Mitigation of Emittance Dilution Due to Wakefields in Accelerator Cavities Using Advanced Diagnostics with Machine Learning Techniques

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INTRODUCTION

The preservation of low-emittance electron beams will continue to be a challenge and an objective in rf-linac-driven accelerators where off-axis steering can lead to both transverse long-range wakefields (LRWs) and short-range wakefields (SRWs) that dilute the emittance [1]. Earlier experimentalists using normal conducting S-band and L-band accelerators have mitigated these effects by steering the beam optimally through the cavities while watching downstream imaging screens [2] or streak camera images [3]. One can even tune the wakefields to cancel some of the effects in a few normal conducting L-band structures by *not* centering the beam on a screen or BPM after each structure in simulations [4]. Since the transverse wakefields depend on $1/a^3$ where a is the cavity bore radius, it was somewhat surprising to identify both LRWs including higher order modes (HOMs) [5] and SRWs [6] in the superconducting rf TESLA-type cavities with their larger 35-mm radii. These cavities are used in major accelerator facilities (FLASH and the European XFEL), the under-construction LCLS-II XFEL, the Superconducting Test Facility in Japan, and proposed for the conceptual International Linear Collider (ILC) in Japan. Recent tests at Fermilab showed that near-resonance conditions of an HOM frequency with a beam harmonic resulted in submacropulse centroid oscillations at 100 kHz that diluted macropulse-averaged beam size [5]. More importantly, the same off-axis steering resulted in the generation of SRWs whose submicropulse transverse head-tail kicks produced projected beam size dilutions of 40% and greater in the sampled distributions, an effect at least 5x larger than that of the HOMs [6]. Such effects would also dilute the emittance values, and they would be a particular problem for ultra-low emittance preservation. These effects were seen after only two TESLA-type cavities with beam injected at 4.5 MeV and a final energy of 41 MeV. The transverse wakes depend on charge, beam offset, and the SQRT of bunch length, but inversely on beam energy. Thus, the emittance dilution threat is highest at the lower energies in the first accelerator cavities after the gun such as occurs in the LCLS-II injector with <1 MeV into the cryomodule. This same principle applies to all accelerators in labs around the country at Fermilab, SLAC, and Argonne. In the case of the SC rf cavities, HOM couplers provide online signals of dipolar modes dependent on beam offset and downstream streak camera images or a rf transverse deflecting cavity (TDC) plus screen provide submicropulse information. Such a scenario of multiple options for steering and tracking beam effects should be a prime application for machine learning techniques with extensions to virtual diagnostics [7].

DIAGNOSTIC TECHNIQUES

Assessments of the beam-quality effects due to wakefields require a suite of diagnostics that provide time-resolved information at the submacropulse and submicropulse time scales for a pulse train. These include the bunch-by-bunch rf beam position monitors (rf BPMs) for the submacropulse beam centroids and either a streak camera viewing an optical transition radiation (OTR) screen or a TDC with a downstream imaging screen. These can be used at a nondispersive location in the beamline to provide x- or y-t images. These time-resolved techniques are supplemented by normal beam imaging screens with cameras that obtain the time-averaged beam sizes. In the case of the TESLA cavities, there is an HOM antenna at both the upstream and downstream end of each cavity to dampen the HOMs. They are clocked at different azimuthal angles with different polarization sensitivity as a compromise to dampen both dipolar and quadrupolar modes with their polarized components [8-11]. In one cryomodule with eight cavities, there are 16 HOM signals that can be processed for beam offsets through the dipolar modes in the 1.6 -1.9 GHz range and at 2.5 GHz. These cavities are only aligned to an rms value of about 350 µm in FLASH [9] and 500 µm for LCLS-II, and the mode centers are not generally at the same offset. Such variances are why machine learning could play a critical role in minimizing the emittance dilution by avoiding the near-resonant cavities offsets or using kick compensation with other cavities. Perhaps this can be done even at the cryomodule level, but the first cavities of the first CM are the early threat to emittance dilution (Grand Challenge #2: Beam quality).

EXISTING FACILITIES FOR WAKEFIELD STUDIES

There are four facilities that are operating, or in construction, in the USA where these wakefield effects over a wide parameter space could be investigated. We believe the SRWs are the most threatening to preserving low emittance. Two facilities are HEP funded and two are BES funded so this is in the area of accelerator R&D with mutual interest to both branches in the Office of Science. Fermilab has two operating single TESLA cavities and a cryomodule at FAST with existing streak camera diagnostic capability for the former and *proposed* for the latter, and SLAC is building a SCRF linac to drive an XFEL as LCLS-II. The injector however has a CW gun which injects beam at <1 MeV into the first cryomodule, so this beam is then susceptible to the SRWs. Plans for a diagnostic line at 100 MeV with one or two TDCs are in progress which could be used for SRW diagnosis. The HOM dipole detectors based on FNAL designs will be used at SLAC on this injector accelerator. Argonne National Laboratory has two different linacs, a normal conducting (NC) L-band linac at Argonne Wakefield Accelerator (AWA) with a high charge capable photocathode (PC) rf gun and a NC S-band linac in the Advanced Photon Source (APS) injector system which also has a PC gun option. It has been calculated that the SRWs in the S-band 3-m long structure are 20 times stronger than that of an 8.28-m long TESLA structure (a cryomodule) [10]. In the former case, cavity structure bowing or sagging of a few mm produces effective beam offsets, SRWs, and significant emittance dilution. It is noted, the SRW effects were seen in only a 1-m long cavity at 33 MeV at FNAL [6]. Some of these facilities' aspects are tabulated in Table 1 showing the wide range of charges, pulse formats, and energies that could be covered in a comprehensive program.

Table 1: Summary of linac facilities and features where one could investigate emittance dilution due to accelerator cavity wakefields. The injector energies are one key.

Facility	Accelerator	Pulse Format	Charge per micropulse (pC)	Energy (MeV)	Diagnostic Capability
FAST/IOTA	SCRF L-band	Pulsed, 3 MHz	1-3000	4-300	Streak camera
LCLS-II Inj.	SCRF L-band	CW, 1 MHz	100-300	1-100	TDC planned
AWA/ANL	NC L-band	pulsed	100-25000	5-70	(TDC)
APS/ANL	NC S-band	Single pulse	100-300	6-425	TDC

SIMULATIONS

These experiments should be supported by simulations beyond the initial ASTRA simulations for the FNAL and APS/ANL cases. They may inform the virtual diagnostics aspect of the machine learning application in the future.

SUMMARY

In summary, opportunities exist: 1) to elucidate the features of emittance dilution due to wakefields generated in accelerator cavities due to off-axis transport over a range of parameters and 2) to mitigate them with input from diagnostics to a machine learning application. The trajectories for low injection energies into the first accelerator cavities particularly need attention.

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