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Transverse emittance diagnostics for high brightness electron beams

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ABSTRACT

Advanced diagnostic tools for high brightness electron beams are mandatory for the proper optimization of plasma-based accelerators. The accurate measurement of beam parameters at the exit of the plasma channel plays a crucial role in the fine tuning of the plasma accelerator. Electron beam diagnostics will be reviewed with emphasis on emittance measurement, which is particularly complex due to large energy spread and strong focusing of the emerging beams.

1. Introduction

The brightness is a figure of merit largely used in the light sources, like Free Electron Lasers, but it is also fundamental in several other applications, as for instance Compton backscattering sources, beam driven plasma accelerators and THz sources. The brightness is defined as [1]

$$B_n = \frac{2I}{\pi^2 \varepsilon_{nx}\varepsilon_{ny}} \tag{1}$$

where I is the beam current, and ε_{nx}, ε_{ny} are the normalized emittance in x and y respectively. It is measured in A/m^2. Typical values of high brightness beams range between 10^{14} and 10^{16} A/m^2. This definition is sometimes called 5-D brightness while when this quantity is divided by the energy spread it is called 6-D Brightness, see for instance [2].

Increasing current or reducing emittance or having together these effects are different ways to produce high brightness beams. However different diagnostics apply in every different conditions. For instance few picoseconds bunch length are highly demanding for longitudinal time resolution, while high charge beams usually require not intercepting diagnostics. So high brightness diagnostics refers to a very wide spectrum of different conditions.

Plasma based accelerators have demonstrated the ability of delivering high energy beams in a very compact dimensions. There are several challenges related with these new techniques and one among the other is the possibility to produce high brightness beams. We focus our attention only on the plasma accelerated beams.

In order to measure the longitudinal and transverse properties of such beams new diagnostics techniques must be used, adapting existing methods or inventing new ones. We concentrate in this paper only on transverse measurements and in particular on emittance measurements. A more complete, albeit not exhaustive, review of both longitudinal and transverse diagnostics can be found in [3].

The main issues for this diagnostics are the shot to shot instabilities and the large energy spread. So mainly only the single shot measurements are eligible for such a task.

2. Single shot incoherent OTR based emittance measurements

When the space charge contribution is negligible the quadrupole scan [4] is the most used technique to measure the emittance. It is based on the measurement of the beam transverse spot changing the current in one or more quadrupoles. But it is a multi shot measurement and because it uses magnetic lenses, it is very sensitive to energy spread [5]. Unfortunately up to now there are not reliable and well established single shot measurements of transverse emittance, while several experiments have been already carried out, as reported in [3].

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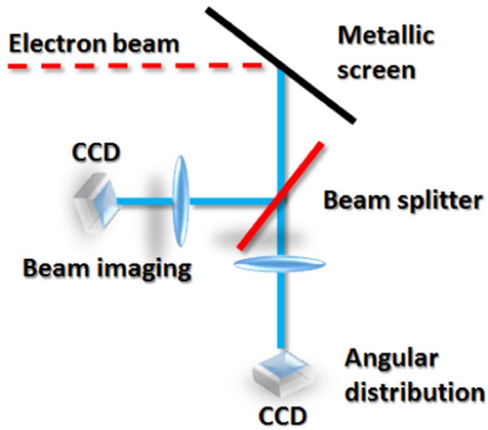

Fig. 1. Simple setup to measure in the same shot both beam size than beam divergence.

Optical Transition Radiation (OTR) is emitted when a charged particle crosses the boundary between two media with different index of refraction. It is well known since many years [6], but only in the 90's received attention as powerful diagnostics tool. We focus here on the incoherent part of the radiation emitted at wavelength shorter than the bunch length. It happens often in the visible range.

While collecting and imaging the emitted radiation is a simple system to measure the beam charge transverse distribution and also its dimensions, there are more information hidden in the angular distribution of the radiation: the energy and the angular spread of the beam that produced it.

A simple setup is shown in Fig. 1 where the radiation, coming from a metallic screen (often a silicon aluminated plate) placed at 45 degrees with respect to the beam line, is later split in two arms. In the first one the detector is placed in the image plane of an optical system, while in second one in the focal plane. With such a device in every single shot the beam image and the radiation angular distribution can be recorded.

In Fig. 2 there is an example of a central line profile of the angular distribution of the OTR for a beam at 125 MeV, in two different conditions: a parallel beam, i.e. without angular spread, and with 1 mrad divergence. The most relevant effect is the reduced visibility of the central minimum.

In both cases the beam is supposed to be monochromatic. The effect of the energy spread is indeed very weak and becomes appreciable only with values higher than several tens of percents.

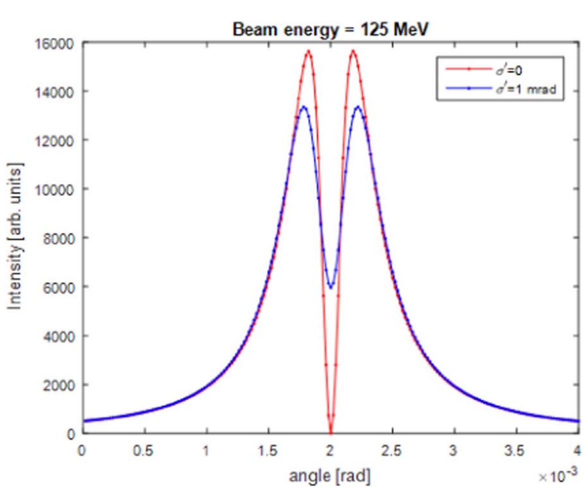

Fig. 2. Line profile of the OTR angular distribution for 125 MeV electron beam with different angular spreads.

Using the conventional formula for the angular distribution of the OTR [6], neglecting constants, and making the ultra relativistic approximation we get:

$$I \propto \frac{\sin^2\theta}{(1-\beta^2\cos^2\theta)^2} \simeq \frac{\theta^2}{\left(\frac{1}{\gamma^2}+\theta^2\right)^2} \tag{2}$$

where β and γ are the usual relativistic factor, while θ is the angle of a ray with respect to the specular reflection on the screen. Convoluting the previous formula with a Gaussian distribution in angle, being σ' the rms beam divergence, we have:

$$I \propto \frac{1}{\sqrt{2\pi}\sigma'}\int_{-\infty}^{\infty}\frac{(\theta-\xi)^2}{\left[\frac{1}{\gamma^2}+(\theta-\xi)^2\right]^2}e^{-\frac{\xi^2}{2\sigma'^2}} \tag{3}$$

By solving the former equation we obtain [7]:

$$I \propto \frac{\mu}{\nu}\,\mathrm{Re}\left[\Phi(z)\left(\frac{1}{2}+\mu\nu z\right)\right]-\mu^2 \tag{4}$$

where $\nu=1/\gamma$

$$\mu=\frac{1}{\sqrt{2\pi}\sigma'}\Phi(z)=\frac{1-erf(z)}{e^{-z^2}}z=\mu(\nu+i\theta)$$

and erf(z) is the complex error function. So there is an analytic formula describing this behavior and it gives the possibility to easily fit the experimental data in order to retrieve the value of the σ'. Using the information coming from the beam image and the radiation angular divergence, both values of beam dimension and beam divergence can be obtained in a single shot. However the correlation term is not measured in this way.

Using a Gaussian for the distribution of the particle transverse momentum is reasonable for most of the cases, especially in the linacs. However where there are strong correlations between position and angle, or mixing of horizontal and vertical planes, or in general when the distribution is not anymore Gaussian this treatment cannot be apply and a reasonable guess of such a distribution must be consider.

With a setup similar of Fig. 1 it was already possible [8,9] to measure the emittance in a beam waist, where the correlation term is zero. The authors used a two foils setup, instead of a single one, a configuration sometimes called Wartski interferometer [10]. In such a configuration the radiation emitted from the first foil interferes with the emission from second foil, leading to an interference pattern. It has the advantage of increasing sensitivity of the effect coming from the beam divergence, but the setup is strongly dependent from the relative distance between foils, where the best setup is related to the ratio between the foils distance and the formation length. When the beam energy changes also the radiation formation length is modified, with a scale law going as γ^2, and so the foils distance should be accommodate every time in order to have the best resolution. Moreover the first interface scatters the beam spoiling the value of the emittance for high brightness beams, if the energy is not in the GeV range.

The sensitivity to the beam divergence is a critical issue for such a diagnostics. If we call visibility

$$V=\frac{I_{MAX}-I_{MIN}}{I_{MAX}+I_{MIN}} \tag{5}$$

where I_{MAX} and I_{MIN} are the maximum and minimum of the intensity distribution. We have the maximum visibility equal to 1 only in the case of a perfect parallel beam, i.e. when the intensity of the central minimum is exactly zero. In optical system usually the visibility is measured through the contrast via the modulated transfer function. It is quite standard to assume as a threshold value for the resolution the 10 % of the visibility. In our case we have to consider that the minimum

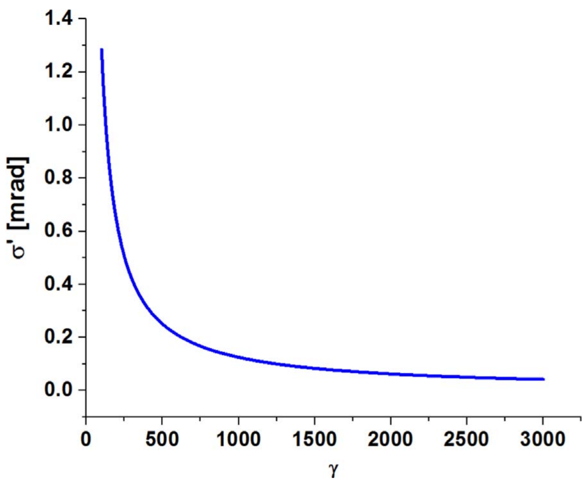

Fig. 3. Resolution limit for the beam divergence vs beam energy.

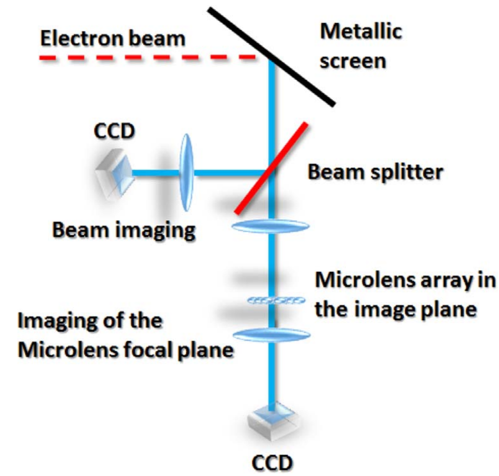

Fig. 4. Experimental setup: a replica of the beam is produced in the two arms. In the second one in the image plane there is a microlens array. Their focal plane is imaged in a CCD detector.

could be also spoiled by some noise, especially in the parallel beam condition, where its value is exactly zero. So this definition fits consistently with our experimental condition.

If we consider to vary the energy and find the value of the σ' that corresponds to 10 % visibility we obtain the plot of Fig. 3.

The described behavior has a simple physics interpretation. Electrons that arrive on the metallic target with a different angle with respect to the beam propagation produce a cone of radiation with a center not at θ=0, but at the angle of their direction with respect to this value.

The overlap of all the distributions resolves in the increasing value of the central minimum. At low energy the angular distribution is very wide. So even in presence of angular spread the overlap of all distributions has not a big impact on the central minimum. However when the energy grows up the angular distribution narrows and even a small change in the angle of the emitted radiation has a big impact. This is the reason why this diagnostics is very appealing for laser plasma accelerated beam where the σ' is usually in the order of mrad, and it has the sensitivity to resolve the value even at 100 MeV. In the conventional accelerators it can be consider only if the energy is high enough to measure the divergence according to the curve in Fig. 3.

3. The problem of the correlation term

So far we described a technique already used but valid only in a beam waist. However for its own nature the plasma acceleration has strong shot to shot fluctuations and a beam waist cannot be guaranteed also because it implies the use of a focusing optics. So the correlation term must be measured for every single shot.

A tentative has been made already in [11] several years ago. Instead of having directly the angular distribution, an image is produced in both arms of the setup in Fig. 1, placing a mask to cut the peripheral part of the beam. Another lens makes the angular distribution of the emerging radiation. This is not a single shot measurement because it was needed to remove the mask, but it gave for the first time the possibility to have two points where divergence and beam size were correlated.

4. Experimental setup

In our setup the correlation term is measured in every single shot. Our experimental setup is shown in Fig. 4. The light coming out from a silicon aluminated screen is divided but a 90:10 beam splitter. The 10 % is then used to image the beam in a Hamamatsu Orca II camera, high quantum efficiency, equipped with a Nikon f=180 mm focal length F/2.8. The other part arrives on a f=400 mm focal length achromatic doublet. In the image plane of such a lens, with a magnification 1:1, is placed a Thorlabs mounted lens array. These are plano-convex lenses, with a pitch of 300 µm, and a focal length of 18.6 mm.

Extensive simulations have been performed in Zemax to understand the effect of possible aberration of such a lens system. A complete virtual measurement has been simulated, starting from the radiation produced by a bunch charge and propagating in the whole optical system. No significant effect of aberration in the microlenses have been found. The focal length of the microlens array is very small, just 18.6 mm, so for geometrical constrains it is impossible to place the detector directly on its focal plane. Instead we put another achromatic lens with focal f=5 cm to image with 1:1 magnification this focal plane into our intensified camera, an Hamamatsu Orca IV.

The experiment has been performed at SPARC_LAB photoinjector [12], using 200 pC bunch charge at 125 MeV. The maximum energy was limited by the use of only two of the three accelerating sections. The third one was not available due to a severe problem on its klystron. Looking at Fig. 3 it is evident that in this energy range the minimum detectable beam divergence is in the order of 0.5 mrad. Even if we have tried to deteriorate the value of the emittance and focus the beam in one dimension in order to push the beam angular spread over this value we did not succeeded.

In Fig. 5 is reported a qualitative comparison between a simulated pattern behavior and a real single shot measurement.

Every illuminated lens produces its own radiation ring. Analyzing the single OTR angular distribution is possible to retrieve the value of the angular spread. The qualitative agreement between simulation and measure is excellent. We extract from every single ring the profile and we fit them. In Fig. 6 there is an example of one of these fits.

As expected the fit is very good but the value of the angular spread is about 500 µrad, totally dominated by the resolution limit at this energy.

From a quadrupole scan measurement we found that the beam angular divergence, even in a waist, it should be around 250 µrad, a factor 2 less than our resolution limit. In Fig. 7 the result of the angular distribution in a beam vertical waist. As expected just one line of the microlens array is illuminated by the radiation. Even if we did not measure the emittance, this preliminary result demonstrates that it is possible to produce the OTR angular distribution from different part of the beam image.

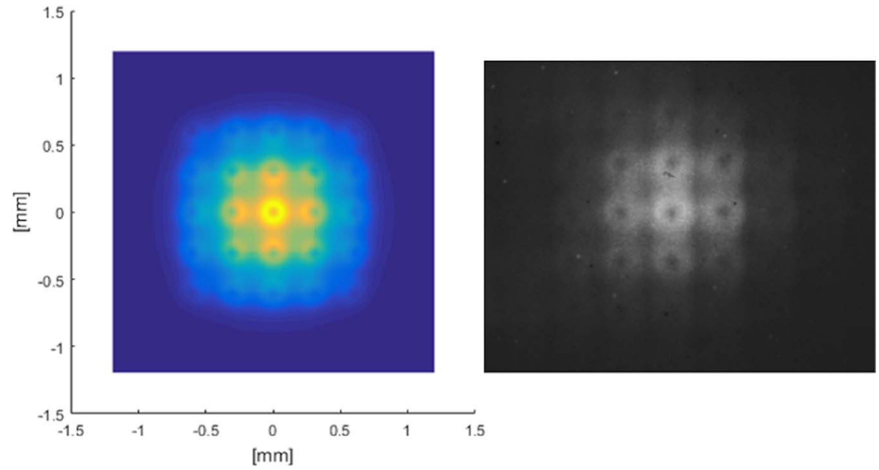

Fig. 5. Comparison between a simulation (left) and a first measurement (right).

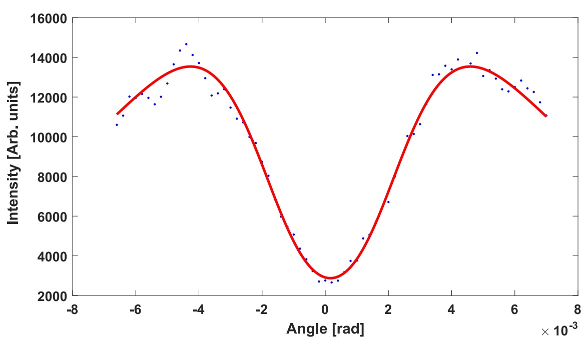

Fig. 6. Comparison between experimental data and a fit for one of the OTR angular distribution.

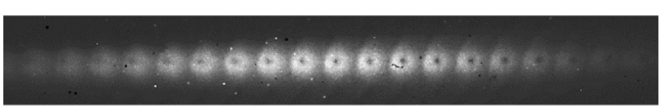

Fig. 7. Image of the angular distribution of a beam in a vertical waist.

5. Conclusion

The diagnostics for high brightness beam are very challenging in particular for measuring transverse phase space of plasma accelerated beams. The usual and consolidated techniques cannot be applied for such beams due mainly to their inherent shot by shot instability and due to the large energy spread.

Several experiments have been already performed in order to find simple and reliable solutions. Whatever some of them are promising, no one so far it was able to properly measure the emittance including the correlation term. And no one is yet state of the art.

In this paper we have shown the very first preliminary results of a new diagnostics, based on the spatial analysis of the incoherent OTR emitted by a particle beam. The use of a microlens array allowed us to sample a replica of the beam image, optically produced, and to measure the angular distribution in different transverse position. However the experimental conditions were not favorable, because we operated at an energy where the resolution of our device was not enough to properly measure the angular spread of the beam. By the way these data demonstrate that the principle works and make us confident in the measures at higher energy.

The resolution in angle is the principal limitation of the device. According to Fig. 5 this diagnostic is useful only if the point describing the status of energy and angular spread lies below such a curve. For LWFA it happens already a very low energy, while in conventional accelerators hundreds of MeV are needed.

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