Advanced beam manipulation experiments at SPARC_LAB

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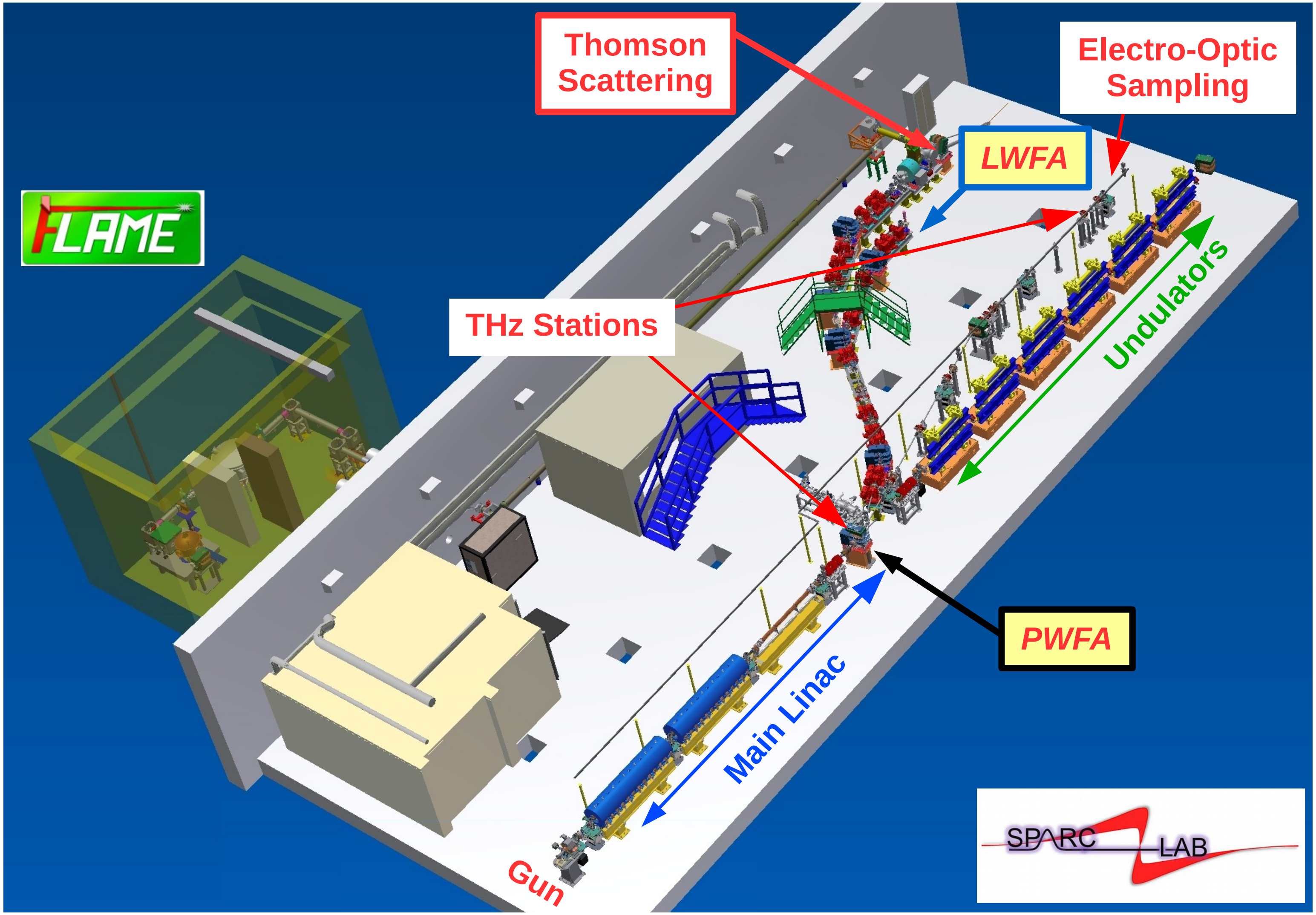
SPARC_LAB test-facility

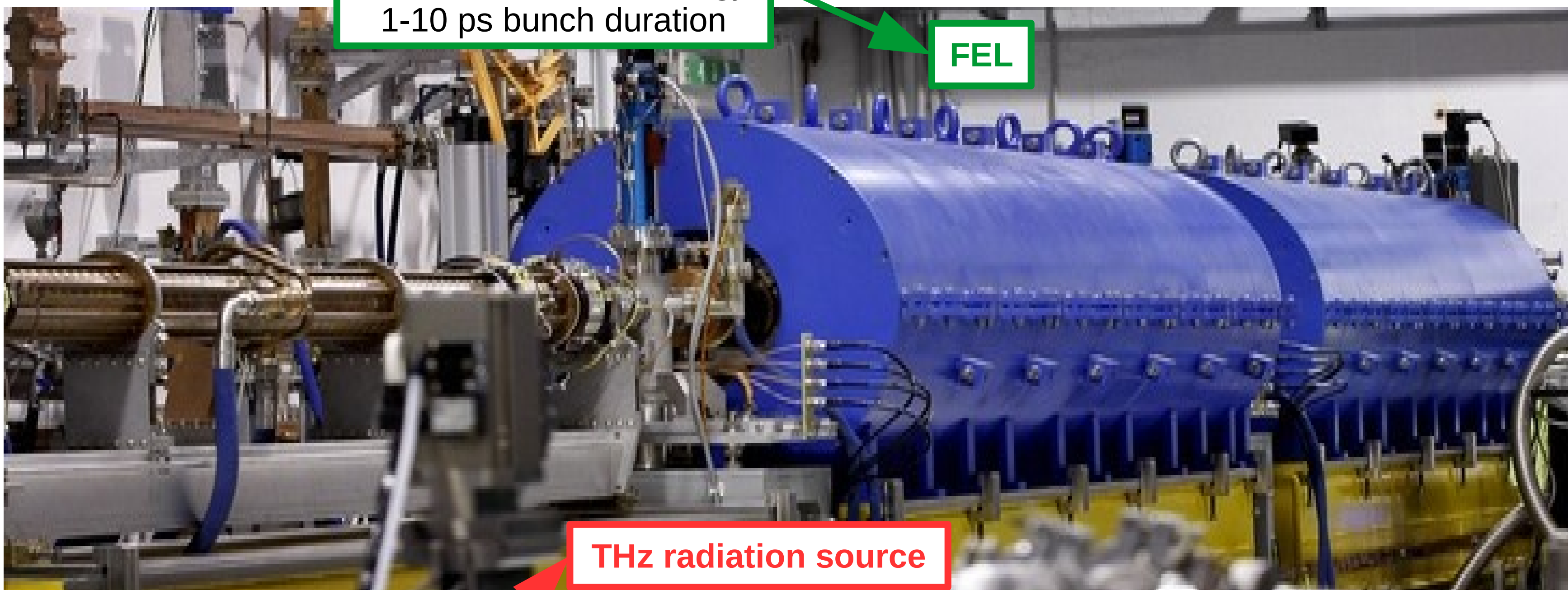


Ferrario, M., et al. "SPARC_LAB present and future." NIMB 309 (2013): 183-188.

High brightness photo-injector

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

→ **Thomson source**
→ **FEL**

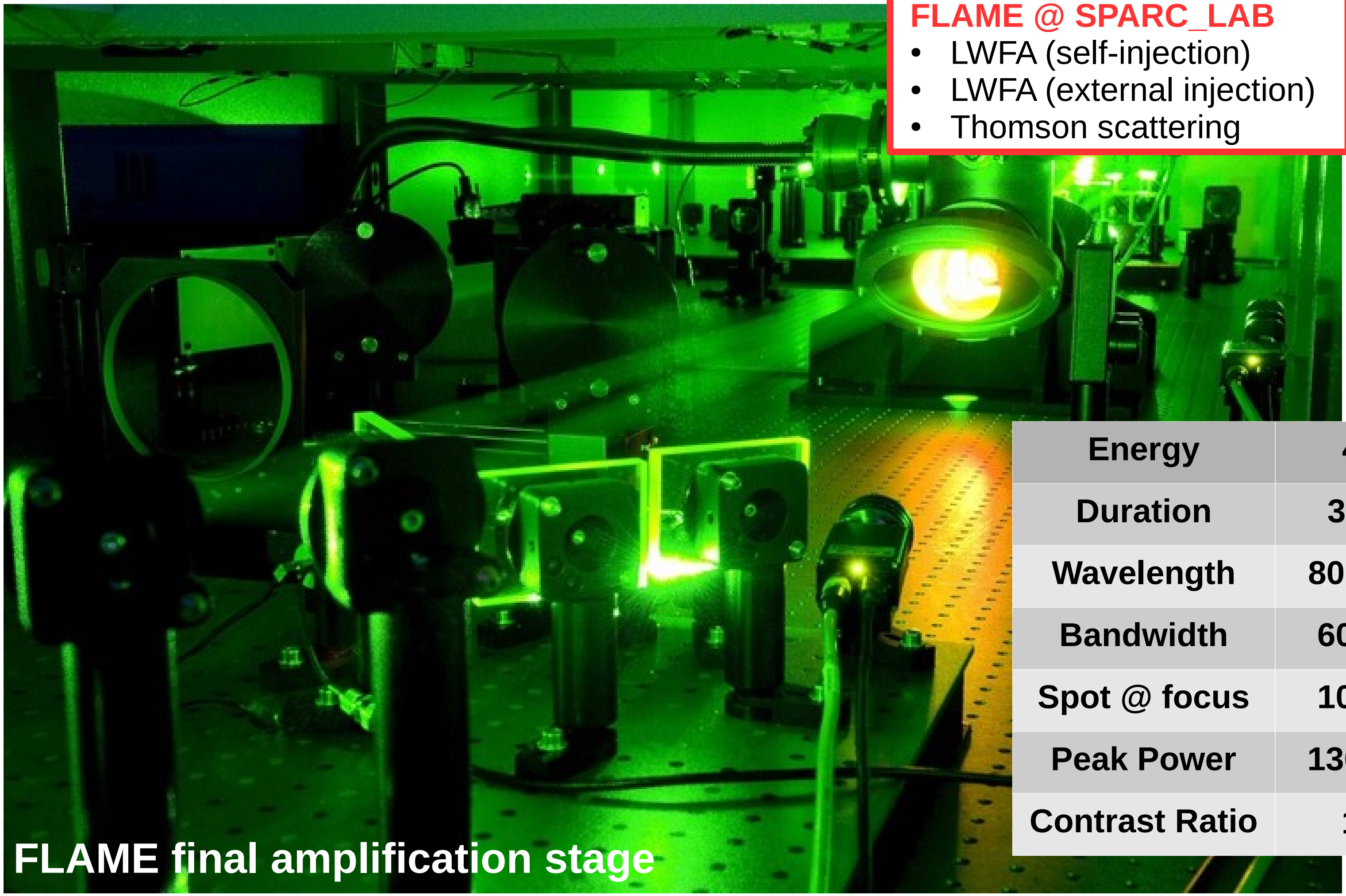


High-current operation (VB)
80-120 MeV beam energy
20 fs - 1 ps bunch duration

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

Serafini L., Ferrario M. "Velocity bunching in photo-injectors." AIP conference proceedings. 2001.
Anderson, S. G., et al. "Velocity bunching of high-brightness electron beams." PRSTAB 8.1 (2005): 014401.

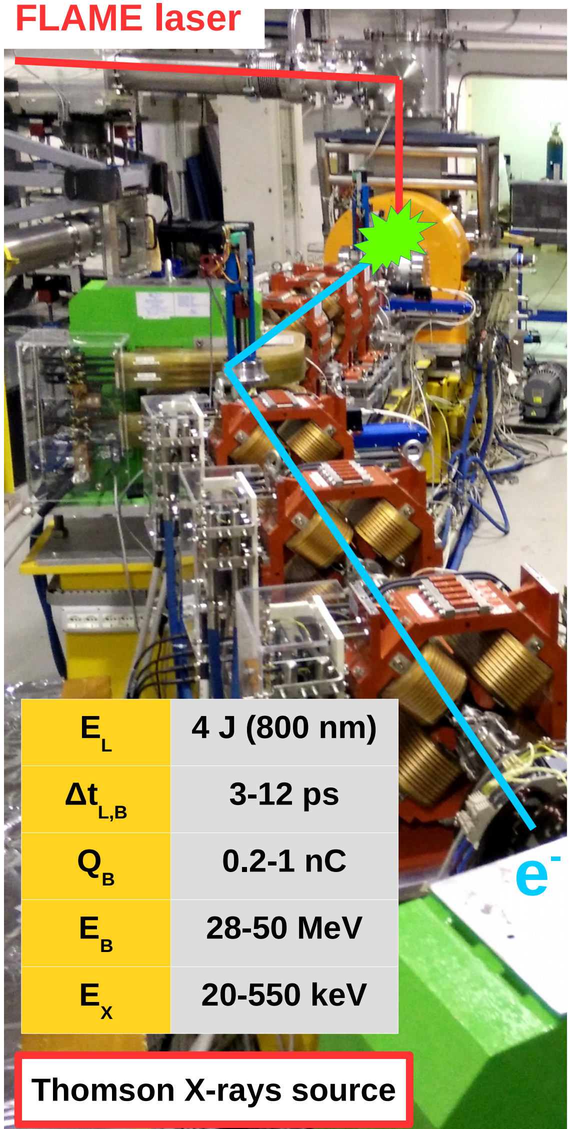
FLAME: a 130 TW Ti:Sa laser



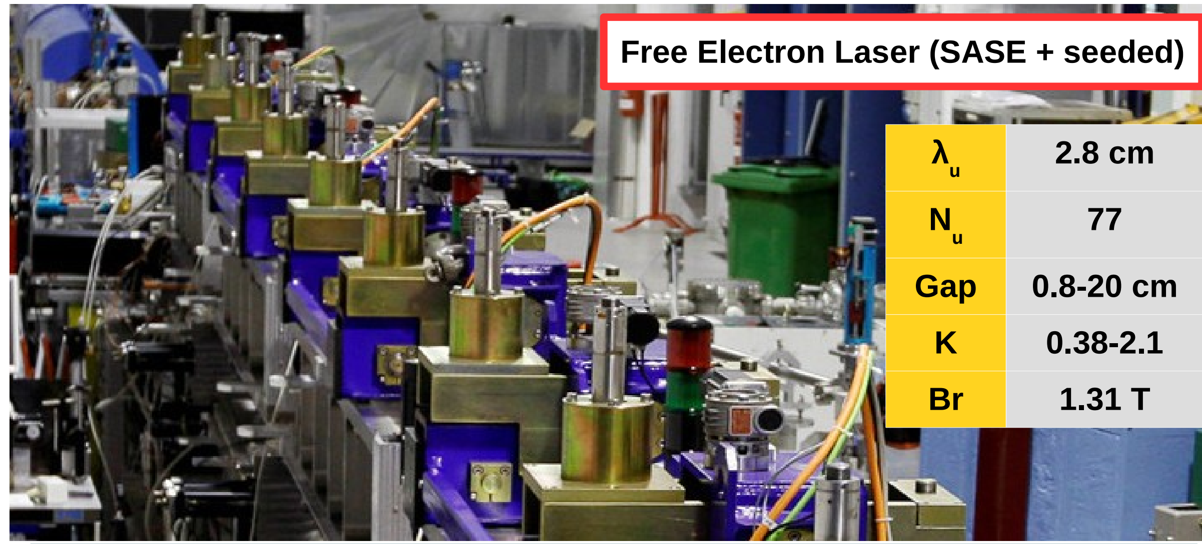
FLAME @ SPARC_LAB
- LWFA (self-injection)
- LWFA (external injection)
- Thomson scattering

Energy	**4 J**
Duration	**30 fs**
Wavelength	**800 nm**
Bandwidth	**60 nm**
Spot @ focus	**10 µm**
Peak Power	**130 TW**
Contrast Ratio	**10^9**

Radiation source activities



E_L	4 J (800 nm)
$\Delta t_{L,B}$	3-12 ps
Q_B	0.2-1 nC
E_B	28-50 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

nature COMMUNICATIONS

ARTICLE

Received 16 Jun 2015 | Accepted 23 Mar 2016 | Published 26 Apr 2016

DOI: 10.1038/ncomms11421 OPEN

Strong nonlinear terahertz response induced by Dirac surface states in Bi_2Se_3 topological insulator

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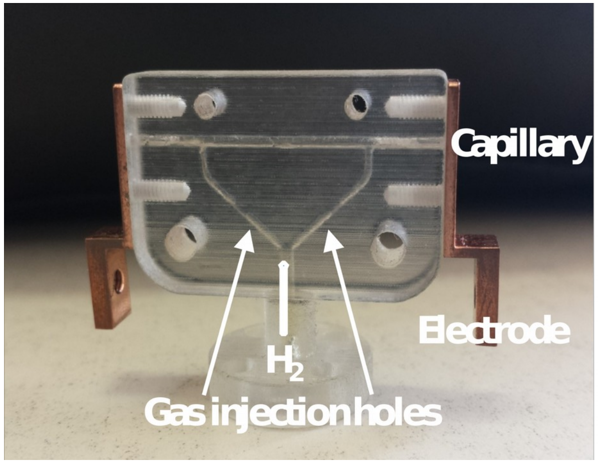
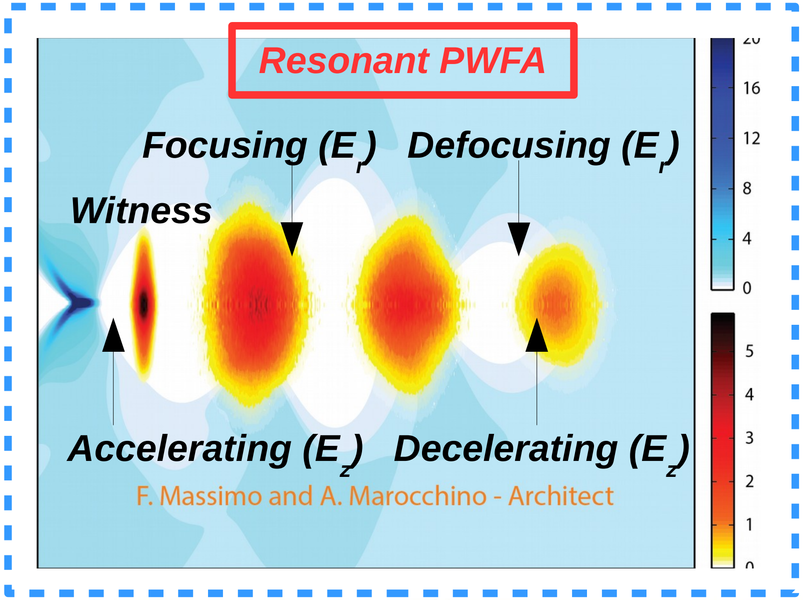
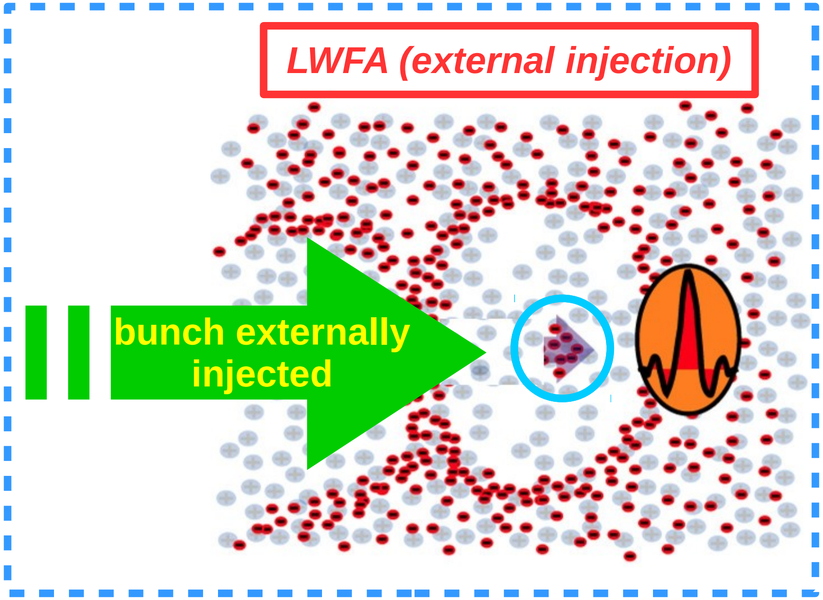
Plasma-based acceleration activities

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

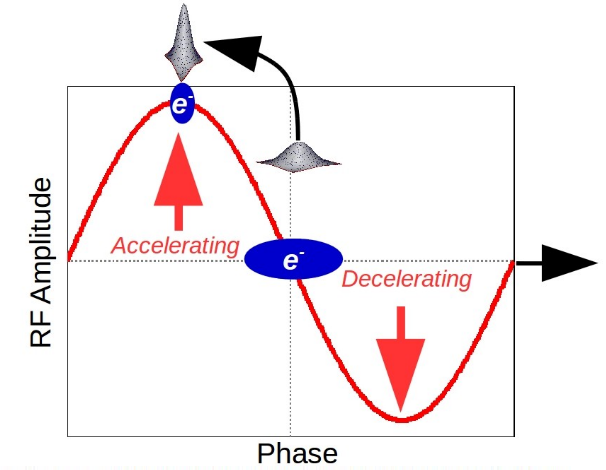


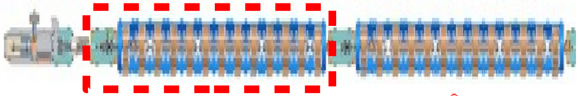


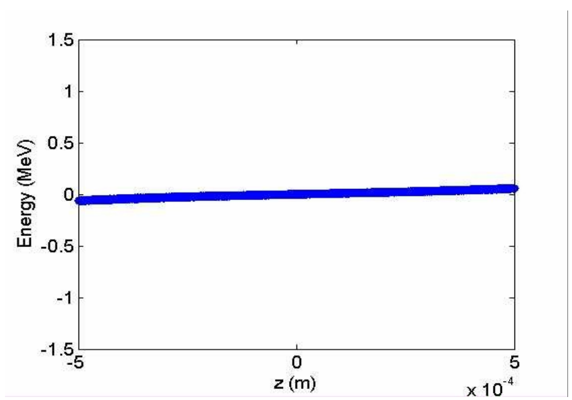


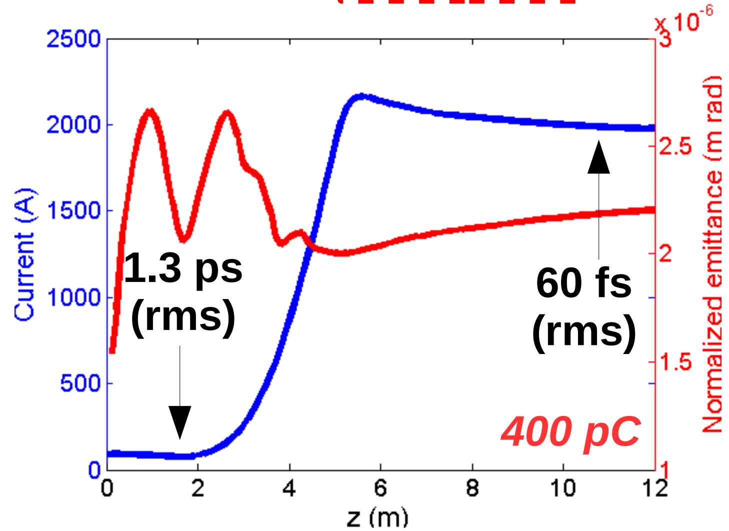
Ultra-short electron beams

- 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***





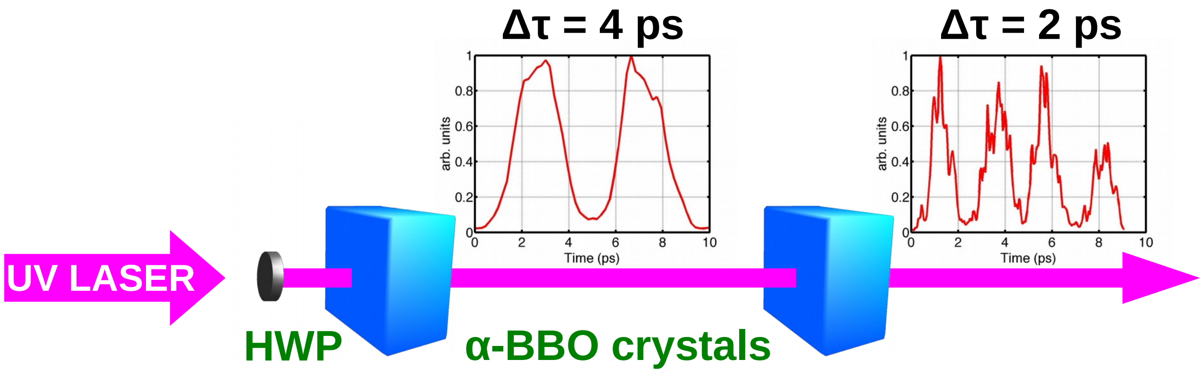




Ferrario, M.et al. "Experimental demonstration of emittance compensation with velocity bunching." PRL 104.5 2010.

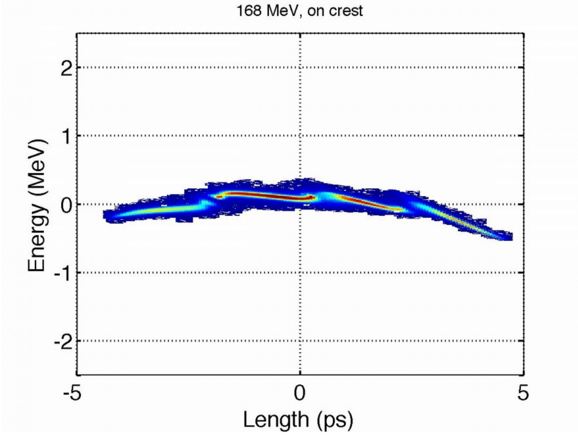
Laser-comb with velocity bunching

- **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…)*



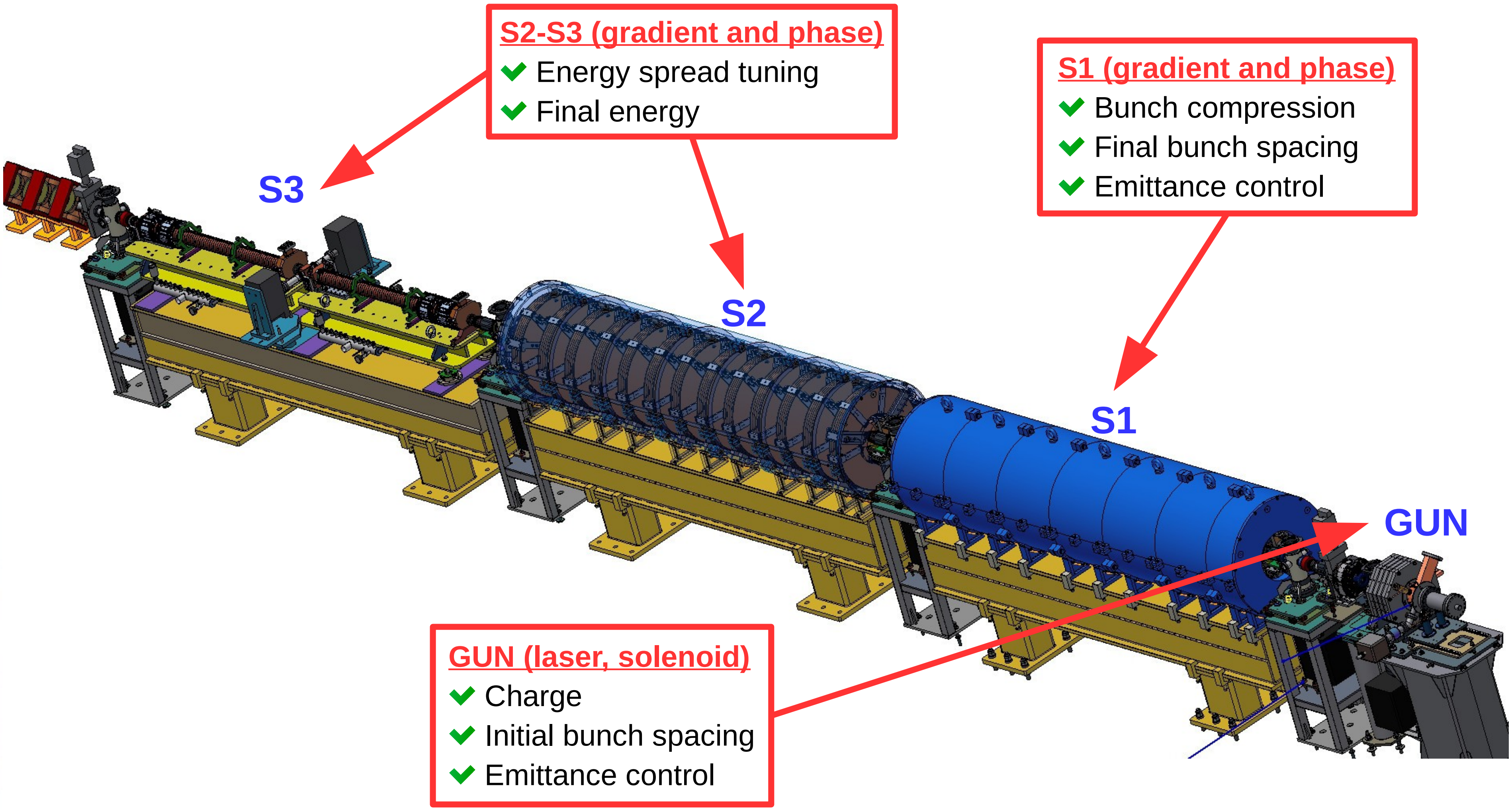
Ferrario, M., et al "Laser comb with velocity bunching: Preliminary results at SPARC." NIM 637.1 2011 S43-S46.

- 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.

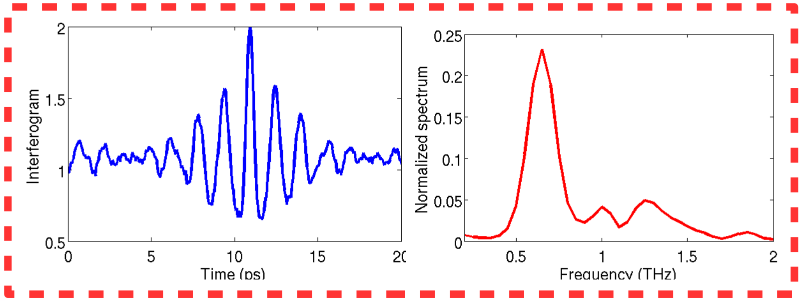
Tuning knobs



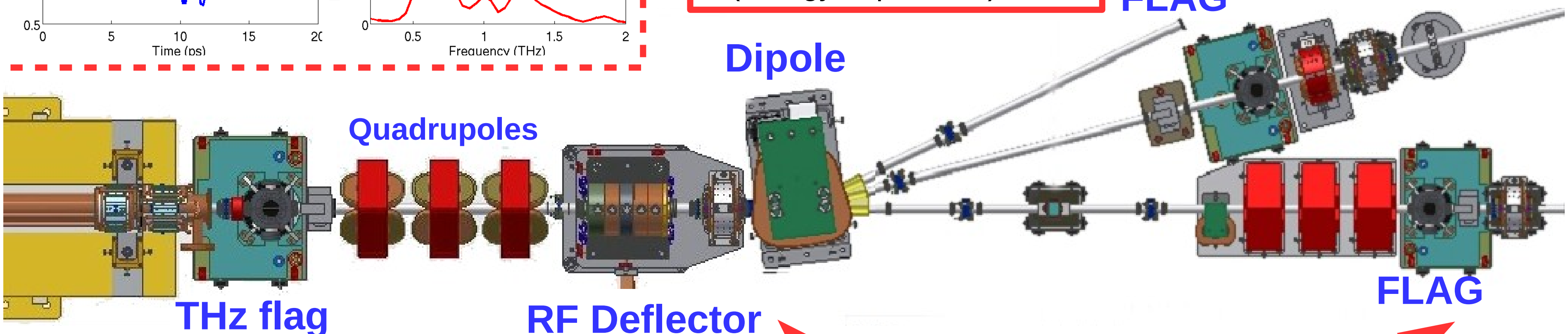
Chiadroni, E., et al. "Characterization of the THz radiation source at the Frascati linear accelerator." RSI 84.2 2013
Mostacci, A., et al. "Advanced beam manipulation techniques at SPARC."Proceedings of IPAC2011

Measurement tools

5 bunches (charge ramp)



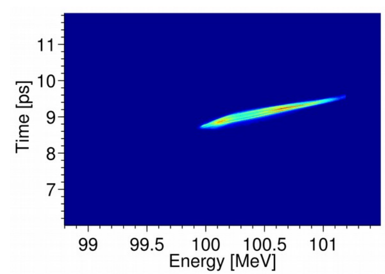
- ✔ Energy measurement
- ✔ Longitudinal Phase-Space
- ✔ Multiple-bunches QSCAN (energy separation)

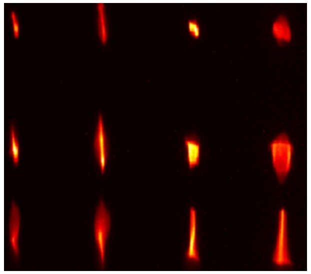


- ✔ CTR/CDR emission in THz range
- ✔ Longitudinal diagnostics

- ✔ 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.

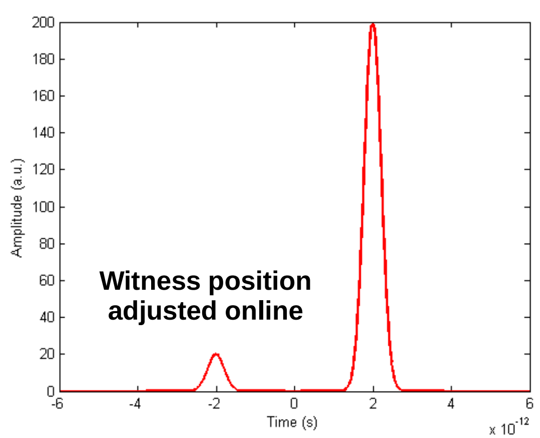
Beam manipulation with velocity bunching

VB dynamics: 1 driver + witness

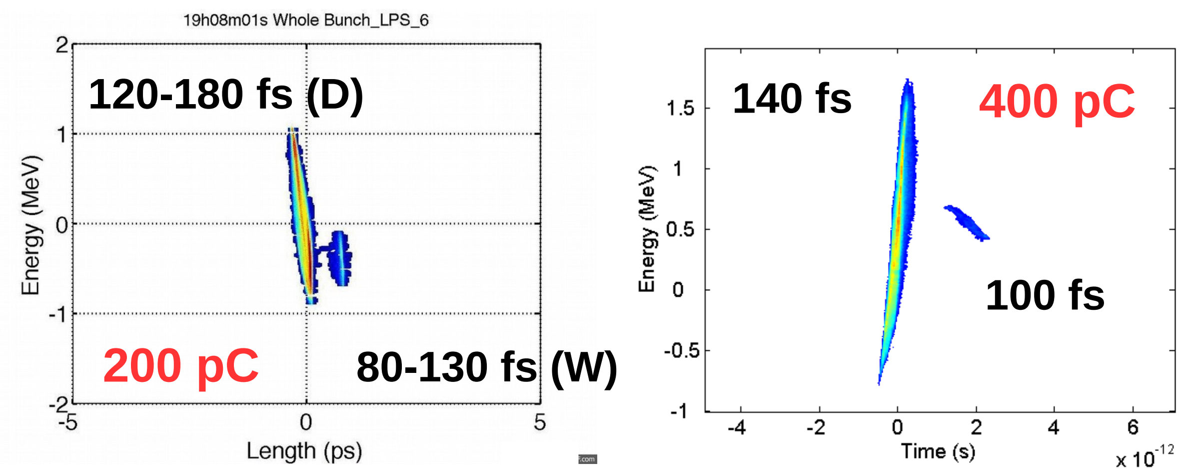
Experimental results!

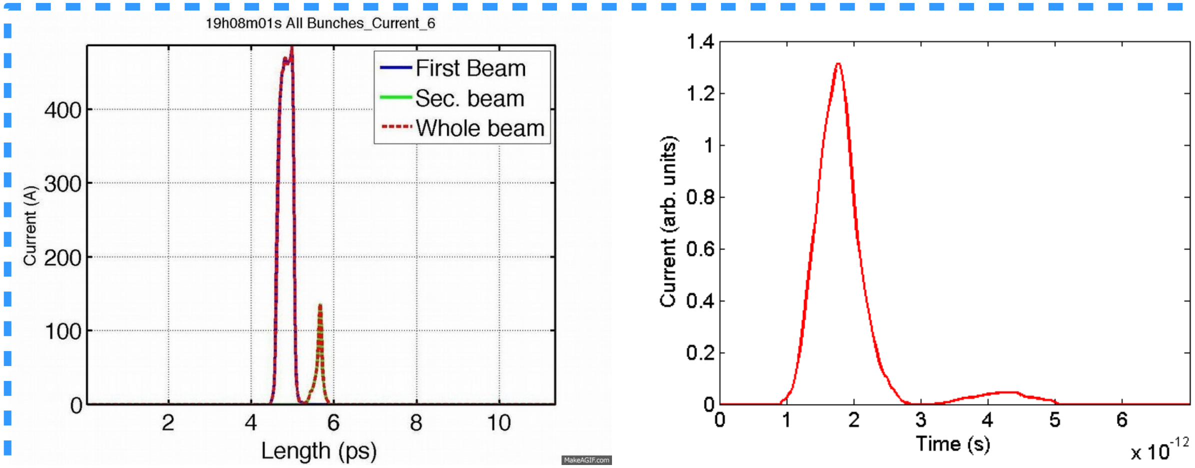
Laser profile on photo-cathode

Driver + witness (20 pC)



LPS at linac exit





Current profile

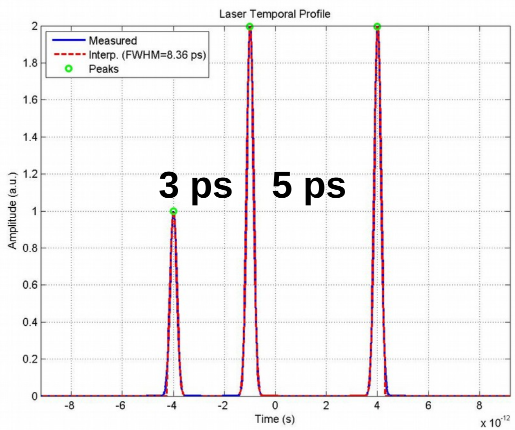
VB dynamics: N driver + witness

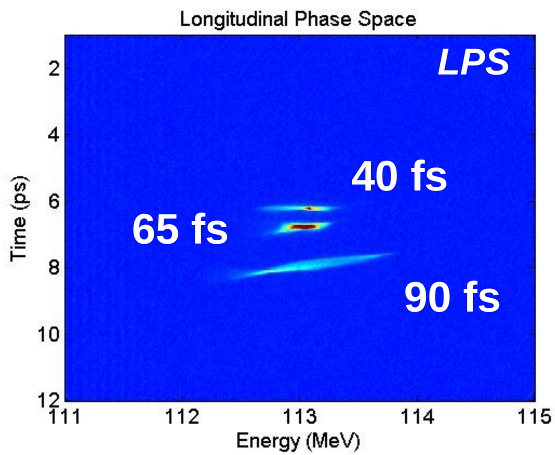
Experimental results!

50 pC drivers + 20 pC witness

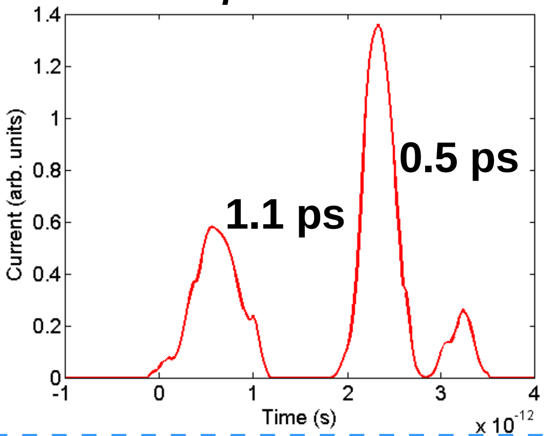
resonant scheme @ $n_p = 10^{16}$ cm^{-3} → bunch distance = λ_p ~ 1.1 ps

Laser profile on photo-cathode

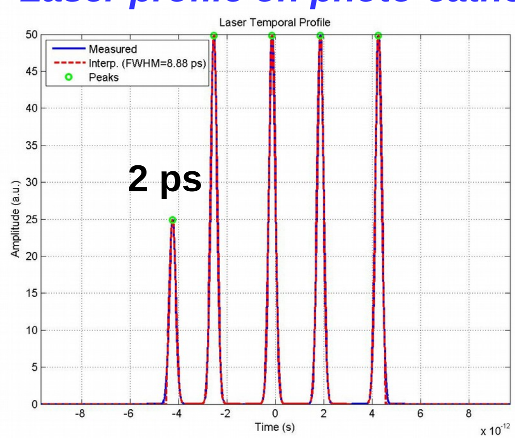


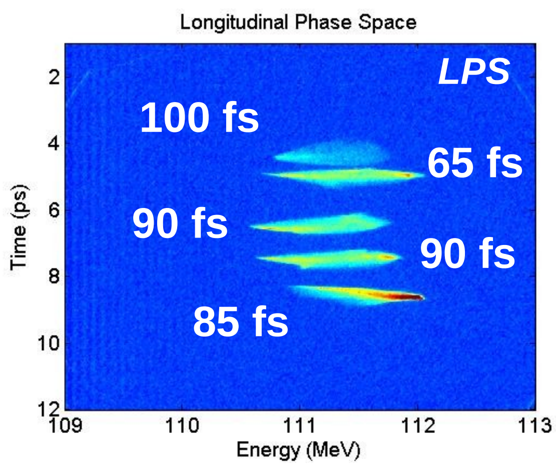


Current profile

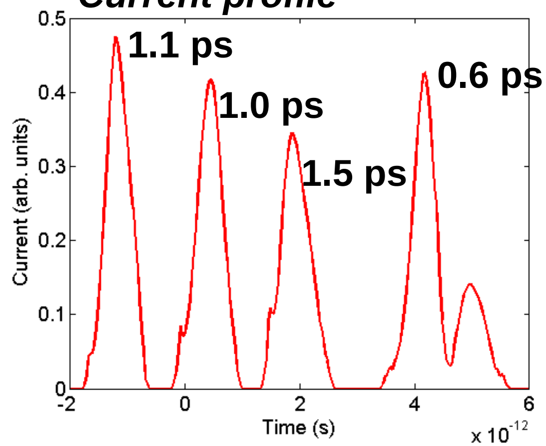


Laser profile on photo-cathode

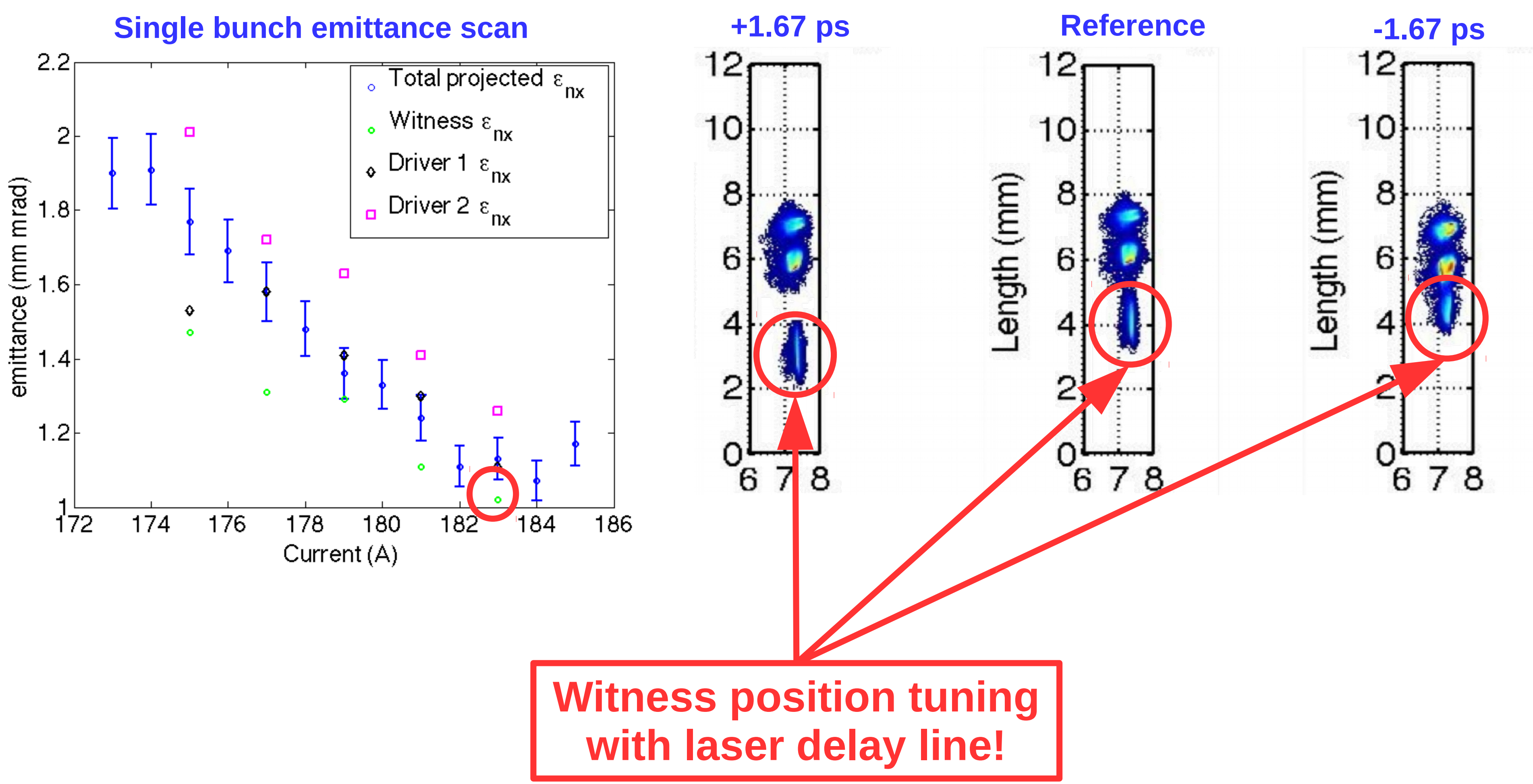




Current profile

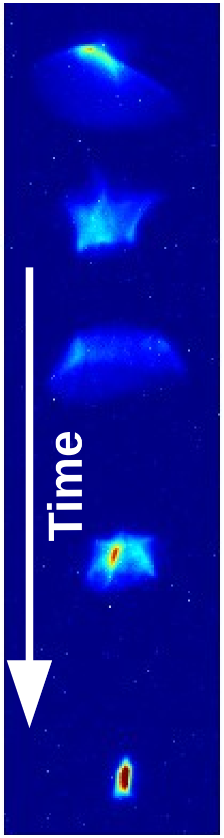


Witness – tuning and characterization

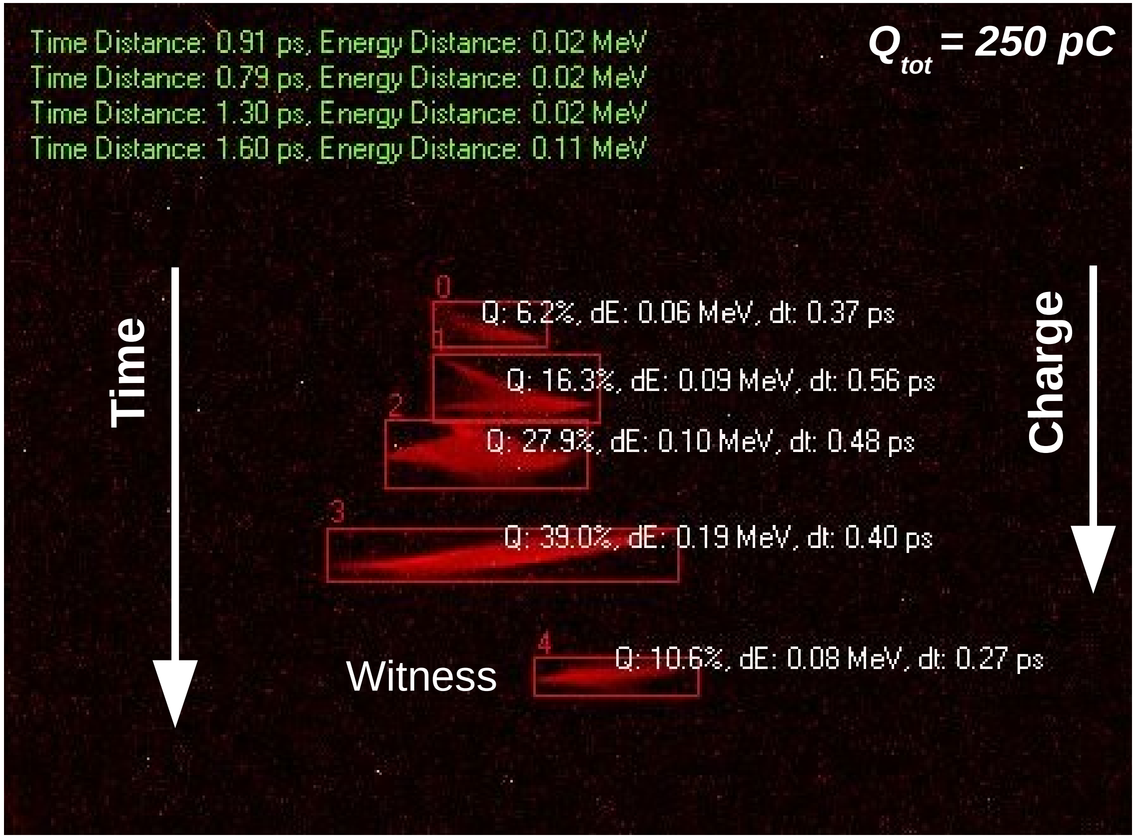


Ramped comb beams

z-x view



Longitudinal Phase Space



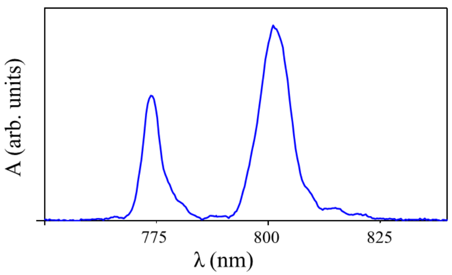
Free Electron Laser exotic schemes

Two colors FEL

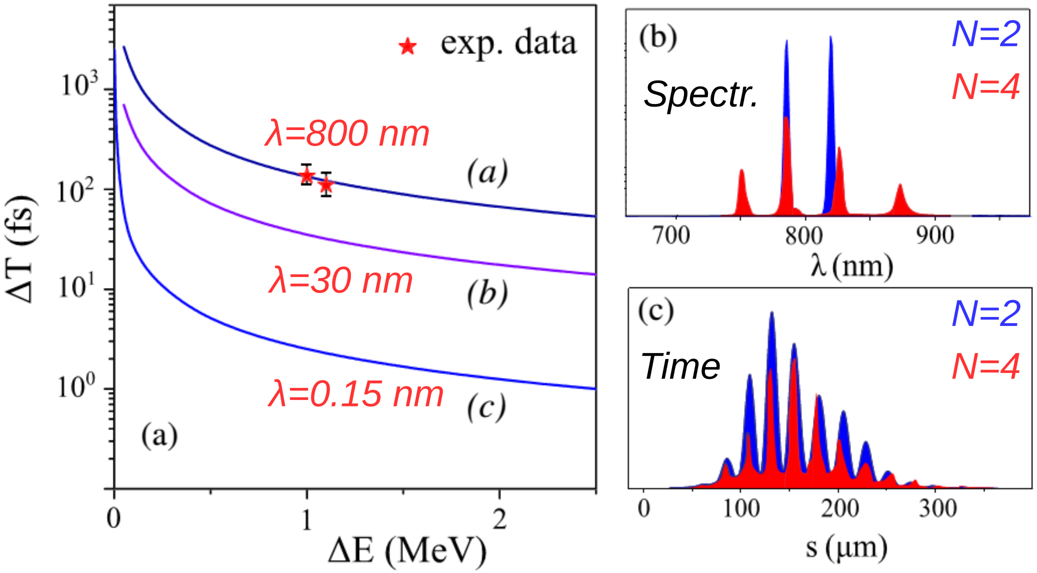
- Novel scheme for the generation of trains of ultra-short radiation pulses
  - ✔ *Based on FEL lasing from a two-level electron energy distribution*
  - ✔ *The FEL amplification process takes place independently if*

energy difference → $$\frac{\Delta\gamma}{\gamma} > 2\rho$$ ← *Pierce parameter*

Measurement

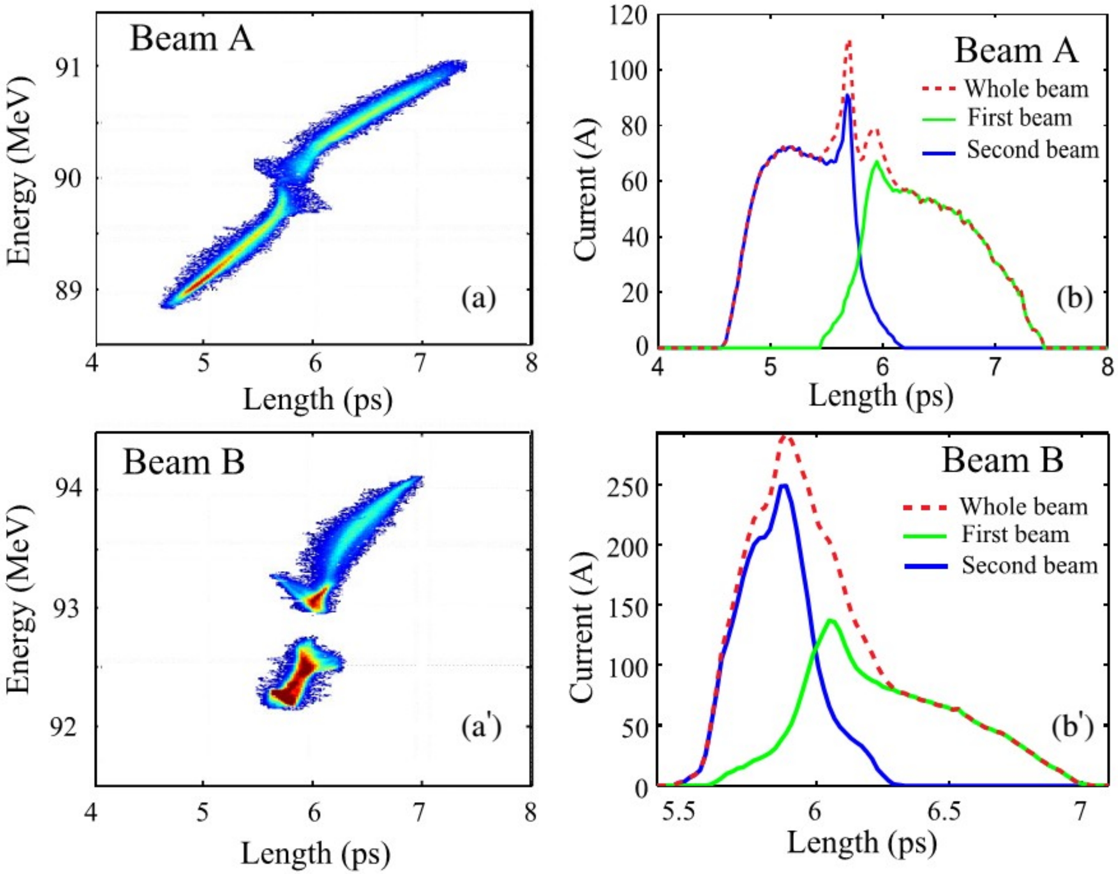


- The total radiation bandwidth is set by the bunch energy separation
  - ✔ *Short time structures (~1/N)*
- Double-peaked spectrum
  - ✔ *Time separation between fringes (**ΔT**) is a function of the energy difference (**ΔE**)*



Petrillo, V., et al. "Observation of time-domain modulation of free-electron-laser pulses by multipeaked electron-energy spectrum." Physical review letters 111.11 (2013): 114802.

Example of bunch train



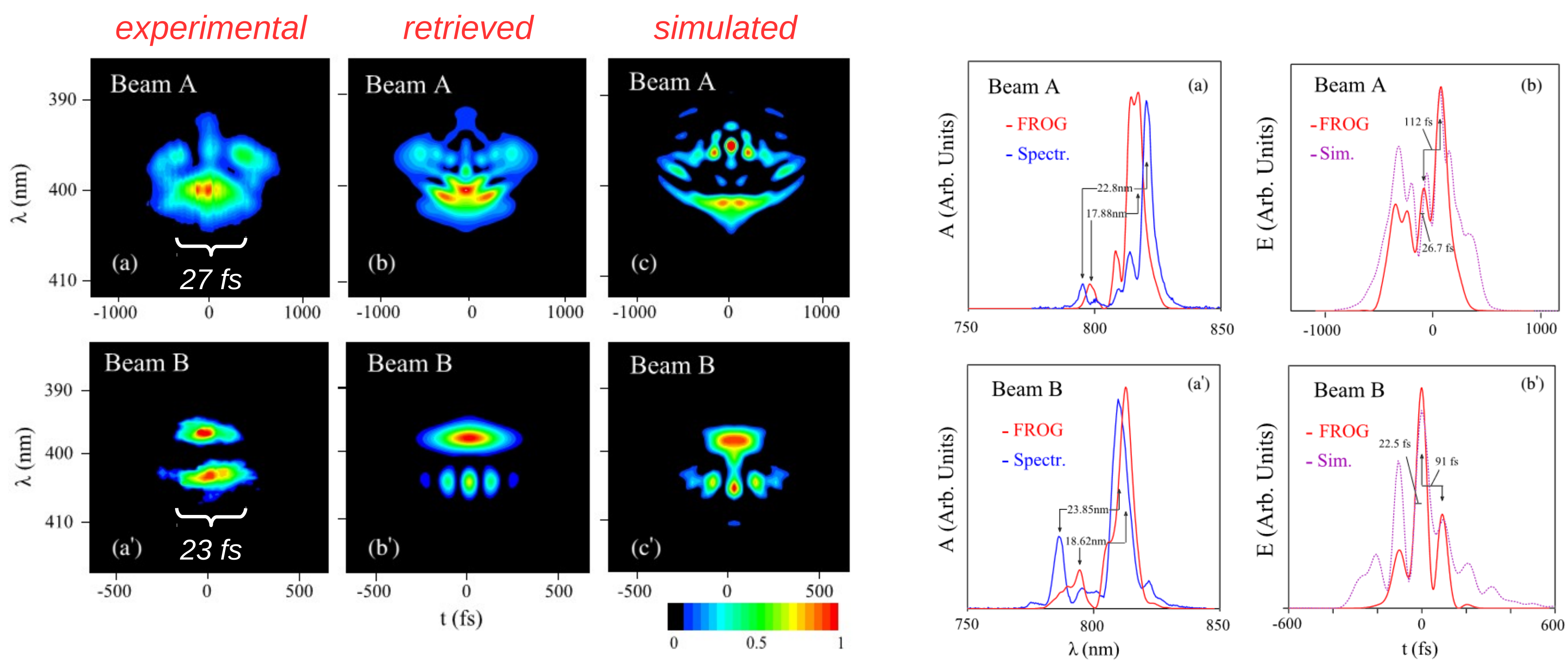
Quantity	Beam A	Beam B
Energy (MeV)	90.11 ± 0.06	93.04 ± 0.10
Total charge (pC)	150 ± 10	165 ± 10
Emittance x (mm mrad)	1.56 ± 0.10	1.68 ± 0.18
Emittance y (mm mrad)	1.70 ± 0.12	1.81 ± 0.15
Energy spread (MeV)	0.62 ± 0.01	0.59 ± 0.01
Energy spread single beamlet (MeV)	0.30 ± 0.01	0.27 ± 0.01
Energy separation (MeV)	1.01 ± 0.11	1.07 ± 0.14
Time duration (ps)	0.63 ± 0.03	0.30 ± 0.01
Corrected FEL parameter single beamlet	5×10^{-4}	1.5×10^{-3}
3D cooperation length single beamlet (μm)	36	12.5

$$L_b \leq 2\pi L_c$$

Single-spike condition is satisfied

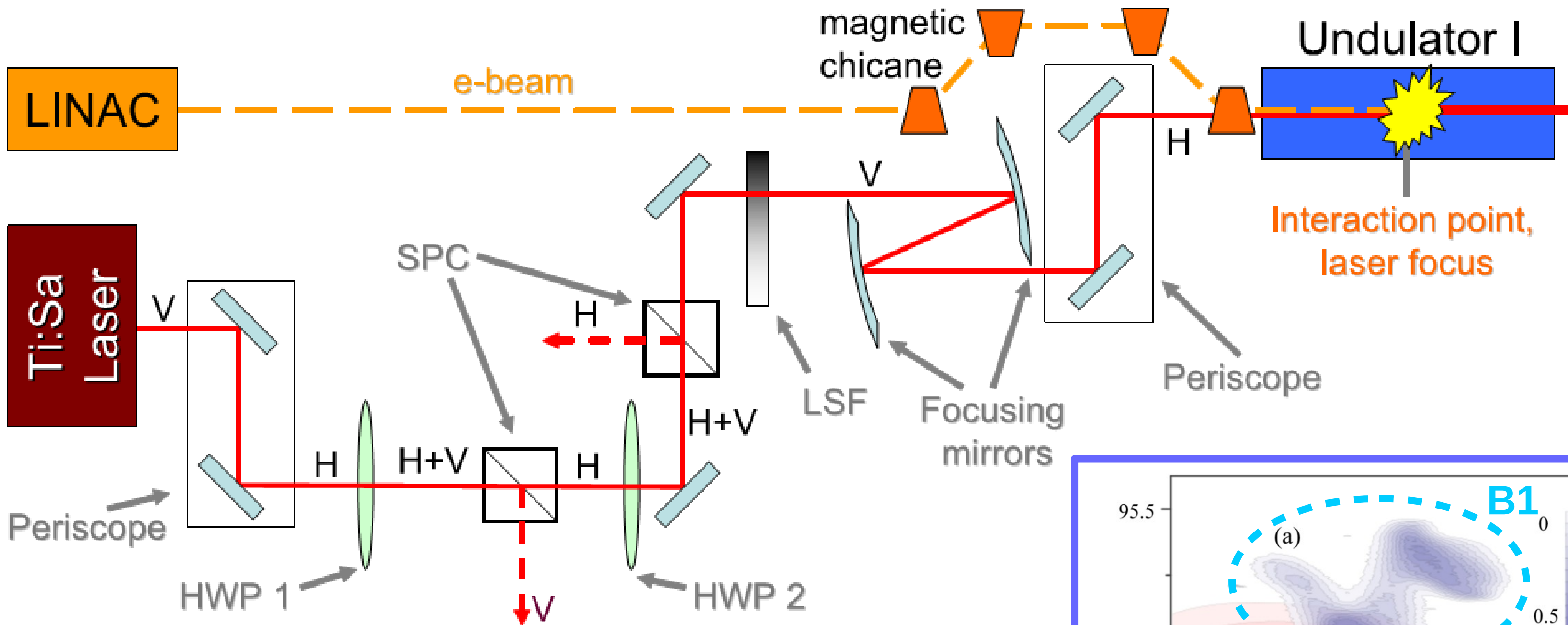
Petrillo, V., et al. "Observation of time-domain modulation of free-electron-laser pulses by multipeaked electron-energy spectrum." Physical review letters 111.11 (2013): 114802.

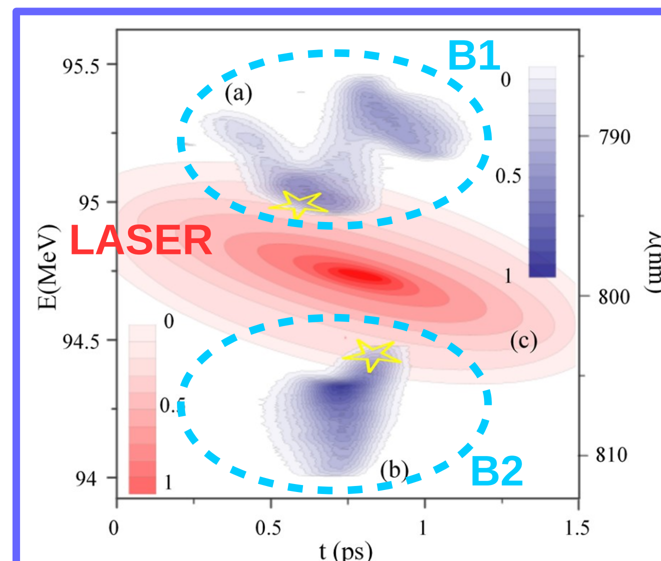
Resulting SASE FEL radiation



- FROG device used for single-shot measurements
  - *Each snapshot contains both the spectral and temporal information*
- FEL radiation phase-space “mimics” the bunch longitudinal phase-space
  - ***Beam A*** *Δλ = 17.88 nm, ΔT = 112 fs* → ***In agreement with ΔE = 1.03 MeV***
  - ***Beam B*** *Δλ = 18.62 nm, ΔT = 91 fs* → ***In agreement with ΔE = 1.1 MeV***

Seeded scheme

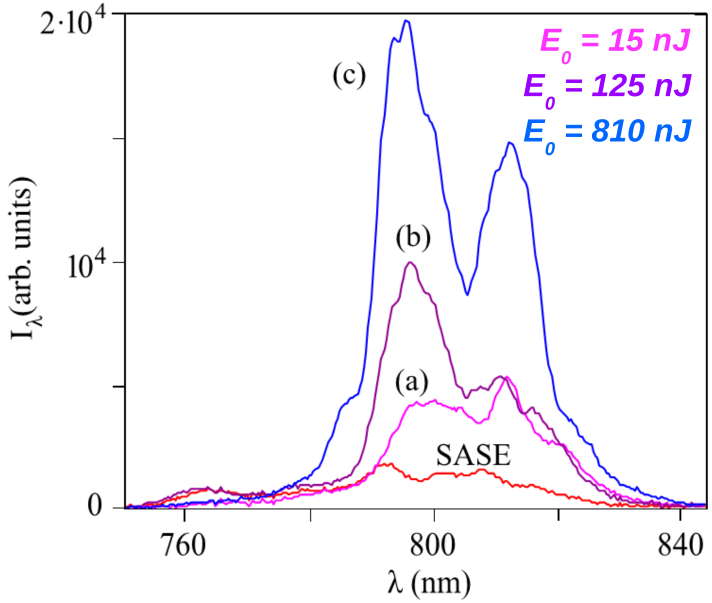




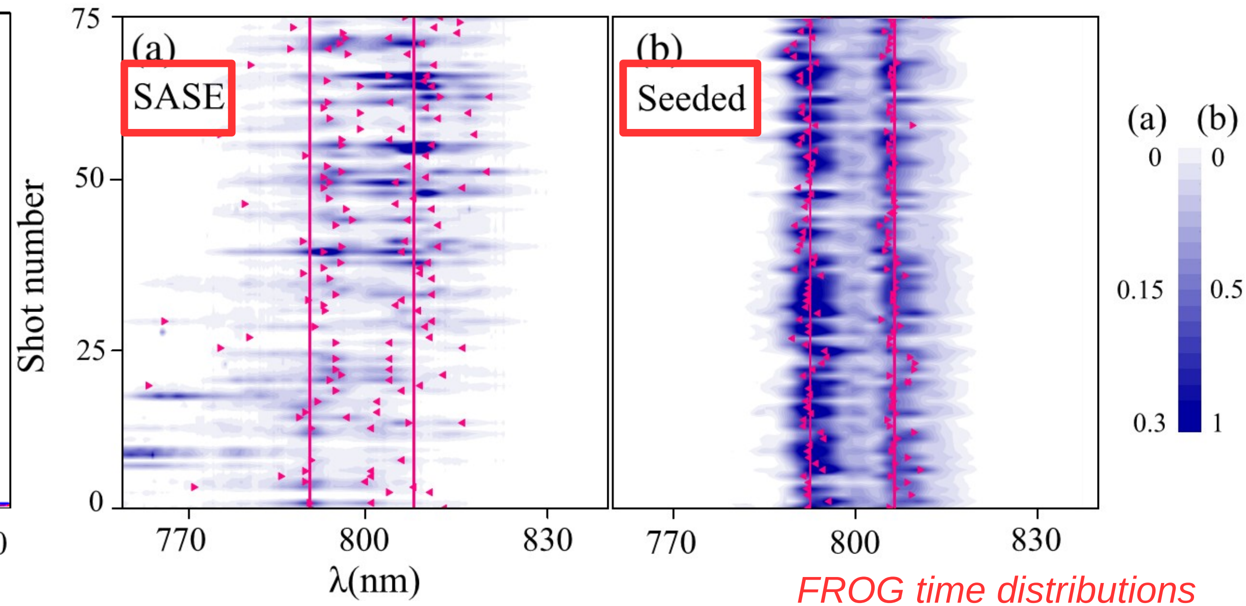
- Single laser pulse (linearly chirped) used to seed simultaneously both bunches
  - *The wings of the laser spectrum actually act as seed*
  - *The (small) linear chirp ensures temporal overlap*
- Two colors enhancement with respect to SASE

Petralia, A., et al. "Two-color radiation generated in a seeded free-electron laser with two electron beams." PRL 115.1 (2015): 014801

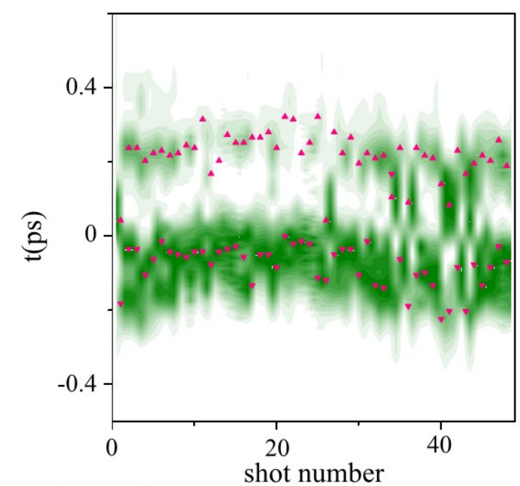
Resulting seeded FEL radiation



Increasing of spectral stability



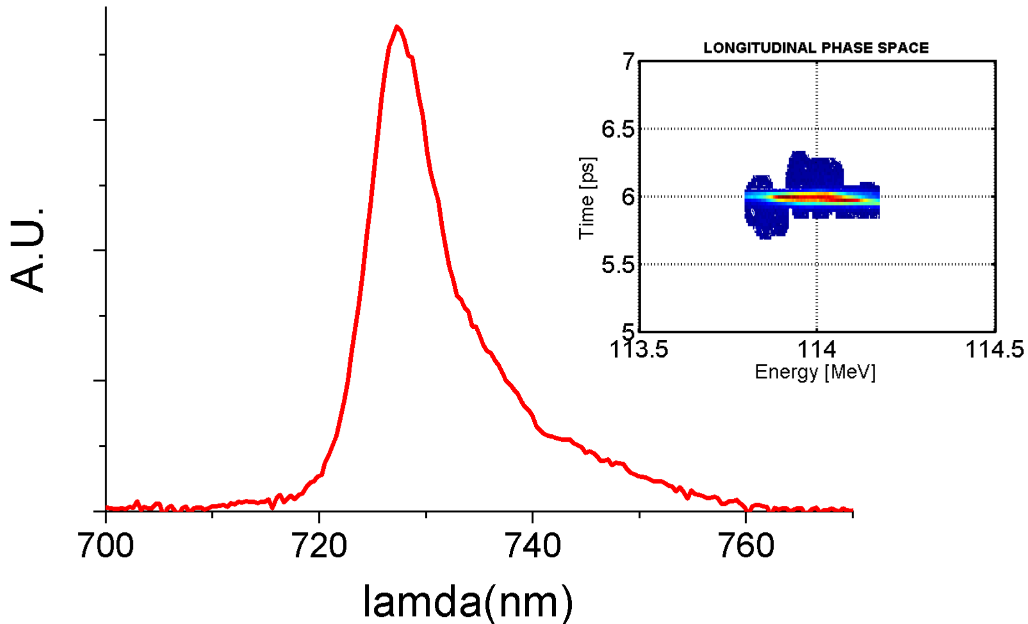
FROG time distributions

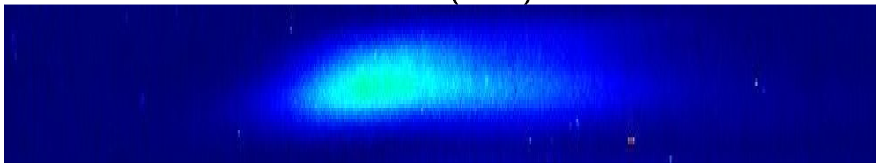


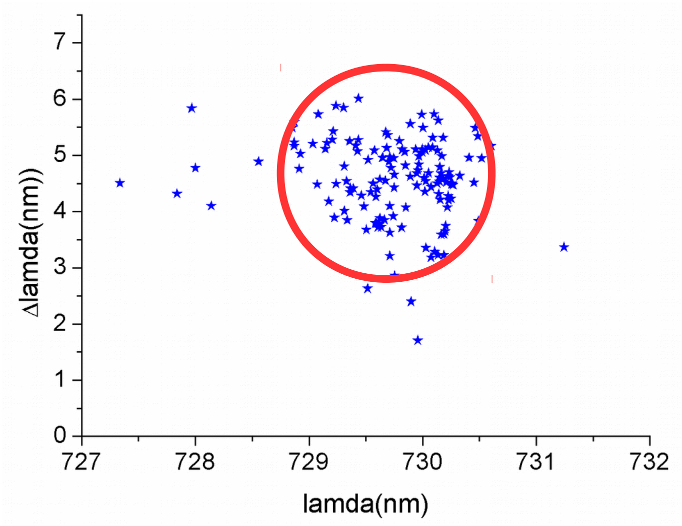
- Two colors stability increased with seed laser
  - ***SASE:*** ***66% (others with single-spike structure)***
  - ***SEEDED:*** ***99%***
- Bandwidth
  - ***SASE (SEEDED) 1st spike:*** ***7.2 (3.1) nm***
  - ***SASE (SEEDED) 2nd spike:*** ***7.9 (2.7) nm***

High quality ultra-short beams with VB

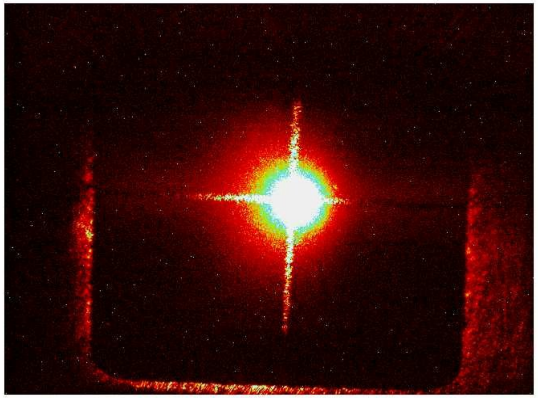
Single-spike FEL means high quality ultra-short beam!







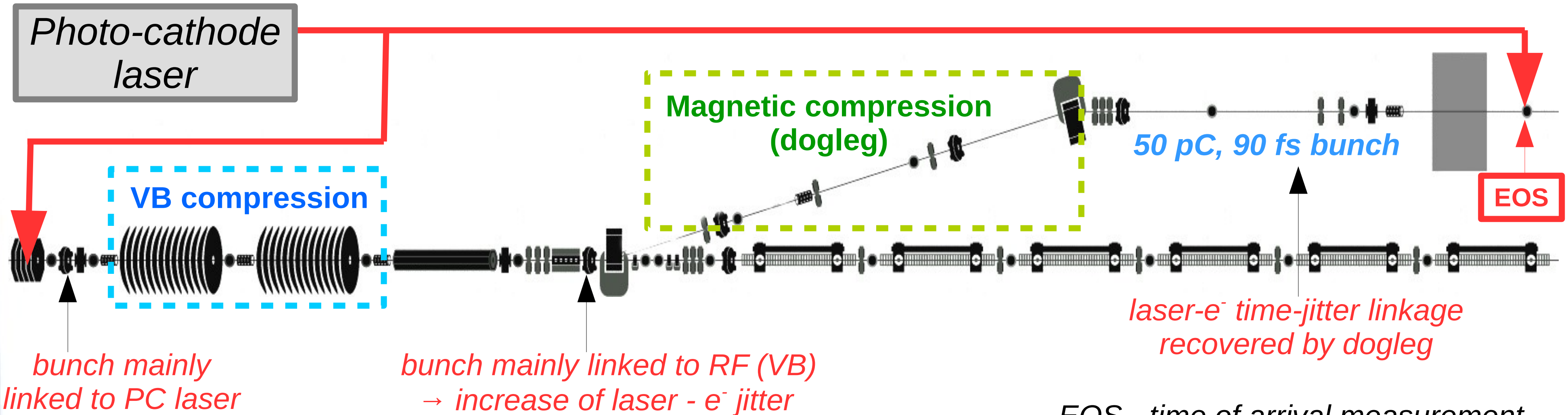
Collected FEL light, 100 fs (rms), 40 μJ



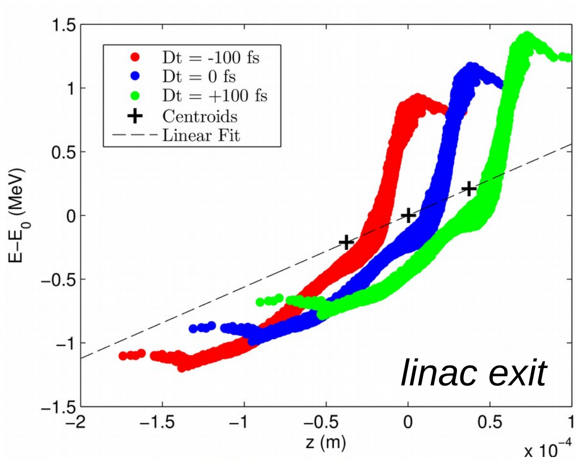
Bunch parameters

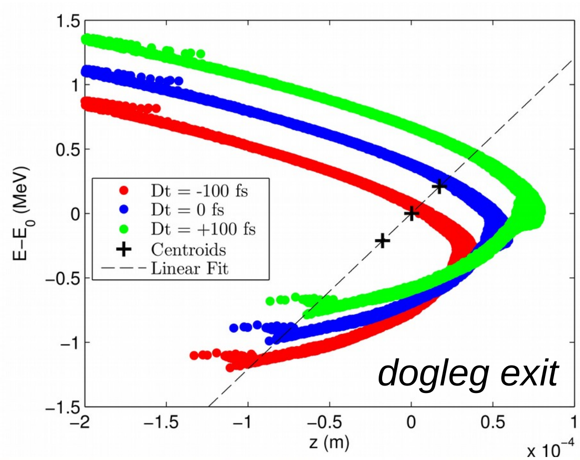
Charge (pC)	Energy (MeV)	Energy Spread (%)	Duration (fs)	Emittance (μm)	Peak current (A)
20	114	0.1	26	1.2	400

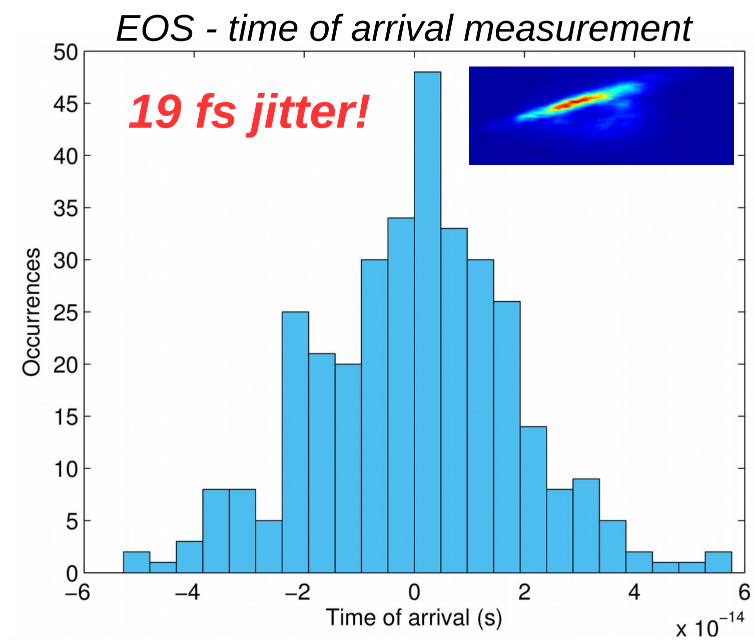
Laser vs e⁻ beam time-jitter reduction



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







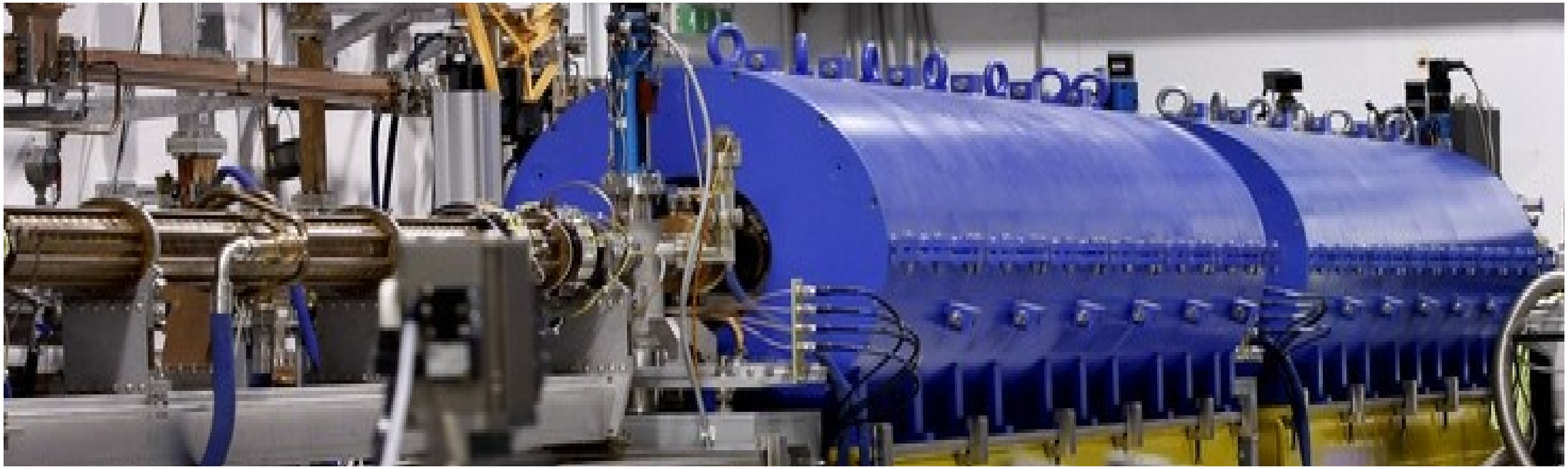
Conclusions

- Advanced electron beam configurations have been produced and tested at the SPARC_LAB test-facility

- Low emittance and ultra-short beams consisting in multiple bunches for
  - *Plasma Wakefield Acceleration (PWFA)*
  - *Advanced radiation source*

- Several results obtained for Free Electron Laser applications by employing exotic electron beams
  - *Two colors FEL, both in SASE and seeded schemes*
  - *Complete characterization of FEL radiation (temporal + spectral)*

Acknowledgments



- *M.P. Anania, M. Bellaveglia, A. Biagioni, F. Bisesto, M. Castellano, E. Chiadroni, D. Di Giovenale, M. Ferrario, G. Di Pirro, S. Romeo, J. Scifo, V. Shpakov, F. Villa (INFN, Frascati)*
- *A. Cianchi (Tor Vergata University of Rome)*
- *F. Filippi, F. Giorgianni, A. Marocchino (Sapienza University of Rome)*
- *F. Ciocci, A. Petralia (ENEA, Frascati)*
- *V. Petrillo, A.R. Rossi (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!

Plasma Wakefield Acceleration

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*

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

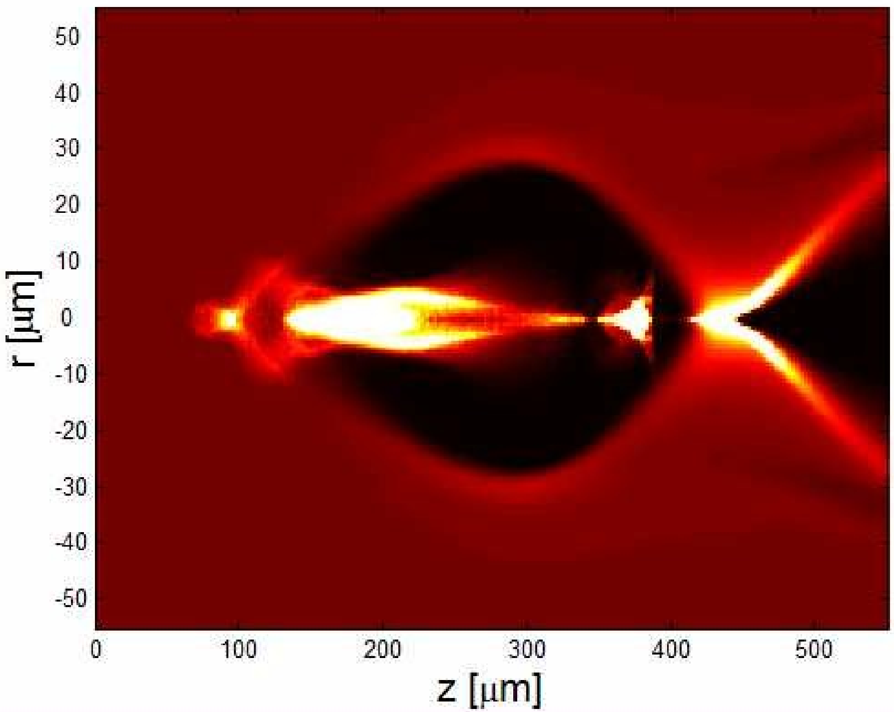
- Using low emittance, high brightness beams we have

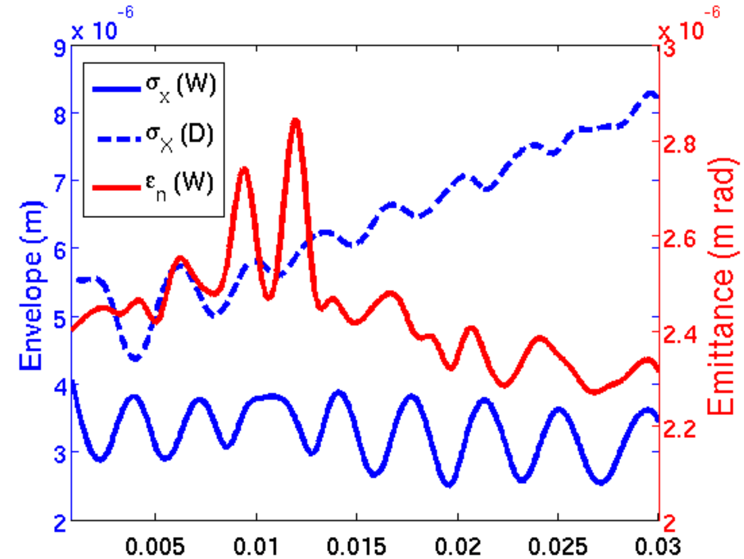
$$\tilde{Q} < 1 \qquad \frac{n_b}{n_p} > 1$$

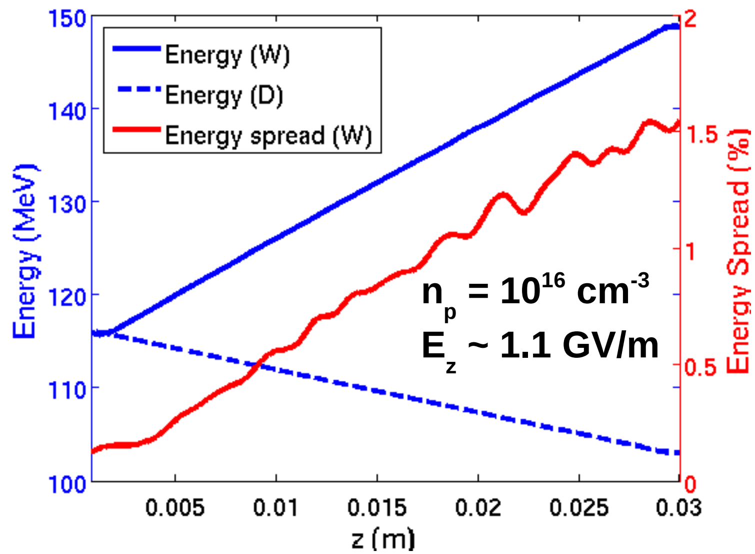
- These conditions define the quasi-nonlinear (QNL) regime
  - ***n_p = 10^{16} cm^{-3}, Q_D = 200 pC, σ_t=180 fs, σ_x=5.5 um → n_b~5n_p*** *and* $\tilde{Q} = N_b k_p^3 / n_p \approx 0.8$

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

Acceleration in plasma





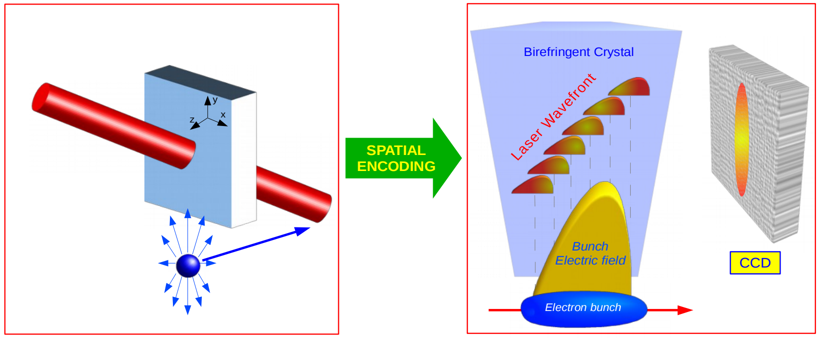


- *Hybrid kinetic-fluid simulation by* ***Architect***
  - ***PIC*** *(bunch),* ***fluid*** *(plasma), 3-5 hours for 3 cm*
  - *Cross-checked with full PIC codes (ALaDyn)*

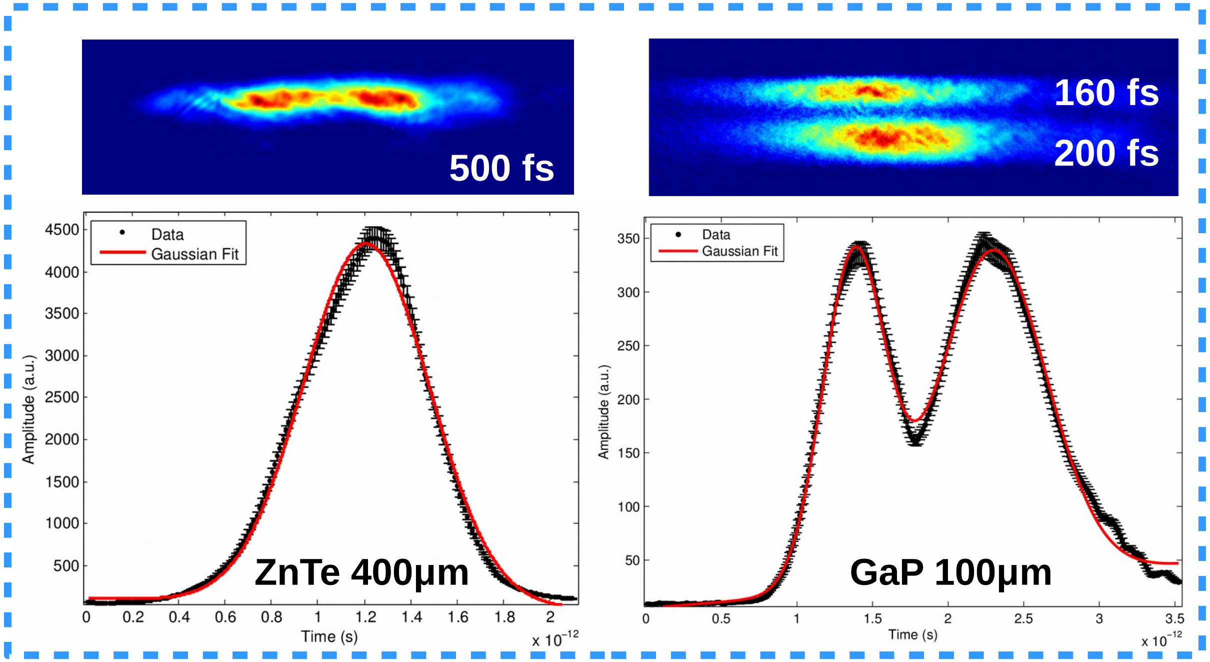
	Q (pC)	σt (fs)	σx (μm)	E (MeV)	ε (μm)
Driver	200	180	5.5	116	4.5
Witness	20	35	3	116	2.4

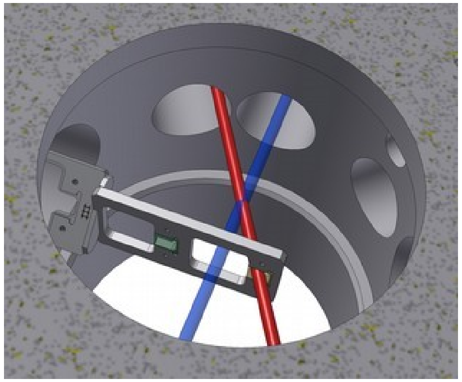
Single-shot and non-destructive tool

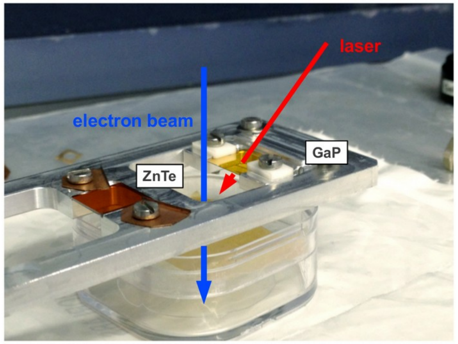
- Multi-bunches trains have been measured with Electro-Optical Sampling
  - ✔ *Single-shot, non-intercepting*
  - ✔ *80 fs (rms) temporal resulution*
- Goal: monitor beam injection in plasma



Spatial decoding

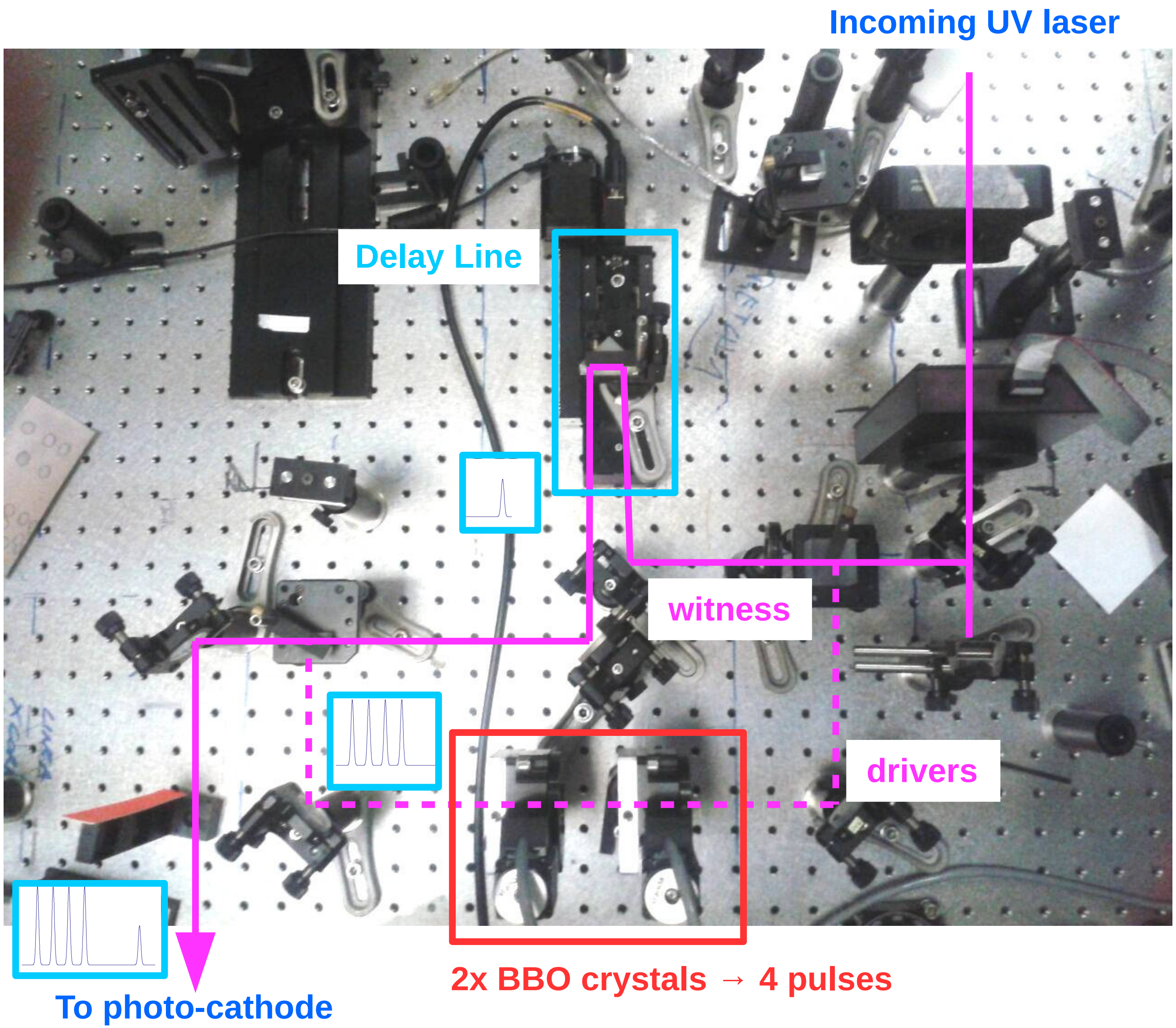






R. Pompili, et al., NIM A: Accelerators. 740, 216 (2014).

Laser comb - optical setup



Courtesy F. Villa

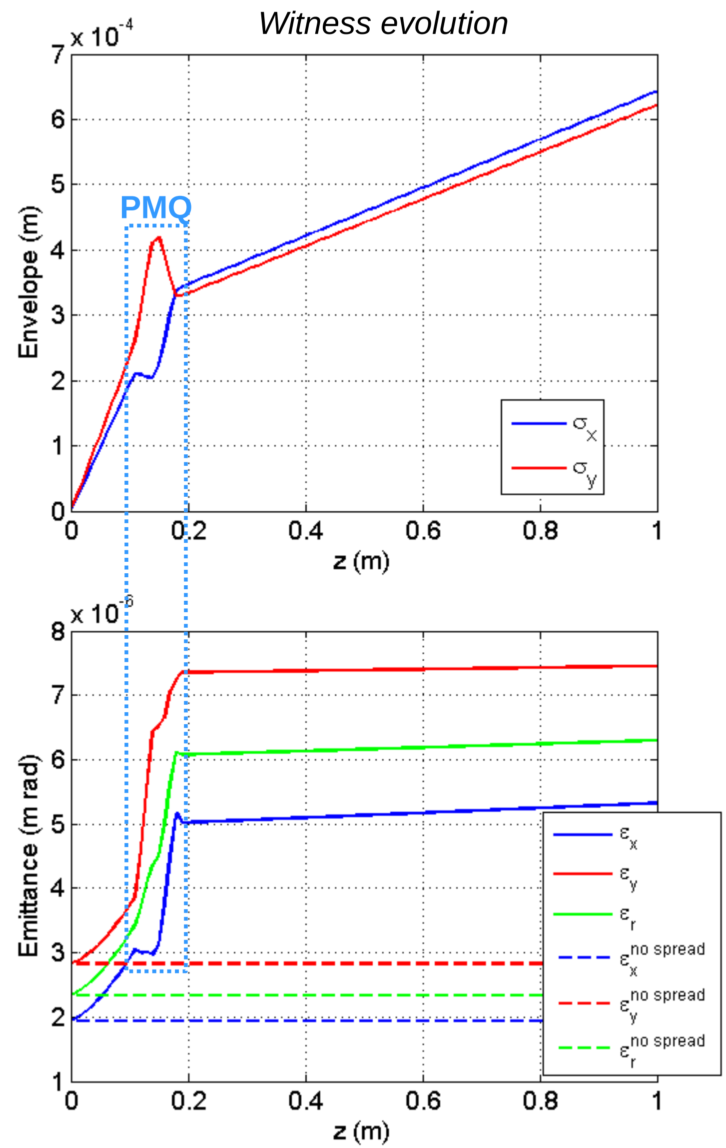
Witness beam extraction

- A second PMQ triplet is needed to catch the witness at plasma exit
  - *First PMQ is 11 cm downstream the capillary*
  - *Large emittance growth in the drift due to the high beam divergence:*

$$\epsilon_n^2 = \langle \beta \gamma \rangle^2 \left(s^2 \sigma_E^2 \sigma_{x'}^4 + \epsilon_g^2 \right)$$

Leading term

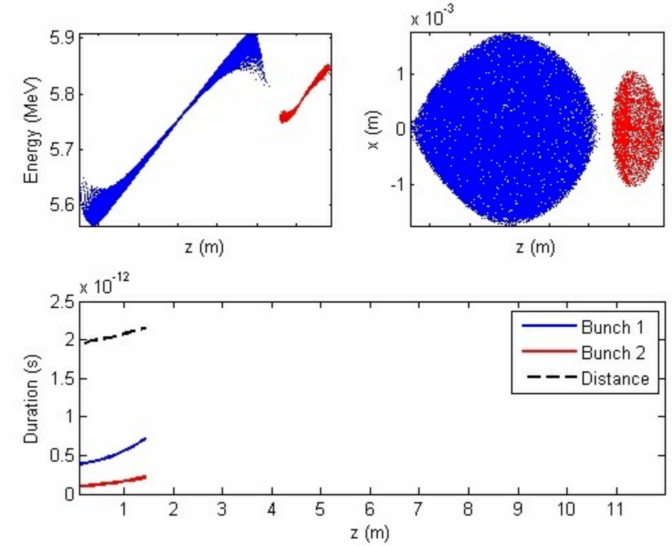
- Tapering A.R. Rossi
  - ...



Migliorati, M., et al. "Intrinsic normalized emittance growth in laser-driven electron accelerators." PRSTAB 16.1 (2013): 011302.

Beam matching

- First attempt to accelerate a witness bunch
  - *Laser duration (rms) at cathode: 150 fs*
  - *Laser pulse distance at cathode: 2.4 ps*
  - *Driver-Witness distance at linac exit: 550 fs*



	Charge (pC)	Energy (MeV)	Duration (fs)	Transverse spot (μm)	Emittance (μm)
Driver	200	107.6	180	5.5	4.5
Witness	20	107.4	35	3	2.4

- Matching the beam injection in plasma
  - *Driver duration: $k_p \sigma_z \sim \lambda_p/4$*
  - *Plasma oscillation requires a Twiss*

$$\beta_{eq} = \sqrt{\gamma / 2\pi r_e n_0}$$

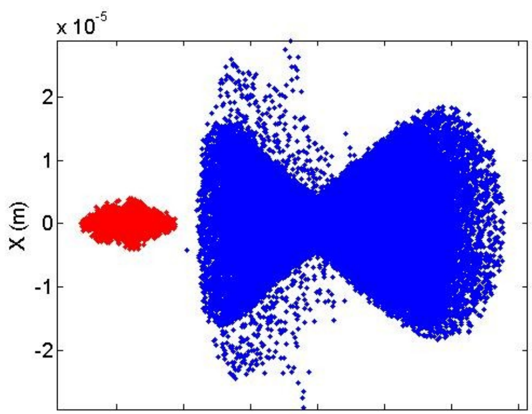
  - *Witness envelope oscillation*

$$\ddot{\sigma}_x + \frac{\dot{\gamma}}{\gamma}\dot{\sigma}_x + \frac{k_p^2}{3\gamma}\sigma_x = \frac{\epsilon_n^2}{\gamma^2 \sigma_x^3} + \frac{k_{sc}}{\gamma^3 \sigma_x}$$

Ion focusing *Space-charge term*

@ $n_0 \sim 10^{16}$ cm^{-3}
- ✔ **β_{eq} = 1.1 mm (D,W)**
- ✔ **σ_x = 2.5 μm (W)**

$$\rightarrow \sigma_x = \sqrt[4]{\frac{3}{\gamma}}\sqrt{\frac{\epsilon_n}{k_p}}$$



Beam @ plasma input

Beam-driven Plasma Wakefield Acceleration

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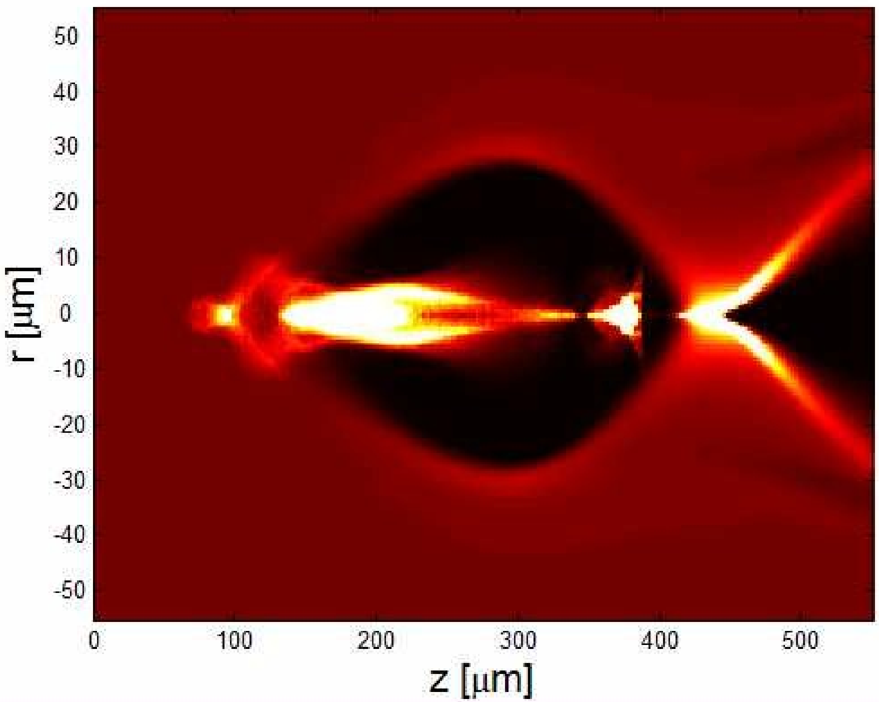
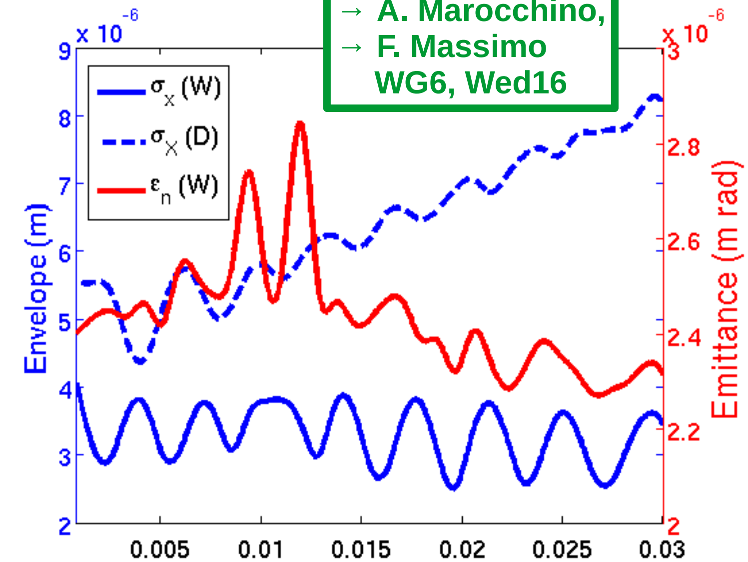
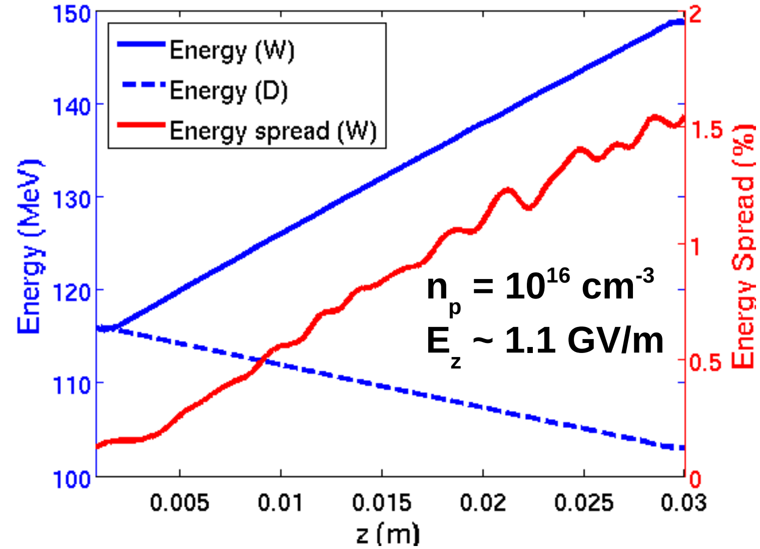


→ A. Marocchino,
→ F. Massimo
WG6, Wed16





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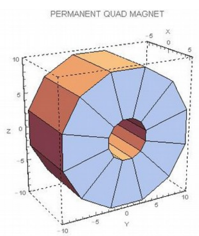
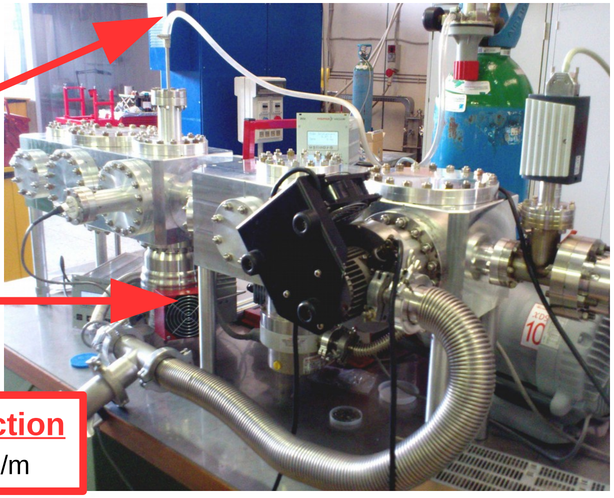
Beam-driven PWFA at SPARC_LAB



Beam injection
- ✔ Longitudinal diagnostics (EOS)
- ✔ Transverse diagnostics (Ce:YAG screen)
- ✔ PMQ (NdFeB, B_r>1.3 T) → 520 T/m

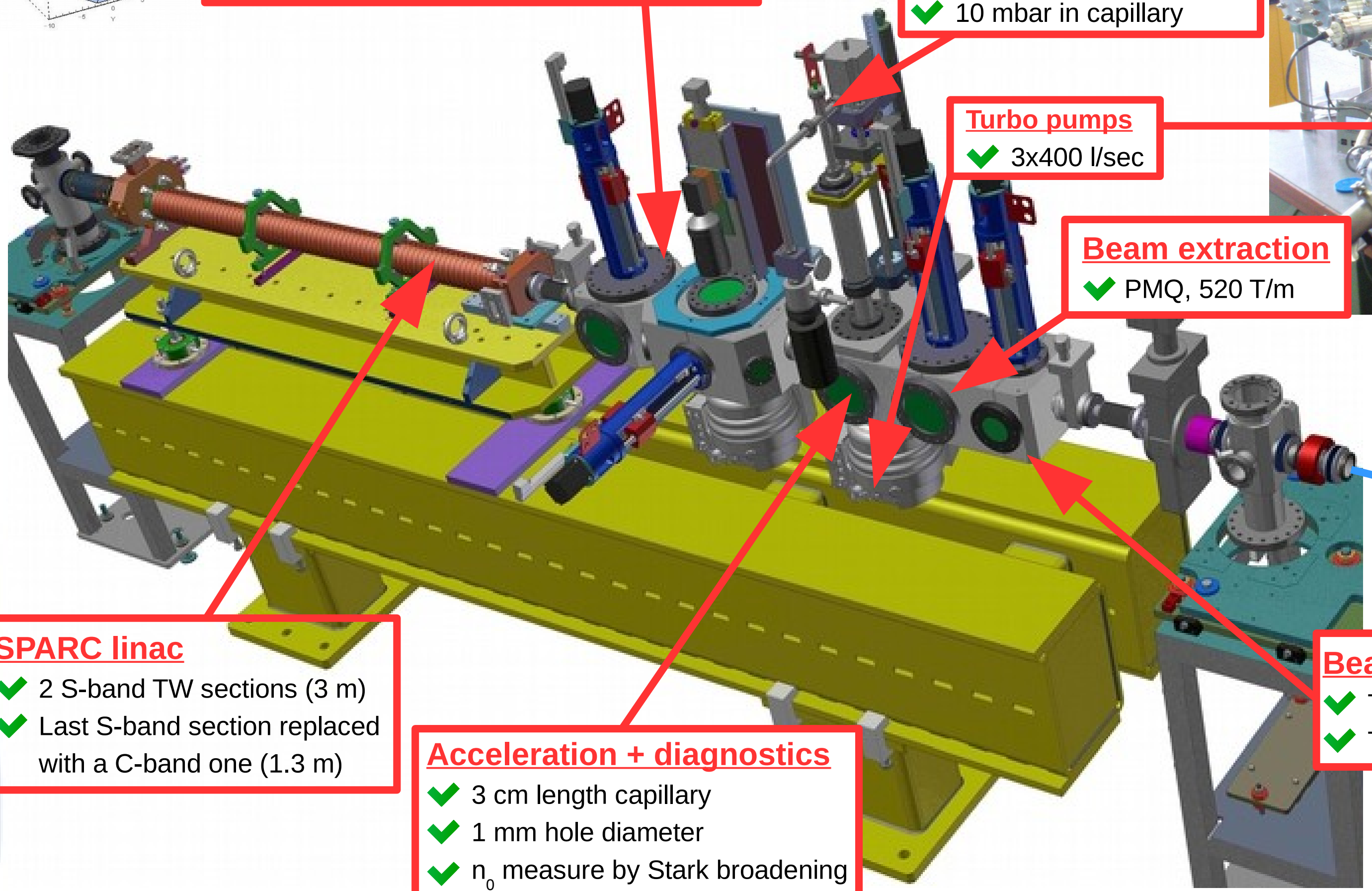
Vacuum tests on the experimental chamber



Hydrogen inlet
- ✔ 50-100 mbar from source
- ✔ 10 mbar in capillary

Turbo pumps
- ✔ 3x400 l/sec

Beam extraction
- ✔ PMQ, 520 T/m



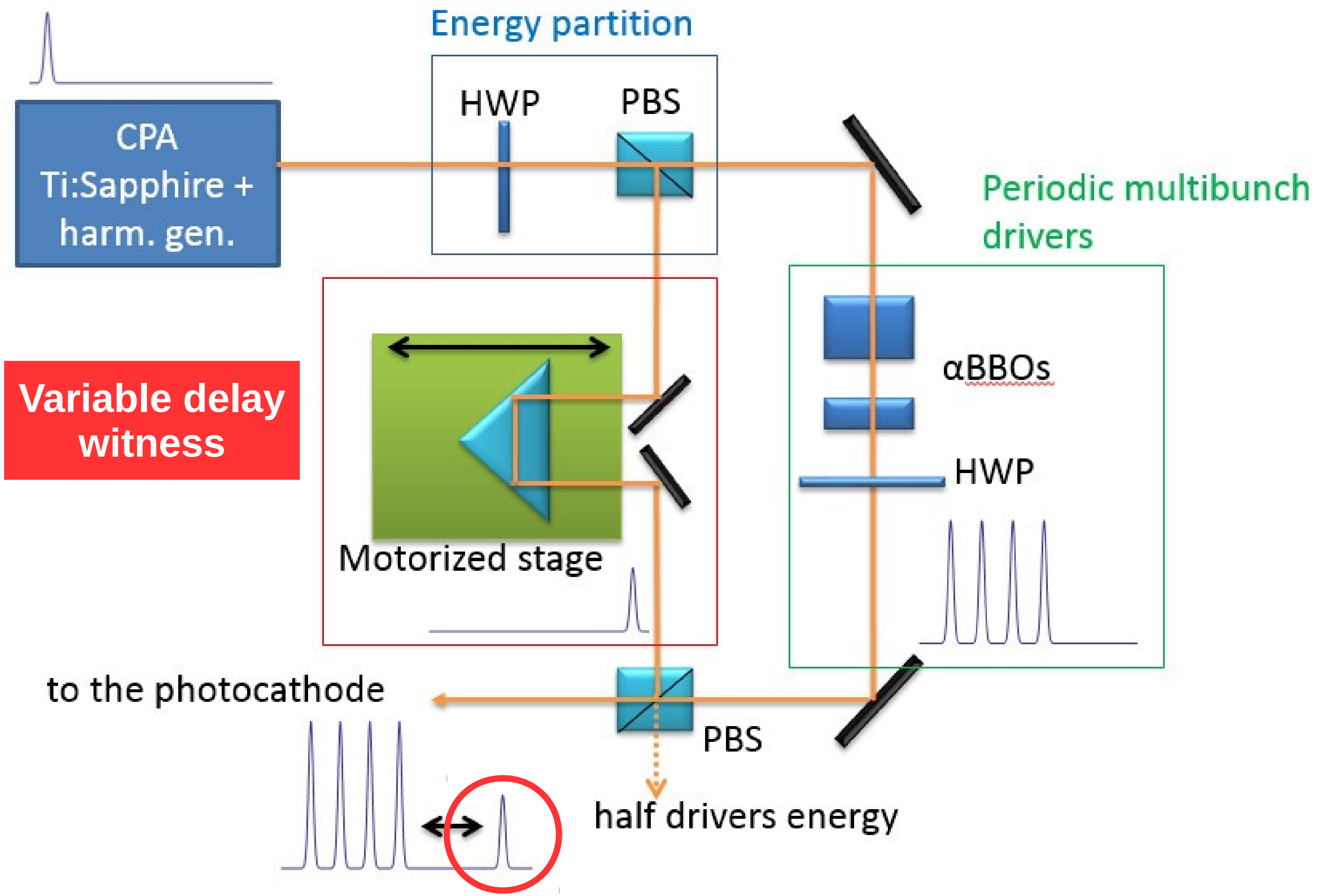
to FEL...

SPARC linac
- ✔ 2 S-band TW sections (3 m)
- ✔ Last S-band section replaced with a C-band one (1.3 m)

Acceleration + diagnostics
- ✔ 3 cm length capillary
- ✔ 1 mm hole diameter
- ✔ n_0 measure by Stark broadening

Beam diagnostics
- ✔ Transverse diagnostics (Ce:YAG screen)
- ✔ THz station (CTR/CDR)

Laser-comb: optical setup



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