ANALYSIS OF A NOVEL DIFFRACTIVE SCANNING-WIRE BEAM POSITION MONITOR (BPM) FOR DISCRIMINATIVE PROFILING OF ELECTRON VS. X-RAY BEAMS*

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Abstract

Recent numerical studies of Free Electron Lasers (FELs) operating in the Self Amplified Spontaneous Emission (SASE) regime indicate a large sensitivity of the gain to the degree of transverse overlap (and associated phase coherence) between the electron and photon beams traveling down the insertion device. Simulations of actual systems imply that accurate detection and correction for this relative loss of overlap, rather than correction for the absolute departure of the electron beam from a fixed axis, is the preferred function of an FEL amplifier's Beam Position Monitor (BPM) and corrector systems. In this note we propose a novel diffractive BPM with the capability of simultaneously detecting and resolving the absolute (and relative) transverse positions and profiles of electron and x-ray beams co-propagating through an undulator. We derive the equations governing the performance of the BPM and examine its predicted performance for the SLAC Linac Coherent Light Source (LCLS), viz., for profiling multi-GeV electron bunches co-propagating with one-to-several-hundred keV x-ray beams. Selected research and development (r&d) tasks for fabricating and testing the proposed BPM are discussed.

I. INTRODUCTION

Beam Position Monitors (BPMs) that operate on the principle of direct scattering are widely employed for characterizing the phase space parameters of particle beams on present-day particle accelerators. One example of this type of diagnostic is the scanning carbon wire [1]. For diagnosing high energy particle beams with small divergences, the wire is typically used to generate bremsstrahlung radiation which is then monitored with an on-axis gamma-ray Position Sensitive Detector (PSD) well downstream of the BPM location. In principle, the directly-scattered beam particle distribution can also be analyzed to extract position-sensitive information.

In contrast to prior art, the recent advent of Å-wavelength Linac Coherent Light Source (LCLS) technology has placed novel and ever more stringent requirements on particle beam phase space diagnostics [2,3,4]. First, due to the sensitivity of the Free Electron Laser (FEL amplifier gain to the beam's emittance parameters along the photon/e-beam interaction region (viz., the undulator), the beam parameters require monitoring over increments on the order of the FEL gain length, i.e., at intervals of approximately 5% of the undulator length. The second, perhaps even more onerous, requirement is for the **simultaneous** characterization of both the electron beam **and** the x-ray beam co-propagating with it along the insertion device axis.

In this presentation we describe and analyze a novel low-Z-wire based BPM structure with the capability of accomplishing both these goals.

II. A NOVEL DIFFRACTIVE WIRE BPM

The configuration for the proposed structure was developed based on earlier investigations of diffractive BPMs [5] coupled with a systematic assessment of those properties of the charged-particle and radiation beams in the LCLS that allow for maximal discrimination. Referring to Table 1, we note that the properties offering the possibility of maximal discrimination are 1), 2), 3), and 5), implying the development of some sort of spectral/angular filter [5]. The structure of the resulting BPM [6] is schematized in Fig. 1.

Table 1. Selected properties of electron and x-ray beams inside a 1.5 Å LCLS undulator with Nu periods.

		e-Beam	**X-Ray Beam**
1)	Wavelength	1 μÅ	1.5 Å
2)	**Long. Coherence**	negligible	quasi-coherent ($1/N_u$)
3)	**Bandwidth**	0.02%	Broadband[b]
4)	**Photoemission yield**[c]	~η	~η
5)	**Scattering angle**	1/γ	large[d]

[a]negligible collective phase coherence. Each individual particle, however, can interfere with itself.

[b]In any paraxial direction, the bandwidth is $\sim 1/N_u$, and the angular width orthogonal to this direction is also $\sim 1/N_u$. The wavelength itself, however, increases rapidly with increasing angles away from the axis.

[c]total e-beasm vs. x-ray yields comparable for a 25μ diameter carbon wire

[d]Dipole scattering from an individual molecule is into ~4π steradians. Preferred scattering directions arise from collective effects and scattering from periodic distributions of matter.

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The basic (and major) component is seen to be, just as in a conventional BPM, a carbon (or an alternative low-Z material) wire, but with a rectangular cross section. In practice, this shape could be micro-machined from a round carbon wire, cut from a substrate on which the multilayer is deposited, or prepared *ab initio* as a carbon "micro-ribbon." This shape is required to allow the deposition of multilayers, composed of layer-pairs of alternating-Z materials, on the top and bottom facets, which, in the application, are oriented parallel to the undulator axis. In operation, the electrons scatter and induce bremsstrahlung off the wire and multilayers (as in an ordinary carbon wire BPM), while the x-ray beam diffracts in transmission through the multilayers. The period, a, of the multilayer, adjustable over a broad range (e.g., easily from 10Å-5000Å) is set to optimize the x-ray diffraction angle, while the number of periods, N, and the dimension d are set to: a) produce a thickness much smaller than the carbon wire's, and 2) optimize the spectral/angular filtering properties of the BPM for diagnostic purposes.

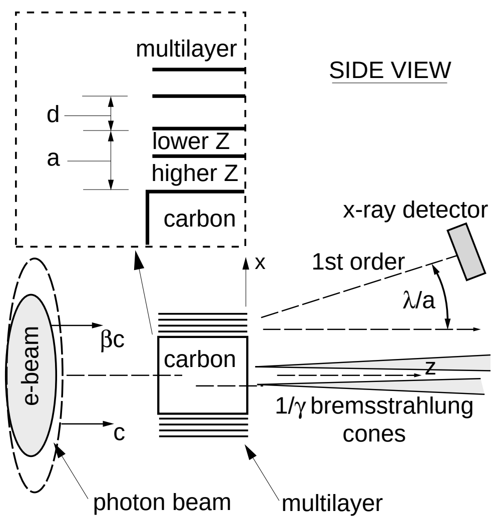

Figure 1. Diffractive wire-BPM structure.

III. ANALYSIS AND MODELED X-RAY PERFORMANCE

The analysis of diffraction induced by the structure in Fig. 1 is straightforward. The electric field distribution at the downstream side of the multilayer is the sum of the electric fields on the downstream facets of the high-Z ($A(x/\lambda)$) and low-Z ($M(x/\lambda)$) materials. This sum, and the fields, are expressed, with all *constant* dimensions in units of "# of wavelengths," as:

$$Ap\left(\frac{x}{\lambda}\right) = \left[M\left(\frac{x}{\lambda}\right) * \frac{1}{a}\sum_{j=-\frac{N}{2}}^{\frac{N}{2}-1}\delta\left(\frac{1}{a}\left(\frac{x}{\lambda}+\frac{d+a}{2}+ja\right)\right)\right] + \left[A\left(\frac{x}{\lambda}\right) * \frac{1}{a}\sum_{j=-\frac{N}{2}}^{\frac{N}{2}-1}\delta\left(\frac{1}{a}\left(\frac{x}{\lambda}+\frac{d}{2}+ja\right)\right)\right].$$

The far-field diffracted amplitude is the Fourier Transform of the field distribution, and is given by:

$$\bar{A}p(s) = e^{-\pi isd}\left\{\bar{M}(s)\sum_{j=-\frac{N}{2}}^{\frac{N}{2}-1} e^{2\pi is(\frac{a}{2}+ja)} + \bar{A}(s)\sum_{j=-\frac{N}{2}}^{\frac{N}{2}-1} e^{-2\pi isja}\right\} = ,$$

$$e^{-\pi isd}\left(\frac{\sin\pi sNa}{\sin\pi sa}\right)\left[\bar{M}(s) + e^{\pi isa}\bar{A}(s)\right]$$

with

$$\bar{M} = \sqrt{I_0}\,(a-d)\left(\mathrm{sinc}((a-d)s)\right)e^{-2\pi iW(\delta_1 - ik_1)},$$

and

$$\bar{A} = \sqrt{I_0}\,(d)\left(\mathrm{sinc}(ds)\right)e^{-2\pi iW(\delta_2 - ik_2)}.$$

This yields

$$\bar{A}p(s) = e^{-\pi isd}\left(\frac{\sin\pi sNa}{\sin\pi sa}\right)\frac{\sqrt{I_0}}{\pi s}e^{-2\pi iW\delta_2}e^{-2\pi Wk_2} \times \left[\sin(\pi(a-d)s)e^{-2\pi W(k_1-k_2)}e^{-2\pi iW(\delta_1-\delta_2)} + e^{\pi isa}\sin(\pi ds)\right]. \quad (1)$$

As is known, the absolute value squared of the factor containing the sine ratio describes the lineshape of the diffracted beam as a function of angle (s). At the non-zero orders peaks (s=m/a), the intensity assumes the value:

$$I^{(1)} = \left|\bar{A}p\left(\frac{m}{a}\right)\right|^2 = I_0 N^2 (d)^2 \,\mathrm{sinc}^2\left(\frac{md}{a}\right)e^{-4\pi Wk_2} \times \left\{1 - 2e^{-2\pi W(k_1-k_2)}\cos(2\pi W(\delta_1-\delta_2)) + e^{-4\pi W(k_1-k_2)}\right\} \quad (2)$$

Equ's. (1-2), describing the distribution of the diffracted x-rays in the far field, now exhibit all the terms necessary to assess the x-ray performance of the BPM. First, we note the overall efficiency of the structure is determined by the material with the lower Z, via the exponential factor exp($-4\pi Wk_2$). This means that for a typical carbon wire diameter of ~25μ, the structure will operate with adequate efficiency over the full spectral range of the LCLS (900 eV(1st harmonic) - 25 keV (3rd harmonic)) [4] as long as at least one of the materials has a Z of less than 20 or so. Second, further spectral/angular filtering action is possible via the dimension d in the sinc^2 factor, which can be set to suppress, for example, all the even angular harmonics, or selected odd angular harmonics. Third, by using one high-Z material, the multilayer can act as a vital "Soller Slit" spectral-angular filter for the impinging undulator light. Fourth, we note that as the BPM is scanned through the radiation, the number N will vary from 1 to its maximum value, allowing the changing angular width of the 1st order to be used as a fine measure of the BPM's location with regard to the desired x-ray beam. Finally, for favorable values of δ_1 and δ_2, we note that the factor in square brackets can significantly enhance the efficiency of the diffraction into the 1st and higher orders vs. the 0th order.

In Fig. 3 we graph the calculated efficiency of 5 different multilayer structures, all featuring a=400Å/λ, d=200Å/λ, N=25, and W=25000Å/λ. It is seen that the predicted performance is excellent for most of the high-Z/low-Z systems over the full operating range of the LCLS. The poorest performing systems, Cr/Ni, and B/C, feature materials with nearly identical Zs, resulting in overly slow development of a transverse phase difference in the transmitted wavefront. For B/C the performance for harder x-rays will significantly improve with increased BPM thickness.

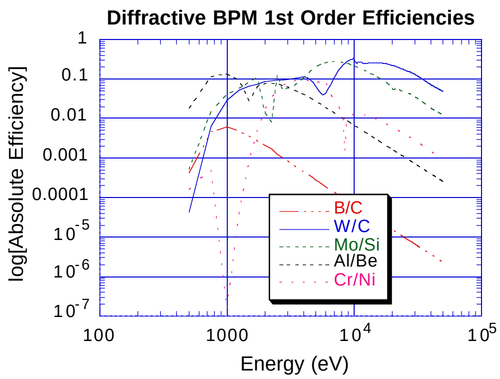

Figure 2. Modeled absolute BPM x-ray diffraction efficiencies.

In Fig. 4 we graph the corresponding ratios of the 1st diffracted order intensity to the 0th, illustrating the effectiveness of 1st order enhancement due to interference effects.

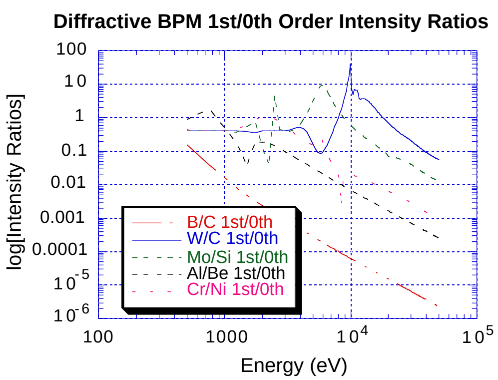

Figure 3. Modeled 1st/0th order diffracted intensity ratios.

For typical LCLS parameters [4], it is easy to calculate that 2 meters of undulator will generate on the order of 10^8 photons/pulse within a 1% BW, in the central cone of the spontaneous radiation's 1st harmonic. At 2 meters, the spatial extent of this central cone will be roughly 25μ. Given the assumed multilayer dimensions, approximately 4% of the light will be subtended by the multilayers, which, for the higher calculated efficiencies in Fig. 2, implies between 10^3-10^6 photons/pulse transmitted to a detector placed at the 1st diffracted order location. Further downstream, the diffracted spontaneous flux will increase roughly proportionally to undulator length, while the coherent FEL flux will peak at 2-3 orders of magnitude higher than the spontaneous.

V. DISCUSSION

The calculations reported here indicate that the proposed BPM structure appears adequate to characterize x-rays vs. e-beams from a 2m -100+m LCLS undulator section. Due to the possibility of lineshape monitoring (e.g., with a CCD), the resolution of the BPM (for x-rays) will be of the order of size of one period (a). Even finer resolution may be attainable by utilizing the relative interference between the two multilayers. Regarding multilayer performance, we note that the relatively large period not only desensitizes their structural quality to substrate imperfections, but to certain radiation-induced damage effects as well, such as accelerated interdiffusion at the interfaces. An expected difficulty, both in fabrication and operation, will be the rather tight requirements for angular orientation of the structure with respect to the beam axis. This may be exacerbated by thermally or mechanically induced distortions in the carbon (or other low-Z) wire, but can be mitigated in part by increasing a. These and other issues are expected to be addressed in a three-phase r&d program. The first phase will investigate the physical realizability and quality of the BPM. The second phase will test the BPMs survivability and performance in e-beams on linacs, and the third phase, if warranted, will focus on developing a working BPM system. Finally, alternative geometries and structures based on multilayer reflection may also be assessed.

V. REFERENCES

[1] X. Q. Wang, T. Groves, A. A. Hahn, G. Jackson, J. Marriner, K. Martin, J. Misek, "Design and Commissioning of Flying Wires in the Fermilab Accelerator," Proc. PAC91 Conference, IEEE Catalog No. 91CH3038-7, pp. 1180-1182.

[2] R. Tatchyn et al, "Research and development toward a 4.5-1.5 å Linac Coherent Light Source (LCLS) at SLAC," NIM A 375, 274(1996).

[3] J. Rossbach, "A VUV free electron laser at the TESLA test facility at DESY," NIM A 375, 268(1996).

[4] M. Cornacchia et al, "Performance and design concepts of a free-electron laser operating in the x-ray region," SPIE Proceedings 2988, 1997, paper 2988-01.

[5] R. Tatchyn and I. Lindau, "Transmission Grating Goniometer Elements for Use at Synchrotron Facilities," Nucl. Instrum. Meth. 195, 419(1982).

[6] R. Tatchyn, "Analysis of a Novel Diffractive Scanning-Wire Beam Position Monitor (BPM) for Discriminative Profiling of Electron vs. X-Ray Beams," SLAC-PUB 7438, March 1997.