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Issues with phase space characterization of laser-plasma generated electron beams

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Abstract

Plasma acceleration is the new frontier in particle beam accelerators. Using the strong electric fields inside a plasma it is possible to achieve accelerating gradients orders of magnitude larger with respect to current technologies. Different schemes, using completely different approaches, have been proposed and several already tested, producing beams of energy up to several GeV. Regardless of the technique used for acceleration a precise determination of the output beam parameters is mandatory for the fine tuning of the process. The measurement of these parameters, in particular the beam distribution in transverse and longitudinal phase space, is not trivial, mainly due to the large energy spread and to the tight focusing of these beams or to the background noise produced in the plasma channel. We illustrate the main problems related to the diagnostic of this kind of beams and some of the proposed or already realized solutions

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1. Introduction

The gradient of the commonly used RF accelerating structures is limited, depending mainly on the employed frequency, at a gradient less than 50-100 MV/m. With such a technology, a high energy linear collider requires tens of km to accelerate the beams up to their final energy (in the order of TeV). A large and intensive program of

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R&D is pursued worldwide to develop alternative methods to accelerate electron beams. The past few years have seen a great progress in the field of accelerating particles by means of plasma acceleration (for instance Faure et al. (2004)-Mangles et al. (2004)-Geddes and al. (2004)-Hidding and al. (2006)-Pukhov and al. (2002)-Leemans and al. (2006)-Nakamura and al. (2007)). However a relatively small effort has so far been dedicated to the development of a reliable diagnostic in order to measure the longitudinal or the transversal phase space of the output beams from high gradient accelerators. This paper does not aim at being an exhaustive review of all the measuring techniques, or all the experiments already done, but it would like to briefly consider the limits and the advantages of some popular techniques to trigger discussions and focus the attention to one of the main problems of the characterization of plasma accelerated beams. It is very optimistic to think that a full characterization of such beams is not needed, because the application itself (for instance when the beam is used to drive a FEL) could be the best diagnostic. At this regard we have to remember that the proper matching of the beam inside an undulator is a mandatory condition to start the power amplification, and only the knowledge of the beam Twiss parameters allows to obtain the right matching.

2. Emittance measurement meaning

Several experiments quoted indeed very small emittance values but using a wrong definition of normalized emittance, or improperly cutting the transverse phase space. In Antici and al. (2012) was clearly demonstrated that, when there is a large energy spread, i.e. $> 1\%$, the definition of normalized emittance often used in many papers concerning plasma acceleration is not accurate. The correct formula (1) has been reported in Antici and al. (2012).

$$\varepsilon_n^2 = \langle \gamma \rangle^2 \sigma_E^2 \langle x^2 \rangle \langle x'^2 \rangle + \langle \beta \gamma \rangle^2 (\langle x^2 \rangle \langle x'^2 \rangle - \langle x x' \rangle^2) \quad (1)$$

where σ_E is the relative energy spread, $\langle x^2 \rangle$ and $\langle x'^2 \rangle$ are the second momentum of the distribution in position and divergence in the trace space. The formula shows two main contributions to the normalized emittance. One is the typical geometrical emittance multiplied by the factor $\beta\gamma$, being γ the usual relativistic factor and β is the ratio between the speed of the particle and the speed of light. In the conventional accelerators the energy spread is quite small, much less than 1% and rms transverse momentum spread is smaller than 1 mrad. But in plasma accelerated beams, especially in case of LWFA (Laser Wakefield acceleration) the energy spread is larger than 1%, and the transverse momentum is also larger than mrad, making the first term the dominant one. In such a case quoting the emittance, as it is usual in many papers regarding LWFA, just multiplying by $\beta\gamma$ the geometrical emittance results in a systematic error. Although the measured quantity is only the geometrical emittance, so it is mainly a problem of definitions. However often the used experimental technique can produce wrong geometrical emittance results.

The so called pepper-pot technique (see Lejeune and Aubert (1980)) is very popular, making use of a pinhole array to sample the transverse phase space, see Fig.1.

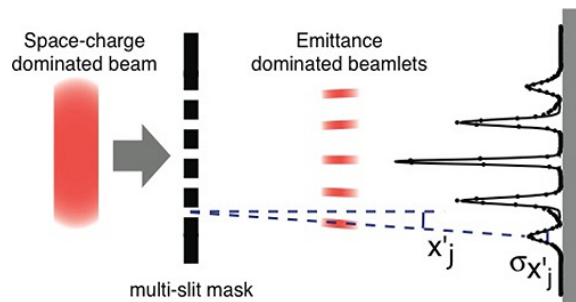


Fig. 1. Pepper pot layout

A mask is used to stop or heavily scatter the beam and after a proper drift, the remaining beamlets are imaged onto a scintillator crystal. From the beamlets transverse dimension, their spacing and their relative intensities it is possible to reconstruct the whole transverse phase space. It is usually adopted at low energy (about 5 MeV) in electron photo-injectors, while a version suitable for high energy beam (about 500 MeV) has been already tested and developed in

Delerue and al. (2010). Anyway in Cianchi et al. (2013) we have already considered the problems related with this method, showing that the main issue related to this technique is the undersampling that occurs when the phase space is strongly correlated, as it is in LWFA beams. In Cianchi et al. (2013) we have also set a threshold value for the dimension of the beam at the beginning of about $10\ \mu\text{m}$. If the source is smaller than that value we have demonstrated that pepper pot measurements are really not meaningful.

3. Single shot techniques

Single shot techniques are a natural candidate for plasma accelerated beams, due to the intrinsic instability of this high gradient acceleration scheme. Betatron radiation is emitted during the acceleration process [Rousse and al. (2004)] and it is widely used to infer the beam dimension. Two techniques are mainly developed, based on the analysis of the spectrum of the radiation [Plateu and al. (2012)] or on the half plane diffraction pattern [Cipiccia and al. (2011)]. Usually the spectrum of the emitted X rays is analyzed and compared with different models of the plasma interaction in order to retrieve the initial beam size and divergence. However, while this work is really remarkable in terms of experimental technique and results achieved, it makes use of a comparison between data and a model to simulate the emission in the process. In some respect it is not a direct measurement and it could suffer of all systematic errors that can arise from the model. Also it is not clear if the models include the transition of the beam from inside of the plasma to free space outside of the plasma. If not, this transition can have a major effect on the beam quality.

A point source illuminating half plane in Fresnel approximation produces a real sharp edge image. If the size is not point-like the profile is a convolution between a step function and a Gaussian distribution, resulting in a complex error function. From the analysis of this profile it is possible to retrieve easily the dimension of the source. Recent papers used profitably this characteristic, measuring simultaneously the beam size and the beam divergence, making the strong assumptions that at the beginning the beam was uncorrelated in the phase space and that the divergence is not affected by the transition between plasma and vacuum. In particular in Fig.2 extracted from Kneipp and al. (2012) several parameters are measured at the same time: energy and energy spread using a dipole, divergence using vertical dimension, transverse dimension by using the betatron radiation.

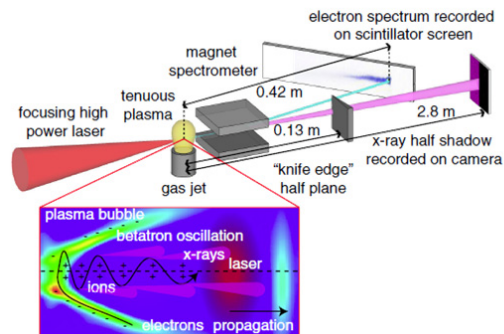


Fig. 2. From Kneipp and al. (2012) a multi parameter single shot measurement.

4. Multi shot techniques

A quadrupole scan (see for instance the book of Minty and Zimmermann (2003)) is so far the most used technique for emittance measurement. It relies in changing the current, i.e. the magnetic field, in one or in several quadrupoles, and measuring how the beam spot size changes after a suitable drift downstream. Using the known information on the beam transport matrix it is possible to use the data to fit the initial beam parameters (Twiss parameters and rms emittance) at the beginning of the beamline. Of course by its nature this is a multishot technique. Two main issues appear in such a case. First of all the need to have enough statistics to alleviate the unavoidable shot by shot fluctuation. But in a chromatic system it is also important to evaluate the impact of the energy spread, usually larger than 1%, as

it was already done in Mostacci and al. (2012). The contribution of the chromatic aberration to the total measured emittance is estimated in that paper. Even with 1% of energy spread, depending on the beam energy and size, it is possible to find situations where the emittance dilution is negligible.

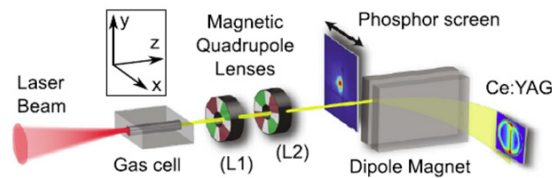


Fig. 3. From Weingartner and al. (2012) a new design of quad scan.

In Weingartner and al. (2012) is introduced a new and innovative design of quad scan, shown in Fig.3. The use of permanent quadrupoles with small diameter greatly reduces the chromatic aberration and allows to place them very close to the beam source. Moving a quadrupole is absolutely equivalent to changing the current in an electromagnetic magnet, because it changes the transport matrix. Beyond the dipole the large energy spread opens the beam in a wide area. Selecting a small slice, corresponding to a roughly monochromatic beam and measuring the horizontal beam size the authors were able to retrieve the horizontal emittance. The diagnostic setup is very challenging and does not allow to measure the emittance on the other axis. Also in this setup the authors have access to a novel way to perform the entire quadrupole scan in a single shot. By slicing the beam after the dipole (i.e. selecting a narrow energy band) they measured the beam size for every different energy fraction. The change in the energy could be equivalent of a change of the transport matrix, so measuring beam size at different energies goes over the need of moving quadrupoles mechanically. While this approach is very fascinating this measurement is not equivalent with respect to the multishot case. In fact there is a strong hypothesis that the emittance must be equal for all beam energies. As the energy is usually correlated with the longitudinal position, it means that slice emittance must be equal all along the bunch.

5. Conclusions

In this paper we focused on the difficulties related to the measurement of the emittance of particle beams accelerated by means of plasma interaction. The main problem of these beams are the large energy spread, larger than 1%, and the huge angular divergence, more than 1 mrad. We pointed out that in this condition the usual definition of normalized emittance must be reconsidered. We also compared several methods in order to measure the emittance. We concluded that single shot methods are preferable, due to the large instability in the plasma acceleration process. In this scenario we evaluated that pepperpot systems cannot be used when the beam is strongly correlated because the tiny phase space is strongly undersampled.

In case of multishot measurements, if we can accumulate enough statistic to dump the fluctuations, also the quadrupole scan technique is feasible under certain conditions. In this case the main constrain is the beam size, that being closely related to the angular divergence sets an upper limit to the distance between the magnetic lens and the plasma channel. The use of the betatron radiation paves the way to interesting single shot measurements, leaving also the possibility to determine at the same time different beam parameters. The single shot quadrupole scan using permanent magnets has been also examined but even if this technique is very promising it is not yet eligible for a complete phase space characterization.

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