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BEAM-DYNAMICS ANALYSIS OF LONG-RANGE WAKEFIELD EFFECTS ON THE SCRF CAVITIES AT THE FAST FACILITY*

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Abstract

Long-range wakefields in superconducting RF (SCRF) cavities create complicated effects on beam dynamics in SCRF-based FEL beamlines. The driving bunch excites effectively an infinite number of structure modes (including HOMs) which oscillate within the SCRF cavity. Couplers with loads are used to damp the HOMs. However, these HOMs can persist for long periods of time in superconducting structures, which leads to long-range wakefields. Clear understanding of the long-range wakefield effects is a critical element for risk mitigation of future SCRF accelerators such as XFEL at DESY, LCLS-II XFEL, and MaRIE XFEL. We are currently developing numerical tools for simulating long-range wakefields in SCRF accelerators and plan to experimentally verify the tools by measuring these wakefields at the Fermilab Accelerator Science and Technology (FAST) facility. A particle-in-cell (PIC) simulation model for the FAST 50 MeV beamline indicates strong bunch-by-bunch variations of beam parameters with the operating conditions at 9 MHz bunch rep-rate along a macro-pulse and 500 pC, 1 nC, and 2 nC per bunch. This paper previews the experimental conditions at the FAST 50 MeV beamline based on the simulation results.

INTRODUCTION

An ILC type cryomodule, consisting of nine 1.3 GHz, 9-cell SCRF cavities, is considered standard for future SCRF accelerators. The XFEL at DESY in Germany and the LCLS-II XFEL in USA are being constructed with these cryomodules with only minor modifications and the same cryomodule is included in the pre-conceptual design of the MaRIE XFEL. In such SCRF cavities, the driving bunch excites effectively an infinite number of structure modes (including higher-order modes (HOMs)) which oscillate within the superconducting cavity, with some even propagating into other cavities. Couplers with loads are used to damp the HOMs. However, these HOMs can persist for long periods of time in superconducting structures, which leads to long-range wakefields. The signals measured via a HOM-detector [1] indicated that the ILC HOM dampers do not act fast enough to damp out the long-range wake-fields and their effects need to be considered for closely spaced electron bunches. Energy in the HOMs clearly persists for at least a few μsecs, and is particularly large over the first few 10's of nanosecs after the drive bunch, which is the time scale for the bunch spacing within burst pulses of high rep-rate X-Ray FELs, e.g. MaRIE XFEL.

Particle tracking simulations with the numerical code Lucretia [2] indicated that HOM couplers are not capable of damping all HOMs: while some are well damped, a limited number of modes remain poorly damped. In this calculation, only the five modes most destructive to the beam are damped to the level of $Q = 10^5$, with the rest of modes having $Q = 10^6$. A train of 500 bunches was injected at a 3 MHz repetition rate and with an offset of 6 μm. Tracking this beam through the linac indicated that a single 9-cell cavity would generate 3 - 5 % of emittance growth for the bunches at the end of the train, which is catastrophic, given that there are on the order of a thousand cavities in a linac for an XFEL and even more for a collider. The duration of the HOM power and its possible effect on an electron bunch from this scoping calculation strongly indicate that more detailed analysis and measurements are needed. Importantly, the alignment of individual cavities in the ILC cryomodules is limited to about 0.2 mm due to the fabrication technique, far larger than the offset used in this scoping calculation.

The experiment to verify the long-range wake effect for the first time was planned at the FAST facility. The beamline consisting of two SCRF capture cavities and a full 8-cavity ILC cryomodule is designed to operate with up to 3000 bunches per macro-pulse, up to 9 MHz in bunch repetition rate, and up to 3 nC per bunch at beam energies from 50 MeV to 300 MeV with several high-resolution beam diagnostics tools, including BPMs and a streak camera. The facility fits well for the long-range wakefield experiment. The experiment is currently scheduled for the 2017 FAST runtime.

As a part of the plan, we have been developing simulation tools for accurately assessing SCRF long-range wakefield effects on beam dynamics and comparing it to the diagnostic capabilities at the FAST 50 MeV beamline. Bunch-to-bunch deviations of the longitudial and transverse beam profiles are analyzed for the current FAST beamline setup. In this paper, the simulation results are discussed with the measurable range of the instruments installed in the 50 MeV beamline.

OVERVIEW

In the FAST beamline (Fig. 1), the two capture cavities (CC1 and CC2) are ILC superconducting cavities. Last year beam commissioning was conducted through the diagnostic stations after CC2 (with up to a 50-MeV electron beam). The 9-cell cavities, operating with 25

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MV/m gradient at a liquid helium temperature (2 K), boost the beam energy up to 55 MeV with a few mm-mrad of rms emittance. The time structure of the bunch train, e.g. number of bunches per macro-pulse and bunch-to-bunch spacing, are controllable depending on charge per bunch. A series of corrector- and quadrupole-magnets are employed to control the transverse beam position/size.

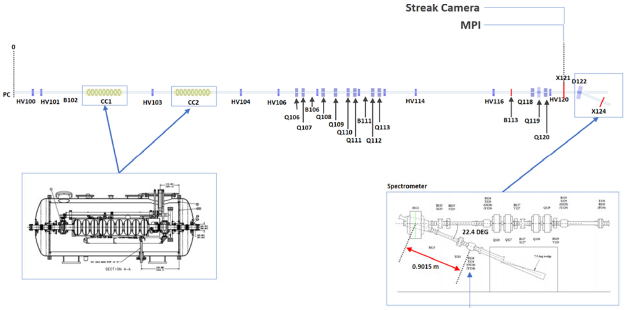

Figure 1: Layout of FAST 50 MeV beamline with the beamline components (HV: H- and V-correctors, Q: quadrupoles, D: dipole, B: BPMs, X: image-screens).

The measured BPM resolutions downstream of the gun are 25 µm at 2 nC, which is increased to 290 µm at 250 pC. Prior to the actual measurements, RF-BPM resolution and beam emittance will be re-measured at various bunch charges. Also, CC1/CC2 gradient-drop from beam-loading loss for a bunch train will be measured at X124 and it will be compensated by adjusting the RF-feedforward. The transverse beam position in CC1/CC2 will be adjusted with correctors until the CC1/CC2 HOM detector-signals are minimum (to minimize transverse HOMs). After the pre-setup, we will measure the bunch-by-bunch deviations of longitudinal and transverse beam parameters, including centroid beam-energy, energy spread, transverse beam position/size, etc, with BPMs (B121/122/123/124), streak-camera, and dipole spectrometer. The measurement will be repeated with various conditions in bunch charge (0.5 – 2 nC), number of bunches (10 – 200), and bunch rep-rate (1, 3, and 9 MHz). For this test plan and experimental conditions we analyzed the bunch-by-bunch dynamics of beam parameters with particle-in-cell (PIC) and wake simulation models based on 2D- (ECHO-2D) and full 3D- (CST-PS) codes.

PIC-SIMULATION ANALYSIS

The PIC models use 5 bunches (500 pC per bunch) equally spaced with 110 ns and each bunch in order was compared with the single-bunch case under the same condition (RF-fields/phase of CC1/CC2). In the model, CC1 and CC2 used a SCRF surface-resistivity ($\sigma = 10^9$ [$\Omega^{-1}m^{-1}$]), leading to $Q \sim 10^{10}$, while the beampipe along the beamline used a lossy metal ($\sigma = 7.69 \times 10^6$ [$\Omega^{-1}m^{-1}$]). The beam injected in the beamline model has 4 MeV centroid beam energy, 1.5 % energy spread, 1.9 mm beam size, and 0.1 mm-mrad geometric emittance. The amplitude and matching-phase of individual RF-pulses in CC1 and CC2 were adjusted until the output beam energies after CC2 reach 50 MeV on-crest. The field maps of the acceleration mode (TEM_{010}) in CC1 and CC2 were obtained from a separate eigenmode simulation and then imported to the cavities in the PIC model. The driving power is adjusted until the output energy reaches 50 MeV. Collective effects, including space charge effects and potential depression, are intrinsically reflected in the PIC model.

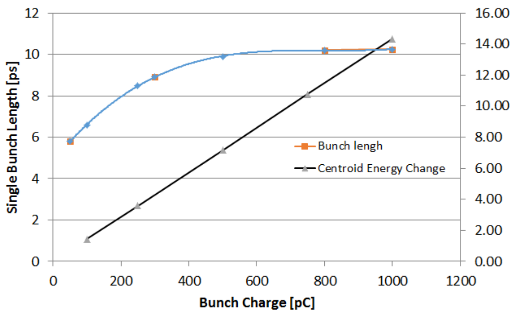

Figure 2: Bunch lengths and centroid energy losses of a single-bunch per bunch charge (wakes for different charges ~ 10 keV maximum).

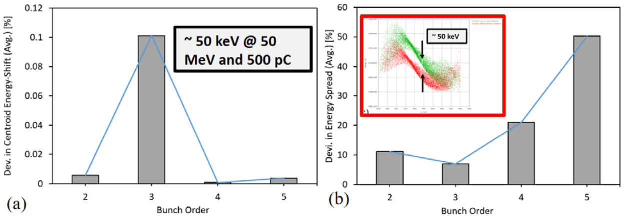

Figure 3: Bunch-by-bunch deviations (single-bunch versus multi-bunch – 2nd, 3rd, 4th, and 5th) in (a) centroid energy and (b) energy spread (inset: bunch charge-distribution in energy versus time (3rd bunches with (green) and without (red) 1st and 2nd bunches)).

We first identified a short wakefield effect on a single bunch prior to multi-bunch simulations. Figure 2 shows the bunch lengths and energy-spreads of a single bunch with various bunch charges, estimated by ECHO-2D in comparison with measured data at FAST beamline. The simulation indicated that the maximum energy spread out of the wake for the 2-cavity system is about 10 keV. Monitoring right after CC2, one sees that the 3rd bunch has the largest shift (~ 50 keV) in centroid beam energy from a single-bunch, while its energy spread is minimum (Figs. 3(a) and (b)) for the 500 pC case.

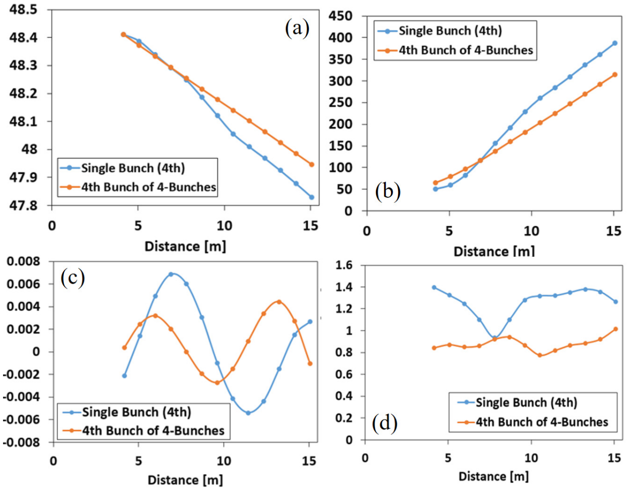

Figure 4: Beam parameters, (a) centroid energy (MeV), (b) energy spread (keV) (c) beam position (mm), (d) beam size (mm), versus distance plots of a single (blue) and multiple (red) bunches of (4th) after CC2 with I = 0 A for H101.

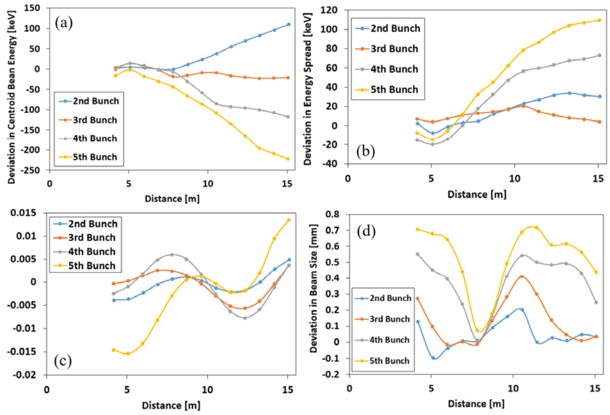

Figure 5: Bunch-by-bunch deviation versus distance plots (single-bunch versus multi-bunch – 2nd, 3rd, 4th, and 5th) in (a) centroid beam energy (b) energy spread (c) transverse beam position and (d) beam size with I = 0 A for H101.

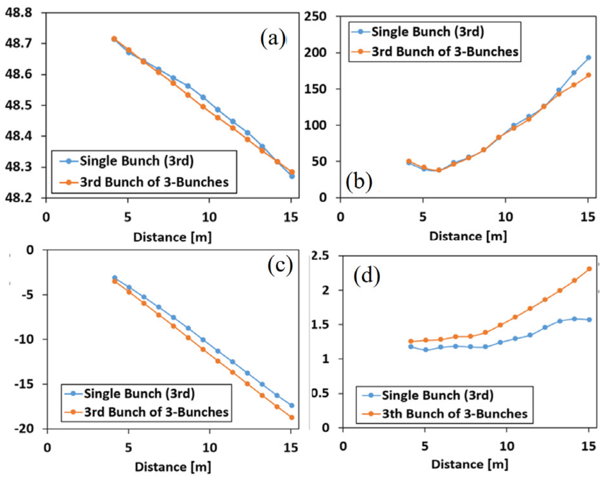

Figure 6: Beam parameters, (a) centroid energy (MeV), (b) energy spread (keV) (c) beam position (mm), (d) beam size (mm), versus distance plots of a single (blue) and multiple (red) bunches of (3rd) after CC2 with I = 0.4 A for H101.

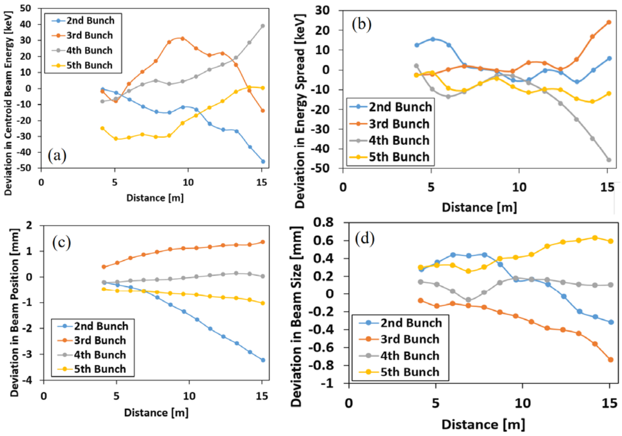

Figure 7: Bunch-by-bunch deviation versus distance plots (single-bunch versus multi-bunch – 2nd, 3rd, 4th, and 5th) in (a) centroid beam energy (b) energy spread (c) transverse beam position and (d) beam size with I = 0.4 A for H101.

The deviations vary from bunch to bunch under the influence of wakefield interferences. The shift would be more prominent when the periodically excited wakefields are constructively superposed.

The beam parameters and their deviations (single-bunch vs bunch-trains) are also traced along the beampipe after CC2 with different corrector currents (H/V101), I = 0 A and 0.4 A. Under the current setup of FAST 50 MeV injector beamline, the horizontal beam position injected into CC1 can be controlled by H101 (or H100). The beampipe is lossy (a few orders of magnitude more than the cavities) and it is an additional source of "resistive wakefields", which add longitudinal and transverse wake potentials to the beam. The transverse and longitudinal effects appear in the centroid beam energy (Fig. 4, (a)) and transverse beam position (Fig. 4 (c)). The energy loss and correlated energy spread of a single-bunch along 10 m long beampipe downstream of CC2 are about 300 keV and 150 keV. For the bunch-train, the numbers fluctuate (± 150 - 200 keV in centroid-energy and ~ ± 120 keV in energy spread) due to wake-potentials accumulated from each bunch in CC1 and CC2, as shown in Figs. 5(a) and (b).

The centroid beam position also oscillates within 5 µm due to the transverse wakefields in the beampipe (Fig. 4 (c)), which is increased up to 15 µm with the bunch-train (Fig. 5(c)). For I (H101) = 0.4 A (Fig. 6), which is the case of off-axis injection, the transverse effects (transverse wake-potentials in CC1 and CC2) are more dominant. Therefore, the deviations (single-bunch vs bunch-train) in centroid energy and energy spread (Figs. 7 (a) and (b)) get rather decreased from the case of I(H101) = 0 A, but those in transverse beam position reach a few mm 10 m away from CC2 (Fig. 7(c)). Their transverse beam positions, especially of the 2nd and 3rd bunch are substantially changed beyond the estimated BPM resolution, ~ 100 µm at 500 pC, due to strong transverse wakefields from off-axis beam injection. The shift is thus measurable by BPMs. In the case that the beam size changes bunch by bunch, which most likely occurs, the streak camera operating in framing mode can more clearly measure the effect.

SUMMARY AND PLAN

The experiment to identify long-range wakefield effects in ILC type cryomodules is being planned at FAST facility for 2017. As a part of the plan, we have been developing simulation tools to estimate long-range wakefield effects on beam dynamics and to lay out the experimental conditions. Our plan is to experimentally benchmark and verify the simulation model, which will have relevance for all current and future projects using ILC SCRF cavities.

ACKNOWLEDGMENT

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