Investigations of Long-range and Short-range Wakefield Effects on Beam Dynamics in TESLA-type Superconducting Cavities (LRW/SRW)

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PERSONNEL

Faya Wang (Co-PI), SLAC, staff scientist, 650-926-5089, fywang@slac.stanford.edu

Alex Lumpkin(Co-PI), AD/FNAL, physicist, 630-840-8393, lumpkin@fnal.gov

Collaborators: Timothy Maxwell (SLAC), physicist, wakefield experiments/analysis.

Bryce Jacobson, (SLAC), physicist, Alan Fisher (SLAC), physicist, John Sikora (SLAC), rf engineer.

Dean Edstrom (FNAL), engineering physicist, laser specialist, and FAST operator.
Peter Prieto (FNAL), rf engineer, HOM detector designer and commissioner.
Jinhao Ruan (FNAL), physicist, laser specialist, and qualified FAST operator.
Randy Thurman-Keup (FNAL), physicist, diagnostics guru, and qualified FAST operator.

PURPOSE AND METHODS

• *Background information:* The LCLS-II accelerator will be a continuous wave superconducting linac based on TESLA-type cavities and cryomodules [1]. Off-axis steering in these cavities may cause emittance dilution due to transverse wakefield effects. This will be particularly critical for the injector where beam will enter the first cryomodule at <1 MeV and be at no more than 9 MeV for the first three cavities [1]. A schematic of the LCLS-II injector is shown in Fig. 1. The transverse kick angles go inversely with energy and directly with offset and charge. These effects can be investigated at the FAST facility with its unique configuration of a PC rf gun, two TESLA single cavities in series, and then a cryomodule. Previous FAST studies were on the observation of sub-macropulse beam centroid oscillations at near-resonant conditions [2] and on the first detection of head-tail kicks due to short-range wakefields in CC1 and CC2 [3]. The latter emittance dilution effects in the first tests in Run 1 were found to be larger than the long-range effects and are very relevant to the LCLS-II injector commissioning. Due to the very tight schedule of LCLS-II injector commissioning, it is very important to test the beam-steering methods based on HOM signals in TESLA-type cavities.

• *Scientific or technical motivation and purpose:* Generation and preservation of low-emittance beams are ongoing challenges for the accelerator community. Off-axis transport of beams in the accelerator cavities can cause long-range (LRW) and short-range wakefields (SRW) with concomitant effects on transverse electron beam dynamics and emittance dilution. This happens on both the sub-macropulse and sub-micropulse time scales due to the LRW and SRW, respectively.

• *Experimental methods:*

1.We first plan to establish the corrector settings that minimize the four HOM detector signals in CC1 and CC2 at the same time as a reference point. We will check for any sensitivity of the reference point to bunch charge.

2. Then, we propose generating long-range wakefields and short-range wakefields in TESLA-type superconducting rf cavities by steering the beam off-axis with the corrector magnets located before CC1 and before CC2. The four existing higher-order-mode (HOM) detectors monitor the dipolar modes in the first two passbands from 1.6-1.9 GHz in these two cavities. We plan to develop a beam-offset monitor (BOM) based on the HOM signals and the correlated beam positions.

3. In addition, a second channel will be tuned for the quadrupole modes near 3.25 GHz in each detector. We will evaluate a new relative beam-size monitor (BSM) based on these HOM signals and beam size changes due to a change in the laser spot size and/or the solenoid settings.

4. The head-tail kicks within a micropulse due to off-axis steering will be evaluated with the downstream X121 OTR screen and the synchroscan streak camera. The bunch-by-bunch rf BPMS will be utilized as warranted.

• *Expected results*: We expect to evaluate/develop the BOM and BSM capabilities based on these HOM tests. These can be used to optimize the FAST linac setup as well as inform the LCLS-II designs of their HOM detectors for their first cryomodule (and linac). The objective is to mitigate emittance dilution due to off-axis beam transport by minimizing the dipolar HOMs. The LCLS-II team also has an interest in using the BOM aspect to give an early warning on potential beam loss conditions in the CMs. In addition, we would obtain a data base for training a possible machine learning (ML) application for minimization of HOM dipolar signals for the FAST setup and then the LCLS-II injector and linac. For the short-range effects, we would extend our streak camera image data base from Run 1 by steering from a reproducible reference in support of a journal article submission.

BEAM CONDITIONS

The initial series of experiments in Run 2 will be performed using the FAST/IOTA injector with beam sent to the LE dump when not in use with a screen. The main goals are: 1) evaluation of the LRW and SRW effects in the single capture cavities denoted as CC1 and CC2 under controlled beam-steering and setup conditions and 2) observations of the resulting electron-beam dynamics as guided by the HOM values.

Beam species: electrons

Intensity: 100-2500 pC/b, 500 pC/b reference

Energy: ~41 MeV at exit of CC2 assuming this is nominal.

Number of bunches: 1-150 depending on charge

Micropulse repetition Freq.: 3 MHz, 1 MHz one run if easy.

Transverse emittance: 2-3 mm mrad normalized, depending on charge

Bunch length: 4-12 ps, uncompressed

Momentum spread: nominal at 0.1%

Orbit modifications: Yes, steering will be done at H/V100, H/V101, and H/V103 to minimize HOMs. Then beam steering will be done with these to induce HOMs and SRWs. These upstream steerings can be compensated with the H/V104 and H/V106 correctors and others to maintain transport to the LE dump or X107 and X121 or other as needed. See Fig. 2 for the locations of the correctors and other diagnostics at FAST.

Laser Spot size: Nominal 0.2 mm rms, but plan to scan size to at least 1.2 mm

Solenoids: Nominal settings, but we may scan them to change beam size at 9-way, CC1,CC2, and X107.

Stability: Need standard laser and electron beam stability for position, size, angle, divergence, phase, energy, and energy spread. We expect the shot-to-shot jitter to be <10 % of the parameter value and <0.1

APPARATUS

• Sketch of the layout with equipment and dimensions: HOM detector boxes are in the racks near CC1 and CC2. X121 Streak camera in optical hut. See Fig. 2. For Run 3, SLAC will provide the necessary hardware and software for their prototype HOM detector (s) on TESLA cavities. FNAL digitizer channels and ACNET may also be used.

• Engineering and technical personnel support: Need FAST machine operators

• Infrastructure needs: rigging, vacuum, clean rooms, cooling, gas lines, cryogenics (NA)

• Instrumentation and detectors: The experiments will rely on all existing diagnostics of the FAST injector linac with particular emphasis on the HOM detectors for CC1 and CC2, the bunch by bunch rf BPMs, X121 streak camera, charge monitors, virtual cathode images, and imaging stations. The B117 and B120 BPMs need to be instrumented for these runs.

• Electronics and data acquisition: power supplies, cables, oscilloscopes, digitizers, controls: We need the existing spare digitizer channels in the crates in Racks 243 and 245, respectively, for the CC1 and CC2 upgraded detector boxes with quadrupole mode channels functional in ACNET.

• Computing: front-end computers, networking, data storage, data backup, off-line analysis. Standard needs for a run. Scripts used before from Chip, Jinhao, and Randy for HOM, rf BPMs, etc. data acquisition and MATLAB-based image acquisition will need some minor revisions. Off-line analysis with ImageTool. Data also will be backed up in Redmine Files.
https://cdcvs.fnal.gov/redmine/projects/lrwsrw/wiki

RUN PLAN

• Proposed installation plan: When ordered parts become available, CC1 and CC2 HOM detector chassis will be augmented with quadrupole mode channels in parallel to the dipolar mode channels. Detectors are installed at this time with dipolar mode channels for passbands 1 and 2 only.

The LCLS-II prototype detectors would be prepared for Run 3 and installed in an appropriate rack. We would start with CC1 or CC2. At some point in Run 3, combining 4 or more detector boxes for CM2 HOMs would be critical to implement and evaluate in collaboration with Dan Broemmelsiek.

- Requested running period and approximate duration: 6 shifts in Run 2 and 6-8 shifts in Run 3.

- Preferred shift duration and distribution in time: When LCLS-II staff travel is involved, we propose ~8-hr shifts, 2 consecutive days in a week with lead time provided for getting flights. Suggest 1200-2000 or 1600-2400. Studies beginning in week of Oct. 28 as estimate if available. Preferably, one preliminary HOM detector commissioning shift (4-6 hrs) with Peter, Alex, and operator should be done before any such travel in Run 2. Shifts with laser spot changes and streak camera would benefit from D. Edstrom or J. Ruan as operators particularly.

Shift 1: Establish reference steering to minimize dipole HOMs at 500pC/b, 50 b. Scan correctors H/V101, HV103 from reference in 0.25-A steps from -1.0 to 0 to +1.0 A, while recording HOMS (dipolar and quadrupolar) and rf BPMs. Use H/V 104, HV106 to compensate trajectory. Laser spot at 0.2 mm, 50 b, Vary charge from 500, 250, 100, 1000, 2000 pC/b for each corrector setup.

Shift 2: With reference of 500 pC/b, vary laser spot size from 0.2 mm to 1.2 mm. Monitor quadrupole HOMs for effects. Normal solenoid settings. Record rf BPMs, Dipolar HOMs, virtual cathode images, 9-way cross images, X107 images. Probably repeat with different charges as practical and time permits.

Shift 3: With 500 pC/b reference, fix laser spot at 0.2 mm and vary the solenoid pair to change spot sizes at 9-way, CC1, CC2 ,and X107. Record HOMS, images, etc. Continue with other charges or laser spot sizes.

Shift 4: Recommission the transport to X121 and streak camera operations for short range wakes under reference steering conditions. Develop set of corrector values to keep trajectory to X121 after steering before CC1 or CC2.

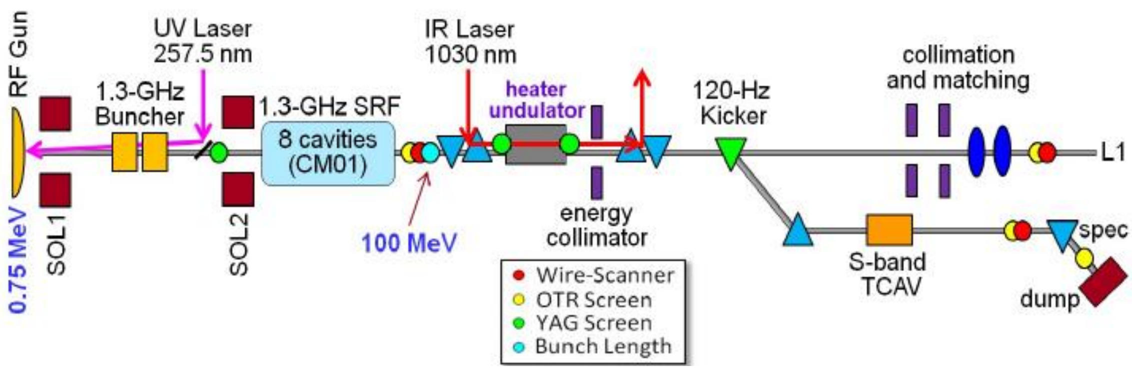
Shifts 5, 6: Continue sets of streak camera evaluations of SRW for stepped, off-axis steering in CC1 and CC2 from a reliable reference steering point with minimal dipolar HOMs. 500 pC/b, 50 b, Save 20+ streak images each setup. Vary charge, 100, 250, 1000, 2000, 2500 pC/b.

- Proposed decommissioning plan: NA for Run 2.

FUNDING

LCLS-II funding for their staff, travel, and prototype HOM detector box(es) and software.

Background documentation:



Fig, 1. Schematic of the LCLS-II injector showing the rf Gun, buncher, cryomodule 01 (CM01), laser heater, and downstream diagnostics [1].

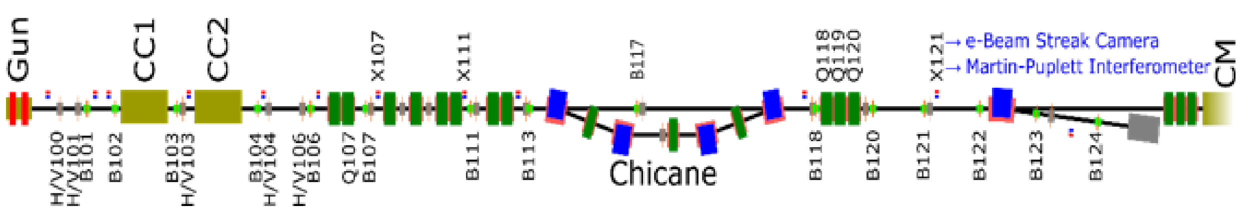


Fig. 2. Schematic of the FAST injector linac showing the gun, CC1, CC2 , and locations of correctors, rf BPMs, and imaging screens (X107, X121) [2].

[1] F. Zhou *et al.*, "LCLS-II Injector Physics Design and Beam Tuning", Proc. of IPAC17, TUPAB138, www.JACoW.org.

[2] A.H. Lumpkin et al., "Submacropulse electron-beam dynamics correlated with higher-order modes in TESLA-type superconducting rf cavities", Phys. Rev. Accel. And Beams, **21**, 064401 (2018).

[3] A.H. Lumpkin et al., "Observations of Short-Range Wakefield Effects in TESLA-type Superconducting rf Cavities", WEP042, Proc. of FEL19, Aug. 26-30, 2019, Hamburg, Germany, www.JACoW.org.