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Observations and diagnostics in high brightness beams

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ABSTRACT

The brightness is a figure of merit largely used in the light sources, like FEL (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. Advanced diagnostics are essential tools in the development of high brightness beams. 6D electron beam diagnostics will be reviewed with emphasis on emittance measurement.

1. Introduction

Nowadays new accelerators techniques are opening completely new scenarios, paving the way to a complete revolution in the field of the accelerators with a reduction in the dimensions of the machine of 1–2 orders of magnitude. As everybody knows the diagnostic is not an ancillary part because as the saying goes: “an accelerator is just as good as its diagnostics”. So, also the diagnostics face new challenges. Shot by shot instabilities dramatically cut the possible usable techniques, while very short bunches, in the order of few tens of femtoseconds, deserve very high temporal resolution.

It is also a big challenge to give an overview of all the works ongoing, because several groups worldwide are trying to address the same questions. Being outside of the scope of this paper to give quotation of every single experiment, we offer mostly a documentation of several working branches in this field. For this reason we just select almost one or two papers for every issue, apologizing since the very beginning for who will not be cited here.

2. Brightness and its meaning for beam diagnostics

The concept of electron beam brightness was adopted from conventional optics where it characterizes the quality of light sources. The beam brightness is defined as the current density per unit solid angle in the axial direction. While it is used from any kind of electron beam, from electron microscopy to FEL (Free-Electron-Laser) community, it is very difficult in the literature to find a unique definition of such a quantity, especially because it is often confused with Brilliance (see for instance [1], [2, p. 255], [3, p. 20], [4, p. 61], [5, p. 419], [6, p. 73]). We follow the definition reported in [3]

$$B_n = \frac{2I}{\pi^2 \varepsilon_{nx} \varepsilon_{ny}} \quad (1)$$

where I is the beam current, and ε_{nx} and ε_{ny} are the normalized emittance in x and y directions respectively. The brightness 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 [7]. The brightness is a figure of merit largely used in the light sources, like FEL (Free Electron Lasers), because it is strictly connected to the gain length and so with the possibility to reach the saturation. But it is also fundamental in several other applications, as for instance Compton backscattering sources [8], beam driven plasma accelerators [9] and THz sources [10].

Which is the meaning of high brightness from the point of view of diagnostics? It could be different depending on how the brightness is obtained. Being brightness a ratio between current and emittance, its high value can be obtained increasing the current or reducing the emittance or having together these effects

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with different weights. And also recently the same general meaning of brightness has been changed. For instance the charge in the single bunch of LCLS should have been in the order of 1 nC, while today is 250 pC and sometimes down to 20 pC, while the beam is still of high brightness. The charge reduction, keeping constant the charge density, decreases the emittance, and allows shorter bunches with higher current. Using 1 nC beam with 1–2 mm mrad emittance means that conventional intercepting diagnostics can be in trouble, especially if the beam is tightly focused. The beam can deposit on the device such an energy that can destroy or severely damage it. On the other hand reducing charge and squeezing the bunch down to 100 fs or even shorter opens new problems in the resolution of longitudinal diagnostics. So high brightness diagnostic covers a wide spectrum of very different scenarios. In recent years the growing interest for acceleration schemes based on the plasma acceleration has even increased this spectrum. In fact in some of the proposed schemes there are more beams to characterize at the same time: the beam injected into the plasma (in case of external injection, we will call it input beam) and the one leaving the plasma (output beam, always present in all of the schemes of self- [11] and external injection [12]). Different diagnostics can be applied to these very different situations (Fig. 1).

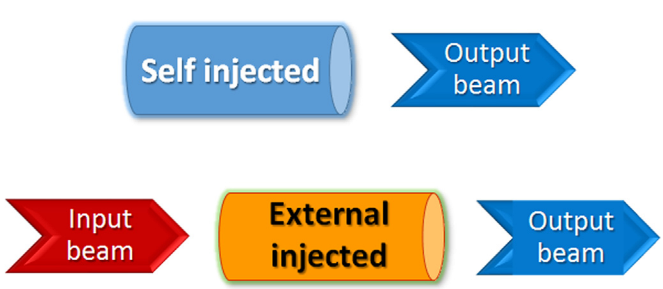

Fig. 1. Different scenarios involved in laser plasma acceleration.

3. Input beam transverse diagnostics

The diagnostics of the input beam are quite standard because were developed for the conventional accelerators, while in case of the output beam are not yet state of the art.

The main parameter to be measured is the emittance. It is important to remember that it is possible to measure only the geometrical emittance. As it was already pointed out (see for instance [13,14]) the normalized emittance is not only just γ times the geometrical emittance, with γ being the relativistic factor, but there is also a contribution from the energy spread and the beam divergence. It is usually negligible in conventional accelerators, but it could be the leading one in such scenario in plasma based accelerators.

The quadrupole scan [15] is the most used technique to measure the emittance, when the beam transport is not dominated by the space charge. It relies on the measurement of the beam spot varying the strength of one or more quadrupoles. It is intrinsically a multi-shot measurement, so it is questionable its use for the output beams. Also, because it involves the use of magnetic elements, a large energy spread can spoil the emittance value [16]. The intercepting nature of this measurement could be a problem in case of high repetition rate machines, or high charge beams, or if it is needed a correlation shot to shot between input and output beams. The not intercepting beam size measurements are not yet state of the art. Here we report briefly three examples of promising techniques: laser wire, bpm (beam position monitor) and diffraction radiation. The laser wire [17] is the not intercepting version of the wire scanner. Basically a tiny but intense laser wire is moved with respect to a beam. The Compton scattered photons in the overlap between laser and beam are collected by scintillators surrounding the vacuum chambers. Some test are still ongoing but it was already demonstrated a resolution at a submicron scale [18]. The main drawback of this technique is the intrinsic multi-shot nature and the stability of the laser wire alignment. Often the whole chamber hosting the laser cavity is moved in front of the beam.

From the signal coming out from a bpm is possible to extract much more than the position of the beam. It has been demonstrated that using combination of signals coming from the different electrodes, it is possible to retrieve also the beam size [19]. A nice follow up [20] demonstrated that this system is really interesting in circular machines, where there is a high repetition rate. However being the signal-to-noise ratio very small, both the electromagnetic design of the electrodes and the mathematical treatment of the signal are fundamental.

The use of diffraction radiation (DR) as beam size monitor from a rectangular aperture was introduced in [21], while other authors have proposed a similar technique by using a circular aperture [22]. The choice of a rectangular slit shape has many advantages, mechanical machining and mathematical treatment, that were at the basis of the success of the first observation of DR [23] as diagnostic tool. However this result has also pointed out some difficulties related to the experimental setup, in particular the low signal-to-noise ratio, mainly affected by the unavoidable synchrotron radiation (SR) background produced by the same beam in the upstream magnetic elements of the transport line and the requirement of an accurate and nontrivial control of the beam trajectory, due to the ambiguity produced by a beam passing off center of the aperture. The use of ODRI (Optical Diffraction Radiation Interference) [24], i.e. a two slits system placed well inside the formation length, can solve both of these problems and it was successfully used to measure the beam emittance [25]. The only advantage of the DR versus ODRI is the mathematical treatment, because only MonteCarlo methods can be applied so far to ODRI, being not yet available the analytic solution of the angular distribution produced by an electron bunch with finite dimensions and angular spread for the ODRI case.

3.1. Comb-like beams

A comb-like beam is a train of short electron pulses, in the order of hundreds of femtoseconds or less with picosecond time separation. The generation of such a beam relies on different schemes, for instance a single long bunch is sliced by a mechanical slits system placed in a dispersive area [26] or a train of bunches is created by the photocathode laser and longitudinally manipulated using velocity bunching [27]. These kinds of beams are assuming an ever growing interest in different fields: in particle-driven plasma wakefield acceleration (PWFA) a train of driver bunches can resonantly excite a plasma wake, which accelerates a trailing witness bunch, injected at the accelerating phase [9]; in a FEL (Free Electron Laser) they can be used for the production of two colors radiation [28,29]; and THz sources driven by comblike beam have been recently developed [30,31] in order to provide tunable, narrowband, few-cycle, and multicycle coherent THz radiation.

Due to the high repetition rate of the bunches, intensified cameras cannot be used to collect and discriminate each bunch in the train, being not fast enough (nanosecond scale) for THz scale repetition rate. The only possibility is to separate the beams and to image them at the same time. A dipole can divide them when they are separated in energy, while a RFD (RF deflector) allows one to distinguish between them when the separation is in time. Mixing these devices with quadrupole scan allowed the measurement of the full 6D properties of every single bunch of such a train [32].

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