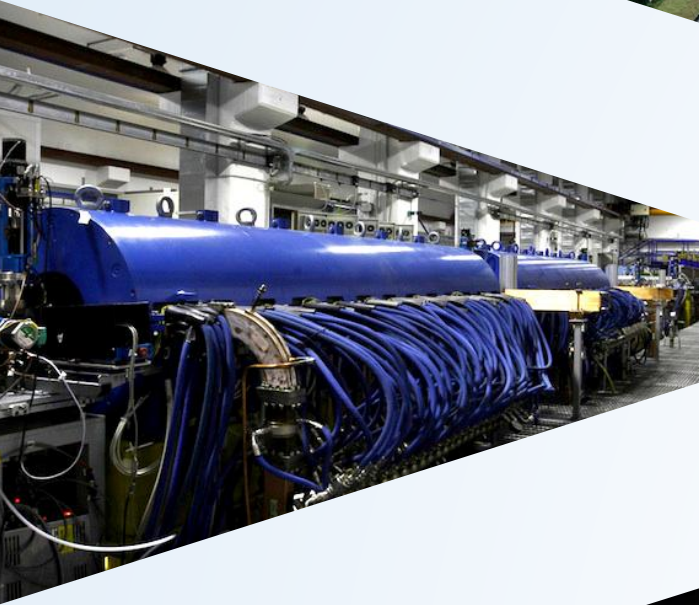
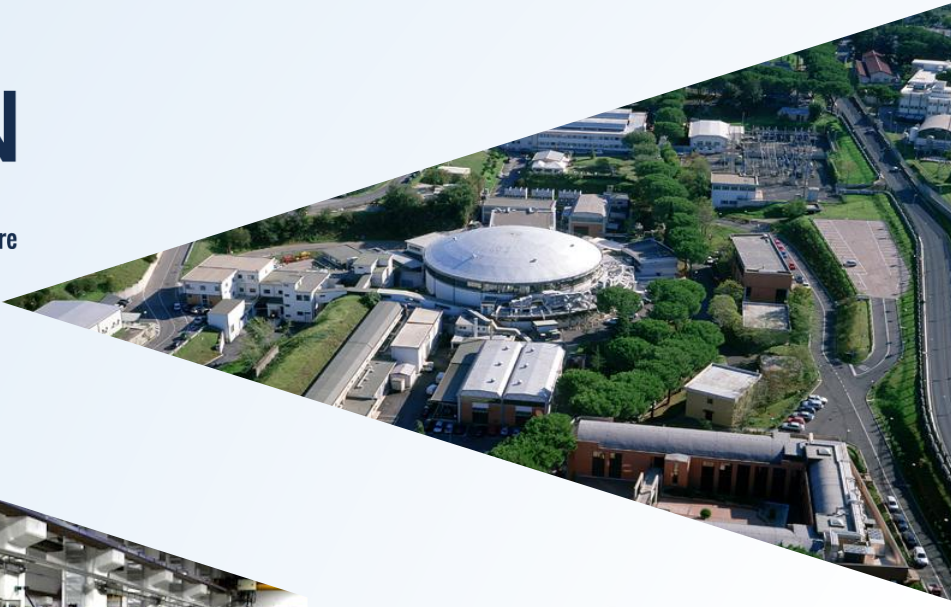




Istituto Nazionale di Fisica Nucleare



From Conventional to Cutting-Edge: A Journey Through Free-Electron Lasers and the Plasma Frontier

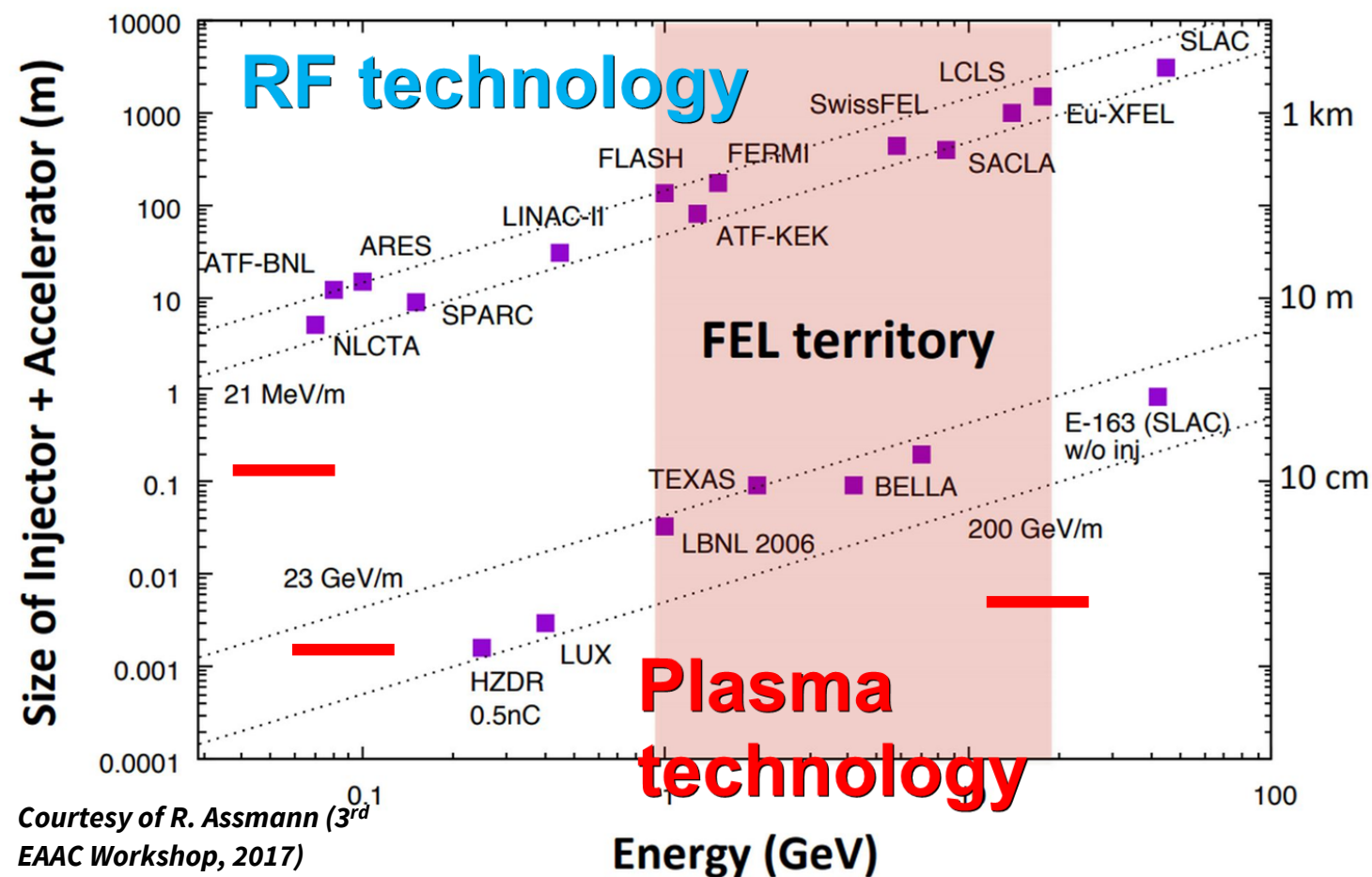
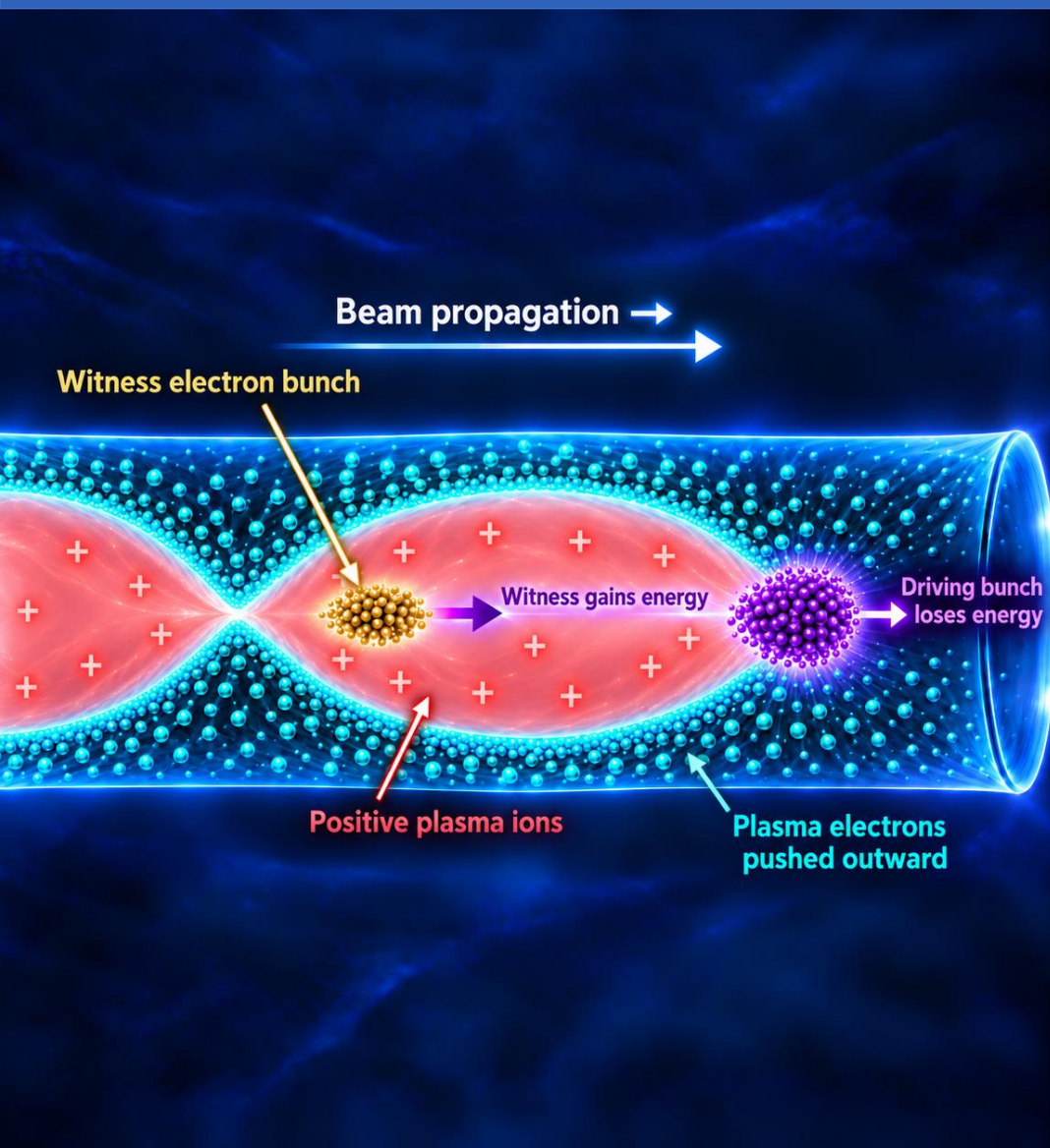
Stefano Romeo stefano.romeo@Inf.infn.it

ENEA, Frascati



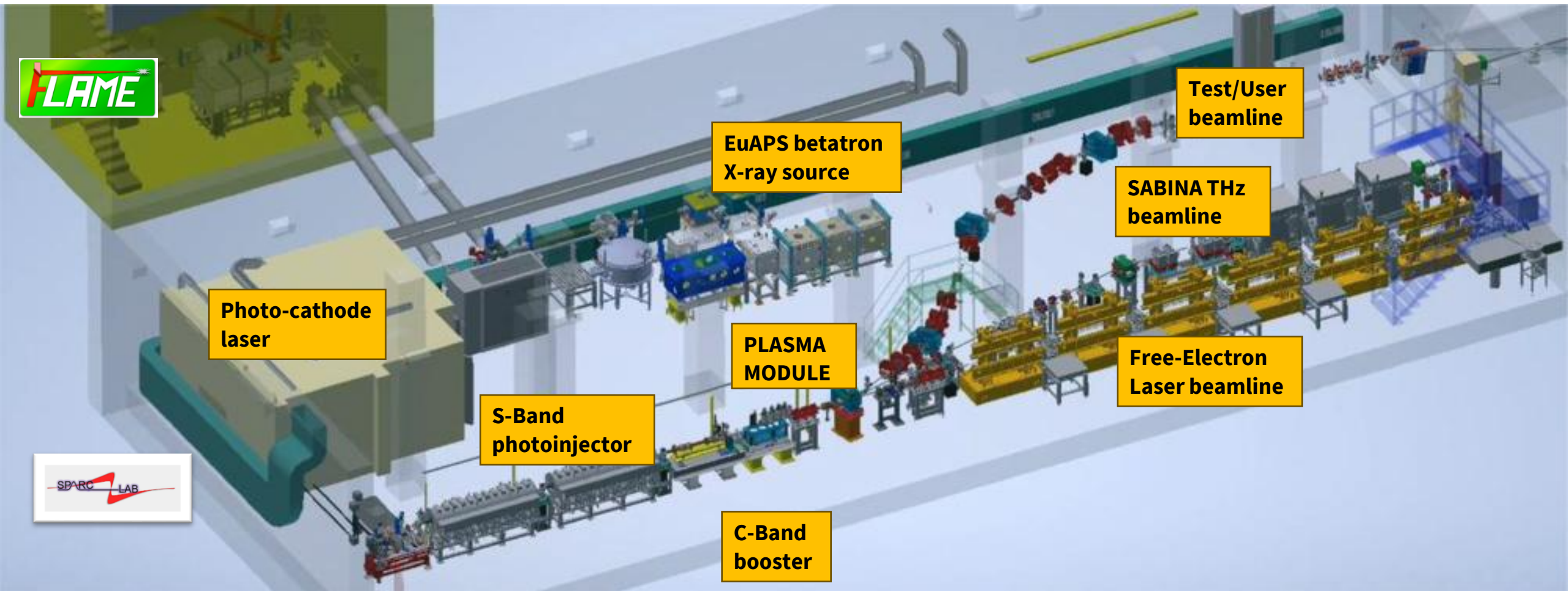
8th International Conference Frontiers in Diagnostics Technologies

A look forward: Standard vs Plasma accelerators



Plasma acceleration allows to reach extreme values of accelerating gradients if compared with RF counterparts, allowing to reach interesting energies for FEL radiation in cm scale

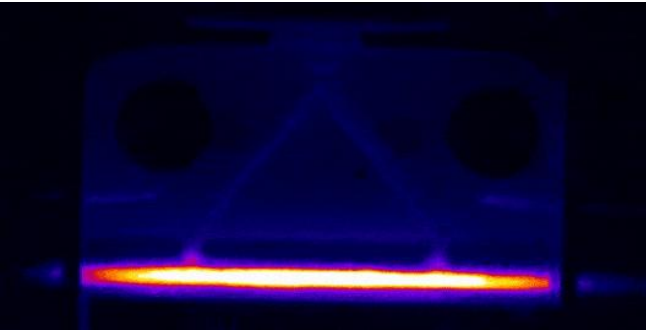
INFN: The SPARC_LAB facility



Pompili, R., et al. "SPARC_LAB facility for advanced acceleration and radiation experiments." *Physical Review Accelerators and Beams* 29.5 (2026): 051602.

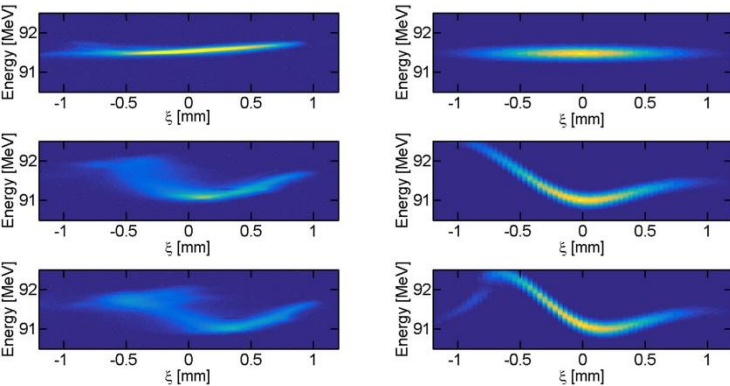
Plasma acceleration: **Experimental layout**

Plasma characterization via Stark broadening effect

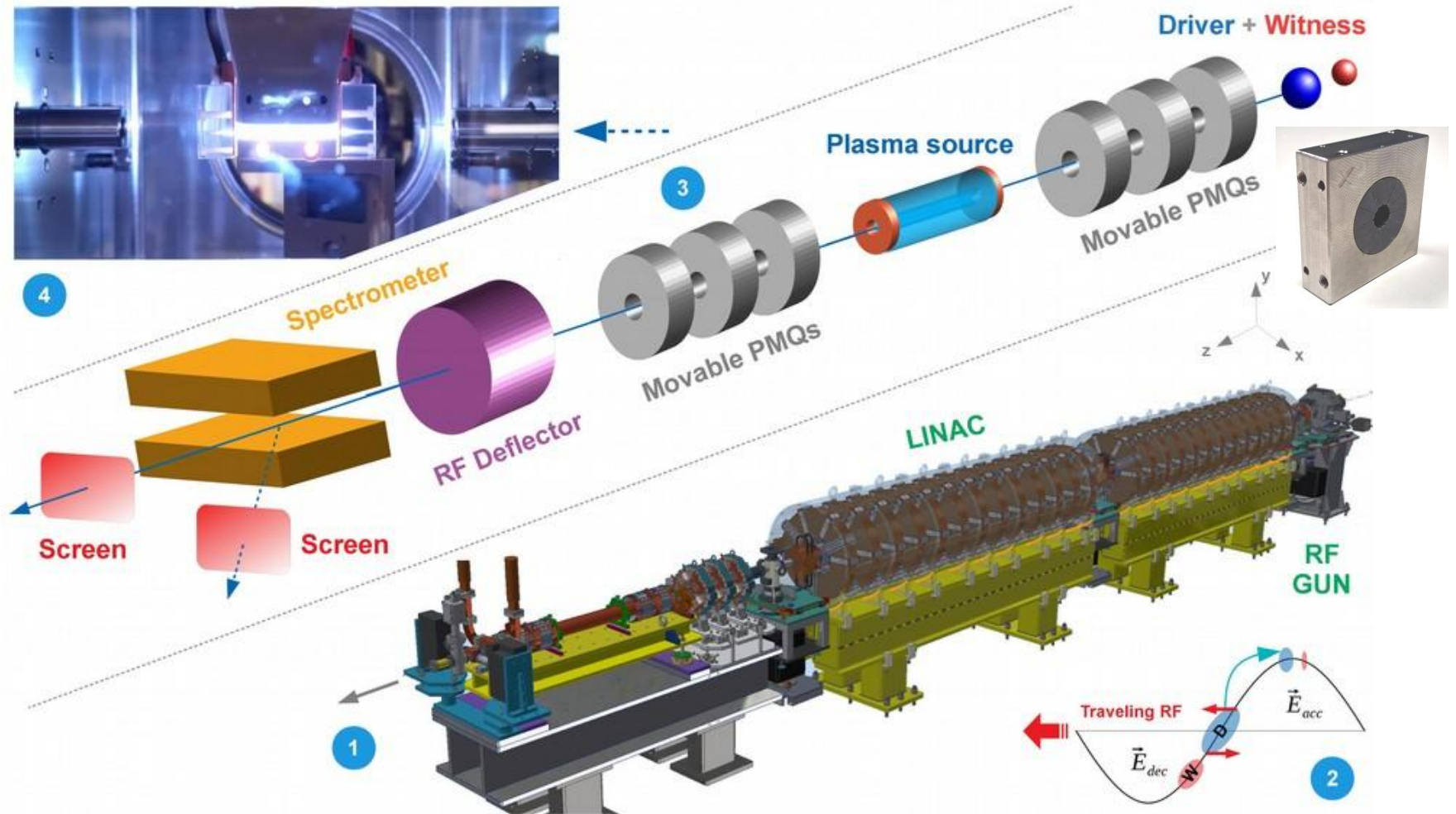


Biagioni A., et al., JINST 11.08 (2016): C08003.

Beam based plasma density evaluation



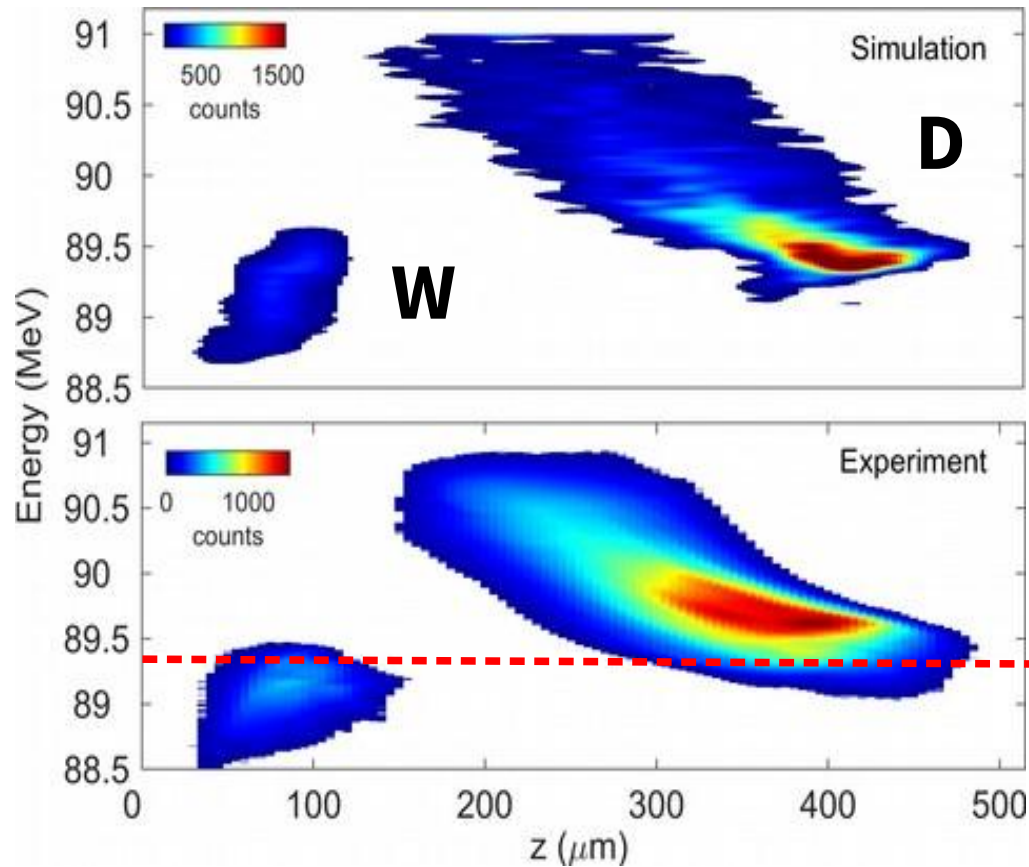
Romeo, S., et al. AIP Advances 11.6 (2021).



Plasma acceleration: Beam configuration



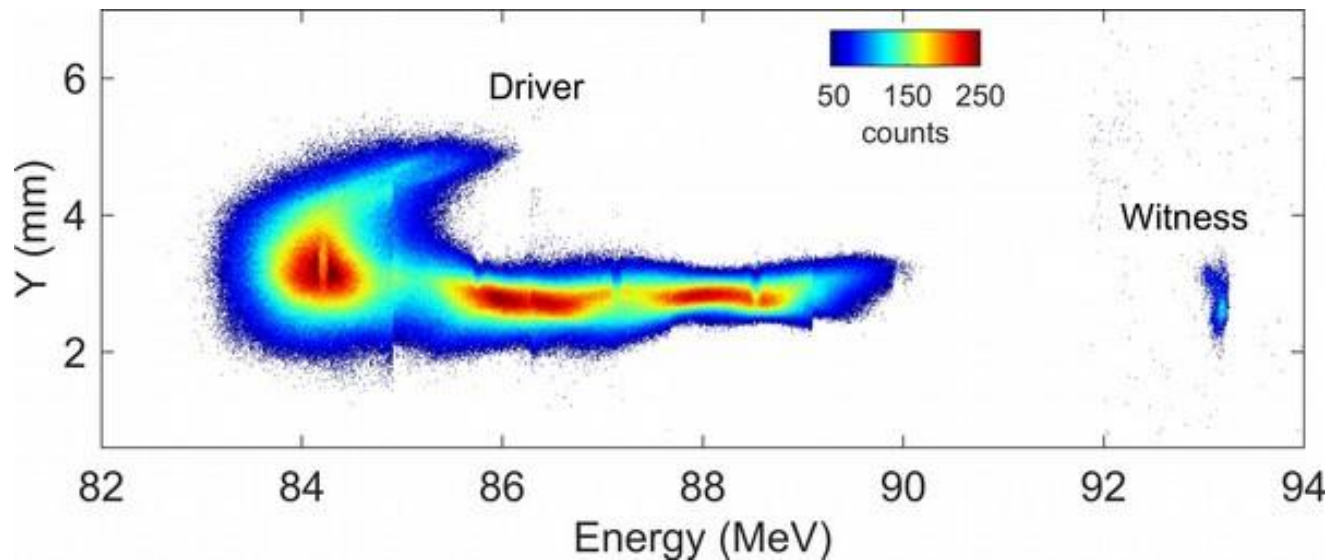
- Two-bunches configuration, produced directly at the cathode with **laser-comb technique**, with a time-separation of approximately ~ 1 ps



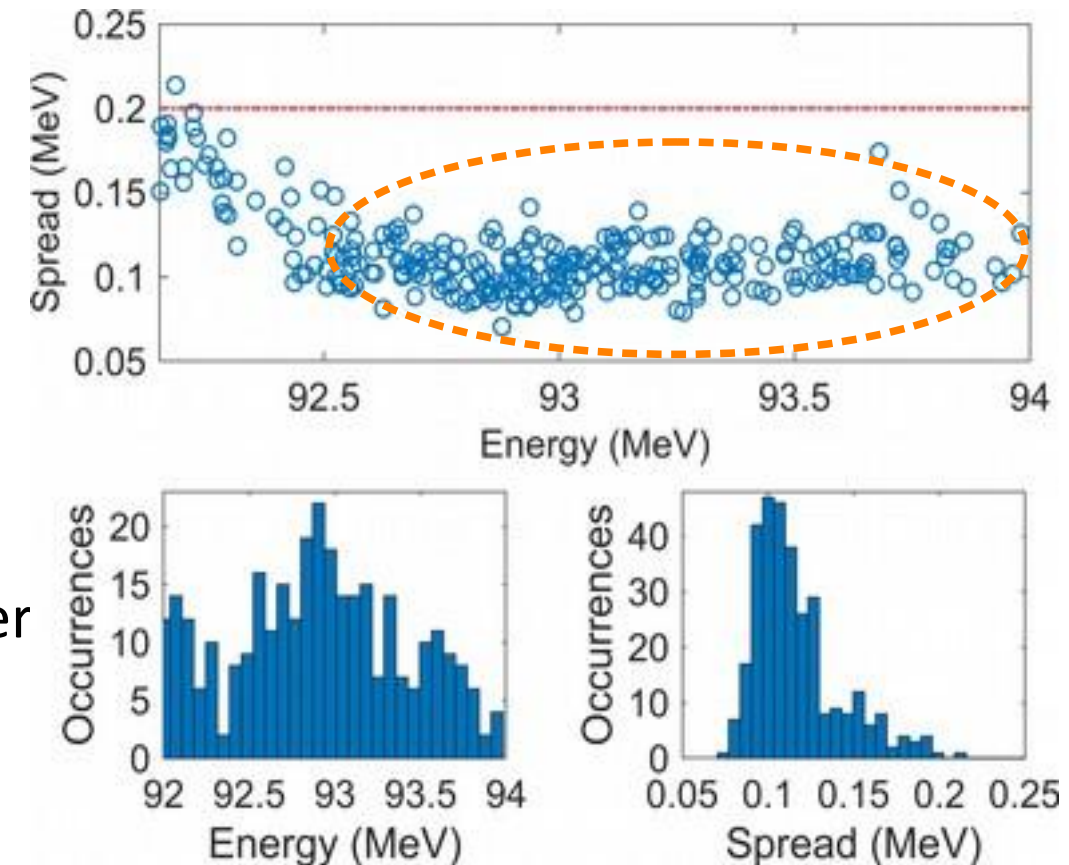
COMB	Driver	Witness
Q (pC)	200	20
τ (fs)	200	30
σ (μm)	20	14
E (MeV)	89.5	89.1
σ_E (MeV)	0.2	0.2
ϵ_x (μm)	2.5	1.4
ϵ_y (μm)	1.7	1.2

Nearly the same energy with plasma OFF

FEL requirements: Towards high quality



- 4 MeV acceleration in 3 cm plasma with 200 pC driver
 - $2 \times 10^{15} \text{ cm}^{-3}$ plasma density
 - $\sim 133 \text{ MV/m}$ accelerating gradient
- **Energy spread**
 - *from 0.2 MeV*
 - *to 0.12 MeV*
 - *adopting the assisted beam-loading technique*



Pompili, R., et al. "Energy spread minimization in a beam-driven plasma wakefield accelerator." *Nature Physics* 17.4 (2021): 499-503.

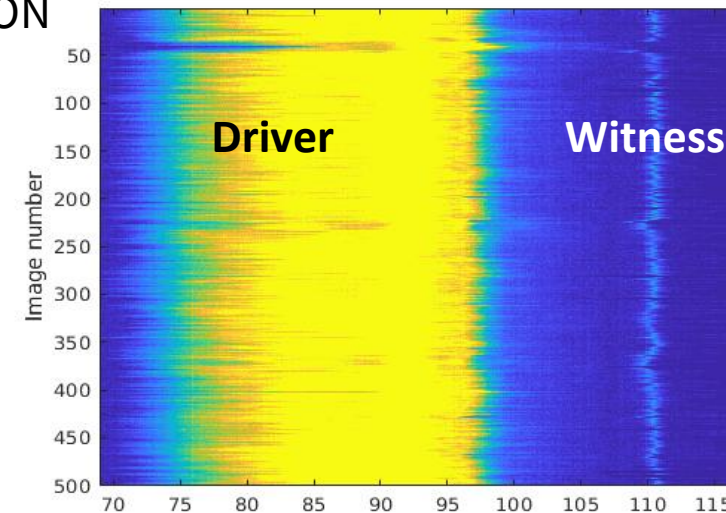
FEL requirements: **Towards stable operation**

- There are two main sources of jitter
 - ❖ Driver-witness separation jitter in a beam-driven plasma is limited by RF sync
 - ❖ Plasma density fluctuations
- To reduce the 2nd source, we pre-ionize the gas with an external laser
 - The laser (~100 uJ, 2mm diameter) reaches the negative electrode hole ~200ns before the discharge trigger.

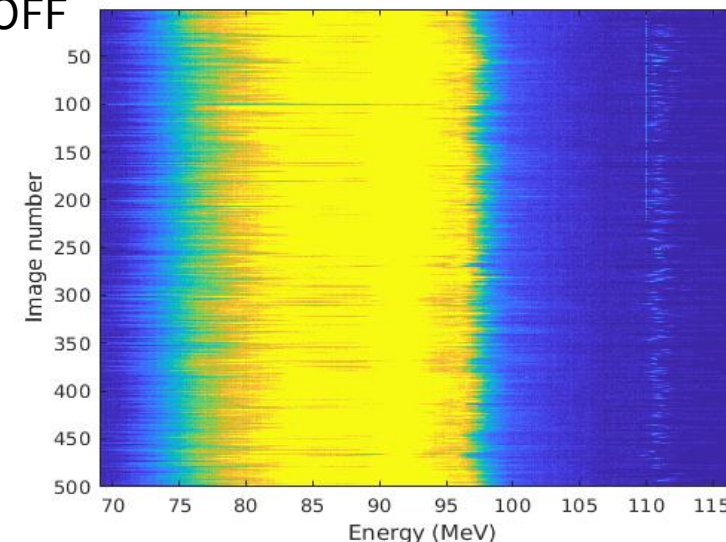
Biagioni A., et al. "Gas-filled capillary-discharge stabilization for plasma-based accelerators by means of a laser pulse." *Plasma Physics and Controlled Fusion*.

M. Galletti, et al.: "Advanced Stabilization Methods of Plasma Devices for Plasma-Based Acceleration." *Symmetry* 2022, 14(3), 450.

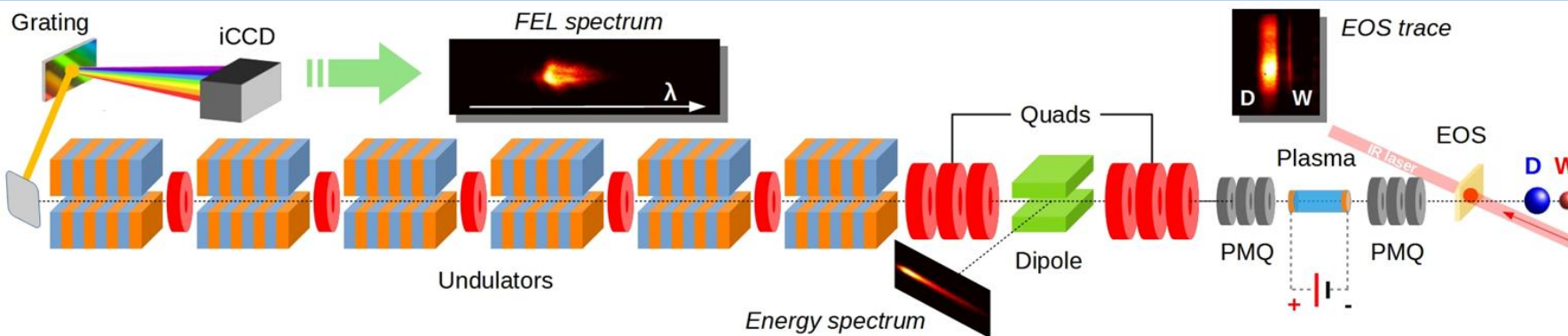
Laser ON



Laser OFF

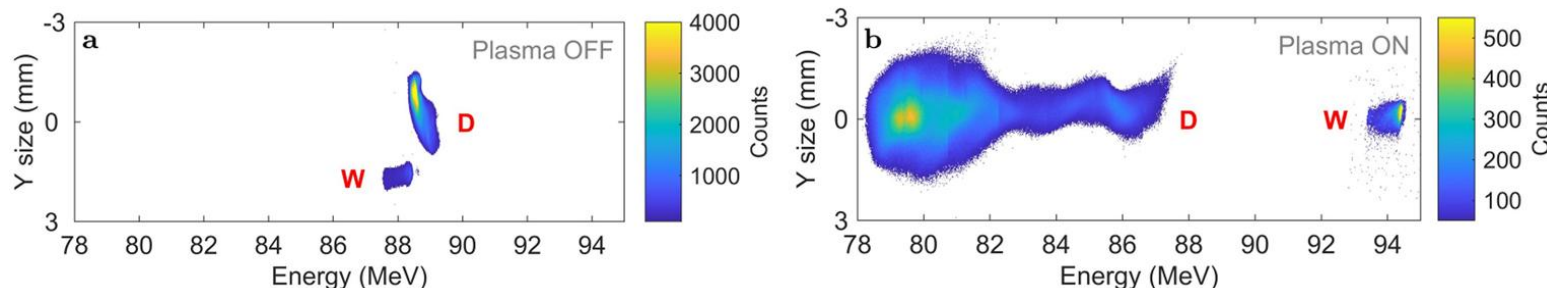


Demonstration: Plasma driven SASE FEL



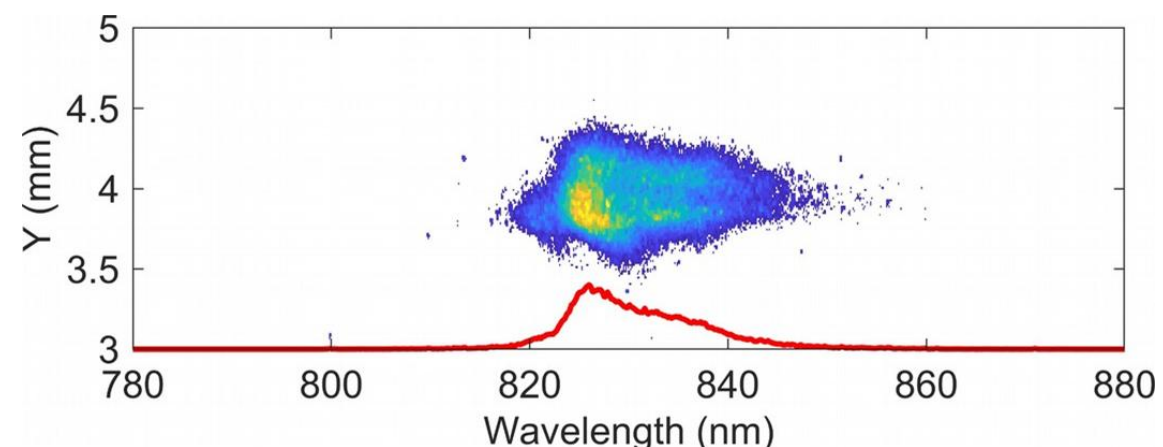
15 m FEL beamline

- $L_u = 2.5$ m
- 77 periods
- $\lambda_u = 2.8$ cm
- $K = 1.4$
- $L_g = 1.1$ m

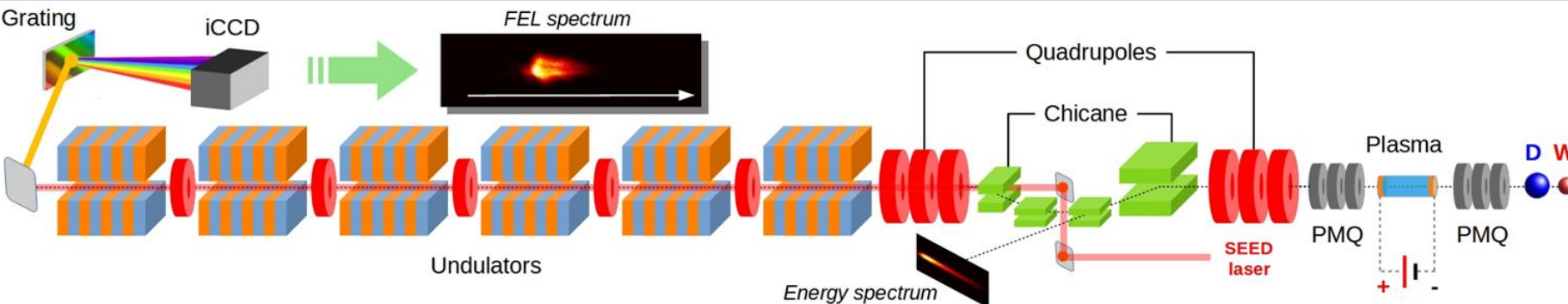


200 MV/m of acceleration with a plasma density $n_p \approx 1.6 \cdot 10^{15} \text{ cm}^{-3}$

Witness		E (MeV)	94
Q (pC)	20	σ_E (MeV)	0.3
τ (fs)	30	ϵ_x (μm)	2.7
$\sigma_{x,y}$ (μm)	200	ϵ_y (μm)	1.3

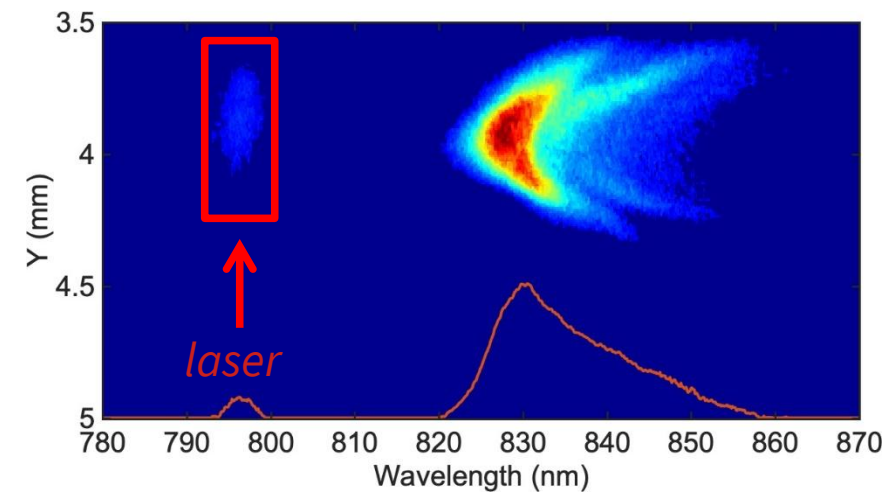


Demonstration: Plasma driven seeded FEL

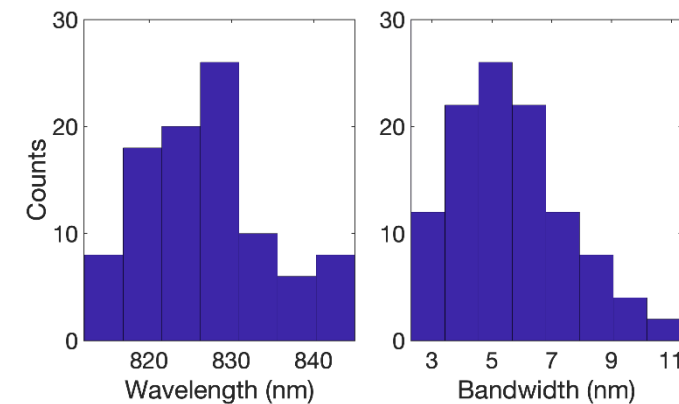
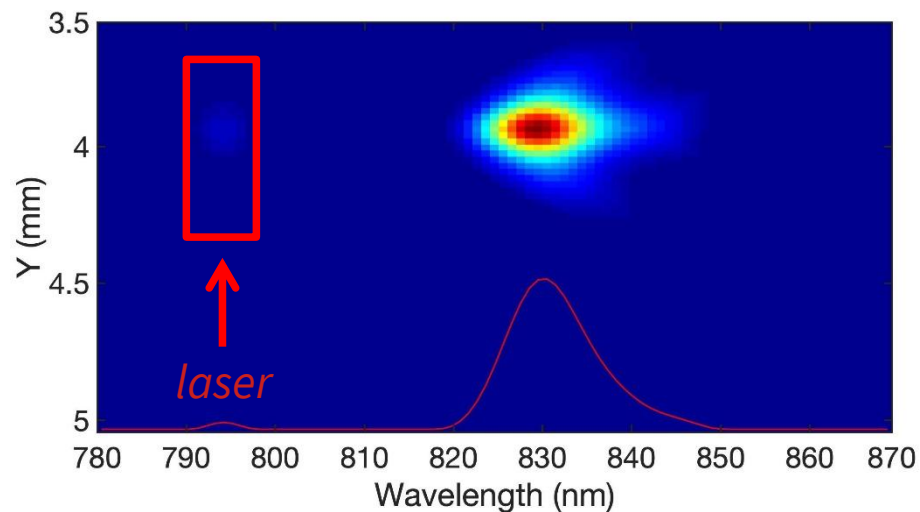


The layout is extended and part of the IR EOS laser is used in order to be used as a seeding for the FEL radiation

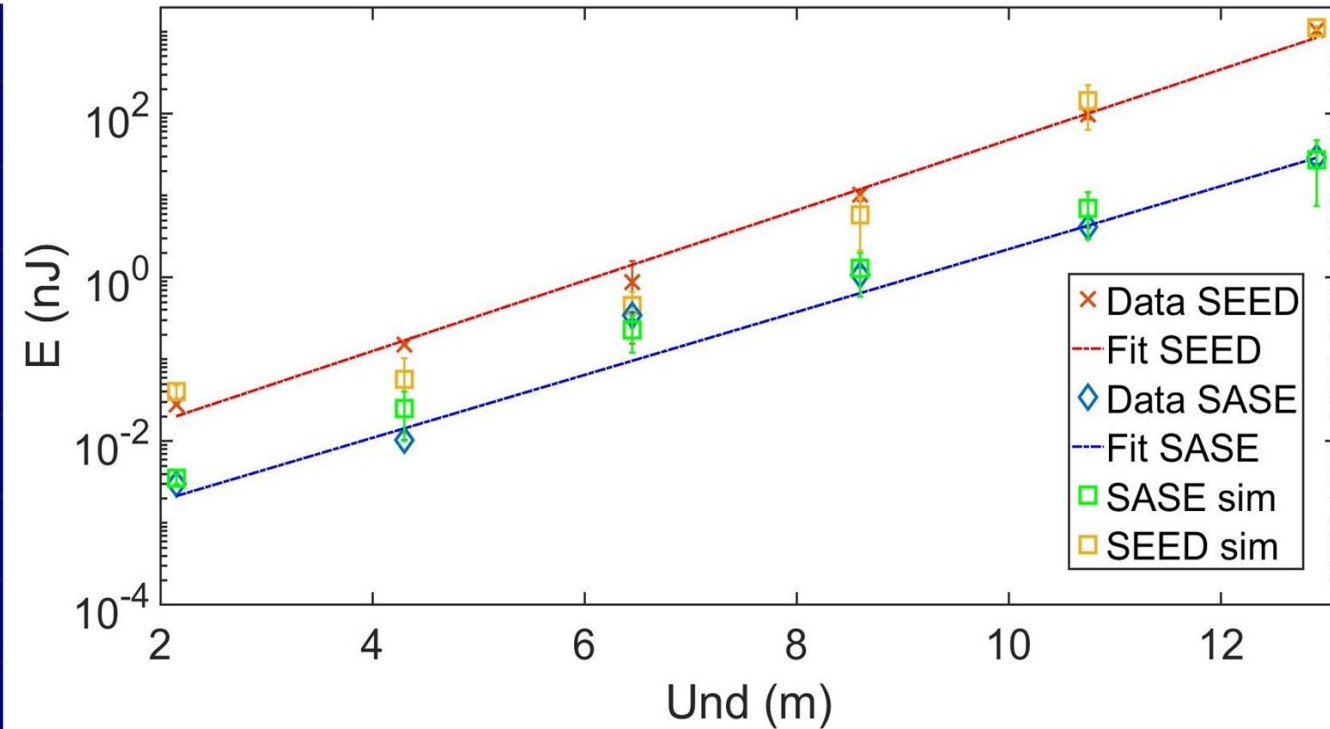
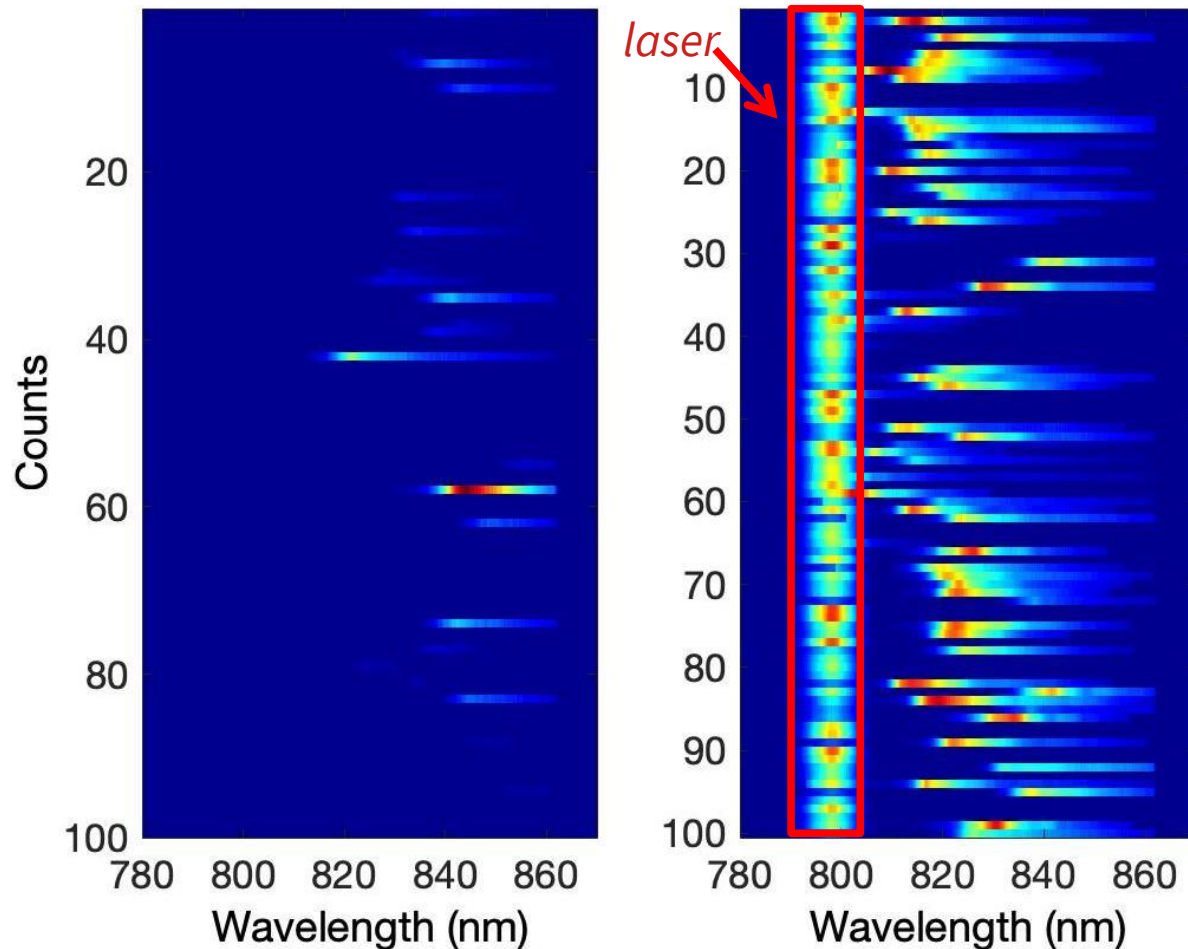
Experimental spectrum



Theoretical spectrum



FEL operation: SASE vs seeded performance

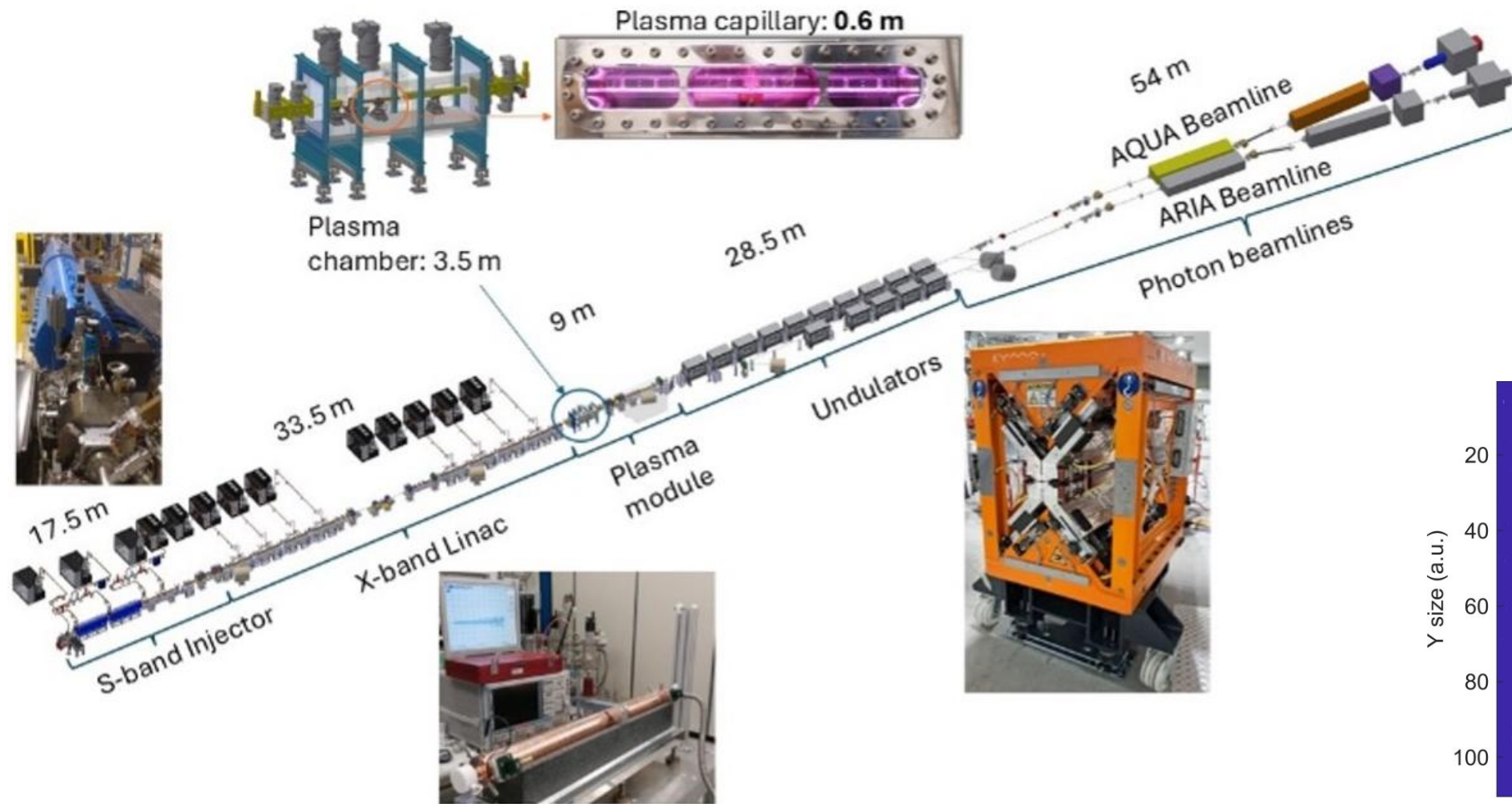


The presence of the seeding dramatically improved the performance of the plasma driven FEL both in terms of power (30 nJ vs 1 μ J) and in stability of the radiation

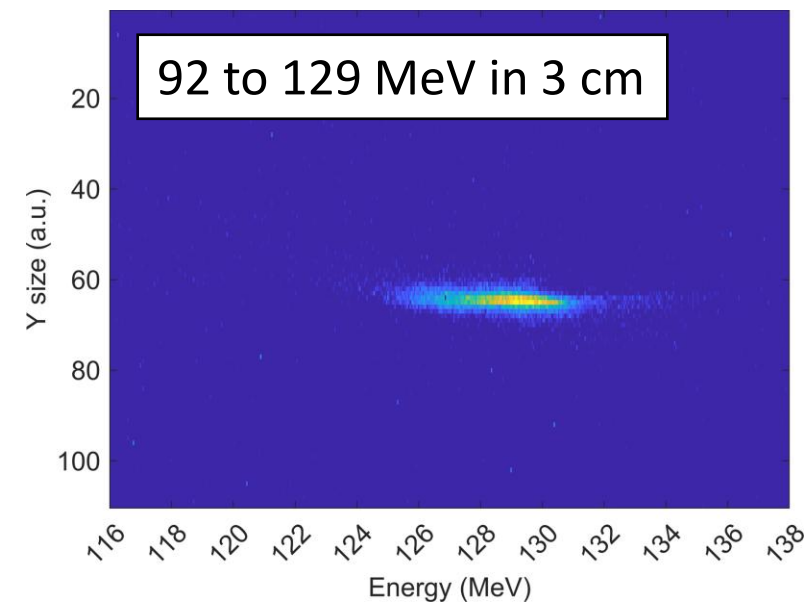
M. Galletti, et al.
“Stable Operation of a Free-Electron Laser Driven by a Plasma Accelerator”,
Physical Review Letters 129 (23), 234801 (2022).

EuPRAXIA: Towards energy doubling

SPARC LAB



First results have shown that we are in principle able to achieve accelerating gradients of the order of GV/m



Thank you
for
the attention!

Stefano Romeo stefano.romeo@Inf.infn.it

ENEA, Frascati

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