Advanced Dielectric Wakefield Accelerator Structures

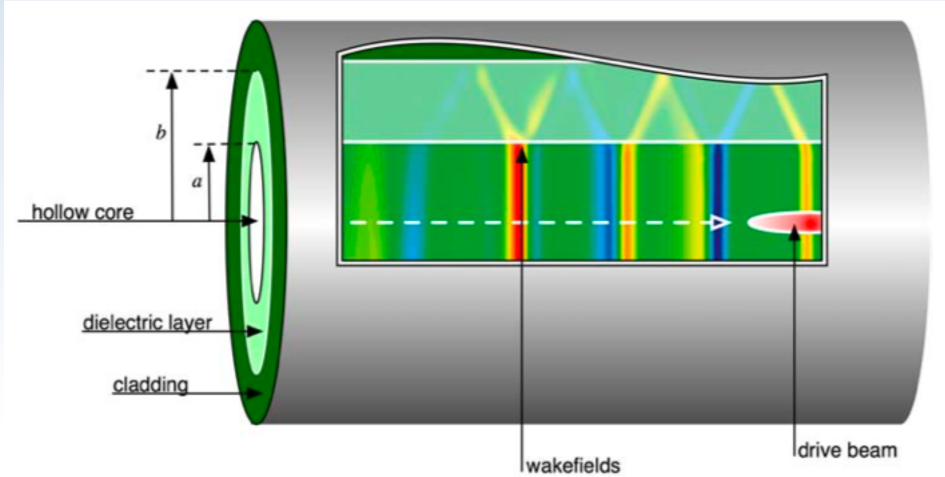
G. Andonian
May 10, 2018
FAST/IOTA Collaboration Meeting
Fermilab

Outline

- DWA background
- Relevant Issues & research directions
- Advanced structures & applications
  - Bragg boundary
  - Planar geometry
  - Woodpile
  - Beam phase space manipulations
- Conclusion

Dielectric Wakefield Accelerator

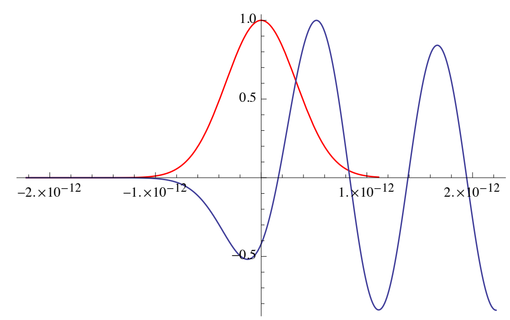
- Candidate for next-gen adv. Accelerator (GV/m field)
- Simple geometry
- Relativistic beam drives wake in material
- Dependent on structure geometry
- Present day beams naturally scale to sub-mm (THz) structures



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 $$f_{01} = \frac{c}{2\pi}\sqrt{\frac{2\epsilon}{(\epsilon-1)a\,(b-a)}}$$



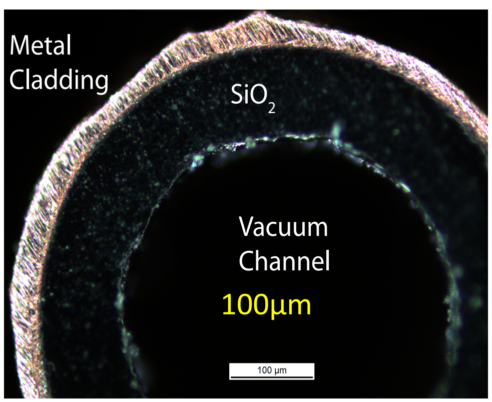
On-axis Ez
(single mode structure)

DWA Applications & Research

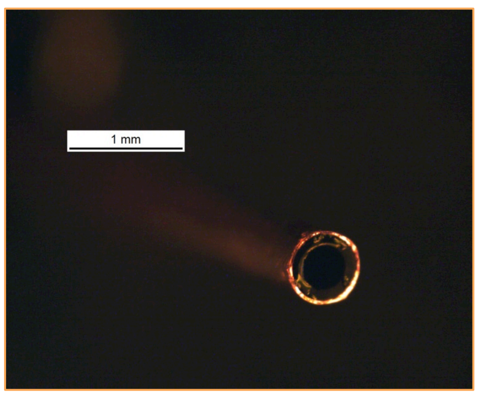
- High gradient applications
  - HEP: future machine (GV/m fields)
    - Thompson PRL 100, 214801 (2008)
    - O'Shea Nat Comm 7, 12763 (2016)
  - Light Source
    - A. Zholents Proc FEL14, 993 (2014)
  - Phase Space manipulation
  - Relativistic e-beam diagnostics
  - THz source
- Relevant Research Issues
  - Practically achievable field gradients
    - Breakdown & High field damping
    - Joule heating at high rep rate
  - Beam break up – transverse modes
  - Efficiency, TR
  - Materials/cladding composition
  - Alternate geometries (slab, woodpile)

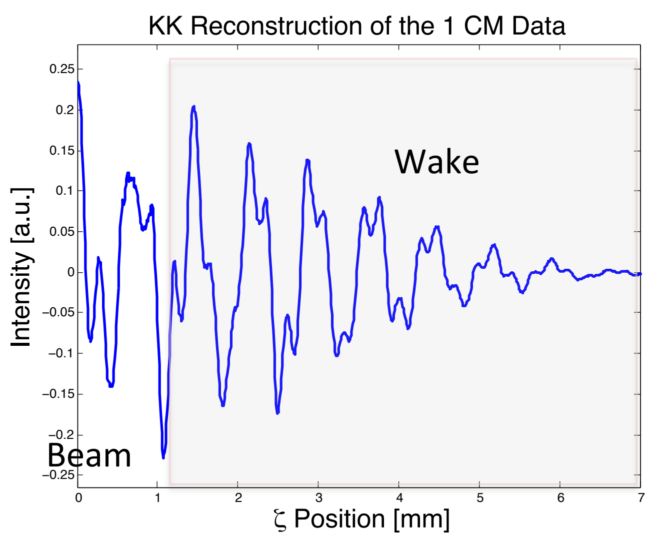
Recent High gradient DWA results

- High field DWA demonstrated (>GV/m) at SLAC FACET
  - 3nC, σz=20μm
  - Cylindrical geometry
  - In long (>15 cm) structures
  - Damping effects (reversible) before reaching breakdown due to high field
- Motivation to explore alternative geometry



O'Shea Nat Comm 7, 12763 (2016)

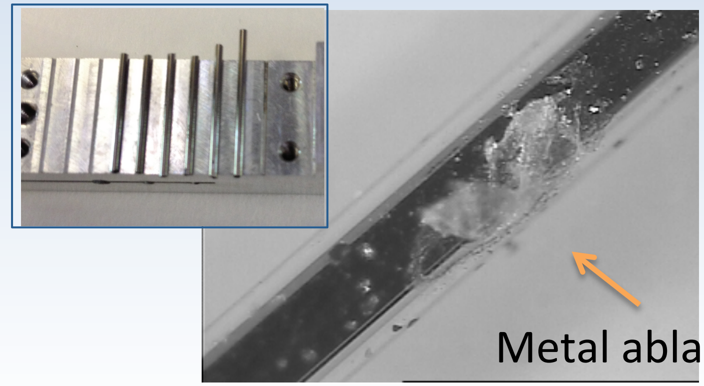




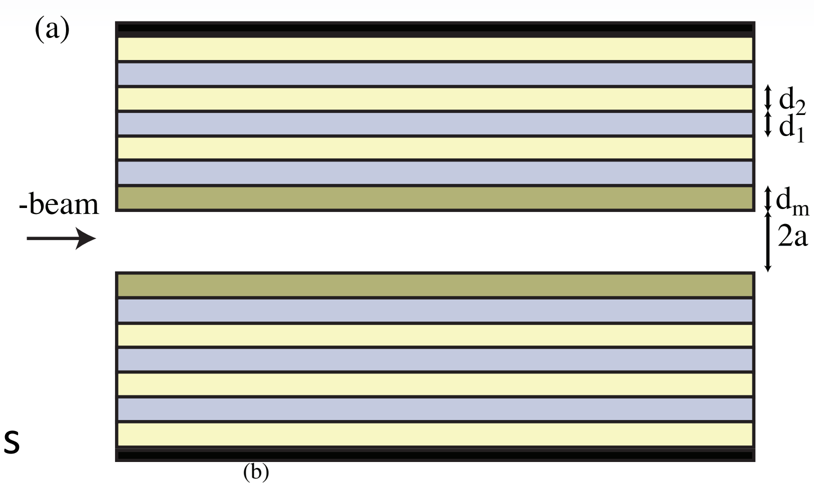
Bragg boundary DWA

- Motivation:
  - Metal ablation at high fields in first tests
  - Explore alternate geometry with no metal
- Concept:
  - Bragg arrays
  - Alternating multilayer stack (high/low ε)
  - Constructive interference
  - Modal confinement in channel

- Test at BNL ATF
- Bragg DWA
  - SiO_2 (ε=3.8) matching layer
  - Bragg layers: SiO_2, ZTA (ε=10.6), 12 periods
  - L = 1cm
  - Gap = 240 µm



Metal ablation



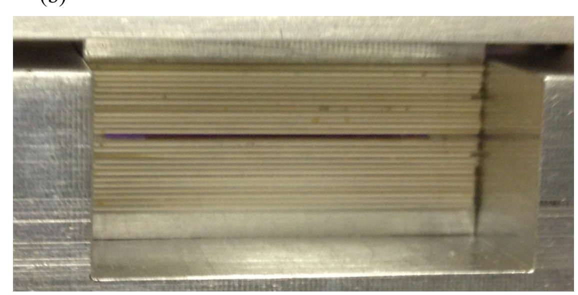
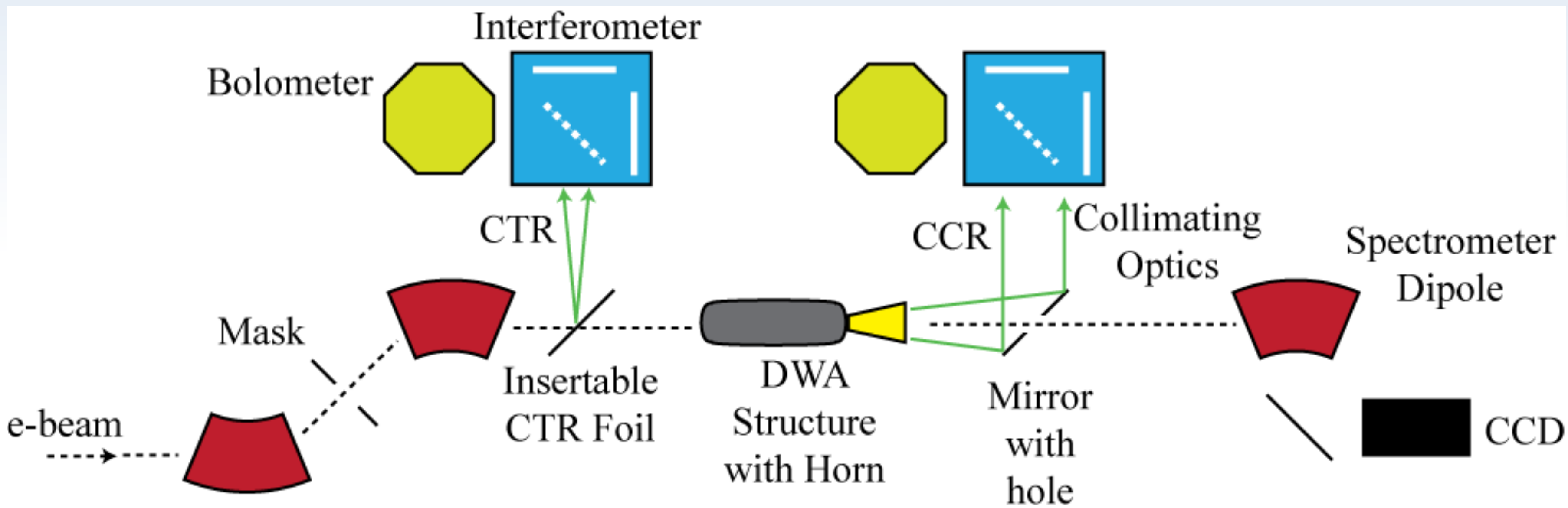


Photo of Bragg array

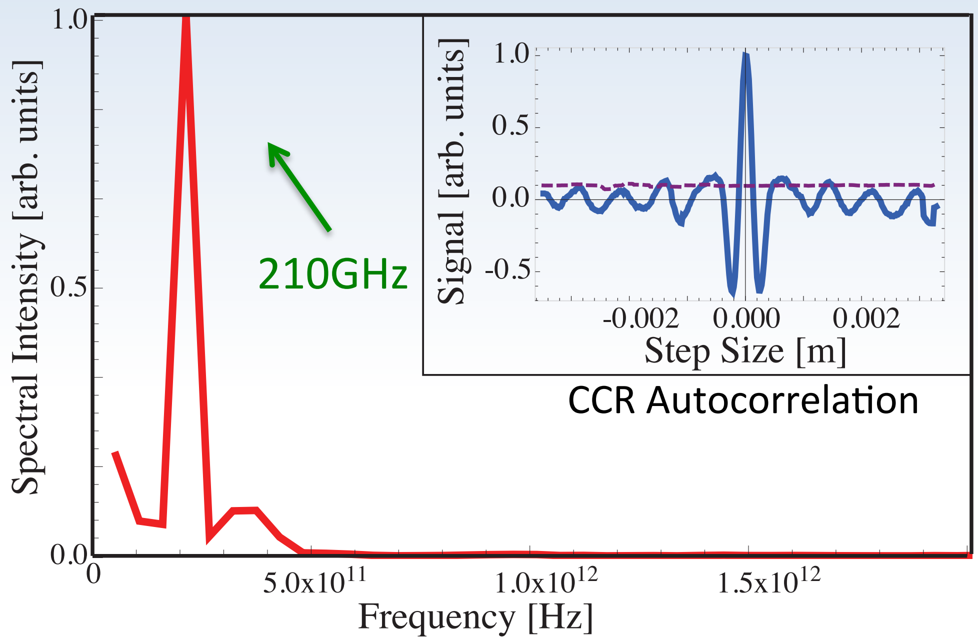
BNL ATF experimental layout



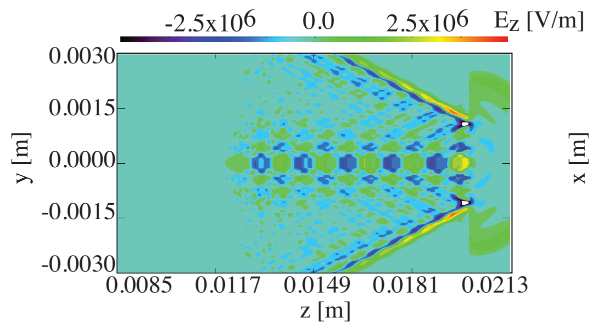
- CTR interferometer for bunch length/profile reconstruction
- CCR interferometer for spectral characterization
- Out-coupling antenna
- Dipole spectrometer for energy modulation
- Similar setup to FACET experiments and techniques can be used at FAST

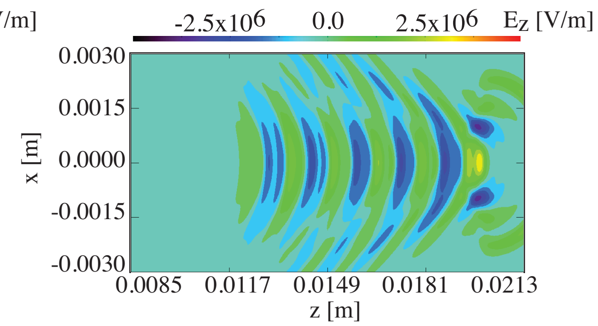
Bragg-boundary DWA

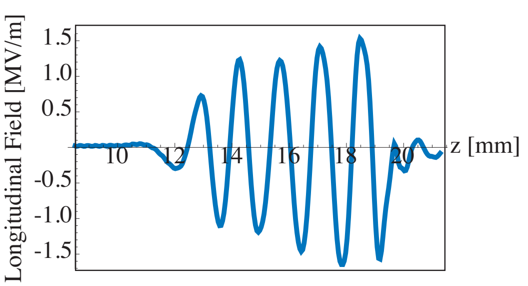
- Experiment:
  - Characterize structure modes
- BNL ATF experiment
  - 57MeV, 100pC, σt~1ps
  - CCR spectral analysis
  - Reconstruction algorithm
  - Energy modulation measured
  - Agreement with theory/ simulation (3D Vorpal, CST)
- Results:
  - Bragg reflector performance
  - Modal purity for THz source apps



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



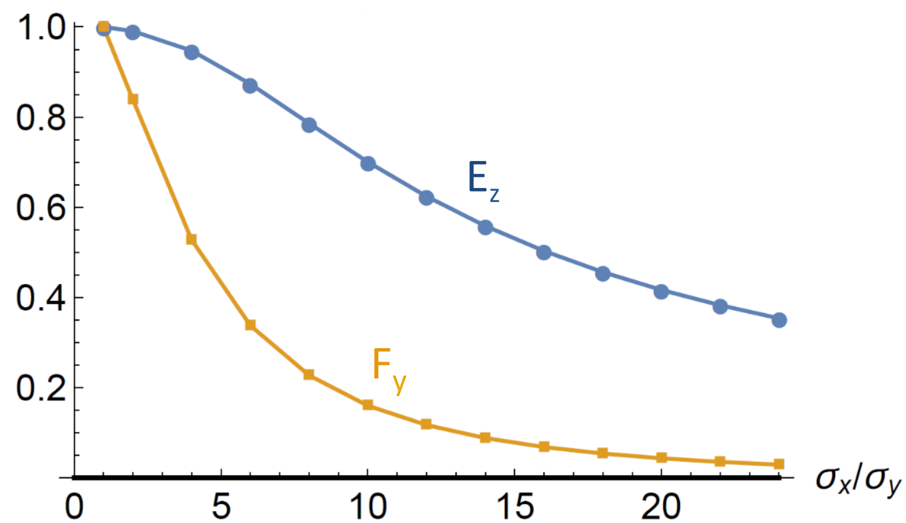




Beam Break up

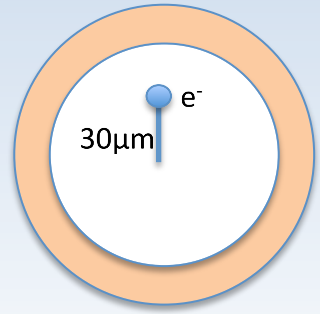
- DWA can sustain GV/m for future machine, but may be limited by BBU
- BBU stems from growth of transverse modes
- Suggested to use external FODO channel
  - C. Li *et al.*, PRSTAB 17, 091302 (2014)
- Suggested to use flat beams with planar structures to mitigate the effect
  - A. Tremaine *et al.*, PRE 56, 7204 (1997)
  - D. Mihalcea *et al.*, PRSTAB 15, 081304 (2012)
  - S. Baturin in prep (2018)

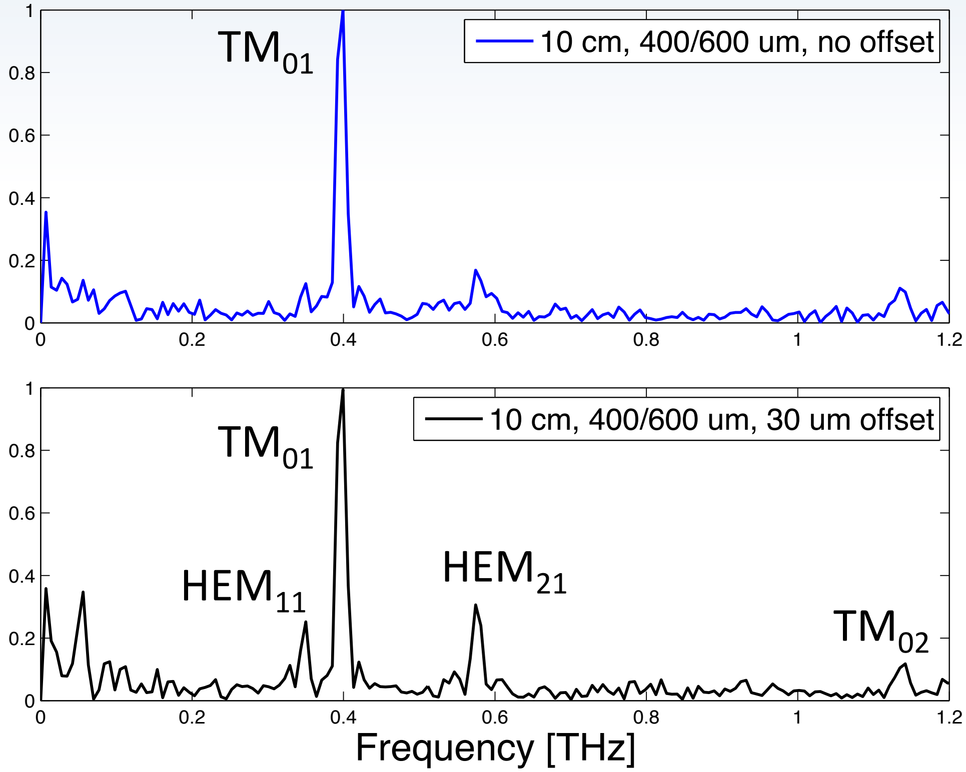
"Trade-off" curves as function of beam ellipticity

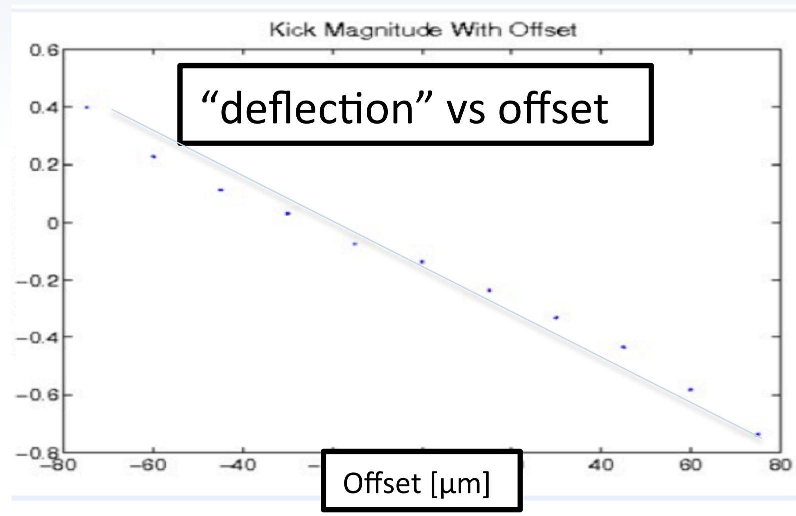


Deflection modes in cylindrical DWA

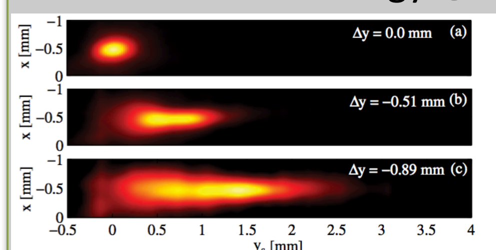
- Experiment to study effects of deflection modes at SLAC FACET
- HEM modes seen in spectrum + integrated effect on screen (“kick”)







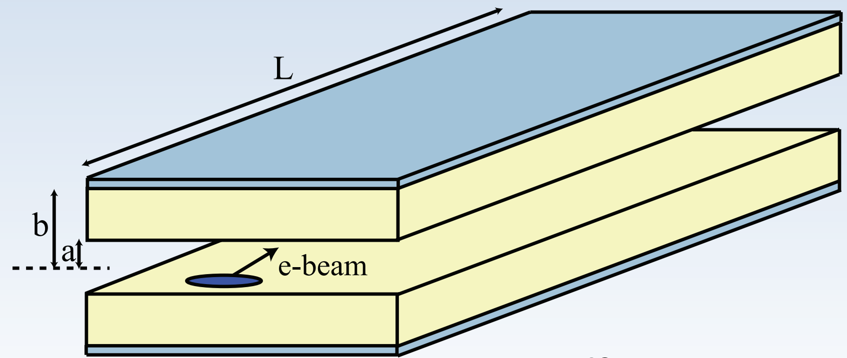
Observed at low energy @ PSI



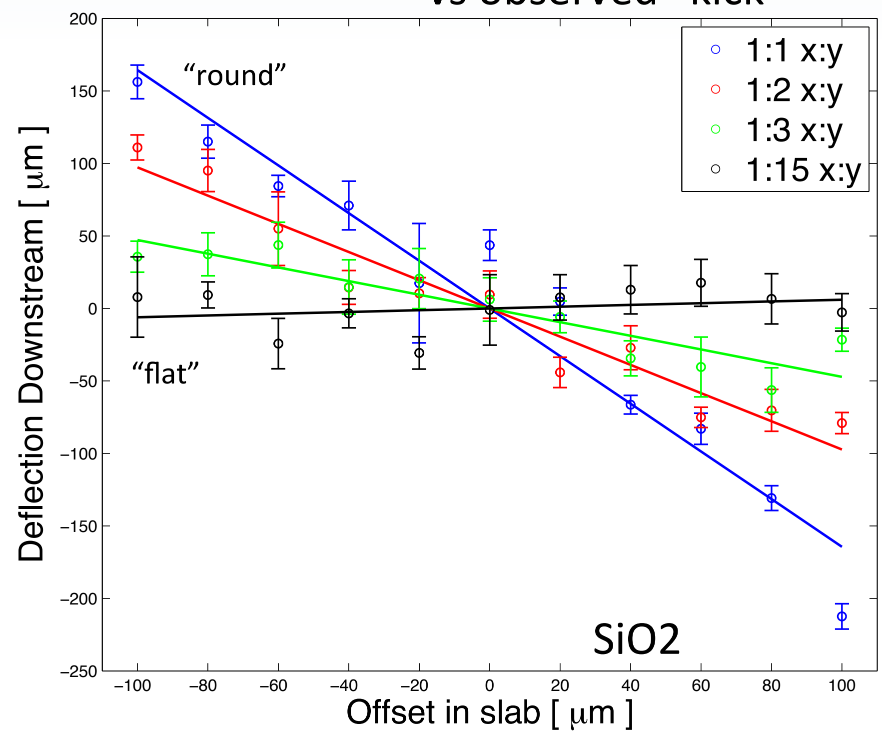
“Passive streaker” Bettoni, et al., PRAB 19, 021304 (2016)

Slab DWA with asymmetric beams

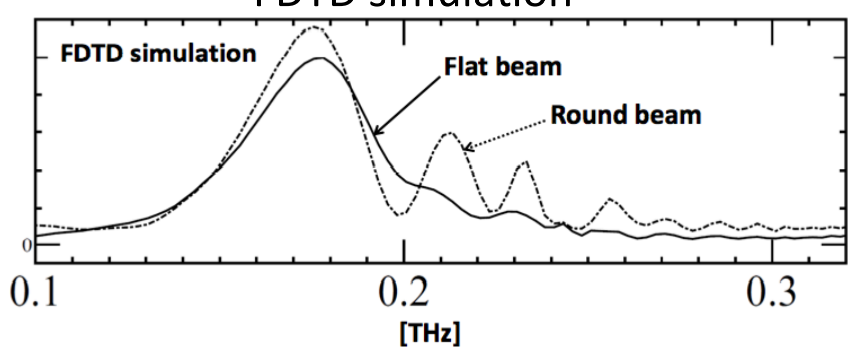
- Experiment:
  - Drive slab geometry with elliptical beams
  - measure effects of deflection modes
- Reproducible results across different materials (SiO_2,ZTA, CVD)
- Results: Suppression of effects from transverse wakes for flat beams



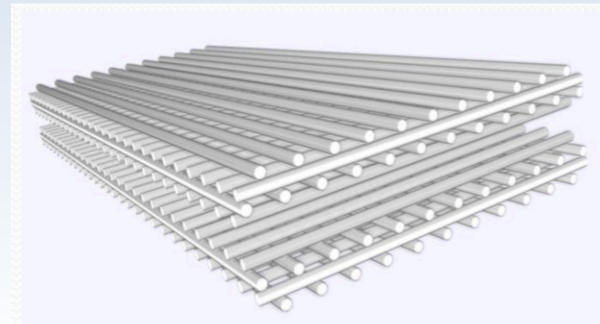
Beam Off-axis injection vs observed "kick"



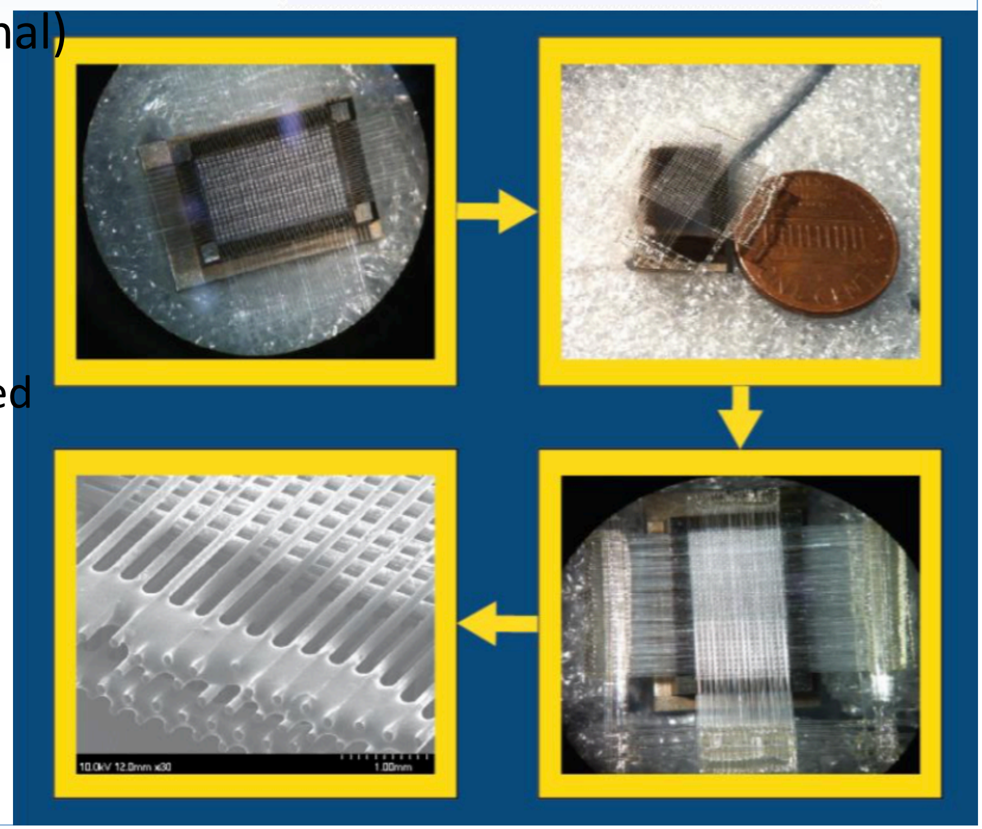
FDTD simulation



Advanced DWA Structure: woodpile

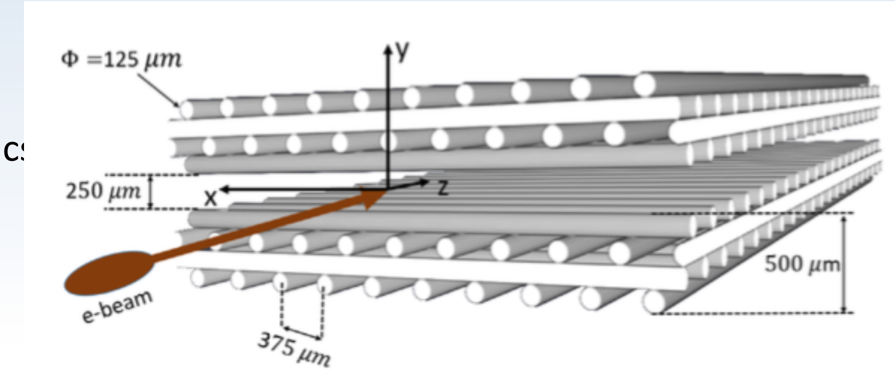


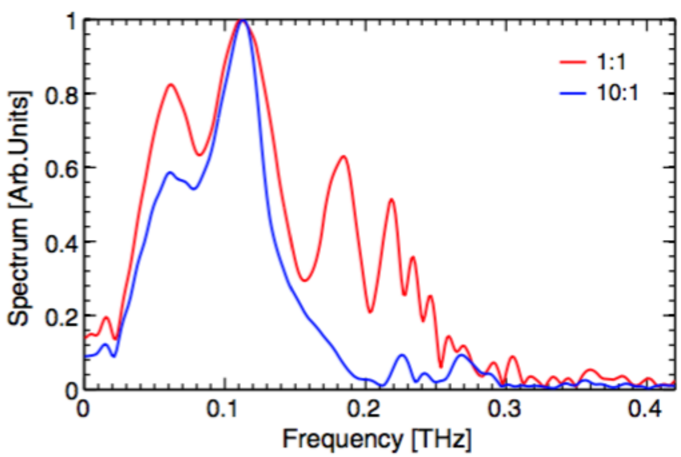
- Build off Bragg and slab results
  - Advanced DWA structures
  - No metals (excessive dissipation into heat)
- Tailor spectrum for reduced coupling to transverse modes (enhance longitudinal)
- Familiar from DLA
  - Extend to DWA
- Engineer spectral content
  - 3D-periodicity gives more control
  - Modes, v_g, ratios
  - Excited modes in bandgap are confined
- Woodpile assembled at UCLA
  - For experiment at BNL ATF
  - 125µm Sapphire rods x 2cm
  - by hand (P. Hoang)



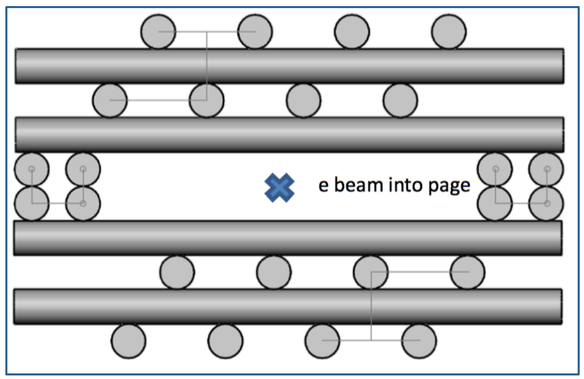
Woodpile simulations

- Woodpile parameters
  - 125µm x 2cm sapphire rods
  - 375µm periodicity in x, and z
  - 250µm gap
  - Single period structure to understand dynamics
- BNL ATF Beam parameters
  - 57 Mev, ε_N =2 mm-mrad, σ_z = 250µm
  - "round beam": 50:50 µm, 150 pC
  - "elliptical beam" 50: 500 µm, 235 pC
- Many modes in spectra for round beam
  - Boundary conditions require computation
  - Flat beam shows only fundamental





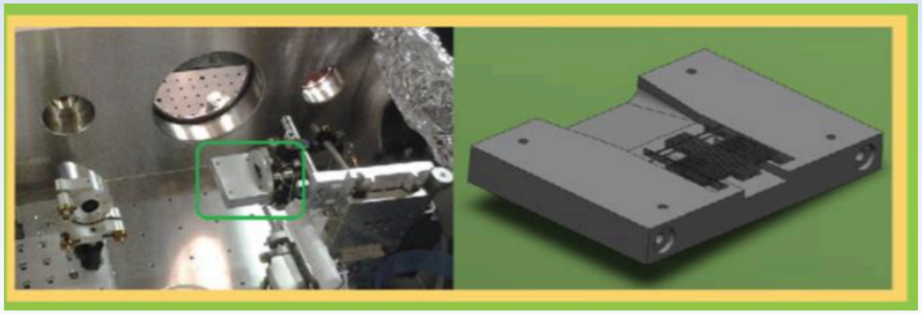
Spectrum of woodpile (simulations)



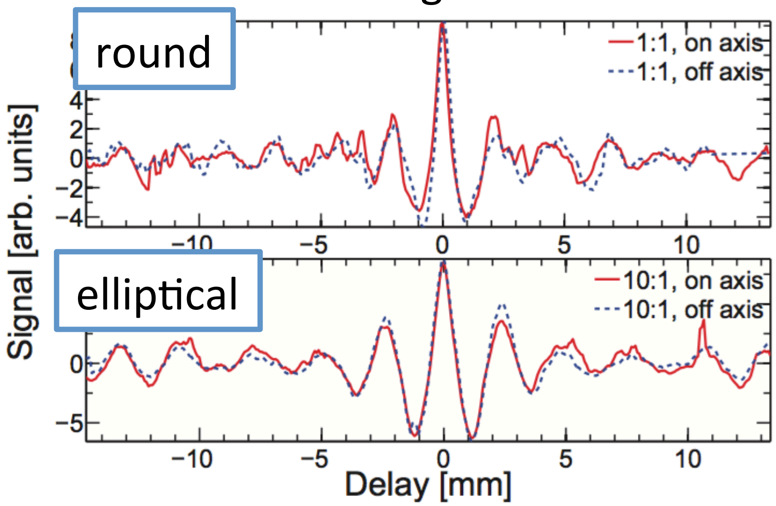
Cross section (beam perspective)

DWA Woodpile experiment

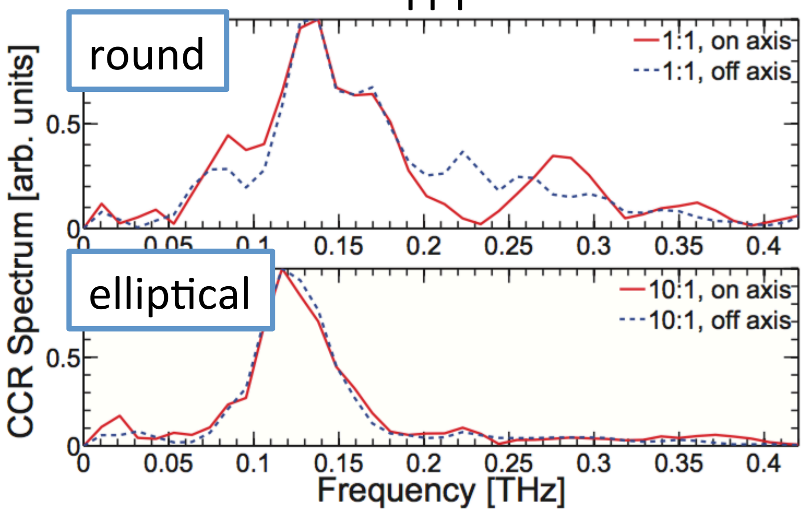
- Experiment at BNL ATF
  - CCR spectral characterization methods
  - Round beam vs elliptical
  - Shows suppression of spectra
  - agreement with simulations
- Results important
  - Design spectrum
  - Use bunch length to couple to desired longitudinal modes
  - Use beam shape to reduce coupling to transverse modes



Interferograms



FFT



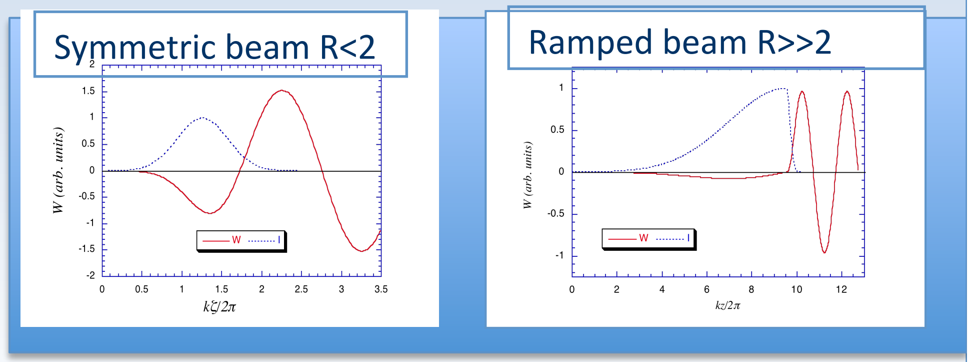
P. Hoang PRL 120, 164801 (2018)

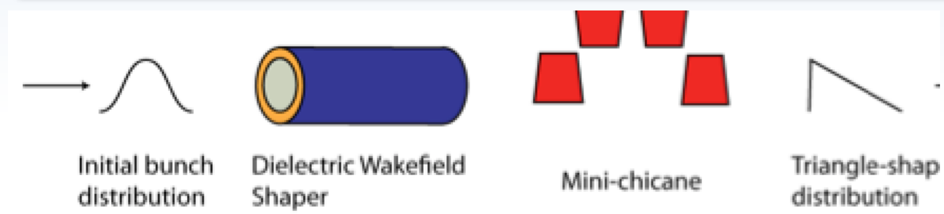
Pulse shaping: High Transformer Ratios

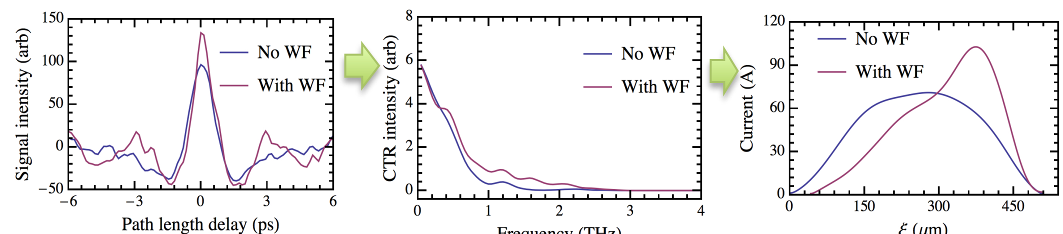
- Efficiency of DWA
- TR enhancement from ramped beams
  - Triangle distribution
  - Novel: doorstep, double triangles

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

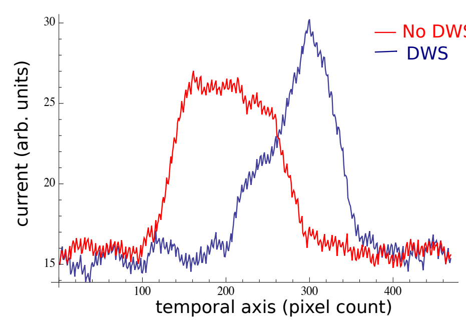
- Techniques:
  - EEX, laser shaping, mask in dispersive section
- Shaping with self wakes
  - Analogous to bunch train with DWA
    - Antipov PRL 111, 134801 (2013)
- Shaping capabilities essential for TR studies
- Experiment at BNL ATF:
  - “Ramped” beam observed
  - CCR autocorrelation
  - Deflecting cavity





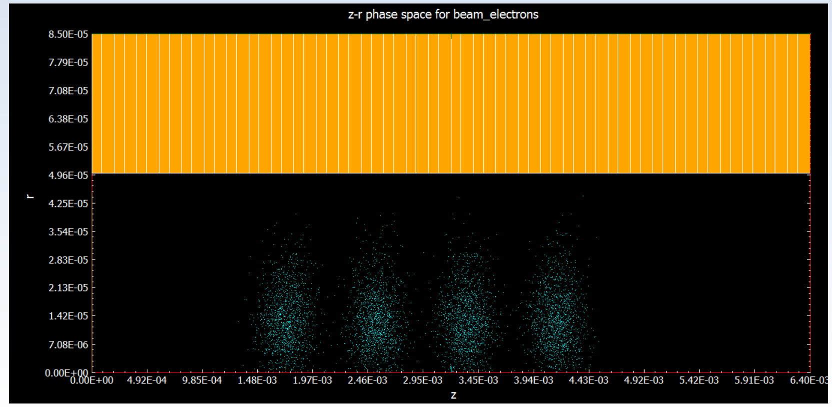


G. Andonian, et al., PRL 118, 054802 (2017)

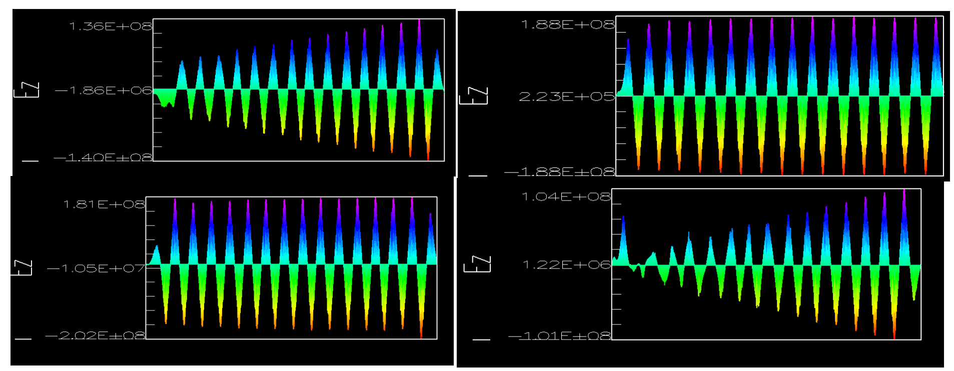


Pulse trains + Longitudinally periodic structures

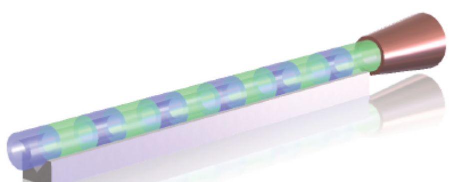
- Motivation:
  - Confine energy of mode inside structure
  - Near zero group velocity
  - Longitudinal periodicity - ε(z)
- OOPIC and HFSS Simulations
  - a = 50 μm, b = 126 μm
  - Periodicity = 300 μm
  - Used both sinusoidal variance of ε and step
  - Base materials SiO2, diamond (ε=3.8, 10.6)
- 500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



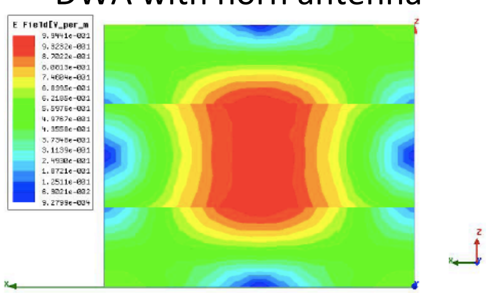
Excite mode with 4-pulse train - OOPIC



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



DWA with horn antenna



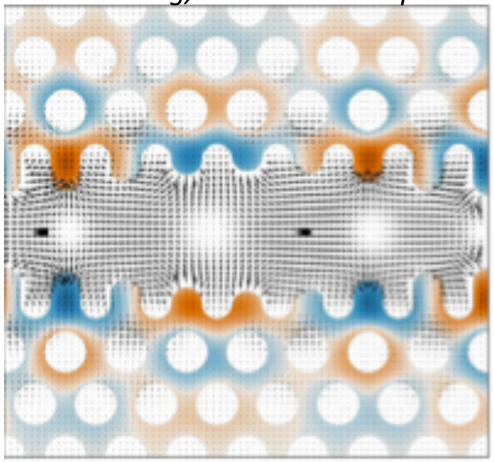
Mode confinement of Ez (HFSS)

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

Summary & Future Work

- DWA useful tool for accelerator applications
  - Advanced accelerator, THz source
  - Phase space manipulation, beam diagnostic
- FAST allows opportunity to study in new regime
  - High average current : Charging/ Heating questions
  - High quality bunches : Small/long structures
  - RTFB transform: Flat beam driven planar DWA

P. Hoang, "Toothed woodpile"



- FAST is unique facility for advanced DWA studies
  - Designer structures for fundamental physics
  - Spectra by design + Beam by design
  - Explore limits and possibilities

Acknowledgements: UCLA: S. Barber (LBNL), A. Fukusawa, P. Hoang, B. Naranjo, N. Sudar, O. Williams, J. Rosenzweig, et al. RadiaBeam: F. O'Shea, M. Harrison, A. Murokh, et al., FACET: B. O'Shea, C. Clarke, M. Hogan, V. Yakimenko, et al. U. Chic: S. Baturin, ATF: M. Fedurin, C. Swinson, et al.,
Work Supported by US DOE HEP