Recent Progress in Dielectric Wakefield Acceleration at FACET and BNL ATF

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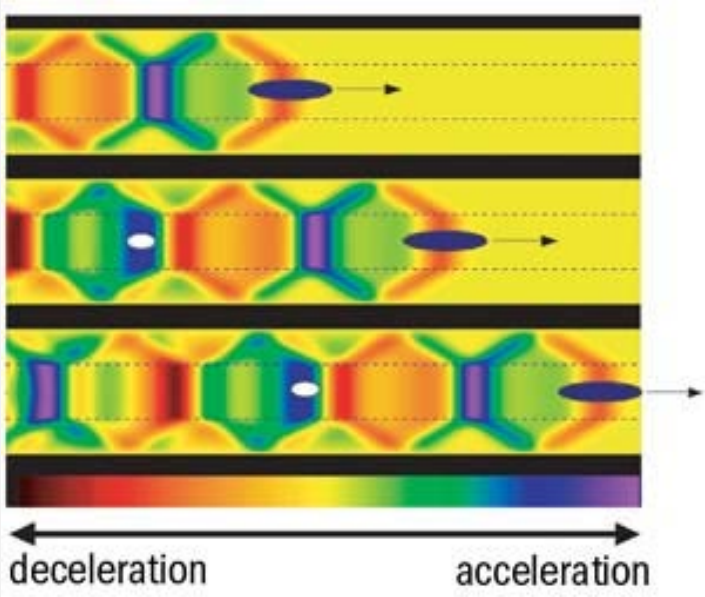
UCLA Dept. of Physics and Astronomy
Dielectric Wakefield Accelerator Workshop
Los Alamos, NM, December 5, 2013

SLAC NATIONAL ACCELERATOR LABORATORY FACET UCLA MPI ATF

DWA background, motivation

- New paradigm for high-frequency, high field acceleration
- High gradient DWA applications
  - Linear colliders and other HEP
  - Advanced accelerator for future FEL
  - Radiation Source (THz)
- Relevant Issues in DWA research
  - Determine achievable field gradients
  - Resonant excitation
  - Transverse modes and BBU
  - Dielectric materials
  - Cladding composition
  - Exploit new geometries (slab)
  - Photonic structure development
  - Transformer ratio enhancement…



Simple 2-beam collinear dielectric wakefield accelerator

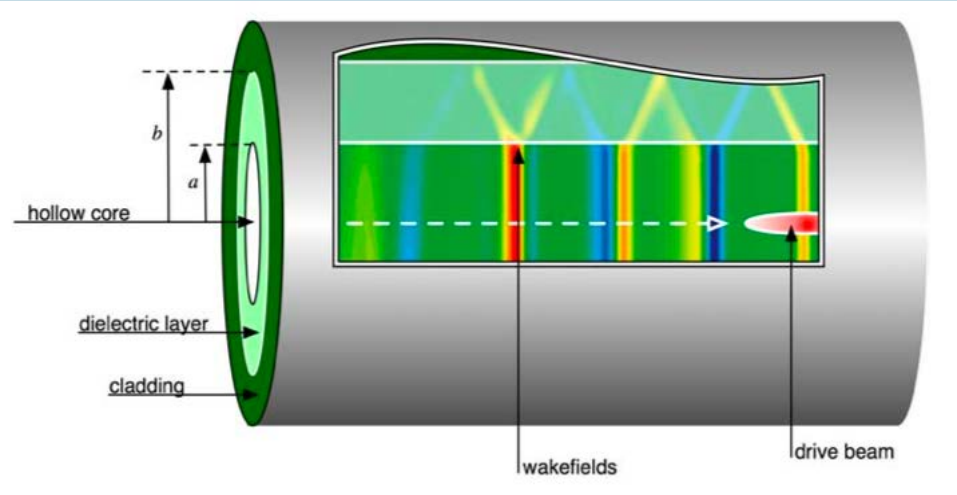
DWA v1.0: metal clad dielectric tube

- Peak decelerating field (heuristic model)

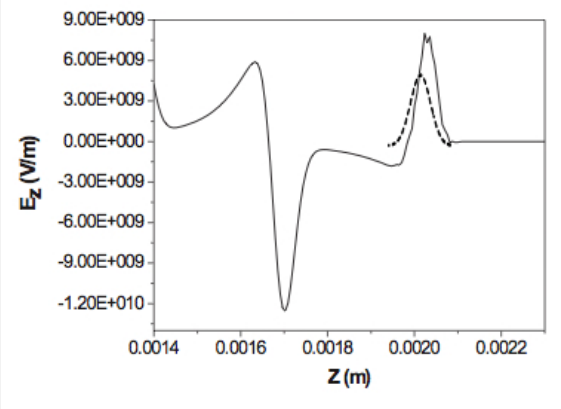
$$eE_{z,dec} \approx \frac{-4N_b r_e m_e c^2}{a\left[\sqrt{\frac{8\pi}{\varepsilon-1}}\varepsilon\sigma_z + a\right]}$$

- Gradient adjustable on the fly via N_b and σ_z (a and b through tube substitution)

- Pioneered at ANL AWA



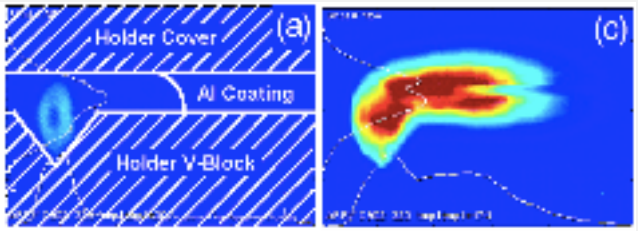
"Tuning" parameters: $a, b, Q, \sigma_z, \varepsilon$



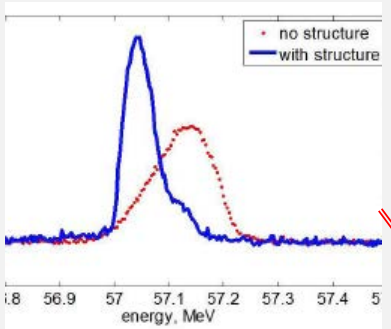
Ez on-axis, OOPIC

Development of Experimental Methods in THz DWA

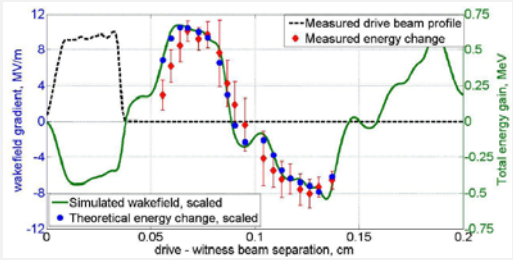
M. Thompson et al., PRL 100, 214801 (2008)
Breakdown studies @ SLAC FFTB



S. Antipov et al., PRL 108, 144801 (2012)
Chirp suppression @ BNL ATF



S. Antipov et al., APL 100, 132910 (2012)
Wakefield map in diamond @ BNL ATF



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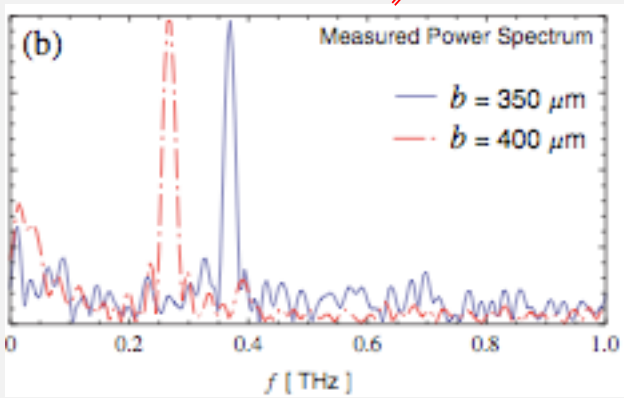
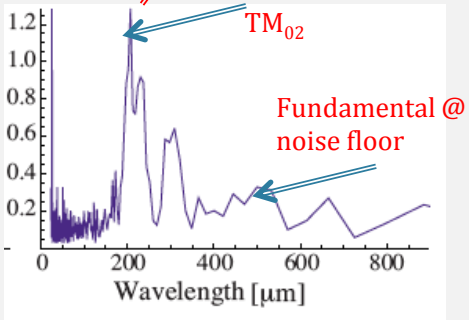
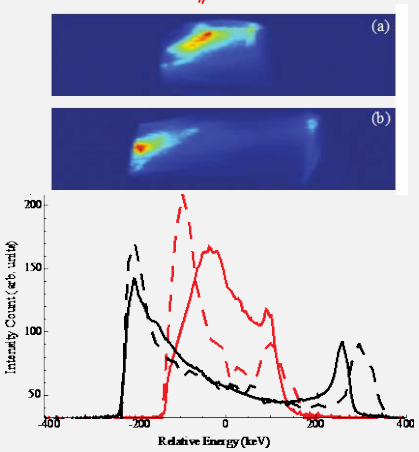


A. Cook et al., PRL 103, 095003 (2009)
CCR spectra @ UCLA Neptune



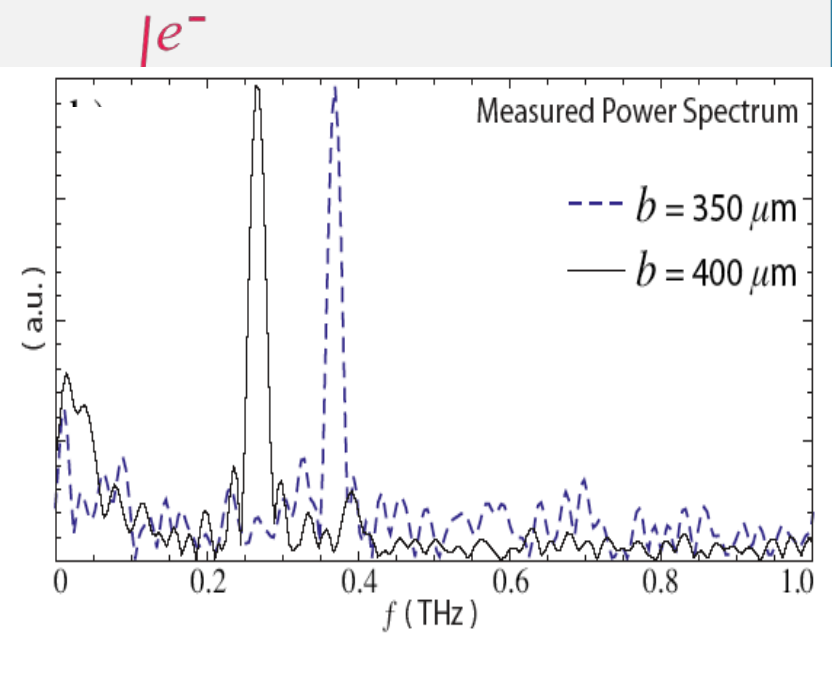
G. Andonian et al., APL 98, 202901 (2011)
Selective mode excitation @BNL ATF



G. Andonian et al., PRL 108, 244801 (2012)
Accel. in slab @ BNL ATF

Spin-off: THz CCR from DWA

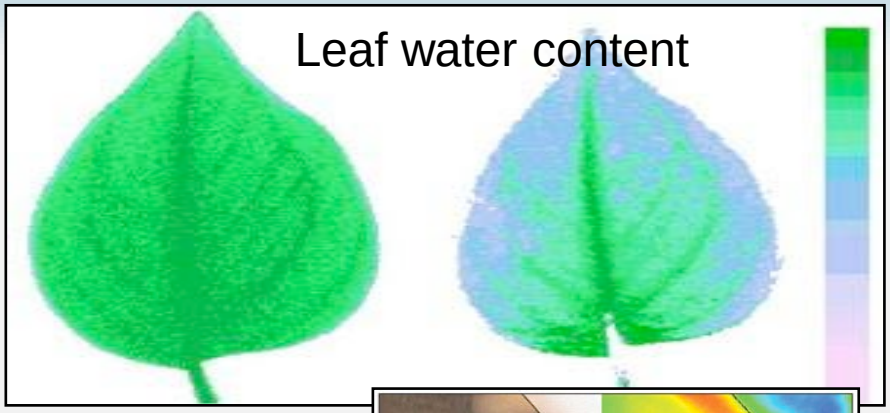
- Chicane-compressed (200 μm) 0.3 nC beam @ UCLA Neptune
  - Focused with PMQ array: σ_r~100 μm (a=250 μm)
- Single mode operation
  - Two tubes, different *b,* THz frequencies
  - Extremely narrow line width in THz
    - Higher power, lower width than THz FEL
    - Higher harmonics possible
- Methodology developed at UCLA CER experiments at BNL ATF
  - Refined further since

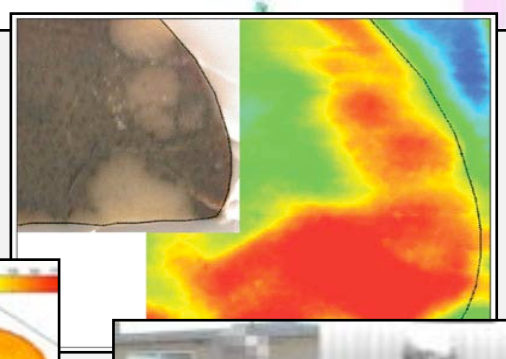


A. Cook, et al., Phys. Rev. Lett. **103**, 095003 (2009)

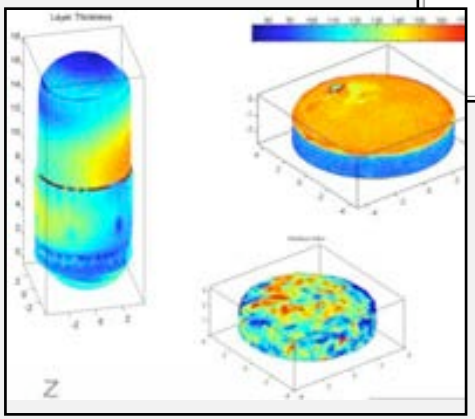
THz applications

- Chemical specificity
- Mainly *broadband* sources
- Biologicial/medical
- Security applications





Liver cancer imaging

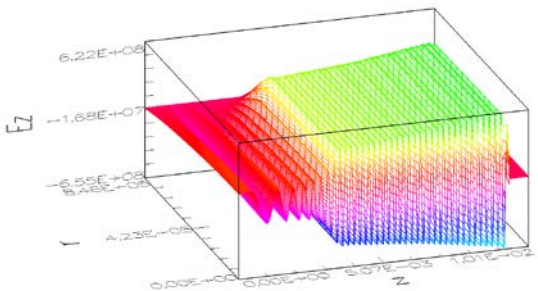


Decay of pill surface

Standoff weapons

Narrow-band THz FEL v. CCR

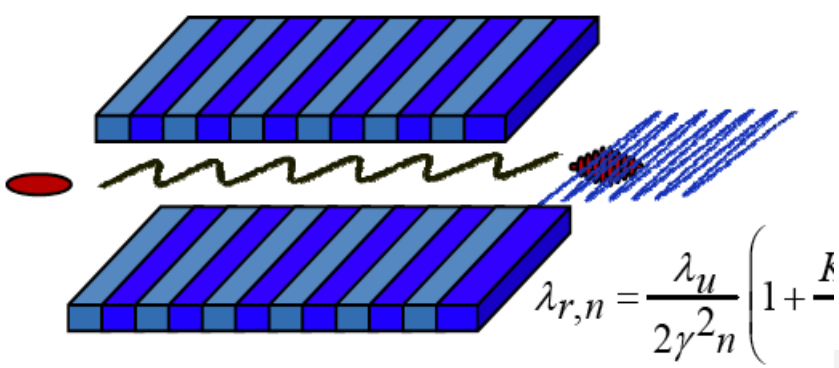
- CCR more efficient
- CCR more *compact*



Parameters: 1 THz case	
Rms beam length σ_r	100 μm
Rms beam radius σ_r	30 μm
Beam total charge Q	1 nC
Fundamental frequency	1 THz
Outer radius b	115 μm
Inner radius a	77 μm
Peak power	21 MW
Peak long. electric field	294 MV/m
Pulse length	69 ps
Total CCR energy	1.47 mJ

CCR THz: 0.5% BW, L=1 cm!

Many wavelengths in the train



Beam Lorentz factor γ	44
Rms bunch length σ_z	100 μm
Rms bunch width σ_r	200 μm
Undulator wavelength λ_u	6.9 cm
Number of undulator periods	15
Undulator strength K	5.6
On-axis radiation wavelength λ	299 μm (1 THz)

THz FEL: 6.5%BW, Power 10 MW,L=1 m

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TOPICAL REVIEW

No emphasis of CCR in field!

Accelerator- and laser-based sources of high-field terahertz pulses

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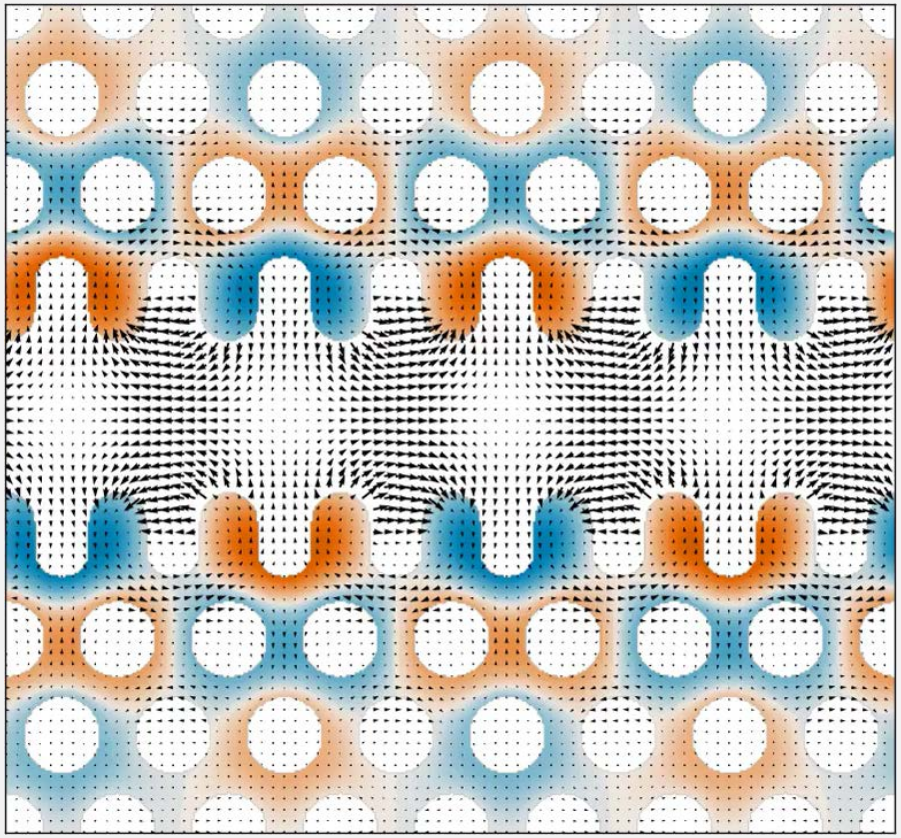
Abstract
At present we are witnessing a rapid development of sources for terahertz (THz) pulses with very strong electromagnetic fields. These pulses are reaching a stage where they can be used to not only probe, but also uniquely control a variety of processes that range from fundamental dynamics in individual atoms and molecules, through phase transitions in solids to a wealth of interactions in biological materials. In this review, we are presenting an overview of two major directions in the generation of such radiation. Large-scale accelerator-based sources offer unprecedented pulse energies coupled with a wide tuning range and extreme repetition rates. Laser-based sources, on the other hand, are laboratory-scale instruments and thus are very attractive in their availability to the wide scientific community. The capabilities of different variants of these THz sources are evaluated and compared with each other. In addition, powerful techniques for the temporal characterization of THz pulses are discussed.

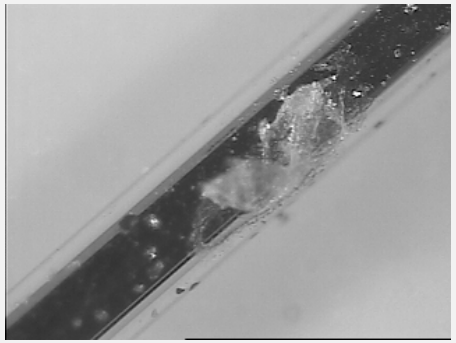
Photonic confinement

- Metals very lossy
- Confinement using a single dielectric
- Synergistic with dielectric laser accelerator
  - Ex: GALAXIE



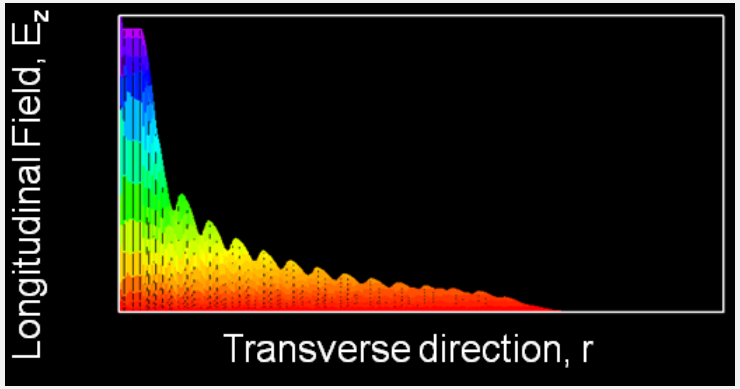
Slab Bragg array: 1D-photonic structure

- Motivation
  - **T481: Al cladding vaporized**
  - **Mode confinement without metal**
  - **1st step to mode control with photonics**
- **Concept: Bragg arrays**
  - **Easier in slab geometry**
  - **Alternate layers of high/low -ε material (quartz, diamond, sapphire, ZTA)**
  - **Confine "defect mode" in bandgap**

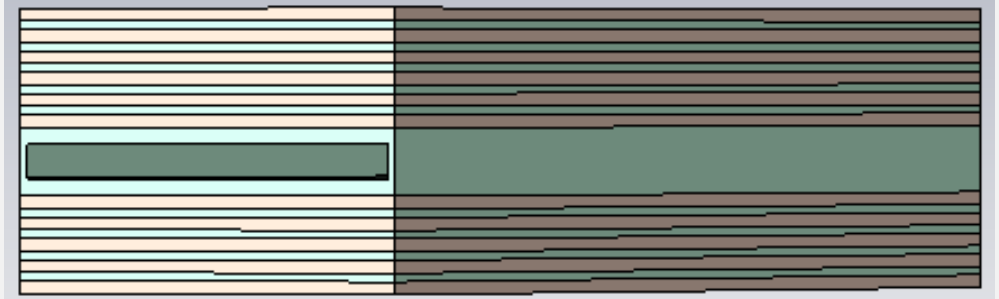


Post-mortem from T481

OOPIC sims: strong confinements

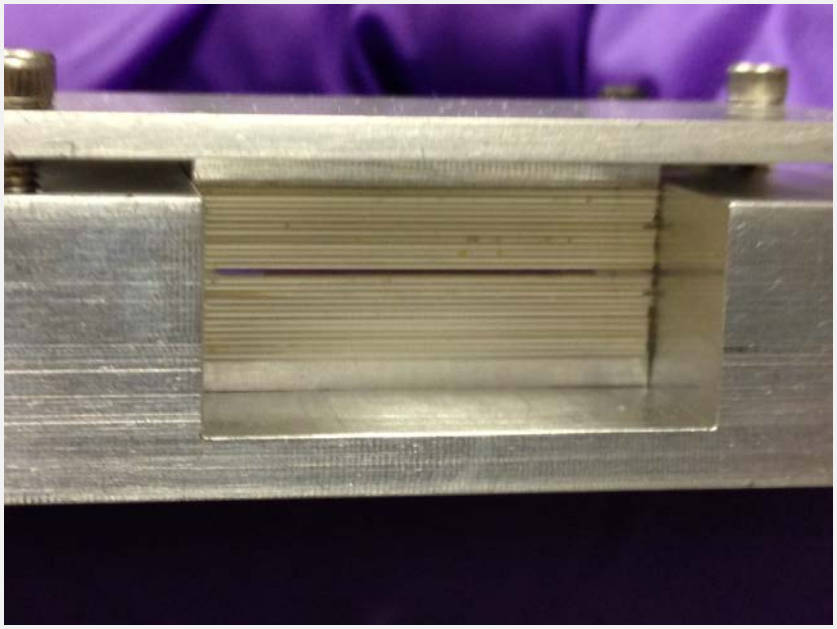


Planar Bragg accelerator (PBA)



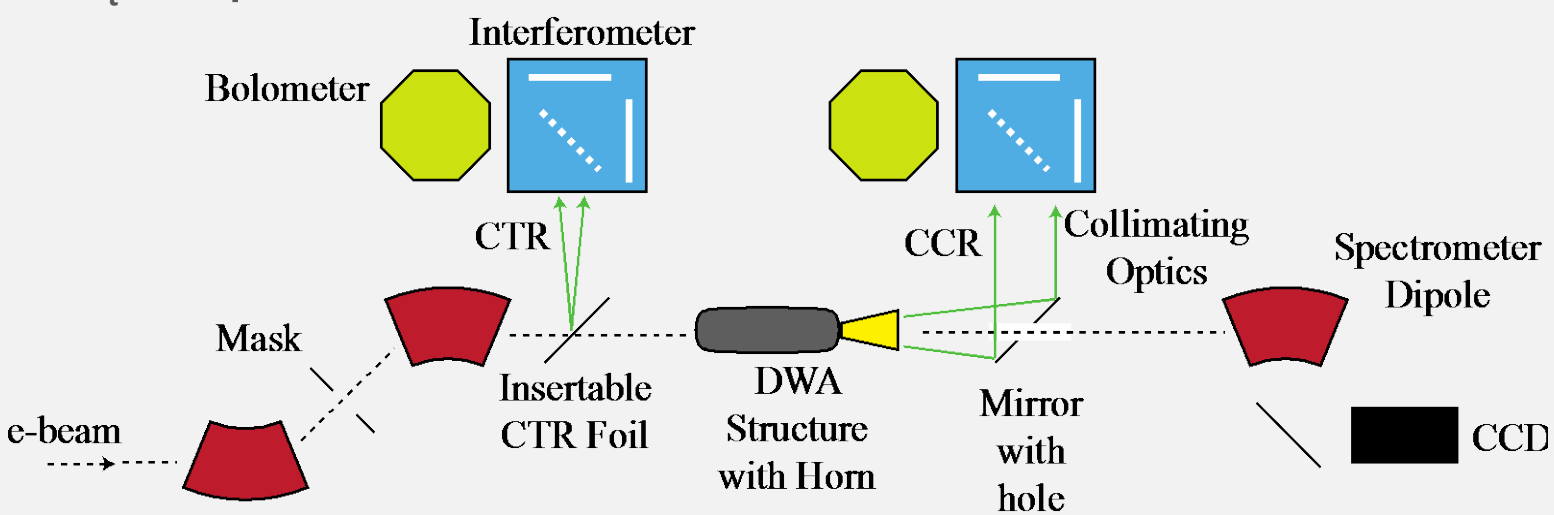
DWA – Bragg structure

- ZTA – SiO2 layers
- SiO2 “matching” layer



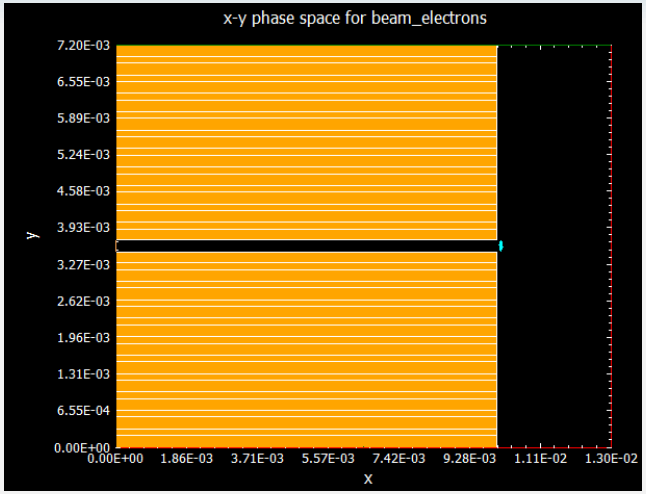
UCLA Bragg DWA experiment at ATF

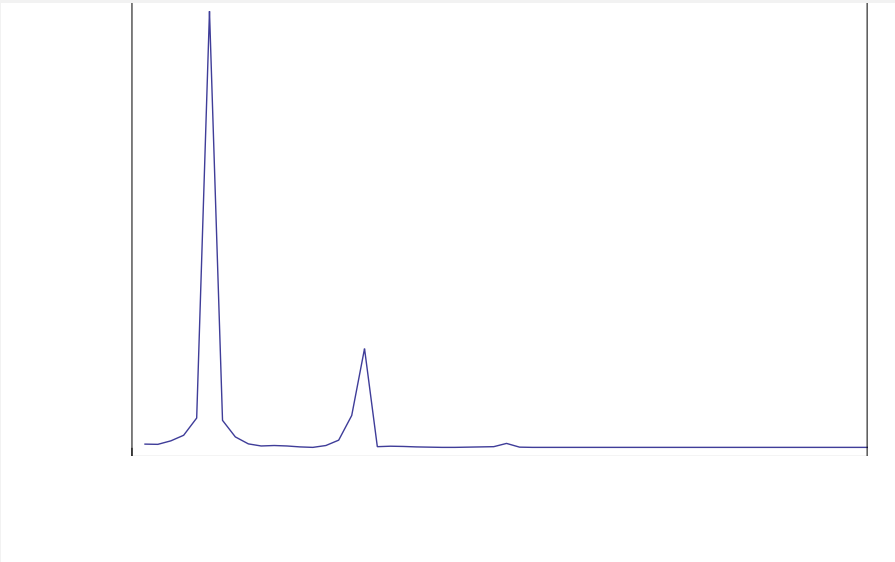
- E = 50 MeV
- σ_x, σ_y = 60μm
- Q ~ 200pC
- σ_t ~ 1ps

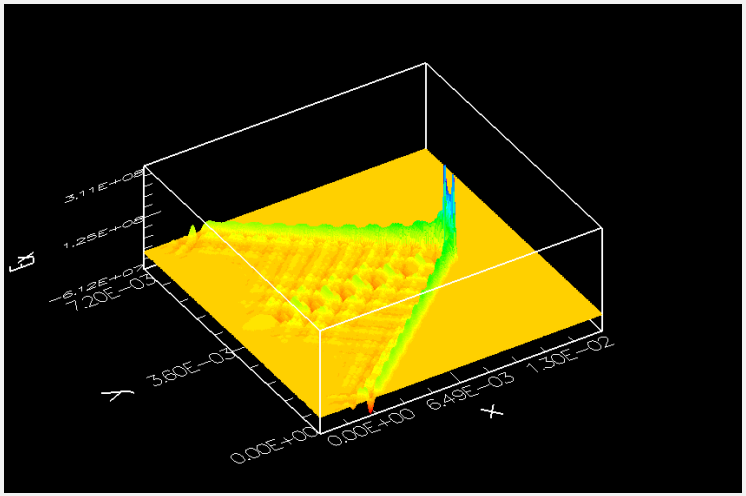


OOPIC (2D) simulations

- 2D slab symmetry
- Layout
- Longitudinal field estimate
- Frequency spectrum

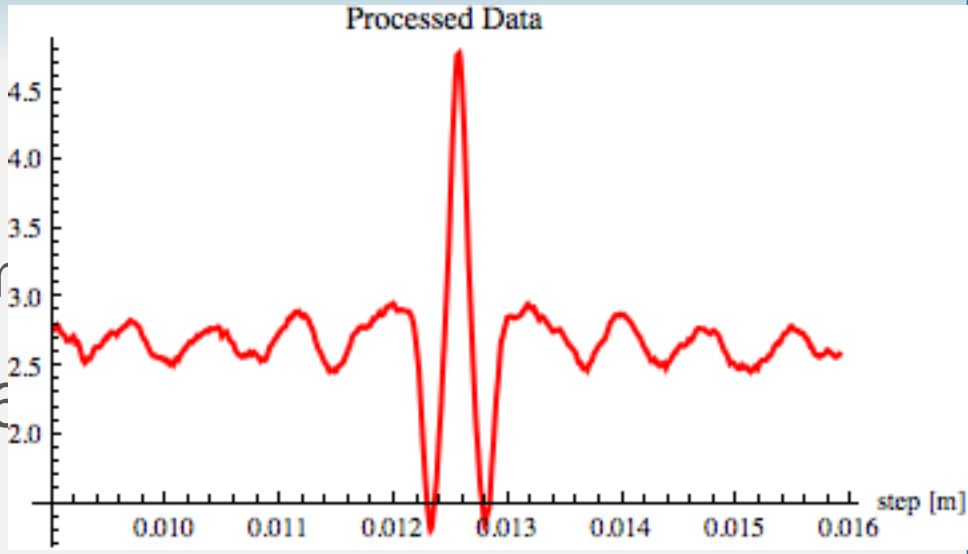


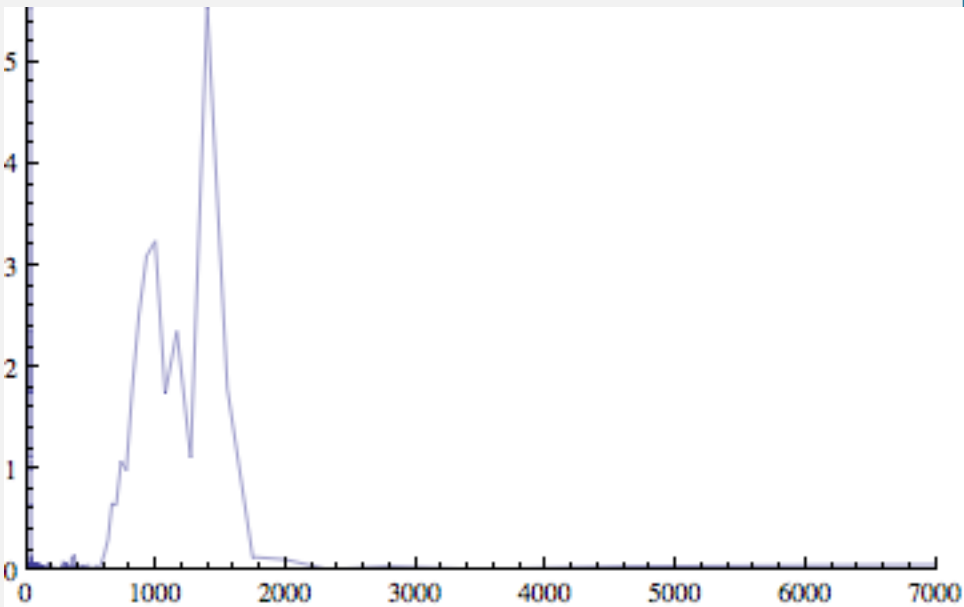




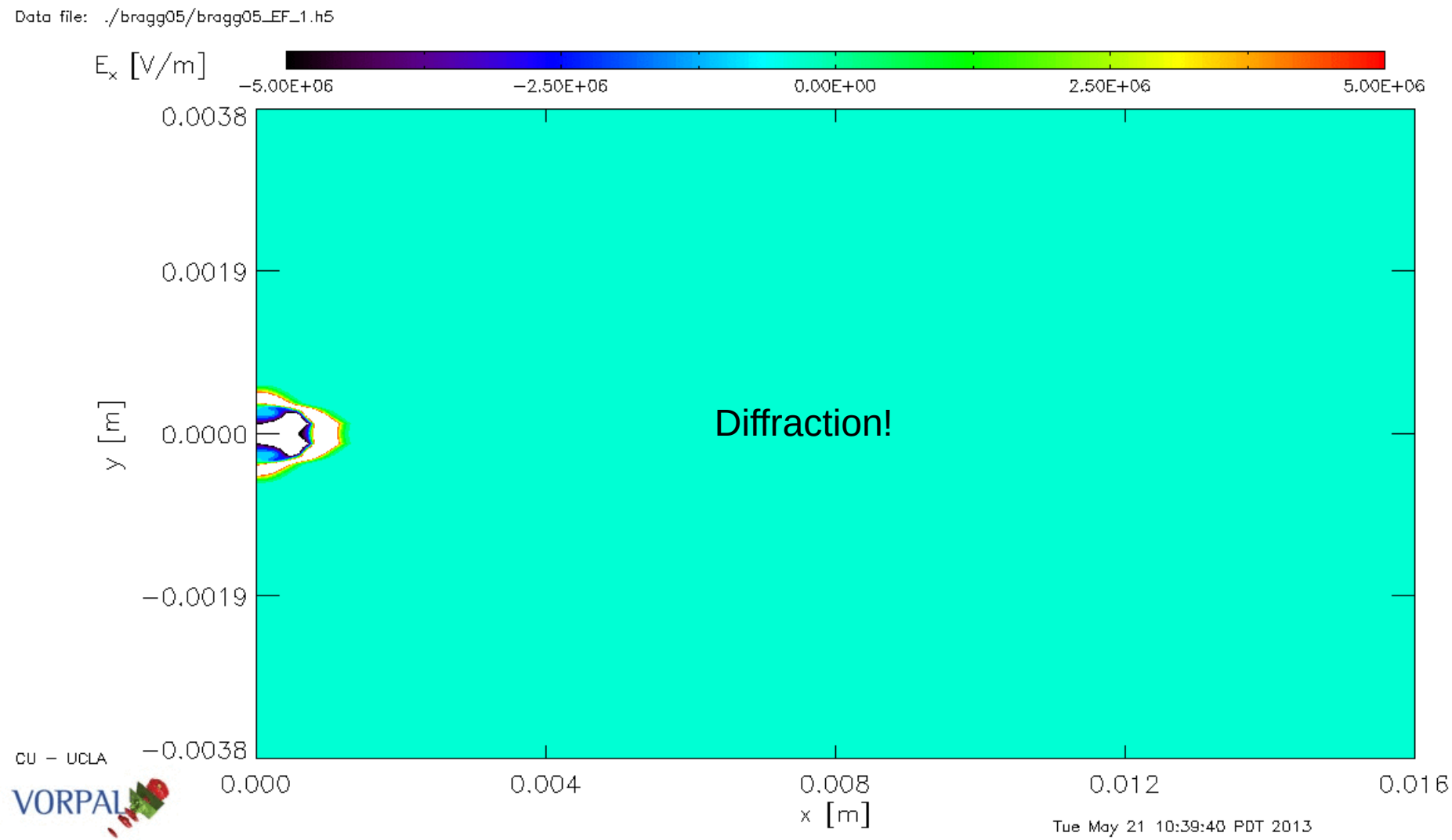
Coherent Cerenkov Data

- Autocorrelation
- FFT for frequency spectrum
- Fundamental mode near 16 GHz observed
  - Confinement works!
  - 1st photonic
- Large “CTR” signal





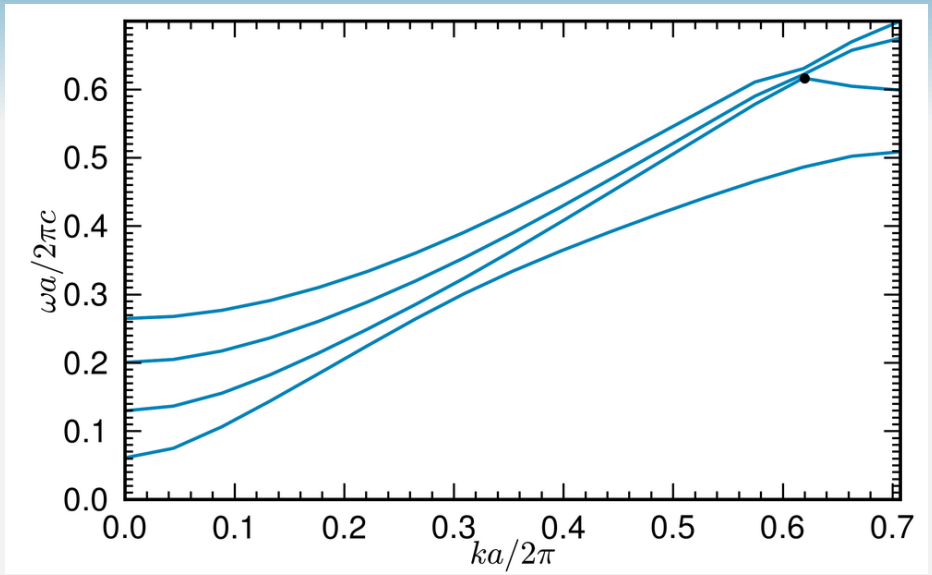
VORPAL 3D: Longitudinal field: E_x in x-y plane, bisecting e- bunch

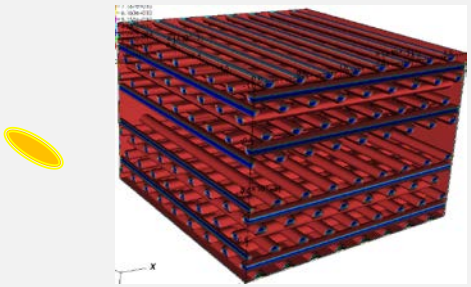


D. Bruhwiler (Univ. Colo.)

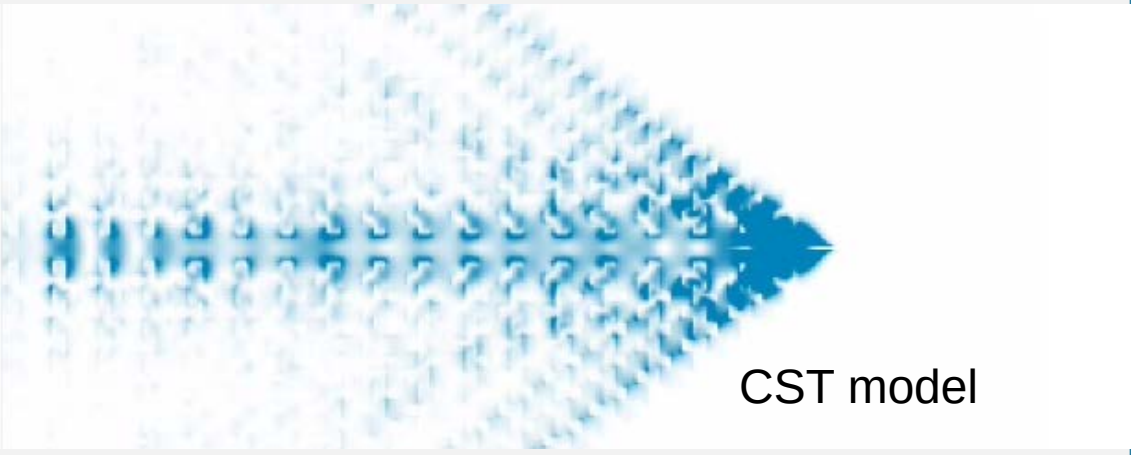
3D Photonic Structure: Woodpile

- 3D photonic structure
  - Take advantage of advances in photonic structure development
  - Synergy with laser-fed structures
  - Defect mode control in 3D.
- Example: Woodpile
  - Canonical problem
  - Laser accelerator favorite
- Microfabrication techniques
  - Sapphire rods (ε=11.5)
- As built gives backward wave!

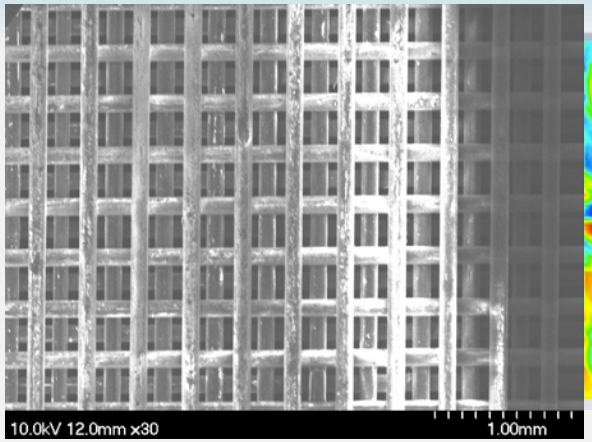




Channel:
250um
125um rods
(Sapphire

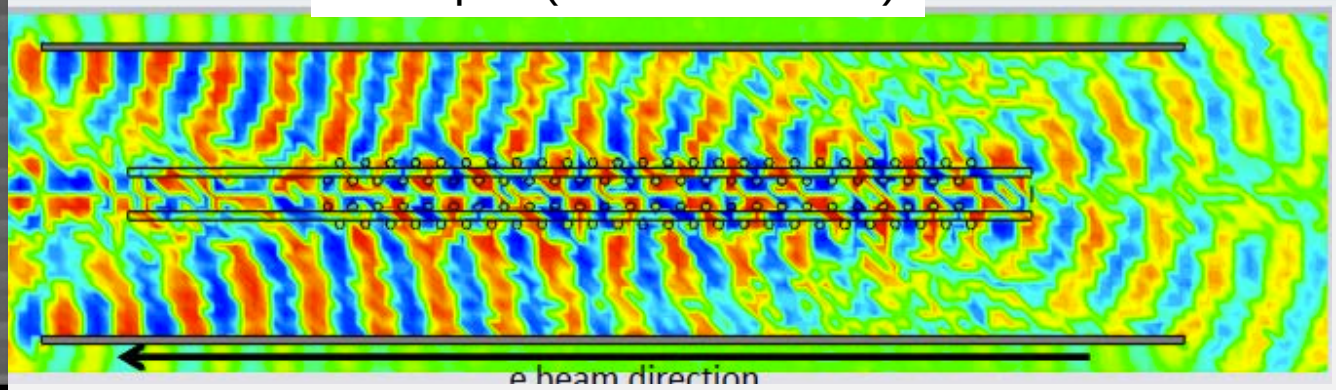


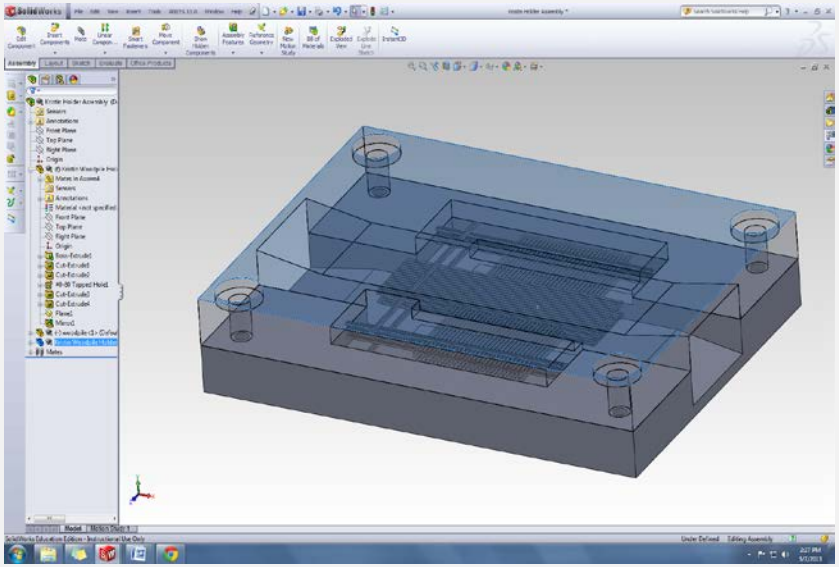
Launching geometry for woodpile



Woodpile as built

Woodpile (CST simulation)

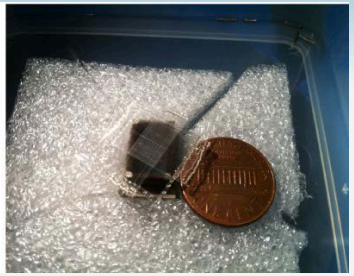


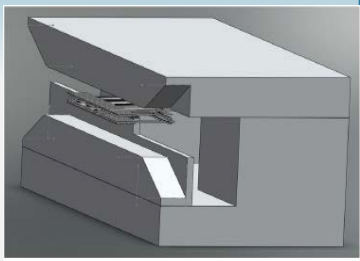


- External fields aid impedance matching for launcher
  - "Standard" UCLA rectangular horn
- Woodpile, holder fabricated

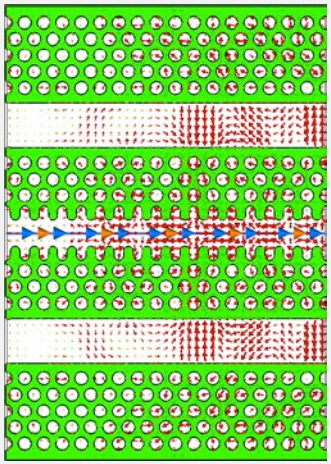
Woodpile Experiment Results

- Woodpile structure
  - Sapphire rods for woodpile (125µm)
  - 240µm beam gap
  - Hand assembled at UCLA
  - Matching horn incorporated
- BNL ATF
  - 50MeV, 100pC
- Results under study
  - Paper in preparation
  - Scaled GALAXIE structure fabricate by *laser assisted etching* of sapphire

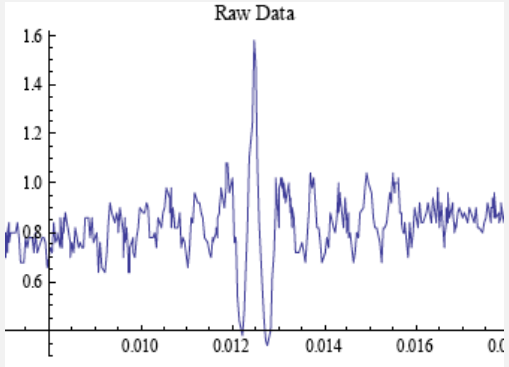


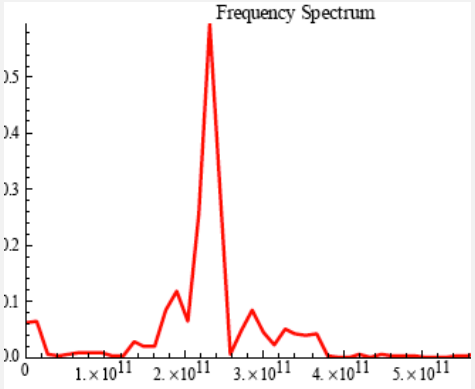


Scaled Galaxie



Interferogram





FFT

E201 goals at FACET

- Nominal Beam parameters
  - 20-23 GeV, Q=3 nC
  - σ_z = 20 μm, $\sigma_{x,y}$=20 μm (hope!)
- Excite >GV/m fields in DWA
  - CCR interferometry
  - Various geometries, materials
    - Slab
    - Bragg (Photonics)
  - Breakdown
  - Energy modulation
  - Acceleration
  - TR enhancement
  - Positrons
- Diagnostics
  - CTR/CCR interferometry
  - Breakdown observation
  - Dipole Spectrometer
  - Transverse/longitudinal measurements

- Planned for 2013 run
- Existing FACET beam and available diagnostics
- Requires variable bunch length
- Requires variable aspect ratio (flat beams)

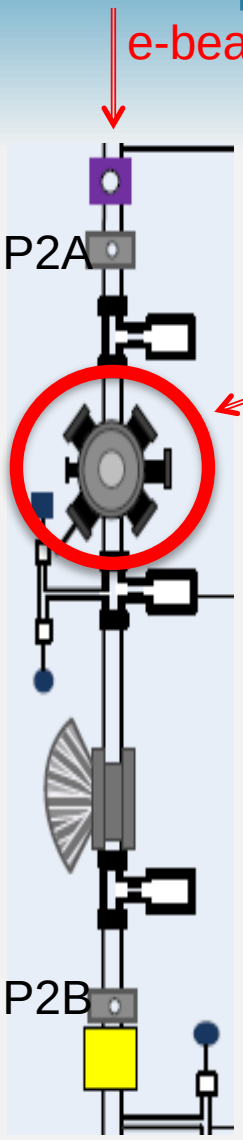
Requires long structure (done!)

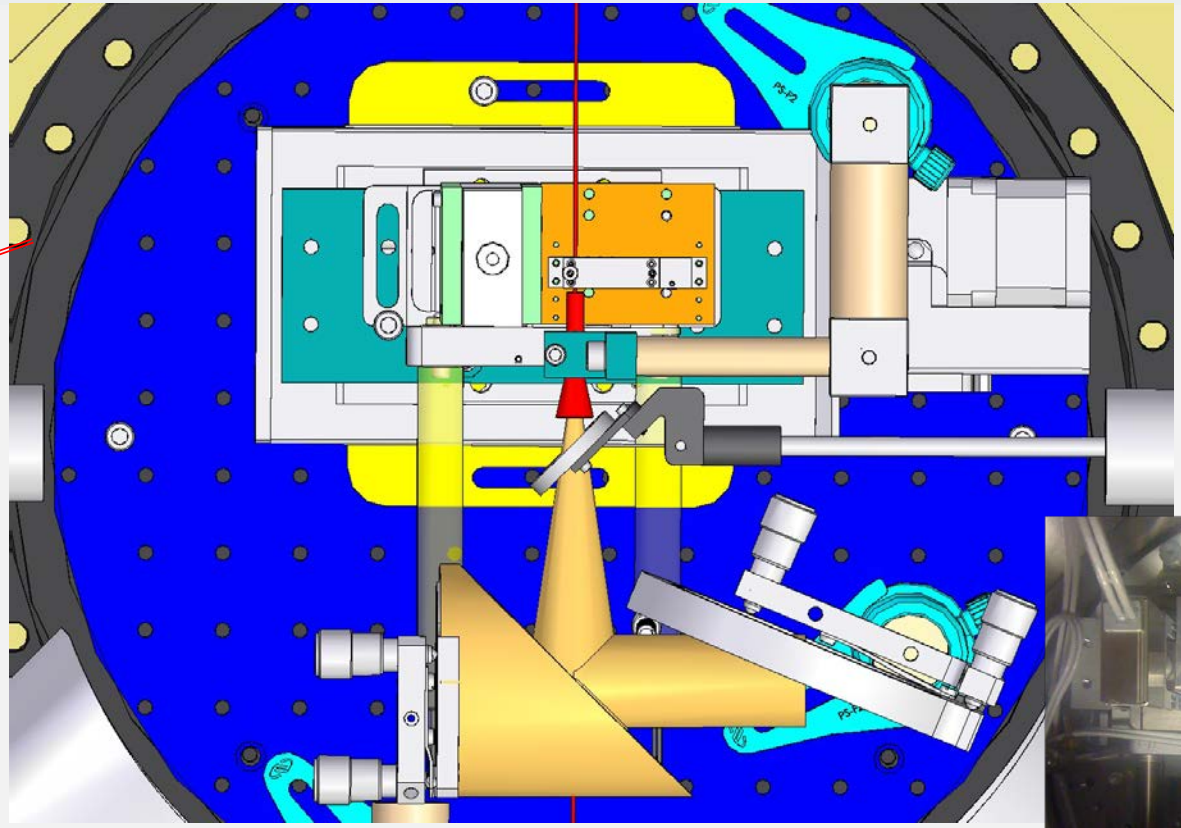
Requires drive-witness pair (next!)

Requires ramped bunch

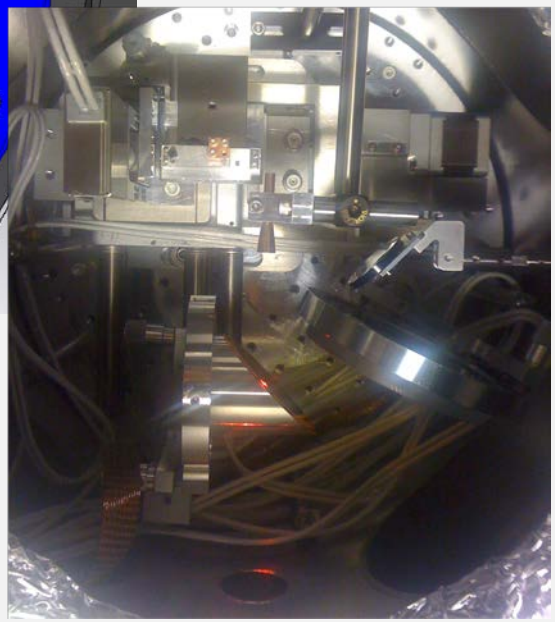
Requires… positrons

Experimental Layout (old)





Kraken
Chamber
(circa 2011)



Horn 4mm clearance
OAP w/ 3mm hole
HeNe laser alignment

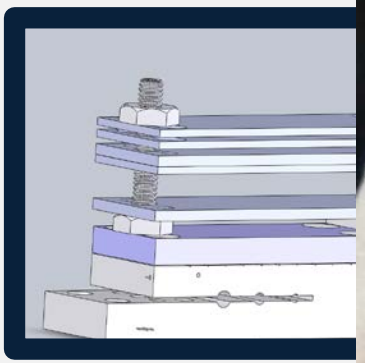
Array of DWA Tubes/Slabs installed

UCLA

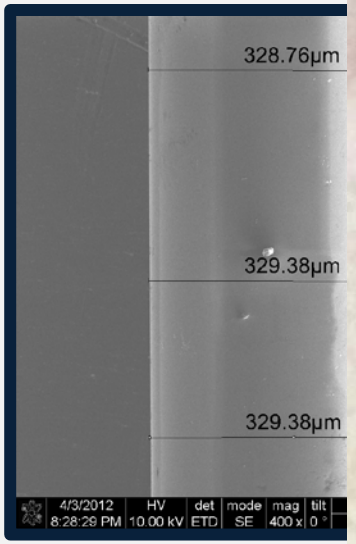
As inst

5-axis motion

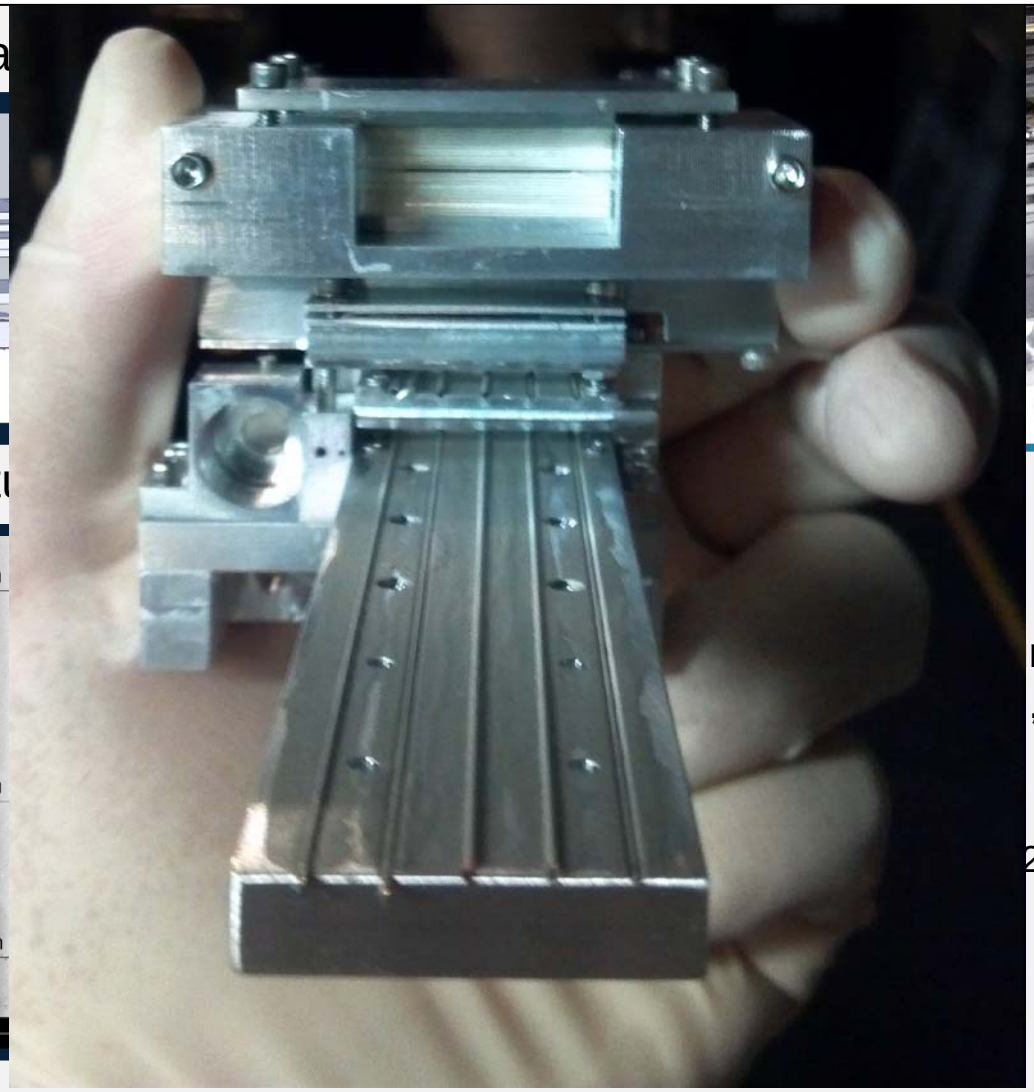
Visual confirma

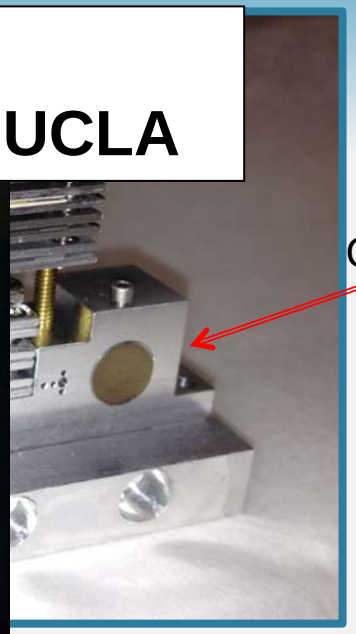


SEM of SiO2 tu



New! Improved! 10 cm tubes!
Excellent metal cladding developed at UCLA





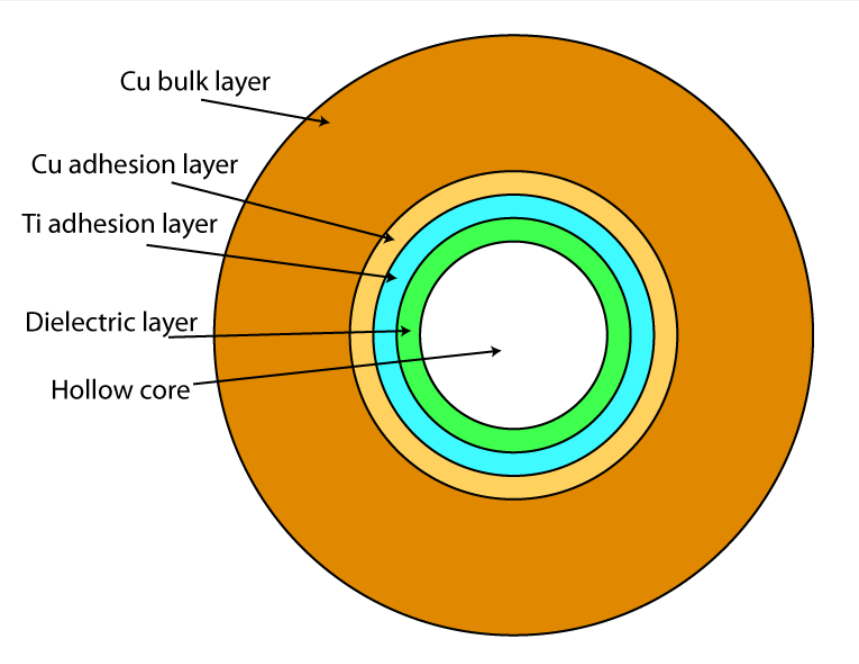
OTR fo

m, L= 1cm)
, L = 1cm)
L = 1-cm)

240/115/210µm,

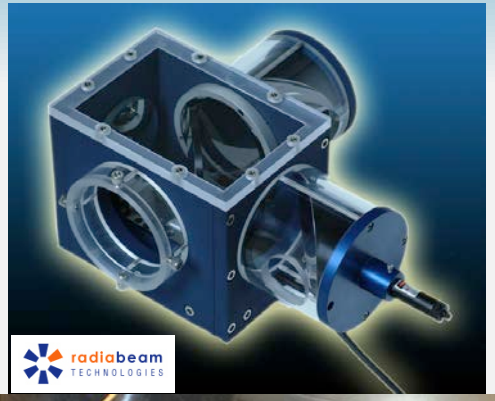
Metallic coating on dielectric

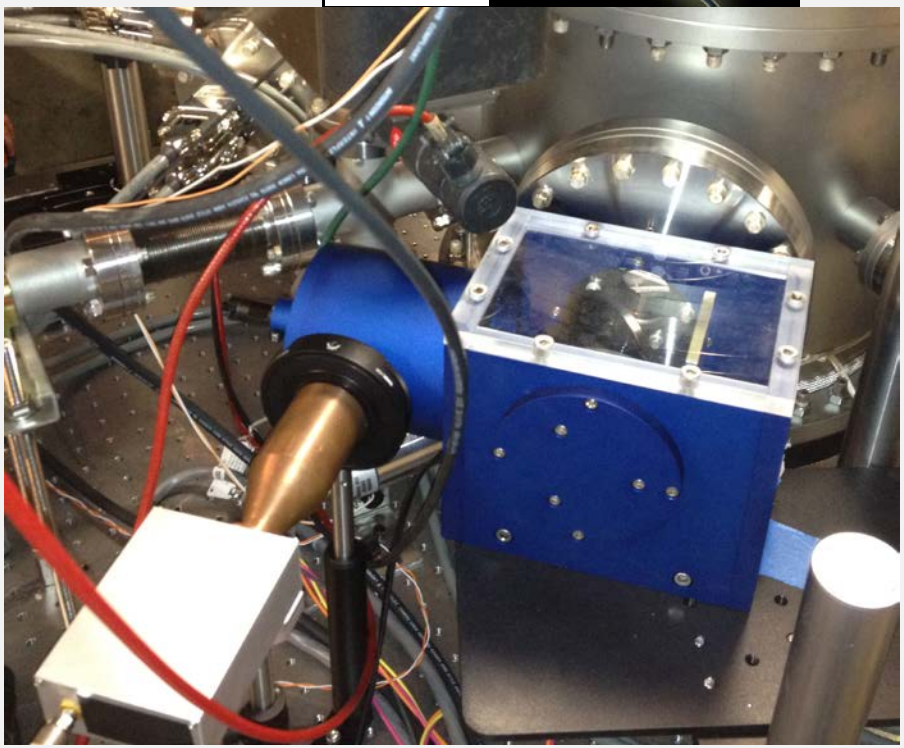
- UCLA Developed robust coating
  - K. Fitzmorris, J. Harrison
- Recipe:
  - 1µm Ti (transition)
  - 1µm Cu (adhesion)
  - 100µm Cu (bulk)
- No problems with coating loss or degradation



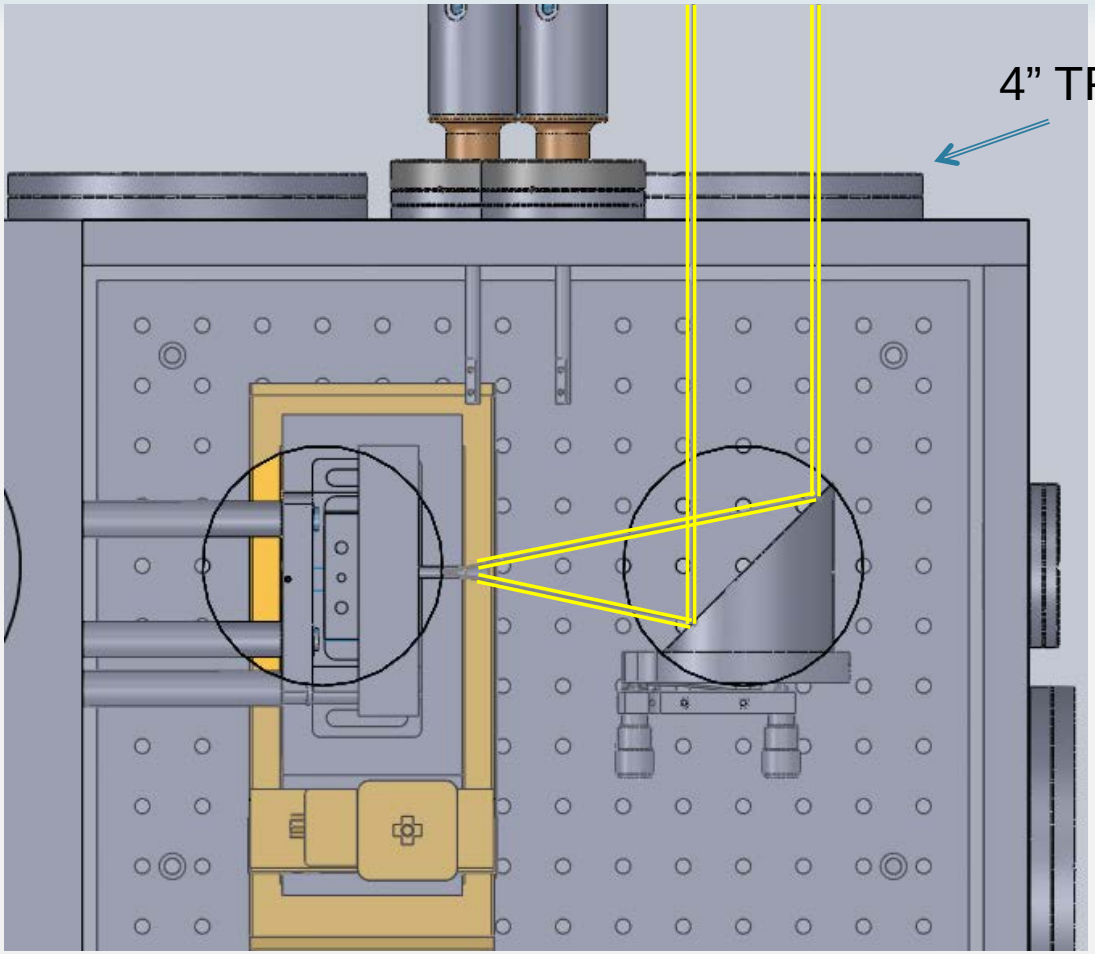
Available Diagnostics

- Dipole (momentum spectrum). Used it!
- Transverse beam imaging
  - OTR
  - Wire scanner (upstream)
- Pulse temporal extent
  - CTR interferometry
    - BLIS + pyro
  - Deflector
- DWA emissions
  - Coherent – CCR interferometry
  - Incoherent –optical (“breakdown camera”)

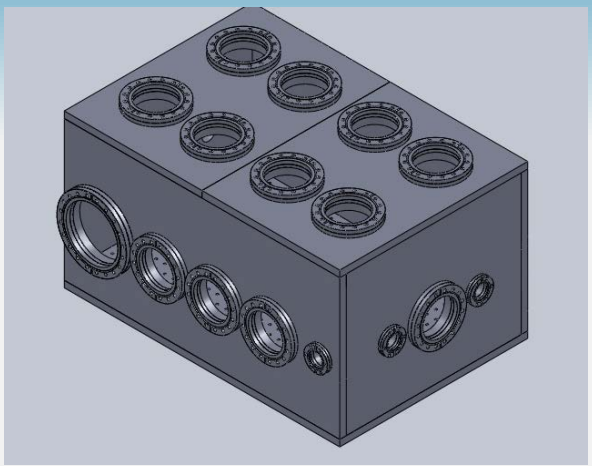




New UCLA/SLAC interaction chamber



Top view

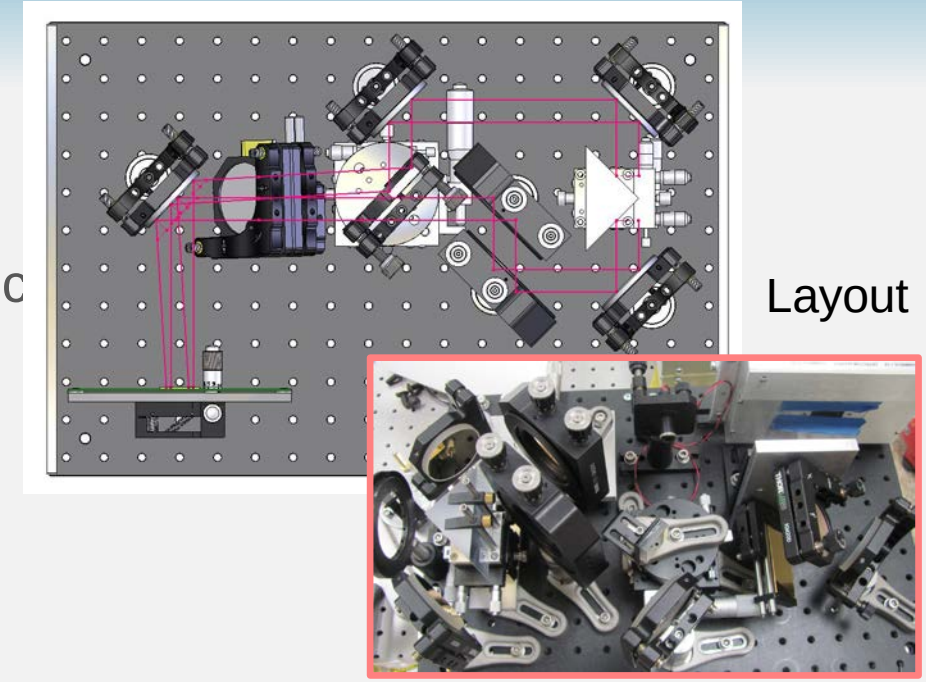


- Sent to vendor (~ 2 months)
- Many ports (small to large)
- Rad-hard stages
- Easier alignment
- Dedicated HeNe injection port
- Halo monitor
- Compact 150 GHz calibration sou

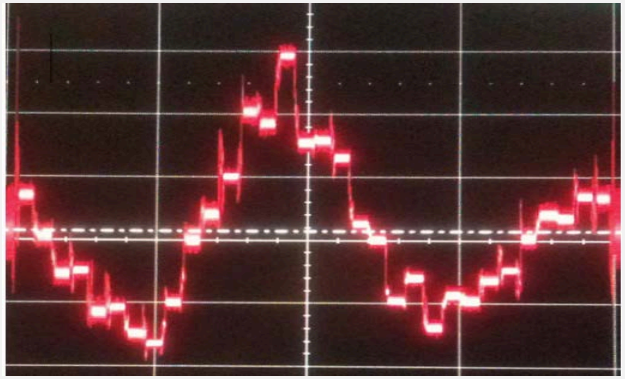
S. Barber

New bunch length measurement

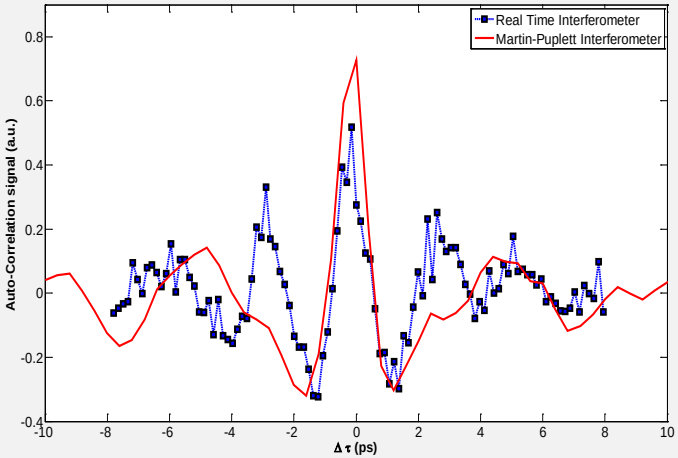
- CTR scan slow
- Use real time interferometer (RTI)
- Single shot, spatial autocorrelation
  - Mix beams at small angle
- Linear pyro array (Radiabeam/Gentec
- Commissioned at Fermilab A0
- Ideal for FACET parameters
  - Rad hard?



Layout



Raw image

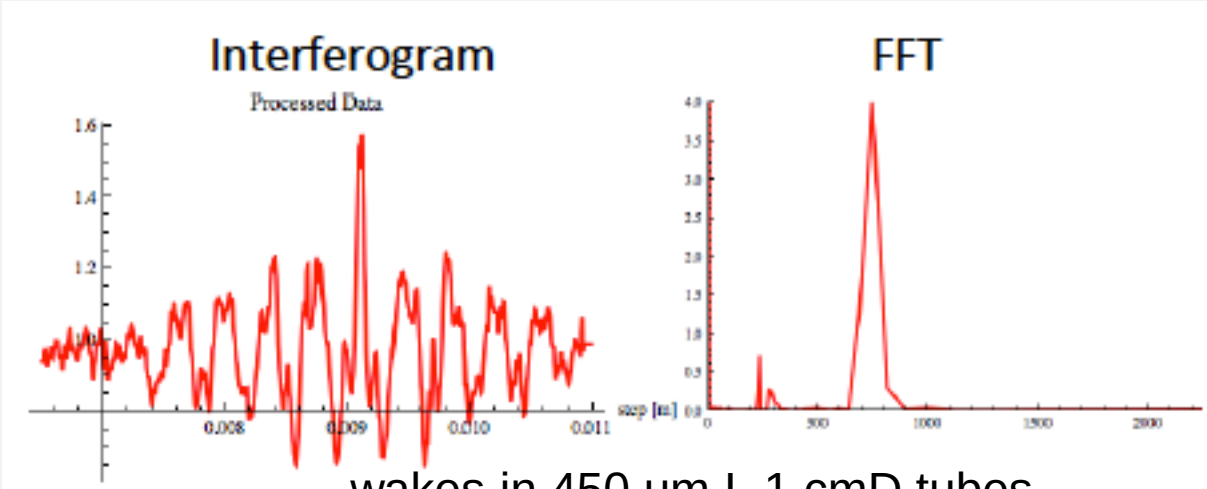


Comparison to Michelson

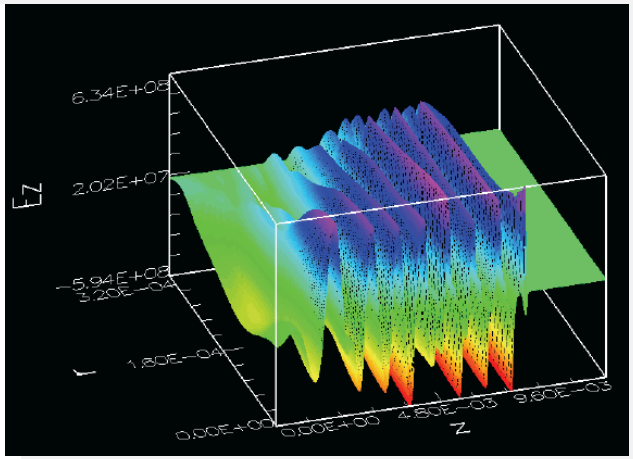
G. Andonian et al., PAC09, 3988 (2009)
J. Thangaraj et al., RSI 83, 043302 (2012)

First FACET results

- ~GV wakes in tubes and slabs observed



wakes in 450 um I, 1 cmD tubes

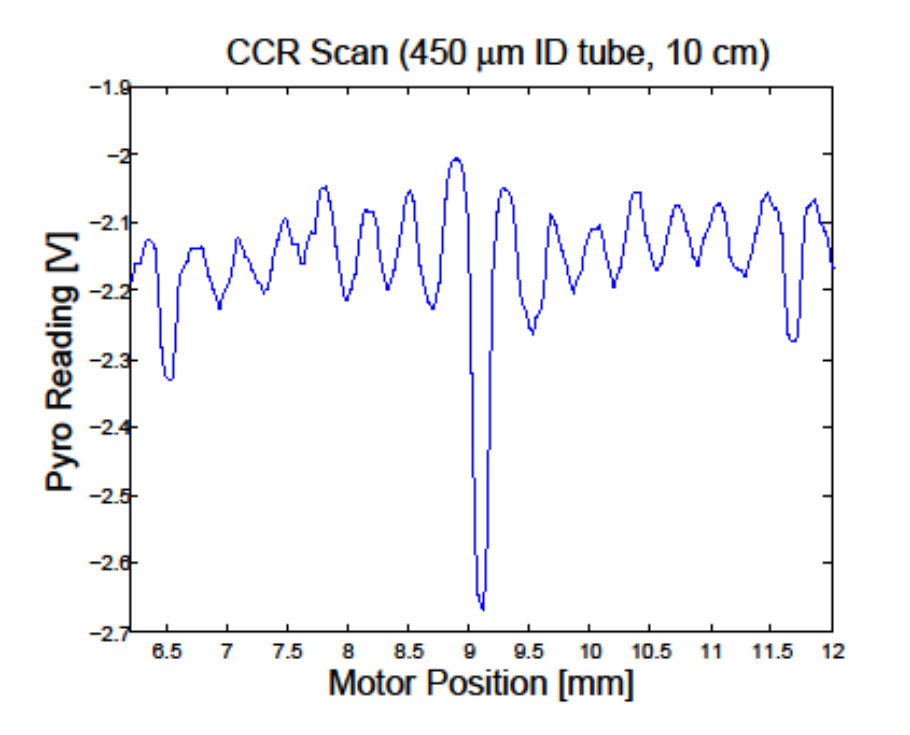


OOPIC sims of tube wake

- 100 MW narrow band THz source

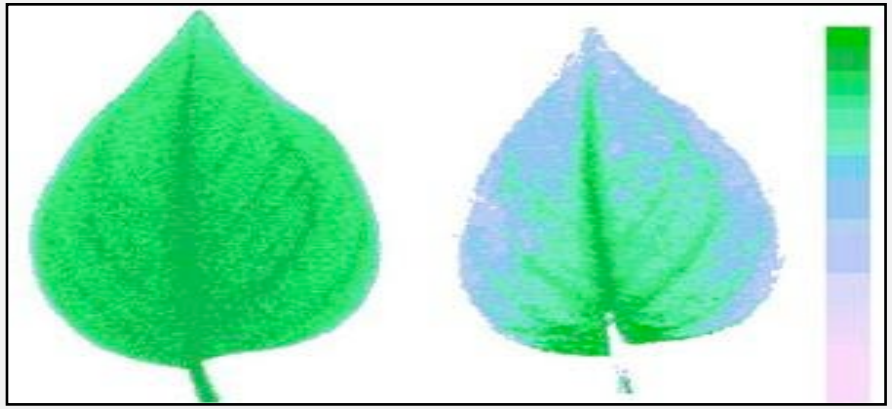
Results: 450 um ID, *L*=10 cm

- Correct fundamental
- λ=750 um
- Several 100 mJ energy



Applications

- Narrow band permits new horizons
- Fully coherent, use for lensless imaging
- Phase contrast imaging
  - Popular in X-rays



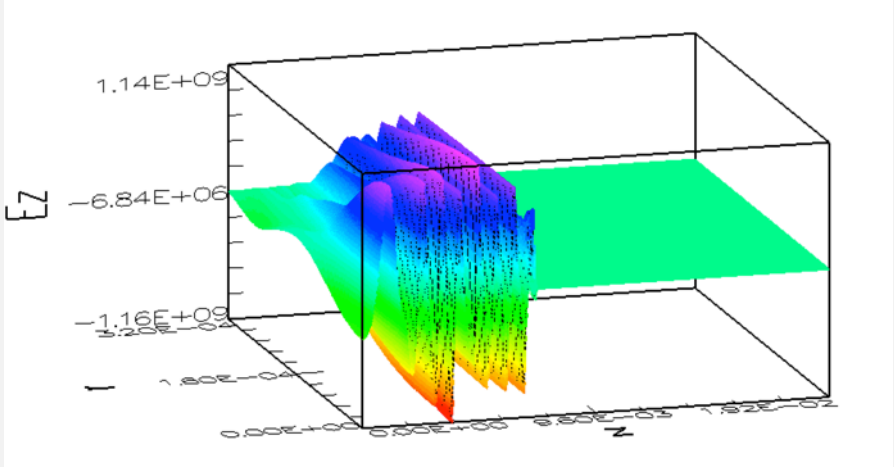
Enhance contrast in image…

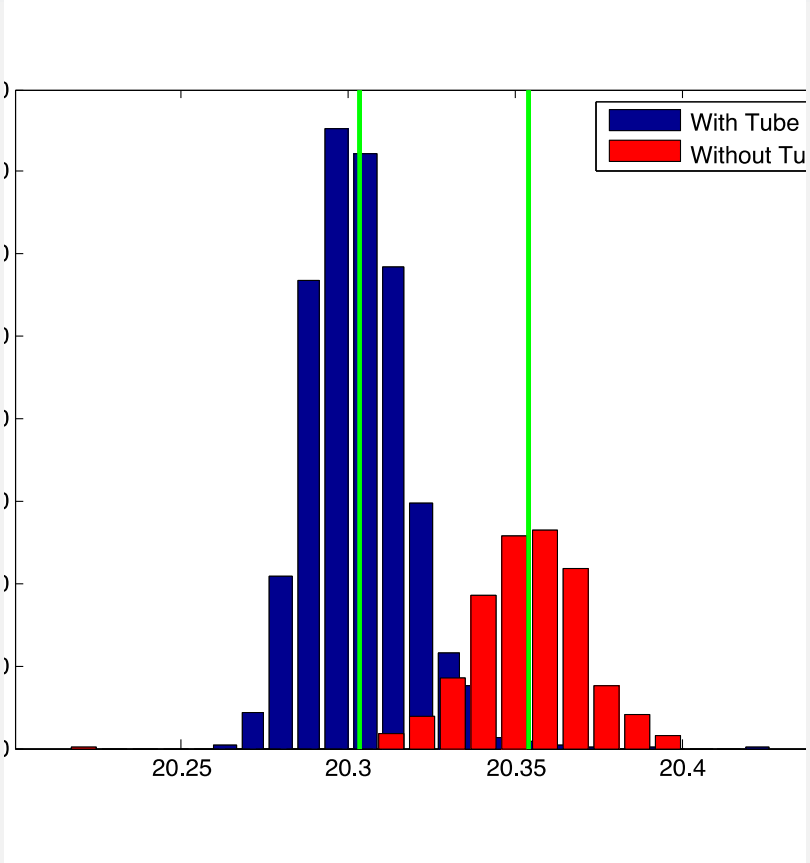
Phase contrast effect from ICS

Experiments at FACET begun in last month

Measured energy loss

- 3 nC, 20x20 um beams
- 10 cm long structures
- GV/m sustained acceleration (June 2013)!





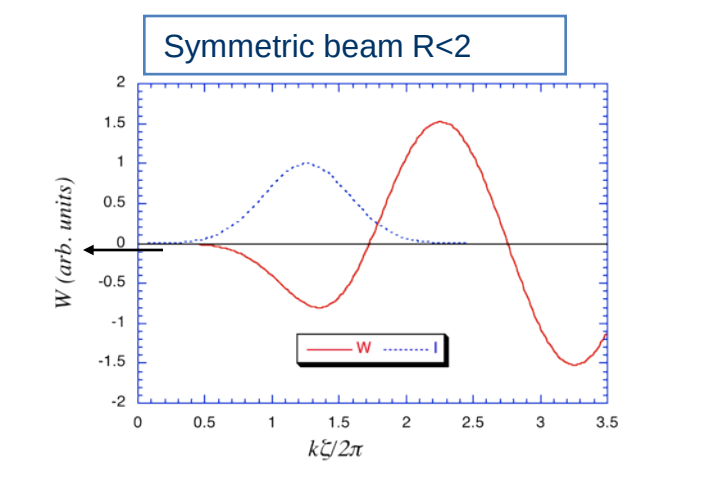
New results point to 2 GV/m peak fields (100 MeV change)!

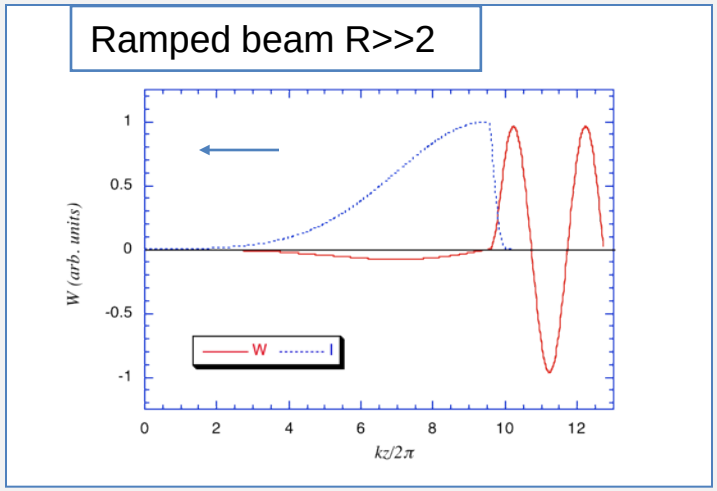
Pulse shaping for FEL: reaching *high transformer ratios*

- How to make wakefield acceleration more powerful
- Reach high (FEL) energy with single DWA module?
- Enhanced transformer ratio with *ramped beam*

$$R \equiv \frac{\left\| E_{acc,witness} \right\|}{\left\| E_{dec,driver} \right\|}$$

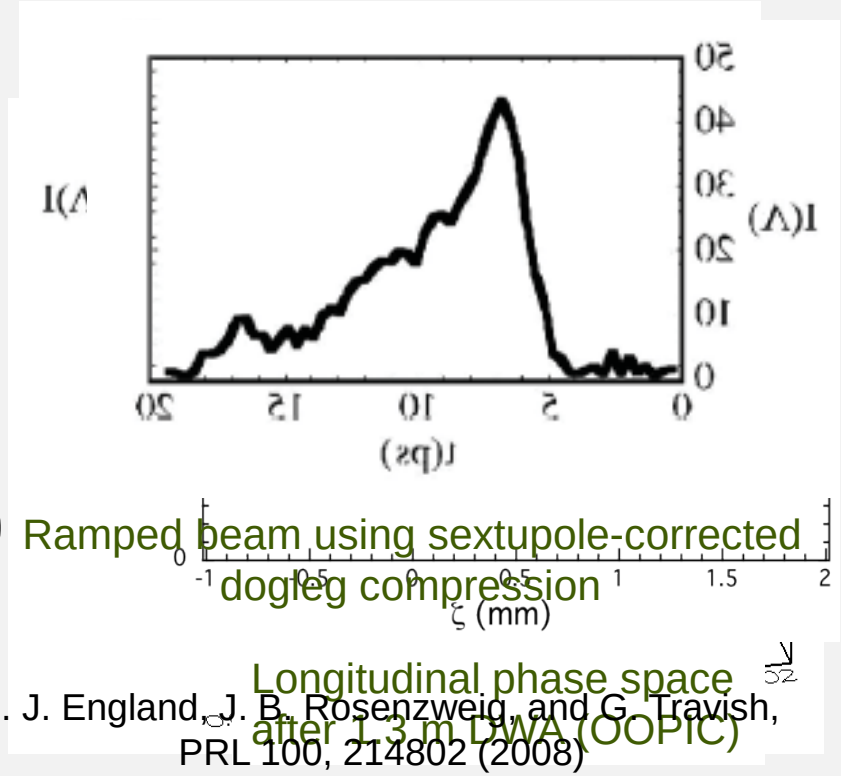
- FEL scenario: 0.5-1 GeV ramp driver; 5-10 GeV X-ray FEL injector in <10 m
  - Matches length of *advanced undulator*





Example: DWA-driven 5th generation light source

- Beam parameters: Q=3 nC, ramp L=2.5 mm, U=1 GeV
  Possible at SLAC FACET
- Structure: a,b=100,150 μm, ε=3.8; fundamental @ f=0.74 THz
- Performance: E_z>GV/m, R=9-10
- Ramp achieved at UCLA, BNL
- Enables hard X-ray source w/high average power, small footprint?



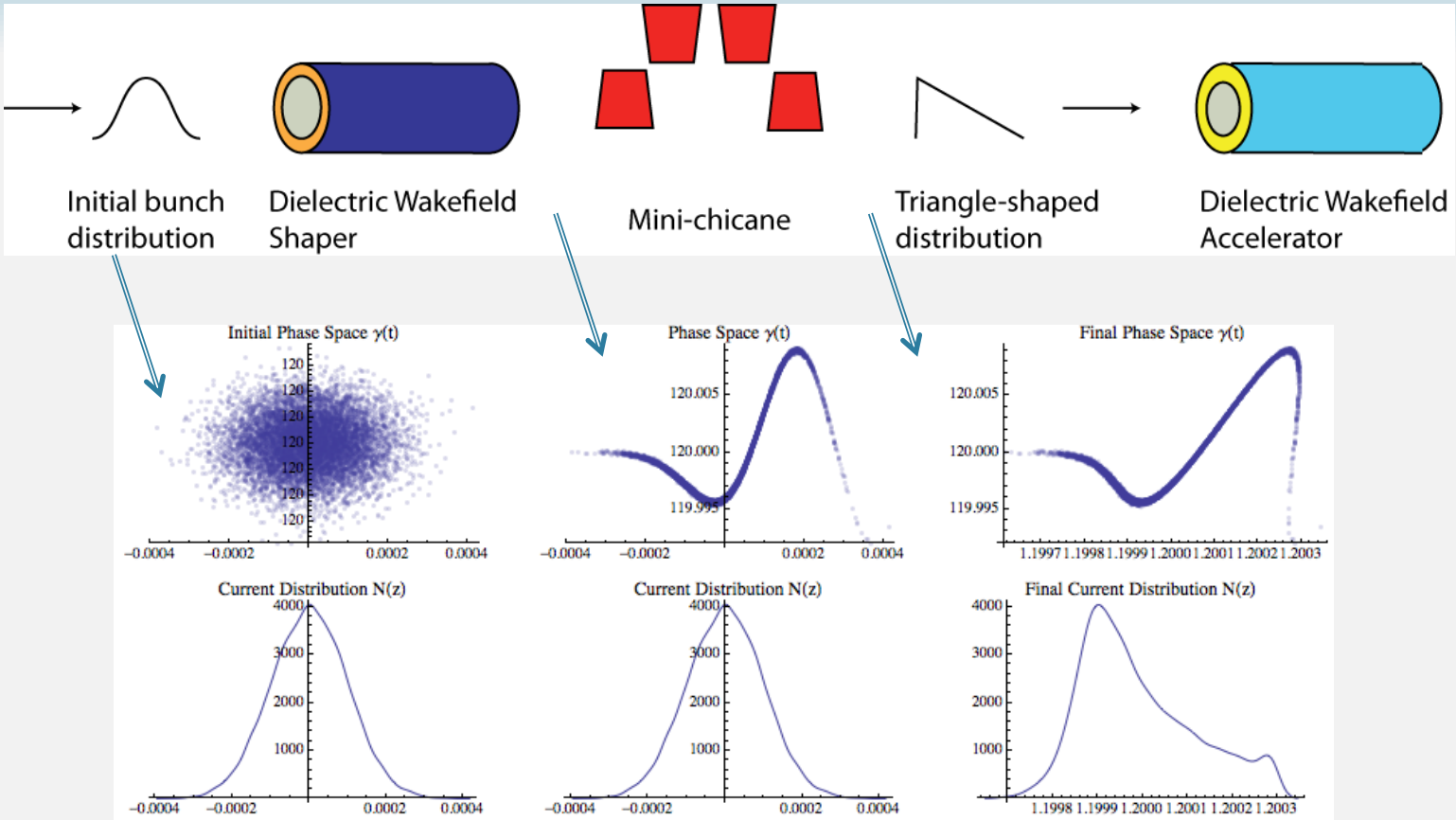
Ramped beam using sextupole-corrected dogleg compression

Longitudinal phase space after 1.3 m DWA (OOPIC)

R. J. England, J. B. Rosenzweig, and G. Travish, PRL 100, 214802 (2008)

Longitudinal wakefields with ramped beam

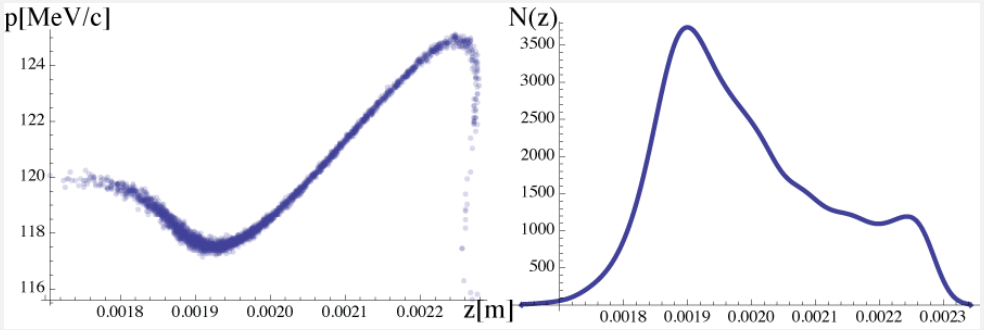
Bunch shaping using self-wakefields



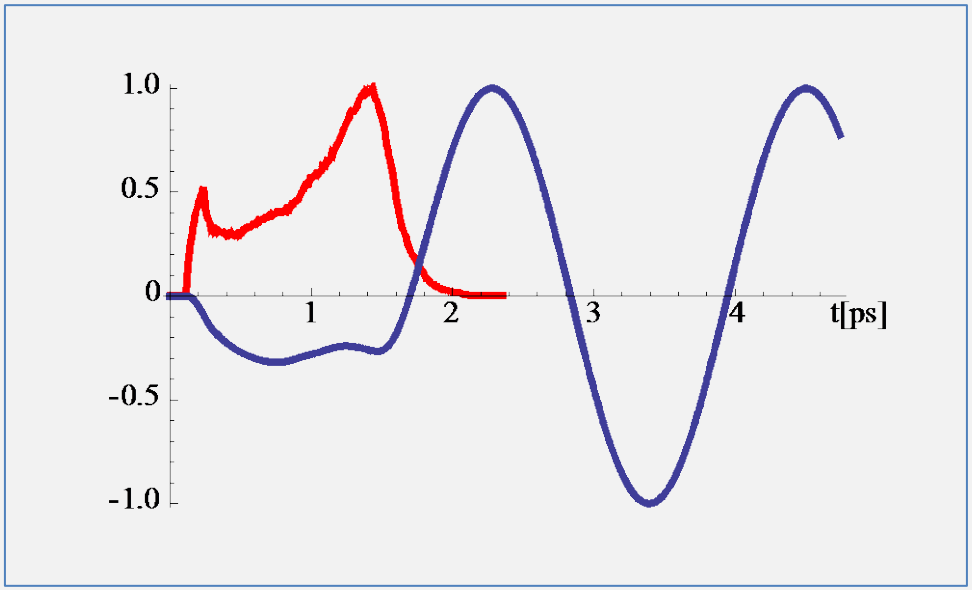
- Design knobs: ID, OD, material, geometry (e.g. planar w/ variable gap)
  - Choose $\lambda \sim \sigma_z/3$
- Also useful for PWFA
- Similar layout used for bunch trains - Antipov, PRL 111, 134802 (2013)

Wakefield shaping outlook

- Phase space for BNL ATF parameters
  - 300pC, σ_z~100µm
  - DWA: 2a/2b=200/340µm, f=0.9THz, L=1cm
  - R56 <4mm



- Mimics ramped dist. w/ "doorstep"
  - Nearly constant Ez w/in bunch
  - Further optimization
  - Expt at BNL ATF
    - TCAV measurement



Summary

- *Progress* in demonstrated gradient
- New photonic structures,
  - needed for high frequency
- On to witness beam (next run), pulse shaping at FACET
  - New scheme test at BNL
- Structure losses, deflecting modes
- Begin to utilize applications (THz)
  - Makes field more rapidly mature