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# FRONTIERS OF BEAM DIAGNOSTICS IN PLASMA ACCELERATORS*

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*Abstract*

Advanced diagnostics tools are crucial in the development of plasma-based accelerators. Accurate measurements of the beam quality at the exit of the plasma channel are mandatory for the optimization of the plasma accelerator. 6D electron beam diagnostics will be reviewed with emphasis on emittance measurement, which is particularly complex due to the peculiarity of the emerging beams.

## INTRODUCTION

High energy particles physics has driven for a long time the accelerators to reach higher energy or intensity. However, nowadays accelerators are also widely used in very different fields, covering a huge range of applications, including light sources for medical and industrial applications. Compared to other novel scheme, like high-frequency W-band metallic RF structures [1], dielectric wakefield structures [2] or direct laser acceleration [3], the plasma acceleration offers the highest gradient and compactness. It paves the way to use compact and cost affordable accelerators in universities, medical centers and small laboratories, with a lot of possible applications.

Laser beams (laser wakefield accelerator, LWFA) or charged particle beams (particle wakefield accelerator, PWFA) may be used to excite space-charge oscillations in plasma. They produce both accelerating and focusing fields.

The EuPRAXIA [4] (European Plasma Research Accelerator with eXcellence In Applications) project is expected to be the first Research Infrastructure devoted to establish the scientific and technological basis required to build a compact and cost effective high energy (up to 5 GeV) machine based on plasma accelerator technology.

While there is not yet a final decision about the acceleration scheme to be used, we noticed that in term of beam diagnostics there is not so much difference between different solutions. In all cases the driver must be removed, being a high power laser or an electron beam, because it prevents to put diagnostics downstream of the plasma interaction. In all cases the high beam divergence and large energy spread will force to capture the beam as soon as possible after the plasma stage. So, it is difficult to put diagnostics between the plasma and the capture optics.

In addition to the complications inherent to the plasma acceleration, as driver removal, shot by shot pointing or timing instabilities, large energy spread, there are specific issues about the resolution in measuring the 6D phase space. Time resolution must be in order of few fs, transverse emittance resolution better than 1 mm-mrad, the charge must be discriminate at the level of pC and the trajectory must be known at µm level. Sometimes it is forgiven that if the accelerator must be compact, the diagnostics have to be compact as well, resulting in a complete redesign of even conventional diagnostics.

At the same time in INFN-LNF Frascati a satellite project has been started [5] showing about the same problems in term of beam diagnostics.

This paper, starting from the state of the art, wants to emphasize the peculiarity of the plasma acceleration, and the challenges in measuring such kind of beams, giving also information about our developments still in progress. Longitudinal diagnostics will be the argument of Section I, while we will focus on transverse diagnostics in Section II, giving also more details about our work.

## SECTION I:LONGITUDINAL DIAGNOSTICS

In a compact machine a longitudinal compressor is more appealing that a magnetic chicane, due to the shorter path required for its implementation. However, to set the correct compression phase in the velocity bunching and to recover the correlated energy spread induced in this way, a longitudinal diagnostics is mandatory. Longitudinal phase space measurement can be performed with a X-band RF deflector (RFD), i.e a RF cavity with a transverse deflecting mode, combined with a magnetic dipole. While the fs resolution is state-of-the-art for these devices, so far only one X-band RFD is operating, at SLAC [6], for an energy one order of magnitude greater than our case. It means that the design must be reconsidered and particular attention must be put in several details that usually are neglected. For instance the reduced iris aperture and the possibility that the beam goes inside out of the center must be evaluated with simulations. Particular attention must be put also in RF time jitter and the structure temperature stability, tailoring this requirements to the beam energy and the available beam line. As a rule of thumb, for GeV level beam, a temperature stability in the order of tens of mK and time stability in the order of tens of femtoseconds are required.

In a plasma accelerator, especially during the commission phase, a one to one correlation between the longitudinal properties of the beam sent into the plasma and the beam

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emerged from it is mandatory. Non-intercepting single shot longitudinal profile measurement is needed.

Diffraction radiation [7] is emitted when a charged particle passes through a hole with transverse dimension smaller with respect to the radial extension of the electromagnetic field traveling with the charge. Coherent emission arises when the observed wavelength is longer with respect to the bunch length [8]. In our case the bunch length can be few ps (on-crest acceleration) down to few fs (compression regime). It reflects in the use of different detector to cover wavelength from far infrared to visible light.

To measure the spectrum in a single shot is needed the dispersion of the radiation by several grating or even several spectrometers. The complete analysis of the spectrum leads to the reconstruction of the longitudinal bunch shape.

Different approaches have been used to this end. A single KRS-5 (thallium bromoiodide) prism [9], dispersing the radiation on a linear detector et al..lowing the measuring of a wide spectrum, or a series of separate spectrometer working in different wavelength scales [10] have been already succesfully tested. Using really a small space in the beamline they can be consider excellent candidate to work also in a plasma machine.

Other single shot devices can be based on EOS (Electro Optical Sampling). The electric field co-propagating with the bunch can rotate the polarization of a laser impinging on a non linear crystal such as GaP or ZnTe.

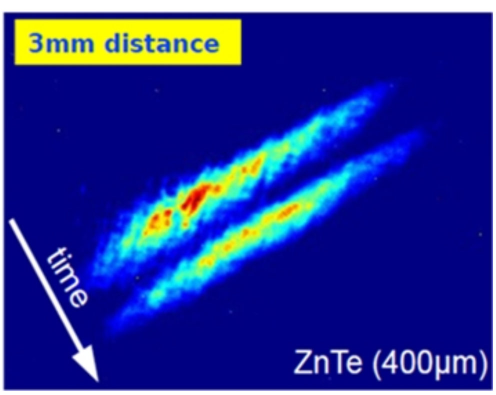


Figure 1: Image EOS of a bunch train of two bunches, 80 pC on each bunch, pulse lenght 160 fs and 200 fs respectively. Their distance was 800 fs.

Using *spatial decoding* scheme [11], realized with an angle of incidence between the probe laser and the crystal, it is possible to retrieve the longitudinal beam profile in one shot. In Fig. 1 is shown the signal retrieved by a ZnTe crystal, placed at 3 mm from the beam line. The train of the two pulses, with a distance of 800 fs is clearly resolved. However, the temporal resolution, limited or by the crystal bandwidth or by the length of the laser probe is in the order of 40-50 fs [12].

Also EOS can be often used as bunch of arrival monitor, that it is very important in some plasma acceleration schemes, as for instance external injection [13].

# SECTION II:TRANSVERSE DIAGNOSTICS

For the beam produced by a RF linac, the emittance measurement can be performed with very well-known techniques, like quadrupole scan and multiple screens [14]. However, in a plasma accelerator single shot measurements are highly desirable. Also, the diagnostics is narrowed between two competitive effects: the driver-witness separation prevents to have any diagnostics just after the plasma channel, while the large energy spread (usually above % level) produce an unwanted increase of the emittance even during a drift [15], making urgent the measurement as soon as possible.

Recentely it was introduced the concept of chromatic lenght [16], defined as the distance where the emittance grows of a factor $\sqrt{2}$ as

$$L_C = \frac{\sigma_x}{\sigma_x' \sigma_E} \tag{1}$$

where $\sigma_x$ is the rms beam size, $\sigma_x'$ is the rms beam divergence and $\sigma_E$ is the relative rms energy spread at plasma extraction. In a conventional accelerator $L_C$ is usually longer than the whole machine, while in plasma accelerators, depending on the value of the energy spread, could be in a range between few centimeters and few meters. To overcome this problem the only solution is a fast capture of this beam and a mitigation of the energy spread, even at cost of some charge reduction.

For all of these reasons we decide to separate the measurements of the properties of the beam inside the plasma channel from the measurements after the capture optics. Being not possible to place anything after the plasma, the only source of information for the beam inside is the radiation emitted during the process of the acceleration.

## *Betatron Radiation Based Techniques*

The diagnostics based on betatron radiation [17] has been developed in recent years in several laboratories, relying on the measurement of the spectrum, (for instance among the other see [18])or on the diffraction from a knife edge [19]. However, these systems were able to measure just the beam profile and divergence, neglecting the correlation term. Only recently a new algorithm to retrieve the correlation term [20] has been developed.

A simultaneous measurement of the electron and radiation energy spectrum and the plasma density allows the reconstruction of the whole phase space. However, being this measurement made on a self-injected beam, some approximation on the initial beam phase space were needed, while if the beam is externally injected inside the plasma, the knowledge of the initial 6D phase space removes this ambiguity.

In Fig. 2 is reported a reconstructed phase space with this technique.

While this algorithm is based on the reconstruction of the beam 1D profile, the full 2D beam profile characterization

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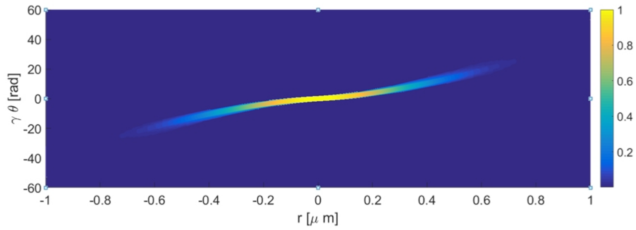


Figure 2: Reconstructed phase space with betatron radiation from self-injected electron beam. [20]. Laser parameters: energy 1J, pulse duration 30 fs (FWHM), 10 μm diameter focus, $a_0 \approx 4.4$; plasma density =$(8{\pm}1)10^{18}$ cm$^{-3}$.

has also been shown to be possible to be measured using the correlation between spectrum and angle [21]. This particular technique could allow to resolve beam size in the order of 50 nm.

The overlap between synchrotron radiation, eventually produced by a downstream magnet to separate beam and radiation, is negligible with respect to betatron radiation. However, an open problem is related to the separation between the betatron radiation coming from the witness and from the driver in the beam driven scheme. The driver contains much more charge with respect to the witness and so only a clear energy separation of the two spectra can solve the problem. Obviously in the case of external injection (i.e. a laser driven case) this problem disappears.

A betatron radiation based measurement can allow to properly tune the plasma source. However, to match the beam with an undulator, for instance, a single shot emittance measurement is needed. The solution of this problem is still unclear, even if a lot of work is ongoing.

### *Single Shot Emittance*

Two papers about a single shot emittance measurement has been recently published [22, 23], relying on a method developed some years ago [24]. An electron beam produced by means of ionization injection is then focused in a triplet of permanent quadrupoles before entering in a dipole. The measurement is performed after the dipole. Due to the large energy spread, common in beams produced with this method and in the level of several %, different energy beam parts are focused in different transverse dimensions. The method is basically the same that conventional quadrupole-scan [14], but in this case the quadrupoles are permanent magnets. It is very remarkable also the calculation of the possible resolution of this method, in the order of 0.1 mm-mrad reported in [25] where the technique is fully described systematically. Of course there is an inherent approximation: different beam parts, belonging to different energies, must have the same emittance. This methods works very well for self-injected beams and it is for sure the solution that we were looking for. However, the reduction on the energy spread, highly desirable for beam that have to drive a FEL, reduces as well also the resolution of the measurement.

Pepper pot like techniques [26] are not easy to be implemented at high energy, because a very tick target is needed to increase the signal to noise ratio in the beamlets. But increasing the thickness reduces the angular acceptance of the beam, resulting in a likely cut of the phase space. However, the pepper pot suffers also for a problem related to the sampling nature of this measurement, as already discussed in [27].

A more careful analysis of the sampling limitation reveals that part of the reduction in the sensitivity of this technique comes from the use of a double sampling, one on the target that selects beamlets, and one on the screen to image them. We have proposed and we are testing a new device [28], a sort of optical pepper pot, where there is only one sampling at the source level. It makes use of Optical Transition Radiation (OTR) produced when a charge passes through a metallic foil. In Fig. 3 there is a sketch of the system

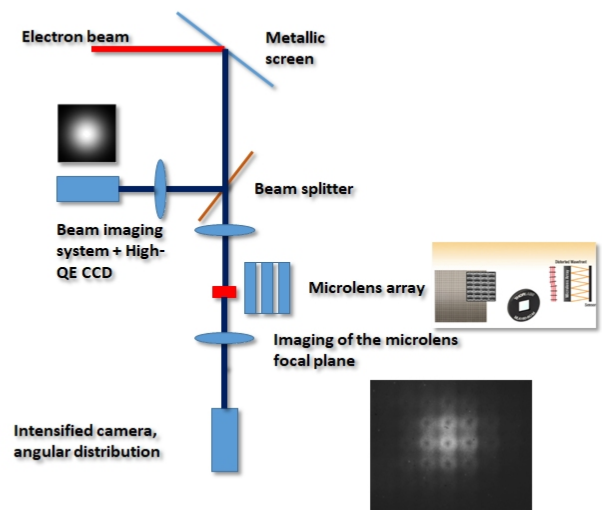


Figure 3: OTR generated by the beam in the interaction with a metallic foil is split in two arms. In the first arm a CCD camera measures the beam size. in the second ones a replica of the source radiation field is propagated on a microlens array. The back focal plane of the array is then imaged on an intensified camera. In the right corner there is a picture of a real image. The OTR angular distribution is reproduced by every single microlens.

The experiment has been performed at SPARC_LAB photoinjector at 125 MeV The angular distribution of the emerging radiation contains information about the angular divergence of the beam. Using an optical system to reproduce outside the vacuum chamber the source radiation field, and sampling by means of a microlens array, it is possible to measure the angular distribution and so the value of the beam divergence, in different transverse positions. It allows the retrievement of the correlation term. Acquiring at the same time also the beam spot allows, in principle, the measurement of the emittance in single shot. While we have already performed a test of this device we were not able so far to retrieve the value of the emittance. The resolution is too poor at actual SPARC_LAB [29] energy value.

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The resolution of the measurement is strictly correlated with the beam energy, due to the narrowing of the angular distribution at higher energy. Using the Fig. 3 of the paper [28] is visible that the resolution change dramatically in the range of the energies below 200 MeV showing an increment, while is flattening for energies above 500 MeV. We are studying this system both for low energy (in any case >200 MeV) than for 1 GeV. The increase in the energy reflects also in the enlargement of the field transverse dimensions. It effects the diffraction of the microlenses. This effect is shown in Fig. 4.

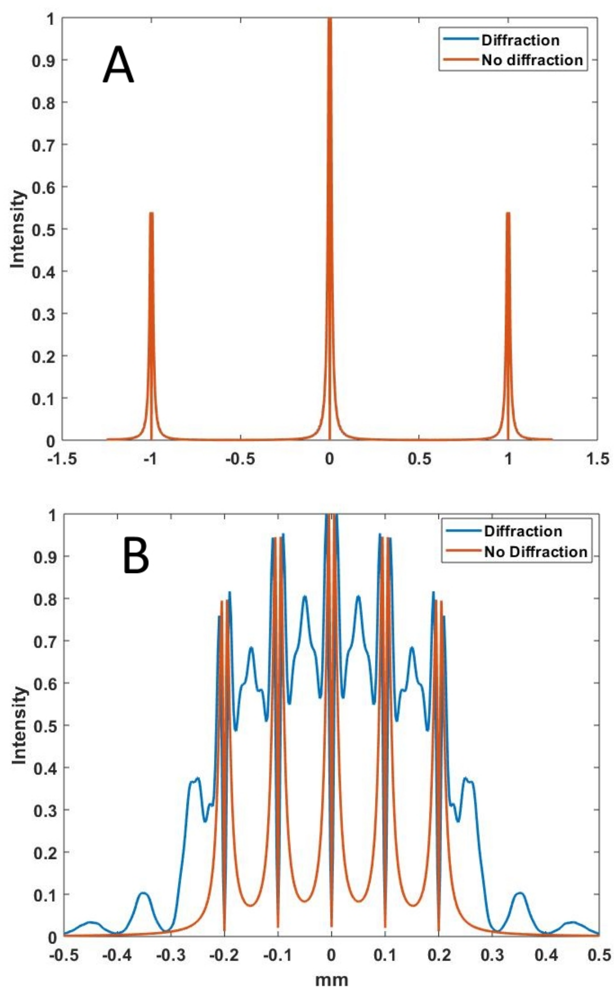


Figure 4: A:lens focal length f=10 mm, diameter D=1mm, beam energy=1 GeV; B: lens focal length f=10 mm, diameter D=.1mm, beam energy=1 GeV

While for energy up to few hundreds of MeV diffraction effects are not relevant, at GeV they impact the choice of the microlens array size. Enlarging the lens dimensions solves the problem, but it impacts on the sampling rate of the measurement. So a fine tuning between energy and array size, taking into the account the possibility to play with moderate magnification with the optics, must be found.

### *Use of Plasma Lenses*

Some years ago a paper [30] showed the possibility to measure the emittance in a single shot, recording at the same time the OTR produced by several very tiny screens. The method is the multiple-screen, a variation of the quadrupole scan method. There are indeed accelerators that have a dedicated space to host multiple screens for such a measurement. For instance at FLASH2 in Desy the space is roughly about 10 meters. Such a long path is not compatible with a plasma accelerator, where the dimensions must be very compact. Also, as pointed out in [31], this system really works only if there is a significant phase advance between every screen. It means that a magnetic optics is mandatory. But again it costs space, and it cannot be the case for a compact machine. Recently several papers have been published about plasma lenses [32–34], a new and compact device, only few cm length. These devices not only show a magnetic field at least one order of magnitude larger than permanent quadrupoles, but they focus also on both planes at the same time, they show much smaller chromaticity with respect to conventional magnets, they can be tuned and they have very short (few cm) focal length.

It is possible to foresee that the use of plasma lenses together with multiple OTR screens will allow the realization of a real compact multiple screens system, maybe less than 1 meter long. Such a device could be installed in every machine, especially in a plasma accelerator.

## CONCLUSION

The plasma acceleration promises to change the field of particle accelerators, not only for high energy physics, but more likely for light source, industrial and medical applications. Compact, single shot, high resolution devices must be foreseen to properly monitor the machine. Working on the project of a future plasma accelerator we found that while there are already several diagnostics for longitudinal parameters, that can be adapted to our case, there is a lack of techniques for single shot emittance. Intrinsic difficulties related to plasma acceleration make difficult to have diagnostics just after the acceleration stage. To overcome this problem we propose a widely use of the betatron radiation, to monitor the beam properties inside the plasma channel, and to test some new ideas outside the plasma, but only after a capture optics, to measure the properties of the beam that will be used for applications.

## ACKNOWLEDGEMENTS

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