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Mitigation of Emittance Dilution Due to Wakefields in Accelerator Cavities Using Advanced Diagnostics with Machine Learning Techniques: LOI-AF7-132

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AF7 rf Accelerator Technology WG (Virtual)

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Los Alamos DESY

I. Introduction

- Generation and preservation of bright electron beams are two of the challenges in the accelerator community given the inherent possibility of excitations of dipolar long-range wakefields (LRWs) (e.g., higher-order modes (HOMs)) and short-range wakefields (SRWs) due to beam offsets in the accelerating cavities. What are the observable effects on the beam?
- Evaluate beam steering offsets and possible emittance dilution by monitoring and minimizing effects in L-band, 9-cell TESLA-type superconducting rf accelerating cavities as one class of tests.
- Such cavities form the drive accelerator for the FLASH FEL, the European XFEL, the under construction LCLS-II, the proposed MaRIE XFEL at Los Alamos, and the International Linear Collider under consideration in Japan.
- We report sub-macropulse effects and sub-micropulse effects on beam transverse position centroids correlated with off-axis beam steering in TESLA-type cavities at the Fermilab Accelerator Science and Technology (FAST) Facility.
- We used a unique two separated-single-cavity configuration, and targeted diagnostics (bunch-by-bunch rf BPMs, streak camera) for these tests.

Some Perspective on Wakefields in Accelerator Cavities 1

- Early work on S-band Cavities at SLAC: Classic paper by Panofsky and Bander (1968) on transverse beam breakup modes from off-axis beam. Steered to minimize beam size.
- SRW seen in NC L-band accelerator in 1993 at Los Alamos using a streak camera. PARMELA simulations by Carlsten.
- Extensive higher-order mode (HOM) studies in TESLA-type cavities at DESY (Baboi et al.) in last 20 years with use for cavity misalignments and recently beam position information.
- First direct observations of submacropulse centroid effects correlated with HOMs in single TESLA cavities at FNAL (PRAB 2018). (Example).
- First direct observations of submicropulse effects from SRWs in single TESLA cavities at FNAL (PRAB 2020). (Example).

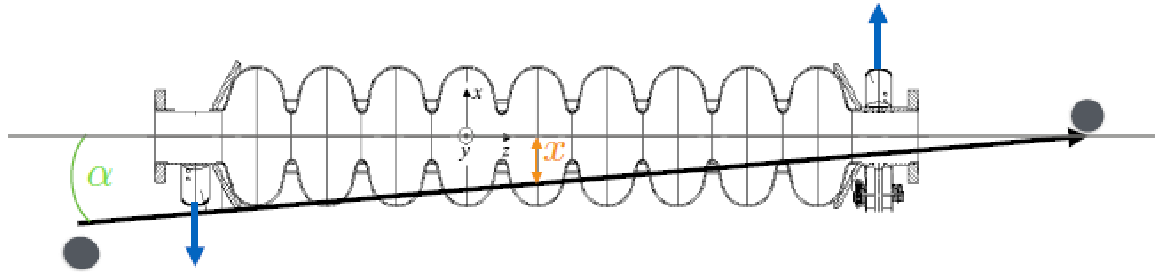
Some Perspective on Wakefields in Accelerator Cavities 2

- First direct observations of submacropulse centroid effects correlated with HOMs in TESLA-type Cryomodule (CM) at FNAL in Fall 2020. (Example).
- Simulation of SRW effects on emittance dilution in the APS S-band accelerator due to a sagging structure resulting in beam offsets. (Example from Yine Sun).
- Proposal for SRW studies on the cryomodule at FAST with the streak camera. (schematic).
- I do not have a C-band example, but the smaller bore means steering must be very good. Los Alamos Interest.
- The LCLS-II injector includes injection of <1 MeV beam into a CM so steering and diagnostics are critical. (collaboration).
- FLASH and European XFEL have 4 to 6 MeV injection into CM.

Experimental Setup

> TESLA cavity
  - 2 HOM couplers

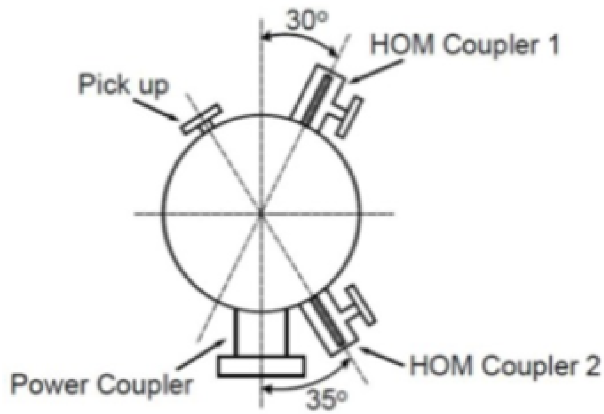
> Dipole HOM
  - $V_x(t) \propto x \cdot e^{-\frac{t}{2\tau}} \sin(\omega t)$
  - $V_{x'}(t) \propto x' \cdot e^{-\frac{t}{2\tau}} \cos(\omega t)$



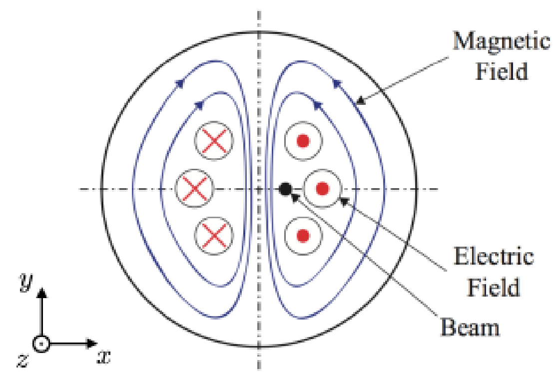
Expected HOMs in TESLA Cavities*

Mode #	Freq.(GHz)	R/Q (Ω/cm²)
MM-6	1.71	5.53
MM-7	1.73	7.78
MM-13	1.86	3.18
MM-14	1.87	4.48
MM-30	2.58	13.16

*R. Wanzenberg, DESY 2001-33



Dipole Mode



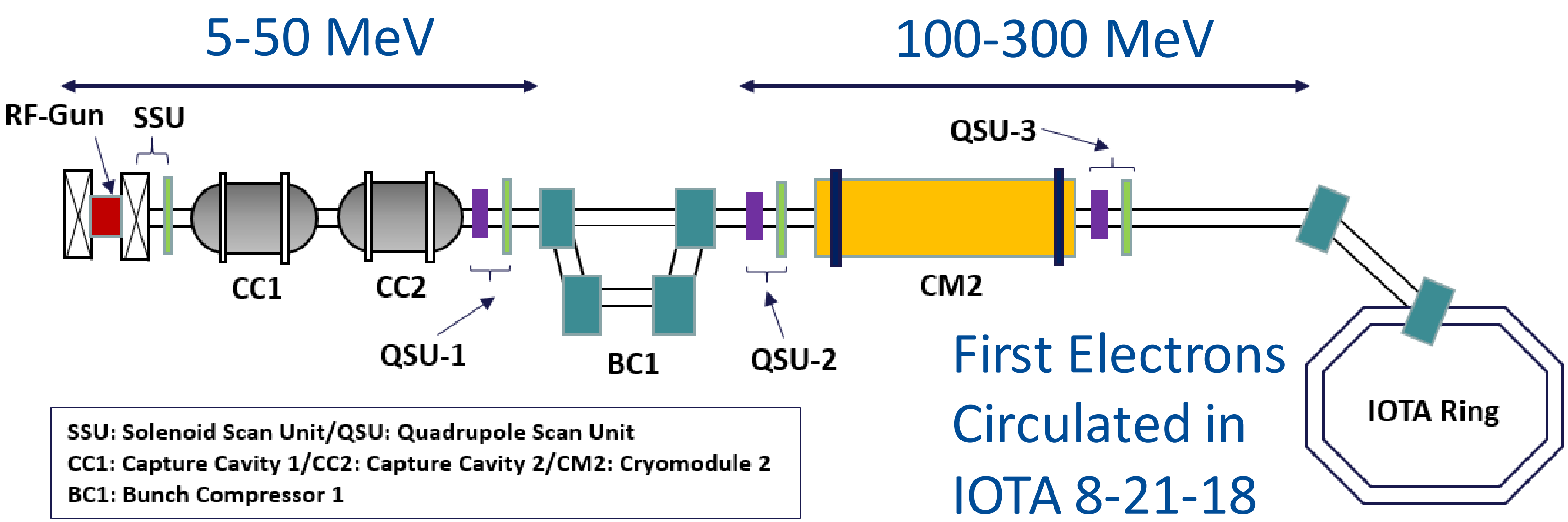
N.B. Modes excited in the cavities at frequencies Higher than the accelerating mode are HOMs.
Amplitude of specific dipole mode, A_d ~ *q* x *r* x *(R/Q)*

THORSTEN HELLERT | FEL SEMINAR | JULY 11 2017 | PAGE 12

T. Hellert 7/11/17 DESY Seminar

FAST/IOTA Facility

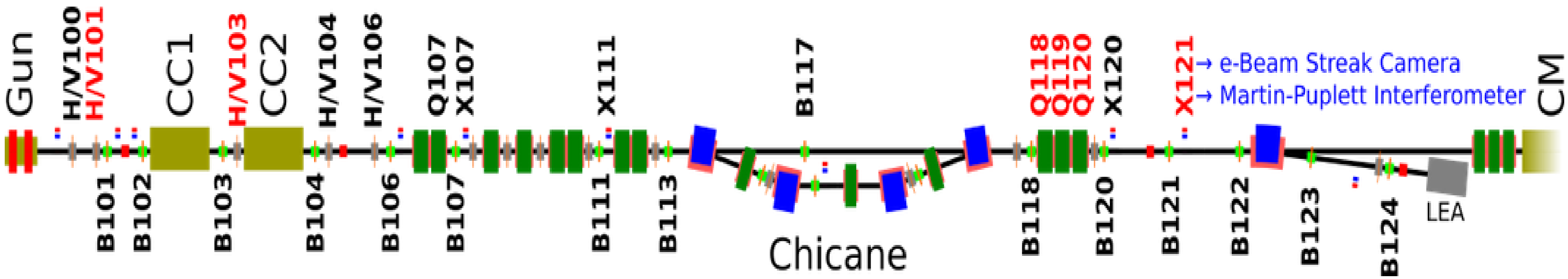
- The Fermilab Accelerator Science and Technology (FAST) Facility is based on a photocathode rf gun and TESLA-type superconducting rf accelerators.
- 300-MeV milestone with full 31.5 MV/m average gradients in cryomodule (CM) attained in November 2017. ILC target.

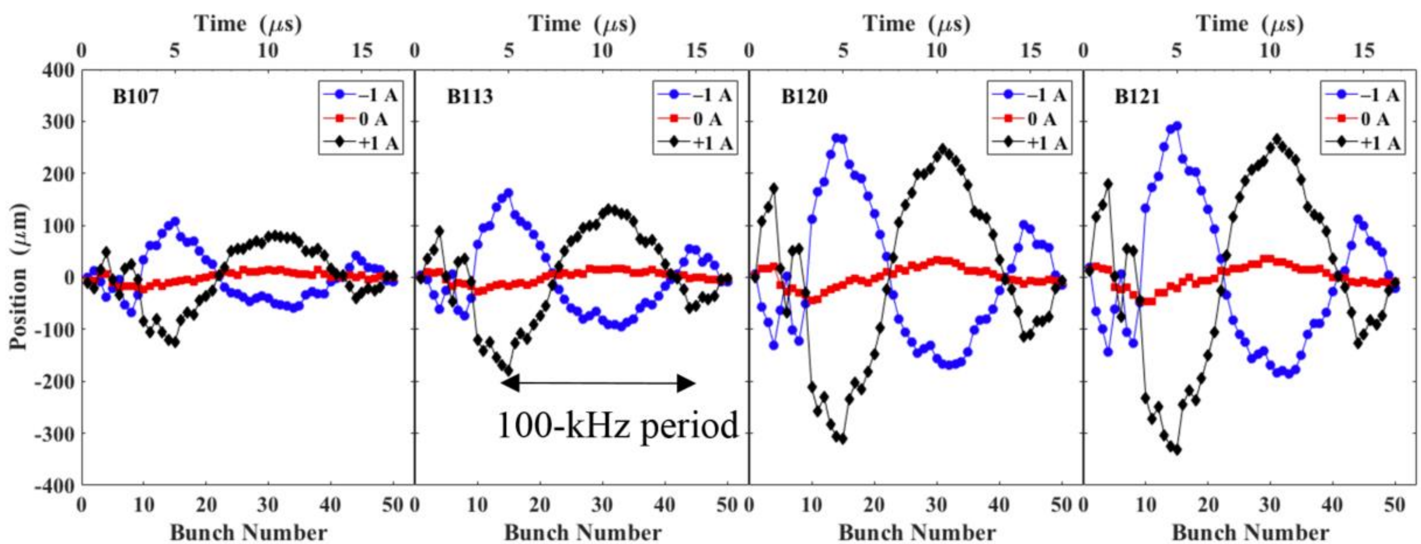


Integrable Optics Test Accelerator (IOTA)

Centroid Vertical Oscillations Observed to Grow with Drift

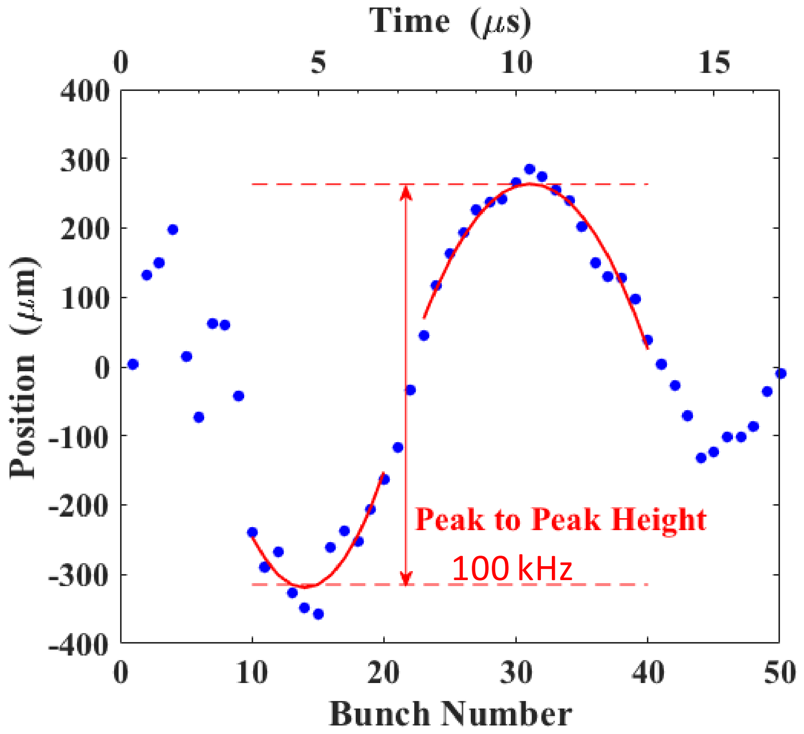
- Attributed to near resonance of beam harmonic and CC2 dipole mode 14 (A.H. Lumpkin et al., Phys. Rev. A-B **21**, June 2018).

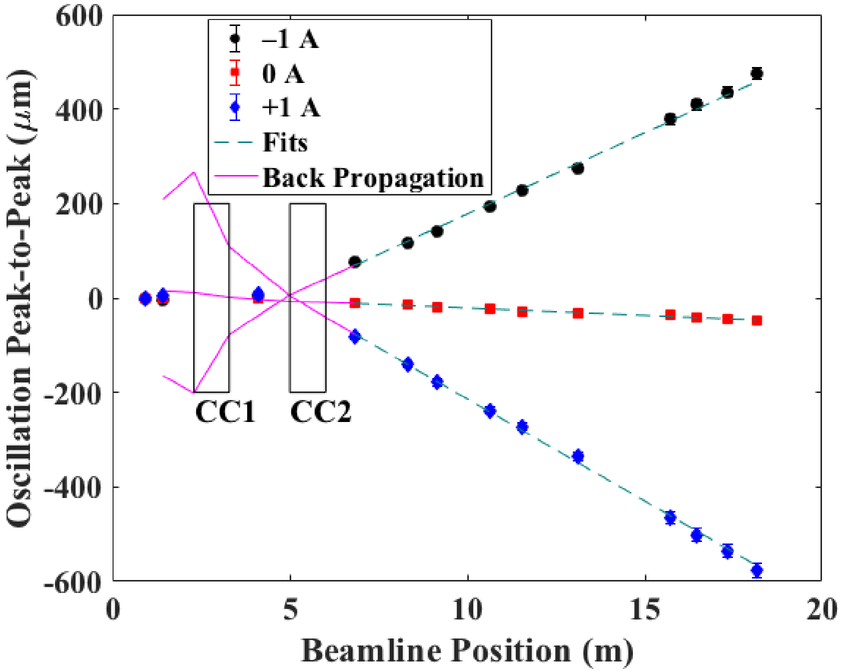




Evaluation of HOM Vertical Kick Angles

- V101 scan results with drift to B122. Kick deduced 84 μrad from CC2 at 1000 pC/b in vertical BPM readings.





A.H. Lumpkin et al., PRAB, 2018

Short-range Wakefield Experiment on LANL Linac 1993

- Streak camera diagnostic showed head-tail kick and observed emittance growth and reduction with steering through normal conducting L-band cavity #4 with 24-mm diam. Iris.
- Q=5 nC/b, ~12 ps sigma,
- Pulse train length 20 µs.
- E =37 MeV.
- Camera in tunnel on lead-shielded optical table.

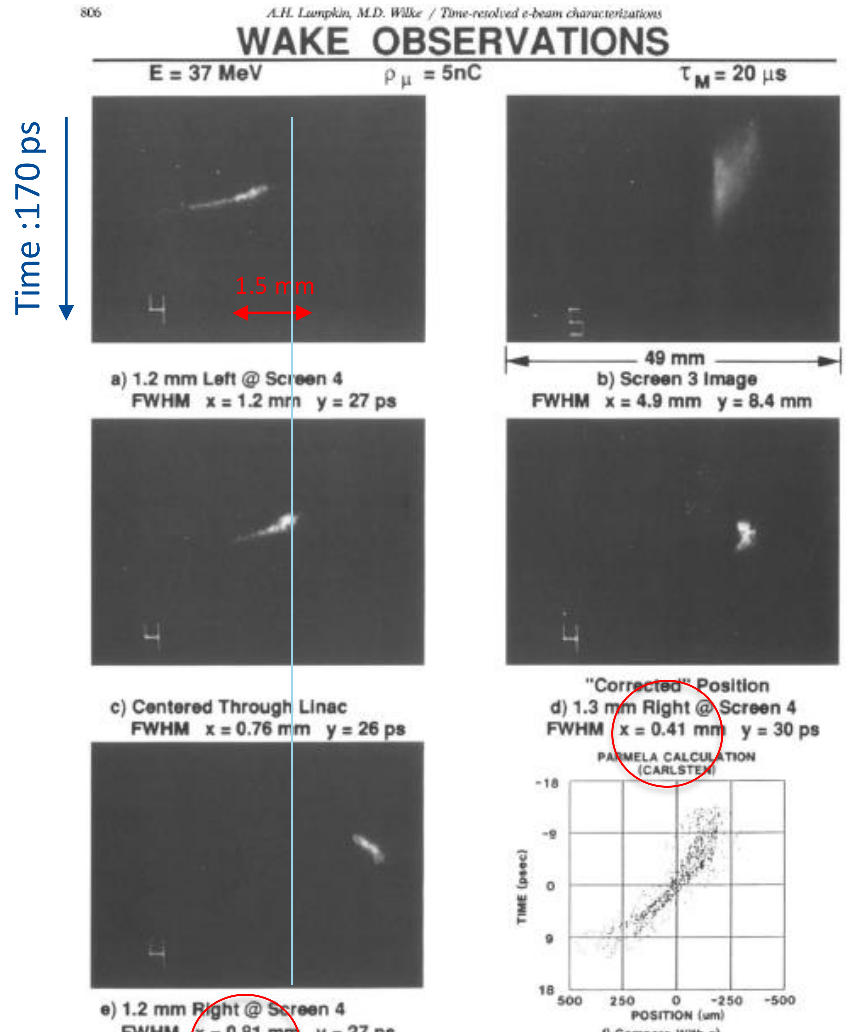
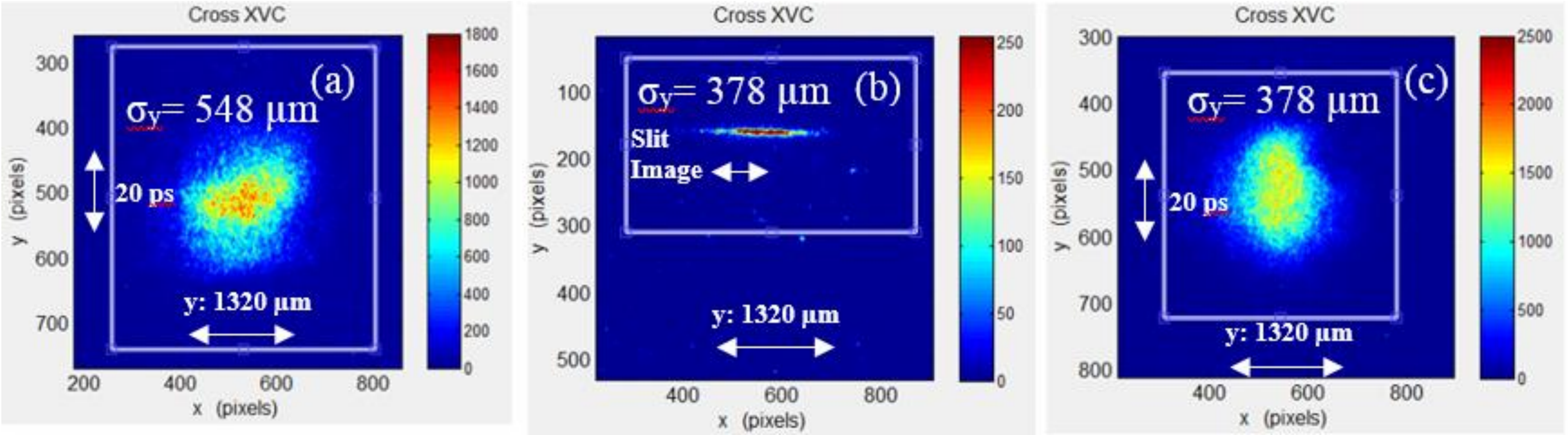


Fig. 6. A composite of streak images at station 4 for steering horizontally "left to right" across the scene. Note the flip in the direction of the head-to-tail kick. Time increases going down on the vertical axis.

A.H. Lumpkin and M. Wilke NIMA (1993)

“As found” Steering Shows Submicropulse SRW Effects

- Beam size dilution due to SRW quantified at >40% in streak camera images (Range 1) at X121. (03-01-19)
- Laser spot 0.2 mm RMS, Q=500 pC/b, E=41 MeV after CC2.
- Later time is upward in streak image.



PRAB May 2020

Observed Centroid Shifts within Micropulse Time 03-01-19

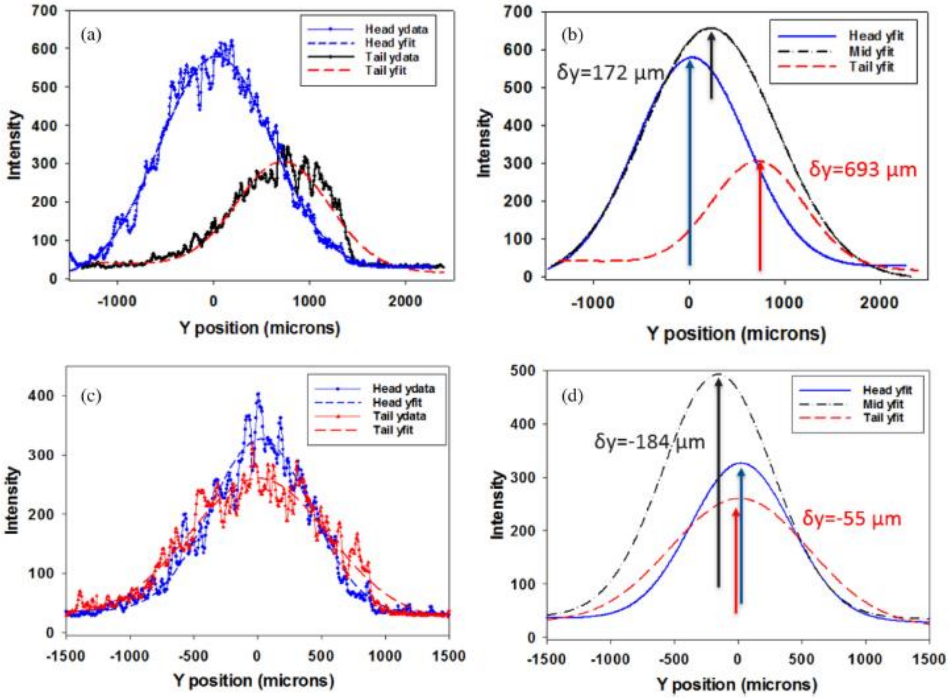
- V103= ±2.4 A (±5 mrad) from ref., 500 pC/b, 150b, MCP=61
- Time samples of y profile at Head, Mid, and Tail of micropulse.
-

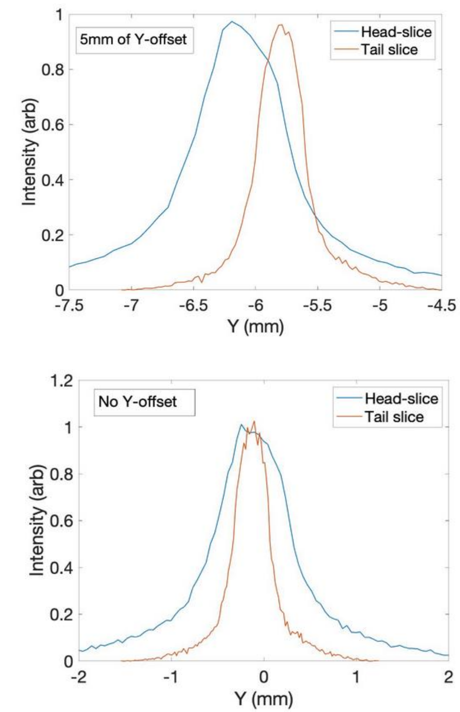
Experimental Results

ASTRA Results

+ 5 mrad

Kick enhanced





-5 mrad

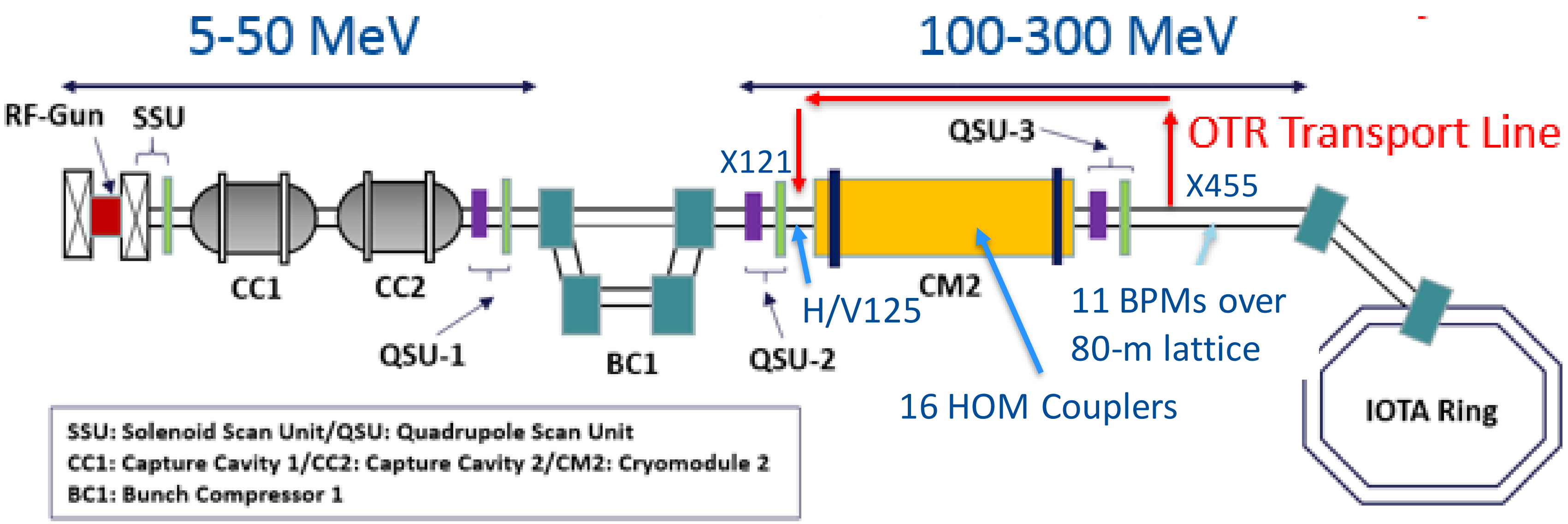
Kick Compen-
sated

A.H. Lumpkin et al.,
PRAB May 2020

Fermilab

Techniques Being Applied to FAST Cryomodule

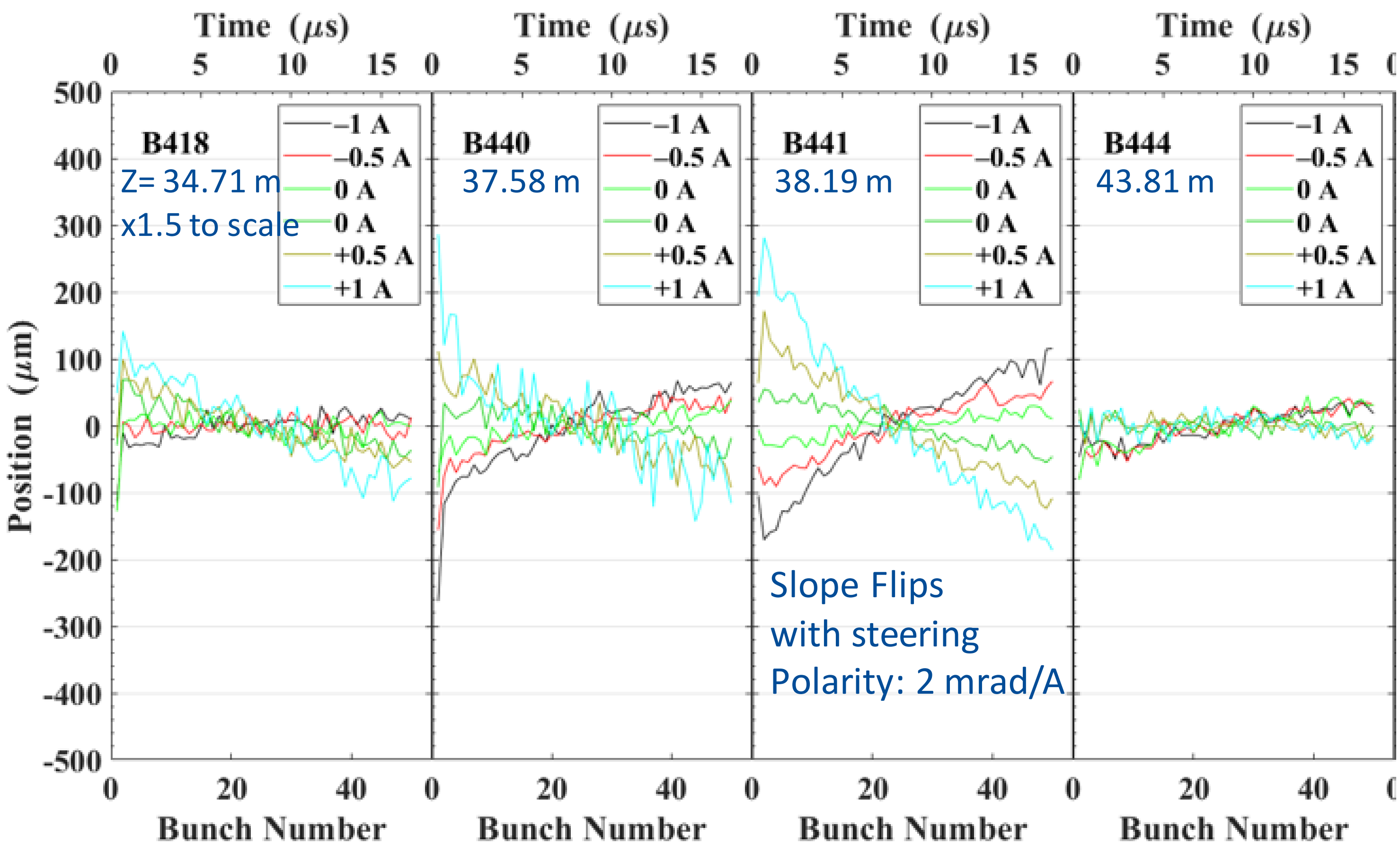
- Possible to extend HOM studies techniques to higher charges and to the cryomodule using an 80-m lattice and 11 rf BPMs distributed in z downstream of it, 8 SLAC HOM det., Run 3
- Run at 100-MeV total energy with 25 MeV into CM2.
- Propose SRW test in cryomodule in Run 4 with new optical line.



Revised YMS

BPM Vertical Array Data Downstream of CM2-C8 Show Slew!

- B418V data and others show offset dependence in scan. V125 corrector is 4 m before CM2 and ~2mrad/A. 11-20-20 +12-03-20
- Mean of each array subtracted from each bunch position for the plots.



RTK Plot

Potential Linac Facilities in USA for Wakefield Studies

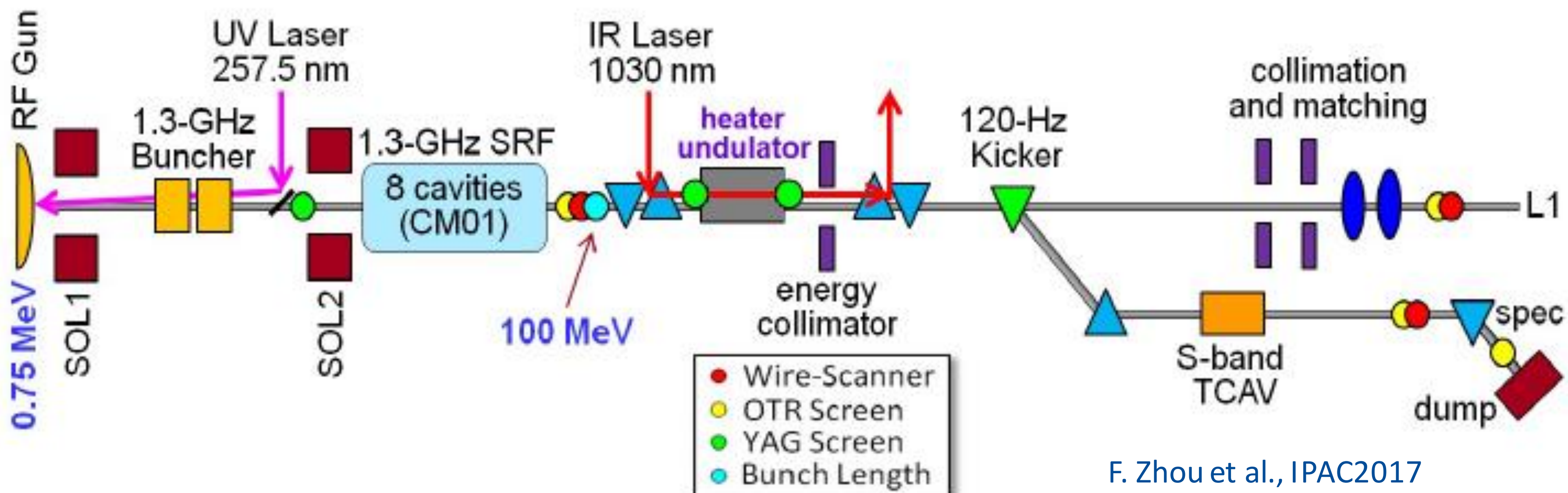
- Table 1: Summary of linac facilities and features where one could investigate emittance dilution due to accelerator cavity wakefields. The injector energies are one key.

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

- FAST/IOTA at FNAL and AWA at ANL are HEP GARD Beam Test Facilities using a collaboration model.
- Transverse Deflecting Mode Cavity (TDC)

Schematic of the Planned Full LCLS-II Injector

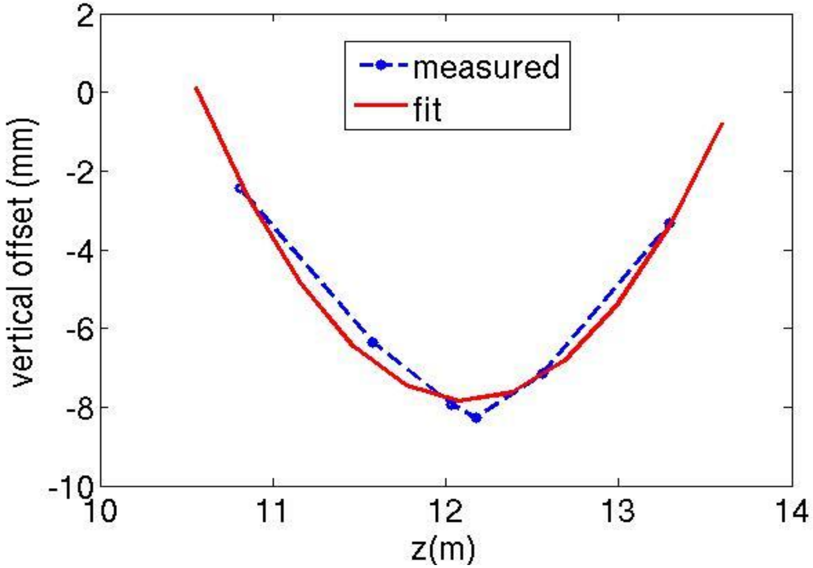
- Potential short-range and long-range wakefields due to off-axis beam in cavities need to be minimized to preserve emittance.
- HOMs in CM01 tracked. Steering at 1-8 MeV critical in first 3 cavities. Cavity 1 at 8 MV/m; Cavities 2,3 at 0 MV/m; Cavities 4-8 at 16 MV/m. Commissioning expected in Jan 2022.
- S-band TCAV could be used for SRW studies.

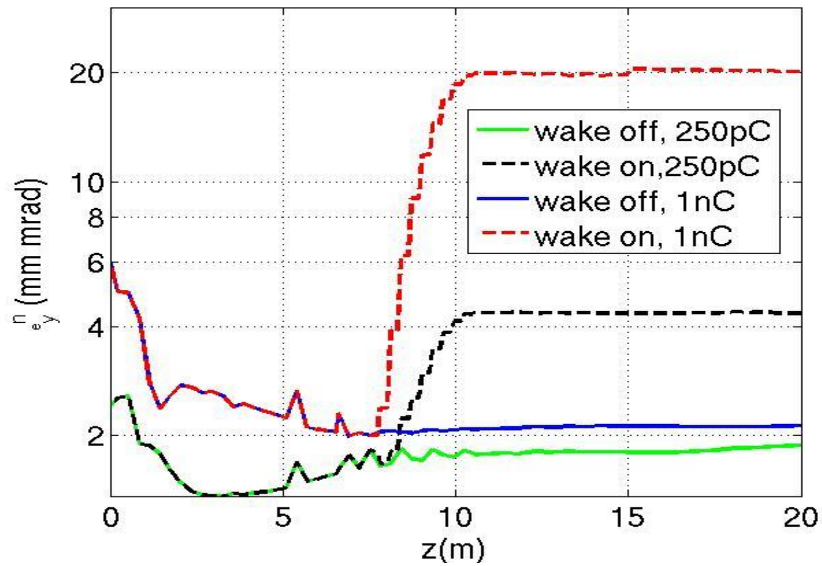


F. Zhou et al., IPAC2017

ASTRA Simulation for APS S-Band Structure Sagging Effect

- Significant sagging of a structure L2AS1 at APS. Emittance dilution due to SRWs assessed by Yine Sun with ASTRA.
- Structure was replaced with much straighter one.





Z-axis used the survey data values. Survey Group measurement data can be retrieved from ICMS under APS_1435365 .

Vertical Emittance: 1 nC: 2.1mm mrad
==>20.0 mm mrad
250pC: 1.9 mm mrad
==>4.4 mm mrad

Machine Learning Application: Emittance Dilution Mitigation

- FAST: 3 H/V correctors, 4 HOM detectors, 10 rf BPMs, Streak camera, Imaging screen, Injection at 4.5 MeV into first of two cavities. We already have a data base for training ML app.?
- FAST-CM: 2 H/V correctors, 16 HOM channels, 18 dipolar modes in first two passbands, 11 rf BPMs in 80-m lattice, etc.
- LCLS-II injector: 4 H/V correctors, Sol. 1,2, 16 HOM channels, imaging screen, TCAV beam line with OTR or YAG screen. Injection at <1 MeV into CM first cavity so must be careful.
- There is demonstrated emittance dilution from both LRW and SRW, although SRWs had bigger effect at the FAST linac.
- Simplest objective is to minimize the HOM signals in all detectors by steering, but there could be special cases in a CM due to unique mode frequencies, misalignments, energy.

SUMMARY

- Both LRWs and SRWs are inherent to off-axis transport through all accelerator cavities as known for decades for smaller apertures. These remain as next-decade issues.
- TESLA-type cavities, even with a large aperture, are now shown to have measurable effects which require mitigation.
- These cavities are the basis of existing (Euro-XFEL), under construction (LCLS-II), and conceptual (ILC) major facilities.
- Linac facilities in the USA could explore these effects over a range of parameters with common interest to HEP and BES.
- Simulations could help to guide further experiments after bench marking with data.
- Machine Learning may help to reduce emittance dilution effects with improved operational efficiency.

Backup Slides

Table 1. FAST Electron Beam Parameters for Studies

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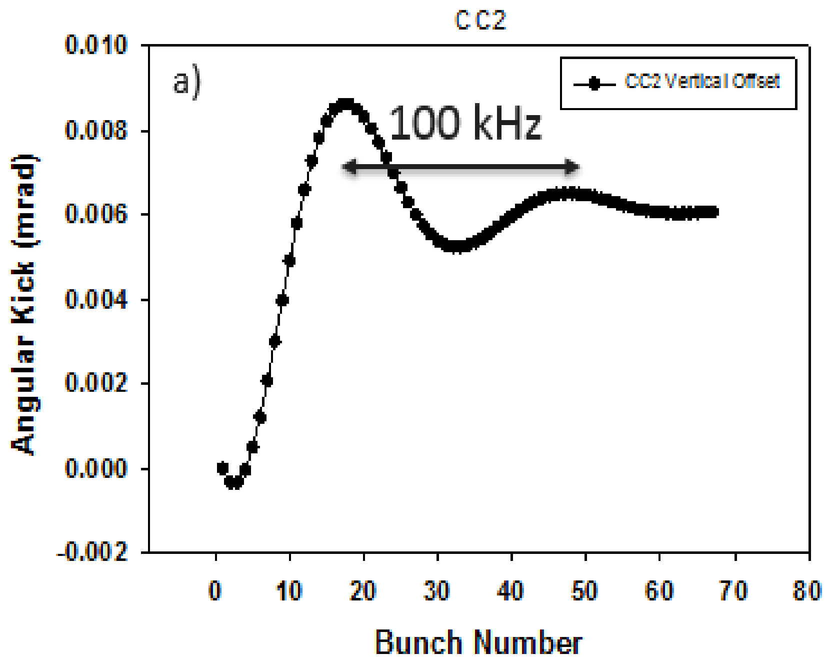
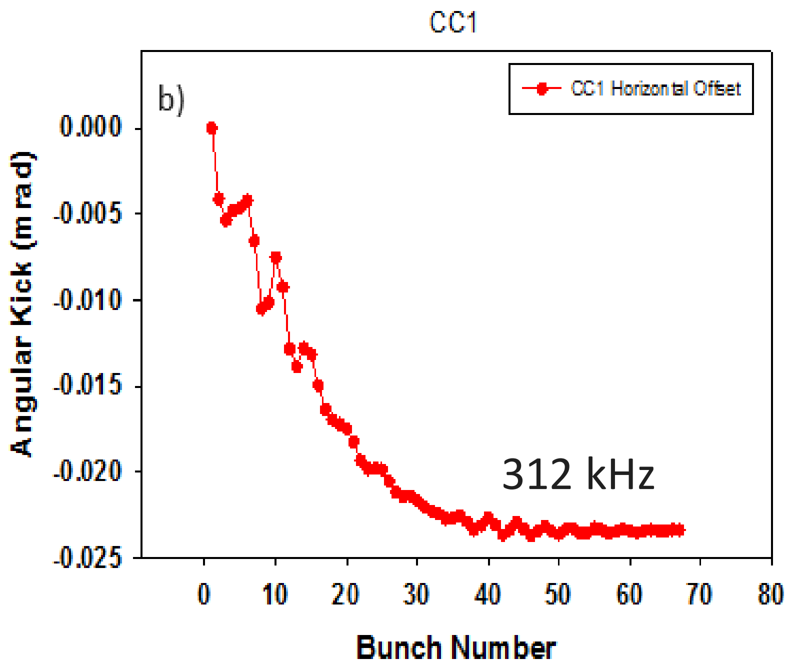
Beam Parameter	Units	Value		
Micropulse Charge (Q)	pC	100-2500		
Micropulse rep. rate	MHz	3		
Beam sizes, σ	µm	100-1200		
Emittance, σ norm	mm mrad	1-5		
Bunch length,σ Compressed	ps ps	4-20 1-3		
Total Energy	MeV	33, 41		
PC gun grad.	MV/m	40-45		
CC1 gradient	MV/m	14.2, 21		
CC2 gradient.	MV/m	14.2		

1-150 bunches used, 3000 max.

CC2 and CC1 Generated Dipole HOM Kicks (Calculations)





CC2: MM-14 with vertical polarization, 5 mm translation, 500 pC/b. Beam sampling at 3.008 MHz, harmonic # 623 within 100 kHz of the HOM frequency.

CC1: MM-7 plus MM-30; 5 mm translation, 500 pC/b.

O. Napoly's calc.

Model of TESLA cavity for transverse SRWs used to predict effect scale (Calculations by V. Lebedev)

For Q= 0.5nC, sigma-t=10 ps, 5-mm offset, M_{12}=20 m, 33 MeV, get 100- to 150-µm kick within the micropulse from 1 TESLA cavity's wakefield. We are at 33 MeV in middle of CC2.

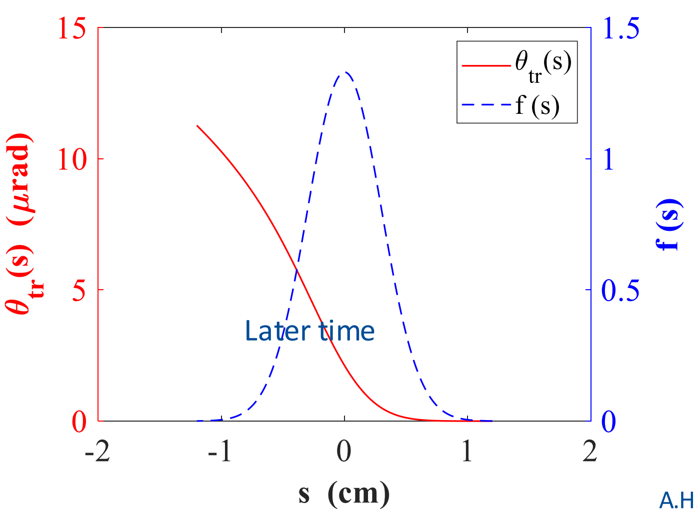
N_{cell} is the number of cells in a cavity, a is the cavity bore radius, g is the cell length, the longitudinal wake γ_{eff} is a fitting parameter, and s is the distance between leading and trailing charges. Parameters for our model cavity are: N_{cell} = 9, a = 3.1 cm, g = 11.511 cm, and γ_{eff} = 0.9 x 10^2.

The transverse wakefield, $W_T(s)$ is given by,

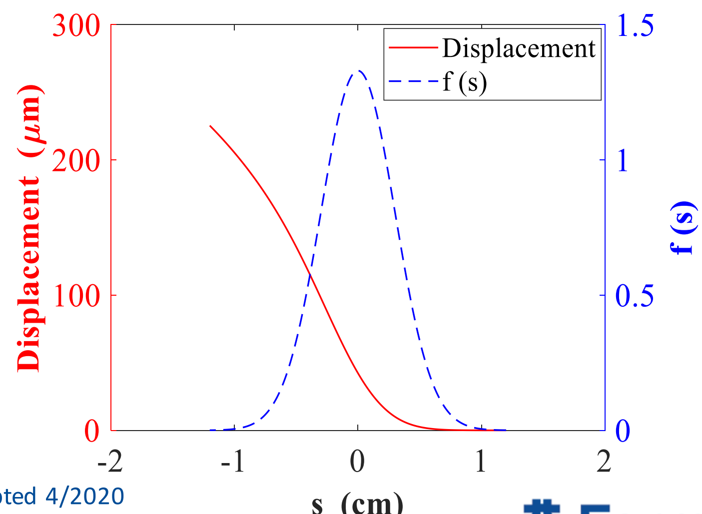
$$W_T(s) = \frac{4N_{\text{cell}}}{\pi a^3}\left\{\frac{5}{4}\left[\sqrt{2g\left(s+\frac{a}{\gamma_{\text{eff}}}\right)}-\sqrt{2g\frac{a}{\gamma_{\text{eff}}}}\right]-s\right\}$$

The transverse kick angle $\theta_{tr}(s)$ is then given by,

$$\theta_{tr}(s) = \frac{e_{conv}e_{SGS}N_e}{P_0}d\int_s^{10} W_T(s_p-s)\,f(s_p)\,ds_p$$



33 MeV,
Δx=5mm
M_{12}= 20 m



A.H. Lumpkin et al., PRAB, accepted 4/2020