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SIMULATION STUDY OF AN RF INJECTOR FOR THE LWFA CONFIGURATION AT EuPRAXIA

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Abstract

The Horizon 2020 Project EuPRAXIA (European Plasma Research Accelerator with eXcellence In Applications) aims at producing a design report of a highly compact and cost-effective European facility with multi-GeV electron beams using a plasma accelerator. LWFA (laser wake field acceleration) with external injection from an RF accelerator is one of the most promising configurations. In order to achieve the goal parameters for the 5 GeV, 30 pC electron beam at the entrance of the undulator, a high-quality electron beam with bunch length of less than 10 fs (FWHM) and beta functions of a few mm at the injection point is required. In addition, from the compactness point of view, the injection energy is desired to be as low as possible. A hybrid compression scheme is considered in this paper and detailed start-to-end simulation result is presented.

INTRODUCTION

The Horizon2020 Design Study EuPRAXIA (European Plasma Research Accelerator with eXcellence In Applications) [1] will in October 2019 propose a first European Research Infrastructure that is dedicated to demonstrate exploitation of plasma accelerators for users. At the first stage, EuPRAXIA is aiming to achieve soft X-ray free-electron lasers using the SASE mode. In the EuPRAXIA study, both laser driven and beam driven approaches as well as combined plasma acceleration schemes - using beams produced by LWFA as drivers of PWFA (plasma wake field acceleration) stages - are taken into consideration.

EuPRAXIA is a site-independent design study. At DESY, we are considering to host EuPRAXIA within the infrastructure of the SINBAD facility [2]. As one of the two experiments at the SINBAD facility, the design of the ARES linac [3,4] was optimized to provide ~100 MeV, 0.5 - 30 pC, sub-fs to dozens of fs electron bunches suitable for testing various novel acceleration concepts, e.g. LWFA, DLA (dielectric laser acceleration). During the design phase of the ARES linac, the future energy upgration has already been taken into account. Therefore, it is natural to extend the current ARES linac to meet the specification of the LWFA configuration at EuPRAXIA. In this paper, we present the proposed layout and the beam dynamics simulation from the photocathode to the injection point (plasma entrance). In addition, some practical concerns such as various jitter are also discussed.

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LAYOUT OF THE PROPOSED INJECTOR

The layout of the proposed RF injector for the LWFA configuration at EuPRAXIA is shown in Figure 1. There are two major differences between the proposed layout and the layout of the ARES linac: 1. three traveling-wave structures were inserted before the matching section; 2. the length of each PMQ (permanent quadrupole magnet) was increased to 3 cm and their gradients were slightly increased to 300 T/m, 600 T/m and 600 T/m, respectively.

The electron bunch will be compressed using a two-stage hybrid compression scheme, i.e. the beam is compressed by means of velocity bunching and magnetic compression successively. The initial bunch charge is 50 pC at the photocathode and about 30 pC charge will be allowed to pass through the slit collimator located in the middle of the chicane with a full width of 0.6 mm. The hybrid-compression scheme was chosen mainly because of the following reasons:

- Both a two-stage compression scheme and the slit collimator help to reduce the nonlinearity of the longitudinal phase-space;
- Compared to the pure magnetic compression scheme, the hybrid-compression scheme has a much lower charge loss at the slit collimator. In addition, since a much less amount of charge is required to be extracted from the photocathde, the beam emittance will be smaller. Compared to the pure velocity bunching scheme, since there is a long distance between the linac exit and the plasma in this layout, it is challenging to transport velocity-bunched beams with the proposed energy and peak currents of several kAs to the plasma without significantly spoiling the beam quality;
- It helps to reduce both the energy and peak current jitter after bunch compression compared to the other two compression schemes [5]. The energy jitter affects the longitudinal location of the focal point, while the peak current jitter affects the beam loading effect as well as the FEL output after the LWFA.

BEAM DYNAMICS SIMULATION

The goal of this study is to achieve a 30 pC electron bunch with a peak current higher than 3 kA and beta functions less than a few mm at the injection point. From the compactness point of view, the injection energy is desired to be as low as possible. However, the space-charge effects make it difficult to preserve the beam quality (e.g. emittance, peak current)

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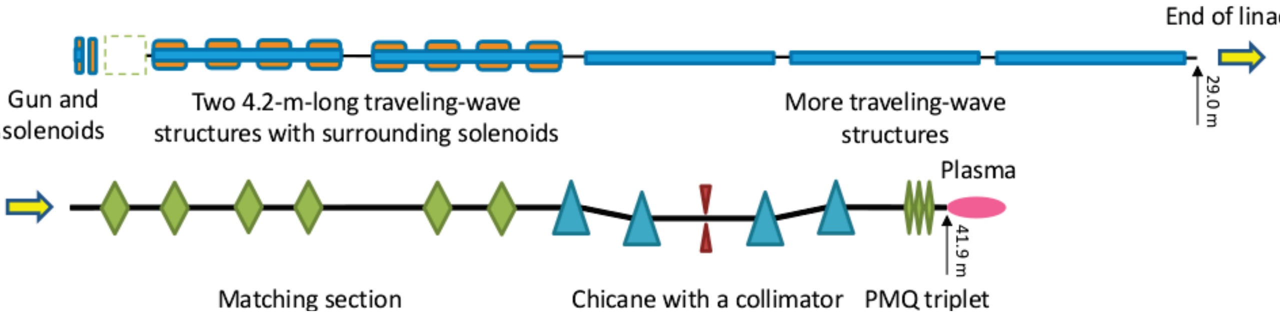

Figure 1: Layout of the proposed RF injector for the LWFA configuration for EuPRAXIA.

at low energies up to the injection point when the beam is strongly compressed [6]. Space-charge effects can also distort the design optics and result in unmatched beams at the plasma. Due to the fixed gradients of PMQs, optics tuning with PMQs is not as flexible as with electromagnetic quadrupole magnets. To conclude, it is desired to find the most economical beam energy.

In the following simulations, the beam dynamics from the photocathode to the linac exit was simulated by using ASTRA [7] with a two-dimensional cylindrical-symmetric space-charge algorithm. Afterwards, it was simulated up to the injection point by using IMPACT-T [8] with a 3D space-charge algorithm and 1D CSR (Coherent Synchrotron Radiation) model.

Minimum Beam Energy Required

A fast estimation was carried out based on the working point 4 (WP4) for the ARES linac [4] to understand the dependency of the peak current on the beam energy. The hybrid compression scheme was adopted for the WP4 at the ARES linac as well. In order to simulate electron bunches with different energies, the beam energy at the linac exit was scaled while the energy chirp was preserved. Moreover, the transverse coordinates (x, x', y and y') of the particles were reduced accordingly in order to preserve the normalized emittances and Twiss parameters. In addition, the PMQ length was increased to 2 cm and the gradients were scaled accordingly to make the optics almost identical for different beam energies. Finally, the width of the slit was increased to slice more charge out of the incoming bunch.

The simulation result is shown in Figure 2. It is found that the peak current reaches 3 kA when the beam energy increases to 200 MeV. As the beam energy increases, the increase of the horizontal emittance can be explained by the stronger CSR effect due to the higher peak current, while the decrease of the vertical emittance is caused by the weakening of the space-charge effects. Finally, the value of 250 MeV was chosen in consideration of both the design margin and the weakening of the space-charge effects.

The Proposed Working Point

According to the previous discussion, a feasible solution of upgrading the ARES linac to meet the specification of EuPRAXIA is to add three more 4.2-m-long traveling-wave

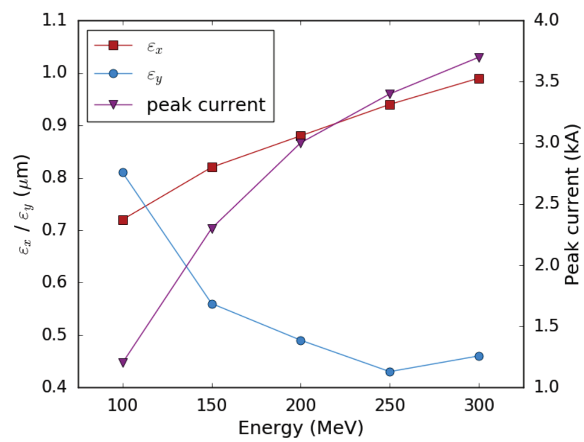

Figure 2: Peak current and transverse emittances as a function of the beam energy.

structures. In the follwing start-to-end simulation, the photocathode laser pulse was assumed to have a Gaussian longitudinal shape with an rms duration of 290 fs, and a uniform transverse laser intensity distribution was taken at the photocathode. The maximum gradient of the 1.5-cell S-band RF gun was assumed to be 110 MV/m. By operating the five structures with the same gradient of 25.5 MV/m and different off-crest phases (-87.0, -55.0, -41.0, -41.0 and -41.0 degrees), the final beam energy is about 240 MeV. The R_{56} of the chicane is about -9 mm. The evolutions of the transverse beam sizes and emittances from the photocathode to the linac exit are shown in Figure 3. The beam optics from the linac exit to the injection point is shown in Figure 4. The beam parameters at the linac exit and the injection point are summarized in Table 1, and the transverse and longitudinal phase-spaces are shown in Figure 5. The FWHM bunch length at the injection point is only 5 fs. However, there is merely one 0.75-μm-long slice with peak current higher than 3 kA. The influence of the space-charge effects after bunch compression is found to be significant. From the chicane exit to the injection point, the rms energy spread of the bunch increases from 0.18% to 0.27% and the vertical slice emittance increases from 0.27 μm to 0.34 μm. It is interesting to find out that the horizontal slice emittance decreases slightly in this region. The decrease of the horizontal slice emittance could be caused by the cancellation of the

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correlations built by the strong CSR effect in the chicane. It should be noted that the chromatic aberration at the PMQ triplet also contributes considerably to the vertical emittance growth [6].

Table 1: Beam Parameters at the Linac Exit and the Injection Point

	Linac exit	**Injection point**
Energy (MeV)	242.0	240.8
Bunch charge (pC)	50.0	29.8
Rms bunch length (fs)	160.0	7.5
Peak current (kA)	0.13	4.0
Projected ε_x / ε_y (µm)	0.30 / 0.30	0.81 / 0.46
Slice ε_x / ε_y (µm)	0.28 / 0.28	0.59 / 0.34
β_x / β_y (mm)	\	3.1 / 3.0
Rms energy spread (%)	0.50	0.27
Slice rms energy spread (%)	0.05	0.23

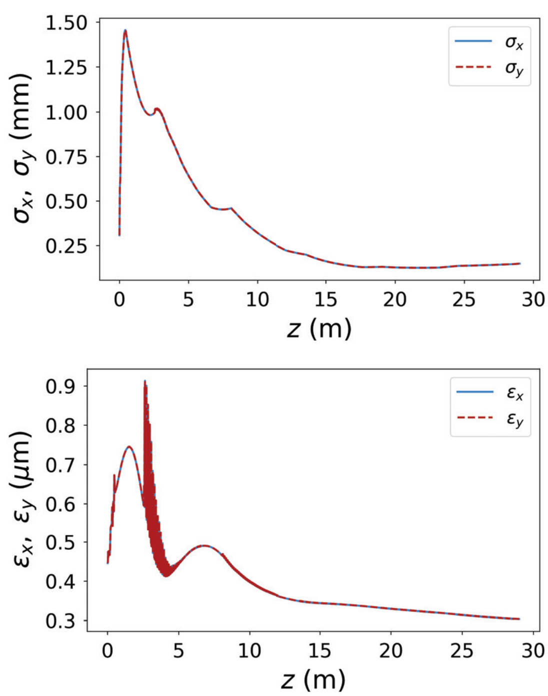

Figure 3: Transverse beam sizes and emittances evolutions from the photocathode to the linac exit.

More Discussions

For an LWFA-driven FEL, there are many other concerns besides the beam dynamics upstream of the plasma [9].

In this proposed working point, the beam is asymmetric (e.g. significantly different emittances and alpha functions in both planes) at the injection point mainly due to the CSR and space-charge effects. The influence of asymmetry on the further acceleration inside a plasma needs to be investigated. In terms of beam symmetry in the transverse plane, the pure velocity bunching scheme has an advantange over the compression scheme which involves a bunch compressor [10].

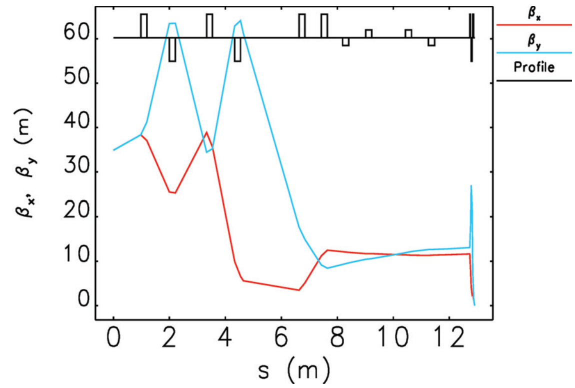

Figure 4: Beam optics from the linac exit to the injection point.

Due to the tiny size of a plasma channel (bubble), the performance of a plasma accelerator will be limited by various jitter in time and space [5]. A mismatch of the transverse position between the external beam and the drive laser, thus the plasma channel, will introduce a rapid projected emittance growth [11]

$$\frac{\Delta\varepsilon}{\varepsilon_0} \propto \left(\frac{\Delta x}{\sigma_{x_0}}\right)^2 \tag{1}$$

due to the large focusing strength. Therefore, the ratio between the beam centroid displacement and the beam size is important. Simulations have shown that this kind of emittance growth can be mitigated by employing a tailored plasma profile [12]. A mismatch of the divergence between the external beam and the drive laser can also result in a transverse position mismatch, which sets an limit on the length of the plasma channel. The pointing jitter of the beam at the focal point after a focusing thin lens is given by

$$\sigma_{<x'>} \approx \sigma_{<x_0>}/f, \tag{2}$$

assuming the initial position and pointing jitter are uncorrelated and the latter is small. For the proposed working point, the focal length of the PMQ triplet is about 10 cm or less, a 10 µm position jitter upstream of the PMQ will introduce about 100 µrad pointing jitter at the focal point. Simulations for the ARES linac have shown that a laser position jitter of 10 µm at the photocathode can result in a divergence jitter of hundreds of µrad at the injection point [9].

CONCLUSION

In this paper, we have proposed an RF injector for the LWFA configuration at EuPRAXIA by upgrading the ARES linac at DESY. The start-to-end simulation has shown that a 240-MeV, 30-pC beam can be achieved at the injection point with a FWHM bunch length of 5 fs (peak current >3 kA) and beta functions of about 3 mm. We have also shown that the pointing jitter at the injection point could be a challenge

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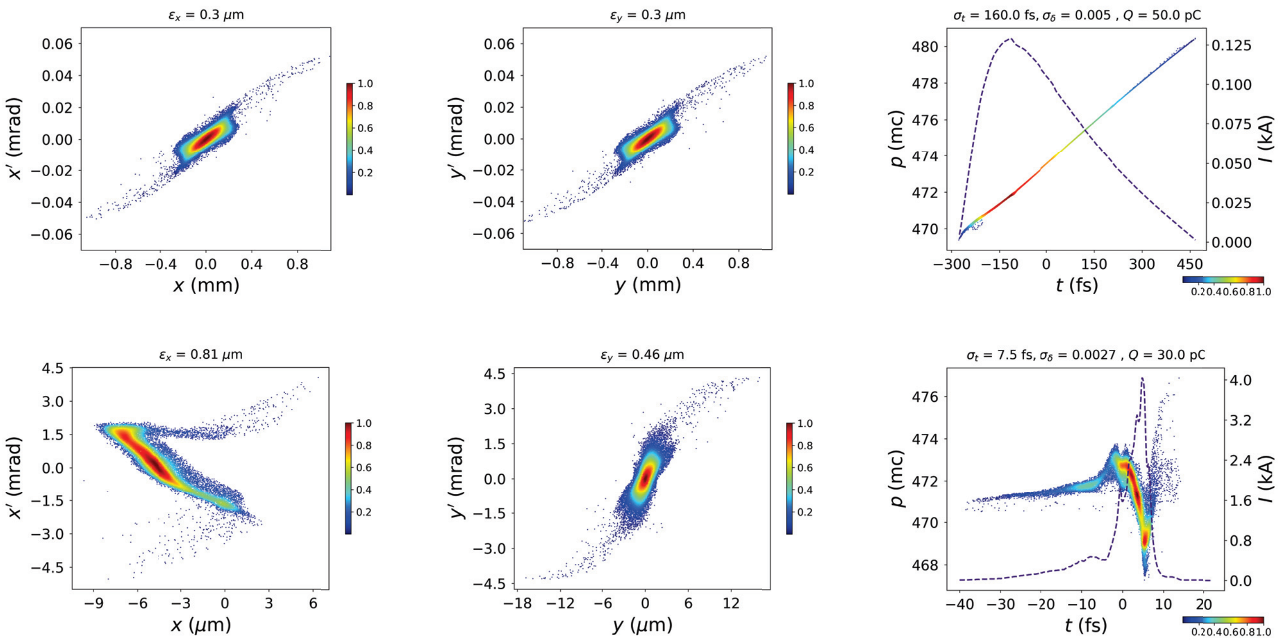

Figure 5: Transverse and longitudinal phase-spaces of the beam at the linac exit (upper row) and the injection point (lower row).

which limits the performance of the LWFA with external injection.

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