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# Compact and tunable active-plasma lens system for witness extraction and driver removal

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**Abstract.** Plasma based technology will allow an unprecedented reduction of the size of accelerating machines. Both fundamental research and applied science and technology will take profit of this feature. The same compactness is required downstream the accelerator module, where the plasma-accelerated beams usually experience a large angular divergences growth. Therefore compact, strong and tunable focusing devices are needed. Active-plasma lenses have been demonstrated to be a compact and affordable tool to generate radially symmetric magnetic fields. We present a new scheme using active-plasma lenses and a metallic collimator to catch and transport the witness bunch while removing the driver. The considered case study is in the context of the EuPRAXIA project.

## 1. Introduction

Plasma-based accelerators are one of the most interesting area of the field of new acceleration technologies. The plasma waves providing the high gradient accelerating field can be driven by lasers or particle beams [1, 2, 3, 4, 5, 6]; in both cases a bottleneck is the extraction of the accelerated witness beam without sizeable degradation of its emittance. After the plasma acceleration the witness bunch has a large angular divergence [7], of several mrad. For non-negligible energy spreads, such a large divergence also leads to a rapid increase of the normalized emittance [8]; therefore the accelerated witness must be caught as soon as possible. At the same time the high-charge driver(s) must be dumped avoiding any degradation of the witness [9]. In these proceedings we present an innovative and compact extraction scheme; it combines an array of two active-plasma lenses (APLs) [10], with a lead collimator in between. This extraction Layout has been applied in the context of EuPRAXIA (European Plasma Research Accelerator with eXcellence In Applications) design study: the project aims at designing the worlds 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 [11].

For the beam-driven scenario the LNF-INFN laboratories in Frascati (Italy) has been selected as a possible hosting site. This facility will exploit an 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.

The Table 1 summarizes the main parameters of the two bunches exiting the PWFA module. In Fig. 1 the simulated longitudinal phase space (LPS) of the driver and witness beam exiting the PWFA module; simulations have been performed using Architect [12], the code uses a hybrid approach: relativistic bunches are treated kinetically as in a Particle-in-cell (PIC) code while the background plasma is modelled as a fluid.

| Parameter | Witness | Driver |
|---|---|---|
| Charge [pC] | 30 | 200 |
| Duration (rms) [fs] | 11.5 | 160 |
| Peack current [kA] | 2.6 | 1.2 |
| Energy [MeV] | 1016 | 460 |
| Energy spread (rms) [%] | 0.73 | 16 |
| Normalized emittance [$\mu$m] | 0.6 | 5 |
| Spot size [$\mu$m] | 1.2 | 7 |

**Table 1.** Witness and driver bunches parameters at the exit of the PWFA module.

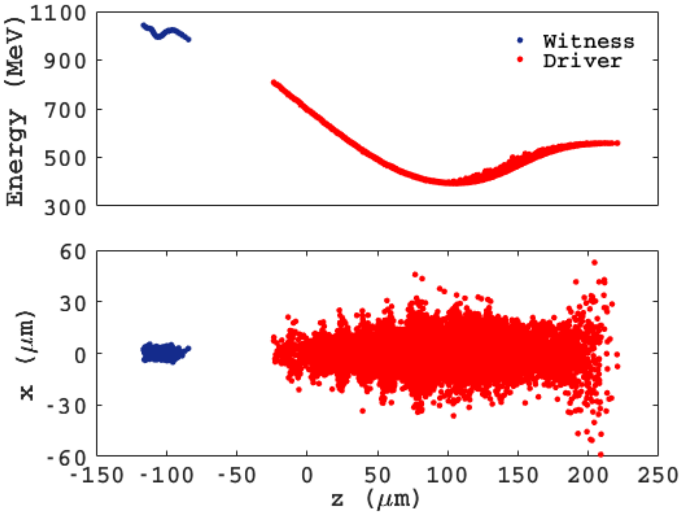


**Figure 1.** Longitudinal phase-space (top) and $x$-$z$ view (bottom) of the driver (red) and witness (blue) bunches downstream the PWFA module.

In the following sections the extraction system and the adopted simulation procedure will be described: particular emphasis will be given to the collimation step; we refer the reader to [13] for more details on phase-space analysis and other effects (i.e. wakefields and temperature effects on the collimator).

## 2. The extraction system

When exiting the plasma, the electron bunch moves from an extremely intense focusing field (generated by the excited plasma wakefield) to a region where the focusing effect suddenly vanishes. Therefore, the bunch divergence $\sigma_{x'} \propto 1/\beta_{eq}$ grows at the plasma exit, where $\beta_{eq} = \sqrt{\gamma/2\pi r_e n_p}$ is the witness Twiss $\beta$-function matched to the plasma [14], $r_e$ is the classical electron radius and $\gamma$ the relativistic Lorentz factor. For non-negligible energy spreads $\sigma_E$, such a large divergence also leads to a rapid increase of the normalized emittance in a drift of length $s$ given by [8]

$$\epsilon_n^2 = \langle\gamma\rangle^2 \left( s^2 \left(\frac{\sigma_E}{E}\right)^2 \sigma_{x'}^4 + \epsilon_g^2 \right) \ , \tag{1}$$

where $E$ and $\epsilon_g$ are the bunch energy and geometrical emittance, respectively. According to eq. (1) it is thus important to catch the accelerated witness bunch with a short focal length focusing system installed downstream the plasma stage and as close as possible to it [15].

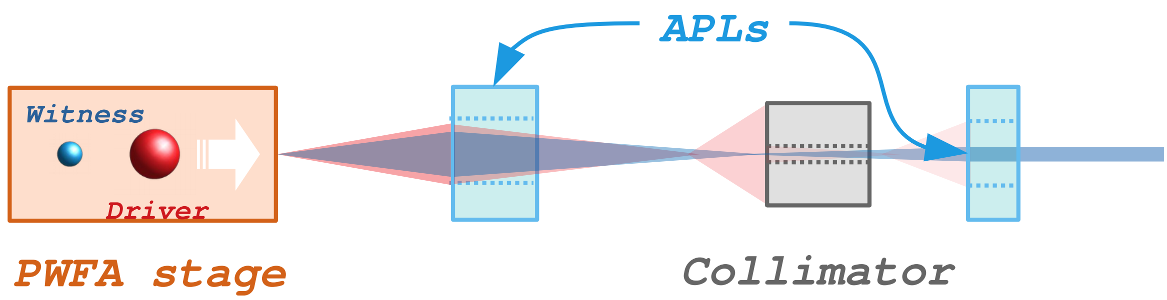


**Figure 2.** Layout of the extraction system consisting of two APLs and a lead collimator between them. The focusing strength of the APLs are set up to rapidly catch the witness bunch (blue) downstream the PWFA stage and allow for its transport without any loss of charge. The driver bunch (red) has a lower average energy and is thus over-focused: its spot size at the collimator entrance is larger than the aperture and its charge is thus cut proportionally.

The proposed extraction system provides: i) an efficient capture of the witness bunch preserving its emittance and peak current, ii) a suitable high-charge driver bunch dumping before the next beamline stage, i.e. a Free Electron Laser undulator. In Fig. 2 a sketch of the proposed extraction system is shown. The two APLs [16, 17, 18, 19, 20, 21, 22] provide the witness capture; such devices are capable to produce large focusing fields, of the order of kT/m [23, 24, 25, 26]. Between the APLs, a lead collimator is used to dump the driver bunch. The removal is based on the different focusing provided by the first APL to the two beams: the witness is focused exactly at the entrance of the collimator (so no charge is cut) while the driver (approximately half of the energy) is over-focused to have a spot size larger than the collimator hole channel.

## 3. Particle-matter interactions: GEANT4 simulation

The interaction of the driver beam with the lead collimator has been numerically simulated by means of the GEANT4 framework (see Fig. 3), a single particle tracker which takes into account all the fundamental radiation-matter interactions [27]. GEANT4 is a toolkit for simulating the passage of particles through matter. It includes many functionalities like tracking, geometry, physics models and hits. Many physics processes are included and cover a wide range of interactions like electromagnetic, hadronic and optical processes, a large set of long-lived particles, materials and elements, over a wide energy range (from hundreds of eV up to TeV). In defining and implementing all the involved components, all aspects of the simulation process have been included: i) the geometry of the collimator system, ii) the material involved (lead), iii) the fundamental particles of interest (electrons), iv) the generation of primary particles of events (electrons, hadrons and photons), v) the tracking of particles through materials, vi) the physics processes governing particle interactions (bremsstrahlung, pair-production, multiple-scattering, etc.).

For the current simulation, we proceeded as in the following. Firstly, in the region between the beam exiting from the first APL up to the collimator entrance, we simulated the beam drift by General Particle Tracer (GPT) [29]. Here we imported and converted the GPT bunch in order to be treated with GEANT4. Finally the GEANT4 simulation output is imported again in GPT and used as input for the second APL. In the GEANT4 simulation the FTFP_BERT physics list has been adopted; it contains the standard electromagnetic and hadronic interactions, the latter ones implemented using the FTF parton string and Bertini cascade models [28].

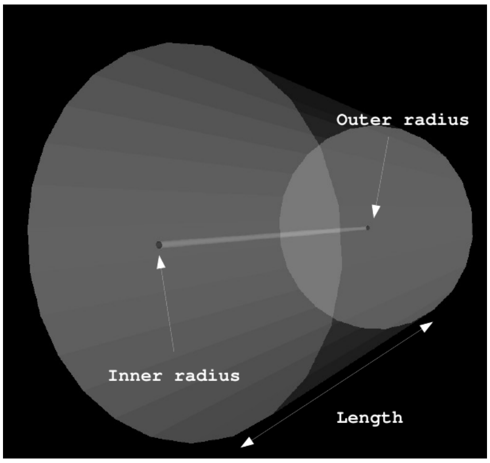


**Figure 3.** Collimator geometry simulated in GEANT4.

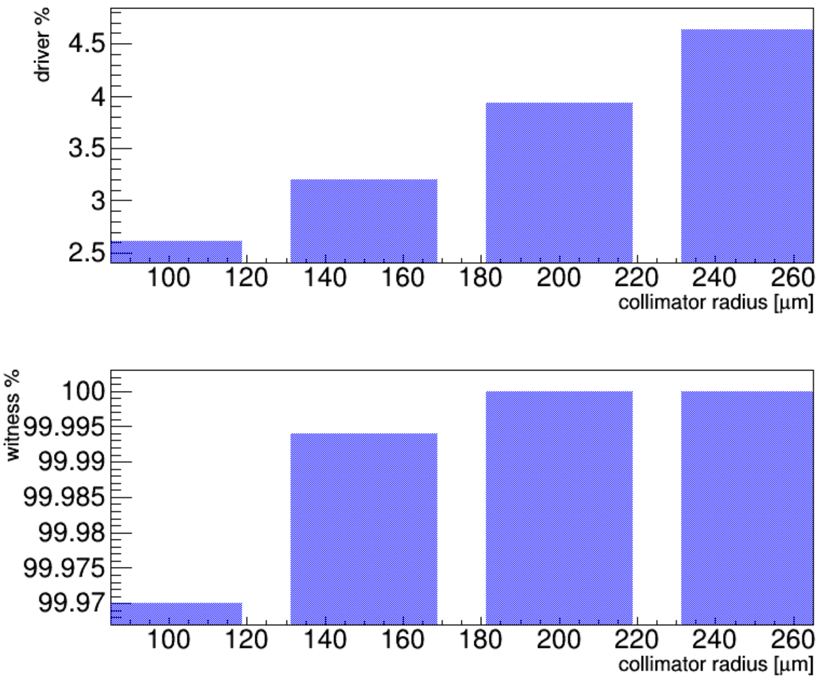


**Figure 4.** Percentage of driver (top) and witness (bottom) bunches surviving after the collimator (placed at 97 cm after the first APL) for different radii (inner and outer radii are equal) .

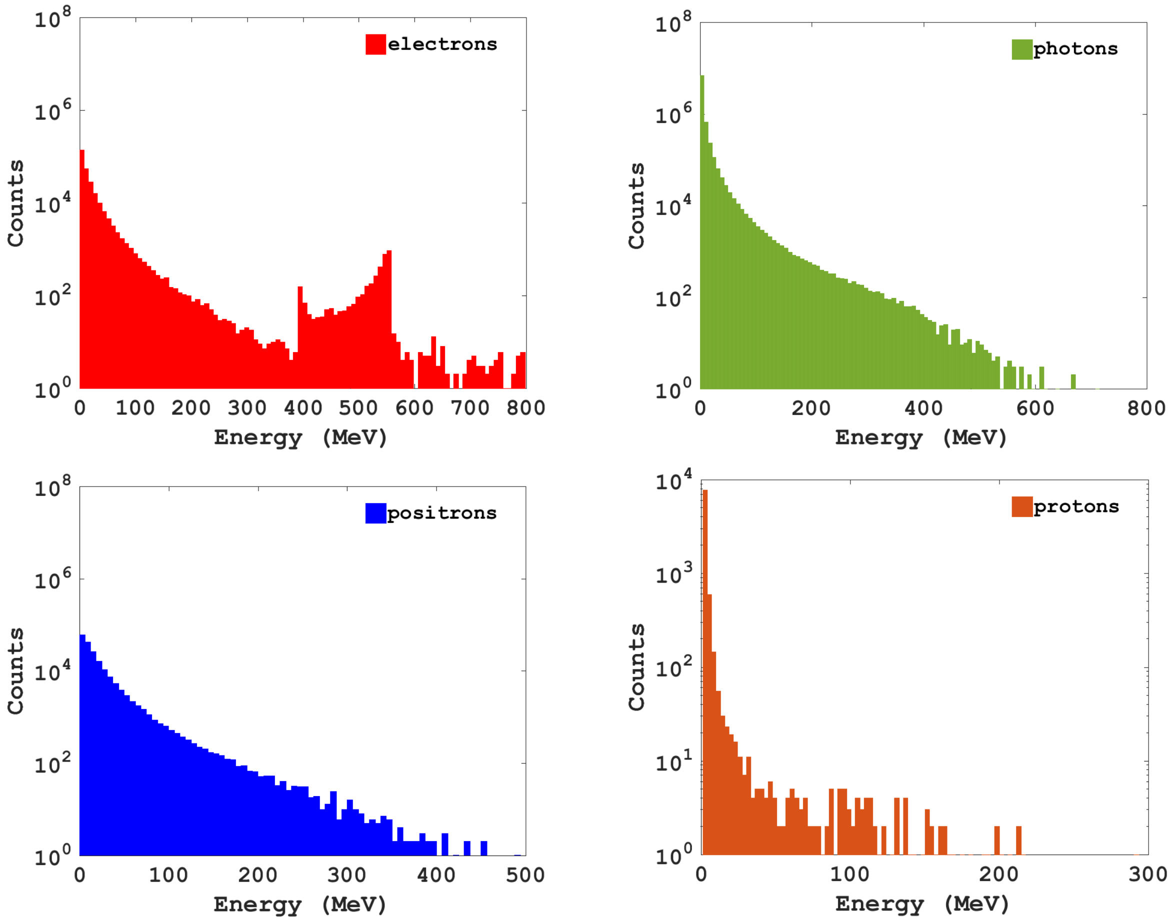


**Figure 5.** Energy spectrum of the scattered and emitted electrons, photons, positrons and protons from the collimator after the interaction with the incoming electron beam. The particles have been collected over a 4 solid angle around the collimator. Details on the angular distributions can be found in [13].

The performances of the collimator have been optimized by varying four parameters in the simulation: the thickness, the inner and outer radii and the distance of the collimator from the first APL. As an example, we report the effect of the variation of the collimator radius, fixing the distance of the collimator from the first APL at 97 cm, see Fig. 4 . Similar studies have been performed by varying the position.

| Element | Length | Radius | Position | Current |
|---|---|---|---|---|
| APL 1 | 2 cm | 500 $\mu m$ | 15 cm | 1 kA |
| Collimator | 3 cm | 200 $\mu m$ | 97 cm | |
| APL 2 | 1 cm | 500 $\mu m$ | 135 cm | 0.6 kA |

**Table 2.** Optimized parameters for the APLs and collimator used in the proposed extraction system. The position of each element is relative to the exit of the PWFA module.

The final configuration reported in Tab. 2 represents the best compromise regarding the driver dumping and the preservation of the witness beam charge. It consists of a 3 cm-long lead cylinder with outer radius of 1 cm and 200 $\mu m$ radius aperture. Such a configuration allows to absorb most of the driver charge in the collimator while the witness remains unabsorbed by the collimator (its normalized emittance that grew from 0.6 $\mu m$ to 1.2 $\mu m$ at the end of the extraction system, see [13] for details on the phase space). The simulation recorded all the scattered and emitted particles after the interaction. In Fig. 5 we show the counts of the electrons, photons, positrons and protons. As shown, it results that a large amount of $\gamma$/X-rays are produced, up to $10^7$ by assuming $3 \times 10^5$ incoming electrons. This is a potential source of background for any detector or diagnostics installed around the collimator that, thus, would require a proper shielding system to be adopted for any practical purpose.

## 4. Conclusions and outlooks

We have presented a possible solution, based on the use of APLs in combination with a lead collimator to properly dump the driver bunch without affecting the witness; this is a compact solution, less than 1.4 m, in the treatment of GeV-class beams.

We used EuPRAXIA design study as reference case, demonstrating that downstream the PWFA booster module, the driver beam can be stopped without affecting the witness. The lead collimator placed between the two APLs is an affordable solution that allows to dump the 200 pC driver bunch to the level of few pC without affecting the witness. Additional study on resistive wakefields excited along the collimator aperture can be found in [13] . The results confirmed that such a compact solution can be implemented in a future facility based on plasma acceleration.

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