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EuPRAXIA
Preparatory Phase

Beam Dynamics S2E Simulations

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INFN-LNF

on behalf on the WA01

November 25th, 2024

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Outline

- Goal parameters and design criteria
- Status of beam dynamics studies and open topics
  - 1 GeV with plasma acceleration
  - 1 GeV RF only
- Implemented strategies to reduce the witness energy jitter shot to shot at the plasma exit
  - RF photoinjector design impact on longitudinal beam shaping
  - Velocity bunching compression vs plasma acceleration contribution
- Details on the 200+30 pC working point
- Schedule
- Conclusions

Funded by the European Union

Goal parameters and design criteria

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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 Bandwidth	%	**0.1**	0.5
Undulator Area Length	m	30	
ρ(1D/3D)	$\times 10^{-3}$	**2**	2
Photon Brilliance per shot	$\left(\frac{s\ mm^2 mrad^2}{bw(0.1\%)}\right)$	$\mathbf{1{-}2 \times 10^{28}}$	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

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Driver-Witness Temporal jitter < 5 fs from the linac that reflects on ≈ 1% for the plasma module setup

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Bold values indicate currently reached ones by means of S2E simulations

All WA01 efforts have been devoted to the **PWFA case** since last TDR Review Meeting (June 2024) → details at the end of the presentation

Status of beam dynamics studies and open topics

- **1 GeV with plasma acceleration**
  - Velocity bunching + Comb technique → we are investigating two working point trying to reduce the witness energy gain jitter in the plasma

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	Transverse matching to be optimised	Emittance growth mitigated with transfer matrix from Linac2Plasma	Waiting for beam as S2E	OK	OK	Repeat after WP refinement

  - Mask comb configuration → progress since June: gradient to be optimised to 1 GV/m – work in progress

- **1 GeV RF only**
  - Hybrid compression (velocity bunching + magnetic compression) → described in the CDR
  - Magnetic compression only to avoid jitter problems → The current layout can host both configurations (to be completed)

- **Investigation of static errors** of electro-magnetic and static elements with mitigation strategies **to be re-checked** in case of higher charges **(400 pC)** → on going. <u>At present, the positions and specifications of steerers and BPMs are not finalized</u> due to a very last revision in the diagnostic system of the X-band linac, which dates back to August 2024.

Implemented strategies to reduce the witness energy jitter shot to shot at the plasma exit (VB case)

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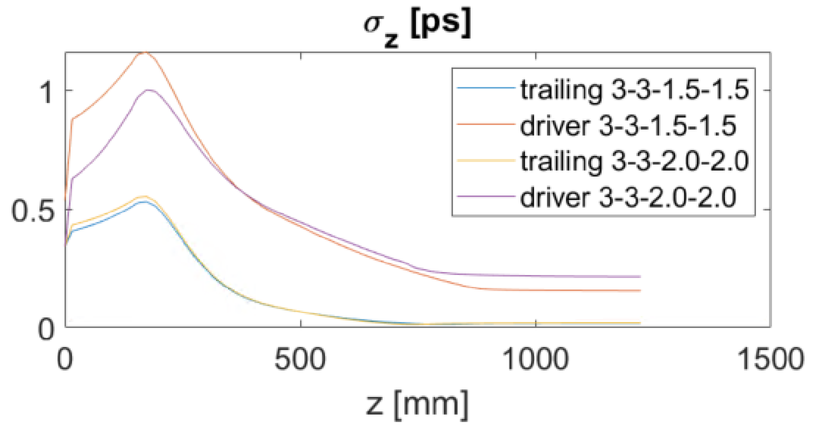
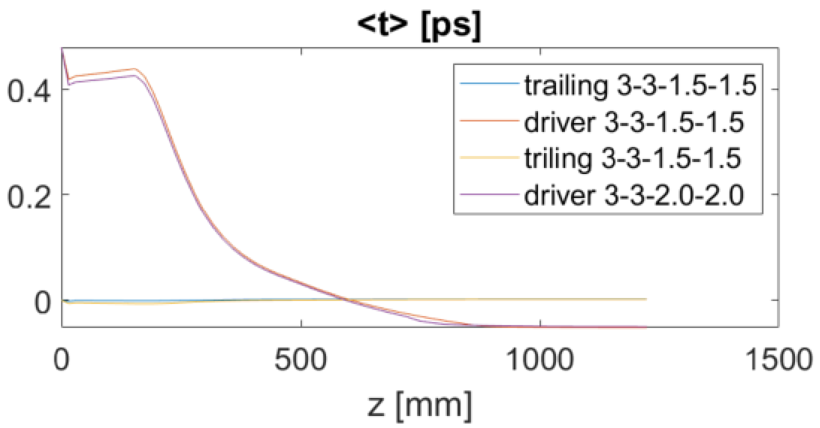
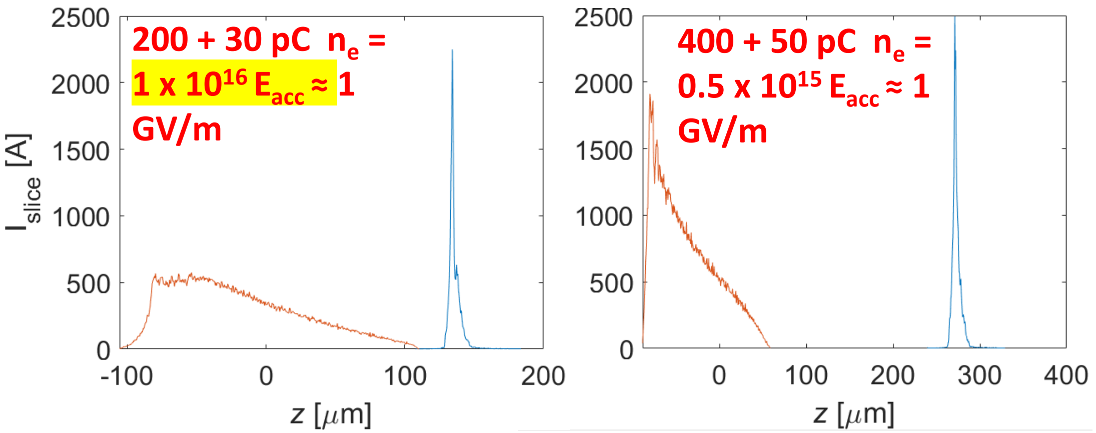
- **RF photoinjector design that impacts on longitudinal beam shaping**
  (→ see E. Chiadroni's contribution for photoinjector)
  - first two accelerating structures: **3+3 meter long instead of 3+2 meter long**
    → back to the CDR configuration
    → easier tuning of the beam separation and driver longitudinal profile (rms and slice)
    - Δt from 148 to 156 μm
    - σ_z from 65 to 45 μm

    ⇨ **From 2 to 1 % rms witness energy jitter @plasma exit**
  - Trailing-Driver bunches now better separated → beam overlapping led to **anomalous dynamics** in the plasma and the downstream transport line to the FEL (driver removal through chicane)
  - 400+50 pC → lower plasma density → less sensitive to temporal jitter





Longitudinal envelope and centroids behaviour through the photoinjector (old vs new layout)



New beam longitudinal profile

Implemented strategies to reduce the witness energy jitter shot to shot at the plasma exit (VB case)

Funded by the European Union

- The contribution to the energy jitter of the witness at the plasma exit, due to the plasma acceleration stage and the velocity bunching scheme, is approximately the same
- From the SPARC_LAB experience and **state of the art** have been considered jitter as in table

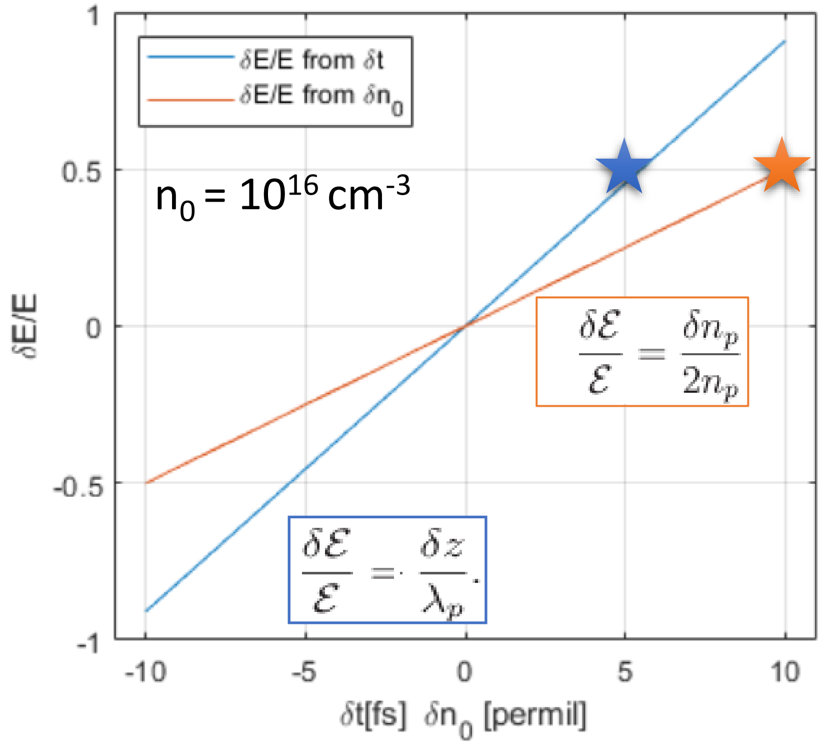
S-band Gun and Accelerating Sections (rms)		
RF Voltage [ΔV]	± 0.02	%
RF Phase [Δϕ]	± 0.02	*deg*
X-band Accelerating Sections (rms)		
RF Voltage [ΔV]	± 0.02	%
RF Phase [Δϕ]	± 0.10	*deg*
Cathode Laser System		
Charge [ΔQ] (max)	± 1	%
Laser time of arrival [Δ*t*](rms)	± 20	fs
Laser Spot size [Δσ]	± 1	%

Plasma density		
n_0	± 1	%

Jitter contribution introduced in S2E simulations

- *from simulations @plasma injection 5 fs W-D distance jitter*

- *adding plasma density jitter @plasma exit*
  δE = 1 % rms   <E> = 1 GeV

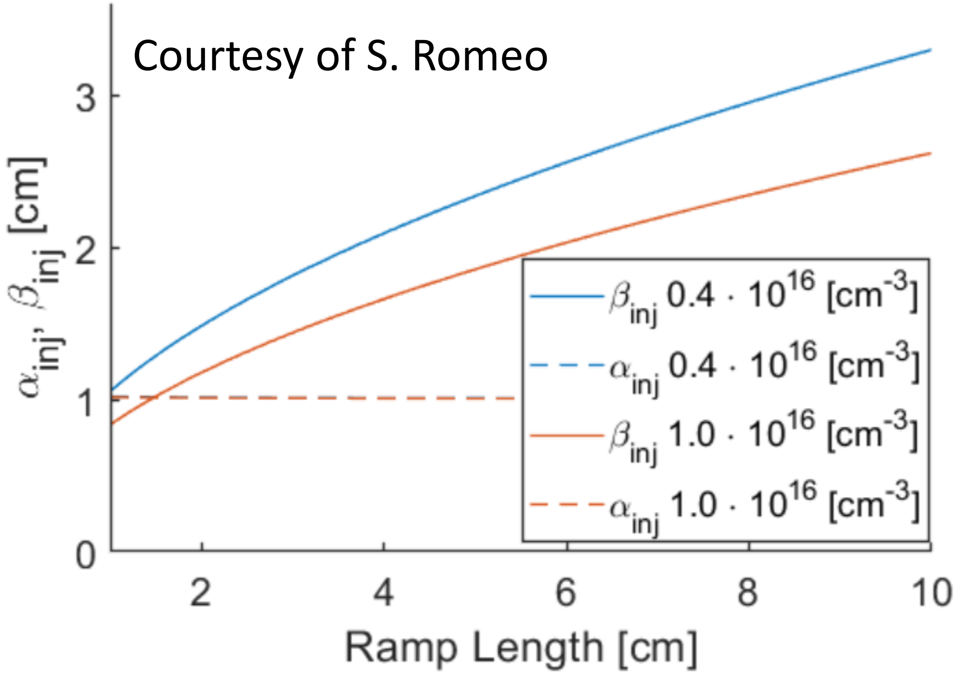


Analytical evaluation of plasma vs linac contribution to energy gain jitter @plasma exit

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

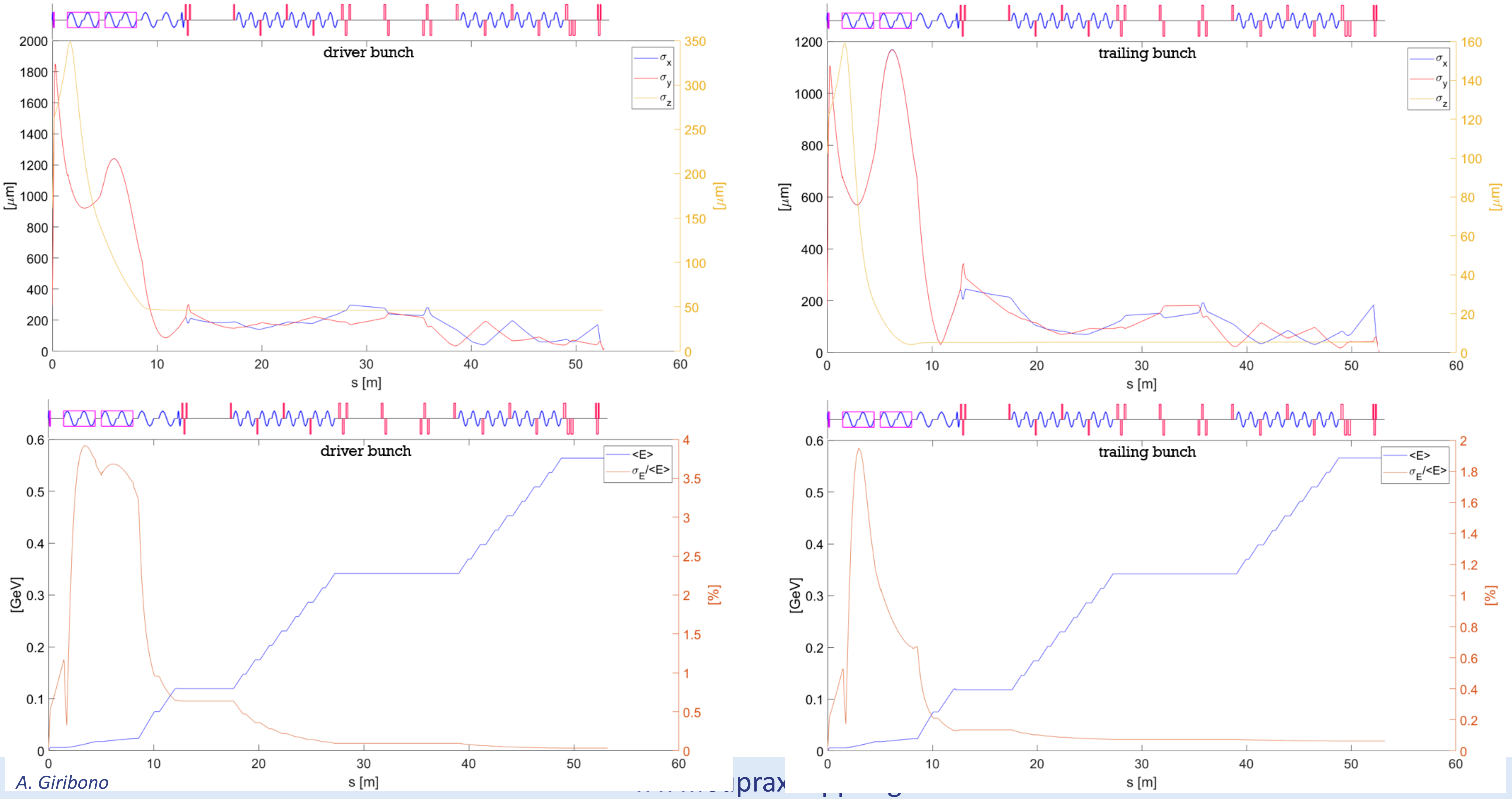
Details on the 200+30 pC

- The working point optimisation is now **complete**
  - Longitudinal phase space → better control on fine-tuning of bunch length and spacing in the photoinjector
  - Transverse phase space → emittance preservation through the insertion of plasma ramps (matching to the plasma in terms of Twiss parameters)
  - matching in the linac refined for more periodic and lower betas → better control of wakefields in case of misalignments



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

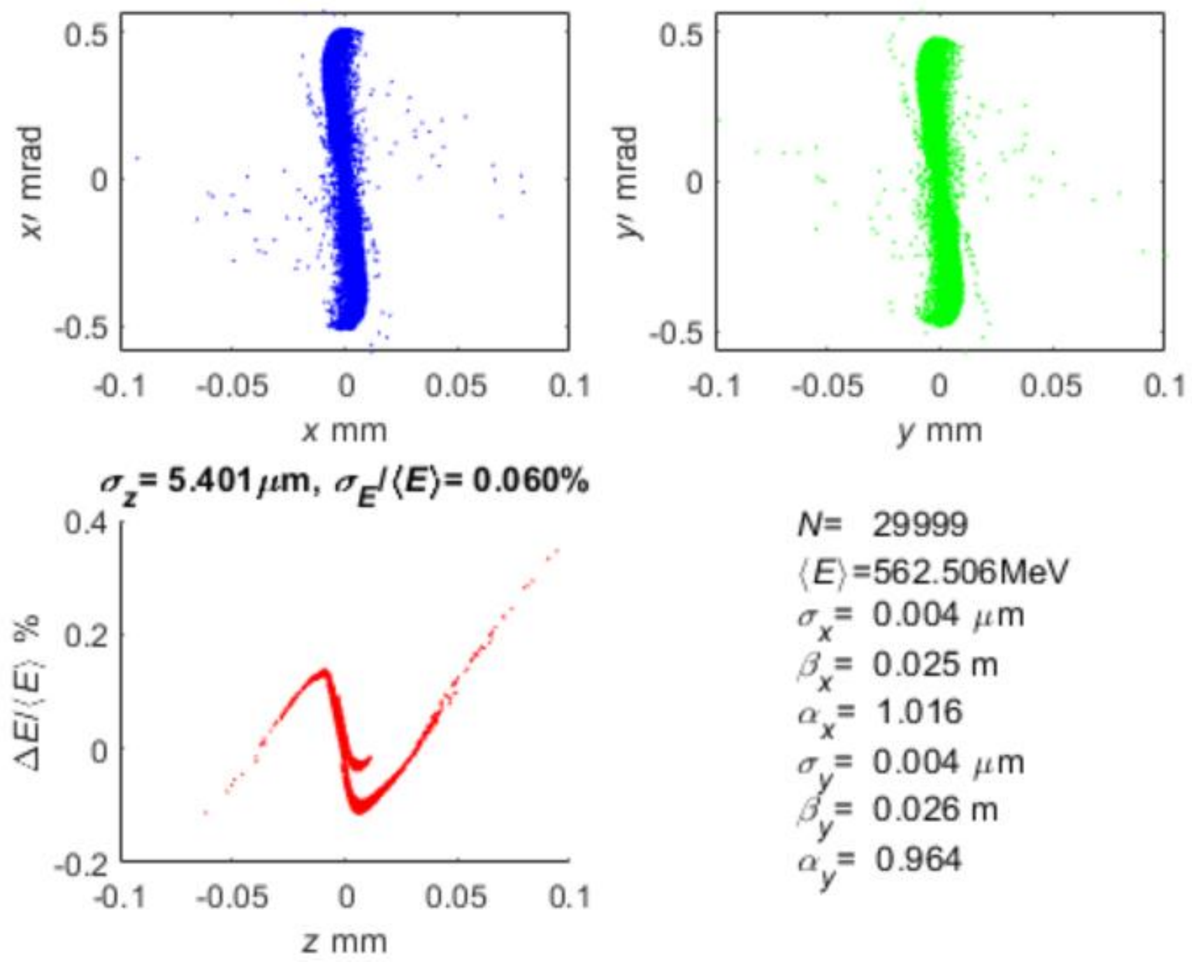
Beam Parameters through the linac



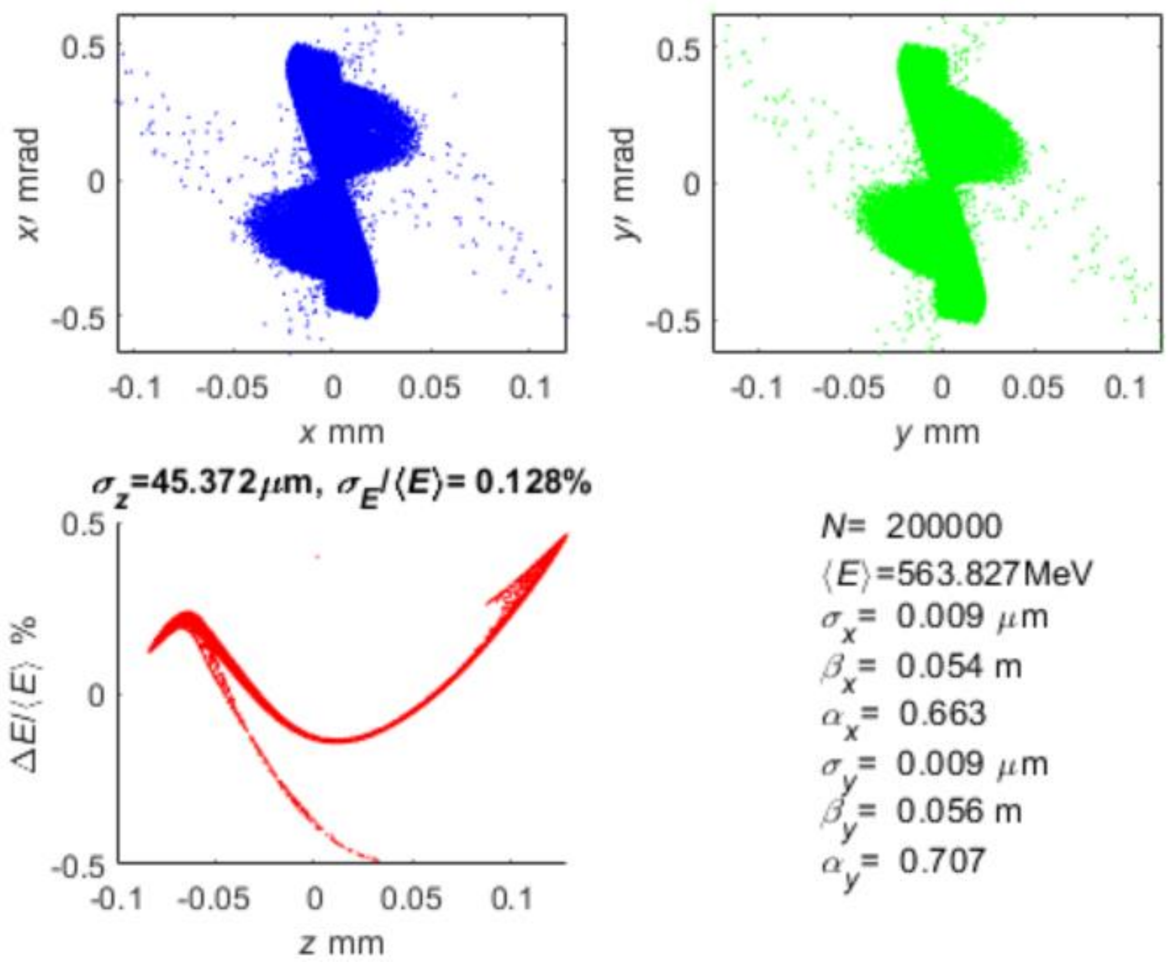
A. Giribono

Electron beam phase space at linac exit

Witness



Driver



Linac Setup for VB based WoP1

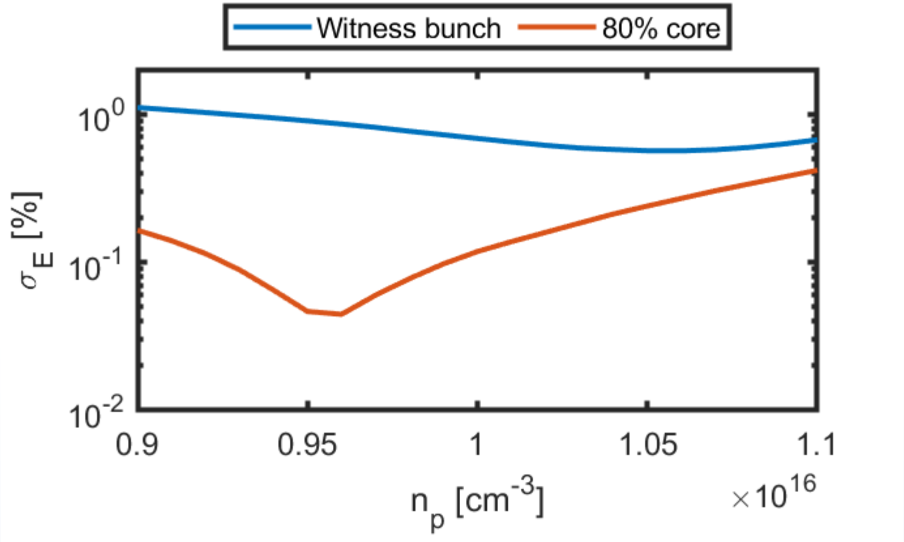
Cathode Laser System			
	Witness	Driver	
Charge [Q]	30	200	pC
Time delay [Δt]	- 4.8	0	ps
Laser Spot size [σ_r]	175	300	µm
Laser Pulse length [σ_t]	0.30	0.40	ps

RF Gun		
RF Peak Voltage [V]	120	MV
RF Phase [ϕ]	-30	*Deg*
S-band Accelerating Sections		
RF Voltage (on average) [V]	21,21,35,35	MV
RF Phase [ϕ]	-92,-84,-10,-10	*deg*
X-band Accelerating Sections		
RF Voltage (on average) [V]	25	MV
RF Phase [ϕ]	-10	*deg*

Magnets			
S-band Photoinjector - Peak Field			
Type	B_{max} (T)	Length (m)	Energy (MeV)
Gun Solenoid	0.3	2 coils (SABINA like)	-
Acc. Structures solenoids	0.035, 0.075	*4triplets,3 triplets (SABINA like),0,0*	-
X-band Linac			
Type	g_{max} (T/m)	Length (m)	Energy (MeV)
Type A	10	0.010	100 - 350
Type B	13	0.015	330 - 550
Type C	20	0.020	550
PMQ in	300	0.005,0.009,0.005	550

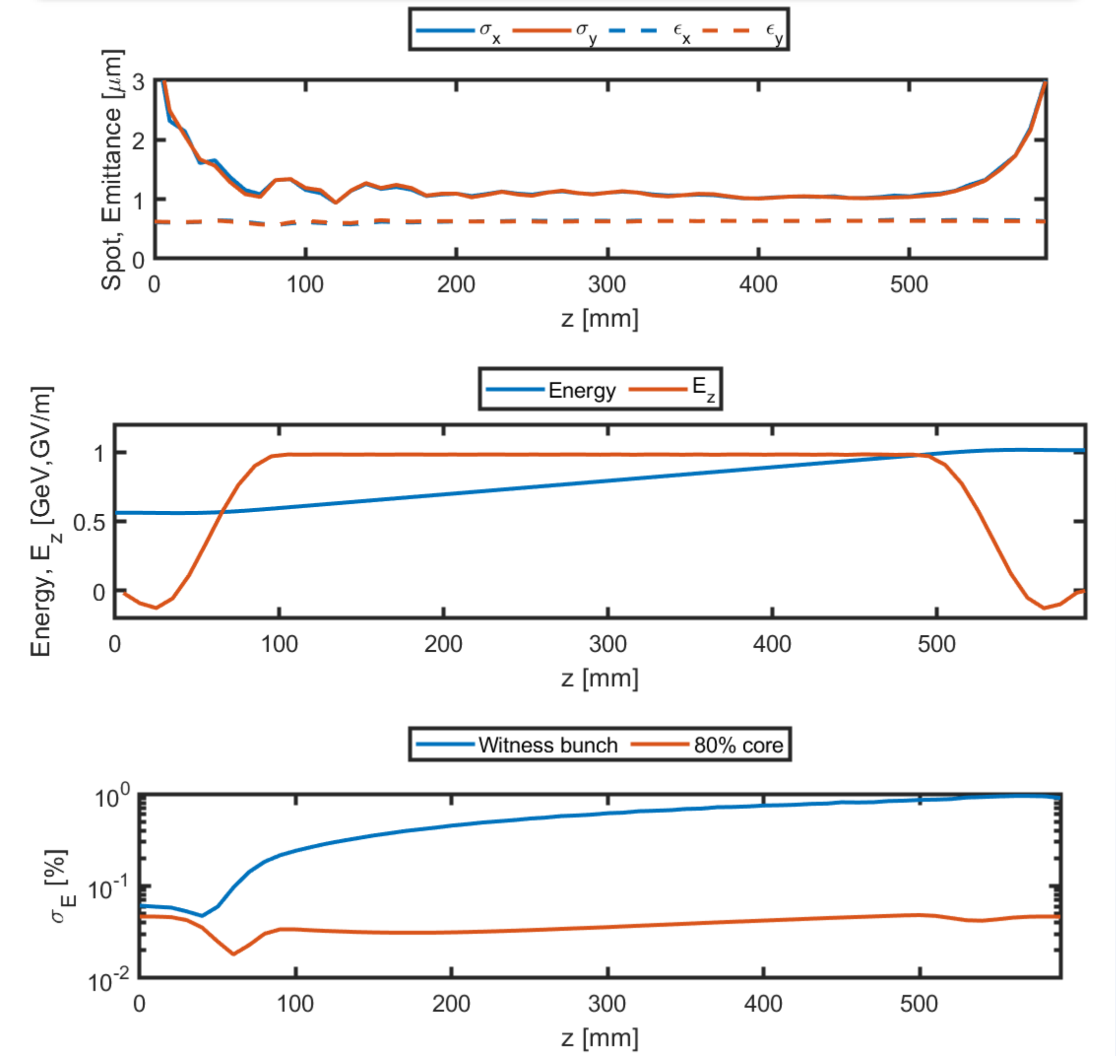
Nominal WP 200+30 pC: Macroparameters evolution

- 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



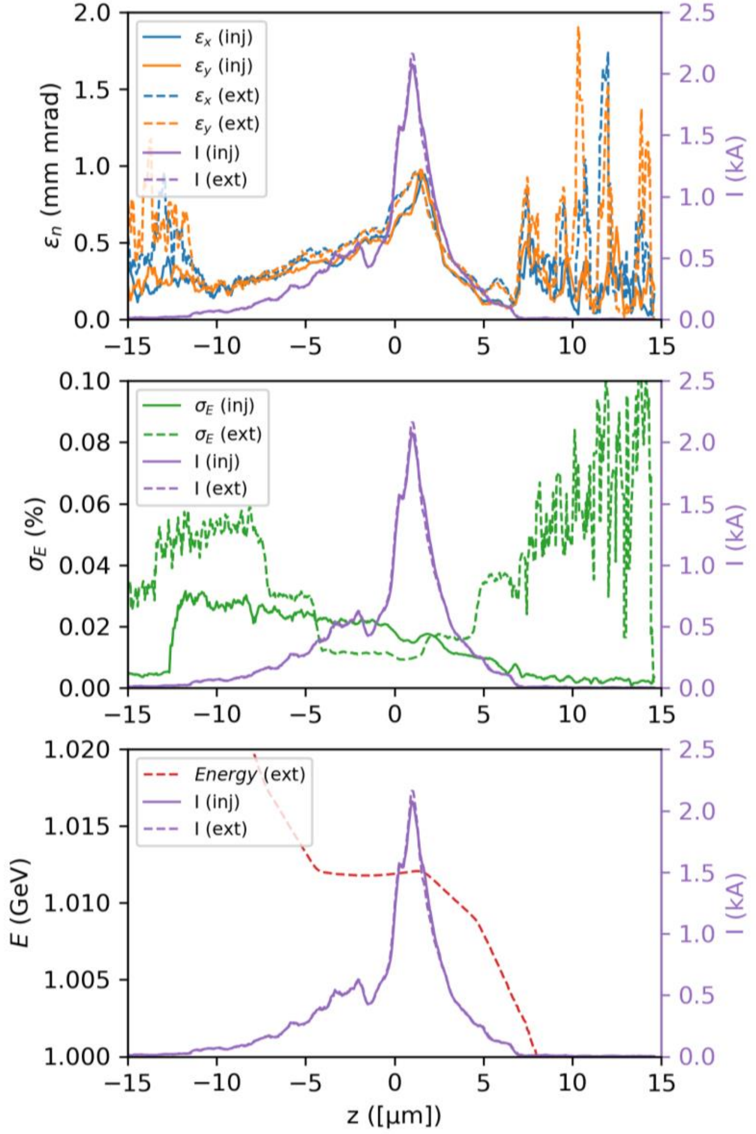
- **Reduction of core energy spread**
- **Energy spread minimum with $n_p = 10^{16}\mathrm{cm}^{-3}$**
- **Full preservation of emittance**
- **Final energy $1.01\ \mathrm{GeV}$**
- **Maximum accelerating gradient $0.98\ \mathrm{GV/m}$**
- **Average accelerating gradient $\approx 0.8\ \mathrm{GV/m}$**

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

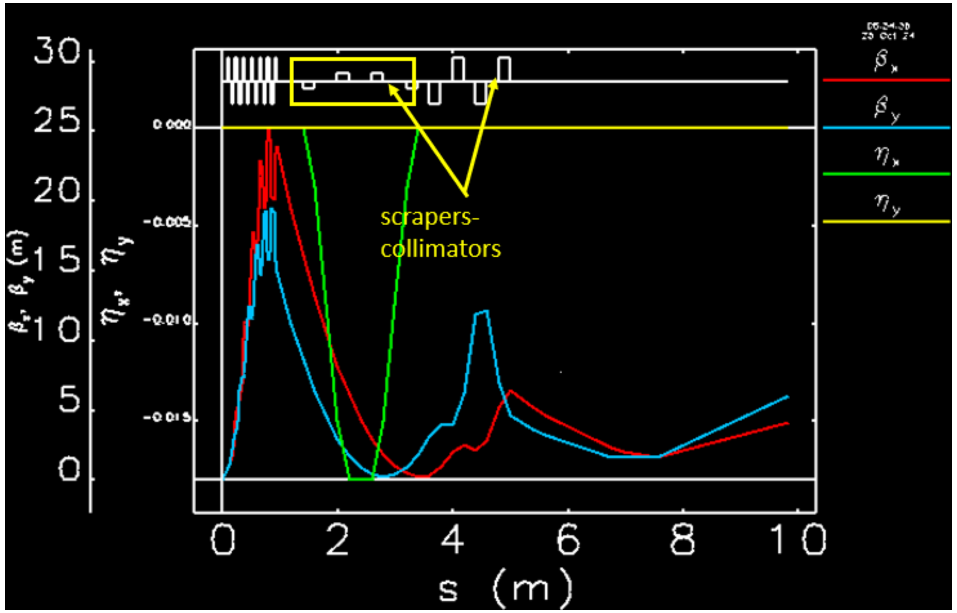


W-D Separation beamline: from plasma module to FEL

Funded by the European Union



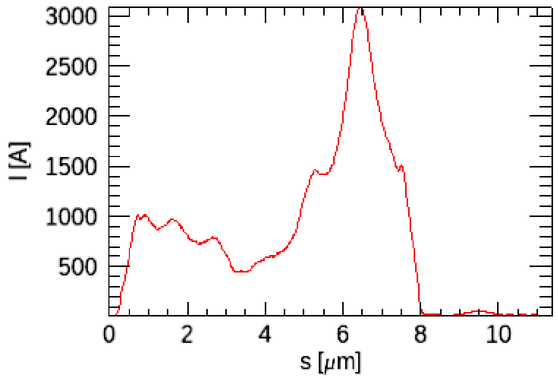
Witness slice analysis @plasma exit



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

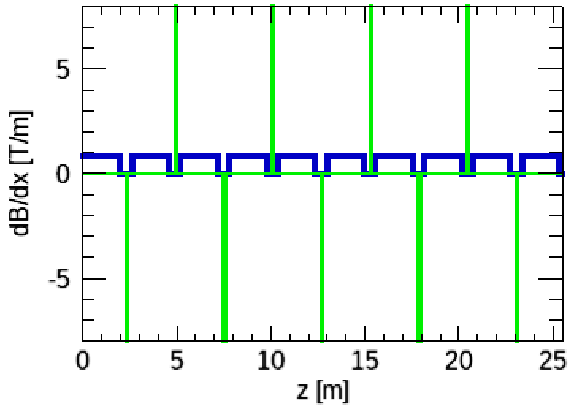
Witness slice analysis (upper) and rms parameters (lower) @FEL entrance

FEL matching and performances

Funded by the European Union

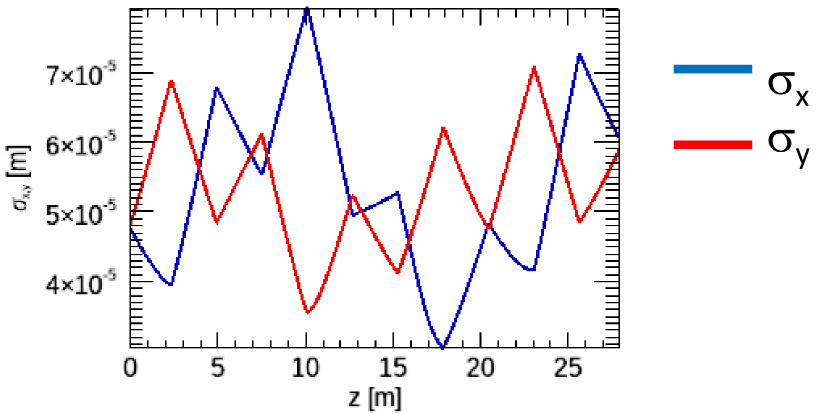
Matching

Undulator structure

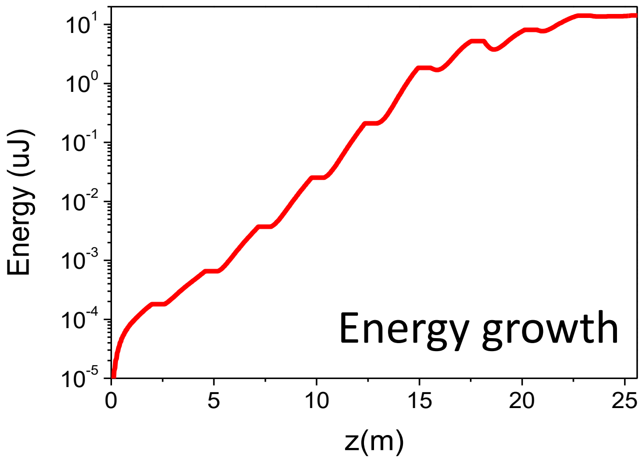


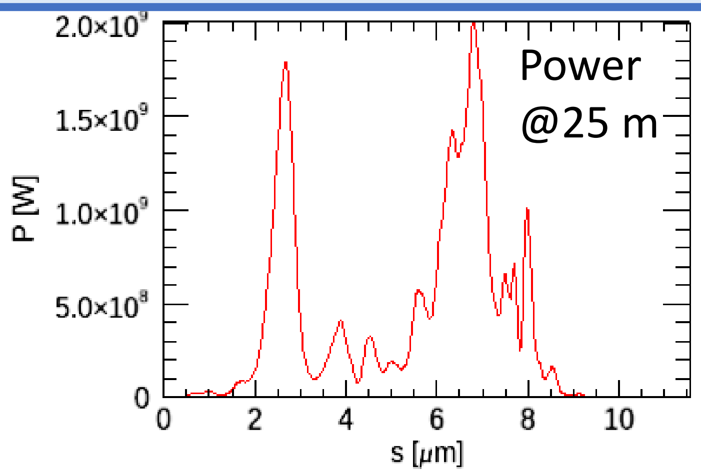
λ_w=1.8 cm
a_w=0.84
dB/dz=8 T/m

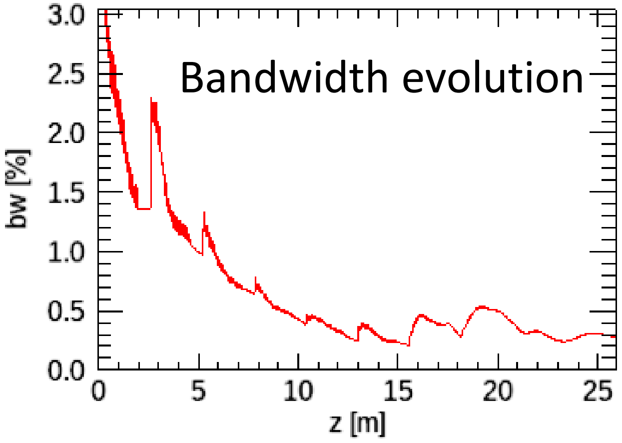
Average matching

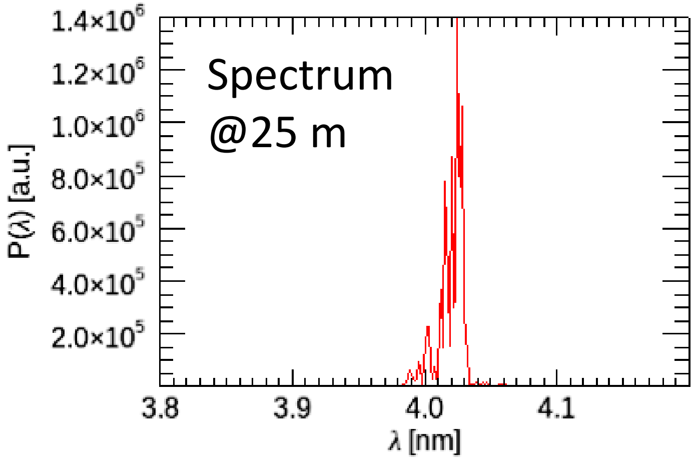


Performances









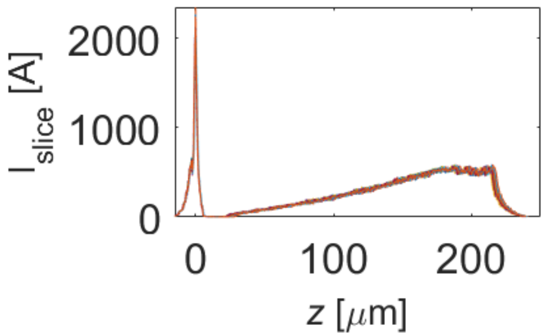
Energy (μJ)	λ (nm)	BW (‰)	Photon number	Size (μm)	Div (μrad)	L_sat (m)	L_rad (μm) FWHM
13.54	4.004	3	2.71 10^{11}	170	27	23	4.5

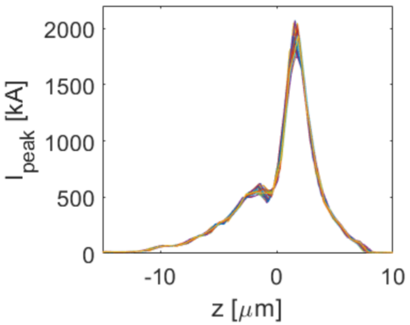
Sensitivity studies: from cathode to plasma exit

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

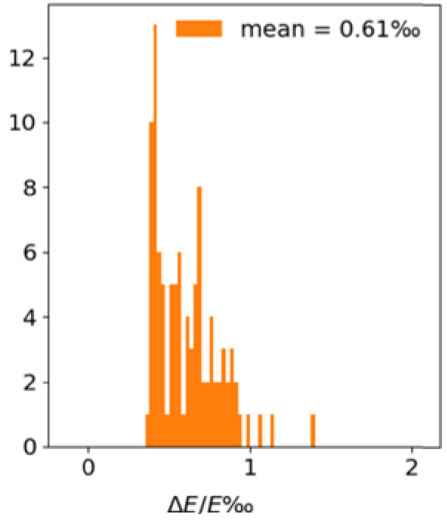


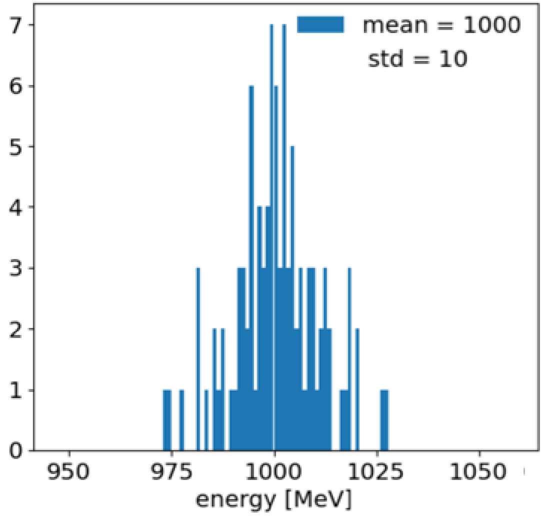


Comb beam current and witness slice analysis

@plasma exit

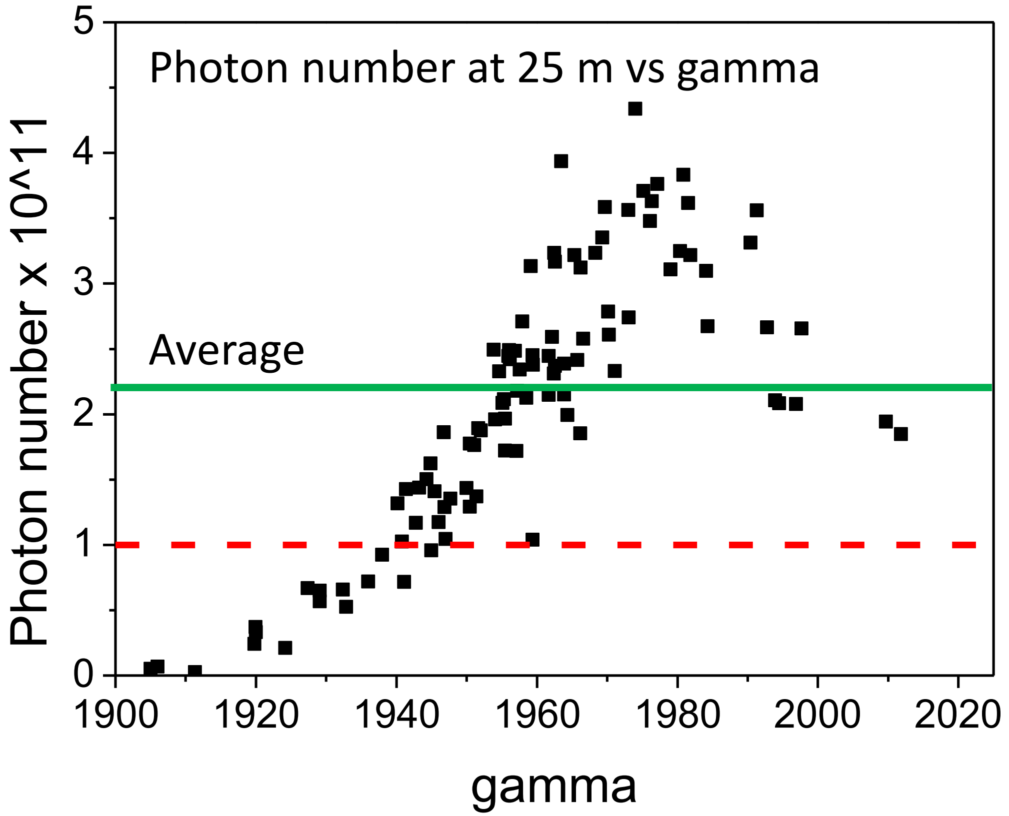
- 200 + 30 pC nominal working point affected by LINAC and plasma jitters
- plasma density is assumed to jitter 1% (one sigma) around the “nominal” longitudinal value



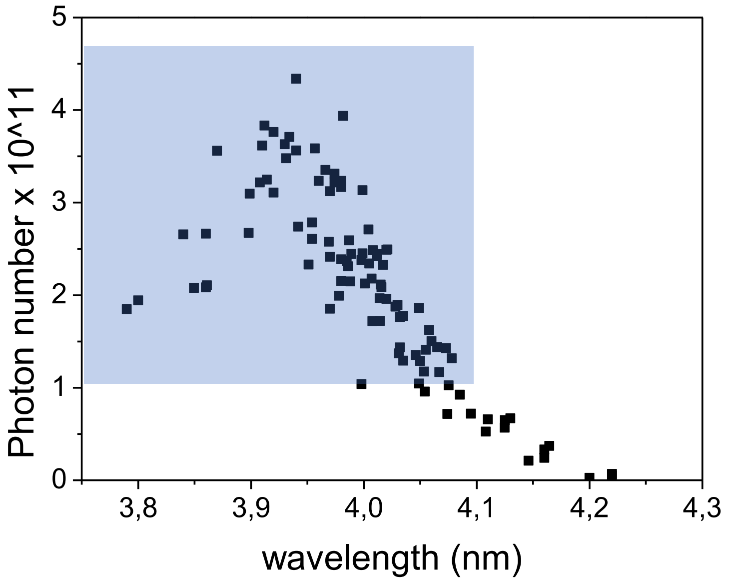


Courtesy of A. Del Dotto

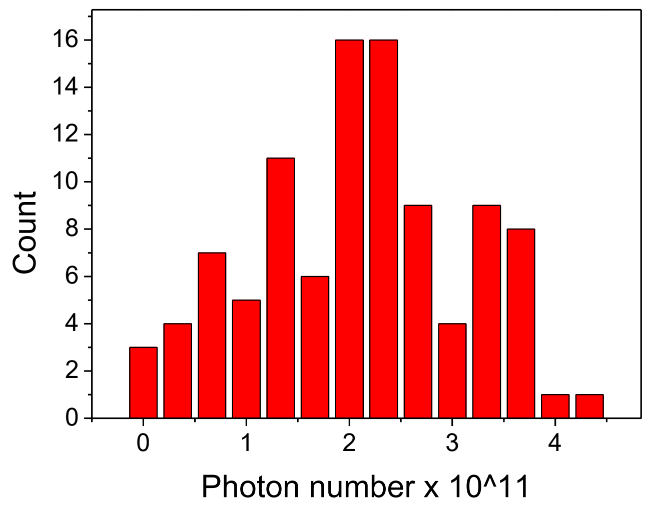
Sensitivity studies: FEL emission (statistics over 101 shots)



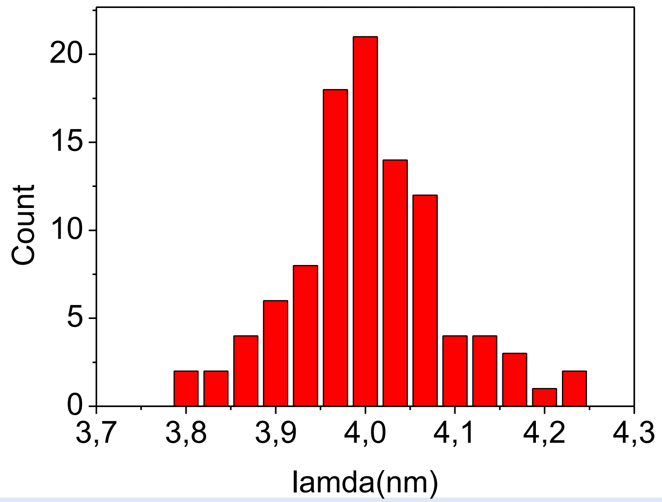
85/101 shots with
- Photon Number **> 10^{11}**
- Wavelength ∈ [3.8 : 4.05] nm



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**

Schedule: proposed timeline

Funded by the European Union

February 2025: completion of the simulation studies on the mentioned items

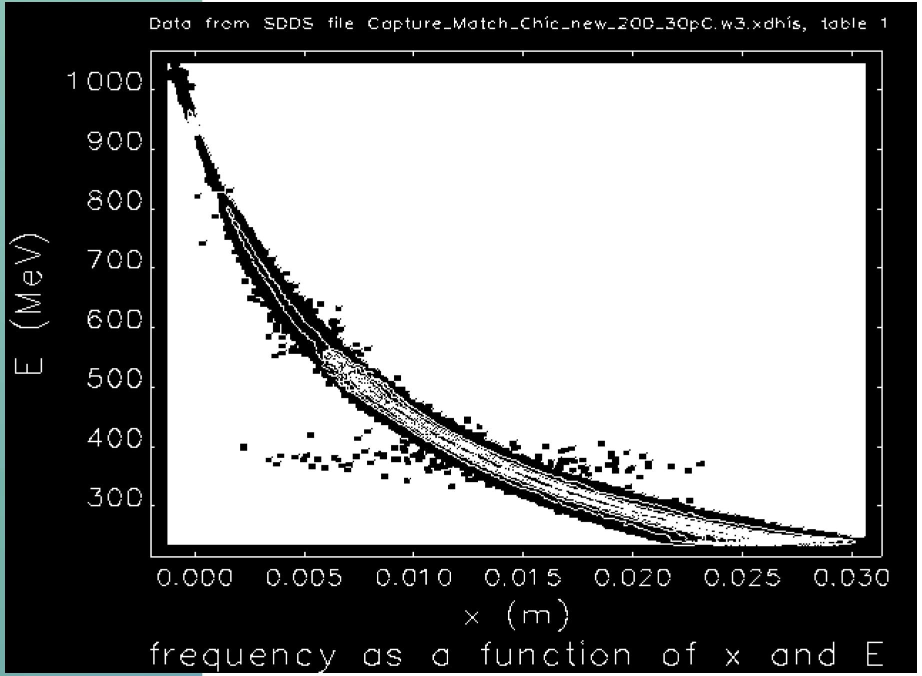
March 2025: results discussion and writing

End of March 2025: Beam Physics Chapter completion

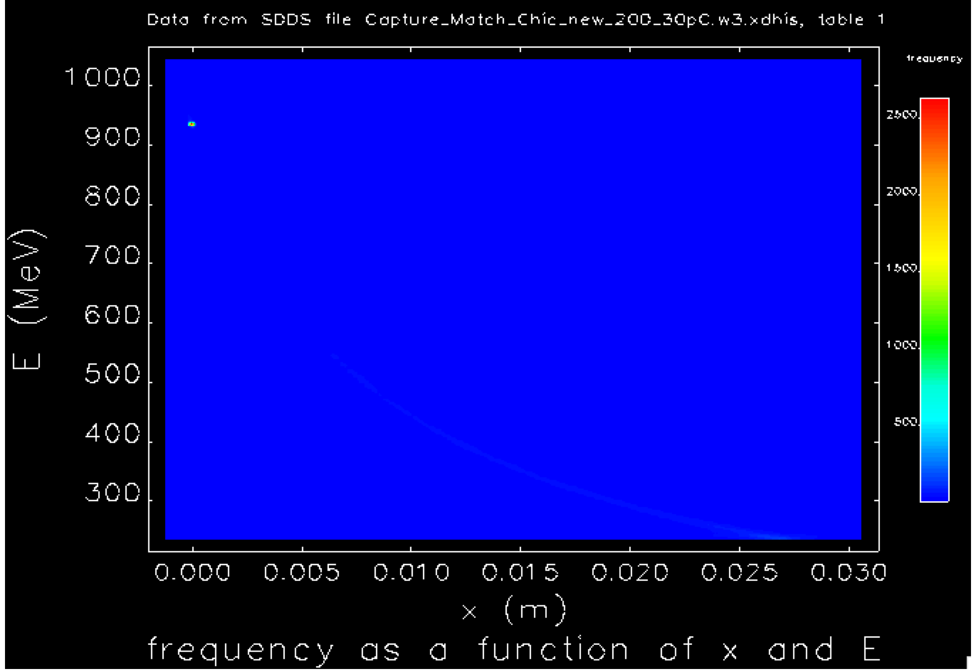
Conclusions

- Start to end simulations for reference working point (200+30 pC) are **complete** together with sensitivity studies
- Numerical studies demonstrate FEL emission of 2.7×10^{11} at 4 nm wavelength. In case of jitter, 85 % of the shots emit at least 10^{11} photons with wavelength error < 0.1 nm.
- The machine layout definition is now **complete** with the inclusion of the W-D separation beamline (chicane) and related diagnostics. However, some refinements to the overall machine layout will follow due to modifications in the diagnostic system from August 2024, along with subsequent changes to magnetic and diagnostic elements.
- A new working point is under study that promises to be less sensitive to linac and plasma jitter and less demanding in terms of transverse matching to the plasma
- Static errors and mitigation methods are under investigation in case of 500 pC bunches
- I would like to emphasize the thanks to : A. Del Dotto, M. Opromolla, V. Petrillo, S. Romeo, A. R. Rossi and C. Vaccarezza for the provided effort since the last R.C. to obtain the shown results.

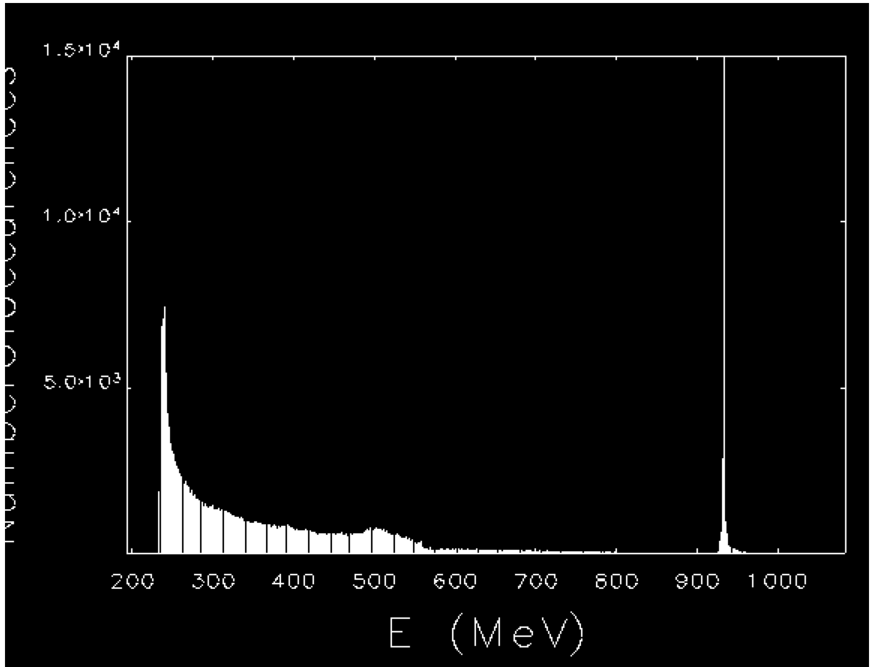
COMB BEAM ENERGY DISTRIBUTION BEFORE CUT



E (MeV) vs x (m) – contour plot



E (MeV) vs x (m) – contour plot with shade



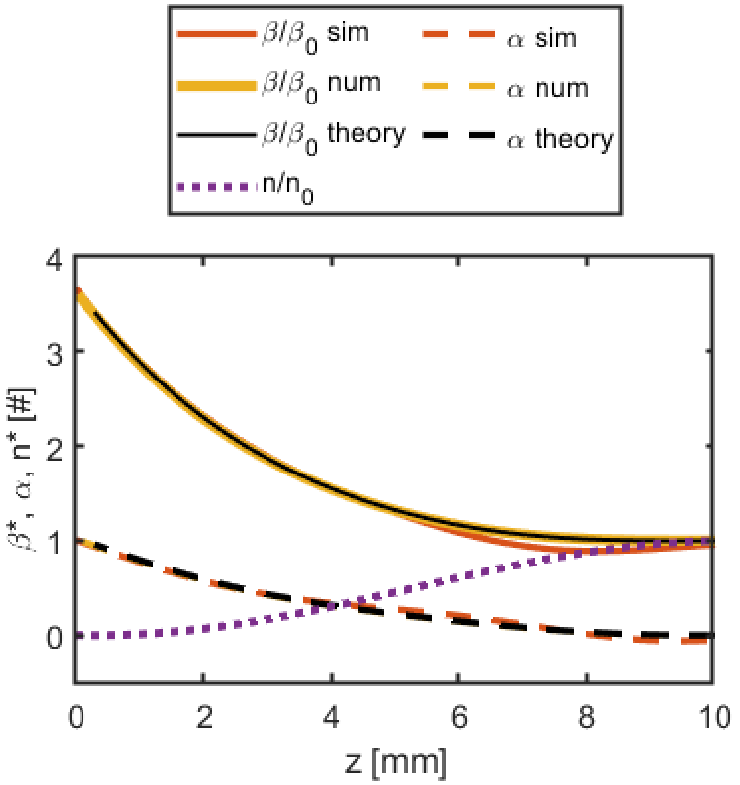
E (MeV) histogram

Courtesy of C. Vaccarezza

Squared cosine ramp: **Transfer matrix**

Ramp shape

$$k_{ext}^2(z) = \frac{1}{\beta_0^2}\cos^2\left(\frac{\pi z}{2L}\right)$$



Extraction

$$\begin{bmatrix}\beta_1/\beta_0\\ \alpha_1\\ \gamma_1\beta_0\end{bmatrix} = \begin{bmatrix} c^2 & -2cs & s^2\\ -cc' & cs'+c's & -ss'\\ c'^2 & -2c's' & s'^2\end{bmatrix}\begin{bmatrix}\beta_2/\beta_0\\ \alpha_2\\ \gamma_2\beta_0\end{bmatrix}$$

Normalized transfer matrices

Injection

$$\begin{bmatrix}\beta_2/\beta_0\\ \alpha_2\\ \gamma_2\beta_0\end{bmatrix} = \begin{bmatrix} s'^2 & -2ss' & s^2\\ -c's' & cs'+c's & -cs\\ c'^2 & -2cc' & c^2\end{bmatrix}\begin{bmatrix}\beta_1/\beta_0\\ \alpha_1\\ \gamma_1\beta_0\end{bmatrix}$$

$$c \approx \sqrt{3}\, R^{\frac{1}{4}}\cos\left(2R+\frac{\pi}{8}\right)$$

$$s \approx \sqrt{3}\, R^{\frac{1}{4}}\sin\left(2R+\frac{\pi}{8}\right)$$

$$c' \approx -\sqrt{\frac{2}{3}}\, R^{-\frac{1}{4}}\sin\left(2R-\frac{\pi}{8}\right)$$

$$s' \approx \sqrt{\frac{2}{3}}\, R^{-\frac{1}{4}}\cos\left(2R-\frac{\pi}{8}\right)$$

$$\beta_0 = \frac{\sqrt{2\gamma}}{k_p}$$

$$R = \frac{L}{\pi\beta_0}$$

$$\beta_{inj} = 3\sqrt{R}\beta_0$$

$$\alpha_{inj} = 1$$

This model was exploited to design from scratch a new nominal working point