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BEAM ENERGY MEASUREMENTS WITH AN OPTICAL TRANSITION RADIATION FOR THE ELI-NP COMPTON GAMMA SOURCE

M. Marongiu*[1], A. Giribono[1], A. Mostacci[1], L. Palumbo[1], M. Pompili, Sapienza University, Rome, Italy
E. Chiadroni, F. Cioeta, G. Di Pirro, G. Franzini, V.Shpakov, A. Stella, C. Vaccarezza, A. Variola
LNF-INFN, Frascati, Italy
D. Cortis, INFN, Rome, Italy
A. Cianchi, Università di Roma II Tor Vergata, Rome, Italy
[1]also at INFN, Rome, Italy

Abstract

A high brightness electron LINAC is being built in the Compton Gamma Source at the ELI Nuclear Physics facility in Romania. To achieve the design luminosity, a train of 32 bunches, 16 ns spaced, with a nominal charge of 250 pC will collide with the laser beam in the interaction point at two electron beam energies, namely 280 MeV and 720 MeV. Electron beam spot size is measured with optical transition radiation (OTR) profile monitors. The paper deals with the possibility of using the OTR monitors to measure also beam energy along the machine; such measurements may help monitoring the accelerating sections performances, especially when the whole bunch train is being accelerated. We discuss the measurement principle, the expected accuracy and the main characteristic of the optical line to retrieve the angular distribution of the emitted radiation.

INTRODUCTION

The Gamma Beam Source [1] (GBS) machine is an advanced source of up to ≈20 MeV Gamma Rays based on Compton back-scattering, i.e. collision of an intense high power laser beam and a high brightness electron beam with maximum kinetic energy of about 740 MeV. The Linac will provide trains of bunches in each RF pulse, spaced by the same time interval needed to recirculate the laser pulse in a properly conceived and designed laser recirculator, in such a way that the same laser pulse will collide with all the electron bunches in the RF pulse, before being dumped. The final optimization foresees trains of 32 electron bunches separated by 16 ns, distributed along a 0.5 µs RF pulse, with a repetition rate of 100 Hz.

The goal of this paper is to verify the possibility of implement an energy measurement technique based on the OTR and to study its expected accuracy; furthermore, the main characteristics of the optical line will be discussed.

In a typical monitor setup, the beam is imaged via OTR or YAG screen using standard lens optics, and the recorded intensity profile is a measure of the particle beam spot [2]. In conjunction with other accelerator components, it will also be possible to perform various measurements on the beam, namely: its energy and energy spread (with a dipole or corrector magnet), bunch length [3] (with a RF deflector), Twiss parameters [4] (by means of quadrupole scan) or in general 6D characterization on bunch phase space [5]. Such technique is common in conventional [6] and unconventional [7, 8] high brightness LINACs.

The optical acquisition system is constituted by the CCD camera “Basler scout A640-70gm” or by the “Hamamatsu Orca-Fash4” with a macro lens. A movable slide is used to place the lens plus camera system closer or farer from the OTR target; such distance is between 60 cm and 130 cm from the OTR target due to mechanical and geometric constraints. In order to avoid possible damage of the optics devices due to the radiation emitted by the beam, a 45° mirror is placed at 40 cm from the target leading to a minimum distance achievable of 60 cm; since the beam pipe is placed 1.5 m from the floor, the maximum distance is instead 130 cm.

OTR RADIATION

Optical Transition Radiation (OTR) monitors are widely used for profile measurements at LINACs. The radiation is emitted when a charged particle beam crosses the boundary between two media with different optical properties [9], here vacuum and a thin reflecting screen (silicon). For beam diagnostic purposes the visible part of the radiation is used; the recorded intensity profile is a measure of the particle beam spot. Advantages of OTR are the instantaneous emission process enabling fast single shot measurements, and the good linearity (neglecting coherent effects). Disadvantages are that the process of radiation generation is invasive, i.e. a screen has to be inserted in the beam path, and that the radiation intensity is much lower in comparison to scintillation screens.

ENERGY MEASUREMENT

Another advantage of the OTR is the possibility to measure the beam energy by means of observation of its angular distribution (see Figures 1 and 2); this can be expressed by the well known formula 1.

$$\frac{dI^2}{d\omega d\Omega} = \frac{e^2}{4\pi^3 c\epsilon_0} \frac{\sin^2\theta}{\left(\frac{1}{\gamma^2} + \sin^2\theta\right)^2} R(\omega,\theta) \tag{1}$$

Where $R(\omega, \theta)$ is the reflectivity of the screen; the peak of intensity is at $\theta = 1/\gamma$.

Due to the beam divergence, the angular distribution of the whole beam will be different from 0 at the center (see

* marco.marongiu@uniroma1.it

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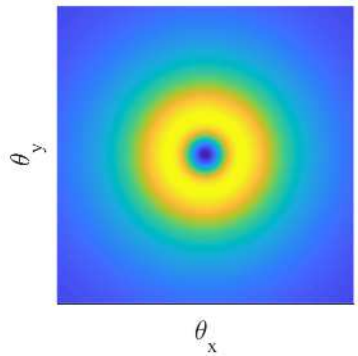

Figure 1: OTR angular distribution of a single electron.

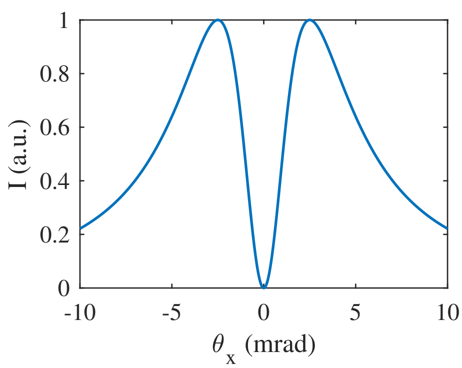

Figure 2: Horizontal profile of the OTR angular distribution of a single electron.

Figure 3); the ratio between the minimum and the maximum intensity is related to the beam divergence. A parameter called visibility can be defined as in Equation (2): the beam divergence measure with the OTR angular distribution can be reliably done if the visibility parameter is greater or equal 0.1 [10] (in analogy with the contrast function). Since the visibility increase with the beam energy, one can also estimate the minimum measurable divergence for a given energy [10].

$$V = \frac{I_{max} - I_{min}}{I_{max} + I_{min}} \tag{2}$$

The presence of OTR screen after each accelerating structure make possible to measure the energy gain of the structure; and, in a multi-bunch configuration, the energy jitter shot to shot if the energy resolution is high enough. These are very interesting features, especially during the commissioning stage of the machine.

OPTICAL LINE

In order to acquire the OTR angular distribution, the distance between the lens and the CCD must be equal to the focal length (f) of the lens; the choice of f determines the dimension Δ of the pixel. Indeed, Δ is given by the physical dimension of the pixel (i.e. 6.5 µm for the Hamamatsu) divided by the focal length. Therefore, f defines the resolution and the field of view of the acquisition; typically, the field of view is in the range $\theta \in [-3/\gamma, 3/\gamma]$, while the resolution must be high enough to distinguish the two peaks and the minimum. For instance, using the Hamamatsu camera (2048x2048 pixels) with a 180 mm lens, one obtains a Δ equal to 36 µrad and a field of view of 74 mrad.

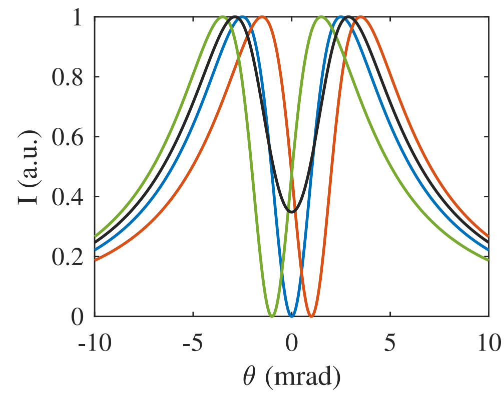

Figure 3: OTR angular distribution for 3 different values of divergence (the blue line represents the 0 divergence, the red one the case of 1 mrad, and the green line the case of −1 mrad) and their sum (black line). All the 4 curves are normalized to their maximum value.

An important parameter to evaluate is the measurement accuracy: one can express it as a function of the number of pixels between the two peaks (N_{px}). This number is proportional to $2/\gamma$: applying the uncertainty propagation rules, the absolute uncertainty reads:

$$\sigma_\gamma = \sqrt{\left(\frac{\partial\gamma}{\partial\theta_1}\right)^2 \sigma_\theta^2 + \left(\frac{\partial\gamma}{\partial\theta_2}\right)^2 \sigma_\theta^2} = \sqrt{\frac{8}{(\theta_1-\theta_2)^2}\sigma_\theta^2}$$
$$= \frac{2\sqrt{2}}{(\theta_1-\theta_2)^2}\sigma_\theta = \frac{\sqrt{2}\gamma}{N_{px}\Delta}\sigma_\theta \tag{3}$$

Where σ_θ is the uncertainty of the position of the peak; the latter can be written as the quadrature sum of the position uncertainty and the fit uncertainty:

$$\sigma_\theta^2 = \frac{\Delta^2}{12} + \sigma_{fit}^2 = \frac{\Delta^2}{12}\left(1 + \frac{12\sigma_{fit}^2}{\Delta^2}\right) \tag{4}$$

Therefore, a bigger focal length reduces the value of Δ and increase the value N_{px}, having a positive effect on the relative uncertainty of the energy measurement. However, if the focal length is increased too much, the tails of the angular distribution are cut out by the optic system, eventually compromising the goodness of the fit. Moreover, when the energy increase, the peaks become closer to each other (N_{px} decreases), but the signal to noise ratio increases and therefore, the goodness of the fit. Hence, if it is required a high resolution measurement of the energy and its shot to shot variation, the optic system must be designed specifically for the energy of interest, at the expense of the flexibility.

Another parameter that must be taken into account is the distance between the OTR target and the lens. This is important in order to quantify the amount of radiation that

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reaches the camera; but it is not a free parameter of the system, due to the geometry and to radiation protection issues of the machine. Moreover, the lens can introduce chromatic aberrations which must be taken into account. In order to estimate the amount of radiation that can be generated by the OTR target and collected by the optic system, one can derive from the Equation (1) the following [11]:

$$n_g(\lambda_1, \lambda_2) = \frac{Q}{e} \frac{\alpha \ln(4\gamma^2 - 1)}{\pi} \ln\left(\frac{\lambda_2}{\lambda_1}\right) \quad (5)$$

Where n_g is the number of photons generated by the OTR as a function of the bandwidth, the beam charge Q and the beam energy. The number of photons that actually are collected by the optic system are related also to the collecting angle $\phi = \arctan(0.5D/a)$, where D is the lens diameter and a is the distance between the lens and the target (as shown by Equation (6)).

$$n_c(Q, \phi, \lambda_1, \lambda_2) = \frac{\alpha}{\pi}\frac{Q}{e} \ln\left(\frac{\lambda_2}{\lambda_1}\right)\left[\ln\left(1 + 4\gamma^2 \tan^2\frac{\phi}{2}\right) + + \frac{\cos\phi}{1+\gamma^2\sin^2\phi} - 1\right] \quad (6)$$

The ratio between the collected photons and the generated photons gives the collecting efficiency of the optic system (see Figure 4). In order to obtain an efficiency of 70%, con-

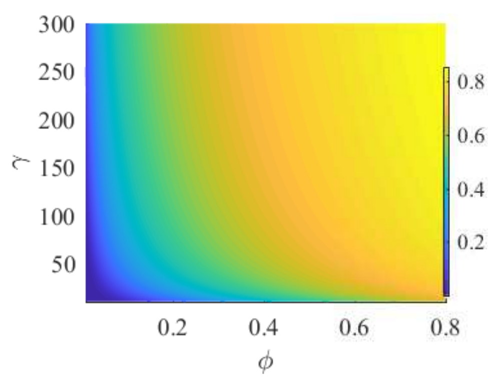

Figure 4: Collecting efficiency of a single lens optic system not taking into account the transmissivity of the lens.

sidering the ELI-GBS geometry and an energy of 150 MeV, a 300 mm lens must be put at a distance 50 cm from the OTR screen ($\theta = 0.3$ rad); different lenses at different distances gives a 70% efficiency.

Due to geometry constraints and to radiation protection of the optic system, it may not possible to get too close to the OTR screen; this issue can be solved using a telescope. A simple scheme is based on a single lens system with focal length f at distance p from the OTR screen; it will replicate the source at a distance q from the lens equals to $pf/(f-p)$. For instance, a 1 : 1 replica gives $p = q = 2f$; in this way, the CCD and the relative electronics can be put at $4f$ distance farer. Another type of telescope is the so called "4f correlator": in this case a lens is put at a distance f from the OTR screen, and a second lens is put at a distance p in order to have its backward focal plane superimposed to the forward one of the first lens. The source is replicated at the forward focal plane of the second lens: the distance gain this time is $2f_1 + 2f_2$. Analytically, the first lens perform a Fourier transformation of the source, while the second lens does the inverse transformation.

However, one should add lenses to the system only if strictly necessary; indeed, each lens adds a chromatic aberration contribution that could compromise the measurement. This effect can be reduce with, for instance, an achromatic doublet or by introducing some frequency filtering in the Fourier plane of the "4f correlator"; however, due to the transmissivity of the lenses and to the fact that the number of photons collected by the optic system are related to the observation bandwidth (see Equation (6)), this techniques reduce the amount of radiation collected.

The Equation (1) applies in the case of far field approximation: this is possible as long as the distance between the lens and the OTR screen is greater then the quantity $\gamma^2\lambda$ (in the GBS case, this limit value is around 4.5 cm for an energy of 150 MeV). If this condition is not satisfied, the near field approach must be used; in this case an analytical analysis became too complex, and a numerical study (i.e. with Zemax) of the optic system is preferred.

CONCLUSION

The OTR could be a very useful diagnostic tool in order to measure the transverse characteristics of the beam and, observing the angular distribution, the energy .

Due to the fact that the OTR screen are placed all along the machine (24 screen), a distributed energy measurement can be performed; the energy jitter shot to shot can also be evaluated. These measurements are particularly useful during the commissioning stage of the machine. As it has been shown, however, a compromise between the flexibility in the energy range and the necessary accuracy need to be done.

Furthermore, the design of the optic line has been discussed in the far field approximation. Numerical analysis are foreseen in order to study the near field case and evaluate all the possible setups.

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