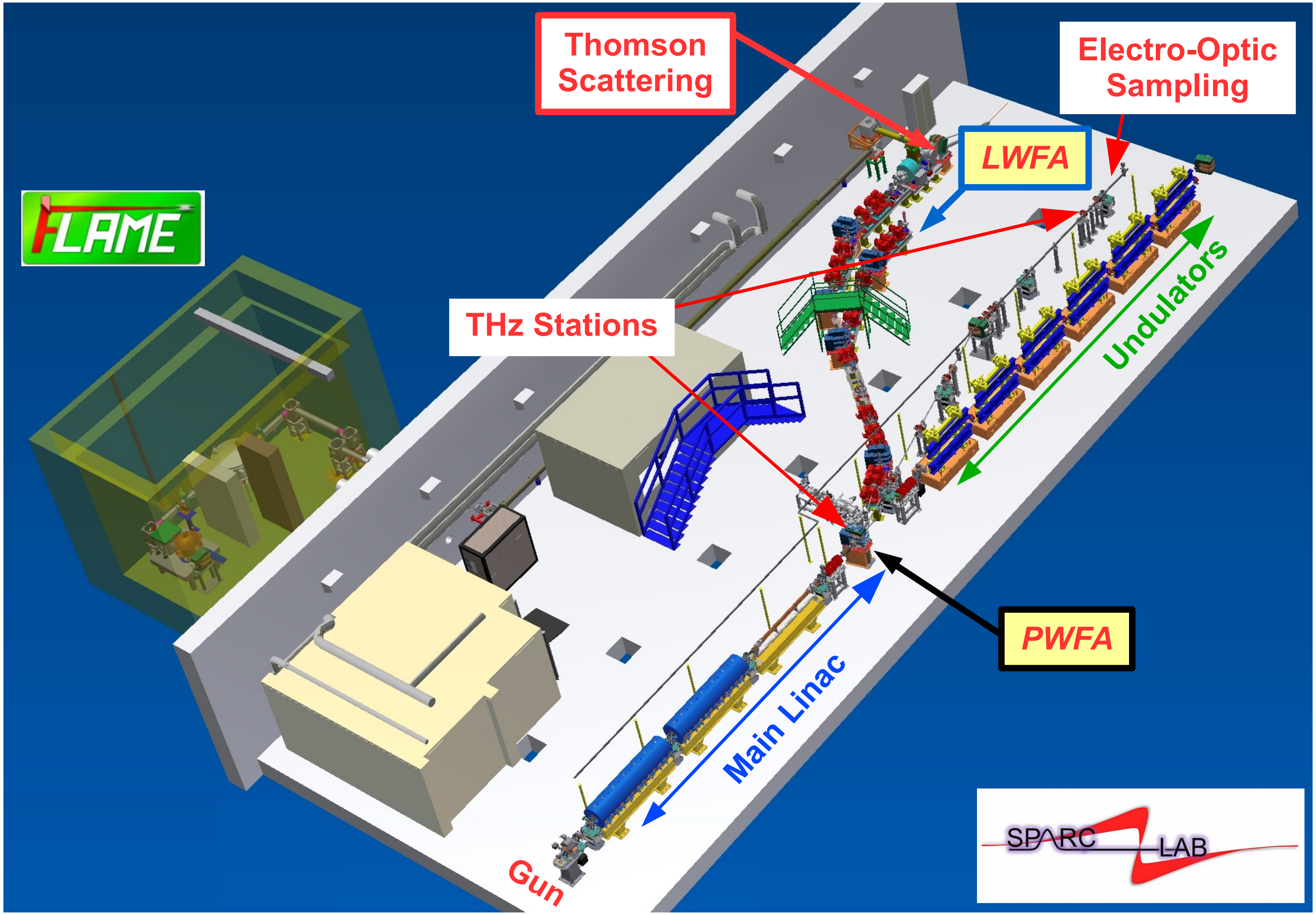
Beam manipulation with velocity bunching for PWFA applications

INFN Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Frascati

Riccardo Pompili
LNF-INFN
on behalf of the SPARC_LAB collaboration

SPARC LAB

SPARC_LAB test-facility



→ A.Marocchino, WG6, Wed 16

→ A. Biagioni, WG5, Tue 15

→ A.R. Rossi, WG1, Tue 15

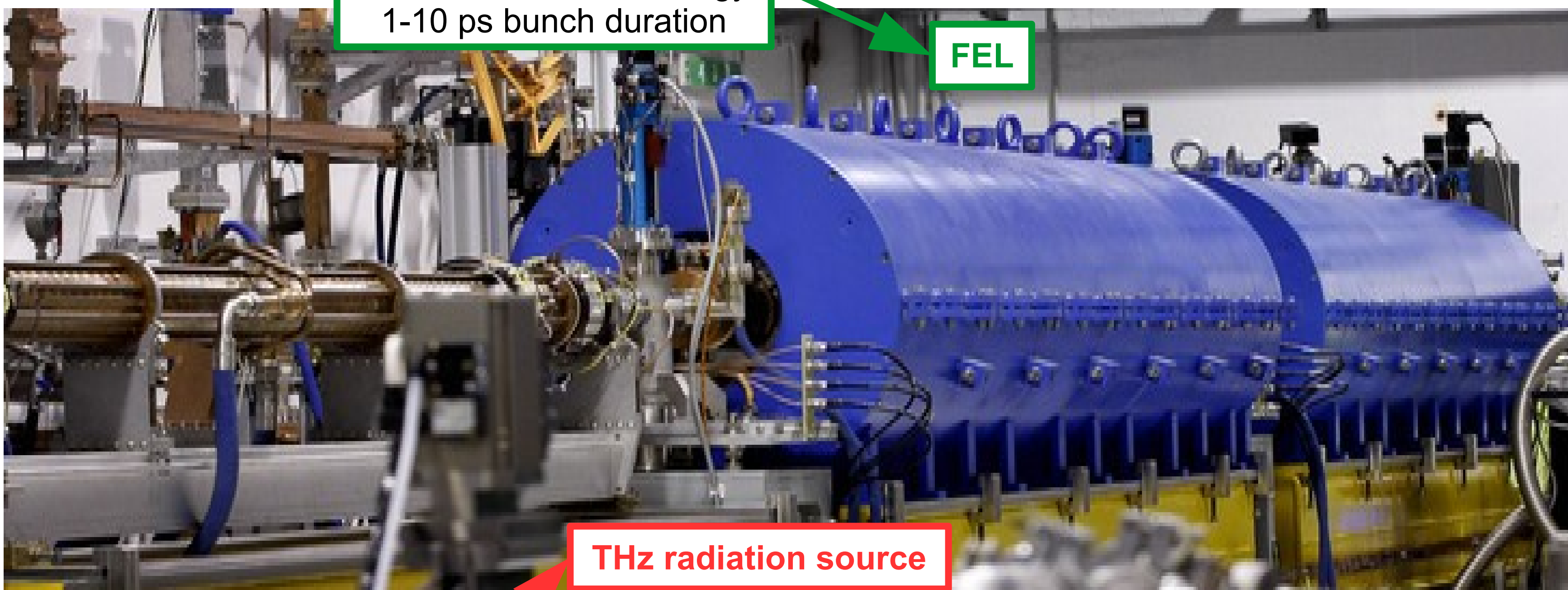
→ C. Vaccarezza, WG4, Mon 14

Ferrario, M., et al. "SPARC_LAB present and future." NIMB 309 (2013): 183-188.

High brightness photo-injector

Low-current operation
30-170 MeV beam energy
1-10 ps bunch duration

→ **Thomson source**
→ **FEL**

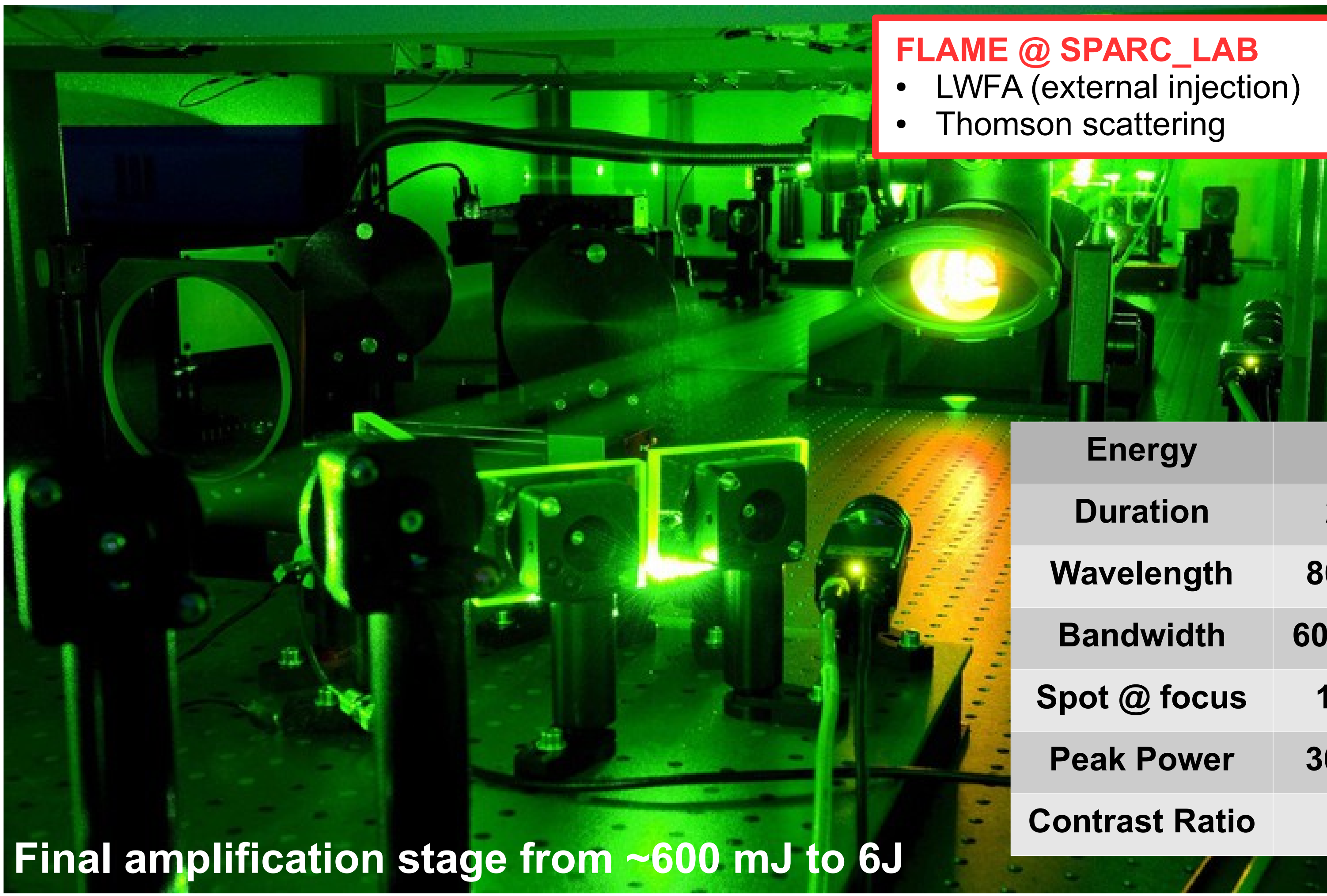


High-current operation (VB)
80-120 MeV beam energy
20 fs - 1 ps bunch duration

→ **THz radiation source**
→ **FEL (single spike + seeding)**
→ **Multi-bunch trains**
  → **Narrowband THz**
  → **FEL (2 colors)**
  → **PWFA (w/ resonant scheme)**
→ **LWFA (external injection)**

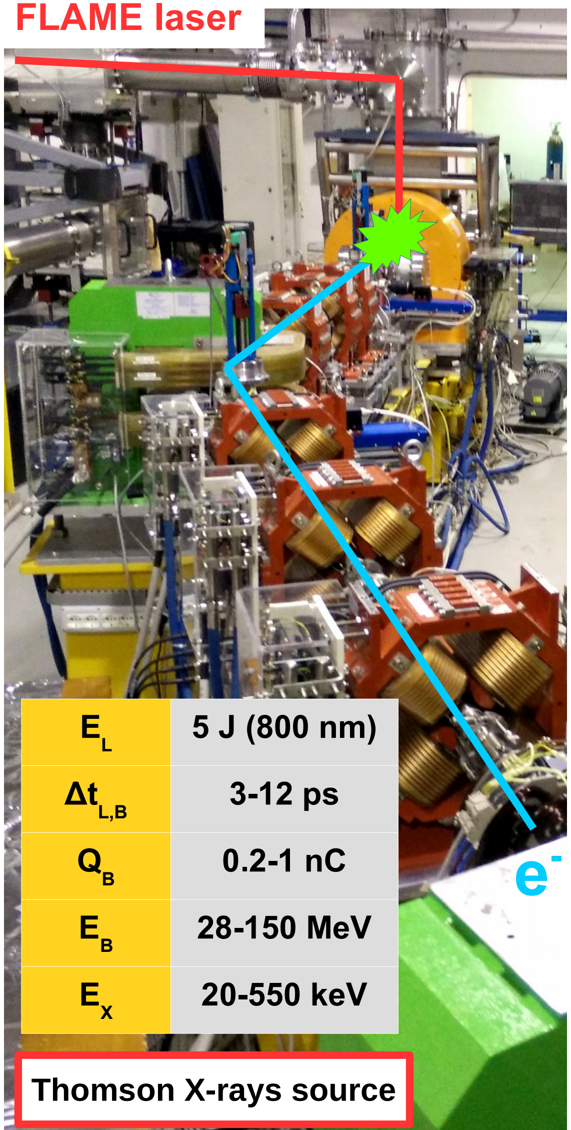
Anderson, S. G., et al. "Velocity bunching of high-brightness electron beams." PRSTAB 8.1 (2005): 014401.
Piot, P. et al. "Subpicosecond compression by velocity bunching in a photoinjector." PRSTAB 6.3 (2003): 033503.

FLAME: a 300 TW Ti:Sa laser

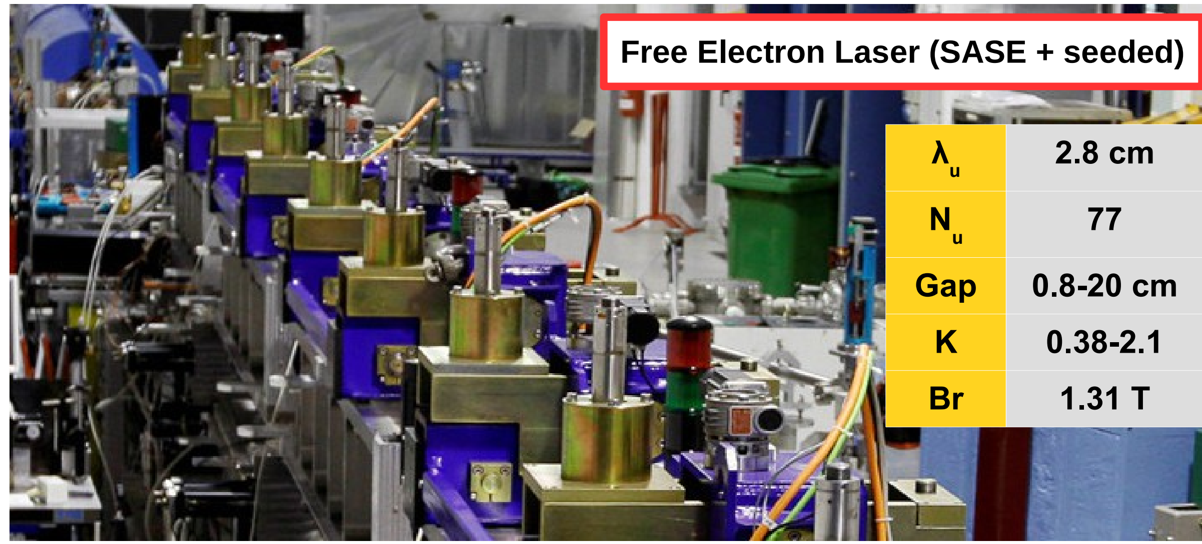


Energy	**7 J**
Duration	**23 fs**
Wavelength	**800 nm**
Bandwidth	**60/80 nm**
Spot @ focus	**10 µm**
Peak Power	**300 TW**
Contrast Ratio	**10^{10}**

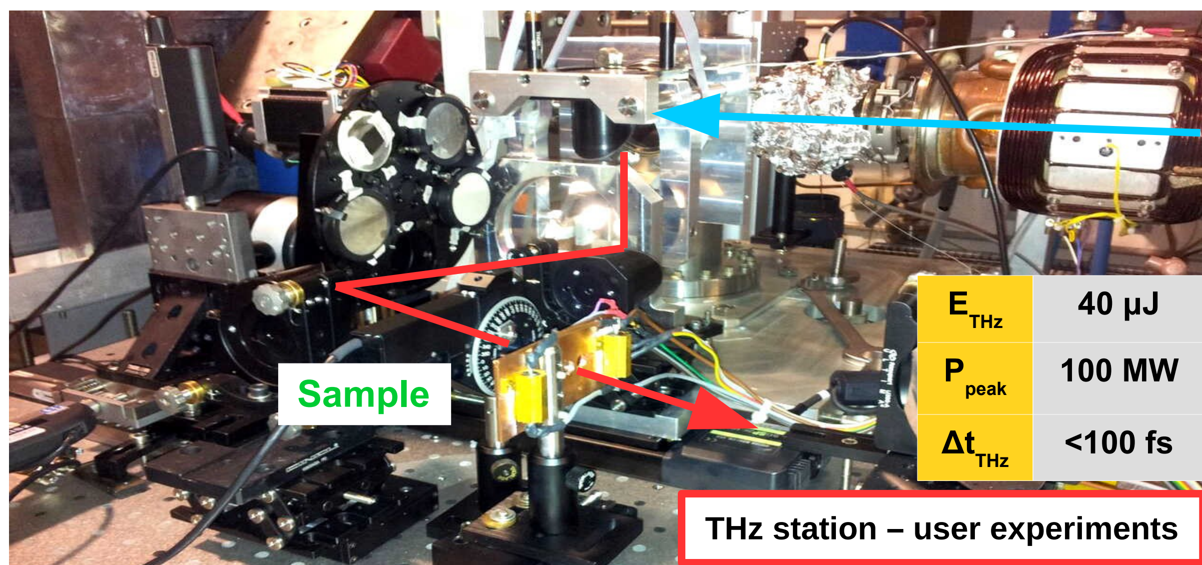
Radiation source activities



E_L	5 J (800 nm)
$\Delta t_{L,B}$	3-12 ps
Q_B	0.2-1 nC
E_B	28-150 MeV
E_X	20-550 keV



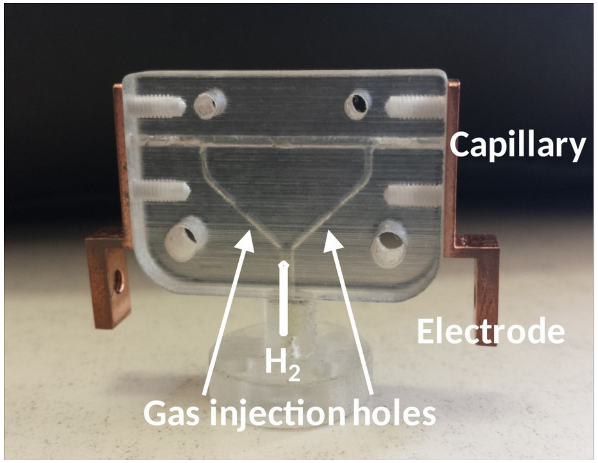
λ_u	2.8 cm
N_u	77
Gap	0.8-20 cm
K	0.38-2.1
Br	1.31 T

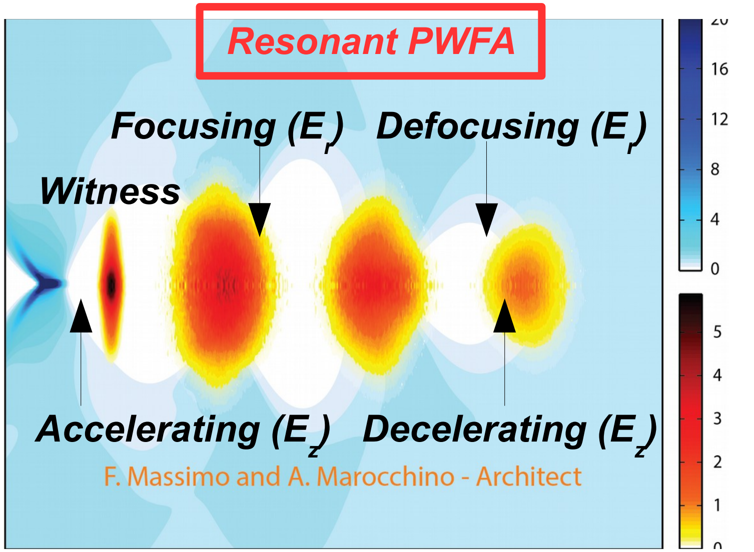


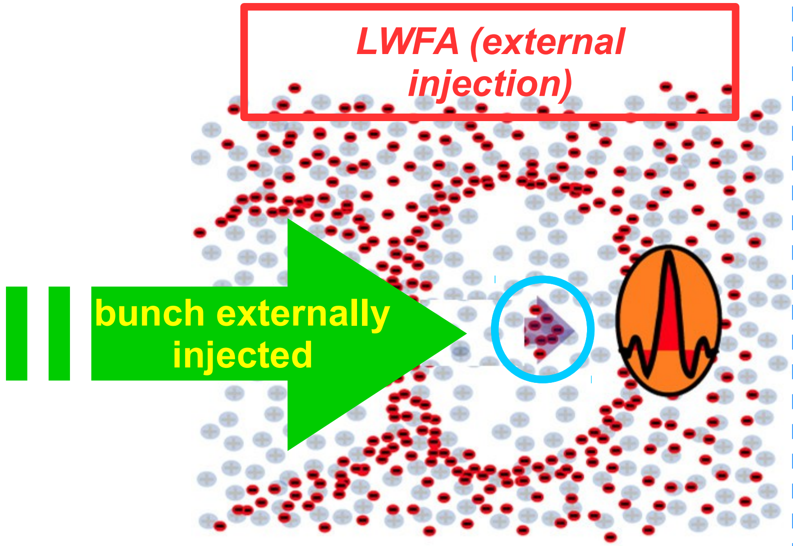
E_{THz}	40 μJ
P_{peak}	100 MW
Δt_{THz}	<100 fs

Plasma-based acceleration activities

- Several plasma-based schemes will be tested
  - *PWFA resonant scheme → 1-2 GV/m expected*
    - n_e~10^{16} cm^{-3}, 1 mm diameter capillary, Hydrogen
  - *LWFA, external injection → 5-10 GV/m expected*
    - n_e~10^{17} cm^{-3}, 100 µm diameter capillary, Hydrogen
- Goal: **high quality** accelerated beams
  - *Maintain the high brightness of injected beams*

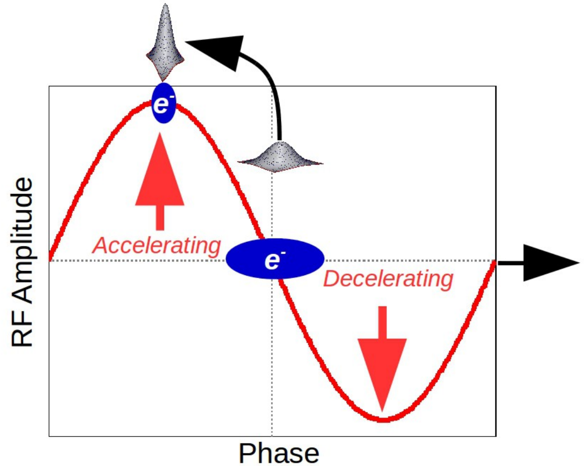


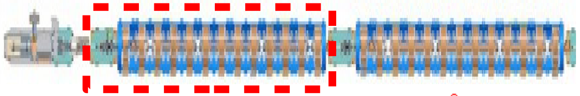


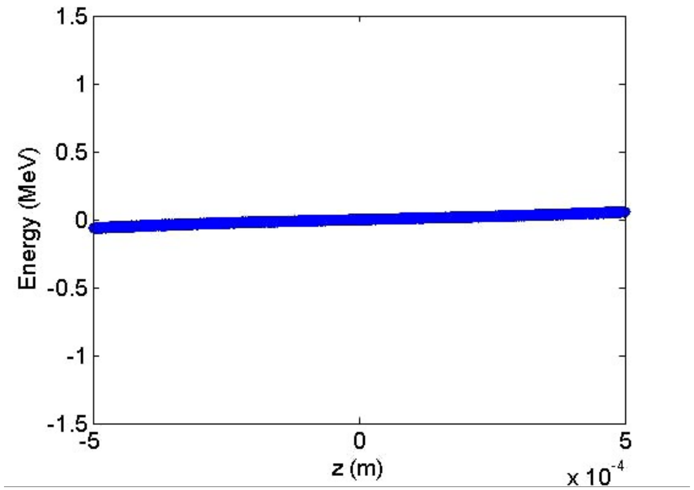


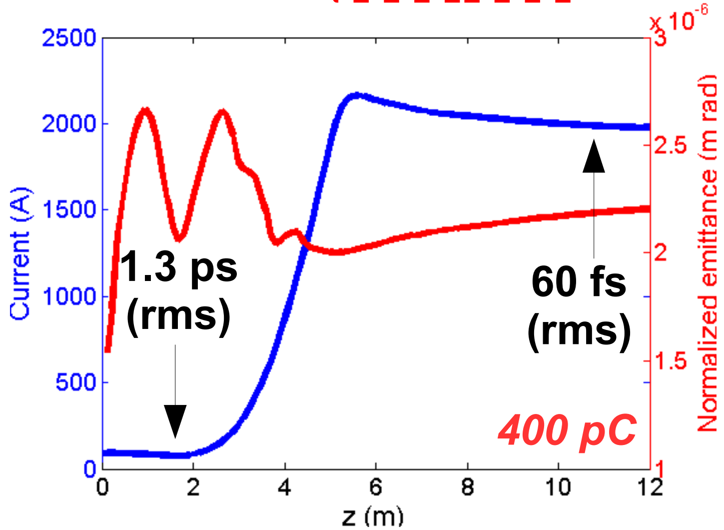
Ultra-short electron beams

- Current demands require high current beams
  - ✔ ***PWFA-LWFA****: high wakefield amplitude (i.e. high driver density), low energy spread (i.e. short witness).*
  - ✔ ***Advanced radiation sources****: high peak currents (FEL), short beams (broadband THz radiation).*
- Velocity bunching @ SPARC_LAB
  - ✔ *RF structure embedded in solenoid fields for **emittance compensation***





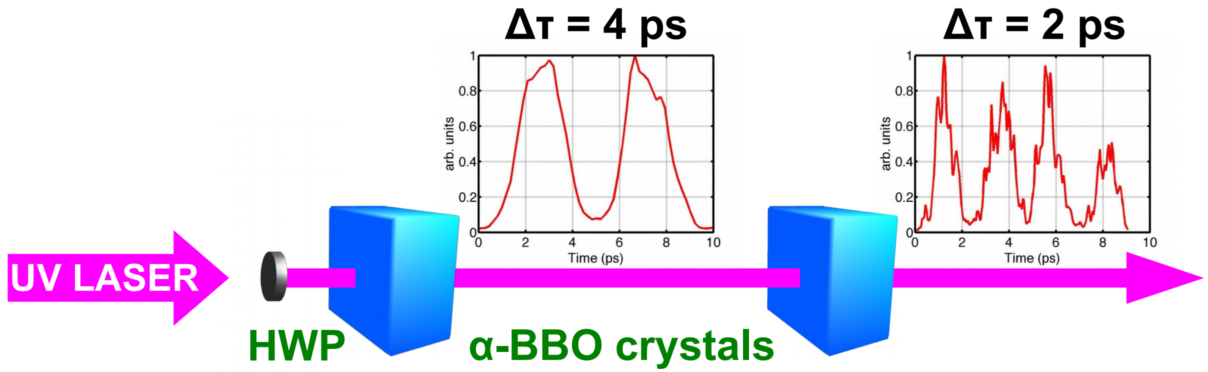




Serafini, L., M. Ferrario. "Velocity bunching in photo-injectors." AIP conference proceedings. 2001.
Ferrario, M.et al. "Experimental demonstration of emittance compensation with velocity bunching." PRL 104.5 2010.

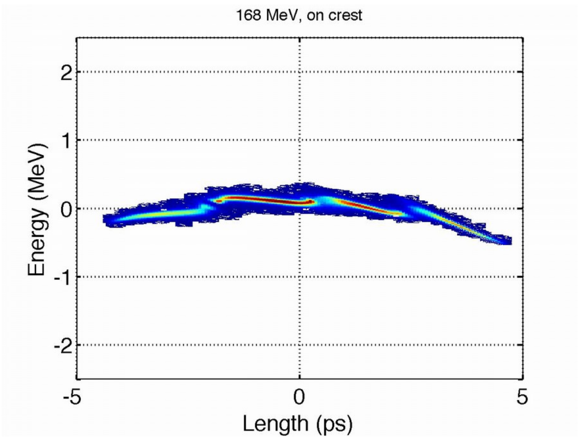
Laser-comb with velocity bunching

- **Laser-comb**: multiple bunches train produced directly at the cathode
  - ✔ *Pulses delayed by birefringent crystals, delay lines to take full control of distances*
  - ✔ *Easy setup, half-wave plates for (un)balancing (charge ramps…)*



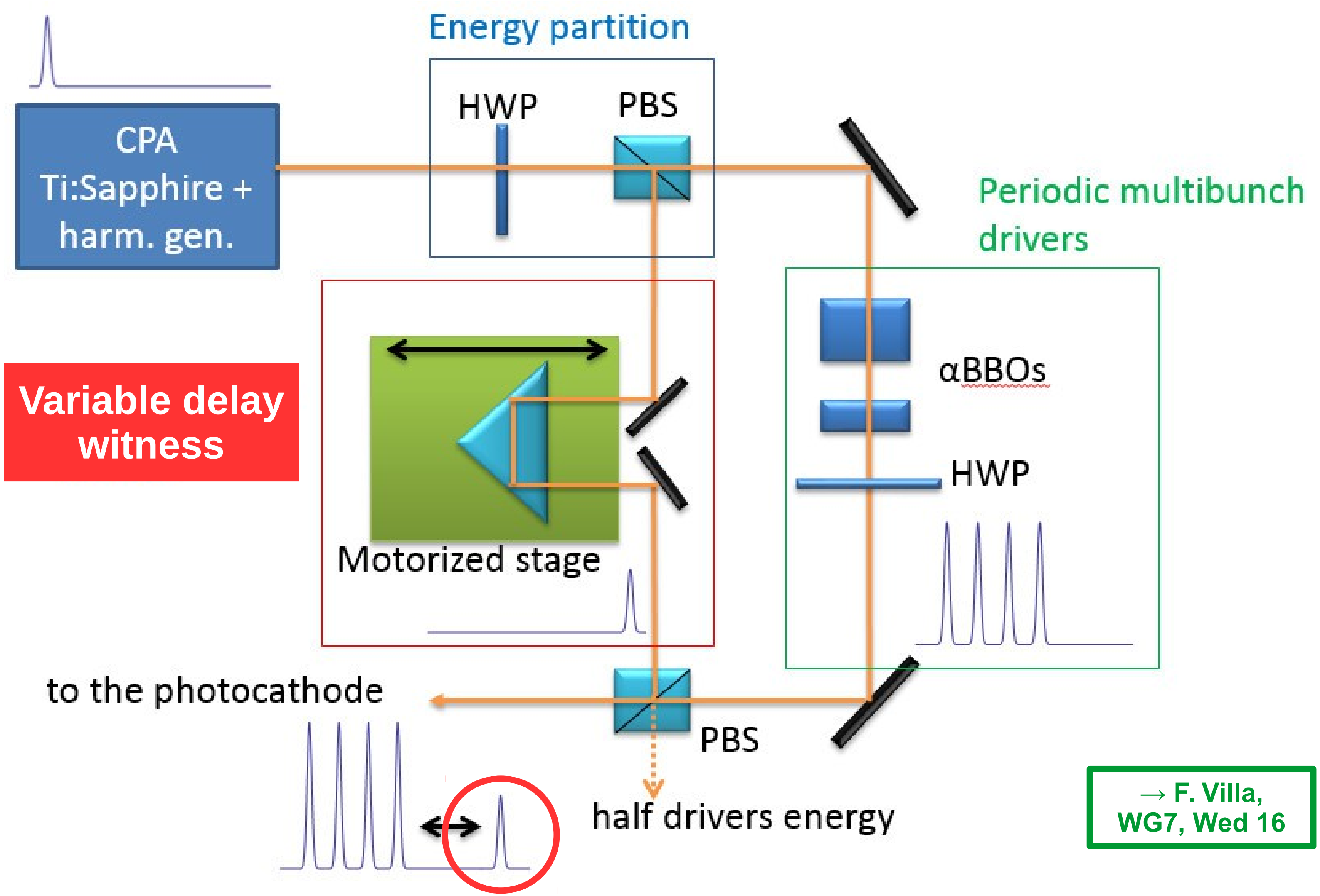
Ferrario, M., et al "Laser comb with velocity bunching: Preliminary results at SPARC." NIM 637.1 2011 S43-S46.

- Velocity bunching for bunch compression
  - *Distance and duration tuning by moving S1 phase*
  - *Different approach with respect to other multi-bunches schemes, e.g. @ FACET.*



C. Ronsivalle et al. "Large-bandwidth two-color free-electron laser driven by a comb-like electron beam." New Journal of Physics (2014): 033018.
Hogan, M. J., et al "Plasma wakefield acceleration experiments at FACET." New Journal of Physics 2010 055030.

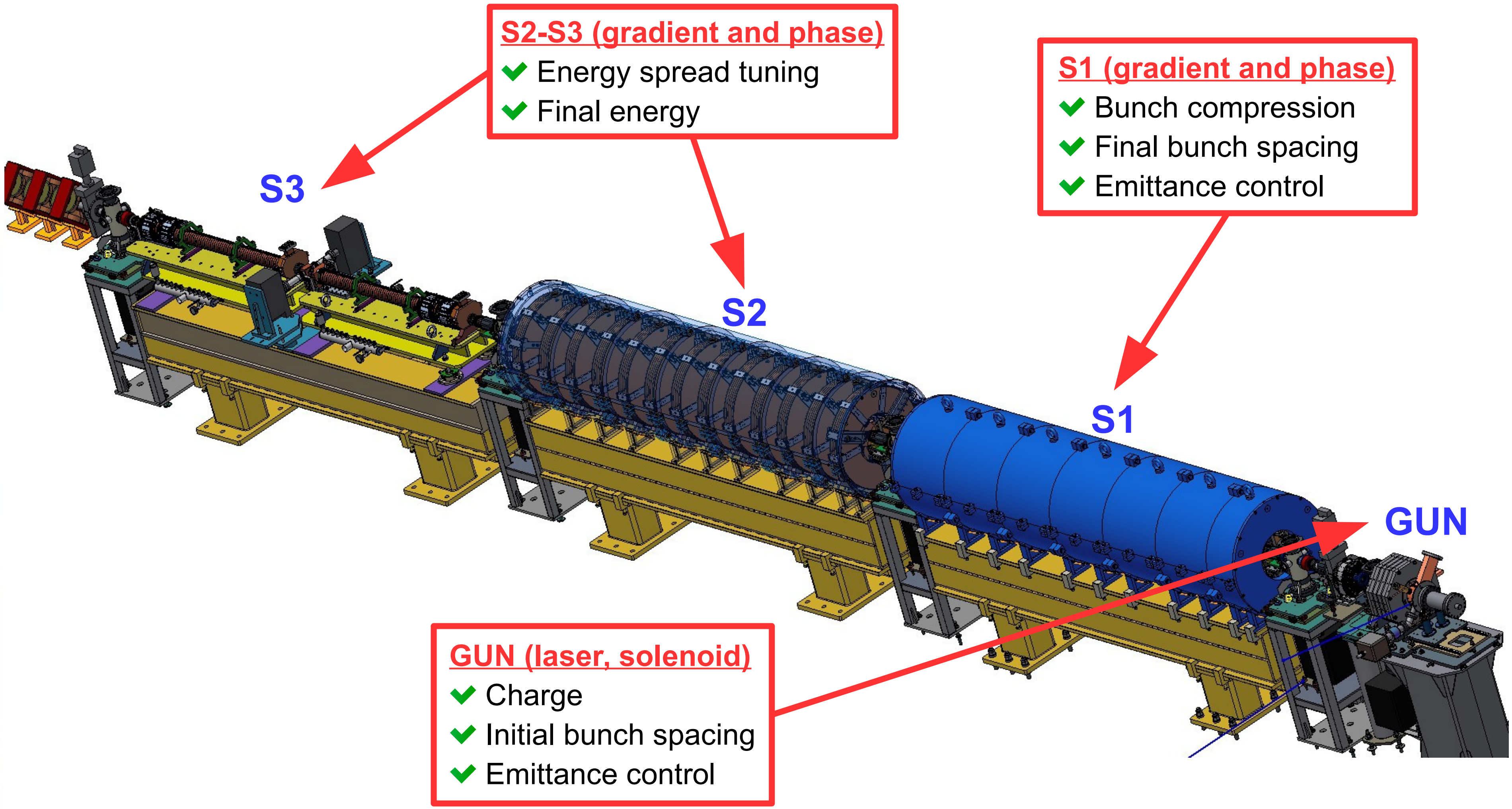
Laser-comb: optical setup



→ F. Villa, WG7, Wed 16

Villa, F., et al. "Laser pulse shaping for multi-bunches photo-injectors." NIM A 740 (2014): 188-192.

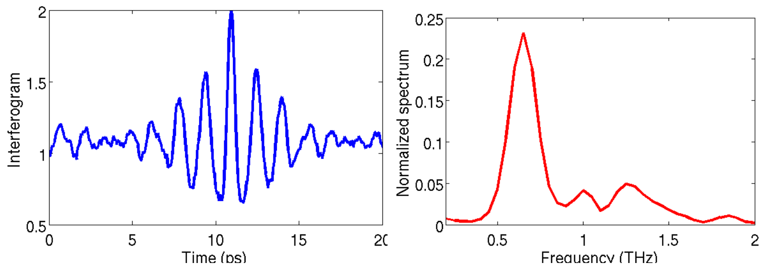
Tuning knobs



Chiadroni, E., et al. "Characterization of the THz radiation source at the Frascati linear accelerator." RSI 84.2 2013
Mostacci, A., et al. "Advanced beam manipulation techniques at SPARC."Proceedings of IPAC2011

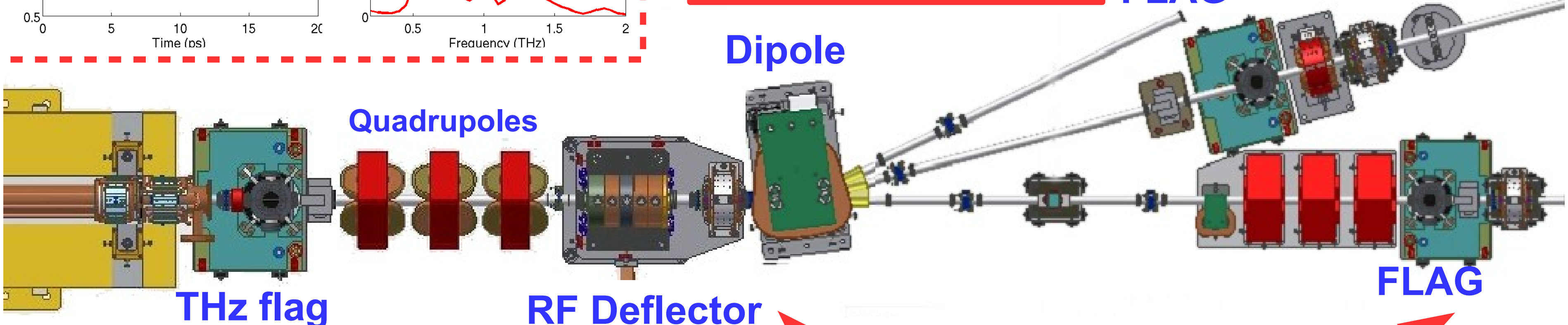
Measurement tools

5 bunches (charge ramp)



- ✔ Energy measurement
- ✔ Longitudinal Phase-Space
- ✔ Multiple-bunches QSCAN (energy separation)

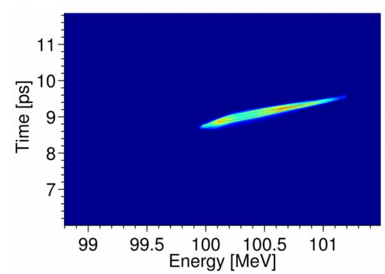
→ A. Cianchi, Thur 17, here

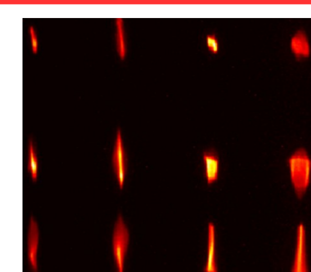


- ✔ CTR/CDR emission in THz range
- ✔ Longitudinal diagnostics

- ✔ Longitudinal diagnostics
- ✔ Phase-Space characterization

- ✔ Emittance (QSCAN)
- ✔ Multiple-bunches QSCAN (time separation) with RFD

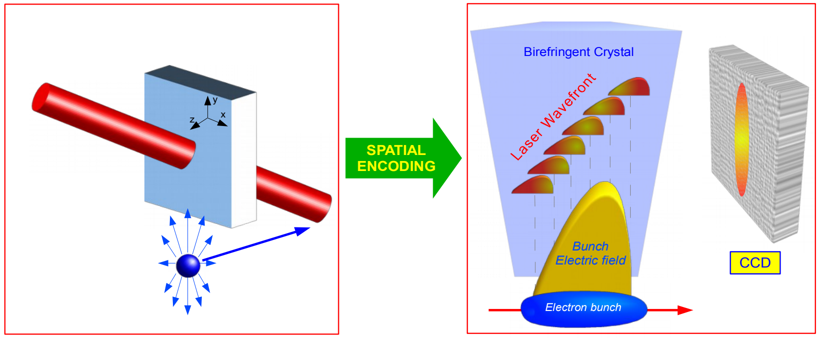




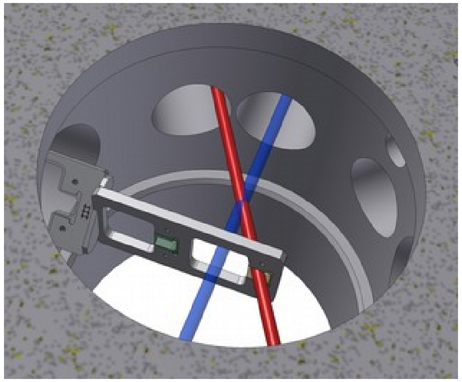
Cianchi, A. et al. Six-dimensional measurements of trains of high brightness electron bunches. PRSTAB 18 082804.

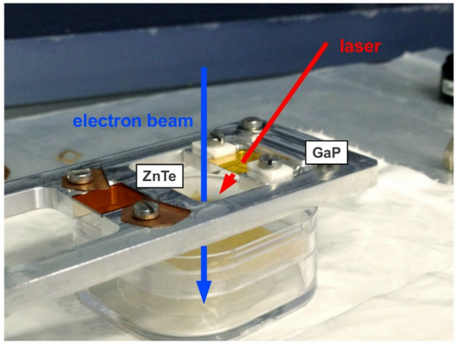
Single-shot and non-destructive tool

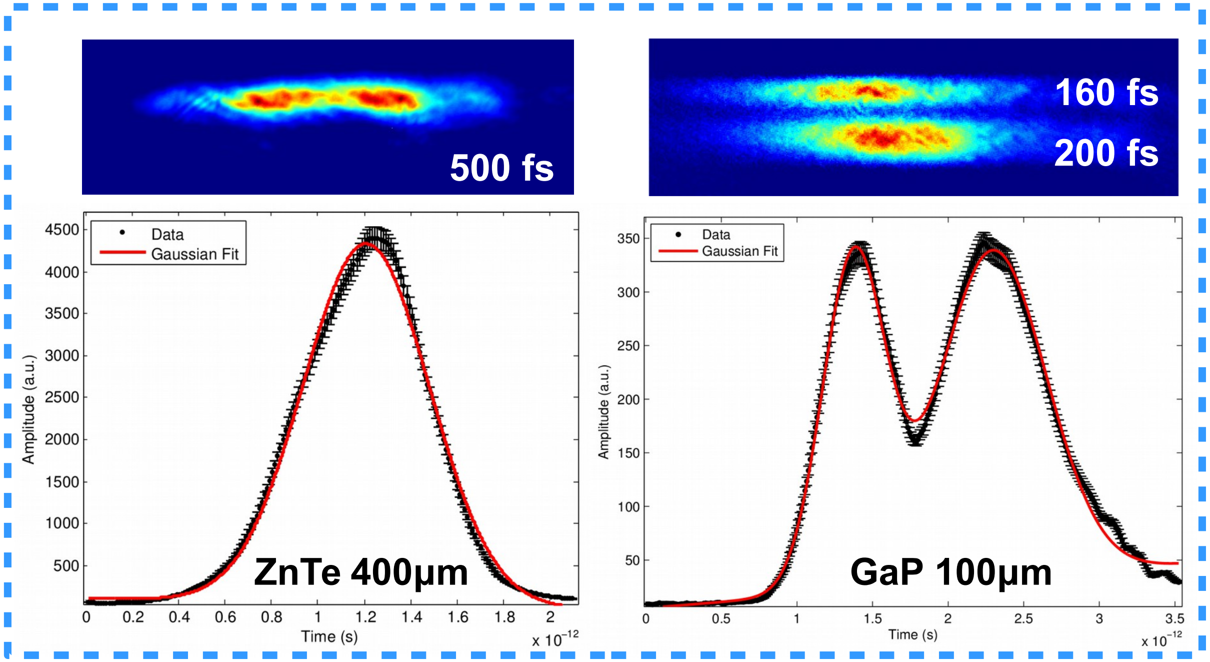
- Multi-bunches trains have been measured with Electro-Optical Sampling
  - ✔ *Single-shot, non-intercepting*
  - ✔ *80 fs (rms) temporal resulution*
- Goal: monitor beam injection in plasma



Spatial decoding



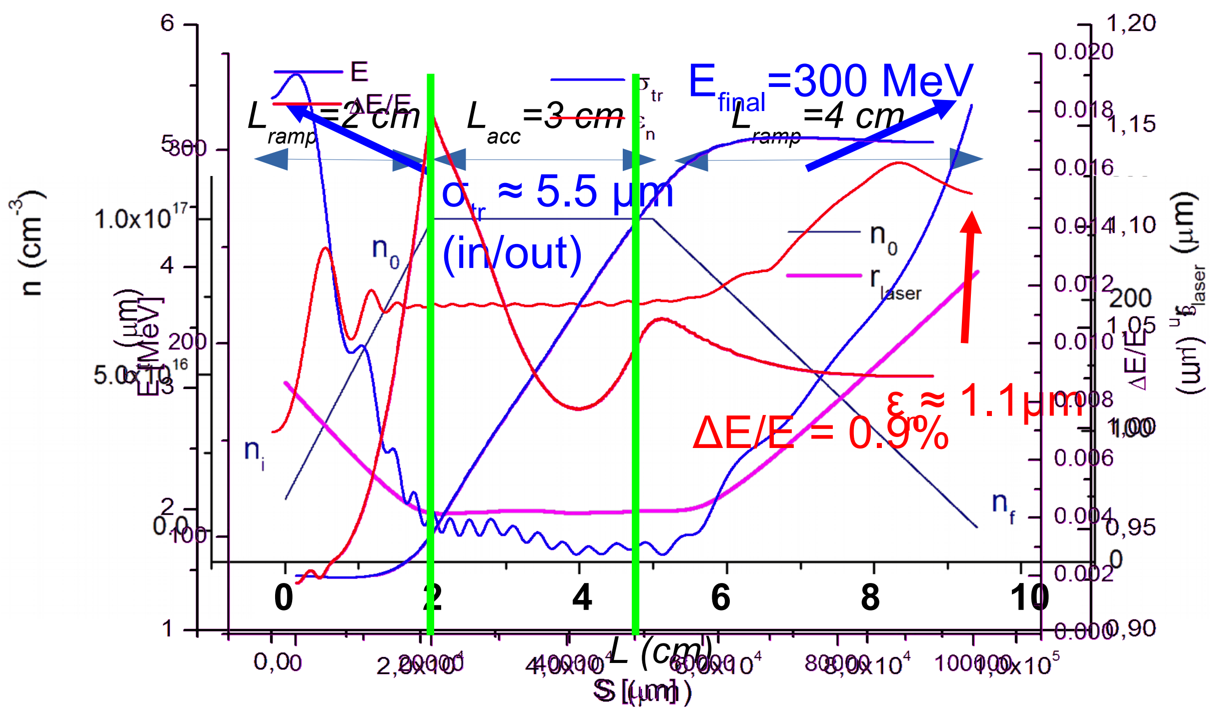




R. Pompili, et al., NIM A: Accelerators. 740, 216 (2014).

PWFA and LWFA requirements

LWFA by external injection (I)



Laser parameters

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

→ A. R. Rossi WG1, Tue 15

Beam parameters

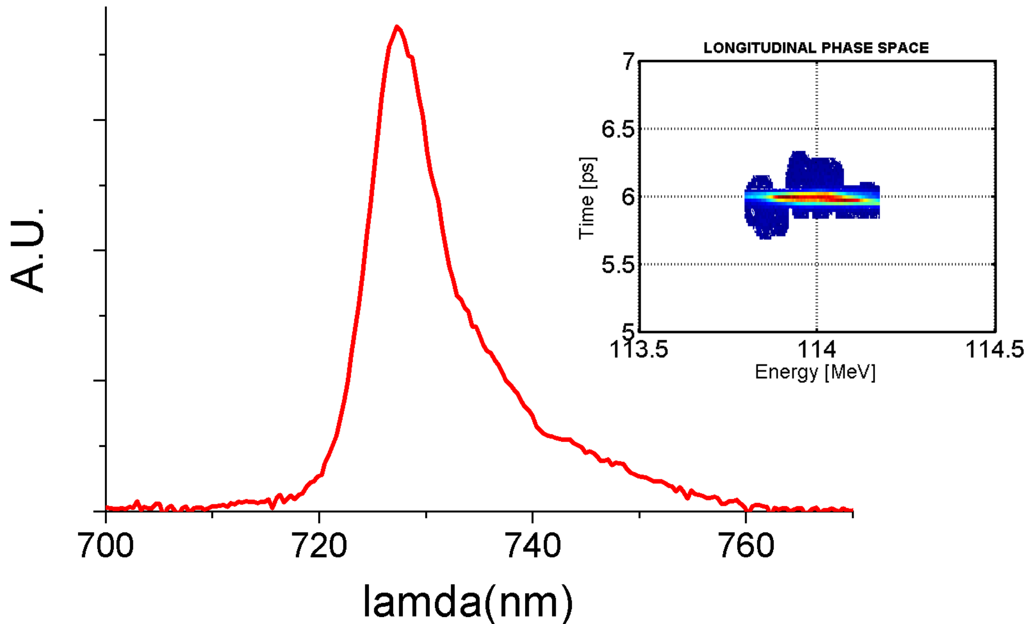
Charge (pC)	**10**
Energy (MeV)	**80**
Emittance (μm)	**1**
Spot (μm)	**5.5**
Duration (fs)	**17**
Time Jitter (fs)	**< 30**

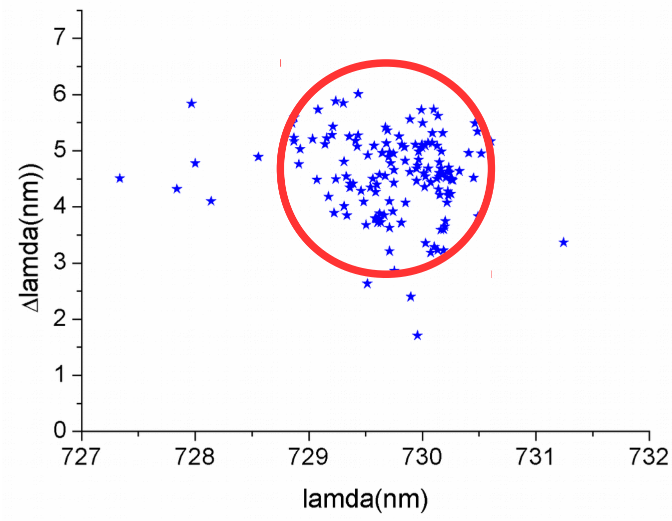
- Average accelerating field: **7 GV/m** ($n_0 = 10^{17}$ cm^{-3})
- Optimized matching
  - *Simulations show emittance growth limited to 10%*
  - *Input ramp: relaxed beam transverse matching*
- Energy spread ~ 0.9%, strongly reduced at exit
  - *Exit ramp: acts as a dechirper (λ_p increases)*

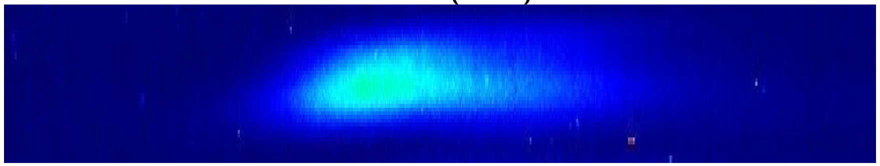
Rossi, Andrea R., et al. "The External-Injection experiment at the SPARC_LAB facility." NIM A 740 (2014): 60-66.

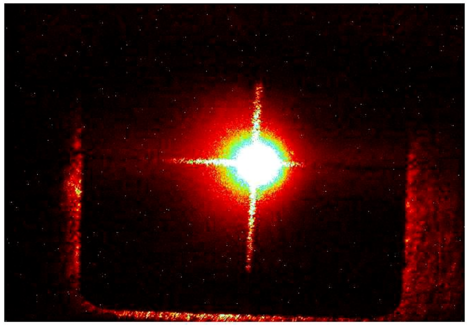
High quality ultra-short beams with VB

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







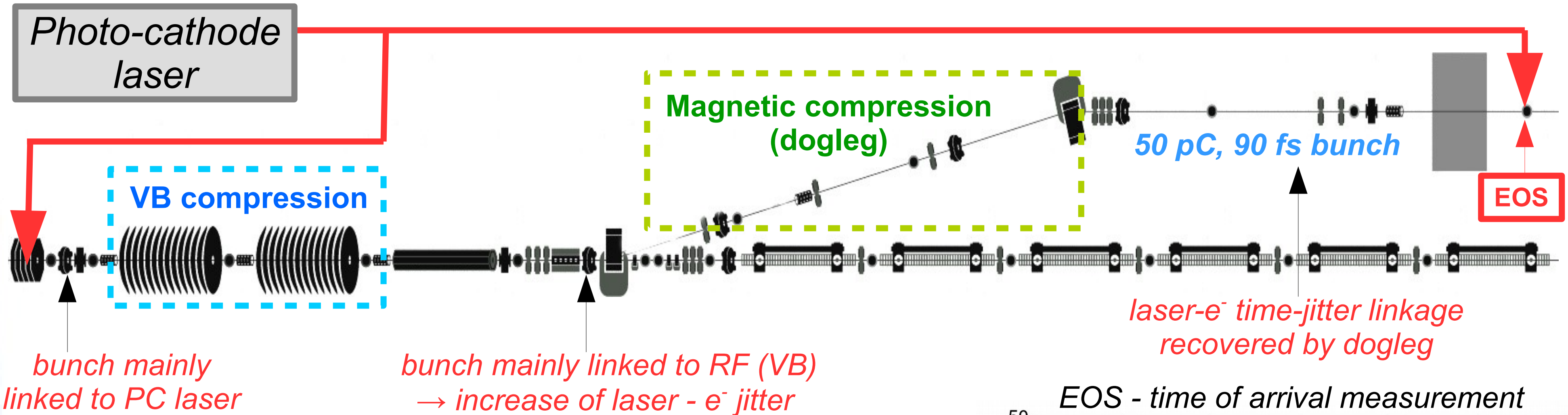


Collected FEL light, 100 fs (rms), 40 μJ

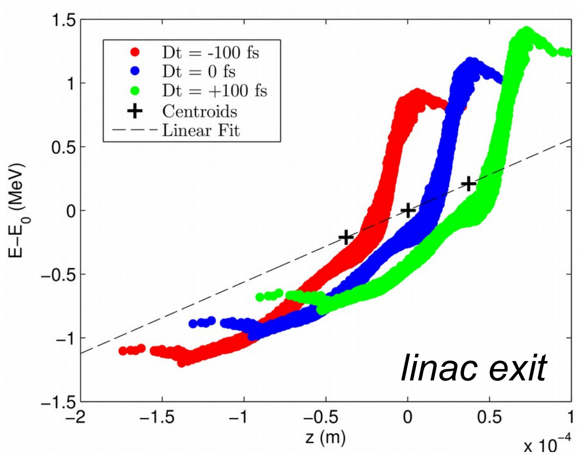
Bunch parameters

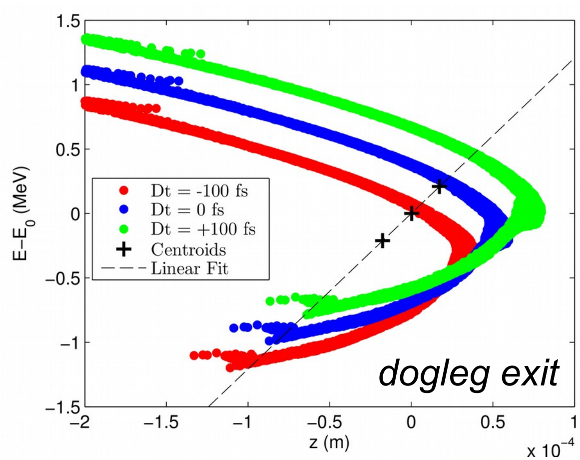
Charge (pC)	Energy (MeV)	Energy Spread (%)	Duration (fs)	Emittance (μm)	Peak current (A)
20	114	0.1	26	1.2	400

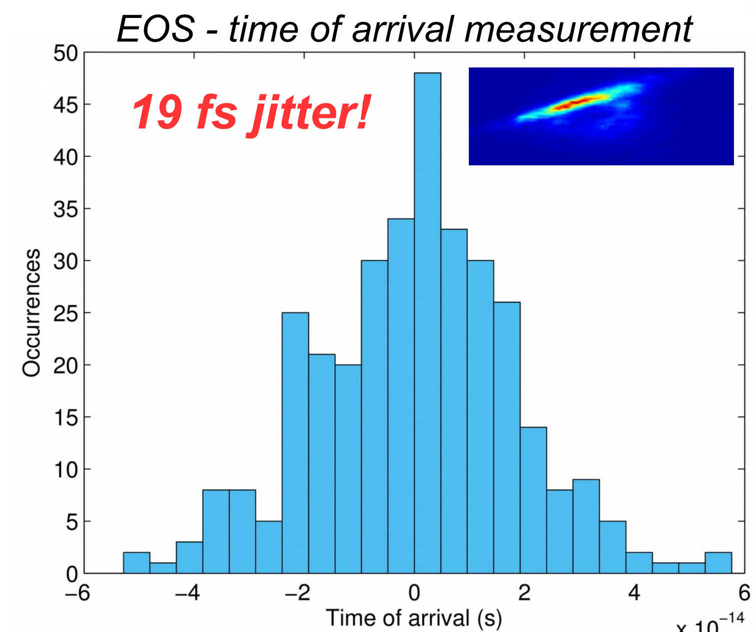
Laser vs e^- beam time-jitter reduction



Hybrid compression: *bunch shortening by* ***VB****, relative ATJ reduction by* ***magnetic compression***







Pompili, R. et al. submitted to PRSTAB.

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*

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

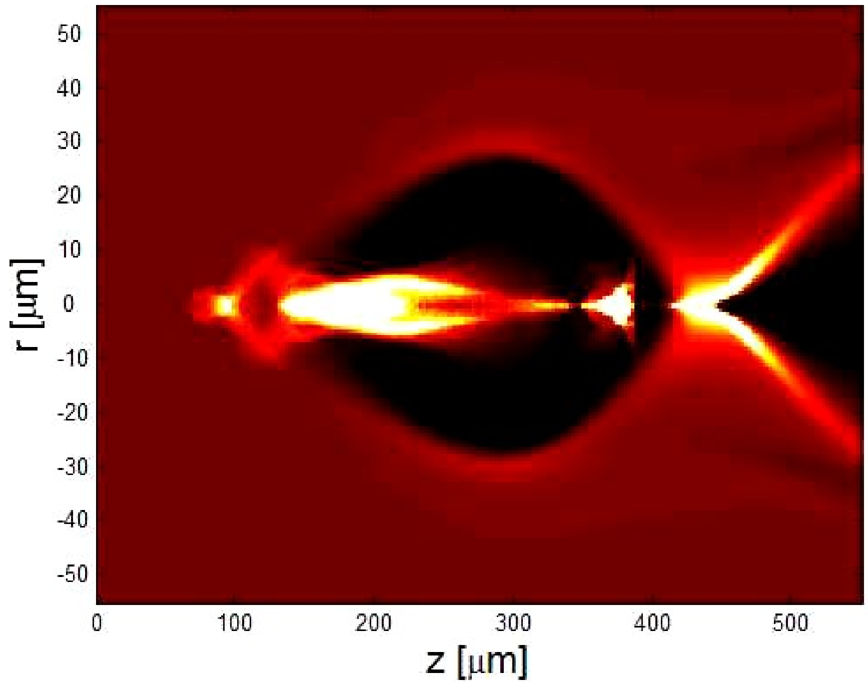
- Using low emittance, high brightness beams we have

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

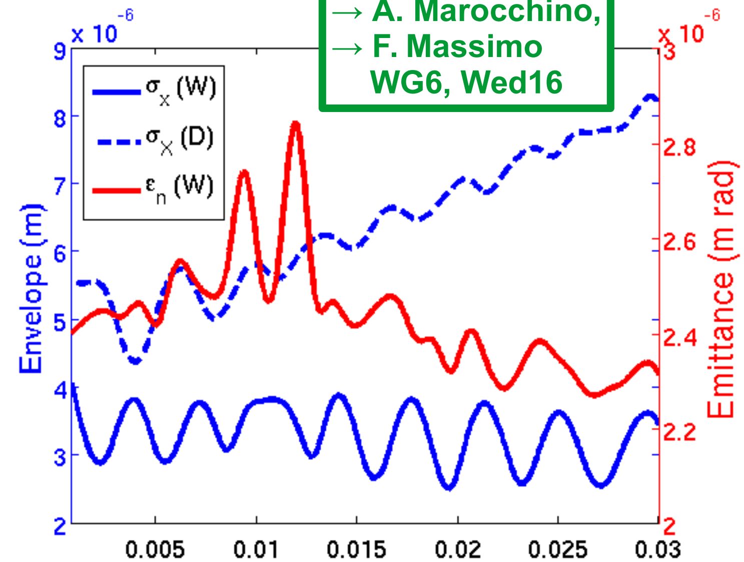
- These conditions define the quasi-nonlinear (QNL) regime
  - ***n_p = 10^{16} cm^{-3}, Q_D = 200 pC, σ_t=180 fs, σ_x=5.5 um → n_b~5n_p*** *and* $\tilde{Q} = N_b k_p^3 / n_p \approx 0.8$

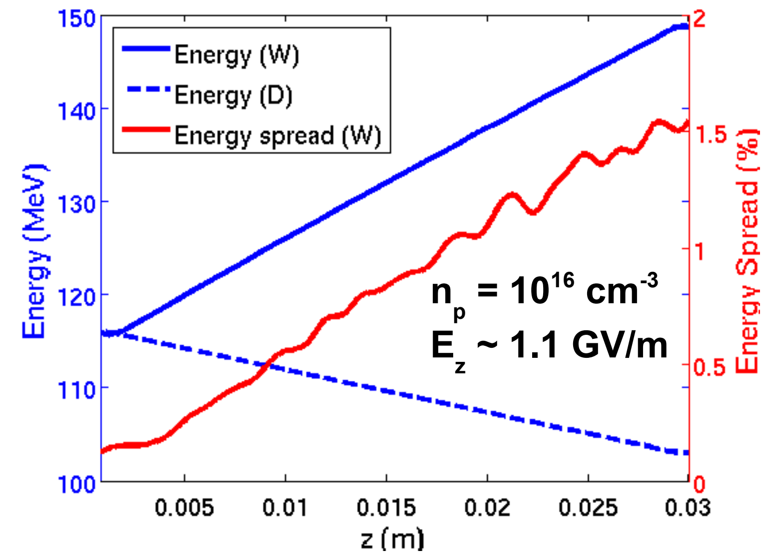
Rosenzweig, J. B., et al. "Plasma Wakefields in the Quasi□Nonlinear Regime." (2010): 500-504.
Londrillo, P., et al. "Numerical investigation of beam-driven PWFA in quasi-nonlinear regime." NIM 740 (2014): 236

Acceleration in plasma



→ A. Marocchino,
→ F. Massimo
WG6, Wed16





- *Hybrid kinetic-fluid simulation by **Architect***
  - ***PIC*** *(bunch),* ***fluid*** *(plasma), 3-5 hours for 3 cm*
  - *Cross-checked with full PIC codes (ALaDyn)*

	Q (pC)	σt (fs)	σx (µm)	E (MeV)	ε (µm)
Driver	200	180	5.5	116	4.5
Witness	20	35	3	116	2.4

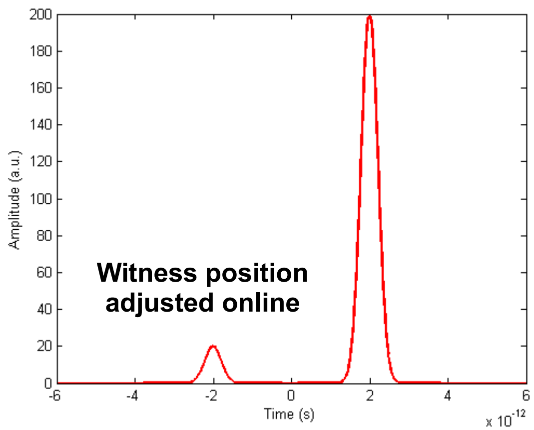
Toward the PWFA

VB dynamics: 1 driver + witness

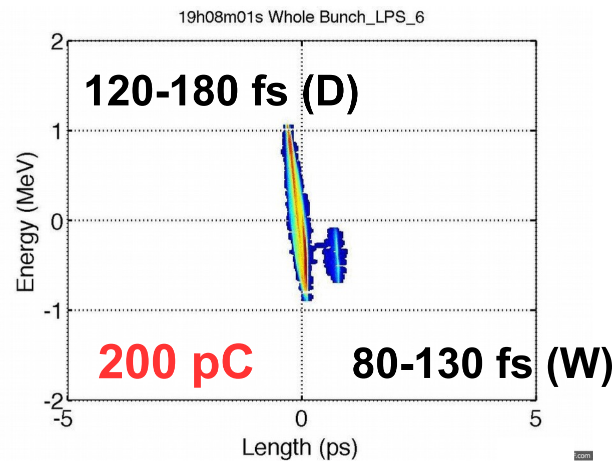
Experimental results!

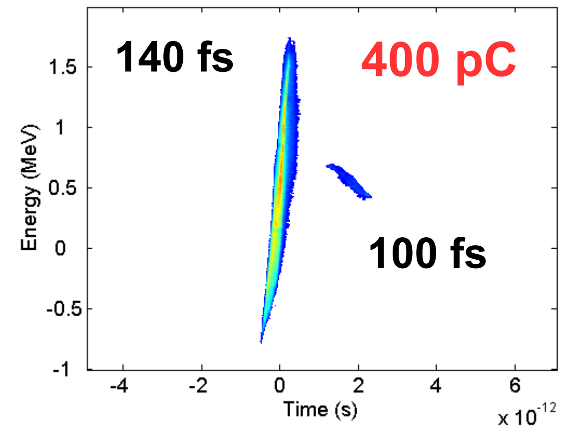
Laser profile on photo-cathode

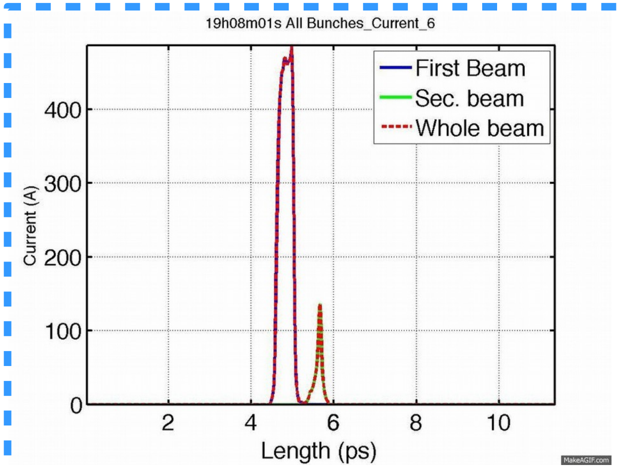
Driver + witness (20 pC)

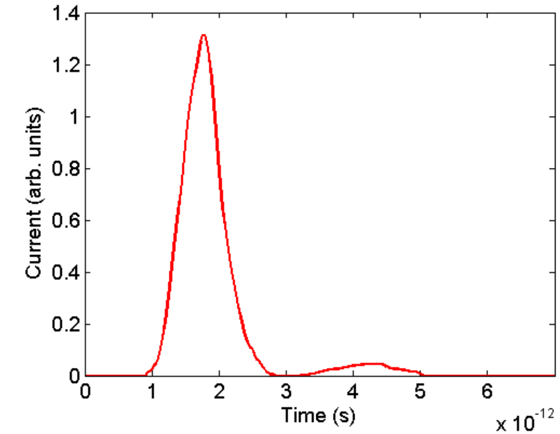


LPS at linac exit









Current profile

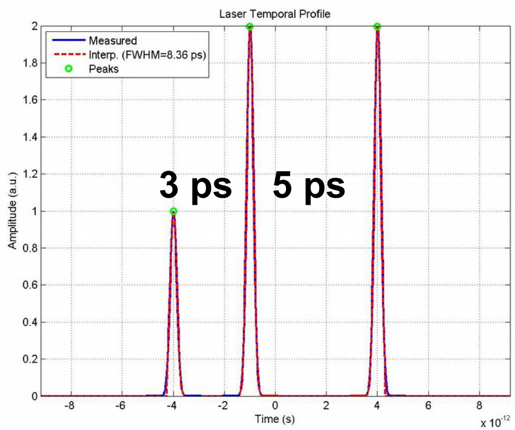
VB dynamics: N driver + witness

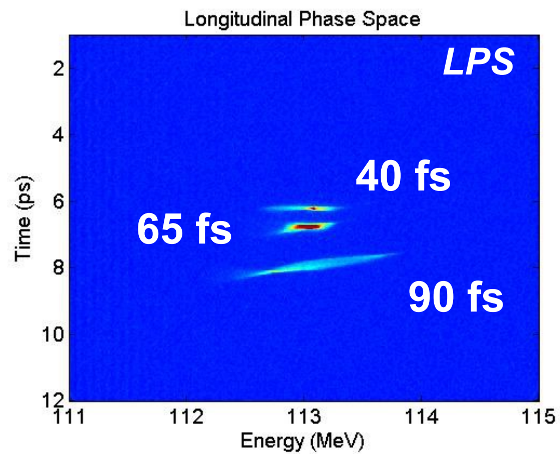
Experimental results!

50 pC drivers + 20 pC witness

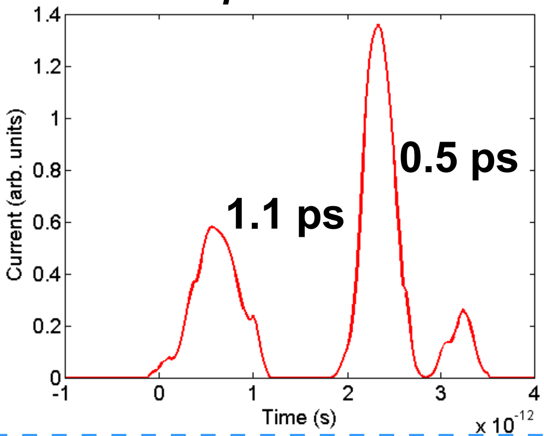
resonant scheme @ $n_p = 10^{16}$ cm^{-3} → bunch distance = λ_p ~ 1.1 ps

Laser profile on photo-cathode

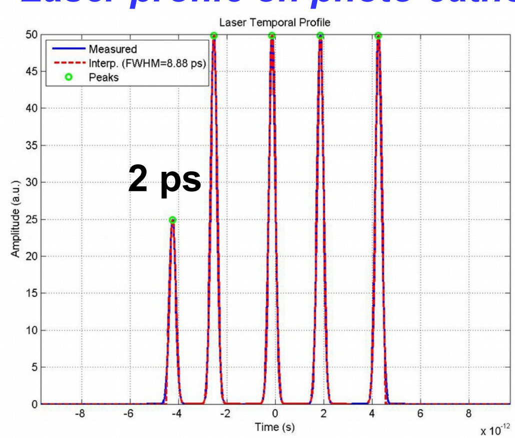


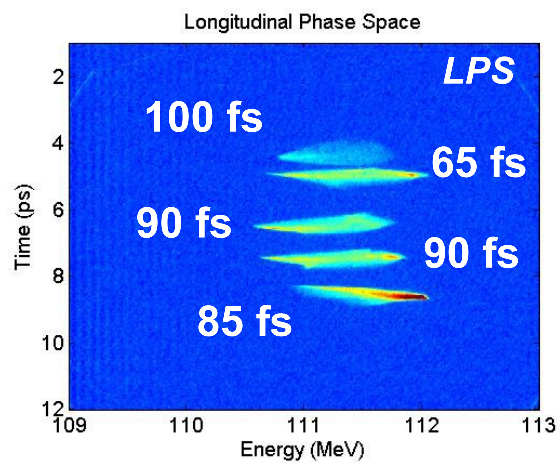


Current profile

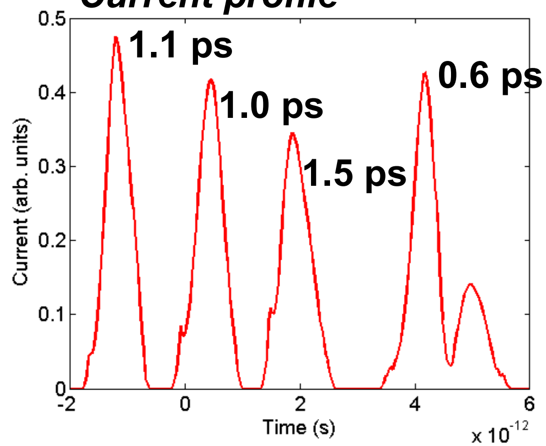


Laser profile on photo-cathode

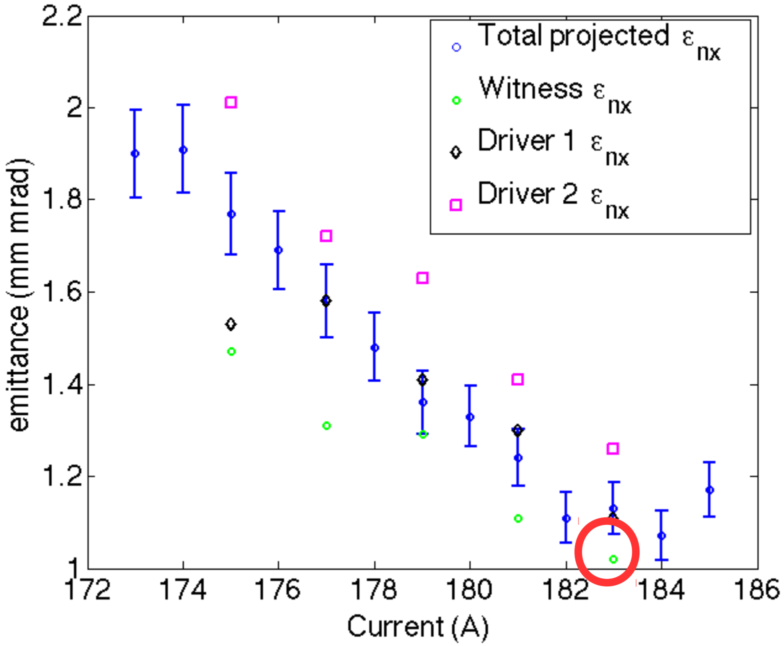


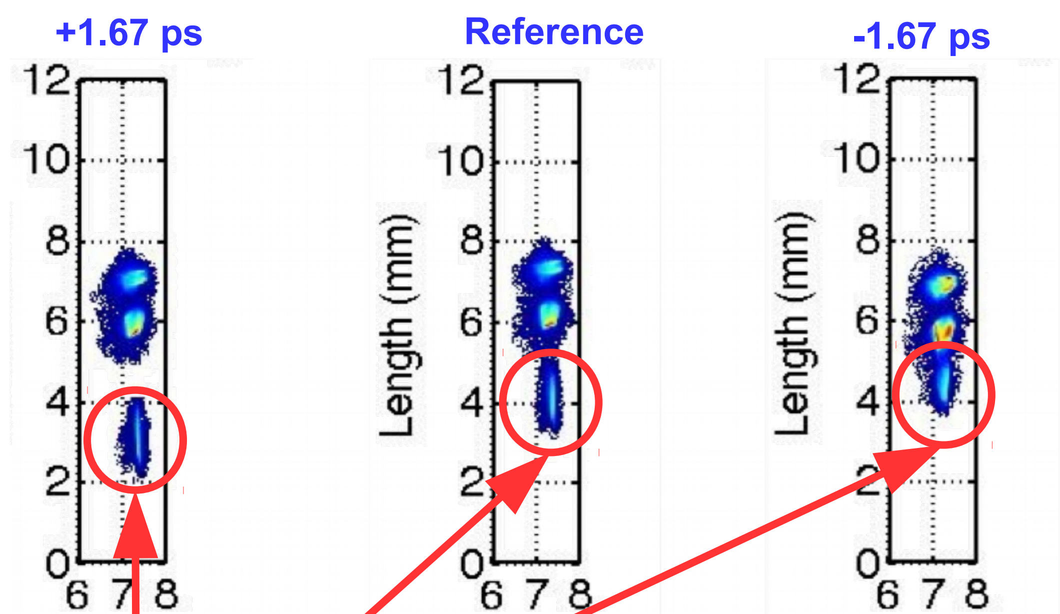


Current profile



Witness – tuning and characterization

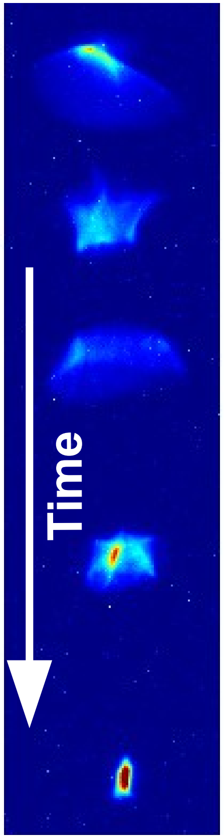




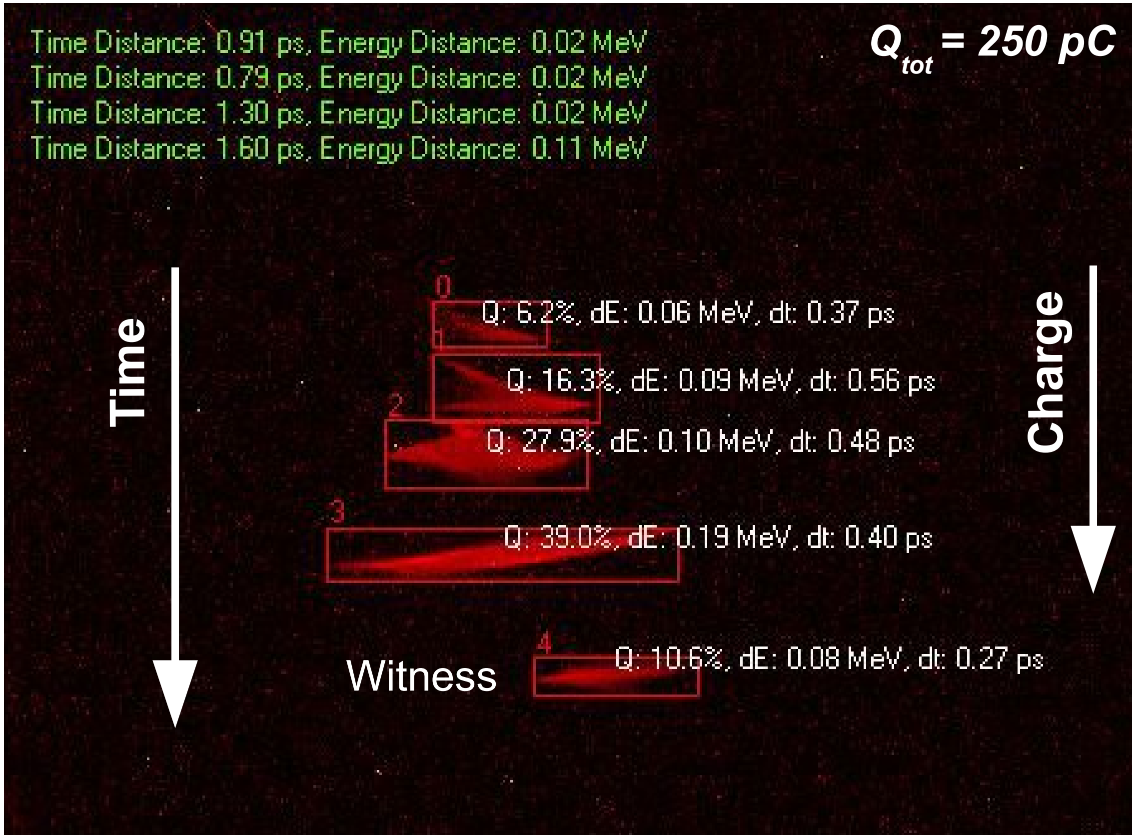
Witness position tuning with laser delay line!

Ramped comb beams

z-x view



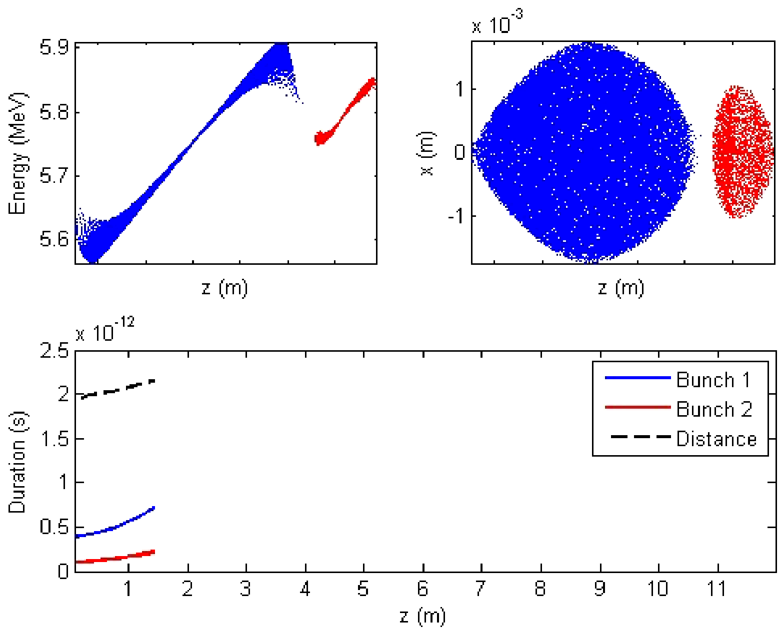
Longitudinal Phase Space

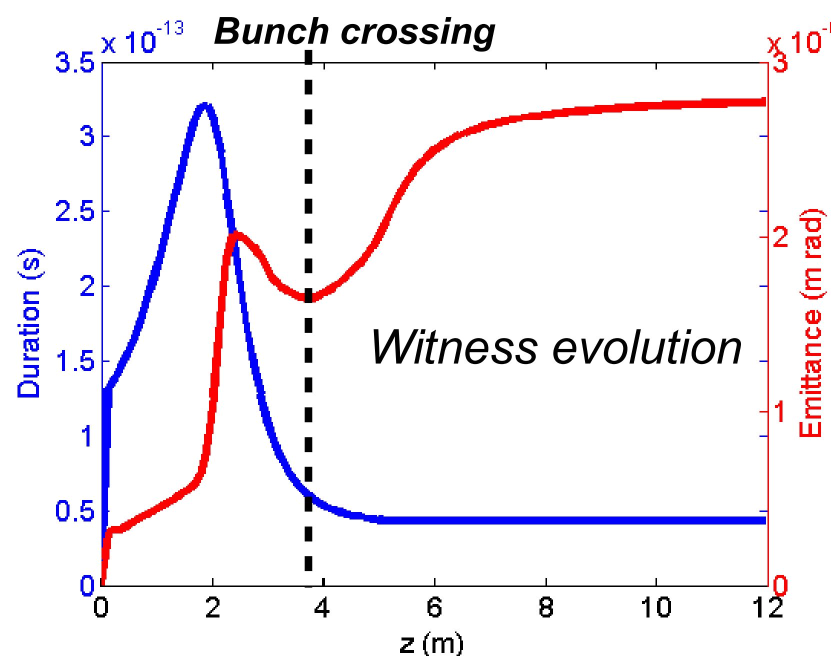


Recipe for PWFA beams

- Generation of the required train bunches
  - σ_t=100 fs (rms) laser @ cathode (blowout [1,2])
  - Laser pulse distance at cathode: 2.4 ps
  - Driver-Witness distance at linac exit: 550 fs

	Driver	Witness
Charge (pC)	200	20
Energy (MeV)	107.6	107.4
Final focus (μm)	5.5	3
Duration (fs)	190	40
Emittance (μm)	3.9	2.7

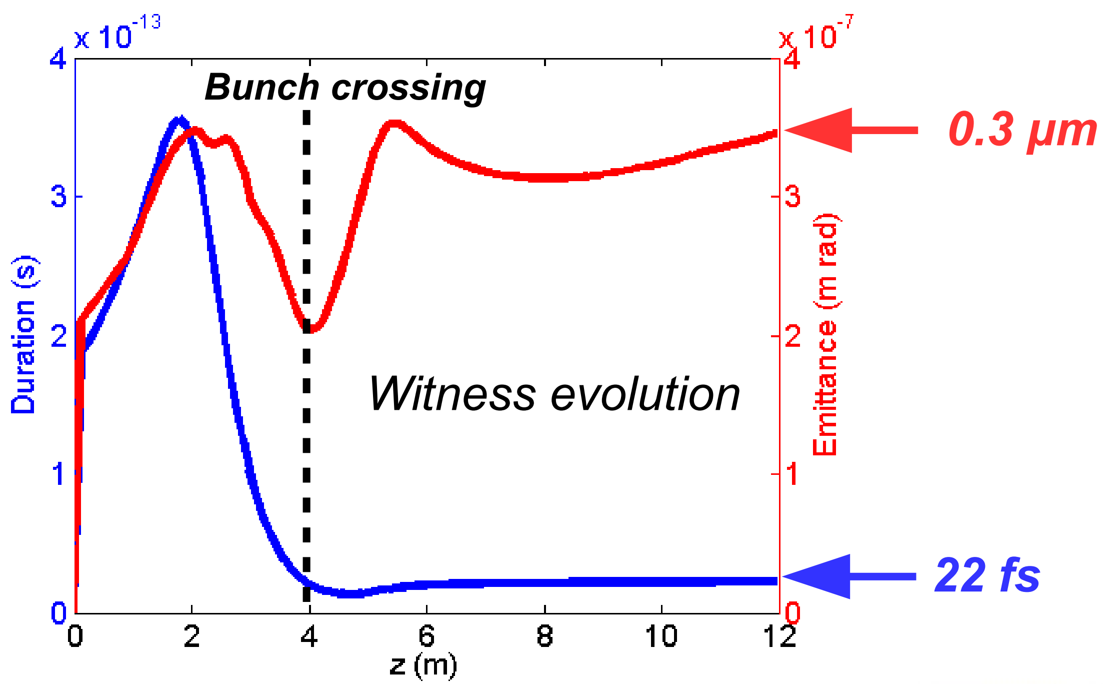


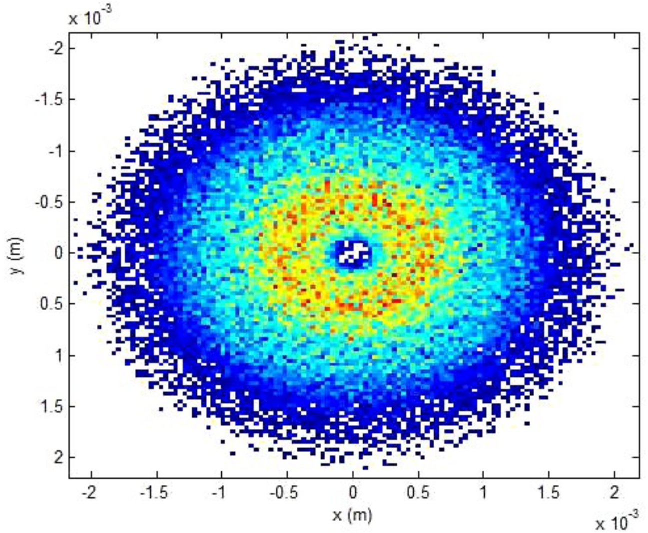


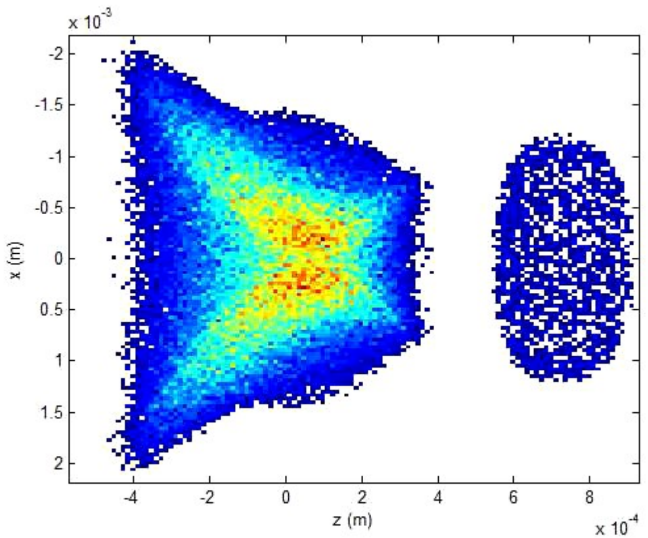
[1] **Musumeci, P., et al.,** Physical review letters 100.24 (2008): 244801.
[2] **Moody, J. T., et al.** Physical Review Special Topics-Accelerators and Beams 12.7 (2009): 070704.

Hollow driver beams

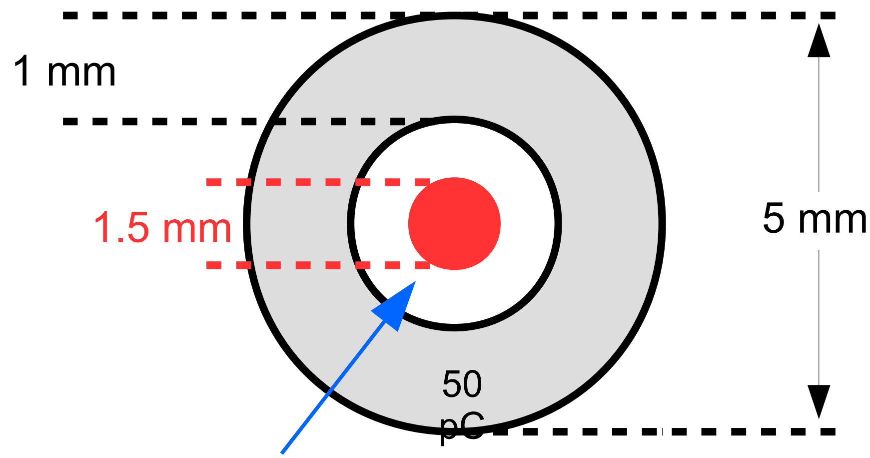
- Witness degradation during bunch crossing
  - *Driver as nonlinear lens → emittance growth*
  - *Driver field opposed to RF → lower compression*
- Use of hollow driver beam
  - ✔ *No beam-beam effects → unperturbed witness*
  - ✖ *Higher driver emittance (larger spot on cathode)*



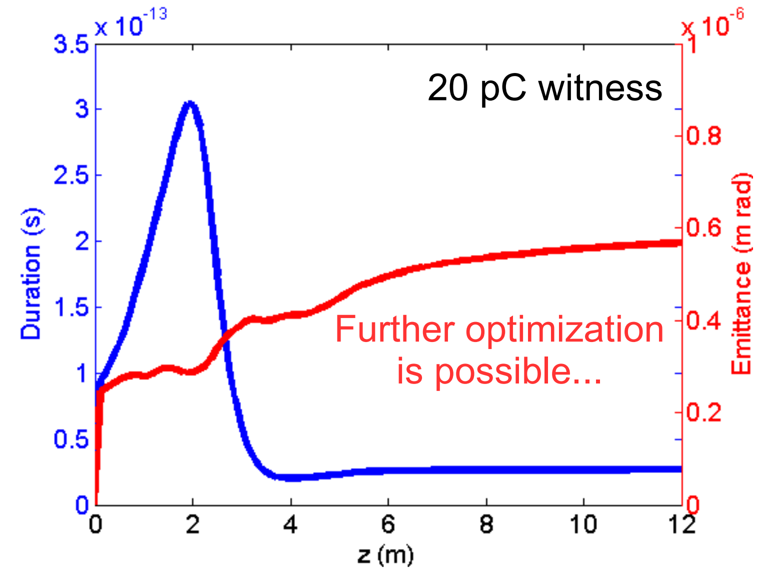




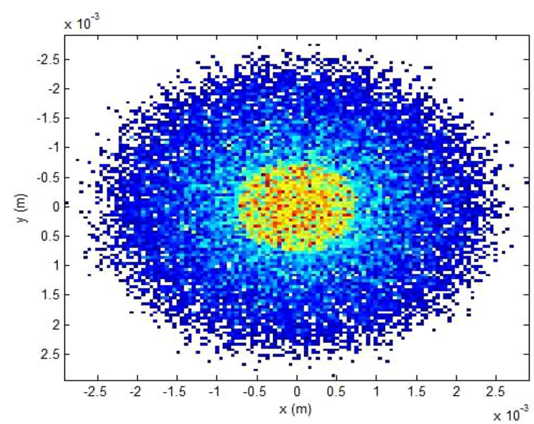
Hollow driver – comb beams

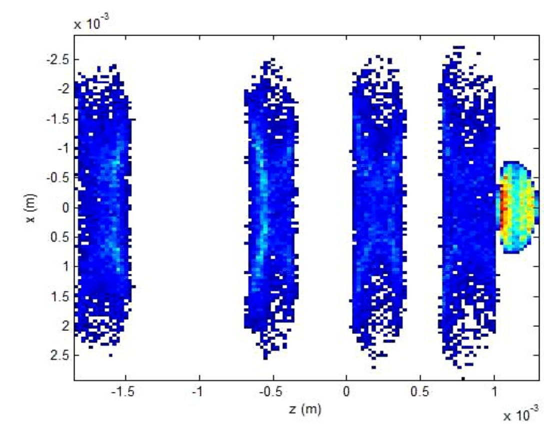


Large hole in order to avoid space-charge filling it!



	Δt (fs)	ε_n (μm)
Driver 1	**164**	**4.8**
Driver 2	**81**	**6.1**
Driver 3	**43**	**5.7**
Driver 4	**40**	**5.3**
Witness	**26**	**0.5**



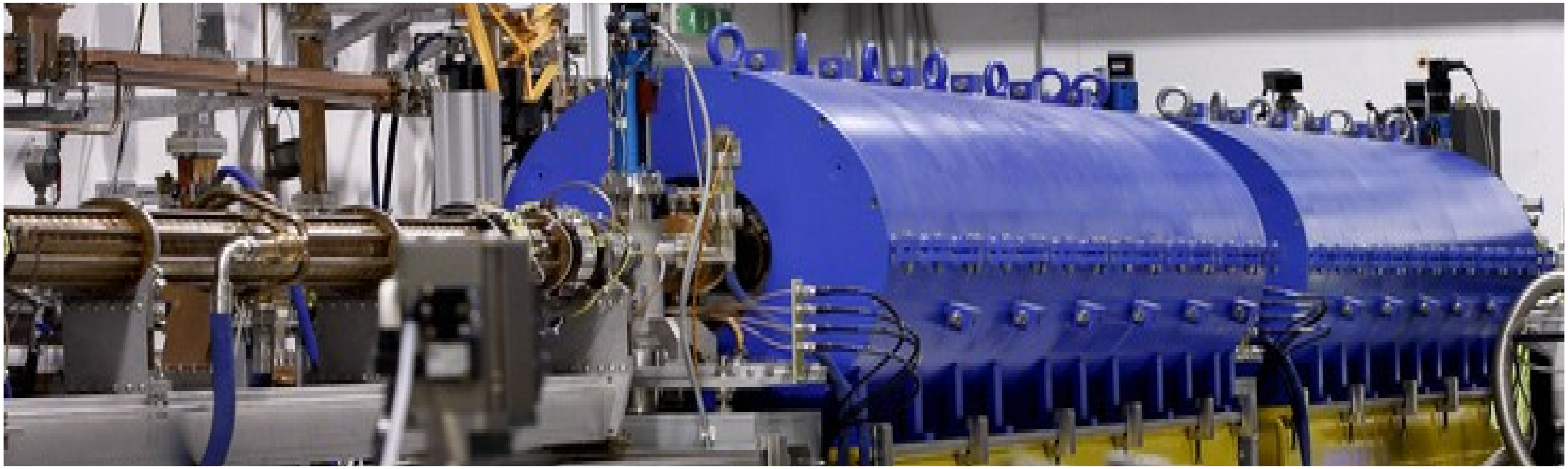


Conclusions

- Velocity bunching with emittance compensation @ SPARC_LAB
  - *Results show that VB scheme is able to produce beams meeting PWFA and LWFA (by external injection) requirements*
- Together with laser-comb technique it allows resonant PWFA schemes, too
  - *Full control of bunch durations, distances and charges demonstrated @ SPARC_LAB*
  - *Current measurement tools allow a complete characterization of all bunches*
- PWFA in quasi-nonlinear regime shows promising results

  → S. Romeo, WG1, Tue 15
  - *High accelerating gradients, emittance preservation, extension to resonant schemes*
- Hollow driver beams avoid witness bunch degradation during VB
  - *Ultra-short bunches with ultra-low emittance can be produced*
  - *Goal: preserve high brightness beams during plasma acceleration process*

Acknowledgments



- D. Alesini, M.P. Anania, M. Bellaveglia, A. Biagioni, F. Bisesto, M. Castellano, E. Chiadroni, M. Croia, D. Di Giovenale, M. Ferrario, G. Di Pirro, S. Romeo, J. Scifo, V. Shpakov, B. Spataro, C. Vaccarezza, F. Villa (INFN, Frascati)
- A. Cianchi (Tor Vergata University of Rome)
- F. Filippi, F. Giorgianni, A. Giribono, S. Lupi, A. Marocchino, F. Massimo, F. Mira, A. Mostacci, M. Petrarca (Sapienza University of Rome)
- F. Ciocci, A. Petralia (ENEA, Frascati)
- A. Bacci, V. Petrillo, A.R. Rossi, L. Serafini (INFN, Milano)

This work has been partially supported by the EU Commission in the Seventh Framework Program, Grant Agreement 312453-EuCARD-2 and the Italian Minister of Research in the framework of FIRB – Fondo per gli Investimenti della Ricerca di Base, Project n. RBFR12NK5K.

Thank you for your attention!