EUROPEAN
PLASMA RESEARCH
ACCELERATOR WITH
EXCELLENCE IN
APPLICATIONS

EuPRAXIA
Preparatory Phase

Beam dynamics simulations of photo-injector and X band LINAC

A. Giribono – C. Vaccarezza
INFN-LNF
on behalf of EuPRAXIA@SPARC_LAB collaboration
material from WA01 – WP1 – Beam Physics Working Group

INFN-ESRF Collaboration Meeting
February 19th, 2025

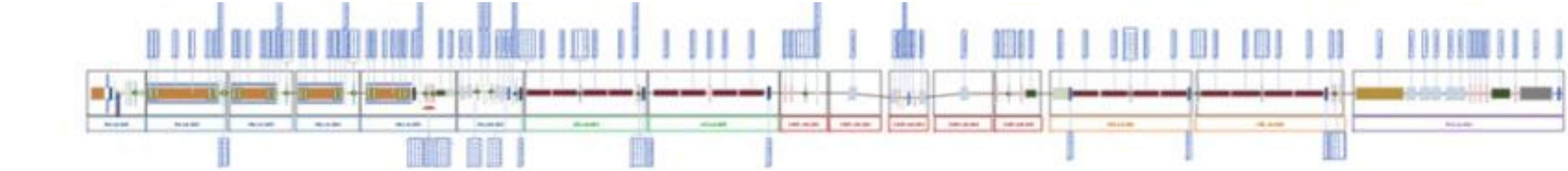
This project has received funding from the European Union´s Horizon Europe research and innovation programme under grant agreement No. 101079773

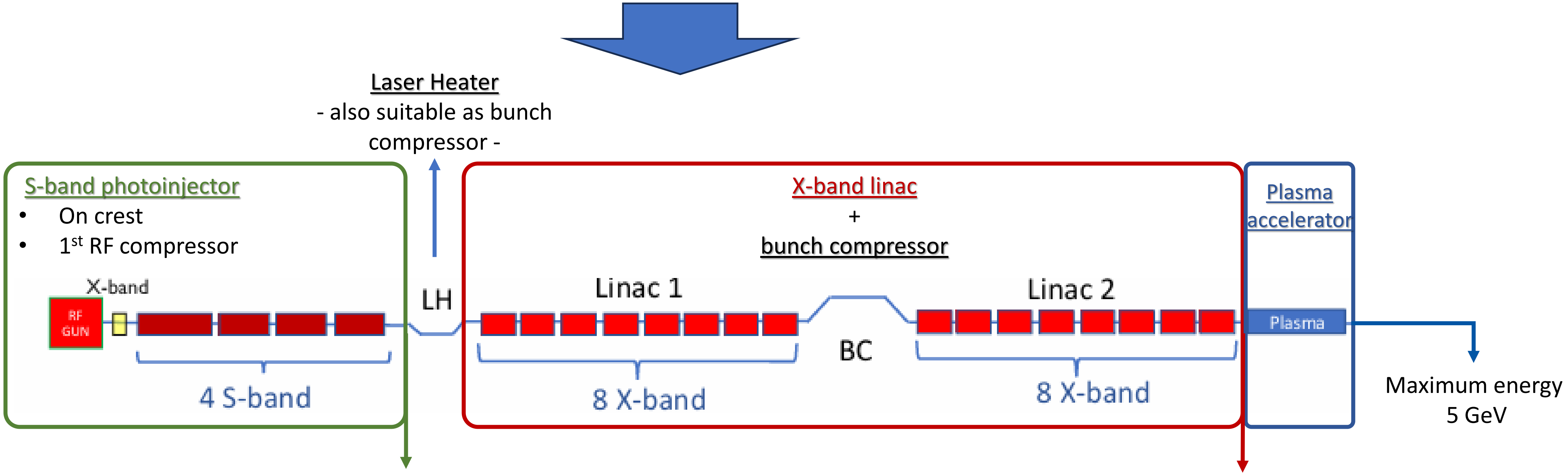
Outline

- The EuPRAXIA@SPARC_LAB accelerator
- Electron Beams from EuPRAXIA@SPARC_LAB accelerator
- 1 GeV electron beams with PWFA
- Tolerances for the EuPRAXIA@SPARC_LAB linac
- High transformer ratio PWFA for EuPRAXIA@SPARC_LAB: the 5 GeV WP
- Conclusions

Funded by the European Union

The EuPRAXIA@SPARC_LAB accelerator





Laser Heater
- also suitable as bunch compressor -

S-band photoinjector
- On crest
- 1st RF compressor

X-band linac
+
bunch compressor

Plasma accelerator

Maximum energy
5 GeV

Maximum Energy
~ 0.24 GeV

Maximum Energy
~ 1.20 GeV

Electron Beams from EuPRAXIA@SPARC_LAB accelerator

Funded by the European Union

- The accelerator has a wide flexibility and can provide very different working points for the electron beams in terms of charge and duration, thus peak current, with an overall high-quality on the transverse phase-space with relatively small projected emittances
- The wide tunability in terms of beam duration is ensured thanks to the on-crest or RF compression operation of the photoinjector and to the following magnetic bunch compressors embedded with a laser heater
- The high beam quality results from the combination of the high brightness S-band photoinjector and the downstream high gradient accelerators (X-band and plasma technology)
- Train of bunches (within same RF bucket) can be generated directly at the cathode, so-called comb beam, or using the magnetic compressors
- The multi-bunch operation is allowed by injecting in different RF bucket

Electron Beam Parameter	Full X-band	PWFA	Unit
Bunch Charge	< 1.00	< 0.05	nC
Energy	< 1.2	< 5	GeV
RMS Energy Spread	> 0.01	> 1	%
RMS Bunch Length	0.01 - 10	< 0.02	ps
RMS norm. Emittance	0.3 - 10	< 1	mm-mrad

Range of electron beam parameters that can be obtained with the EuPRAXIA@SPARC_LAB accelerator.

[1] L. Serafini and M. Ferrario, 'Velocity bunching in photoinjectors' AIP Conf. Proc., vol. 581, no. 1, pp. 87–106, 2001. doi:10.1063/1.1401564

Electron Sources as Drivers of High Gradient Accelerators and Radiation Sources

Funded by the European Union

[1] ICS X-ray source

high phase space density, high charge, low emittance intended as projected quantities.

Low energy spread → high spectral density and/or monochromaticity

$$N_\gamma^{bw} = \frac{4.1 \times 10^8 U_L[\mathrm{J}] Q_b[pC]\Psi^2}{h\upsilon_l[\mathrm{eV}]\left(\sigma_x^2[\mu\mathrm{m}] + \frac{W_0^2}{4}\right)}$$

$$\frac{\Delta\upsilon_\gamma}{\upsilon_\gamma} = \sqrt{(\gamma\theta)_{\mathrm{rms}}{}^4 + \left(\frac{\Delta\gamma}{\gamma}\right)^2 + \left(\frac{\varepsilon_n}{\sigma_x}\right)^4 + \dots}$$

Acceptance Angle

[2] X-ray FEL

high intensity phase space → high peak current, low emittance and energy spread intended as **slice** quantities

$$\rho = \frac{1}{4\pi\gamma}\sqrt[3]{2\pi\frac{J}{I_0}\left(\lambda_u K f_b(K)\right)^2}$$

$$\frac{\Delta\omega}{\omega} \approx \rho \qquad \text{and} \qquad P_S \simeq \sqrt{2}\rho P.$$

$$L_g = \frac{\lambda_u}{4\pi\sqrt{3}\rho}.$$

$$L_S \simeq 1.066 L_g \ln\left(\frac{9P_S}{P_0}\right)$$

PWFA acceleration [3]

longitudinal and transverse dimensions in the micrometer range → high intensity phase space intended as rms quantities

$$k_p = \frac{2\pi}{\lambda_p} = \sqrt{\frac{e^2 n_0}{\varepsilon_0 m_e c^2}}$$

$$\beta_x = \frac{2\sqrt{\gamma}}{k_p} \qquad k_p\sigma_z = \sqrt{2}$$

Brightness as beam quality factor

$$B[\mathrm{A/m^2}] = \frac{Q}{\varepsilon_{nx}\varepsilon_{ny}\sigma_t\sigma_\gamma},$$

[2] O. Adriani et al.'Technical Design Report EuroGammaS proposal for the ELI-NP Gamma beam System' (2014) Editor L. Serafini - https://arxiv.org/abs/1407.3669
[3] Assmann, R.W., Weikum, M.K., Akhter, T. et al. EuPRAXIA Conceptual Design Report. Eur. Phys. J. Spec. Top. (2020). https://doi.org/10.1140/epjst/e2020-000127-8
[4] D. Alesini et al. 'EuPRAXIA@SPARC_LAB CDR' – Editor M. Ferrario, Report number: INFN-18-03/LNF (2018)

Working Point Optimisation

- Beams are generated in the S-band photo-injector and boosted in energy in the downstream linac
  - Single bunch or train of bunches
  - Transverse phase space: emittance compensation according to the invariant envelope criteria
  - Longitudinal phase space:
    - $\sigma_z < 100$ μm should be injected in the X-band linac to avoid energy spread dilution due to RF curvature degradation effects keeping $\Delta\gamma/\gamma < 1$ ‰
    - Linearization by means of X-band accelerating cavity right after the gun or the fourth S-band accelerating structure
    - Bunch compression by means of RF compression

      → very compact beamline - no off-axis trajectories → less sensitive to transverse layout and active element imperfections

      → no charge losses being not required any mask or scraper in a dispersive sections
    - Bunch compression by means of magnetic chicane (plus laser heater)

      → larger energy thanks to the on-crest operation

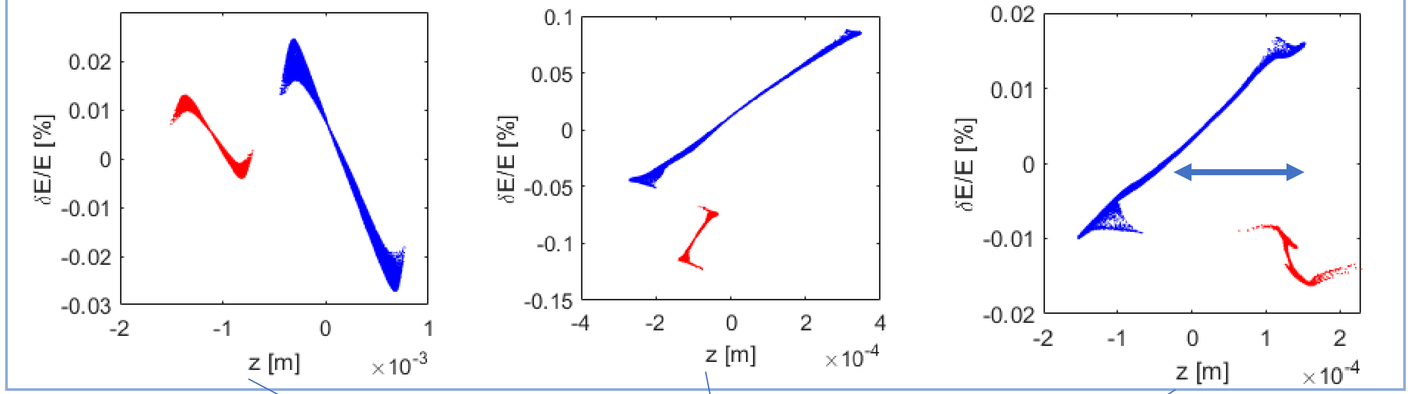
      → less sensitive to electromagnetic element temporal jitter

[5] B. E. Carlsten, NIM A 285, 311-319 (1989)
[6] L. Serafini, J. B. Rosenzweig, Phys. Rev. E 55, 75657590 (1997)

Funded by the European Union

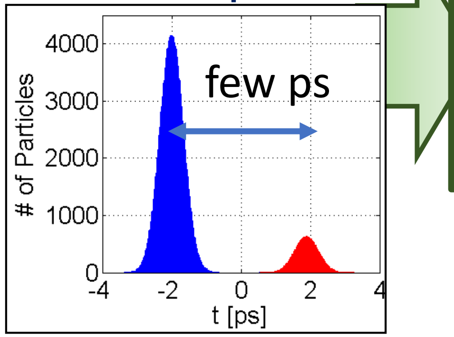
Train of bunches

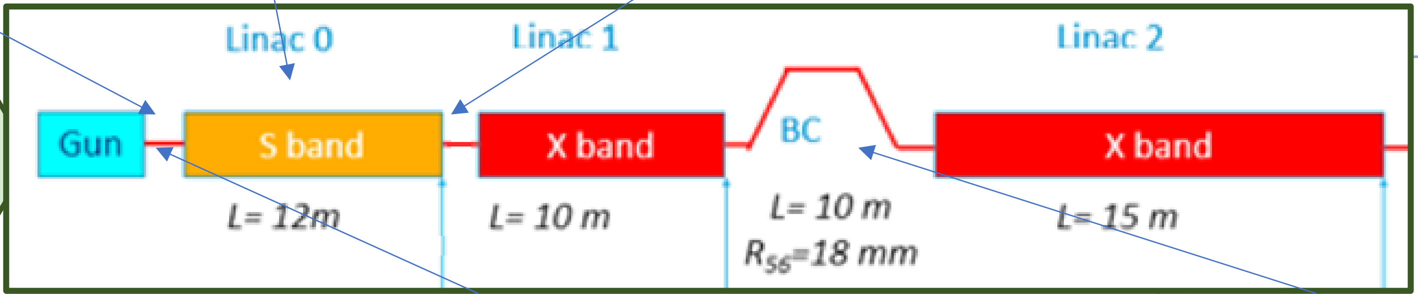
Velocity bunching technique



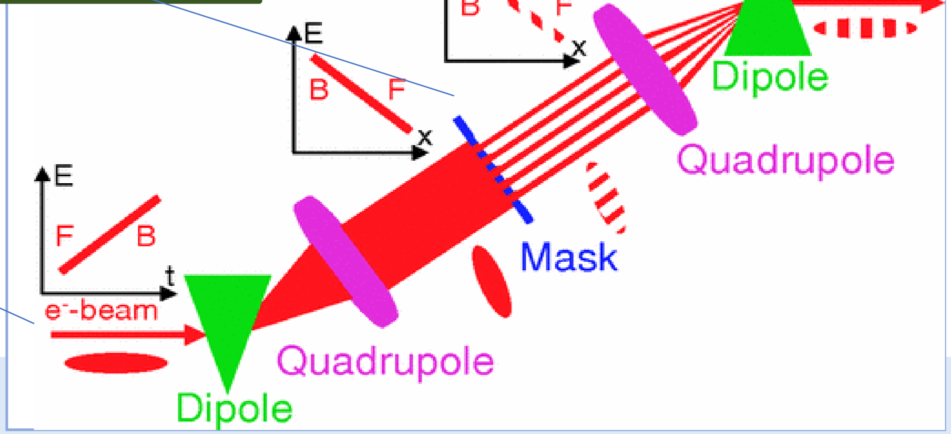
- Distance between beams down to few hundreds of fs
- Delays higher than tens of ps can be generated through single bunch operation and/or by injecting in different RF bucket (one X-band RF period corresponding to 87 ps)

Laser comb technique





Mask/Notch + Chicane



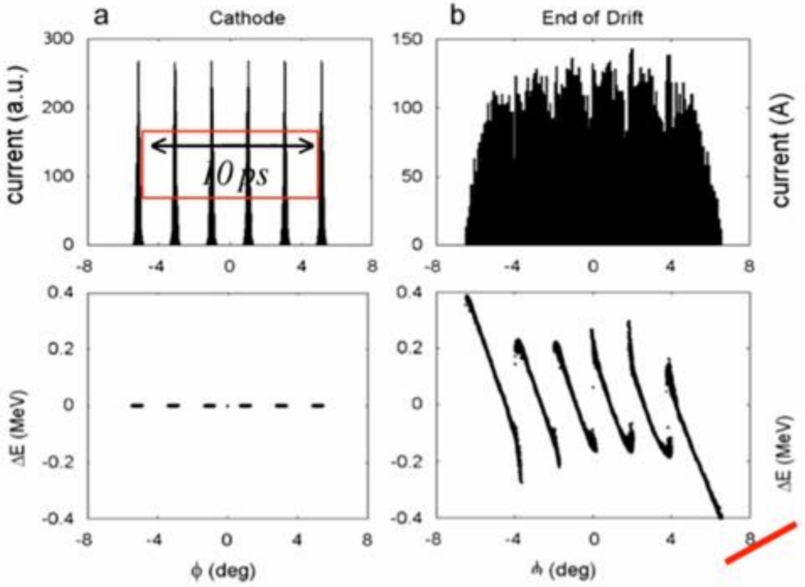
[7] M. Ferrario et al, NIMA Vol. 637, Issue 1, pp 43-46 (2011) doi: https://doi.org/10.1016/j.nima.2010.02.018

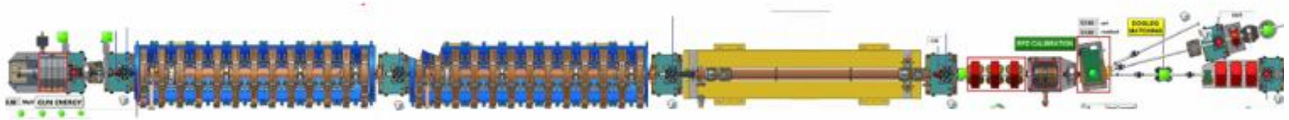
[8] P. Muggli et al., Phys. Rev. ST Accel. Beams **13**, 052803 – (**2010)**

DOI: https://doi.org/10.1103/PhysRevSTAB.13.052803

Train of bunches: the SPARC_LAB experience

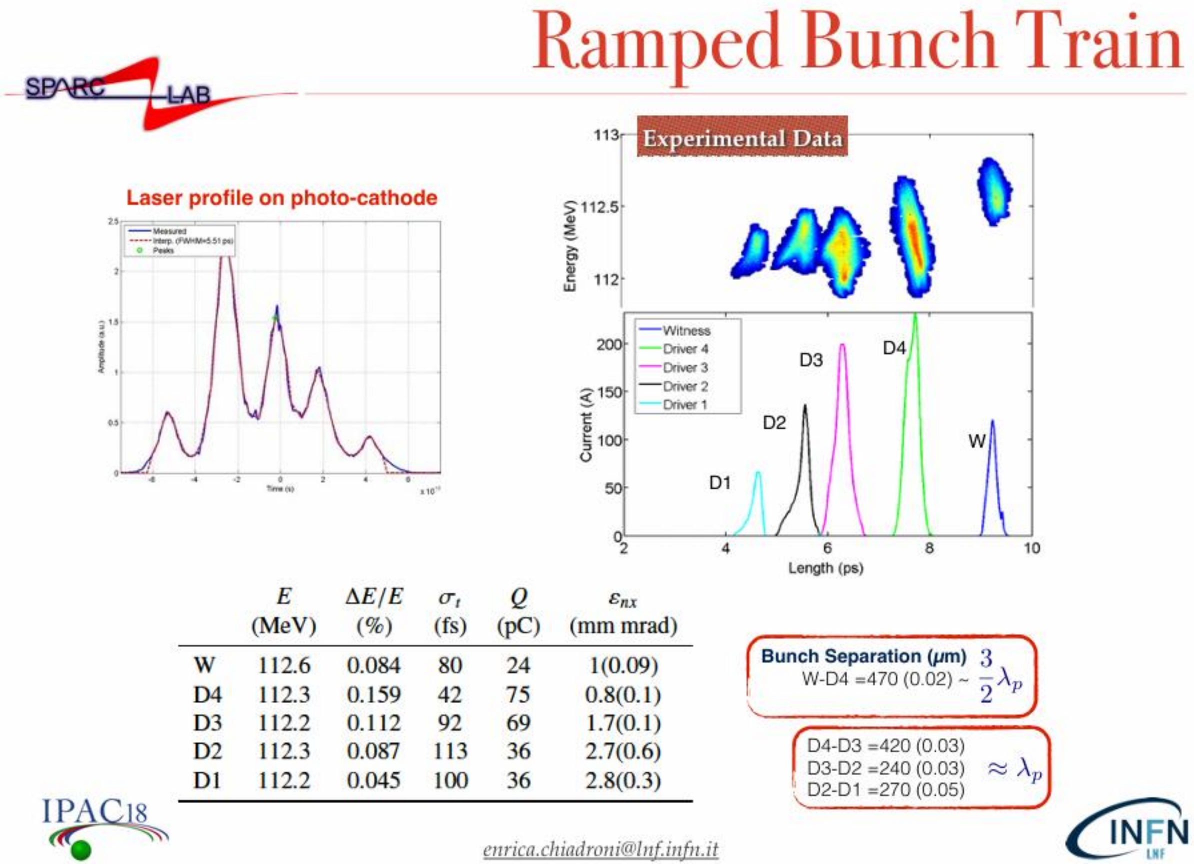
Start2End beam dynamics simulations in the SPARC_LAB photoinjector





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

Experimental results obtained at SPARC_LAB



Ramped Bunch Train

	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) $\approx \lambda_p$
D2-D1 =270 (0.05)

enrica.chiadroni@lnf.infn.it

EuPRAXIA@SPARC_LAB goal parameters

Funded by the European Union

Radiation Parameter	**Unit**	PWFA	Full X-band
Wavelength	nm	**3-4**	4
Pulse length (fwhm)	fs	**15.0**	-
Photons per Pulse	$\times 10^{12}$	**0.1- 0.25**	1
Photon Bandwidth	%	**0.1**	0.5
Undulator Area Length	m	30	
ρ(1D/3D)	$\times 10^{-3}$	**2**	2
Photon Brilliance per shot	$\left(\begin{matrix} s\,mm^2 mrad^2 \\ bw(0.1\%) \end{matrix}\right)$	$\mathbf{1-2\times 10^{28}}$	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	**~ 2**	1-2
RMS Energy Spread	%	**< 1**	0.1
RMS Bunch Length	μm	**3-6**	24-20
RMS norm. Emittance	μm	**1**	1
Slice Energy Spread	%	**≤0.05**	≤0.05
Slice norm Emittance	mm-mrad	**0.5**	0.5
Energy jitter	%	**< 1**	0.1

- **Bold values indicate the main working point**

Status of beam dynamics studies

- **1 GeV with plasma acceleration**
  - Velocity bunching + Comb technique → we are investigating the **robustness** of the adopted WPs with respect to **static and dynamics errors** in the X-band linac within mitigation strategies

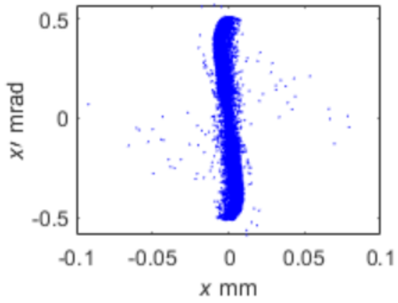
Charges [pC]	n_e [10^{16} cm^{-3}]	Nominal WP			Sensitivity (jitter)		
Setup for 1 GV/m accelerating gradient		Linac (beam quality, matching @plasma)	Plasma (acc. gradient, beam quality)	FEL (photons/pulse, radiation quality)	Linac	Plasma	FEL
200+30	**1.0**	**OK**	**OK**	**OK**	**OK**	**OK**	**OK**
400+50	0.5	OK	OK	On going	On going	On going	On going

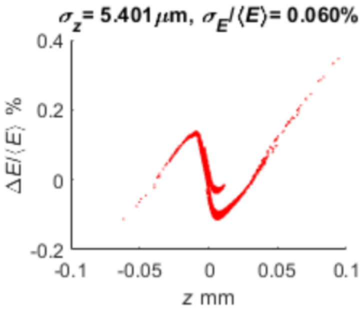
  - Mask comb configuration → work in progress: gradient to be optimised to 1 GV/m
- **1 GeV RF only**
  - Hybrid compression (velocity bunching + magnetic compression) → described in the CDR – to be completed
  - Magnetic compression only to avoid jitter problems → The current layout can host both configurations (to be completed)

1 GeV electron beams with PWFA

Funded by the European Union

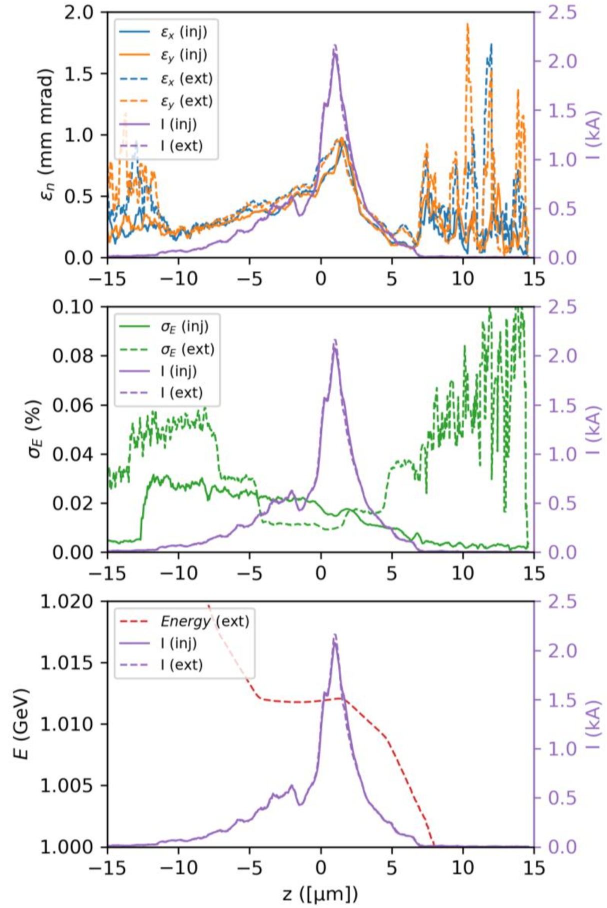
- It relies on the velocity bunching + laser comb technique
- 1 GV/m accelerating gradient in the plasma (plasma density ~10^{16}) → Driver-witness separation of $\lambda_p/2$ → < 1 ps
- Beam quality defined by final FEL performances and plasma acceleration efficiency



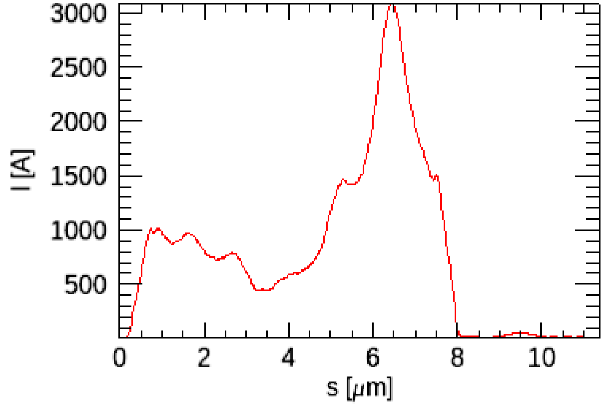


@linac exit	witness	driver
Charges	30-50	200 - 500
Energy (GeV)	0.5 – 1.0	0.5 – 1.0
I_{peak} (kA)	2 - 3	0.5 – 2.5
dE/E (‰)	0.06 – 0.08	0.13 – 0.20
Proj. Emitt xy (mm-mrad)	0.65	1.5 – 4.0
Delay (ps)	0.5 – 1.0	1.5 – 4.0

Beam parameters @linac exit



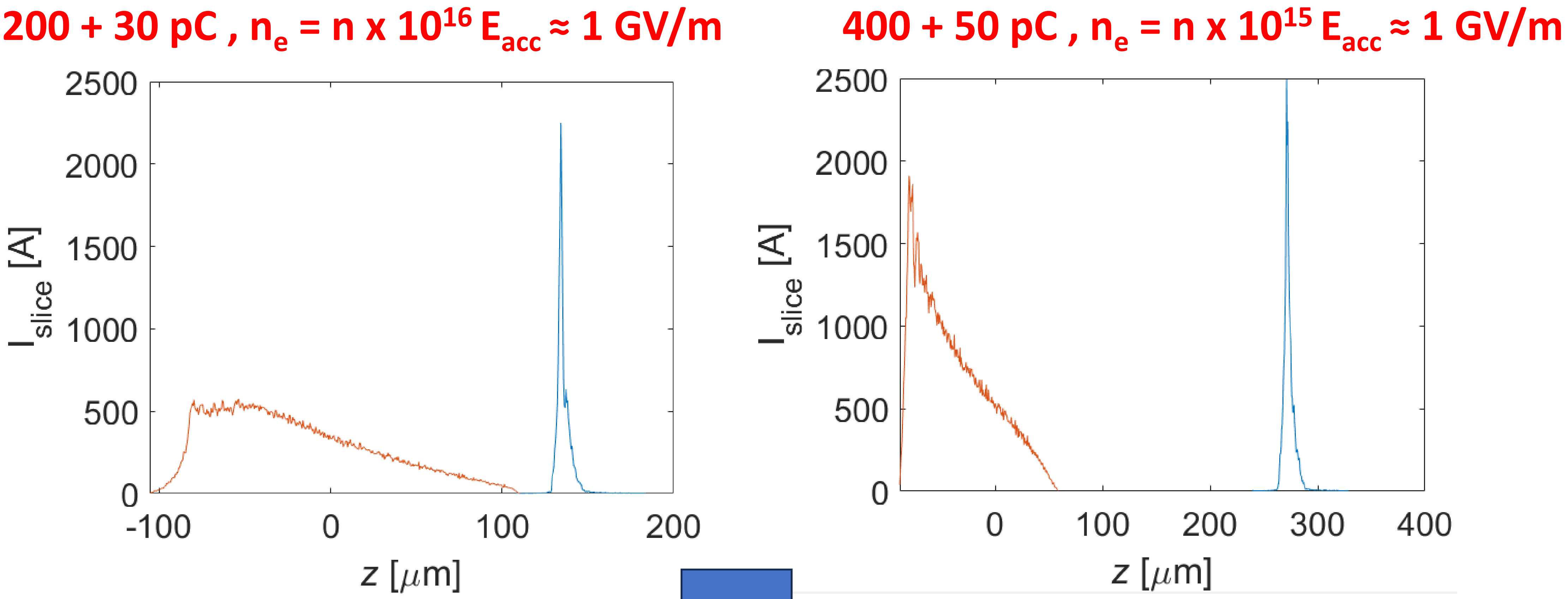
Witness slice analysis @plasma exit



Energy (GeV)	1
Energy jitter (%)	1
I_{peak} (kA)	3.07
dE/E (‰)	0.46
Proj. Emitt x	0.69
Proj. Emitt y	0.65

Witness slice analysis (upper) and rms parameters (lower) @FEL entrance

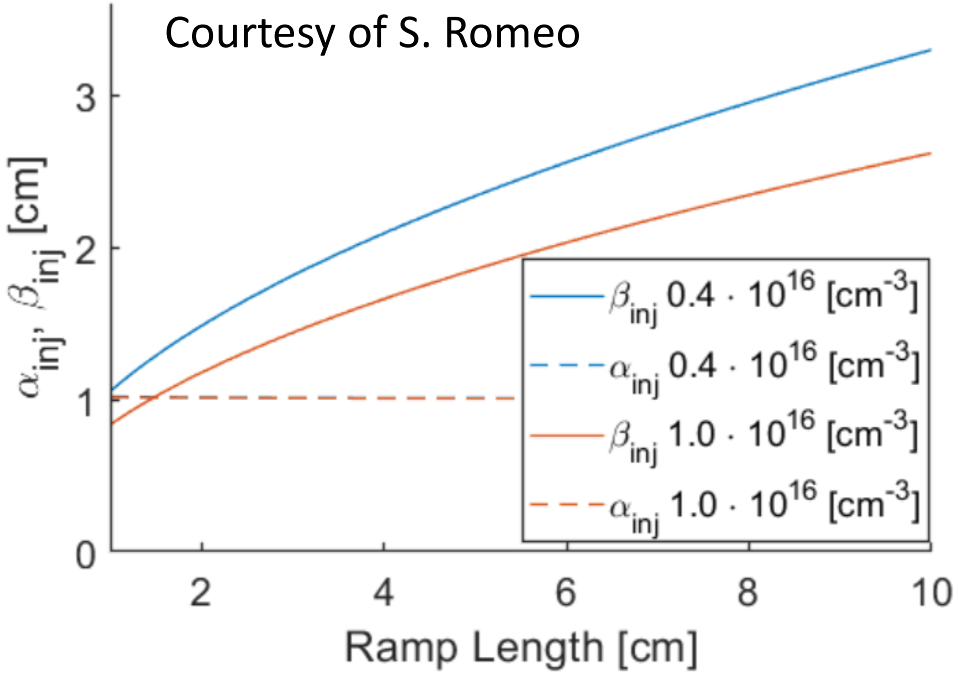
Possible WPs for the PWFA case: comb beams



- Driver beam with higher charge and shorter length → higher gradients at lower plasma density → less sensitive to temporal jitter
- Driver beam with lower charge is less sensitive to wakefield and misalignments

Working point optimisation of the comb beam for plasma acceleration

- The working point optimisation is **completed with following considerations**
  - **Longitudinal phase space** → fine-tuning of bunch length and shape and spacing in the photoinjector
    - Efficient acceleration in the plasma
    - Avoid beam overlapping that leds to anomalous dynamics in the plasma and the downstream transport line to the FEL (driver removal through chicane)
  - **Transverse phase space** → matching to the plasma in terms of Twiss parameters
    - emittance preservation through the insertion of plasma ramps
  - **Matching in the X-band linac** with *'fodo'-like* behaviour and low beta function (<30 m) → better control of wakefields in case of misalignments

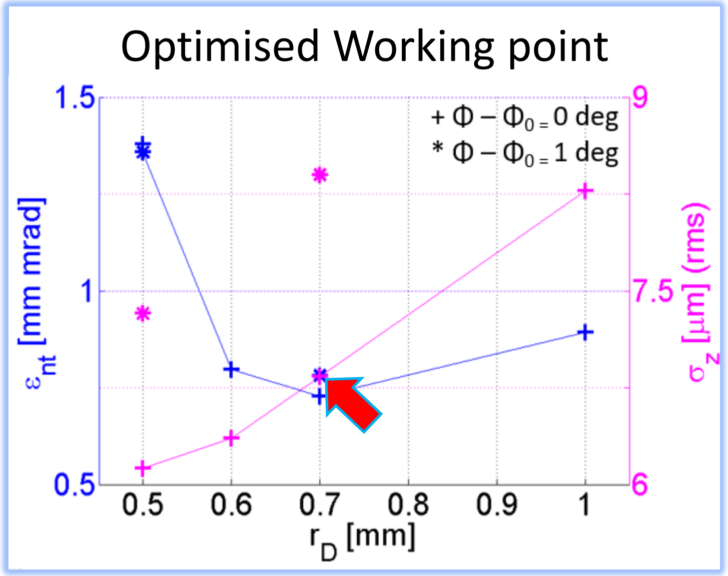


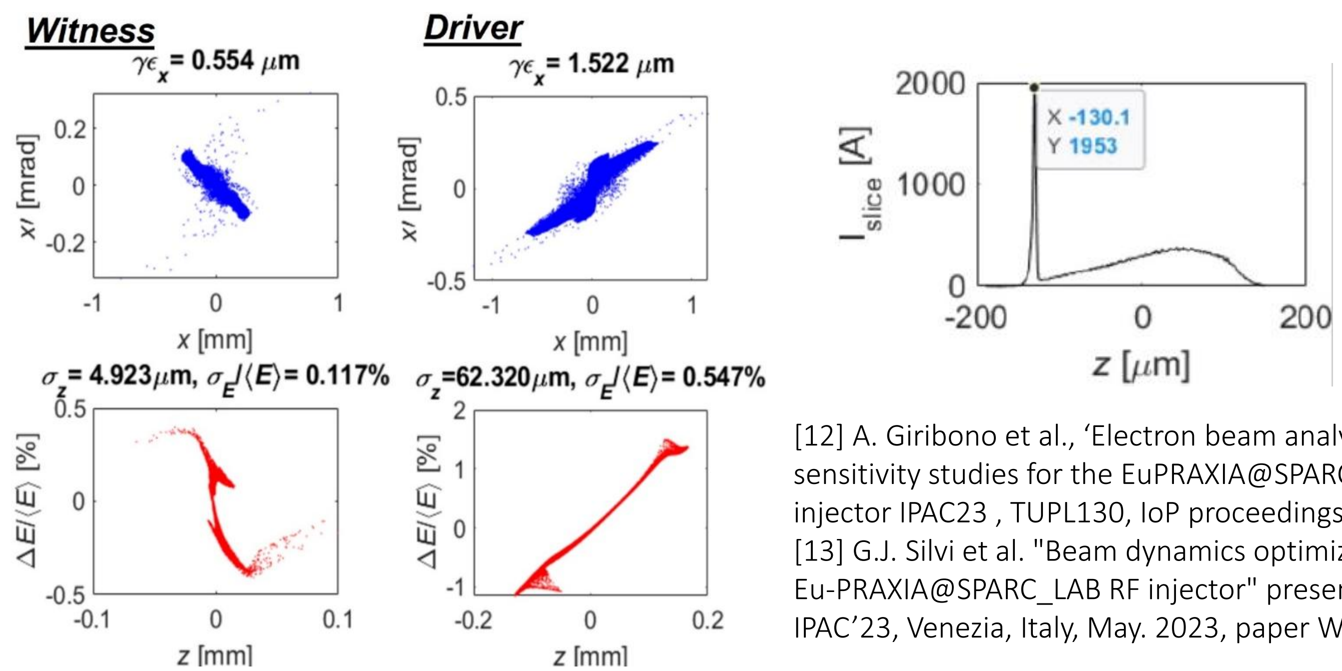
[11] S Romeo *et al* 2023 *Plasma Phys. Control. Fusion* **65** 115005**DOI** 10.1088/1361-6587/acfbf6

Beam generation for the PWFA case

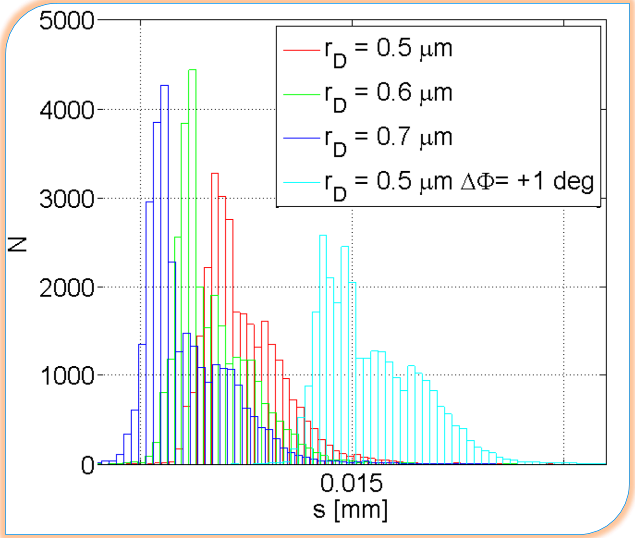
Funded by the European Union

- The beam dynamics has been studied by means of simulations with
  - TStep (and ASTRA) code →space charge regime
  - Elegant code → emittance dominated regime
  - The photoinjector sets the beam separation, emittance and current
  - The photoinjector is operated in the double hybrid RF compression scheme → this scheme ensures at same time up to 2 kA peak current and separation lower than 0.6 ps [8,9] and good flexibility





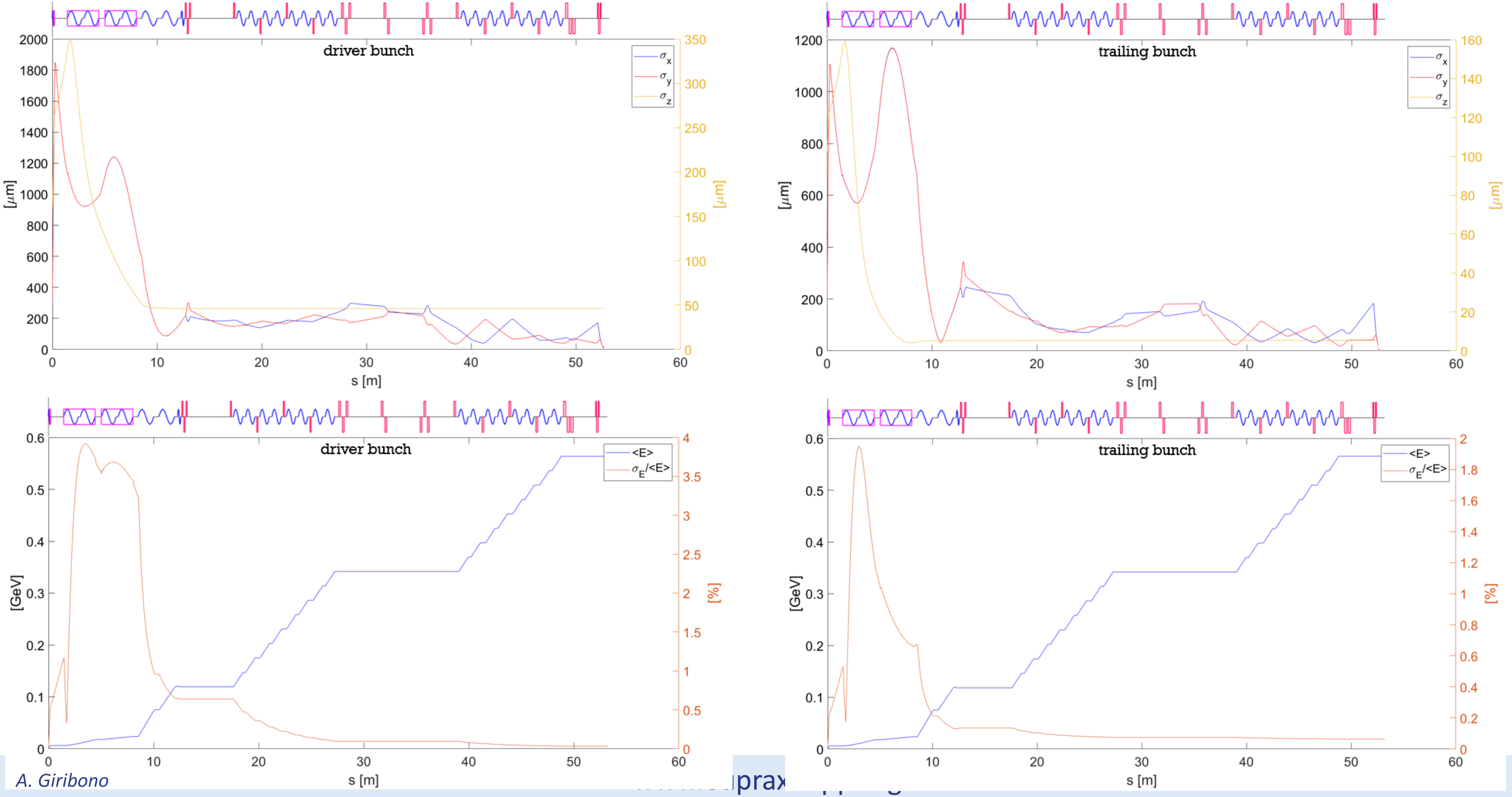
[12] A. Giribono et al., 'Electron beam analysis and sensitivity studies for the EuPRAXIA@SPARC_LAB RF injector IPAC23 , TUPL130, IoP proceedings
[13] G.J. Silvi et al. "Beam dynamics optimization of Eu-PRAXIA@SPARC_LAB RF injector" presented at the IPAC'23, Venezia, Italy, May. 2023, paper WEPA040



[14] 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

Beam Parameters through the linac

Funded by the European Union

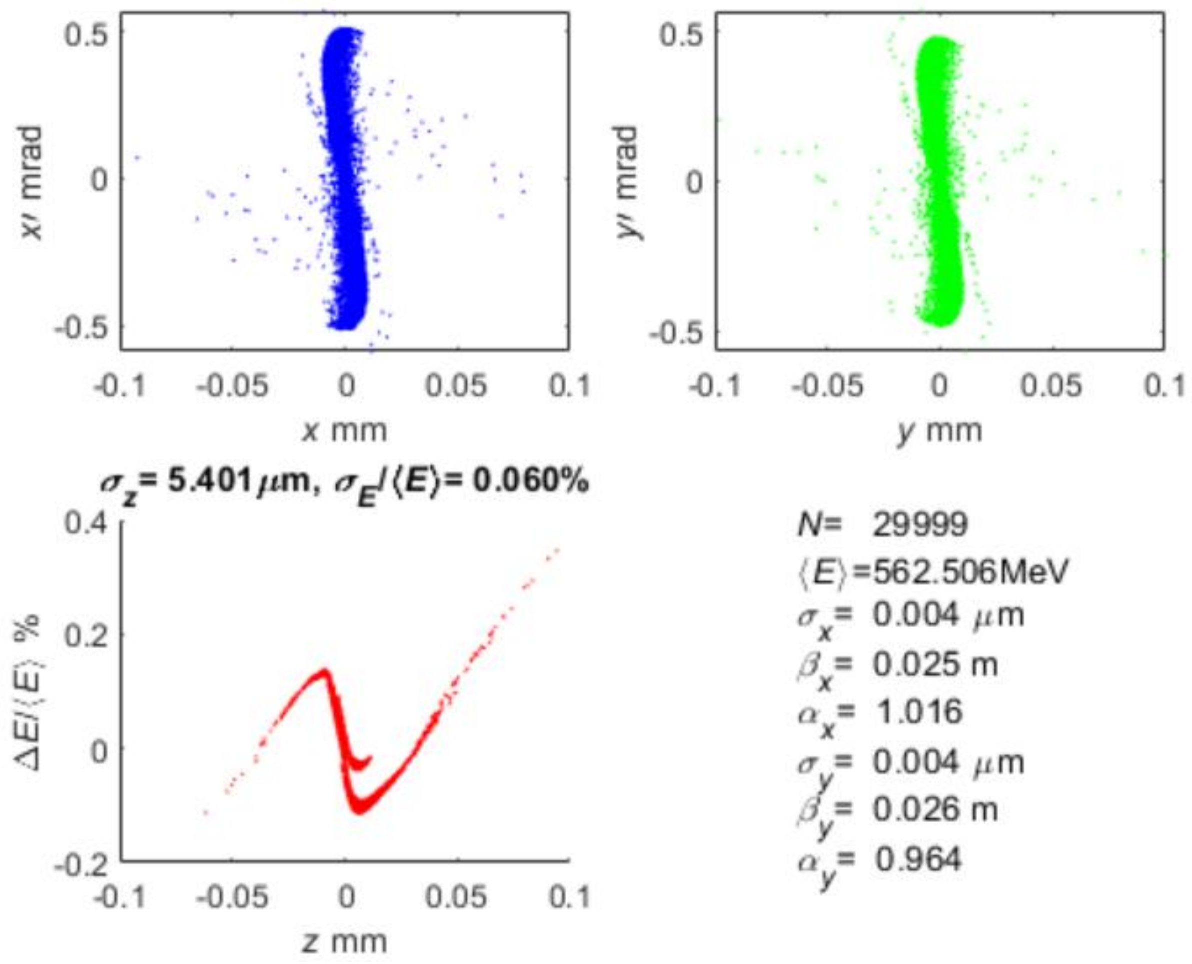


A. Giribono

Electron beam phase space at linac exit

Funded by the European Union

Witness



N= 29999

$\langle E\rangle$=562.506MeV

σ_x= 0.004 μm

β_x= 0.025 m

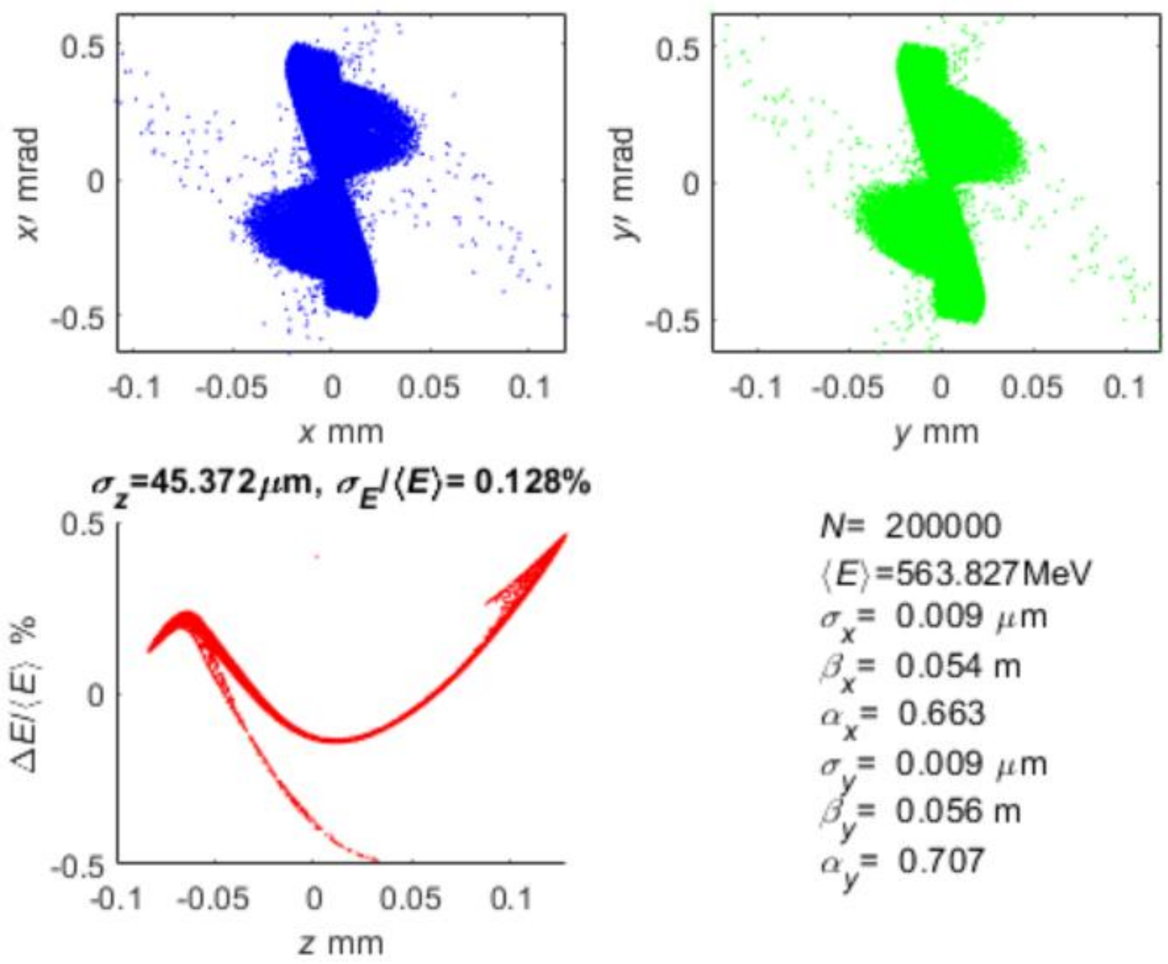
α_x= 1.016

σ_y= 0.004 μm

β_y= 0.026 m

α_y= 0.964

Driver



N= 200000

$\langle E\rangle$=563.827MeV

σ_x= 0.009 μm

β_x= 0.054 m

α_x= 0.663

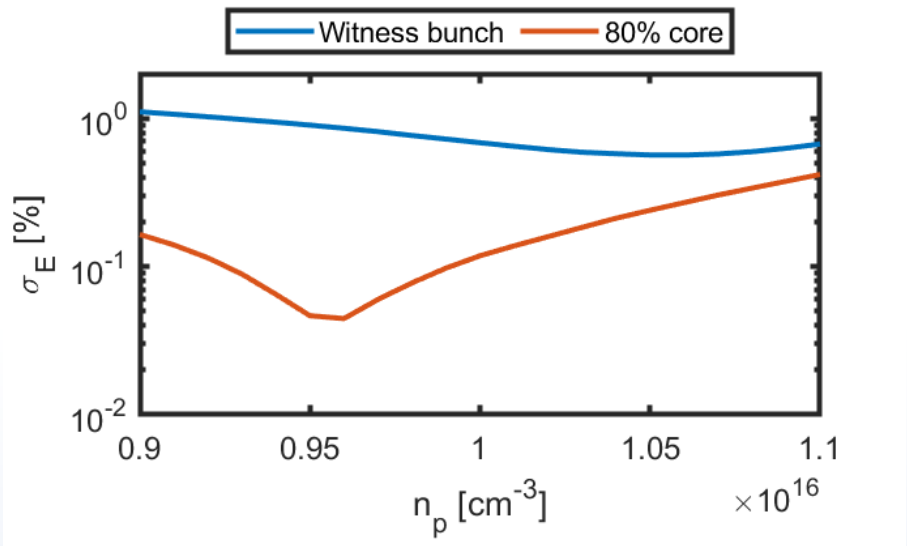
σ_y= 0.009 μm

β_y= 0.056 m

α_y= 0.707

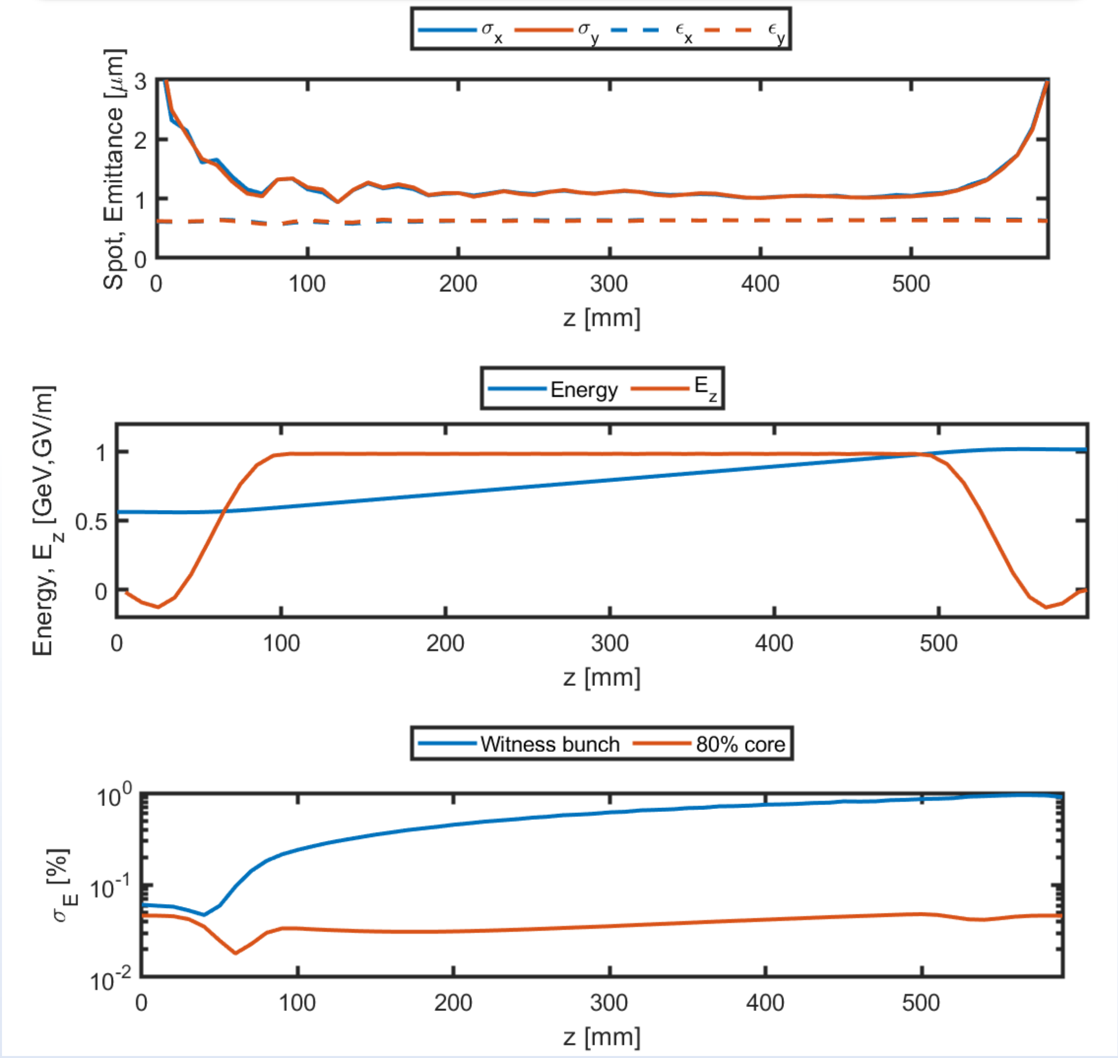
Nominal WP 200+30 pC: **Macroparameters evolution**

- Plasma ramp, 10 cm long, have been introduced in beam dynamics simulations following the numerical studies [] consistent with experimental results →see A. Biagioni's contribution

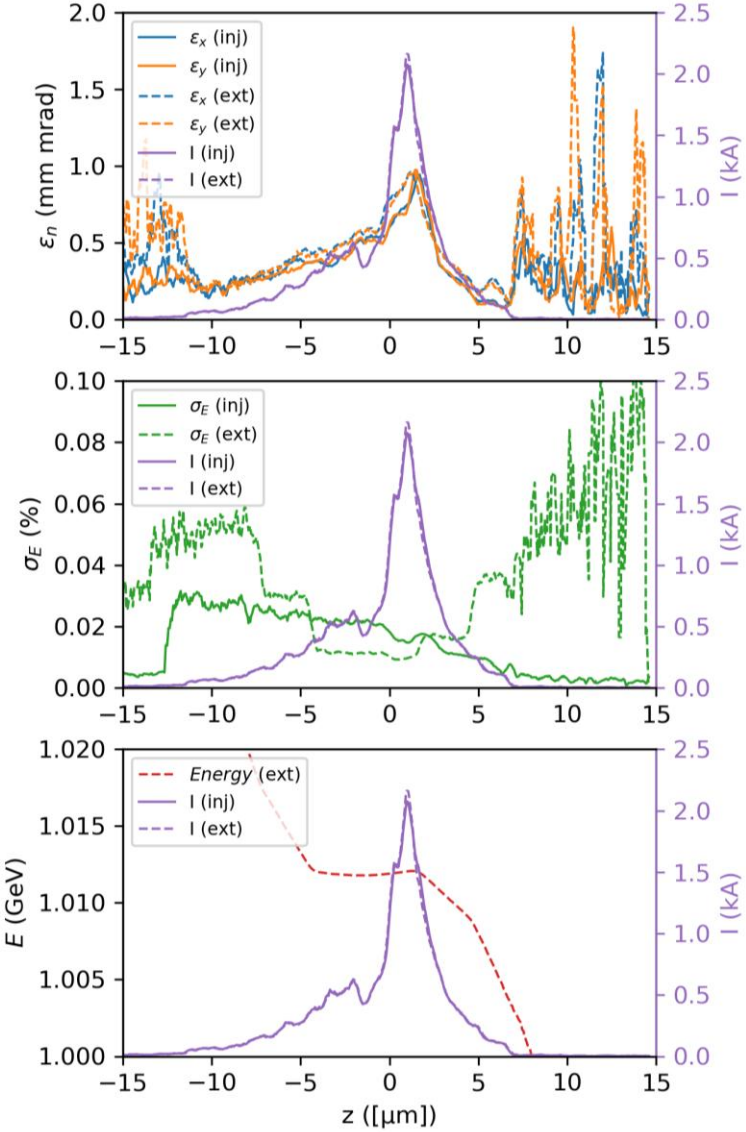


- **Reduction of core energy spread**
- **Energy spread minimum with $n_p = 10^{16}\mathrm{cm}^{-3}$**
- **Full preservation of emittance**
- **Final energy $1.01\ \mathrm{GeV}$**
- **Maximum accelerating gradient $0.98\ \mathrm{GV/m}$**
- **Average accelerating gradient $\approx 0.8\ \mathrm{GV/m}$**

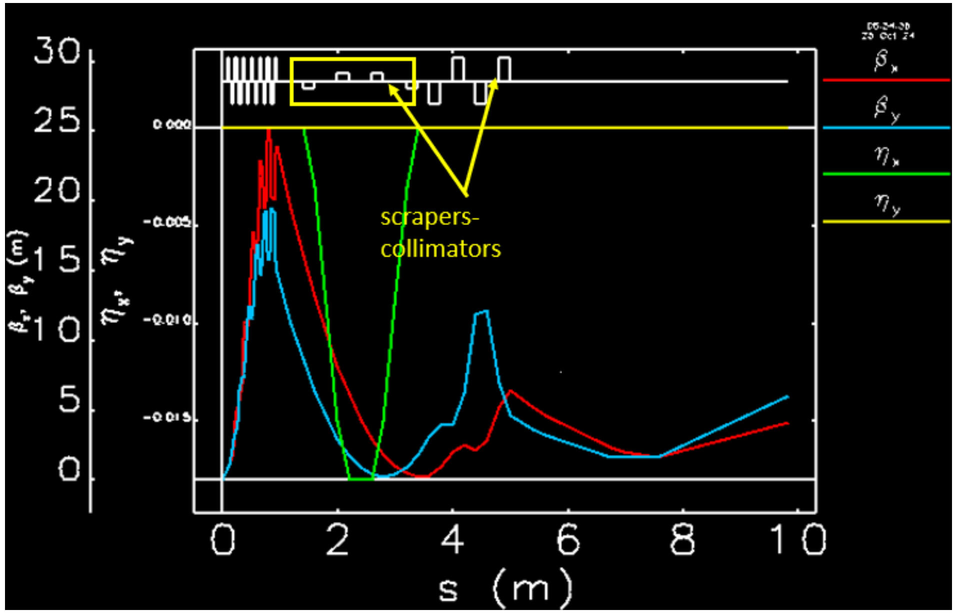
Nominal Working Point $n_p = 10^{16}\mathrm{cm}^{-3}$



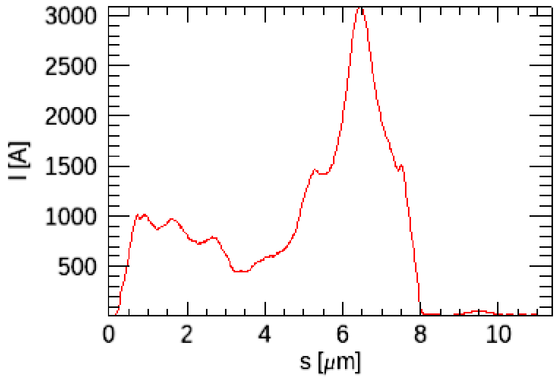
W-D Separation beamline: from plasma module to FEL



Witness slice analysis @plasma exit



Separation beamline matching
(fodo + chicane + collimators)
Simulation input file contains the
entire beam (W+D)



Energy (GeV)	**1**
γ	1957.95
I_{peak} (kA)	3.07
dE/E (‰)	0.46
Proj. Emitt x	0.69
Proj. Emitt y	0.65

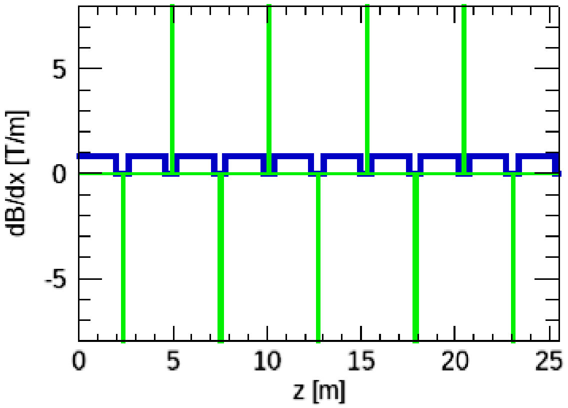
Witness slice analysis (upper) and rms parameters (lower) @FEL entrance

FEL matching and performances

Funded by the European Union

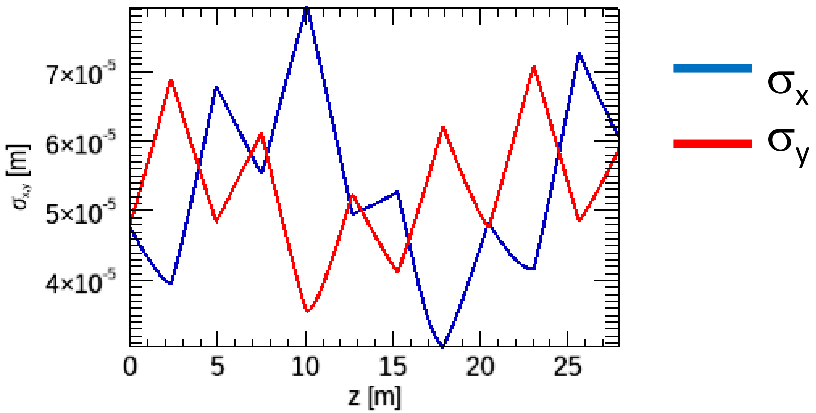
Matching

Undulator structure

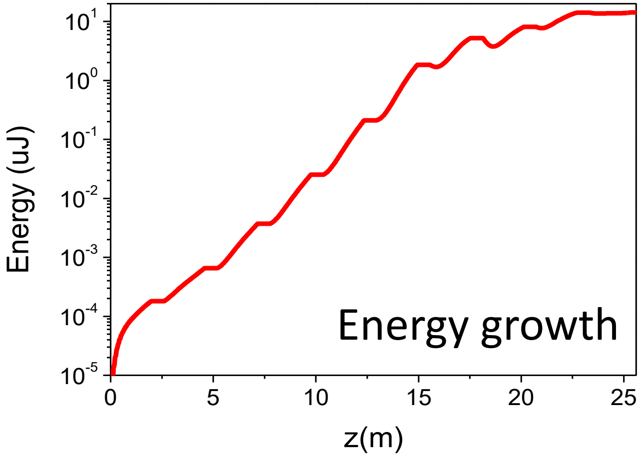


λ_w=1.8 cm
a_w=0.84
dB/dz=8 T/m

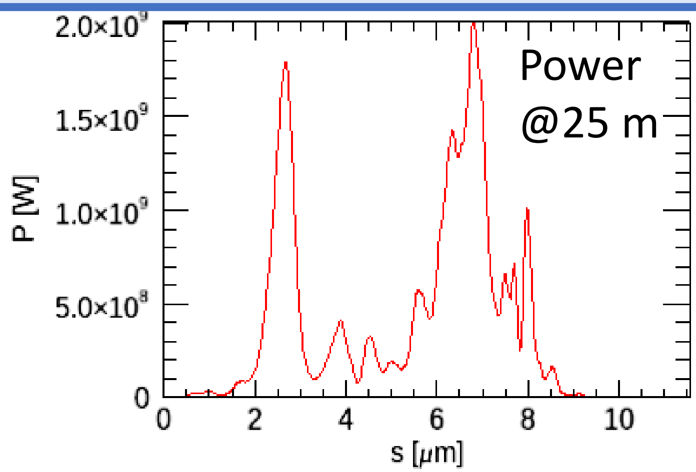
Average matching



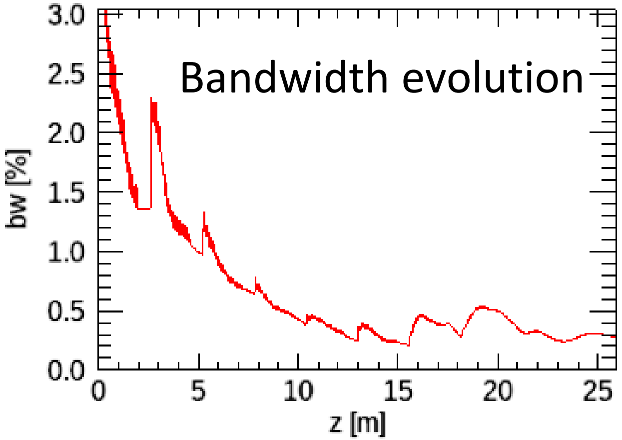
Performances



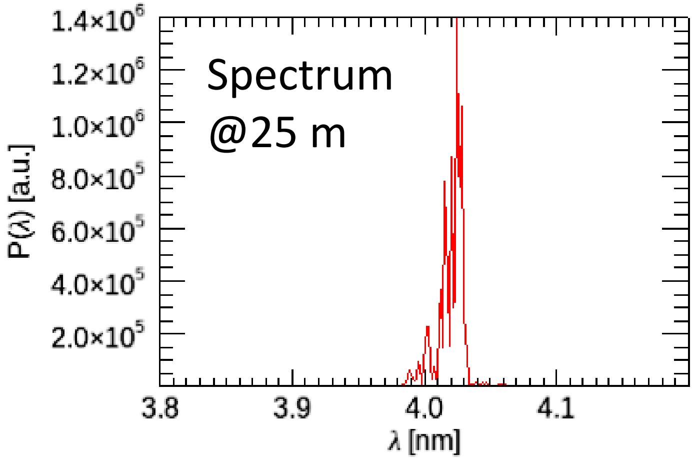
Energy growth



Power @25 m



Bandwidth evolution



Spectrum @25 m

Energy (μJ)	λ (nm)	BW (‰)	Photon number	Size (μm)	Div (μrad)	L_sat (m)	L_rad (μm) FWHM
13.54	4.004	3	$2.71\ 10^{11}$	170	27	23	4.5

Courtesy of V. Petrillo – M. Opromolla

Accelerator sensitivity

Funded by the European Union

- From the SPARC_LAB experience and **state of the art** are considered jitter as in table

S-band Gun and Accelerating Sections (rms)		
RF Voltage [ΔV]	± 0.02	%
RF Phase [Δϕ]	± 0.02	*deg*
X-band Accelerating Sections (rms)		
RF Voltage [ΔV]	± 0.02	%
RF Phase [Δϕ]	± 0.10	*deg*
Cathode Laser System		
Charge [ΔQ] (max)	± 1	%
Laser time of arrival [Δ*t*](rms)	± 20	fs
Laser Spot size [Δσ]	± 1	%

from simulations
for main working point
(VB - CF. 20)
@plasma injection

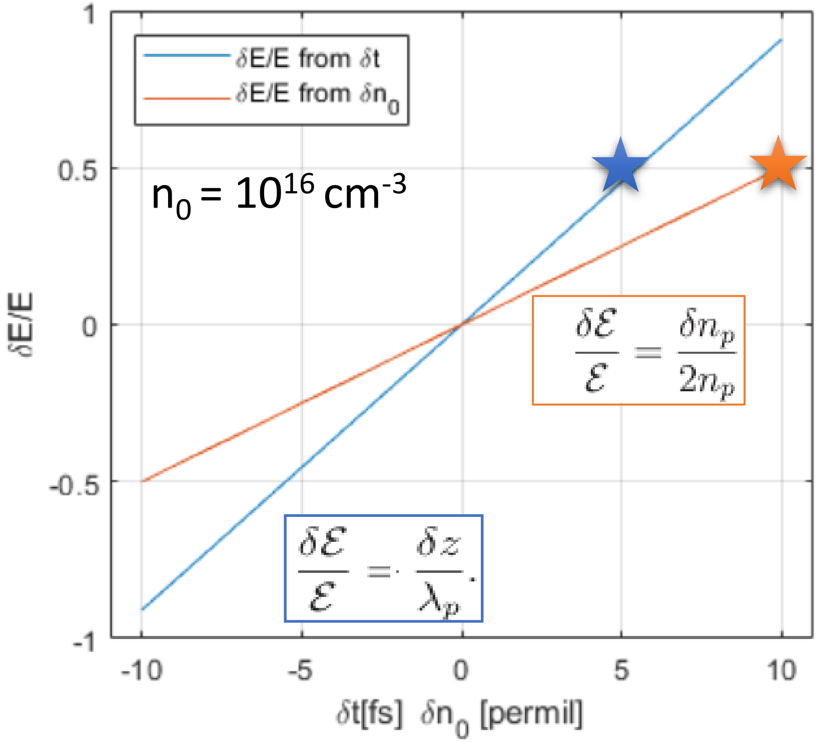
- *5 fs W-D distance jitter*

Plasma density		
n_0	± 1	%

adding plasma density jitter
@plasma exit

- *δE = 1 % rms <E> = 1 GeV*

Jitter contribution introduced in S2E simulations



Analytical evaluation of plasma vs linac contribution to energy gain jitter @plasma exit

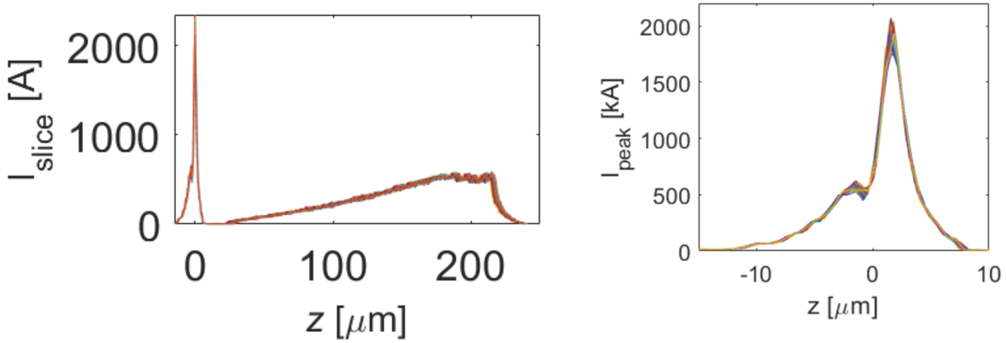
[15] S. Romeo *et al* 2024 *J. Phys.: Conf. Ser.* **2687** 042008**DOI** 10.1088/1742-6596/2687/4/042008

Sensitivity studies: from cathode to plasma exit

Funded by the European Union

@linac exit	Witness	Driver	Units
Charge	30.00 ± 0.04	200.00 ± 0.30	pC
Energy	562.53 ± 0.32	563.86 ± 0.30	MeV
Energy spread	0.06 ± 0.0003	0.128 ± 0.0006	%
Bunch length	18.00 ± 0.22	151.5 ± 0.81	fs
I_{peak}	2.055 ± 101	-	kA
Δt	0.529 ± 0.004	-	ps
$\varepsilon_{n_{x,y}}$	0.77 ± 0.008	1.6 ± 0.018	mm mrad
$\sigma_{x,y}$	4.4 ± 0.3	8.9 ± 0.13	µm
$\beta_{x,y}$	25.8 ± 3.5	55.0 ± 1.4	mm
$\alpha_{x,y}$	1.0 ± 0.15	0.70 ± 0.030	

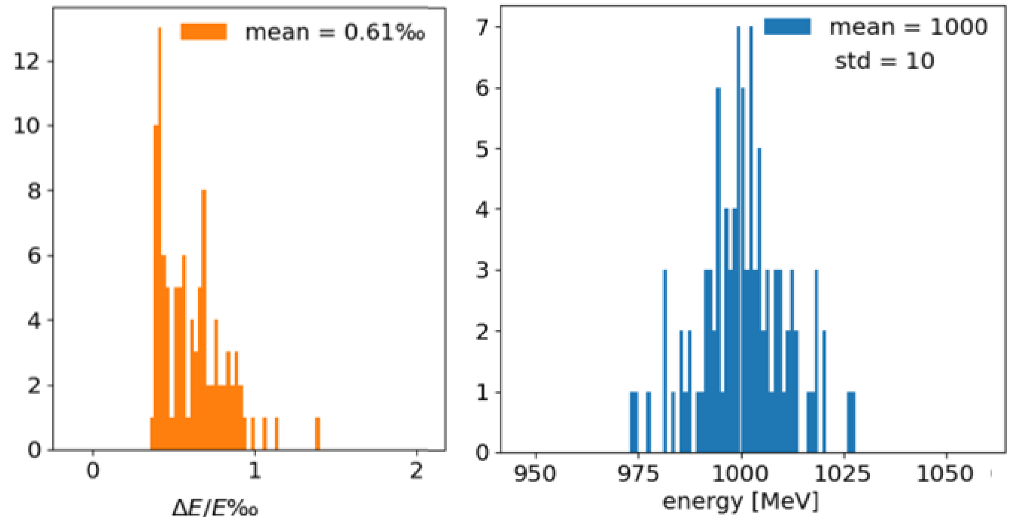
Errors are intended as rms quantities



Comb beam current and witness slice analysis

@plasma exit

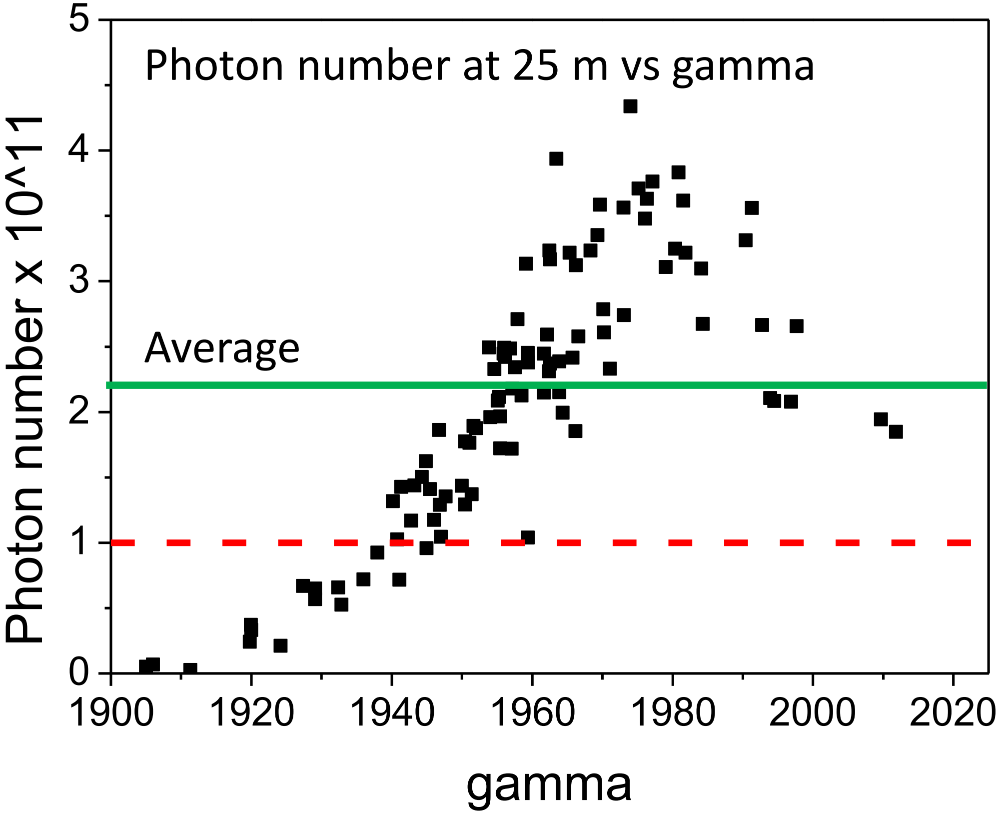
- 200 + 30 pC nominal working point affected by LINAC and plasma jitters
- plasma density is assumed to jitter 1% (one sigma) around the “nominal” longitudinal value



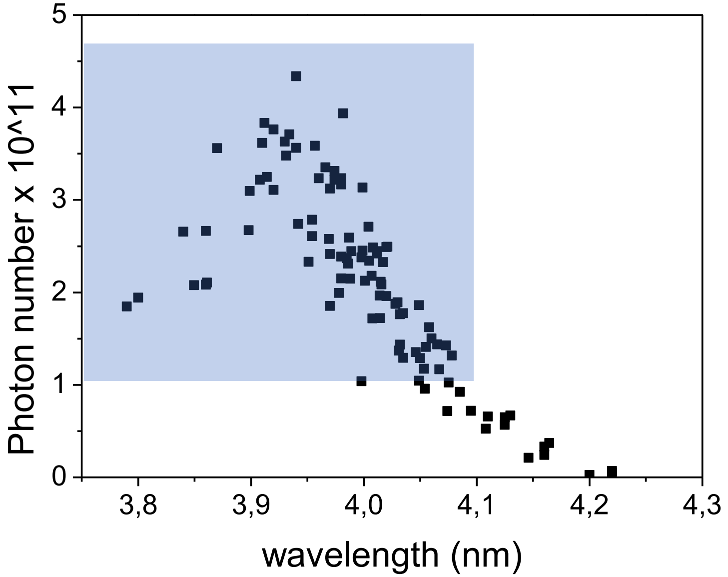
Courtesy of A. Del Dotto

Sensitivity studies: FEL emission (statistics over 101 shots)

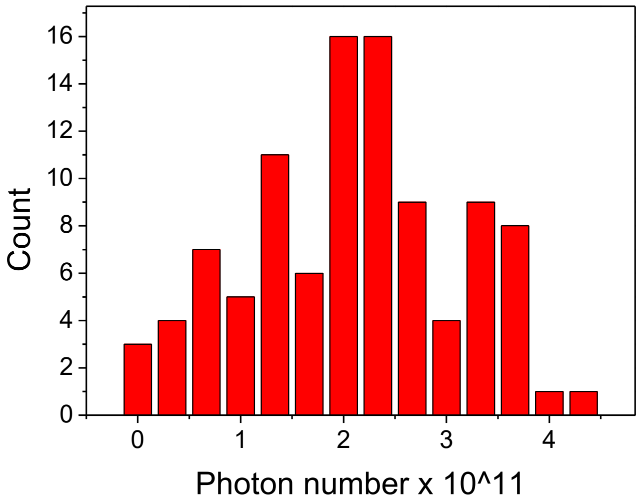
Funded by the European Union



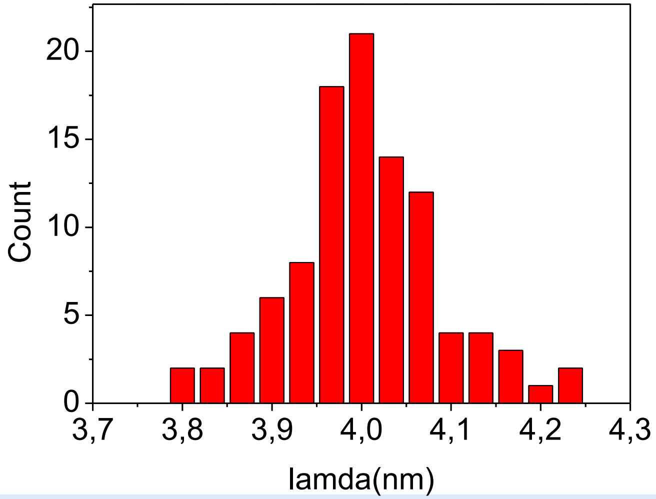
85/101 shots with
- Photon Number **> 10^{11}**
- Wavelength ∈ [3.8 : 4.05] nm



Photon number distribution



Wavelength distribution



	Unit	Average value	Error	Relative error
Wavelength	**nm**	**4.0037**	**0.084**	**0.02**
Energy (25 m)	**uJ**	**10.54**	**5.2**	**0.49**
Photon number	**x 10^{11}**	**2.092**	**1.01**	**0.48**

Courtesy of V. Petrillo – M. Opromolla

Tolerances for the EuPRAXIA@SPARC_LAB linac

- Misalignments on input beam distribution at X-band linac entrance, accelerating and magnetic elements

- The study has been performed with the Elegant code looking at the comb WP performances at the plasma entrance
  - Beam quality
  - Witness-driver transverse alignment

- Errors have been added as in table in according to following considerations:
  - All quantities are expressed as the rms values of a random Gaussian distribution, with a cutoff at 2σ
  - An initial offset is applied to the beam to simulate a potential off-axis trajectory in the upstream photoinjector
  - The X-band accelerating cavities are paired together in sets of two
  - **Bold values are intended as result of BBA technique**

Error type	Value	Units
Beam distribution @linac entrance		
X-Y Misalignment	**25**, 50	*μm*
X-band Accelerating Sections		
X-Y Misalignment	**25**, 70	*μm*
Quadrupoles		
X-Y Misalignment	**25**, 70	*μm*
Rotation about longitudinal axis	**25**, 70	*μrad*

Steerers and BPMs distribution

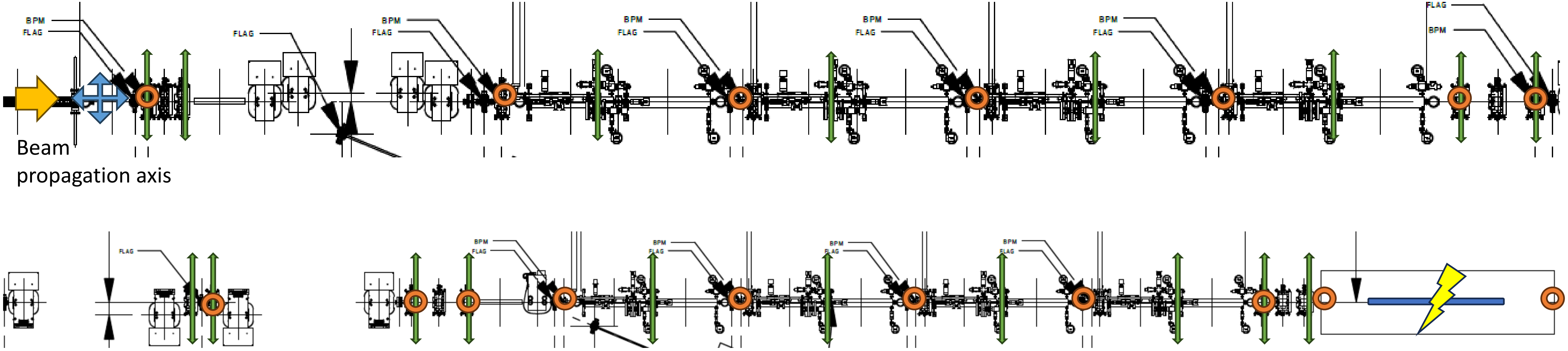
- BD simulations have been performed over a sample of 50 machine runs including the trajectory correction
  - Cavity BPMS in the X-band linac with 1 μm resolution
  - Global and one-to-one approach (completed)
  - Wakefield and dispersion free steering on going (with RF-track code in collaboration with CERN)

Legend

↕ HV steerers

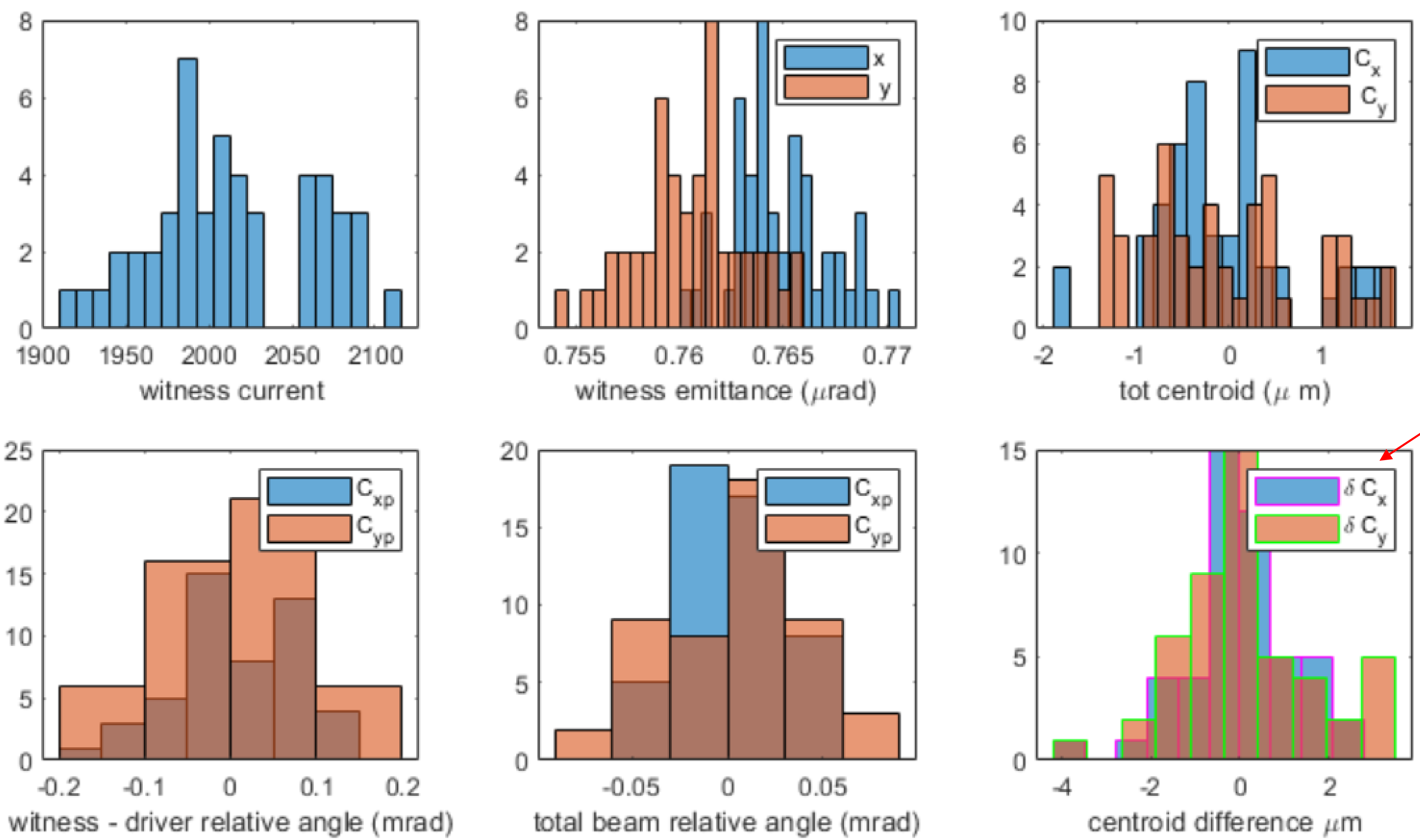
✥ Inj. Offest

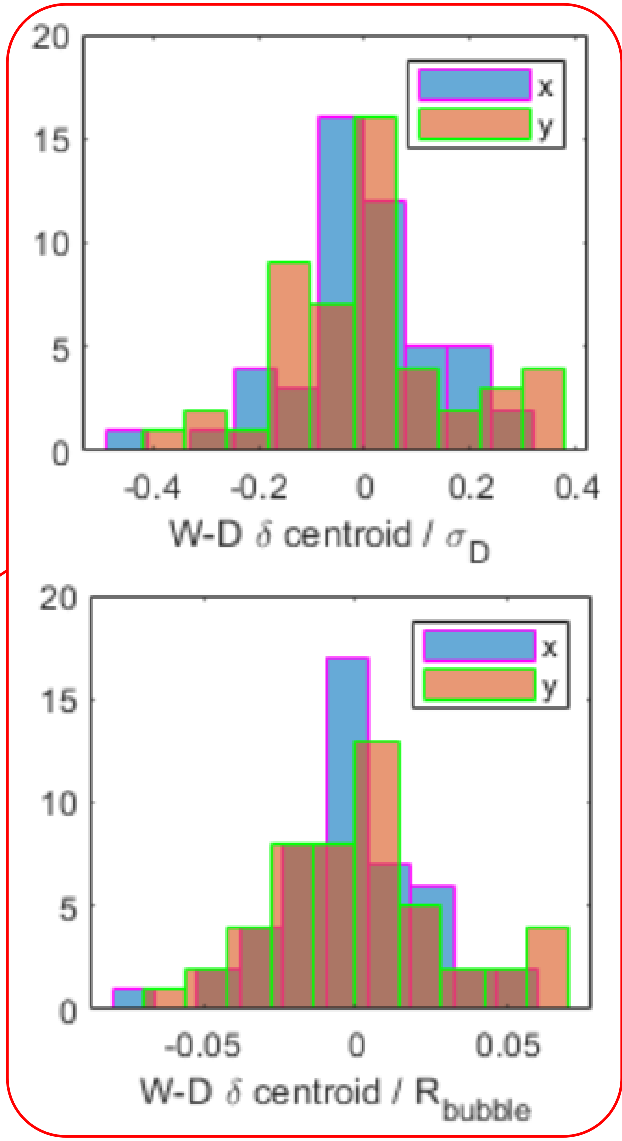
○ BPMs



30+200 pC (worst case – pre-BBA)

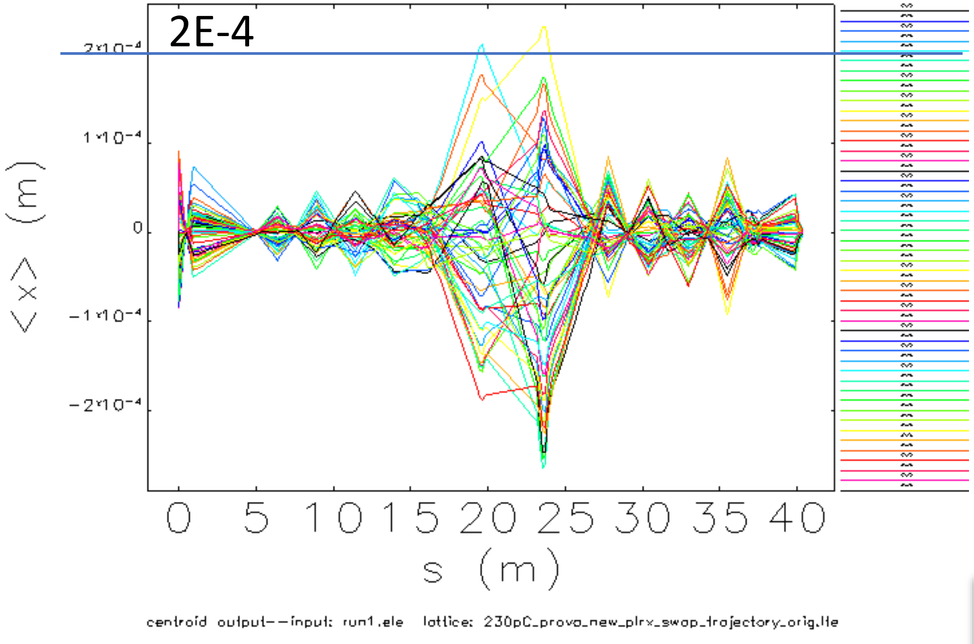
Funded by the European Union

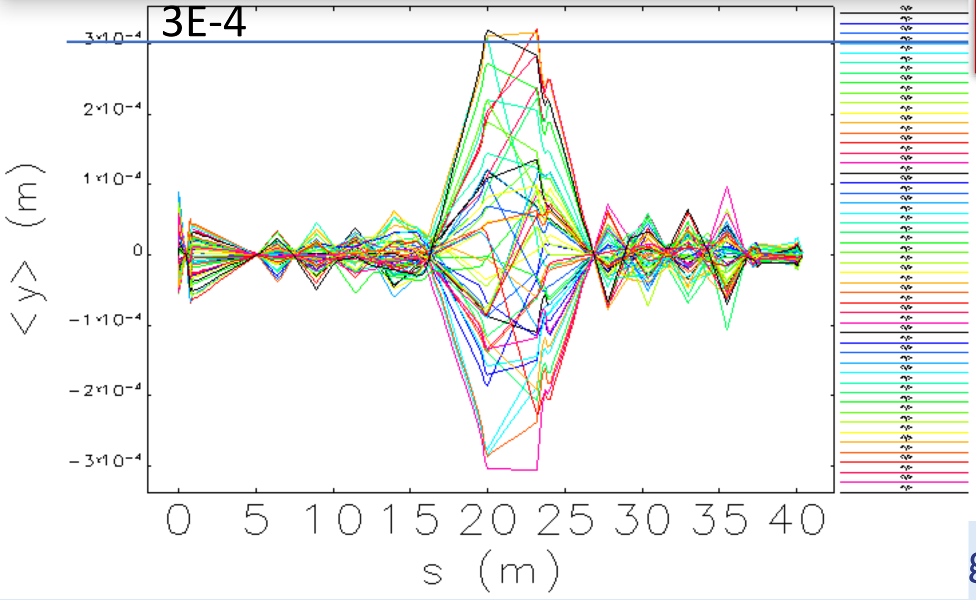




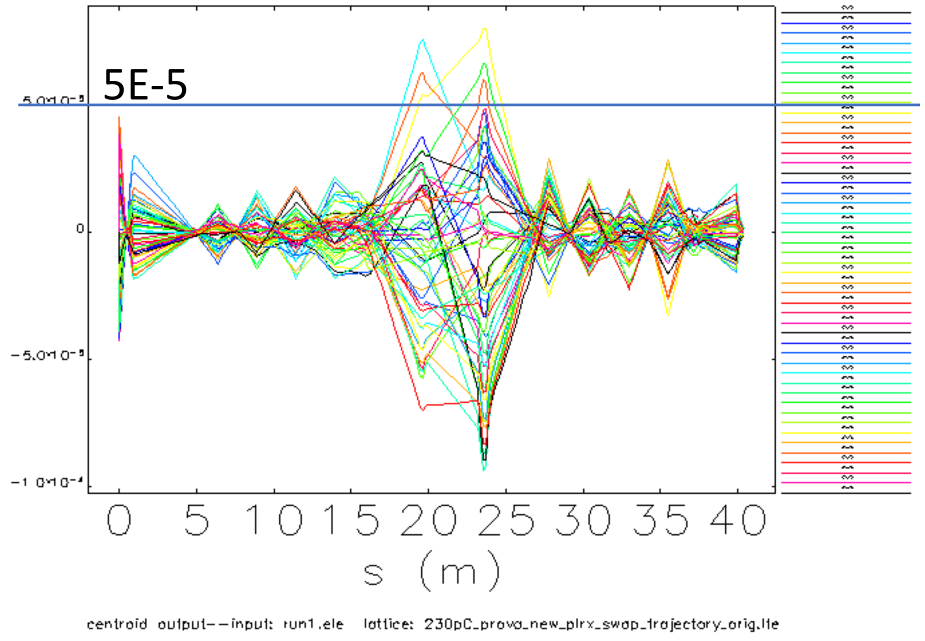
30+200 pC

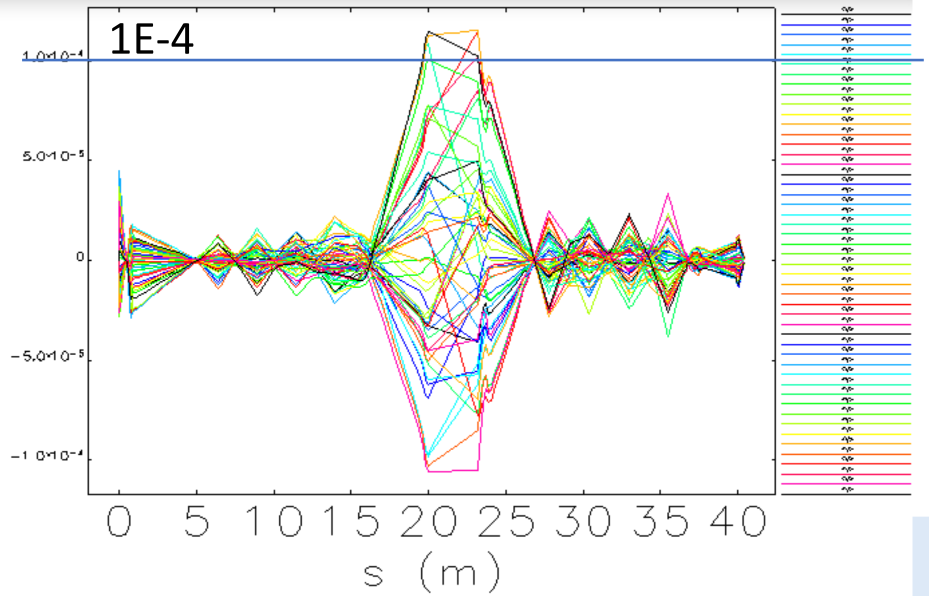
Pre-BBA





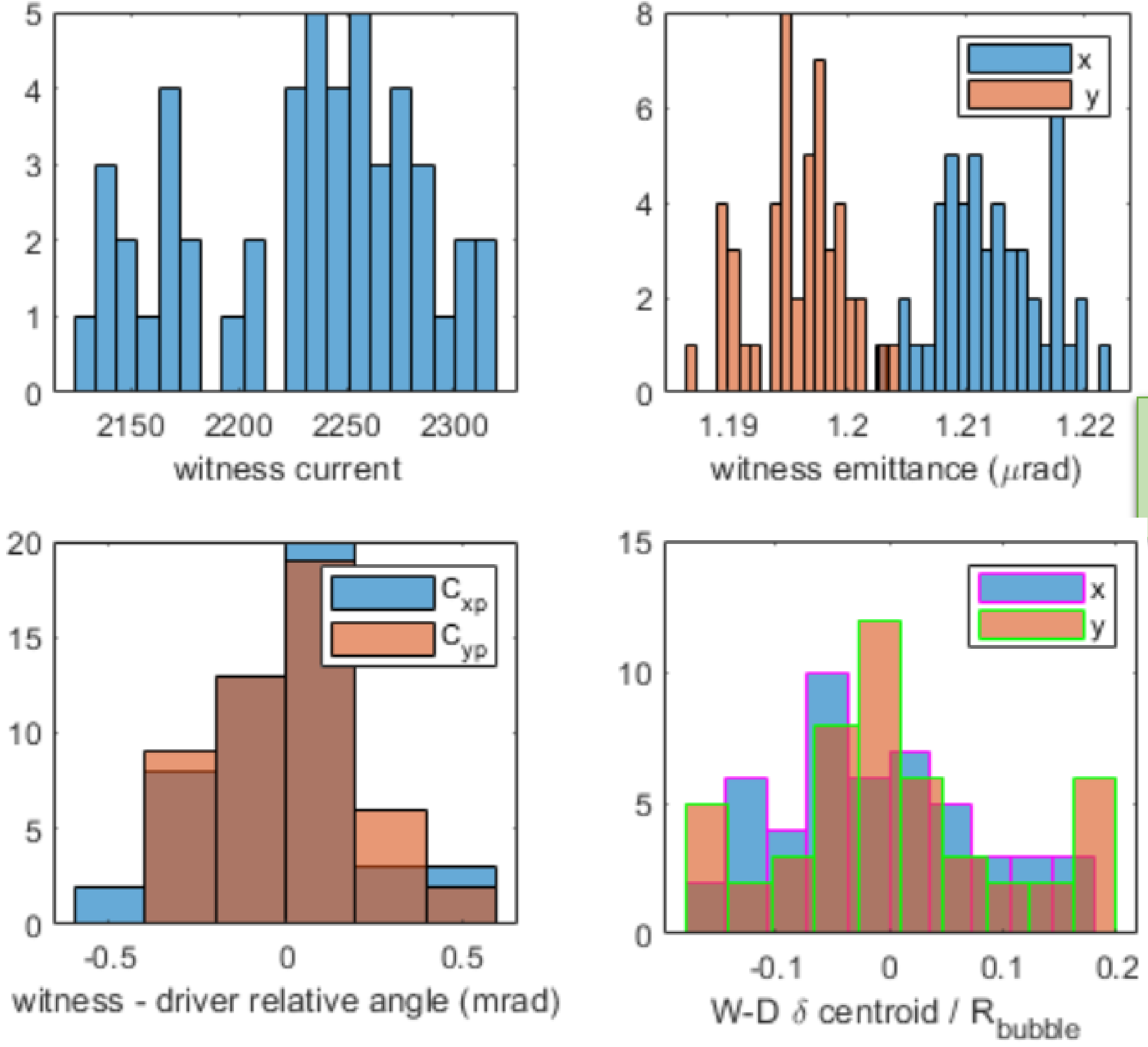
Post BBA



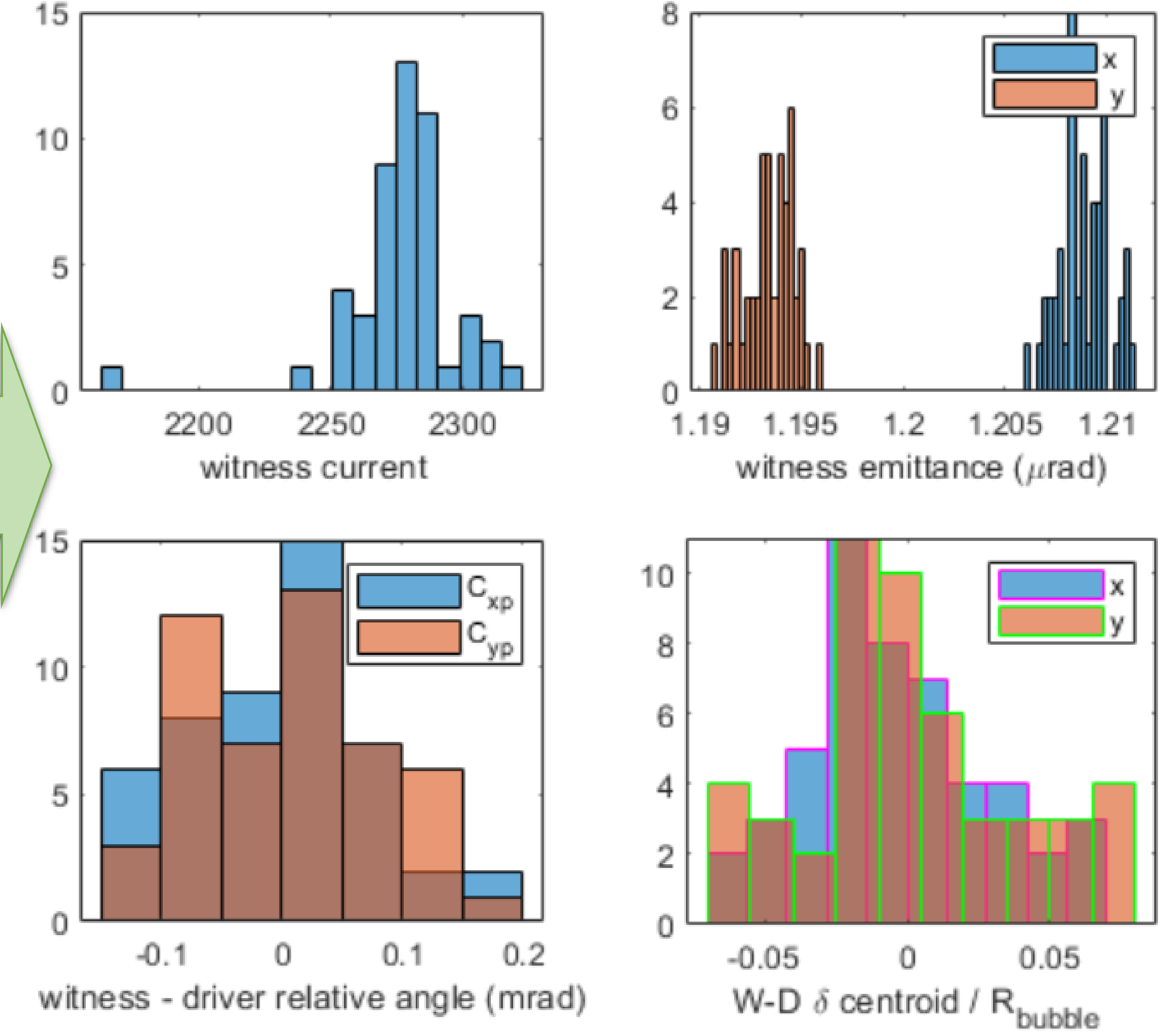


50+400 pC

Pre-BBA



Post BBA



A. Giribono

High transformer ratio PWFA for EuPRAXIA@SPARC_LAB: the 5 GeV WP

Funded by the European Union

In perspective of the draft of EuPRAXIA@SPARC LAB technical design report, we have explored through numerical simulations two ideal scenario suitable for the 5 GeV case trying to maximize the

$$R_T = \frac{|E^{+}_{max}|}{|E^{-}_{max}|}$$

- Quasi non-linear regime to exceed $R_T = 2$ and preserve beam quality

$$\tilde{Q} = \frac{N_b k_p^3}{n_p} \leq 2 \qquad n_b/n_p \gg 1$$

- Two bunches operation
- Resonant scheme

- The simulations have been performed in 2D by means of the Hybrid Fluid Kinetic code Architect [2]

- Plasma accelerating module → 2.4 m long flat top plasma profile with a background density $n_p = 2.5\ 10^{16}$ cm^{-3}, preceded by a 1 cm long injection ramp
  → beam energy at injection 1.2 GeV

[1] S. Romeo et al - High transformer ratio resonant PWFA ideal working point design for EuPRAXIA@SPARC_LAB - 2020 J. Phys.: Conf. Ser. 1596 012061
[2] F Massimo, S. Atzeni and A. Marocchino 2016 Journal of Computational Physics 327 841–850

High transformer ratio PWFA for EuPRAXIA@SPARC_LAB

Funded by the European Union

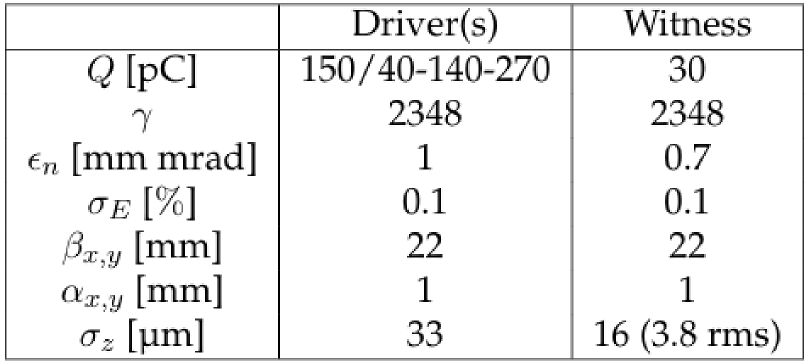
Two scenarios have been explored consisting in

a) Two bunches: 150 pC + 30 pC

b) Train of bunches → 40 – 140 – 270 pC + 30 pC

Same results in terms of final beam energy

Table 1. Driver(s) and witness parameters at the injection



	Driver(s)	Witness
Q [pC]	150/40-140-270	30
γ	2348	2348
ϵ_n [mm mrad]	1	0.7
σ_E [%]	0.1	0.1
$\beta_{x,y}$ [mm]	22	22
$\alpha_{x,y}$ [mm]	1	1
σ_z [μm]	33	16 (3.8 rms)

- Driver-driver separation of around $\lambda_p/2$ (105.6 μm)
- Driver-witness separation of around $\lambda_p/2$ (97 μm)

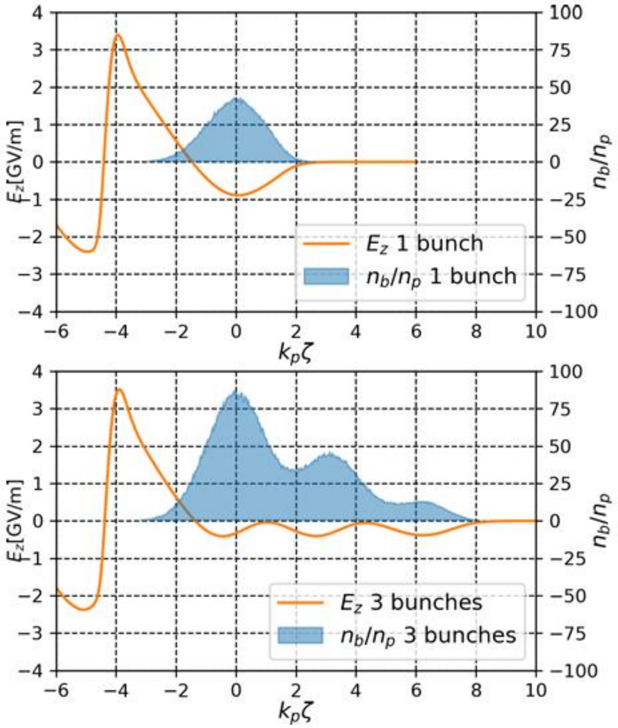
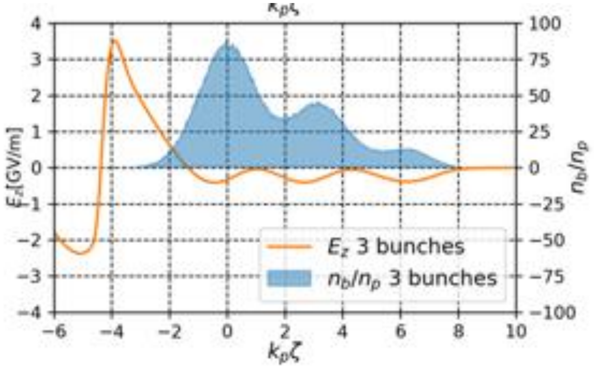


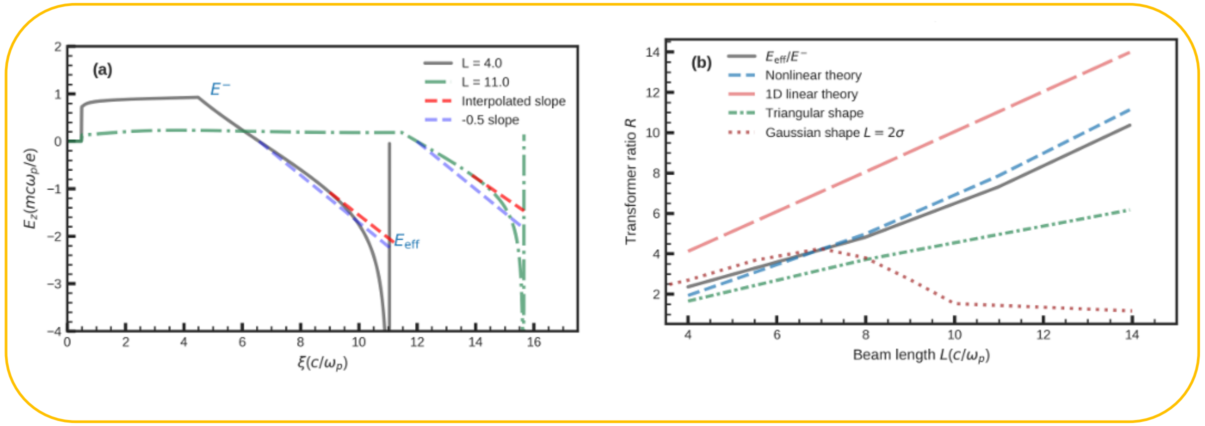
Figure 1. Longitudinal field on axis and longitudinal current profile for single bunch scheme (top) and 3 bunch train scheme (bottom) at $z = 0$.

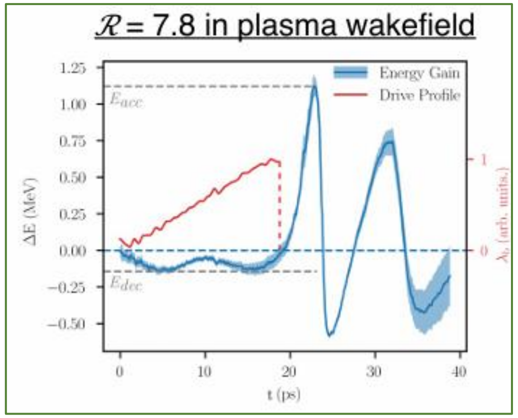
High transformer ratio PWFA for EuPRAXIA@SPARC_LAB: beam tailoring

- Driver:
  - train of three bunches with the same shape
  - final design that is in between a single bunch with ***triangular shape*** and a train of bunches
- *Witness:*
  - *Triangular current shape in order to minimize the energy spread growth* [3]



- Moderate beam quality
  - Higher accelerating gradients in the non-linear blow-out regime → smaller footprint
  - Hybrid LWFA + PWFA
- Further optimisation methods also suggest that customised tailoring exists to produce much higher R_T (for example up to 10 in [4,5])




$\mathcal{R} = 7.8$ in plasma wakefield

[3] M. Tzoufras, W. Lu, F. Tsung, C. Huang, W. Mori, T. Katsouleas, J. Vieira, R. Fonseca and L. Silva 2008 Physical Review Letters 101 145002
[4] Q. Su et al. Optimization of transformer ratio and beam loading in a plasma wakefield accelerator with a structure-exploiting algorithm (2023)
[5] Roussel, R., et al. PRL 124 (2020): 044802 - Gao, Q., et al. PRL 120 (2018): 114801 - Loisch, G., et al. PRL 121 (2018): 064801

High transformer ratio PWFA for EuPRAXIA@SPARC_LAB

- The average accelerating gradient is E_z = 1.65 GV/m and the effective transformer ratio is R_T = 3.65 → 5 GeV in 2.4 meter long plasma channel

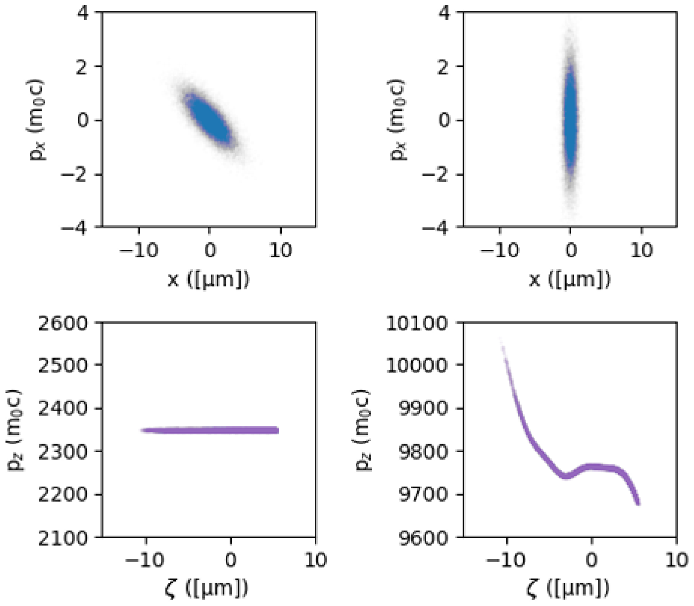


Figure 3. Witness phase space at the initialization (left) and at the end of the simulation (right). The transverse phase space is perfectly matched while the longitudinal phase space presents an energy spread growth mostly located on bunch tail.

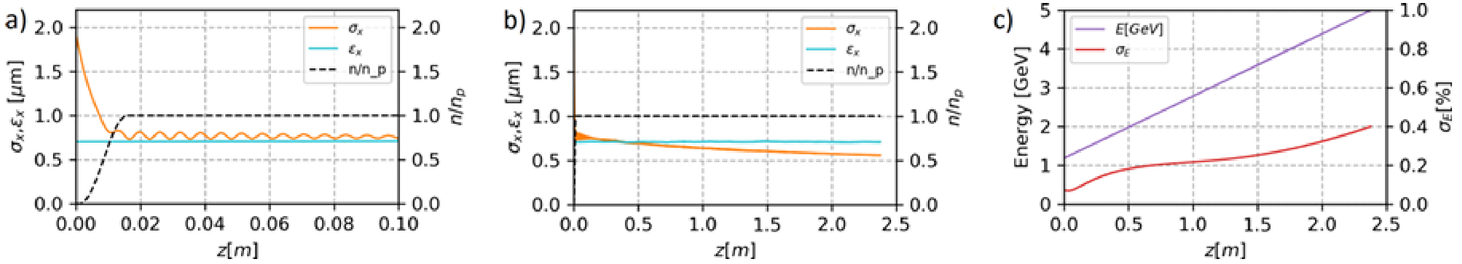


Figure 2. Integrated parameters evolution of Witness bunch. We report the evolution of the transverse spot size and emittance in a) (for the first 10 cm) and in b) (for the entire channel) along with the density of the plasma channel. We report in c) the evolution of energy and energy spread.

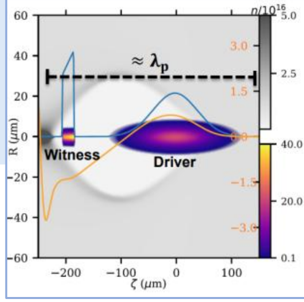
The emittance of the witness is preserved along the entire plasma channel and the energy spread grows up to 04%

Conclusions

- The EuPRAXIA@SPARC_LAB accelerator layout and related beam dynamics have been reported
- The accelerator has a wide flexibility and is able to provide very different working points for the electron beams in terms of charge and duration, thus peak current, with an overall high-quality on the transverse phase-space with relatively small projected emittances
- Machine performances in terms of rms parameters and stability have been described, with a focus on the main working point
- The machine layout can host very different beam generation systems thanks to its tools: RF and magnetic compression, microbunching mitigation, longitudinal phase space linearization or shaping

Thank you for your attention!

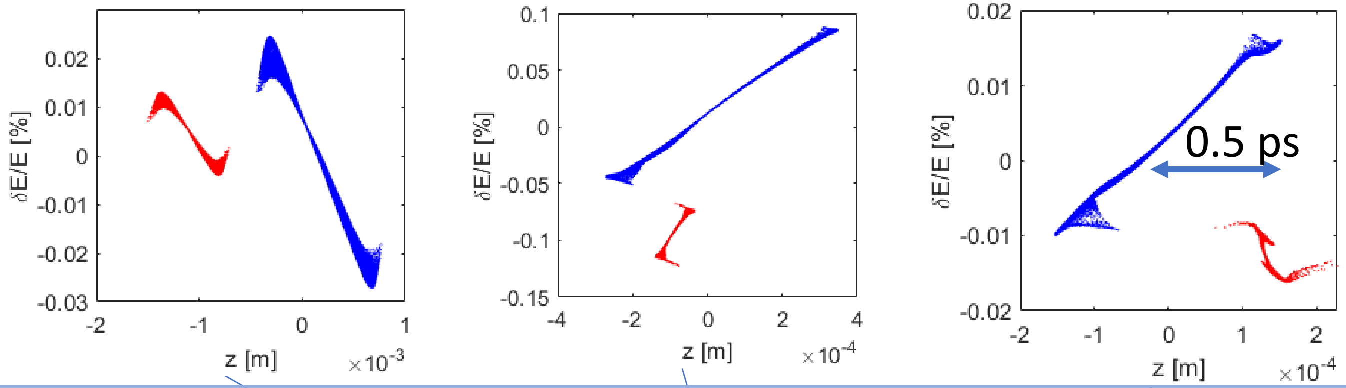
1 GeV with plasma acceleration working point



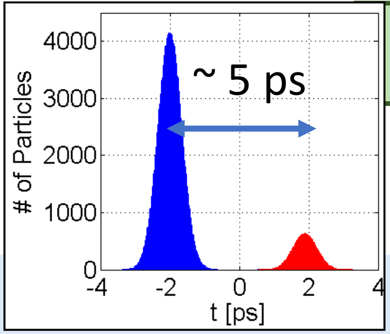
- The **reference working point** is determined by the FEL performances and the plasma module
  - Accelerating gradient of the order of GV/m
  - Weakly non-linear regime (bubble with resonant behaviour)

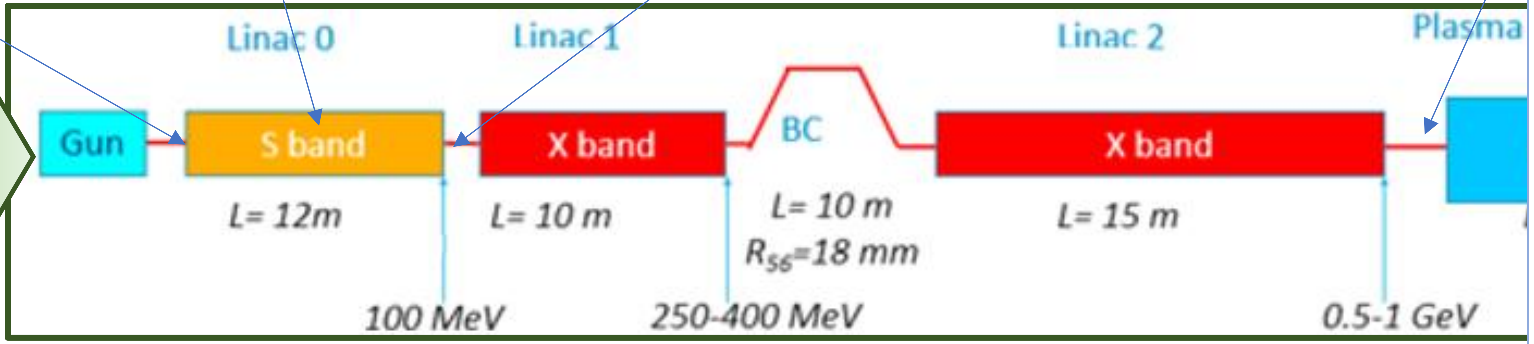
1. 200 (400) pC driver + 30 (50) pC witness
2. plasma density of the order of $10^{16}\ cm^{-3}$ ($0.4\ 10^{16}\ cm^{-3}$)
3. Driver-witness separation of around $\lambda_p/2$ → 0.5 ps (1 ps)
4. Driver and witness bunches of 50 (24) and 6 μm rms
5. Driver and witness spot size <10 μm with α=1

Velocity bunching technique

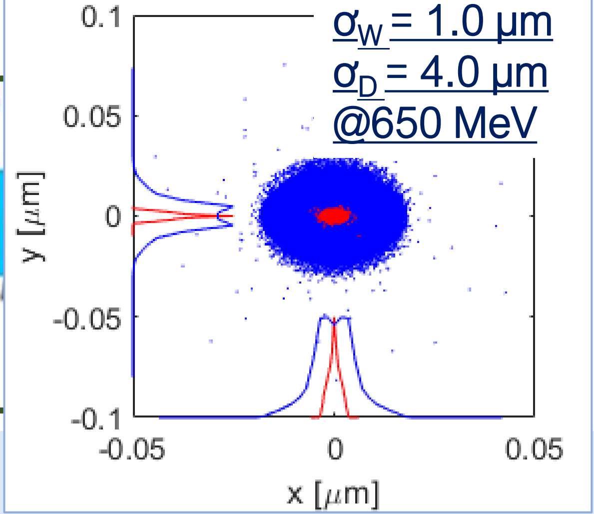


Laser comb technique



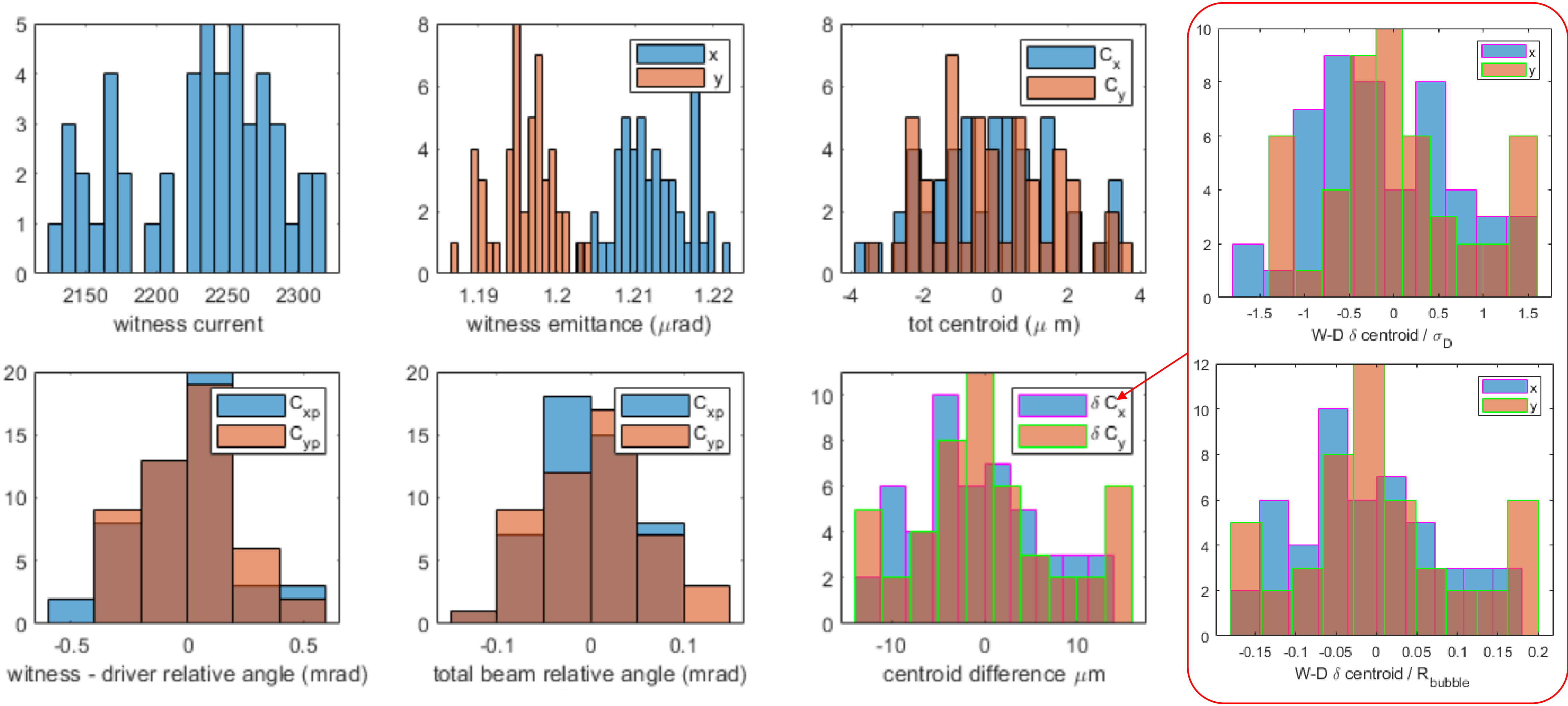


Strong focusing system



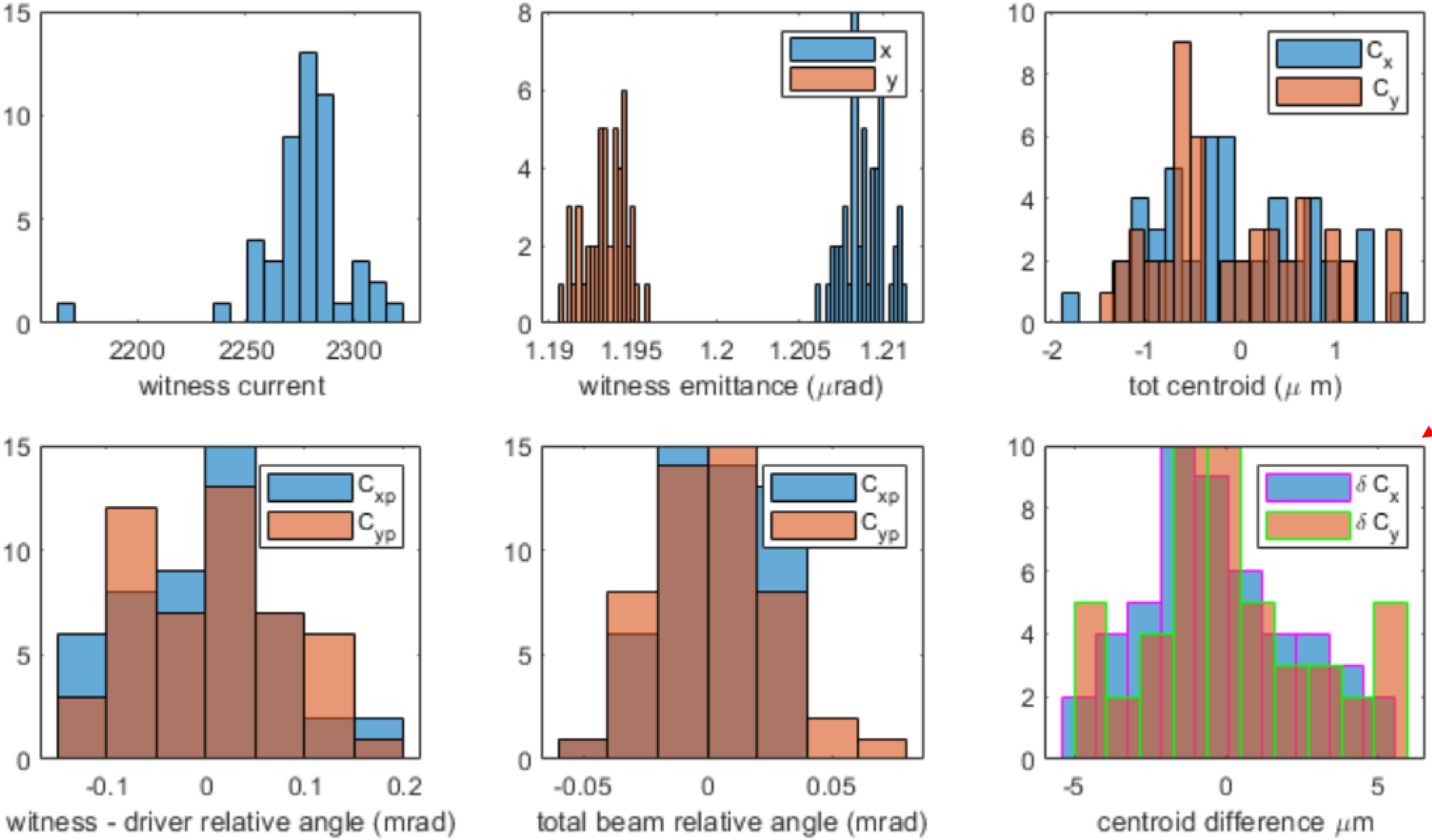
50+400 pC (worst case – pre-BBA)

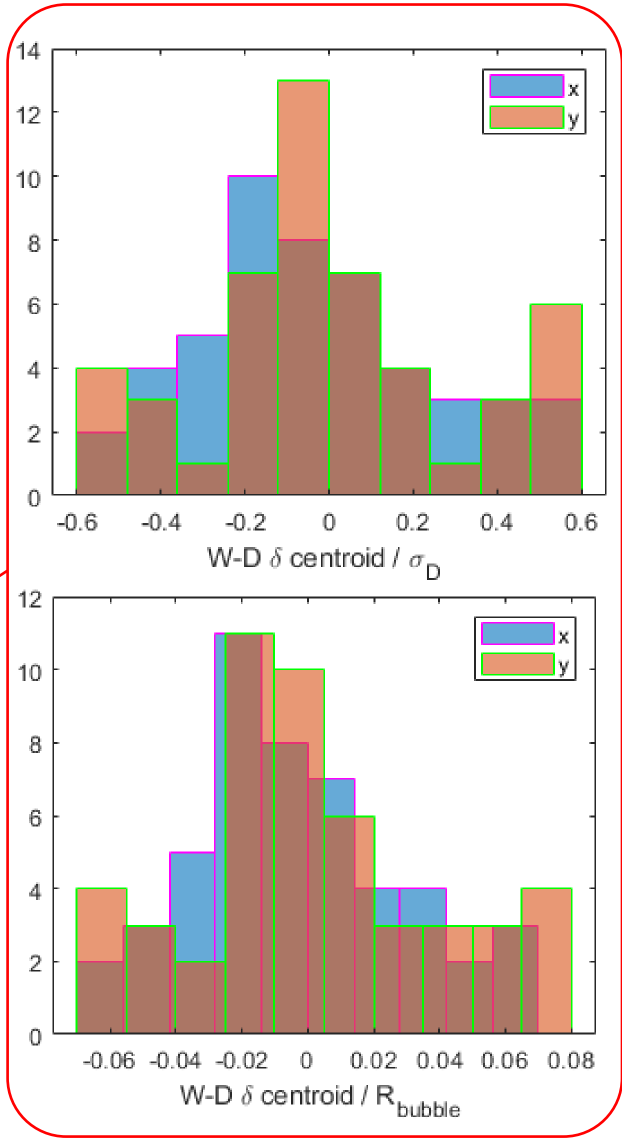
Funded by the European Union



50+400 pC (post-BBA)

Funded by the European Union





Tolerances studies including jitter

S-band Gun and Accelerating Sections (rms)		
RF Voltage [ΔV]	± 0.02	%
RF Phase [Δϕ]	± 0.02	*deg*
X-band Accelerating Sections (rms)		
RF Voltage [ΔV]	± 0.02	%
RF Phase [Δϕ]	± 0.10	*deg*
Cathode Laser System		
Charge [ΔQ] (max)	± 1	%
Laser time of arrival [Δt](rms)	± 20	fs
Laser Spot size [Δσ]	± 1	%

Plasma density		
n_0	± 1	%

Error type	**Value**	**Units**
Beam distribution @linac entrance		
X-Y Misalignment	**25,** 50	*μm*
X-band Accelerating Sections		
X-Y Misalignment	**25**, 70	*μm*
Quadrupoles		
X-Y Misalignment	**25**, 70	*μm*
Rotation about longitudinal axis	**25**, 70	*μrad*

Electron beam diagnostics

- The electron beams are fully characterized
  - after generation at the photoinjector
  - before and after each X-band linac section
  - Before the injection in and after extraction from the plasma module
- The main parameters that must be monitored and controlled are listed below along with the required sensitivity and precision, and with the envisioned diagnostics tool

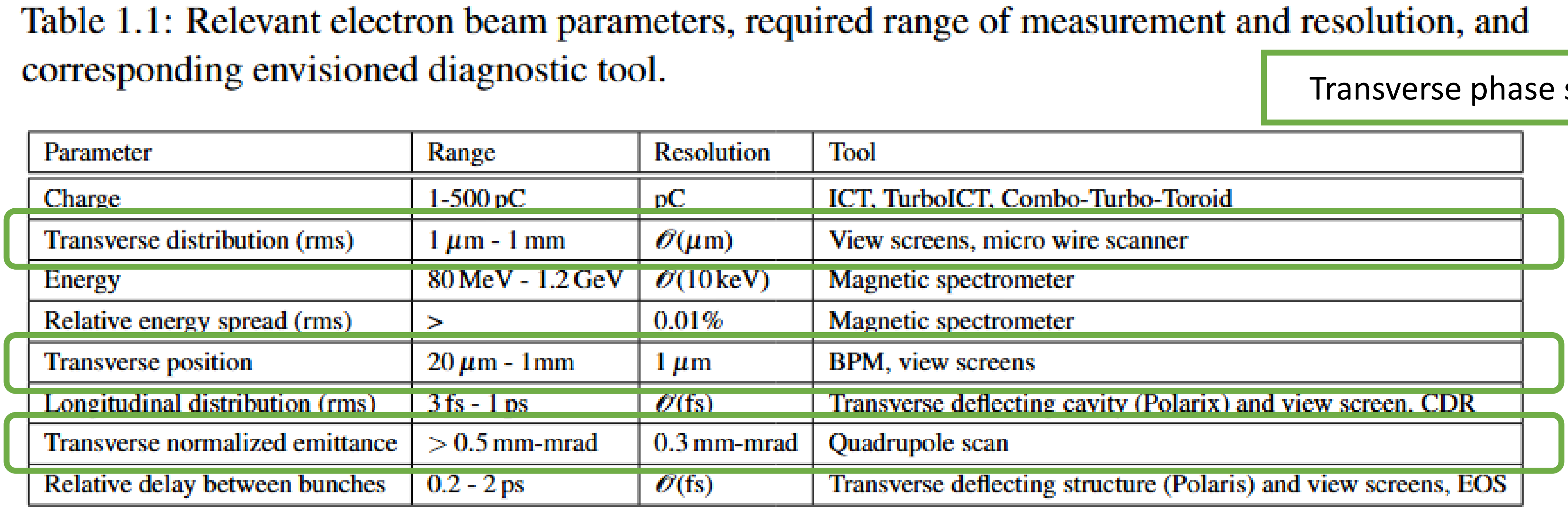


Table 1.1: Relevant electron beam parameters, required range of measurement and resolution, and corresponding envisioned diagnostic tool.

Parameter	Range	Resolution	Tool
Charge	1-500 pC	pC	ICT, TurboICT, Combo-Turbo-Toroid
Transverse distribution (rms)	1 μm - 1 mm	$\mathcal{O}(\mu\mathrm{m})$	View screens, micro wire scanner
Energy	80 MeV - 1.2 GeV	$\mathcal{O}(10\,\mathrm{keV})$	Magnetic spectrometer
Relative energy spread (rms)	>	0.01%	Magnetic spectrometer
Transverse position	20 μm - 1mm	1 μm	BPM, view screens
Longitudinal distribution (rms)	3 fs - 1 ps	$\mathcal{O}(\mathrm{fs})$	Transverse deflecting cavity (Polarix) and view screen, CDR
Transverse normalized emittance	> 0.5 mm-mrad	0.3 mm-mrad	Quadrupole scan
Relative delay between bunches	0.2 - 2 ps	$\mathcal{O}(\mathrm{fs})$	Transverse deflecting structure (Polaris) and view screens, EOS

Transverse phase space

[10] EuPRAXIA@SPARC_LAB Technical Design Report (on going)

Electron beam diagnostics

Funded by the European Union

- The electron beams are fully characterized
  - after generation at the photoinjector
  - before and after each X-band linac section
  - Before the injection in and after extraction from the plasma module
- The main parameters that must be monitored and controlled are listed below along with the required sensitivity and precision, and with the envisioned diagnostics tool

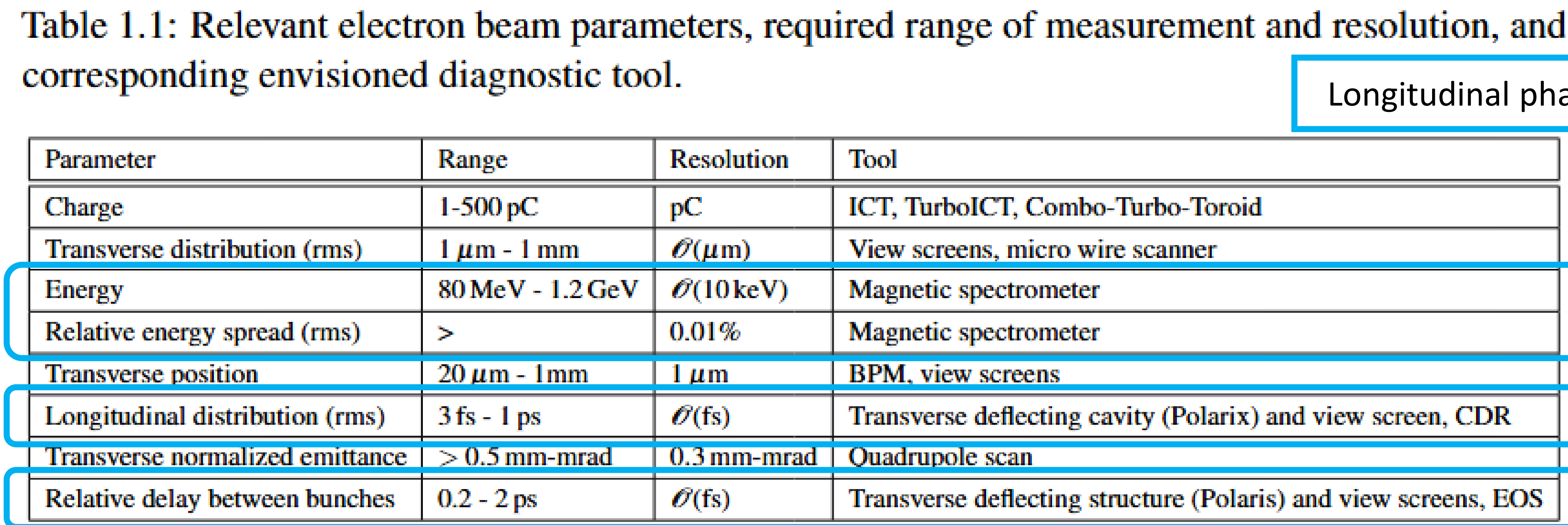


Table 1.1: Relevant electron beam parameters, required range of measurement and resolution, and corresponding envisioned diagnostic tool.

Parameter	Range	Resolution	Tool
Charge	1-500 pC	pC	ICT, TurboICT, Combo-Turbo-Toroid
Transverse distribution (rms)	1 μm - 1 mm	$\mathcal{O}(\mu\text{m})$	View screens, micro wire scanner
Energy	80 MeV - 1.2 GeV	$\mathcal{O}(10\,\text{keV})$	Magnetic spectrometer
Relative energy spread (rms)	>	0.01%	Magnetic spectrometer
Transverse position	20 μm - 1mm	1 μm	BPM, view screens
Longitudinal distribution (rms)	3 fs - 1 ps	$\mathcal{O}(\text{fs})$	Transverse deflecting cavity (Polarix) and view screen, CDR
Transverse normalized emittance	> 0.5 mm-mrad	0.3 mm-mrad	Quadrupole scan
Relative delay between bunches	0.2 - 2 ps	$\mathcal{O}(\text{fs})$	Transverse deflecting structure (Polaris) and view screens, EOS

Longitudinal phase space

[10] EuPRAXIA@SPARC_LAB Technical Design Report (on going)

Longitudinal phase space and slice analysis

Funded by the European Union

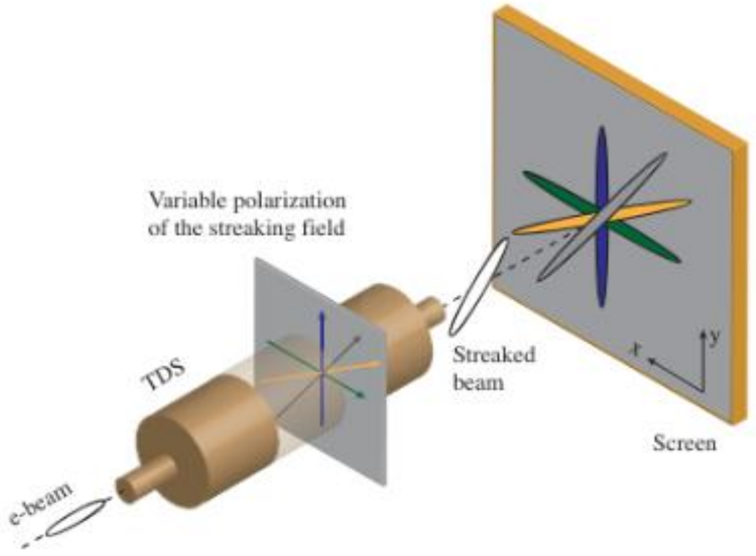


Figure 1.10: Working principle of the PolariX TDS, which is able to streak the beam at various direction by changing the field polarization [13].

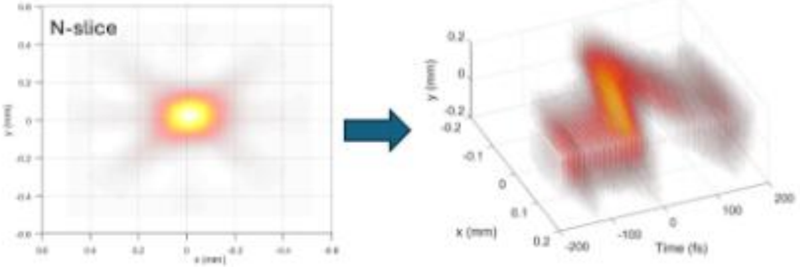


Figure 1.13: 2D reconstructed distribution (on the left) obtained for each slice with a tomographic technique are combined to obtain the 3D beam charge distribution (on the right) [17].

Table 1.7: Parameters of TDS Measurements at the low-energy and high-energy diagnostics stations.

Parameter	Low-Energy	High-Energy
Nominal Energy [MeV]	118	1000
Natural Beam Size [μm]	60	14
Bunch Length [fs]	17	15
Drift TDS-Screen [m]	3.45	3.07
TDS Length [m]	0.6	0.96
Max Voltage [MV]	23	56
Max Resolution [fs]	1.1	0.9

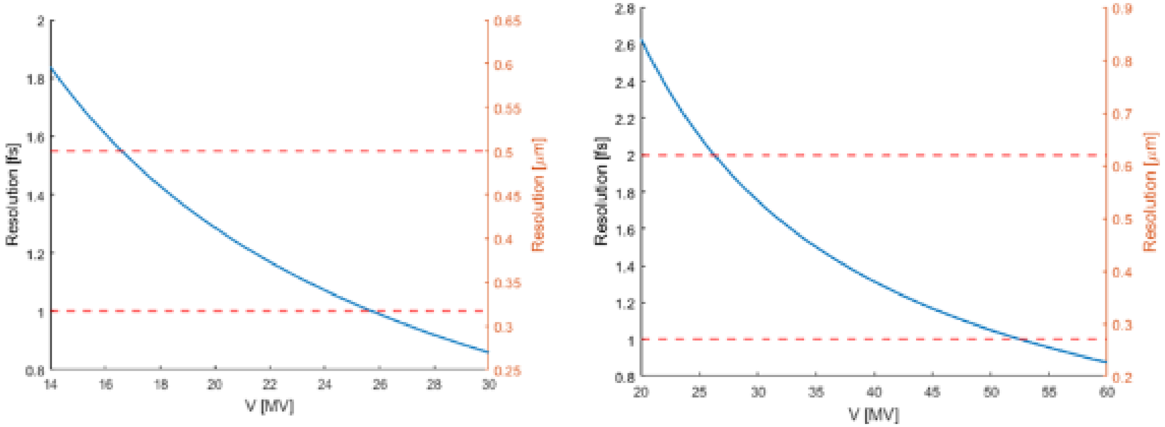


Figure 1.11: Left: Longitudinal resolution for the low-energy station, assuming a nominal natural beam transverse size of $\sigma_y \sim 60\ \mu m$, and for a 0.6 m long PolariX. Right: Longitudinal resolution for the high-energy station, assuming a nominal natural beam transverse size of $\sigma_y \sim 14\ \mu m$, and for a 0.96 m long PolariX.