SAPIENZA
UNIVERSITÀ DI ROMA

Study of the transfer and matching line for PWFA-driven FEL

Dottorato di Ricerca in Fisica degli acceleratori – XXXV Ciclo

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Outline

- Scientific context
- Problem and requests at beam extraction from plasma accelerating module
- Starting point
PRAB 2019, 22.12: 121302.
- Studies of different plasma based extraction lines
- Comparison between the different simulations
- Experimental and simulation studies on the conventional transfer line for SPARC_LAB PWFA experiment
- Outlook
- Conclusion

Motivation

→Plasma-based acceleration techniques have demonstrated multi-GeV acceleration in cm scale structures

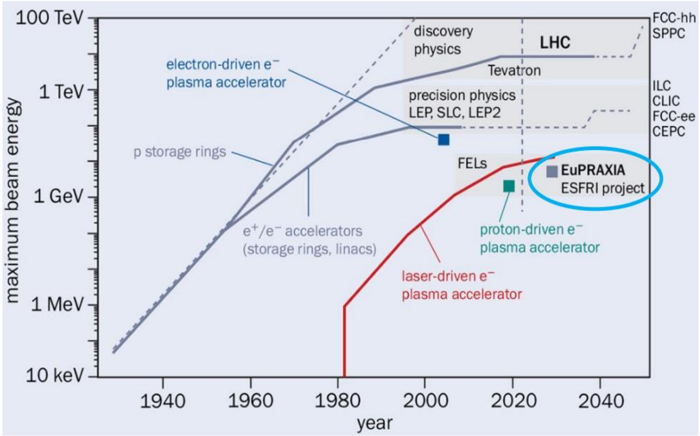
- J. Rosenzweig et al., Phys. Rev. Lett. 61, 98 (1988): First experimental demonstration of PWFA
- Mangles, Geddes, Faure et al., Nature 431, (2004): The dream beam
- W. P. Leemans, Nature Physics vol. 2, p.696-699 (2006): GeV electron beams from a centimetre-scale accelerator
- I. Blumenfeld et al., Nature 445, p. 741 (2007): Doubling energy in a plasma wake
- P. Muggli et al, in Proc. of PAC 2011, TUOBN3: Driving wakefields with multiple bunches
- Aihua Deng, et al.Generation and acceleration of electron bunches from a plasma photocathode. NaturePhysics, 15(11):1156–1160,2019

→Extraction and transport of stable and reliable high brightness electron beams for applications (in particular FELs) still require great effort to properly match the beam to the final application.

- M. Litos et al., Nature 515, 92 (2014): High efficiency acceleration in the driver-trailing bunches
- Wentao Wang, et al.Free-electron lasing at 27 nanometres based on a laser wakefield accelerator. Nature, 595(7868):516–520, 2021.
- R Pompili et al, Free-electron laser with a compact beam-driven plasma accelerator. Nat. Phys, 2021.

→Plasma-based user facility

- Assmann, R. W., et al. "EuPRAXIA conceptual design report." *The European Physical Journal Special Topics* 229.24 (2020): 3675-4284.
- Ferrario, M., et al. "EuPRAXIA@ SPARC_LAB Design study towards a compact FEL facility at LNF. " Nucl. Instrum. Methods Phys. Res., Sect. A, Accel., Spectrom. Detect. Assoc. Equip.909 (2018): 134-138.



Updated Livingston plot for accelerators, showing the maximum reach in beam energy versus time.

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

Critical issues for plasma accelerated beam

Plasma fields are 10^2–10^3 times stronger than in conventional accelerator
PMQ → 500 T/m
Plasma lens → G (MT/m) ≈ 3 n_p (10^{17} cm^{-3}) .

➢Extraction from plasma accelerating module

•beams experience huge transverse size variation when propagating from the plasma outer surface to the conventional focusing optics $\sigma_x \sim \mu m$ $\sigma_{x'} \sim mrad$

➢particle transverse motion becomes extremely sensitive to energy spread

$$\varepsilon_n^2 = \langle\gamma\rangle^2 \left(s^2 \left(\frac{\sigma_E}{E}\right)^2 \sigma_{x'}^4 + \varepsilon_0^2 \right)$$

❋ M. Migliorati et al., PRST AB **16**, 011302 (2013)

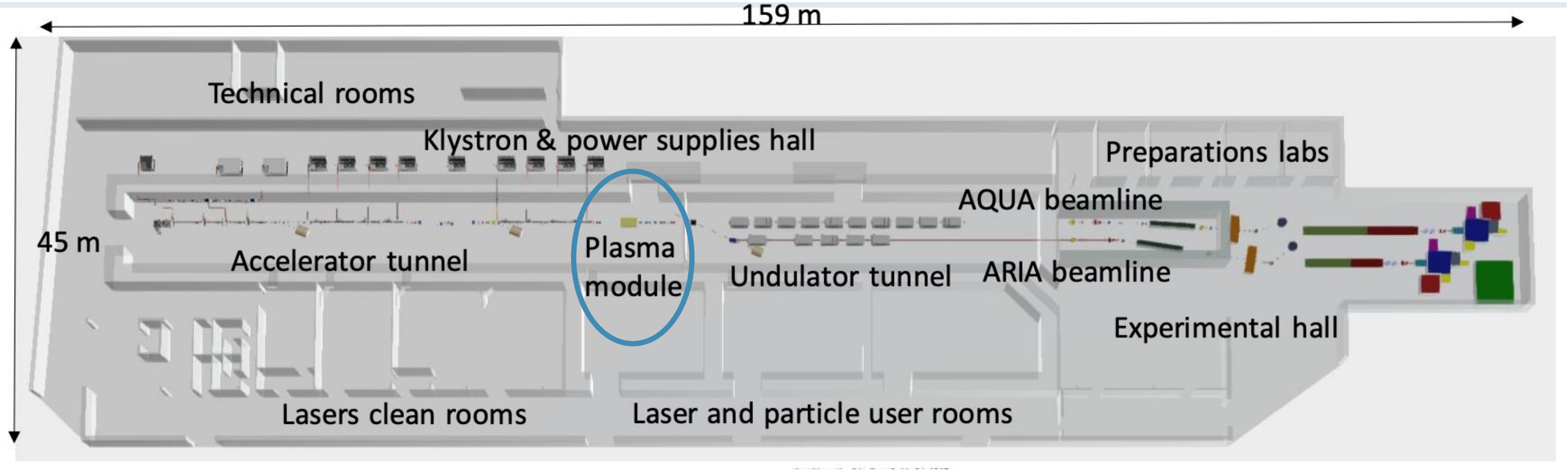
⬇

$$L_C \cong \frac{\varepsilon_0}{\sigma_E (\sigma_{x'}^0)^2} = \frac{\sigma_x^0}{\sigma_E \sigma_{x'}^0} = \frac{\gamma(\sigma_x^0)^2}{\sigma_E \varepsilon_n}$$

❋ Conti, M. Rossetti et al., NIM A **909** (2018): 84-89

➢ In addition the energy depleted driver beam must be removed

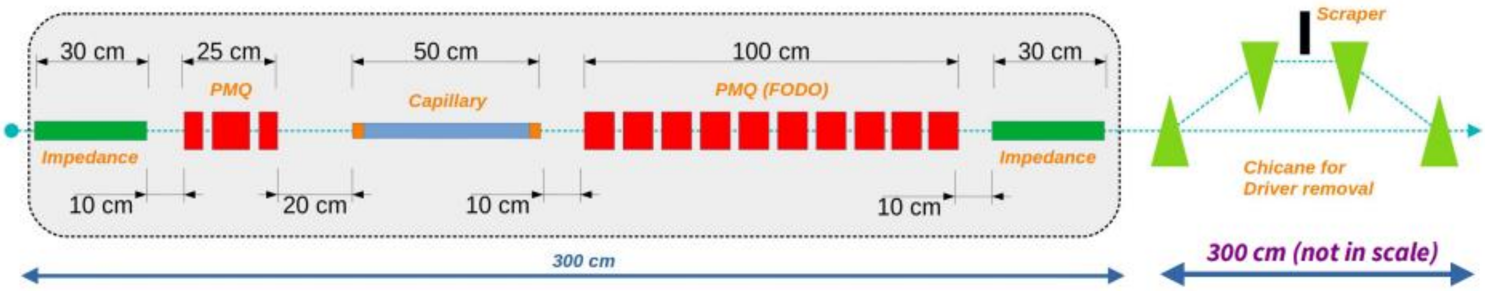
EuPRAXIA@SPARC_LAB layout



-High brightness S-band RF injector
-X-band linac
-Plasma module for PWFA

EuPRAXIA@SPARC_LAB Plasma Module

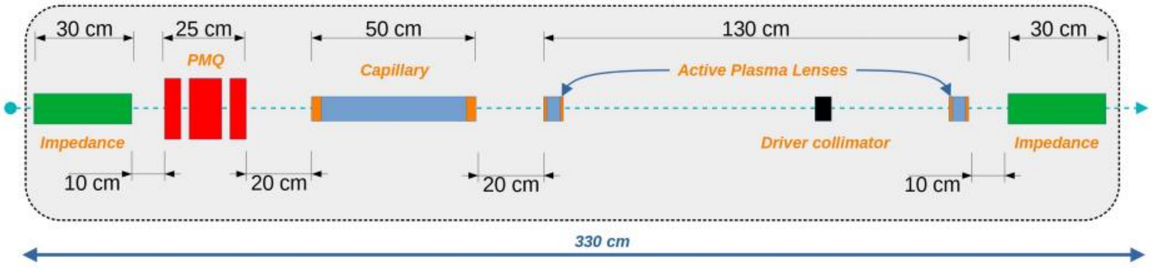
First layout



FODO to extract
the witness.

❖ Nucl. Instrum. Methods Phys. Res., Sect. A, Accel., Spectrom. Detect. Assoc. Equip 909 (2018): 84-89.

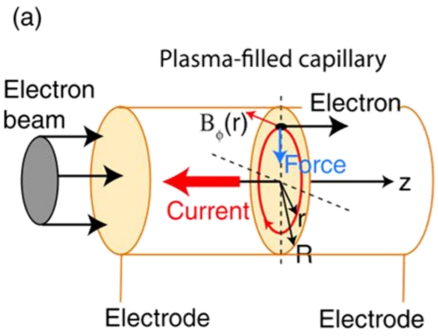
Second layout



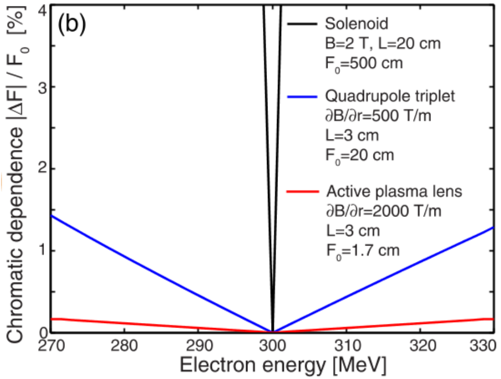
Active-Plasma lenses to extract the witness and remove driver

❃ PRAB 2019, 22.12: 121302

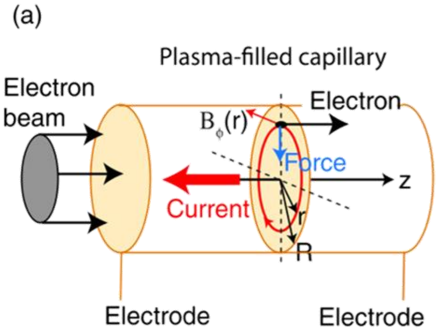
Active Plasma Lens



- $B_{\phi(r)} = \frac{\mu_0}{r}\int_0^r J(r')r'dr'$
- Cylindrical symmetry
- Focusing strength $k \propto \frac{1}{\gamma}$
- High focusing gradient ~ kT/m
- Short focal length
- weak chromaticity



Active Plasma Lens



- $B_{\phi(r)} = \frac{\mu_0}{r} \int_0^r J(r')r'dr'$
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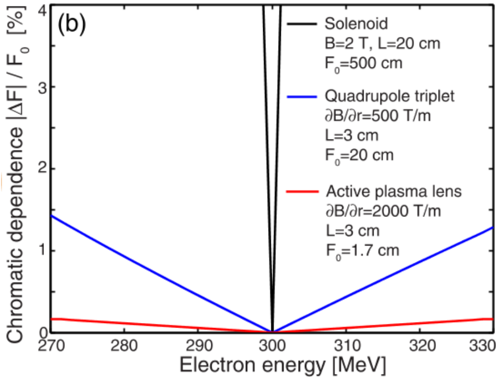
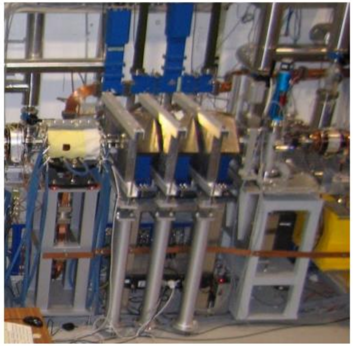
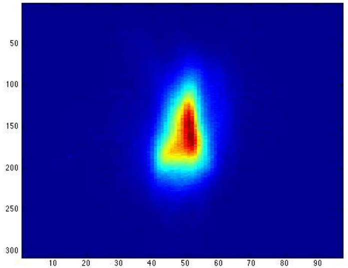
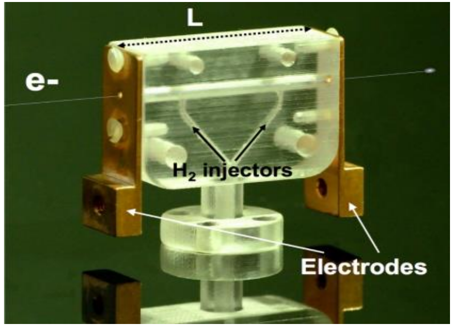


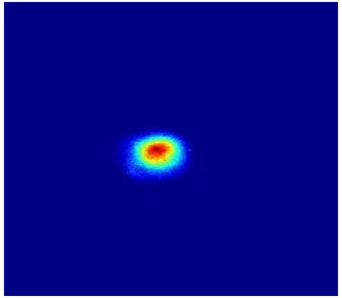
QUADRUPOLES



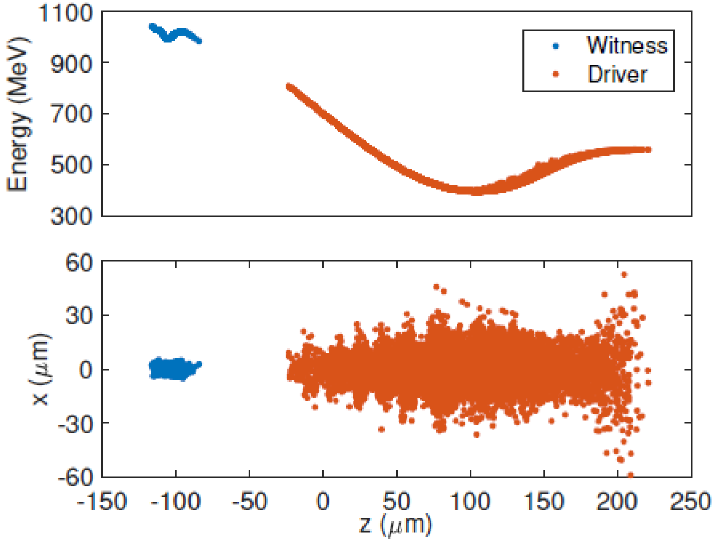


APLs





Driver and witness bunches parameters



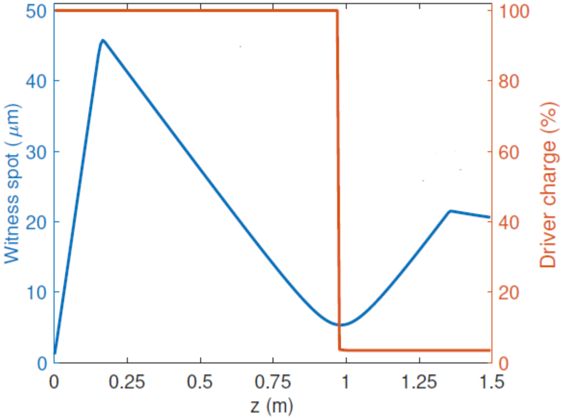
Longitudinal phase-space (top) and x-z view (bottom) of the driver (red) and witness (blue) bunches downstream the PWFA module

Parameter	Units	Witness	Driver
Charge	pC	30	200
Duration (rms)	fs	11.5	160
Energy	MeV	1016	460
Energy Spread (rms)	%	0.73	16
Emittance	µm	0.6	5
Spot size	µm	1.2	7

Simulated bunches by means of Architect code, a hybrid code that works as a Particle-In-Cell (PIC) for the electron bunches while treating the plasma as a fluid.

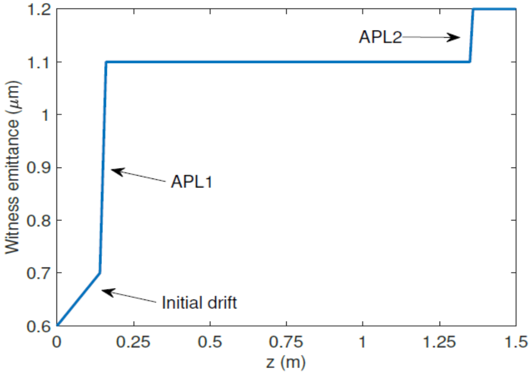
- ❖ A Marocchino,et al.Efficient modeling of plasma wakefield acceleration in quasi-non-linear-regimes with the hybrid code Architect. Nucl. Instrum. Methods Phys. Res., Sect. A, Accel., Spectrom. Detect. Assoc. Equip , 829:386–391,2016.

Starting point for plasma based extraction



- 1.9% driver
- Emittance growth almost double

Element	Length	Radius	Position	Current
APL 1	2 cm	500 μm	15 cm	1 kA
Collimator	3 cm	200 μm	97 cm	-
APL 2	1 cm	500 μm	135 cm	0.6 kA



❃ POMPILI, R., et al. Plasma lens-based beam extraction and removal system for plasma wakefield acceleration experiments. Physical Review Accelerators and Beams, 2019, 22.12: 121302.

Simulation tools for beam propagation and interaction in plasma lens

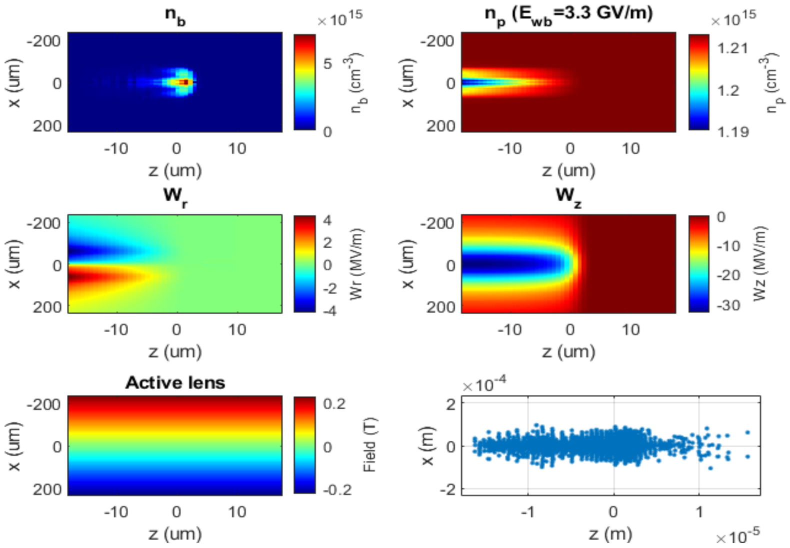
Simulations have been perfomed by means of GPT for beam dynamics and a Matlab and Architect code for the plasma lens.

MATLAB

$$W_z(z,r) = \frac{q_e}{\epsilon_0} R(r) \int_{-\infty}^{z} n_{b,l}(z') cos(k_p(z-z'))dz'$$

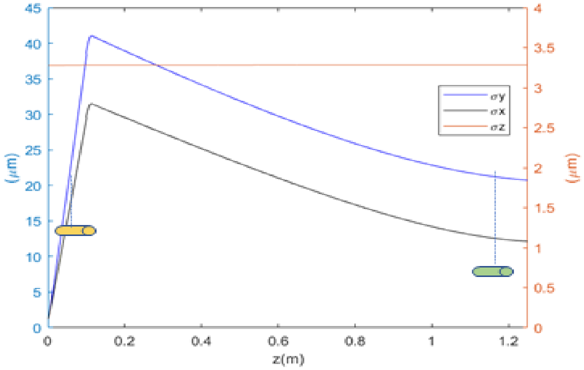
$$W_r(s,r) = \frac{q_e}{\epsilon_0 k_p} \frac{dR(r)}{dr} \int_{-\infty}^{z} n_{b,l}(z') sin(k_p(z-z'))dz'$$

$$F_{z,r} = q_e W_{z,r}$$



Studies of the first transfer line

- ✓ transfer line of 125cm
- ✓ 2 elements along transfer line
- ✓ 28 % increase in rms emittance

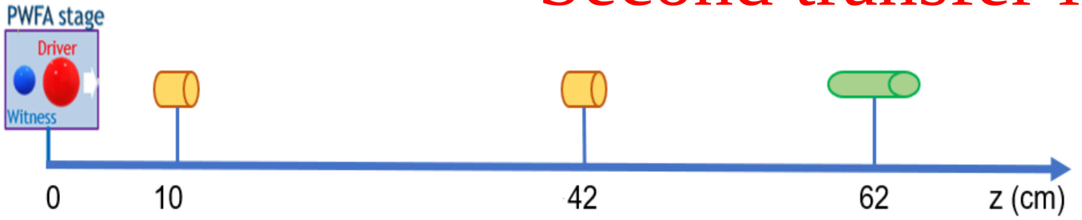


- ✓ Energy spread remains about constant
- ✓ 2.5% driver charge at 125 cm
- ✓ No change in bunch charge

Element	Length	Radius	Position	Current
APL 1	1.5 cm	500 μm	10 cm	1.8 kA
Collimator	2 cm	300 μm	119.5 cm	

Witness parameters	Z start (0 cm)	Z end (125cm)
Charge (pC)	30	30
ε_{nrrms},ε_{nx}, ε_{ny} (mm mrad)	0.61, 0.47, 0.81	0.79, 0.57, 1.16
σ_x,σ_y(μm)	1.20 , 1.19	12 , 21
σ_z (μm)	3.28	3.28
Energy (MeV)	1016	1016
σ_E (MeV)	7.4	7.5
Driver charge (pC)	200	5.1

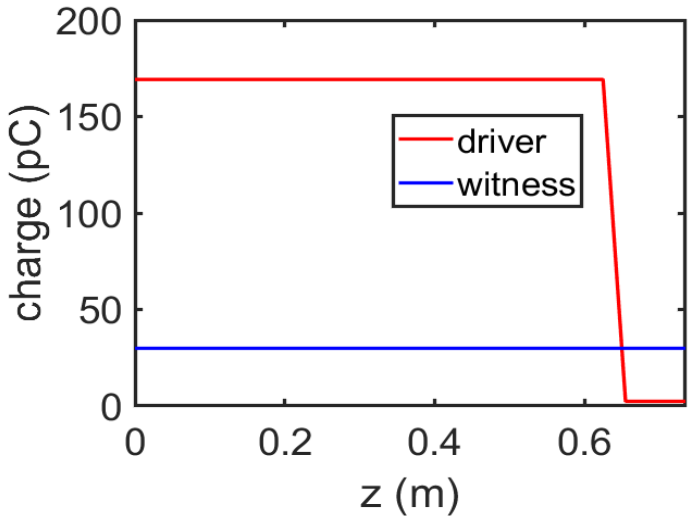
Second transfer line



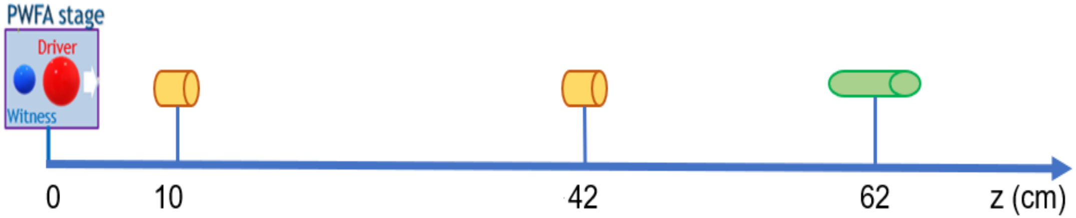
- ✓ transfer line of 63 cm
- ✓ No change in bunch charge

- ✓ 5% driver charge at 63 cm
- ✓ 3 elements along transfer line

Element	Length	Radius	Position	Current
APL 1	1 cm	500 µm	10 cm	3 kA
APL 2	1 cm	500 µm	42 cm	0.1 kA
Collimator	2 cm	300 µm	62 cm	

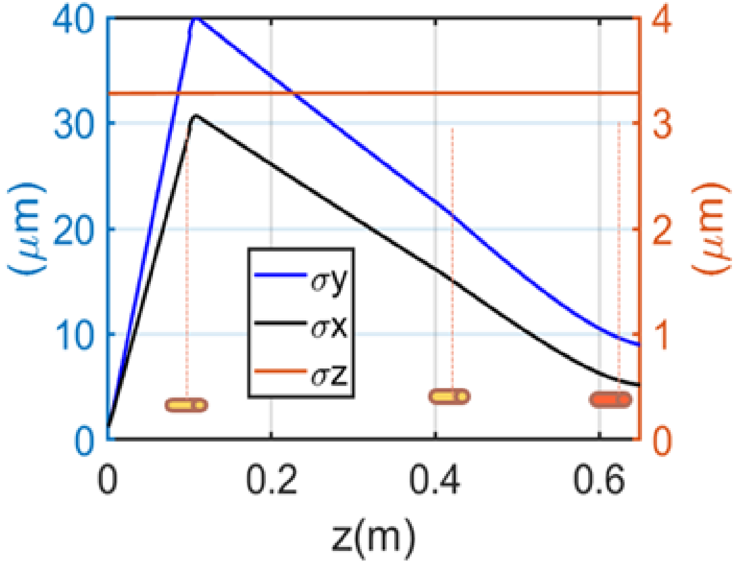


Second transfer line



- ✓ 38 % increase in rms emittance
- ✓ Energy spread remains about constant

Witness parameters	Z start (0 cm)	Z end (63 cm)
Charge (pC)	30	30
ε_{nrrms},ε_{nx}, ε_{ny} (mm mrad)	0.61, 0.47, 0.81	0.85, 0.60, 1.27
σ_x,σ_y(μm)	1.20 , 1.19	6 , 10
σ_z (μm)	3.28	3.28
Energy (MeV)	1016	1016
σ_E (MeV)	7.4	7.5
Driver charge (pC)	200	10.7



Comparison between the three lines

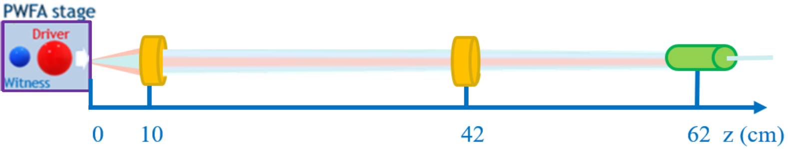
These configurations are tunable changing the current of the lenses
In all configurations witness particles are preserved

At zend (136 cm)

- 1.9% driver
- emittance growth double

At zend (121.5 cm)

- 2.7% driver
- 30% in emittance growth



At zend (63 cm)

- 5% driver
- 38% in emittance growth

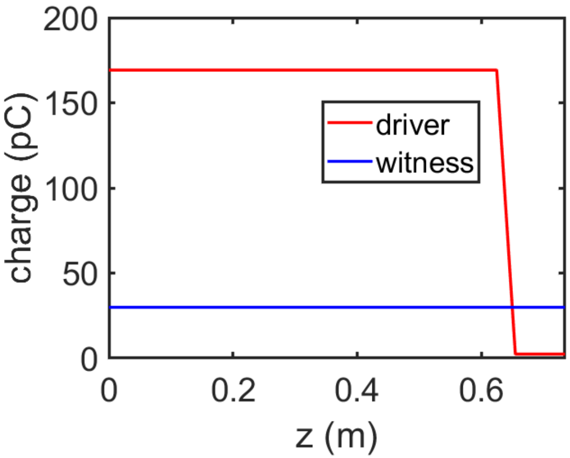
Compact and tunable beam line

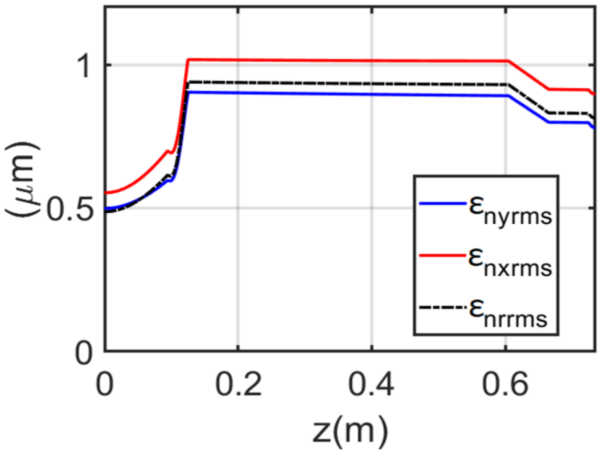
Parameter	Units	Witness	Driver
Charge	pC	30	169
Duration (rms)	fs	18	160
Energy	MeV	1000	300
Energy Spread (rms)	%	1.20	56.86
Emittance	µm	0.5	2.6
Spot size	µm	1	4

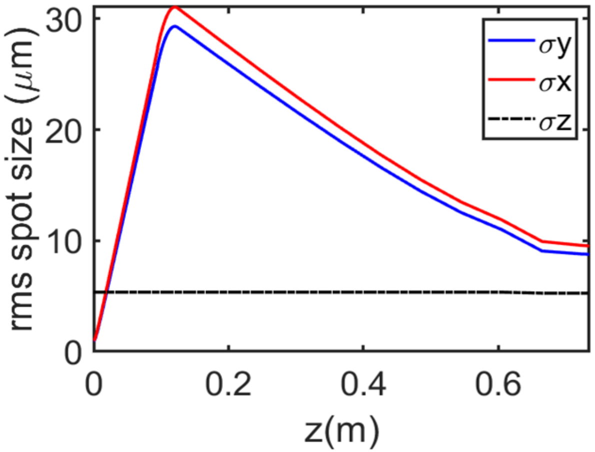
Element	Length	Radius	Position	Current
APL 1	3 cm	500 µm	11 cm	0.9 kA
Collimator	3 cm	150 µm	64 cm	
APL 2	1 cm	500 µm	73 cm	0.4 kA

- ✓ **transfer line of 74 cm**
- ✓ **60 % increase in rms emittance**
- ✓ **No change in bunch charge**

Witness parameters along the beamline



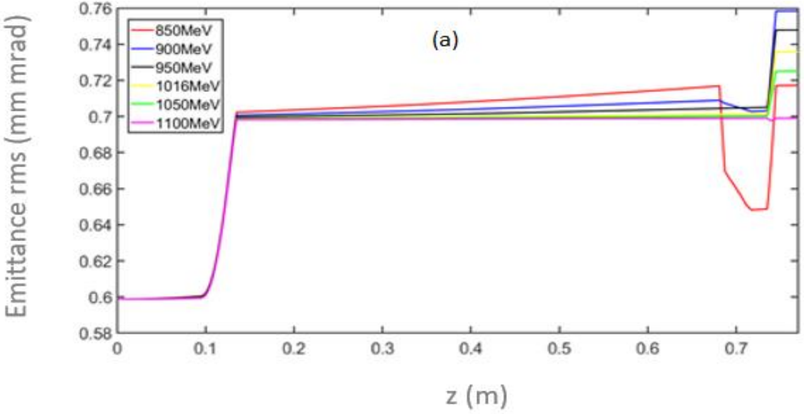


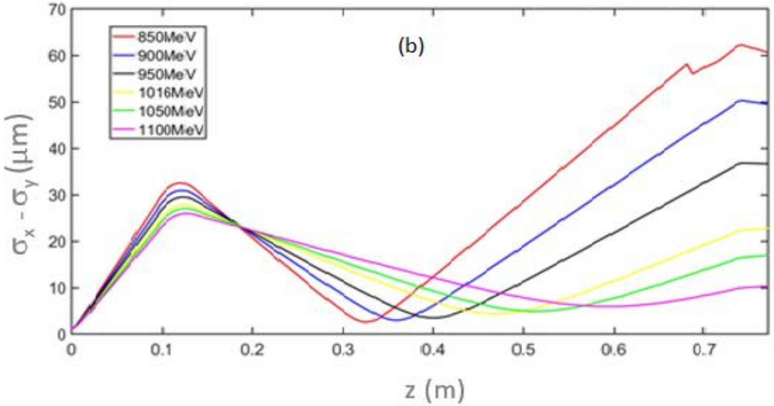


- ✓ **The driver is cut to 1.4% of its initial charge while the witness cut is not significant, being only 0.07 % of its initial charge.**

- ✓ **Emittance grows from 0.5 mm mrad to 0.8 mm mrad. As expected, this increase is in the initial drift downstream the PWFA module and in APLs.**

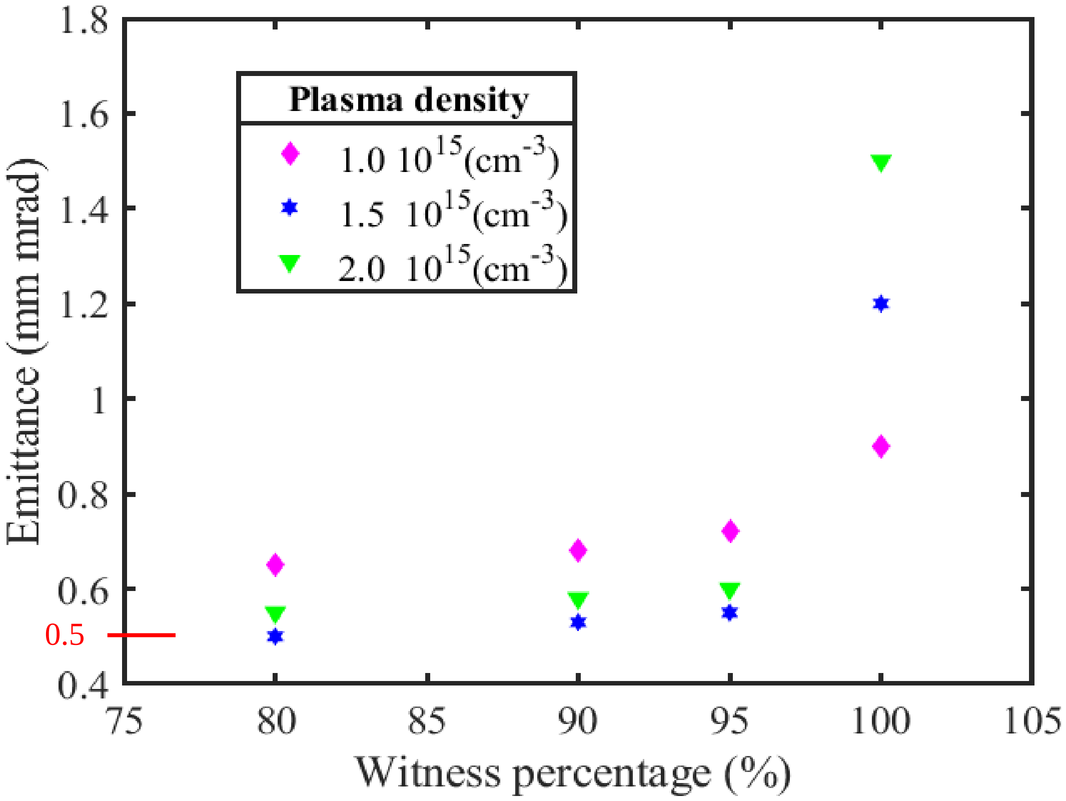
Parametric studies on the line





- ✓ Varying beam energy emittance (a) and sigma x (y) trends are preserved (b).
- ✓ At the energies of 850 MeV and 900 MeV the witness beam is cut in the collimator and it is reduced respectively of 5.7% and 0.4%

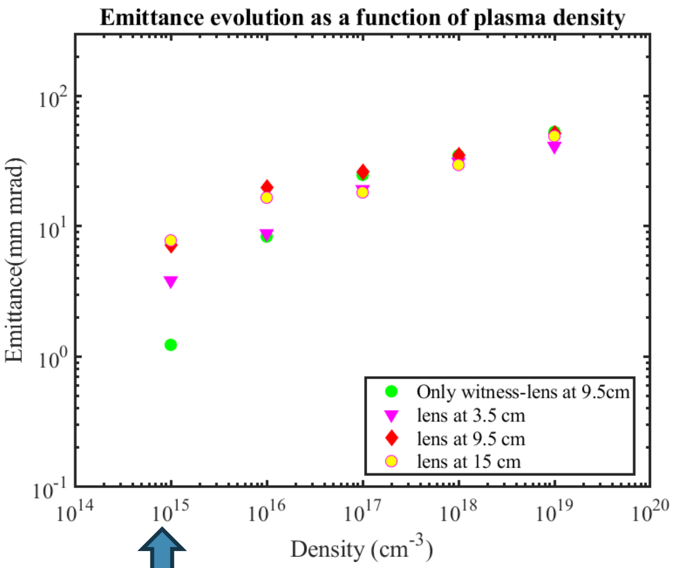
Simulation studies with MATLAB code

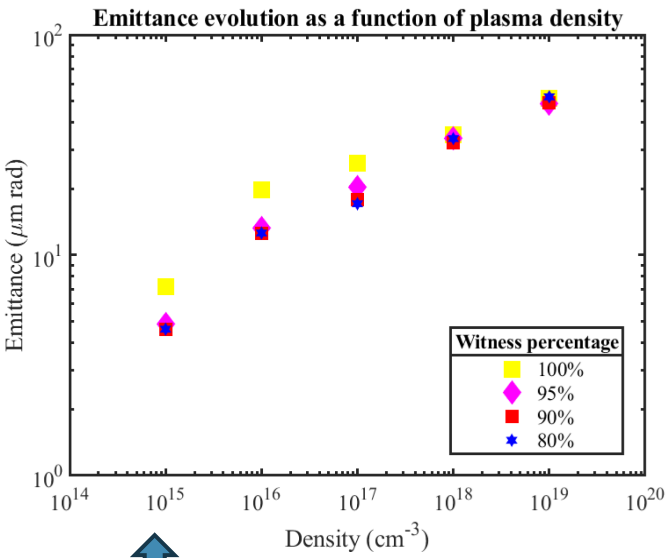


- ✓ The emittance growth is significantly reduced changing bunch initial percentage

Single bunch dynamics!

Emittance growth in active plasma lenses with Architect code

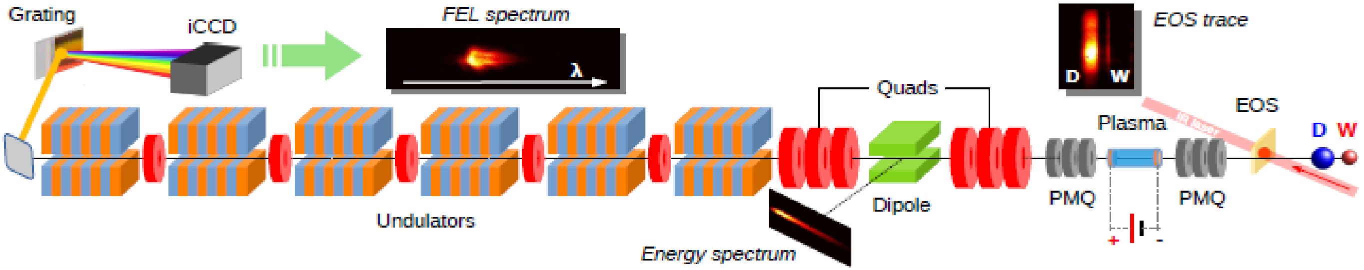




Emittance grows →with the plasma density
→with the distance of the first lens from the accelerating module
Emittance decreases with different witness percentages at the entrance of the first lens

Witness and driver bunches interaction in the plasma !

Low-energy case: SL_COMB2FEL experiment



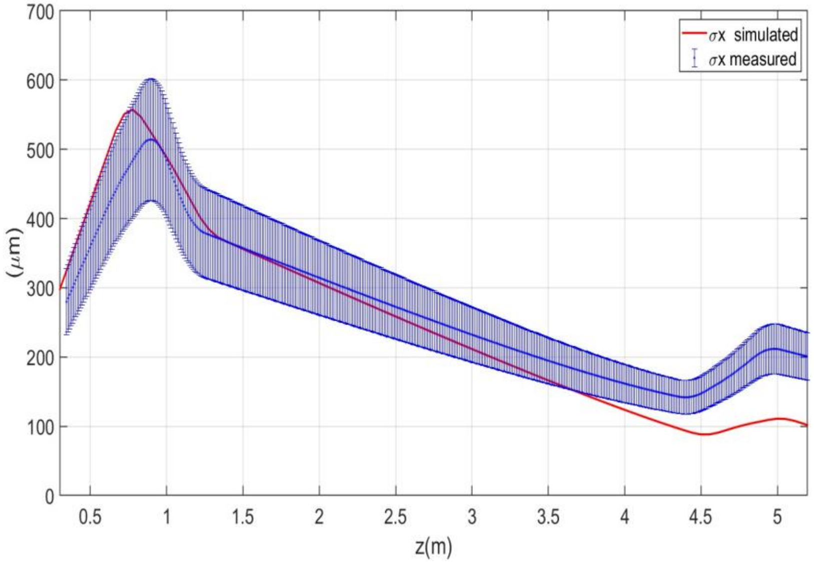
Witness of 93MeV

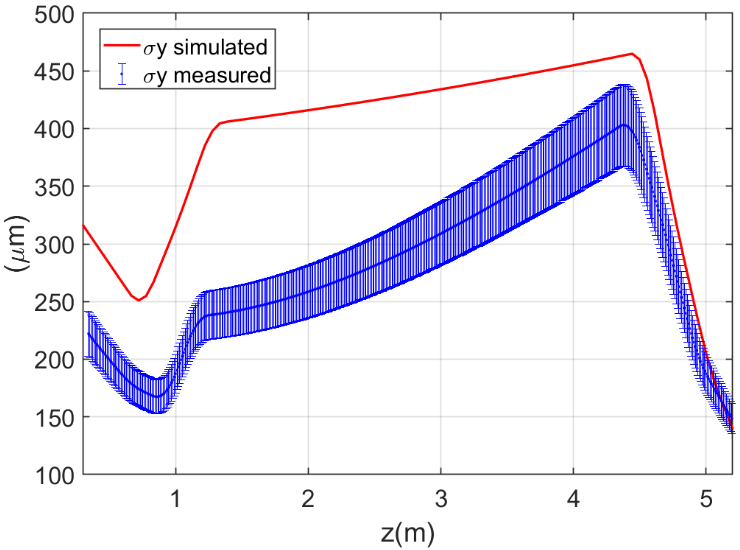
- ❖ R. Pompili et al., Nature **605**, 659–662 (2022)

- ✓ First proof-of-principle demonstration of FEL lasing with a beam-driven PWFA module
- ✓ Due to the deterioration of the magnets, their magnetic field gradient was varied from the nominal one (520T/m) to reproduce the experimental results of SPARC_LAB experiment
- ✓ Simulations have been perfomed by means of GPT for beam dynamics

Element	Position from the plasma module (m)	Length (cm)	Gradient (T/m)
PMQ03	0.1142	1.07	474.20
PMQ04	0.1353	2.10	462.15
PMQ05	0.1580	1.07	519.90
PTL01	0.7446	17.17	3.2156
PTL02	1.0246	17.26	0.2690
PTL03	1.2746	17.19	1.4736
PTL04	4.5246	16.99	2.5751
PTL05	4.7746	17.26	0.5734
PTL06	5.0346	17.17	2.0257

Simulated and extrapolated envelope of witness bunch along transfer and matching line

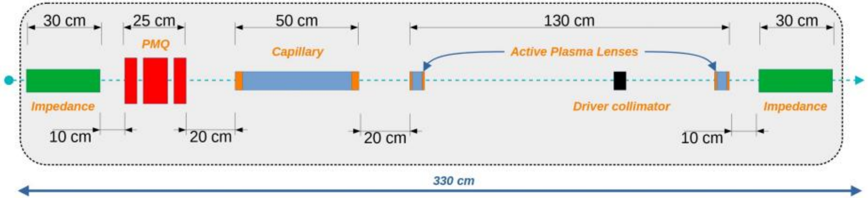




- ✓ Simulations have well reproduced the trend of the experimental results
- ✓ Simulated values are in red
- ✓ Values extrapolated from the Twiss parameters are in blue. They are obtained from the emittance measurement of the accelerated witness in the plasma.

Outlook

Second layout



- Contribution to the EuPRAXIA@SPARC_LAB

Technical Design Report

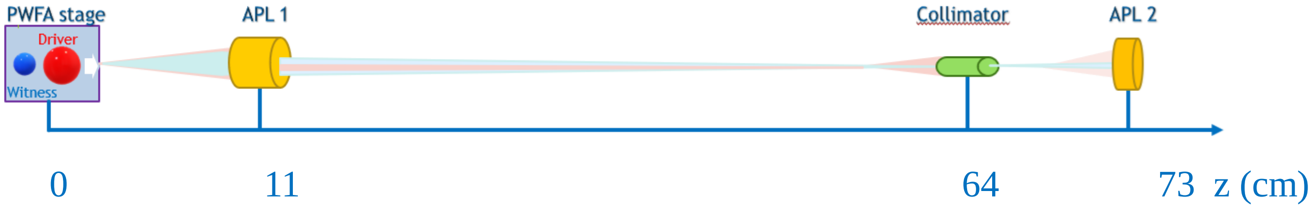
Compact and tunable transfer line

Element	Length (cm)	Radius (μm)	Position (cm)	Current (kA)
Lens1	3	500	11	0.9
Collimator	3	150	64	
Lens2	1	500	73	0.4

- Line optimization with the use of higher currents.
- Quantitative comparative study between plasma-based and conventional transfer and matching line => FEL simulations .
- Experimental feasibility of the line.
- To contain emittance increases→ Studies on integrated plasma module at SPARC_LAB.

Conclusion

Thanks to the tunability, the simmetric focusing and compactness of active plasma lenses these elements could become a viable alternative to conventional magnets by allowing transfer line of the order of the meter.

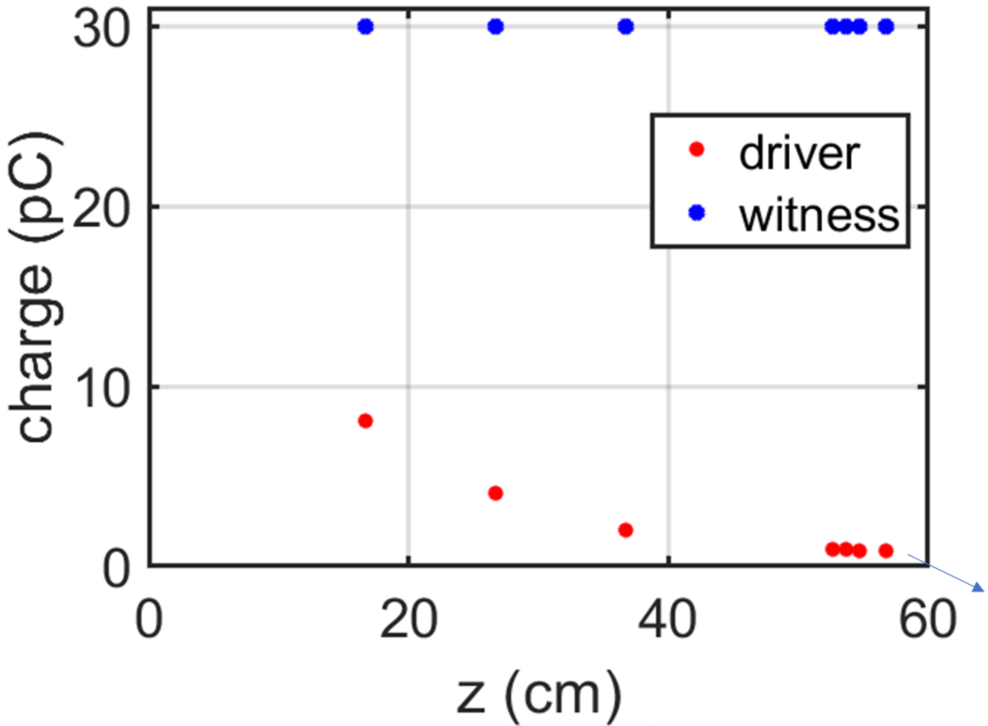


➢ The proposed scheme represents an alternative solution:

- ✓ to driver charge removal along the transport line;
- ✓ to meet the demand for compactness in plasma facilities;
- ✓ to preserve the witness charge considering the emittance growth due to bunches interaction in plasma lenses.

Thank you for your attention!

Backup slides

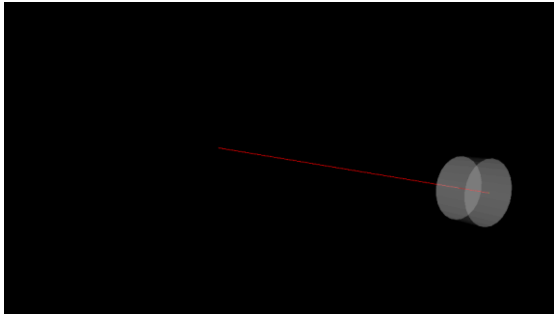


4% della carica del driver

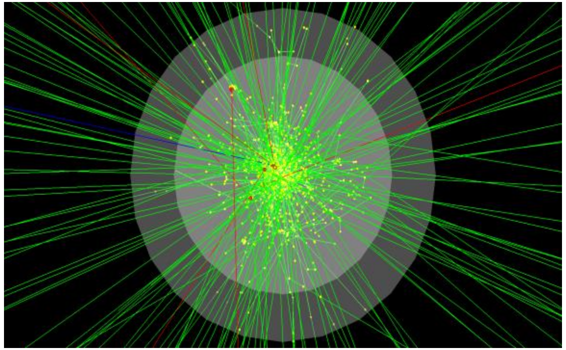
Z collimatore

increasing the distance from the lens the collimator cuts more driver

Geant4 simulation



Wtness electrons in collimator



Interaction of driver electrons with collimator.

Negative charges ->red
Positive charges -> blue
Neutral charges -> green

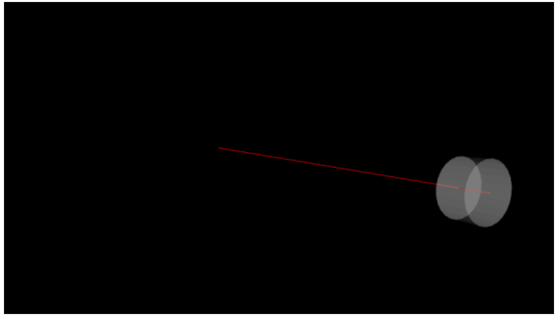
Main electromagnetic processes included:

- *Ionization energy loss*
- *Production of gamma rays*
- *Bremsstrahlung*
- *Multiple scattering*
- *Photoelectric Effect, Compton scattering, Pair production*

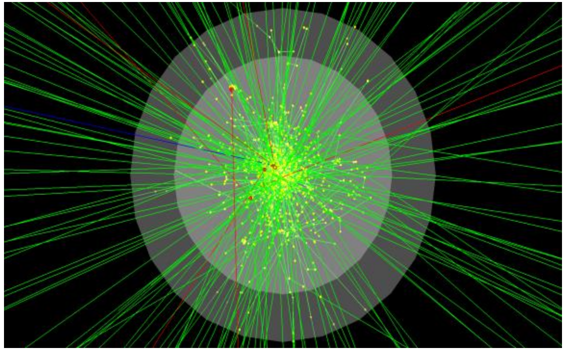
→ *The rest of the simulations made only with primary electrons*

Thanks to Dr.Alessio Del Dotto

Geant4 simulation



Wtness electrons in collimator



Interaction of driver electrons with collimator.

Negative charges ->red
Positive charges -> blue
Neutral charges -> green

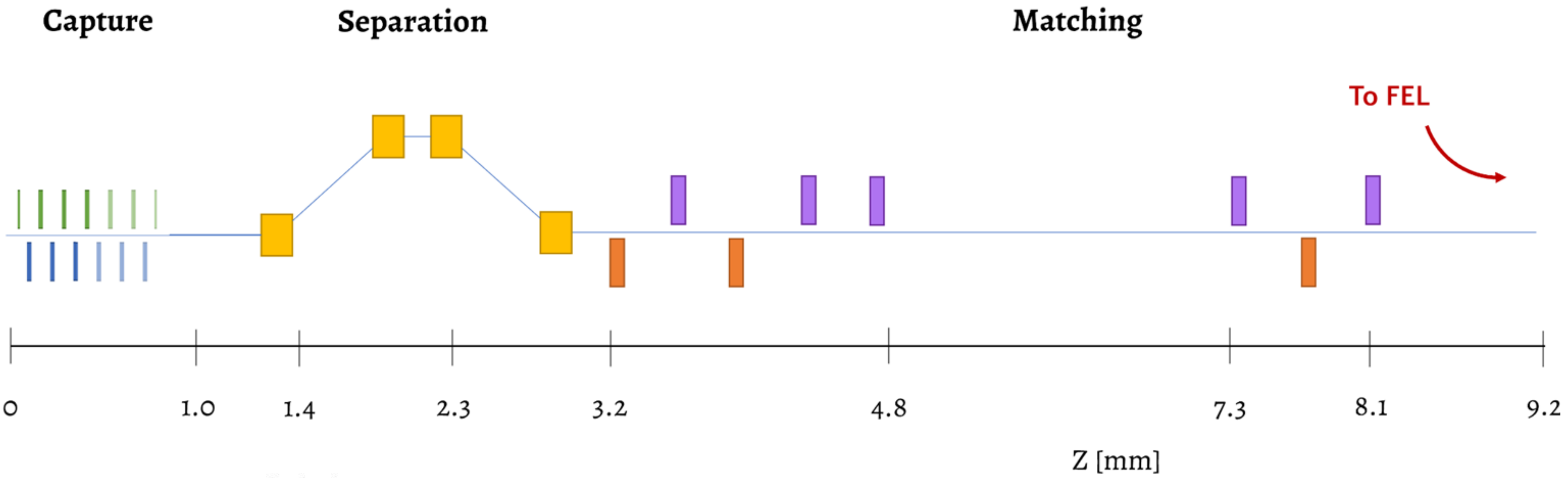
Main electromagnetic processes included:

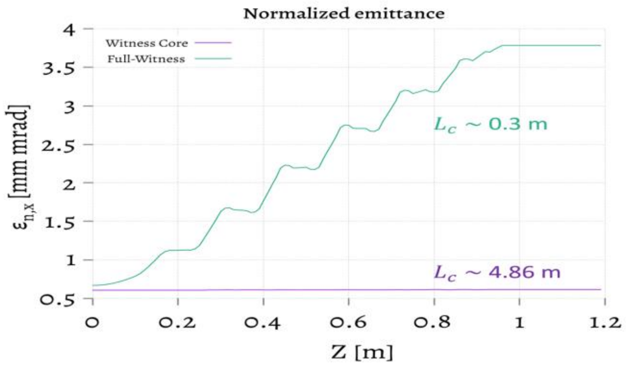
- *Ionization energy loss*
- *Production of gamma rays*
- *Bremsstrahlung*
- *Multiple scattering*
- *Photoelectric Effect, Compton scattering, Pair production*

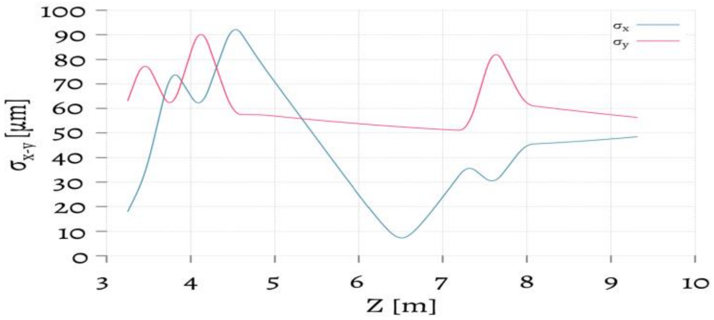
→ *The rest of the simulations made only with primary electrons*

Thanks to Dr.Alessio Del Dotto

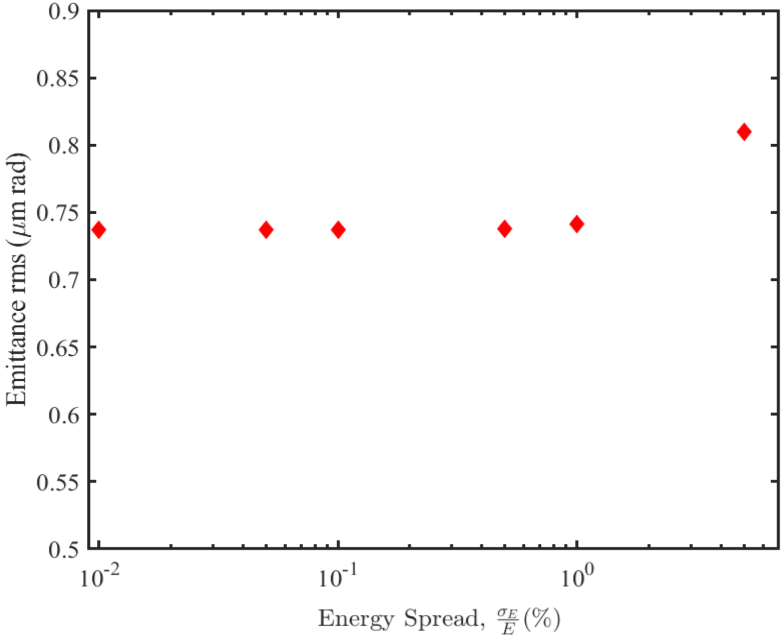
A conventional extraction and transpor





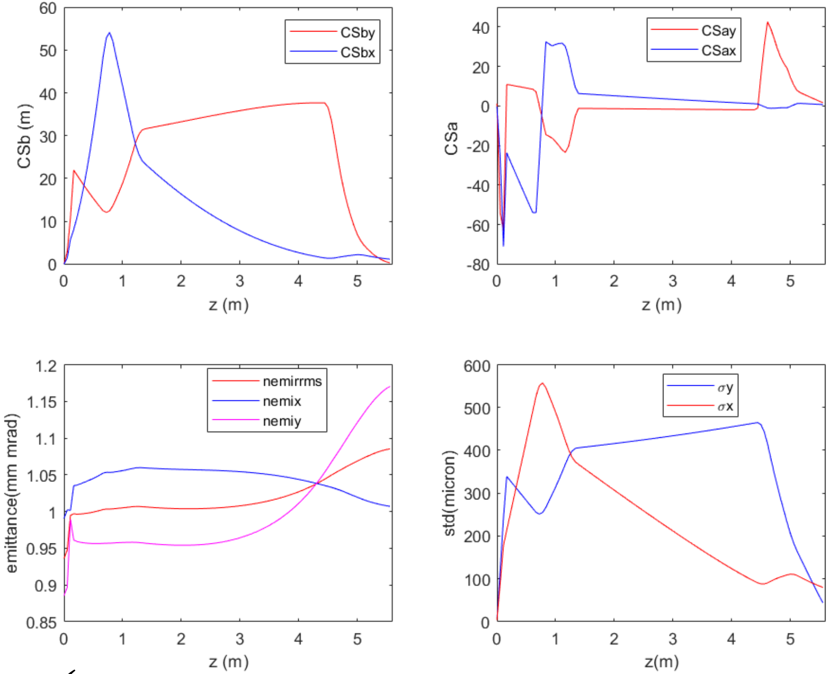


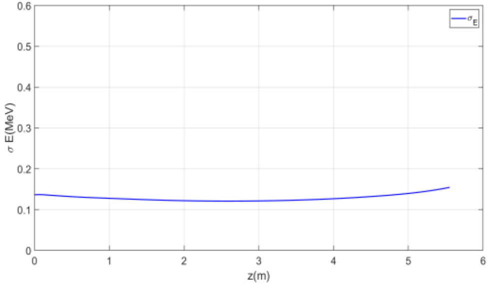
Parametric studies



At the end of line (z= 73.5 cm) the emittance growth is the same (~ 0.74mm mrad) for energy spread ranging from 0.01 to 1 % while it reaches the value of 0.81 mm mrad when energy spread is 5 %.

Simulated witness parameters along transport line





witness	*Z start (0 cm)*	*Z end (5,5 m)*
α_x	-0.3	0.7
α_y	1.2	1.6
β_x(m)	0.002	1.45
β_y (m)	0.003	0.74

Witness parameters	*Z start (0 cm)*	*Z end (5.5m)*
Charge (pC)	30	30
ε_{nrrms}, ε_{nx}, ε_{ny} *(mm mrad)*	0.93, 0.99, 0.88	1.08,1.0, 1.16
σ_x, σ_y *(μm)*	3.5,3.5	80 , 44
σ_z *(μm)*	8.86	8.97
Energy (MeV)	93.74	93.75
σ_E *(MeV)*	0.137	0.154

- ✓ By changing the gradient of the permanent quadrupoles, transverse beam size trends similar to those obtained from emittance measurements were obtained.
- ✓ The final values of the Twiss functions after the transfer line, thus obtained, can be injected into the FEL simulation code.
- ✓ Energy spread and bunch charge remain about constant.