Beam manipulation for resonant PWFA

Enrica Chiadroni on behalf of the SPARC_LAB collaboration

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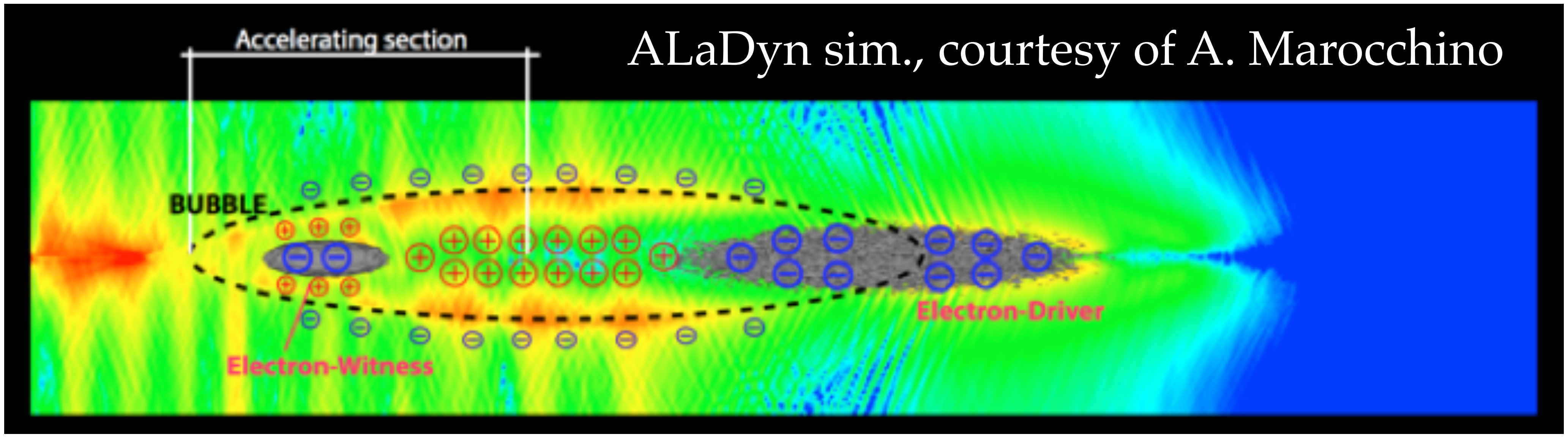
Laboratori Nazionali di Frascati

Motivation

- 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)
  - Litos, 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*
- **Resonant excitation of plasma wakes** increases
  - energy transfer from driver bunches to the witness beam, encouraging the preservation of the plasma-accelerated beam quality
- **High brightness multi-bunch trains** are mandatory for a significant improvement of the efficiency of PWFA

Plasma-based Accelerators



- 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

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Limitation of PWFA

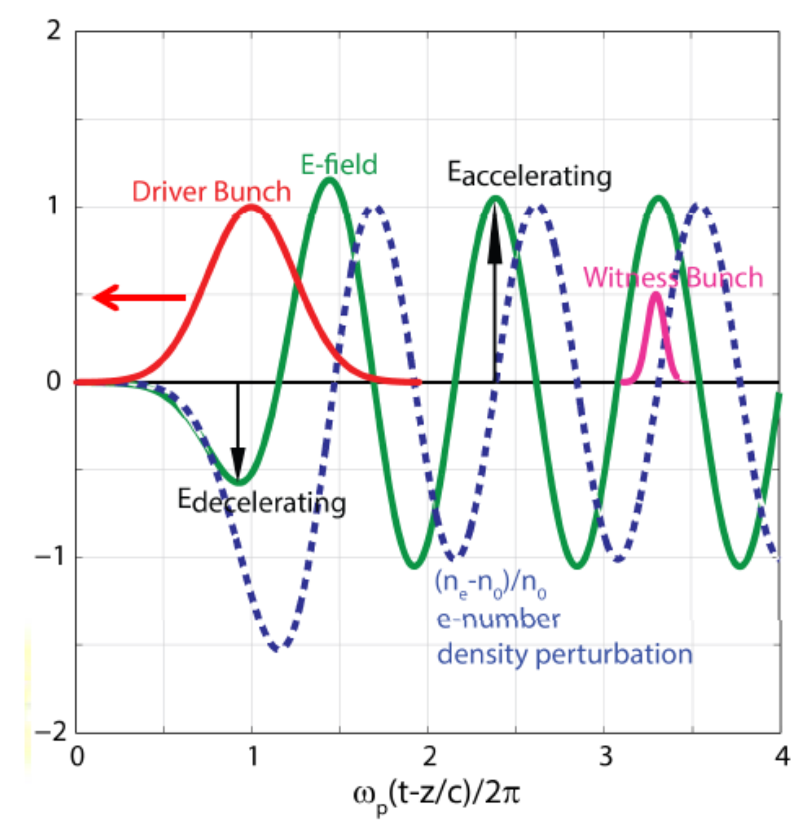
- **PWFA** acting as an **energy transformer** has the great potential to double beam energy in a single stage

- The energy transfer from the drive bunch to the plasma is optimized by maximizing the **transformer ratio**

$$R = \frac{|E_{+,max}|}{|E_{-,max}|}$$

Wakefield theorem*

- **Symmetric drive bunch current profile** in a single-mode structure: the **maximum accelerating field** behind the drive bunch **cannot exceed 2 times the maximum decelerating field** amplitude along the drive bunch



F. Massimo et al., NIM A **740**, 242–245 (2014)

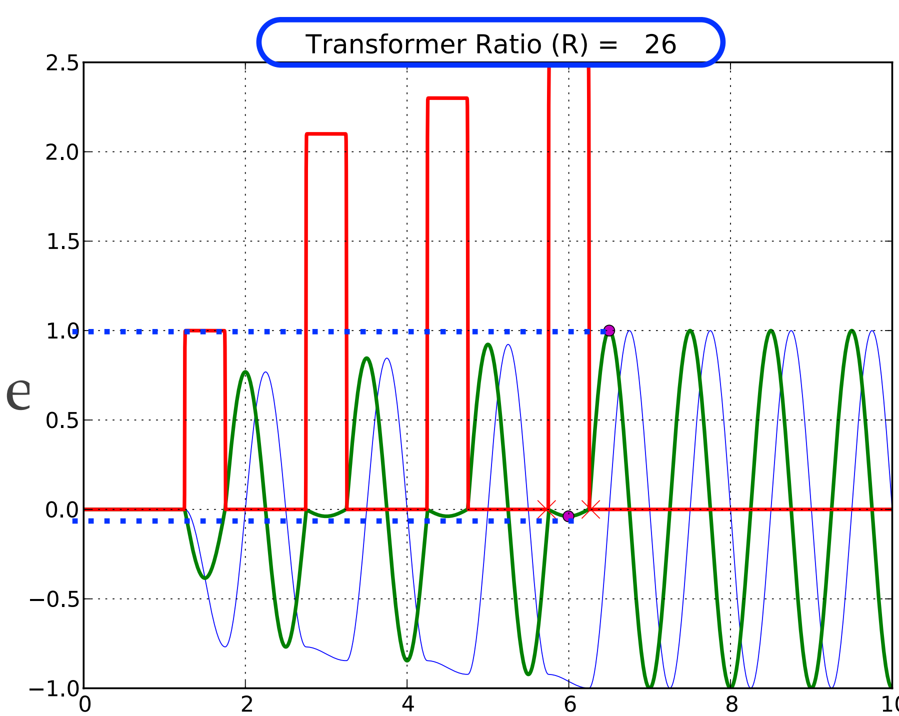
*V. V. Tsakanov, Nucl. Instrum. Methods Phys. Res., Sect. A 432, 202 (1999)

Enhancing Transformer Ratio

- By properly **tailoring the driver bunch shape**, the witness beam energy might be more than doubled when

*The maximum possible transformer ratio for a bunch with given length and total charge corresponds to that charge distribution which causes all particles in the bunch to see the same retarding field**

- 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 (R.Ruth et al., PA 1985; W. Lu e PAC 2009)



*K. Bane, P. Chen, and P. B. Wilson, *SLAC-PUB-3662*,1985

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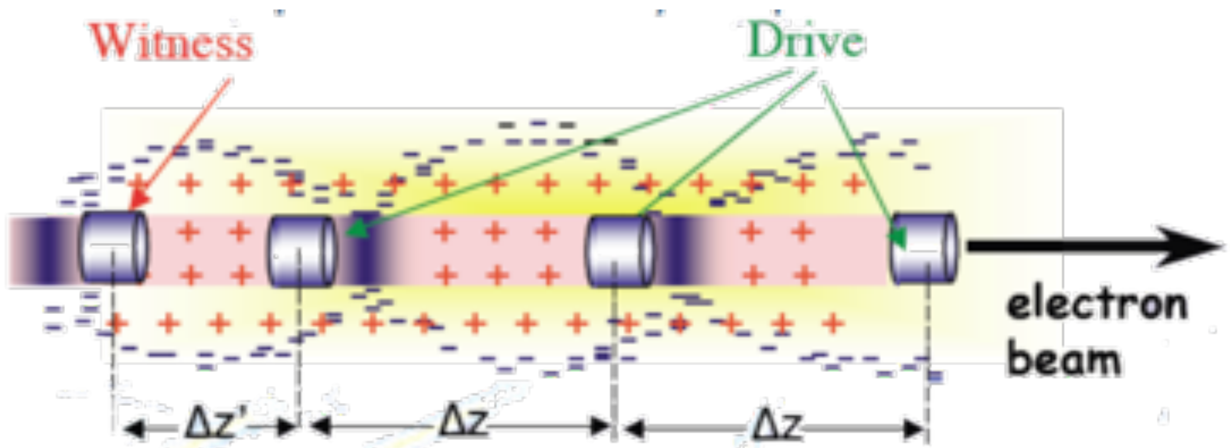
Courtesy of F. Massimo

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}

- **Multi-bunch shaping is one of the most promising candidates**
  - Increase in energy of a trailing particle $\Delta\gamma = R\gamma$
  - Preservation of witness emittance and length
  - Better control of the energy spread

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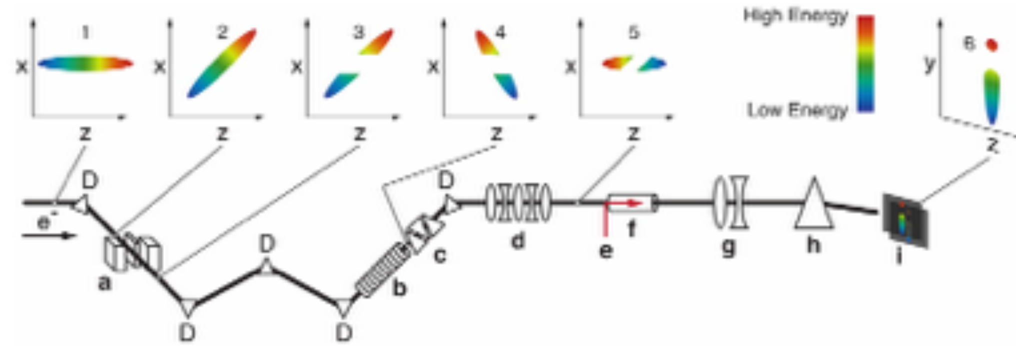
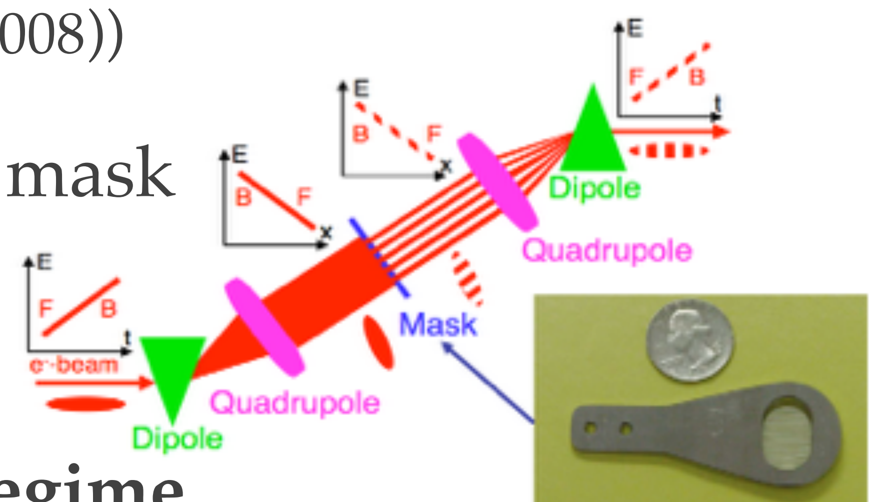
Tailoring Beam Shape

FACET



- Notching device in a dispersing section
  - *High-efficiency acceleration of an electron beam in a plasma wakefield accelerator*, M. Litos et al., Nature **515**, 6 (2014)
- Emittance Exchange (EEX) beam line and transverse mask
  - Double triangular current profile (G. Ha et al., AIP Conf. Proc. **1507**, 693 (2012))
- Anisochronous dogleg beam line
  - ramped bunch trains (R. J. England et al., PRL 100, 214802 (2008))
- Multi-bunch via collimation: dogleg and multi-wire mask
  - P. Muggli et al, PRL 101, 054801 (2008)



- Beam shaping via **photo-emission**
  - **Laser comb generation and velocity bunching regime**
    - Ramped bunch trains (NIM A 637, S43–S46 (2011))
      - **The SPARC_LAB Experience**

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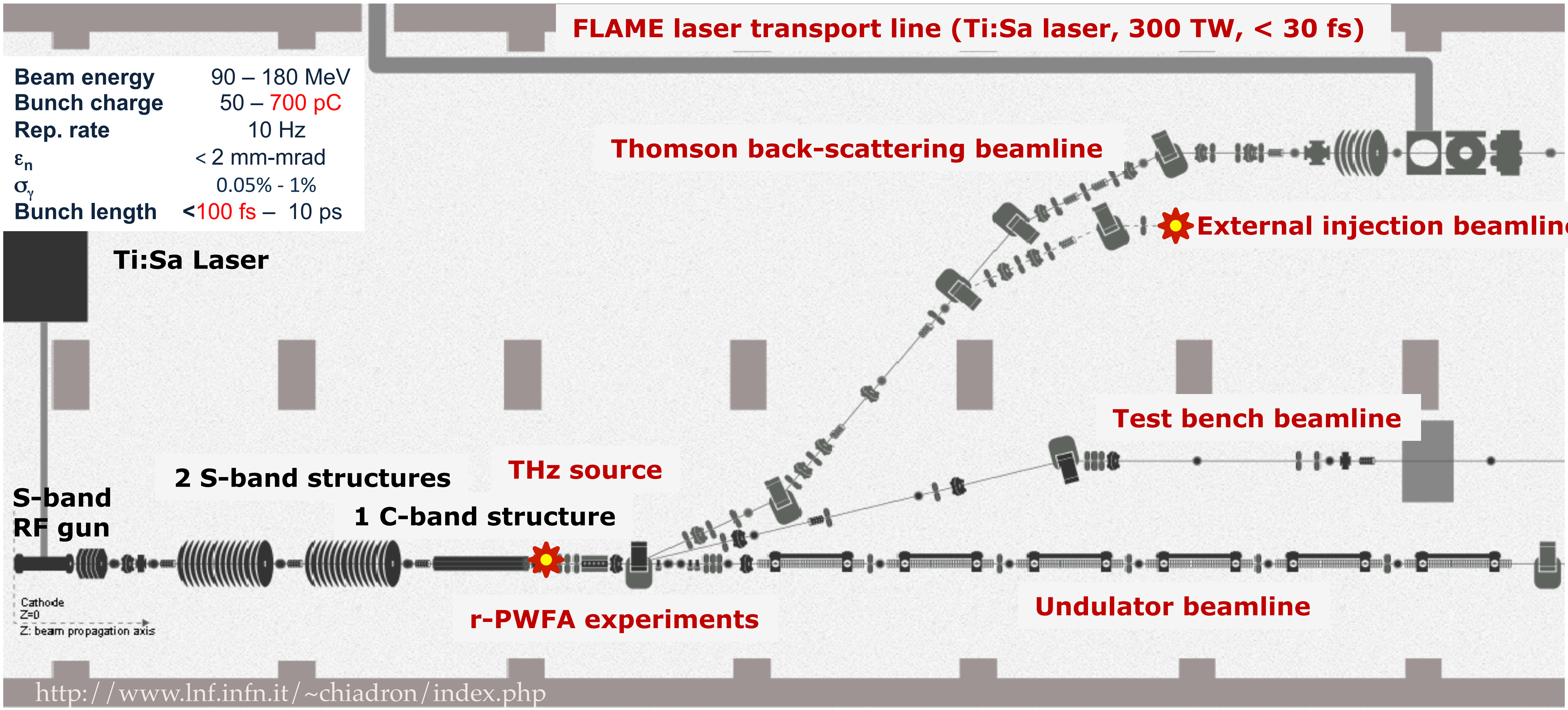
The SPARC_LAB Test Facility



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

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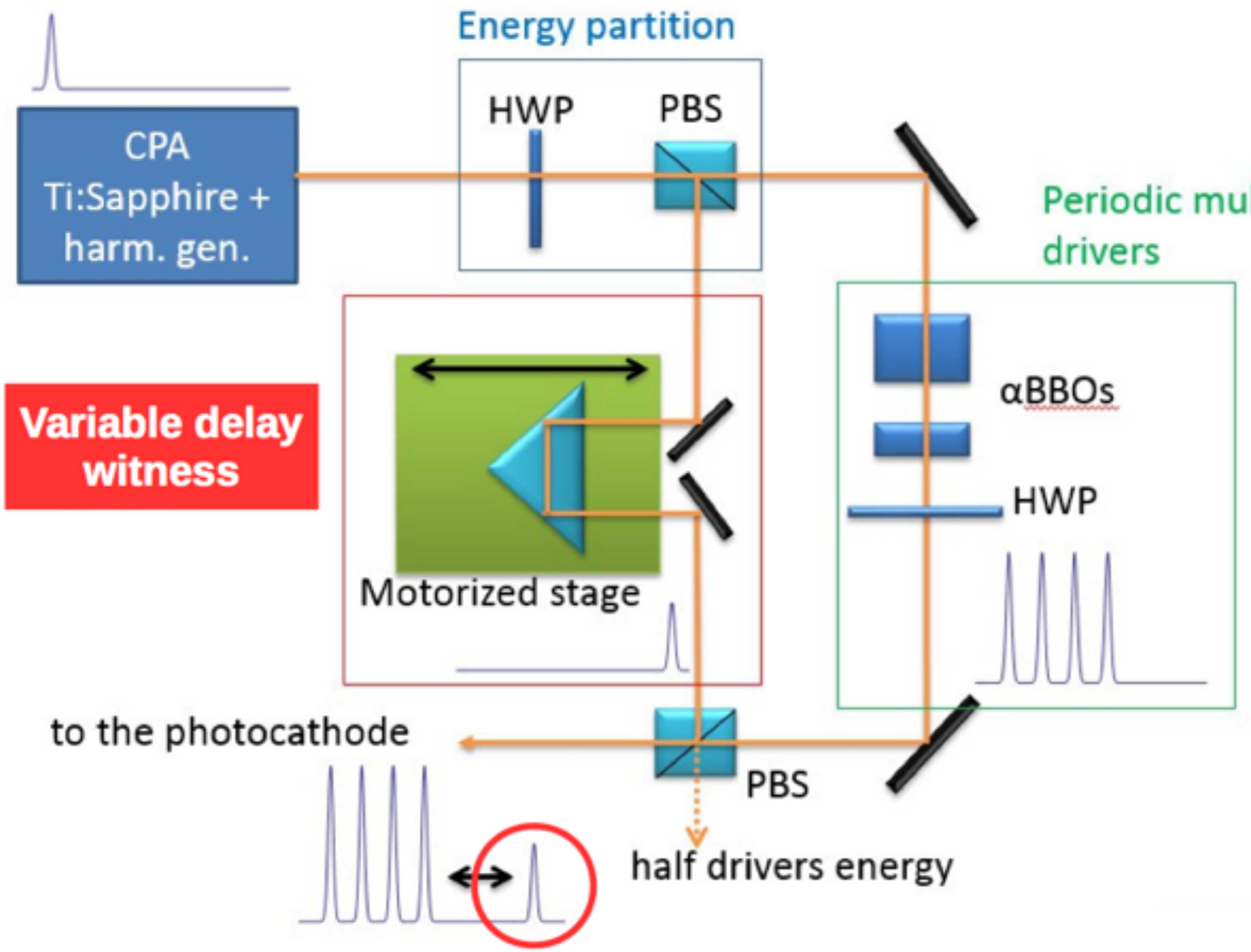
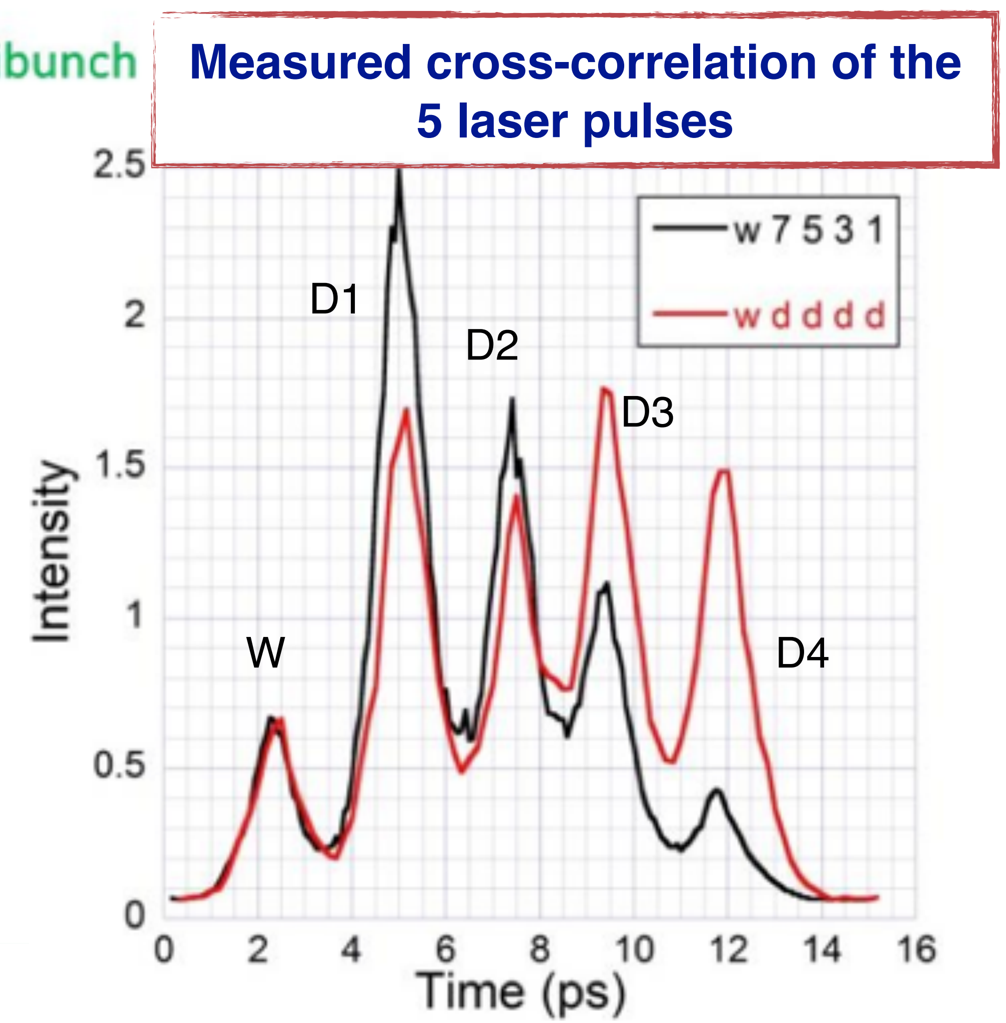
Laser comb pulse shaping

- **Laser comb**: **multiple bunch trains** are produced directly at the cathode
  - Pulses delayed by **birefringent crystals** (aBBO) **and delay lines** to fully control bunch inter-distance
  - **Half-wave plates** (HWP) for unbalancing intensity
    - **ramped charge**

$$\Delta\tau = \left| \frac{1}{v_{ge}} - \frac{1}{v_{go}} \right| L_{crystal}$$





F. Villa et al., Proc. of the 2nd EAAC 2015

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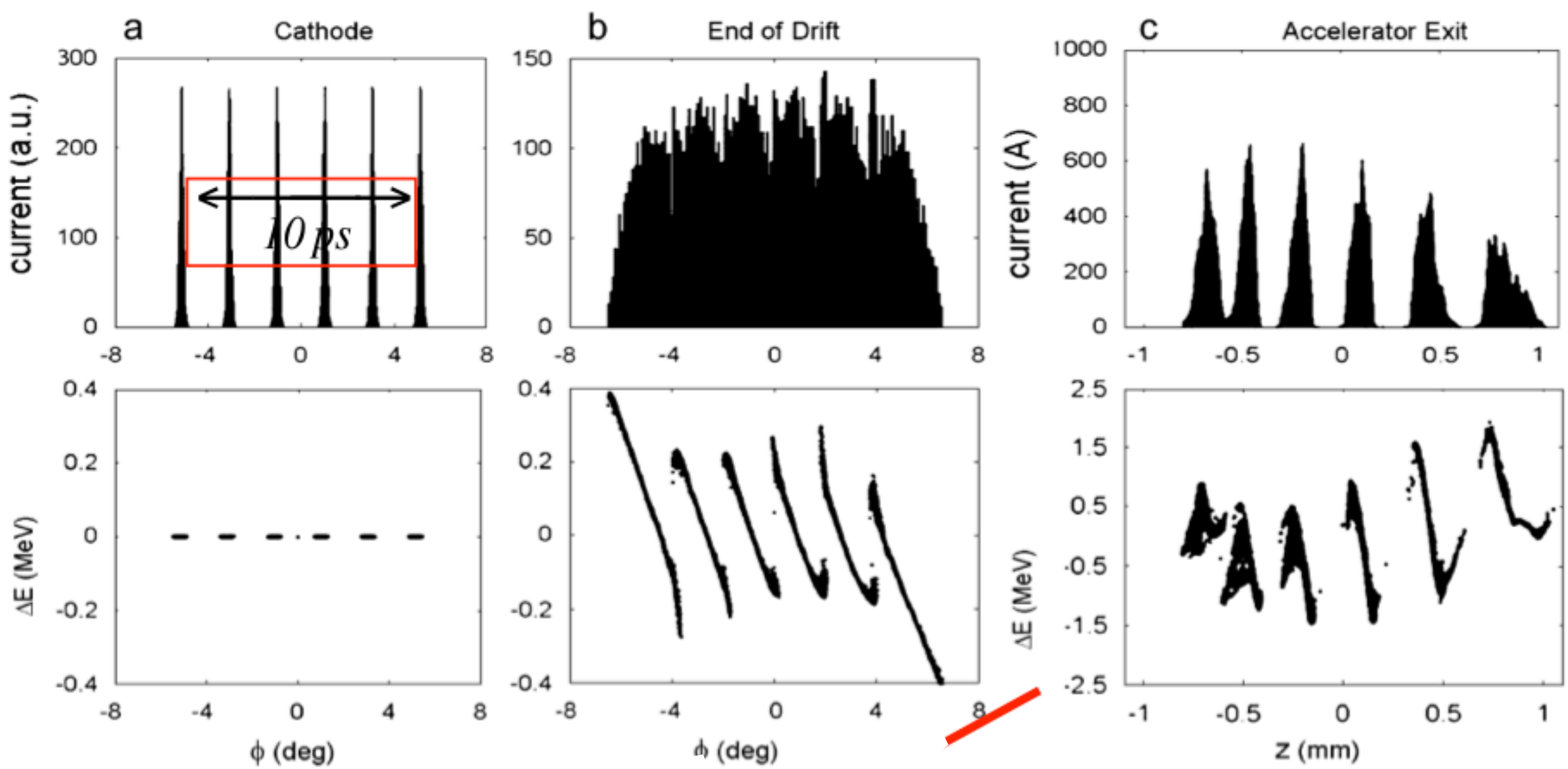
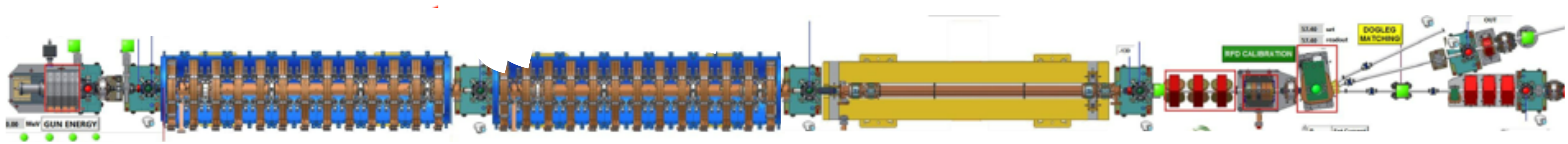
Velocity Bunching

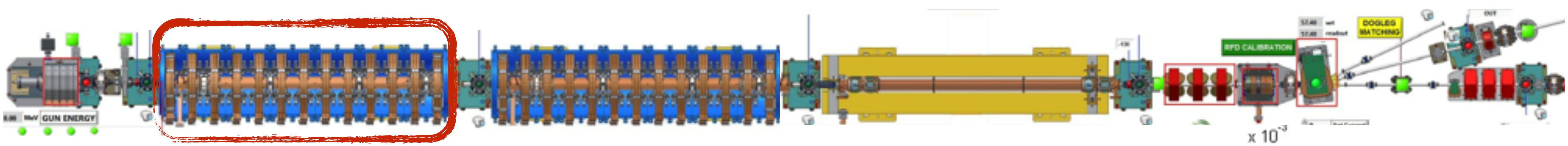
P. O. Shea et al., Proc. of 2001 IEEE PAC, Chicago, USA (2001) p.704.
M. Ferrario et al., Int. J. of Mod. Phys. B, 2006

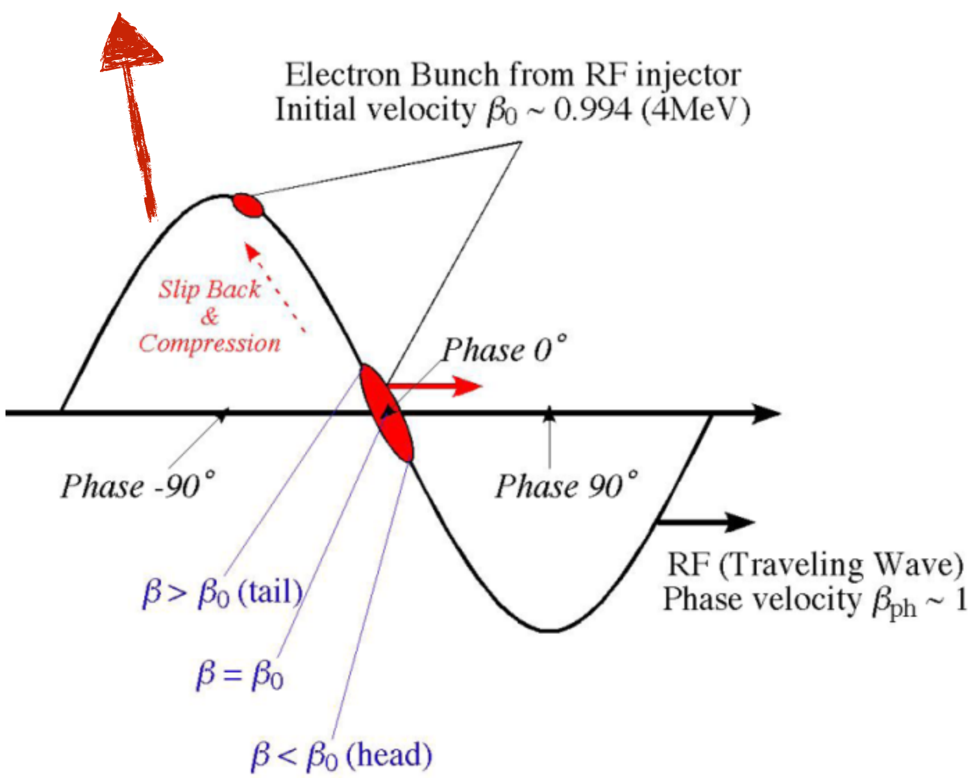


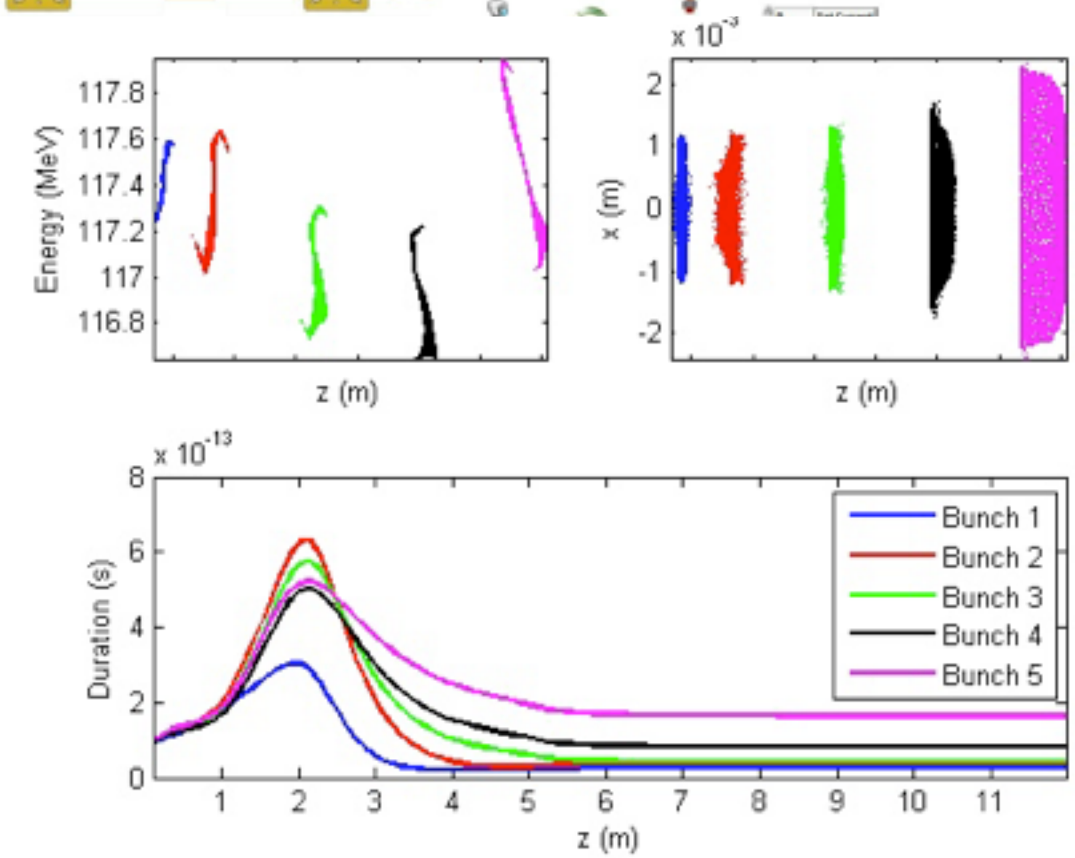


Velocity Bunching

- **Velocity bunching for longitudinal compression**: 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
  - Distance and duration optimized by tuning RF phase of first accelerating section
  - Rectilinear trajectories => no coherent synchrotron radiation emission







Serafini, L., M. Ferrario. "Velocity bunching in photo-injectors" AIP conference proceedings. 2001.
Ferrario, M.et al. "Experimental demonstration of emittance compensation with velocity bunching" PRL 104.5 2010

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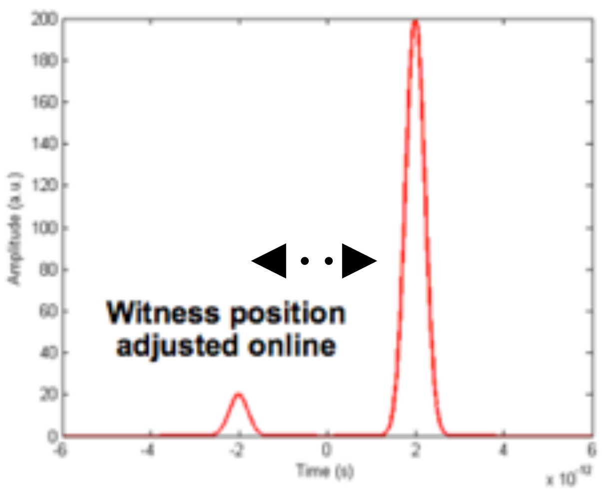
Driver and witness

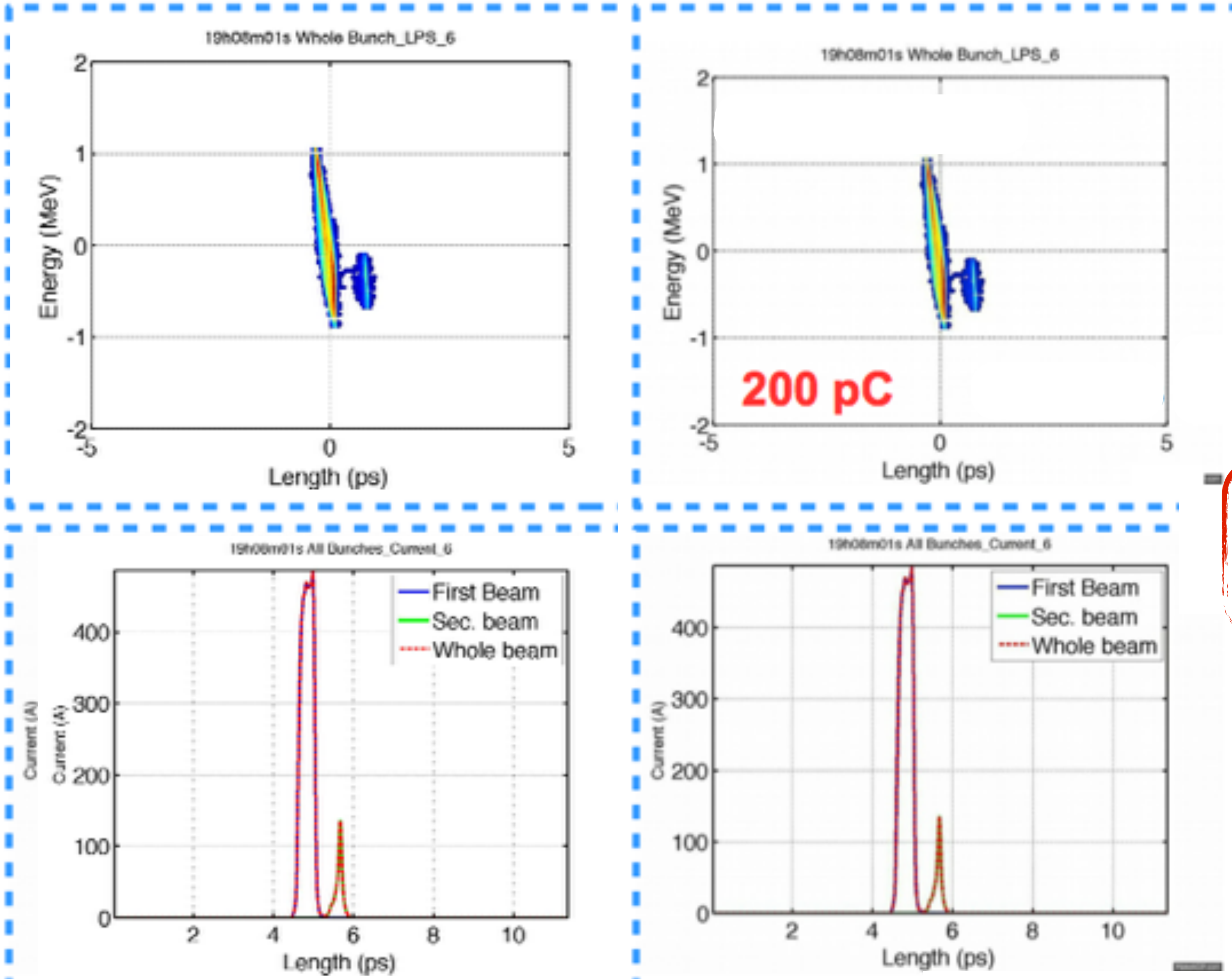
Experimental results!

Laser profile on photo-cathode

Driver + witness (20 pC)



LPS at linac exit *LPS at linac exit*



Current profile *Current profile*

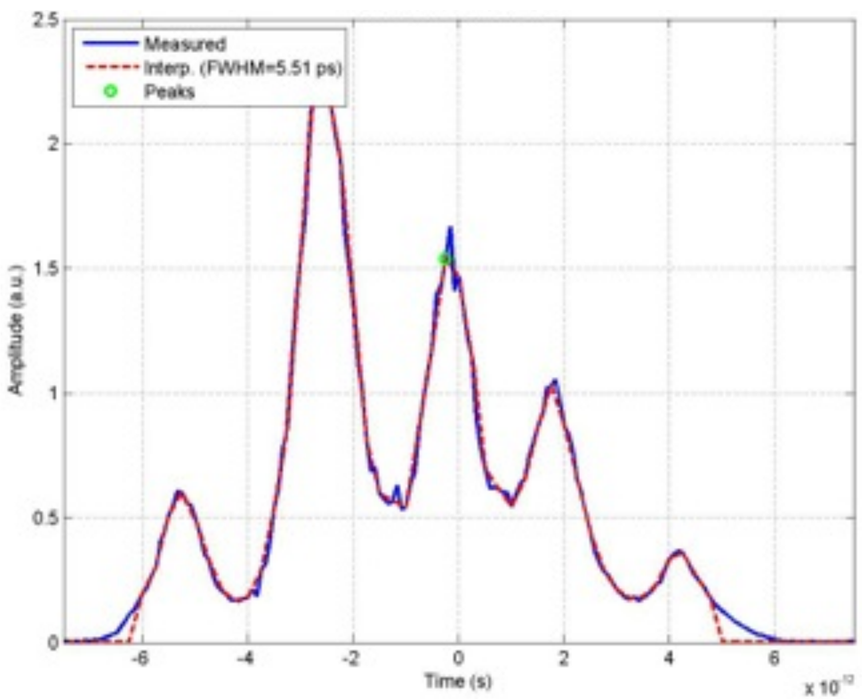
TimeSeparation ~ $\frac{\lambda_p}{2}$
0.77 (0.05) ps

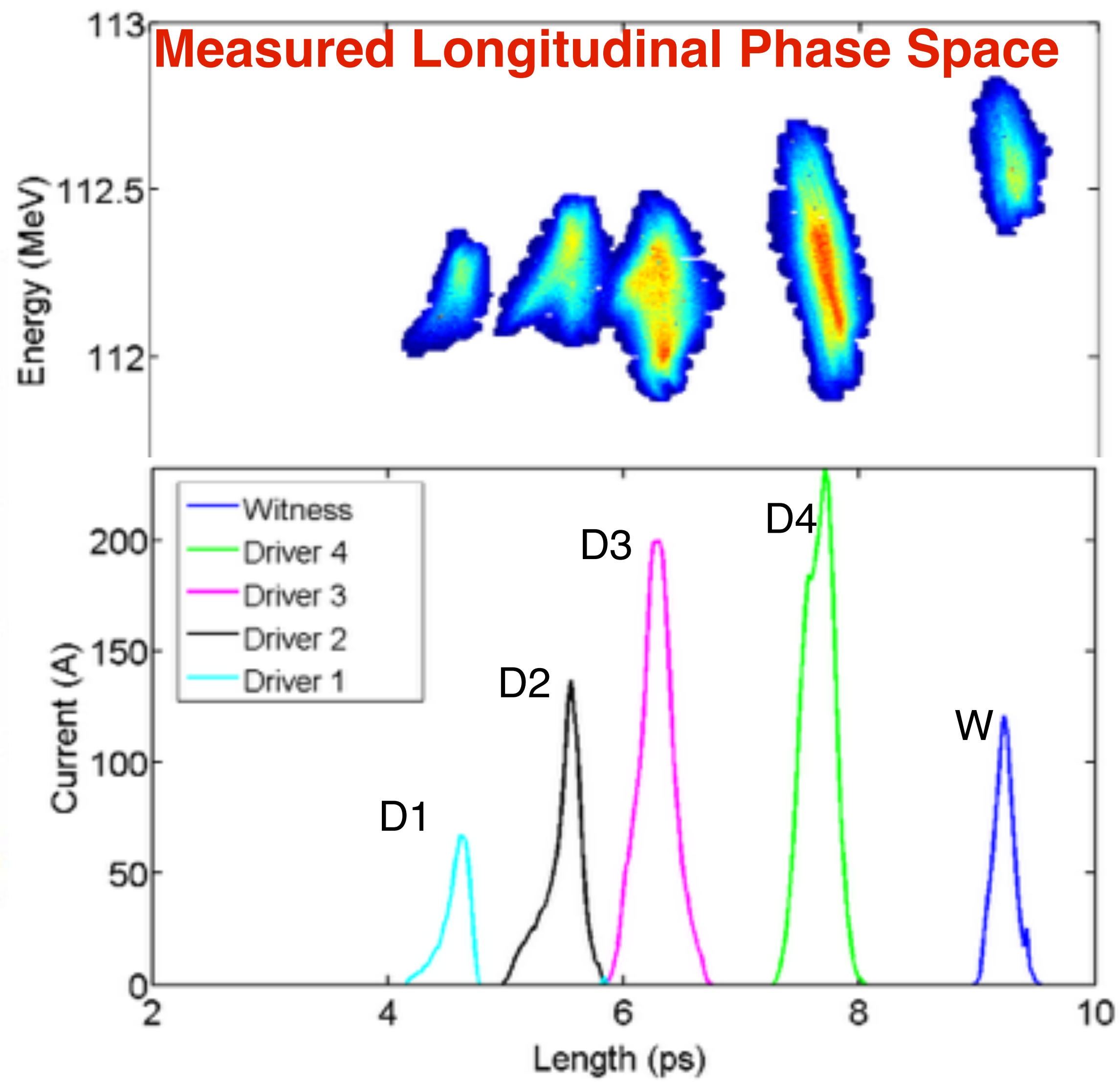
R. Pompili et al., Proc. of the 2nd EAAC 2015

	Beam Energy (MeV)	Energy spread (%)	Bunch duration (ps)	Charge (pC)	Hor Emittance (mm mrad)
Driver Beam	115.36(0.06)	0.39(0.02)	0.082(0.006)	200(10)	4.0 (0.3)
Witness Beam	114.95(0.06)	0.138(0.006)	< 0.086(0.006)	20(2)	1.3 (0.1)
Whole Beam	115.33(0.06)	0.39(0.02)	0.253(0.009)	22011)	4 (0.3)

Ramped bunch train

Laser profile on photo-cathode





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)

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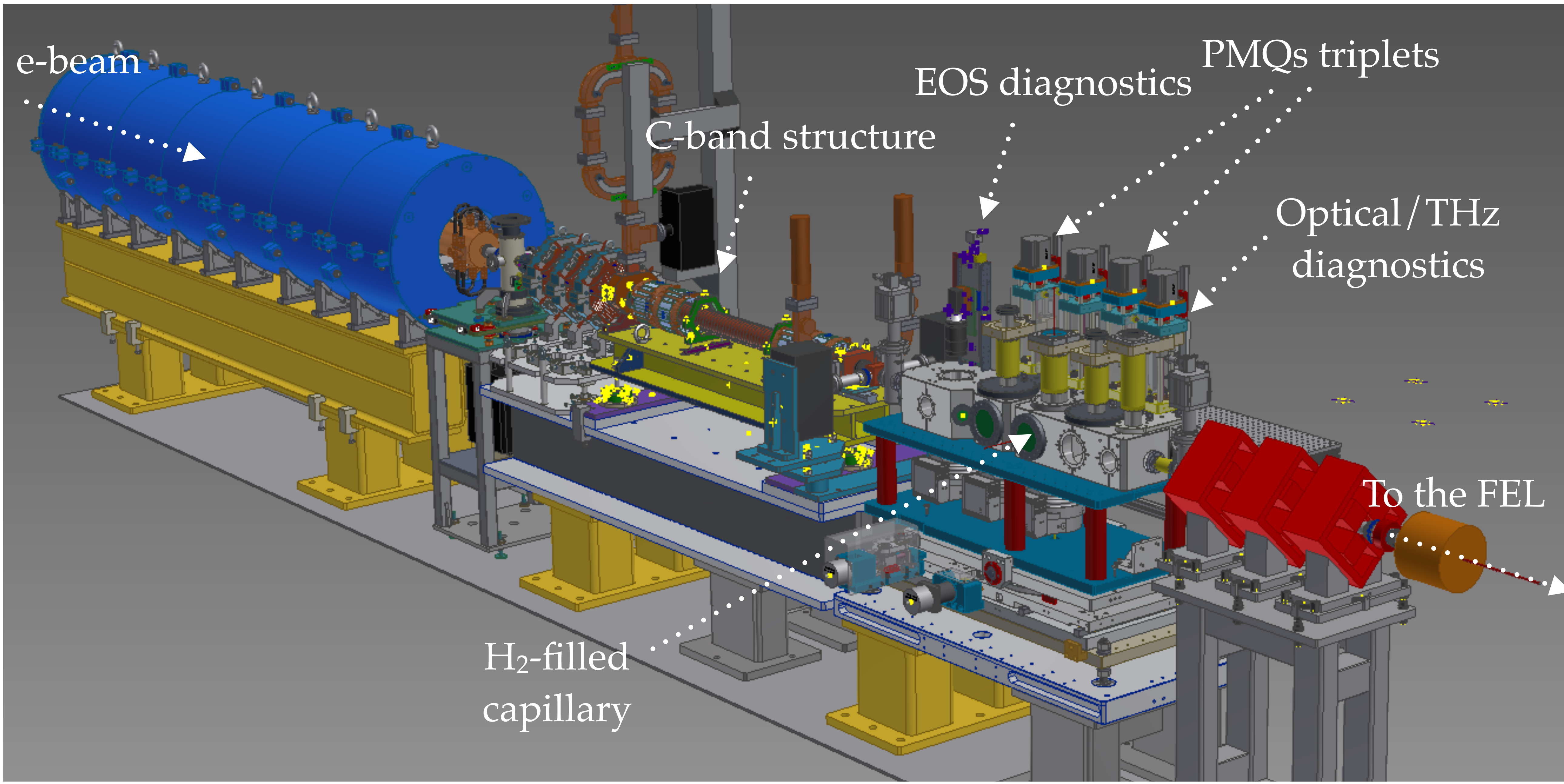
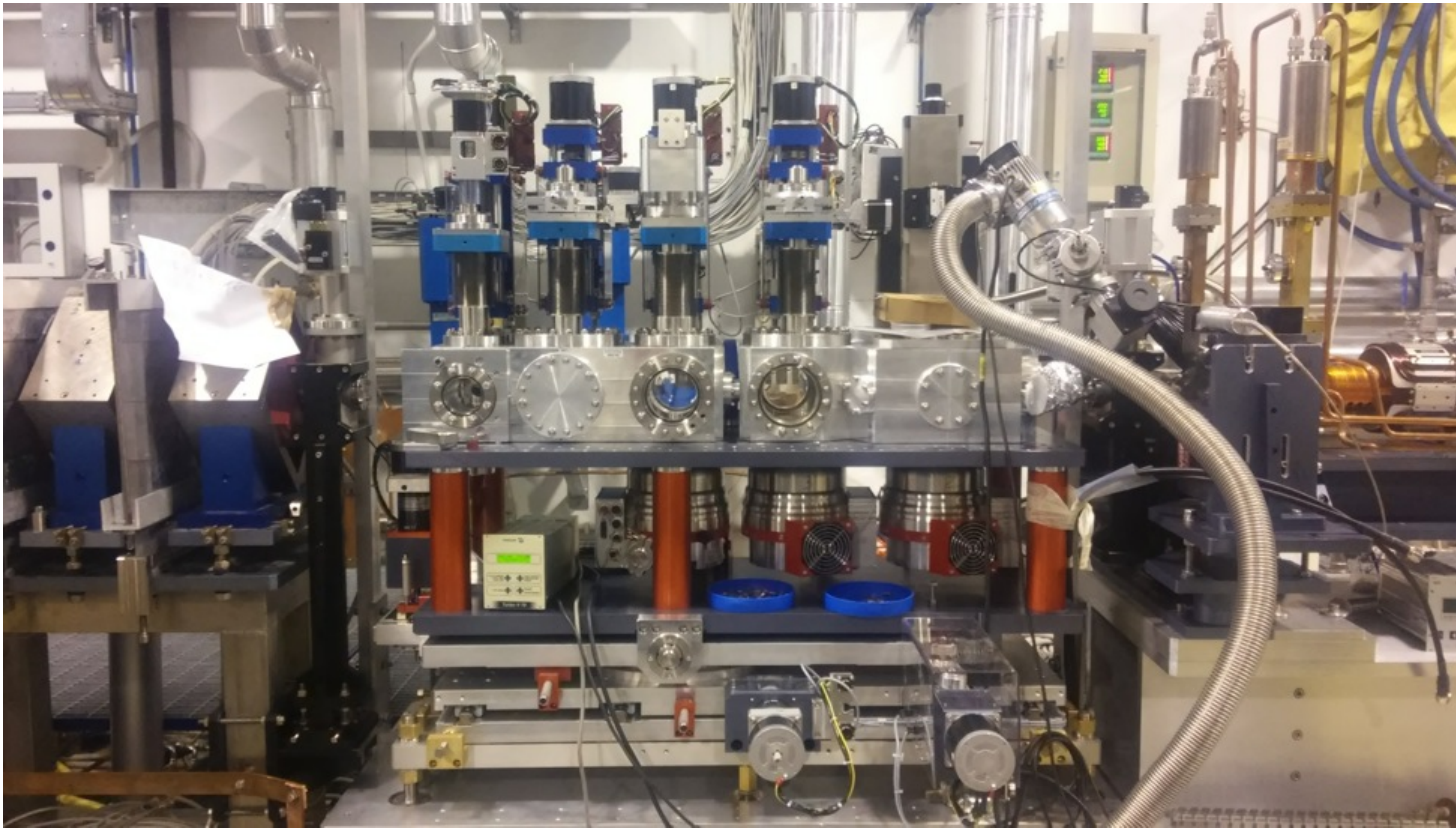
PWFA at SPARC_LAB



Interaction chamber



Quasi-non linear 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 is preserved

- A measure of non-linearity is the **normalized charge**

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

- Using low emittance, high brightness beam we have

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

- These conditions define **quasi-non-linear regime**
  - $n_p = 10^{16}\,\text{cm}^{-3}$, $Q_D = 200$ pC, $\sigma_t = 180$ fs, $\sigma_x = 5.5$ um → $n_b \sim 5 n_p$ and $\tilde{Q} \approx 0.8$

J.B. Rosenzweig et al., "Plasma Wakefields in the Quasi−Nonlinear Regime" 500-504 (2010)

P. Londrillo et al., "Numerical investigation of beam-driven PWFA in quasi-nonlinear regime" NIM **740**, 236 (2014)

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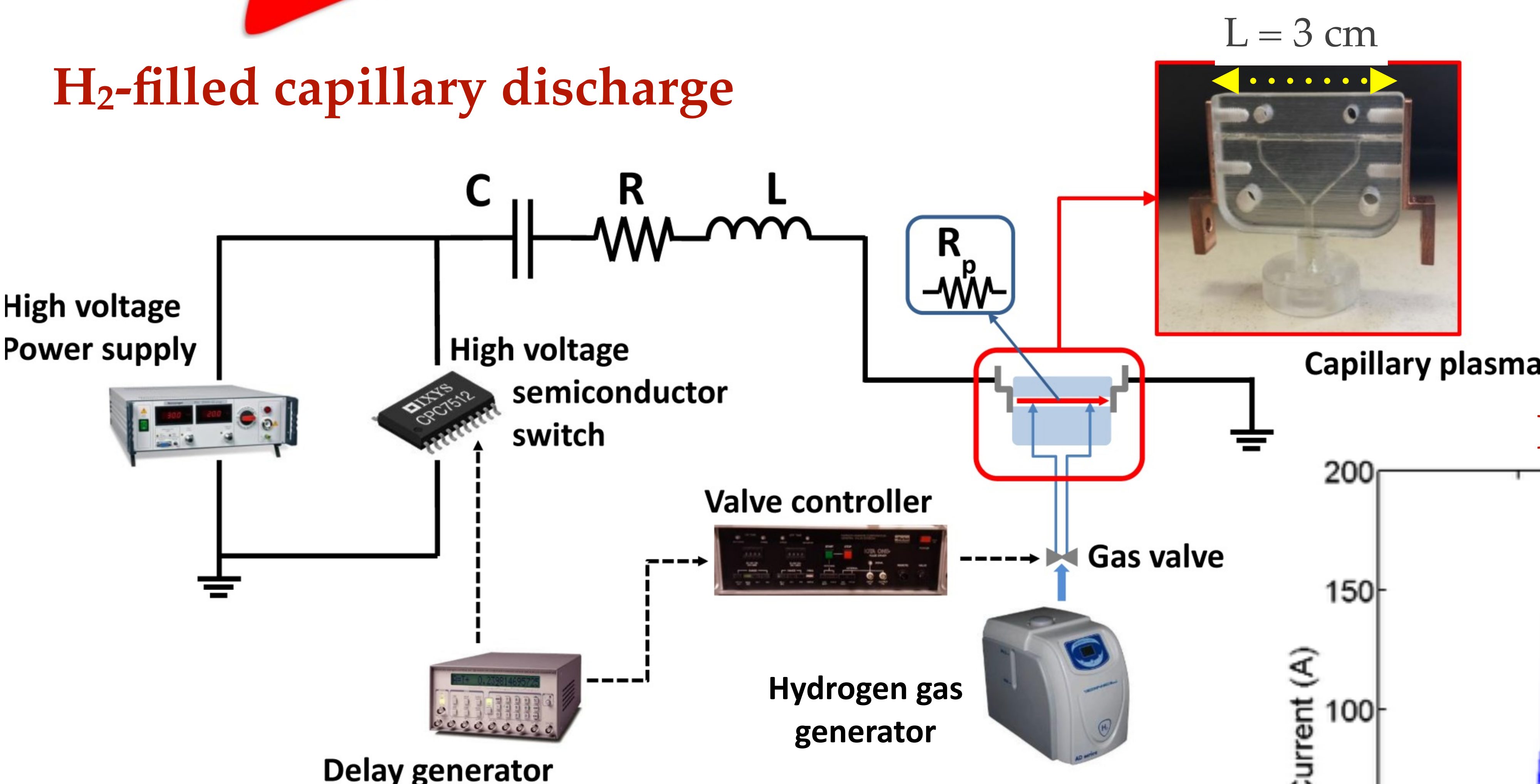
Plasma Source

H_2-filled capillary discharge



P_{H2} = 10 mbar

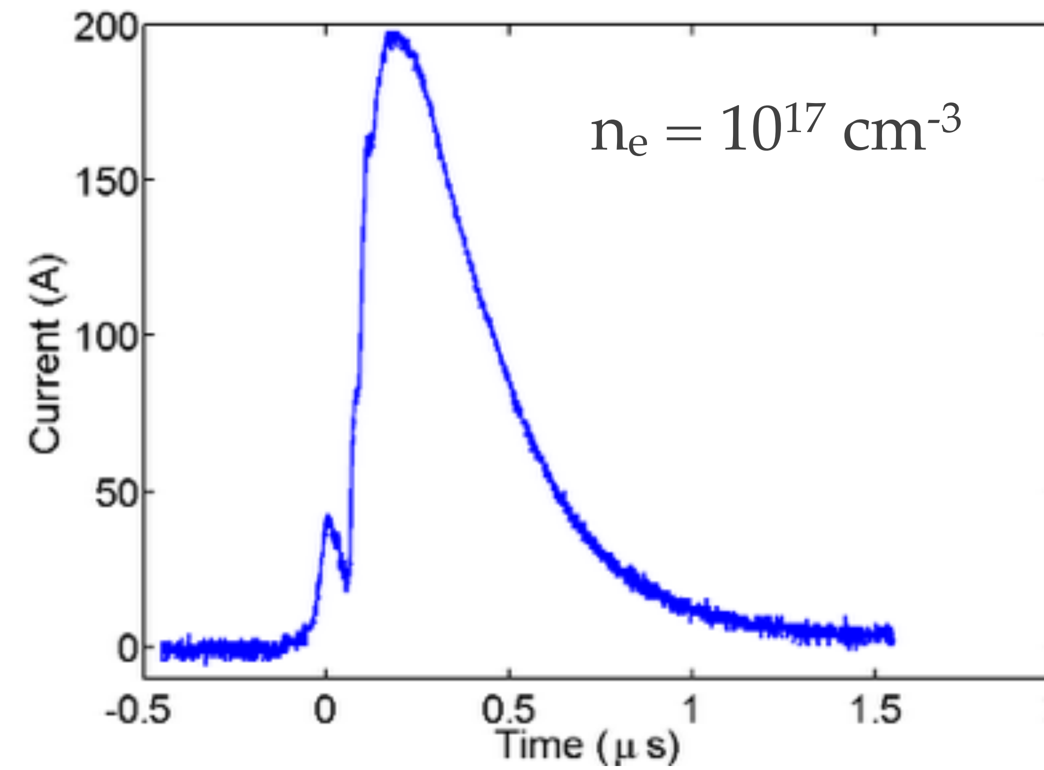
Total discharge duration :800 ns

Voltage : 20 kV

Peak current : 200 A

Capacitor : 6 nF

Measured current



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

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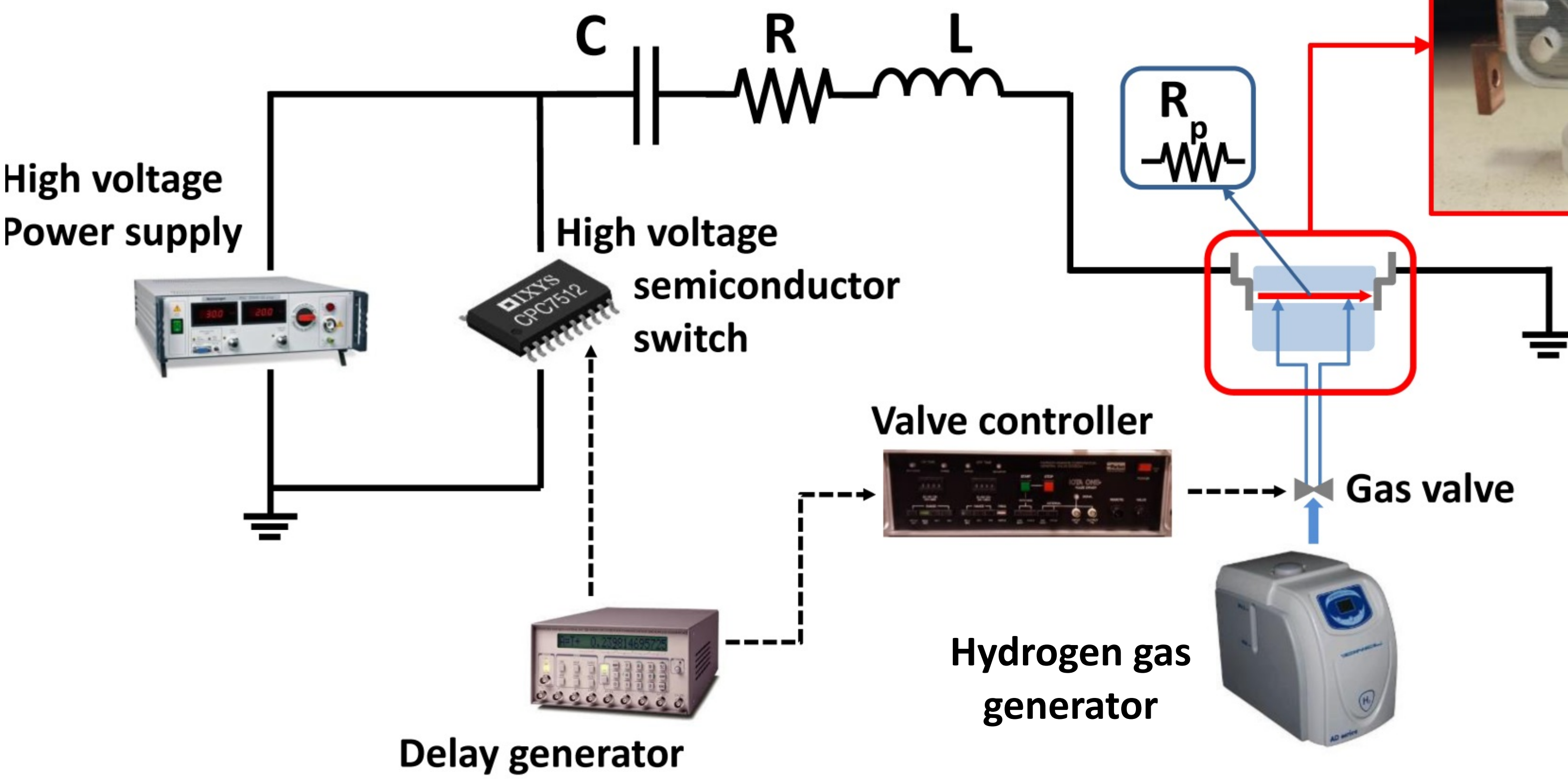
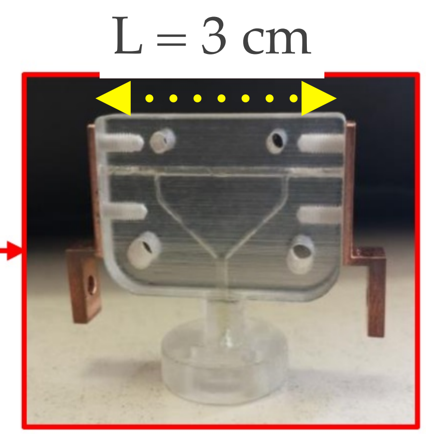
Plasma Source

H_2-filled capillary discharge





Capillary plasma

P_{H2} = 10 mbar

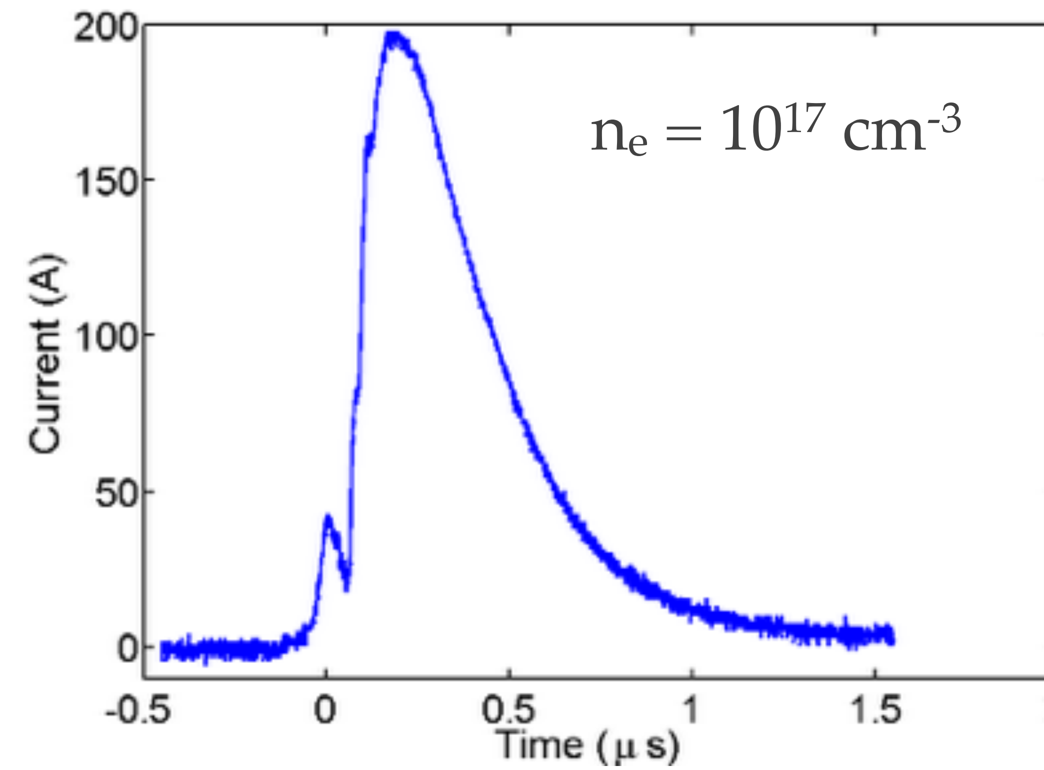
Total discharge duration :800 ns

Voltage : 20 kV

Peak current : 200 A

Capacitor : 6 nF

Measured current



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

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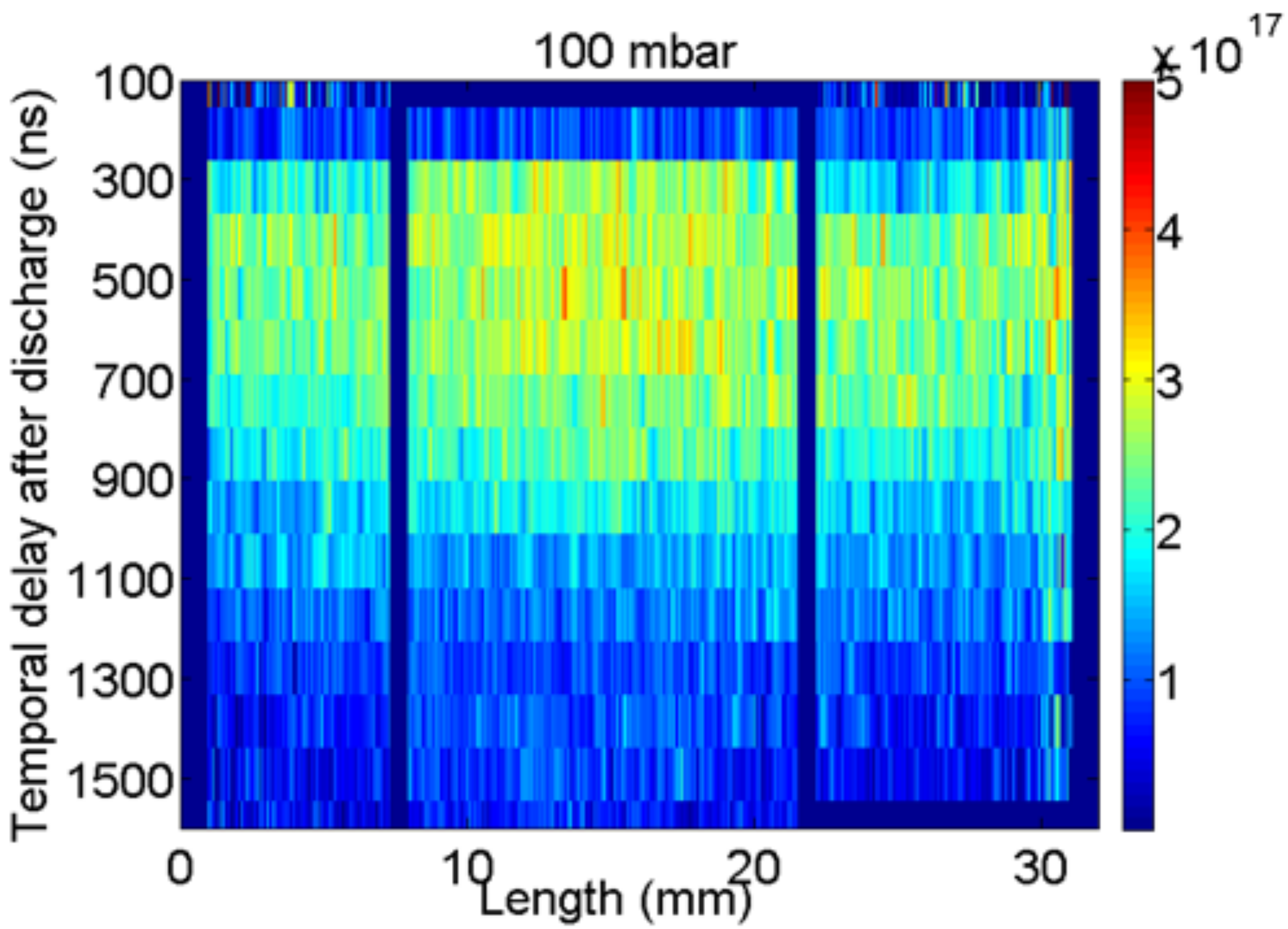
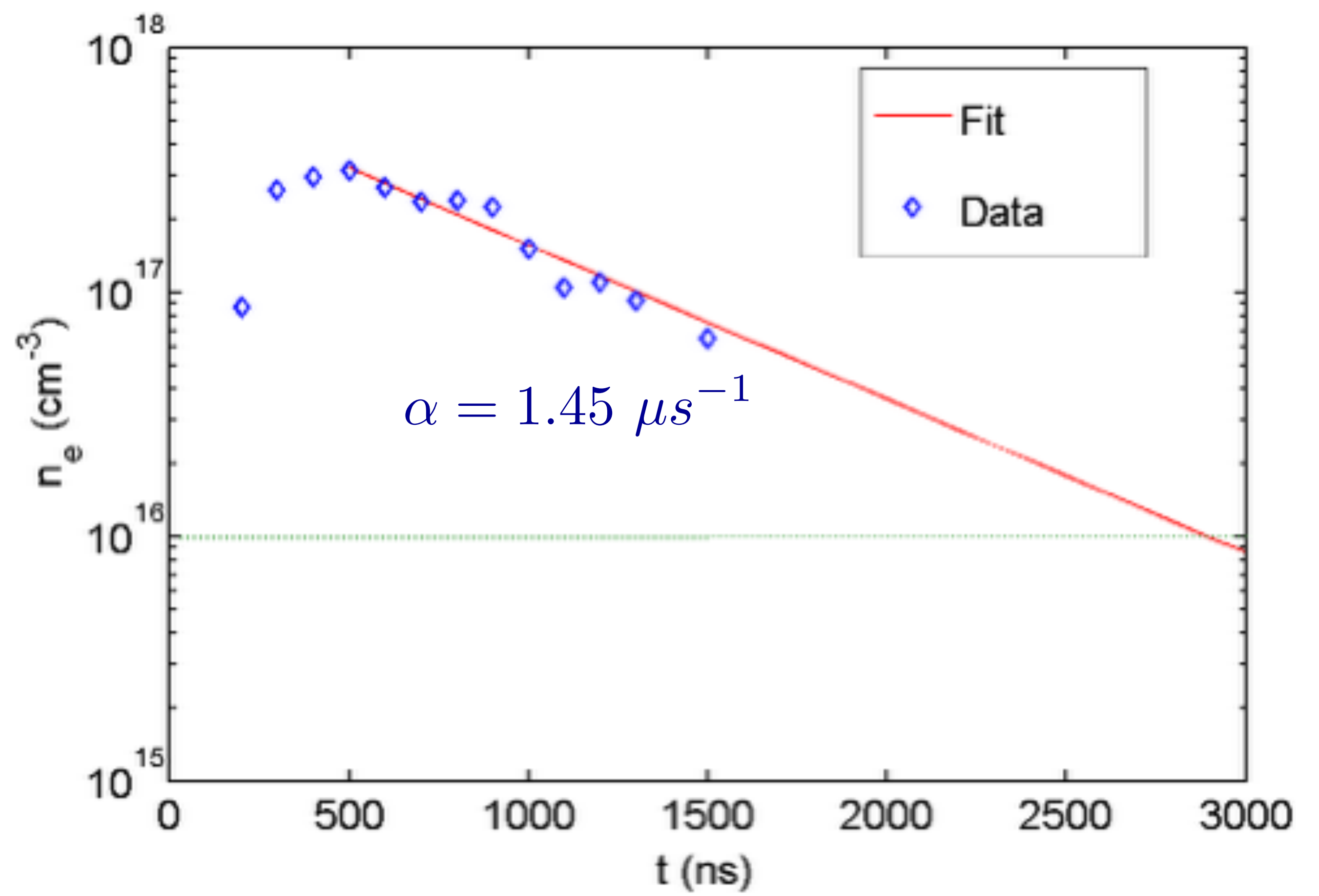
Plasma Characterization

Plasma density measurement from H_α Stark broadening

The plasma density is controlled through the delay after the discharge



Fit function: $n_e = n_{e_0} e^{-\alpha t}$

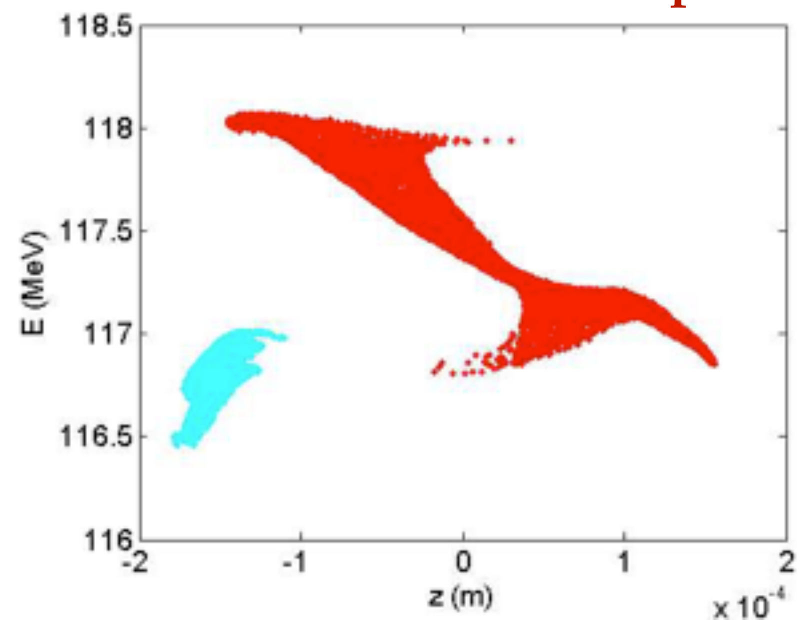


Courtesy of M. P. Anania, A. Biagioni, F. Filippi, A. Ziegler

Start-to-End Simulation

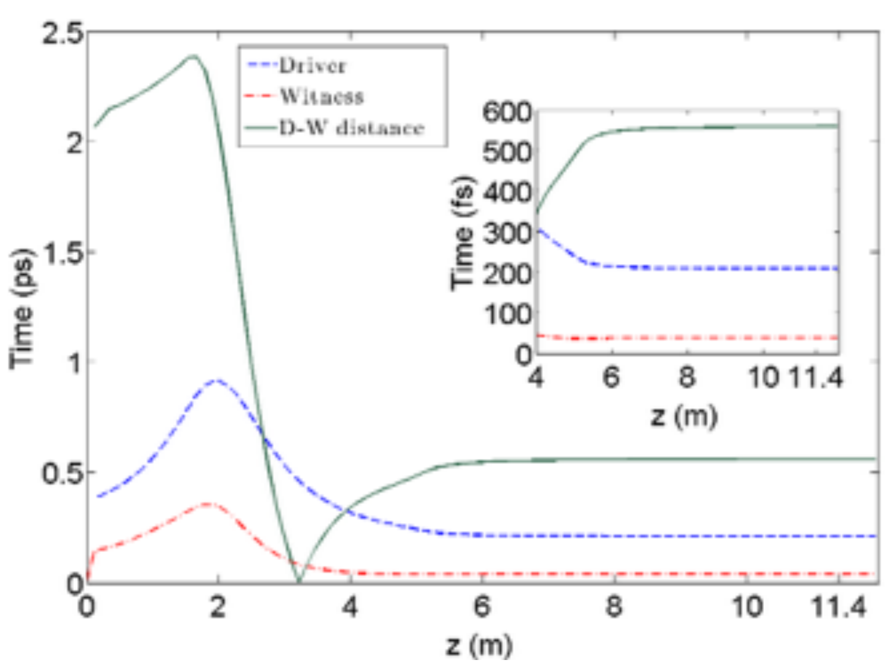
GPT simulation from the cathode to the plasma

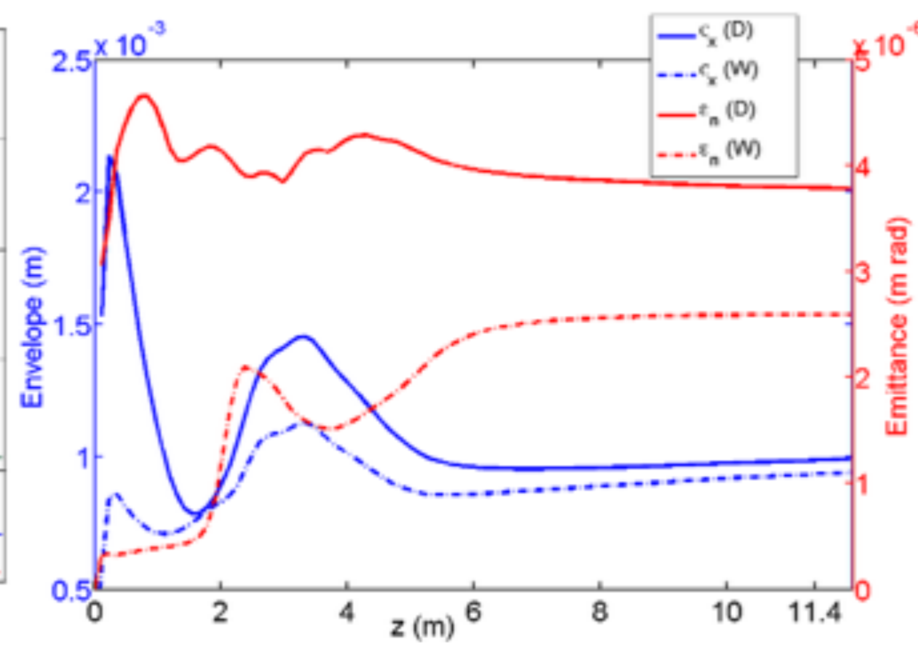
- σ_t=100 fs (rms) laser @ cathode (blowout [1,2])
- Laser pulse distance at cathode: 2.4 ps
- Driver-Witness distance at linac exit: 560 fs

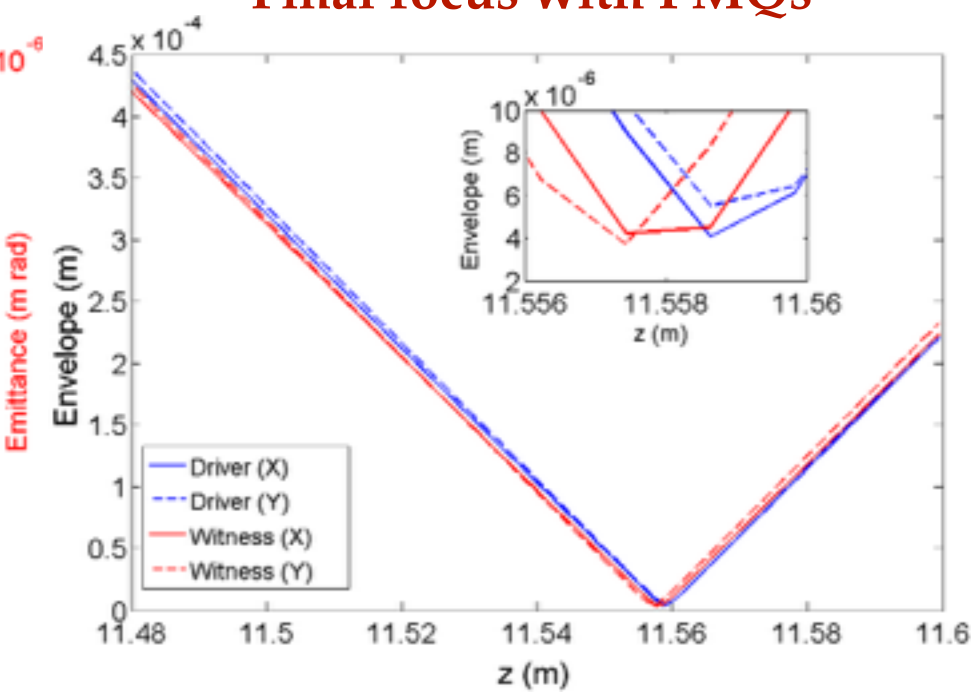


	Driver	Witness
Charge (pC)	200	20
Energy (MeV)	117.5	116.75
Final focus (um)	5.5	3
Duration (fs)	180	35
e_n	4.5	2.4

Final focus with PMQs







*[1] **Musumeci, P., et al.**, PRL **100**, 244801 (2008)*
*[2] **Moody, J. T., et al.** PRST AB **12**, 070704 (2009)*

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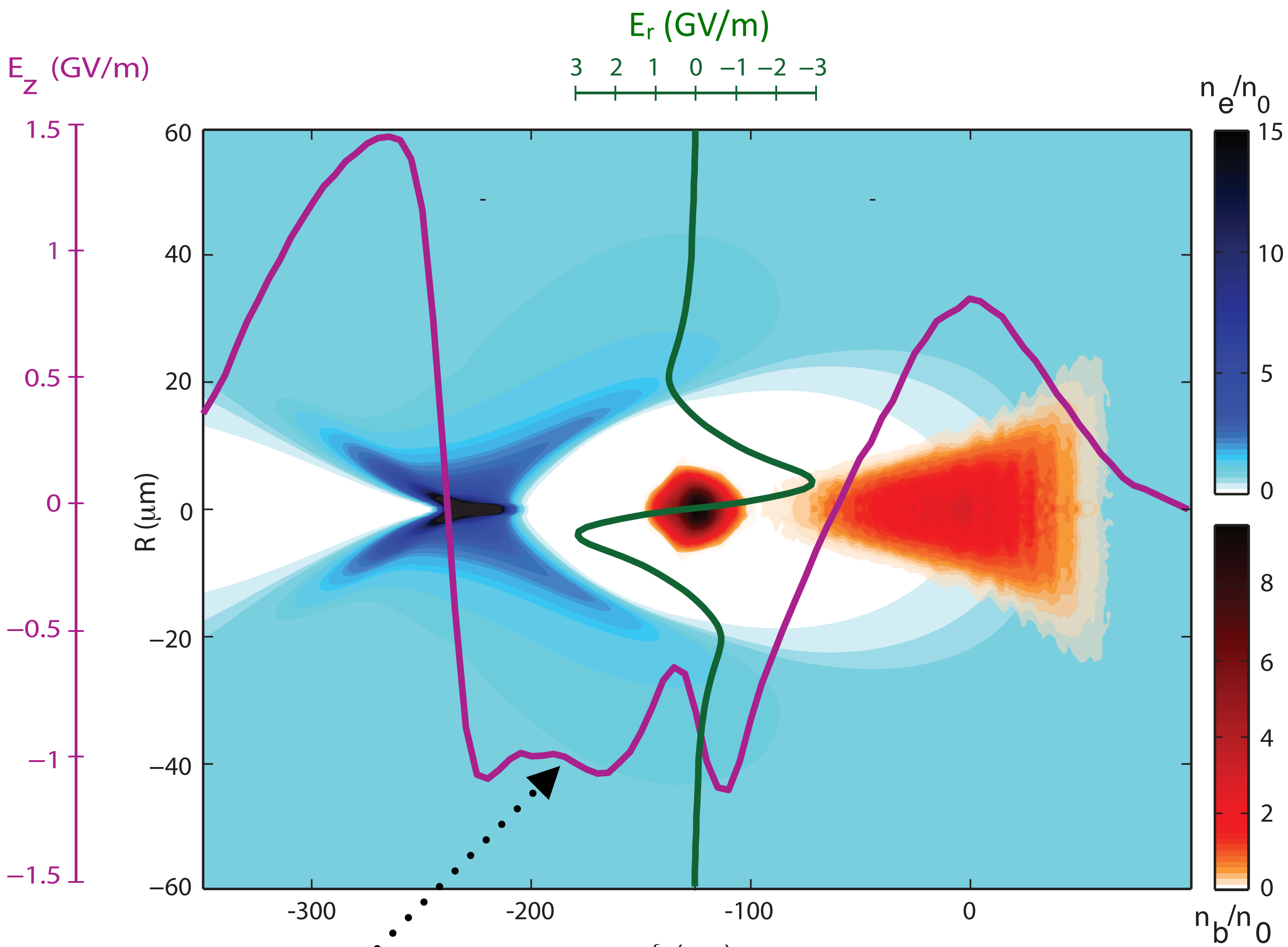
Courtesy of R. Pompili

Plasma Interaction

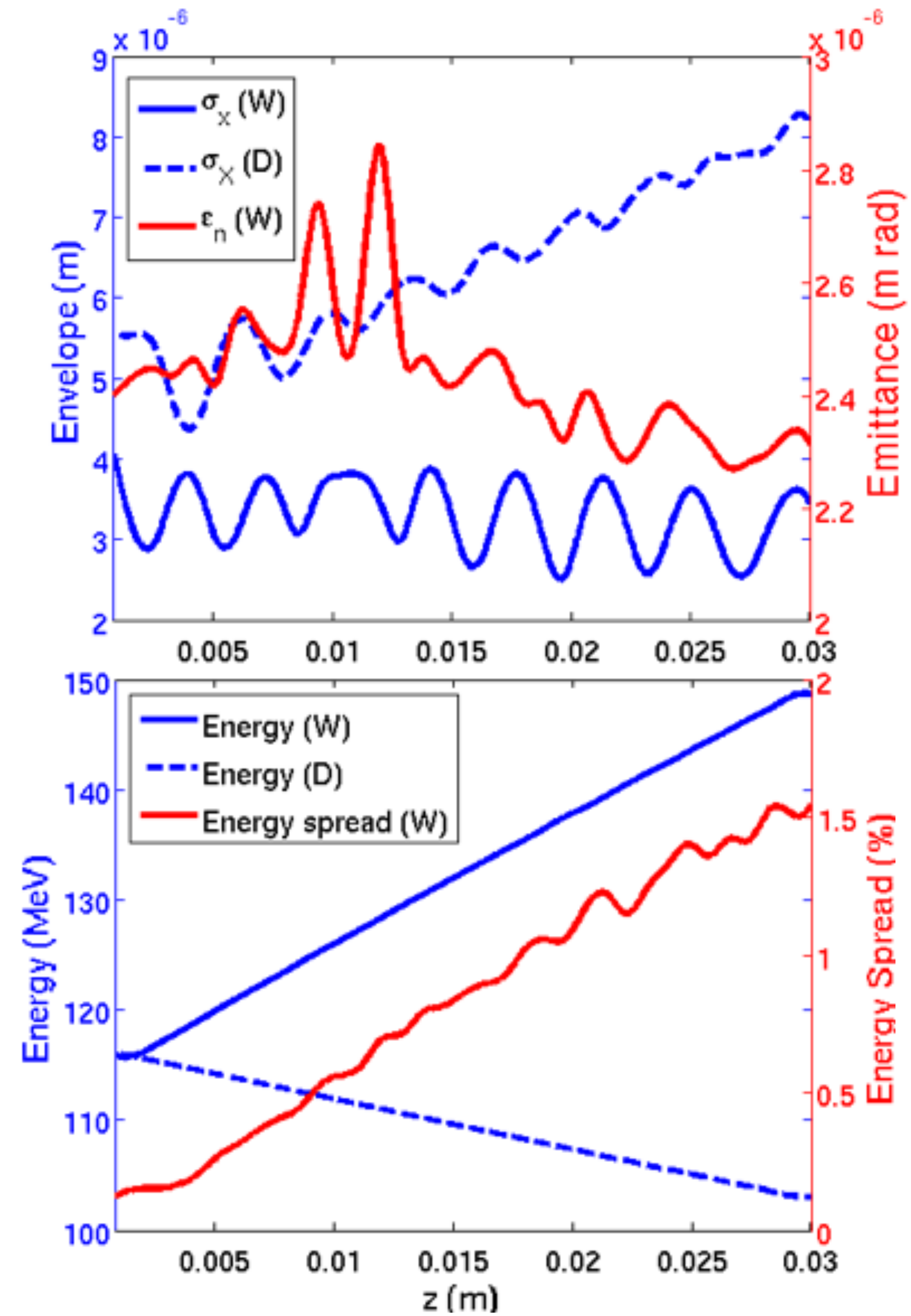
Hybrid kinetic-fluid simulation by Architect*

- **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)

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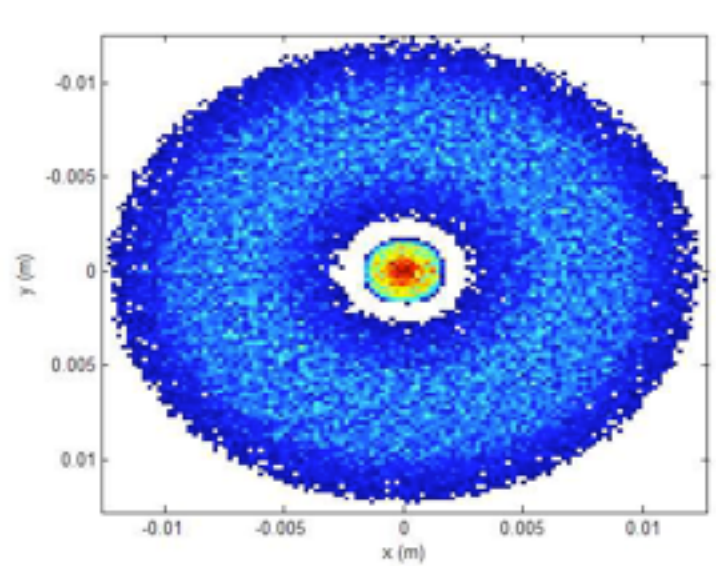
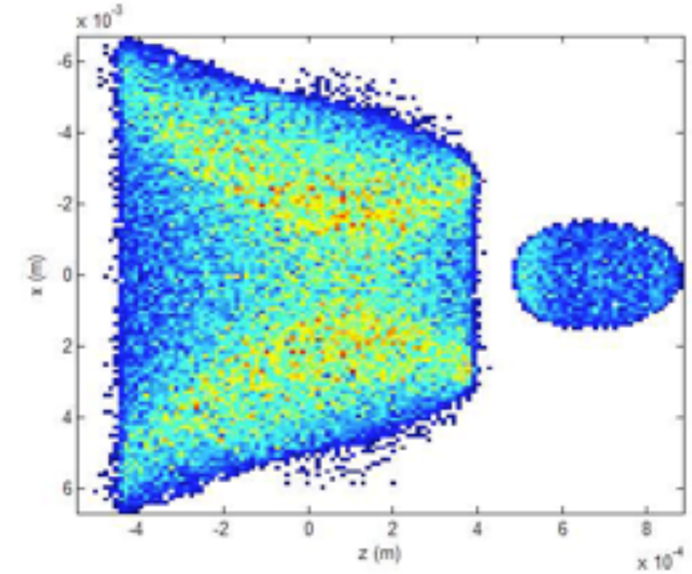
Courtesy of A. Marocchino, A. R. Rossi

Hollow driver beam manipulation

Witness degradation occurs during bunch crossing

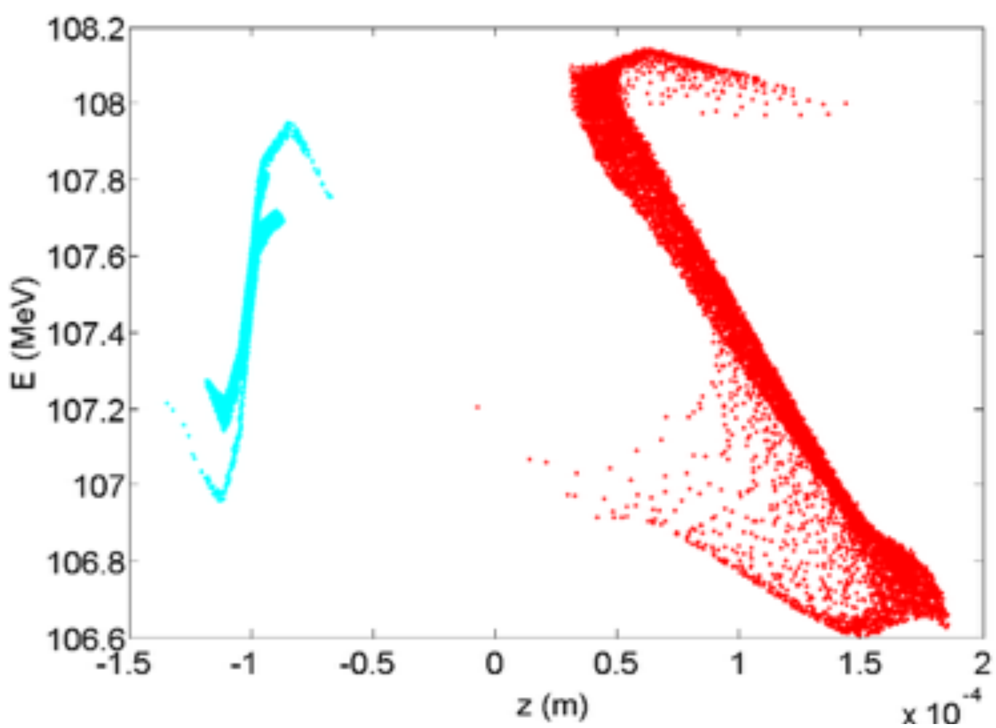
- Driver acts as nonlinear lens
  - emittance growth
- Driver field is opposed to RF
  - lower compression

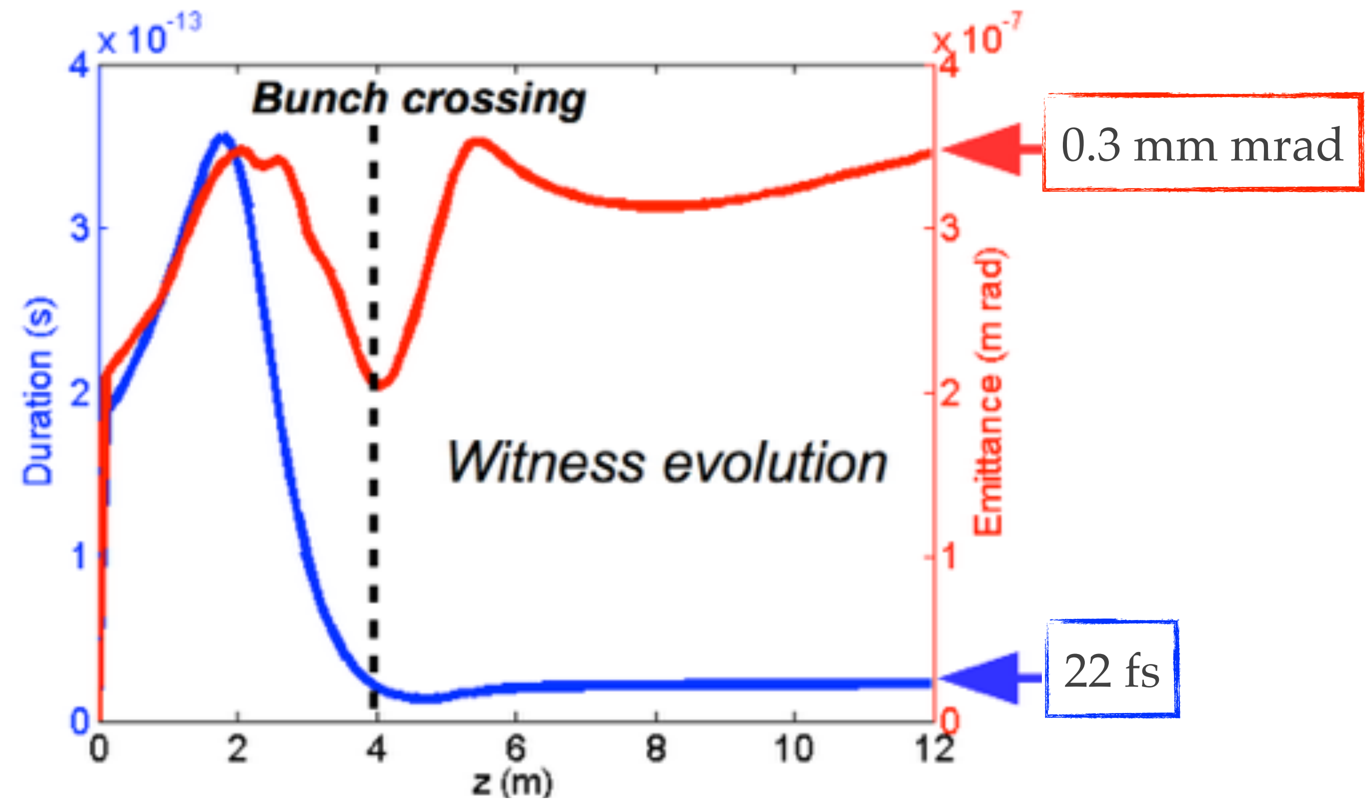




Hollow driver beam

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





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Courtesy of R. Pompili

Conclusions

- Plasma-based acceleration ***is able to*** provide ultra-high, several GV/m, gradients
- Plasma-based accelerators ***must*** provide high brightness beams
- The **resonant amplification of plasma waves by a train of HBEBs** injected into the preformed plasma is one of the schemes proposed to this scope
- Manipulation of electron beam phase spaces is mandatory to enhance the energy transfer and preserve the beam quality

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Thank you!