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Plasma Beam Dumps for EuPRAXIA Facility

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Abstract: Beam dumps are indispensable components for particle accelerator facilities to absorb or dispose beam kinetic energy in a safe way. However, the design of beam dumps based on conventional technology, i.e. the energy deposition via beam-dense matter interaction, makes the beam dump facility complicated and large in size, partly due to nowadays' high beam intensities and energies achieved. In addition, these high-power beams generate radioactive hazards, which need specific methods to deal with. On the other hand, the EuPRAXIA project can advance the laser-plasma accelerator significantly by achieving 1-5 GeV high quality electron beam in a compact layout. Nevertheless, the beam dump based on conventional technique will still produce radiation hazards and make the overall footprint less compact. In this paper, we propose to implement a plasma beam dump to absorb the kinetic energy from the EuPRAXIA beam. In doing so, the overall compactness of the EuPRAXIA layout will not be impacted, and the radioactivity generated by the facility can be mitigated. In this paper, results from particle-in-cell (PIC) simulations are presented for plasma beam dumps based on EuPRAXIA beam parameters.

Keywords: beam dump, laser plasma accelerator, plasma beam dump

1. Introduction

The development of laser-plasma based compact, high-quality electron accelerators have already attracted tremendous interests worldwide since the initial idea was proposed by Tajima and Dawson more than 40 years ago [1-5]. The basic principle behind this is to utilize the strong electric field associated with collective electron oscillations in the plasma to accelerate either an internally or an externally injected electron beam behind the driver pulse. Due to the collective nature of this technique, it is possible to achieve an extremely high acceleration gradient, usually more than three orders of magnitude higher than the RF field used in conventional accelerators. Nowadays, several-GeV electron beams can routinely be achieved in laser wakefield accelerators (LWFA) within centimetre-long plasmas by using terawatt (10^{12} Watt) or petawatt (10^{15} Watt) laser drivers [6-8].

On the other hand, the use of plasma wakefields for deceleration of relativistic beams have not been fully explored ever since. In 2010, Tajima et al. proposed the collective deceleration of beams in plasmas for the first time [9]. The idea is to utilize the large decelerating wakefields, with amplitudes as high as those of accelerating fields, to absorb the beam energy as fast as possible. This would allow beam deceleration to be achieved in a short distance if compared to equivalent conventional beam dumps. Moreover, this could mitigate the conventional beam dump requirements, which usually suffer from complicated design and large sizes (and costs) when the beam power is high. In addition, the use of a low-density plasma greatly reduces radio activation hazards if compared to conventional beam dumps, in which energetic particles interact with dense media such as metals, graphite or water, causing nuclear reactions and production of secondary particles.

The *European Plasma Research Accelerator with eXcellence in Application* (EuPRAXIA) is an EU design study proposed with the aim to produce a conceptual design for a worldwide first 1-5 GeV plasma-based accelerator with industrial beam quality and user areas [10]. One of the important advantages of this project is the compactness of facility. With the plasma beam dump, the overall footprint of facility can be reduced further, and the radioactive hazards can be diminished significantly.

2. Plasma beam dumps

Generally speaking, there are two types of plasma beam dumps, the so-called passive plasma beam dump (PPBD) and the active plasma beam dump (APBD) [11-12]. For the PPBD, a relativistic particle bunch propagates in an undisturbed plasma and excites its own wakefield. As a consequence, the head of the bunch will experience no decelerating field due to finite response time of the plasma, while particles at the bunch tail will experience a decelerating field. After some time, the fraction of the bunch experiencing the maximum decelerating field will become non-relativistic, and it will fall behind the rest of the bunch until it reaches an accelerating phase of the wakefield. This causes beam re-acceleration, which eventually leads to saturation of the beam net energy loss [9,13-14]. In order to eliminate the beam re-acceleration, several schemes have been proposed which include inserting foils in the plasma to absorb the re-accelerated particles, and tailoring the plasma density along the beam propagation direction to change the relative phases of wakefield along the beam driver. Recent studies have shown that the beam energy deposition in plasma can be greatly enhanced through finely tailoring the plasma densities [13-14]. On the other hand, in the APBD this beam re-acceleration is eliminated. In this scheme, a laser pulse is employed to excite a wakefield in the plasma prior to the beam propagation, in such a way that the combination of both laser-driven and beam-driven wakefields flattens the decelerating field along the bunch. This enables a quasi-uniform energy extraction, thus preventing formation of re-acceleration peaks [11-12]. Although the energy extraction is more efficient in the APBD, the need of a laser pulse and a precise synchronization between the laser and the beam causes this scheme to be far more complex to be experimentally implemented than the PPBD.

3. Simulation results of plasma beam dump for EuPRAXIA beam

In order to simplify the design and implementation of a plasma beam dump for the EuPRAXIA facility, we propose the adoption of the passive scheme. We aim to absorb most of the energy from the electron bunch by tailoring the plasma density profile. Typical EuPRAXIA beam parameters [10,15] used in our studies are listed in Table. Here, two sets of beam parameters are considered in our simulation, one with beam energy of 1 GeV and the other 5 GeV. Other beam parameters are the same. This corresponds to a beam density of ~3.0×10^{18} cm^{-3}. The Particle-in-Cell (PIC) code FBPIC is used to perform simulations of beam-plasma interaction [16].

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Table 1. EuPRAXIA beam parameters used in simulation.

Beam energy	**1 GeV**	**5 GeV**
Bunch charge	30 pC	30 pC
Transverse bunch size	1.4 μm	1.4 μm
Longitudinal bunch length	2.0 μm	2.0 μm
Energy spread	1.0%	1.0%
Angular divergence	1.0×10^{-5}	1.0×10^{-5}

3.1 Plasma beam dump for 1 GeV beam

As a first step, we choose the plasma density of 9.9×10^{17} cm^{-3} so that the wakefield excited is in the quasi-linear to nonlinear regime, and the whole beam is contained in the first phase of its self-driven wakefield, which is longitudinally decelerating and transversely focusing. The results show that the particles lose their energies very quickly. After propagating about 6 cm in the plasma, the particles at the tail of the bunch lose most of their energies, suffering phase slippage towards the next accelerating phase of the longitudinal wakefield. As a result, the bunch length increases during the energy dumping. If the bunch continues to propagate further in plasma, the particles at the tail of the bunch will reach an acceleration phase and start to absorb energy from the wakefield.

Figure 1 shows the beam longitudinal phase space after propagating 6 cm in plasma. It can be seen clearly that the beam energy at the head of bunch does not change, while the particles at the tail start to gain energy. If this location is chosen as the saturation length (which defines the length over which the particles in the bunch tail lose most of their energies), the corresponding decelerating gradient is about 16.7 GeV/m. In order to eliminate the particles gaining energy from the wakefield, the plasma density is tuned just before energy loss saturation occurs. In doing so, the defocusing phase of the transverse wakefield will move towards the low energy particles at the bunch tail, causing them to be ejected before restoring high energies due to acceleration. Figure 2 shows a typical plasma density profile in which the density increases in a non-linear fashion from $n_0 = 9.9\times10^{17}$ cm^{-3}, at 6 cm, to $10\ n_0 = 9.9\times10^{18}$ cm^{-3}, at approximately 17 cm. This particular plasma density profile can be obtained by imposing a constant rate of change for the plasma wavelength λ with respect to the propagation distance s, i.e., $d\lambda/ds = \text{constant}$ [14]. As a comparison, the beam longitudinal phase space after 16 cm plasma is shown in Figure 3. It is found that the re-acceleration peak (as shown in Figure 1) is eliminated, and particles continue to lose their energies in the plasma. Figure 4 gives the energy plots in terms of propagation distance in plasma, for the plasma density profile shown in Figure 2. The results show that the total beam energy reduces to 12% of its initial energy. Almost 80% of the beam initial energy is deposited in the plasma, and only approximately 10% of the beam initial energy is transversely ejected. The average energy of the ejected particles is approximately 150 MeV. This tailored plasma-density profile guarantees a relatively low beam energy deposited in the plasma vessel, ensuring a safe operation of the plasma beam dump.

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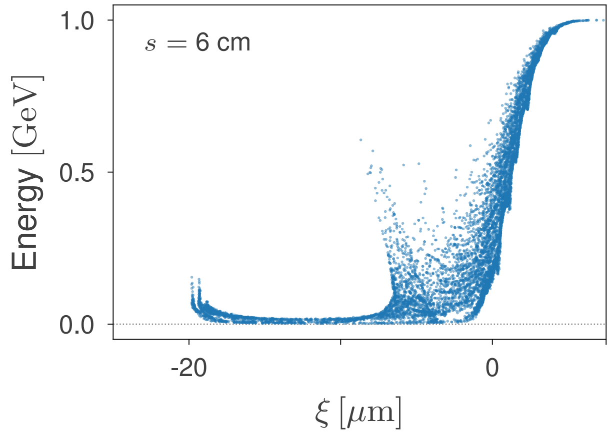

Figure 1: EuPRAXIA 1 GeV beam longitudinal phase space after 6 cm propagation in plasma.

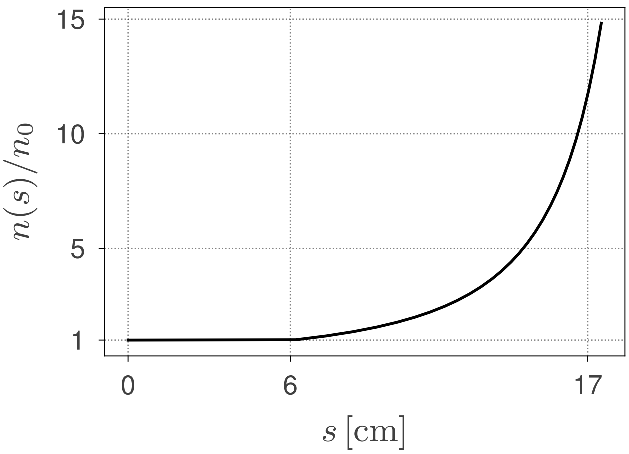

Figure 2: Tailored plasma-density profile designed to eliminate the re-acceleration of particles in the bunch tail in the EuPRAXIA 1 GeV beam. The plasma density exhibits a uniform behaviour until s = 6 cm, followed by a non-linear growth that reaches a 10 times higher density at s = 16 cm, if compared to the former uniform plasma density.

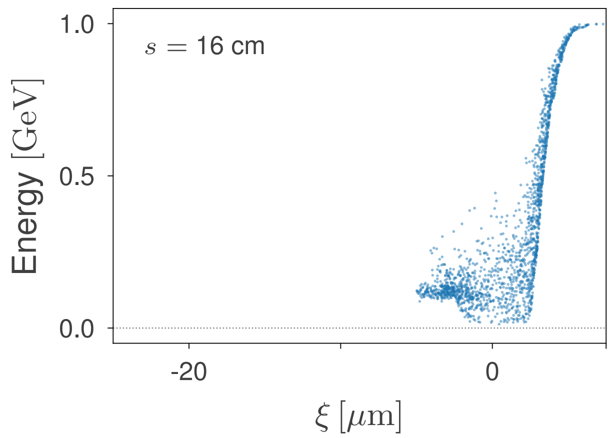

Figure 3: EuPRAXIA 1 GeV beam longitudinal phase space after 16 cm propagation in plasma. At this propagation distance, particles with lower energies, which can be clearly seen in Figure 1, are not present since they were ejected by the defocusing phase of the transverse wakefield.

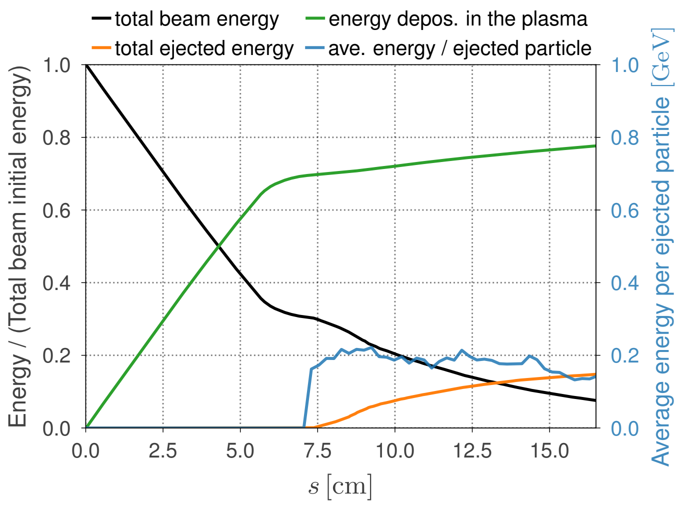

Figure 4: EuPRAXIA 1 GeV beam energy plots as a function of propagation distance in plasma, for the plasma density profile shown in Figure 2.

3.2 Plasma beam dump for 5 GeV beam

When electron beam energy reaches up to 5 GeV, the beam dump will be challenging if the conventional beam dump method is used, especially when the electron bunch is low emittance and ultrashort. For this reason, in this section a passive plasma beam dump simulation is presented for the 5 GeV EuPRAXIA beam. For a highly relativistic beam, the rate of total beam-energy loss in a uniform plasma is constant [12], which value only depends on the beam and plasma density profiles. In this way, since the beam and plasma parameters remain the same of the previous case, the 5 GeV beam has to propagate for a longer distance in the plasma to reach the saturation distance, if compared to the 1 GeV beam simulation.

Figure 5 shows the 5 GeV beam longitudinal phase space after 26 cm propagation in a plasma with density of 9.9×10^{17} cm^{-3}, i.e., the same value adopted in the previous case. Qualitatively, this phase space is equivalent to the one shown in Figure 1, for the 1 GeV case; particles at the middle and tail of bunch lose their energies, and some particles at the tail already started picking up energy from the wakefield. However, since in this case the beam energy is 5 times higher, the propagation distance to reach this point is 26 cm, which is approximately 4.3 times longer with the 6 cm observed in Figure 1. A plasma density tuning as shown in Figure 6 is adopted to mitigate the re-acceleration of particles in the tail. In this case, the plasma density profile, which is constant up to s = 26 cm, is increased by a factor of ~15 within a distance of 10 cm (from s = 26 cm to s = 36 cm). The effect of applying this tailored plasma-density profile can be observed in Figure 7, in which the longitudinal beam phase space is presented after 36 cm propagation in the plasma. If compared to the phase space at s = 26 cm (Figure 5), this figure shows that the particles with lower energies at the beam tail were eliminated. In other words, the adoption of the plasma density profile from Figure 6 provides the same effect observed in the previous section for the 1 GeV beam.

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The beam energy loss as a function of the propagation distance in the plasma is shown in Figure 8. Clearly, it can be seen that, after a 37 cm propagation, the beam loses almost 80% of its initial energy, being 75% of the beam energy deposited in the plasma, and 5% carried out by the transversely ejected particles.

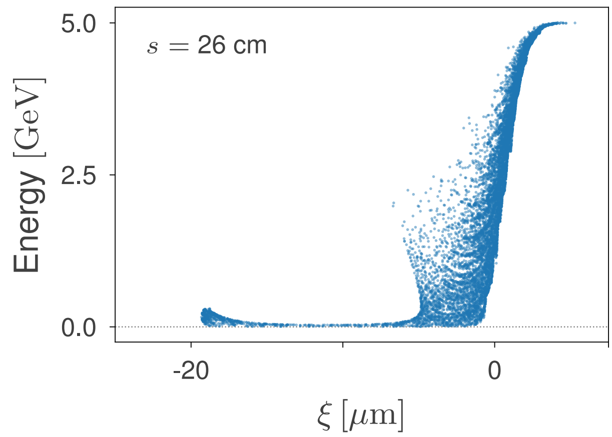

Figure 5: Beam longitudinal phase space after 26 cm propagation in plasma for EuPRAXIA 5 GeV beam.

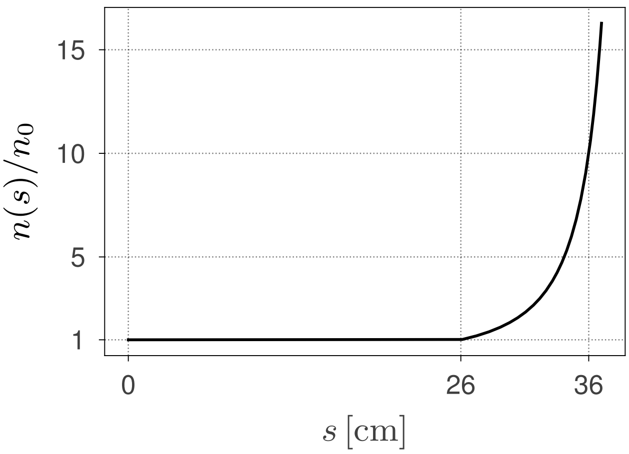

Figure 6. Tailored plasma-density profile designed to eliminate the re-acceleration of particles in the bunch tail in the EuPRAXIA 5 GeV beam. The plasma density exhibits a uniform behaviour until s = 26 cm, followed by a non-linear growth that reaches a 15 times higher density at s = 36 cm, if compared to the former uniform plasma density.

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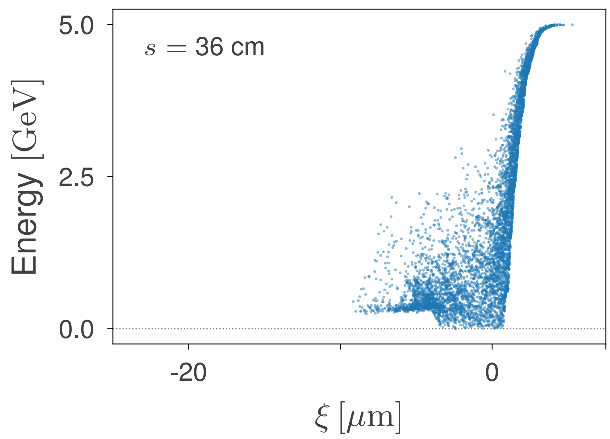

Figure 7: EuPRAXIA 5 GeV beam longitudinal phase space after 36 cm propagation in plasma. If compared to Figure 5, this figure shows that the density profile from Figure 5 if effective to eliminate lower energy particles, preventing the formation of a re-acceleration peak.

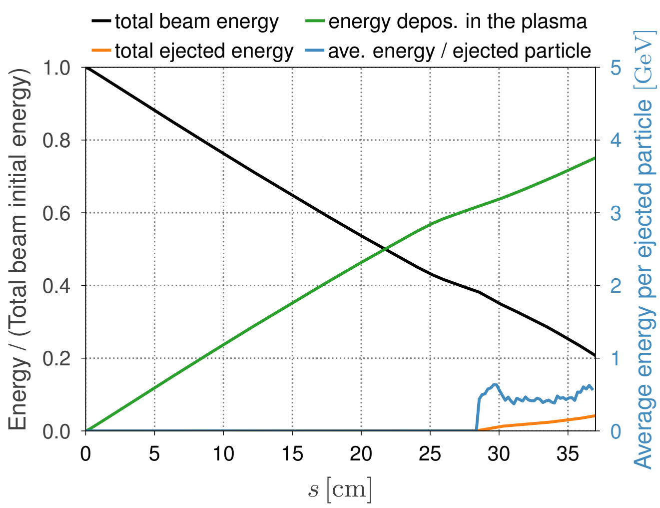

Figure 8: The energy plots as a function of propagation distance in plasma, for the plasma density profile shown in Figure 6 for EuPRAXIA 5 GeV beam.

4. Discussion and Conclusions

The study shown here demonstrates the viability of the PPBD for the EuPRAXIA 1 GeV and 5 GeV beams, respectively. It shows that, for the 1 GeV case, a 16 cm long PPBD with a tailored plasma-density profile can remove almost 90% of beam total energy, being 80% absorbed by the plasma, and 10% ejected with particles carrying average energies of ~150 MeV. On the other hand, for the 5 GeV beam, simulation results show that a 37 cm long plasma cell can cope with 80% of beam energy as well, among which 75% is deposited in the plasma, and 5% transported by the ejected particles. Although the percentage of the total ejected energy is lower for the 5 GeV PPBD, if compared to the 1 GeV case, attention must be made to the average energy of the ejected particles. While in the 1 GeV PPBD particles are ejected with average energies of ~150 MeV, in the 5 GeV case the ejected particles have average energies of ~500 MeV. Otherwise, it remains undoubted that, if compared to

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conventional beam dumps, the adoption of the PPBD can help keeping the overall facility compact and safer, as the conceptual EuPRAXIA design precepts.

On the other hand, we have not discussed the APBD scheme here due to the complexity associated with its implementation. However, since the EuPRAXIA project requires a laser infrastructure, an active beam dump might be a viable option. By using a laser-driven wakefield, in principle, almost 100% of the beam energy could be deposited in plasma. As for the next step, how to recycle or reuse the energy deposited in the plasma will be a key step forward. Interestingly, a recent experiment performed at Rutherford Appleton Laboratory (RAL) on multiple laser pulses driven plasma wakefield has shown possibility of energy recovery as the trailing laser pulse picking up energy from plasma [17]. All these will pave the way for the future very compact and green beam dump facilities.

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References

1. Tajima, T.; and Dawson, J. M., J. M, Phys. Rev. Lett., 43, 267 (1979).
2. Mangles, S.; et al., Nature 431, 535 (2004).
3. Geddes, C.G.R.; et al. Nature 431, 538 (2004)
4. Faure, J.; et al., Nature 431 541 (2004)
5. Esarey, E.; Schroeder, C. B. and Leemans, W. P.; Rev. Mod. Phys. 81 1229 (2009).
6. Leemans W P.; et al.; Nat. Phys. 2 696. (2006).
7. Geddes, C. G. R.; et al. Phys. Rev. Lett. 100, 215004 (2008).
8. Gonsalves, A, J.; Nakamura, K.; Daniels, J.; et al., Phys. Rev. Lett. 122, 084801 (2019).
9. Wu, H. C., et al., Phys. Rev. ST Accel. Beams 13, 101303 (2010).
10. Li, X.; Mosnier, A.; and Nghiem, P. A. P., Nuclear Inst. and Methods in Physics Research, *A*, 1–5 (2018).
11. Bonatto A., et al., Phys. Plasmas 22, 083106 (2015).
12. Bonatto, A., Schroeder, C.B., Vay, J-L., Geddes, C.R., Benedetti, C., Esarey, E., Leemans, W.P., AIP Conference Proceedings 1777 (1), 040002 (2016).
13. Hanahoe, K., et al., Phys. Plasmas 24. 023120 (2017).
14. Jakobsson, O.; Bonatto, A.; Li, Y.; Zhao, Y.; Nunes, R.P.; Williamson, B.; Xia, G.; and Tajima, T., Plasma Phys. Controlled Fusion 61 (12), 124002 (2019).
15. Nunes, R.; Bonatto, A.; and Xia, G., Proceedings of IPAC'19, pp 3581–3 (2019).
16. Lehe, R.; et al., Comput. Phys. Commun. 203, 66–82 (2016).
17. Cowley, J.; et al., Phys. Rev. Lett. 119, 044802 (2017).