Summary and Highlights of the Diagnostics Working Group

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Abstract. The working group on beam diagnostics at the 2nd "High Power, High Brightness" Workshop held a series of meetings during the Workshop. The measurements and monitoring of bright beams in high-average-current electron accelerators were discussed with special emphasis on non-invasive techniques.

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GENERAL COMMENTS

The "Diagnostics" Working Group focused on sharing of preliminary ideas on techniques to monitor and measure key parameters associated with high brightness bunches produced in high-average-current electron accelerators. The goal of the working group is to eventually produce a list of suggestions of possible paths for developing and possibly testing new diagnostics at existing test facilities. In particular we hope to discuss diagnostics capable of measuring the transverse and longitudinal phase spaces, and if possible, with as high of dynamic range as needed to be able to detect faint halos. Although the emphasis was placed on identifying possible non-invasive diagnostics well suited to diagnose high current beams, several single-bunch interceptive diagnostics were also discussed because of recent significant developments. Our Working Group was very informal and essentially consisted of discussions of past experiments/work and future needs. Our summary reflects this, and the reader is encouraged to see the individual papers for greater detail. Unless otherwise specified, references within the text are to the papers and presentations given at this Workshop.

INTRODUCTION

Over the past decade, the advance in high-brightness electron beams has led to the development of high-precision state-of-the-art diagnostics. It is now possible, for instance, to measure transverse beam sizes below 100 nanometers [1] and pulse durations with ~30 femtosecond resolution [2]. Most of the diagnostics available today were developed to operate in single bunch mode and transplanting them to high-average-current electron beams is a challenging task. In a high-average-current electron accelerator operating in "production mode", e.g., at its full power, only non-invasive diagnostics can be used.

It is however conceivable to devise a low-average-current setting, henceforth referred to as "tune-up mode", with a beam power below the damage threshold of standard high-brightness beam diagnostics developed for single bunch applications. In fact this is precisely the scheme implemented in the Jefferson Lab's FELs [3]. Such a scheme can be used to tune the accelerator magnetic lattice and the intricate longitudinal phase space manipulation needed in, e.g., energy-recovering linacs.

Halo formation is a special concern for high-average-current accelerators. Machine protection involves an automated system that will turn off the beam if the loss on the accelerator walls exceeds a certain threshold current. Typically the threshold current is set to ~1 μA/m, a value determined from concerns about accidentally burning through the beamline vacuum chamber or damaging sensitive instrumentation and electronics via x-ray radiation from electrons impinging the chamber. For a MW-class FEL, the threshold current is a tiny $\sim 10^{-6}$ of the total beam current per meter. It is therefore crucial to develop diagnostics capable of measuring such low fraction of the beam especially to guide the optimization of prototypical machines.

Diagnostics for commissioning and tuning

When the accelerator operates in tune-up mode, all the single-bunch diagnostics already developed for high-brightness accelerators can be readily used. The main beam parameters and the associated diagnostics commonly used for single-bunch measurements, as compiled by the participants, are gathered in Table 1.

TABLE 1. Beam parameters to be measured and typical single-bunch measurement techniques that could be used in "tune-up" mode; see text for details. The acronyms are BPM: beam position monitor, rf: radio-frequency, TR, DR, SR: transition radiation, diffraction radiation, synchrotron radiation (the added "O" prefix in some of the table entries stands for "optical"), YAG: Yttrium Aluminum: Garnet.

Parameter	range	method
Charge per bunch (pC)	50-5000	Toroid, sum signal of BPM, cavity BPMs
Energy (MeV)	0.5-5000 with 10^{-4} resolution at best	Dispersive section with transverse profile monitor
Position (μm)	Centerline ± 50	Cavity, stripline, button BPMs
Time-of-flight monitor (ps)	0.1	Pick-up and rf (or optical) mixing technique, electro-optical imaging

Temporal duration and profile (ps)	0.1-10	TM_{110} mode cavity, zero-phasing technique, analysis of coherent radiation (e.g. TR, DR, SR,…)
Bunch duration monitor (ps)	nominal ± 20%, micron bunching	Integrated power emitted via coherent radiation, polychromators
Intrinsic energy spread (keV)	>1	TM_{110} cavity with dispersive section
Transverse size and profile (μm)	50-5000	YaG screens, OTR, ODR, OSR[1], laser wire
Transverse emittance (μm)	0.1-20	Profile monitor(s) located at proper phase advance, quadrupole scan method
Halo monitor (fraction of total population)	10^{-8}-10^{-6}	Wire, collimation and dispersive section with scintillator

Diagnostics techniques during full power runs

When the accelerator operates at full power, e.g. in CW mode, only non-interceptive diagnostics are used. For diagnostics considerations, two situations arise. A first scenario where only one bunch in the train is diagnosed and possibly its parameters are tracked along the beamline. This clearly implies (1) the capability to gate the diagnostics with time scale below the bunch interspacing and (2) the synchronization of all diagnostics to see the selected bunch. In an extreme situation, it might be needed to have the parameters of many bunches, if possible consecutive bunches, in the train. Such a feature would allow the diagnosis and cure of bunch-to-bunch instability issues arising from the rf system or long range wakefield.

TABLE 2. Beam parameters and associated CW-compatible diagnostics. See Table 1 caption the meanings of the acronyms used in the Table.

Parameter	method	comments
Charge per bunch (pC)	BPM sum signal or cavity	Toroid, sum signal of BPM, cavity BPMs
Energy (MeV)	Dispersive section with BPM	Dispersive section with transverse profile monitor
Position (μm)	Cavity, stripline, button BPMs	Cavity, stripline, button BPMs
Time-of-flight monitor (ps)	Pick-up and rf (or optical) mixing technique, electro-optical imaging	Pick-up and rf (or optical) mixing technique, electro-optical imaging

[1] All these optical techniques might have limitations in the presence of strong electron-beam microbunching as recently observed at the Linac Coherent Light Source (LCLS) facility at the Stanford Linear Accelerator Center (SLAC); see reference [4]

Temporal duration and profile (ps)	CDR electro-optical imaging	Model dependent Issues with crystal resistance to radiation
Bunch duration monitor (ps)	CSR, CDR	Integrated power emitted via coherent radiation, polychromators
Intrinsic energy spread (keV)	>1	TM_{110} cavity with dispersive section
Transverse size and profile (μm)	50-5000	YaG screens, OTR, ODR, OSR
Transverse emittance (μm)	0.1-20	Profile monitor(s) located at proper phase advance, quadrupole scan method
Halo monitor (fraction of total population)	10^{-8}-10^{-6}	Wire, collimation and dispersive section with scintillator

BUNCH PICKER

Bunch picker and related issues

The possibility to "pick" a single bunch out of a train (either a macropulse or CW beam) is attractive since it allows a measurement of a single bunch out of a train using conventional invasive diagnostics. In such a scheme, a fast kicker deflects a bunch in an analysis beamline; see Figure 1. In the case of a CW beam with a repetition rate of 1.5 GHz (t=667 ps) a kicker with rise and fall times of ~30 ps would be needed. Although such a rise time is challenging, it is similar to fast kickers needed to extract or inject the 5-GeV beam in the damping ring of the international linear collider (ILC) and solutions for such ultra-fast kickers are readily available; see References [5]. Ideally the extraction scheme should be achromatic and isochronous in order to allow meaningful transverse emittance and bunch length measurements. A dogleg composed of two rf-deflectors with opposite deflecting kick with proper dispersion control could in principle realize an achromatic extraction with small R_{56}.

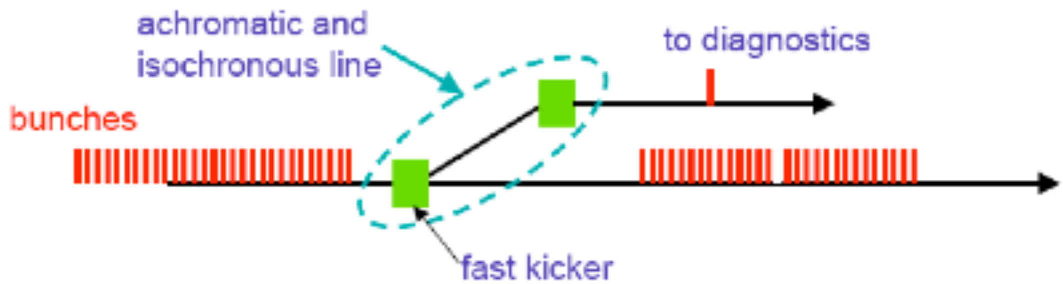

Figure 1: Principle of bunch picking: a fast deflector deflects the beam into a diagnostics beam line instrumented with single-bunch, possibly interceptive, diagnostics.

A question that arises in the context of energy recovery linacs is the energy imbalance created by removal of a bunch and its possible implication on the multi-bunch energy spread. This topic was discussed in the working group and during the closing session of the workshop without a completely obvious answer being revealed.

Recent developments in single-bunch diagnostics techniques

Provided bunch picking is possible, several interceptive diagnostics involving the single "picked" pulse were discussed at the Workshop.

Pietro Musumeci (UCLA) presented the recent result on direct snapshot of the longitudinal phase space. The technique used a vertically-deflecting TM_{110} mode cavity followed by a spectrometer. By properly controlling the betatron contribution to the beam size on the dispersive density monitor, an intrinsic energy spread of approximately 1 keV was measured along with a temporal resolution of 50 fs. Such diagnostics would be crucial to precisely tune the longitudinal emittance, a critical parameter in, e.g., long-wavelength FELs.

Nikolai Vinogradov (NIU) discussed the possibility of measuring halo via an interceptive diagnostics. The diagnostic uses a slit to transversely sample the beam followed by a dispersive section tuned to the beam's main energy. Downstream of the dispersive section is a scintillating material coupled to a photomultiplier tube is used to detect the incoming particles. In principle the proposed diagnostics could detect few electrons (the claim was as low as 10 electrons) and therefore should be able to measure halo at the 10^{-8} level. Preliminary background tests conducted at the Argonne Wakefield Accelerator support the proposed concept.

EXISTING DIAGNOSTICS FOR CW BEAMS

Synchrotron radiation emitted as the beam propagates on a curved trajectory can in principle be imaged to measure the beam size in a dispersive section. Shukui Zhang (Jefferson lab) reported on a direct measurement of the longitudinal phase space (t,E) by collecting and imaging the synchrotron radiation radiated by a ~40 MeV, 135 pC, beam as it is transported in one of the FEL recirculation arcs. To minimize optical diffraction, the imaging system only includes reflective optics. The horizontally-dispersed beam was imaged on a vertically-streaking streak camera thereby providing a direct picture of the longitudinal phase space [6]. This type of diagnostic is well suited for making sure, even during CW operation, that the longitudinal phase space manipulation needed to recirculate and energy recover the beam is performing as expected.

Patric Muggli (USC) and Gil Travish (UCLA) showed the implementation of a simple X-ray synchrotron radiation monitor to measure the energy spread at the SLAC test beam line [7]. The monitor consists of a scintillator screen located outside of the beam pipes. Such implementation only works with high-energy electron beams when the critical frequency associated to synchrotron radiation lies in the X-ray wavelengths.

Residual gas monitors (RGMs) were also mentioned as viable candidate for monitoring the beam profiles of high power electron beams. In an RGM, the passing beam ionizes residual gas and the resulting ions (or electrons) drift to a multichannel plate via an electrostatic field. RGMs are a popular diagnostic in proton and heavy ions accelerators [8] but, to the participants' knowledge, have not been demonstrated in electron accelerators. Nevertheless, the accelerators considered in this workshop (with mA typical average currents) would probably yield enough ions/electron events via ionization of the residual gas to produce a beam profile (averaged over many bunches).

Diffraction radiation (DR) radiated as the beam's surrounding boundary conditions changes can also be used to infer some of the beam properties. Typically the diffracted field in the far-field have a wavelength $\lambda > a/\gamma$ where a is the aperture size (assuming DR is generated as the beam passes through a circular aperture in an infinite plane) and γ is the beam's Lorentz factor [9,10]. In low energy accelerators, a spectral analysis of coherent DR can provide information on the bunch's temporal profile. At high energy, optical DR may be used to measure the transverse beam size [10].

POTENTIALLY CW-COMPATIBLE BEAM DIAGNOSTICS

The working group discussed several potential candidates for measuring the transverse density of first and second order moments only of a CW beams.

Second order moments can be measured using the beam-induced field. The idea, initially proposed by Miller and co-worker [11], was demonstrated by Russell et al

[12] using the four antennae of a button beam position monitor. Recently more complex electromagnetic structures specifically optimized for measuring the beam's second order moments have been proposed [13]. The structure operates on the TM_{220} mode and an analysis of the produced signal can provide the beam's 2nd order moments. Higher order mode cavities (TM_{330}) have also been proposed to extract 3rd order moments which might indicate beam dilution to, e.g., transverse wakefield. In principle this type of cavity could be a non-invasive beam moment monitor but further design iterations might be needed for high repetition rate accelerators to assess and minimize higher (or lower) order modes which could be excited.

For measuring emittance a series of such beam moment monitors could be located along the accelerator with the proper betatron phase advances (e.g. three beam size monitors separated by a 60 deg phase advance) so that the emittance could be inferred.

Electro-optical imaging is becoming a popular diagnostic for measuring the temporal profile of an electron bunch with sub-100-fs resolution. The diagnostic makes use of the electro-optical imaging of the non-radiative field traveling with the electron bunch. It is based on the fact that the local field of a highly relativistic electron bunch moving in a straight line is almost entirely concentrated perpendicular to its direction of motion. Consequently, the Pockels effect induced by the electric field of the passing electron bunch can be used to induce birefringence in an electro-optic (EO) crystal properly located in the vicinity of the electron bunch. The produced birefringence can be probed by measuring the change in polarization of an ultra-short "probe laser" propagating through the crystal parallel to the electron bunch: an incoming linearly polarizer probe laser will generally transform into an elliptic polarization. The probe laser is then passed through appropriate optical components to convert the induced polarization change into an amplitude modulation. The latter can be detected by a diode or CCD camera. Three variations of this diagnostics have been proposed and implemented by various groups: (1) the delay-scan method [14], (2) the wavelength detection of chirped probe beams [15], and (3) the spatial encoding technique [16].

Cheyne Scoby (UCLA) presented an implementation of electro-optical imaging using the spatial encoding scheme proposed in Ref. [17]. The diagnostics, capable to resolve the E-field of a ~5-MeV beam down to low charge (few pC), will be used as a time-stamp for ultra-fast electron diffraction experiments. A limitation inherent to electro-optical imaging is the finite time resolution imposed by the beam energy. Typically given the beam's Lorentz factor and its impact parameters to the crystal the finite opening of the electric field line imposes a temporal smearing. This might be a serious limitation in high-average-power medium-energy (~100-MeV) accelerators. This limitation could in principle be overcome by locating the birefringent crystal as close as possible to the beam axis (provided that the wakefield-induced beam degradation is tolerable). However crystal lifetime in such environment has not been thoroughly studied to date. An experiment performed at BNL indicates that if the electron beam hits the electro-optical crystal, the crystal response to the beam field is considerably degraded (due to an increase in opacity). The crystal opacity eventually decay with characteristic time of few hours [17]

Finally William Graves (MIT) discussed the optical replica synthesizer method. The technique, proposed by Saldin et al. [18], essentially operates as an inverse FEL. A seed laser is co-propagated with the electron beam in an undulator thereby inducing an energy modulation. A small achromatic chicane transforms the energy modulation into a density modulation. The parameters are chosen such that the density modulation has a wavelength lying in the optical regime [typical wavelengths are 800 nm (Ti:Sa lasers) or 1500 nm (Yb:Er fiber lasers)]. If this density-modulated beam radiates via any process (e.g. undulator, transition, synchrotron radiation), it will have a coherent component at the modulation wavelength and standard optical techniques, such a frequency-resolved optical gating (FROG) [19] can be used to measure this "optical" wave-packet which, under certain conditions, mirrors the electron bunch properties. A preliminary demonstration of the optical replica synthesizer physics was recently reported [20].

NEW IDEAS

William Graves (MIT) discussed several possible improvements of the optical replica scheme. He suggested the possible use of a modulator in the beam line along with a series of radiators located at various point along the beamline (located with the proper phase advance) to enable emittance measurement using the multi-monitor technique. W. Graves especially explored the use of a chirp seed laser to frequency-encode the time profile associated to the electron beam. The technique could provide a single shot bunch length and timing jitter measurement.

Philippe Piot (FNAL/NIU) brought up an old idea initially proposed and tested by John Pasour (NRL) [21] to use a low energy electron beam (few pC) to probe the high-average-current beam. The technique was implemented in the VEPP-3 accelerator by Pavel Logatchov (BINP) and promising measurement on multi-bunch wakefield instability were presented [22]. In the two aforementioned references, the low energy beam is few ns long, however using a low energy photoemission electron source capable of producing extremely short low-charge electron bunch (e.g. see [23]) might open new applications for this electron beam probe diagnostics for high-brightness high average power beams.

CLOSING REMARKS

We are grateful to the organizers and host facility of UCLA for facilitating a forum for active discussions related to high power and high-brightness electron beams for light sources under construction and of the future. We look forward to the next interaction.

REFERENCES

1. P. Tennebaum and T. Shintake, *Annual Rev. of Nuclear and Particles Science* **49**, 125 (1999).

2. G. Berdeen et al., *Phys. Rev. Lett.* **99**, 164801 (2007).
3. G. R. Neil, C.L.Bohn, *et al*., *Phys. Rev. Lett*. **84**, 662 (2000).
4. H. Loos. et al., "Observation of Coherent Optical Transition Radiation in the LCLS linac", in Proceedings of FEL 2008, Gyeongju, Korea, (in press); preprint SLAC-PUB-13395 (2008).
5. see for instance G. Gollin's talk at the ILC-Americas Workshop, SLAC, October 14, 2004.
6. S. Zhang et al., "Longitudinal Phase Space Characterization of Electron Bunches At the JLab FEL Facility" in Proceedings of FEL 2006, BESSY, Berlin Germany, 740 (2006).
7 C. Barnes et al., "Determination of Longitudinal Phase Space in SLAC main accelerator beams" in Proceedings of PAC 2005, Knoxville, Tennessee, 1856 (2005).
8 P. Forck et al. "Development of a Permanent Magnet Residual Gas Profile Monitor With Fast Readout" in Proceedings of DIPAC 2003, Mainz, Germany, 134 (2003).
8. G. Bass and V. M. Yakovenko, *Sov. Phys Usp*, **8**, 420 (1965).
9 M. Castellano, Nucl. Instrum. Methods Phys. Res., Sect. A 394, 275 (1997).
10 R. H. Miller J. E. Clendenin, M. B. James, and J. C. Sheppard, Proceedings of the 12th International Conference on High Energy Accelerators, Fermilab, 602 (1983).
11 S. J. Russell and B. E. Carlsten, *Rev. Sci. Instrum*. **70**, 1362 (1999).
12 N. Barov, et *al*., "High-efficiency resonant cavity quadrupole moment monitor" in Proceedings of the 12th Advanced Accelerator Concepts Workshop (AAC 2006), Lake Geneva, Wisconsin, 10-15 Jul 2006, *AIP Conf. Proc.* **877**, 590 (2006).
13 X. Yan *et al., Phys. Rev. Lett.* **85**, 3404 (2000) ; M.J. Fitch *et al*., *Phys. Rev. Lett* **87**, 034801 (2001).
14 I. Wilke *et al., Phys. Rev. Lett.* **88**, 124801 (2002) ; G. Berden, *et al., Phys. Rev. Lett.* **93**, 114802 (2004).
15 A. L. Cavalieri *et al*., *Phys. Rev. Lett.* **94**, 114801 (2005).
16 T. Srinivasan-Rao *et al., Phys. Rev. ST Accel. Beams* **5**, 042801 (2002).
17 E. L Saldin, E. A. Schneidmiller, M. V. Yurkov, *Nucl. Instrum. Meth.* **A 539**, 499 (2005).
18 D. J. Kane and R. Trebino, *Opt. Lett.,* **18**, 823 (1993).
19 G. Angelova et *al*., *Phys. Rev. ST Accel. Beams* **11**, 070702 (2008).
20 J. A. Pasour and M. T. Ngo, *Rev. Sci. Instrum*. **63** (1992).
21 P. V. Logatchov, *et al*., "Non-destructive single-pass monitor of longitudinal charge distribution in an ultrarelativistic electron beam" in Proceedings of 2005 Particle Accelerator Conference (PAC05), Knoxville, Tennessee, 1856 (2005).
22 P. V. Logatchov et al., "Low energy electron beam as a nondestructive diagnostics tool for high power beams, in Proceedings of the 2006 Russian Particle Accelerator Conference (RuPAC06), Novosibirsk, Russian, 40 (2006).
23. T. van Oudheusden, *et al*., J. Appl. Phys. **102**, 093501 (2007).