EUROPEAN
PLASMA RESEARCH
ACCELERATOR WITH
EXCELLENCE IN
APPLICATIONS

EuPRAXIA

Linac-driven Beam Physics at EuPRAXIA@SPARC_LAB

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on behalf of the EuPRAXIA@SPARC_LAB collaboration

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

A New European High-Tech User Facility

European Plasma Research Accelerator With Excellence In Applications

a European project "which aims to develop the first dedicated research infrastructure based on novel plasma-acceleration concepts"

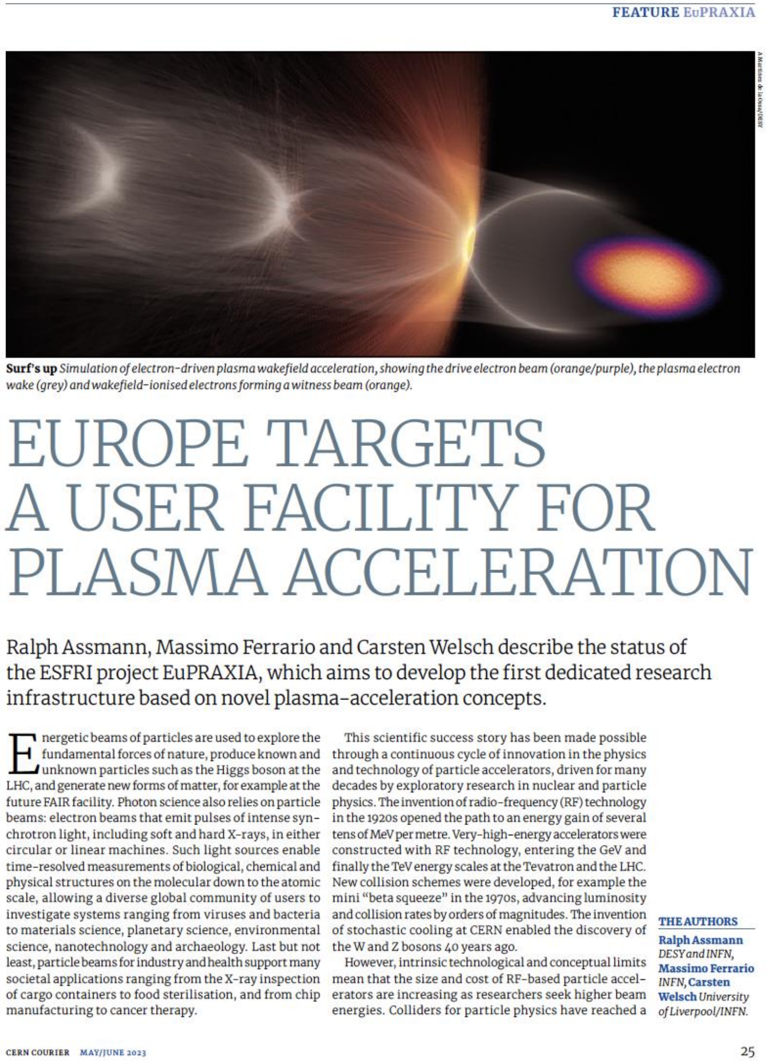
Building a facility with very high field plasma accelerators, driven by lasers or beams

1 – 100 GV/m accelerating field

Shrink down the facility size

Provide a practical path **to more research facilities** and ultimately to **higher beam energies** for the same investment in terms of size and costs

Enable frontier science in new regions and parameter regimes



FEATURE EuPRAXIA

Surf's up *Simulation of electron-driven plasma wakefield acceleration, showing the drive electron beam (orange/purple), the plasma electron wake (grey) and wakefield-ionised electrons forming a witness beam (orange).*

EUROPE TARGETS A USER FACILITY FOR PLASMA ACCELERATION

Ralph Assmann, Massimo Ferrario and Carsten Welsch describe the status of the ESFRI project EuPRAXIA, which aims to develop the first dedicated research infrastructure based on novel plasma-acceleration concepts.

Energetic beams of particles are used to explore the fundamental forces of nature, produce known and unknown particles such as the Higgs boson at the LHC, and generate new forms of matter, for example at the future FAIR facility. Photon science also relies on particle beams: electron beams that emit pulses of intense synchrotron light, including soft and hard X-rays, in either circular or linear machines. Such light sources enable time-resolved measurements of biological, chemical and physical structures on the molecular down to the atomic scale, allowing a diverse global community of users to investigate systems ranging from viruses and bacteria to materials science, planetary science, environmental science, nanotechnology and archaeology. Last but not least, particle beams for industry and health support many societal applications ranging from the X-ray inspection of cargo containers to food sterilisation, and from chip manufacturing to cancer therapy.

This scientific success story has been made possible through a continuous cycle of innovation in the physics and technology of particle accelerators, driven for many decades by exploratory research in nuclear and particle physics. The invention of radio-frequency (RF) technology in the 1920s opened the path to an energy gain of several tens of MeV per metre. Very-high-energy accelerators were constructed with RF technology, entering the GeV and finally the TeV energy scales at the Tevatron and the LHC. New collision schemes were developed, for example the mini "beta squeeze" in the 1970s, advancing luminosity and collision rates by orders of magnitudes. The invention of stochastic cooling at CERN enabled the discovery of the W and Z bosons 40 years ago.

However, intrinsic technological and conceptual limits mean that the size and cost of RF-based particle accelerators are increasing as researchers seek higher beam energies. Colliders for particle physics have reached a

THE AUTHORS
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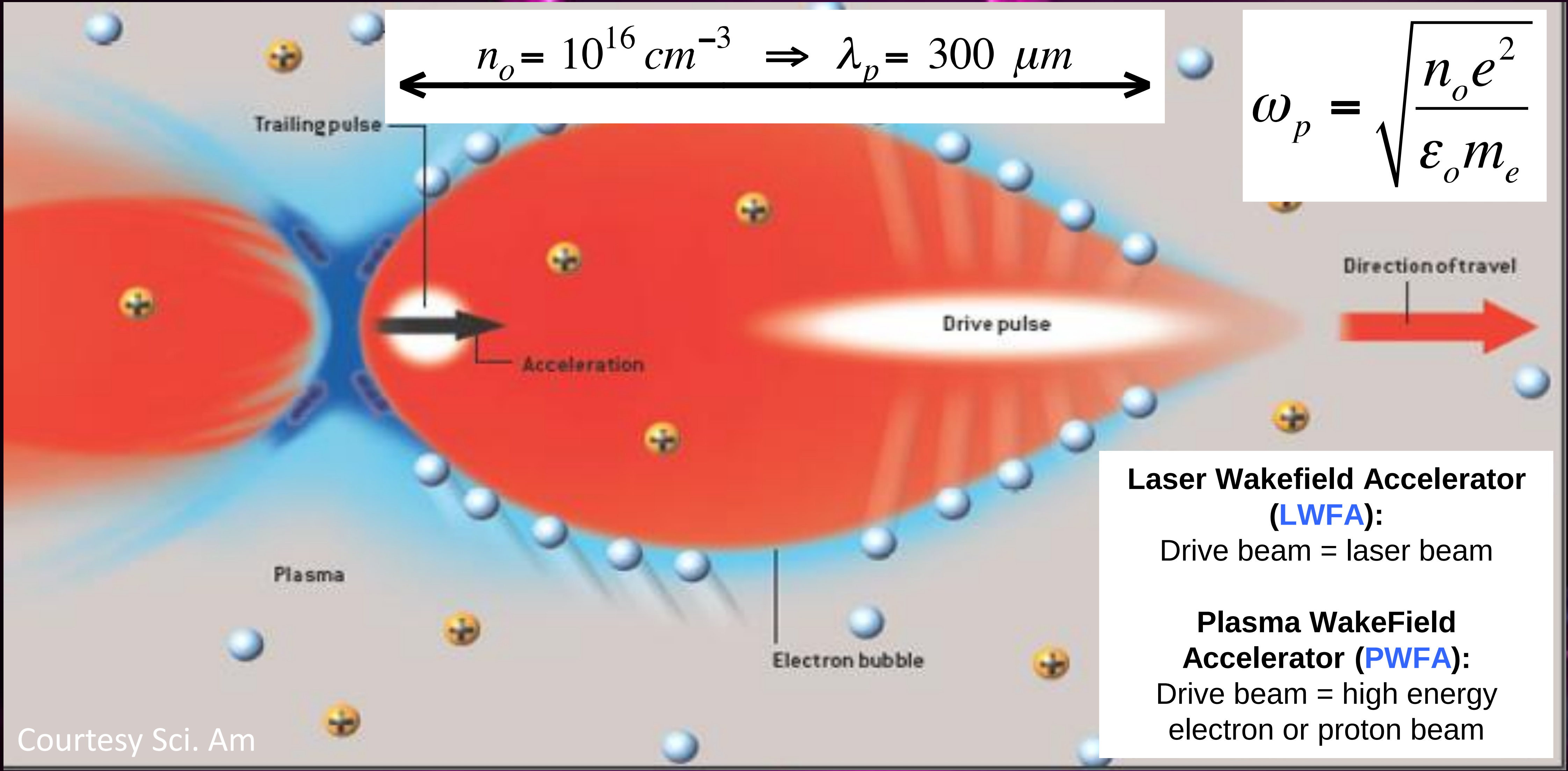
https://cerncourier.com/a/europe-targets-a-user-facility-for-plasma-acceleration/

https://www.eupraxia-facility.org/

Principle of plasma acceleration



Courtesy Sci. Am

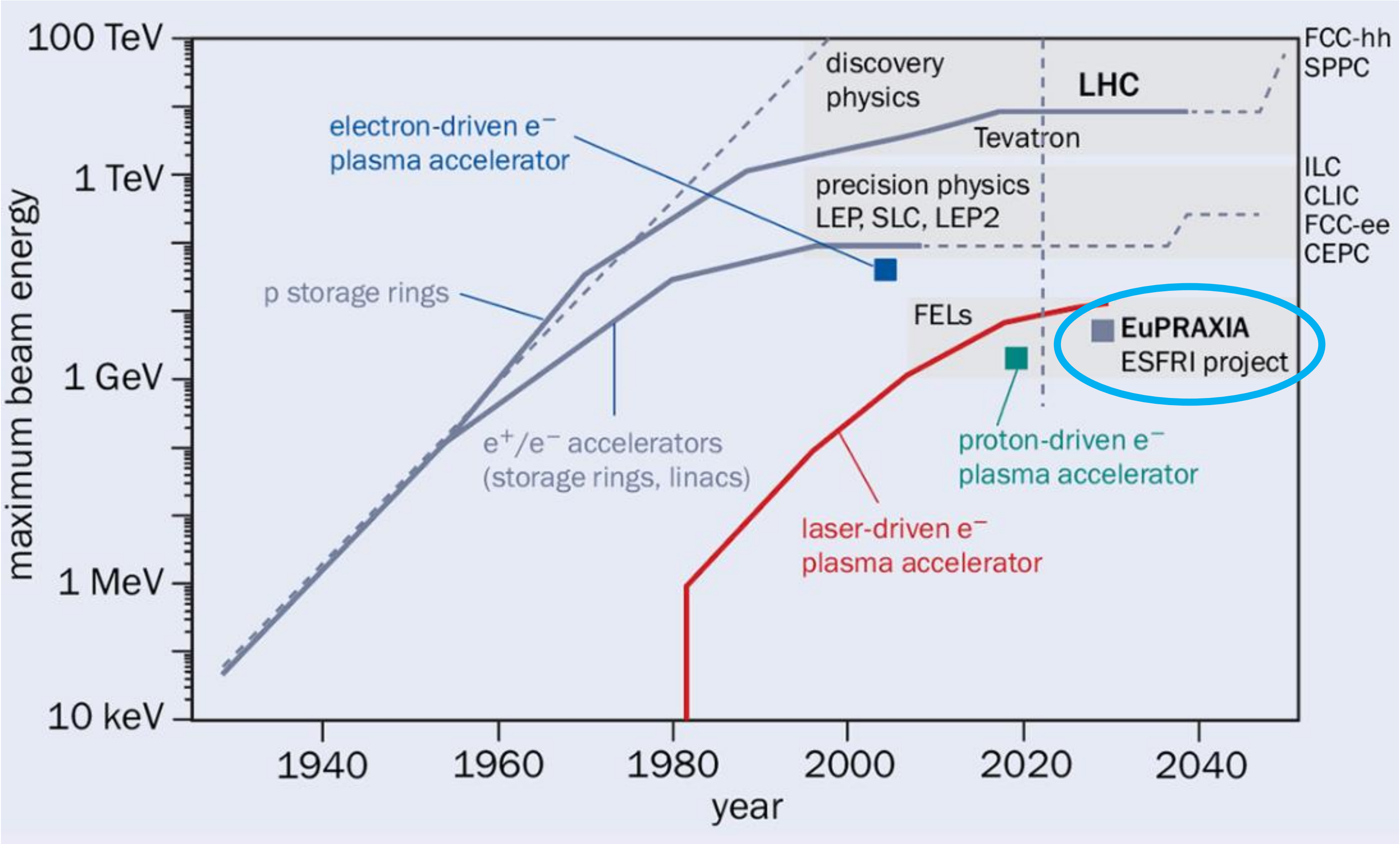
$$n_o = 10^{16}\ cm^{-3} \Rightarrow \lambda_p = 300\ \mu m$$

$$\omega_p = \sqrt{\frac{n_o e^2}{\varepsilon_o m_e}}$$

Laser Wakefield Accelerator (LWFA):
Drive beam = laser beam

Plasma WakeField Accelerator (PWFA):
Drive beam = high energy electron or proton beam

The Livingstone Diagram



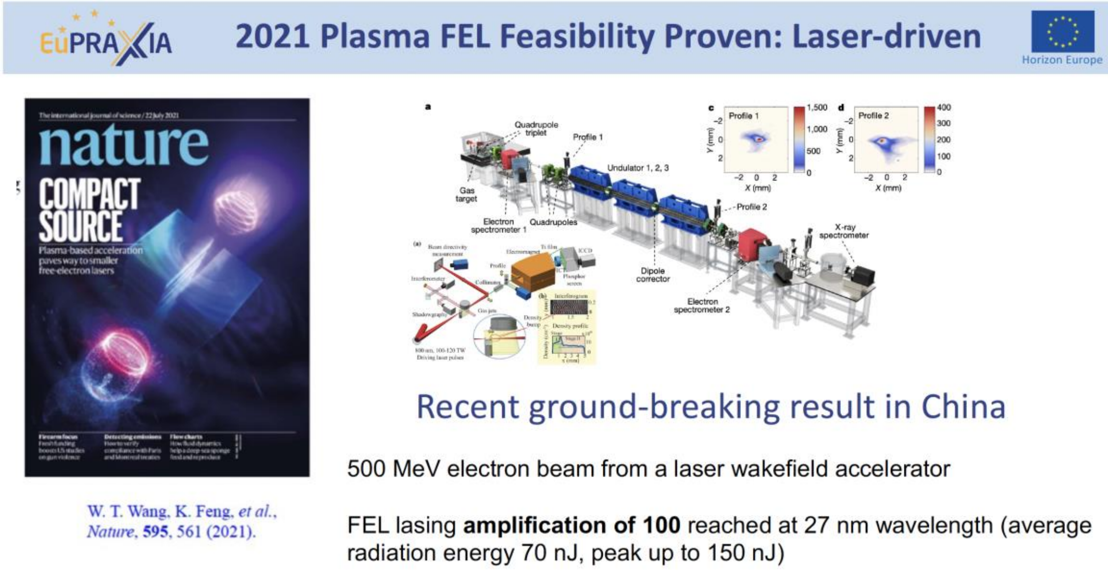
Updated Livingston plot for accelerators, showing the maximum reach in beam energy versus time. Grey bands visualize accelerator applications

Plasma Accelerator Achievements

- Gradients up to **100 GV/m**
- Acceleration > 10 **GeV** of electron beams
- Basic beam **quality for FEL** demonstrated

The most demanding in terms of beam brightness, stability and control

Basic beam quality achieved in pilot FEL experiments



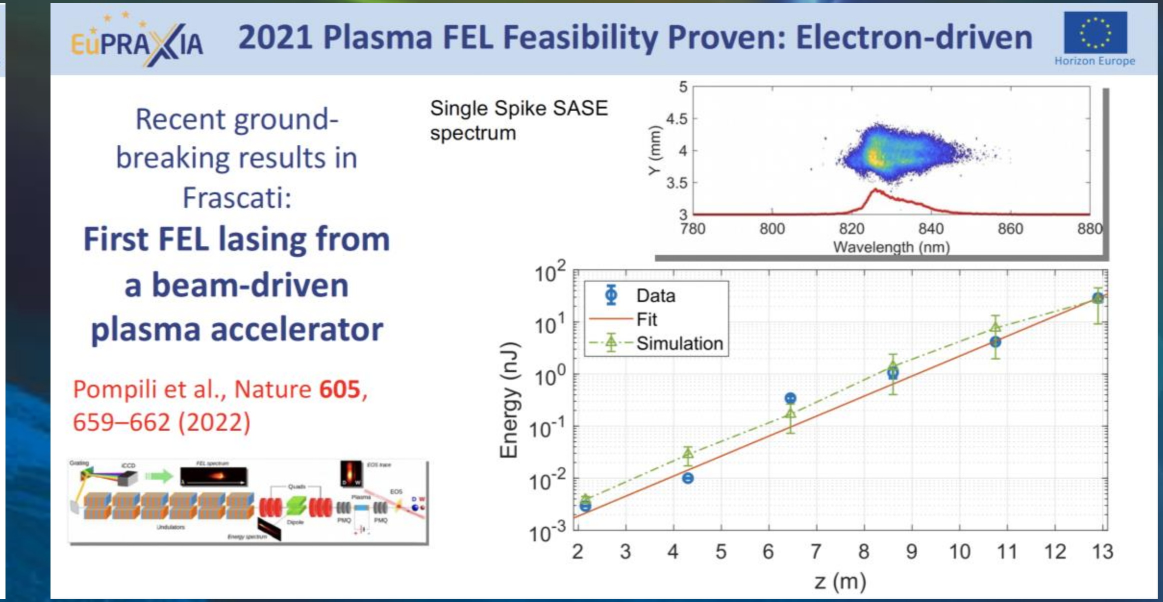
2021 Plasma FEL Feasibility Proven: Laser-driven

W. T. Wang, K. Feng, *et al.*, *Nature*, **595**, 561 (2021).

Recent ground-breaking result in China

500 MeV electron beam from a laser wakefield accelerator

FEL lasing **amplification of 100** reached at 27 nm wavelength (average radiation energy 70 nJ, peak up to 150 nJ)

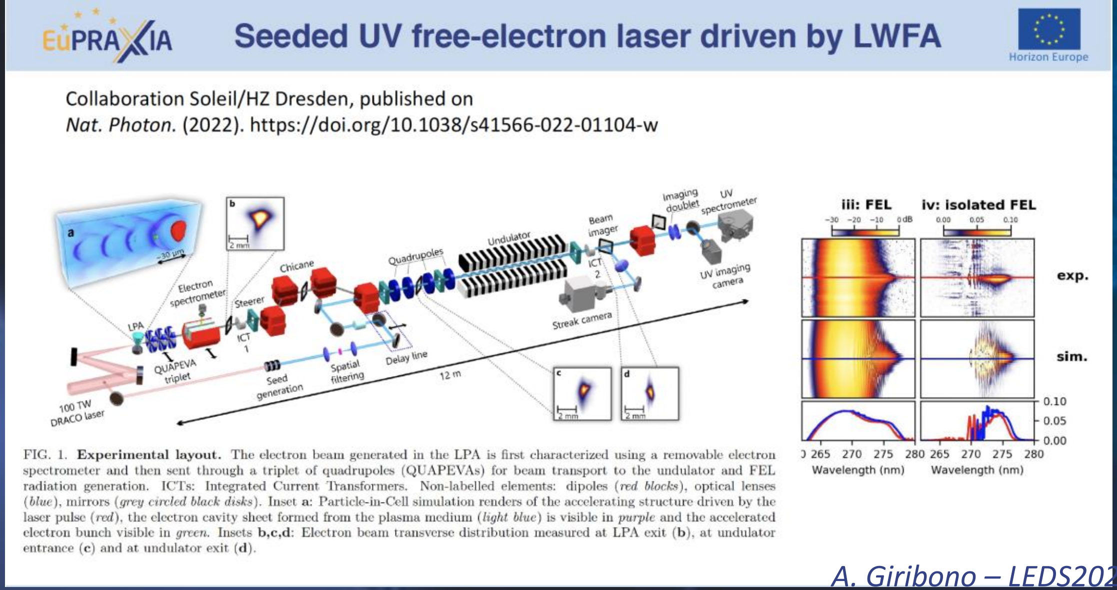


2021 Plasma FEL Feasibility Proven: Electron-driven

Recent ground-breaking results in Frascati:

First FEL lasing from a beam-driven plasma accelerator

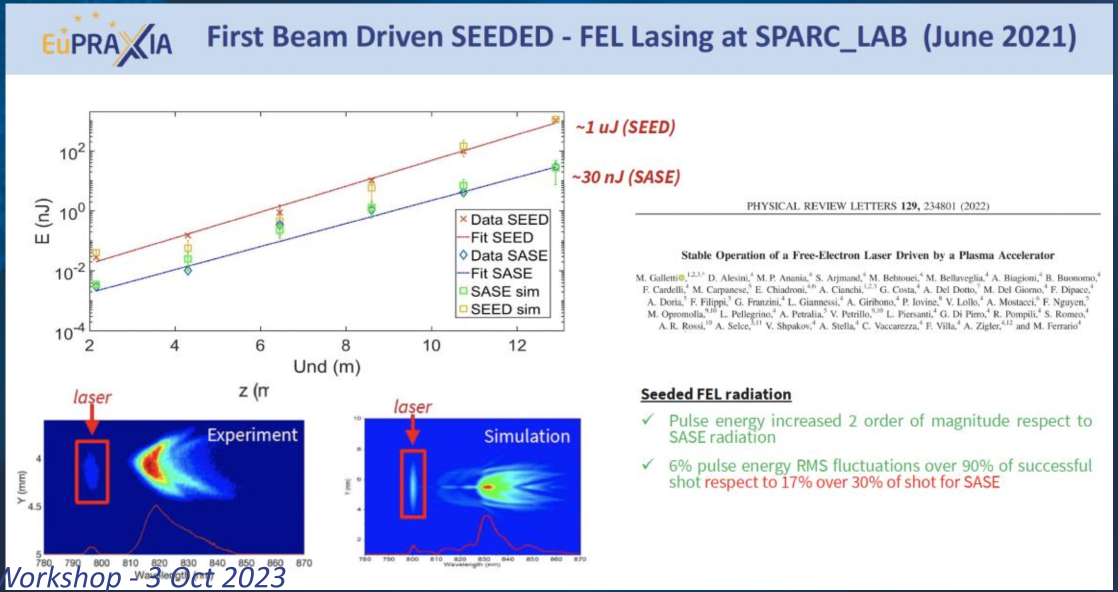
Pompili et al., Nature **605**, 659–662 (2022)



Seeded UV free-electron laser driven by LWFA

Collaboration Soleil/HZ Dresden, published on
Nat. Photon. (2022). https://doi.org/10.1038/s41566-022-01104-w

FIG. 1. **Experimental layout.** The electron beam generated in the LPA is first characterized using a removable electron spectrometer and then sent through a triplet of quadrupoles (QUAPEVAs) for beam transport to the undulator and FEL radiation generation. ICTs: Integrated Current Transformers. Non-labelled elements: dipoles (*red blocks*), optical lenses (*blue*), mirrors (*grey circled black disks*). Inset **a**: Particle-in-Cell simulation renders of the accelerating structure driven by the laser pulse (*red*), the electron cavity sheet formed from the plasma medium (*light blue*) is visible in *purple* and the accelerated electron bunch visible in *green*. Insets **b,c,d**: Electron beam transverse distribution measured at LPA exit (**b**), at undulator entrance (**c**) and at undulator exit (**d**).



First Beam Driven SEEDED - FEL Lasing at SPARC_LAB (June 2021)

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

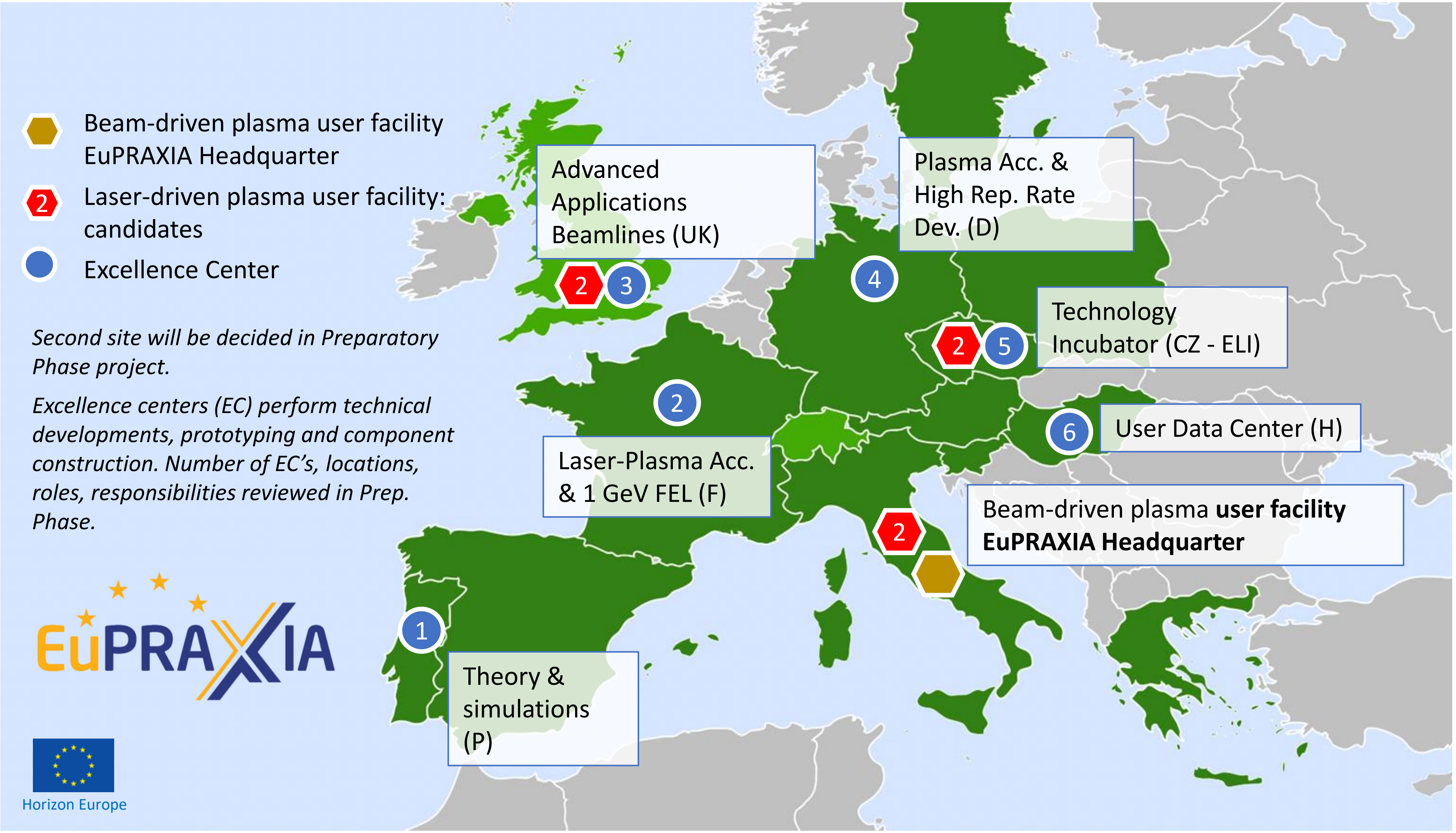
Stable Operation of a Free-Electron Laser Driven by a Plasma Accelerator

M. Galletti,[1,2,3,*] D. Alesini,[4] M. P. Anania,[4] S. Arjmand,[4] M. Behtouei,[4] M. Bellaveglia,[4] A. Biagioni,[4] B. Buonomo,[4] F. Cardelli,[4] M. Carpanese,[5] E. Chiadroni,[4,6] A. Cianchi,[1,2,3] G. Costa,[4] A. Del Dotto,[7] M. Del Giorno,[4] F. Dipace,[4] A. Doria,[5] F. Filippi,[5] G. Franzini,[4] L. Giannessi,[4] A. Giribono,[4] P. Iovine,[8] V. Lollo,[4] A. Mostacci,[6] F. Nguyen,[5] M. Opromolla,[9,10] L. Pellegrino,[4] A. Petralia,[5] V. Petrillo,[9,10] L. Piersanti,[4] G. Di Pirro,[4] R. Pompili,[4] S. Romeo,[4] A. R. Rossi,[10] A. Selce,[3,11] V. Shpakov,[4] A. Stella,[4] C. Vaccarezza,[4] F. Villa,[4] A. Zigler,[4,12] and M. Ferrario[4]

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

Distributed Research Infrastructure



⬢ Beam-driven plasma user facility EuPRAXIA Headquarter

2 Laser-driven plasma user facility: candidates

● Excellence Center

Second site will be decided in Preparatory Phase project.

Excellence centers (EC) perform technical developments, prototyping and component construction. Number of EC's, locations, roles, responsibilities reviewed in Prep. Phase.

Advanced Applications Beamlines (UK)

Plasma Acc. & High Rep. Rate Dev. (D)

Technology Incubator (CZ - ELI)

Laser-Plasma Acc. & 1 GeV FEL (F)

User Data Center (H)

Beam-driven plasma **user facility EuPRAXIA Headquarter**

Theory & simulations (P)

Today`s status

- Excellence centers: several (6 – 10) assumed to be realized
- First site: EuPRAXIA@SPARC_LAB
- Second site: one to be selected
- Connect with WP´s to Horizon Europe and national funding lines

Headquarter and Site 1: EuPRAXIA@SPARC_LAB

Frascati`s future facility

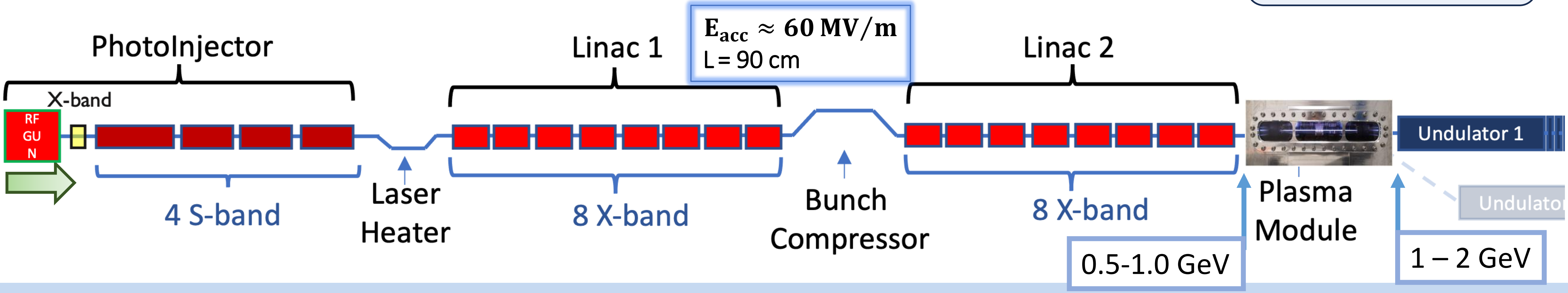
- > 130 M€ invest funding
- Beam-driven plasma accelerator - *PWFA*
- Europe`s most compact and most southern FEL
- The world`s most compact RF accelerator **X band with CERN**

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

A Beam-Driven Plasma Wake-field Accelerator

- **EuPRAXIA@SPARC_LAB** is a multi-GeV plasma-based accelerator with outstanding beam quality to drive a user facility whose main application concerns the operation of a soft X-ray FEL (3-5 nm)
- The FEL is driven by a 1 GeV high brightness electron beam, that turns into less than 1 mm-mrad emittance and up to 2 kAmps peak current.
- The accelerator is based on the unique combination of an advanced high-brightness RF injector and a plasma-beam driven accelerator
- Beam dynamics in the EuPRAXIA@SPARC_LAB machine has been studied by means of **start to end simulations** from the cathode including the FEL emission

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	
Δγ/γ (%)	< 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	

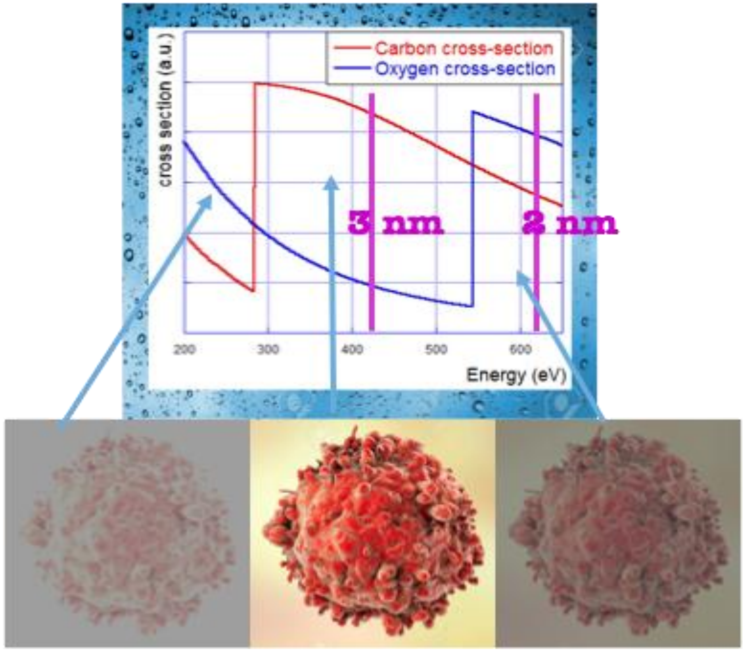


Expected SASE FEL performances

Radiation Parameter	**Unit**	PWFA	Full X-band
Radiation Wavelength	nm	**3-4**	4
Photons per Pulse	$\times 10^{12}$	**0.1-0.25**	1
Photon Bandwith	%	**0.1**	0.5
Undulator Area Length	m	30	
ρ(1D/3D)	$\times 10^{-3}$	**2**	2
Photon Brilliance per shot	$mm^2 mrad\ bw(0.1\%)$	$\mathbf{1-2 \times 10^{28}}$	1×10^{27}

Electron Beam Parameter	**Unit**	PWFA	Full X-band
Electron Energy	GeV	**1-*1.2***	1
Bunch Charge	pC	**30-50**	200-*500*
Peak Current	kA	**1-2**	1-2
RMS Energy Spread	%	**0.1**	0.1
RMS Bunch Length	μm	**6-3**	24-20
RMS norm. Emittance	μm	**1**	1
Slice Energy Spread	%	**≤0.05**	≤0.05
Slice norm Emittance	mm-mrad	**0.5**	0.5

In the energy region between Oxygen and Carbon K-edge 2.34 nm – 4.4 nm (530 eV -280 eV) water is almost transparent to radiation while nitrogen and carbon are absorbing (and scattering)



Coherent Imaging of biological samples protein clusters, VIRUSES and cells living in their native state

Possibility to study dynamics

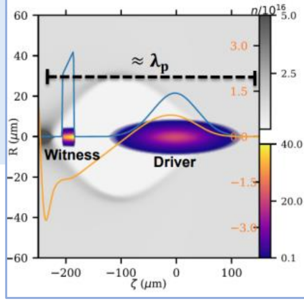
~10 ^{11} photons/pulse needed

Courtesy C. Vaccarezza

Courtesy F. Stellato (UniTov)

The PWFA operation: WoP1

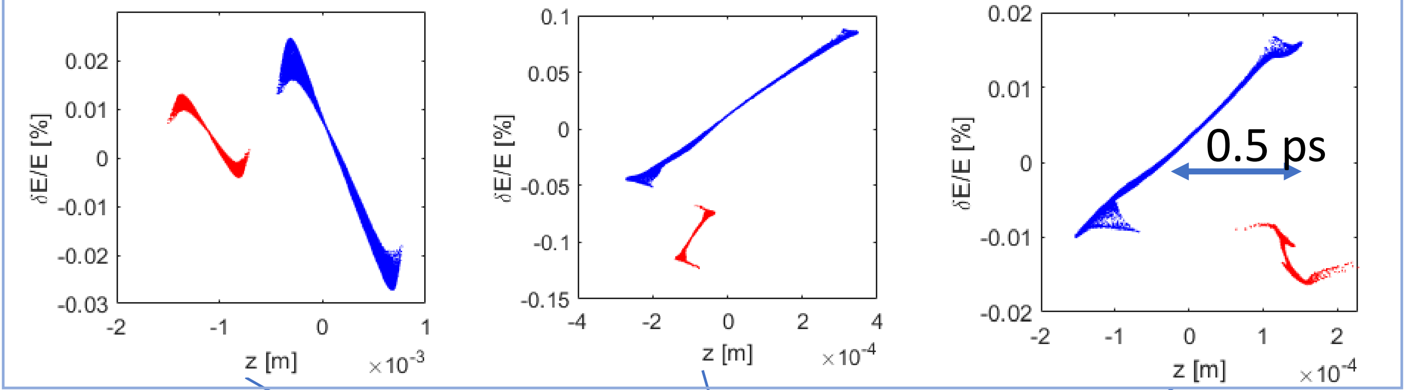
The PWFA Working Point



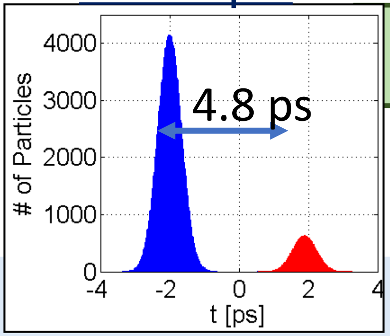
- Beside the FEL specifications, the **reference working point** has been determined by the plasma module
  - Accelerating gradient of the order of GV/m
  - Weakly non-linear regime (bubble with resonant behaviour)

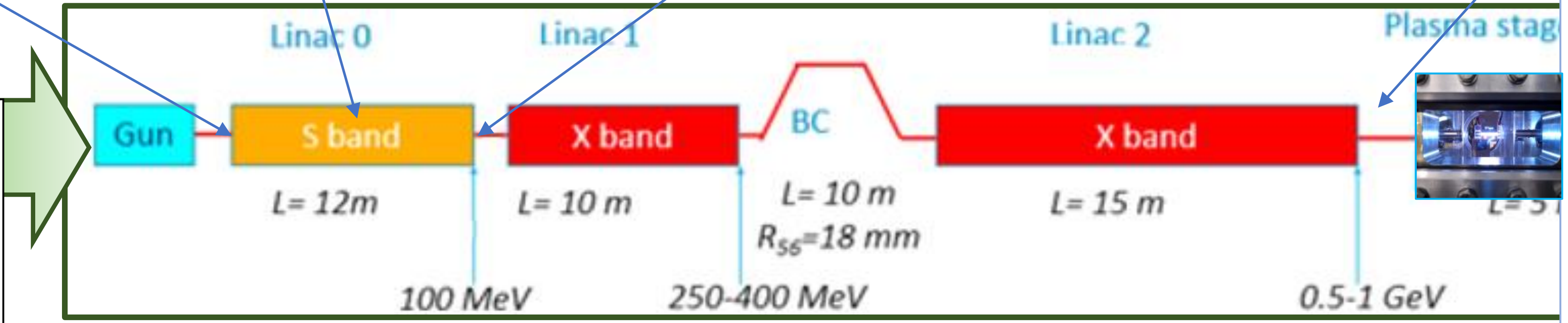
1. 200-500 pC driver + 30-50 pC witness
2. plasma density of the order of $10^{16} cm^{-3}$ (λ_p = 334 μm)
3. Driver-witness separation of around 0.5 ps (i.e. λ_p /2)
4. Driver and witness bunches of 200 fs and 10 fs rms
5. Driver and witness spot size of 4 and 1 μm with α=1

Velocity bunching technique



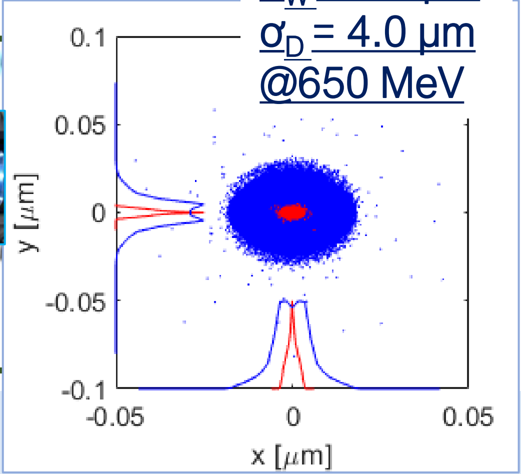
Laser comb technique





Strong focusing system

σ_W = 1.0 μm
σ_D = 4.0 μm
@650 MeV

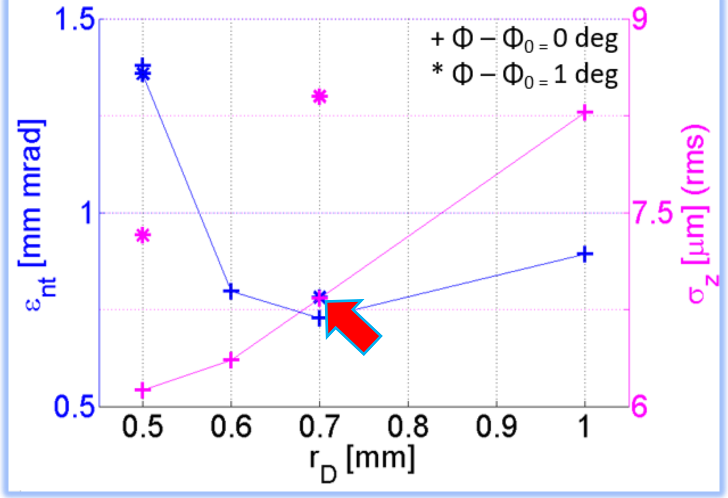


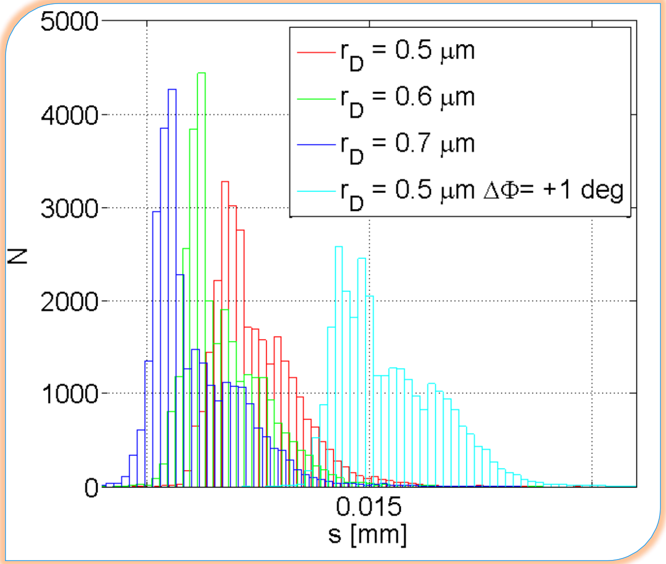
The Photoinjector

(TStep,ASTRA)

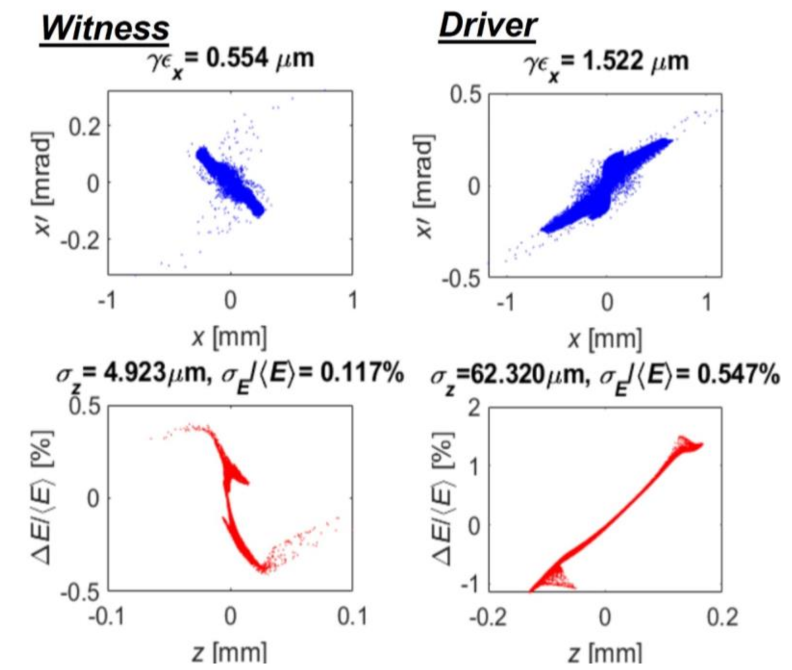
- The beam dynamics has been studied by means of simulations with the TStep (*and ASTRA)* code
  - The photoinjector sets the beam separation, emittance and current
  - The witness and driver distribution on the cathode has been chosen looking at the witness quality that depends on the density of the 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]

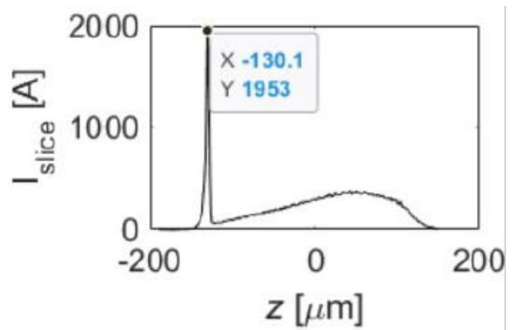
Optimised Working point





[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





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

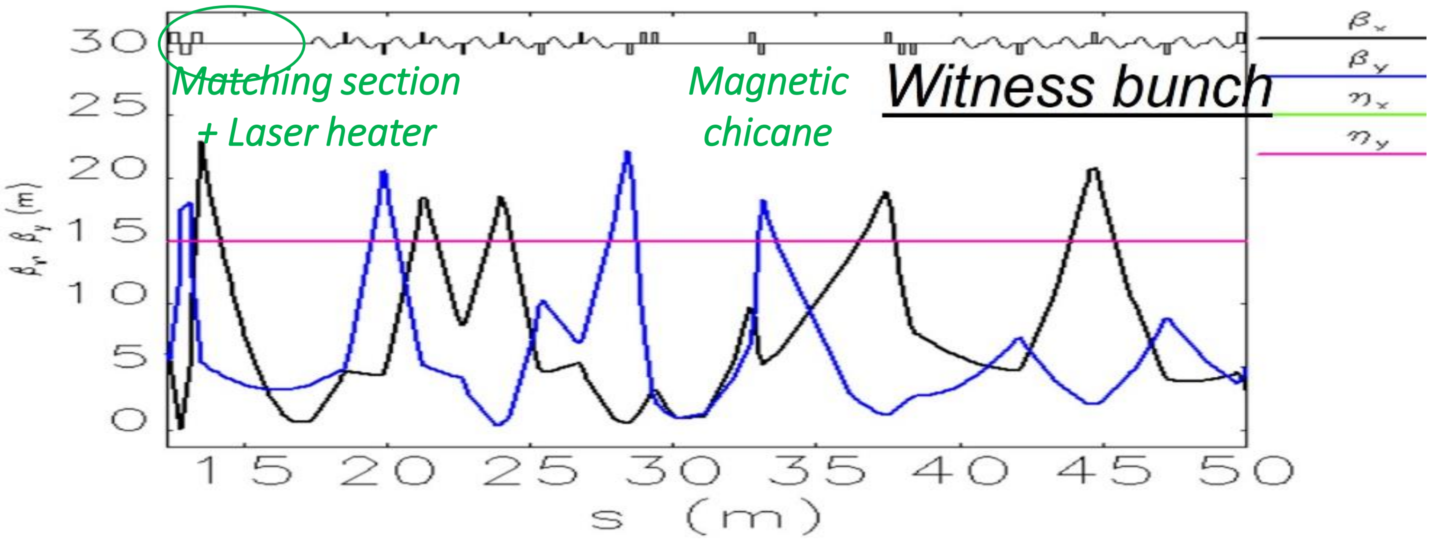
[3] G.J. Silvi et al. "Beam dynamics optimization of Eu-PRAXIA@SPARC_LAB RF injector" presented at the IPAC'23, Venezia, Italy, May. 2023, paper WEPA040

The X-band Linac

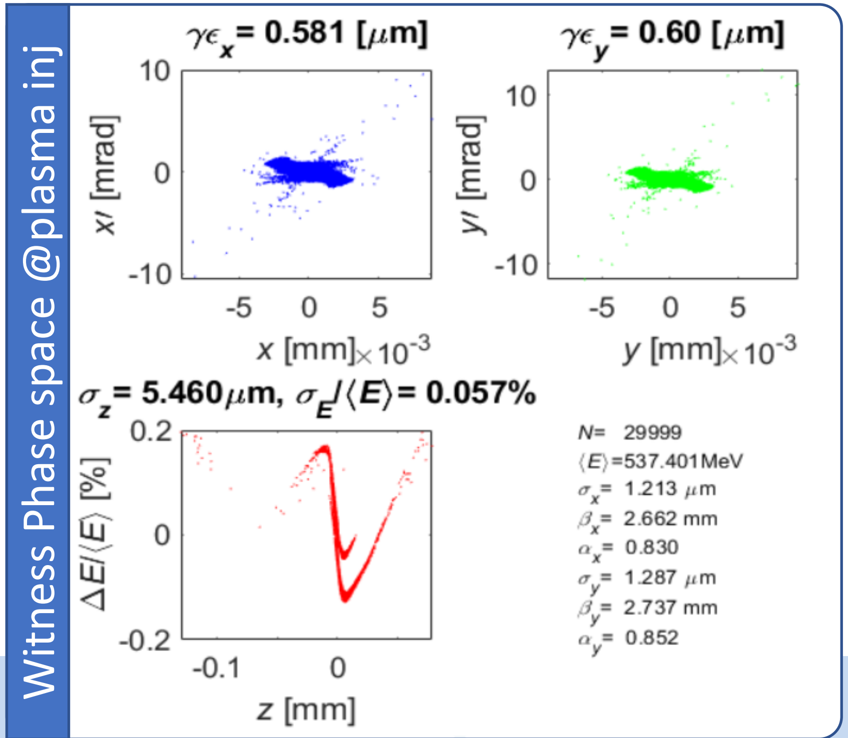
(Elegant, TStep)

- **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 S and X band technologies
  - Minimization of the final beam energy spread

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]	158	
$\sigma_{x\text{-rms}}$ [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**



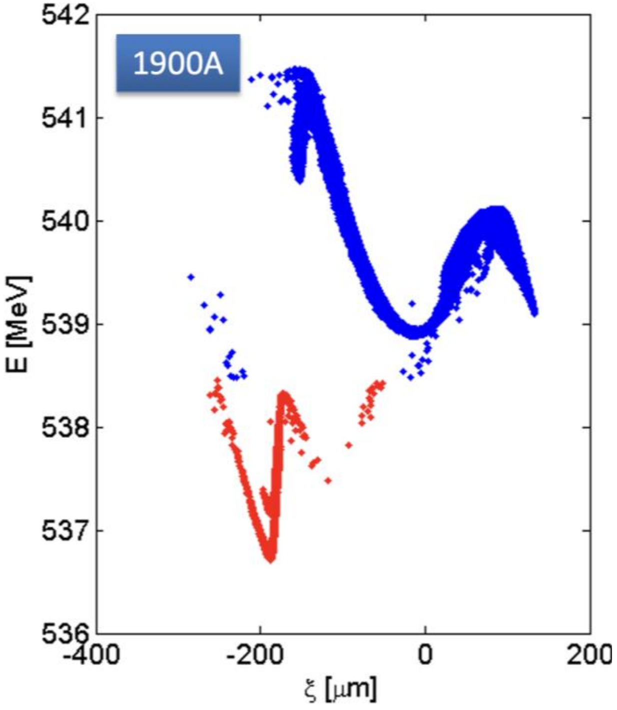
Twiss parameters along the linac for the witness bunch. The overall beam transverse size remains always smaller than the X-band irises with maximum spot size in the matching quadrupoles of the order of 0.7 mm.



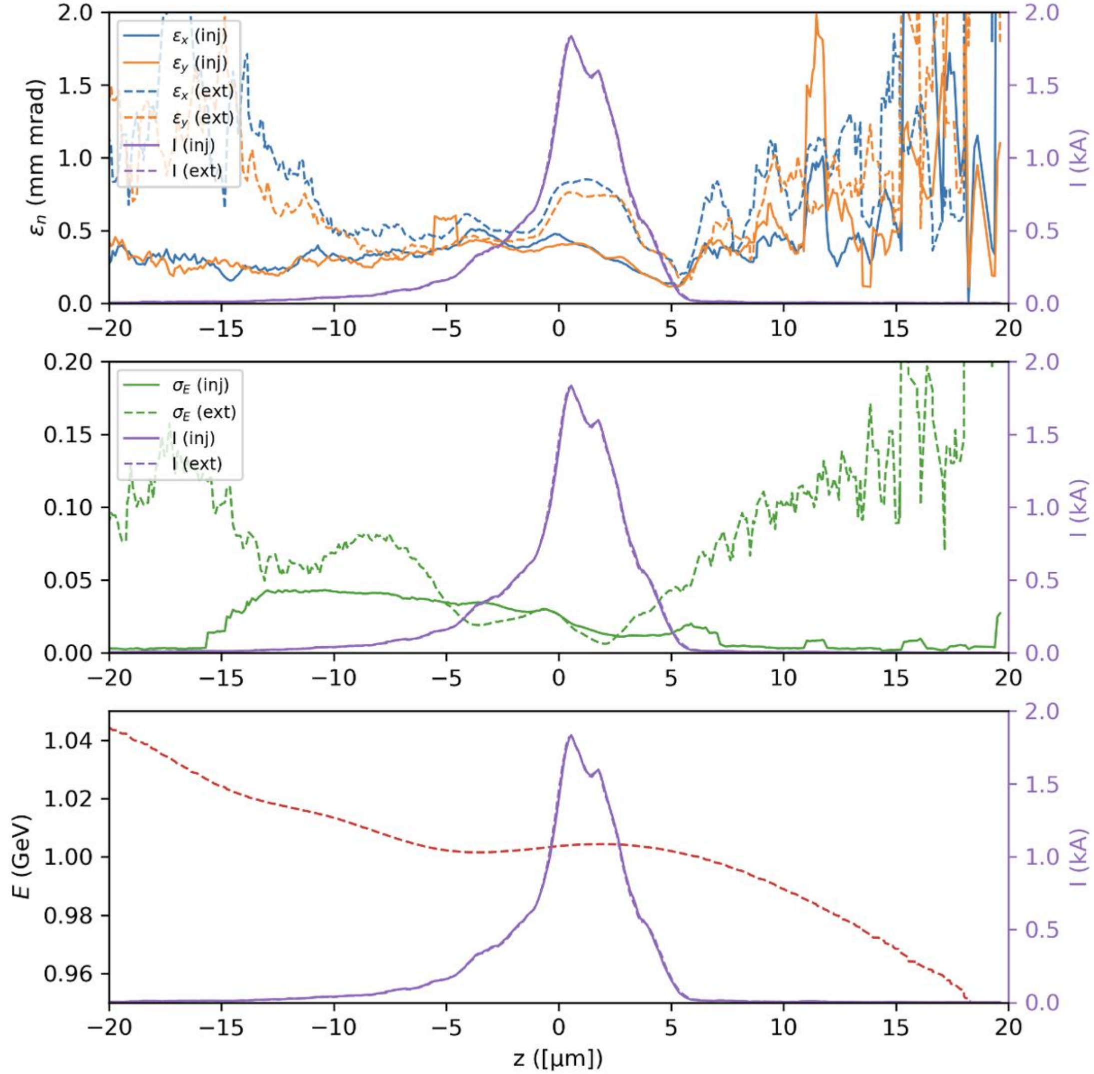
The Plasma

(Architect)

@plasma entrance



- ☐ $\Delta z = 158\ \mu\mathrm{m}$
- ☐ $n_p = 0.9 \cdot 10^{16}\ \mathrm{cm}^{-3}$
- ☐ $\sigma_E = 0.06\%$
- ☐ $E_z = 0.9\ \mathrm{GV/m}$ *(including 1 cm injection ramp)*
- ☐ Slice energy spread virtually untouched
- ☐ Slight emittance increase *(to be improved with ramps)*
- ☐ Accelerating length 56 cm



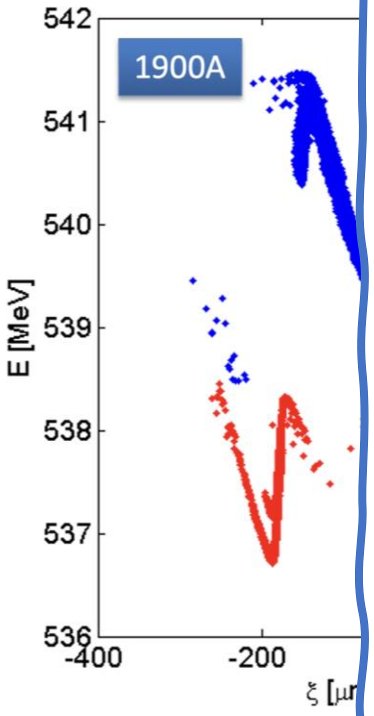
Witness slice analysis @plasma exit

Courtesy S. Romeo- A. Del Dotto

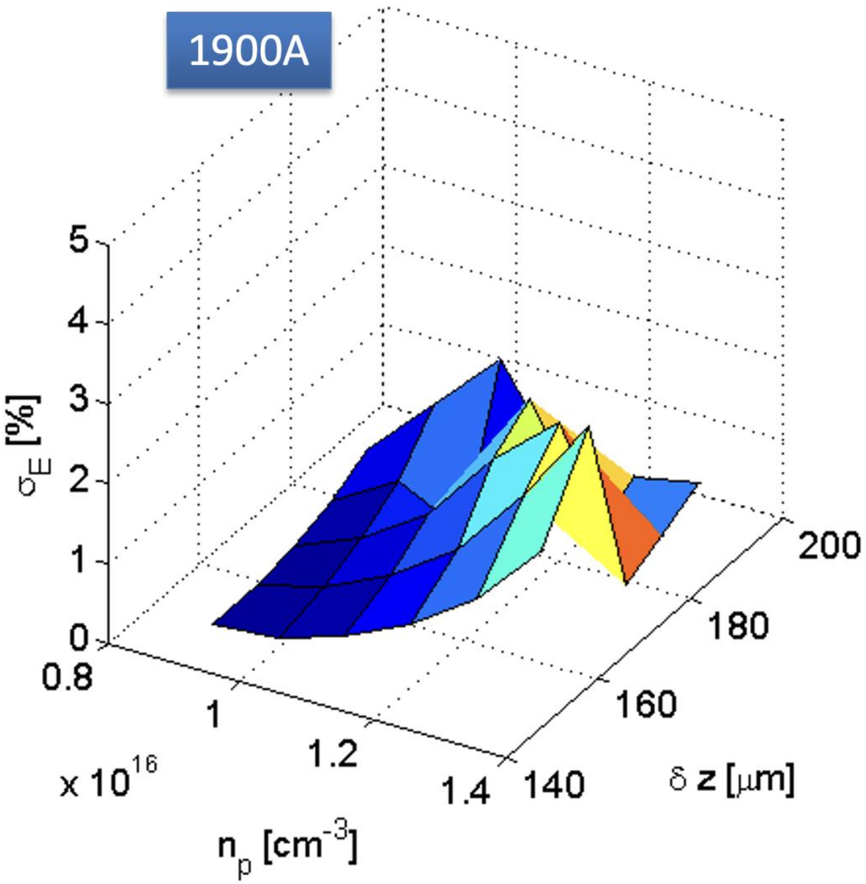
The Plasma

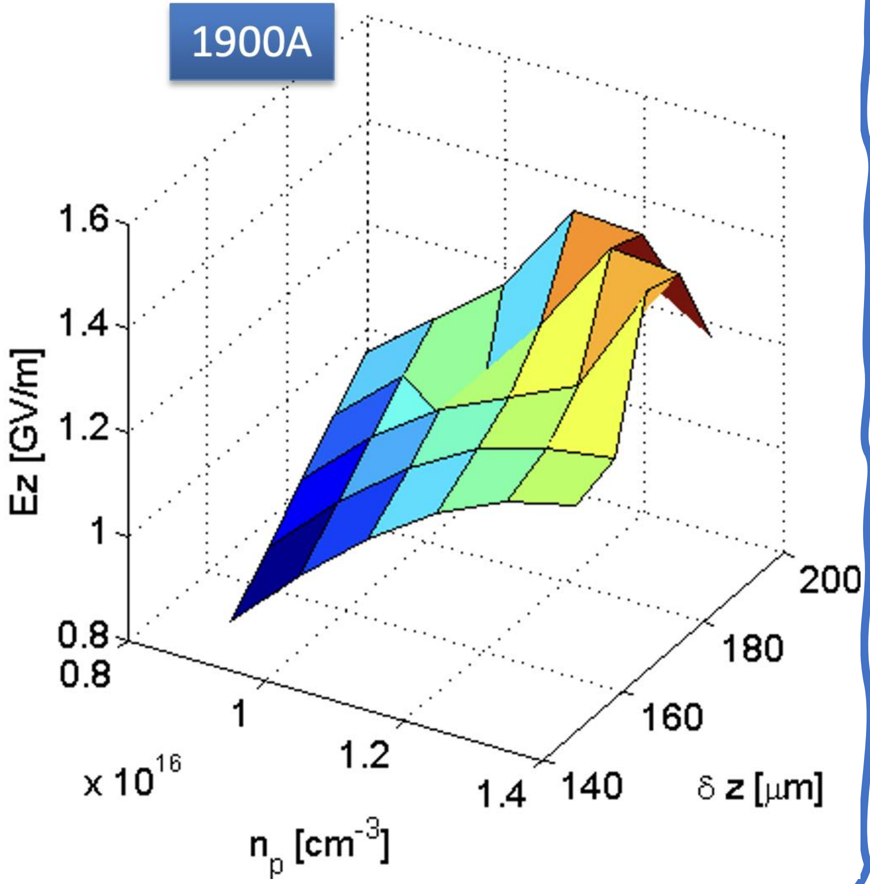
(Architect)

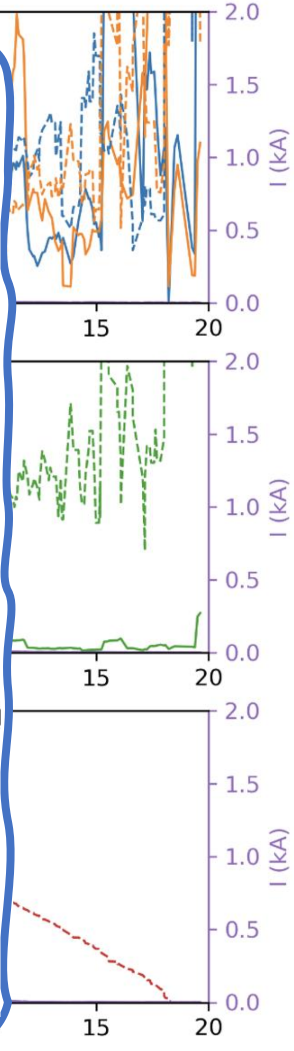
@plasma



This is the result of plasma density and witness-driver time distance scan





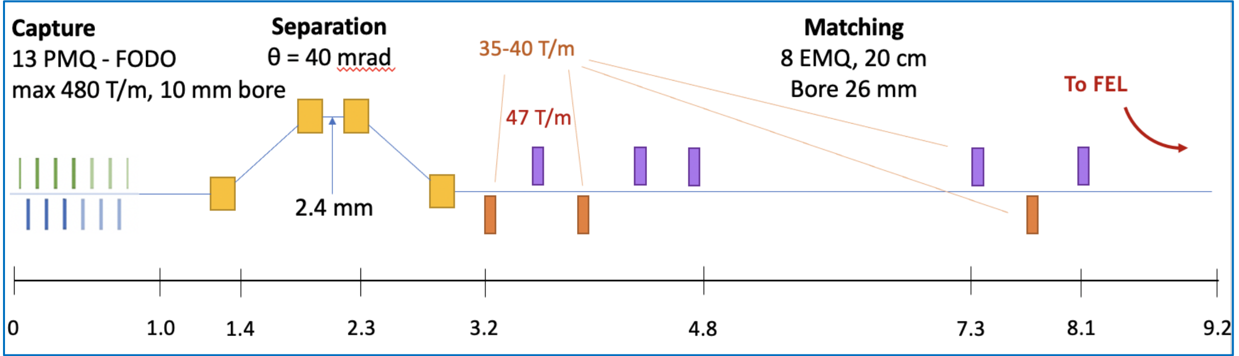


Witness slice analysis @plasma exit

Courtesy S. Romeo- A. Del Dotto

The transfer line: from the plasma to the undulator
(Elegant, ASTRA)

Layout



Capture
13 PMQ - FODO
max 480 T/m, 10 mm bore

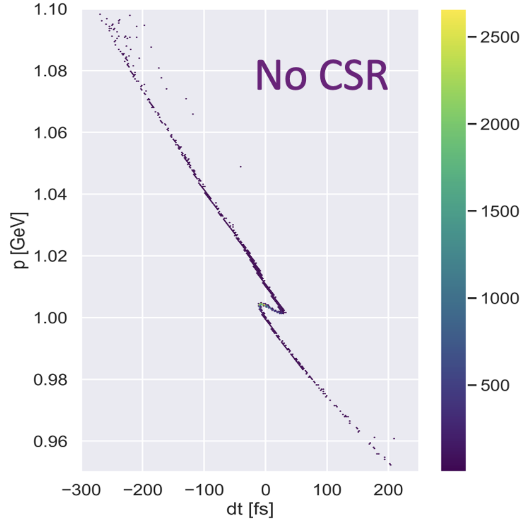
Separation
θ = 40 mrad

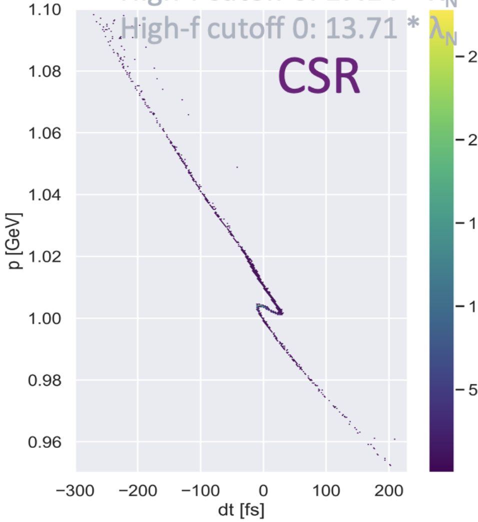
Matching
8 EMQ, 20 cm
Bore 26 mm

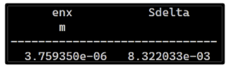
Evaluation of CSR (Elegant)

70 Bins

Nyquist wavelegth : 3.4 µm
High-f cutoff 0: 17.14 * λ_N
High-f cutoff 0: 13.71 * λ_N

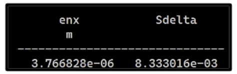






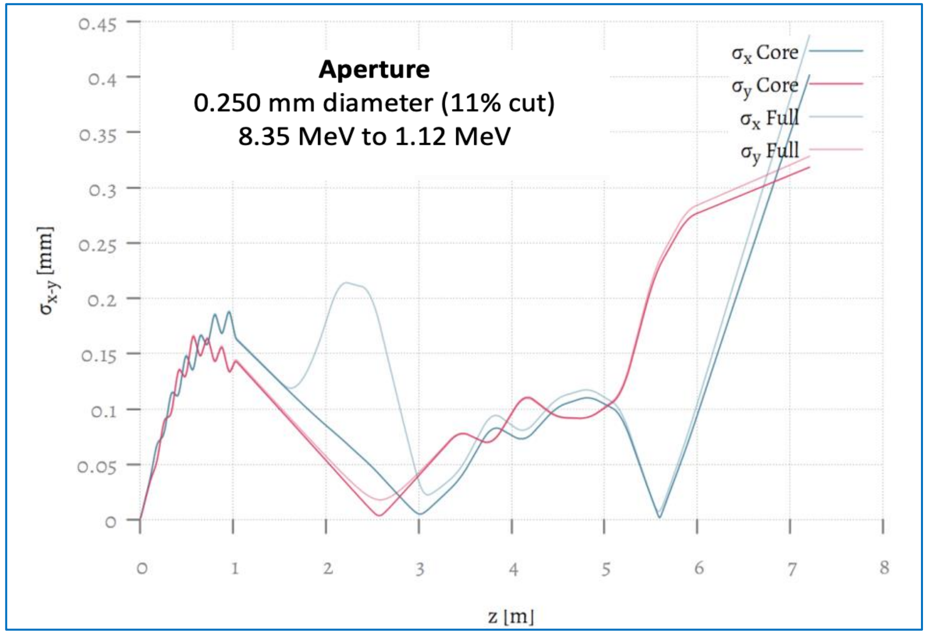
```
      enx                Sdelta
       m
----------------------------------
  3.759350e-06   8.322033e-03
```

Variation of emittance and energy spread: < 2‰

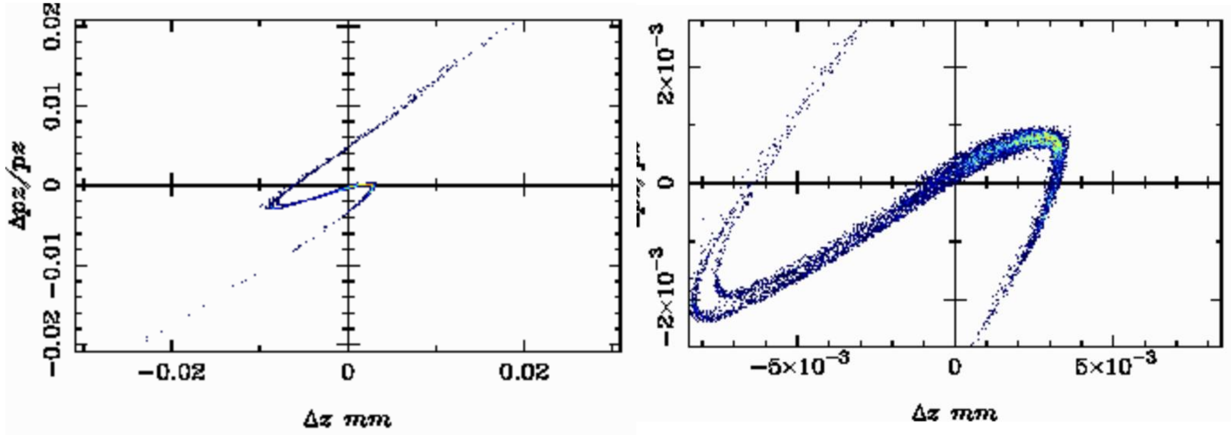


```
      enx                Sdelta
       m
----------------------------------
  3.766828e-06   8.333016e-03
```

Transverse beam size evolution w Space Charge (Astra)



Aperture
0.250 mm diameter (11% cut)
8.35 MeV to 1.12 MeV

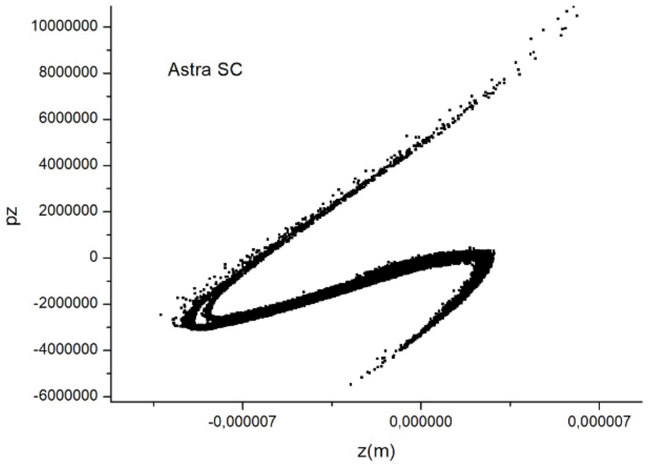


Courtesy M. Rossetti Conti

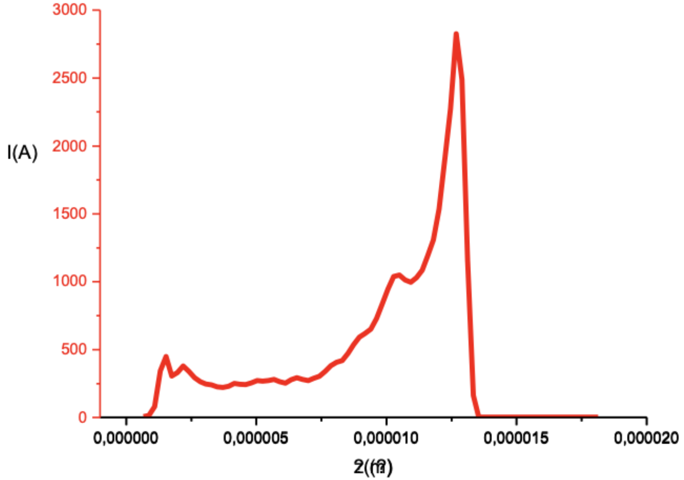
The FEL
(Genesis 3D)

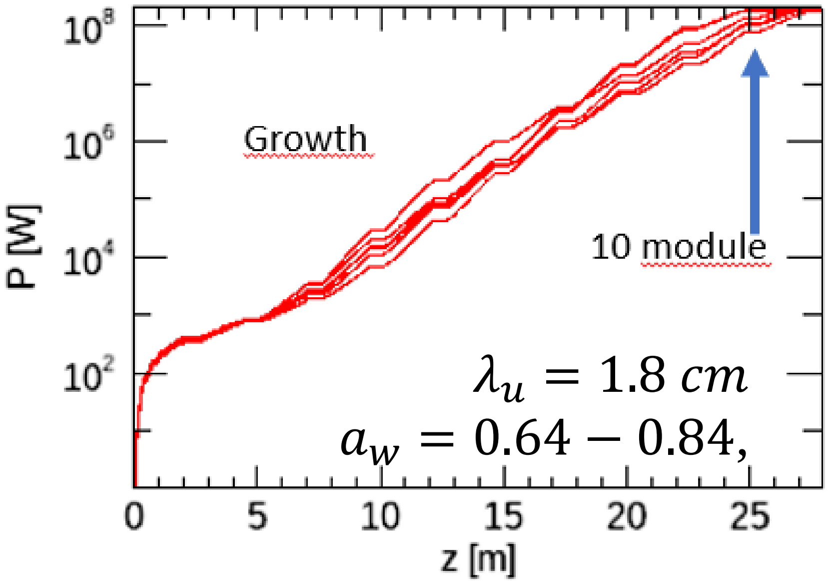
Electron beam at undulator entrance

Phase space

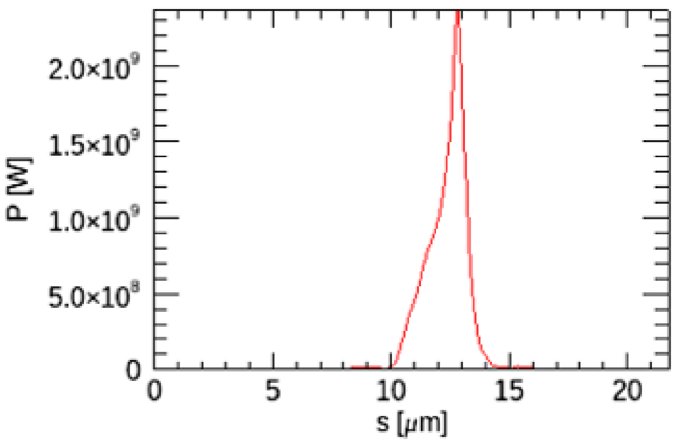


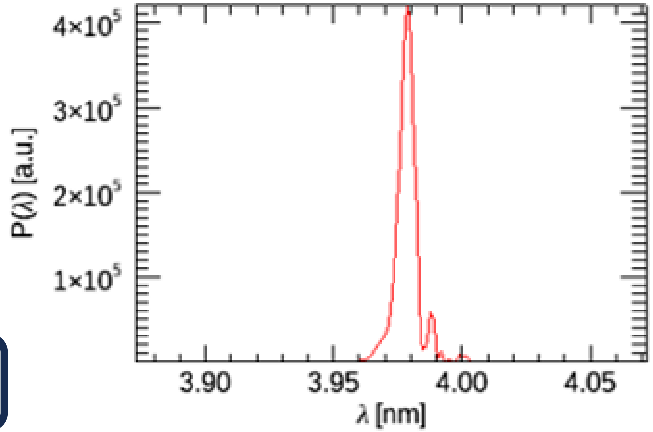
Current





Clean single spike at 25 m





Energy at 25 m	**J**	**$11.5\ 10^{-6}$**
bandwidth	%	0.1
size	m	$1.4\ 10^{-4}$
div	rad	$1.7\ 10^{-5}$
Photon number		**$2.2\ 10^{11}$**
wavelength	nm	3.975

Electron beam energy : 1 GeV, matching at 4 nm. Top,left: growth of the radiation power along the undulator. Bottom, left: table with main parameters of the radiation. Right: power and spectral distribution of the radiation.

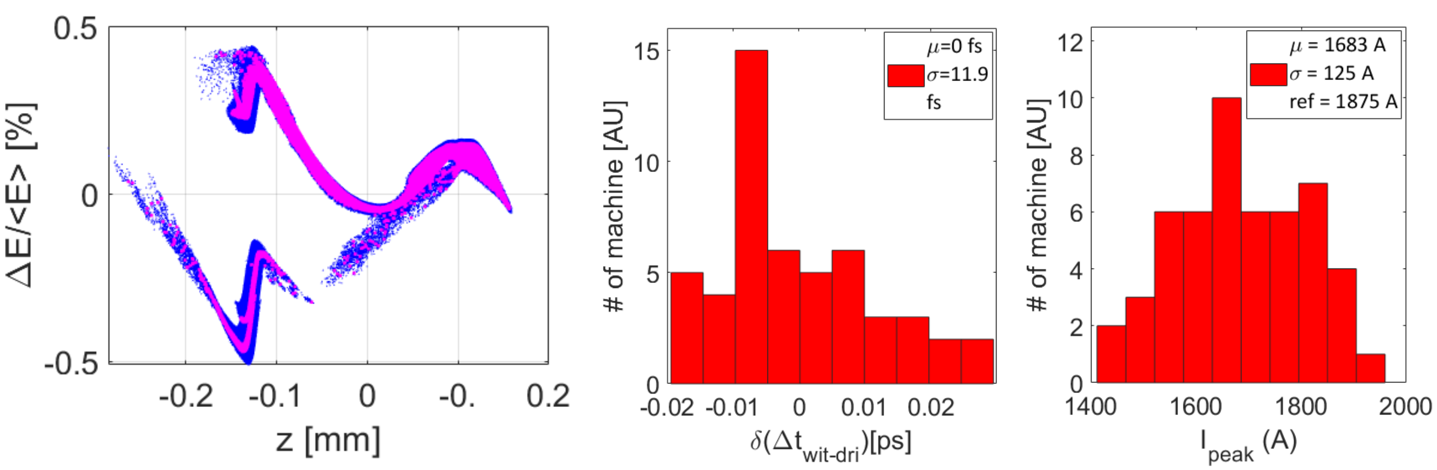
Courtesy V. Petrillo

Accelerator sensitivity studies

Considering state of the art technology:

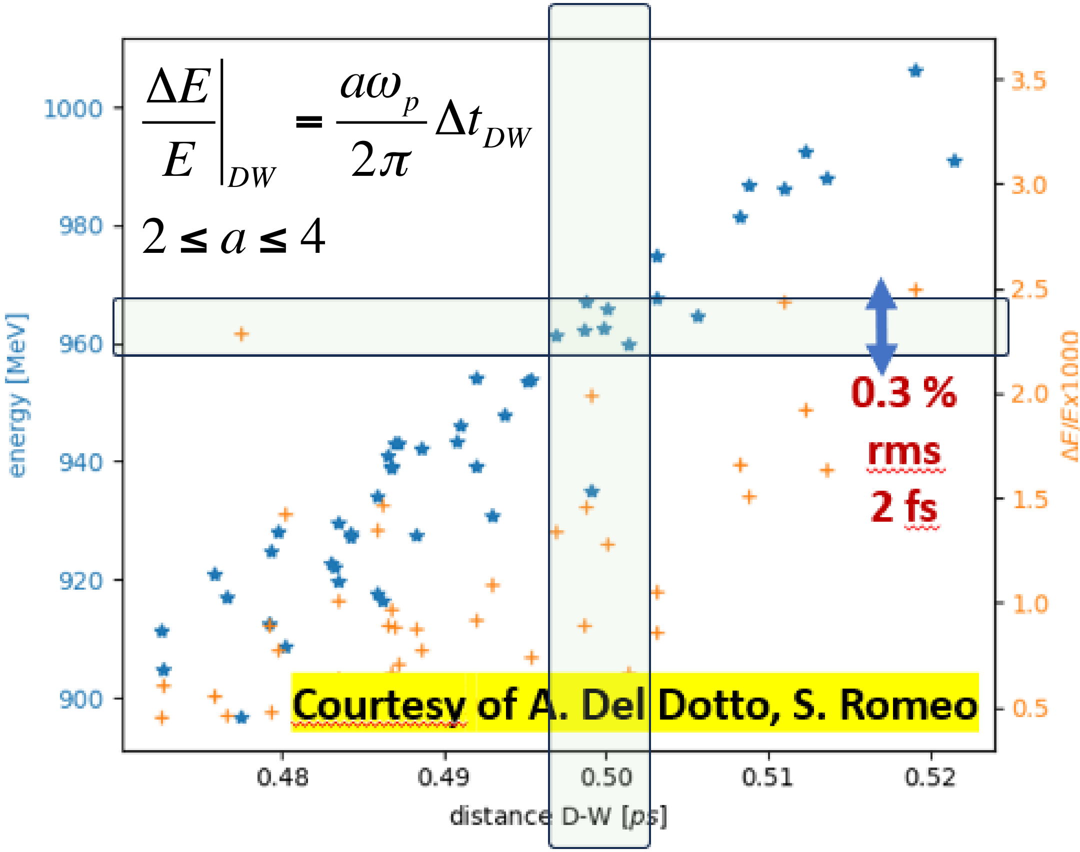
- ❑ Jitter on S/X-band: phase : 0.3 ps rms
  voltage: 0.1% rms
- ❑ Jitter on laser: TOA : 0.3 ps rms
  charge : ± 2 %
  Laser Spot size: ± 1%

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



$$\left.\frac{\Delta E}{E}\right|_{DW} = \frac{a\omega_p}{2\pi}\Delta t_{DW}$$

$$2 \le a \le 4$$

Courtesy of A. Del Dotto, S. Romeo

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

Accelerator sensitivity studies

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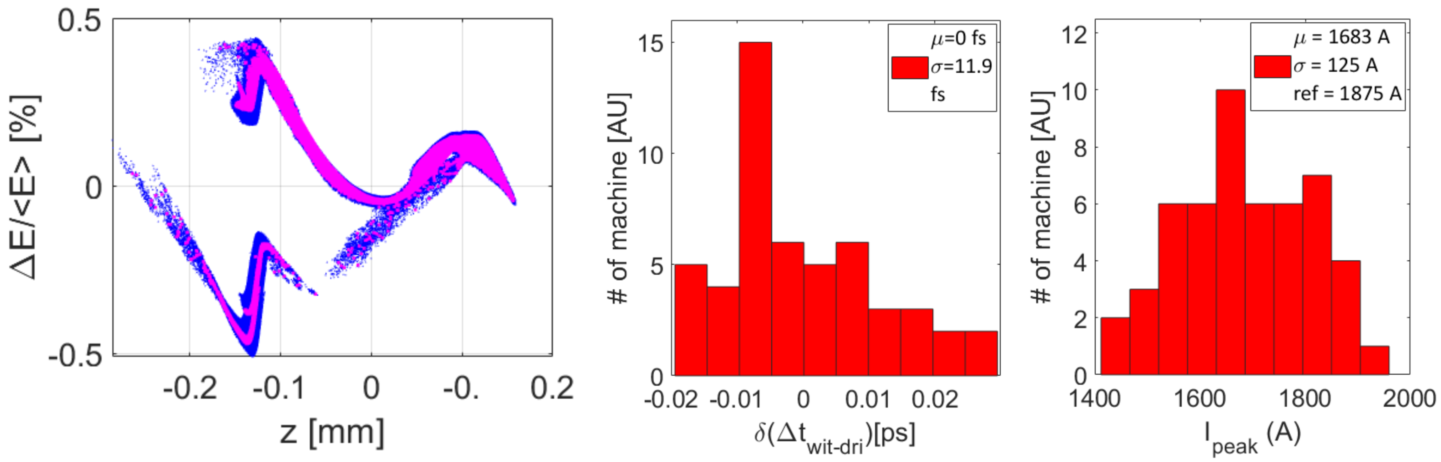
  Laser Spot size: ± 1%

Solid state C-band modulator phase : 0.15 ps rms

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



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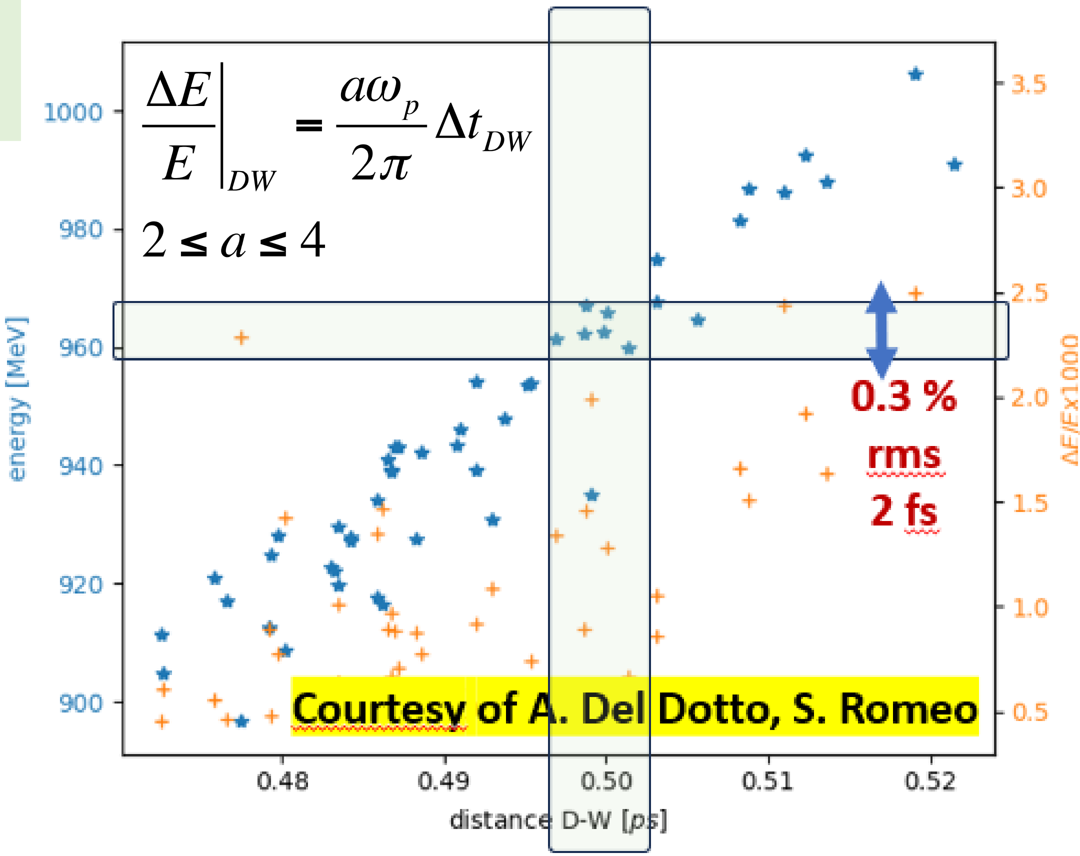

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$$2 \le a \le 4$$

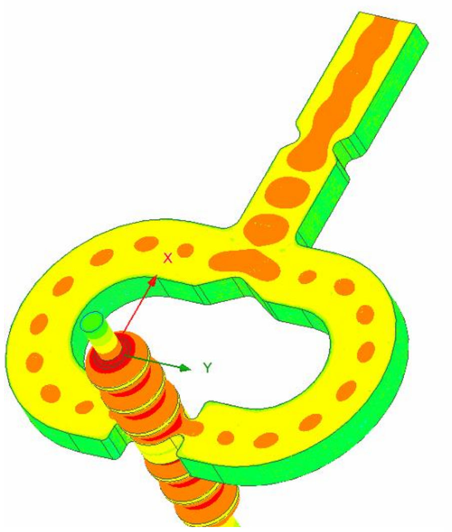
Results obtained by means of start to end simulations taking into account state of the art jitters in conventional RF photoinjector

Complete jitter simulations

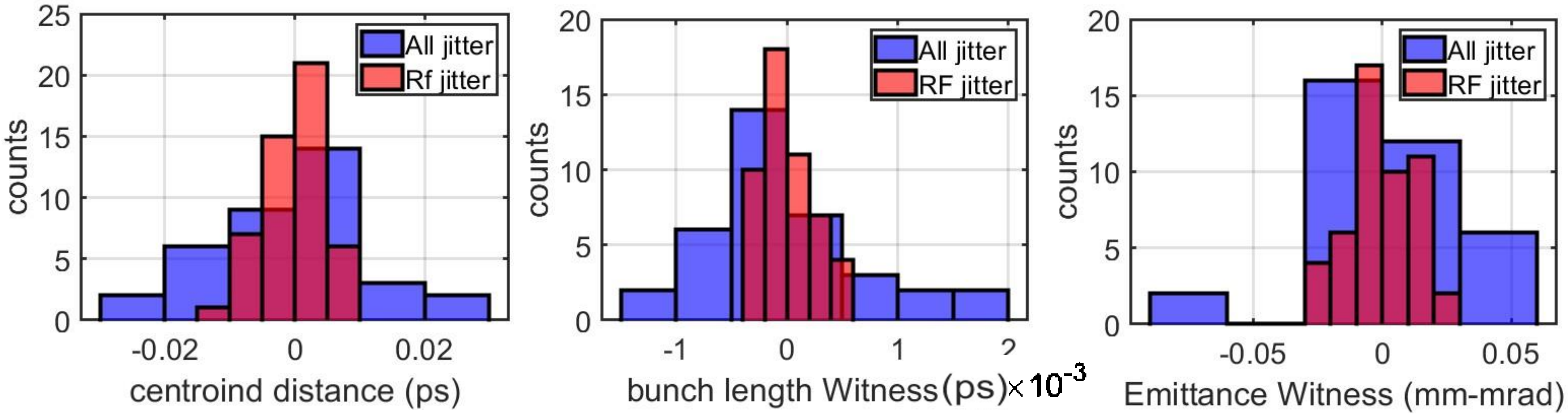
- X-band accelerating structure right after the RF gun
- Sensitivity jitter study for all RF injector components in parallel with the generation of the cathode beam parameters.

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
<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

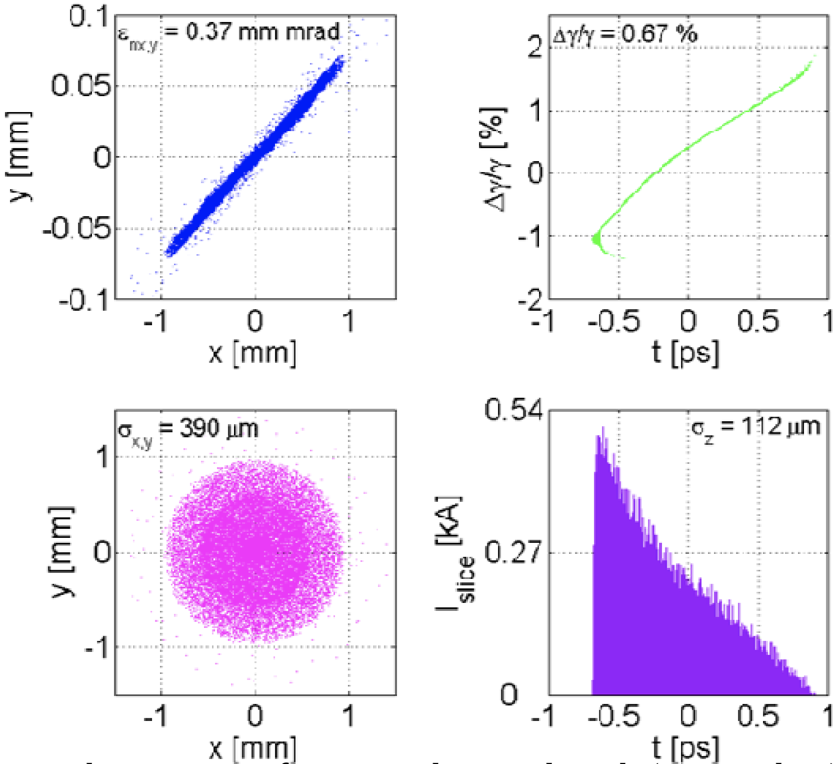
The full X-band operation: WoP2

The Photoinjector

(TStep,ASTRA)

- **The beam dynamics has been studied by means of simulations with the TStep (*and ASTRA)* code**
- The photoinjector in this case is operated in a milder velocity bunching scheme in the first S-band cavity to shorten the RMS beam length from 270 to ≈ 110 μm

@170 MeV



6D phase space of 200 pC electron bunch (upper plots), and transverse distribution and current profile (lower plots) at the Photoinjector exit.

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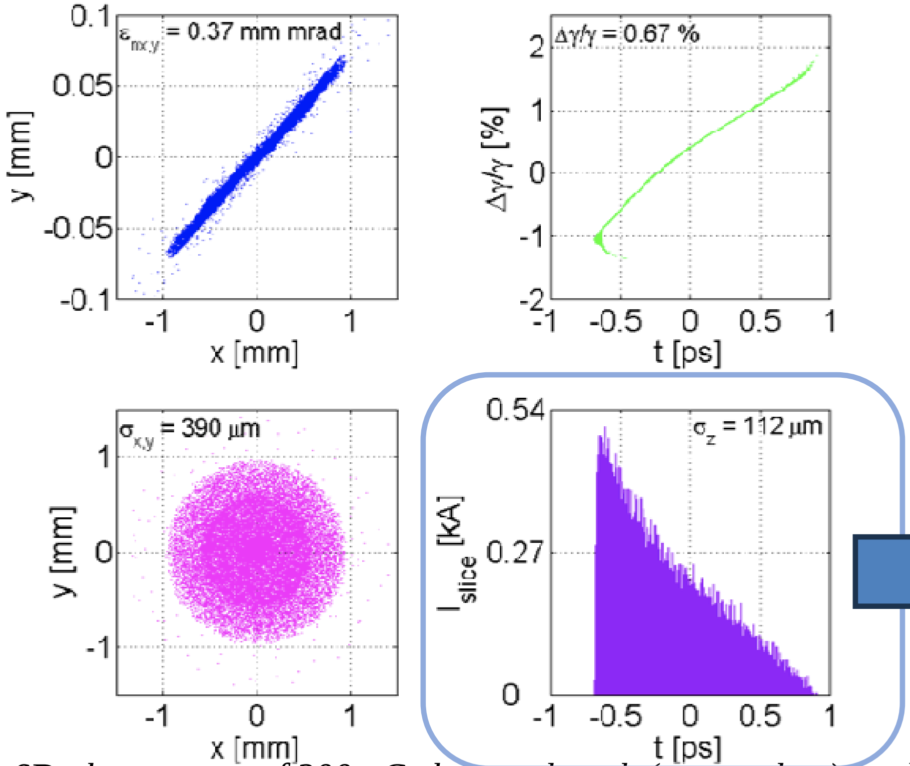

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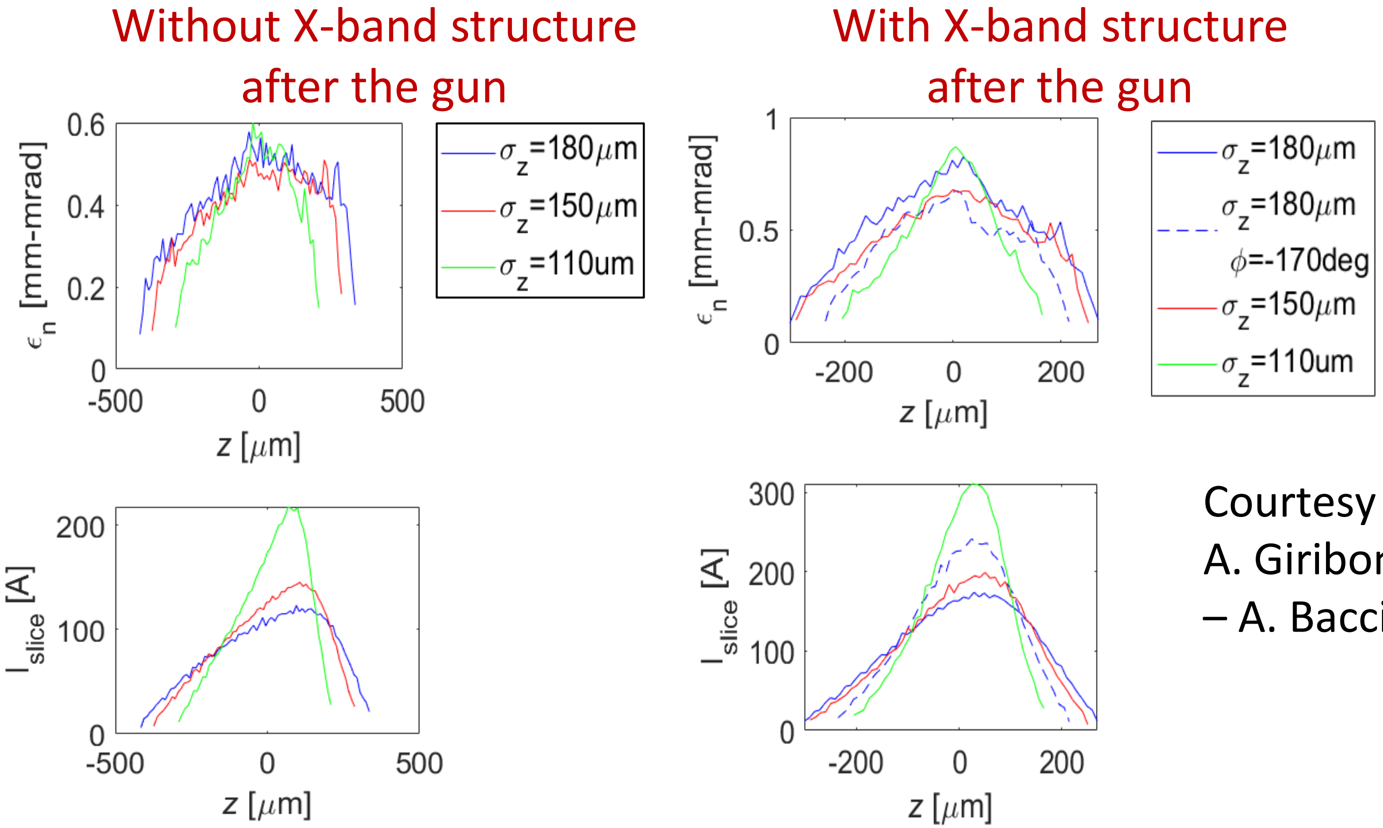


Courtesy
A. Giribono
– A. Bacci

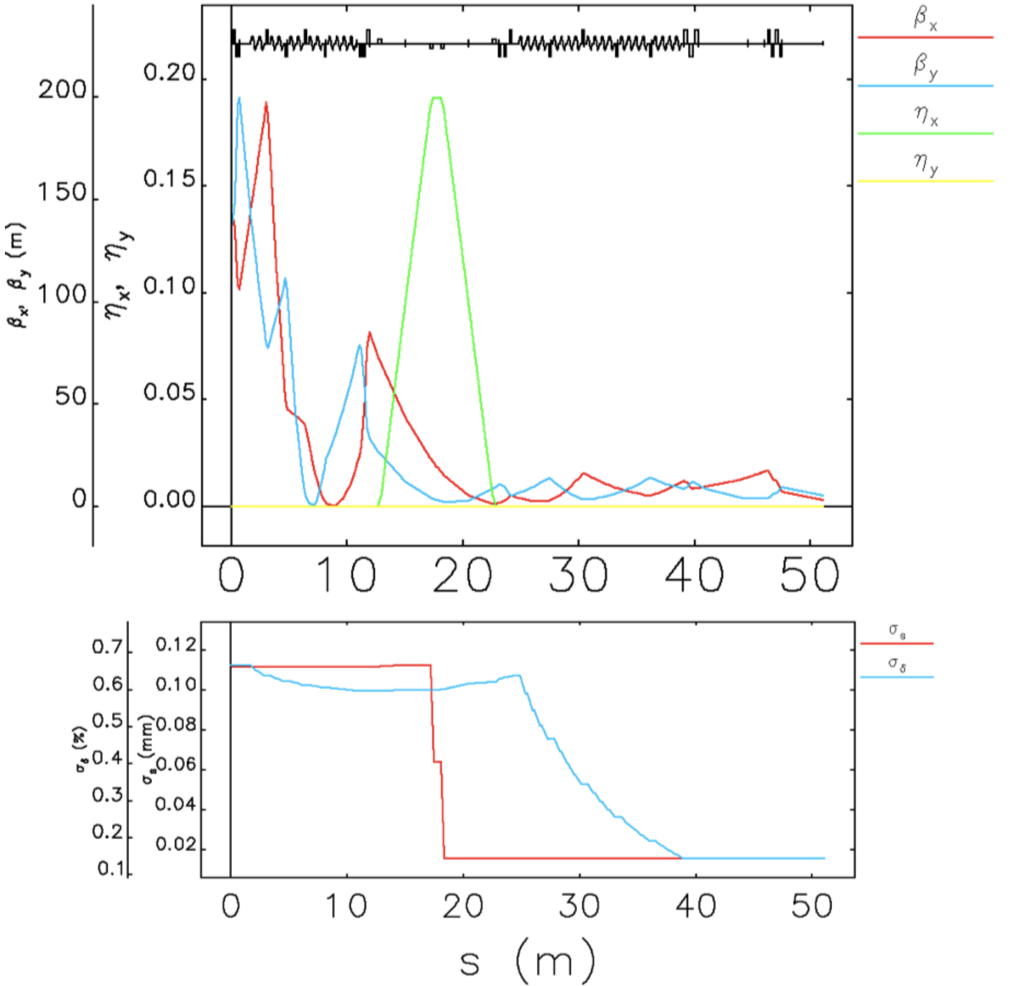
Slice analysis at the Photoinjector exit for different compression factor and introducing an X-band cavity after the gun

The X-band Linac

(Elegant)

- The beam dynamics in the X-band linac has been studied by means of Elegant simulations
  - The beam length at photoinjector exit is set to avoid the energy spread dilution due to RF curvature degradation effects in the linac
  - The X-band linac is set slightly off-crest to control and recover the correlated energy spread needed for the compression in the magnetic chicane
  - No phase space linearization is applied at this time prior the bunch compression in the chicane since the residual curvature of the longitudinal phase space distribution of the electron beam present at the photo-injector exit appears negligible and is quite completely recovered at the linac L1 exit

Linac2 Exit Parameters	
Charge (pC)	200
Spot Size (μm)	20-30
Bunch length (μm)	16
Emittance (mm-mrad)	0.5
Energy (GeV)	1.03
Energy Spread (%)	0.06

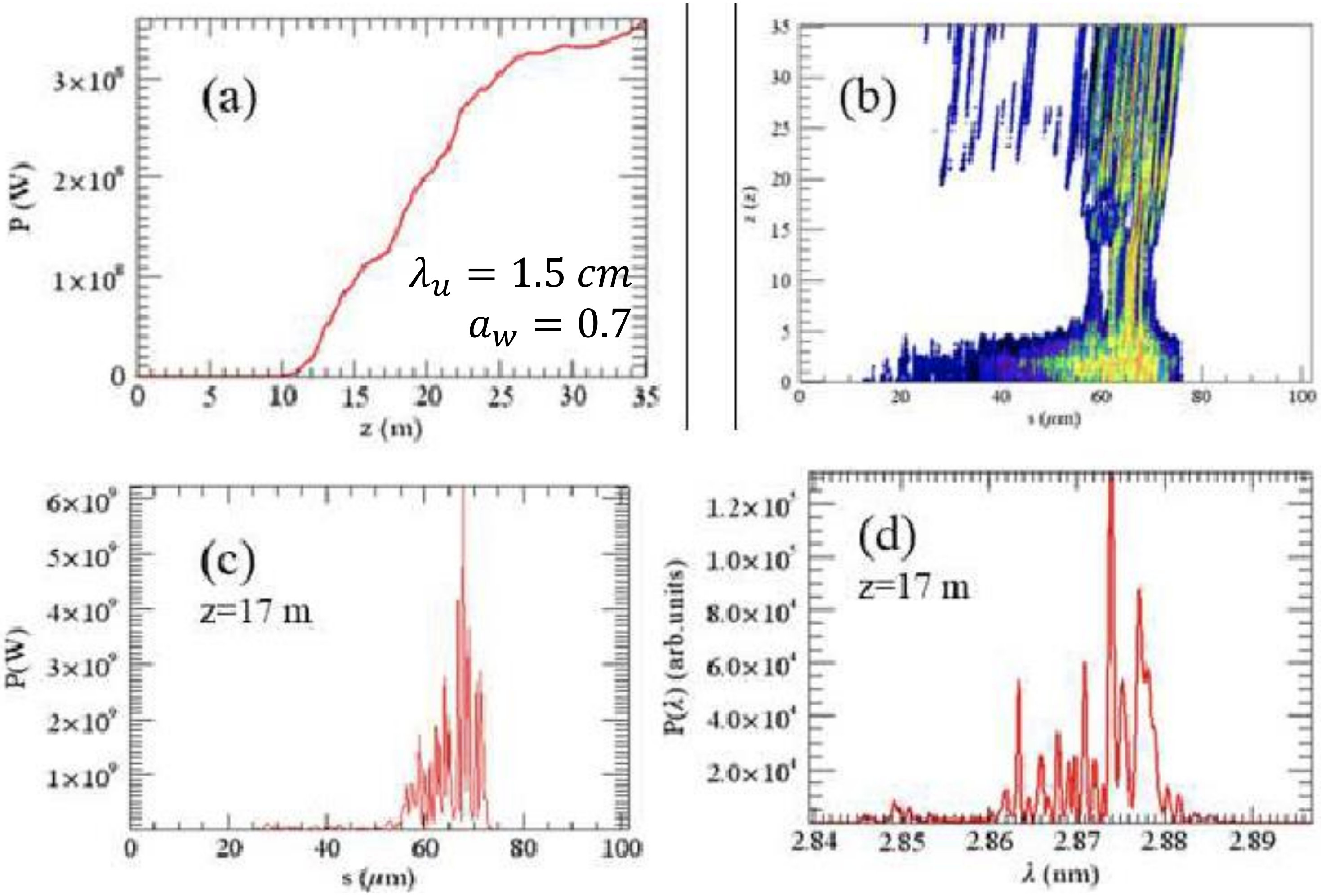


Upper plot: Twiss parameters and dispersion function through all the Linac, from photo-injector exit to the undulator entrance. Lower plot: Nominal RMS energy spread (blue) and RMS bunch length (red) along the entire Linac from photo-injector exit at 171 MeV to undulator entrance at 1 GeV

Courtesy C. Vaccarezza

The FEL
(Genesis 3D)

Parameter	Unit	Full X-band
Radiation Wavelength	nm	4
Photons per Pulse	$\times 10^{12}$	1
Photon Bandwith	%	0.5
Undulator Area Length	m	30
ρ(1D/3D)	$\times 10^{-3}$	2
Photon Brilliance per shot	$\left(\frac{s\,mm^2 mrad^2}{bw(0.1\%)}\right)$	$1\ \times 10^{27}$


$\lambda_u = 1.5\ cm$
$a_w = 0.7$

Electron beam energy : 1 GeV, matching at 4 nm. SASE radiation simulation for the 200 pC beam (WoP2): (a) power growth P(W) as function of the undulator coordinate z(m). (b): contour plot of the radiated power in the (s; z) plane, with s (mm) coordinate along the electron beam, (c) power and (d) spectral density at z = 17 m.

Courtesy V. Petrillo

Conclusions and Perspectives

➢ Conclusions

- The EuPRAXIA@SPARC_LAB project aims to design and build
  - world's most compact RF accelerator → 1 GeV X-band RF linac
  - First ever FEL user facility driven by a high gradient plasma accelerator module (Europe`s most compact and most southern FEL)
- The beam physics has been shown by means of start to end simulations (including the radiation generation)
- The studies show a relatively stable accelerator able to drive a radiation source
- The research activity performed at the SPARC_LAB test facility is crucial for the forthcoming EuPRAXIA@SPARC_LAB project

➢ Perspectives

- *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*
- *Further beam phase space manipulation is under investigation for the full X-band case*
- *On the road for the Technical Design Report*

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

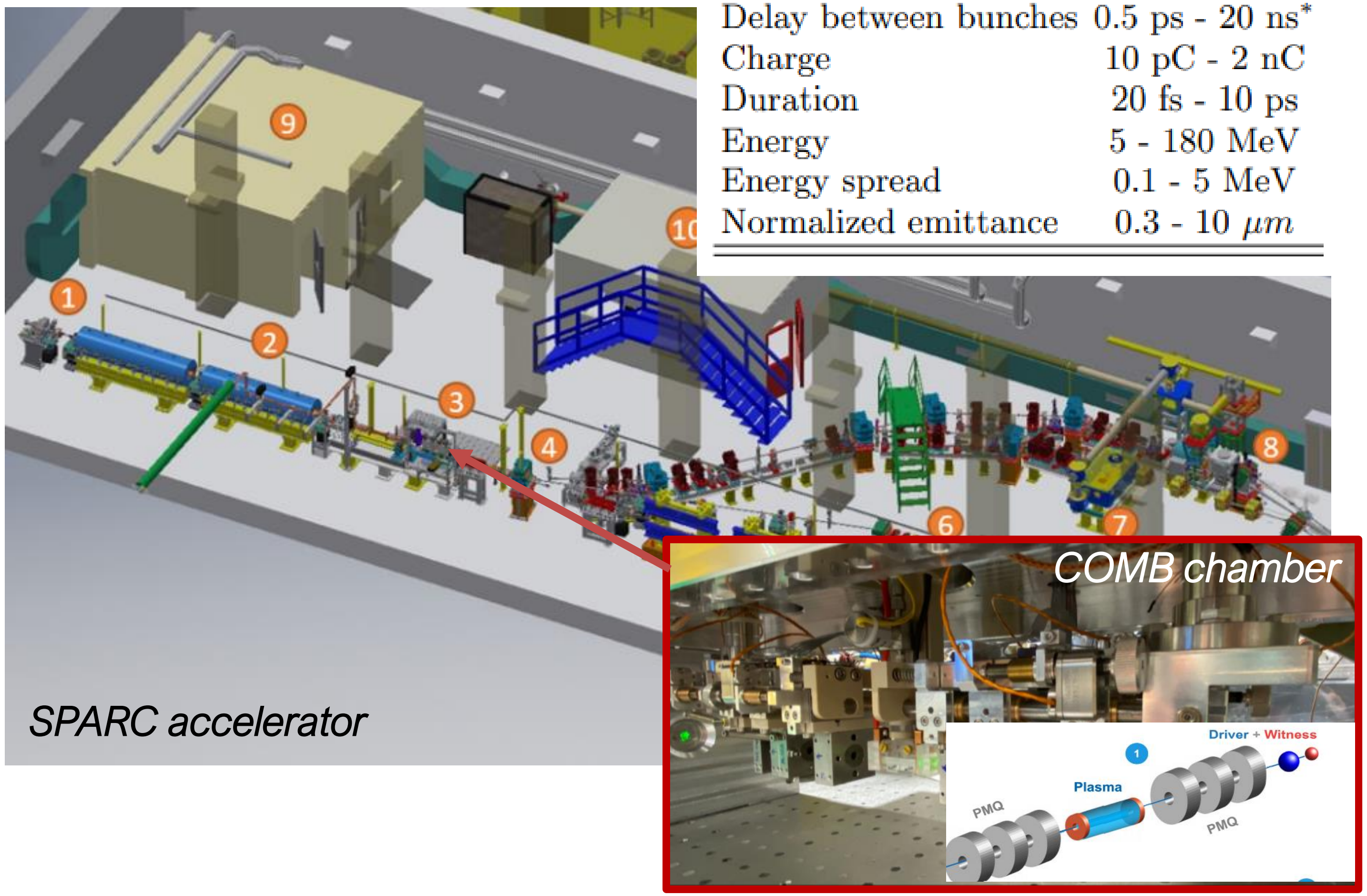
Thank for your attention

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



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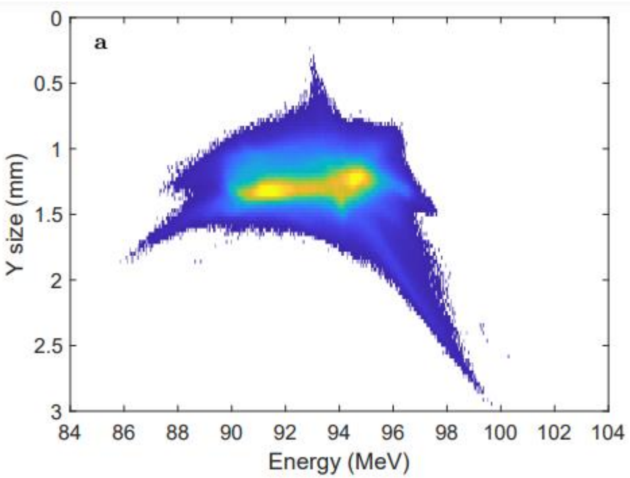
[1] R. Pompili et al. "Recent results at SPARC_LAB", NimA 909, doi.10.1016/j.nima.2018.01.071 (2018)

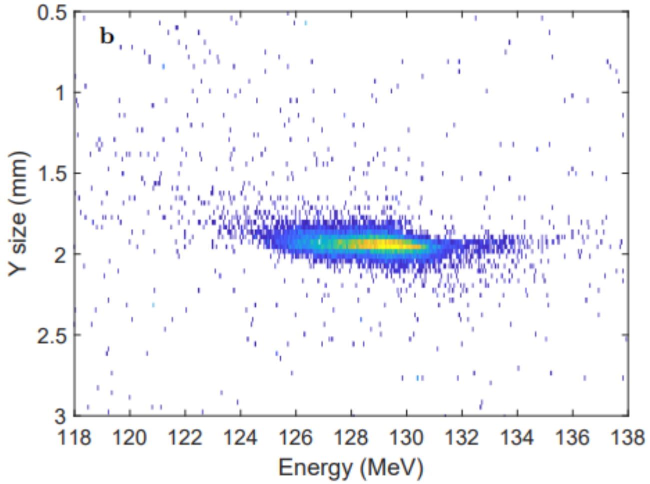
[2] R. Pompili et al., "Free-electron lasing with compact beam-driven plasma wakefield accelerator", Nature 605, 7911, doi.org/10.1038/s41586-022-04589-1 (2022)

Recent results @SPARC_LAB: 1 GV/m gradient in the plasma

Witness energy measurement before and after the plasma



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



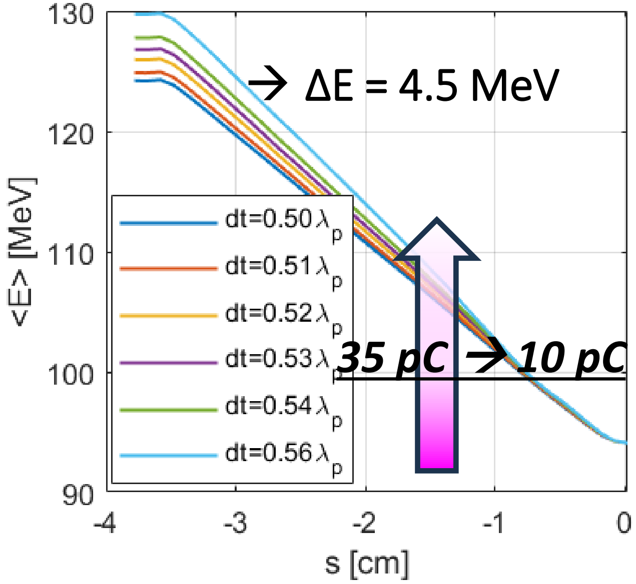
Measured energy spectrum:

→ ΔE = 6 MeV

→ δE = 2 MeV rms @ 128 MeV

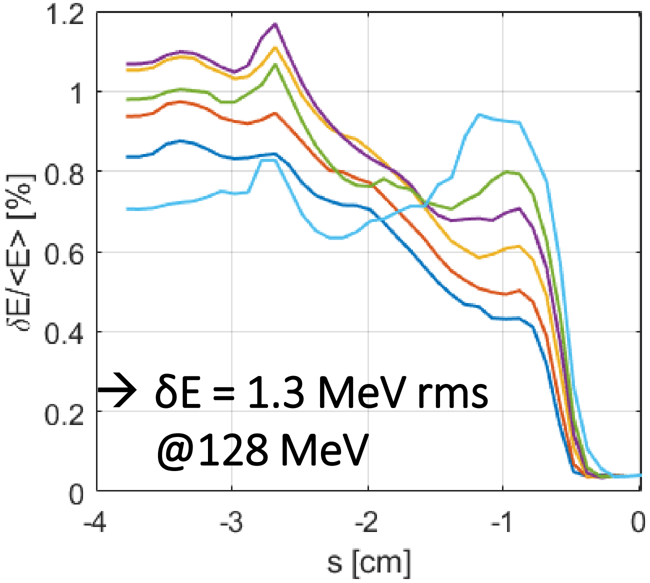
6D phase space to be characterized in next future

Numerical Studies

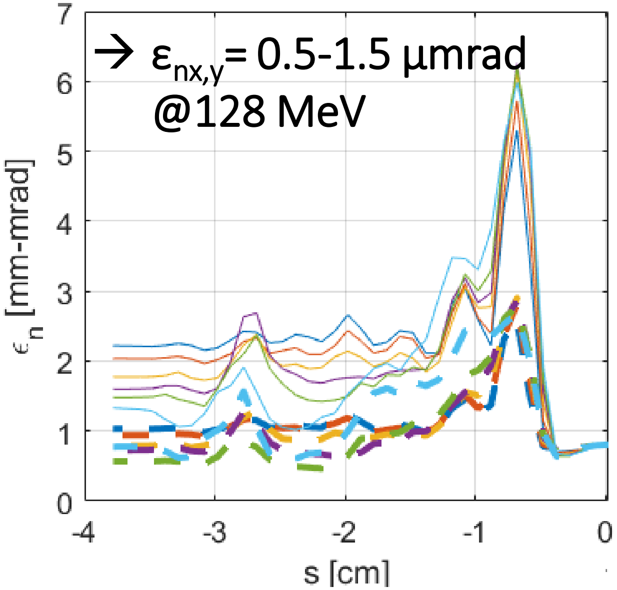


→ ΔE = 4.5 MeV

35 pC → 10 pC



→ δE = 1.3 MeV rms @128 MeV



→ $\varepsilon_{nx,y}$ = 0.5-1.5 μmrad @128 MeV

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*

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	%

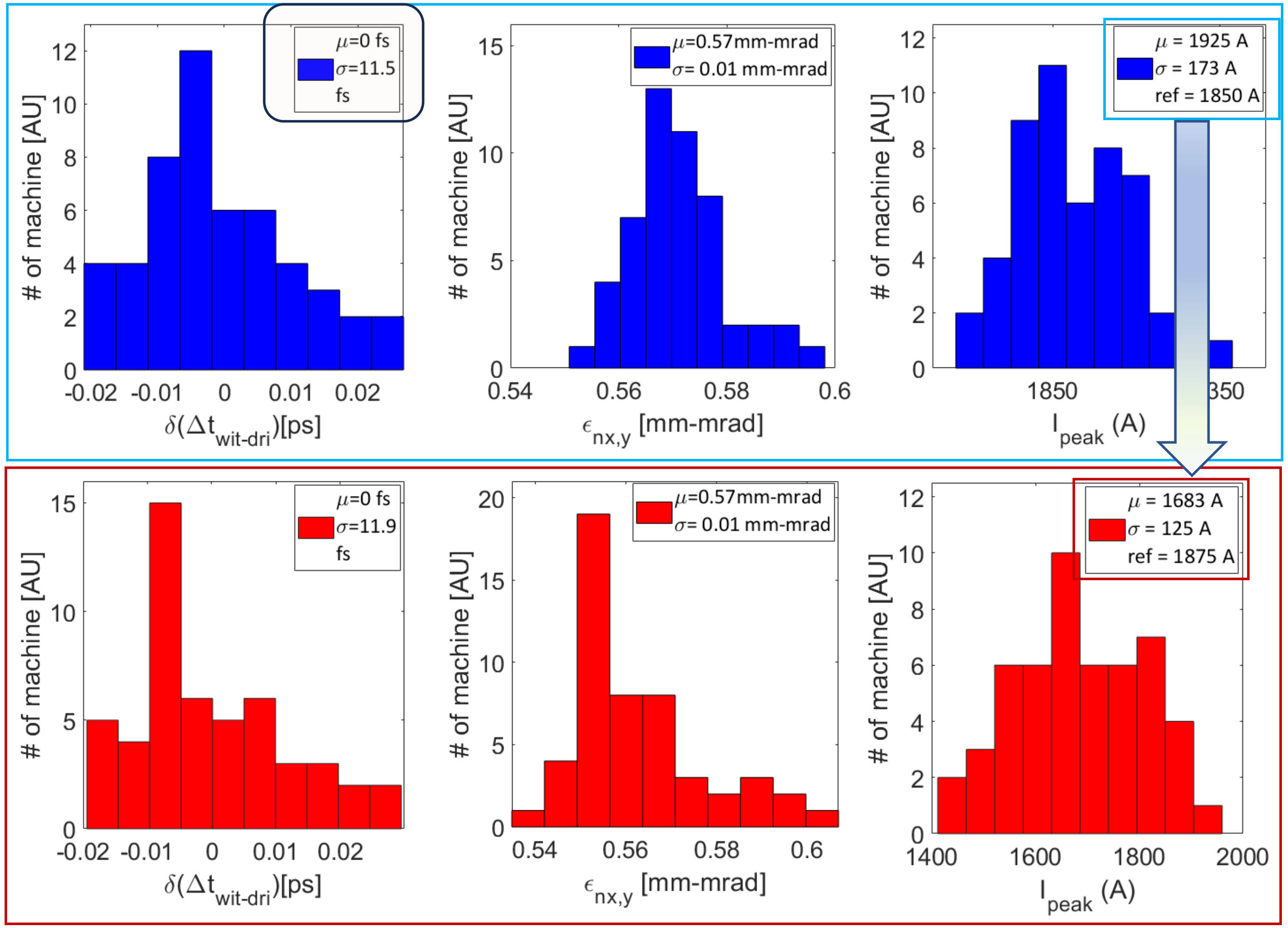
[4] F. Bosco et al. "Beam dynamics optimization of Eu-PRAXIA@SPARC_LAB RF injector" presented at the IPAC'23, Venezia, Italy, May. 2023, paper WEPA040

Machine Sensitivity Studies – The RF accelerator

- The analysis is performed over 50 samples obtained by means of S2E simulations
- 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

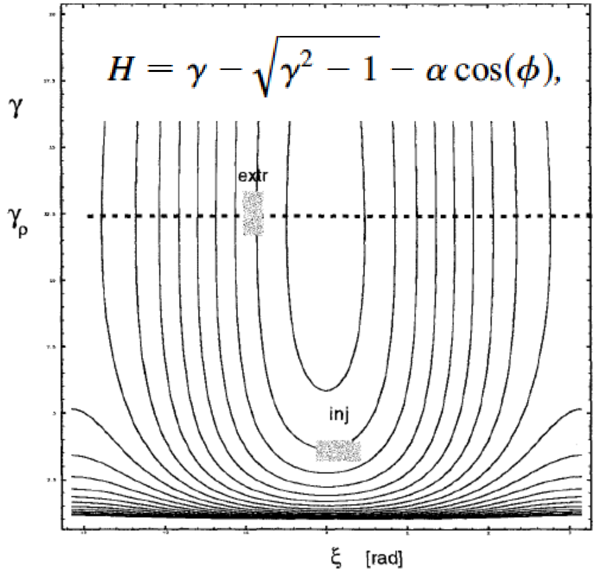
Jitter analysis in terms of beam delay, witness emittance and peak current at the photoinjector (upper) and X-band linac (lower) exit



Velocity Bunching And Temporal Jitter

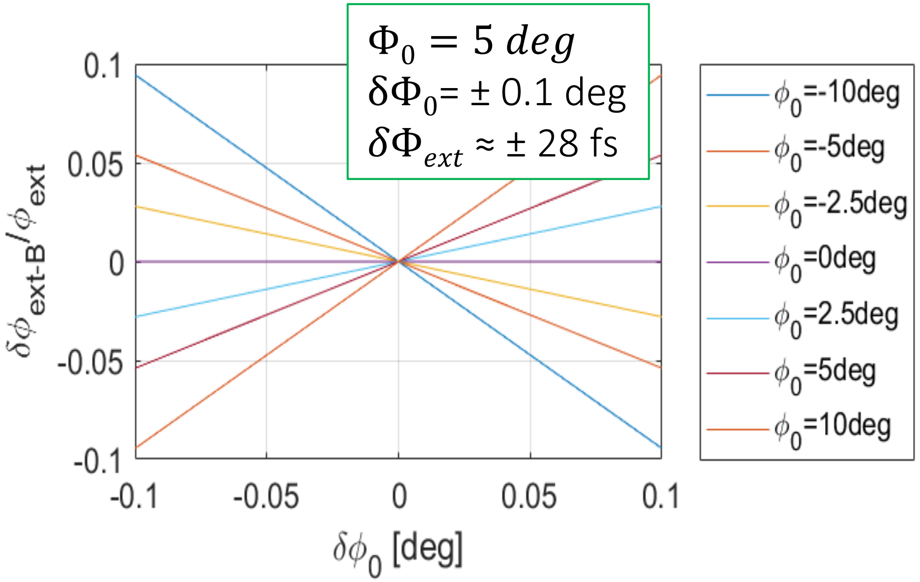
- The *RF compression* represents a powerful tool to shorten the beam to achieve the required high peak current in *relatively compact machine*
- The velocity bunching is used in tandem with the laser comb technique to generate the train of bunches
- It is based on a rotation of the longitudinal phase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

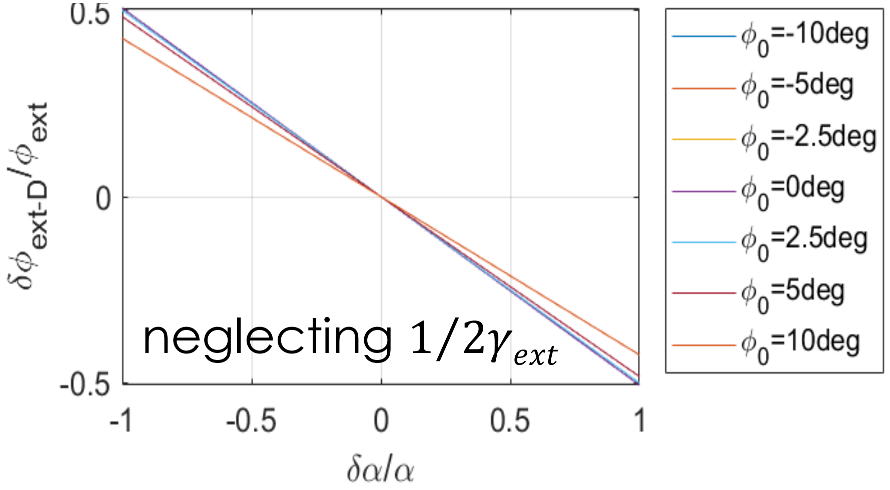
$E_0 = 20MV/m\ ;\ \gamma_0 \approx 10\ ;\ f_{RF} = 2.856\ Ghz$


$$H = \gamma - \sqrt{\gamma^2 - 1} - \alpha\cos(\phi),$$

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

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


$\Phi_0 = 5\ deg$
$\delta\Phi_0$= ± 0.1 deg
$\delta\Phi_{ext}$ ≈ ± 28 fs


neglecting $1/2\gamma_{ext}$

[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)

Machine Sensitivity Studies – The PWFA module

Funded by the European Union

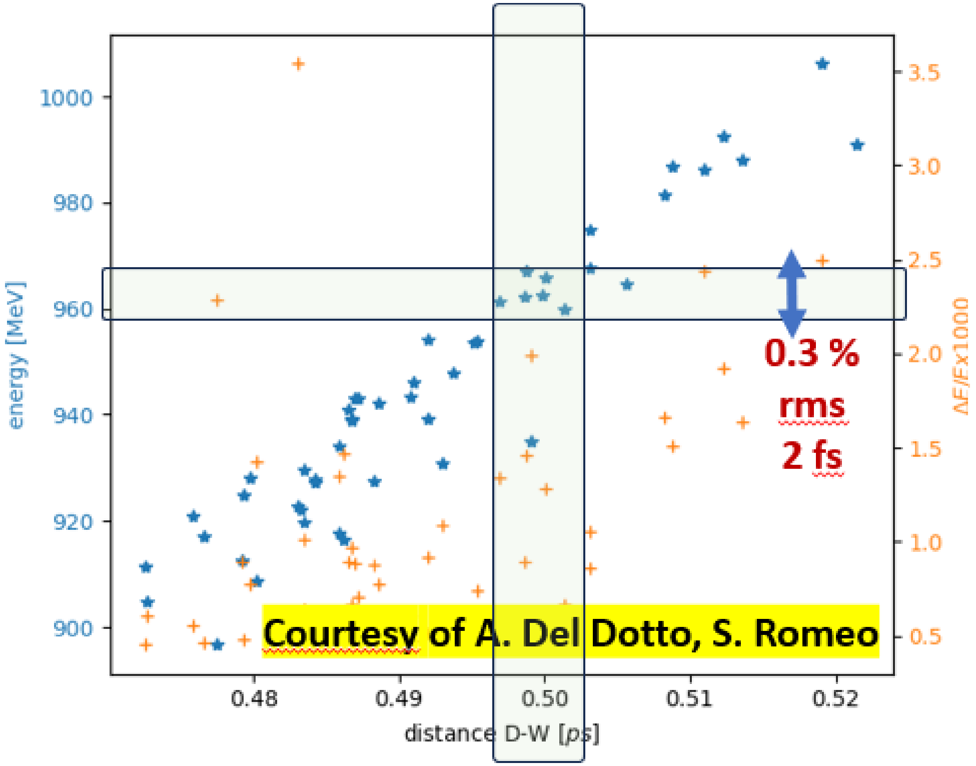
FEL requirement

$$\frac{\Delta\lambda}{\lambda} \propto \frac{\Delta E}{E} \propto \rho \approx 10^{-3}$$

D-W separation

$$\left.\frac{\Delta E}{E}\right|_{DW} = \frac{a\omega_p}{2\pi}\Delta t_{DW}$$

$$2 \le a \le 4$$



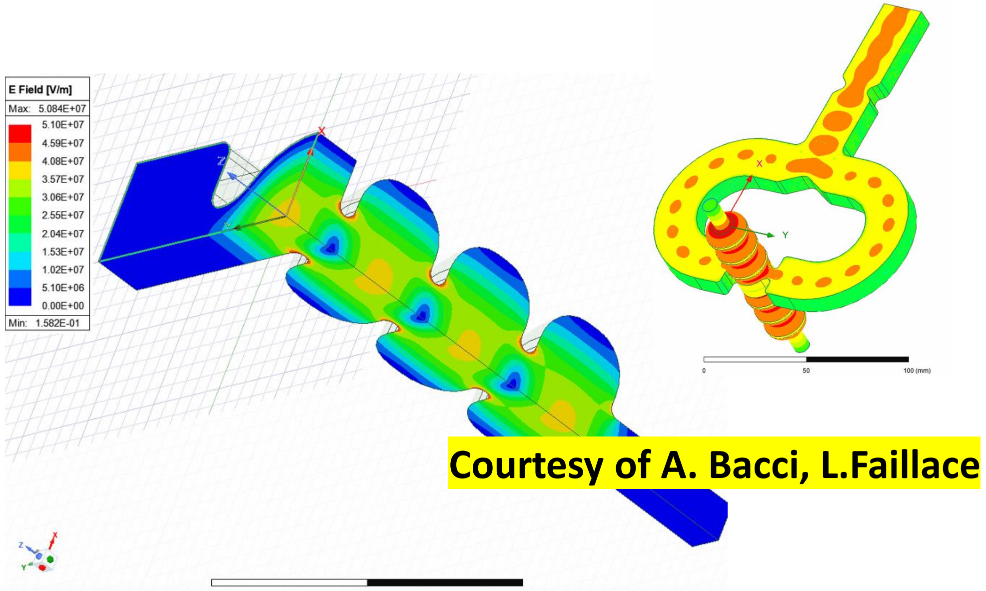
0.3 % rms 2 fs

Courtesy of A. Del Dotto, S. Romeo

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

R&D Activities On The Photoinjector

1. Stabilization methods and technologies for the RF element power sources → promising results on the solid-state modulator technology
2. New WPs
3. Insertion of an higher harmonic accelerating cavity to stabilize the beam current profile



Courtesy of A. Bacci, L.Faillace