INFN ACCELERATORI ERICE Accelerator School

ETTORE MAJORANA FOUNDATION AND CENTRE FOR SCIENTIFIC CULTURE
TO PAY A PERMANENT TRIBUTE TO ARCHIMEDES AND GALILEO GALILEI, FOUNDERS OF MODERN SCIENCE AND TO ENRICO FERMI, THE "ITALIAN NAVIGATOR", FATHER OF THE WEAK FORCES

27 July 2023 - 2 August 2023
Ettore Majorana Center (Sicily, IT)

Technology of Beam Driver for Plasma Accelerators

Enrica Chiadroni (Sapienza Univ. - SBAI Dept. and INFN - LNF)

Dipartimento di Scienze di Base e Applicate per l' Ingegneria
Sapienza Università di Roma

Outline

- Particle-driven Plasma Accelerators
- Driver beam generation and optimization towards a beam-driven plasma-based user facility
    - EuPRAXIA@SPARC_LAB through the SPARC_LAB Experience
- Conclusions

Challenges of beam-driven PWFA

- Typically in plasma wakefield accelerators we have
  - gradient of several GV/m
  - strong focusing fields of several 100 kT/m
  - the matched beam size of the witness beam is small , $\sigma w \approx \mu m$
  - optical beta function of witness beam is small, e.g. $\beta \approx \mu m$
  - tolerances for emittance growth is small! (100% growth for 1σ offset)
- Energy spread <-> uniformity of the accelerating fields (in r, z)
  - Control charge and beam loading to compensate energy spread
  - Use short bunches to minimize energy spread
- Emittance preservation <-> focusing field (in r,z)
- Alignment control between wakefield driver and witness electron bunch at 1 μm level
- Stability

Beam-driven PWFA worldwide

Credits: E. Gschwendtner, 2019

Facility	Where	Drive (D) beam	Witness (W) beam	Start	End	Goal
AWAKE	CERN, Geneva, Switzerland	400 GeV **protons**	Externally injected electron beam (PHIN 15 MeV)	2016	2020+	**Use for future high energy e-/e+ collider.** - Study Self-Modulation Instability (SMI). - Accelerate externally injected electrons. - Demonstrate scalability of acceleration scheme.
SLAC-FACET	SLAC, Stanford, USA	20 GeV **electrons** and **positrons**	Two-bunch formed with mask (e^-/e^+ and e^--e^+ bunches)	2012	Sept 2016	- Acceleration of witness bunch with high **quality and efficiency** - Acceleration of positrons - FACET II preparation, starting 2018
DESY-Zeuthen	PITZ, DESY, Zeuthen, Germany	20 MeV **electron** beam	No witness (W) beam, only D beam from RF-gun.	2015	~2017	- Study Self-Modulation Instability **(SMI)**
DESY-FLASH Forward	DESY, Hamburg, Germany	X-ray FEL type **electron** beam 1 GeV	D + W in FEL bunch. Or independent W-bunch (LWFA).	2016	2020+	- **Application (mostly) for x-ray FEL** - Energy-doubling of Flash-beam energy - Upgrade-stage: use 2 GeV FEL D beam
Brookhaven ATF	BNL, Brookhaven, USA	60 MeV **electrons**	Several bunches, D+W formed with mask.	On going		- **Study quasi-nonlinear PWFA regime.** - Study PWFA driven by multiple bunches - Visualisation with optical techniques
SPARC Lab	Frascati, Italy	150 MeV	Several bunches	On going		- Multi-purpose user facility: includes laser- and beam-driven plasma wakefield experiments

Beam-driven PWFA worldwide

Credits: E. Gschwendtner, 2019

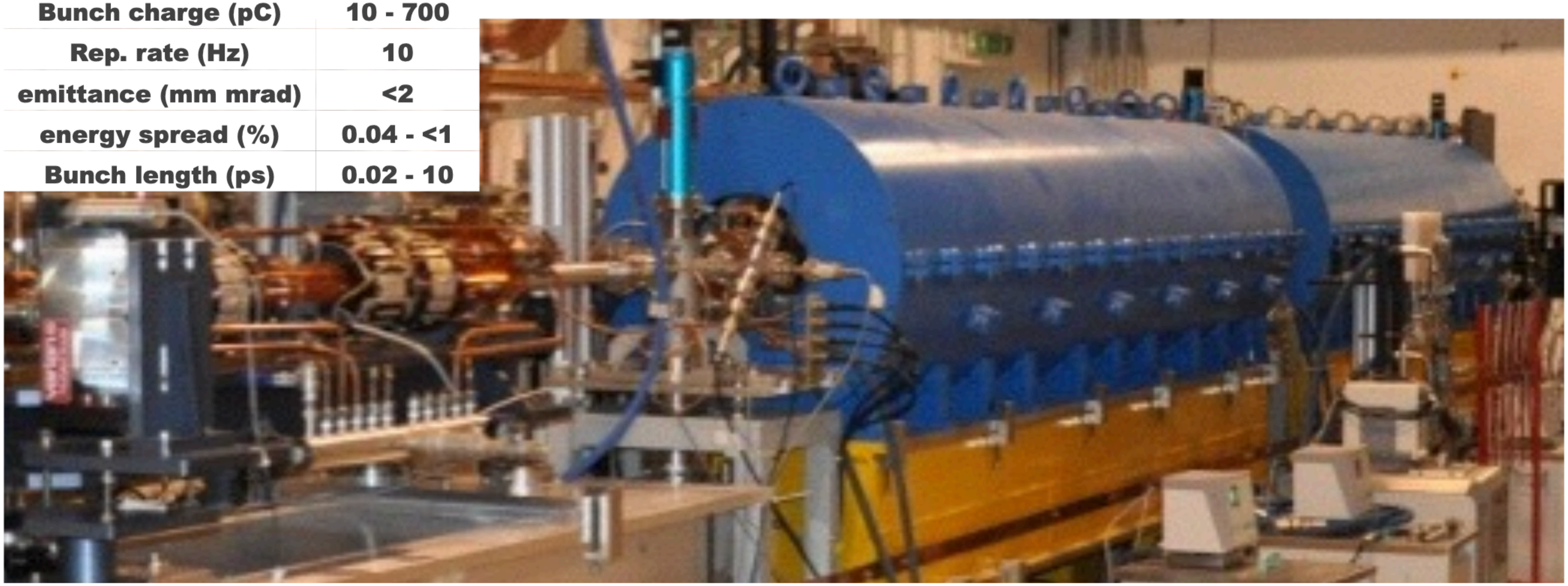
Facility	Where	Drive (D) beam	Witness (W) beam	Start	End	Goal
AWAKE	CERN, Geneva, Switzerland	400 GeV **protons**	Externally injected electron beam (PHIN 15 MeV)	2016	2020+	**Use for future high energy e-/e+ collider.** - Study Self-Modulation Instability (SMI). - Accelerate externally injected electrons. - Demonstrate scalability of acceleration scheme.
SLAC-FACET	SLAC, Stanford, USA	20 GeV **electrons** and **positrons**	Two-bunch formed with mask (e^-/e^+ and e^--e^+ bunches)	2012	Sept 2016	- Acceleration of witness bunch with high **quality and efficiency** - Acceleration of positrons - FACET II preparation, starting 2018
DESY-Zeuthen	PITZ, DESY, Zeuthen, Germany	20 MeV **electron** beam	No witness (W) beam, only D beam from RF-gun.	2015	~2017	- Study Self-Modulation Instability **(SMI)**
DESY-FLASH Forward	DESY, Hamburg, Germany	X-ray FEL type **electron** beam 1 GeV	D + W in FEL bunch. Or independent W-bunch (LWFA).	2016	2020+	- **Application (mostly) for x-ray FEL** - Energy-doubling of Flash-beam energy - Upgrade-stage: use 2 GeV FEL D beam
Brookhaven ATF	BNL, Brookhaven, USA	60 MeV **electrons**	Several bunches, D+W formed with mask.	On going		- **Study quasi-nonlinear PWFA regime.** - Study PWFA driven by multiple bunches - Visualisation with optical techniques
SPARC_LAB	Frascati, Italy	150 MeV	Several bunches	On going		- Multi-purpose user facility: includes laser- and beam-driven plasma wakefield experiments

High Brightness Photo-injector

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

- **Broad-band THz radiation**
- **FEL (single spike + seeding)**
- **Laser comb**
  - **Narrow-band THz radiation**
  - **Two-color FEL**
  - **resonant PWFA**
- **LWFA (external injection**

Beam energy (MeV)	30 - 170
Bunch charge (pC)	10 - 700
Rep. rate (Hz)	10
emittance (mm mrad)	<2
energy spread (%)	0.04 - <1
Bunch length (ps)	0.02 - 10



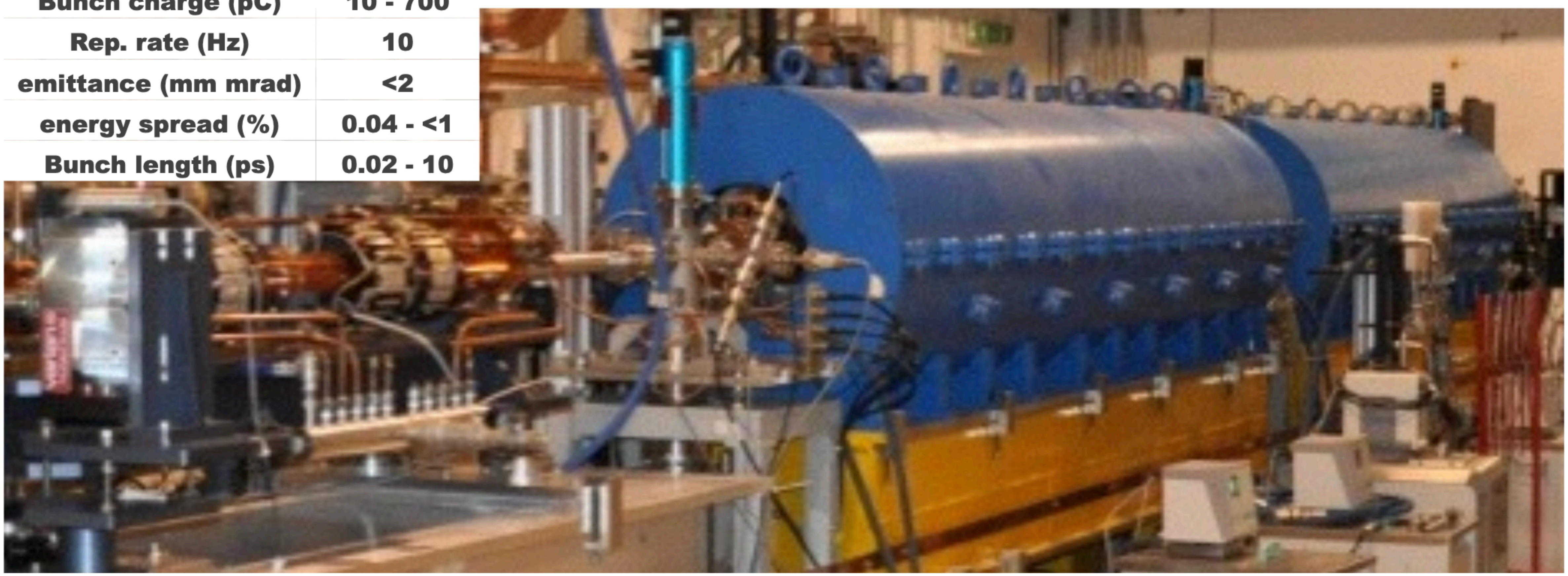
- **L. Serafini and M. Ferrario**, Physics of, and Science with the X-Ray Free-Electron Laser, edited.by S. Chattopadhyay et al. © 2001 American Institute of Physics
- **M. Ferrario et al.**, Phys. Rev. Lett. **104**, 054801 (2010)

High Brightness Photo-injector

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

- Broad-band THz radiation
- FEL (single spike + seeding)
- Laser comb
  - Narrow-band THz radiation
  - Two-color FEL
  - resonant PWFA
- LWFA (external injection

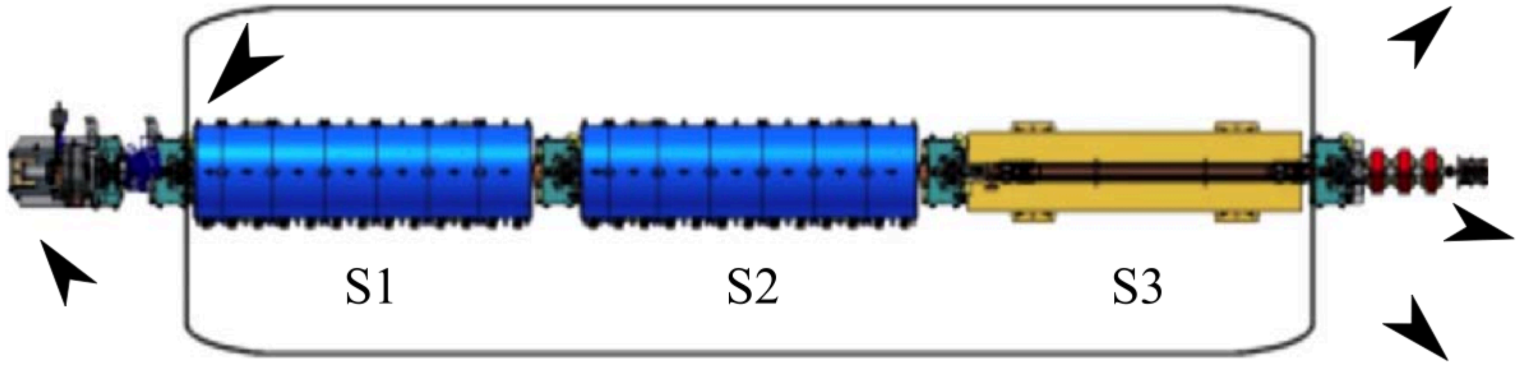
Beam energy (MeV)	30 - 170
Bunch charge (pC)	10 - 700
Rep. rate (Hz)	10
emittance (mm mrad)	<2
energy spread (%)	0.04 - <1
Bunch length (ps)	0.02 - 10



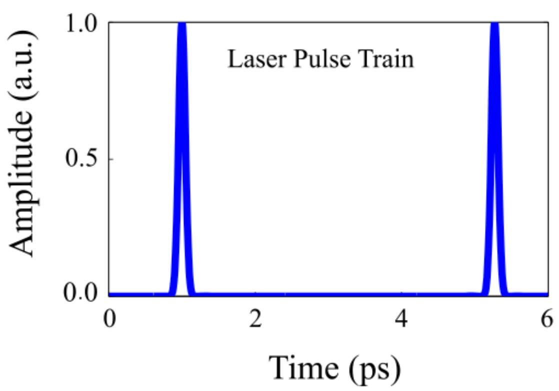
- **P. O. Shea et al.**, Proc. of 2001 IEEE PAC, Chicago, USA (2001) p.704.
- **M. Ferrario et al.**, Int. J. of Mod. Phys. B, 2006

Multi-bunch Shaping in a Photo-Injector

Laser Comb Technique at SPARC_LAB (INFN)



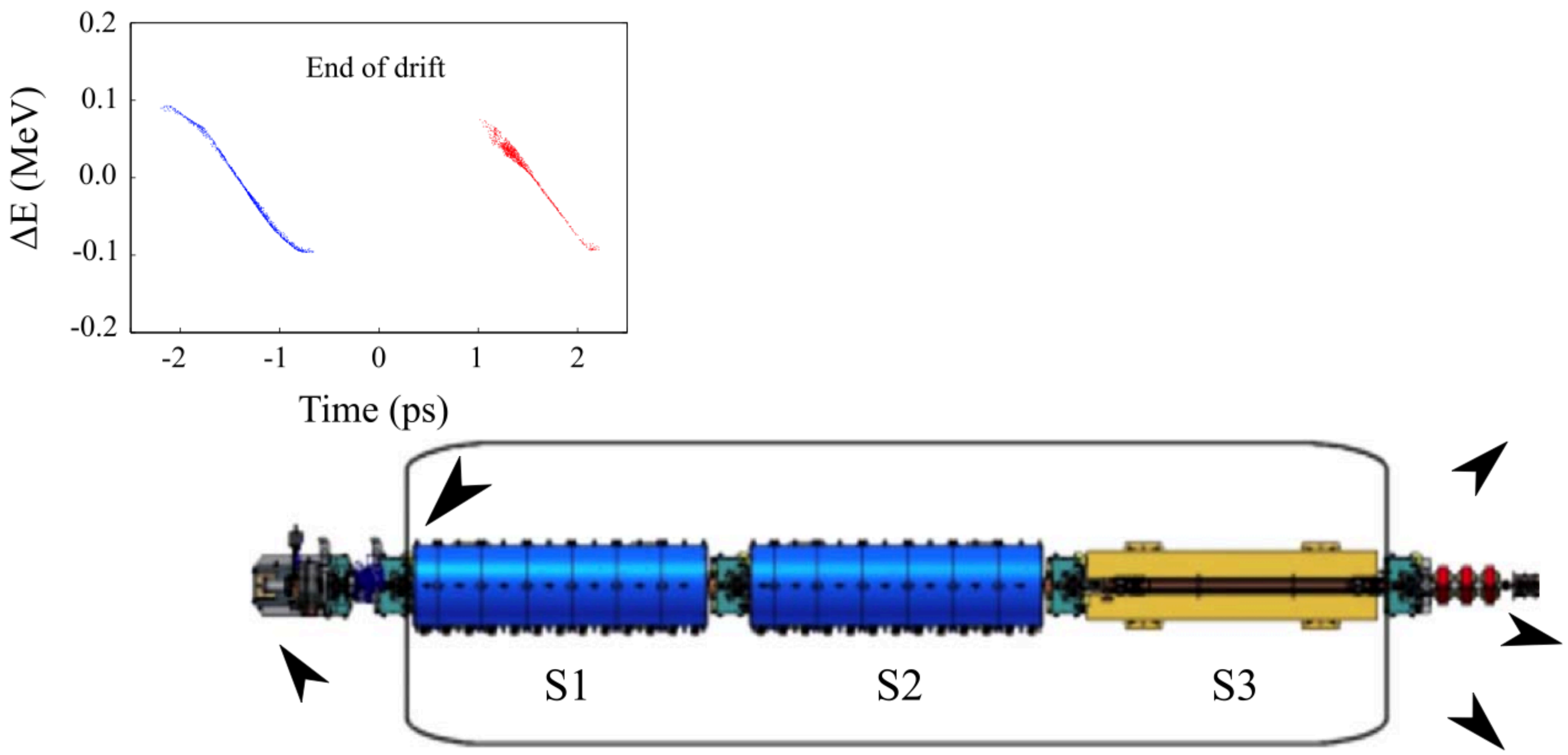
Comb-like laser



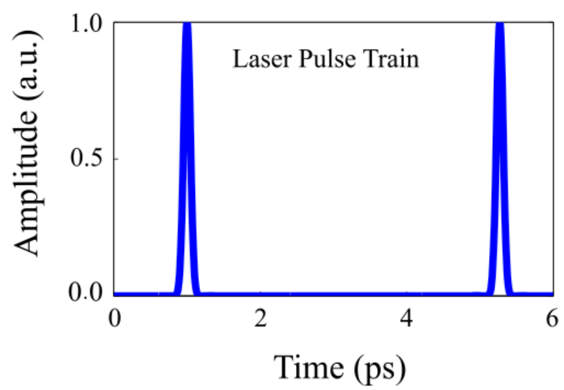
P. O. Shea et al., Proc. of 2001 IEEE PAC, Chicago, USA (2001) p.704.
M. Ferrario et al., Int. J. of Mod. Phys. B, 2006

Multi-bunch Shaping in a Photo-Injector

Laser Comb Technique at SPARC_LAB (INFN)



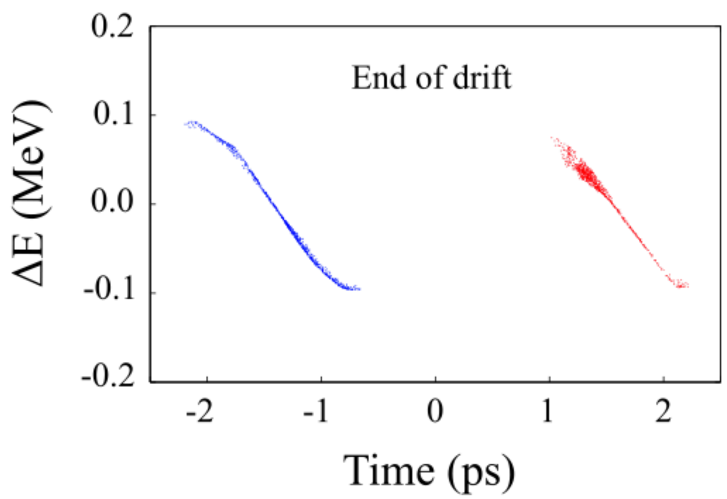
Comb-like laser

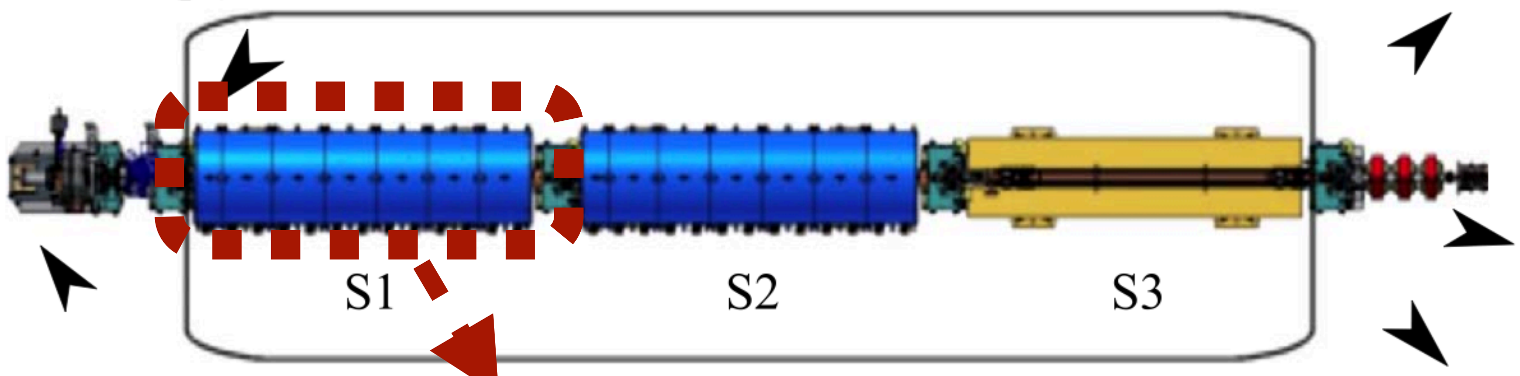


P. O. Shea et al., Proc. of 2001 IEEE PAC, Chicago, USA (2001) p.704.
M. Ferrario et al., Int. J. of Mod. Phys. B, 2006

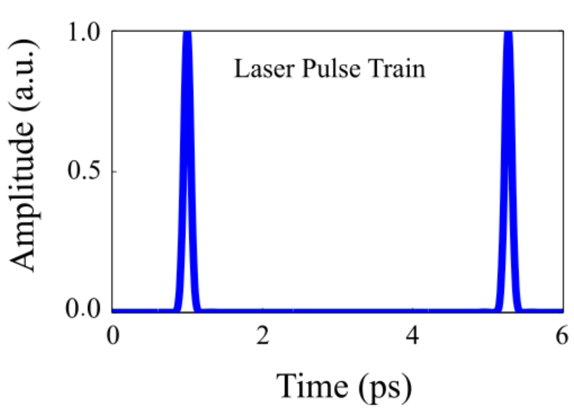
Multi-bunch Shaping in a Photo-Injector

Laser Comb Technique at SPARC_LAB (INFN)

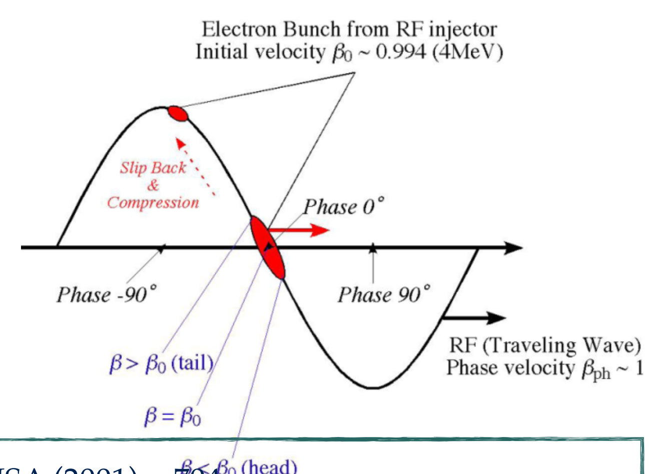




Comb-like laser



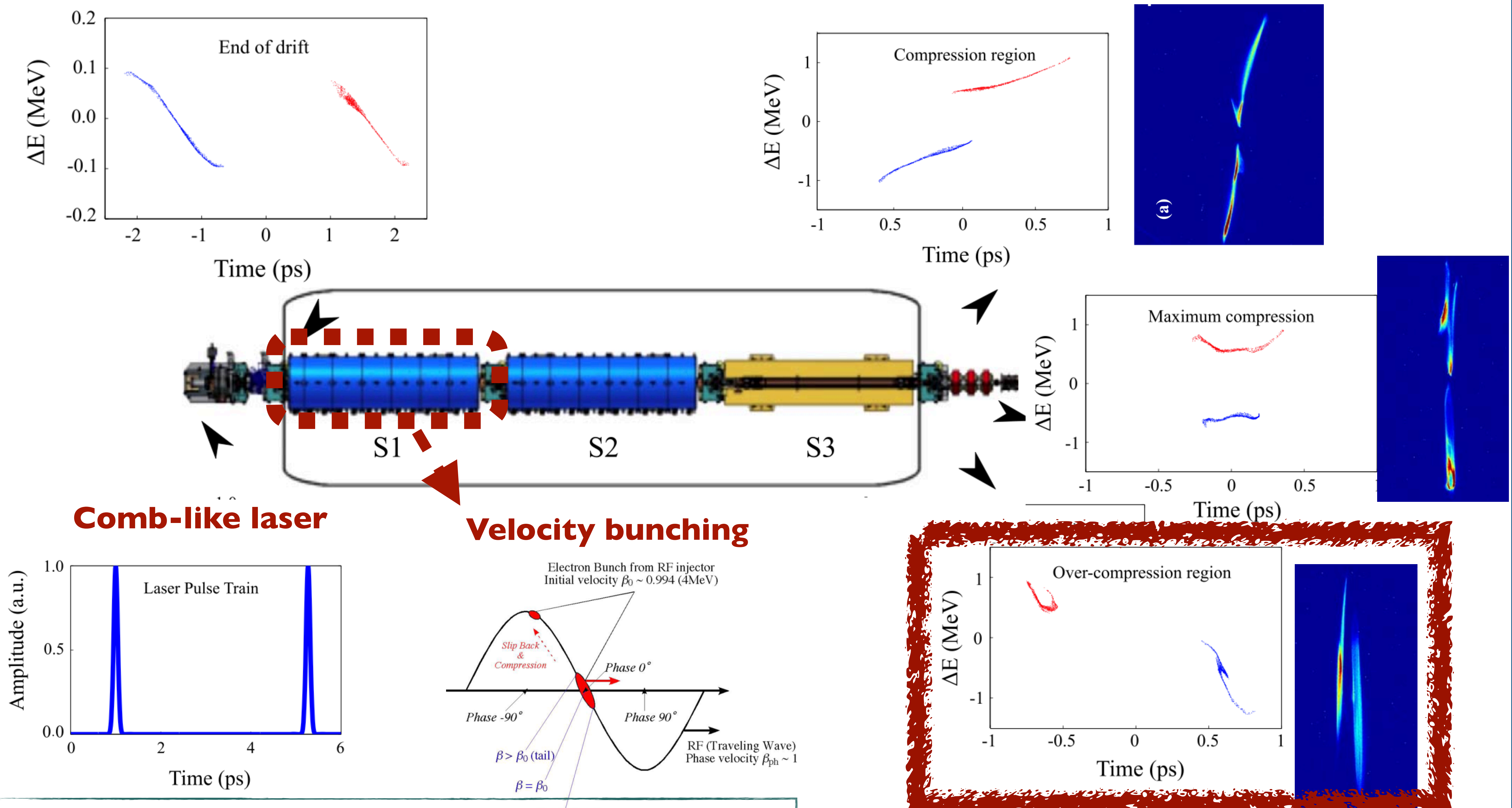
Velocity bunching



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

Multi-bunch Shaping in a Photo-Injector

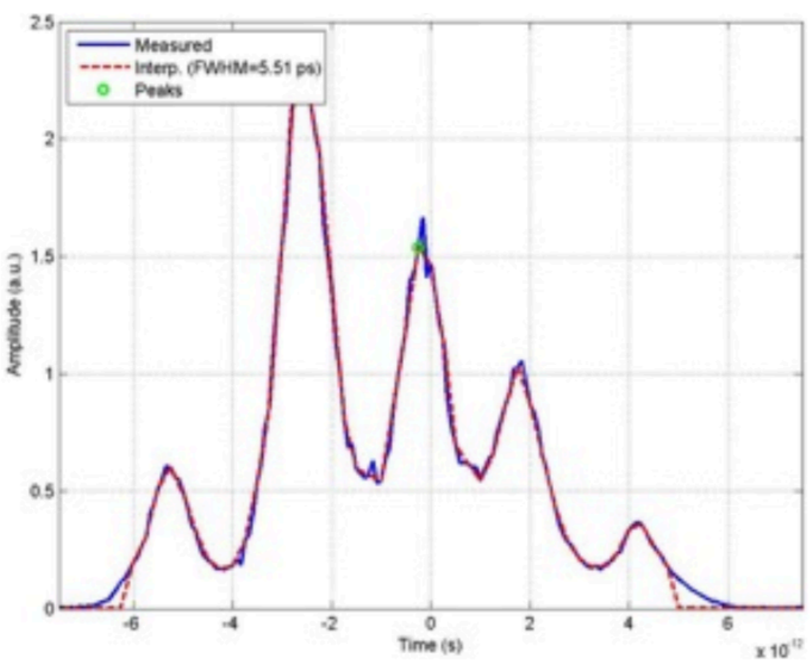
Laser Comb Technique at SPARC_LAB (INFN)

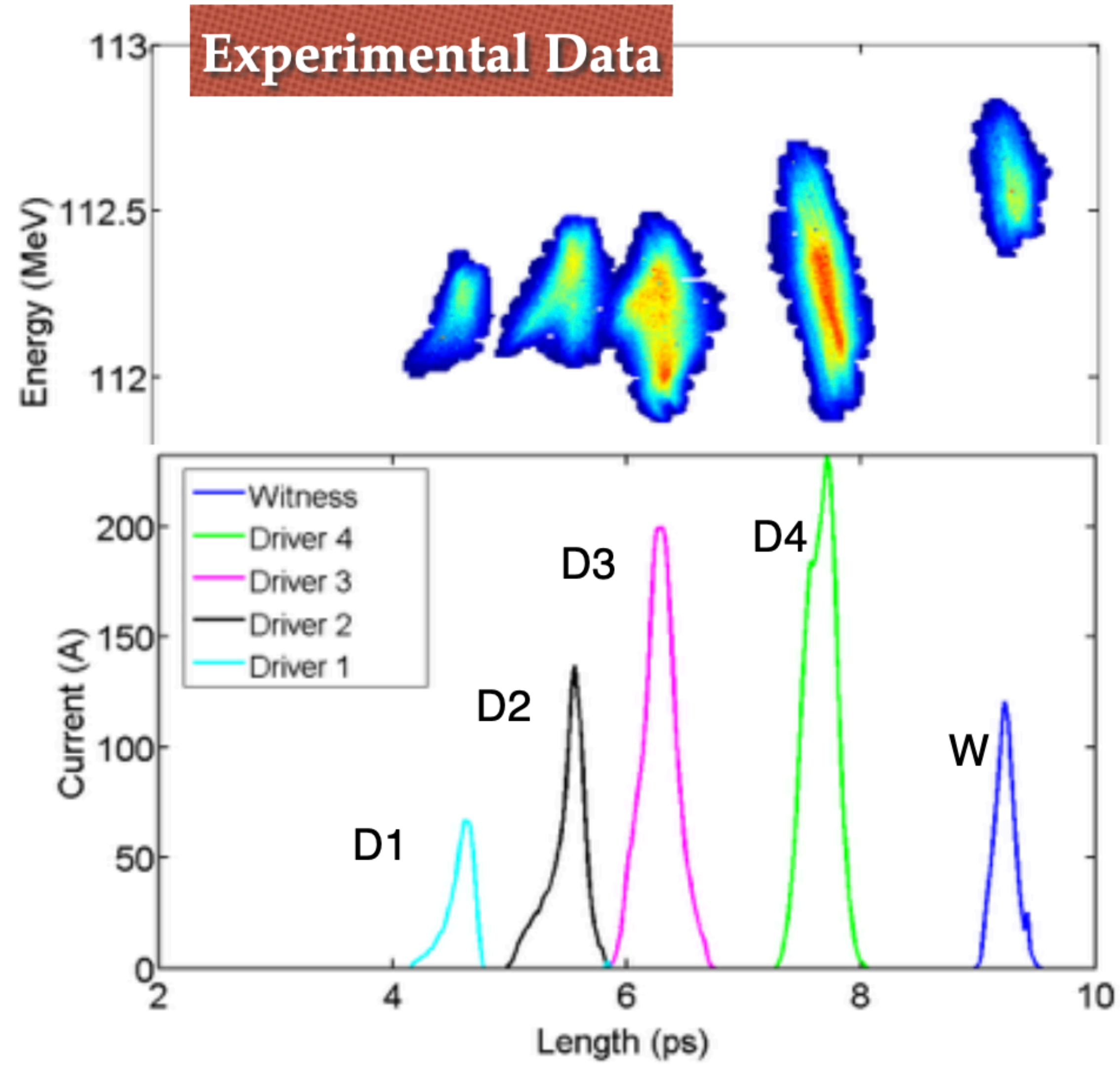


P. O. Shea et al., Proc. of 2001 IEEE PAC, Chicago, USA (2001) p.704.
M. Ferrario et al., Int. J. of Mod. Phys. B, 2006

Ramped Bunch Train

Laser profile on photo-cathode





	E (MeV)	$\Delta E/E$ (%)	σ_t (fs)	Q (pC)	ε_{nx} (mm mrad)
W	112.6	0.084	80	24	1(0.09)
D4	112.3	0.159	42	75	0.8(0.1)
D3	112.2	0.112	92	69	1.7(0.1)
D2	112.3	0.087	113	36	2.7(0.6)
D1	112.2	0.045	100	36	2.8(0.3)

Bunch Separation (μm)
W-D4 =470 (0.02) ~ $\frac{3}{2}\lambda_p$

D4-D3 =420 (0.03)
D3-D2 =240 (0.03)
D2-D1 =270 (0.05)
$\approx \lambda_p$

Interaction with Plasma

Hybrid kinetic-fluid simulation by Architect from measured drivers parameters

Beam parameters

- Q *witness* = 24 pC
- Q *drivers*(tot) ~ 200 pC
- E = 112 MeV
- ΔE/E = 0.1%
- ε_n ~ 1 mm mrad
- σ_t *drivers* < 100 fs
- σ_t *witness* ~80 fs

Weakly non-linear regime*

$n_p = 10^{16} cm^{-3}$

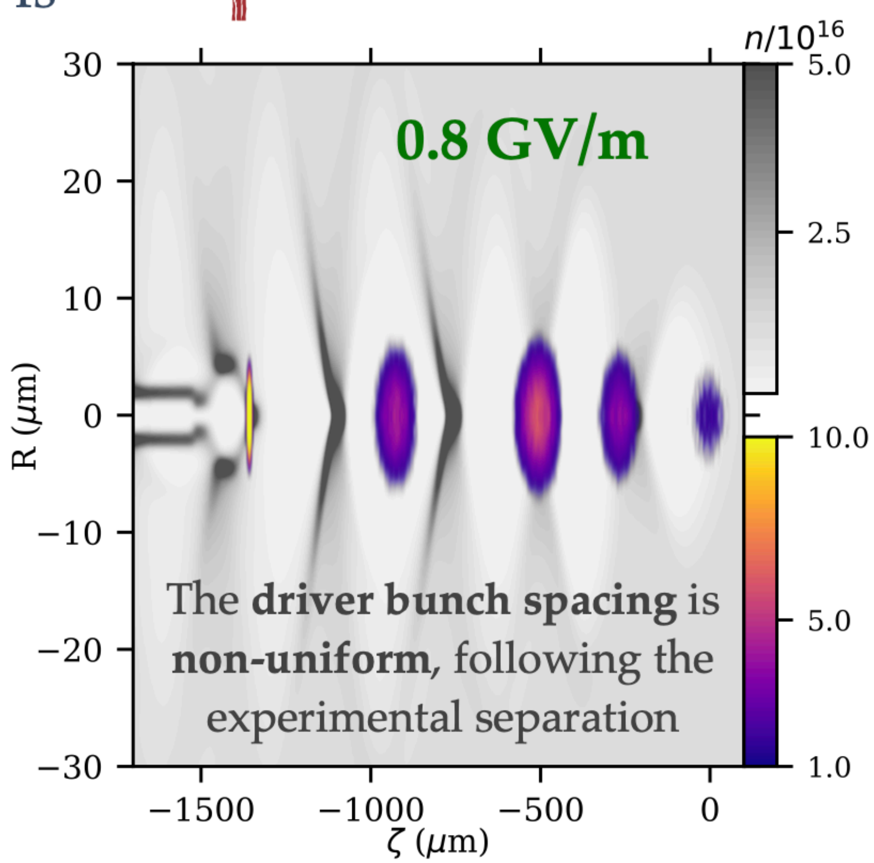
$\sigma_x = 2\ \mu m$

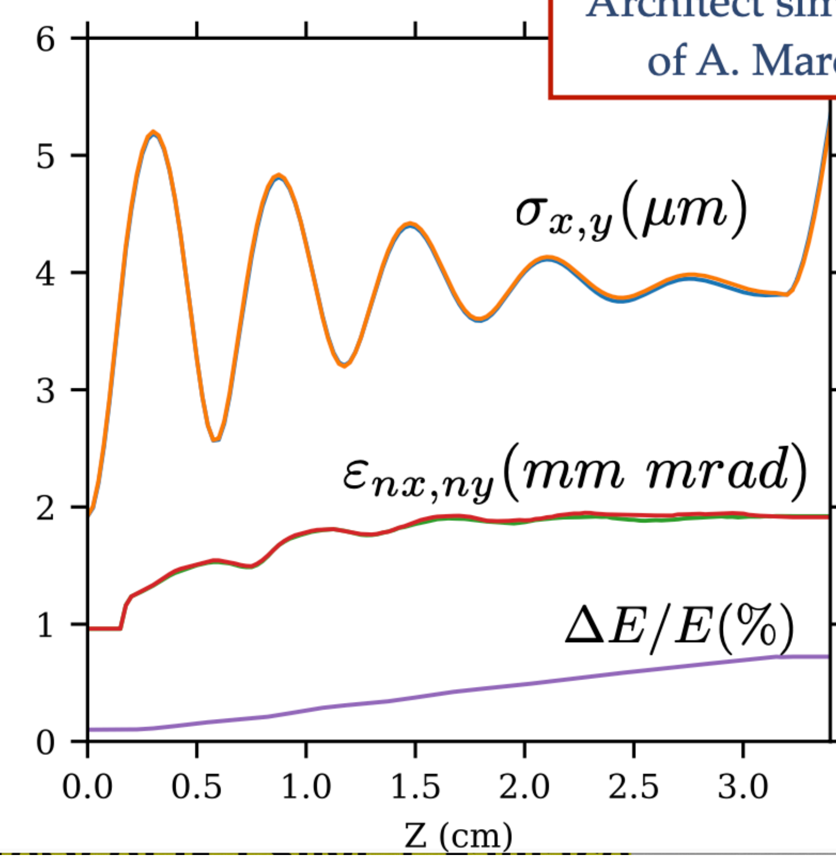
$$\alpha = \frac{n_b}{n_p} > 1$$

$$\tilde{Q} \equiv \frac{N_b k_p^3}{n_p} < 1$$

$n_b \sim 5 n_p$ and $\tilde{Q} \approx 0.8$

*J. B. Rosenzweig et al., in 14th AAC Workshop, AIP Conference Proceedings, 1299, pp. 500-504 (2010)
*P. Londrillo et al., NIM **740**, 236 (2014)



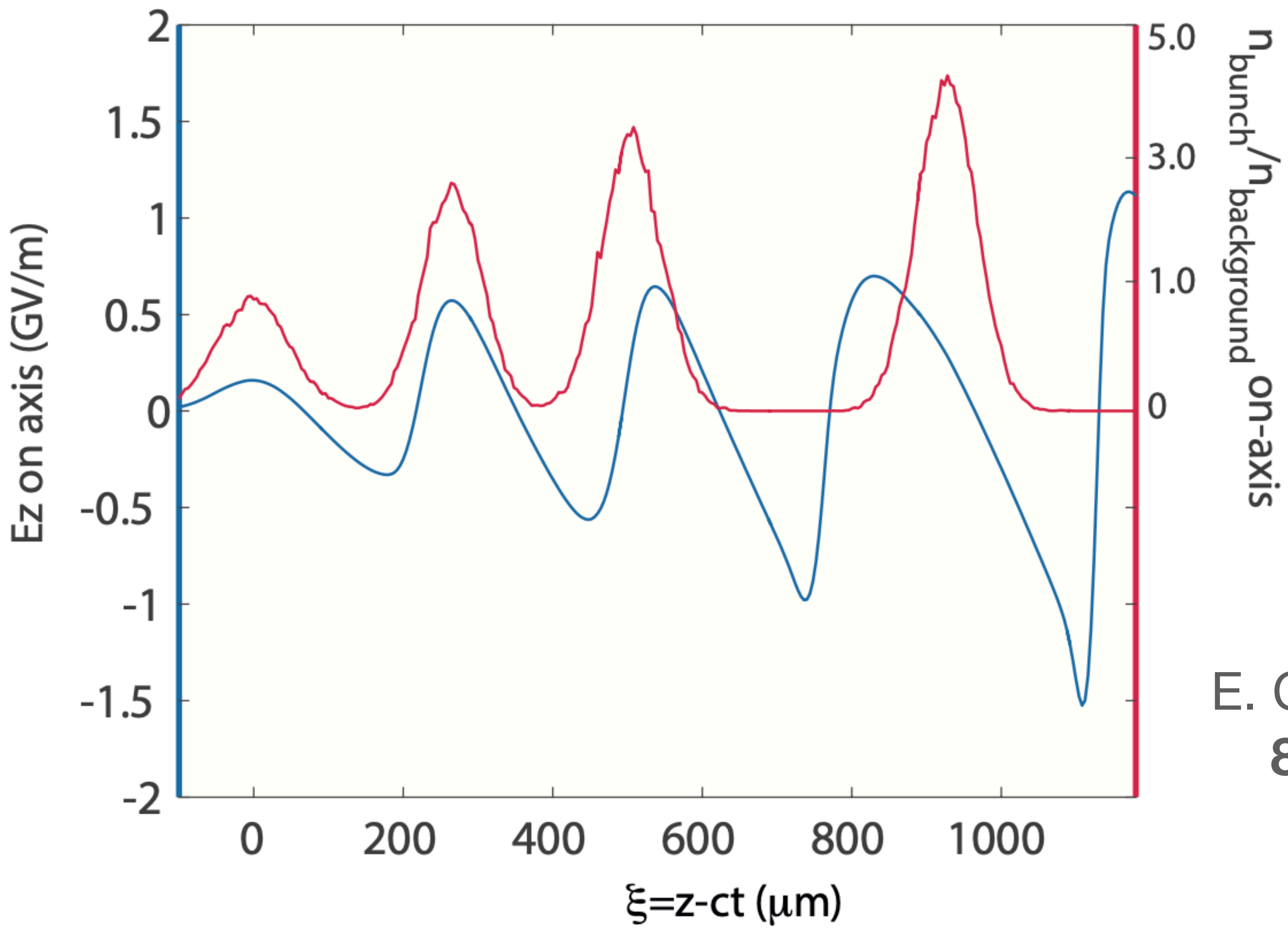


Architect sim., courtesy of A. Marocchino

Interaction with Plasma

Hybrid kinetic-fluid simulation by Architect from measured drivers parameters

Realistic case



E. Chiadroni et al., NIM A **865**, 139-143 (2017)

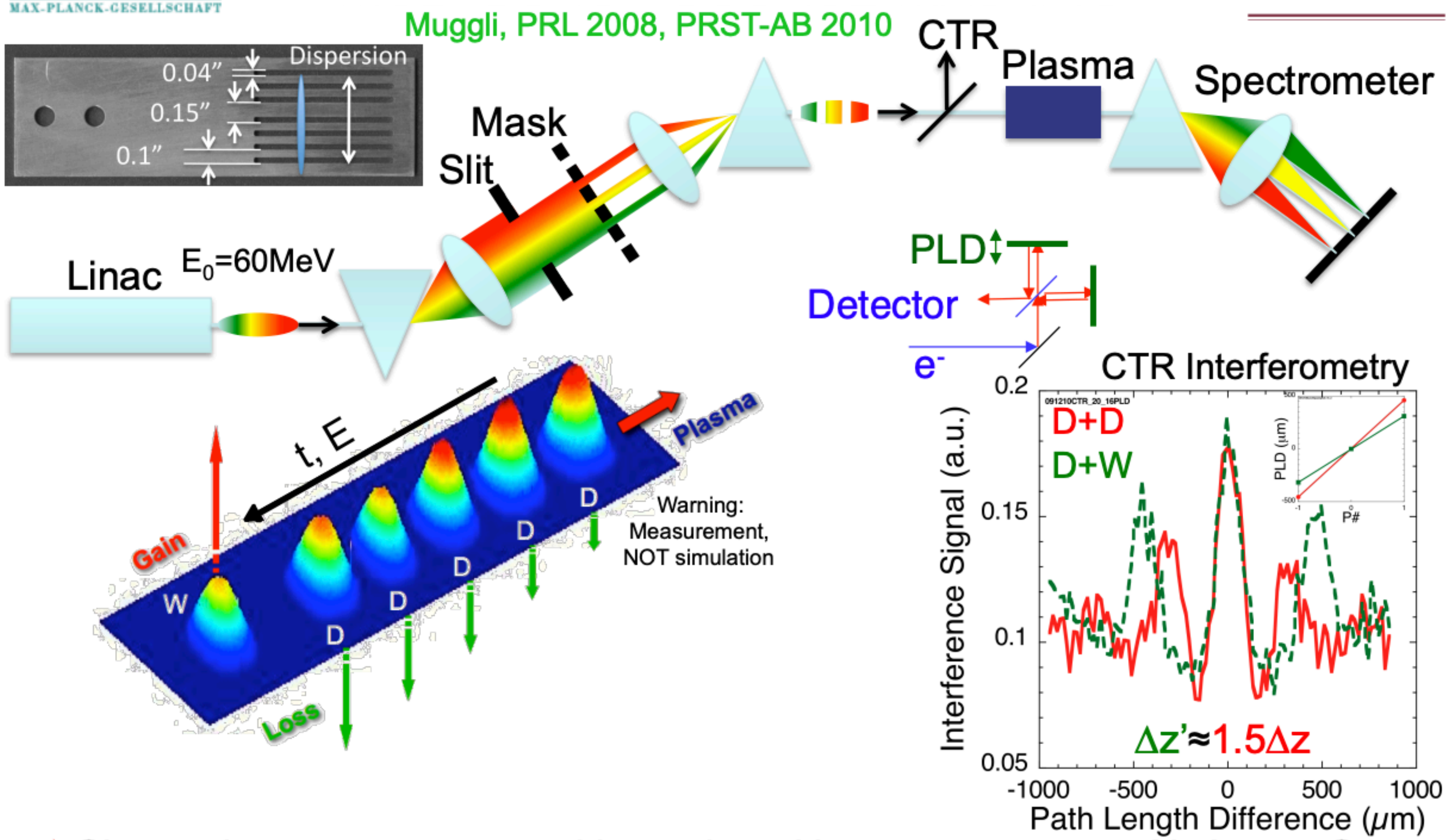
Longitudinal electric field on axis and normalized bunch density profile, $\alpha = n_b / n_0$, for a ramped charge profile (ratio 1:3:5:7) in the weakly non-linear regime:

α **>>1** and $\tilde{Q}$ **= 0.75**.

The **driver bunch spacing** is **non-uniform**, following the experimental separation, *i.e.* 270 – 240 – 420 μ*m* (λ_p= 330 μ*m*).

The calculated transformer ratio is *R* > 3.

Multibunch Source Masking

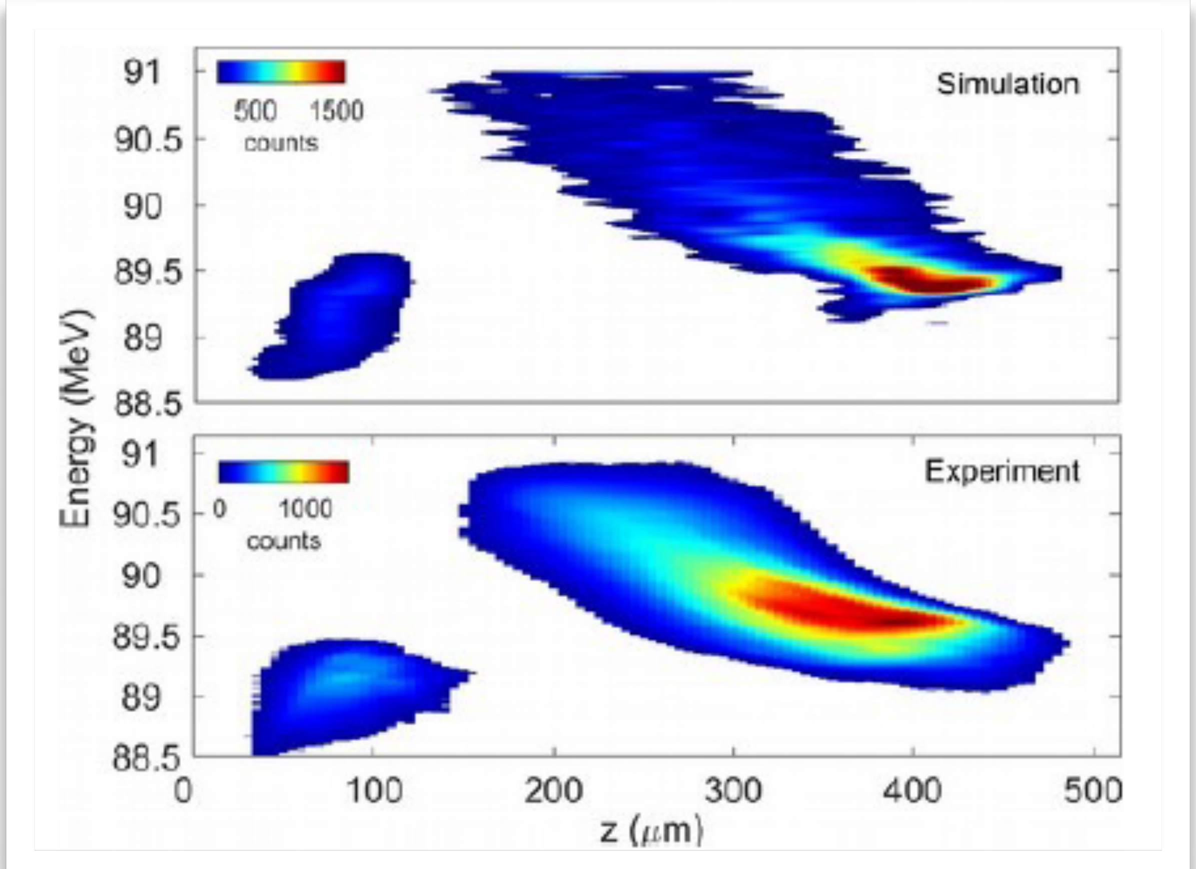


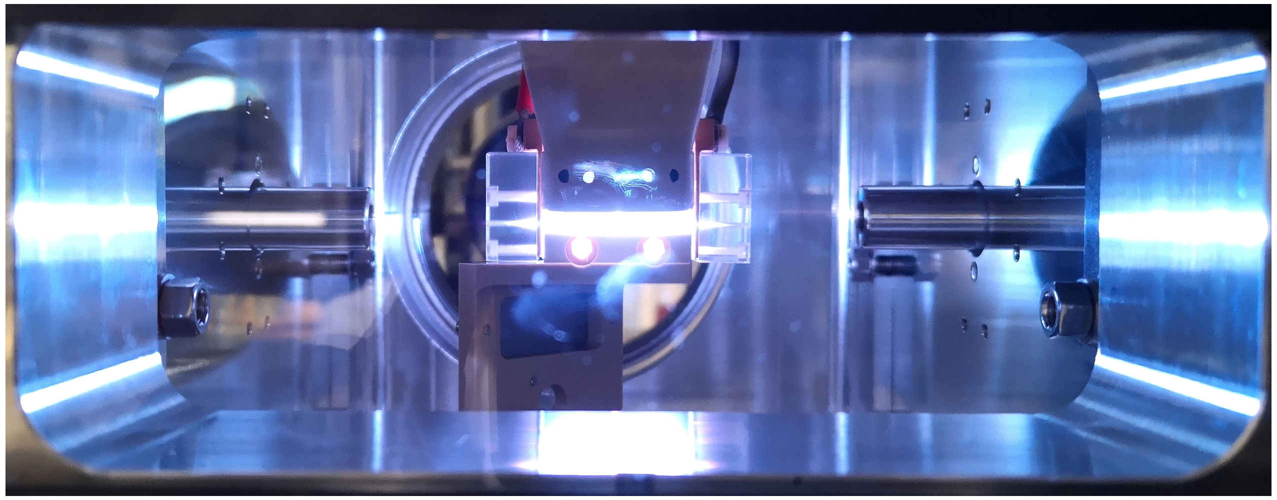
- Choose beam parameters with mask and beam parameters: N, Δz, σ_z, Q
- Test bed for two bunches at FACET

(similar to COMB@SPARC)

Two-beam configuration

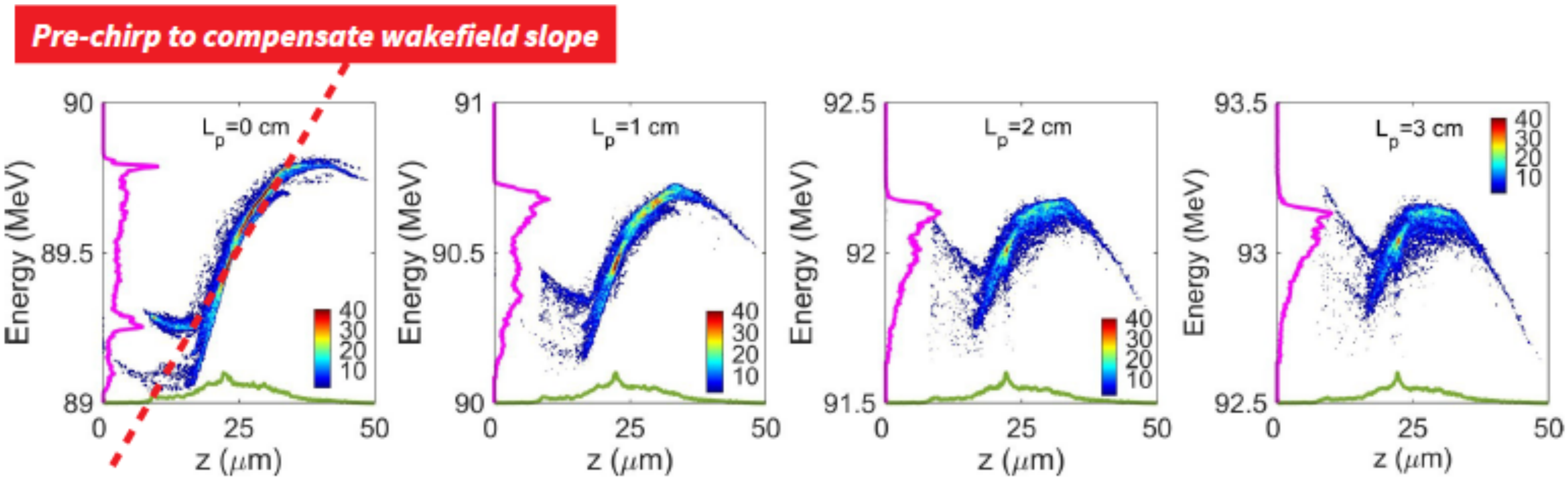
- Two-bunches configuration produced directly at the cathode with laser-comb technique
  - 200 pC driver followed by witness bunch (20 pC)
- Ultra-short durations (200 fs + 30 fs)
- Separation approximately equal to half plasma wavelength (~1.2 ps)

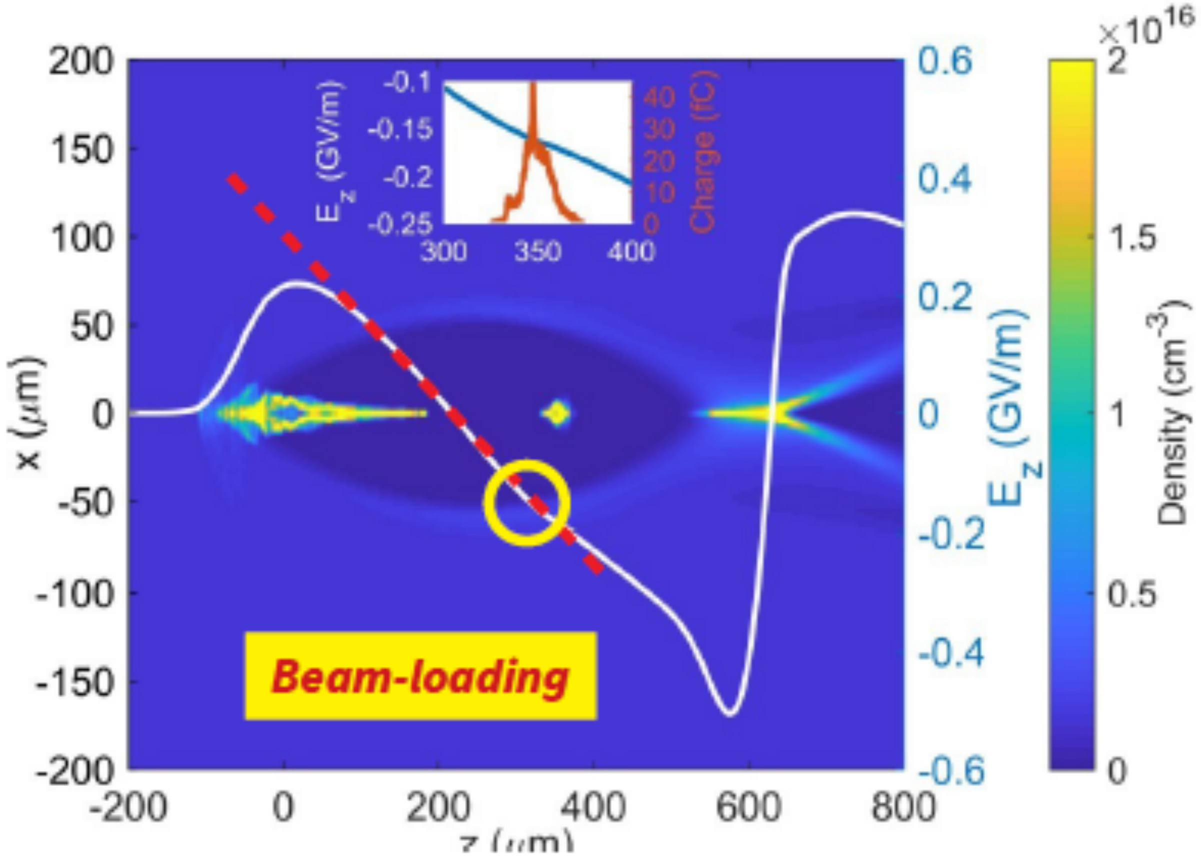


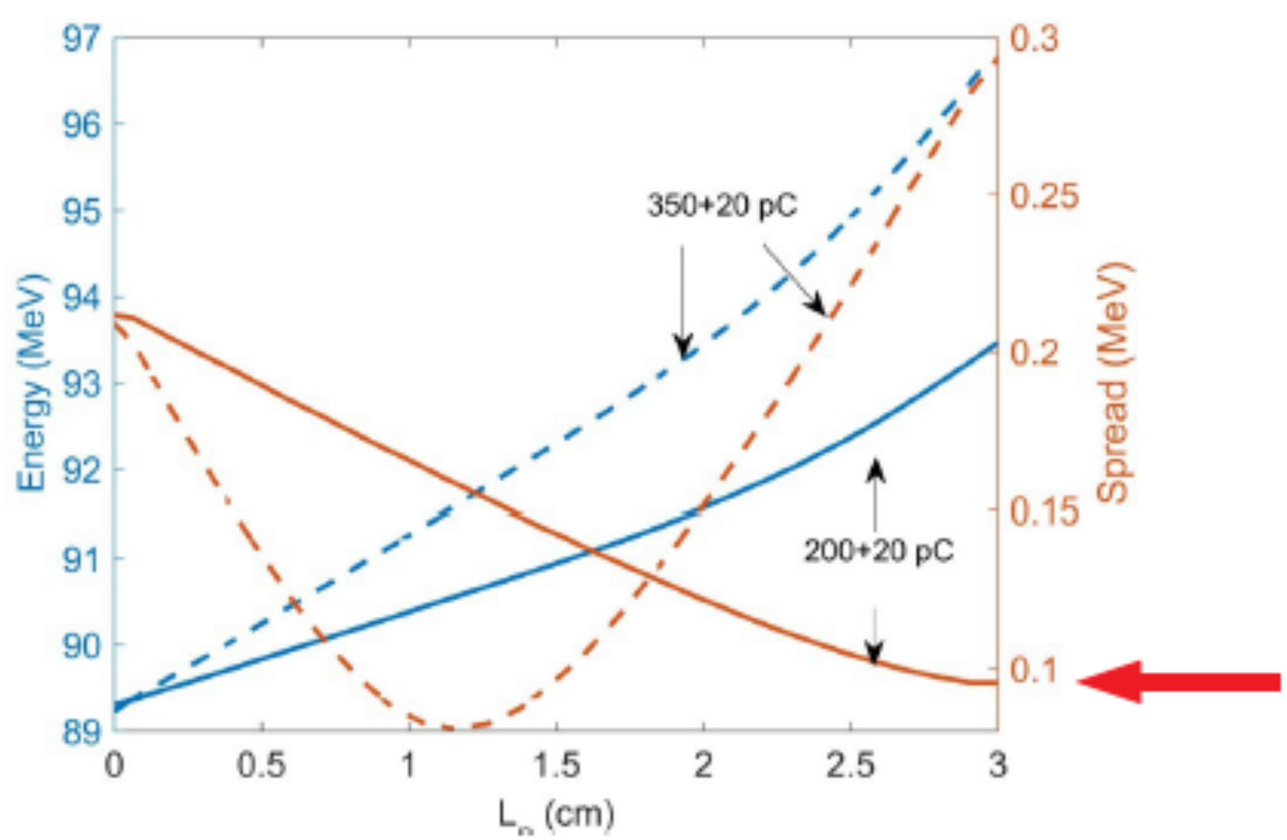


- 3 cm long 3D-printed plastic capillary, 1 mm diameter aperture
- plasma is produced by ionizing hydrogen gas, injected through two inlets, by means of a high-voltage discharge (12 kV, 300 A) at 1 Hz repetition rate

Beam Quality Preservation



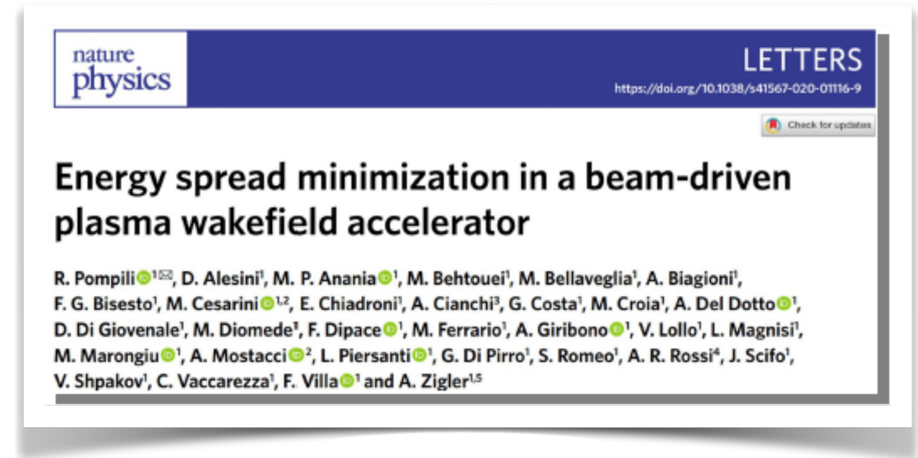




Beam Quality Preservation

Energy spread compensation at SPARC_LAB

- 4 MeV acceleration in 3 cm plasma with 200 pC driver
  - ~133 MV/m accelerating gradient
  - $2x10^{15}$ cm^{-3} plasma density
- First ever demonstration of energy spread reduction
  - Spread from 0.2% to 0.12%


nature physics

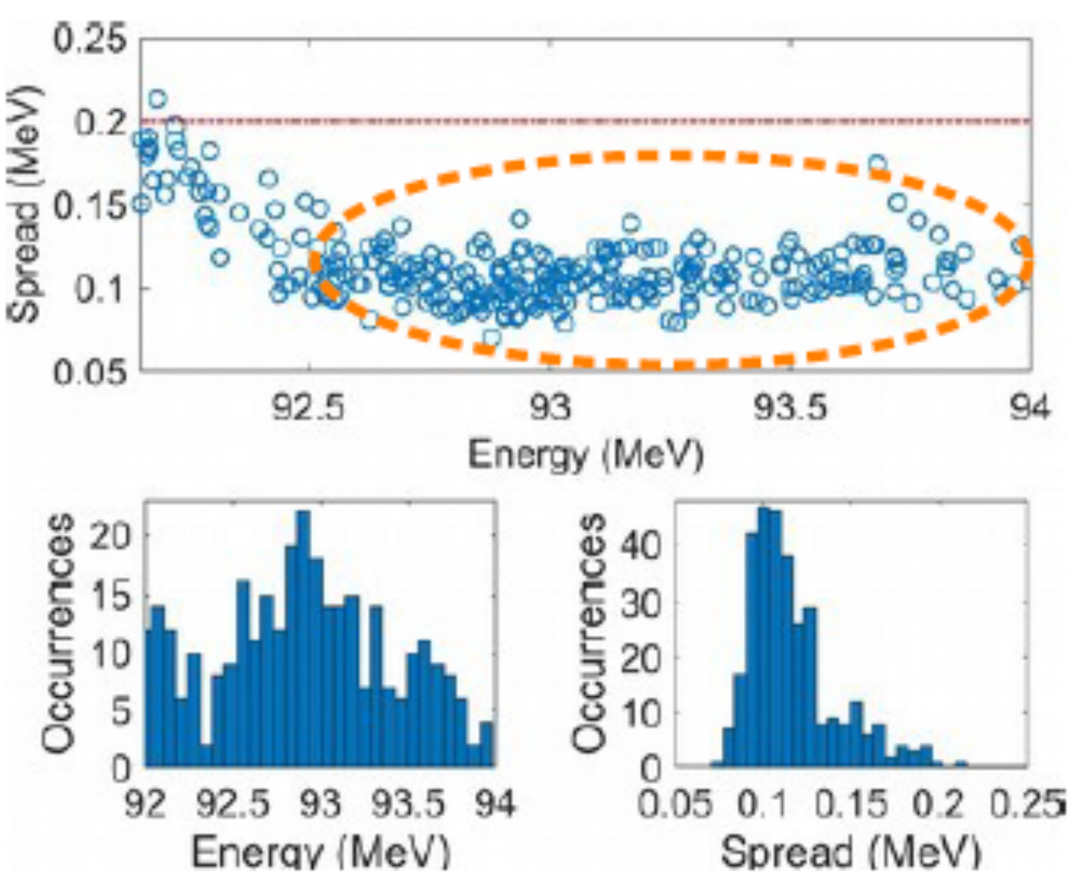
LETTERS

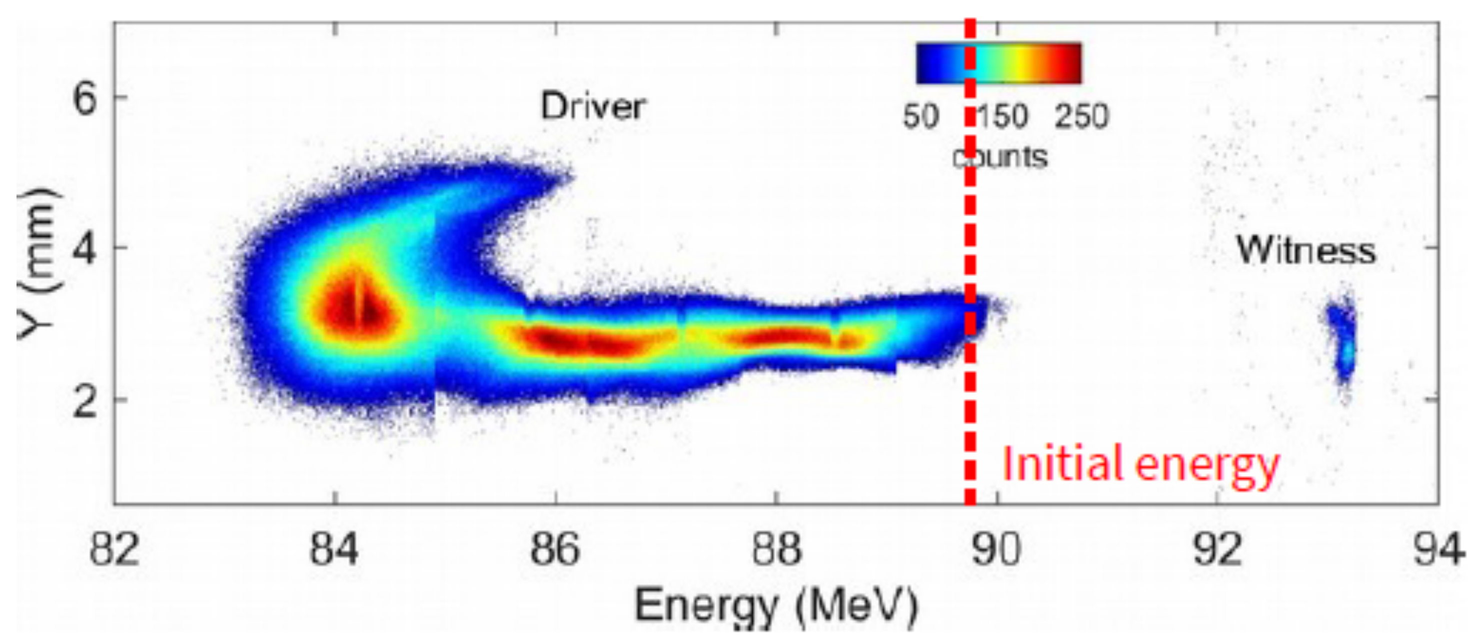
https://doi.org/10.1038/s41567-020-01116-9

Check for updates

Energy spread minimization in a beam-driven plasma wakefield accelerator

R. Pompili[1], D. Alesini[1], M. P. Anania[1], M. Behtouei[1], M. Bellaveglia[1], A. Biagioni[1], F. G. Bisesto[1], M. Cesarini[1,2], E. Chiadroni[1], A. Cianchi[3], G. Costa[1], M. Croia[1], A. Del Dotto[1], D. Di Giovenale[1], M. Diomede[1], F. Dipace[1], M. Ferrario[1], A. Giribono[1], V. Lollo[1], L. Magnisi[1], M. Marongiu[1], A. Mostacci[2], L. Piersanti[1], G. Di Pirro[1], S. Romeo[1], A. R. Rossi[4], J. Scifo[1], V. Shpakov[1], C. Vaccarezza[1], F. Villa[1] and A. Zigler[1,5]



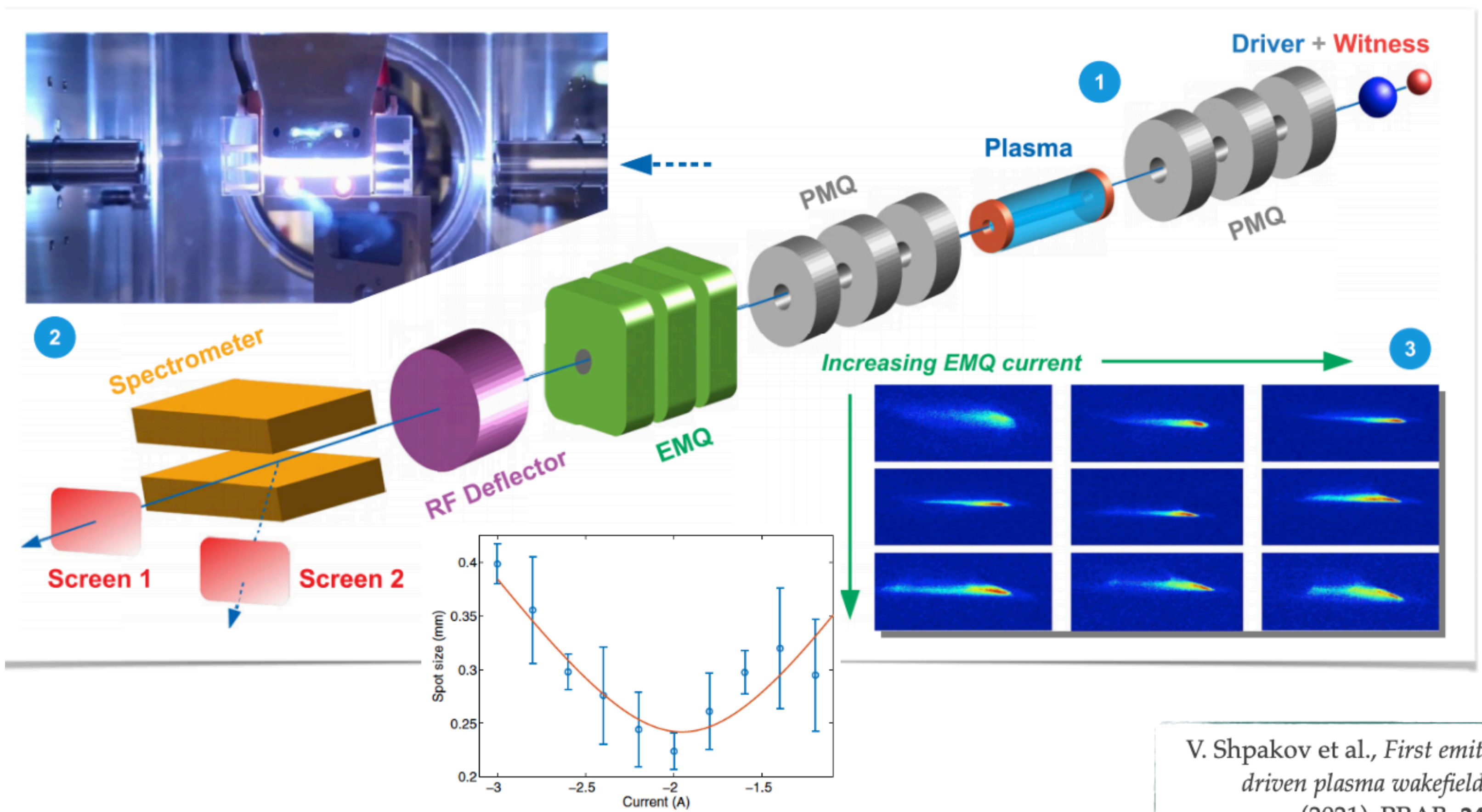


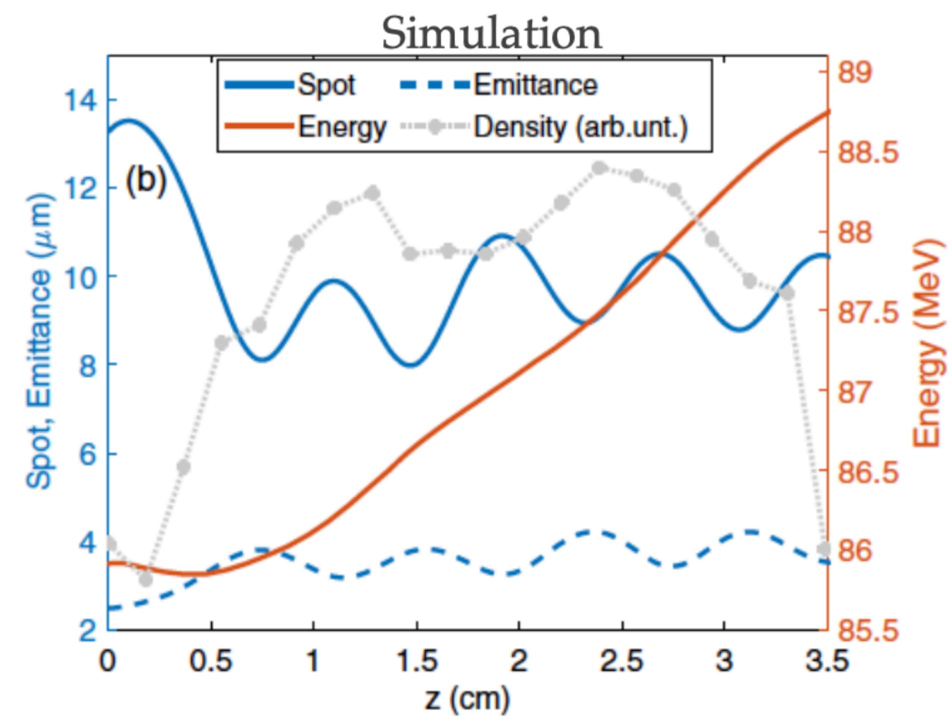
Energy jitter of the witness energy is 0.5 MeV

Beam Quality Preservation

Normalised emittance measurement

- **First PWFA transverse normalized emittance characterization**
  - Multi-shot quadrupole scan technique to measure the plasma-accelerated witness normalized emittance
    - emittance increase from 2.7 um to 3.7 um (rms) during acceleration because of non optimized matching





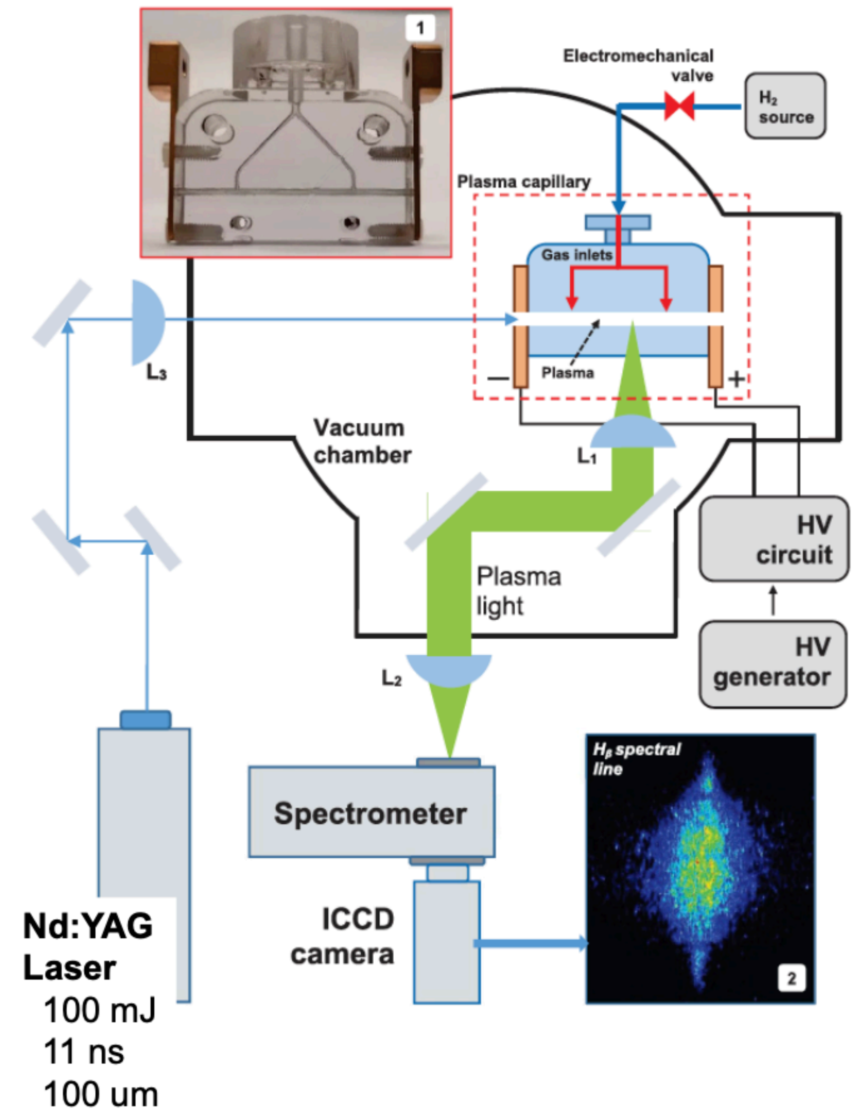
V. Shpakov et al., *First emittance measurement of the beam-driven plasma wakefield accelerated electron beam*, (2021), PRAB, **24** (5), art. no. 051301

Gas-filled Capillary

Discharge Stabilisation

Courtesy of A. Biagioni (INFN-LNF)

- **Discharge ignition depends on the operating conditions**, since the breakdown voltage depends on the molecules distribution inside the capillary (pressure and length)
- Discharge timing jitter is affected by the **voltage** and the **gas pressure** in the capillary
- To **decrease the time jitter** (and so the shot-to-shot instability) **a laser pulse** can be used **to ignite the discharge**

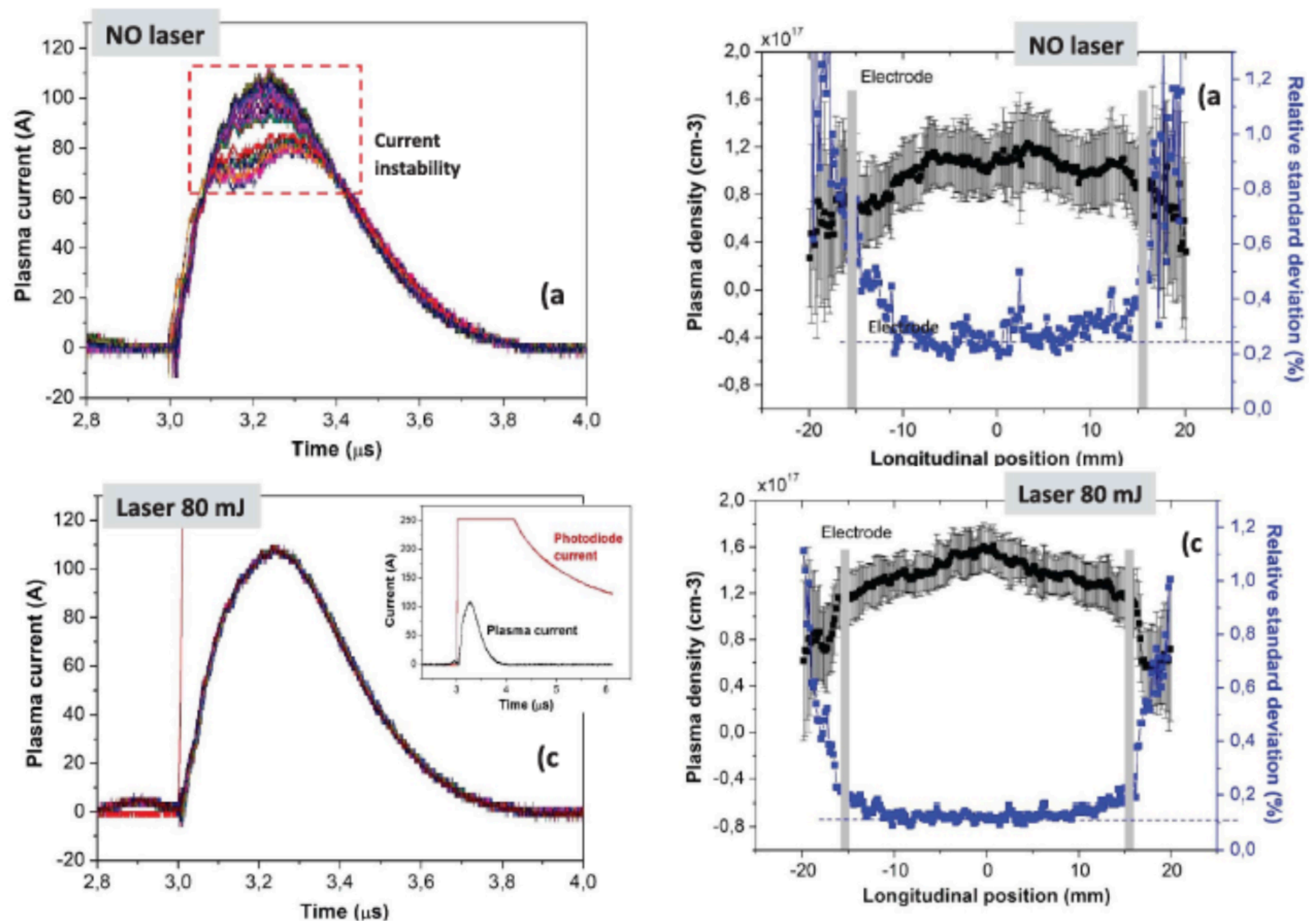


Gas-filled Capillary

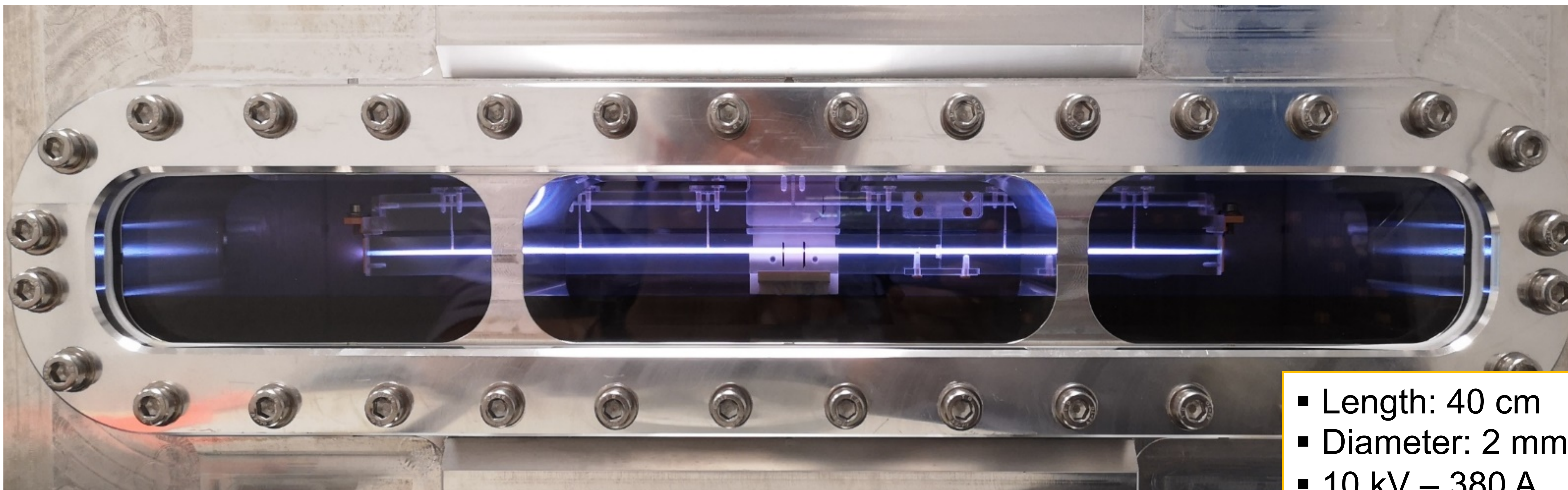
Discharge Stabilisation

Courtesy of A. Biagioni (INFN-LNF)

- Plasma density instability reduced **from 25% to 11%** at 5kV
- Instability of **5%** when operating **at 8 kV** (evaluated from Stark measurement)



First EuPRAXIA plasma source enabling **1.1 GeV** (1.5 GV/m) in **40 cm** length capillary ($n = 10^{16}$ cm^{-3})

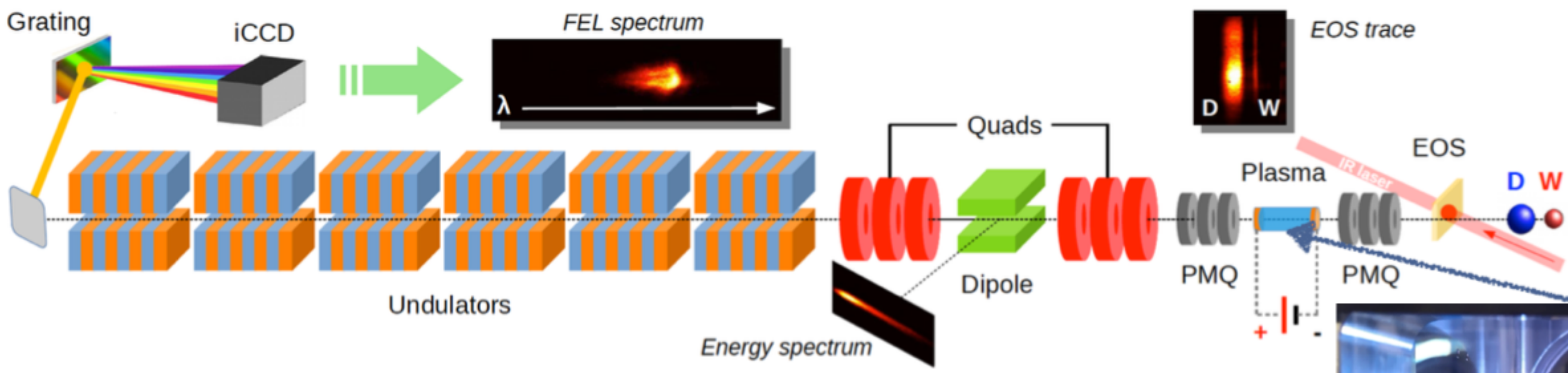


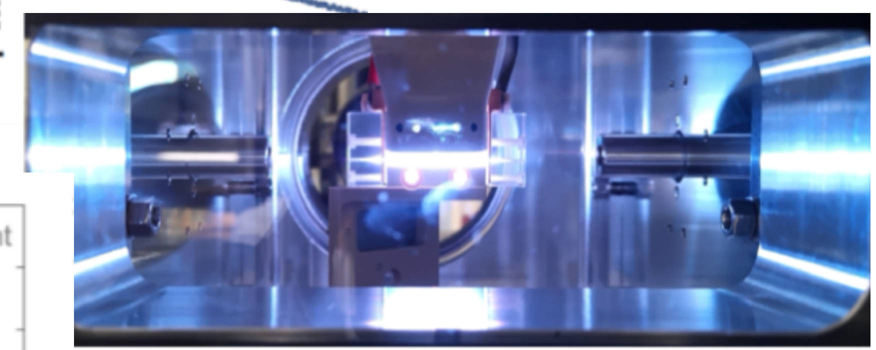
- Length: 40 cm
- Diameter: 2 mm
- 10 kV – 380 A (10^{17} cm^{-3})
- 6 inlets of 1 mm in diameter

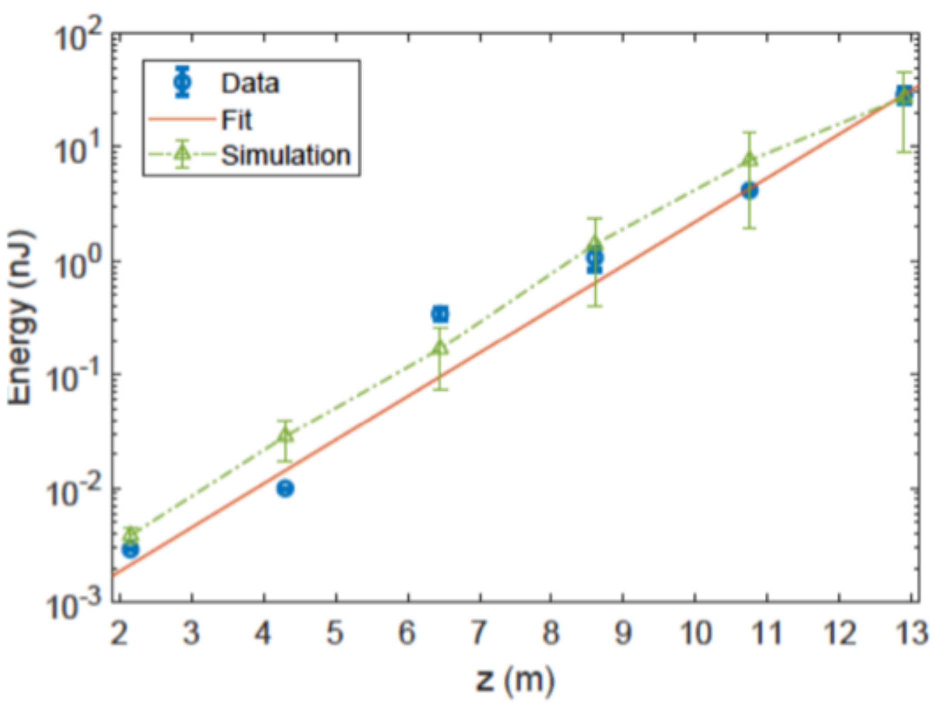
Courtesy of A. Biagioni (INFN-LNF)

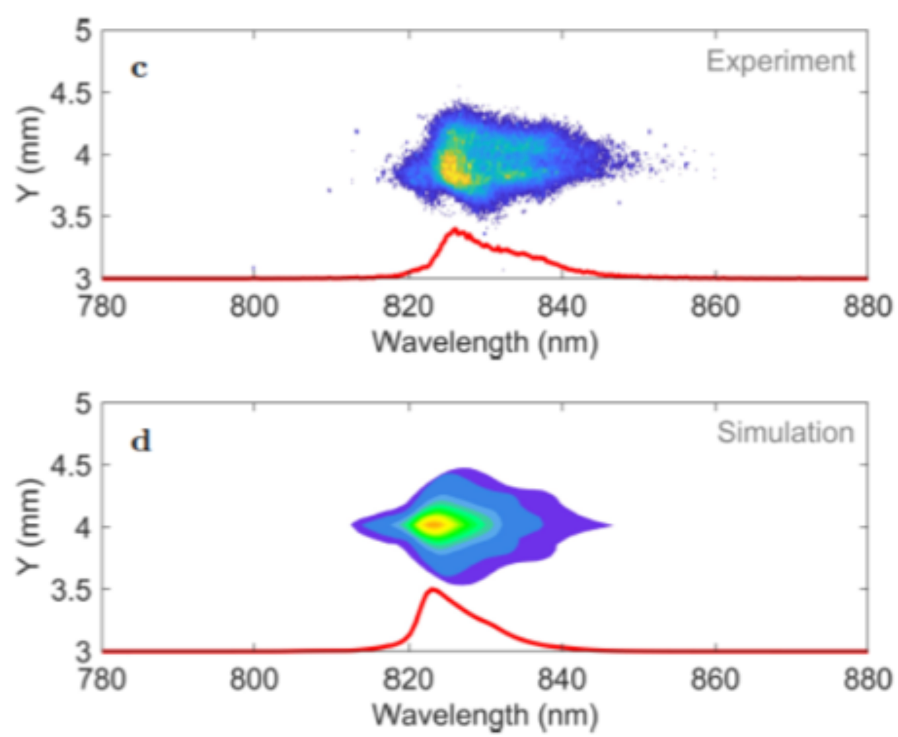
First SASE FEL lasing **from a beam-driven PWFA**

Feasibility proof at at SPARC_LAB (INFN, Frascati)





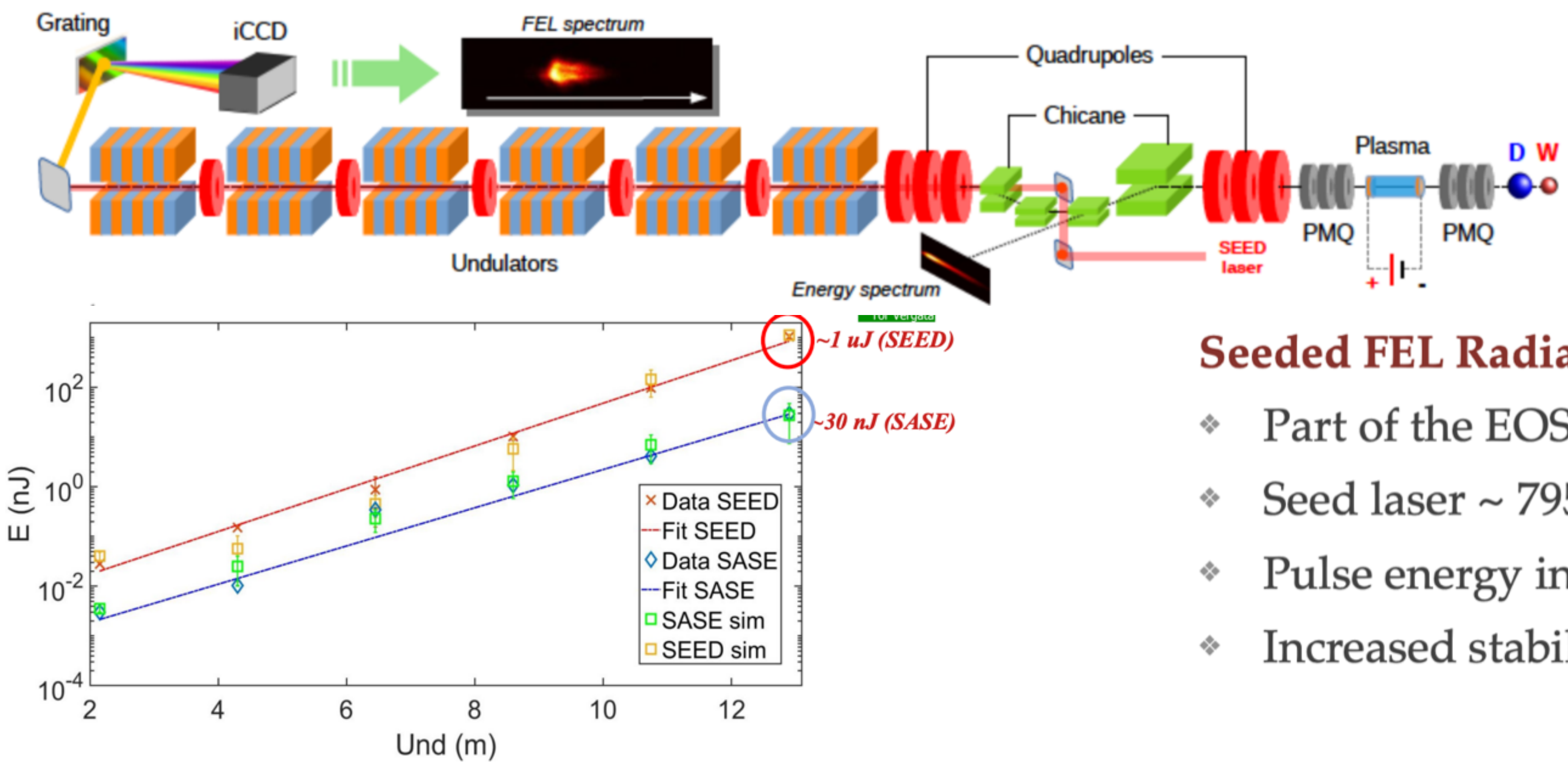




R. Pompili et al., Nature **605**, 659–662 (2022)

First Seeded FEL lasing **from a beam-driven PWFA**

Feasibility proof at SPARC_LAB (INFN, Frascati)



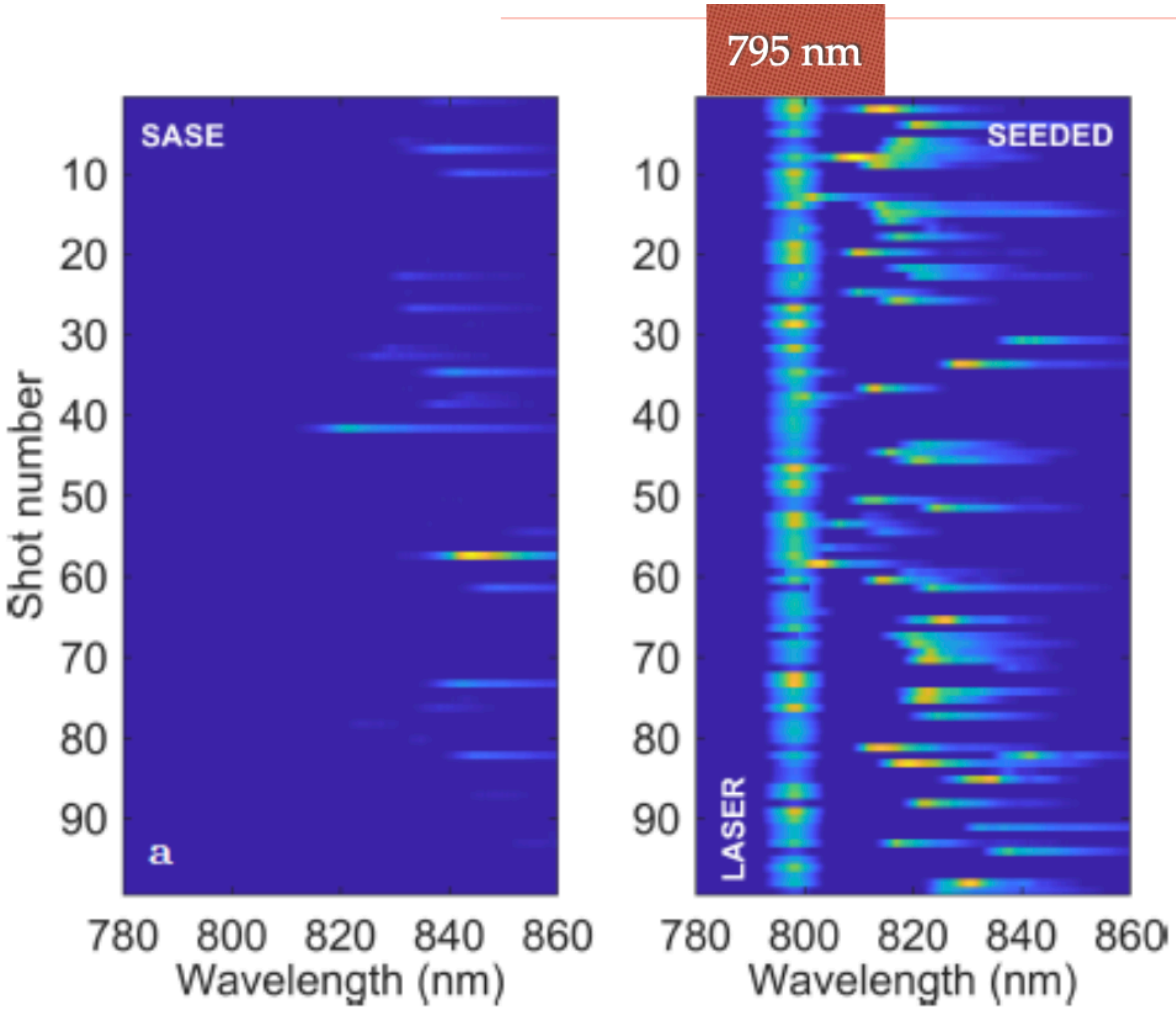
Seeded FEL Radiation

- Part of the EOS laser used as seed
- Seed laser ~ 795 nm, FEL peak 827 nm
- Pulse energy increase from 30 nJ up to 1 µm
- Increased stability of emitted radiation

M. Galletti et al., Phys. Rev. Lett. **129**, 234801 (2022)

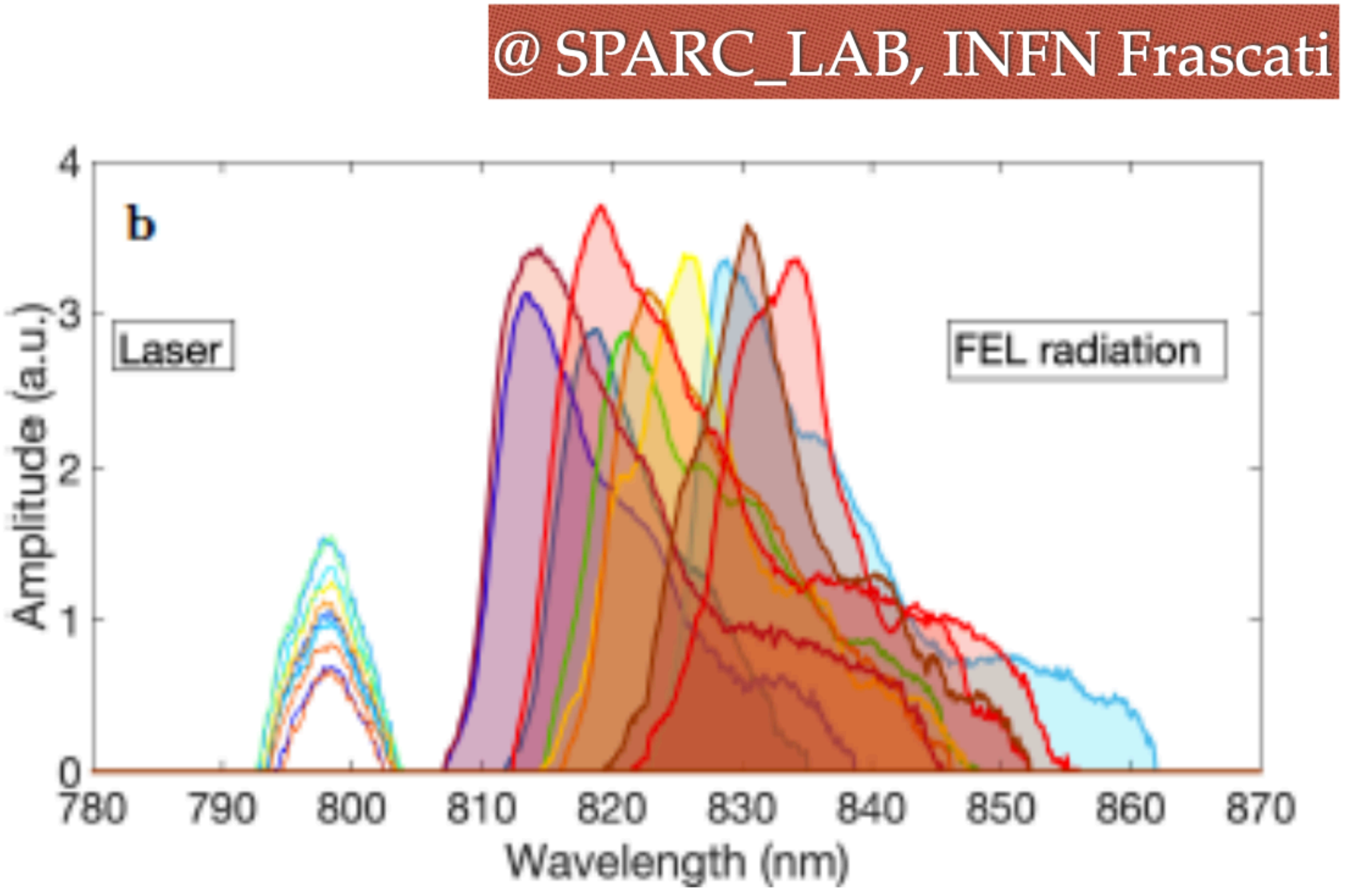
First Seeded FEL lasing **from a beam-driven PWFA**

Feasibility proof at SPARC_LAB (INFN, Frascati)



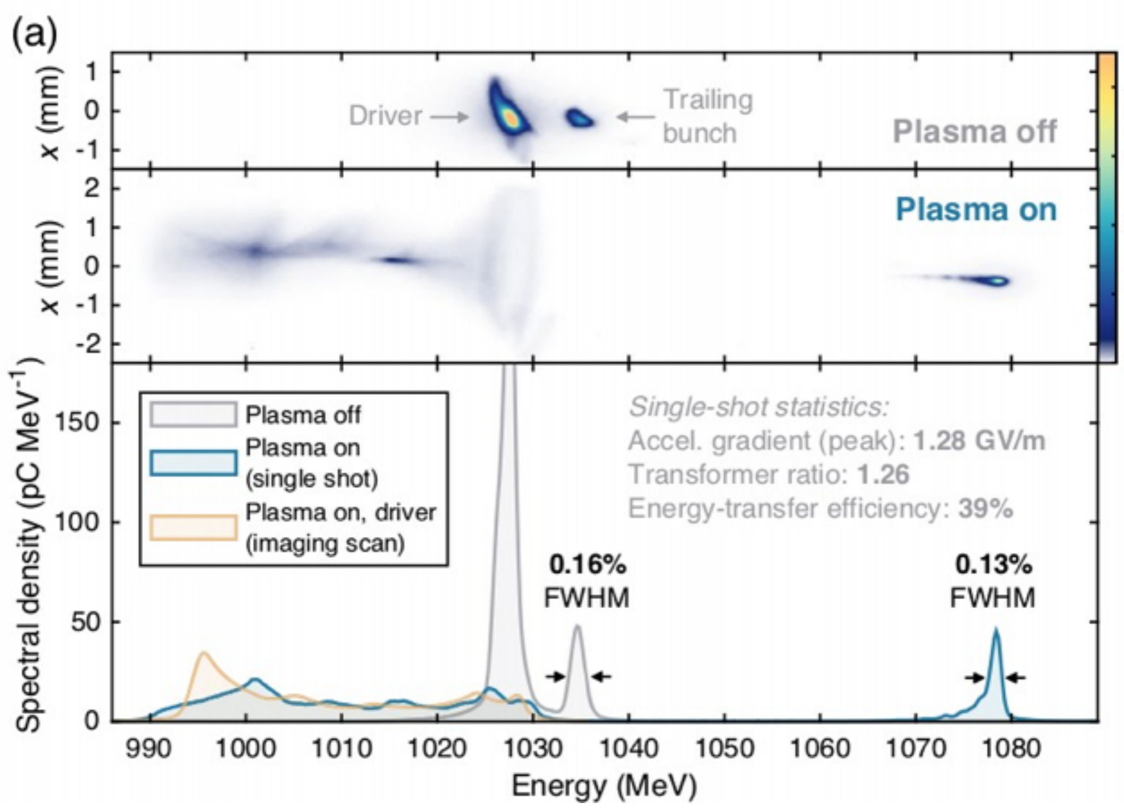
27% stability

90% stability

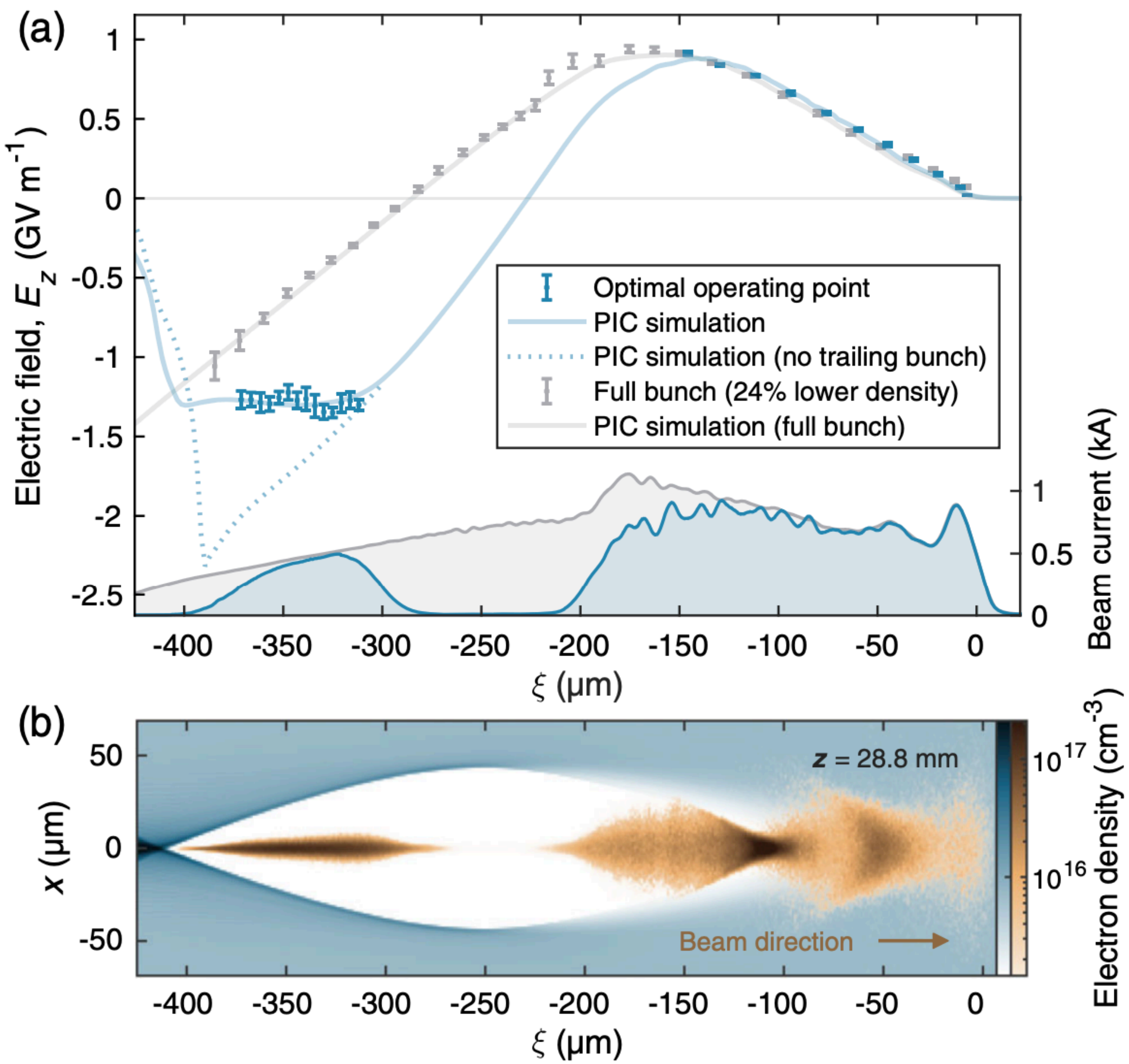


Other Advances towards Beam Quality

Lindstrøm, Carl Andreas, et al. "Energy-spread preservation and high efficiency in a plasma-wakefield accelerator." Physical review letters 126.1 (2021): 014801.



Direct measurement of the wakefield flattening



Solving Beam Quality Issues

- Several key challenges facing plasma-based facility operation **under control**
  - **stabilization and control of the acceleration process** (R. Pompili et al., Energy spread minimization in a beamdriven plasma wakefield accelerator, Nat. Physics **17**, no. 4, pp. 499-503, 2021; Ferran-Pousa et al., PRL 123, 054801, 2019)
    - energy spread mitigation, normalized emittance preservation, overall stability gain
- **Improvements still needed** to guarantee continuous operation
  - sub-percent to sub-per-mille energy spread and **mm mrad to sub-mm mrad emittances**
  - increase of the **repetition rate** from a few hertz to kilohertz (R. D Arcy et al., *Recovery time of a plasma-wakefield accelerator*, Nature **603**, pp. 58–62, 2022)
  - improvement of shot-to-shot stability

Conclusions

- **Impressive progress worldwide has been done toward the operation of a FEL user facility**
  - Recent demonstration of SASE FEL driven by PWFA (SPARC_LAB, INFN -Frascati), LWFA (SIOM, Shangai) and LWFA Coxinel experiment at HZDR (Dresden)
    - The success of these research efforts is predicated on the ability of the community to overcome several key challenges facing plasma-based FEL operation
      - **stabilization and control of the acceleration process**, which turns into **energy spread mitigation**, normalized **emittance preservation**, overall stability gain
- However, still improvements are needed in terms of
  - electron beam quality
    - sub-percent to sub-per-mille energy spread and mm mrad to sub-mm mrad emittances
  - increase of the repetition rate from a few hertz to kilohertz
  - improvement of shot-to-shot stability
- An entire community is working hard to achieve this result and the selection of EuPRAXIA, as first ever plasma accelerator project, in the ESFRI Roadmap is the validation of the quality and readiness of the work done and the technology
- The R&D now concentrates on **beam stability, staging, high repetition rate, continuous operation**, as necessary steps **towards the realization of compact plasma-based accelerator facilities**
- Plasma-based, ultra-high gradient accelerators therefore open the realistic vision of very compact accelerators for scientific, commercial and medical applications