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Diffraction Radiation as ultra-high intensity electron beams non-intercepting diagnostics

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Summary. — Diffraction Radiation is receiving ever more consideration as a non-intercepting diagnostic tool. On the superconducting linac at FLASH diagnostic instruments based on DR are routinely used, and new developments are continuously experimented. The analysis of the coherent part of DR spectrum allows the measurement of the longitudinal charge distribution in the bunch, while the incoherent emission at optical wavelengths can give information on the transverse beam size.

PACS `07.05.Fb` – Design of experiments.
PACS `07.05.Pj` – Image processing.
PACS `07.05.Hd` – Data acquisition: hardware and software.
PACS `07.60.Ly` – Interferometers.

1. – Introduction

The problem of measuring and controlling small beam sizes (of the order of tens of μm and smaller) is particularly crucial for Linear Colliders (LC) and linac-driven Free-Electron Lasers. For the particular case of LC, the electron beam transverse size in the final focus can be of the order of tens of nm. Thus, the small beam size, together with high intensity and high charge density, makes non-invasive techniques of large interest as beam diagnostics, both transverse and longitudinal.

As non-invasive beam profile monitors, two are based on laser technology, *i.e.* the laser wire and the laser interferometer technique, and are more suitable for beam sizes of the order of nm. Diffraction Radiation (DR) is rather the most promising candidate for measurement of beam sizes of the order of tens of μm, typical for ILC in the first acceleration stage and XFEL. DR-based diagnostics will be fully described in the paper together

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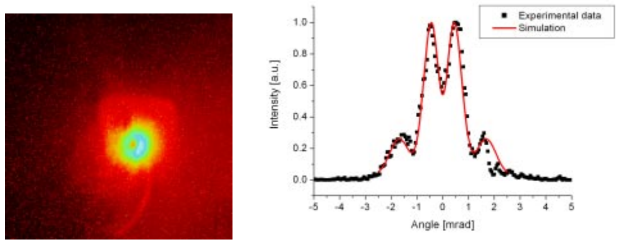


(a) (b)

Fig. 1. – a) OTR angular distribution covered by the SR background. b) Experimental ODR profile, after background subtraction, and comparison with theory.

with experimental results obtained during our experience on both transverse and longitudinal measurements at FLASH (DESY, Hamburg) [1]. Details on laser interferometry techniques can be found in [2] and [3].

2. – Theory of Diffraction Radiation

When a charged particle crosses the boundary between two media with different dielectrics constants, transition radiation (TR) is emitted both in forward (FWD) and backward (BWD) direction as a result of the interaction of the electromagnetic (EM) field of the traveling particle with the screen surface. When only part of the particle field interacts with the surface, DR is produced [4]. The extension of the EM field of a relativistic particle is a flat circle of radius $\frac{\gamma\lambda}{2\pi}$, so that, in case of an infinite long slit of aperture a, DR is emitted if $\frac{\gamma\lambda}{2\pi}$ is comparable with a. Typically the slit aperture is of the order of mm, thus in case of high energy ($\gamma \approx 10^3$), optical wavelengths are emitted allowing a transverse beam diagnostics. At low energies, the emitted wavelength is of the order of mm, thus coherent DR (CDR) can be detected and from the measurement of the coherent spectrum the electron bunch longitudinal structure can be retrieved.

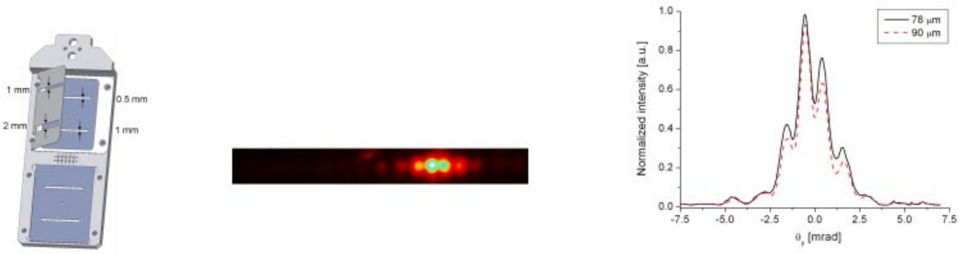
Since the beam goes through the slit, DR is a non-intercepting diagnostics and, therefore, excellent to be used parasitically without disturbing the electron beam.

3. – ODR as transverse diagnostics

First in 1997, Castellano [5] suggested that the visibility of the interference fringes could be used to determine the transverse size of the beam. As a matter of fact the ODR angular distribution produced by a beam going through the center of the slit and with a given transverse rms size (σ) is the same as the one produced by a single electron moving through the slit at a distance σ from the center. The ODR angular distribution is also affected by the beam angular divergence so that, in case the beam is in a waist, a single shot emittance measurement can be done.

3˙1. *Experimental layout*. – We set an experiment up at FLASH to transversely characterize the beam. Details on this experiment can be found in [6] and [7]. The experimental set-up is placed in the by-pass beam line far from the dipole magnets with the intention to minimize the contribution of synchrotron light coming from them.

3˙2. *Experimental results*. – During the first phase of the experiment we were severely limited by the synchrotron radiation (SR) background produced by all the magnets of



(a) (b) (c)

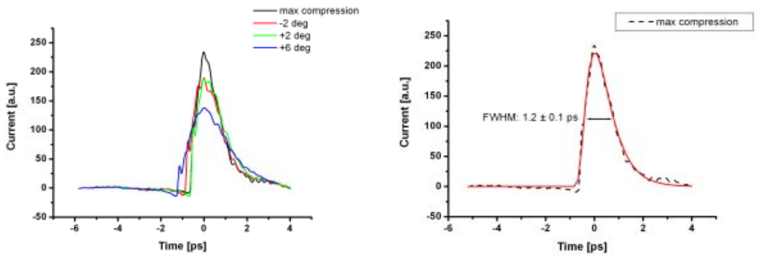
Fig. 2. – (Colour on-line) a) Sketch of the new screen together with its shielding mask. b) and c) ODRI experimental angular distribution for two different rms beam sizes, $\sigma_y = 78\,\mu$m (black straight line) and $\sigma_y = 90\,\mu$m (red dashed line).

the by-pass transport line. Since the vacuum pipe acted as an optical guide, the pattern shown in fig. 1a was produced on the measurement screen. During data analysis a big effort has been done in order to effectively subtract background by software filtering. Eventually, results obtained allowed us to evidence the good agreement between data and simulations, as shown in fig. 1b.

In a second phase we considered the installation of a stainless steel shield (fig. 2a) with larger cut, at 45 deg with respect to the DR target and normally to the beam propagation, in order to reduce the SR background. The effect of the shield was, in fact, very effective in reducing the background level, but for the smaller slit a new phenomenon appeared. For the 0.5 mm slit the corresponding cut in the shield is 1 mm, and this width notably reduces, but not completely cancels, the FWD ODR at 800 nm wavelength. This radiation is reflected by the screen and interferes with the BWD ODR radiation produced on the 0.5 mm slit. Since the amplitudes of the two sources are different in intensity and angular distribution, the effect is a suppression of the central peaks and the enhancement of the lateral ones. This is what we call Optical Diffraction Radiation Interferometry (ODRI). Figure 2b shows the ODRI angular distribution image measured with the beam in the center of the 0.5 mm slit and fig. 2c the corresponding profile for two different transverse beam sizes, $90\,\mu$m and $78\,\mu$m. The comparison demonstrates the sensitivity of the technique even on smallest variations of the transverse beam size in the order of a few micrometer. During these measurements FLASH was operated with 13 bunches per macropulse, 0.8 nC per bunch. Polarizers to remove the residual horizontal polarization and interference filter to select the 800 nm wavelength were inserted. The measured energy was about 900 MeV.

4. – CDR as longitudinal diagnostics

At low energies, for a slit aperture of few mm, the emitted wavelength is in the THz region. The total radiation intensity emitted by an electron bunch is $I_{\text{tot}}(\omega) = I_{\text{sp}}(\omega)[N + N(N-1)F(\omega)]$. I_{sp} is the single particle intensity depending on the source considered, N is the number of electrons in the bunch and $F(\omega) = |\int_{-\infty}^{\infty} S(z)e^{i\frac{\omega}{c}z}\text{d}z|^2$ is the longitudinal form factor of the bunch, $S(z)$ being the longitudinal density distribution of the bunch. $F(\omega)$ is dominant in case of wavelengths equal or longer than the bunch length. Thus measuring the coherent spectrum it is possible to estimate the bunch length and reconstruct its longitudinal structure. In the THz frequency region, this can be done by means of a Martin-Puplett interferometer [8]. The results of the bunch length



(a) (b)

Fig. 3. – a) Bunch longitudinal profiles derived from the measured spectra and b) fit of the maximum compression case with the theoretical expectation.

measurements performed at FLASH are shown in fig. 3. More details are found in [9]. The measured coherent spectra have been corrected taking into account the transfer function of the entire system and the detectors frequency response. Several bunch length measurements have been performed even during FEL operation showing no significant disturbances on the emission process, demonstrating the effective non-invasive and non-intercepting nature of DR. Furthermore CDR can be used as a fast bunch compression monitor to optimize the compression. As a matter of fact, to the maximum intensity of the radiation corresponds the shortest bunch.

5. – Conclusions

DR is a versatile tool for longitudinal and transverse diagnostics of high-energy and high-density electron beams. It is totally non-intercepting, which means that not only high-density beams can be measured, but also that they do not loose their quality. Furthermore, from the analysis of the angular distribution, beam size and angular divergence can be determined, allowing in the beam waist a single shot emittance measurement.

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