Advanced beam diagnostics R&D

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Introduction

The grand challenge for beam diagnostics is to characterize the complete 6D phase-space distribution with non-destructive, single-shot, low-latency, high-dynamic range, high-accuracy and high-resolution methods. Such capabilities will be critical to controlling the beam distribution in future high-energy colliders. All current accelerator facilities would benefit from progress in this research direction but future accelerators will produce beams that surpass the limits of current diagnostics so advanced diagnostics are a must. As accelerator advanced, their more complicated systems place and increase demand on the diagnostics for performance optimization. At least factor of ten improvement in resolution will be required in the near future to make progress on both accelerator technology development and building future accelerators. Now is the time to make significant improvements of diagnostics to be ready for future accelerators. We are advocating that advanced diagnostics R&D should be considered in the SNOWMASS process and that more support from the community is required. Here we describe three research directions for advanced diagnostics.

Measurement of extreme beams

One of the most important research directions in advanced diagnostics R&D is to improve their resolution. Beam brightness increases with advancements in accelerator technologies and produce extreme beams; i.e., beam parameters beyond the current state of affairs. Examples include, nanometer scale beams at the interaction point [1], beam's with attosecond bunch length [2] and picometer emittances [3,4], etc, which is smaller than he resolutions diagnostics have [5-9]. Under certain conditions, these resolutions can be improved, but it is usually not close to the collider's operating condition. It is important for the accelerator community to prepare now, before we start to generate and use extreme beams for a real machine. This effort has excellent synergy with other accelerator fields as there are already many on-going efforts to develop diagnostics for other applications such as XFELs and UED/UEM. Many different methods are under-development for the emittance measurement [5,6], and bunch length measurement [9,10] for example. Now is a good time to develop and make significant progress on the diagnostics development through synergy from collaborative and collective researches.

Single-shot measurement of 6D phase space

Measuring the 6D phase space would reveal all information about the beam needed to improve the performance and control of the beam. Although it is the most valuable information, there is currently no fast way to measure this 6D phase space. The current state of the art 6D phase space measurement uses a scan-based method [11], but scanning measurements lose shot-to-shot information and is slow. Thus, the information we can achieve is relatively limited. On the other hand, single-shot characterization of the 6D phase space would provide all information of the beam on every single shot. The goal of this effort would be to enable single-shot 6D phase space measurements which will provide a turning point to the accelerator community in understanding the beam and lead to significant advances in accelerator applications. This would be the goal of the measurement techniques.

We recognize that the goal of a single-shot measurement of the 6D phase space is the ideal and it will be extremely difficult to achieve in practice. A reasonable starting point would be the development of single-shot diagnostics for 2D phase space with a high resolution and a large dynamic range. The aim of this research path is to continually expand the method to include the 4D and eventually the 6D phase spaces.

Non-destructive measurements

Non-destructive measurements have always been pursued due to its importance for machine tuning or maintenance. It also provides valuable beam information to the users without interrupting the experiment. Although several methods have already been developed, most of them have significant limitations such as limited resolution [8] or working at only at limited locations [12]. We also note that most of the methods that have been developed were for longitudinal measurements, but non-destructive transverse measurements are scarce. Further development of the non-destructive method will not only provide efficient operation but also improve accelerator performance and provide beam conditions to the users for a better analysis of the data.

The need for non-destructive diagnostics is perfectly match to emerging importance of machine learning techniques applied to accelerators. This coupling has tremendous progress on applications to beam prediction and control [13,14]. Non-destructive measurements can provide continuous information to machine learning algorithms and make their prediction more accurate. These two research thrusts make good synergy. In our view, the development of the non-destructive method should go together with current large investment in machine learning techniques to maximize the benefit out of both.

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Reference

[1] C. Adolphsen et al., The international linear collider technical design report – volume3.II: accelerator baseline design, arXiv: 1306.6328 (2013).

[2] J. Seok et al., Sub-fs electron bunch generation using emittance exchange compressor, in Proc. of IPAC2018, p. 1501 (2018).

[3] J. Maxon et al., Direct measurement of sub-10 fs relativistic electron beams with ultralow emittance, Phys. Rev. Lett. 118, 154802 (2017).

[4] J. B. Rosenzweig et al., Next generation high brightness electron beams from ultrahigh field cryogenic rf photocathode sources, Phys. Rev. Accel. Beams 22, 023403 (2019).

[5] F. Ji et al., knife-edge based measurement of the 4D transverse phase space of electron beams with picometer-scale emittance, Phys. Rev. Accel. Beams 22, 082801 (2019).

[6] D. Marx et al., Single-shot reconstruction of core 4D phase space of high-brightness electron beams using metal grids, Phys. Rev. Accel. Beams 21, 102802 (2018).

[7] M. K. Weikum et al., Preliminary measurements for a sub-femtosecond electron bunch length diagnostics, Nucl. Instrum. Methods Phys. Res A 909, 369 (2018).

[8] I. Nozawa et al., Measurement of < 20 fs bunch length using coherent transition radiation, Phys. Rev. ST Accel. Beams 17, 072803 (2014).

[9] G. Andonian et al., Longitudinal profile diagnostic scheme with subfemtosecond resolution for high-brightness electron beams 14, 072802 (2011).

[10] G. Ha et al., High resolution longitudinal property measurement using emittance exchange beam line, in Proc. of IPAC2015, p.320 (2015).

[11] B. Cathey et al., First six dimensional phase space measurement of an accelerator beam, Phys. Rev. Lett. 121, 064804 (2018).

[12] R. Fiorito et al., Noninvasive emittance and energy spread monitor using optical synchrotron radiation, Phys. Rev. ST Accel. Beams 17, 122803 (2014).

[13] C. Emma et al., Machine learning-based longitudinal phase space prediction of particle accelerators, Phys. Rev. Accel. Beams 21, 112802 (2018).

[14] A. Edelen et al., Machine learning for orders of magnitude speedup in multiobjective optimization of particle accelerator systems.