Plasma lens-based beam extraction and removal system for Plasma Wakefield Acceleration experiments

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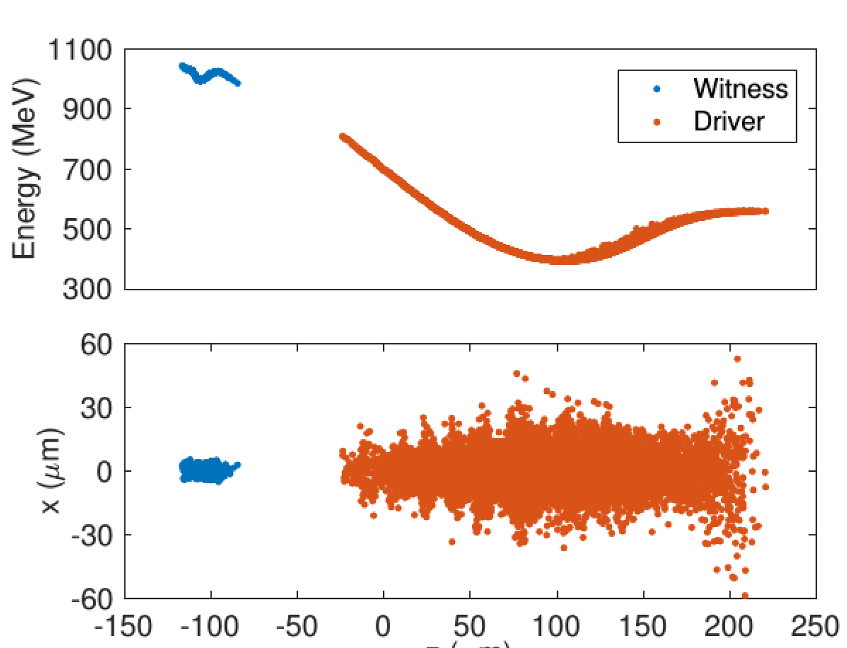
Abstract

A theoretical study demonstrating the possibility of removing the driver bunch from the witness beam in Plasma Wakefield Acceleration (PWFA) making use of plasma lenses and collimator is presented. The considered case study is in the context of the EuPRAXIA project.

The EuPRAXIA design study

In the context of accelerator research, a fundamental milestone is represented by the realization of a plasma-driven facility that will integrate high-gradient accelerating plasma modules with a short-wavelength Free Electron Laser (FEL). In such a context, the Horizon 2020 design study EuPRAXIA (European Plasma Research Accelerator with eXcellence In Applications) project aims at designing the world's first accelerator facility based on advanced plasma-wakefield techniques to deliver 1-5 GeV electron beams that simultaneously have high charge, low emittance and low energy spread, which are required for applications by future user communities. EuPRAXIA foresees the realization of two facilities: one exploiting laser-driven and the other beam-driven plasma acceleration. For the beam-driven scenario the LNF-INFN laboratories in Frascati (Italy) has been selected as a possible hosting site. To generate FEL this facility will make use of X-band linac to produce and pre-accelerate a driver-witness beam up to 500 MeV and then inject it into a PWFA-based booster to increase the energy up to 1 GeV.

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
Emittance	μm	0.6	5
Spot size	μm	1.2	7



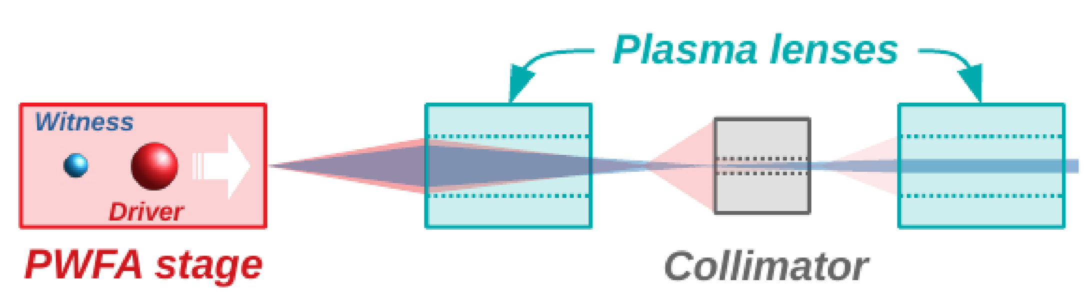
The figure shows the simulated longitudinal phase space of 200 pC driver bunch followed by a 30 pC witness beam downstream the PWFA module.
The table summarizes the mail parameters of the two bunches exiting the PWFA module.

References

- Ferrario, M., et al. "EuPRAXIA@ SPARC_LAB Design study towards a compact FEL facility at LNF." NIMA 909 (2018): 134-138.
- Pompili, R., et al. "Plasma lens-based beam extraction and removal system for Plasma Wakefield Acceleration experiments." arXiv preprint arXiv:1909.01001 (2019).

Extraction system

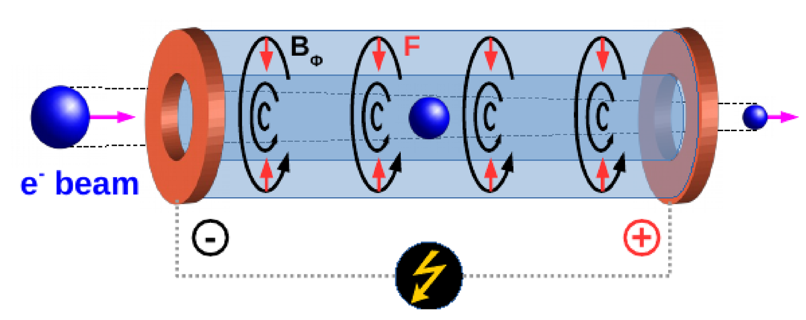
Exiting the plasma the beam moves from a region with an intense focusing field to free space → divergence growth → emittance growth. Two conditions have to be fulfilled: witness preservation and driver removal.
The capture and focusing of the witness beam are provided by two Active Plasma Lenses (focusing fields of the order of kT/m); between the lenses a lead collimator is used to remove the driver bunch.



The focusing strength of the lenses are set up to rapidly catch the witness bunch (blue) downstream the PWFA stage and allow for its transport without any loss of charge. The driver bunch (red) has a lower average energy and is thus overfocused.

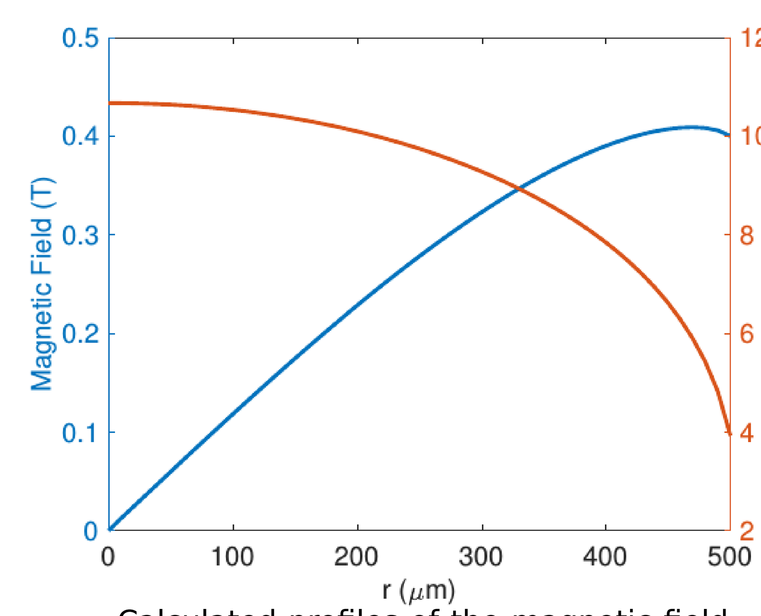
Active-plasma lens

An APL essentially consists of a current-carrying cylindrical conductor whose axis is parallel to the beam. Here the plasma (produced after the ionization of the gas confined within the capillary) only acts as a conductor, while the net focusing effect is produced by the flowing discharge current.



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

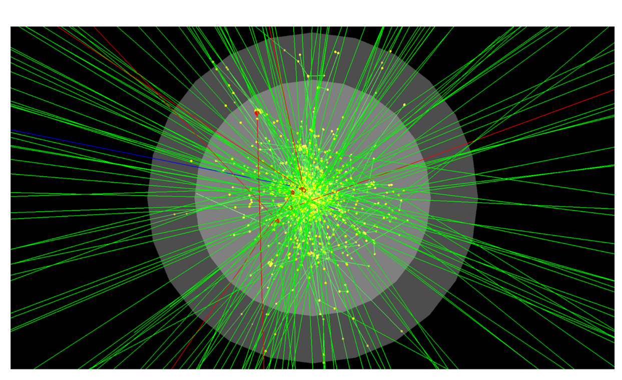
Resulting magnetic field is simply given by the Ampere law



Calculated profiles of the magnetic field (blue) and plasma temperature (red) along the capillary radius.

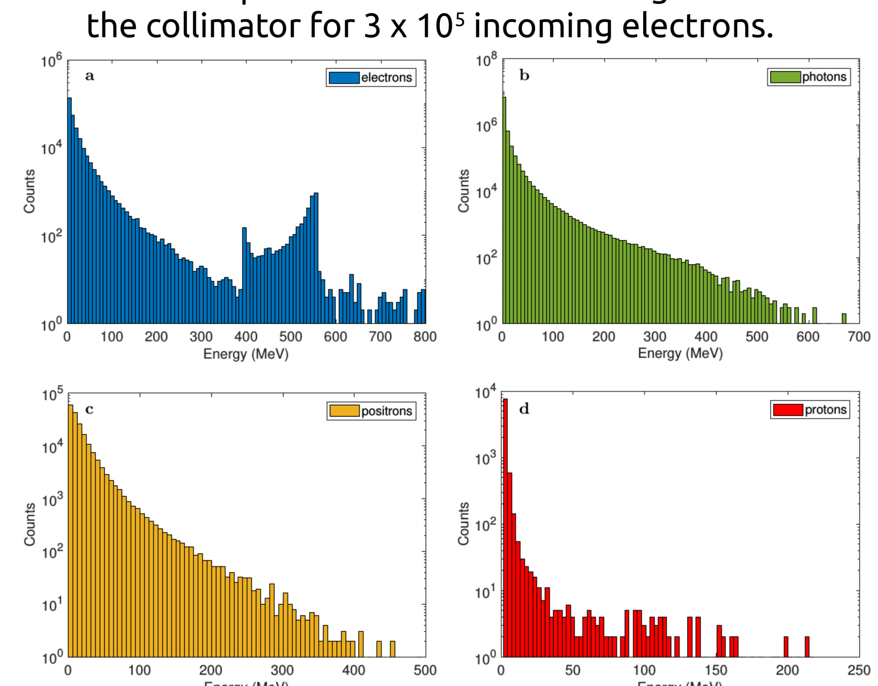
Beam interaction with the collimator

The interaction of the driver beam with the lead collimator has been numerically simulated by means of the GEANT4 framework, a single particle tracker which takes into account all the fundamental radiation-matter interactions.



3 cm-long lead cylinder with outer radius of 1 cm and 200 µm radius aperture allows to absorb/deviate ≈ 98% of the driver charge in the collimator while the witness remains untouched.

Particles produced in a 4π solid angle around the collimator for 3 x 10^5 incoming electrons.

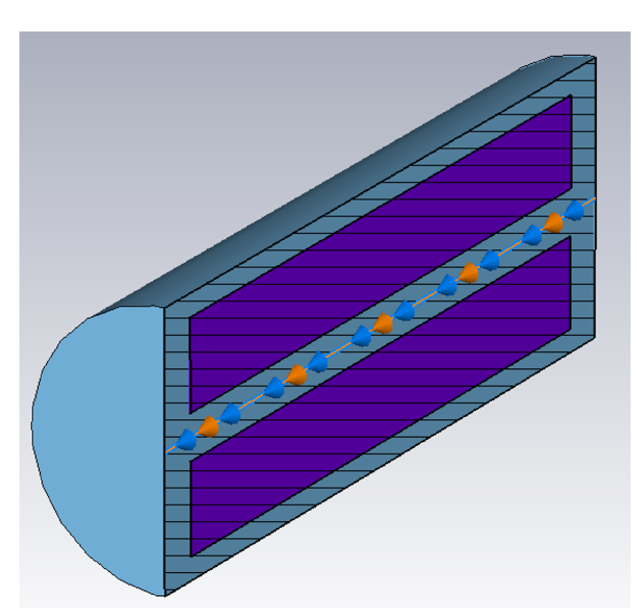


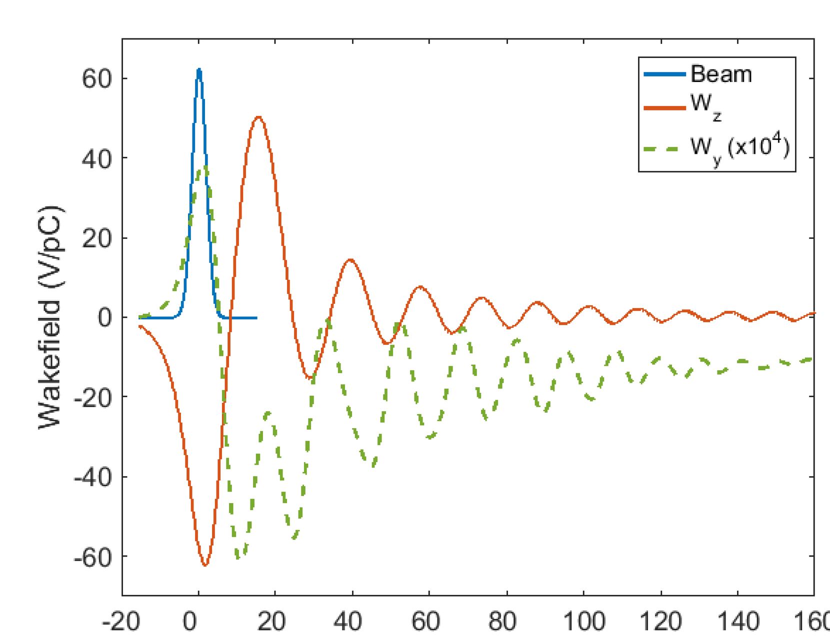
Resistive wakefields

The witness bunch passing trough the lead collimator is affected by resistive wakefields. The collimator structure has been simulated with CST.
The resulting energy loss and the angular deflection of the witness bunch are negligible:

$$\Delta E \approx 50\ keV$$

$$\Delta\theta \approx 2.88 \times 10^{-9}\ rad$$





System performances

- The position of the lens with respect to the PWFA module has been carefully optimized to preserve the witness emittance;
- ≈ 98% of the driver charge is removed by the collimator, with only 4 pC remaining;
- the second APL catches the witness downstream the collimator and allow for its transport in the rest of the beamline.

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