OBSERVATIONS OF LONG-RANGE WAKEFIELD EFFECTS GENERATED IN AN OFF-RESONANCE TESLA-TYPE CAVITY*

A. H. Lumpkin#, D. Edstrom Jr., A. Lunin, R. Thurman-Keup, P. Prieto, J. Ruan
Fermi National Accelerator Laboratory, Batavia, IL 60510 USA
B. Jacobson, J. Diaz-Cruz[1], J. Sikora
SLAC National Accelerator Laboratory, Menlo Park, CA 94025 USA
[1]also at University of New Mexico, Albuquerque, NM 87131 USA

Abstract

The interest in controlling emittance dilution effects due to off-axis beam transport in accelerator cavities and the resulting dipolar modes is especially important for the facilities with lower emittance beams. The dipolar higher-order modes (HOMs) which are at frequencies higher than the fundamental at 1.3 GHz are a set of transverse long-range wakefields (LRWs) that may also be generated in off-resonance TESLA-type cavities and cause significant submacropulse beam centroid slewing effects. These conditions occurred recently at the Fermilab Accelerator Science and Technology (FAST) facility. This has a unique configuration of two single cavities after the photocathode rf gun followed by a cryomodule. The second capture cavity (CC2) was run 15.2 kHz off resonance and without rf power while a 25-MeV beam was injected into it. The beam centroid effects were tracked by 10 rf button BPMs with bunch-by-bunch position readout capability downstream in a 12-m drift. A clear submacropulse centroid oscillation at ~220 kHz was observed which appears to be the combined effects of magnetic dipole mode 7 and mode 14 near resonances and their difference frequencies with beam harmonics.

INTRODUCTION

The preservation of the low emittance of electron beams during transport through the accelerating structures of large facilities is an ongoing challenge. In the cases of the TESLA-type superconducting rf cavities currently used in the European X-ray Free-electron Laser (FEL) [1] and the currently-under-construction Linac Coherent Light Source upgrade (LCLS-II XFEL) [2], off-axis beam transport may result in emittance dilution due to transverse long-range (LRW) and short-range wakefields (SRW) [3-5]. To investigate such effects, experiments were performed at the Fermilab Accelerator Science and Technology (FAST) facility with its unique two-cavity configuration after the photocathode rf gun [6].

We report effects on beam transverse position centroids correlated with transport through an off-resonance TESLA-type cavity, CC2. We used a 3-MHz micropulse repetition rate and targeted diagnostics for these tests. These LRW effects seemed to dominate our previously observed near-resonant HOM effects at mode 14 in this cavity. That mode also shifted in frequency compared to that of the tuned case based on network analyzer measurements. Submacropulse vertical position slewing of 1400 microns at 11 m downstream was observed with a 125 pC/bunch, 50 bunches (b) per macropulse, and 25-MeV beam. An extrapolation of the y-position slew as a function of z indicated the kick source was in CC2. Horizontal positions also showed a slew effect. Both are emittance-dilution effects which one wants to mitigate or avoid.

We used the higher-order mode (HOM) detectors and rf BPMs to establish first the reference trajectory, next the targetted off-axis steering, and then evaluated the long-range wakefield effects on the beam dynamics.

EXPERIMENTAL ASPECTS

The IOTA Electron Injector Linac

The Integrable Optics Test Accelerator (IOTA) electron injector at the FAST facility (Fig. 1) begins with an L-band rf photoinjector gun built around a Cs_2Te photocathode (PC). When the UV component of the drive laser, described elsewhere [7] is incident on the PC, the resulting electron bunch train with 3-MHz micropulse repetition rate exits the gun at < 5 MeV. Following a short transport section with a pair of trim dipole magnet packages (H/V100 and H/V101), the beam passes through two superconducting rf (SCRF) capture cavities denoted CC1 and CC2, and then a transport section to the low-energy electron spectrometer, D122. Diagnostics used in these studies include the rf BPMs, the imaging screens at X107, X108, X121, and X124, and HOM couplers at the upstream and downstream ends of each SCRF cavity. The rf BPMs' electronics were configured for bunch-by-bunch capability with optimized system attenuation. At 2 nC per micropulse, the rms noise was found to be 25 μm in the horizontal axis (x) and 15 μm in the vertical axis (y) at B101 in the test with 4.5-MeV beam from the gun.

The HOM Detectors

The HOM signals were processed by the HOM detector circuits with the zero-bias Schottky diode output provided online though ACNET, the Fermilab accelerator controls network [4]. The HOM detectors' bandpass filters were optimized for two dipole passbands from 1.6 to 1.9 GHz, and the 1.3-GHz fundamental was reduced with a notch filter. In addition, the signal was split after the filter to provide a parallel port for analysis of filtered signals.

---

*This manuscript has been authored by Fermi Research Alliance, LLC under Contract No. DE-AC02-07CH11359 with the U.S. Department of Energy, Office of Science, Office of High Energy Physics.
#lumpkin@fnal.gov

ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-TUPAB272

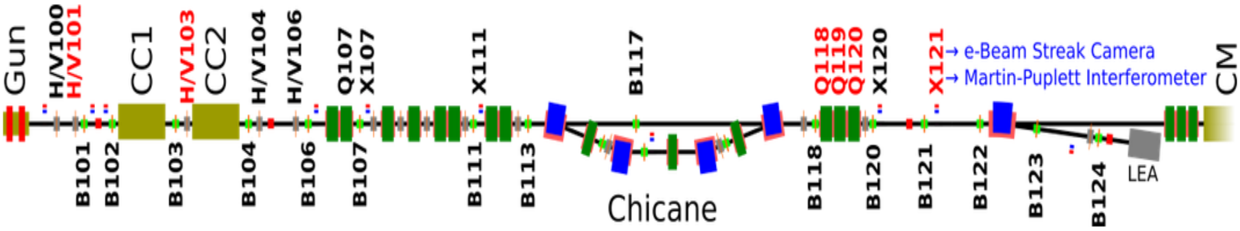

Figure 1: Schematic of the FAST beamline layout showing the PC rf gun, capture cavities (CCn), correctors (H/Vnnn), rf BPMs (Bnnn), chicane, OTR and YAG:Ce screens (Xnnn), the spectrometer dipole bend magnet (D122), and the beginning of the cryomodule (CM).

Basically, 18 modes are accessed and can be individually evaluated. An 8-GHz, 20 GSa/s oscilloscope was used to record the time domain information with 4 channels with a low jitter trigger derived from the BPM timing [8].

The CC2 Cavity Tune

The resonant cavity frequency and Q value were evaluated using a Marconi 2042 signal generator to provide some input rf signal (-6-dBm) into the klystron, and then we digitized the response waveform with a generic 16-bit digitizer. The CC2 frequency was found to be 15.2 kHz above the natural 1.300 GHz.

The Network Analyzer Tests

An Agilent C5071C network analyzer (NWA) using LabView data acquisition was used to evaluate the frequencies and Q values of the modes in the off-resonance CC2 cavity. This was done with the rf power off and cryocooling to about 5 K instead of the normal 2 K. These results were compared to previous data and the beam-based spectral results.

EXPERIMENTAL RESULTS

Initial CC2 HOM Data

In order to investigate the long-range, wakefield-driven submacropulse effects, we used the CC2 HOM detector signals as a measure of how far off axis the beam was in the cavities. We minimized the HOMs in CC1 and CC2 as the reference point, and then stepped magnet current values of the V103 corrector located just before CC2 as seen in Fig. 1. For the 20-MeV post-CC1 beam energy, a change of 1 A in corrector current corresponded to an ~2-mrad angular steering change into CC2. In Fig. 2, we show the results of the scans for the upstream (US) in blue and downstream (DS) in red HOM peak signals at 500 pC/ b and 750 pC/b. Our reference vertical corrector current value appears to be off by 0.25 A or 0.5 mrad on this run. The HOM peak signals for 750 pC/ b seem to be higher than the expected 1.5 charge ratio, perhaps due to the opening of the laser iris which then resulted in a double spot in transverse horizontal axis at the virtual cathode.

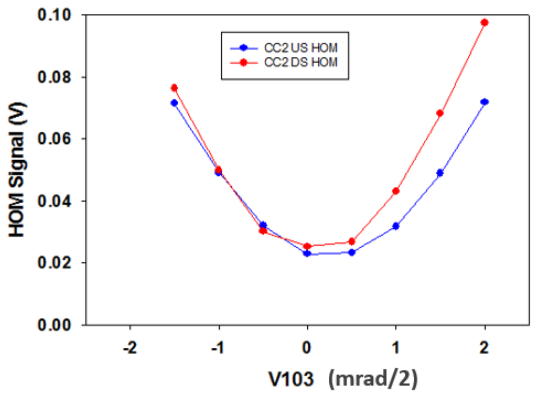

Figure 2: CC2 US and DS HOM peak signals at (a) 500 pC/b and (b) 750 pC/b.

HOM Spectral Analyses

The single-bunch HOM signals were split so that the filtered signals in the 1.6- to 1.9-GHz range could have their time domain aspect recorded in an 8-GHz, 20-GSa/s oscilloscope. Using a low-jitter trigger from the BPM system allowed the retrieval of both amplitude and phase information [8]. The FFT post processing provided the spectral frequencies as shown in Fig. 3. The key dipolar modes at 1.73 and 1.87 GHz are displayed in high resolution in Fig. 3. One can see that the signal amplitudes from the coupler change with the steering of the beam with V103 corrector current values from -1.5 A to 1.5 A. The cursor boxes allow us to determine the difference frequency with a beam harmonic of 267 kHz for mode 7 and of 181 kHz for mode 14. These two modes normally have a higher coupling to the beam than other modes in this passband, but we are in an altered state with CC2 tuned 15.2 kHz higher than the normal tune frequency.

Bunch by Bunch rf BPM Data

We also evaluated the potential long-range wakefield or HOM effects on the beam centroid by using the rf BPM data. An example of the centroid motion *within* the 50- micropulse train of a macropulse is shown in Fig. 4 with both noise-reduction and bunch-by-bunch capabilities implemented. The ~220-kHz oscillation seen in the B120

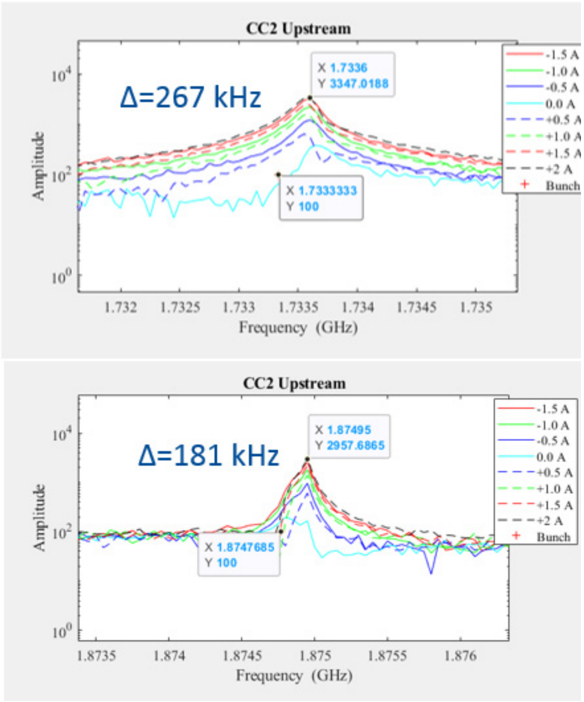

Figure 3: Spectral intensity plots of the frequencies at 1.73 GHz and 1.87 GHz for dipolar mode 7 and mode 14 of CC2, respectively. The horizontal and vertical polarization components are not resolved in this off-resonance state due to the lower Q values of the modes [8].

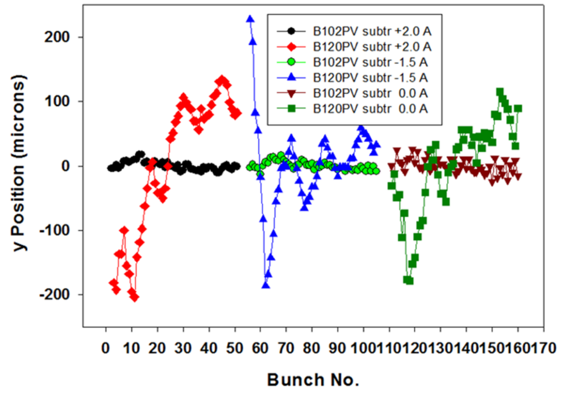

Figure 4: Examples of the variation of the beam vertical centroids bunch by bunch for 50 micropulses at B102 and B120 for V103 settings of +2A, -1.5 A, and 0.0 A from the reference. These were all 100-shot BPM data averages to show the 220-kHz oscillation effects generated in CC2.

data is ascribed to a combination of the difference frequencies between HOM dipolar mode 7 and 14 in CC2 and a beam harmonic identified in the previous subsection.

We note that previous studies with CC2 on resonance and powered resulted in a 100-kHz difference frequency for mode 14 and small mode-7 effects [4]. The field oscillations kicked different micropulses according to the amplitude at that point in time, resulting in the submacropulse effects. The surprise is that the oscillation and slew seem to be dominated by a base effect that does not go away at our normal on-axis steering setting through CC2 as shown in Fig. 4. The three pairs of plot curves are for V103= +2.0, -1,5, and 0.0 A from the reference corrector current value with a steering effect of ~2 mrad/A. We compare the data from the vertical B102 BPM located before CC1 to the B120 BPM located 11 m downstream of CC2. We see a strong submacropulse centroid oscillation of about 220 kHz for all three B120PV cases (red, blue, and green curves), including the reference. This is in contrast to the normal behaviour in the outcoupled HOM signals in both the broadband Schottky data of Fig. 2 and the single mode FFT data of Fig. 3 with its phase data in ref. [8]. The variation of the extremes of the vertical beam positions in the ten rf BPMs after CC2 were assessed graphically as shown in Fig. 5, and the backward extrapolation of the data supports the assignment of the beam kicks as a function of time to CC2 HOM fields.

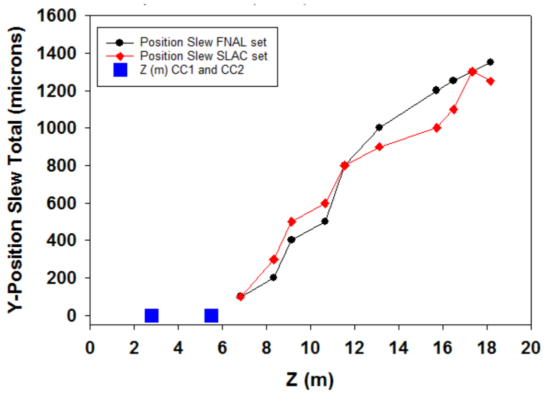

Figure 5: Coarse estimate of the z-dependent slew magnitude (the extremes of the motion) from the BPM data in the ten downstream locations after CC2. Two sets of BPM data were evaluated with the back extrapolation pointing to CC2 as the source of the time dependent kicks to the beam at 24 MeV.

SUMMARY

In summary, the off-resonant CC2 cavity appears to be the source of the significant submacropulse centroid oscillations observed downstream of CC2. The ~220 kHz oscillation is ascribed to the combination of the dipolar Mode 7 and 14 difference frequencies of 267 and 181 kHz as compared to a beam harmonic. This centroid oscillation is an example of emittance dilution effects that can be encountered if one does not run on resonance or on axis in SCRF cavities.

ACKNOWLEDGMENTS

The Fermilab authors acknowledge the support of C. Drennan, A. Valishev, D. Broemmelsiek, G. Stancari, and M. Lindgren, all in the Accelerator Division at Fermilab. The SLAC/NAL authors acknowledge the support of J. Schmerge (Superconducting Linac Division, SLAC).

REFERENCES

[1] H. Weise and W. Decking, "Commissioning and First Lasing of the European XFEL", in *Proc. 38th Int. Free Electron Laser Conf. (FEL'17)*, Santa Fe, NM, USA, Aug. 2017, pp. 9-13. `doi:10.18429/JACoW-FEL2017-MOC03`

[2] P. Emma, "Status of the LCLS-II FEL Project at SLAC", in *Proc. 38th Int. Free Electron Laser Conf. (FEL'17)*, Santa Fe, NM, USA, Aug. 2017, JACoW-FEL2017-MOD01.

[3] J. T. Seeman *et al.*, "Transverse Wakefield Control and Feedback in the SLC Linac", in *Proc. 12th Particle Accelerator Conf. (PAC'87)*, Washington D.C., USA, Mar. 1987, pp. 1349-1353.

[4] A. H. Lumpkin *et al.*, "Submacropulse electron-beam dynamics correlated with higher-order modes in Tesla-type superconducting rf cavities", *Phys. Rev. Accel. Beams,* vol. 21, p. 064401, 2018. `doi:10.1103/physrevaccelbeams.21.064401`

[5] A. H. Lumpkin, R. M. Thurman-Keup, D. Edstrom, and J. Ruan, "Submicropulse electron-beam dynamics correlated with short-range wakefields in Tesla-type superconducting rf cavities", *Phys. Rev. Accel. Beams,* vol. 23, p. 054401, 2020. `doi:10.1103/physrevaccelbeams.23.054401`

[6] M. Church *et al.*, "The ASTA User Facility Proposal", Fermi National Accelerator Laboratory, Batavia, USA, Rep. Fermilab-TM-2568, Oct. 2013.

[7] J. Ruan, M. D. Church, D. R. Edstrom, T. R. Johnson, and J. K. Santucci, "Commissioning of the Drive Laser System for Advanced Superconducting Test Accelerator", in *Proc. 4th Int. Particle Accelerator Conf. (IPAC'13)*, Shanghai, China, May 2013, paper WEPME057, pp. 3061-3063.

[8] R. Thurman-Keup *et al.*," Observation of Polarization-Dependent Changes in Higher-Order Mode Responses as Function of Transverse Beam Position in Tesla-Type Cavities at FAST", presented at IPAC'21, Campinas, Brazil, May 2021, paper MOPAB232, this conference.