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EuPRAXIA Preparatory Phase

High repetition rate C-band photoinjector

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EuPRAXIA_PP Annual Meeting 2024

On behalf of the EuPRAXIA@SPARC_LAB collaboration

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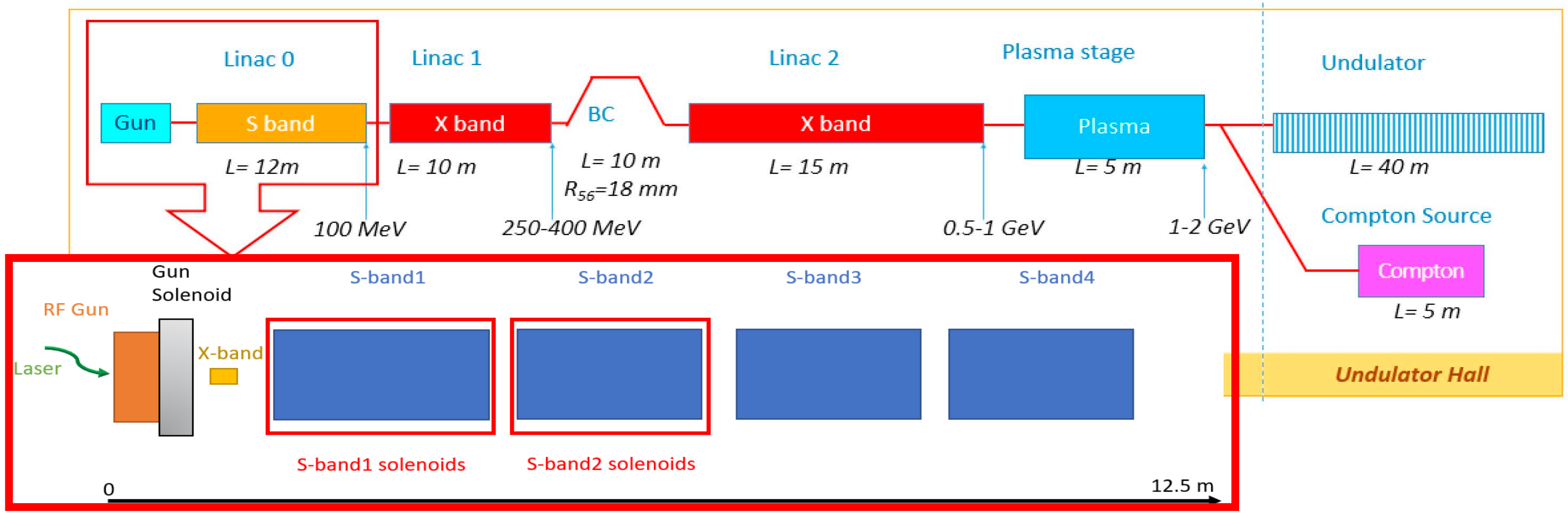
OUTLINE

- EuPRAXIA@SPARC_LAB injector base-line
- Motivation for the upgrade to a full C-band Injector
- Preliminary layout and beam dynamics studies
- C-band injector proposal for future upgrade
- Improvement in beam dynamics
- Conclusions and future prospectives

EuPRAXIA@SPARC_LAB base-line RF injector



Injector exit parameters	Witness	Driver
Spot Size	0.118 mm	0.127 mm
Bunch Length	5 μm	62 μm
Emittance	0.55 μm	1.5 μm
Energy	124 MeV	126 MeV
Energy spread	0.18 %	0.55 %
Bunch separation	0.5 ps	- -
Peak current	1.8 kA	- -

- 1,6 cells S-band RF Gun equipped with a solenoid
- 4 TW S-band accelerating structures, the first one 3 m long while the other 2 m
- 2 emittance compensation solenoids around the VB sections
- Overall length of ≈ 13 m

[1] A. Giribono et al. EuPRAXIA@SPARC_LAB, The high brightness RF photo injector layout proposal, NIMA (2018)

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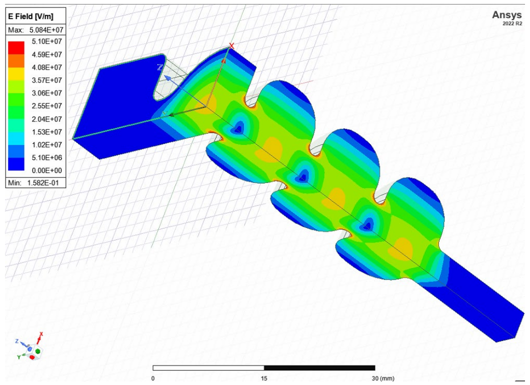
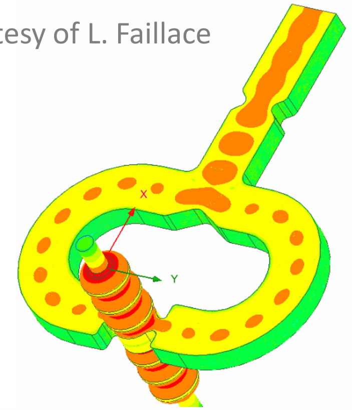
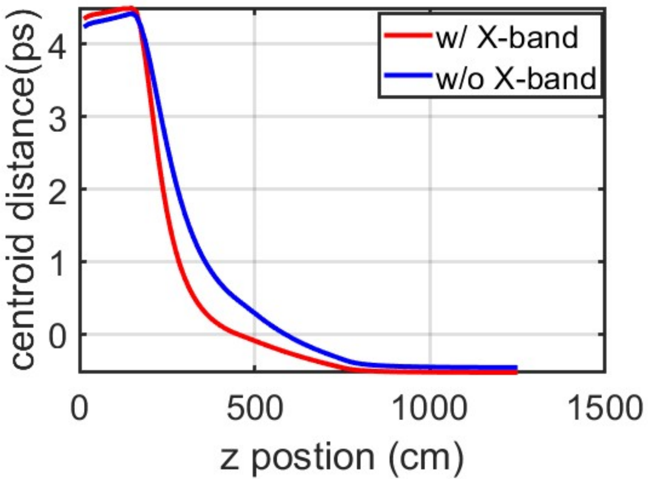
Working point optimization

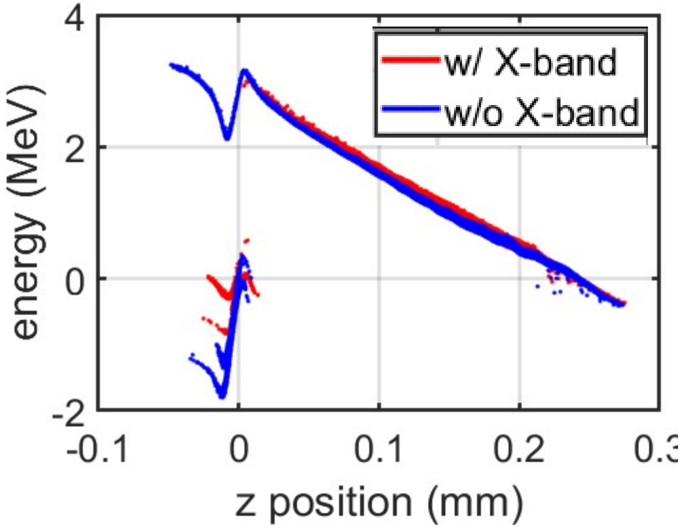
X-band	
Resonant frequency	11.9942 GHz
E acc	20 MV/m
E peak	38 MV/m
Number of cells	7
Length	11 cm

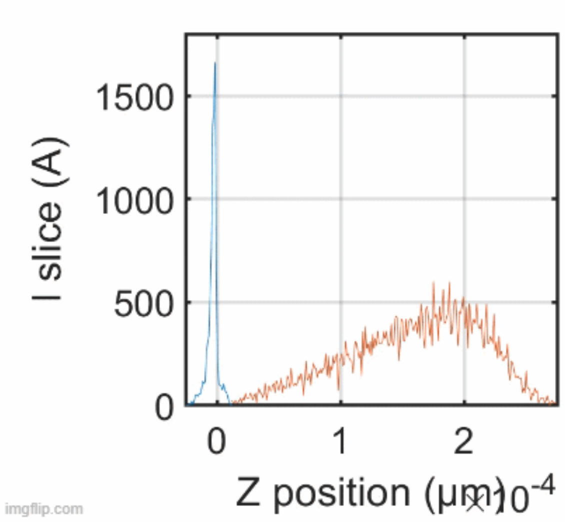


Courtesy of L. Faillace









[2] *Bacci A, Faillace L and Rossetti Conti M 2018 Extreme high brightness electron beam generation in a space charge regime.*
[3] *Alesini D et al., 2015 Study of a C-band harmonic RF system to optimize the RF bunch compression process of the SPARC beam 6th International Particle Accelerator Conference TUPWA058*
[4] *Emma P., 2001 X-Band RF harmonic compensation for linear bunch compression in the LCLS SLAC Nation Accelerator Laboratory Technical Note SLAC-TN-05-004, LCLS-TN-01-1*
[5] G.J Silvi et al., Optimizing beam dynamics in the EuPRAXIA@SPARC_LAB RF injector, *SIF CONGRESS 2023,* 10.1393/ncc/i2024-24323-5

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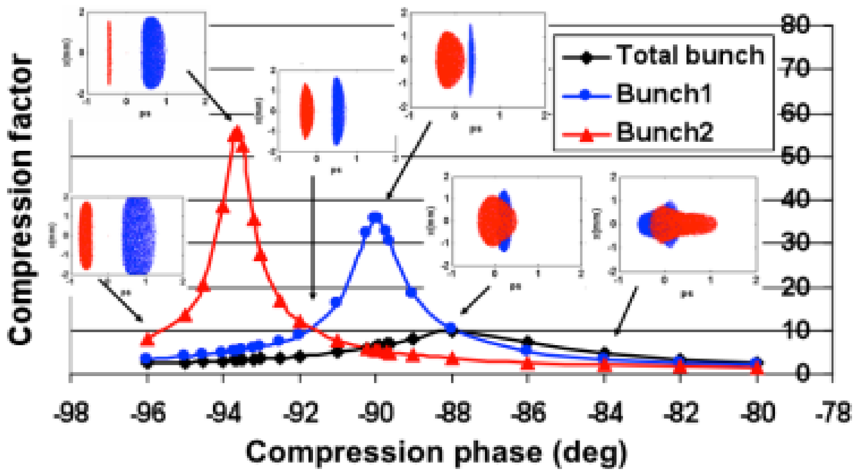
Stability studies

For a working point with the characteristics of the EuPRAXIA setup, the temporal jitter between the driver and witness beams of approximately δt ≈ few fs for an energy jitter of 0.1%.



[13] A Mostacci et al. Proceedings of IPAC2011, San Sebastián, Spain

Charge	Spot Size	RF phases (S/X)	Acc field amplitude
2 %	1 %	0,02/0,08 deg	0.02% rms

Jitters	ϵ(mm-mrad)	Bunch separation(ps)	Bunch Length (ps)
phase X & gradients S&X, charge	0.6611 ± 0.0190	0.5467 ± 0.0018	$0.0136 \pm 9.65 \times 10^{-5}$
phase X & gradients S&X	0.6619 ± 0.0132	0.5462 ± 0.0022	$0.0136 \pm 1.12 \times 10^{-4}$
All (no time of arrival)	0.6683 ± 0.0222	0.5460 ± 0.0037	$0.0138 \pm 3.8 \times 10^{-4}$
phases & gradients S&X	0.6693 ± 0.0165	0.5448 ± 0.0030	$0.0137 \pm 1.42 \times 10^{-4}$
phase X, gradients S&X ,charge spot	0.6698 ± 0.022	0.5463 ± 0.0025	$0.0138 \pm 4.29 \times 10^{-4}$
All	0.6602 ± 0.0194	0.5469 ± 0.0039	$0.0136 \pm 3.5 \times 10^{-4}$
phase & gradient X	0.6576 ± 0.0042	0.5464 ± 0.0012	$0.0136 \pm 1.83 \times 10^{-5}$
phase & gradient S, spot, charge	0.6611 ± 0.0212	0.5458 ± 0.0029	$0.0136 \pm 3.5 \times 10^{-4}$

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Motivation for a C-band RF injector

The C-band technology allows for:

- ✓ **Higher efficiency** suitable for **applications requiring repetition rates in the 100 Hz ÷ 400 Hz range**.
- ✓ **Reduce injector footprint by maintaining high-quality high-brightness beams.**
- ✓ **Easier transition to the X-band booster.**
- ✓ **Peak field Higher than S-band.**
  - **Gun 160-180 MV/m**
  - **TW structures 60 MV/m (35 MV/m S-band) [6]**

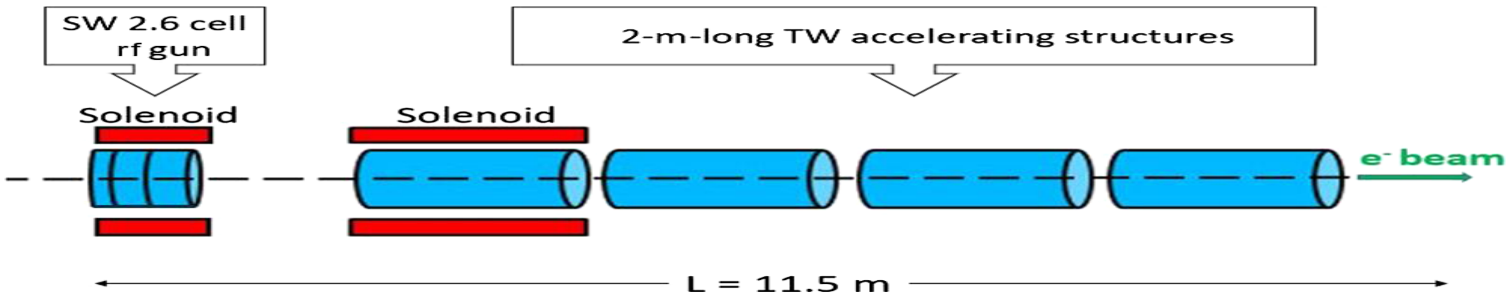
[6] W. Fang et al., “Design, fabrication and first beam tests ofthe c-band rf acceleration unit at sinap,” Nuclear Instru-ments and Methods in Physics Research Section A: Acceler-ators, Spectrometers, Detectors and Associated Equipment,vol. 823, pp. 91–97, 2016, issn: 0168-9002. doi: https ://doi.org/10.1016/j.nima.2016.03.101. https://www.sciencedirect.com/science/article/pii/S0168900216301474
[7] D.Alesini,A.Bacci,M.Bellaveglia.,BeamenergyupgradeofthefrascatiFEL LINACwithaC-bandRFsystem,in:ProceedingsoftheIPAC10,Kyoto,Japan, 2010,pp.3682–3684.

Preliminary layout and beam dynamics studies

Funded by the European Union

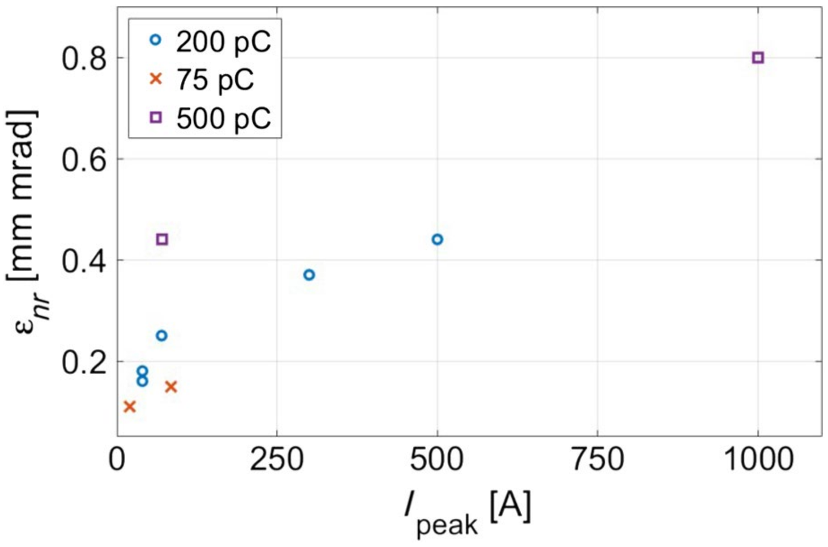
The beam dynamics has been studied to generate a single bunch with a variable length in the range 55–280 μm and different charges.

Compact

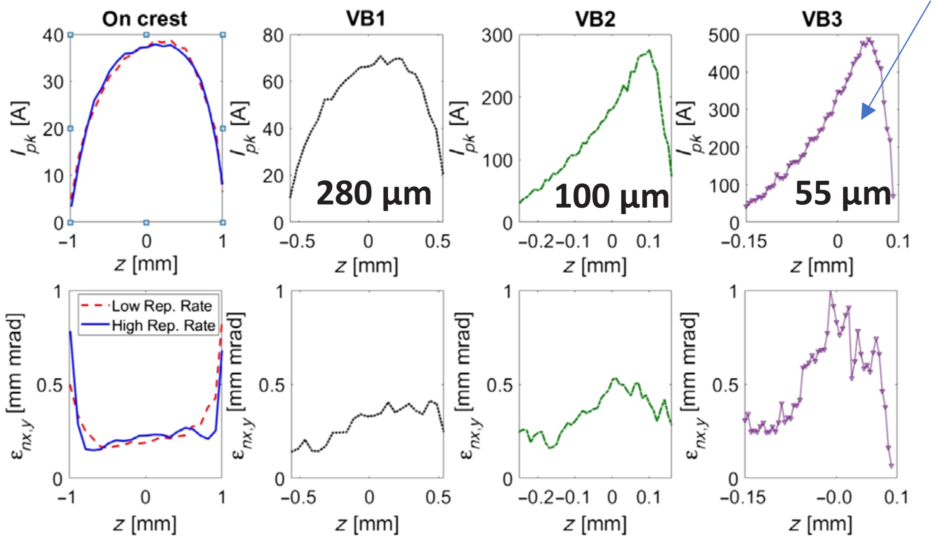


iFAST

[8] Giribono et al. - Dynamics studies of high brightness electron beams in a normal conducting, high repetition rate C-band injector, PHYSICAL REVIEW ACCELERATORS AND BEAMS 26, 083402 (2023)
[9] G. D'Auria et al, Compact-Light Design Study, doi:10.18429/JACoWIPAC2019-TUPRB032



driver for PWFA



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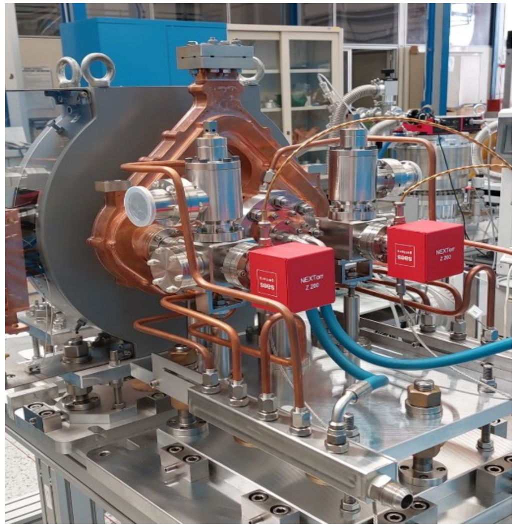
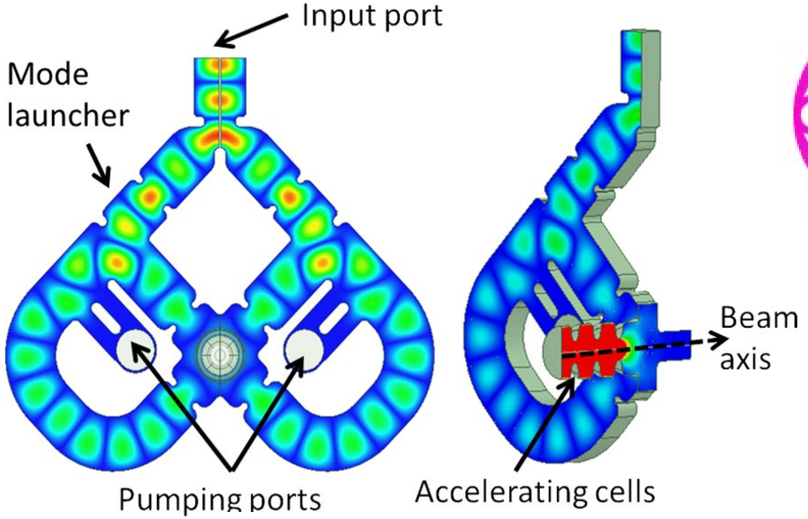
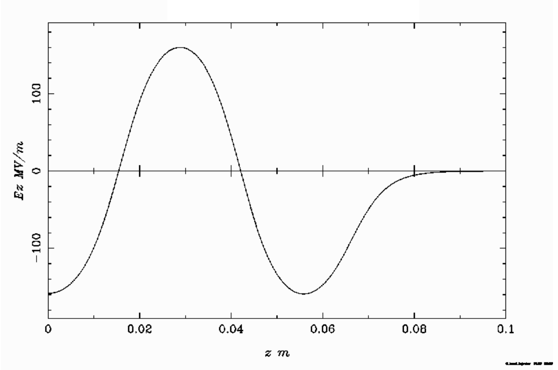
The C-band Gun layout

The Gun peak field is set to 160 MV/m, the limitation over the higher peak field for the high rep rate operation has been overcome by elongating the gun up 2,6 [10] cells so the beam energy after the Gun is 5,7 MeV

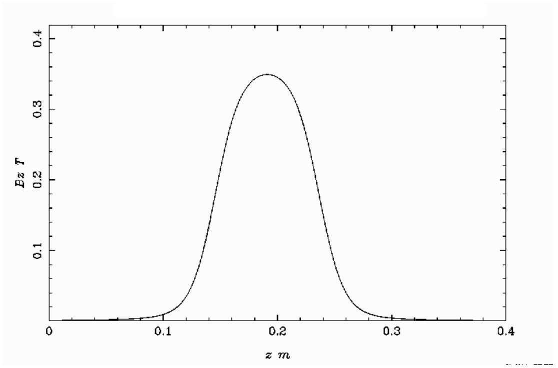




Gun Field



Solenoid Field



[10] M. Croia, D. Alesini, F. Cardelli, M. Diomede, M. Ferrario, A. Giribono, S. Romeo, C. Vaccarezza, and A. Vannozzi, High gradient ultra-high brightness C-band photoinjector optimization, J. Phys. Conf. Ser. 1596, 012031 (2020)

C-band Gun specs

- **2.6 cells Standing wave** RF Gun
- **Coupling coefficient** $\beta = 3$
  - Short RF Pulses
  - Reducing BDR, pulsed heating,
  - Reducing power dissipation
- **Elliptical iris profile** with large aperture
  - Reduce surface peak field
  - Increase frequency separation,
  - Increase pumping efficiency
- **4 port mode launcher** on-axis coupling [*]
  - Low pulsed heating
  - compensation of the dipole and quadrupole field components
  - Integrate 2 pumping units

Parameter	Unit	Value
Frequency	GHz	5.712
Number of cells		2.6
$E_{cath}/\sqrt{P_{diss}}$	$MV/(m\cdot MW^{0.5})$	51.4
Peak input power	MW	18
Cathode field	MV/m	160 (180)
Cathode type		OFHC copper
Rep. rate	Hz	100 (400)
Quality factor		11900
Filling time	ns	166
Coupling coefficient		3
RF pulse length	ns	300
Mode sep. π-π/2	MHz	47
E_{surf}/E_{cath}		0.96
Mod. Poy. Vect.	$W/\mu m^2$	2.5
Pulsed heating	°C	<16
Av.diss. Power	W	250 (1000)

Courtesy of F. Cardelli

* [11] Design based on G Castorina et al 2018 J. Phys.: Conf. Ser. 1067 082025
[12] D. Alesini et al., Design, realization and high-power RF test of the new brazed free C band photo-gun, Proc. IPAC'24, 2024
[13] F. Cardelli et al., Design and realization of high-gradient C-band standing wave RF gun, *SIF CONGRESS 2023*, 10.1393/ncc/i2024-24272-y

C-band TW structures, the INFN-LNF expertise

Funded by the European Union

ELI-NP dumped cells for multi-bunch operation (100 Hz)

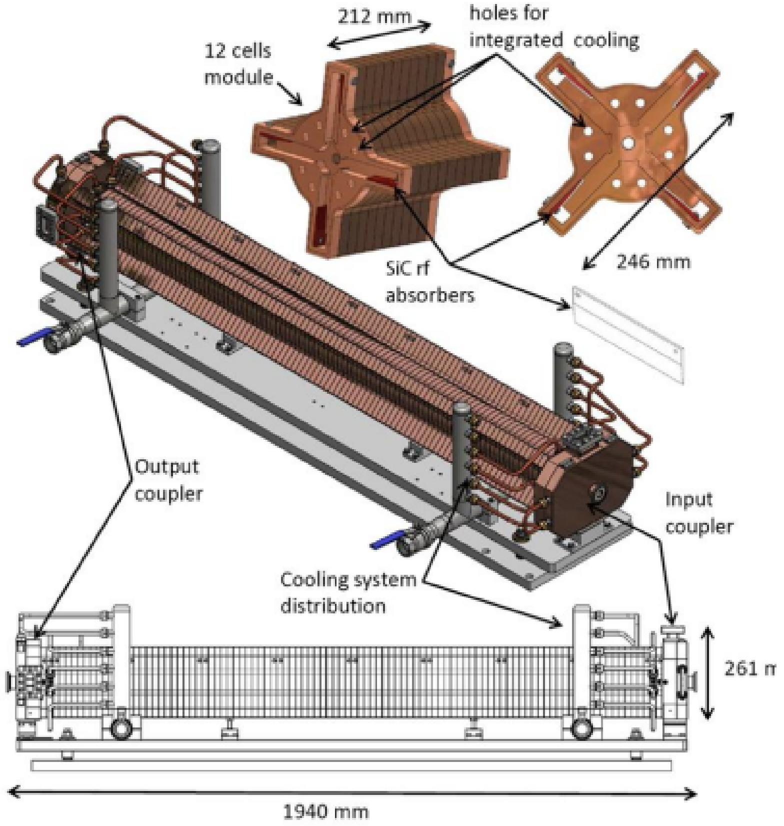


TABLE I. Main parameters of the ELI-NP accelerating structures.

Parameter	Value
Working frequency (f_{rf})	5.712 GHz
Cell phase advance	$2\pi/3$
Number of cells	102
Structure length	1.8 m
Iris aperture radius	6.8–5.78 mm
Repetition rate	100 Hz
Average quality factor	8850
Average accelerating field	33 MV/m
Shunt impedance	67–74 MΩ/m
Group velocity (v_g/c)	0.025–0.015
Filling time	313 ns
rf input power (P_{in})	40 MW
Output power (P_{out})	$0.29P_{in}$
Pulse duration for beam (τ_{beam})	<512 ns
Pulsed heating (input coupler)	<21 °C
Average wall-loss power	2.3 kW
Working temperature	30 °C

[14] D. Alesini et al,0.1103/PhysRevAccelBeams.23.042001

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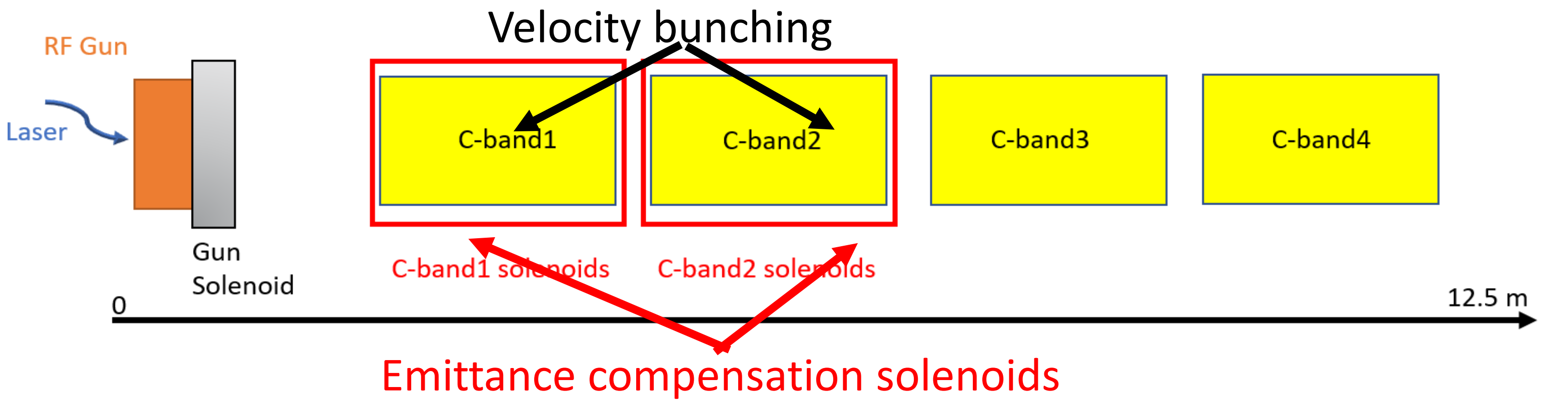
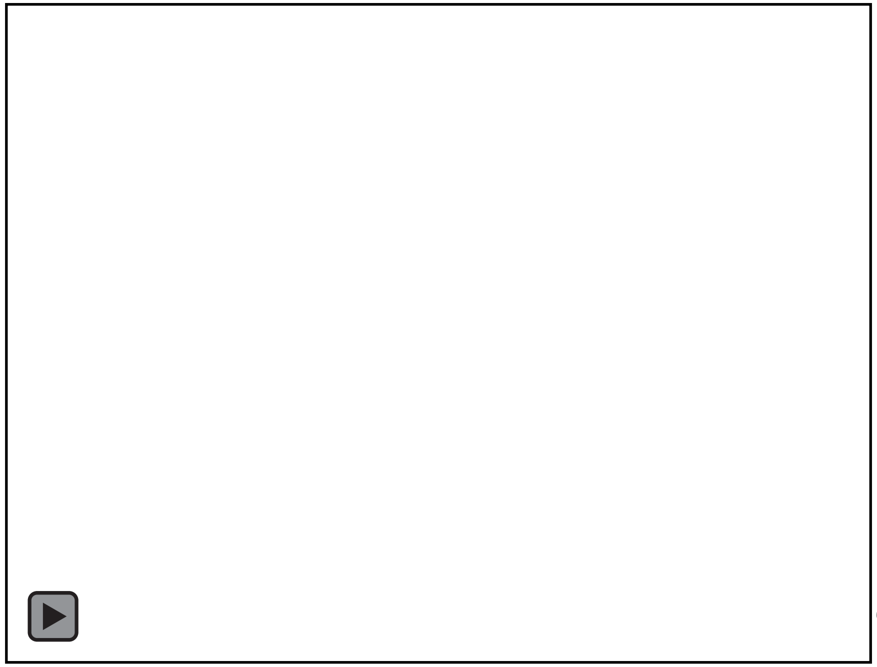
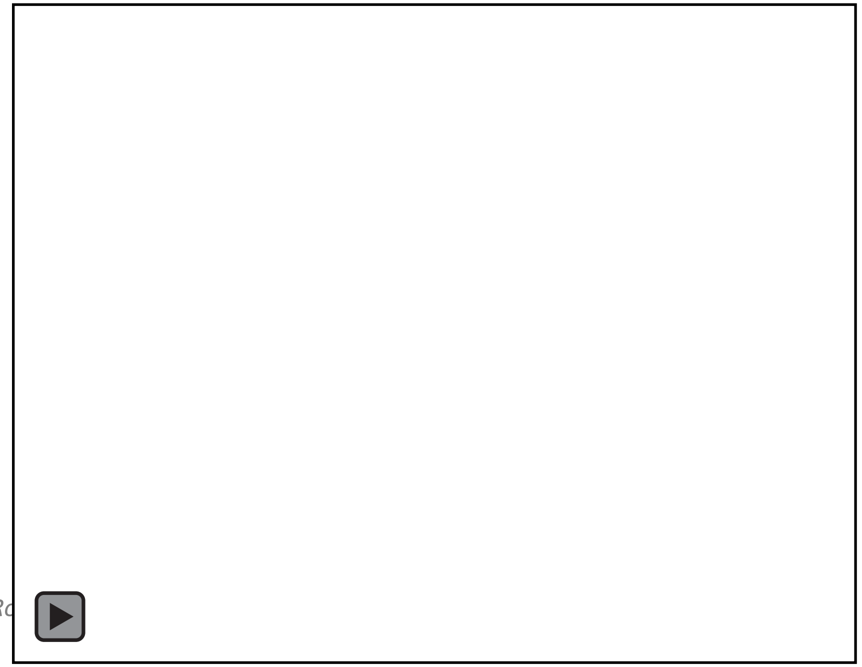
Comb working point



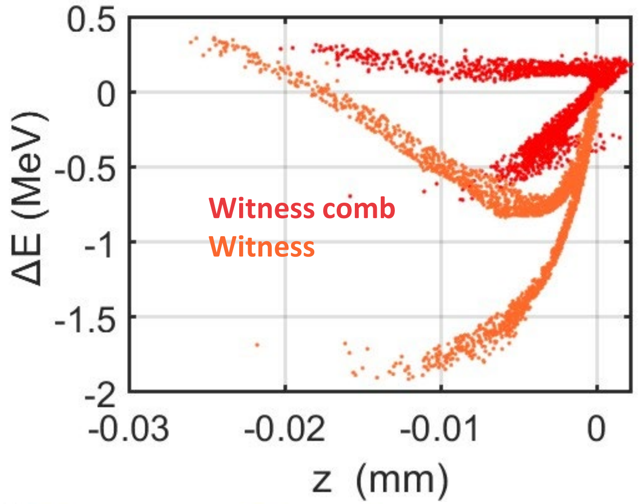


of M. R

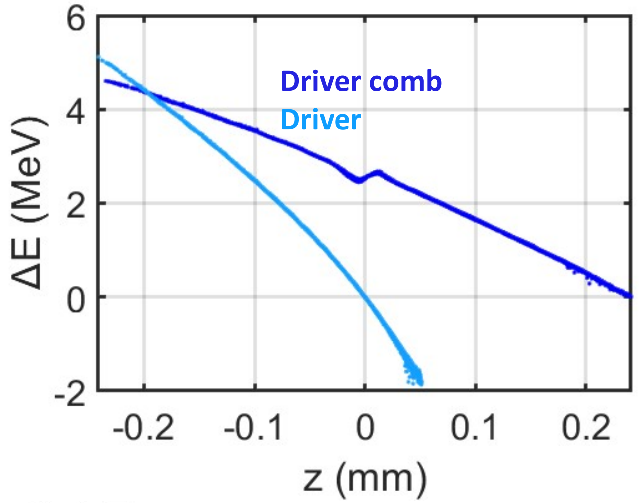


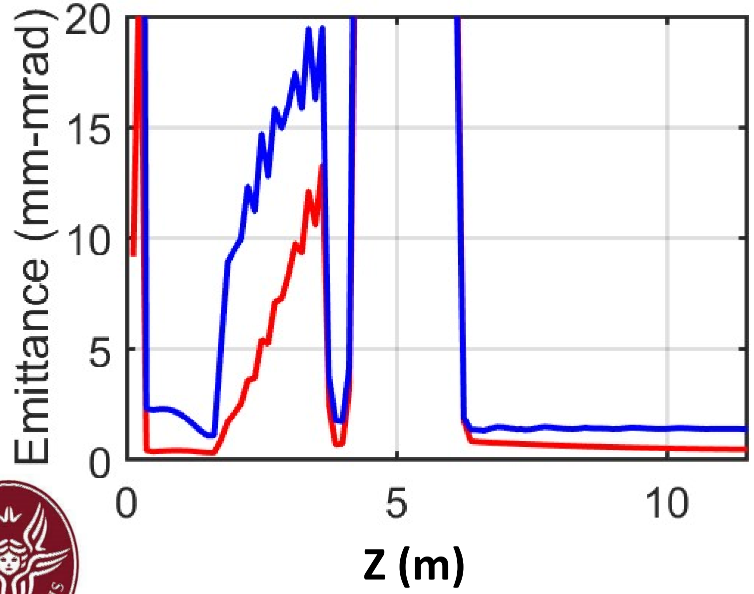
Comb beam dynamics results

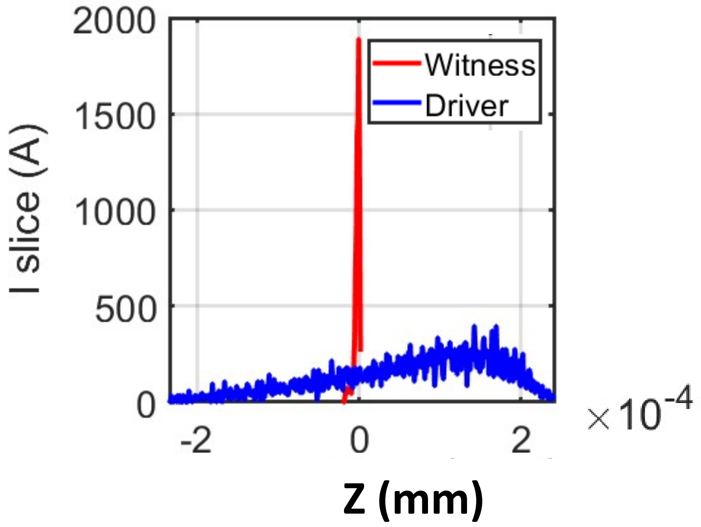
Funded by the European Union



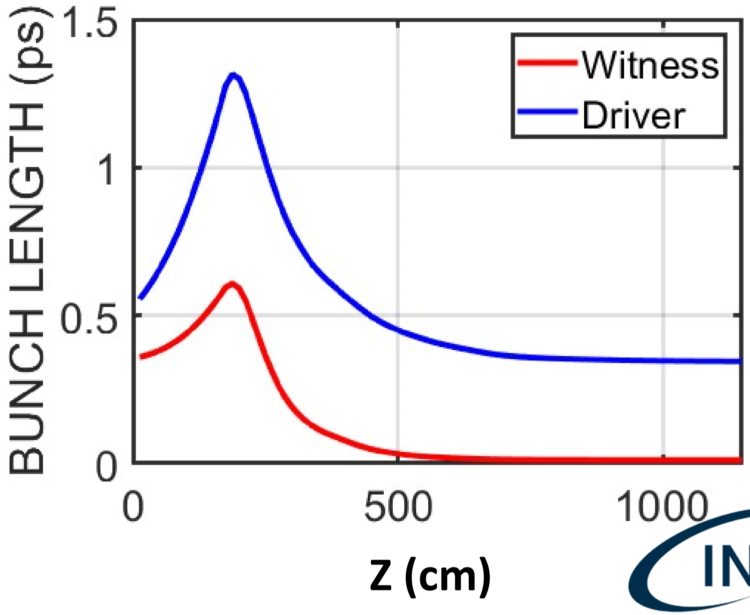
Beam parameters @ cathode	Witness	Driver
Spot Size	0.175 mm	0.35 mm
Bunch Length	220 fs	220 fs
Charge	30 pC	200 pC
Bunch separation	6.3 ps	- -







C-band Injector exit parameters	Witness	Driver
Bunch Length	3.4 μm	100 μm
Emittance	0.48 μm	1.40 μm
Energy spread	0.2 %	1.1 %
Bunch separation	0.22 ps	
Peak current	1.9 kA	0.3 kA



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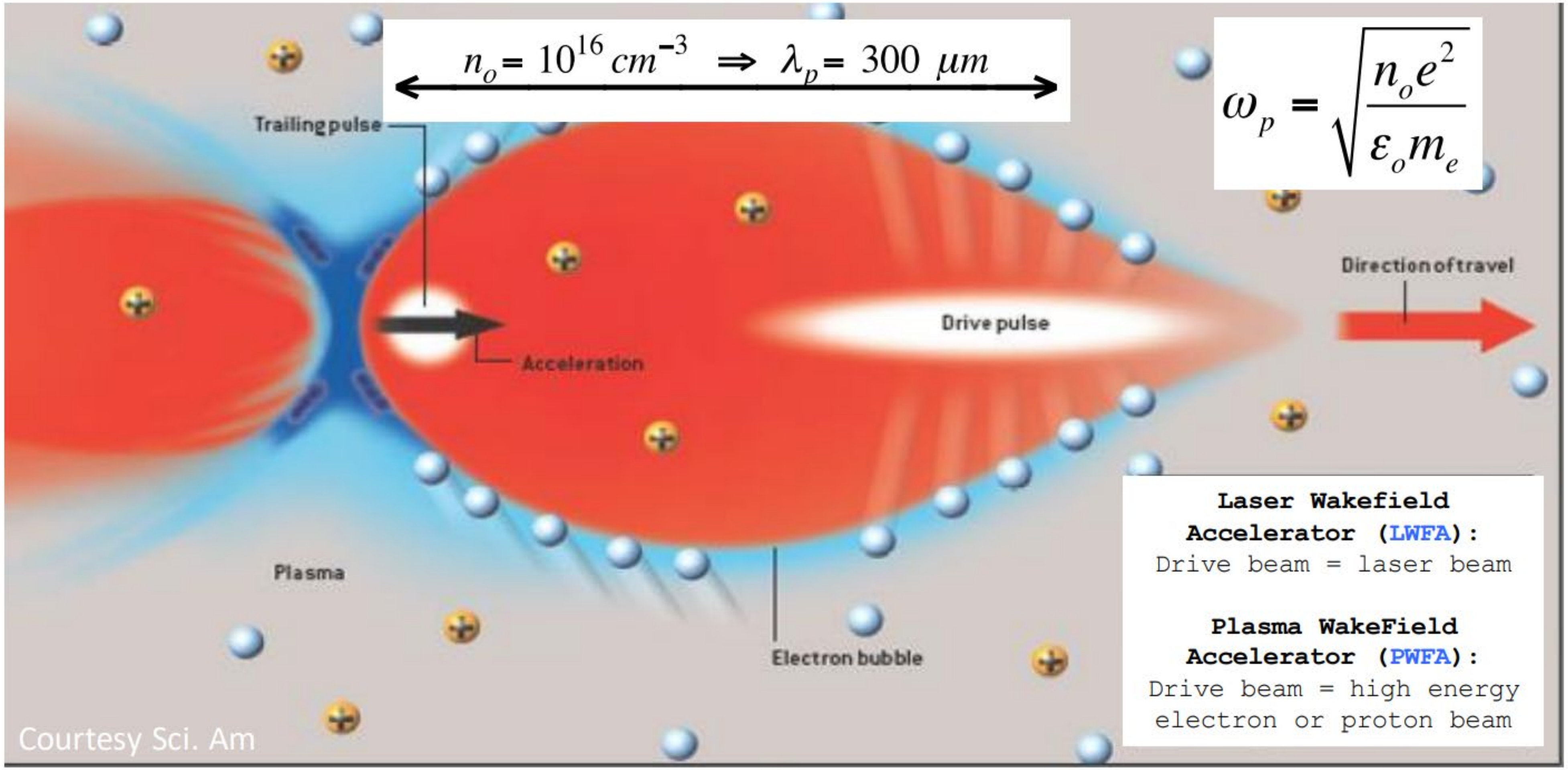
Matching condition in plasma



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

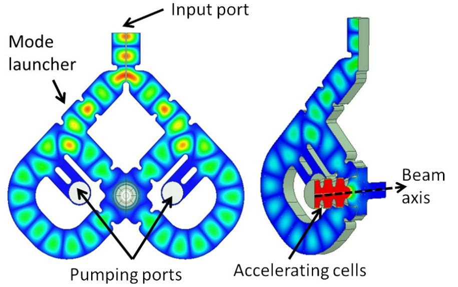
Laser Wakefield Accelerator (LWFA):
Drive beam = laser beam

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

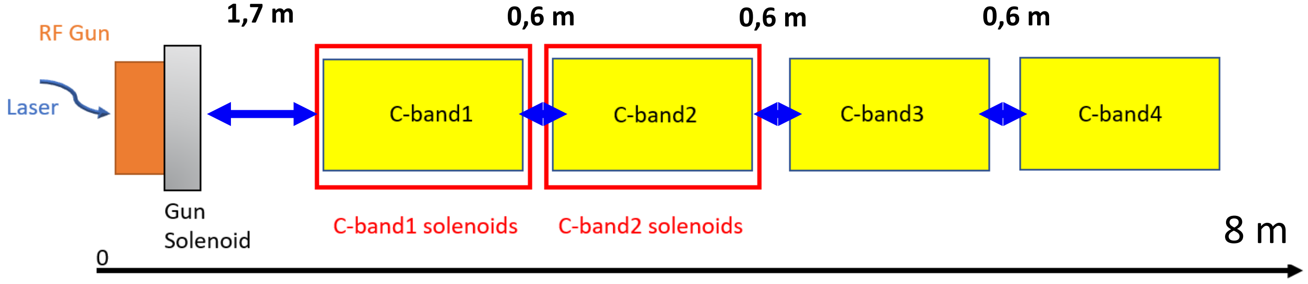
C-band injector layout proposal

Funded by the European Union

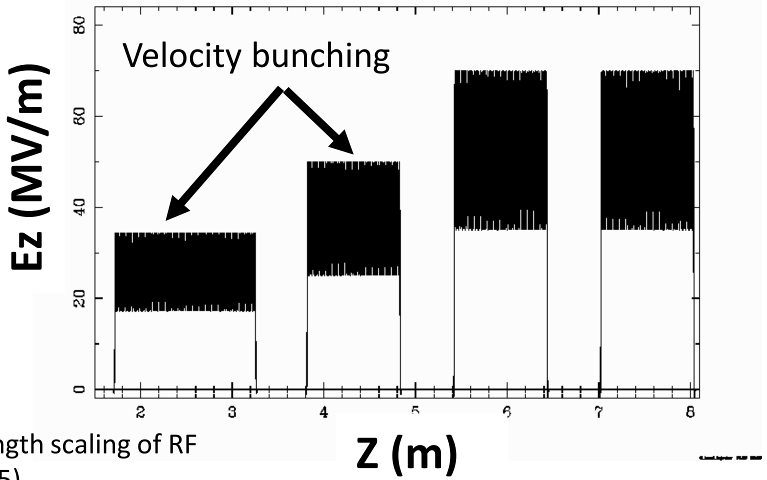
The C-band injector, scaled [15] from the S-band design, features an initial cavity length of 1.5 meters, with subsequent cavities measuring 1 meter each. The electric fields within the cavities are doubled compared to the S-band configuration. The first cavity operates with a peak electric field of 34 MV/m to support VB operations. Additionally, the magnetic field in the solenoid cavities is also doubled in accordance with the scaling laws.



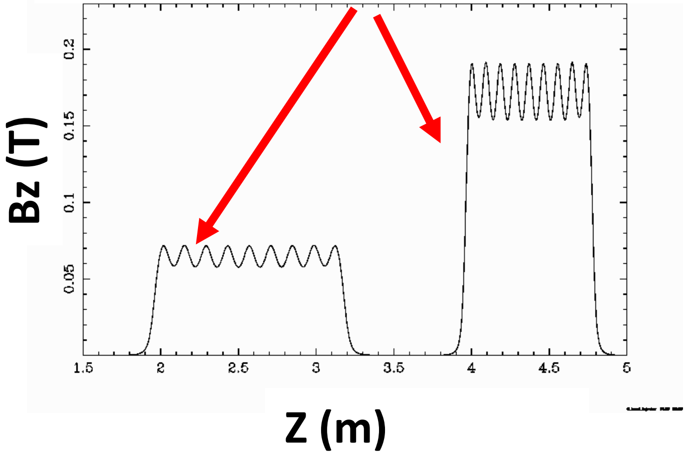
2,6 cells RF Gun



Beam@cathode	Witness	Driver
charge	30 pC	200 pC
Spot size	0,2 mm rms	0,32 mm rms
Bunch length	100 fs	100 fs
Bunch separation	11,5 ps	



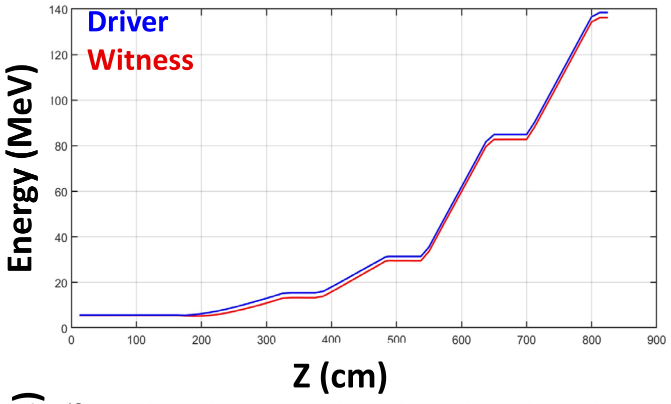
Emittance compensation solenoids

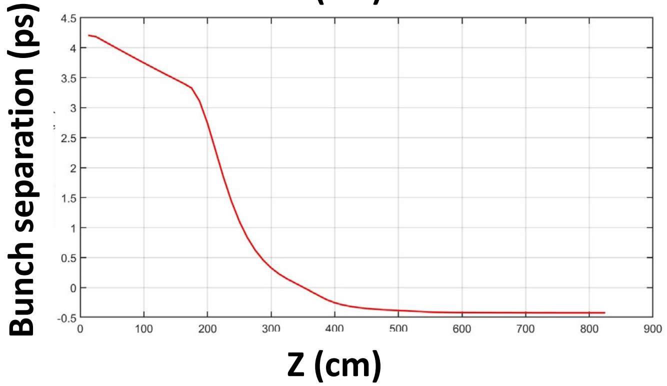


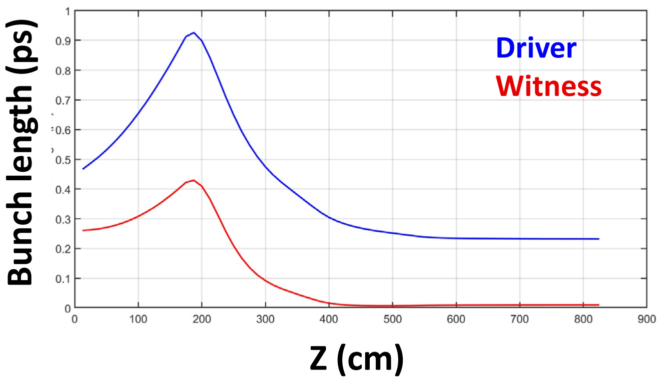
[15] J. Rosenzweig and E. Colby, Charge and wavelength scaling of RF photoinjector designs, AIP Conf. Proc. 335, 724 (1995).

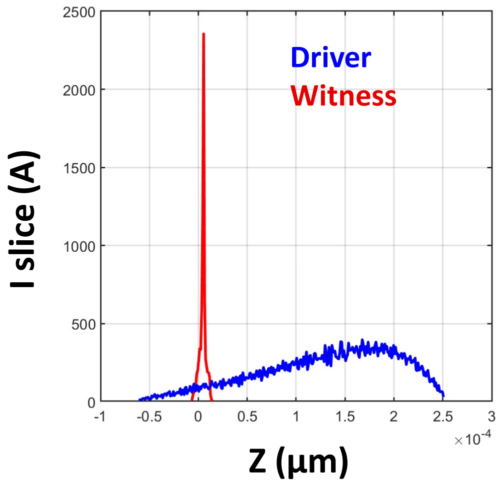
Beam dynamics simulations

Funded by the European Union

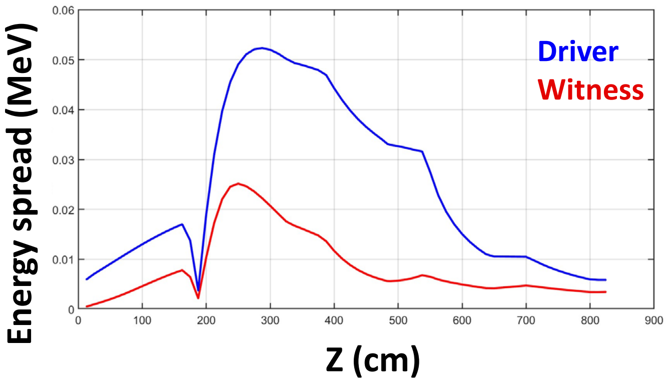


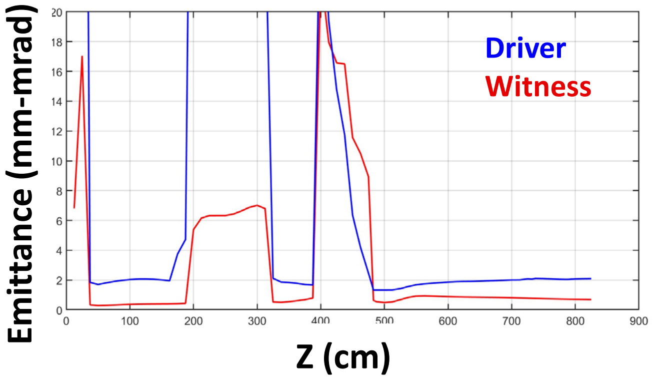


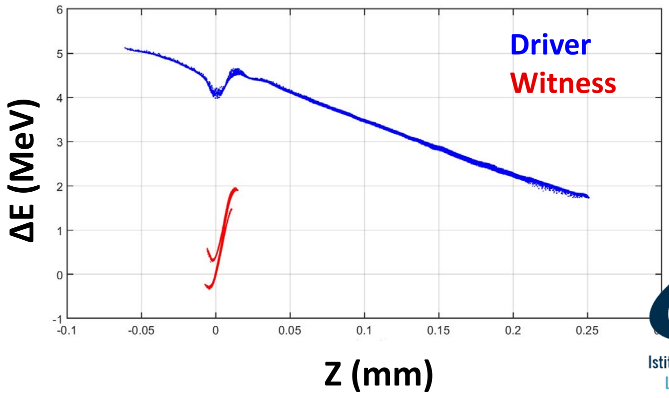




Injector exit parameters	Witness / Driver
Emittance (mm-mrad)	0,65 / 2
Energy (MeV)	136 / 138
Energy spread (KeV)	3,5 / 5,8
Bunch separation (ps)	0,45
Bunch length (um)	3,2 / 70







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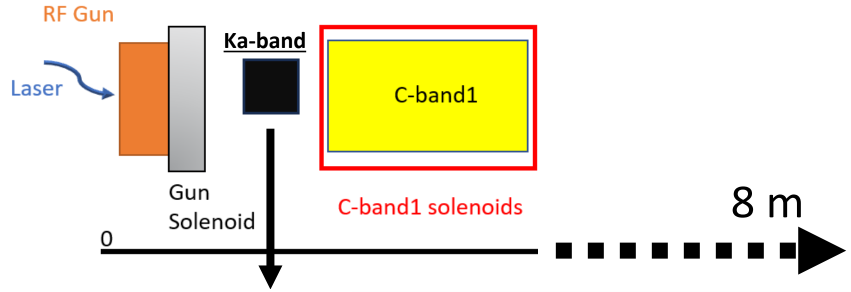
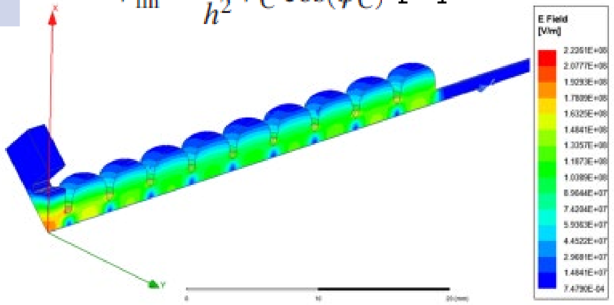
Phase space manipulation with a SW Ka-band cavity

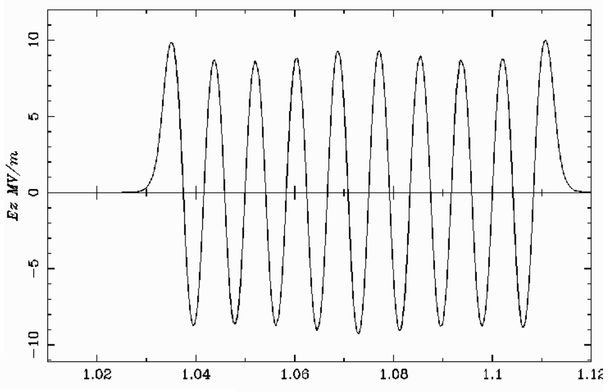
Funded by the European Union

SW Ka-band	
Resonant Frequency	36 GHz
E acc	10 MV/m
Number of cells	19
Length	8 cm
Radius	3,5 mm



$$V_{\text{lin}} = \frac{1}{h^2} V_C \cos(\phi_C) \quad [17]$$

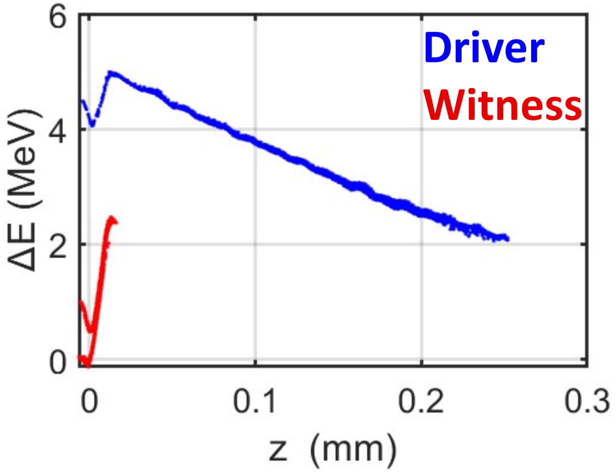


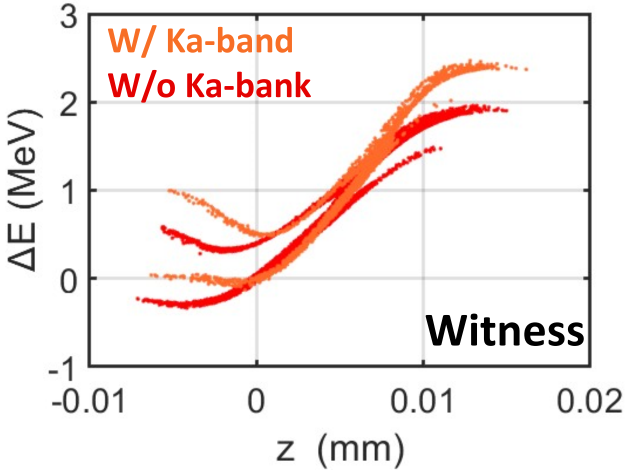


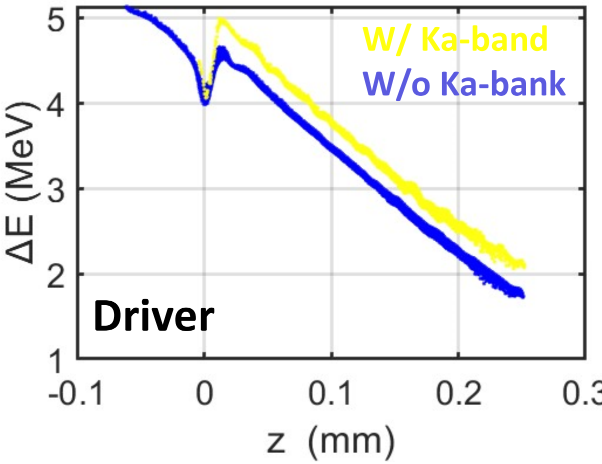
[16] M. Behtouei et al. 'A SW Ka-Band linearizer structure with minimum surface electric field for the compact light XLS project, NIMA vol 894 (2020) https://doi.org/10.1016/j.nima.2020.164653

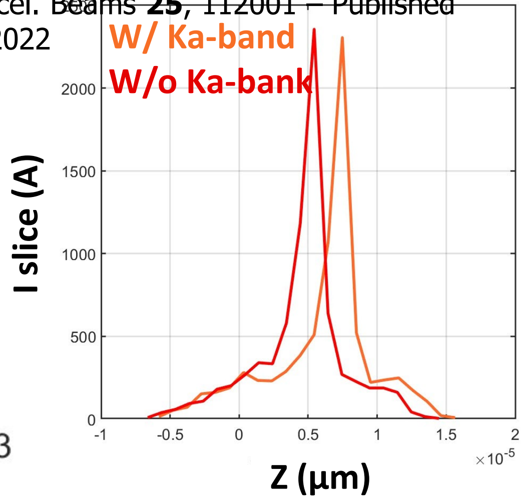
Injector exit parameters	Witness / Driver
Emittance (mm-mrad)	0,45 / 2,46
Energy (MeV)	136 / 138
Energy spread (KeV)	4,6 / 4,8
Bunch separation (ps)	0,5
Bunch length (um)	3,7 / 56

[17] J. Scifo et al. 'BEAM DYNAMICS STUDIES IN A STANDING WAVE Ka-BAND LINEARIZERIPAC2021, Campinas, SP, Brazil, doi:10.18429/JACoW-IPAC2021-MOPAB270
[18] A. Castilla, R. Apsimon, G. Burt, X. Wu, A. Latina, X. Liu, I. Syratchev, W. Wuensch, B. Spataro, and A. W. Cross Phys. Rev. Accel. Beams **25**, 112001 – Published 9 November 2022









Conclusions and future prospectives

- This study demonstrates that operating a plasma stage with a complete C-band injector is feasible. This machine is expected to enhance the repetition rate and reduce the injector's footprint while maintaining high-quality beams through a more compact system.

- Further optimizations of the new C-band injector are ongoing. Additional focus will be placed on beam dynamics simulations to address the time separation required for PWFA application.
  - Further investigation into the layout, including the Ka-band cavity, is needed to assess its impact on the bunch separation and stability.
    - technological feasibility must be demonstrated.

- Jitter studies must be performed to assess the working point stability.

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Thank you for your attention

Gilles Jacopo Silvi* (Sapienza University of Rome & INFN-LNF)
EuPRAXIA_PP Annual Meeting 2024
On behalf of the EuPRAXIA@SPARC_LAB collaboration
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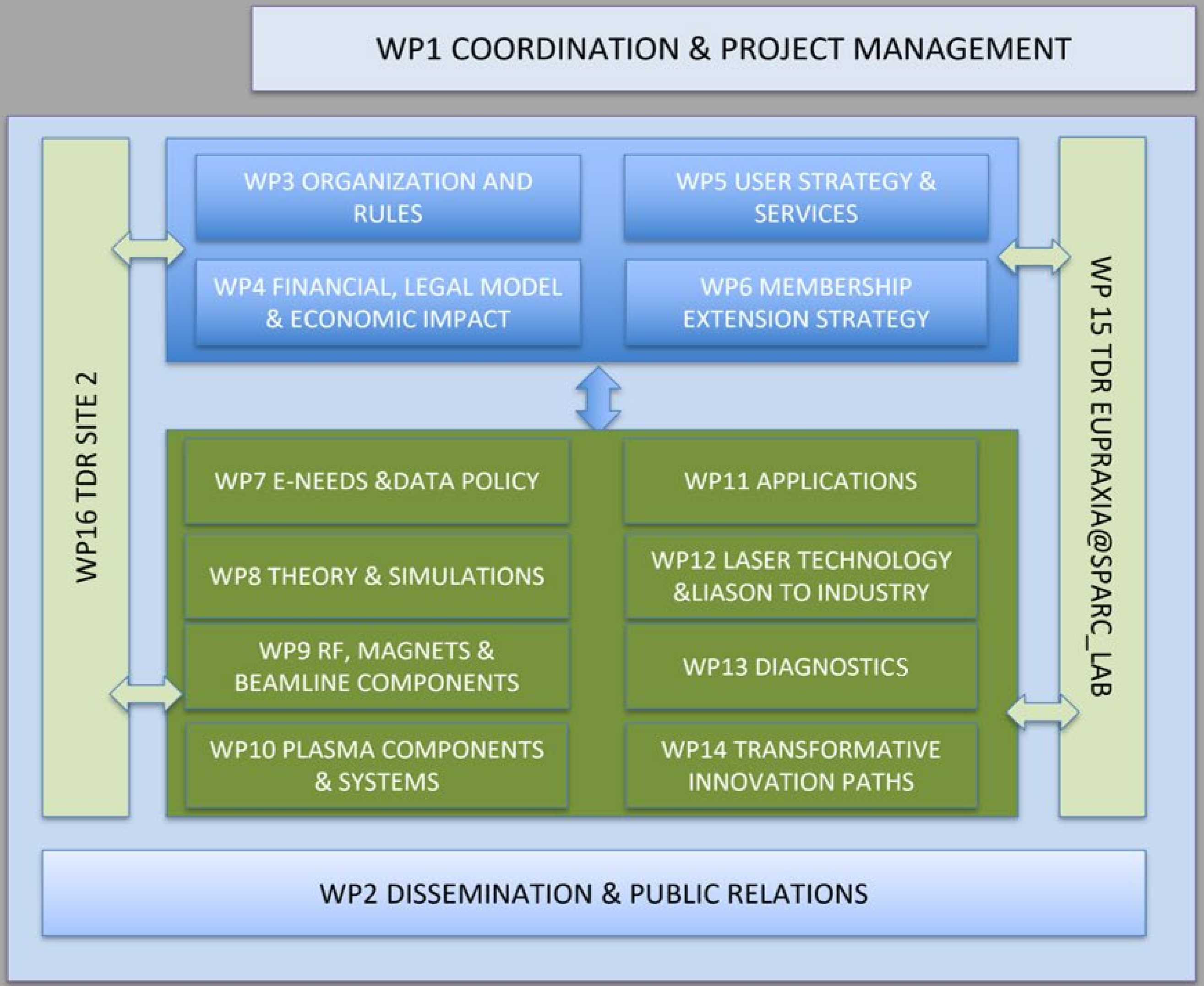

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