EUROPEAN
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APPLICATIONS

EuPRAXIA
Preparatory Phase

Plasma-Based Solutions for Beam Handling and Driver Extraction

Martina Carillo

On behalf of the SPARC_LAB collaboration

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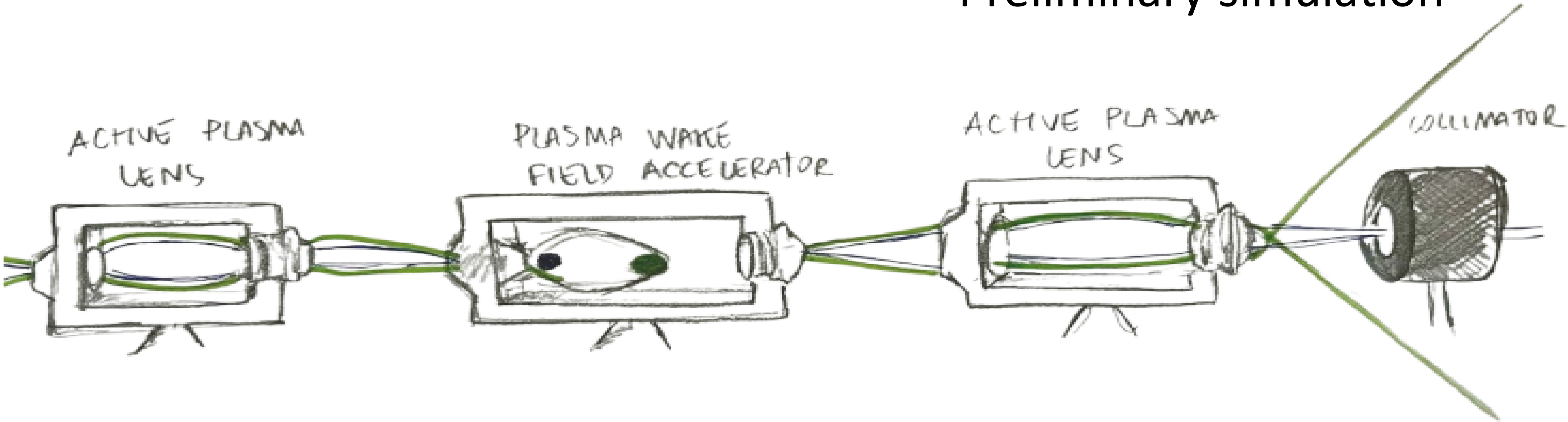
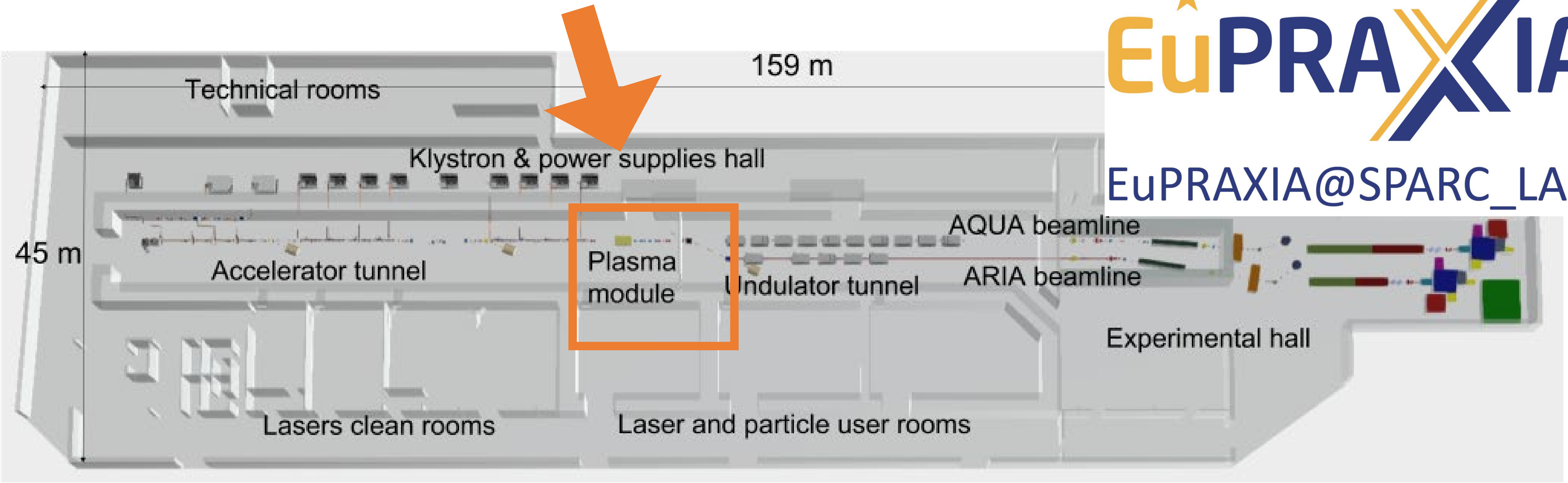
Outline

1. Eupraxia Framework
2. Beams Plasma Matching
   - SPARC_LAB configuration
   - All-in-one Capillary
3. Driver removal system
   - Magnetic elements
   - Plasma lens solution
4. Plasma-Based Solutions
   - Proposed layout
   - Preliminary simulation



EuPRAXIA Framework



EuPRAXIA@SPARC_LAB

1. Beams Plasma Matching

Motivation: PWFA beams handling

Funded by the European Union

Witness

Driver

A plasma acceleration stage consist in three sections:

Plasma Booster section

Injection

Specific matching conditions are required

$$\beta_{eq} = \sqrt{\frac{\gamma}{2\pi r_e n_p}} \longrightarrow \sigma_r = \sqrt{\beta_{eq}\epsilon_n/\gamma} \sim \mu m$$

Acceleration

Exctraction

Beam handling to reduce large angular divergence and control emittance growth

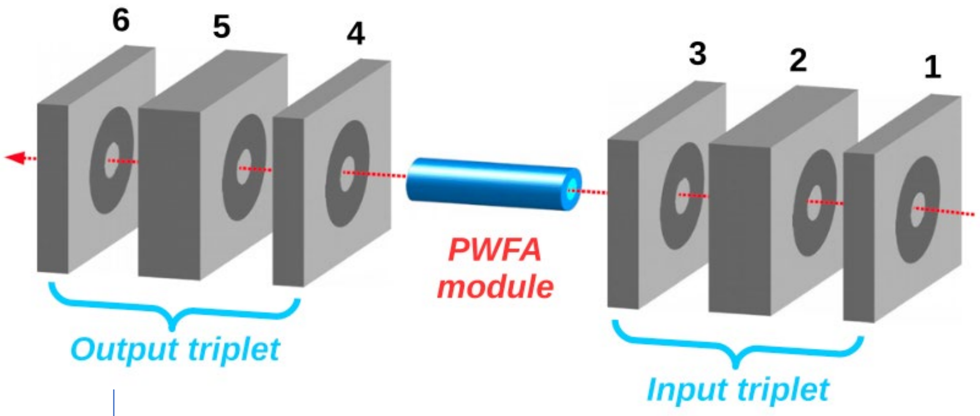
$$G[MT/m] = \frac{F_r}{ecr} \sim 3n_p\ [O(10^{15-16}\ )]$$

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

Injection/Extraction scheme in PWFA

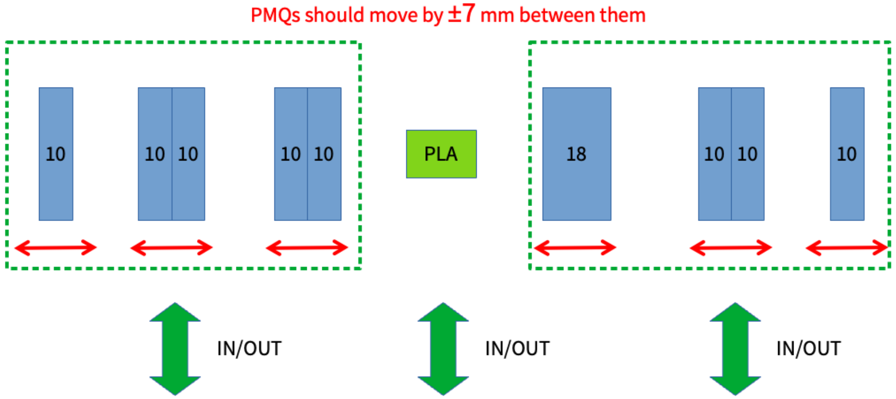
[*]Pompili et al., Rev. Sci. Instrum. 89, 033302 (2018)

PMQs currently represent the sate of the art:

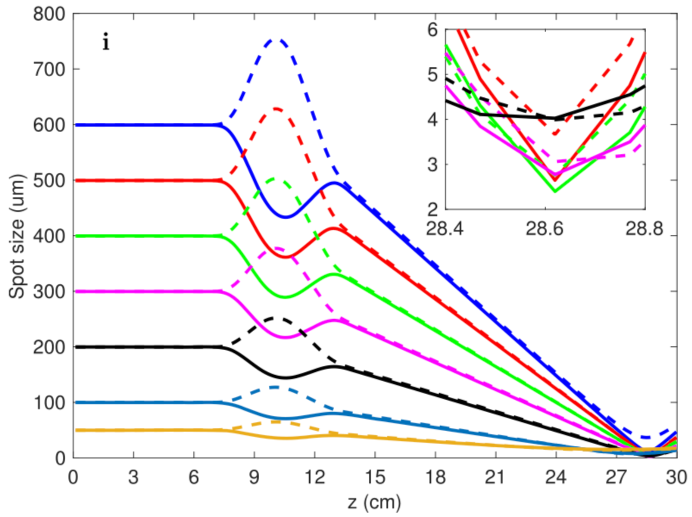


Extraction of the accelerated bunch

Focus multiple bunches into PWFA module



$$\beta_f \approx \frac{f^2}{\beta_i}$$



Symmetric focusing is achieved with a triplet system

- focusing strength: K∝ $1/\gamma$
- focal length ~ 10 cm (not easily tunable focal length)
- a single system covers only a narrow range of energy
- non-trivial adjustable holder are needed to remotely control the focal length

Plasma Lens

Plasma Lenses: Focusing Mechanisms

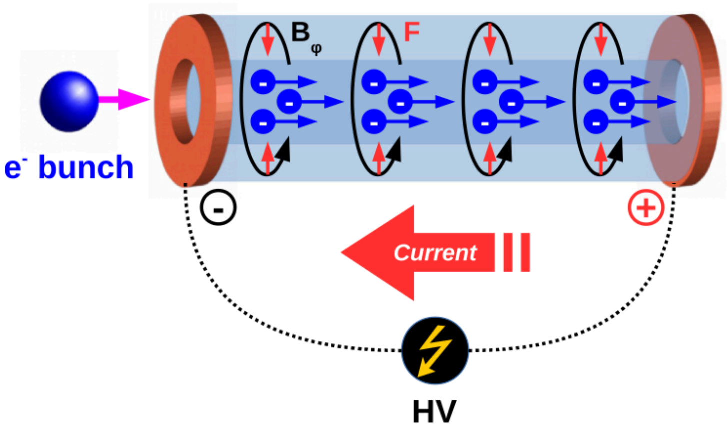
1. Passive Plasma Lens:

- **Mechanism**: Self-focusing.
- **Process**: Shielding produced by background plasma, which reorganizes to maintain overall neutrality after the passage of a driver beam.

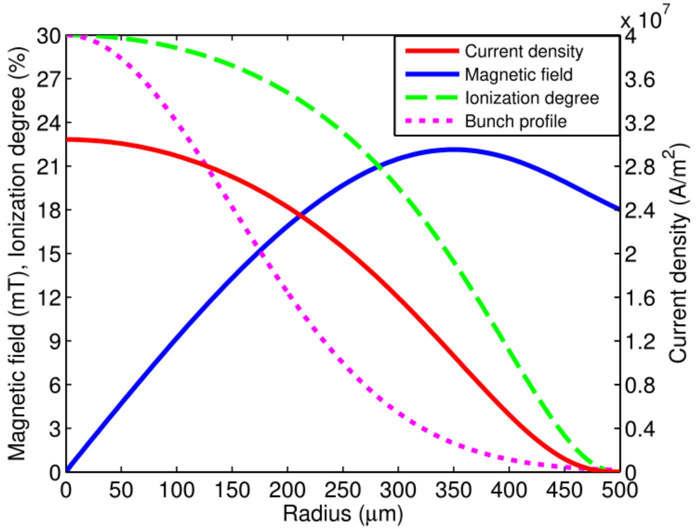
2. Active Plasma Lens:

- **Mechanism**: Azimuthal magnetic field.
- **Process**: Generated by an externally driven axial current.

Magnetic Field (B_φ) vs Force on electrons (F)



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



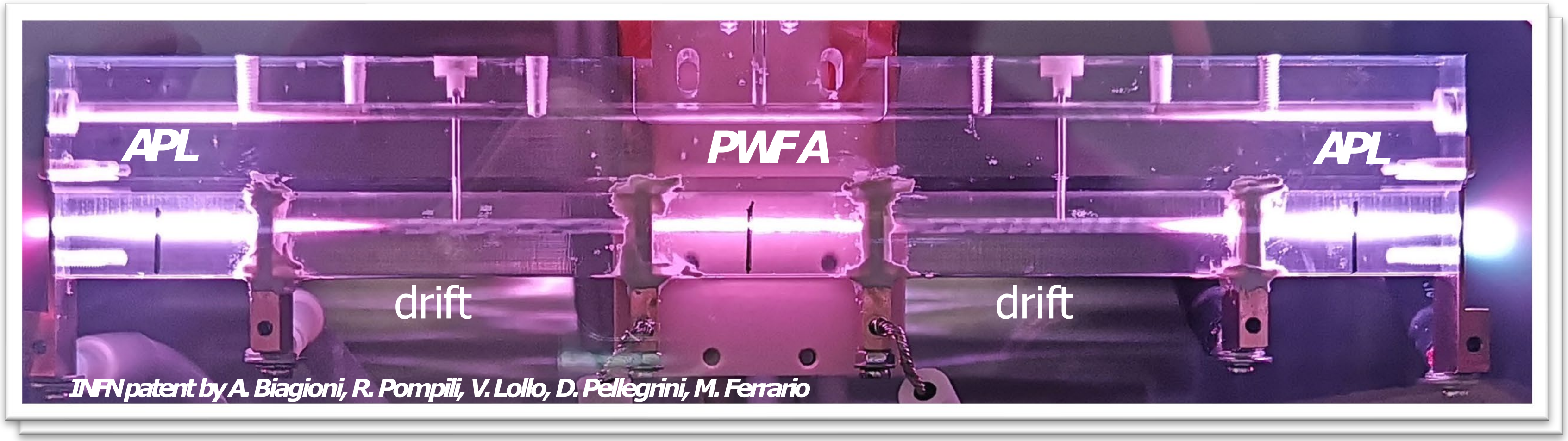
[*]E. Chiadroni et al. Overview of plasma lens experiments and recent results at SPARC_LAB, Nuclear Inst. and Methods in Physics Research, A 909 (2018) 16–20

[*]R.Pompili, et al., Experimental characterization of active plasma lensing for electron beams, Appl. Phys. Lett. 110 (10) (2017) 104101.

- Cylindrical symmetry
  - purely radial focusing effect
- Tunability
- Focusing strength: K$\propto 1/\gamma$
- High focusing gradient ~ kT/m
  - short focal length
  - weak chromaticity

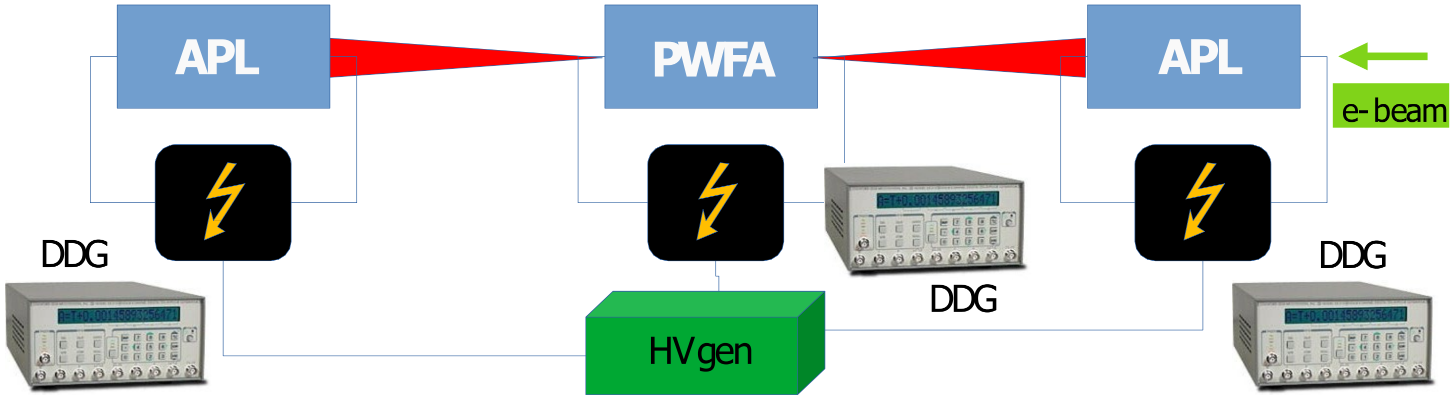
Compact Plasma Device for Acceleration and Focusing

[*]R. Pompili et al., Phys. Rev. E **109**, 055202 – Published 3 May 2024



- **19 cm capillary length** and 2 mm diameter
- Laser pre-ionizes the gas, stabilizing the discharge and reducing **jitter to a few nanoseconds**
- The high-voltage **discharge currents are provided by three pulsers** capable of generating up to 1.6 kA peak current

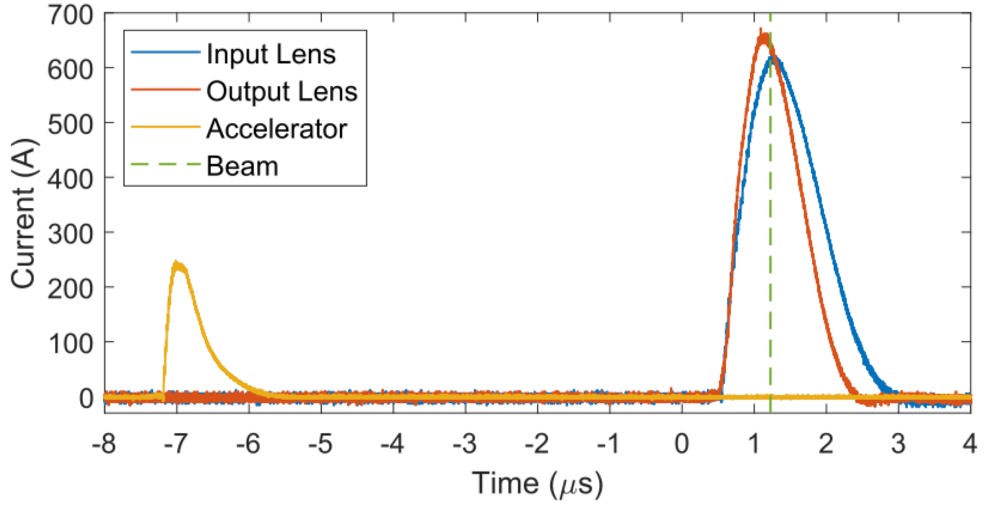
The discharge current and plasma density can be independently tuned and controlled in each plasma stage.



Experimental Results

SPARC_LAB RF photinjector beams:

	Driver	Witness
Energy [MeV]	71.6± 0.1	71.9±0.1
Energy spread [MeV]	0.49 ±0.03	0.72 ±0.04
Duration [fs]	185 ±39	55 ±32
Emittance [μmrad]	6.2±0.7	4.8±0.4
Dealy [ps]	1.15±0.03	

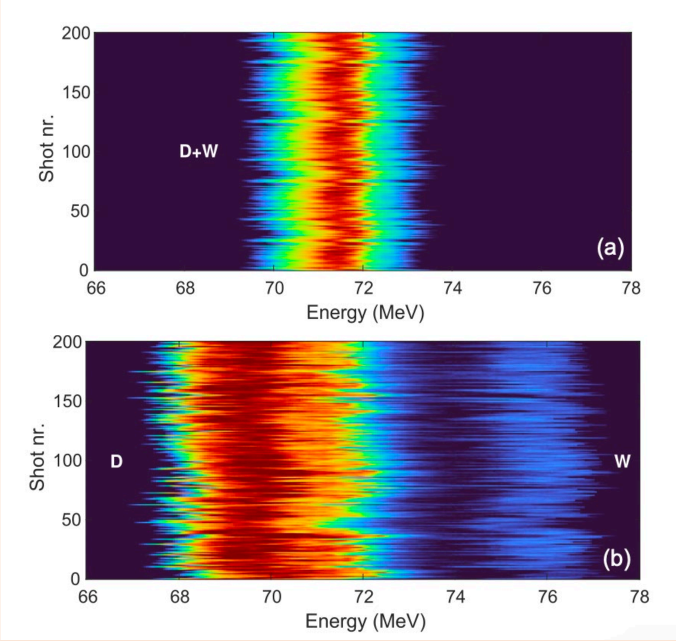


$n_{p_{APL,1}} \approx 2 \times 10^{17} cm^{-3}$

$n_{p_{PWFA}} \approx 4 \times 10^{15} cm^{-3}$

Witness Energy gain of 4.5 MeV over a distance of 3 cm

A proof-of-principle experiment merged three plasma stages into a compact device that can focus, accelerate, and extract a witness bunch in a plasma-based accelerator.



[*]R. Pompili et al., Phys. Rev. E **109**, 055202 – Published 3 May 2024

2. Driver removal system

Motivation: PWFA driver removal system

Funded by the European Union

Driver Removal
System

One of the most significant drawbacks occurs at the end of the acceleration process: the need to remove the depleted high-charge driver beams while maintaining the key characteristics (emittance and peak current) of the accelerated witness bunch.

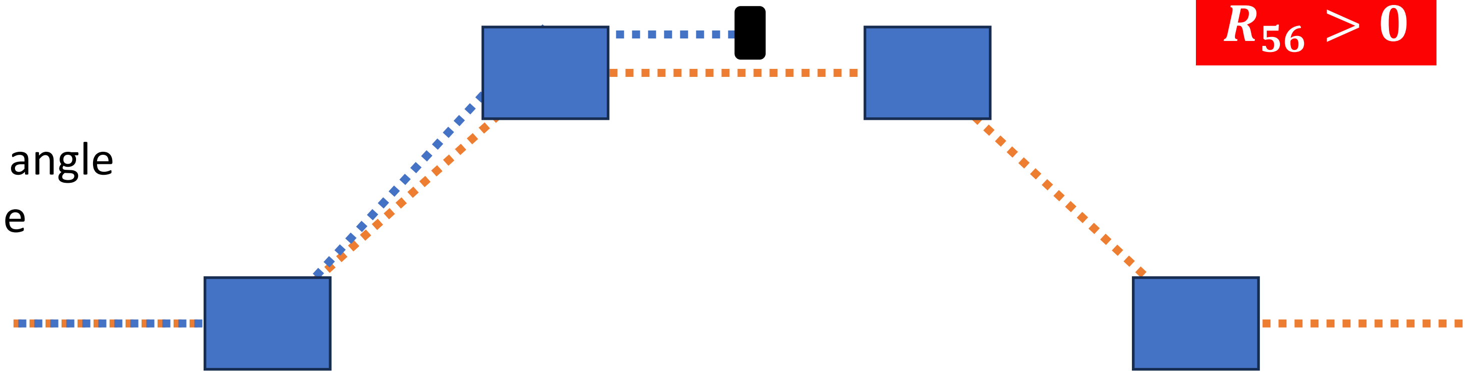
Magnetic Solution: Chicane & Dogleg

Funded by the European Union

MAGNETIC CHICANE

More energetic witness → smaller deflection angle
Less energetic driver → larger deflection angle

Transverse separation



$R_{56} > 0$

Length: from $3\ to\ 10\ m$

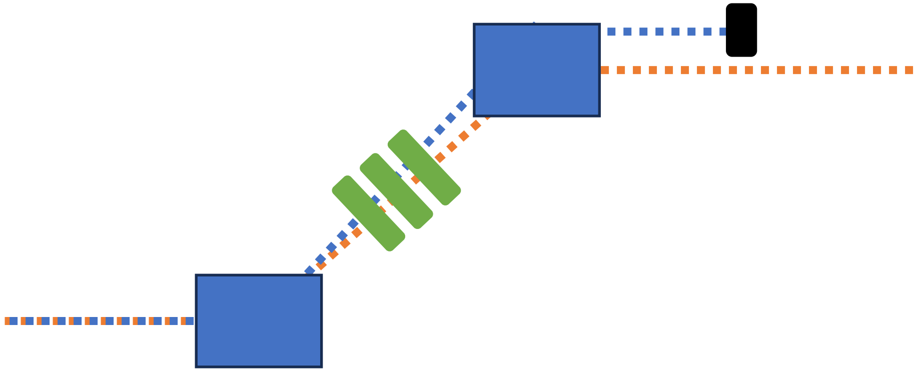
$$R_{56} = \frac{\Delta z}{\delta} \cong -2L_1\theta_0^2$$
for $\theta_0 \ll 1$

DOGLEG

Same principle of chicane

More compact

More magnetic elements (like quadrupoles) are needed



$R_{56} < 0$

Plasma Lens Solution: scheme

Plasma lens-based beam extraction and removal system for plasma wakefield acceleration experiments

R. Pompili,[1,*] E. Chiadroni,[1] A. Cianchi,[2] A. Del Dotto,[1] L. Faillace,[3] M. Ferrario,[1] P. Iovine,[4] and M. R. Masullo[4]

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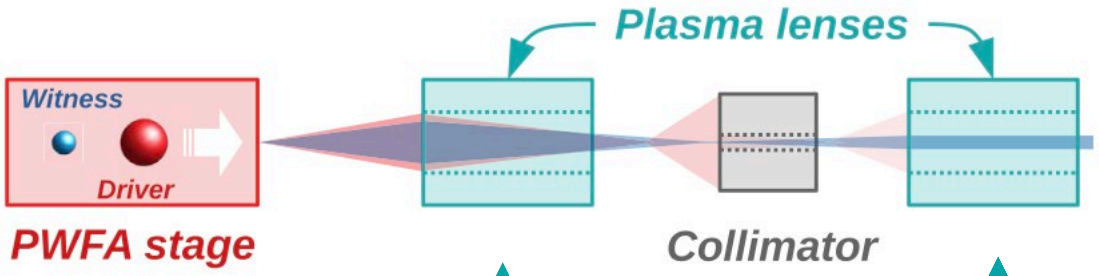
$R_{56} = 0$

Two goals:

(i) **transport the witness** bunch by preserving its charge, normalized emittance, and peak current;

(ii) **remove** the high-charge **driver** bunch during the transport to completely discard it before the FEL undulator beamline.



The focusing is provided by two active-plasma lenses (APLs)

Collimator remove the driver bunch overfocused to a spot size much larger than the collimator clear aperture.

Plasma Lens Solution: simulations

[*]P.Iovine, PhD Thesis, Study of the transfer and matching line for PWFA-driven FEL

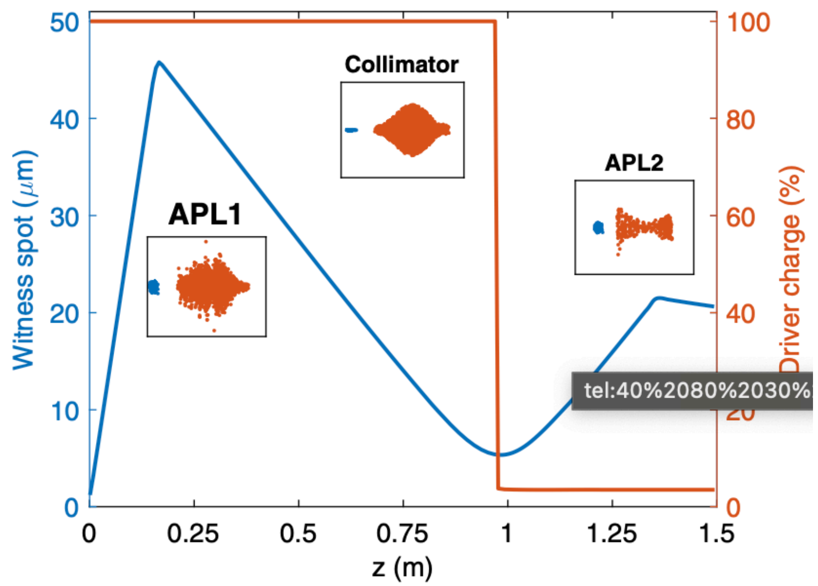
The dynamics of the beam in the plasma lenses is then computed by a 2D code written to solve the wavefield equations in the linear regime

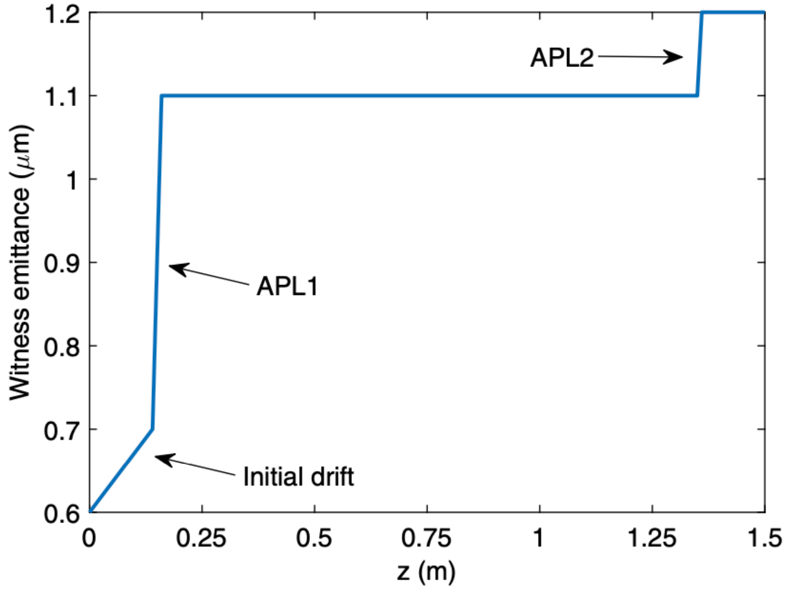
TABLE I. Witness and driver bunches parameters at the exit of the PWFA module.

Parameter	Units	Witness	Driver
Charge	pC	30	200
Duration (rms)	fs	11.5	160
Peak current	kA	2.6	1.2
Energy	MeV	1016	460
Energy spread (rms)	%	0.73	16
Normalized emittance	μm	0.6	5
Spot size	μm	1.2	7

TABLE II. Optimized parameters (size, radius, and position) for the APLs and collimator used in the proposed extraction system. The position of each element (along z) is relative to the exit of the PWFA module. For the APLs, the current discharge (I_D) and plasma density (n_p) are also reported.

	Size (cm)	Radius (mm)	z (cm)	I_D (kA)	n_p (cm^{-3})
APL 1	2	0.5	15	1	10^{16}
Collimator	3	0.2	97		
APL 2	1	0.5	135	0.6	10^{16}



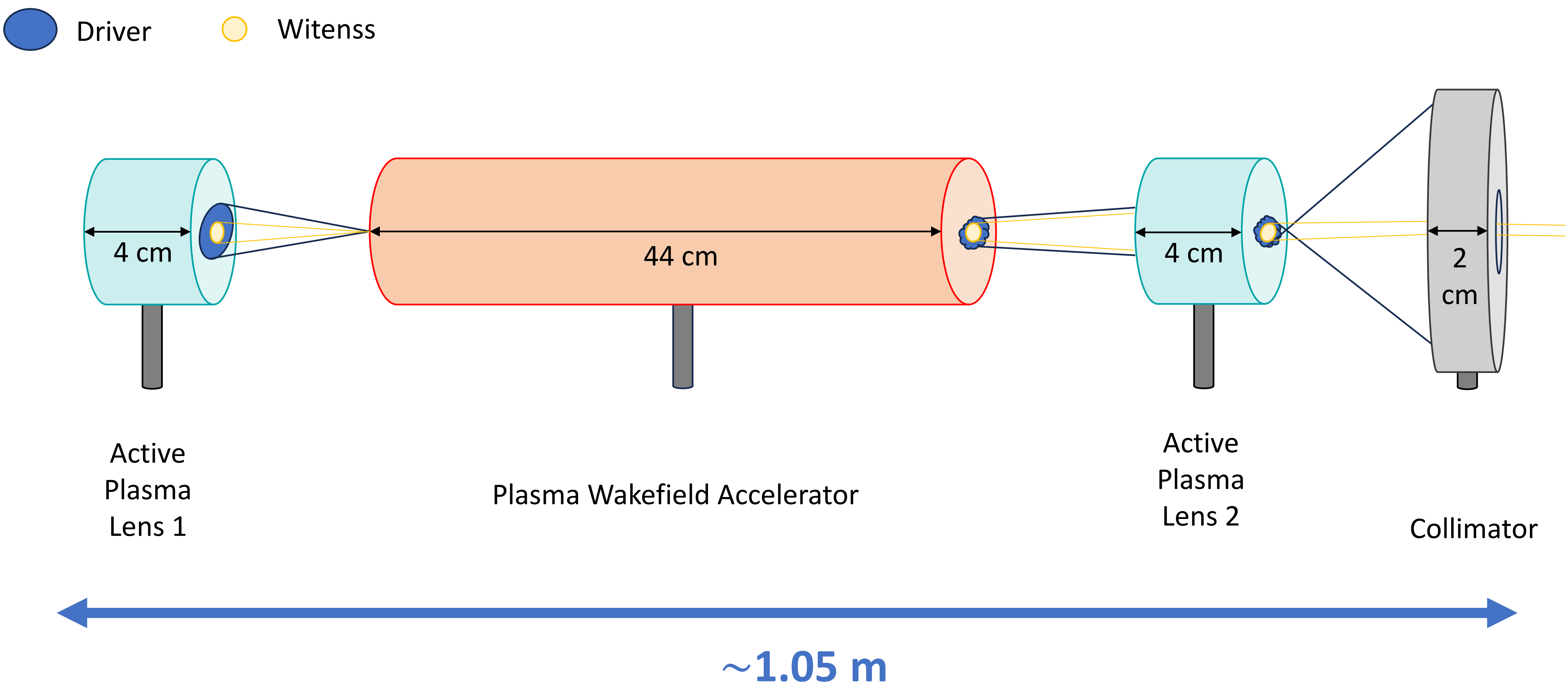


Considering all the elements and drift spaces involved,
the total length of the system is 1.4 m.

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

3. Plasma-Based Solutions for Beam Handling and Driver Extraction

Layout


Driver
Witenss
4 cm
44 cm
4 cm
2 cm
Active Plasma Lens 1
Plasma Wakefield Accelerator
Active Plasma Lens 2
Collimator
~1.05 m

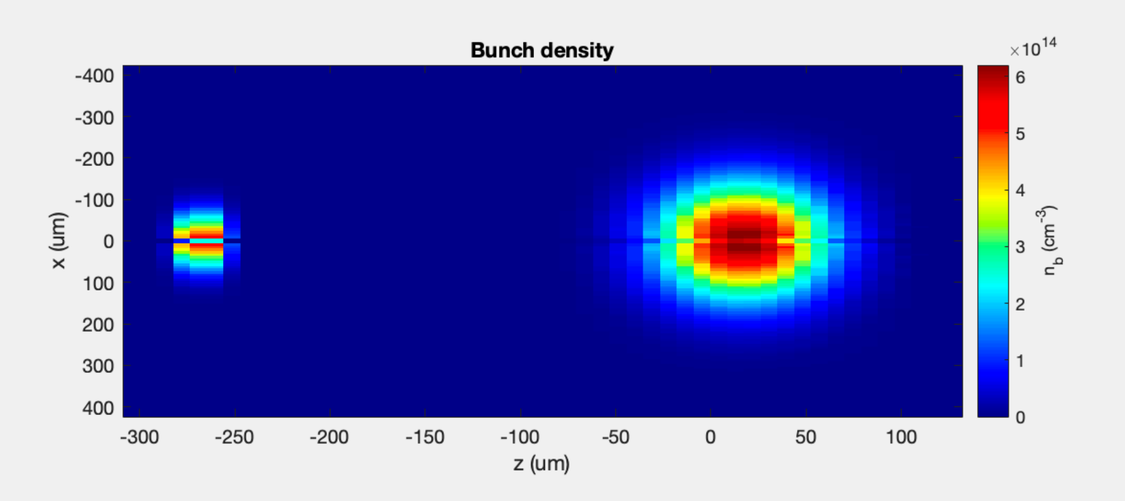
Beam Configuration

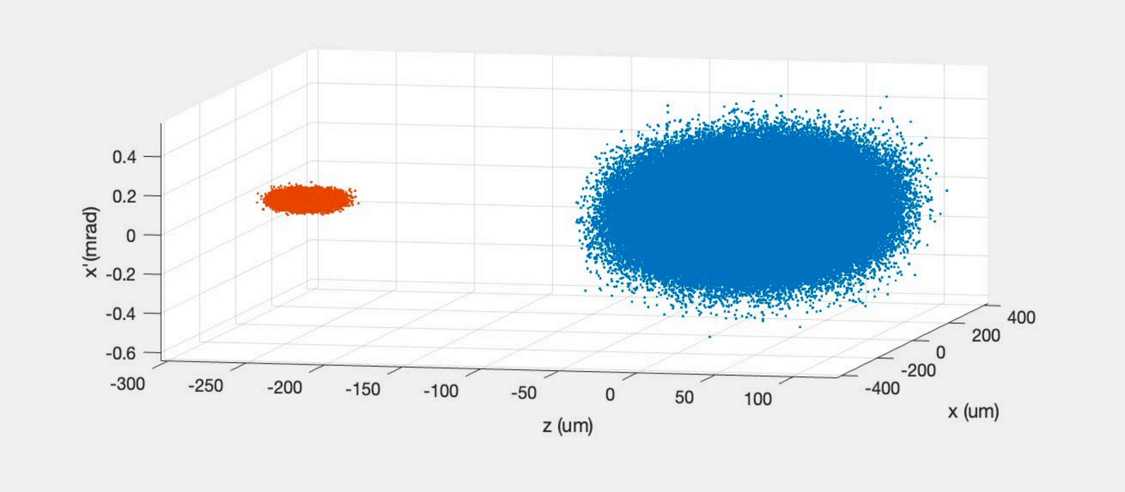
Input Beam Parameters:

	Driver	Witness
Charge $[pC]$	500	50
Energy $[MeV]$	540	540
Energy Spread $[MeV]$	0.5	0.4
SpotSize $[\mu m]$	150	50
Bunch Length $[fs]$	100	20
Norm. emittance $[\mu mrad]$	13	1

*Beam Gaussian Distribution

Bunch distances: $\Delta t = \ 0.95\ ps$



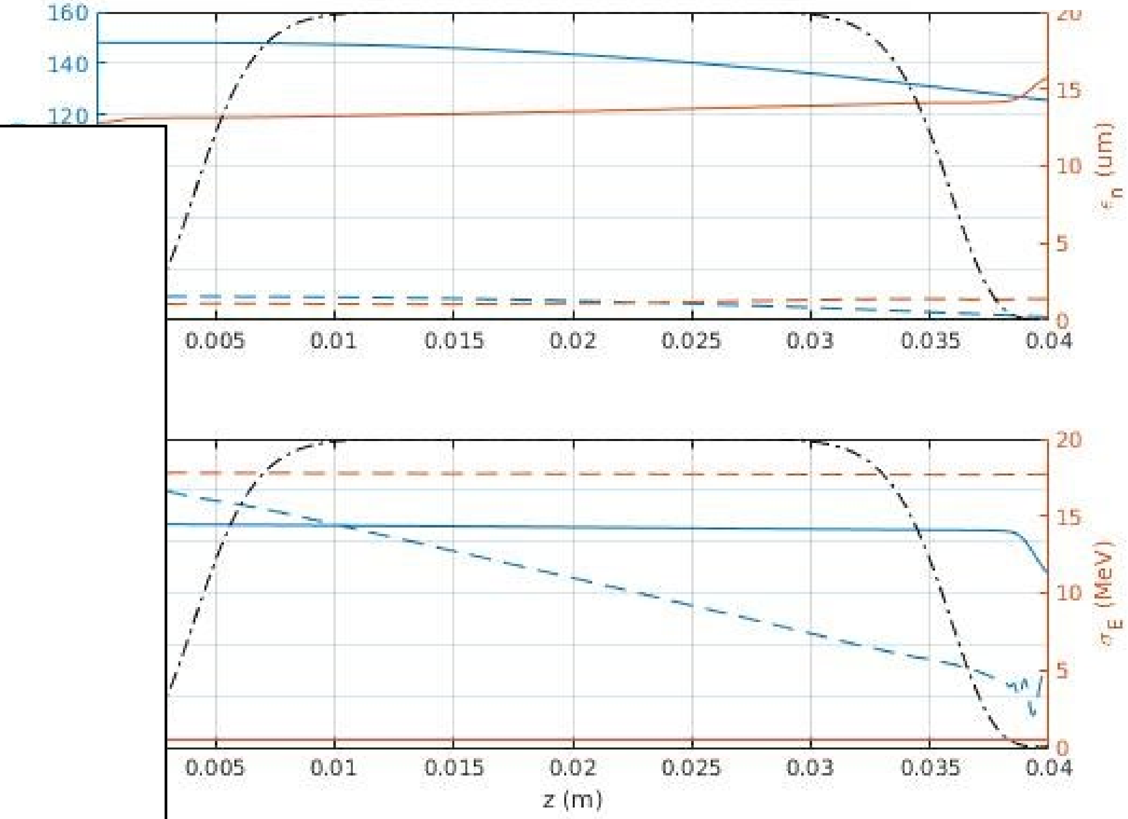


Active Plasma Lens 1

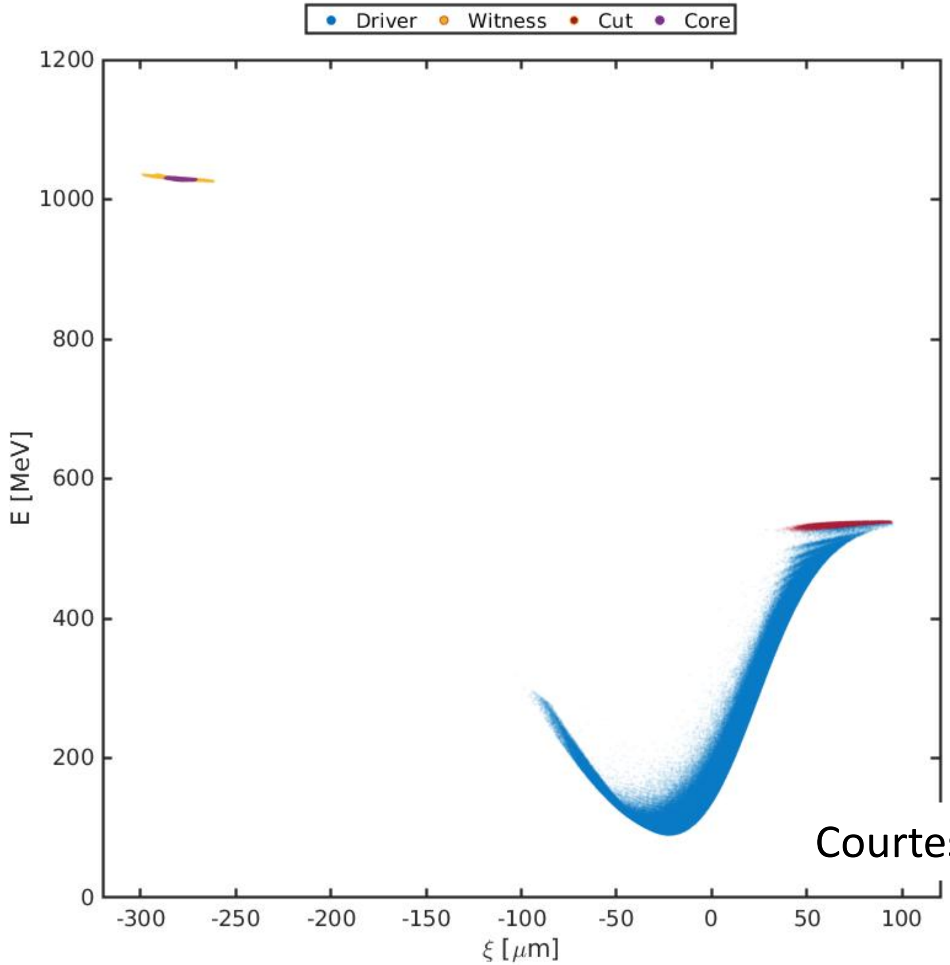
Plasma Simulation Parameters:

Peak Density	$5 \times 10^{18}\ \mathrm{cm}^{-3}$
Lenght	$3\ cm + 2 * 0.5\ cm$ (ramps)
Current	$2kA$

Continuos lines: Driver
Dashed lines: Witness



Plasma WakeField Acceleration



Peak Density	$3.8 \times 10^{15}\ \mathrm{cm}^{-3}$
Lenght	$38\ cm + 2 * 3\ cm$ (ramps)

Accelerating gradient: $\sim 1.4\ GeV/m$

Witness exit emittance $\epsilon_n = 4.2\ \mu mrad$
Witness exit spotsize $\sigma_x \sim 5\ \mu m$

Courtesy of S. Romeo and A. Del Dotto

Active Plasma Lens 2

Funded by the European Union

Plasma Simulation Parameters:

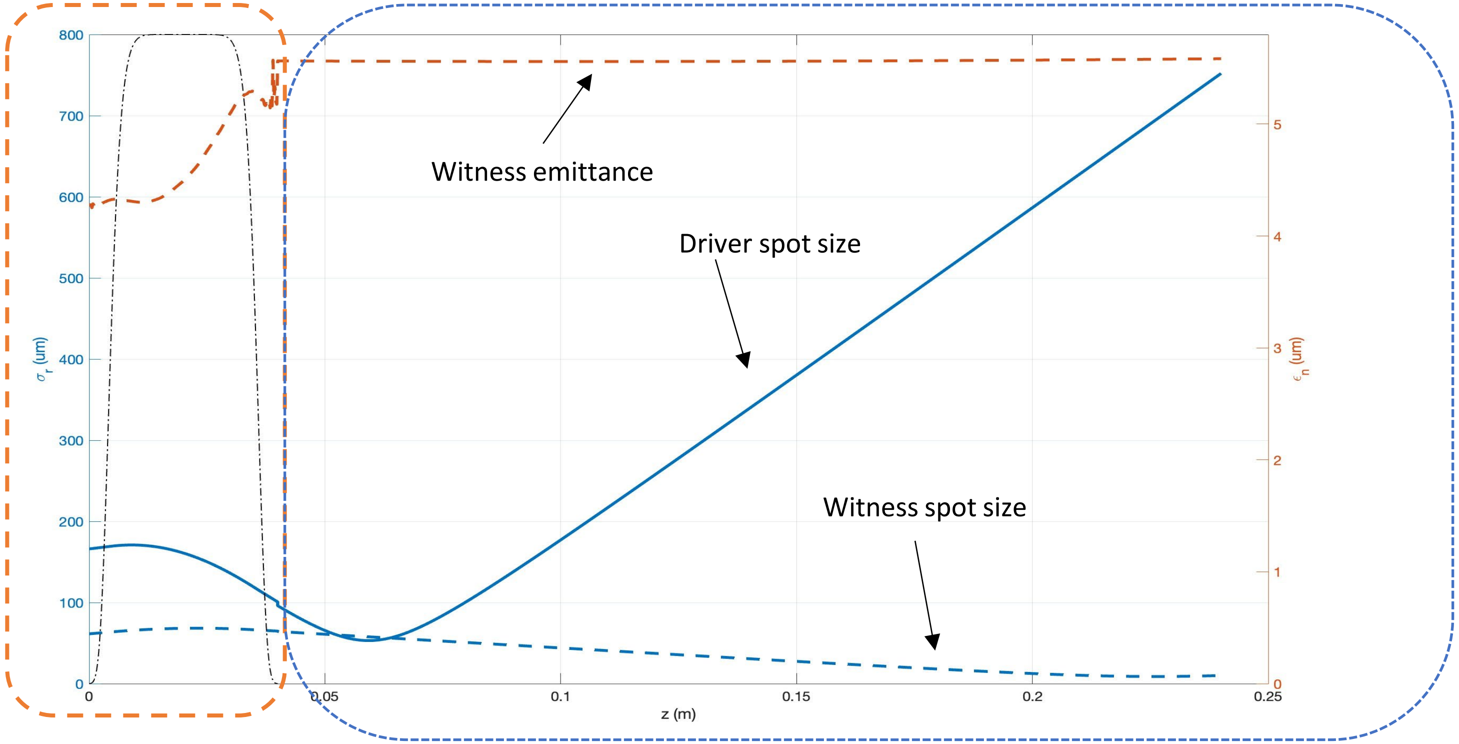
Peak Density	$5 \times 10^{18}\ \mathrm{cm}^{-3}$
Lenght	$3\ cm + 2 * 0.5\ cm$ (ramps)
Current	$5.5\mathrm{k}A$

Drift Evolution:
20 cm long

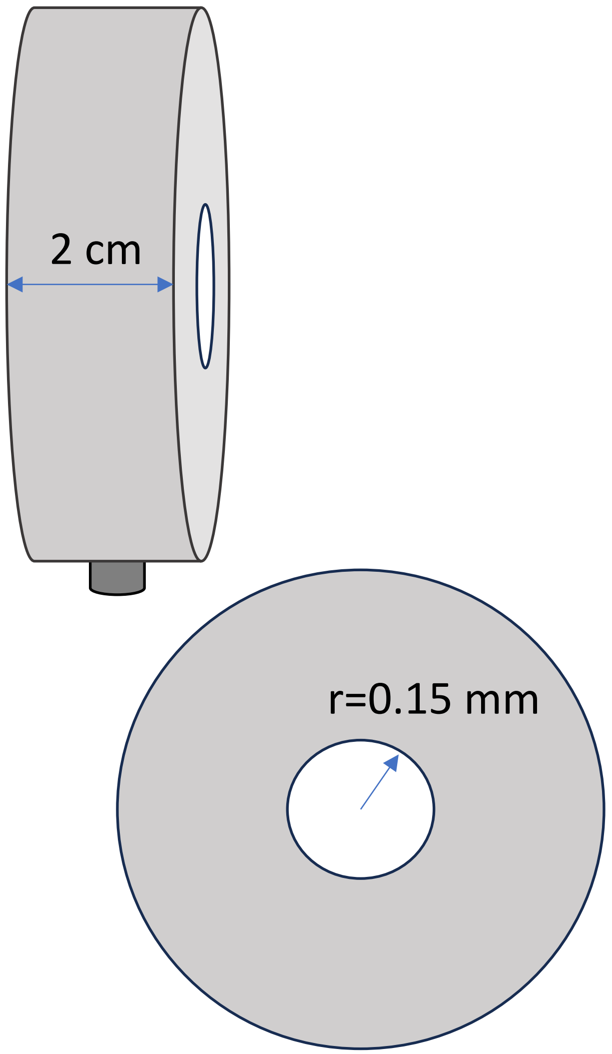
Witness Output transverse parameters:

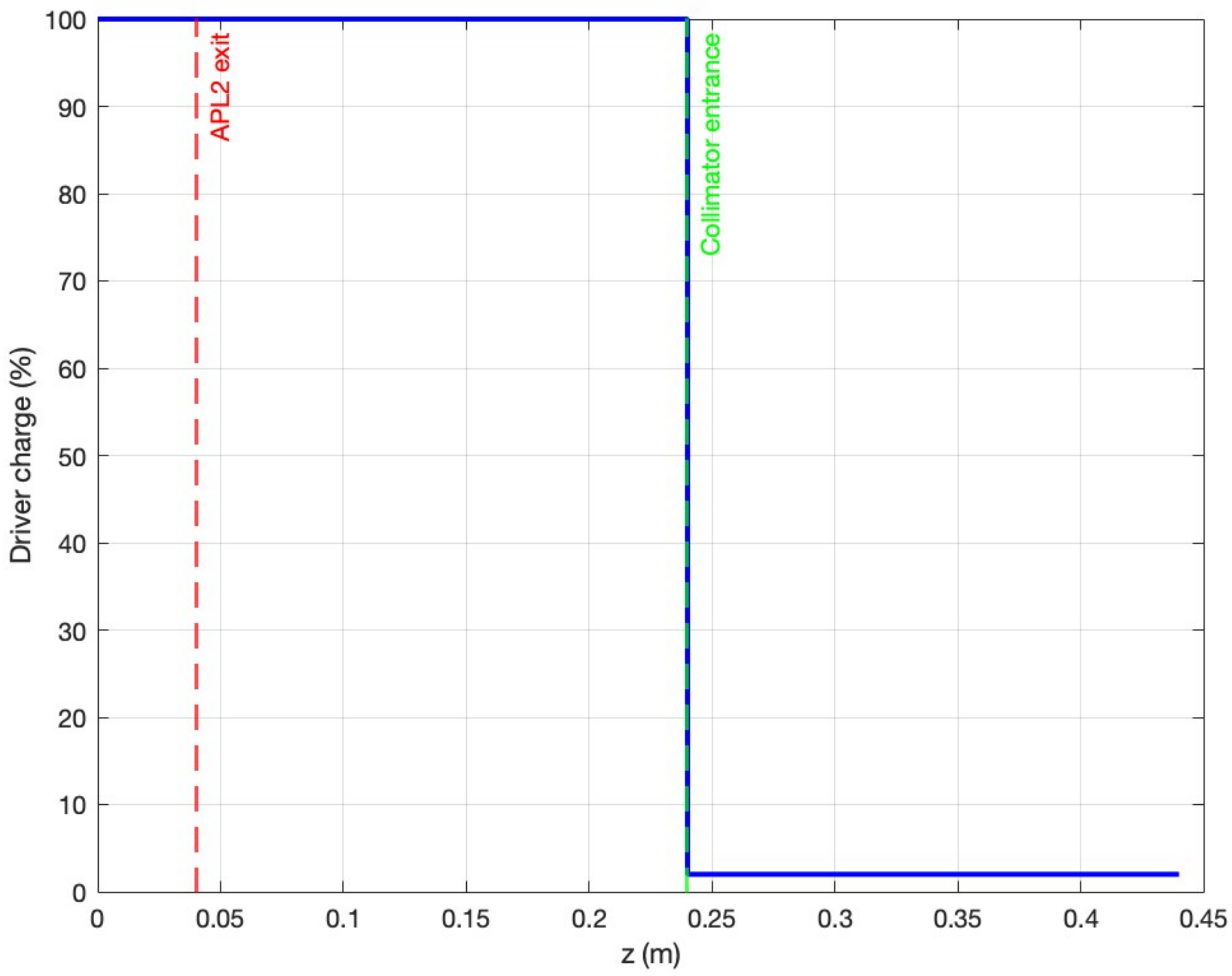
$\sigma_x \approx 10\ \mu m$
$\epsilon_n \approx 5.5\ \mu mrad$

Second Active Plasma Lens



Collimator





98% of the driver charge has been removed

Conclusion

A new **plasma-based** model has been presented, featuring:

- ✓ **Beam handling and driver removal** using APL
- ✓ **Compact structure** (< 1.5 m)
- ✓ Preservation of longitudinal dynamics ($R_{56} = 0$)

Preliminary Simulation results: Good performance in terms of beam dynamics.

Next Steps:

Improve the simulation studies and feasibility study:

- **Study parametric scans** for optimization
- Use **more accurate simulation codes**
- **Analyze the interaction** with the collimator
- Matching up to undulator and validation to FEL simulations

Thank you for your attention

Funded by the European Union