Dielectric wakefield accelerator program at FACET and FACET II

Gerard Andonian, UCLA
On behalf of E-201 collaboration

FACET-II Workshop
SLAC
October 17-20, 2017

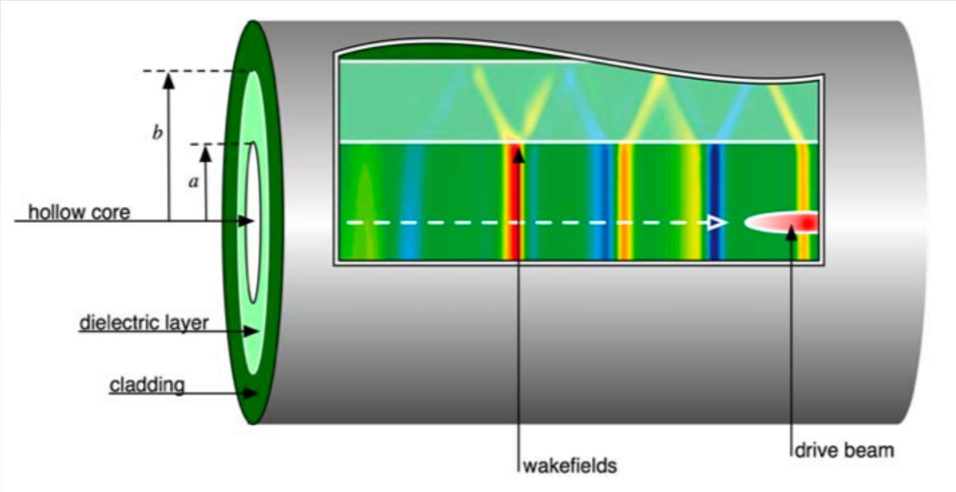
E-201 Team:
UCLA: G. Andonian, S. Barber (LBNL), A. Fukusawa, P. Hoang, B. Naranjo, O. Williams, J. Rosenzweig, et al.
SLAC FACET: B. O'Shea, C. Clarke, M. Hogan, V. Yakimenko, et al.
Work Supported by US DOE HEP

Outline

- Background
- FACET E201 Results summary
- Next steps at FACET-II

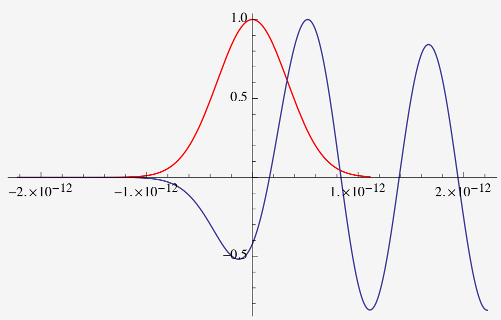
Dielectric Wakefield Accelerator

- Candidate for next-gen adv. accelerator
- Electron bunch (β ≈ 1) drives wakefield in dielectric structure
- Wakefields accelerate trailing bunch
- Dependent on structure geometry
- Present day beams naturally scale to sub-mm (THz) structures



Design parameters: $a, b, Q, \sigma_z, \varepsilon$

- Peak field $$eE_{z,dec} \approx \frac{-4N_b r_e m_e c^2}{a\left[\sqrt{\frac{8\pi}{\varepsilon-1}}\varepsilon\sigma_z + a\right]}$$
- Fundamental mode $$f_{01} = \frac{c}{2\pi}\sqrt{\frac{2\epsilon}{(\epsilon-1)a\,(b-a)}}$$
- Transformer ratio (unshaped beam) $$R = \frac{E_{z,acc}}{E_{z,dec}} \leq 2$$



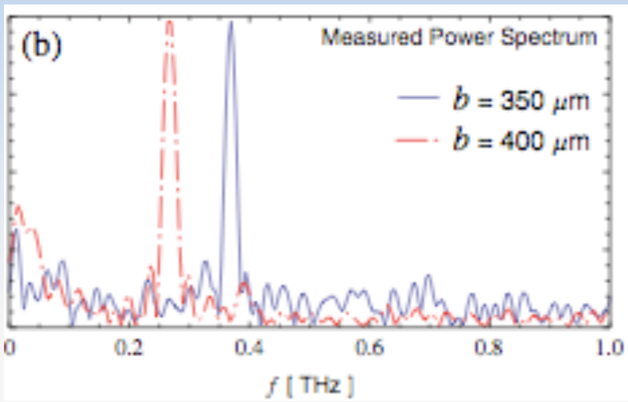
On-axis Ez
(single mode structure)

Applications and Research

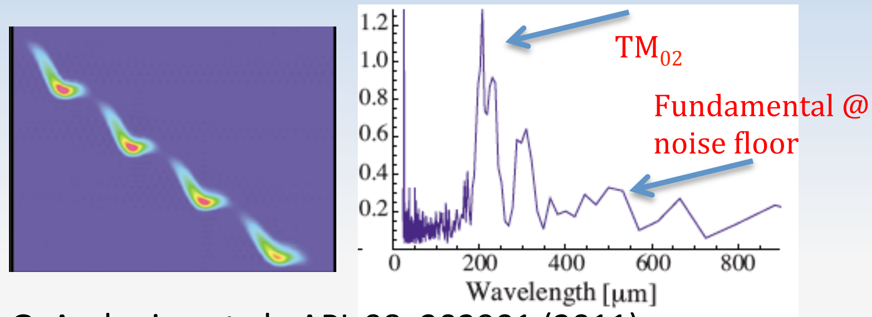
- High gradient applications
  - HEP: future machine (GV/m field)
  - Compact Light Source driver
    - A. Zholents Proc FEL14, 993 (2014)
  - Radiation Source (THz)
  - Phase space manipulations
    - Self-wake interactions
- Relevant Issues in DWA research
  - Determine achievable field gradients
  - Resonant excitation
  - Transverse modes and beam-breakup
  - Dielectric materials & Cladding composition
  - Alternate geometries (slab)

Some recent DWA experiment results

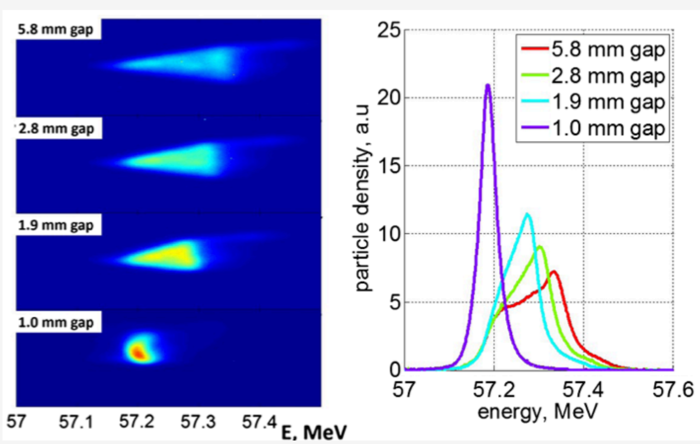
Pioneering expt work at ANL @GHz: *W. Gai, et al., PRL 61, n.24, 2756 (1988)*



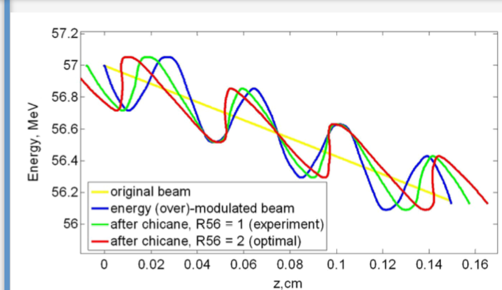
A. Cook et al., PRL 103, 095003 (2009)
CCR spectra @ UCLA Neptune



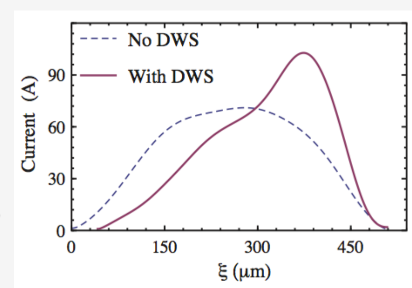
G. Andonian et al., APL 98, 202901 (2011)
Selective mode excitation @BNL ATF



S. Antipov et al., PRL 112, 144801 (2014)
Chirp suppression @ BNL ATF



S. Antipov et al., PRL 111, 134802 (2013)
Microbunching @ BNL ATF



G. Andonian et al., PRL 118, 054802, (2017)
Ramped beam @ BNL ATF

… and other demonstrations (at "low" fields).
Building the foundation for high-gradient studies…

DWA program at SLAC FACET

UCLA

Experiment: E-201 – Dielectric wakefield acceleration: A suite of groundbreaking measurements to ascertain the viability of DWA as next-generation accelerator using the unique beam capabilities available at FACET

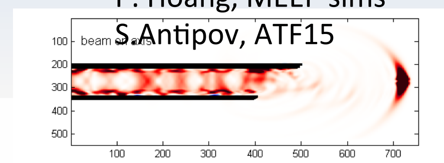
FACET: 20GeV, 3nC, σ_z<20µm

<u>Experimental highlights from E-201 DWA</u>

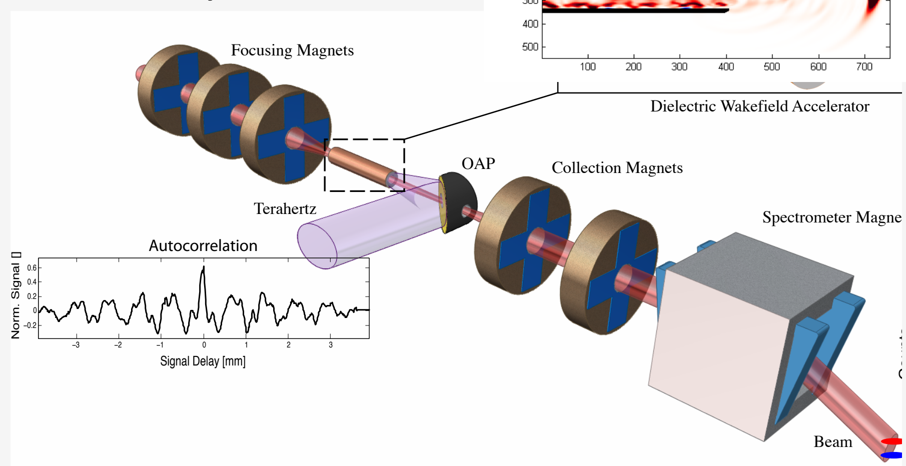
1. Spectral characterization
2. Highest gradient fields
3. Witness beam acceleration
4. Wakefield damping mechanisms
5. Deflecting modes
6. DWA with slab geometry
7. Alternate materials and geometries
8. Positron-driven DWA

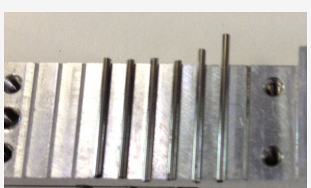
P. Hoang, MEEP sims

S.Antipov, ATF15



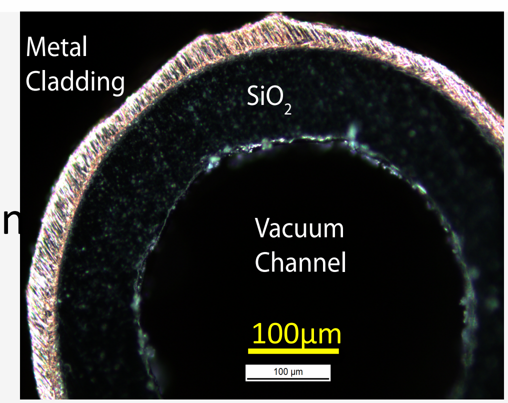
DWA layout FACET





Initial FACET runs

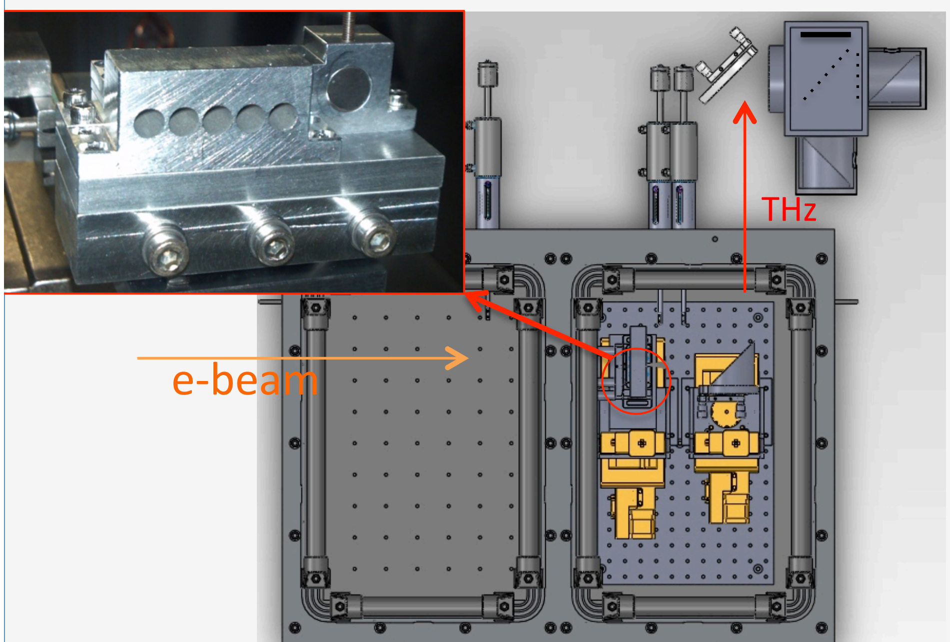
Advances in metallurgy fabrication enables high-field studies

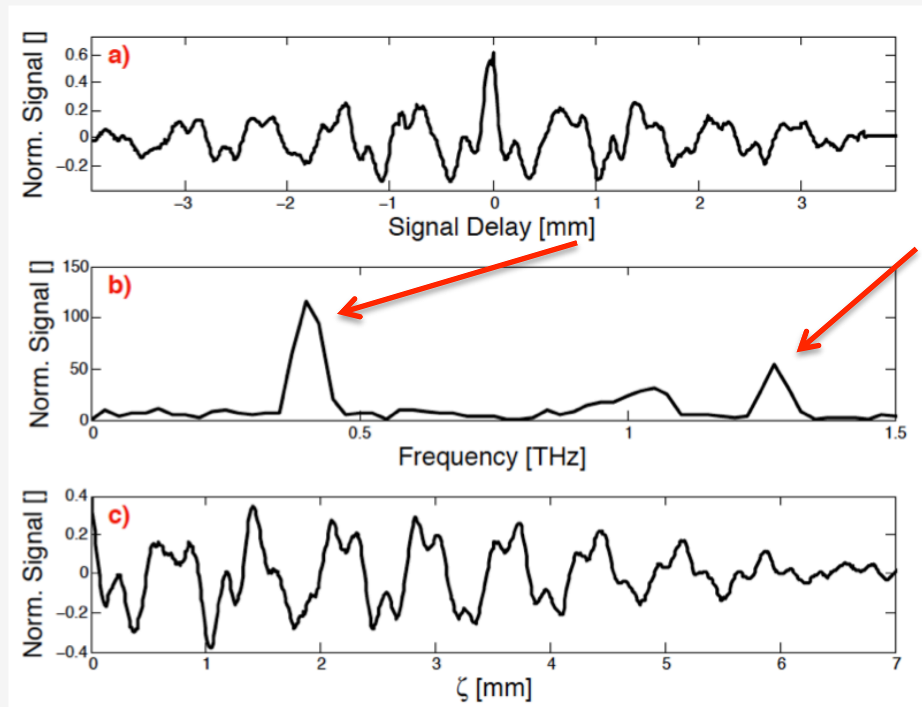


Spectral Mode Characterization

- CCR autocorrelation
  - Extraction & transport to interferometer
  - Unfold spectral content
  - Multi-modes observed
  - Wakefield reconstruction (Kramers Kronig)

DWA structure:
- a/b = 225/320 μm
- L = 1cm
- TM01,TM02 = 422GHz, 1.27 THz
- Cylindrical, SiO_2

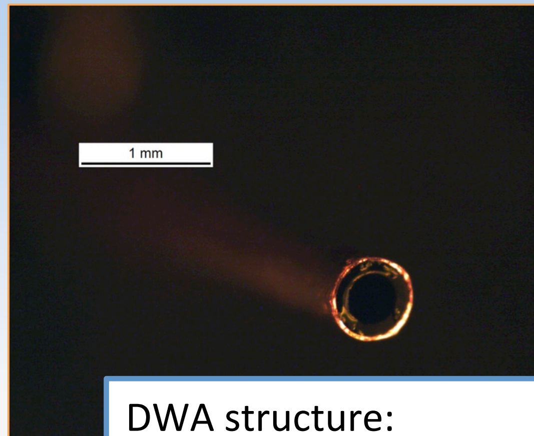


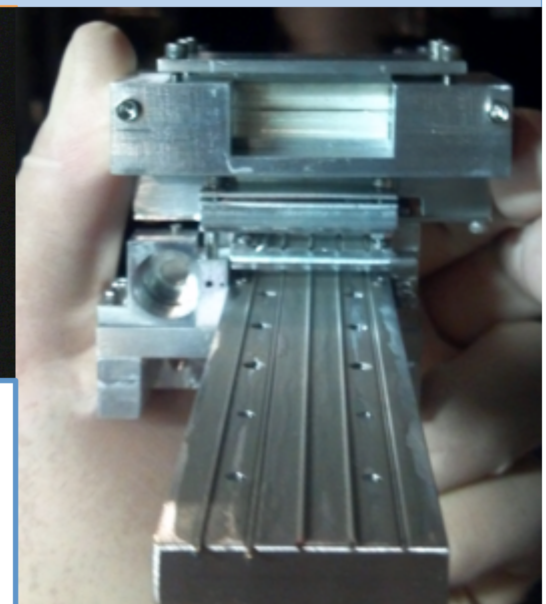


B. O'Shea, et al. Nat. Comm. 7, 12763 (2016)

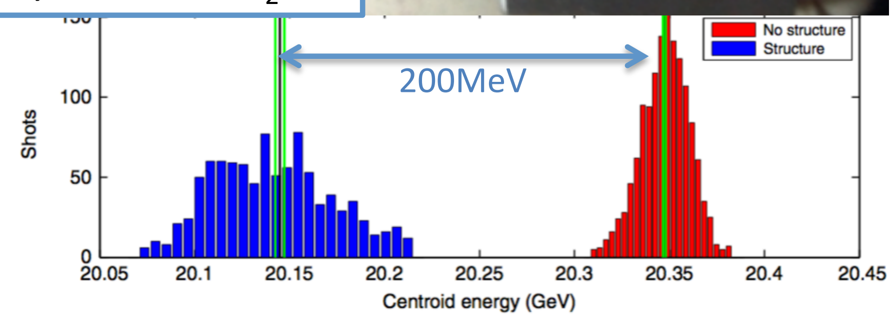
GV/m fields in DWA

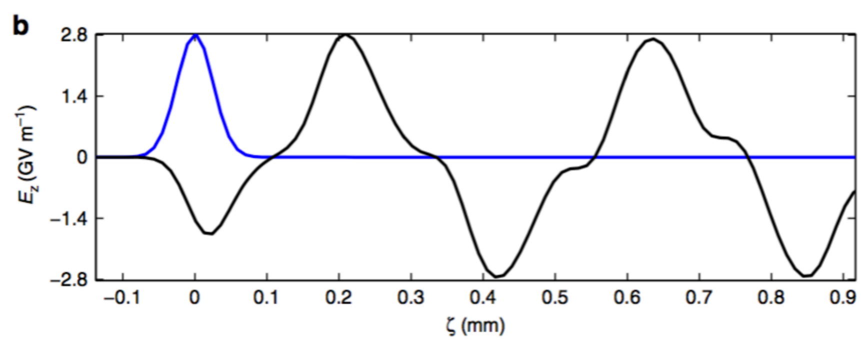
- High-fields with small ID structures
  - Compressed beam (<25μm)
  - High charge (3nC)
- Beam centroid data
  - Measured Energy loss of 200 MeV
  - 1.3 GeV/m deceleration
  - 2.6 GeV/m peak field
  - Strong agreement with PIC simulations
- Continuous operation of >28hours (>100k shots at 10 Hz rep)
- No signs of damage or performance deterioration

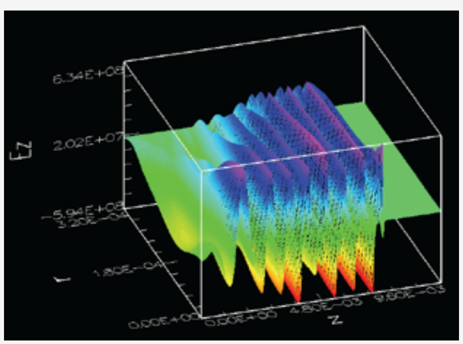




DWA structure:
- a/b = 150/200 μm
- L = 15cm
- Cylindrical, SiO_2

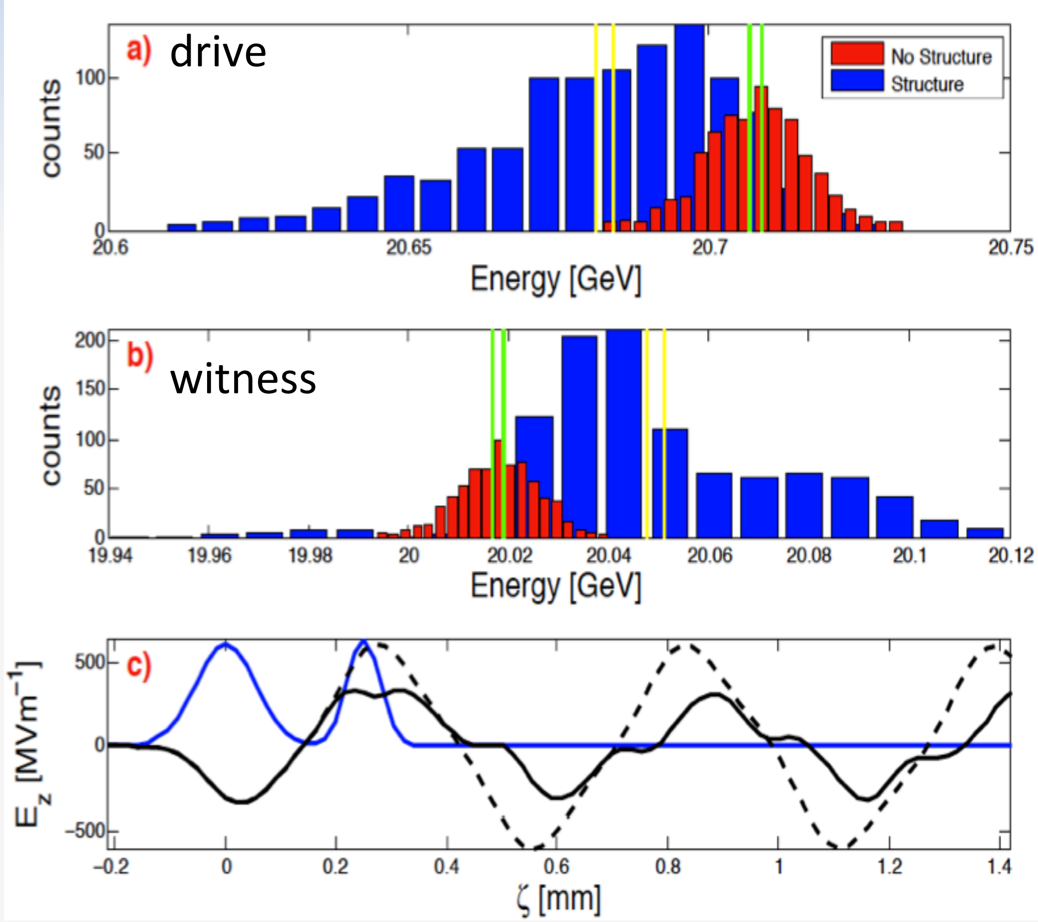






Acceleration of witness bunch

- 2-bunch modality
  - Notch collimator
  - Drive-witness spacing ~ $\lambda/2$ (250μm)
- Drive beam:
  - 1nC, σ_z=55μm
  - E_z ~ 300MeV/m
- Witness beam:
  - 500pC, σ_z = 30μm
  - Measured energy gain: 30 MeV
  - Agrees with theory

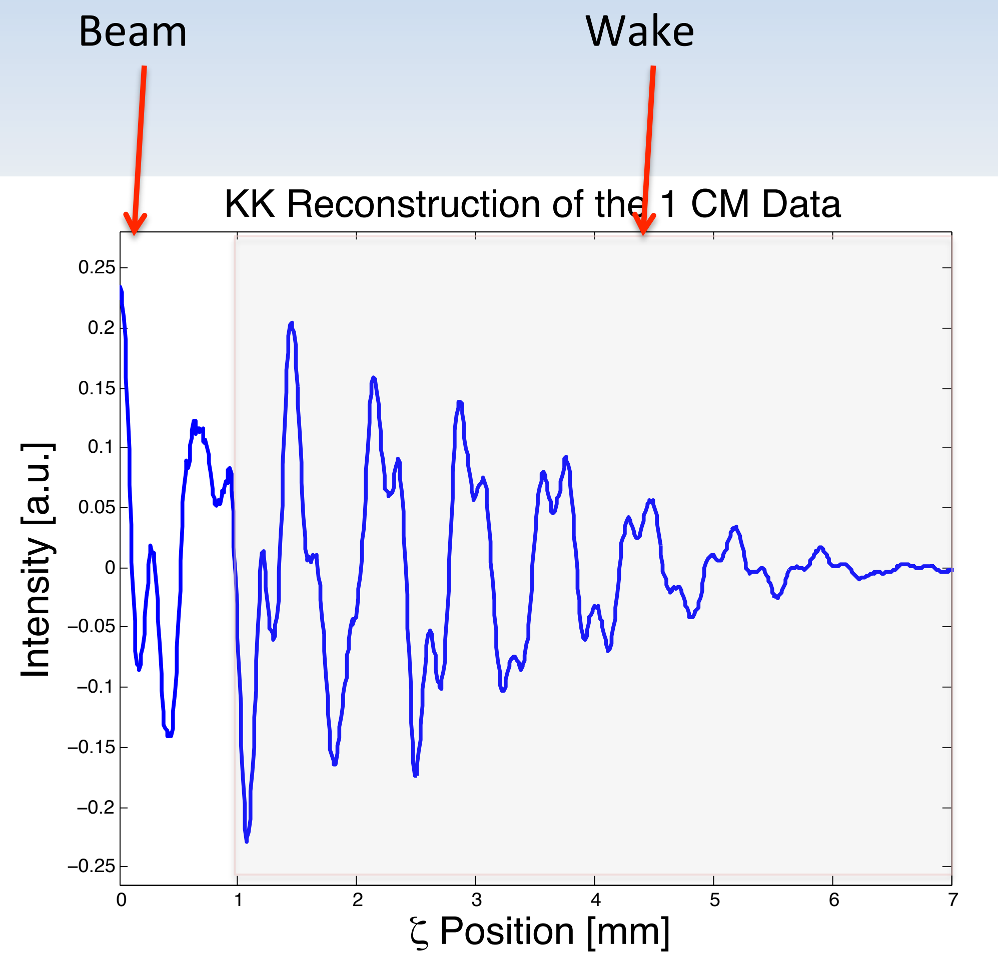


DWA structure:
- a/b = 200/280 μm
- TM01 = 560μm
- L = 10cm
- Cylindrical, SiO_2

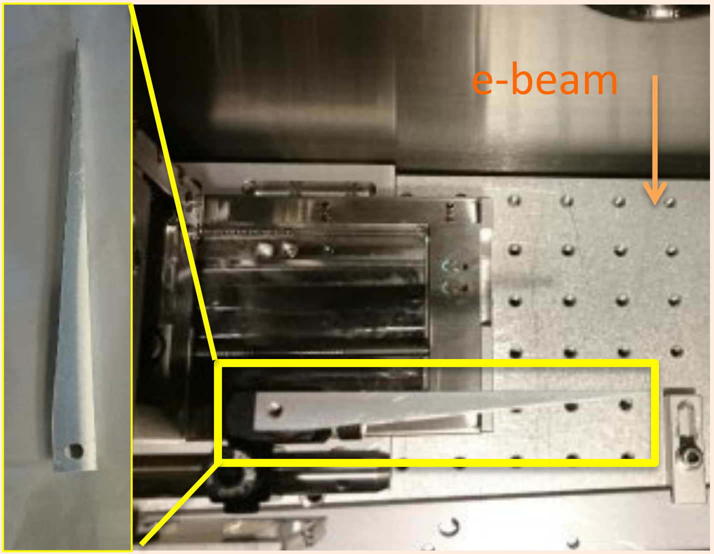
B. O'Shea, et al. Nat. Comm. 7, 12763 (2016)

Pulse train damping

- Strong damping observed in wakefield
  - L=1cm DWA should produce pulse train >2cm
    - $\tau_{pulse} = L/v_g\ (1 - v_g/\beta c)$
  - Longer structures did not produce linearly longer pulses
- Temporary conductivity introduced (reversible)
- Possible Mechanisms
  - Conduction band electrons from showers
  - High-field (GV/m) conductivity due to band distortions
- Use systematic studies to unfold details

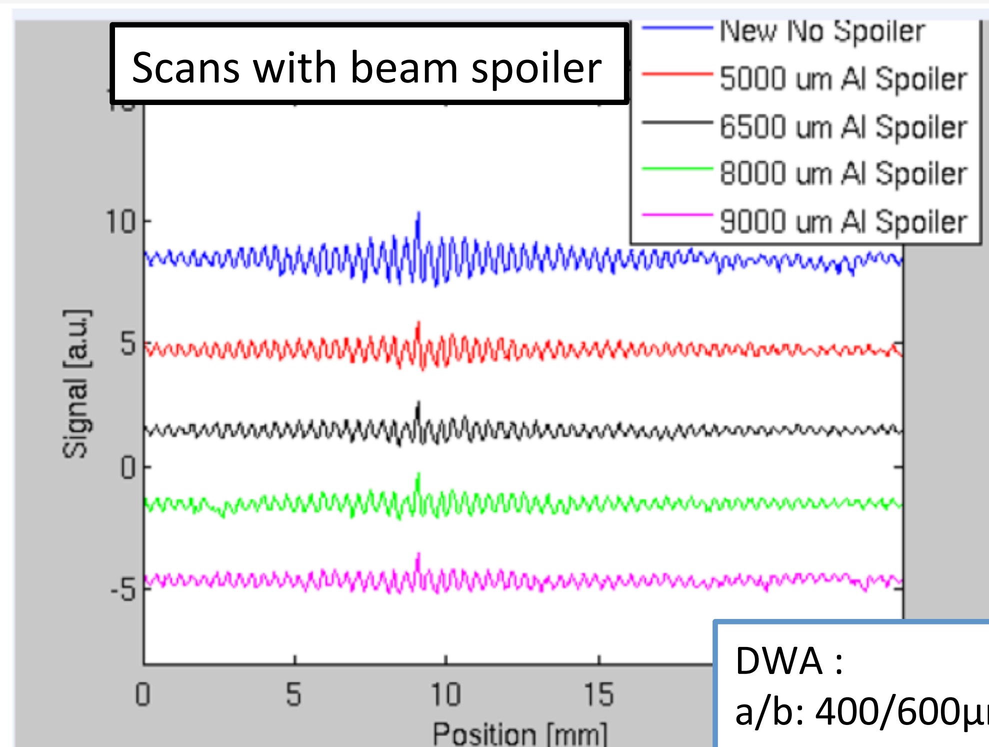


Pulse train damping: e^- shower



Aluminum wedge

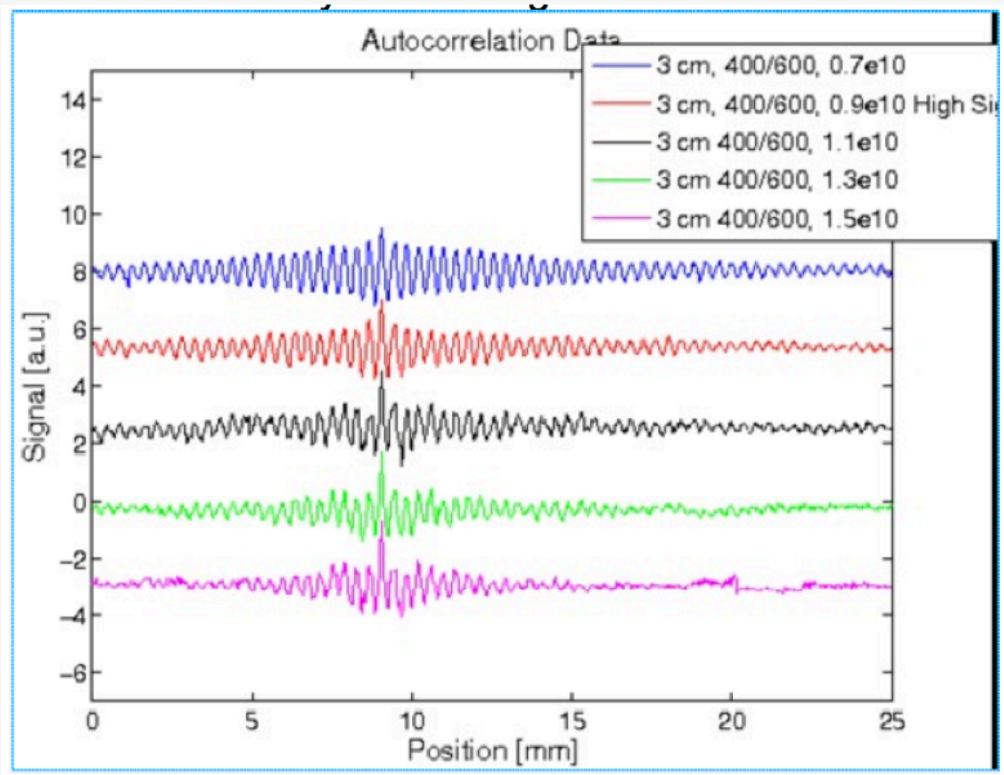
- 20 GeV e- striking upstream end of DWA tube
- Can produces significant EM cascade (shower)
- Goal: Investigate effects scattering on damping
- Spoiling wedge: Al (500µm-10mm)
- Practically no pulse damping observed

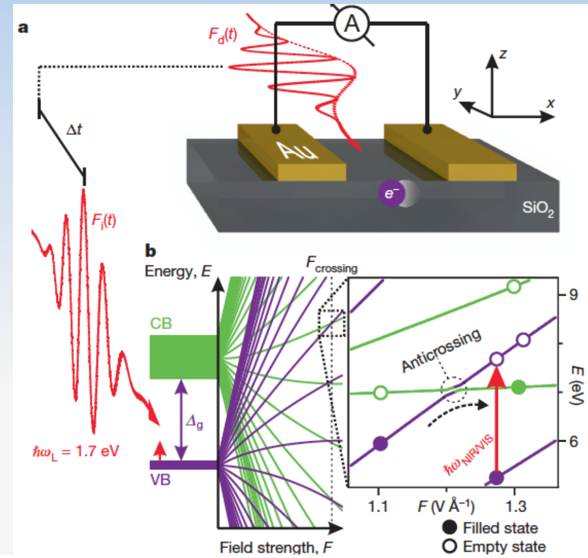


DWA :
a/b: 400/600µm
L=3cm
SiO2, Cylindrical

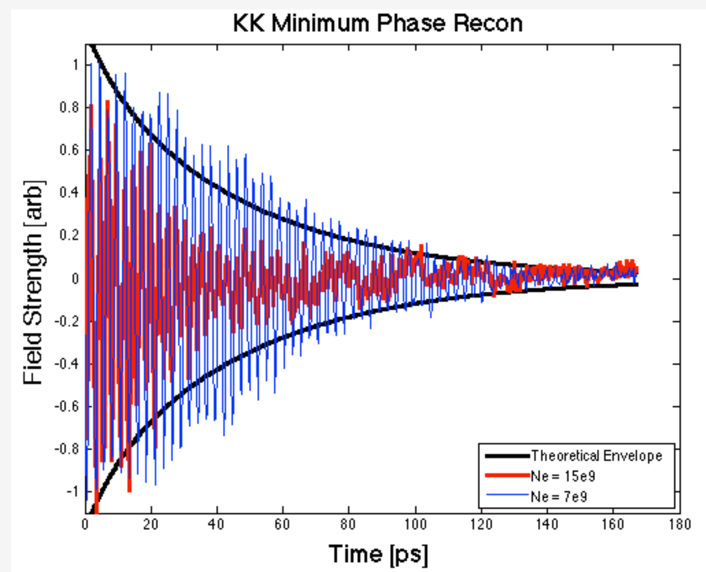
Pulse train damping: High-fields

- Goal: Dependence of damping on field strength
  - Systematic field scan (charge)
- Damping observed at high-fields
  - Onset ~750MV/m
- Similar to “Stark broadening” of bandgap recently observed in optical regime
- Evidence suggests semi-metallization of SiO2 @ THZ



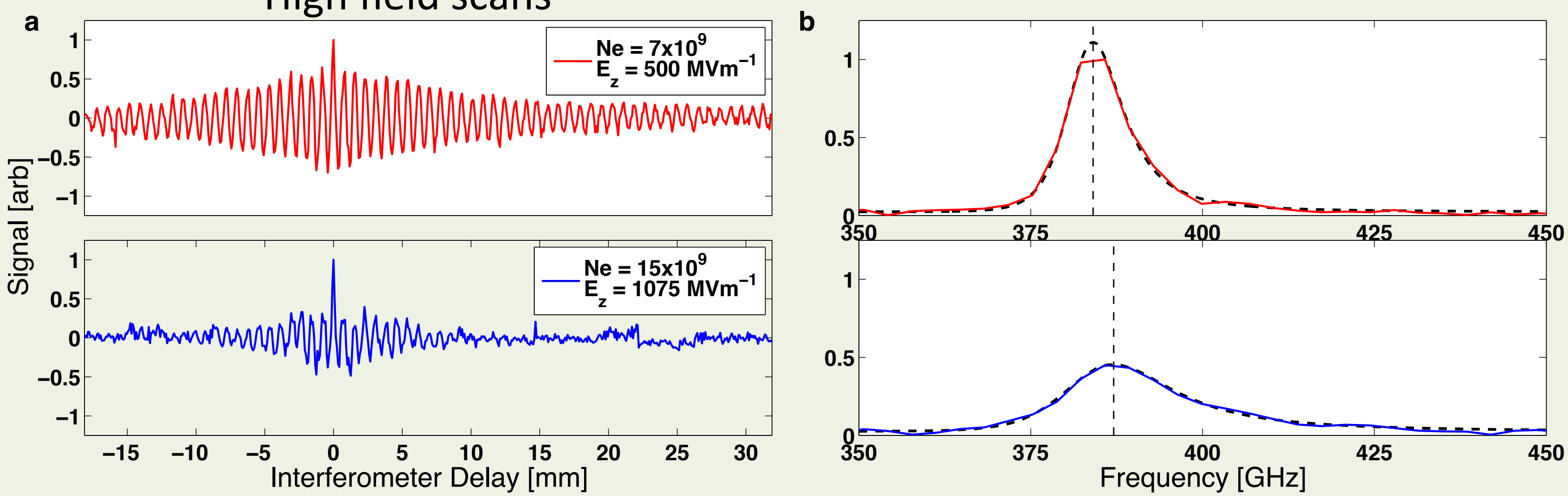


A. Schiffrin, et al., Nat. Lett. 493, 70 (2013)

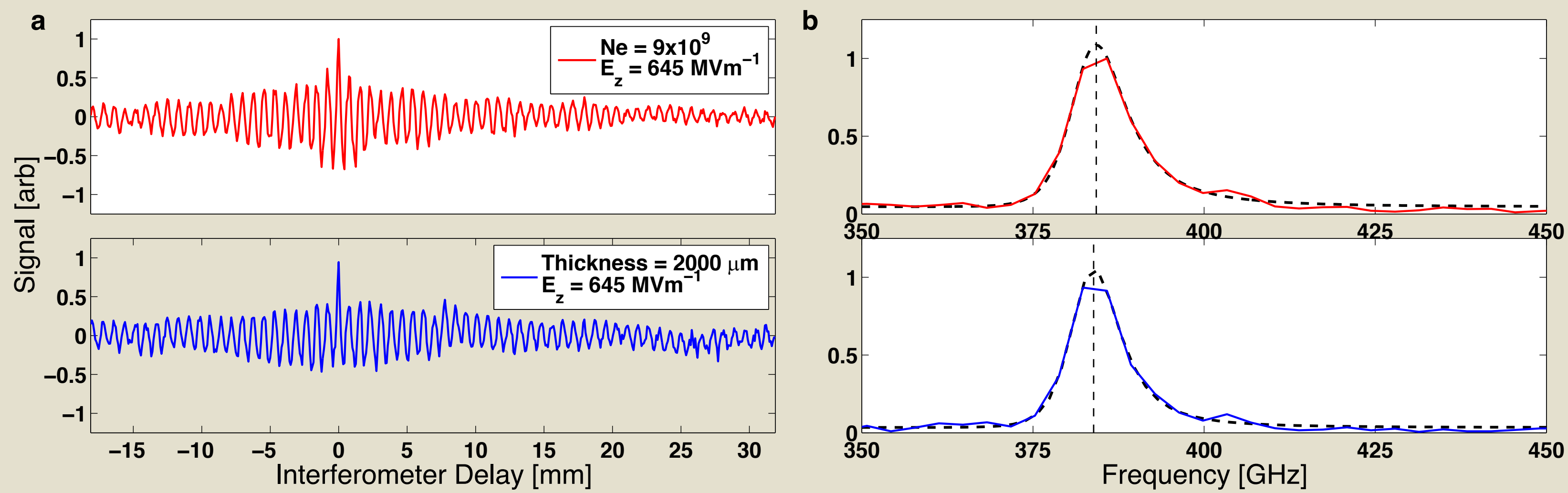


Side-by-side comparison

High field scans



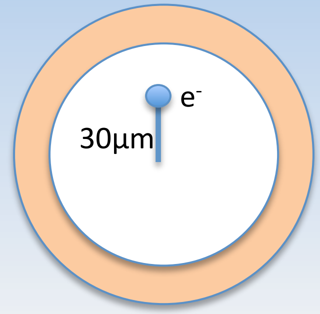
e⁻ shower scan

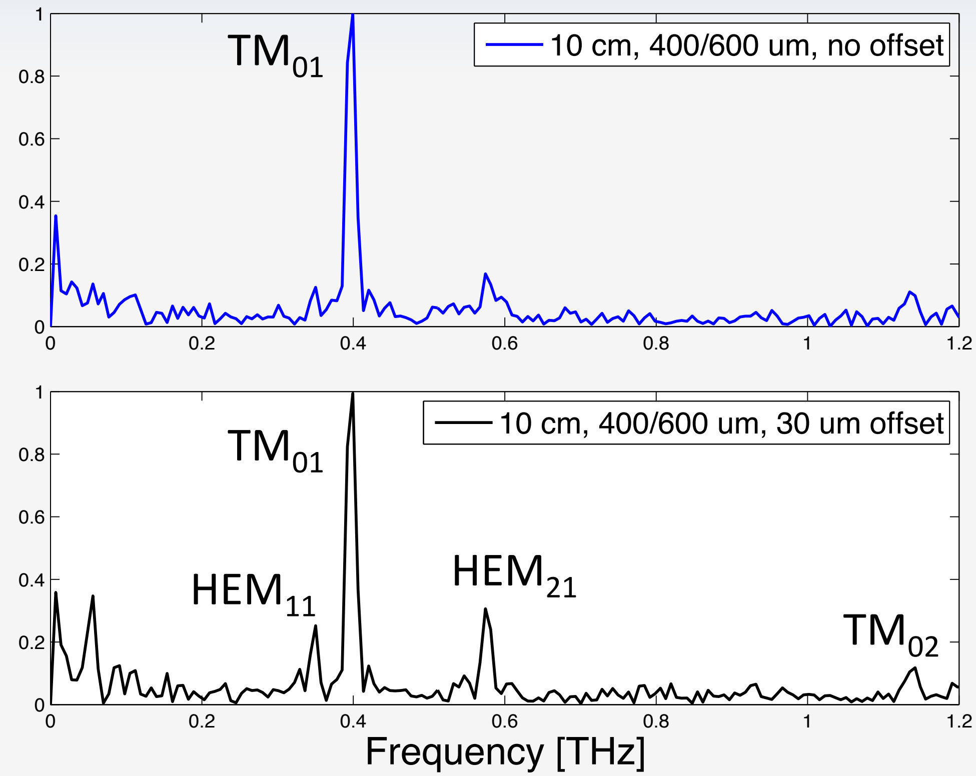


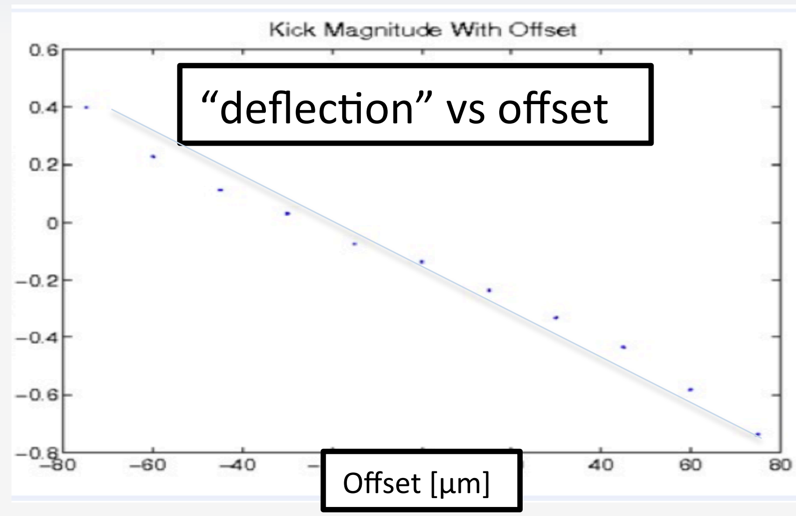
B. O'Shea, et al. in preparation Nat. Mat. 2019 ,(also EAAC 2017)

Deflection modes in cylindrical DWA

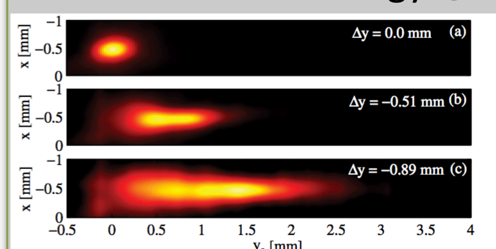
- Transverse modes can lead to beam break up in DWA
- Goal: study effects of deflection modes at FACET
- HEM modes seen in spectrum + integrated effect on screen







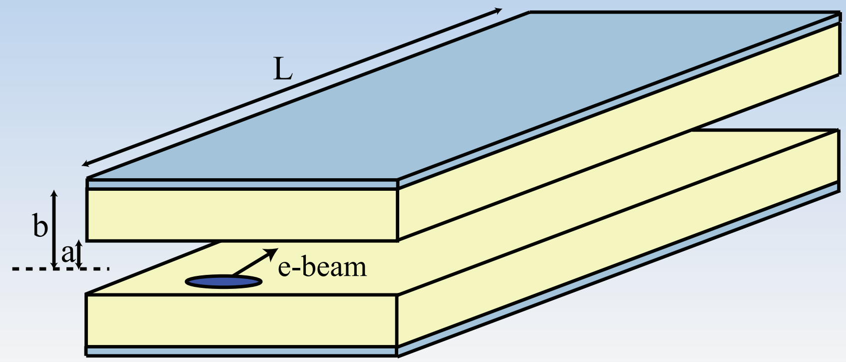
Observed at low energy @ PSI

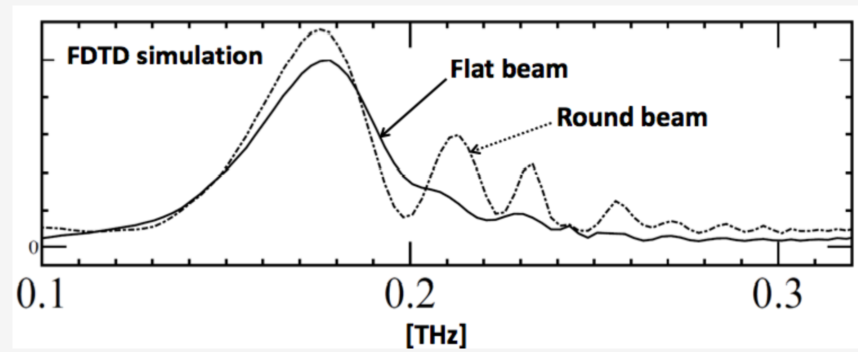


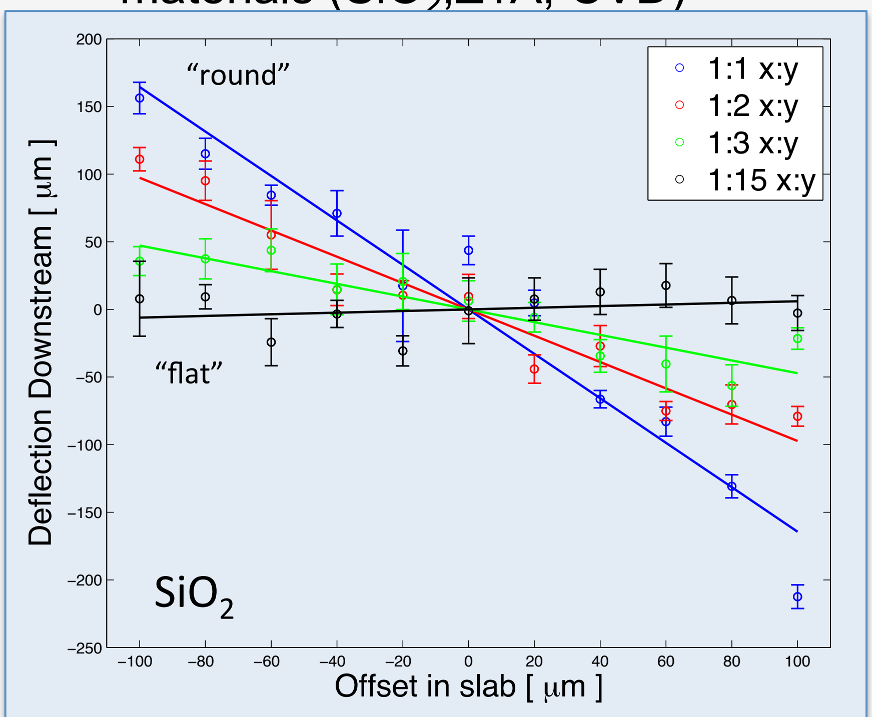
"Passive streaker" Bettoni, et al., PRAB 19, 021304 (2016)

Slab DWA with asymmetric beams

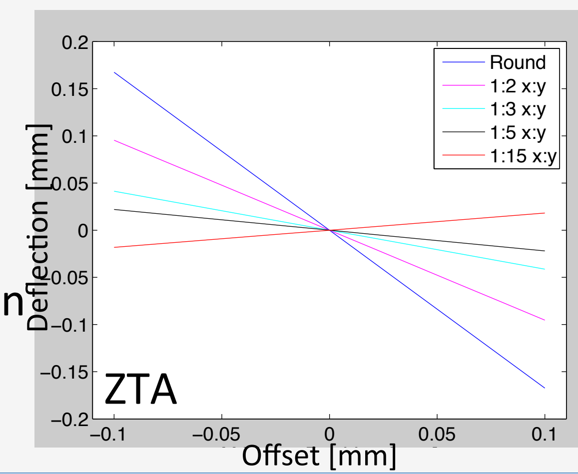
- Slab geometry with elliptical beams can mitigate effects of deflection modes
  - A. Tremaine, et al. PRE 56, 7204 (1997)
- Goal: Study effects of beam aspect ratio in slab structures
- Suppression of effects from transverse wakes
- Reproducible results across different materials (SiO_2,ZTA, CVD)





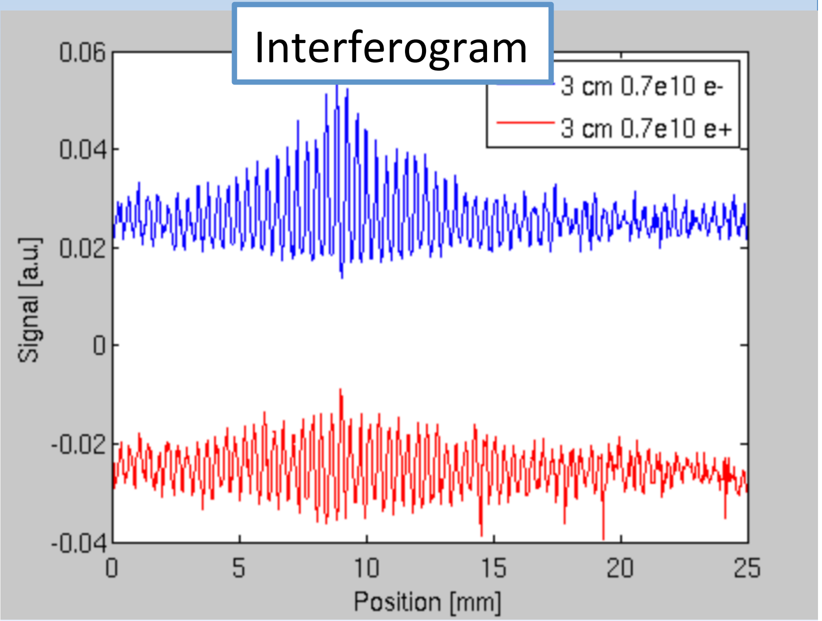


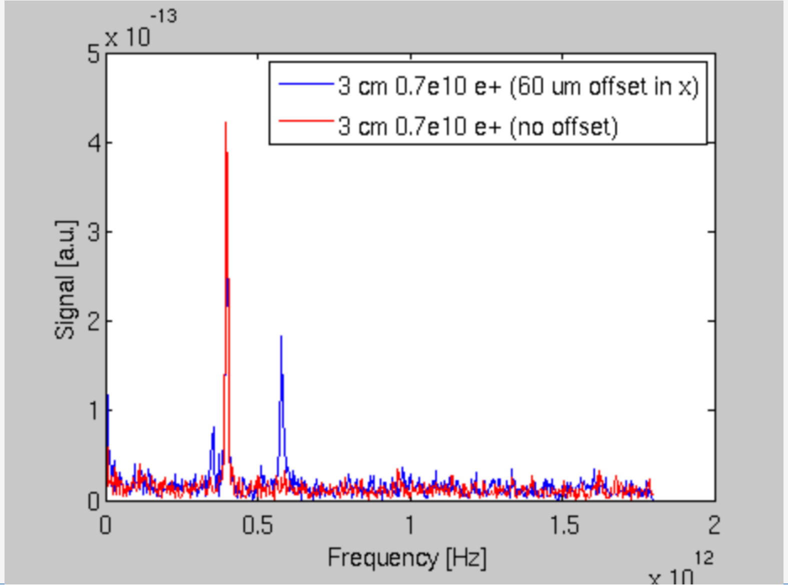
Beam Off-axis injection vs observed "kick"



Positron driven DWA

- Positron beam at FACET
- Comparison to e-beam DWA with similar parameters
  - $\sigma_z \sim 40\mu m$
  - $\sigma_x = \sigma_y \sim 40\mu m$
- Similar behavior to e^- driven DWA, as expected





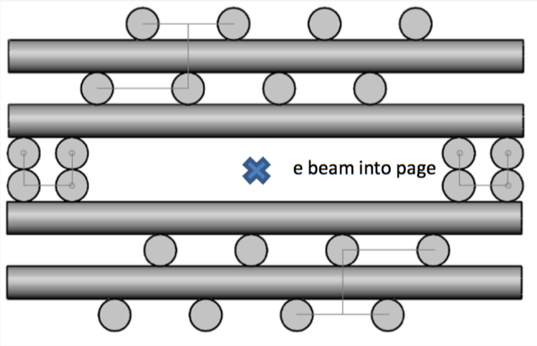
Frequency content:
Coupling observed to HEM-modes
for off-axis injection

FACET-II: DWA Program

- Use successes and lessons learned from FACET E201 and unique capabilities of FACET-II to address relevant issues in DWA

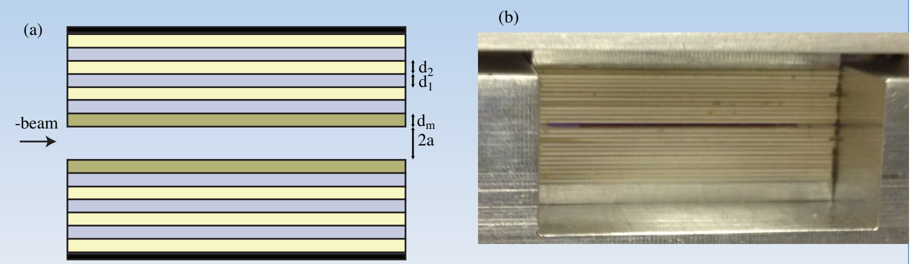
- Studies at FACET-II
  - FACET: GV/m fields, but damping effects
    - New materials
    - Photonic structures (field exclusion)
  - FACET: Transverse mode coupling, can lead to BBU effects
    - Structure modal content: control and confinement
    - High aspect ratio beams with photonic structure driving GV/m fields

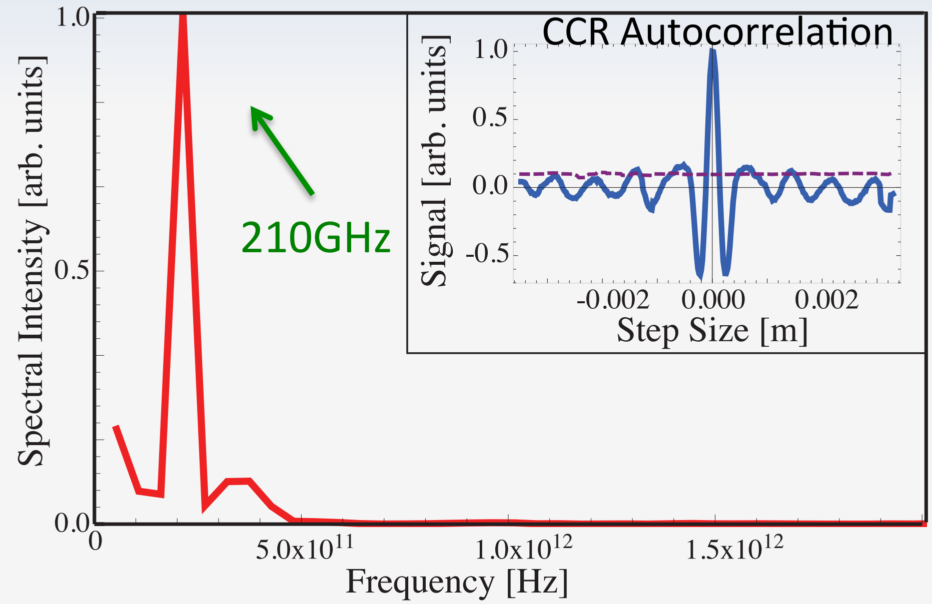
Field control through “designer” photonic structures in full 3D



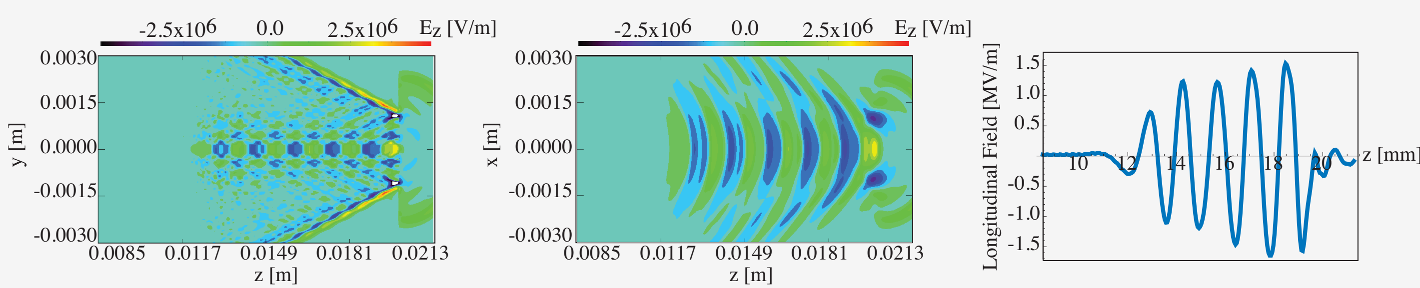
Bragg-boundary DWA

- Demonstration at “low” fields
- Goal: Eliminate metal cladding in DWA
- Modal confinement
  - Alternating dielectric layers
  - Constructive interference
- Bragg-reflector structure
  - SiO_2 matching layer
  - Bragg layers SiO2, ZTA
  - Assembled at UCLA
- BNL ATF experiment
  - 50MeV, 100pC, $\sigma t \sim 1ps$
  - Agreement with theory/ simulation



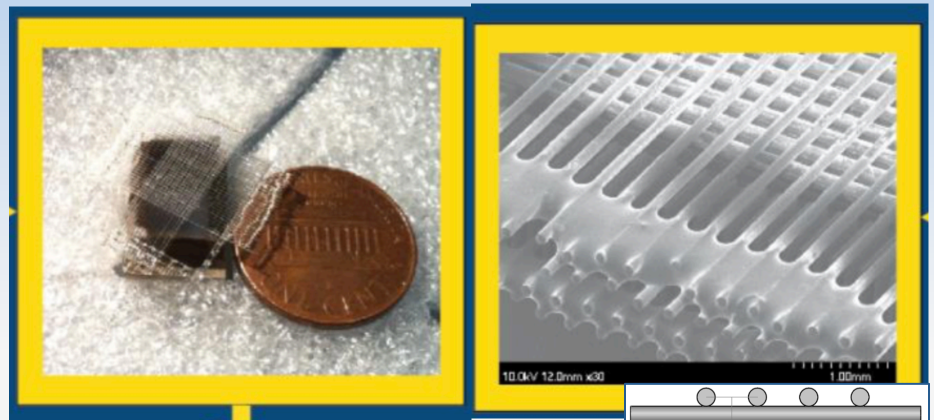


G. Andonian, et al., PRL 113, 264801 (2014)

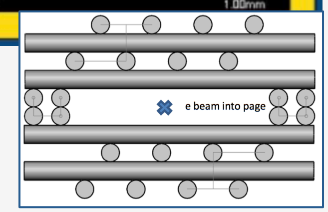


DWA with Woodpile geometry

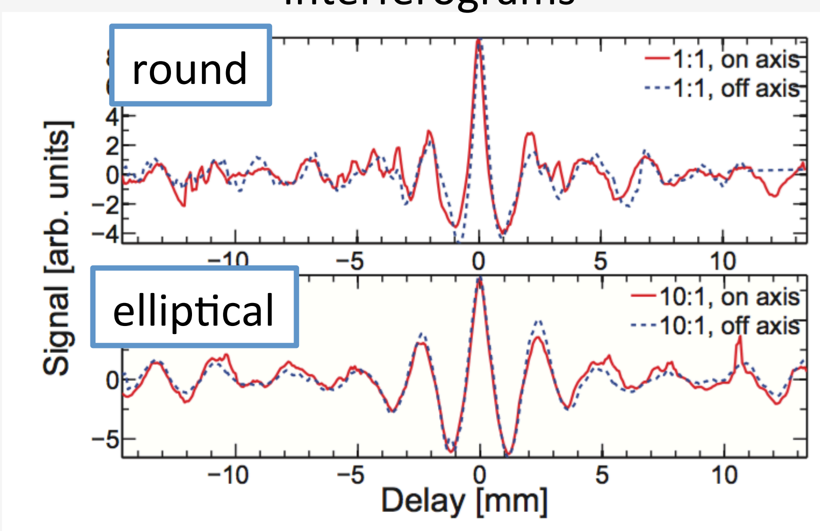
- Build off Bragg DWA results
  - 3D “photonic-like” structure
  - Precision control of spatial modes
  - Familiar from DLA
  - Extend to beam driven DWA using established methods
- Experiment at BNL ATF
  - CCR spectral characterization
  - agreement with simulations



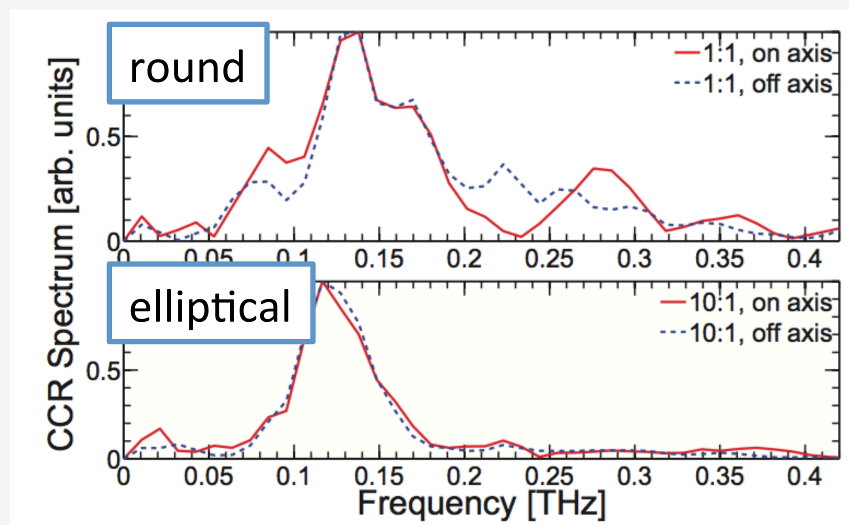
125μm x 2cm sapphire rods



Interferograms



FFT

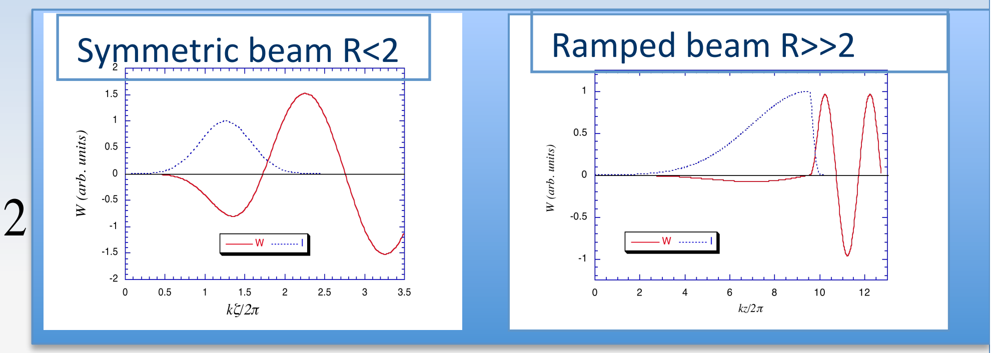


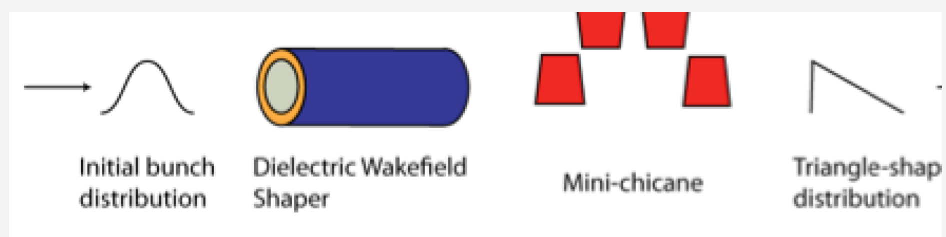
P. Hoang et al., submitted Phys. Rev. 2017

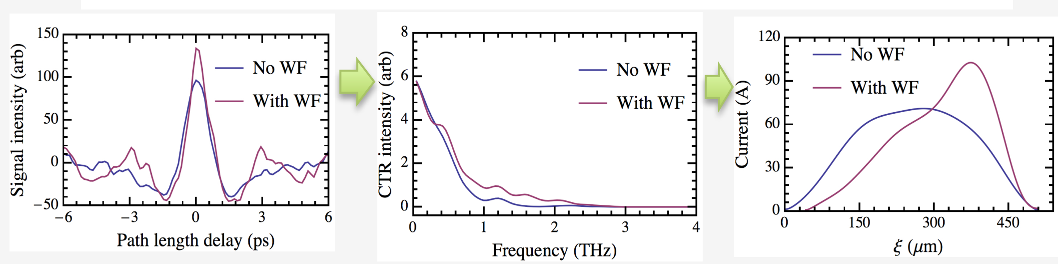
Pulse shaping: High Transformer Ratios

- TR enhancement from ramped beams
  - Triangle distribution
  - Novel: doorstep, double triangles
- Techniques:
  - EEX, laser shaping, mask in dispersive section, shaping with self-wakes
- Shaping capabilities essential for TR studies

$$R = \frac{E_{z,acc}}{E_{z,dec}} \leq 2$$



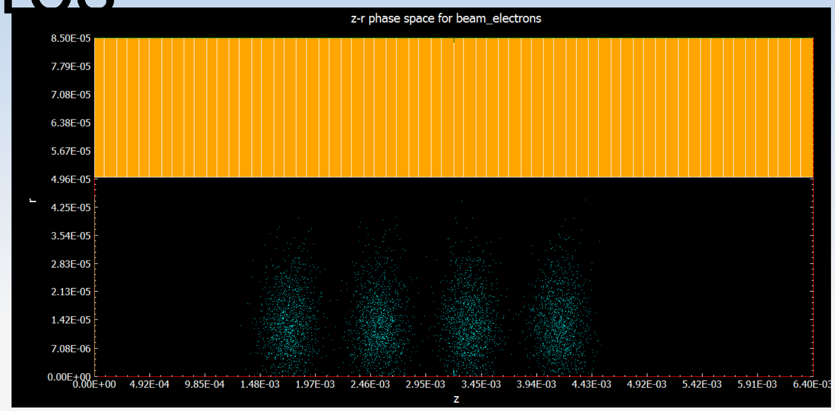




G. Andonian, et al., PRL 118, 054802 (2017)

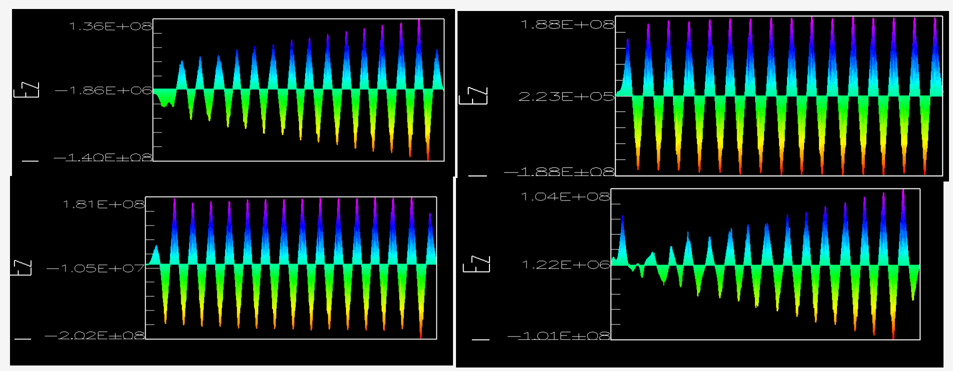
Pulse trains + Longitudinally periodic structures

- Motivation:
  - Confine energy of mode inside structure
  - Near zero group velocity
  - Longitudinal periodicity - ε(z)
- OOPIC and HFSS Simulations
  - a = 50 μm, b = 126 μm
  - Periodicity = 300 μm
  - Used both sinusoidal variance of ε and step
  - Base materials SiO2, diamond (ε=3.8, 10.6)
- 500 GHz structure
  - Mode confinement

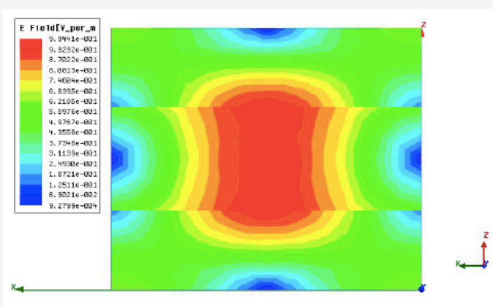


Excite mode with 4-pulse train - OOPIC

DWA with horn antenna



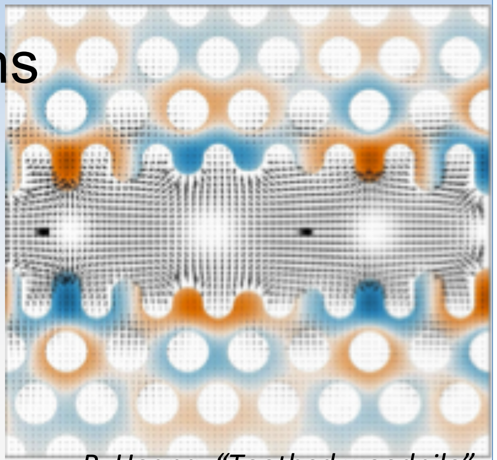
Standing wave structure seen in sims after beam has passed through structure (OOPIC)



Mode confinement of Ez (HFSS)

J. B. Rosenzweig, G. Andonian, D. Stratakis, X. Wei

Summary and Outlook


P. Hoang, "Toothed woodpile"

- DWA already useful tool for accelerator applications
  - THz source
  - Phase space manipulations (shaping, bunching, chirp)
  - Diagnostic tool ("passive streaker")
- FACET GV/m results opened new questions
  - Wakefield damping
  - BBU control
  - Photonics and new materials
- FACET-II holds promise for advanced DWA program
  - High quality bunches to test long structures, staging
  - Bunch shaping, trains, drive/witness beam
  - High aspect ratio beams
  - "Designer" structures for field exclusion, modal confinement

E-201 Team:
UCLA: G. Andonian, S. Barber (LBNL), A. Fukusawa, P. Hoang, B. Naranjo, O. Williams, J. Rosenzweig, et al.
SLAC FACET: B. O'Shea, C. Clarke, M. Hogan, V. Yakimenko, et al.
Work Supported by US DOE HEP