Beam Dynamics Studies For A Stable, Reliable And Reproducible High Brightness, High Gradient Plasma Wakefield Accelerator

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On behalf of SPARC_LAB collaboration

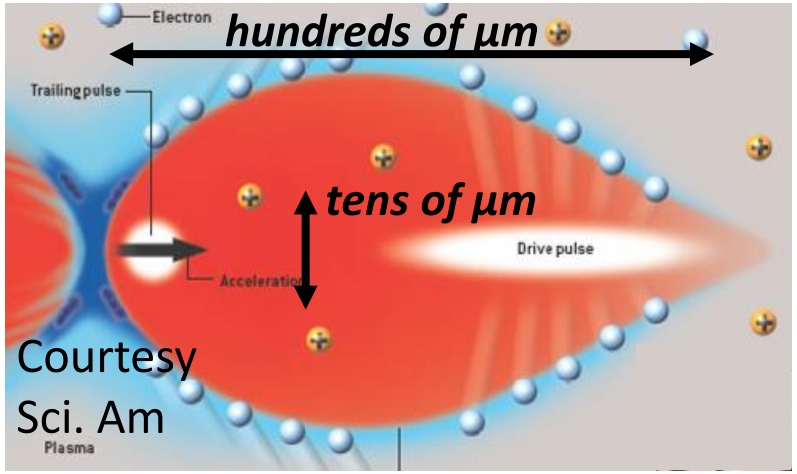
Outline

- Compact high brightness RF injector as guide of PWFA
- The SPARC_LAB plasma acceleration experiment
- The EuPRAXIA@SPARC_LAB case study
- Conclusions and Perspectives

Compact high brightness RF injector as guide of PWFA

Critical parameters for an efficient and stable operation of a PWFA are

- μm scale bunch length and twiss parameters at plasma injection↔ accelerated beam quality
- fs scale precision of the temporal distance between the bunches ↔ energy jitter
- Shape and peak current of the witness bunch ↔ energy spread (beam loading)



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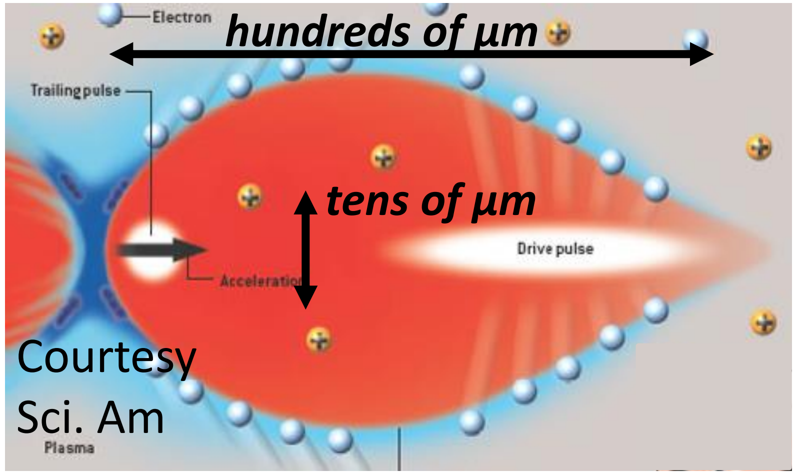
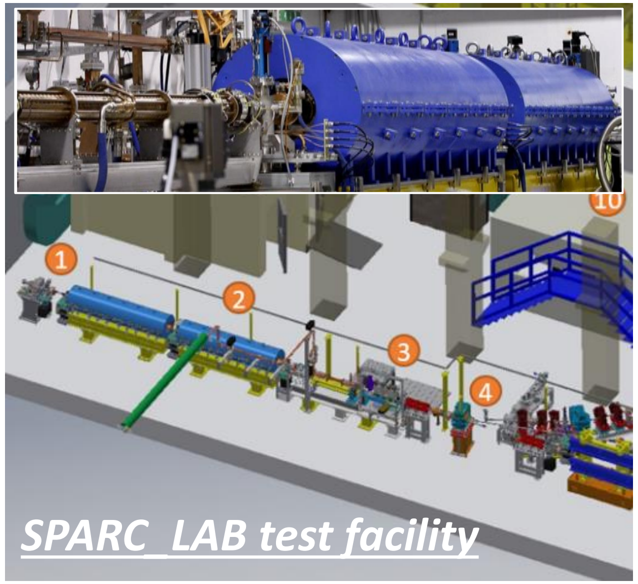
- A *compact high brightness RF injector* could provide e^- beams with parameters in a very wide range





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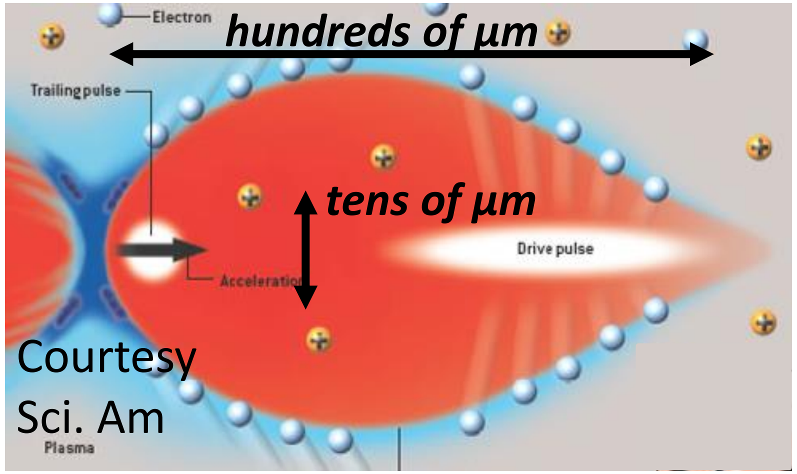
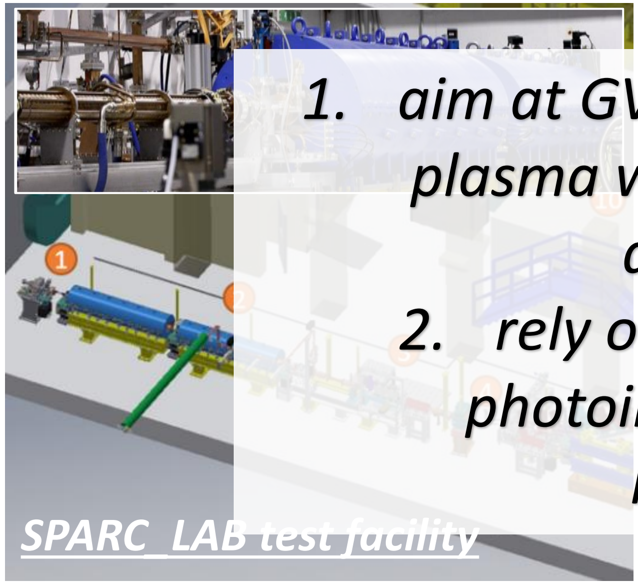
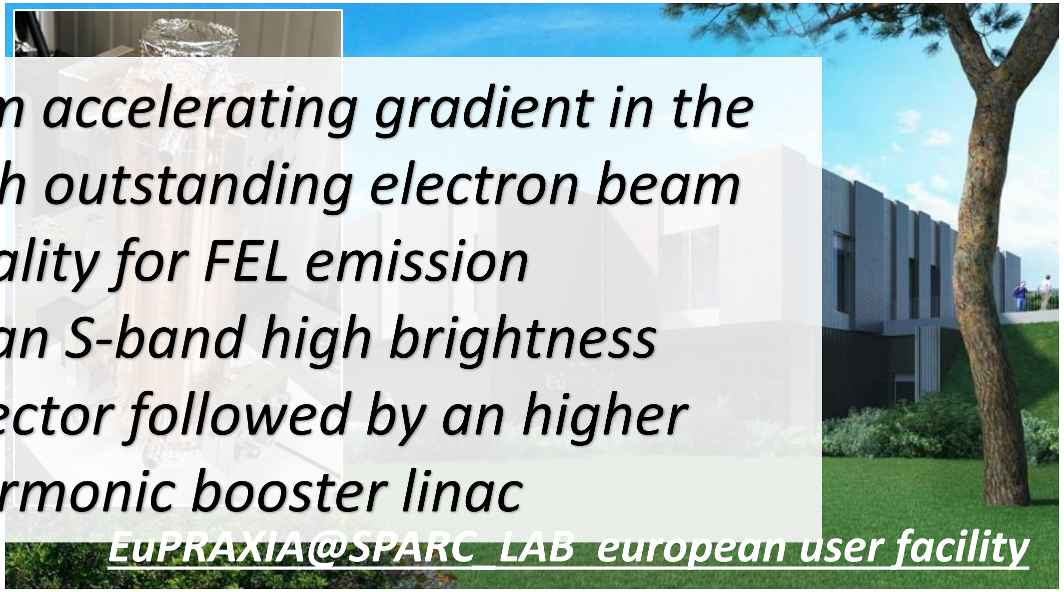


Courtesy Sci. Am





The Working Point Definition

- Beside the FEL specifications, the working point is determined by the plasma module
  - Accelerating gradient of the order of GV/m
  - Weakly non-linear regime (bubble with resonant behaviour)

1. 200-500 pC driver + 30-50 pC witness
2. plasma density of the order of $10^{16}\ cm^{-3}$ (λ_p = 334 μm)

3. Driver-witness separation of $\lambda_p/2$ (around 0.5 ps)
4. Driver and witness bunches of 200 fs and 10 fs rms
5. Driver and witness spot size of few μm rms with α=1

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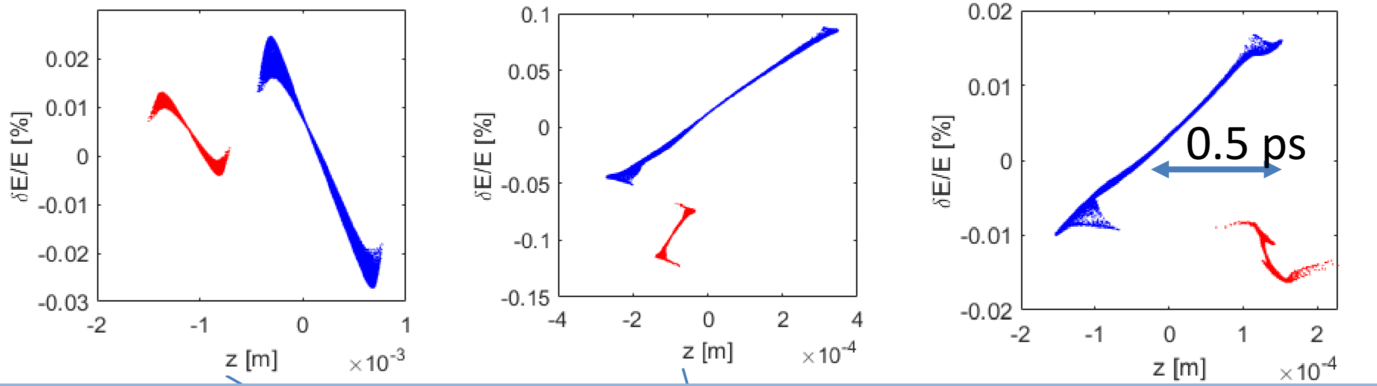
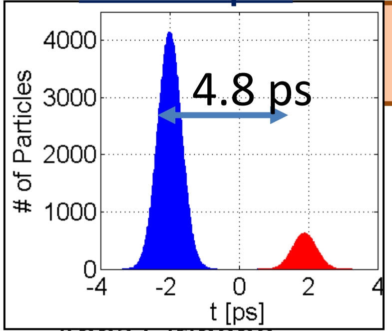
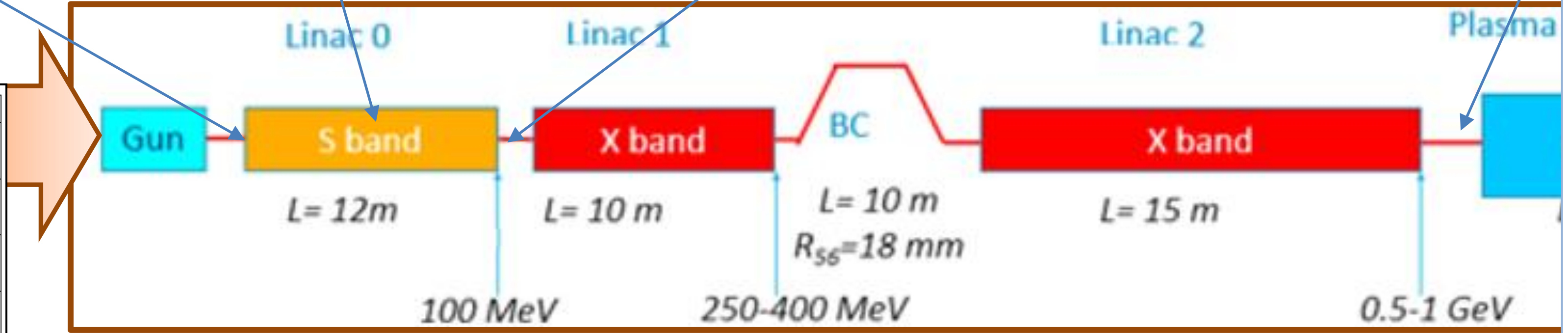
Velocity bunching technique

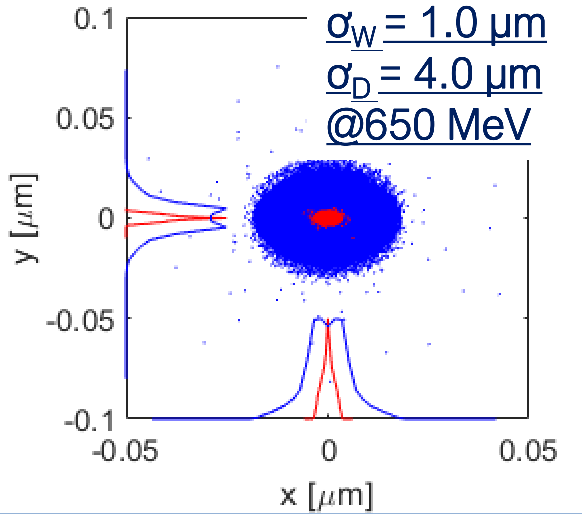


Laser comb technique





Strong focusing system

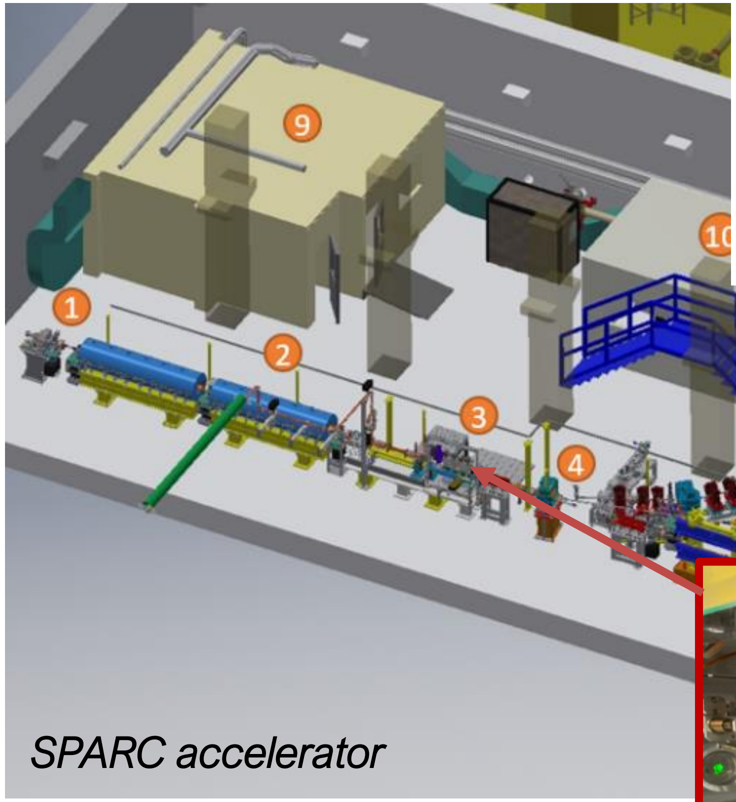


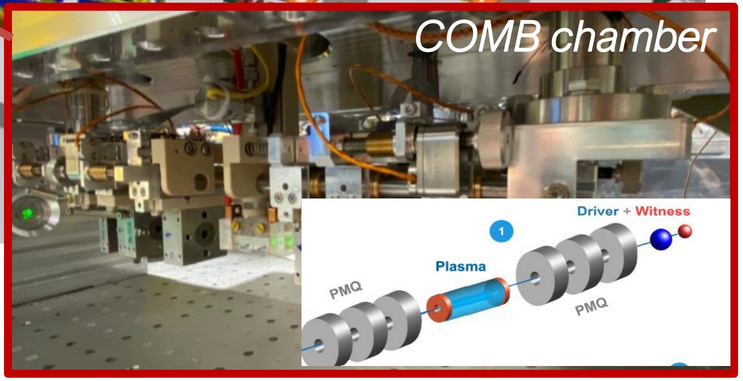
The SPARC_LAB test facility and the COMB2FEL experiment

- SPARC_LAB [1] is a test facility located at the INFN National Laboratories in Frascati
- The test facility hosts a 180 MeV high brightness photoinjector which feeds a 12 m long undulator.
- Main research activities regard the investigation of beam manipulation techniques and linac matching schemes useful for
  - linac-based radiation sources
  - new advanced acceleration concepts, such as plasma-based acceleration

generation of an FEL radiation source driven by a plasma beam-driven accelerator module (PWFA) [2]

Parameter	Value
Number of bunches	1 - 5
Delay between bunches	0.5 ps - 20 ns*
Charge	10 pC - 2 nC
Duration	20 fs - 10 ps
Energy	5 - 180 MeV
Energy spread	0.1 - 5 MeV
Normalized emittance	0.3 - 10 μm





[1] R. Pompili et al. "Recent results at SPARC_LAB", NimA 909, doi.10.1016/j.nima.2018.01.071 (2018)
[2] R. Pompili et al., "Free-electron lasing with compact beam-driven plasma wakefield accelerator", Nature 605, 7911, doi.org/10.1038/s41586-022-04589-1 (2022)

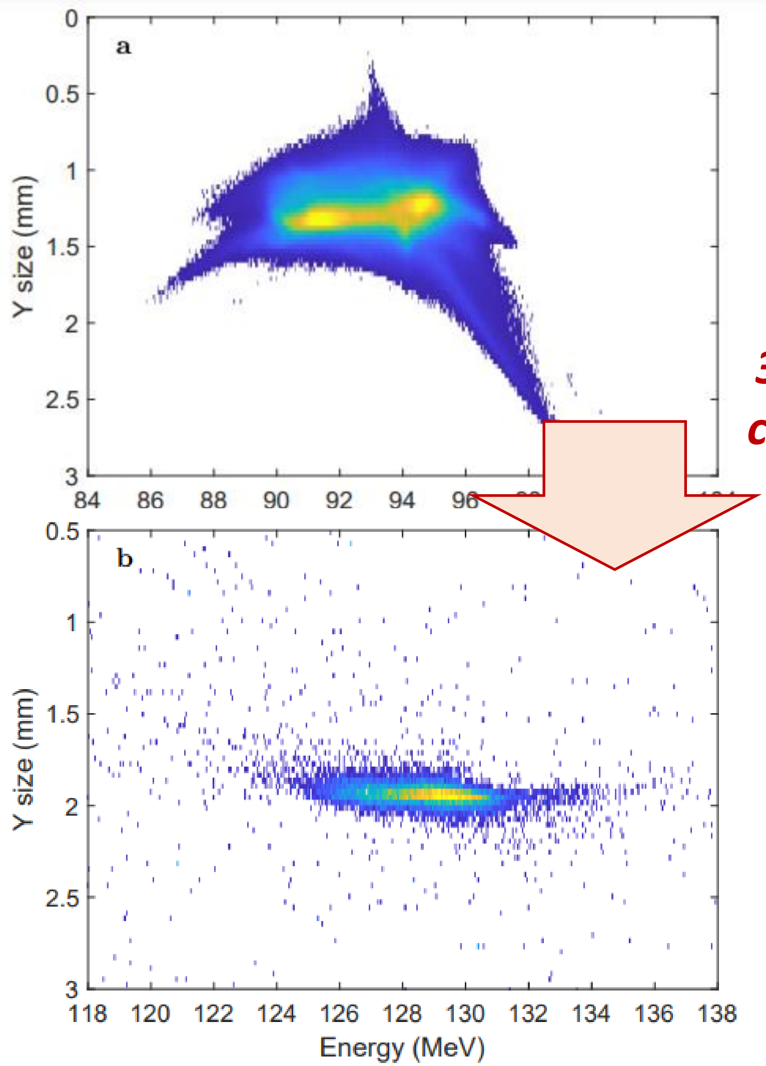
The GV/m plasma acceleration experiment @SPARC_LAB

- The accelerating gradient in the plasma has been magnified of a factor four with respect to the past thanks to
  - an upgrade of the SPARC facility with the installation of a new RF gun system in the framework of the *SABINA* project [4]
  - a ***new working point*** with a comb beam consisting of higher beam charges, i.e. a 500 pC driver followed by a 50 pC trailing bunch.
- The WP has been defined looking at the minimum temporal distance between the two beams that can be obtained within the SPARC_LAB photoinjector, i.e. almost 0.8 ps, while keeping the beam length itself smaller than 300 fs
- The temporal distance, that should correspond to half of the plasma wavelength for an efficient acceleration, set the plasma background density to few 10^{15} cm^{-3}

lower Δt → higher λ_p → higher accelerating gradient

Maximum accelerating gradient of the order of 1 GV/m has been measured last November.

Witness energy measurement before and after the plasma



30 MeV in 3 cm long gas-filled capillary-discharge

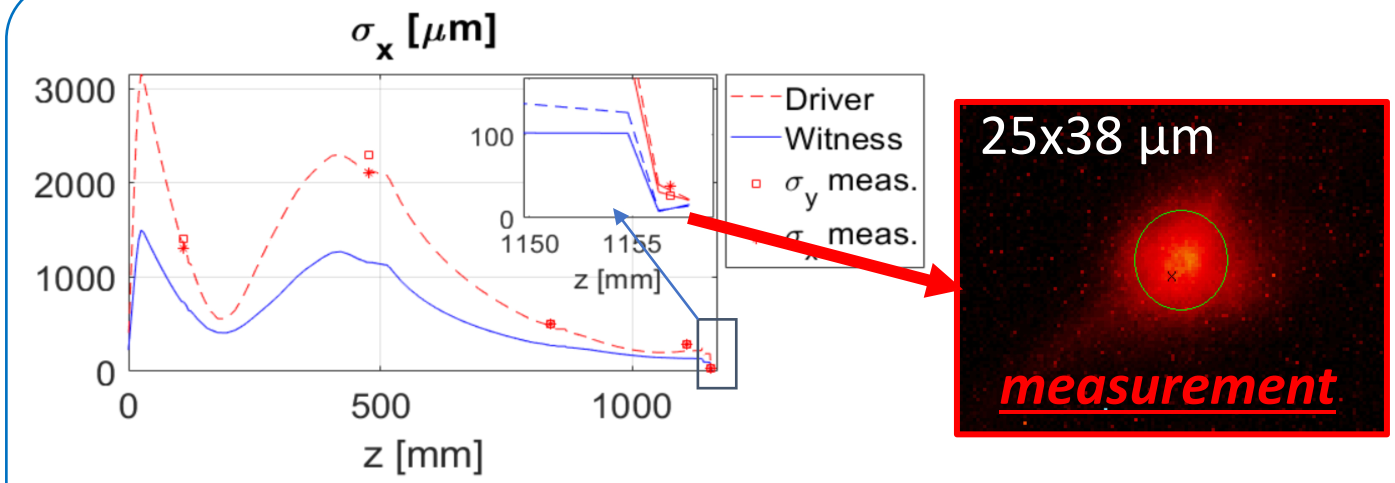
[4] V. Shpakov et al , Design, optimization and experimental characterization of RF injectors for high brightness electron beams and plasma acceleration - 2022 JINST 17 P12022

Beam dynamics studies: the photoinjector

- Beam dynamics has been studied by means of start to end simulations with the multiparticle TStep code to guide and reproduce experimental results
- Comb technique in tandem with the velocity bunching to generate
  - **driver-witness distance in** the range 0.8 - 1.8 ps
  - the driver and witness **bunch length** of about 200 fs and 50 fs
  - Twiss beam parameters at the focusing channel entrance, β < 10 m and α = 0 to provide at the capillary entrance a driver and witness beams with 20 and 5 μm rms spot size respectively

@plasma entrance	Witness		Driver	
	Sim	Meas	Sim	Meas
Emittance [$\mu mrad$]	1.25	-	6.05	6.8
Spot Size [μm]	8x9	-	27x36	25x38
Energy [MeV]	92.4	93.5	94.0	93.85
Energy Spread [keV]	140	104*	580	507
Length σ_z [fs]	75	60*	230	220
Distance Δt [ps]	1.0	1.1	0	0

Measured and simulated parameters for the driver and witness beams. The asterisk indicates noisy measurements [5,6]



Beam spot size evolution along the photo-injector and measured spot size with an insight on the plasma capillary entrance region

e^- beam stability evaluation @plasma entrance

- ❑ Jitter on S-band: phase : 0.1 ps rms
  voltage: 0.2% rms
- ❑ Jitter on laser: TOA : 0.1 ps rms
  charge : 5 % rms

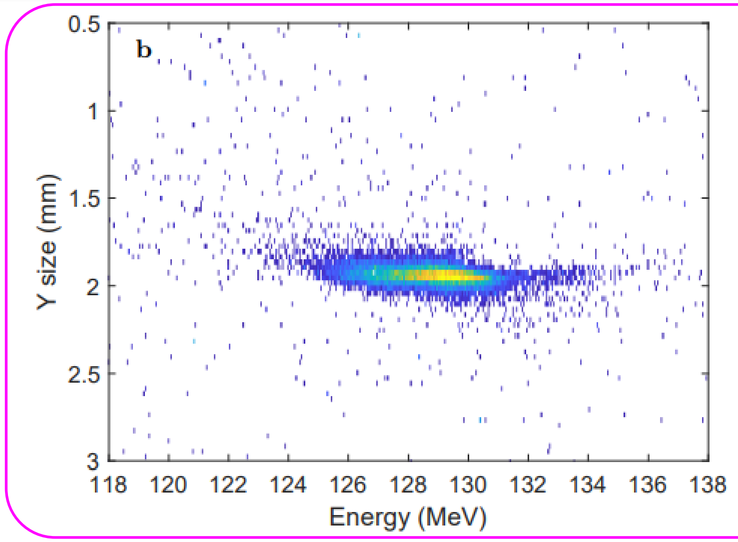
Jitter (rms)	Witness		Driver		
	Sim	Meas	Sim	Meas	
Δt	47	43	-	-	fs
$\sigma_{x,y}$	2.9	-	5.5	3.5	μm

[5] M. Carillo et al. "Beam dynamics optimization for high gradient beam driven plasma wakefield acceleration at SPARC-LAB" presented at the IPAC'23, THOGB1

[6] M. Carillo et al., "Witness-driver beam dynamics optimization in the SPARC_LAB photoinjector, EAAC2023

Beam dynamics studies: the plasma

- Measurements shown that the major contribution to the energy stability comes from the timing jitter with linear dependence (see Measurement of the timing-jitter effects on a beam-driven plasma wakefield accelerator, F. Demurtas this conference)



Measured energy spectrum:

→ ΔE = 6 MeV

→ δE = 2 MeV rms @ 128 MeV

6D phase space to be characterized in next future

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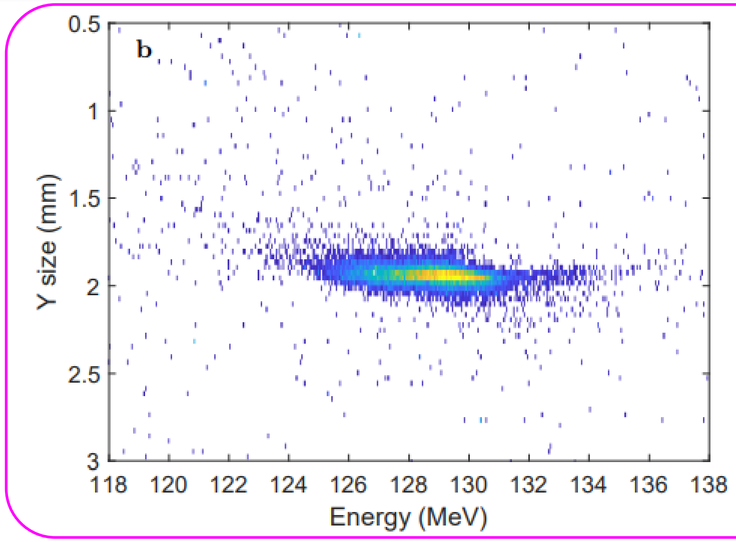
- The beam dynamics has been studied with the Architect fast tracking code [7]



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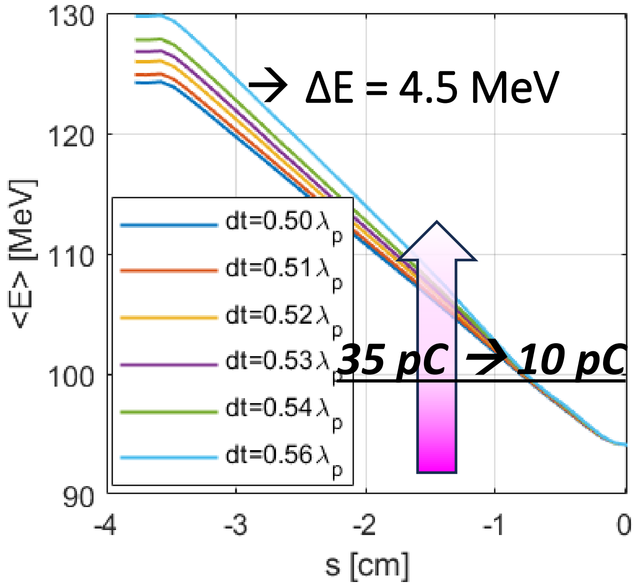
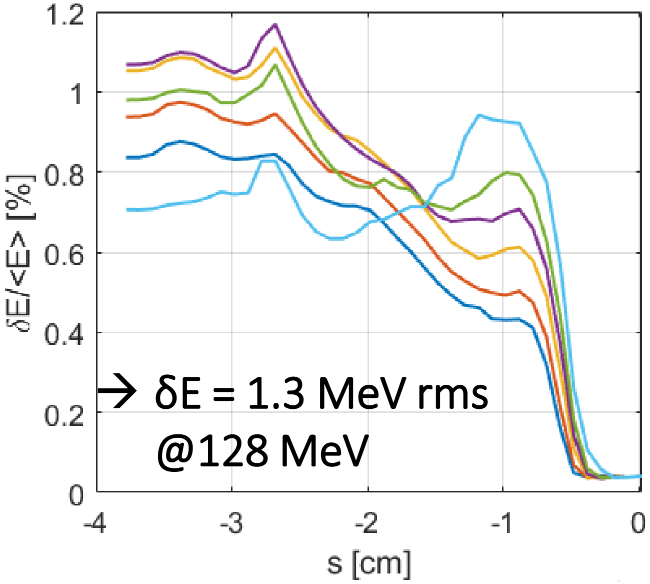
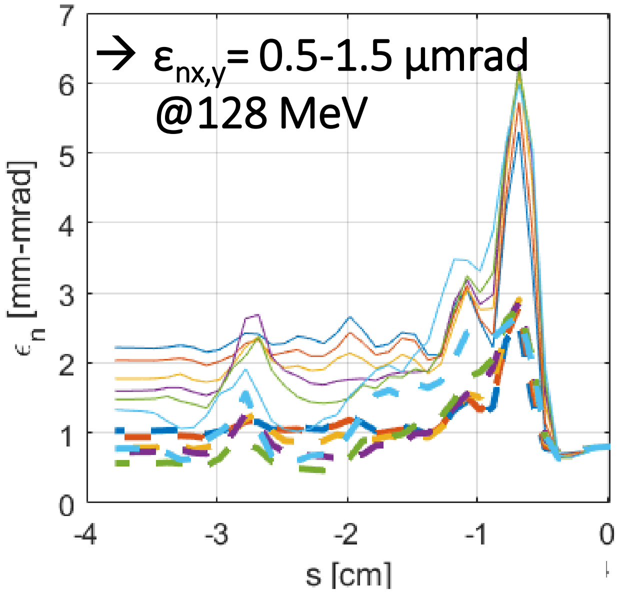
Numerical Studies



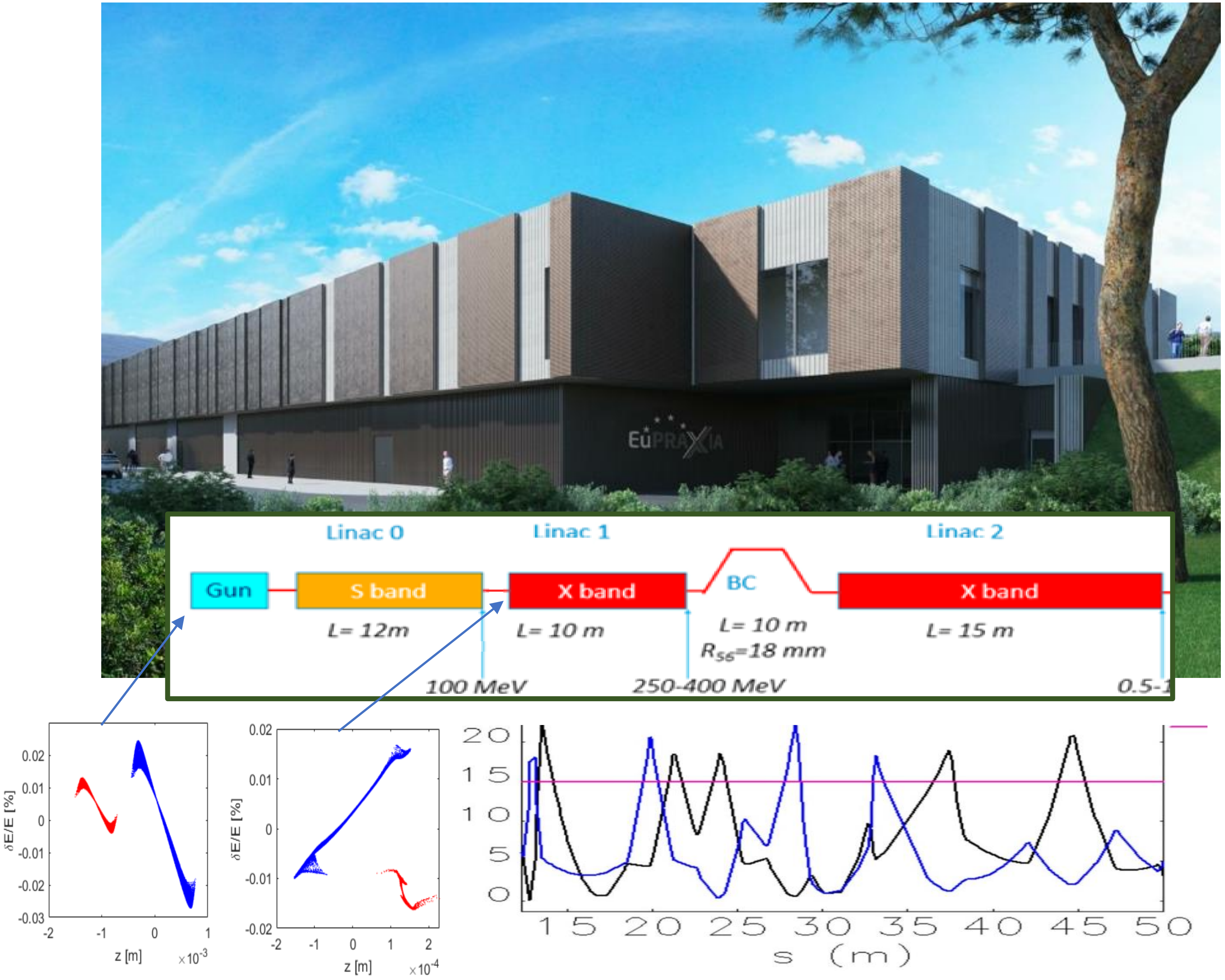




Evolution of the *energy, energy spread and emittance* in the plasma stage for the witness for different witness-driver delay. The maximum energy gain is of about 1.0 GeV/m as measured

[7] F. Massimo et al. "Comparisons of time explicit hybrid kinetic-fluid code Architect for Plasma Wakefield Acceleration with a full PIC code" Journal of Computational Physics 327, 841-850 2016

Headquarter and Site 1: EuPRAXIA@SPARC_LAB



Frascati`s future facility

- > 130 M€ invest funding
- Beam-driven plasma accelerator - ***PWFA***
- Europe`s most compact and most southern FEL
- The world`s most compact RF accelerator **X band with CERN**

RMS e- beam parameters @plasma module entrance			
	Single bunch (WoP2)	Comb beam operation (WoP1)	
		Witness	Driver
Q (pC)	200 - 500	30 -50	200 -500
E (GeV)	up to 1.0	Up to 0.650 GeV	
$\Delta\gamma/\gamma$ (%)		< 0.10	
$\varepsilon_{nx,y}$ (mm·mrad)	< 1.0	0.5 - 1.0	2.0 -5.0
$\sigma_{z\text{-}rms}$ (µm)	20 - 50	< 6	< 65
$I_{peak\text{-}slice}$ (kA)	1.0 – 2.0	> 1.5	

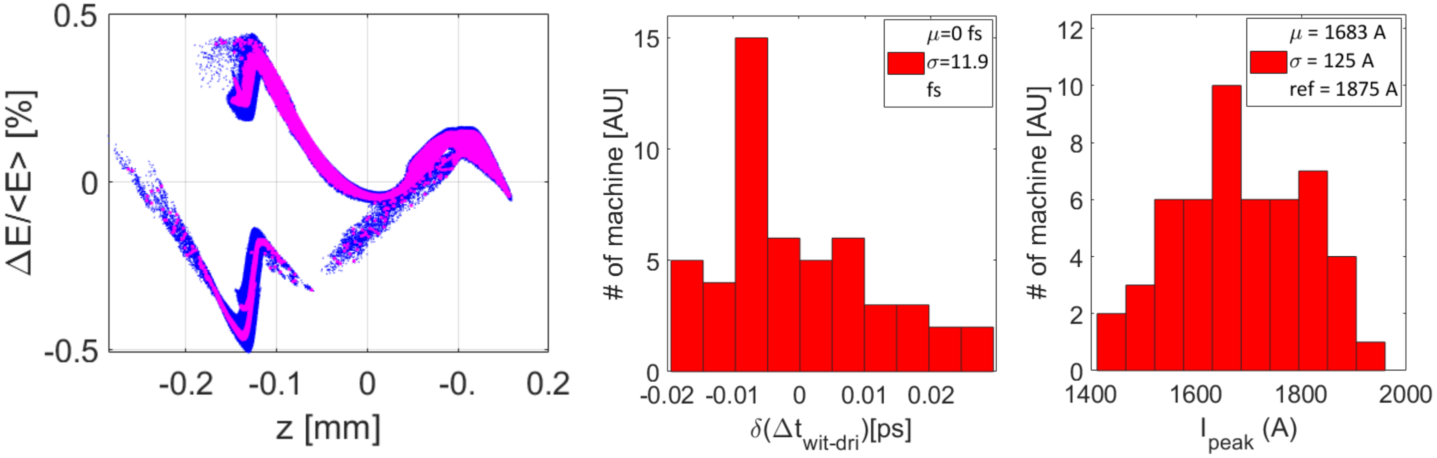
Credit: INFN and Mythos – consorzio stabile s.c.a.r.l.

Stable, reliable and reproducible electron beams

Considering state of the art technology:

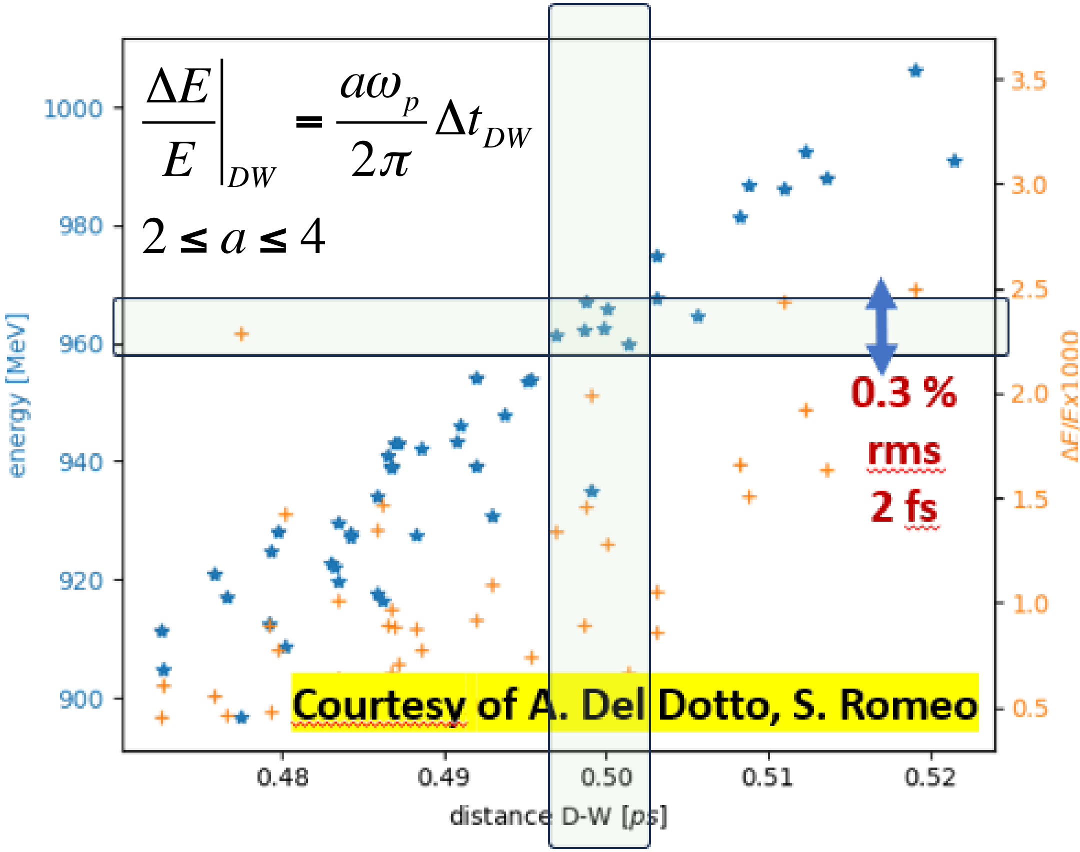
- ❑ Jitter on S/X-band: phase : 0.3 ps rms
  voltage: 0.1% rms
- ❑ Jitter on laser: TOA : 0.3 ps rms
  charge : ± 2 %
  Laser Spot size: ± 1%

Results of S2E simulations with TStep and elegant codes @plasma entrance. The magenta is related to the refence WP



- In the worst-case scenario the emittance and the peak current are ruined of maximum 10% (still in specification)
- The most critical parameter is the witness-driver separation → 11.9 fs rms

Energy gain and energy spread at plasma exit vs driver-witness time distance



Results obtained by means of start to end simulations taking into account state of the art jitters in conventional RF photoinjector

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Funded by the European Union

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⇨ Solid state C-band modulator phase : 0.15 ps rms

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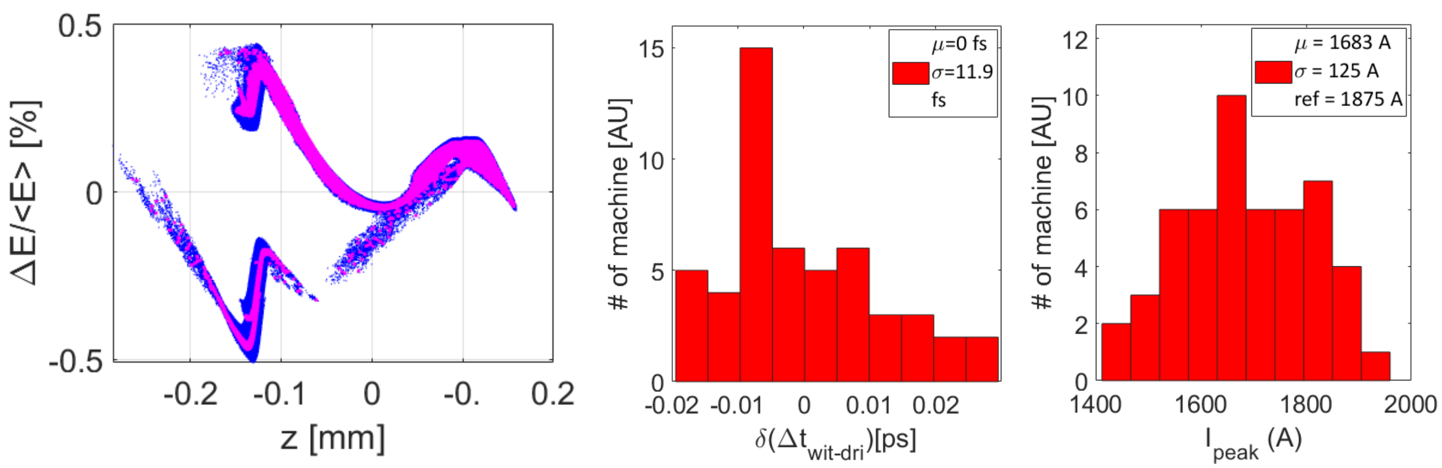

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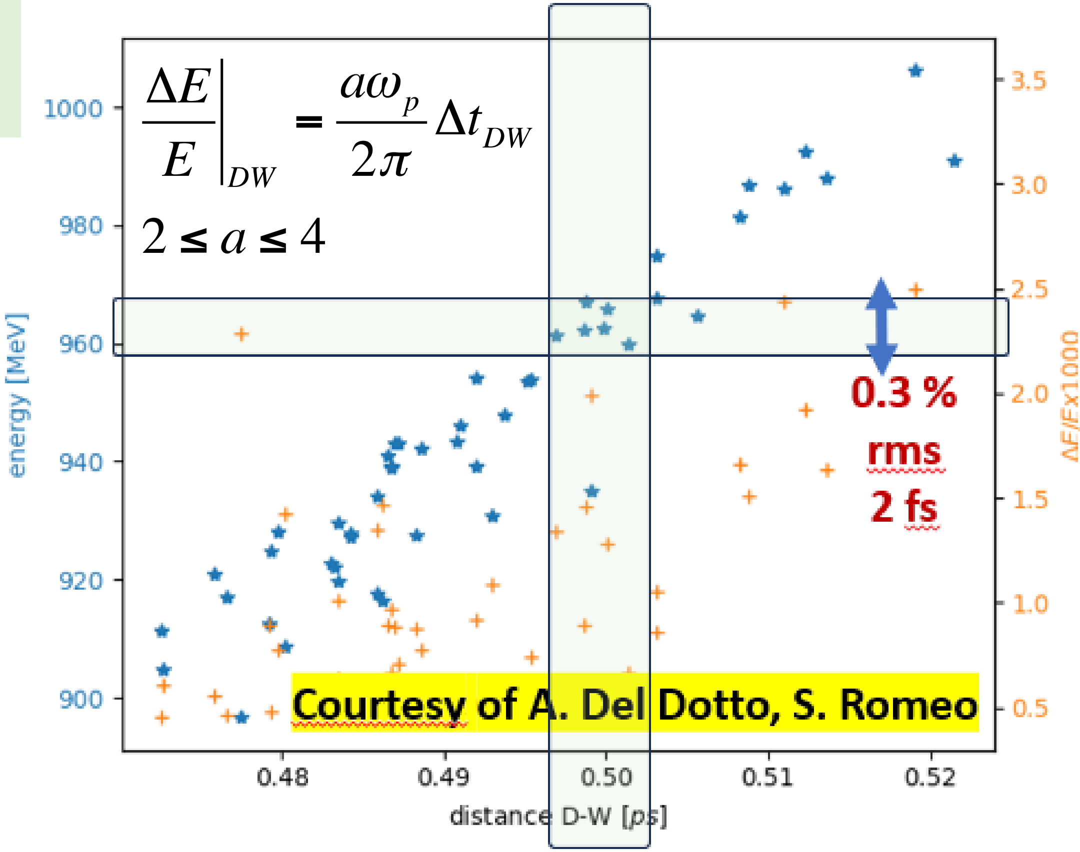


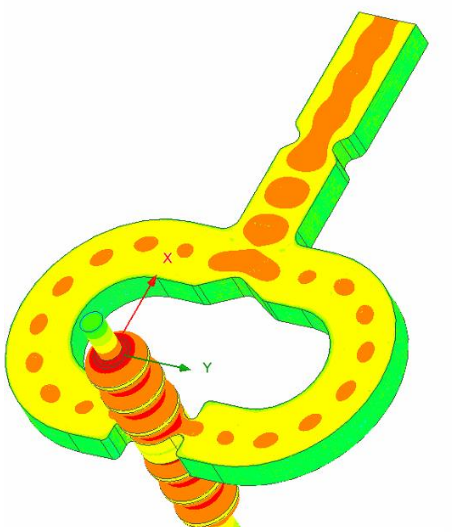
Results obtained by means of start to end simulations taking into account state of the art jitters in conventional RF photoinjector

Complete jitter simulations

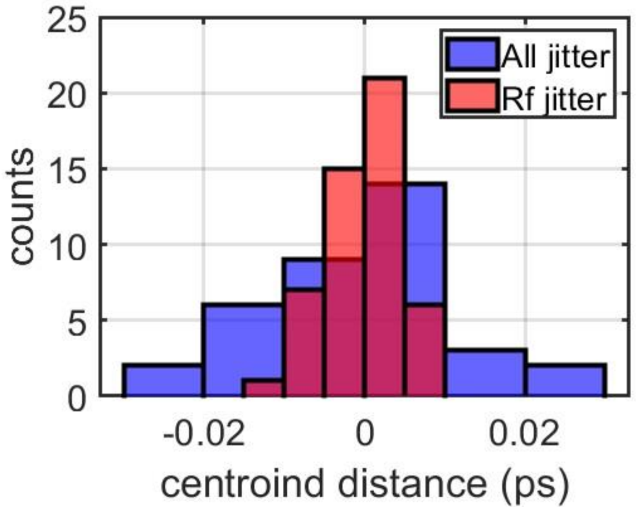
- X-band accelerating structure right after the RF gun
- Sensitivity jitter study for all RF injector components in parallel with the generation of the cathode beam parameters.

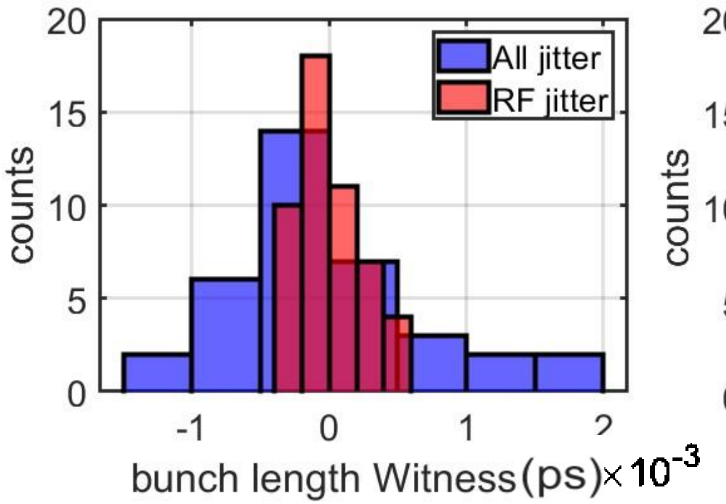
Total Charge	Spot Size	Time of arrival	RF phases	Voltage
2% of the total	1% of the total	30 fs RMS	30 fs RMS	0.2% of the total

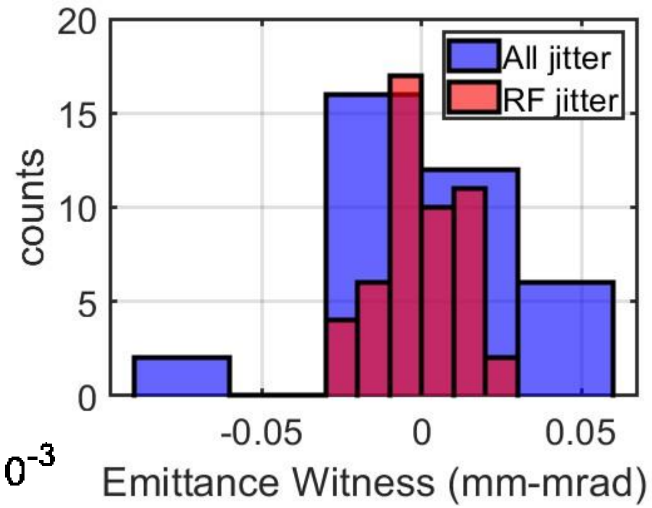
Beam parameters	w/ X-band all jitter	w/ X-band RF jitter	w/o X-band all jitter
<ε> (mm-mrad)	0.672 ± 0.031	0.676 ± 0.013	0.5710 ± 0.091
<Bunch length> (ps)	0.0137 ± 7e-4	0.0140 ±2e-4	0.0180 ± 7e-4
<peak current> (A)	1733 ± 230	1728± 56	1923 ± 173
<centroid distance> (ps)	0.5337 ± 0.0117	0.5462 ± 0.0048	0.5011 ± 0.0115



Courtesy of L. Faillace







Courtesy of G. Silvi

Conclusions and Perspectives

➢ Conclusions

- Beam dynamics studies for SPARC_LAB and EuPRAXIA@SPARC_LAB have been shown with
  - beam brightness preserved from a shot to another → emittance, current and energy spread are well preserved
  - beam energy lies instead in a relatively large range (less than 10 MeV)
- This is crucial step for the forthcoming EuPRAXIA@SPARC_LAB project that aims to be the first ever plasma beam-driven facility at LNF

➢ Perspectives

- A complete 6D phase space characterization will be performed in the next future at SPARC_LAB (after some other upgrade of the facility)
- *Further manipulation and technology is under investigation for the EuPRAXIA@SPARC_LAB facility to stabilize the e^- beam energy and enable a stable FEL emission*

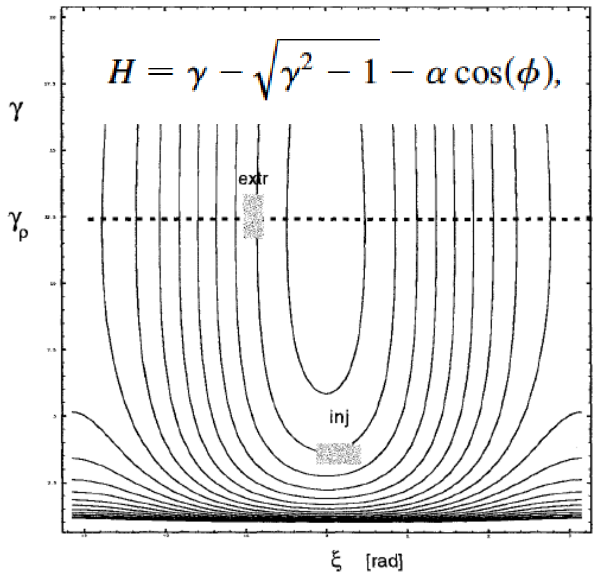
This project has received funding from the European Union's Horizon 2020 Research and Innovation programme under grant agreement No 777431 and No. 653782.


THANK YOU!!!

Velocity Bunching And Temporal Jitter

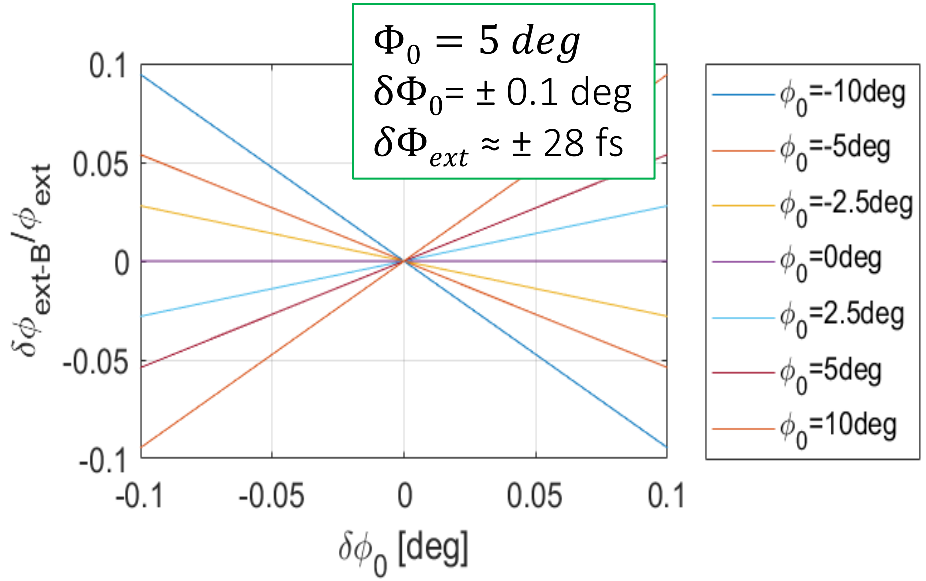
- The *RF compression* represents a powerful tool to shorten the beam to achieve the required high peak current in *relatively compact machine*
- The velocity bunching is used in tandem with the laser comb technique to generate the train of bunches
- It is based on a rotation of the longitudinal phase space in the space charge regime → very sensitive to phase and voltage jitter of RF elements

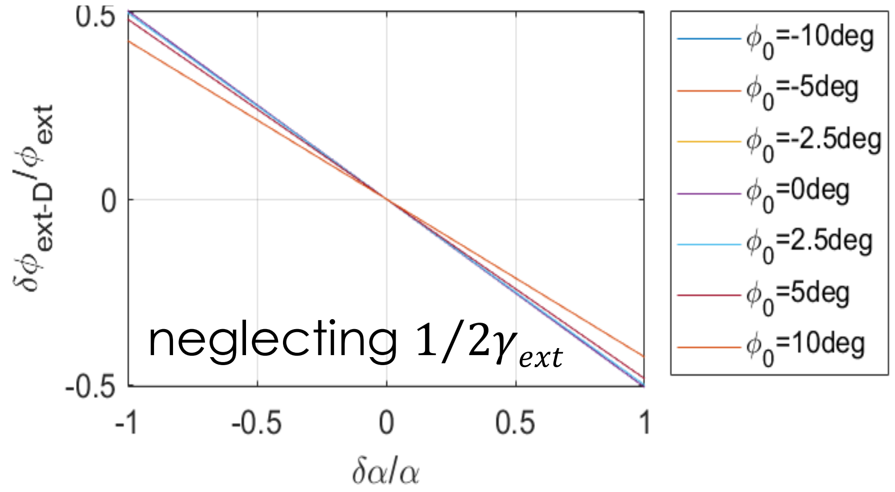
$$\phi_\infty \cong \cos^{-1}\left[\cos\phi_0 - \frac{1}{2\alpha\gamma_0}\right],$$



$$\delta\Phi_{ext} \propto \underbrace{\{(\sin(\Phi_0))/\sin(\Phi_{ext}))\delta\Phi_0\}}_{\text{Jitter} \propto \delta\Phi_0} + \underbrace{\delta\alpha/\alpha^2\,(1/2\gamma_{ext} - 1/2\gamma_0)/\sin(\Phi_{ext})}_{\text{jitter} \propto \delta\alpha}$$

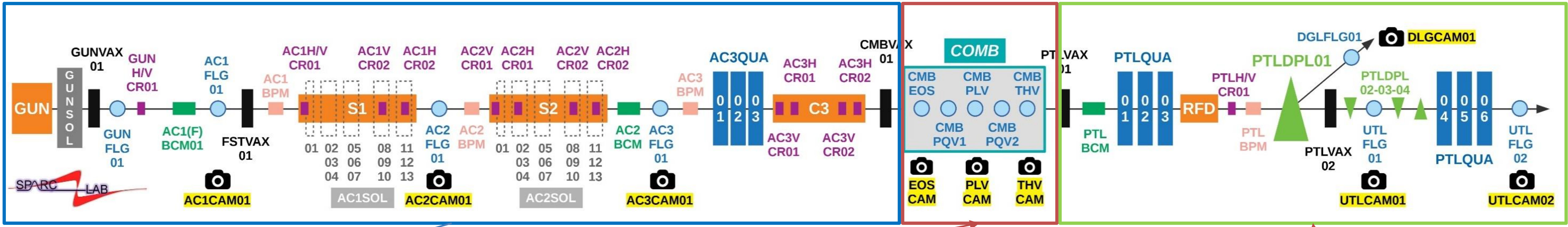
$E_0 = 20MV/m\ ;\ \gamma_0 \approx 10\ ;\ f_{RF} = 2.856\ Ghz$

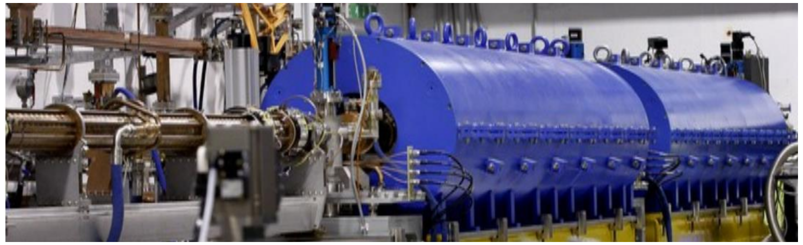




[5] L. Serafini and M. Ferrario, Velocity Bunching in PhotoInjectors, AIP Conf. Proc. No. 581 (AIP, New York,
[7] S. G. Anderson et al., Phys. Rev. ST Accel. Beams 8, 014401 (2005)

The SPARC_LAB accelerator





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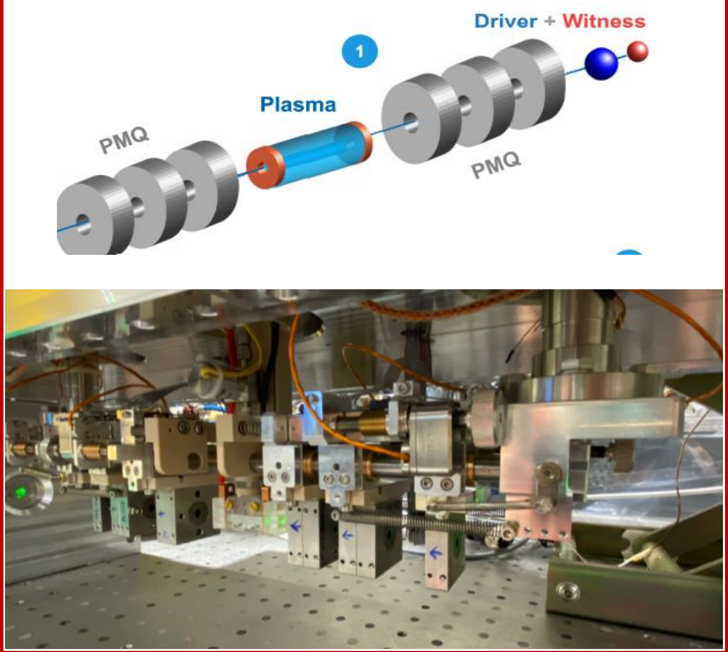
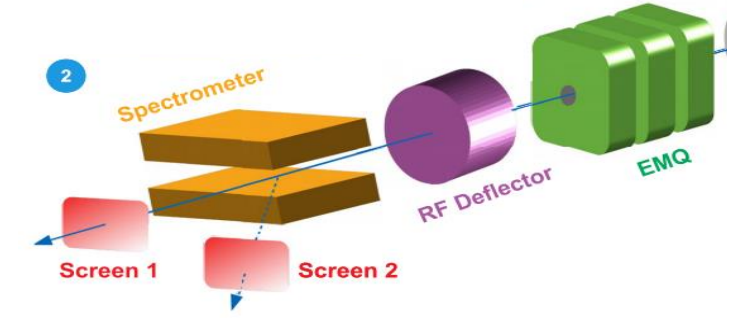
e- beam parameters @Photoinjector exit





Diagnostic beamline

Machine Sensitivity Studies

- Tolerance studies to actual **check** the **robustness and reliability** of the adopted working point with regards to the *RF elements and laser system stability*
- Critical parameters for an efficient operation of the plasma module are
  - μm scale bunch length ↔ witness quality and plasma density choice
  - fs scale precision of the time delay between the bunches ↔ energy jitter
  - Witness peak current ↔ energy spread (beam loading)
  - Beam Twiss parameters at plasma injection ↔ witness quality and plasma density choice (in turn energy gain)
- The errors treated as jitter by means of gaussian distributions defined on the basis of the SPARC_LAB (and TeX) experience as in Table
- An evaluation of off-axis beam dynamics along the linac has been also performed with Elegant and MILES as described in [4]

RF Gun (rms)		
RF Voltage [ΔV]	± 0.1	%
RF Phase [Δϕ]	± 0.03	*deg*
S-band Accelerating Sections (rms)		
RF Voltage [ΔV]	± 0.1	%
RF Phase [Δϕ]	± 0.03	*deg*
X-band Accelerating Sections (rms)		
RF Voltage [ΔV]	± 0.2	%
RF Phase [Δϕ]	± 0.1	*deg*
Cathode Laser System (max)		
Charge [ΔQ]	± 2	%
Laser time of arrival [Δt]	± 100	fs
Laser Spot size [Δσ]	± 1	%

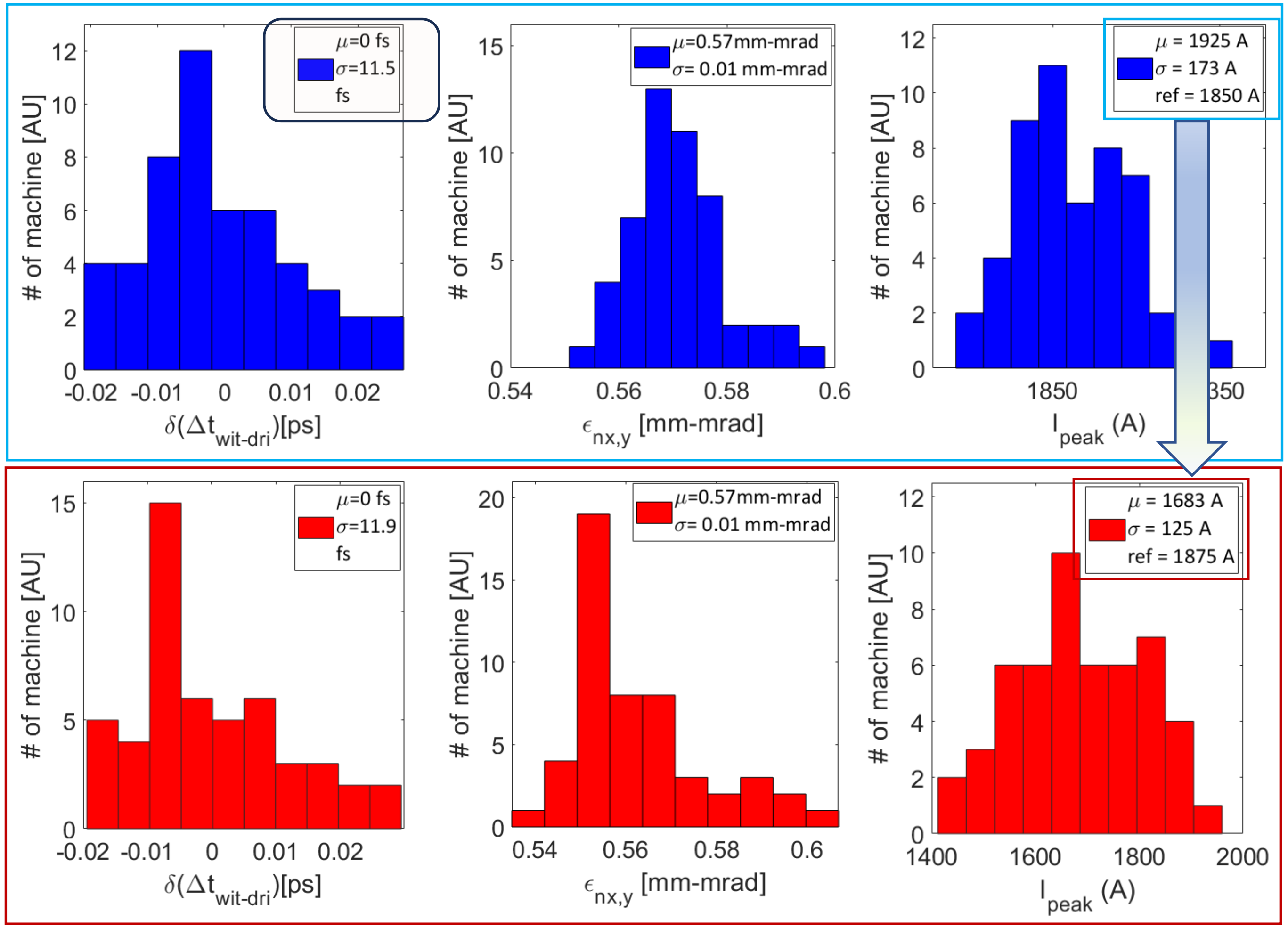
[4] F. Bosco et al. "Beam dynamics optimization of Eu-PRAXIA@SPARC_LAB RF injector" presented at the IPAC'23, Venezia, Italy, May. 2023, paper WEPA040

Machine Sensitivity Studies

- The analysis is performed over 50 samples obtained by means of S2E simulations with Tstep and Elegant codes
- The **photoinjector** is the source of the jittering of the beam separation and final rms beam length and current
- The **X-band linac** is the main responsible for
  - the energy jitter that is negligible with respect to other parameters ← it operates almost on crest
  - final Twiss parameters that are almost stable ← the final focusing system is made of permanent magnet
  - the definition of the witness peak current

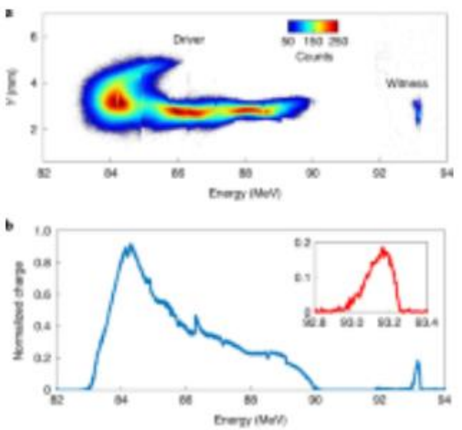
The mean value over the 50 samples is reduced with respect to the photoinjector one with the benefit of a ***reduced deviation*** around the mean value

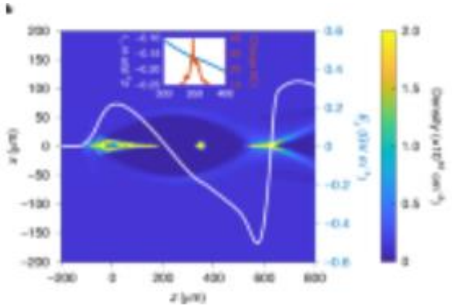
Jitter analysis in terms of beam delay, witness emittance and peak current at the photoinjector (upper) and X-band linac (lower) exit



The SPARC_LAB experience

Energy spread minimization in a beam-driven plasma wakefield accelerator

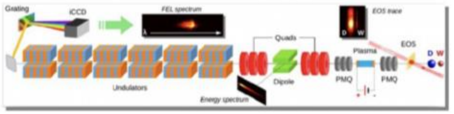




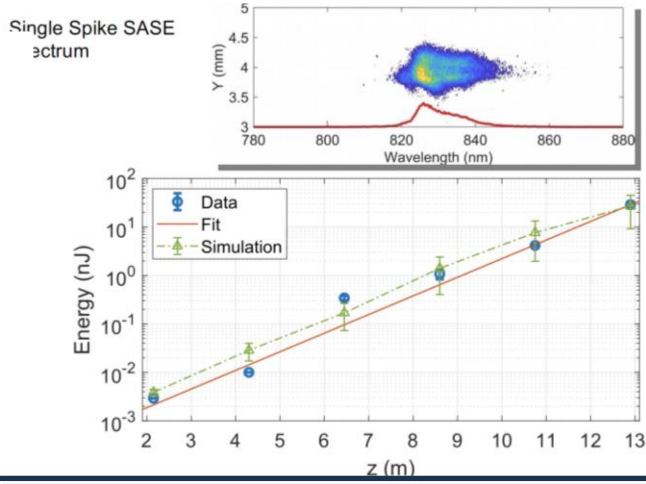
Nature Physics 17, 499-503
R. Pompili et al. (2021)

Free-electron lasing with compact beam-driven plasma wakefield accelerator

First FEL lasing from a beam-driven plasma accelerator

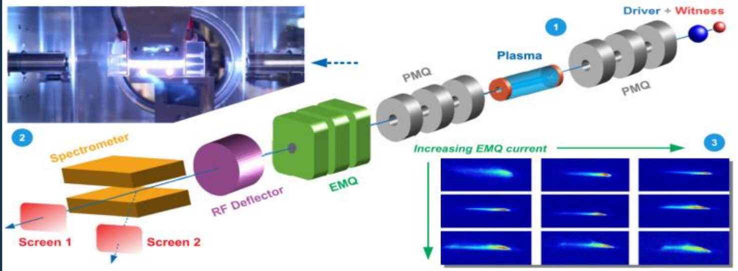


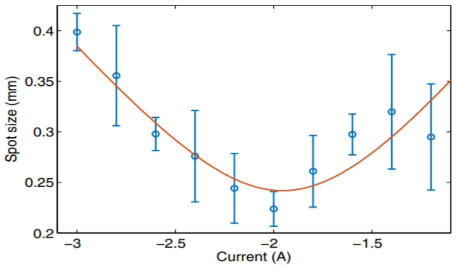
Nature 605, 659-662
R. Pompili et al. (2022)



PHYSICAL REVIEW ACCELERATORS AND BEAMS **24,** 051301 (2021)

First emittance measurement of the beam-driven plasma wakefield accelerated electron beam

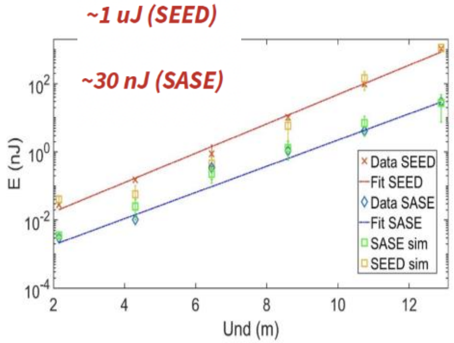




PRAB 24, 051301 V. Shpakov et al. (2021)

PHYSICAL REVIEW LETTERS **129,** 234801 (2022)

Stable Operation of a Free-Electron Laser Driven by a Plasma Accelerator



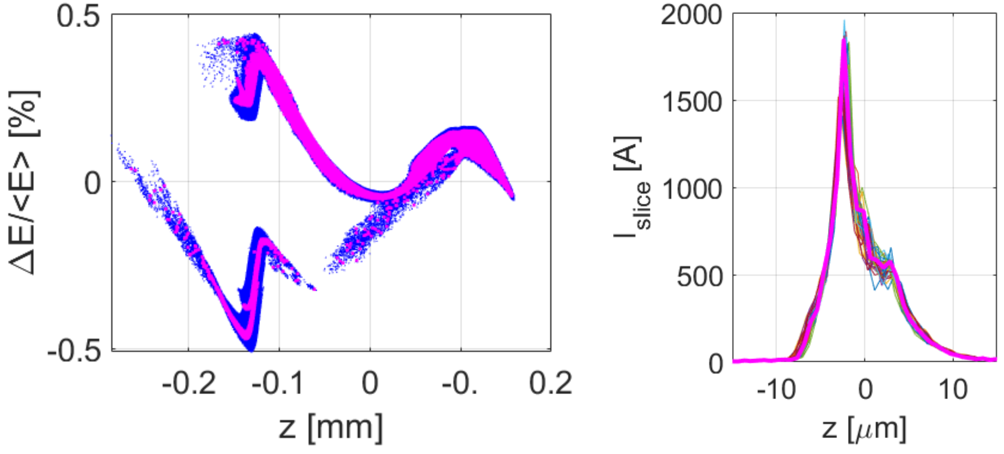
Seeded FEL radiation

- ✓ Pulse energy increased 2 order of magnitude respect to SASE radiation
- ✓ 6% pulse energy RMS fluctuations over 90% of successful shot respect to 17% over 30% of shot for SASE

PRL, 129 234801 M.Galletti et al. (2022)

Machine Sensitivity Studies – Results At Plasma Injection

- In the worst-case scenario the emittance and the peak current are ruined of maximum 10% (still in specification)
- The most critical parameter is the witness-driver separation → 11.9 fs rms



Longitudinal phase space and witness current profile. The magenta is related to the refence WP

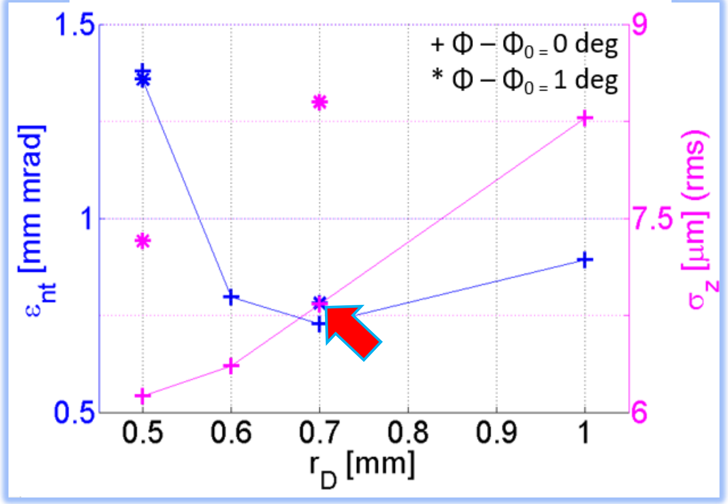
Rms quantities	Witness		Driver		
	Without errors	With errors	Without errors	With errors	
Energy	537.44	537.45 ± 0.30	539.55	539.57 ± 0.33	MeV
Energy spread	0.71	0.7102 ± 0.007	0.92	0.92 ± 0.026	‰
Bunch length	5.460	5.927 ± 0.21	61.71	61.81 ± 0.73	µm
I_{peak}	1.875	1.683 ± 0.125	-	-	kA
Δt	0.503	0.501 ± 0.012	-	-	fs
$\varepsilon_{nx,y}$	0.55	0.56 ± 0.015	4.18	4.24 ± 0.25	mm mrad
$\sigma_{x,y}$	1.5	1.52 ± 0.25	5.84	5.95 ± 1.21	µm
$\beta_{x,y}$	4.3	4.5 ± 1.4	9.3	9.3 ± 3.7	mm
$\alpha_{x,y}$	1.2	1.2 ± 0.25	3.34	3.39 ± 0.75	

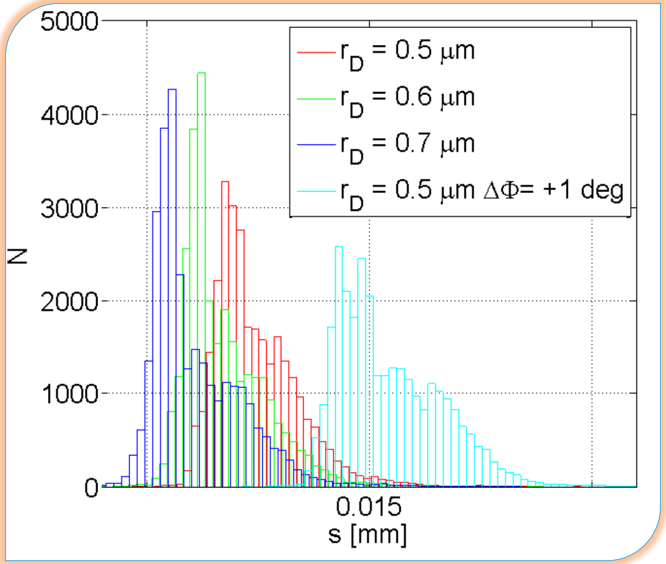
Beam parameters at plasma injection. The mean value and the related standard deviation over the 50 samples is reported for each parameter in case of errors.

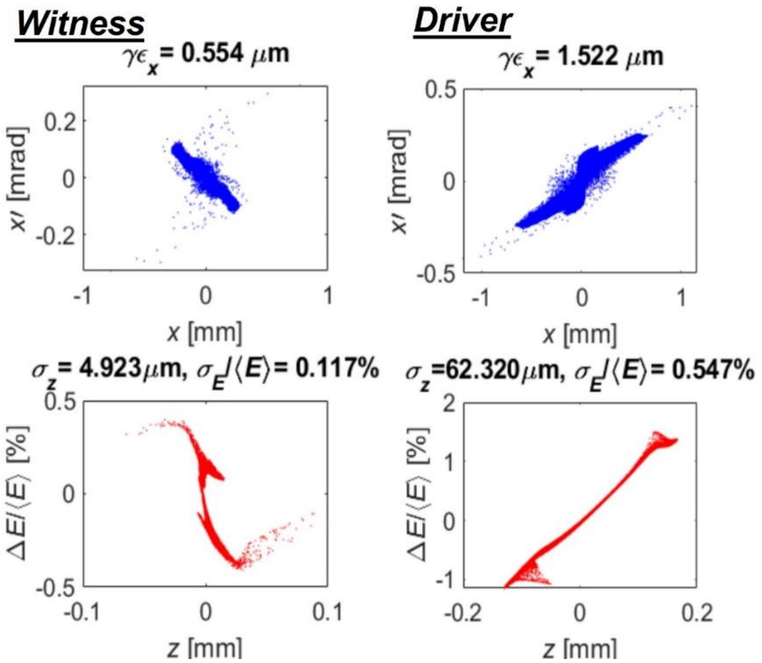
The Photo-injector

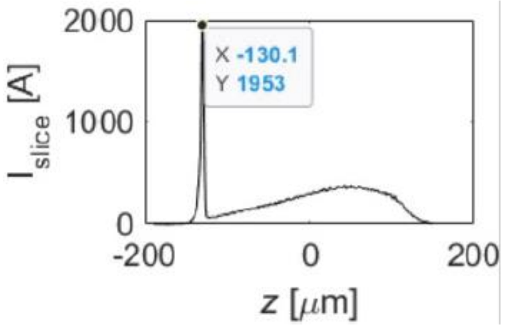
- The beam dynamics has been studied by means of simulations with the TStep *(and ASTRA)* code
  - The photoinjector sets the beam separation, emittance and current
  - The witness and driver distribution on the cathode has been chosen looking at the witness quality that depends on the density of the beams at the overlapping point [1]
  - Double-VB is applied in the *first and second S-band acc. structures* → this scheme ensures at same time up to 2 kA peak current and separation lower than 0.6 ps [2,3]

Optimised Working point









[2] A. Giribono et al., 'Electron beam analysis and sensitivity studies for the EuPRAXIA@SPARC_LAB RF injector IPAC23 , TUPL130, IoP proceedings

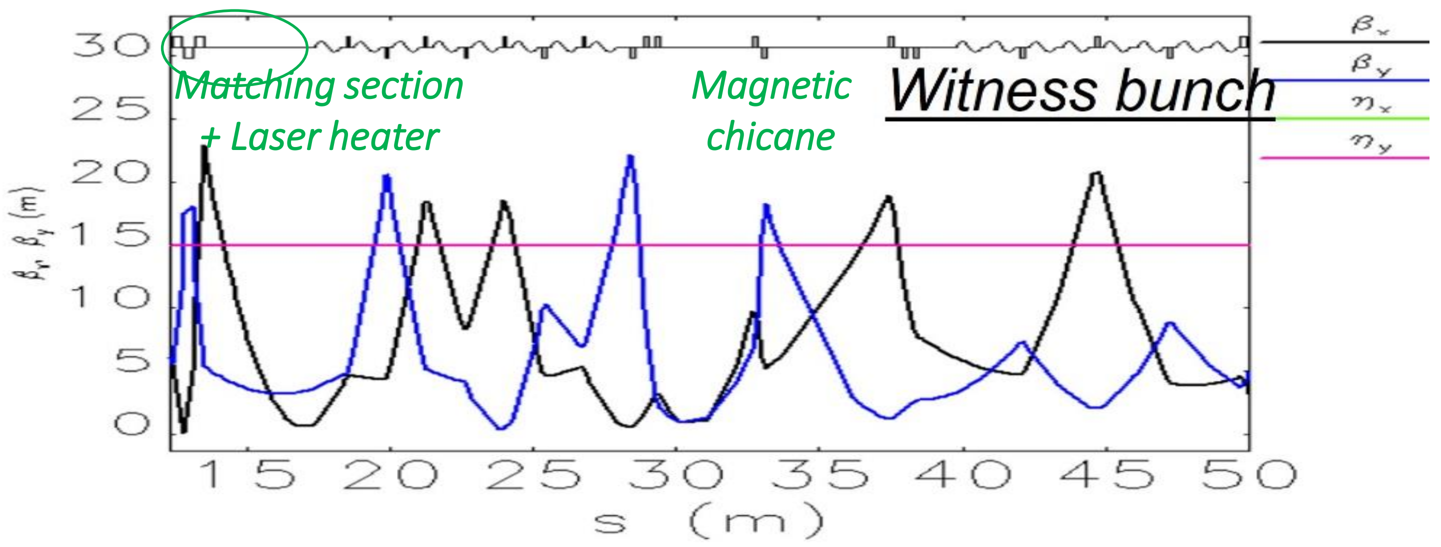
[3] G.J. Silvi et al. "Beam dynamics optimization of Eu-PRAXIA@SPARC_LAB RF injector" presented at the IPAC'23, Venezia, Italy, May. 2023, paper WEPA040

[1] A. Giribono et al. EuPRAXIA@SPARC_LAB: The high-brightness RF photo-injector layout proposal, https://doi.org/10.1016/j.nima.2018.03.0

The X-band Linac

- The beam dynamics in the X-band linac and in the final focusing system has been studied by means of simulations with the Elegant and TStep code respectively.
  - The X-band linac sets the beam energy (up to 1.0 GeV) and Twiss parameters at the plasma entrance → $\alpha = 1.0$, $\beta = 1.0 – 3.0$ mm @650 MeV
- It is operated off-crest as
  - manipulation of the beam current profile, a ‘second order effect’ that is amplified by the coupling of two systems, the photoinjector and the linac, operating at different RF frequencies

Beam parameters @Plasma inj.		
	Witness	Driver
E [MeV]	537.6	539.5
$\varepsilon_{x,y}$ [μrad]	0.58-0.60	2.9-5.3
$\sigma_{z\text{-rms}}$ [μm]	5.460	59.620
ΔE/E [%]	0.057	0.095
Δt [μm] (ps)	150 (0.503)	
$\sigma_{x\text{-rms}}$ [μm]	**1.2-1.3**	**4.5-6.3**
$\beta_{x,y}$ [mm]	**2.7-2.7**	**7.4-7.8**
$\alpha_{x,y}$	**0.83-0.85**	**3.2-3.2**



Twiss parameters along the linac for the witness bunch. The overall beam transverse size remains always smaller than the X-band irises with maximum spot size in the matching quadrupoles of the order of 0.7 mm.