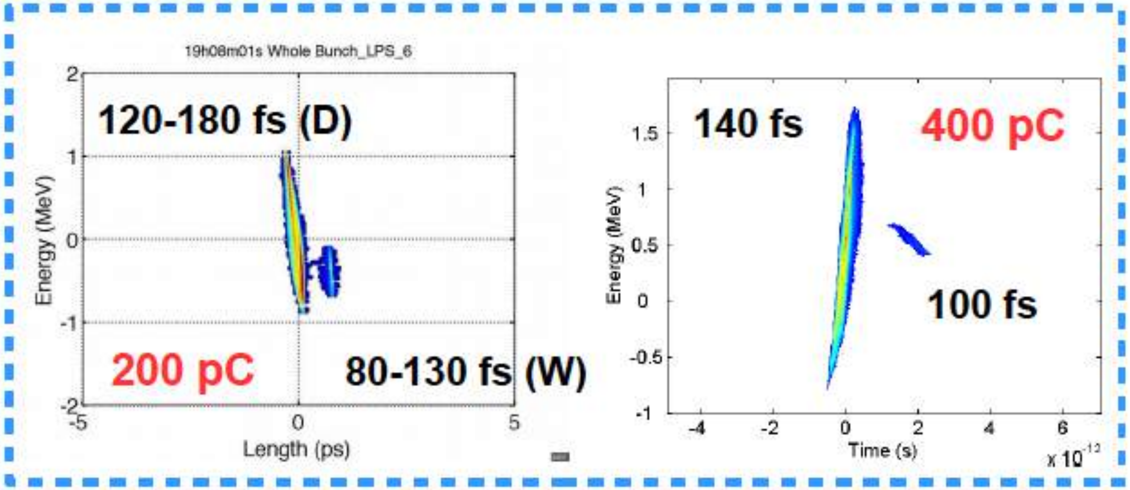
Experimental results!

Laser profile on photo-cathode


Driver + witness (20 pC)

Witness position adjusted online

LPS at linac exit


120-180 fs (D)

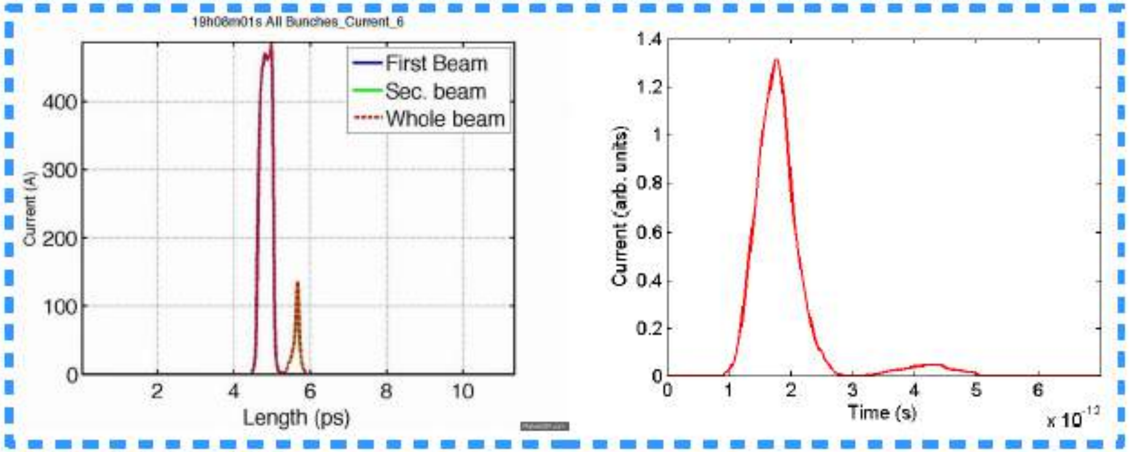
200 pC

80-130 fs (W)

140 fs

400 pC

100 fs



Current profile

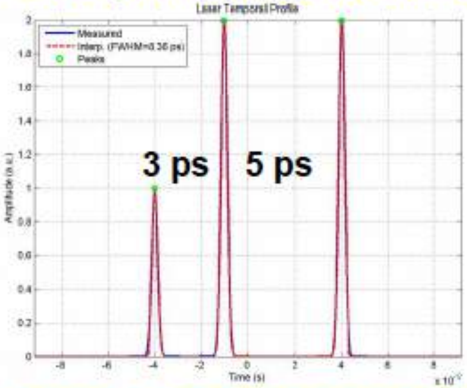
VB dynamics: N driver + witness

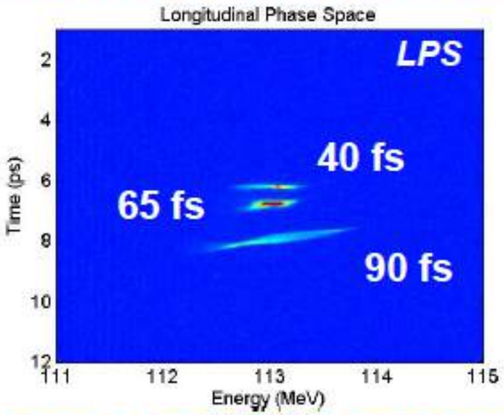
Experimental results!

50 pC drivers + 20 pC witness

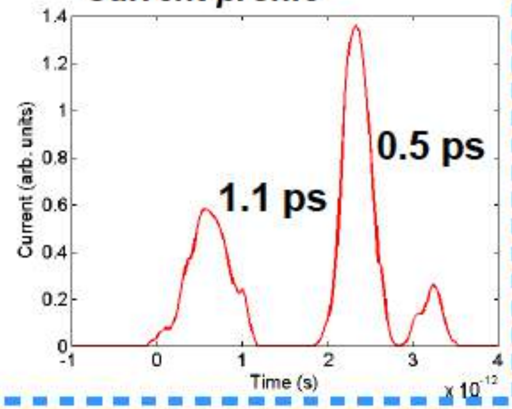
resonant scheme @ $n_p = 10^{16}$ cm^{-3} → bunch distance = λ_p ~ 1.1 ps

Laser profile on photo-cathode

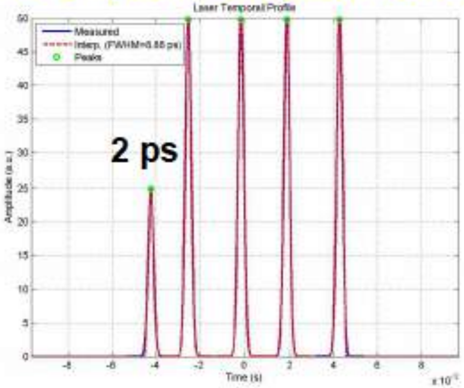


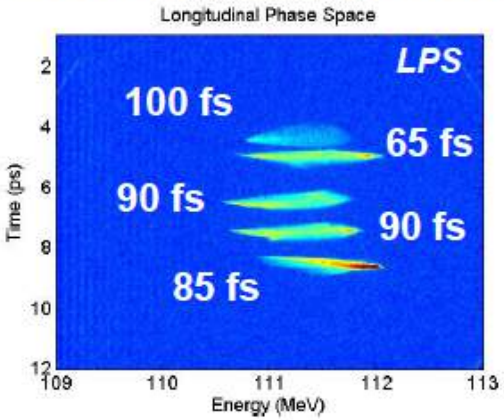


Current profile

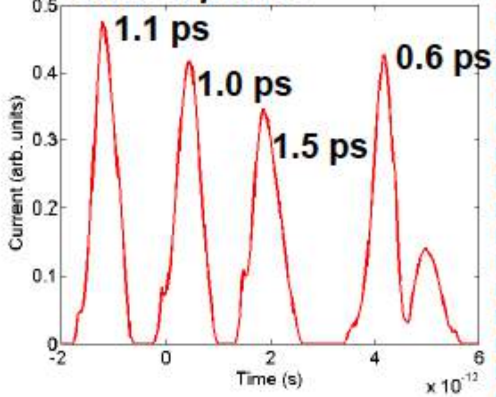


Laser profile on photo-cathode

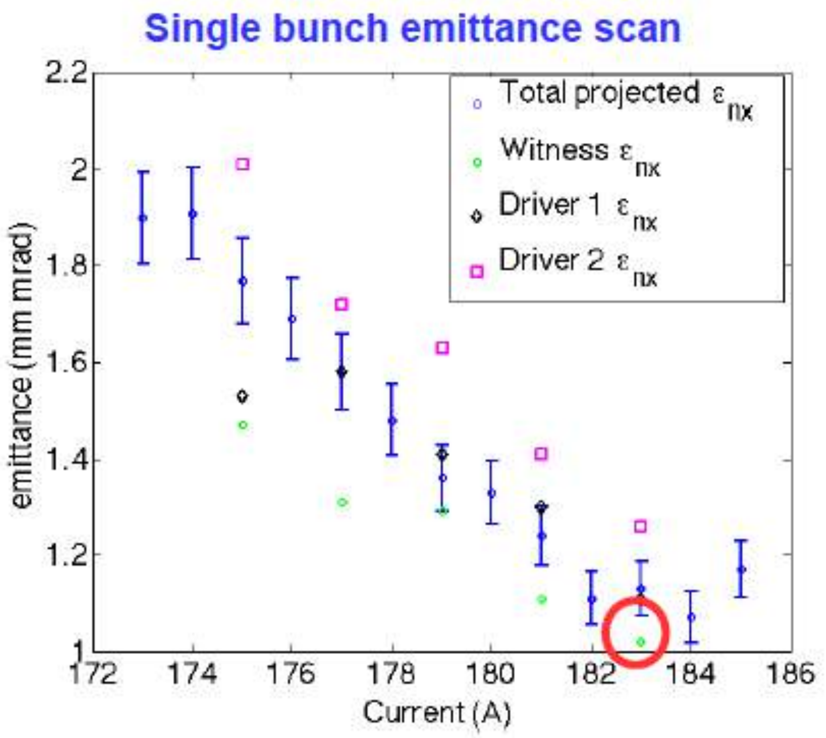


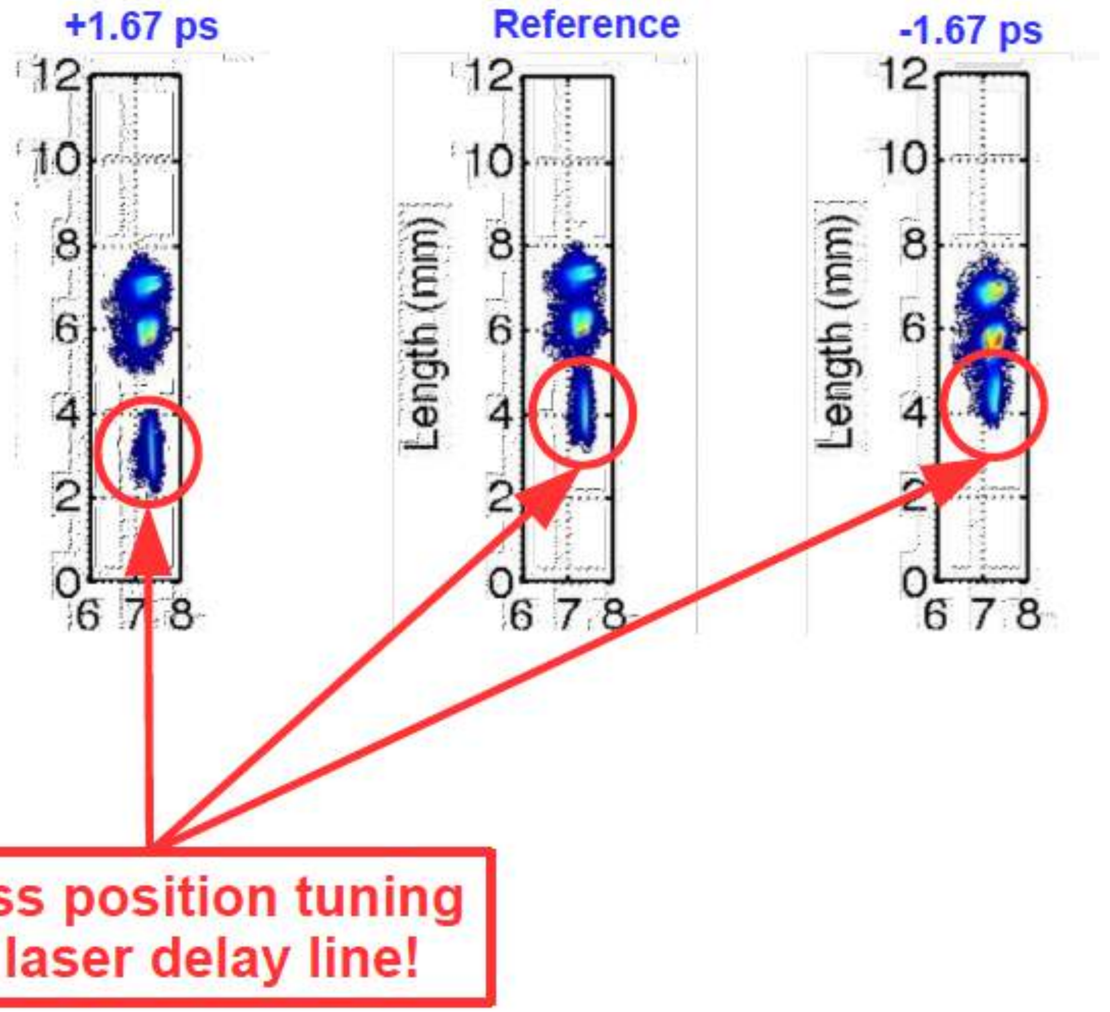


Current profile



Witness – tuning and characterization


Single bunch emittance scan

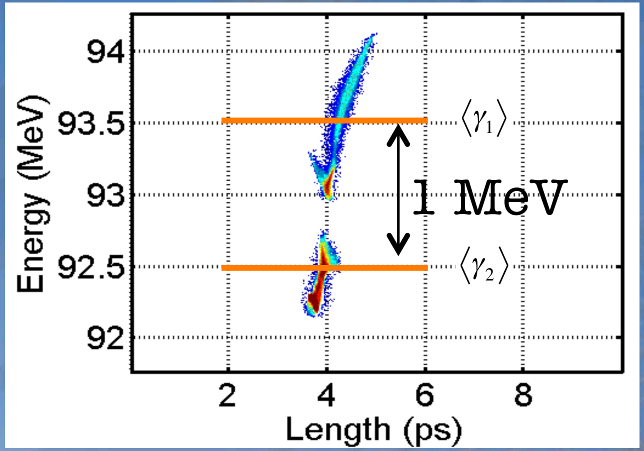

+1.67 ps

Reference

-1.67 ps

Witness position tuning with laser delay line!

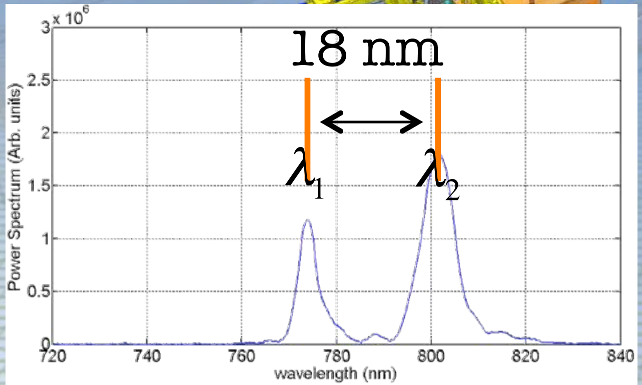
TWO COLORS SASE FEL



two bunches with
a two-level energy distribution
and time overlap (Laser COMB tech.)

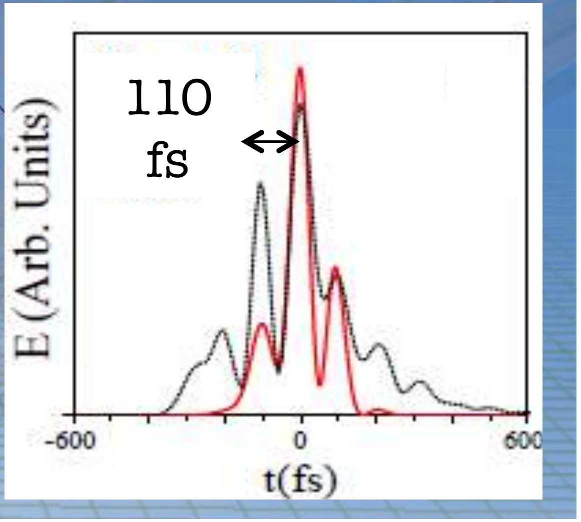
$$\lambda_r = \frac{\lambda_u}{2\gamma^2}\left(1+K_{rms}^2\right)$$

$$\frac{\Delta\lambda_r}{\langle\lambda_r\rangle} = 2\frac{\langle\gamma_1\rangle-\langle\gamma_2\rangle}{\langle\gamma\rangle}$$



produce two wavelength
SASE –FEL radiation
with time modulation

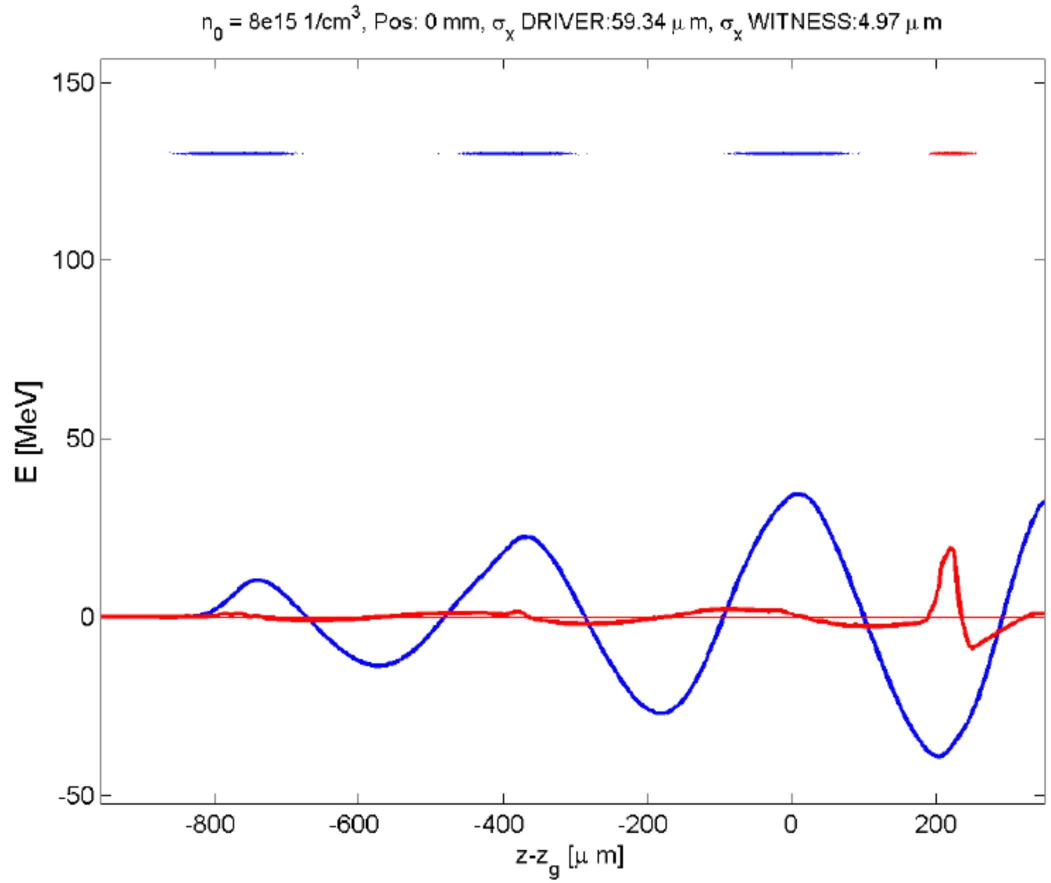
$$\Delta t = \frac{\lambda_u\left(1+K_{rms}^2\right)}{4c\langle\gamma\rangle\langle\gamma_1\rangle-\langle\gamma_2\rangle}$$

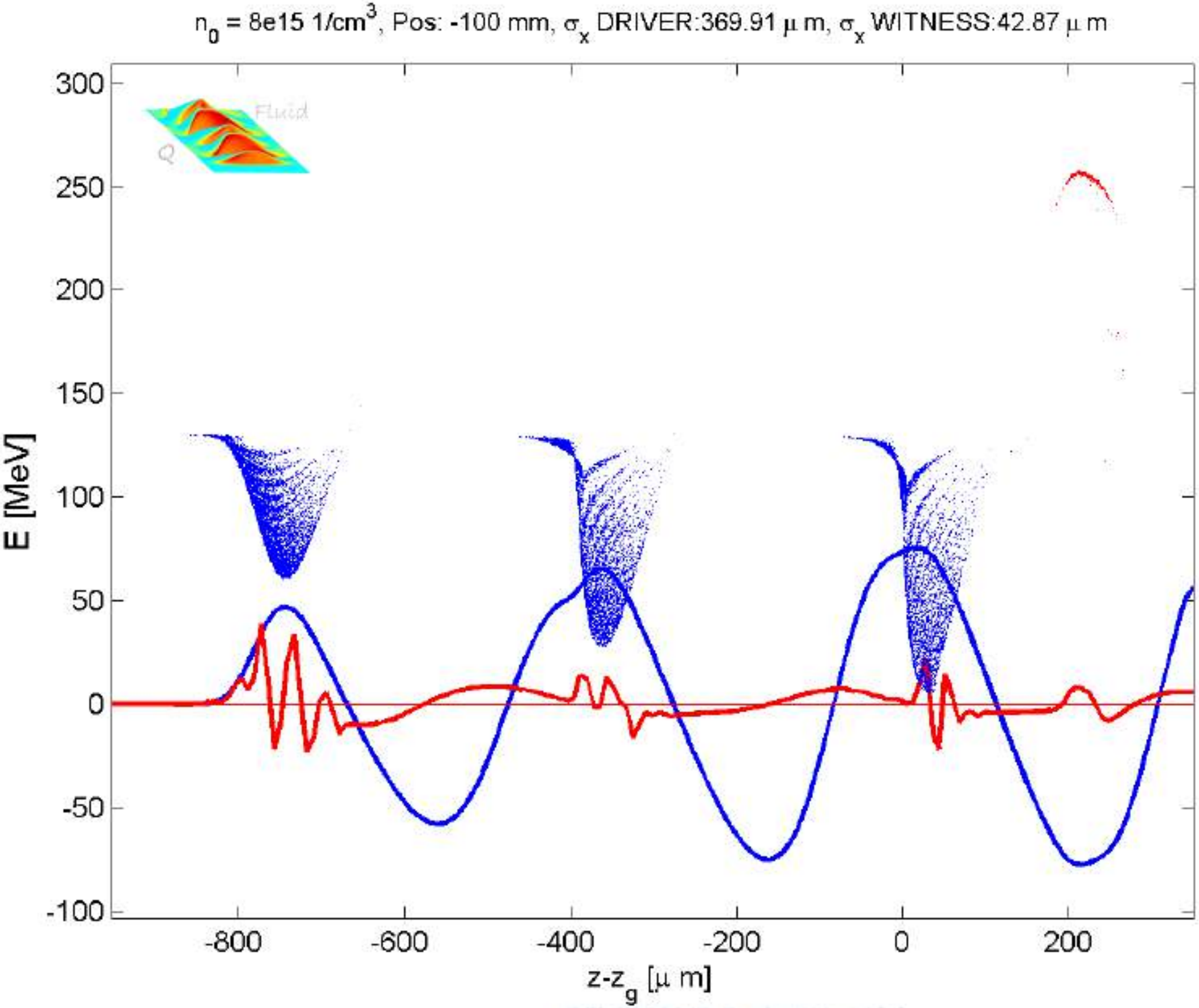


Particle Wake Field Acc.

no=0.75e16 1/cm^3 Lambda_p=383 um, Lacc=10cm Ez=1.2GV/m

	DRIVER (each, pC)	WITNESS
Charge (pC, each)	200	20
sigma_x (um)	**60**	**5**
Sigma_z (um)	25	10





n_0 = 8e15 1/cm^3, Pos: -100 mm, σ_x DRIVER:369.91 μm, σ_x WITNESS:42.87 μm

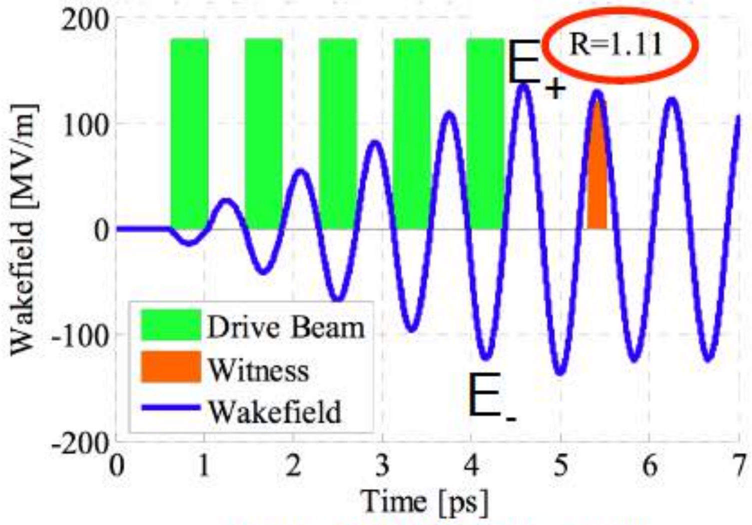
MULTIBUNCH PWFA

Transformer Ratio: $R = E_{+}/E_{-}$ Energy Gain: $\leq RE_0$

σ_r=125 μm, n_e=1.8x10^{16} cm^{-3}, λ_p=250 μm E_0: incoming energy

Q=30 pC/bunch, Δz=250 μm≈λ_p

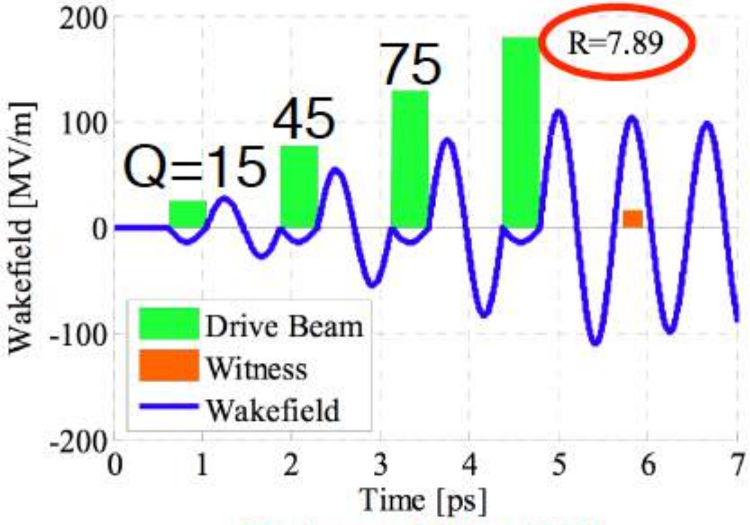
Bunch Train



Kallos, PAC'07 Proceedings

Δz=375 μm≈1.5λ_p

Ramped Bunch Train*

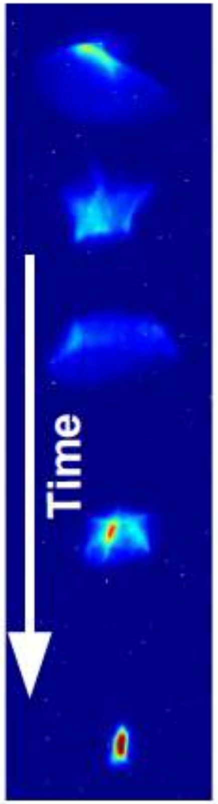


*Tsakanov, NIMA, 1999

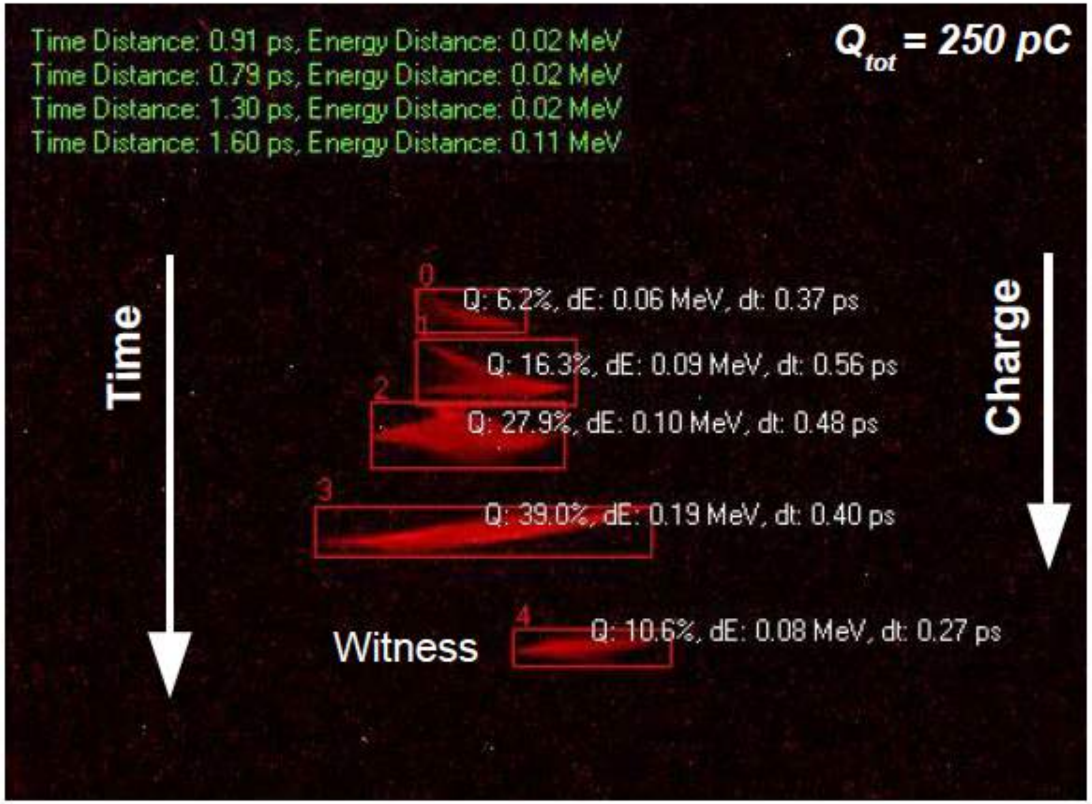
- Linear (2D) theory for n_b<<n_e!
- R=7.9 => multiply energy by ~8 in a single PWFA stage!

Ramped comb beams

z-x view



Longitudinal Phase Space

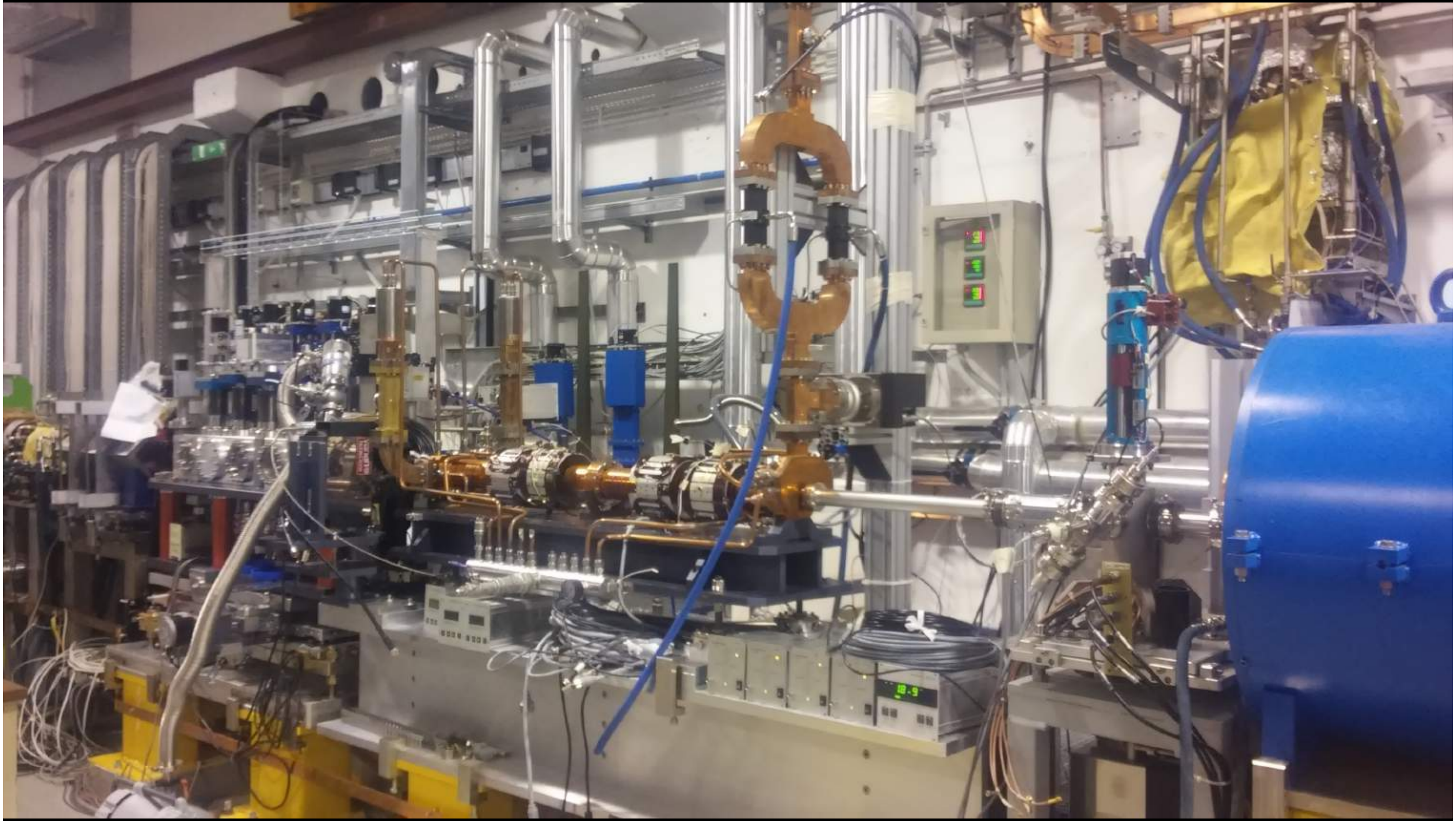


```
Time Distance: 0.91 ps, Energy Distance: 0.02 MeV
Time Distance: 0.79 ps, Energy Distance: 0.02 MeV
Time Distance: 1.30 ps, Energy Distance: 0.02 MeV
Time Distance: 1.60 ps, Energy Distance: 0.11 MeV
```

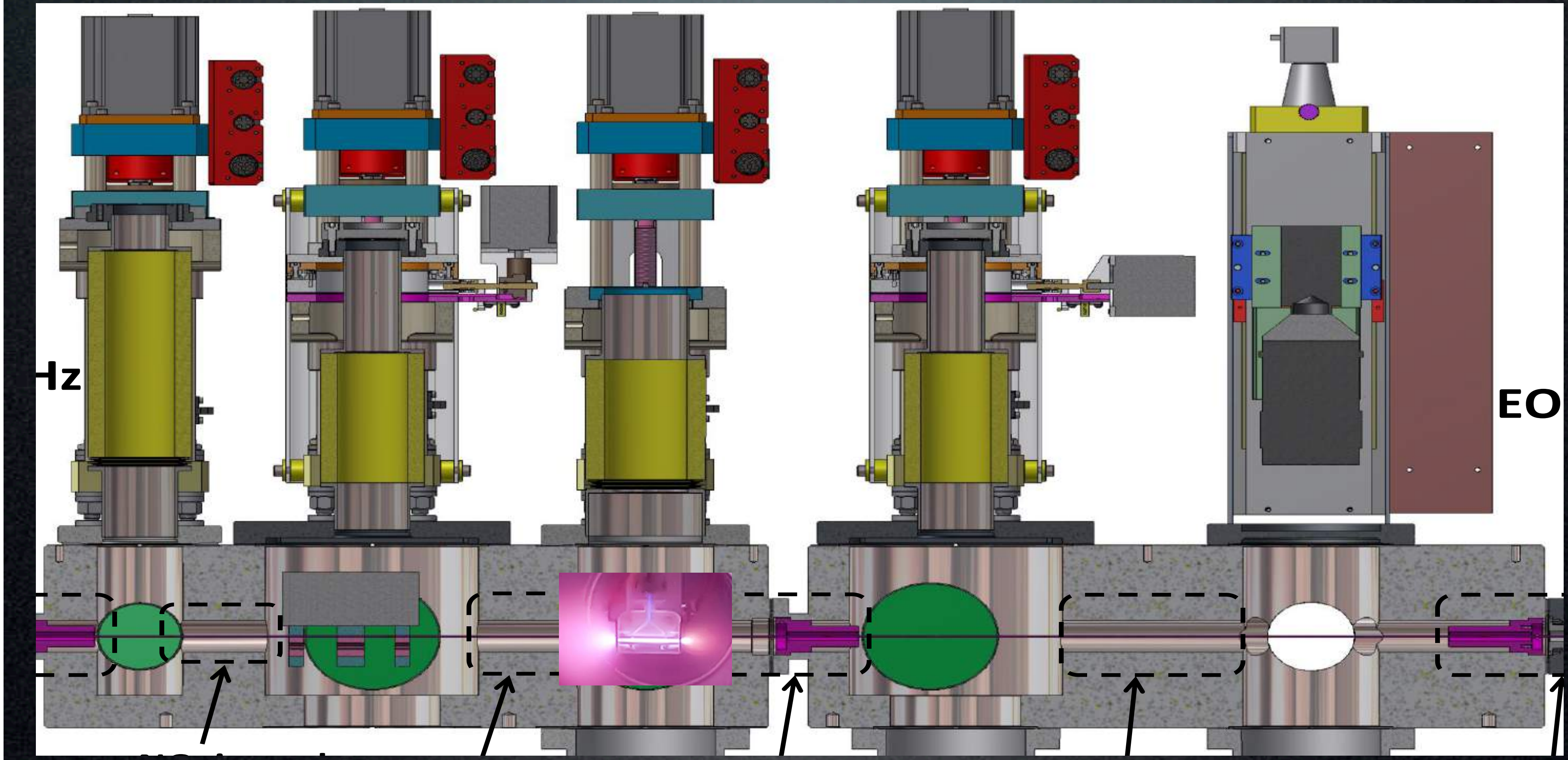
$Q_{tot} = 250\ pC$

```
0 Q: 6.2%, dE: 0.06 MeV, dt: 0.37 ps
1 Q: 16.3%, dE: 0.09 MeV, dt: 0.56 ps
2 Q: 27.9%, dE: 0.10 MeV, dt: 0.48 ps
3 Q: 39.0%, dE: 0.19 MeV, dt: 0.40 ps
4 Q: 10.6%, dE: 0.08 MeV, dt: 0.27 ps
```

C-Band accelerating structure and PWFA chamber



PWFA – Particle Wake Field Accelerator

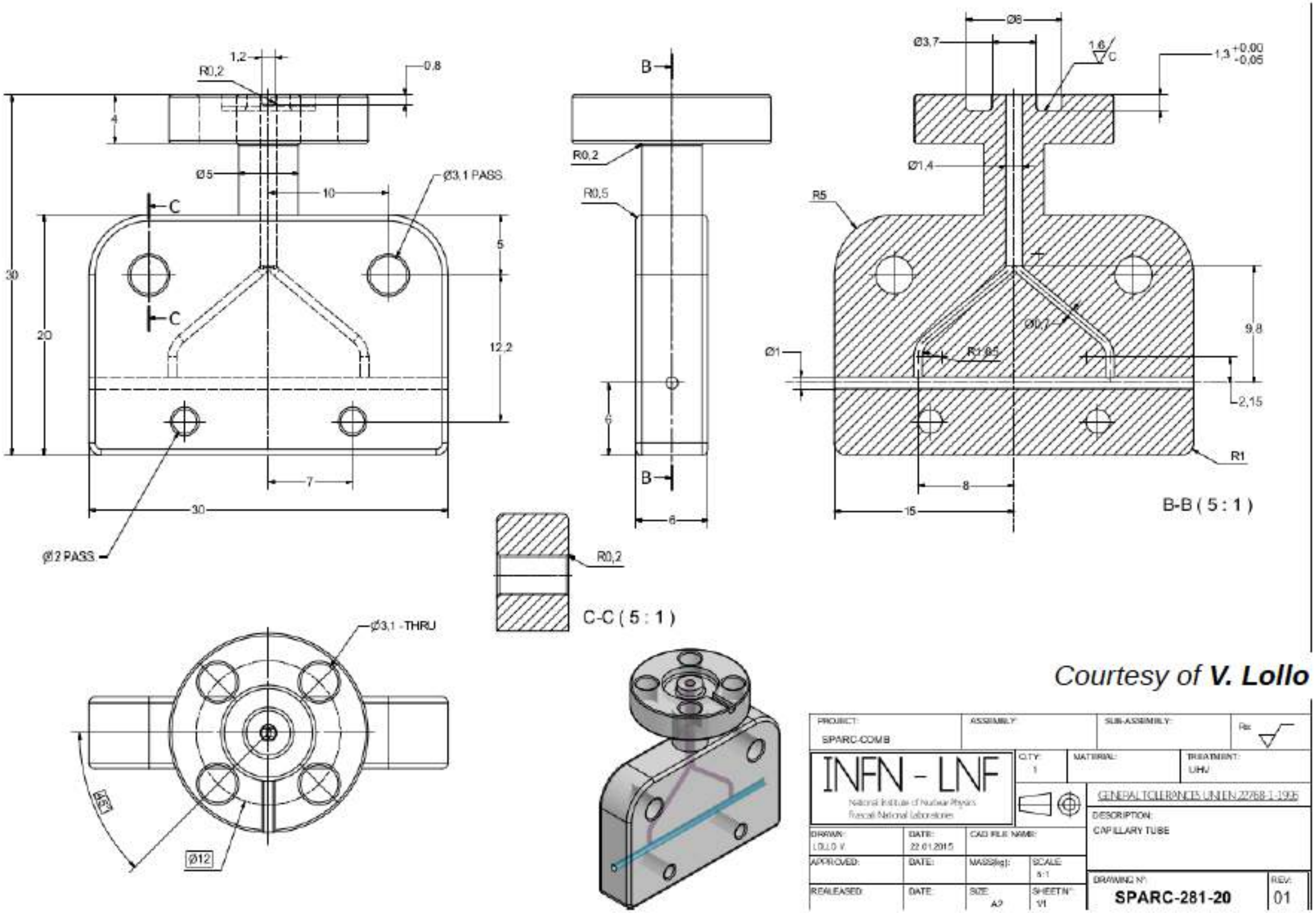


Focusing PMQ

PWFA module

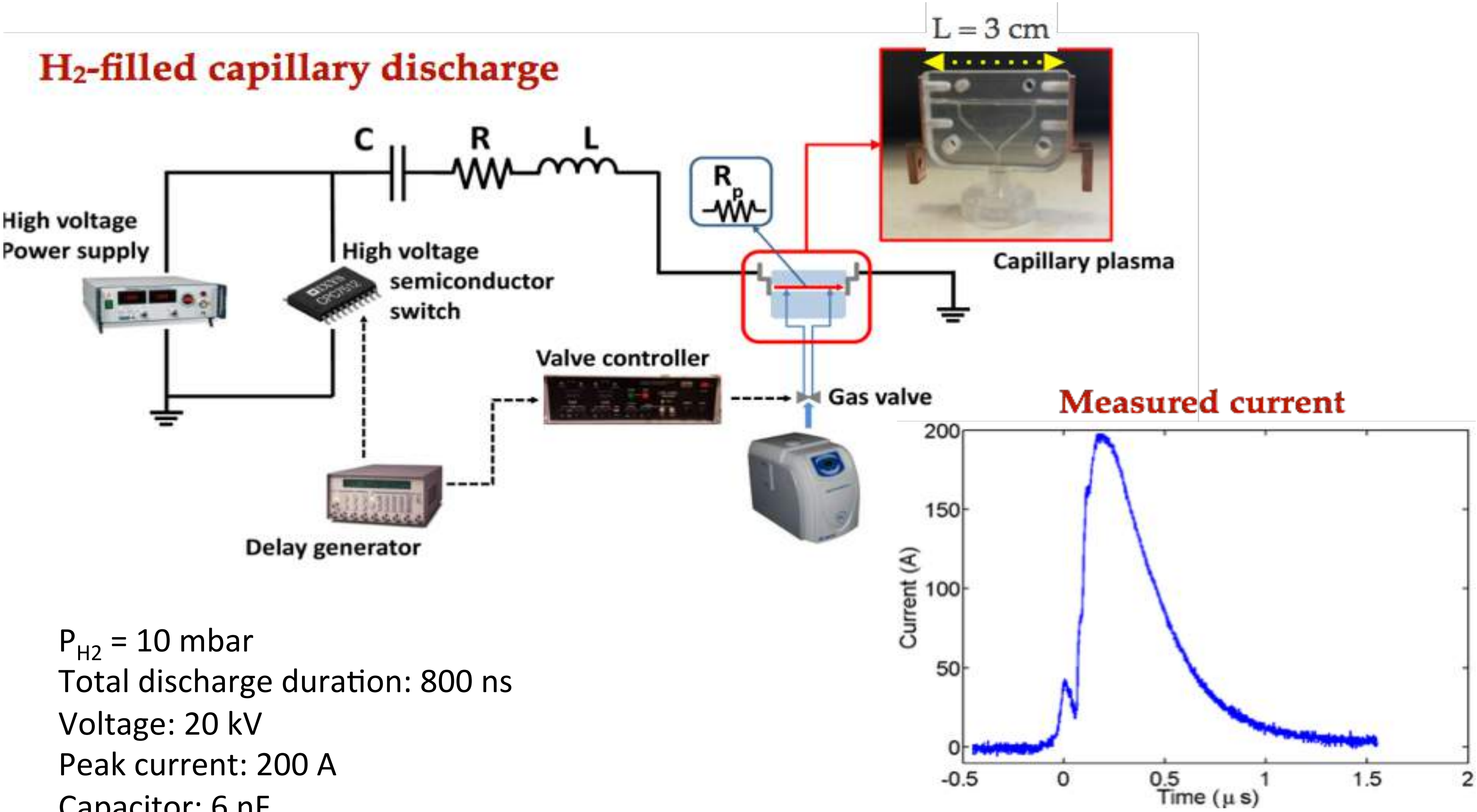
Capture PMQ

Plasma capillary



Courtesy of ***V. Lollo***

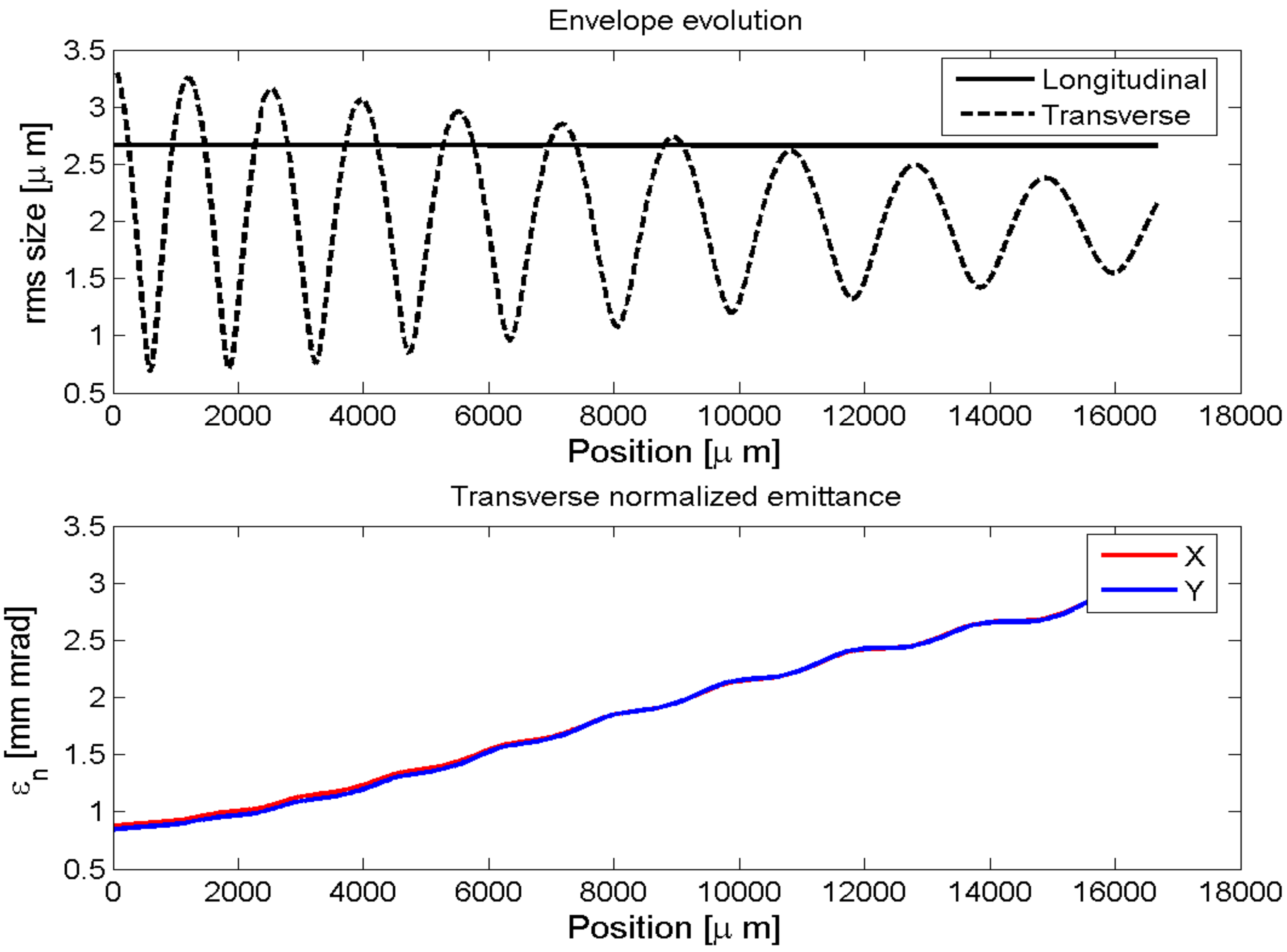
Plasma Source



P_{H2} = 10 mbar
Total discharge duration: 800 ns
Voltage: 20 kV
Peak current: 200 A
Capacitor: 6 nF

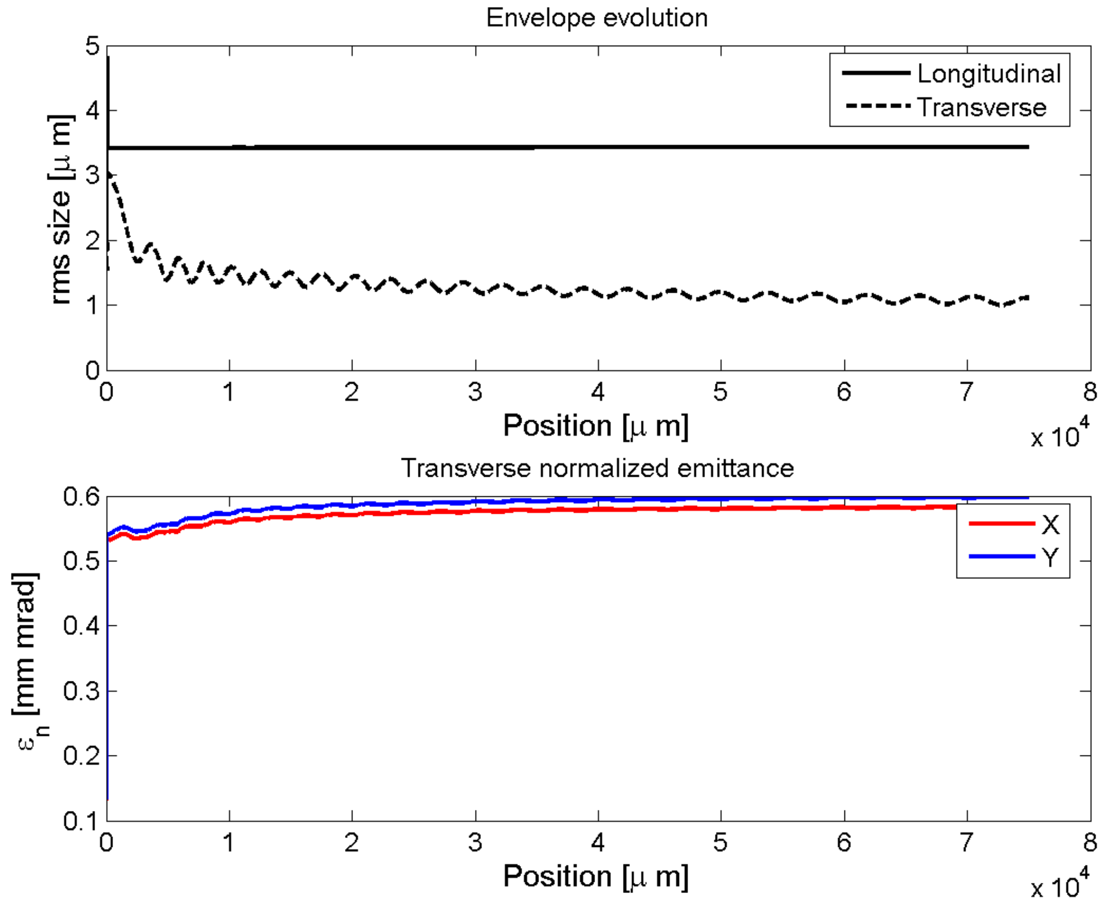
Courtesy of M. P. Anania, A. Biagioni, D. Di Giovenale, F. Filippi, S. Pella

First Capillary Discharge (Oct. 23 - 2015)



Courtesy P. Tomassini

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

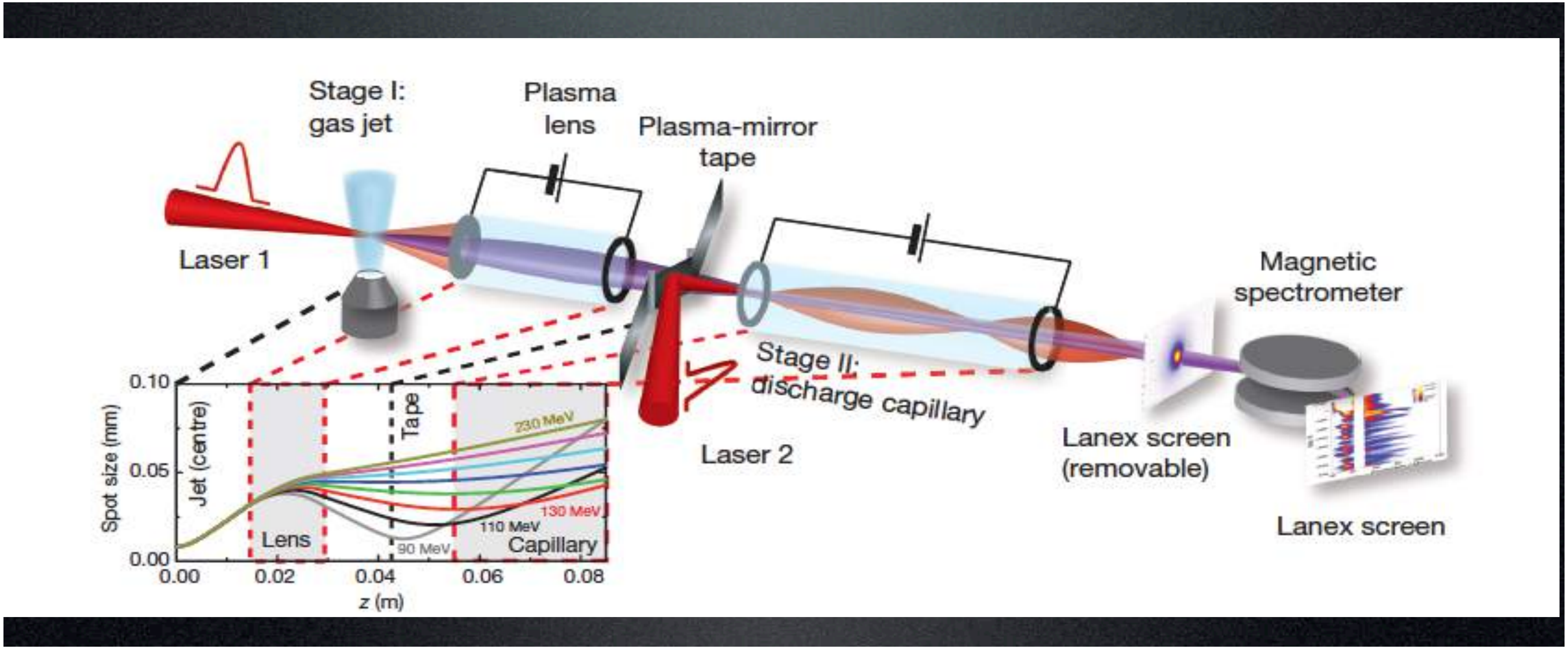


LETTER

doi:10.1038/nature16525

Multistage coupling of independent laser–plasma accelerators

S. Steinke[1], J. van Tilborg[1], C. Benedetti[1], C. G. R. Geddes[1], C. B. Schroeder[1], J. Daniels[1,3], K. K. Swanson[1,2], A. J. Gonsalves[1], K. Nakamura[1], N. H. Matlis[1], B. H. Shaw[1,2], E. Esarey[1] & W. P. Leemans[1,2]

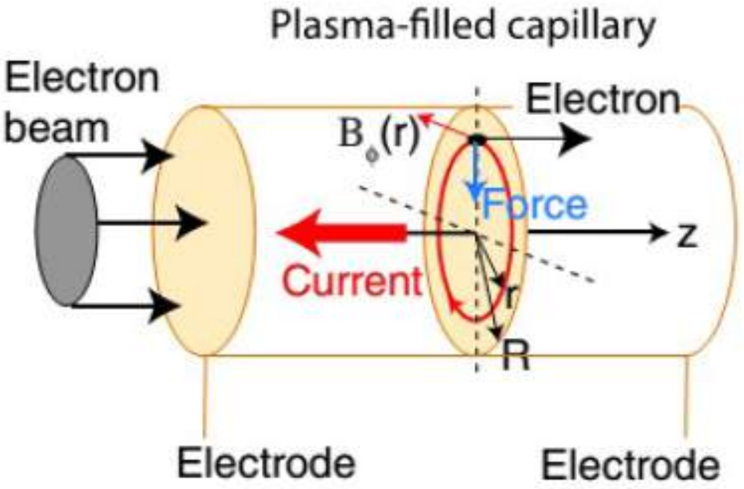


Active plasma lens

- Focusing field produced by electric discharge in a plasma-filled capillary
  - *Focusing field produced, according to Ampere's law, by the discharge current*

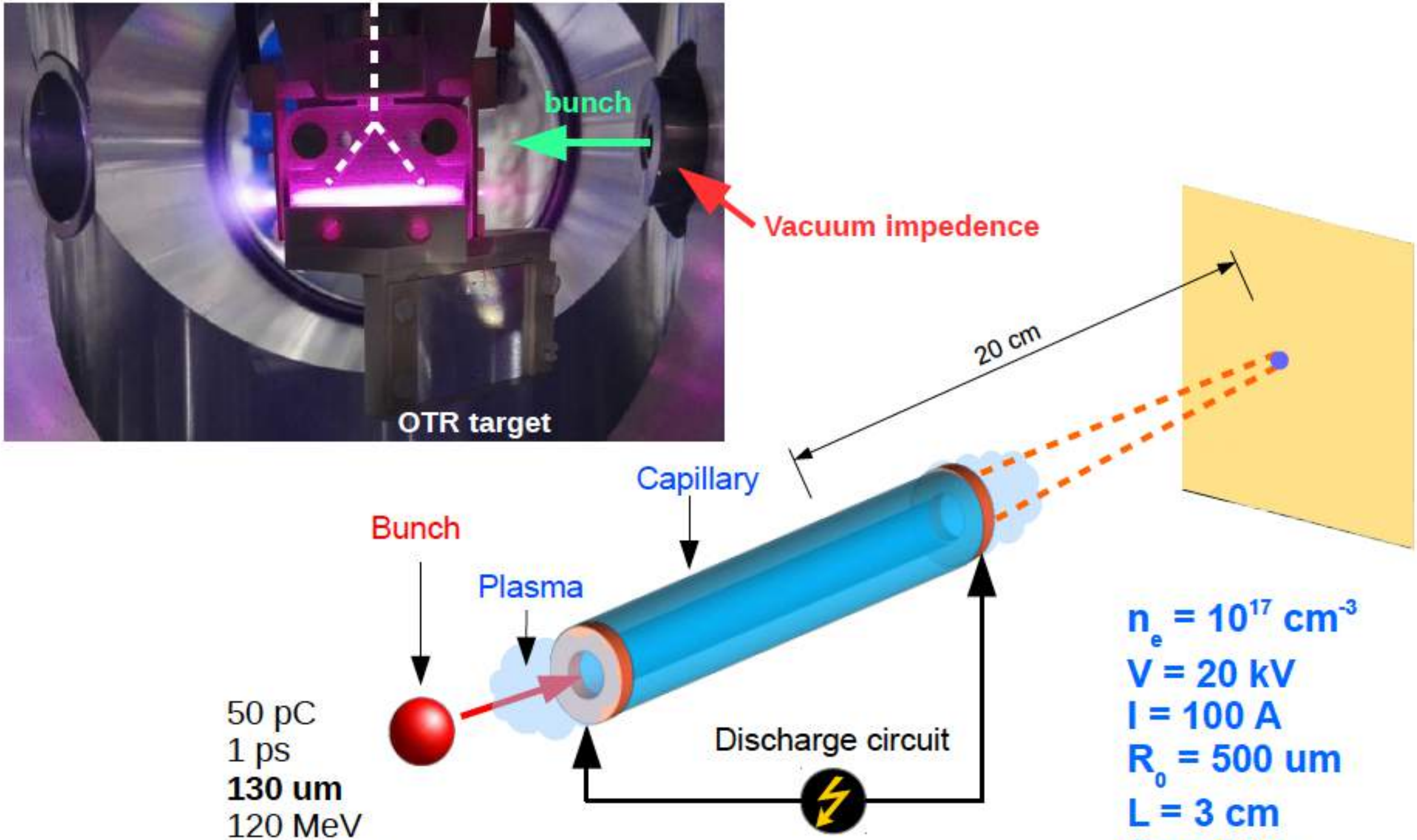
$$\boxed{B_\phi(r)=\frac{1}{2}\int_0^r \mu_0 J(r')\,dr'}$$

- ✓ Radial focusing
  - *X/Y planes are not dependent as in quads*
- ✓ Weak chromaticity
  - *Focusing force scales linearly with energy*
- ✓ Compactness
  - *Higher integrated field than quad triplets*
- ✓ Independent from beam distribution
  - *Not sensitive to longitudinal/transverse charge profile as in passive plasma lenses*



Van Tilborg, J., et al. "Active plasma lensing for relativistic laser-plasma-accelerated electron beams." Physical review letters 115.18 (2015): 184802.

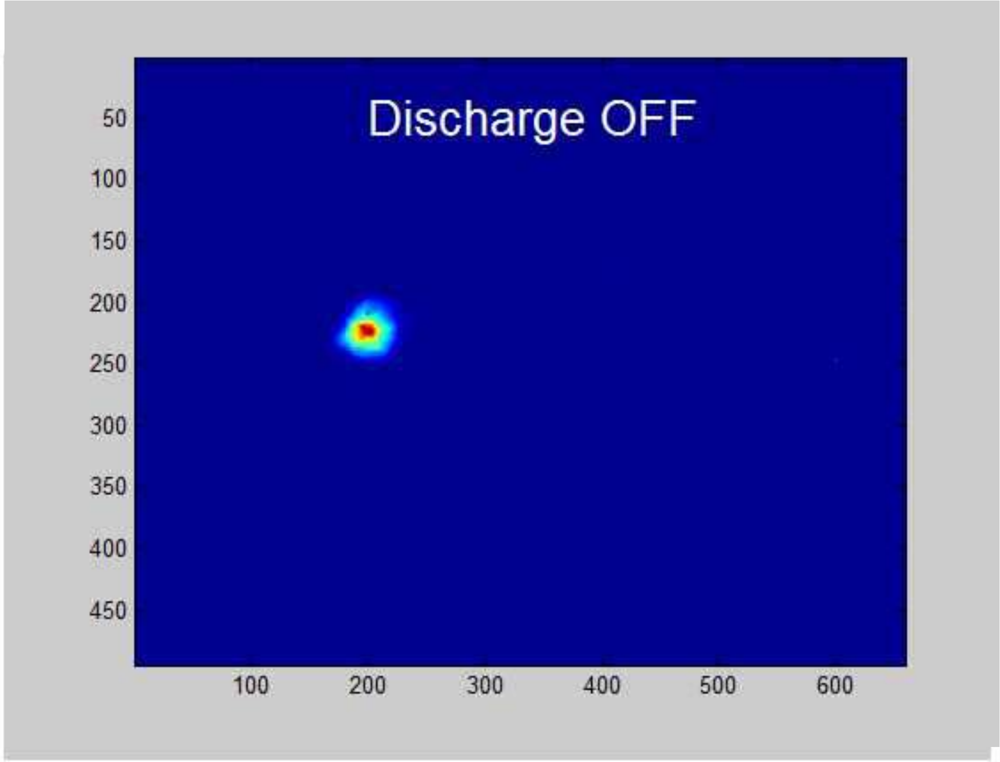
Experimental layout

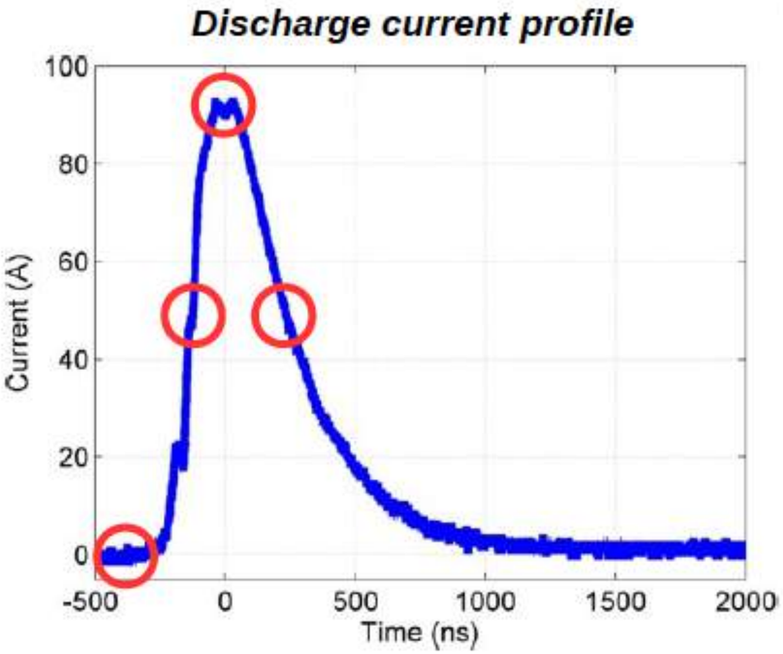


50 pC
1 ps
130 um
120 MeV
1 mm mrad

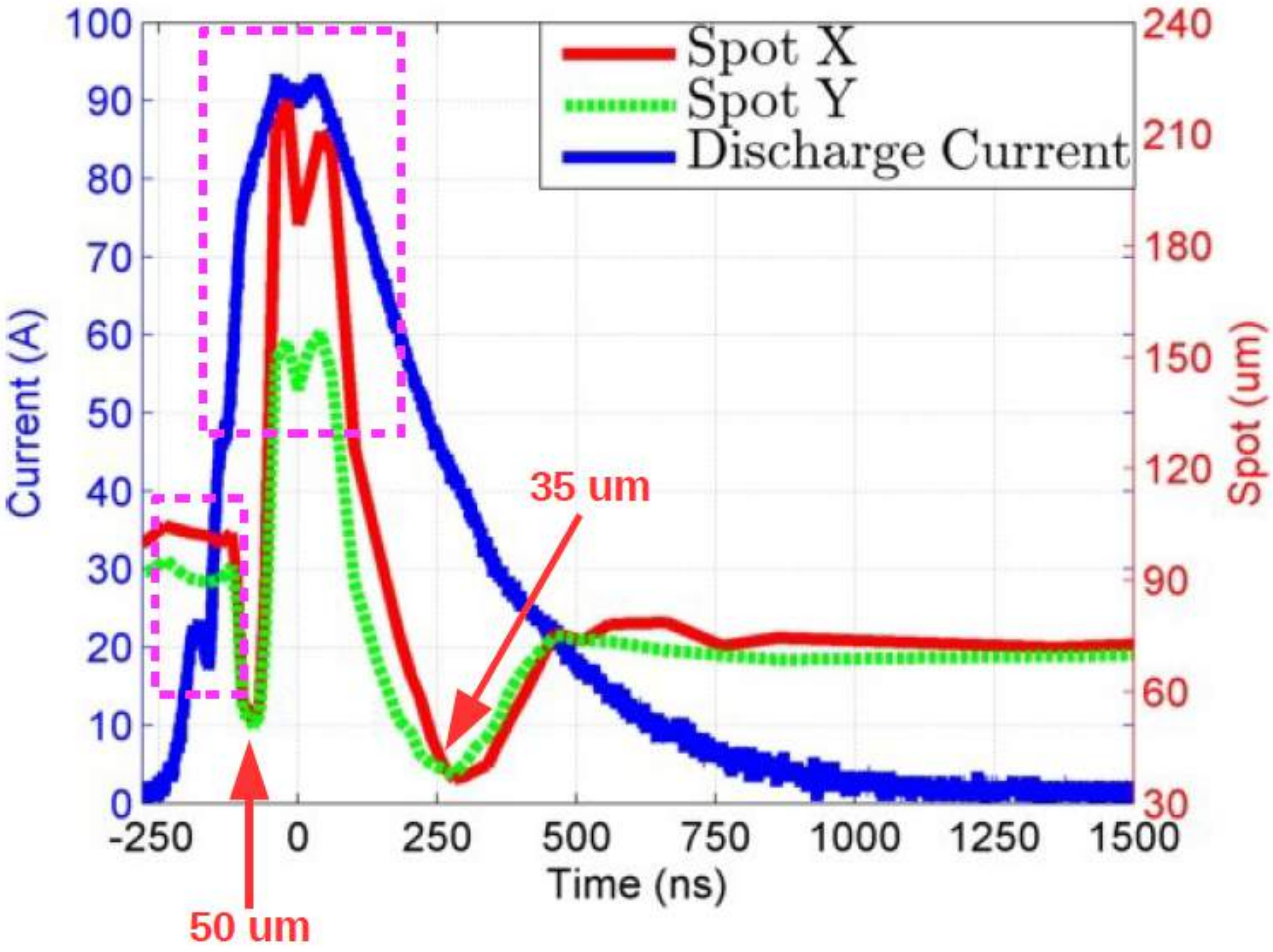
$n_e = 10^{17}$ cm^{-3}
V = 20 kV
I = 100 A
R_0 = 500 um
L = 3 cm
Sapphire

Preliminary results

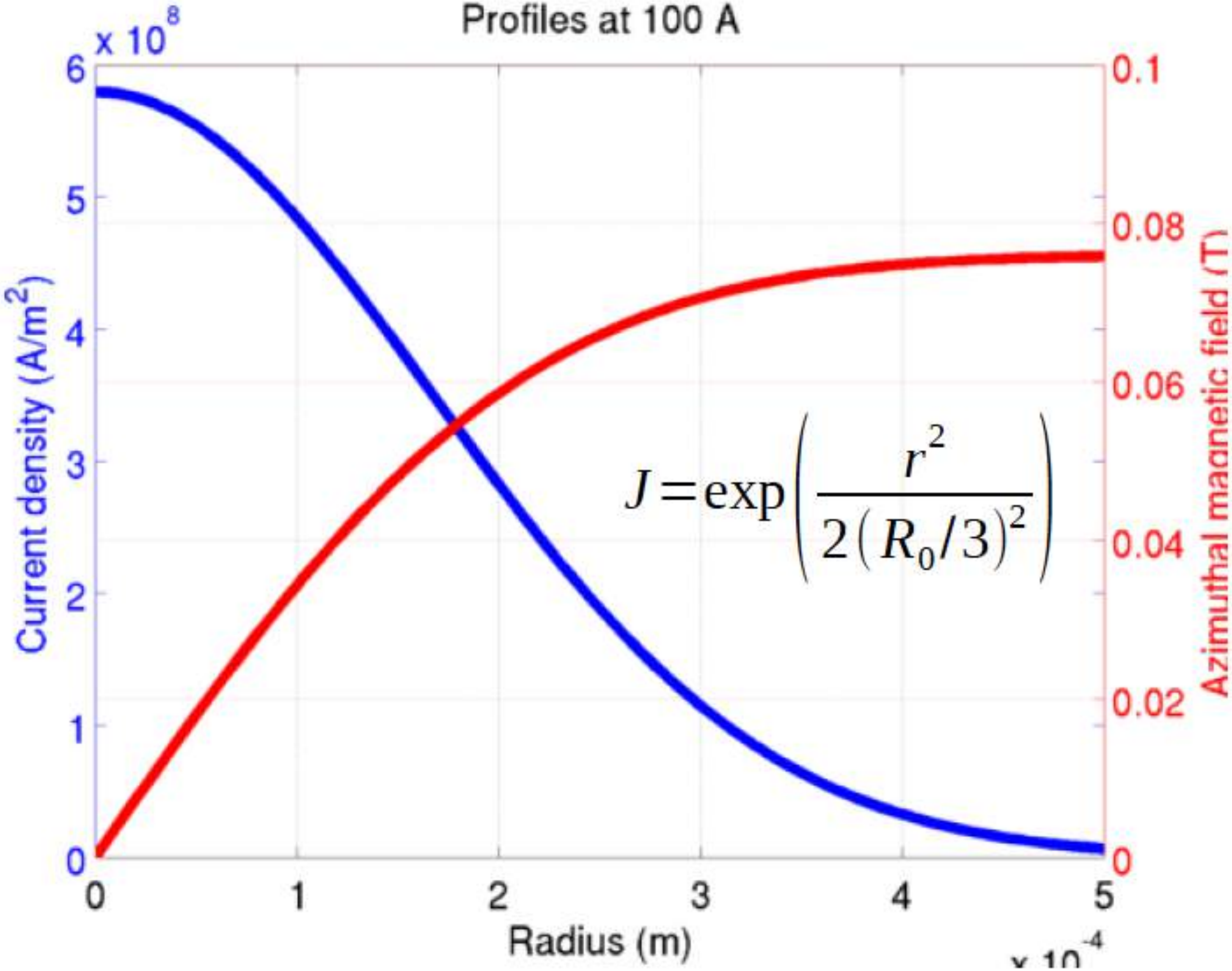




Preliminary results

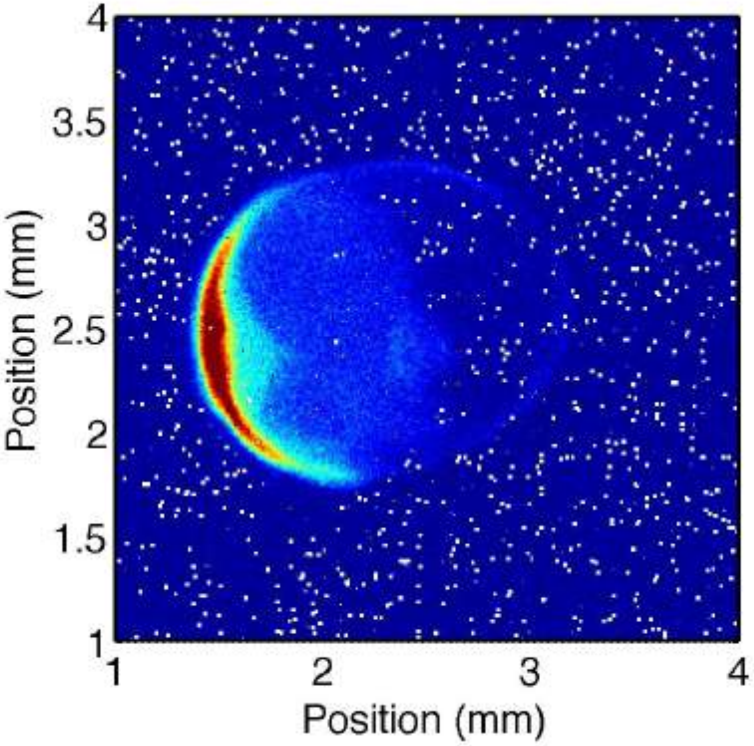


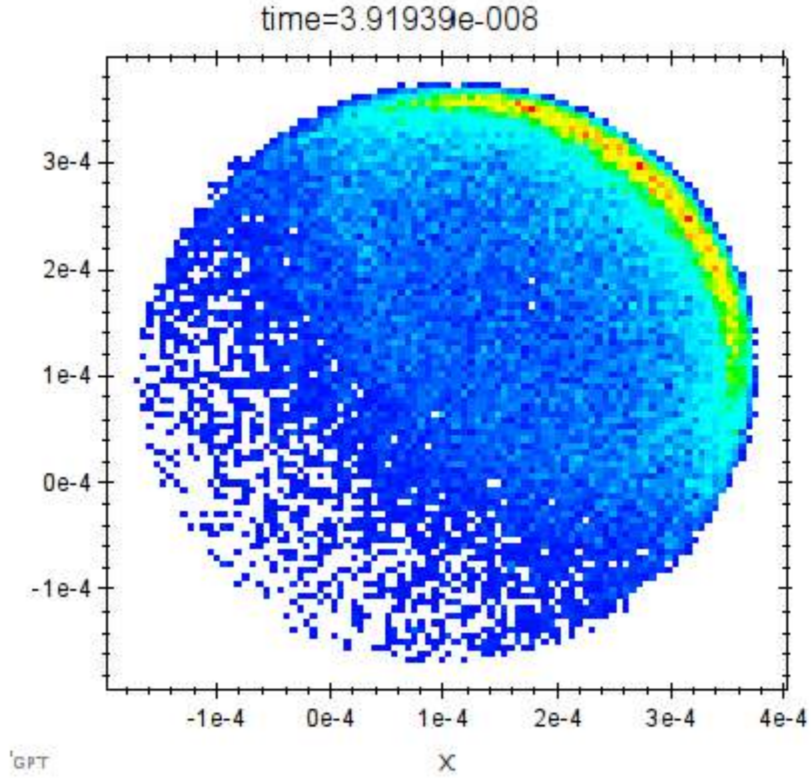
Gaussian current profiles



$$J = \exp\left(\frac{r^2}{2\left(R_0/3\right)^2}\right)$$

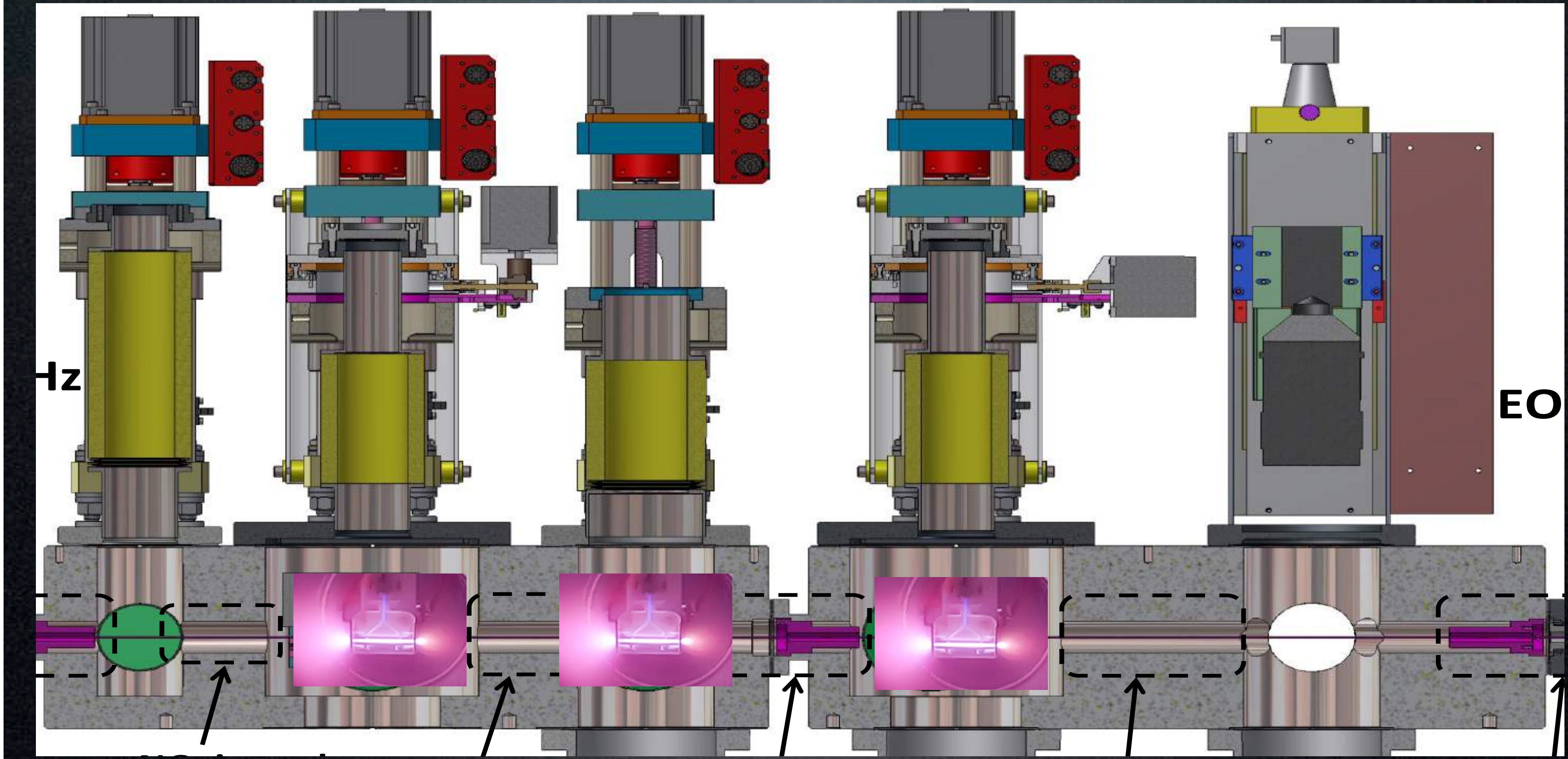
Over focusing (max current)





100 um offset

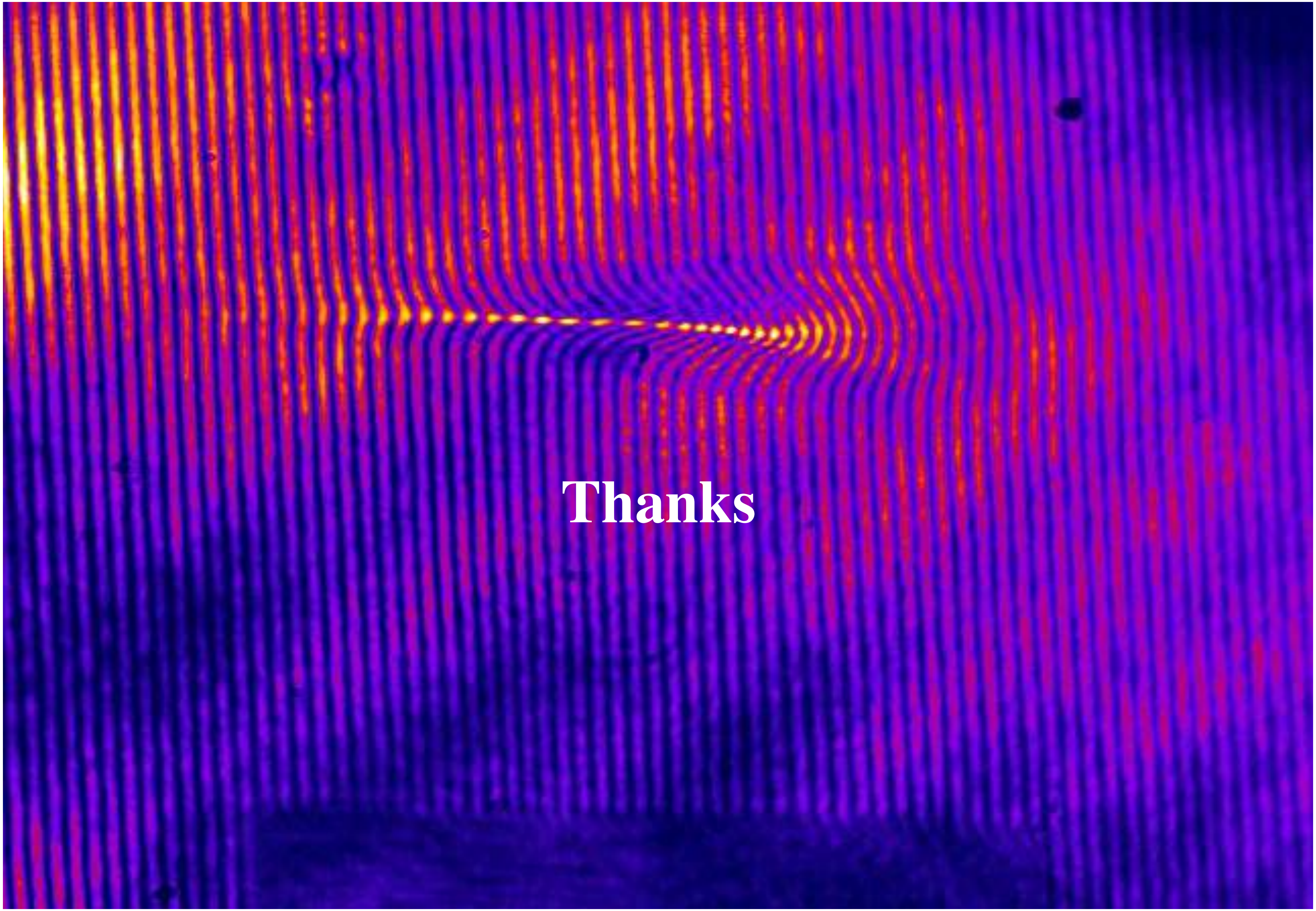
Plasma Driven FEL under investigation



Focusing
Plasma Lens

PWFA
module

Capture
Plasma Lens



Thanks