Dielectric wakefield acceleration: application to linear colliders

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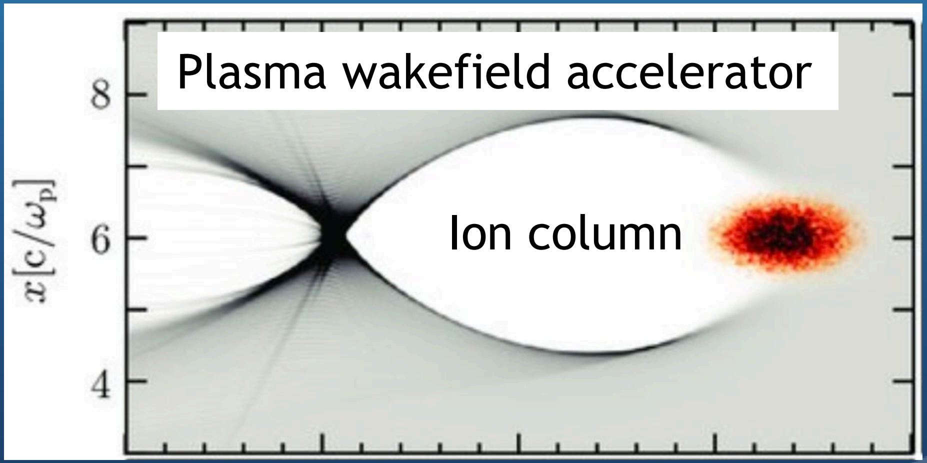
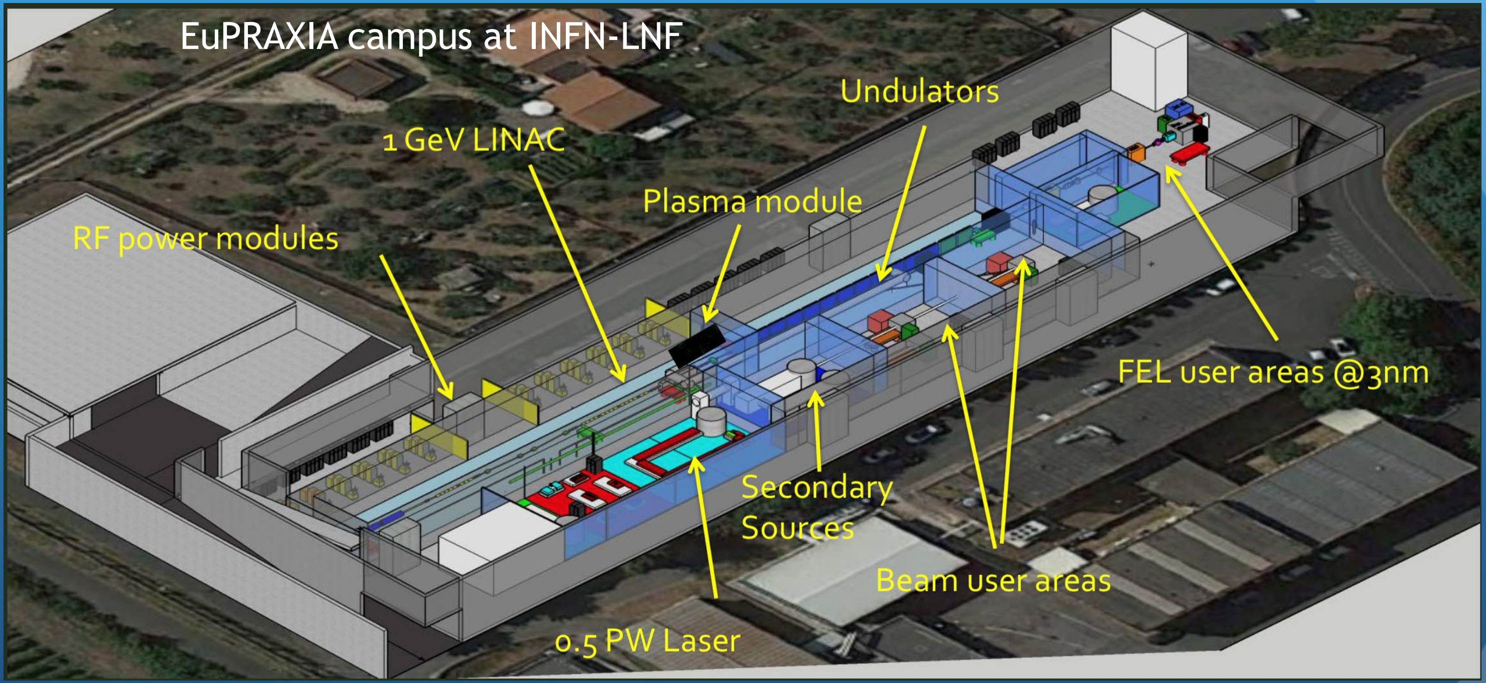
Wakefield accelerators are now key candidates for TeV colliders

- Beam (or laser) driven
  - Any slow wave medium supports wave, $v_\phi \sim c$
- Short wavelength goes hand in hand with high gradient
- Emerging technology – need a “stepping stone” to future application



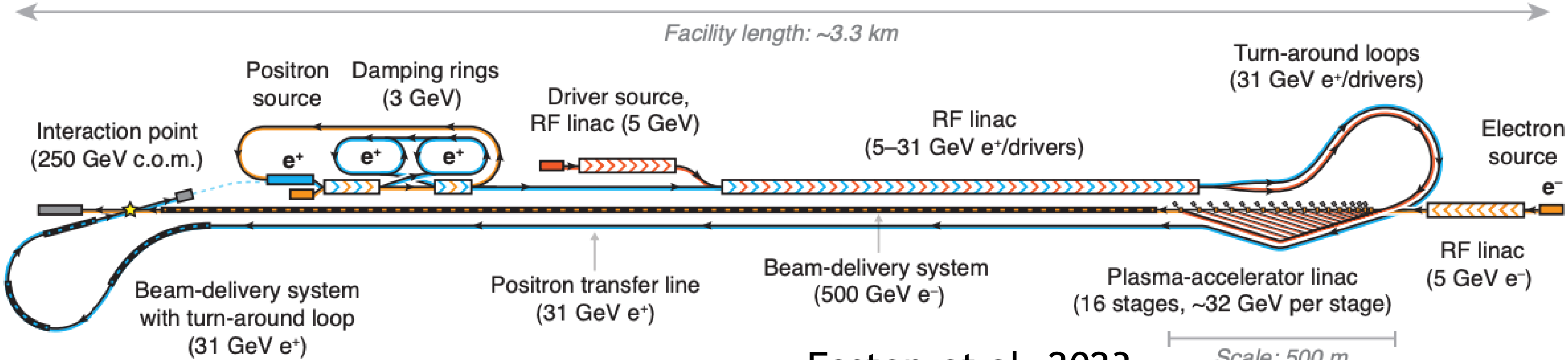
PWFA-based FEL as stepping stone

- *EuPRAXIA* plasma accelerator-based FEL, **first dedicated facility**
- Test bed for fundamental science challenges of PWFA in application



Good news for light sources. Is this enough for the HEP community?

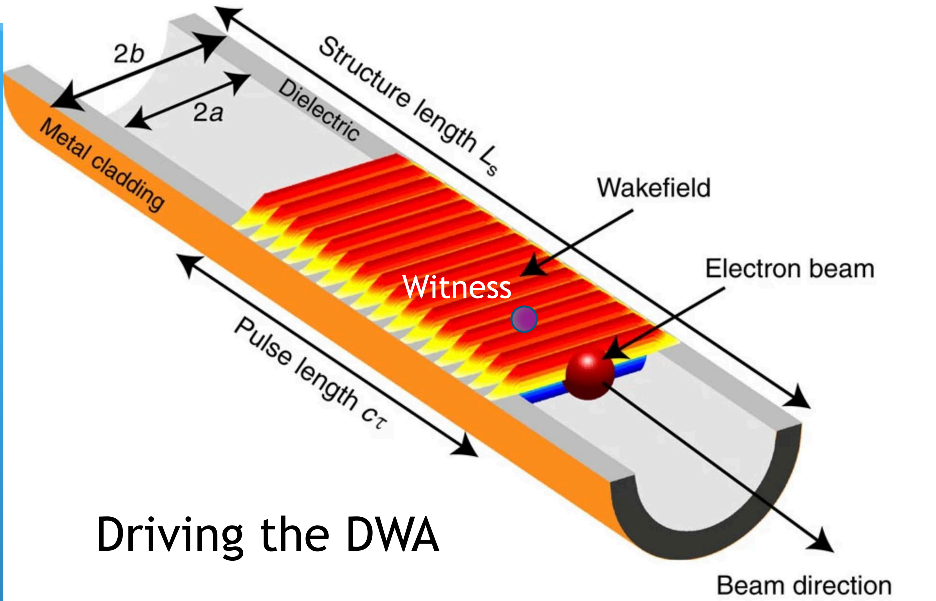
Hybrid, asymmetric linear Higgs Factory (HALHF)



Foster, et al, 2023

- Higgs factories are an urgent issue in HEP
- Avoids positron issue in PWFA via use of RF linac
- Asymmetric design minimizes footprint, adapts current detectors
  - 31 GeV e+ on 500 GeV e-
- *Examine use of DWA on the e+ side (or both). Symmetric collider?*

Dielectric wakefield acceleration: overview



Driving the DWA

- "Traditional" DWA capillary tube is scaled THz linac
  - Diverse, and more elaborate, structures possible
  - Coherent Cerenkov emission into TW guide mode
  - *Agnostic to charge*
- *THz operation possible*
  - Single bunch or resonant operation (sub-psec driver)
  - Unique THz source (reach nearly 1 Joule)
  - Over GV/m before breakdown (with caveats)

Dielectric loaded waveguide modes

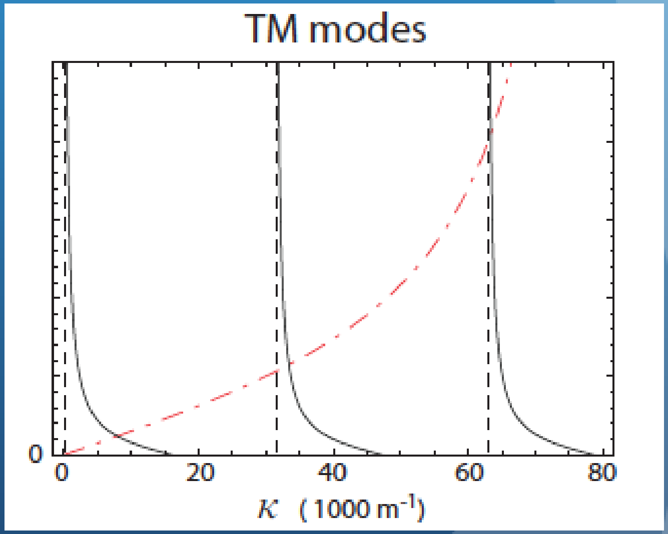
- Accelerating modes TM_{0n} in hollow capillary within tube
- Simple application of dielectric and metal boundary conditions
- Dispersion relation in the two regions:

$$k_\rho \cong k_z \times \begin{cases} 0, & \text{in vacuum tube} \\ \sqrt{\varepsilon - 1}, & \text{in dielectric} \end{cases}$$

$$k_z \cong \omega / c, \qquad \beta \to 1.$$

- Frequencies are sol'ns of Wronskian transcendental equation:

$$J_1\left(k_{\rho,n} b\right) N_0\left(k_{\rho,n} a\right) - J_0\left(k_{\rho,n} a\right) N_1\left(k_{\rho,n} b\right) = 0$$



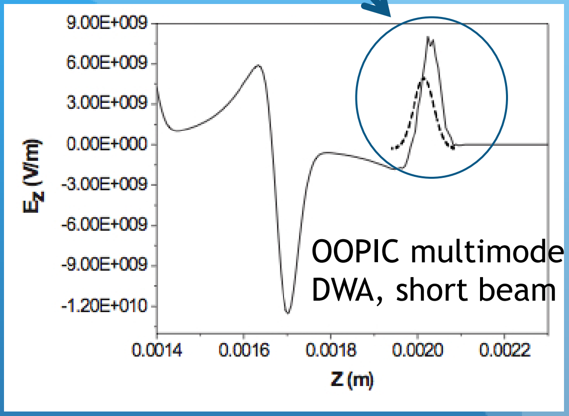
Note: $k_{zn} \sim k_{z1} \times 1,3,5\ldots$

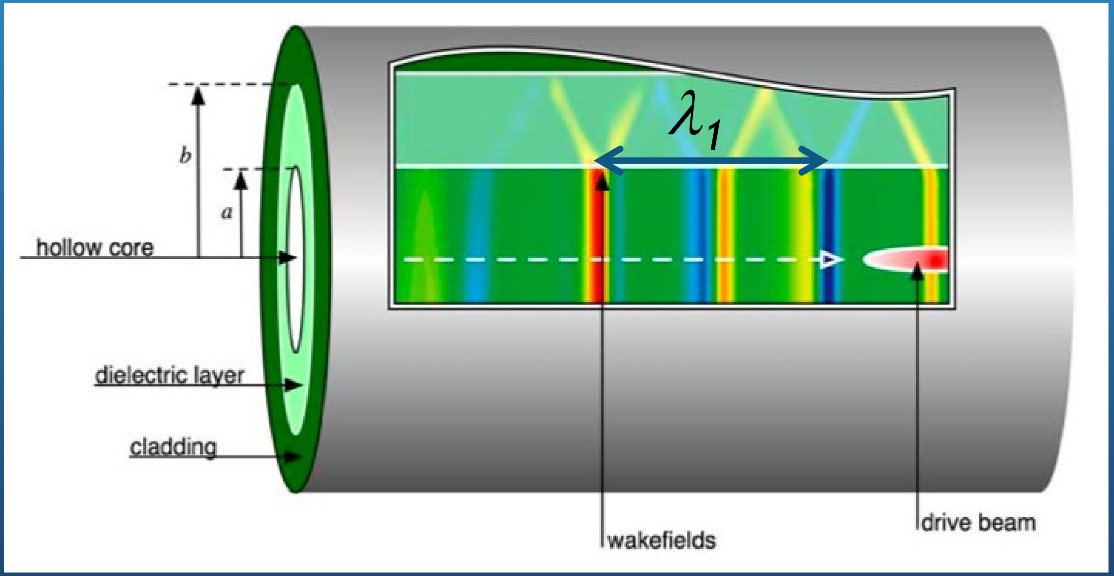
Quasi-optical model: λ

- Geometrically, the accelerating modes in

$$\lambda_n \approx \frac{4(b-a)}{n}\sqrt{\varepsilon-1}, \quad n=1,3,5...$$

Note, multi-mode wake follows $I(\zeta)$





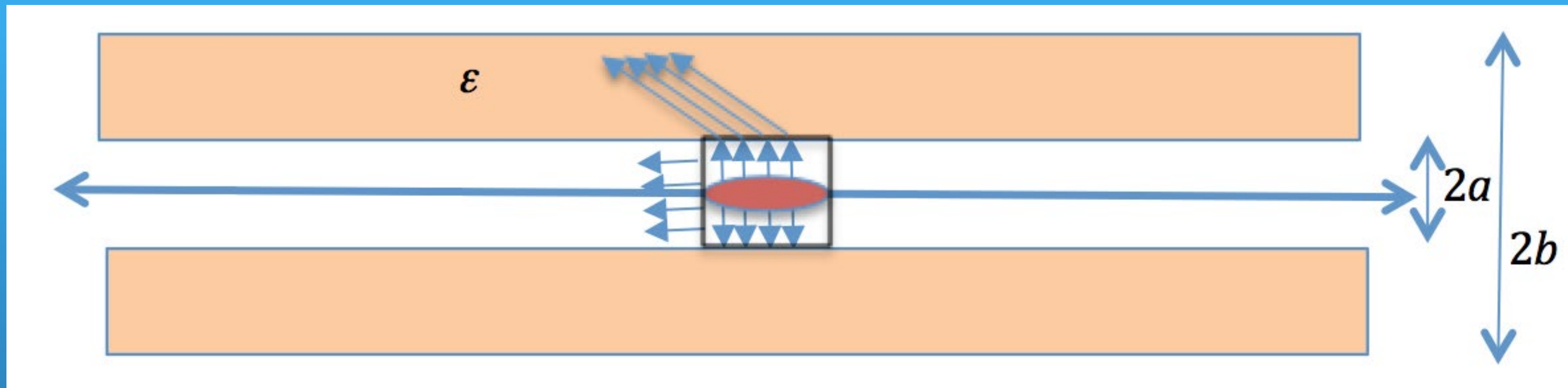
Fundamental is determined by bounce of Cerenkov radiation twice between *b* and *a*

Angle given by Cerenkov:

$$\tan\theta_c = \sqrt{\varepsilon-1}, \; n=1,3,5...$$

$$\tan\theta_c = k_\rho / k_z \text{ checks}$$

Quasi-optical energy loss



- Gauss' law in pill-box, plus Cerenkov condition, yields *decelerating* field coupling

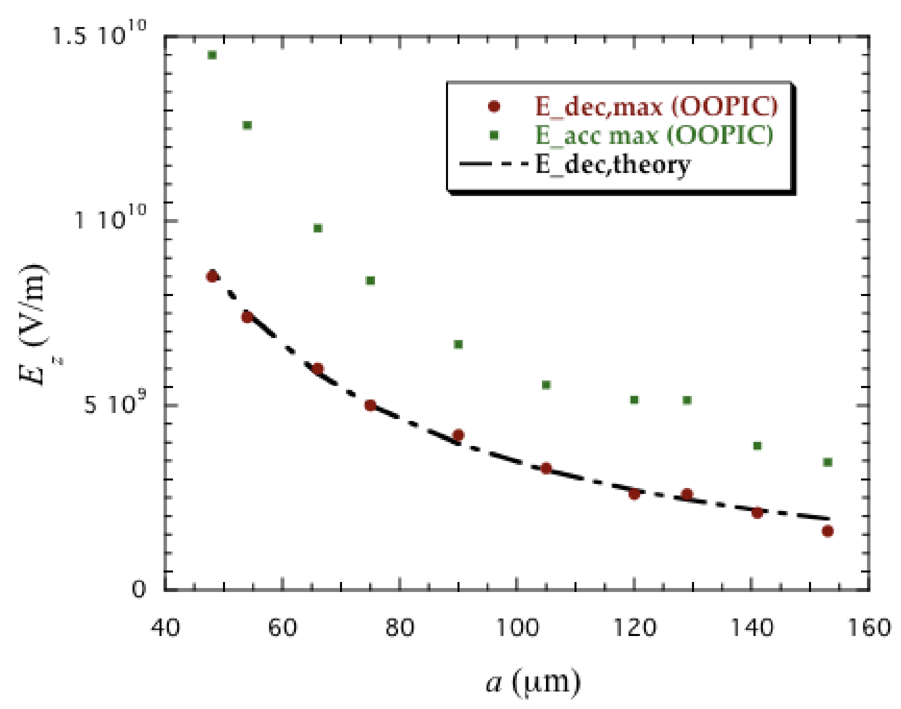
See HW

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

High quality beam needed, small σ_z and a (emittance)

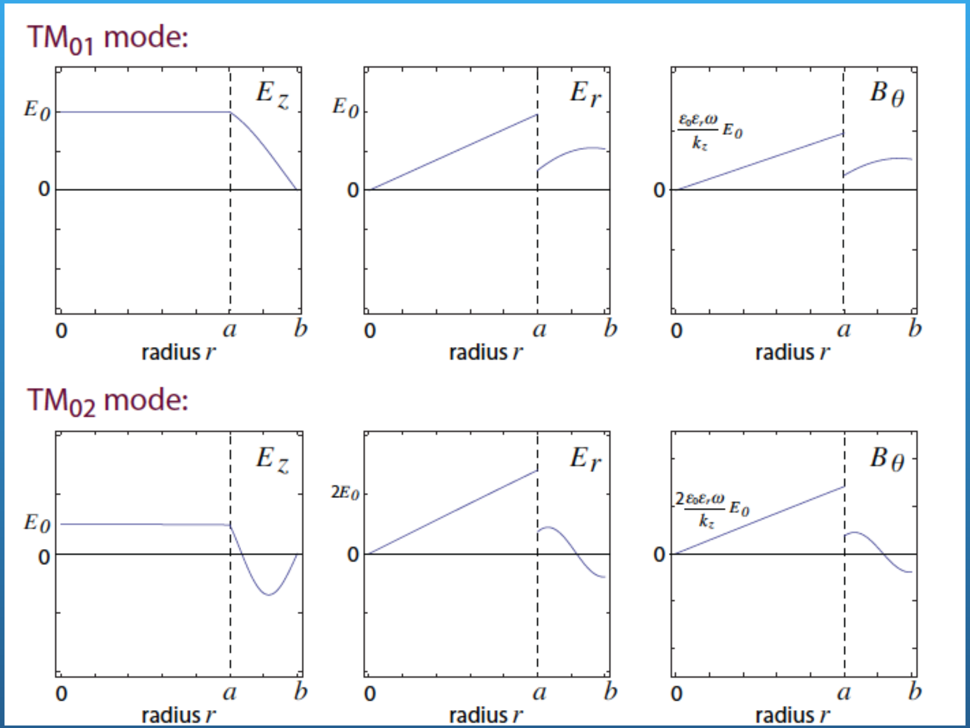
- With $a \propto \lambda \propto \sigma_z$ we recover <u>*Cerenkov scaling*</u> $eE_{z,dec} \propto \frac{N_b}{\sigma_z^2}$

Benchmark to simulation



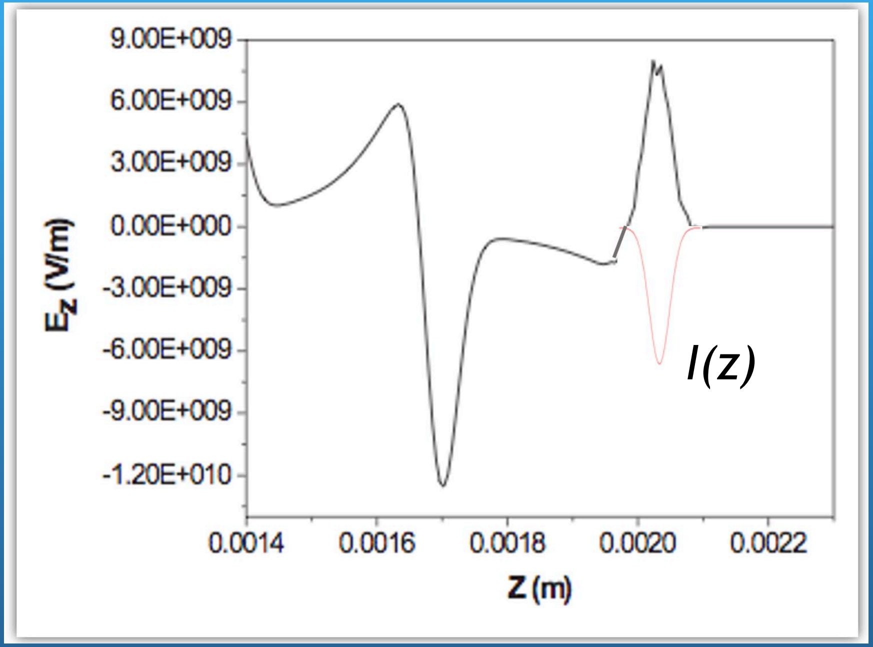
- Excellent agreement with 2D PIC codes
- Quick estimates of operating conditions available

Axisymmetric DWA Mode profiles, full wave picture



- Transverse E_z variation ($k\rho \neq 0$) exists only in dielectric
- Panofsky-Wenzel adhered to; *no net monopole focusing*
- Dipole coupling to HEM mode strong. Other multipoles?

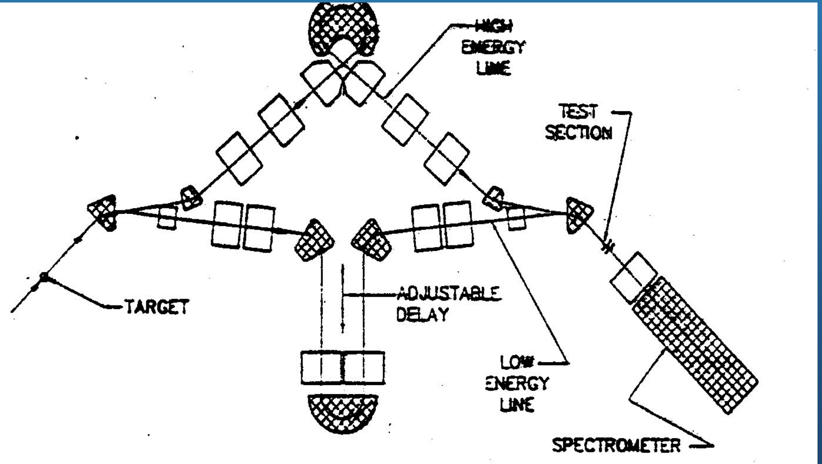
Multi-mode DWA gives "surprising" wake



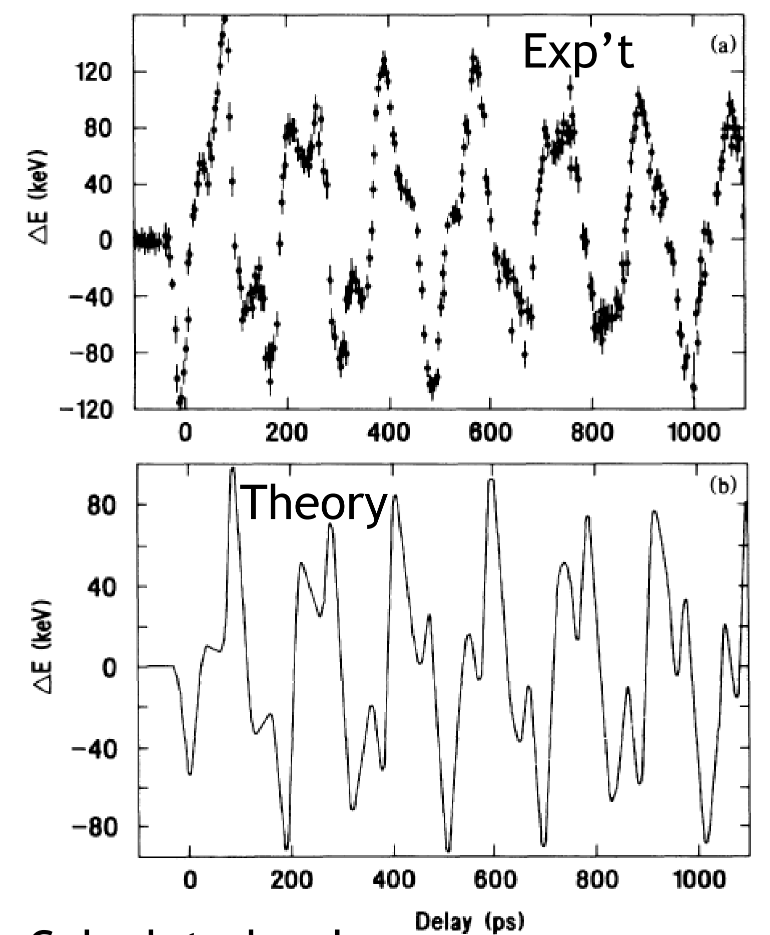
- Single mode akin to linear PWFA – E_z is convolution of I
- Longitudinal wake follows form of drive current in multi-mode
  - Exploit when we look at focusing/defocusing effects

DWA experiments: origin story

- Fundamental (GHz), harmonics observed with drive-scanning witness beam at Argonne (1988)
- Same facility as PWFA POP expt
- Less than 1 MeV/m gradient
- High charge; large *a*, σ_z=1 cm
  - Cerenkov scaling not exploited



AATF drive-witness beam scheme

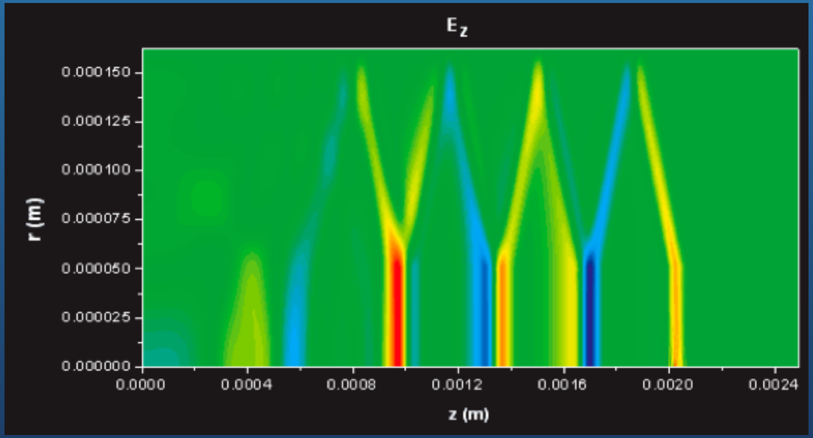


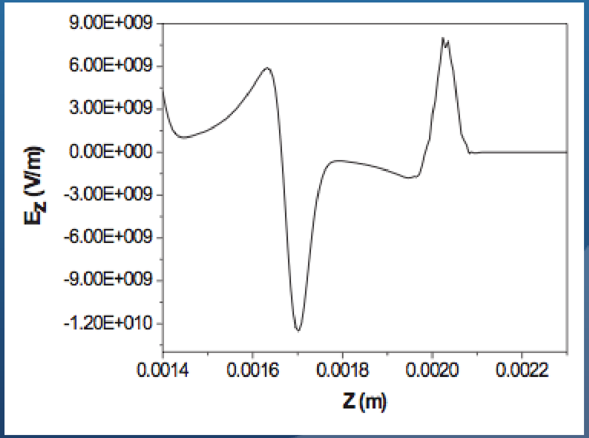
Calculated wakes

SLAC FFTB gives ultra-high gradient opportunity

- Excellent beam for DWA: 3 nC, $\sigma_z \sim 20$ μm (65 fs), $\sigma_x \sim 20$ μm, U=28.5 GeV, a=50-100 μm, ε=3.8
- New frontier in DWA, to the breakdown frontier
  - Quasi-optical estimate of decelerating field $eE_{z,dec} \cong 7.9$ GeV/m
  - Corresponds to (multi-mode) OOPIC simulations

$$eE_{z,dec} \cong 7.9 \text{ GeV/m}, \ eE_{z,acc} \cong 12 \text{ GeV/m!}$$





T-481 @ SLAC: exploring limits of dielectric breakdown in ps/THz regime

1^{st} DWA with ultra-short, high Q beams

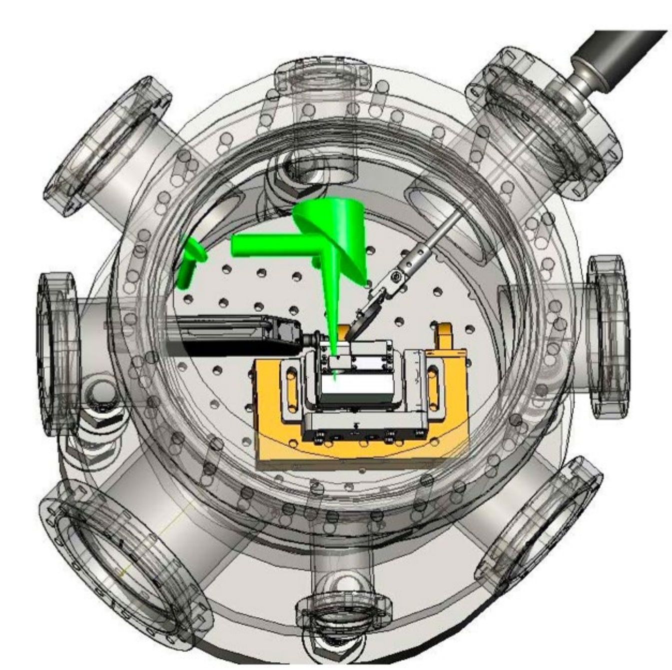
Leveraged off E167 PWFA at FFTB

- Excellent beam 3 nC, $\sigma_z \geq 20$ μm, 28.5 GeV

Goal: THz breakdown studies

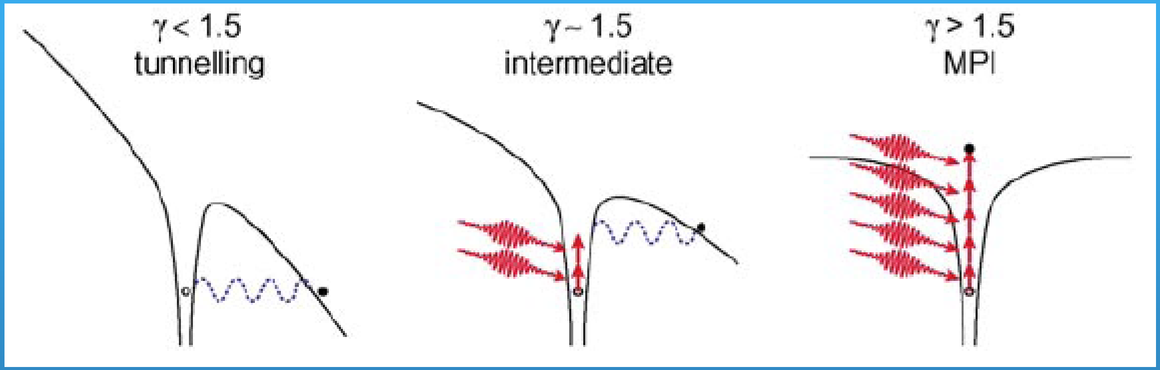
- Al-clad fused SiO_2 fibers
  - ID 100/200 μm, OD 325 μm, L=1 cm
- Avalanche (MPI) v. tunneling ionization

Prediction of E_z =12 GV/m *much higher than optical-IR limit* (DLA)



"Octopus" chamber
DWA holders, CCR collecting horn and transport, optical inspection

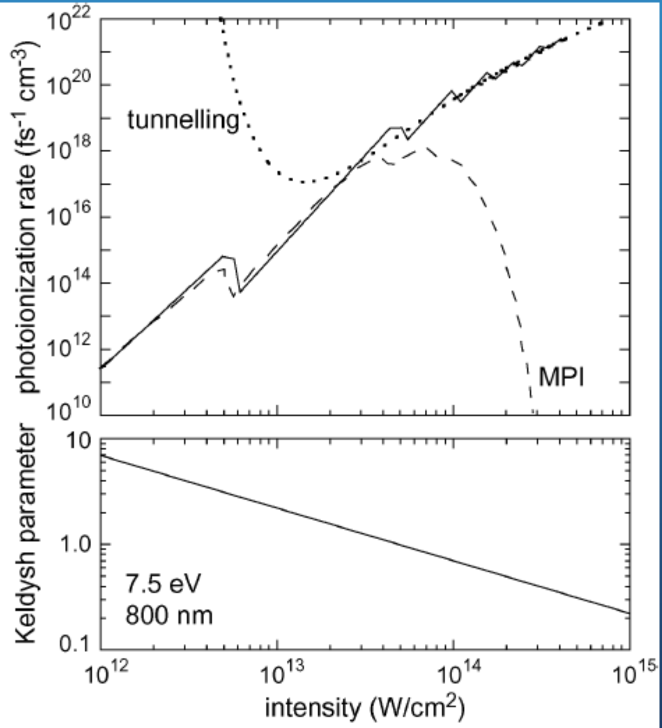
Breakdown in optical-to-mid-IR



Large distortion of electronic states pre-breakdown

- Tunneling and multi-photon ionization present
- Controlled by Keldysh parameter (unified theory of MPI/tunneling)

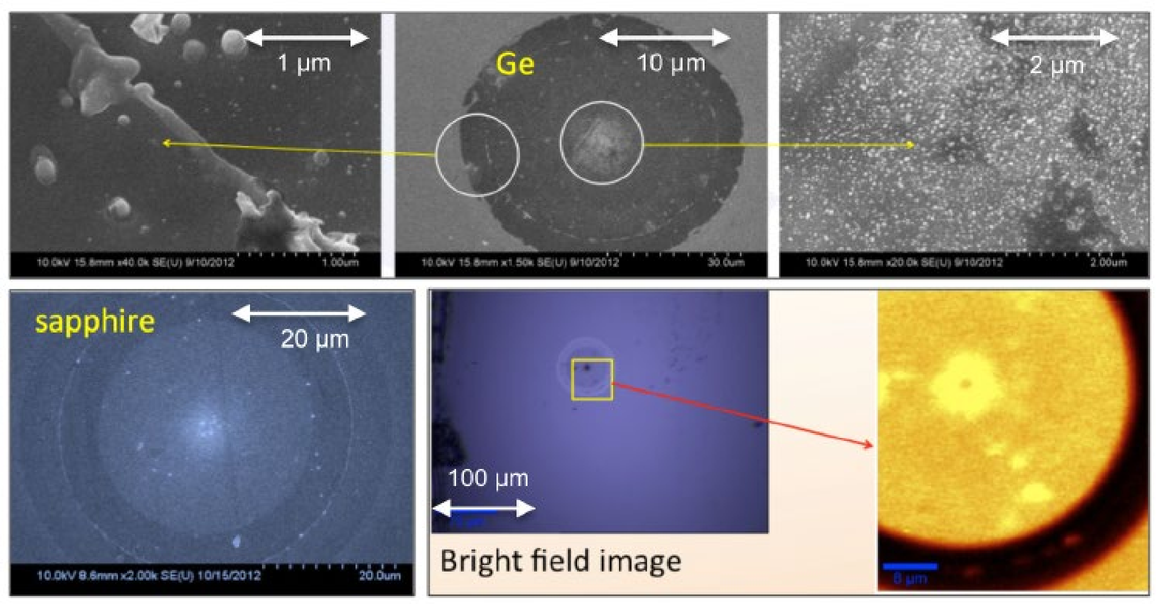
$$\gamma = \frac{\omega}{e}\left[\frac{mcn\varepsilon_0 E_g}{I}\right]^{1/2}$$



Optical-IR ionization dominated by MPI γ~3

Mid-IR laser results emphasize MPI elimination when $h\nu << E_{gap}$

- 5 um (60 THz) light, 5 ps FWHM illumination
- Relevant to DWA (long pulse)

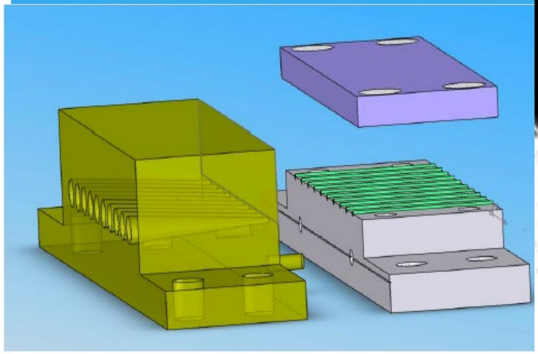


Si threshold: 400 MV/m!
Sapphire: 2 GV/m

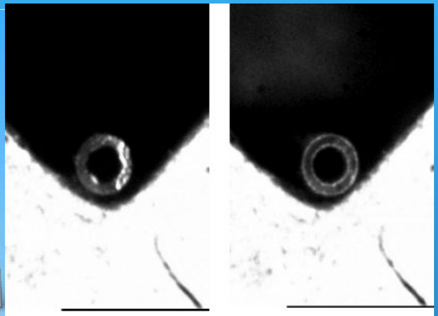
High ratio of bandgap to photon energy promising

Material	Germanium	Silicon	Sapphire
Band Gap (eV)	0.67	1.1	8.7(e)/8.8(o)/9.9 direct
Peak Fluence [J/cm^2]	0.44 ± 0.04	0.58 ± 0.04	14.0 ± 0.6
Damage Threshold [J/cm^2]	0.22	0.29	7.0

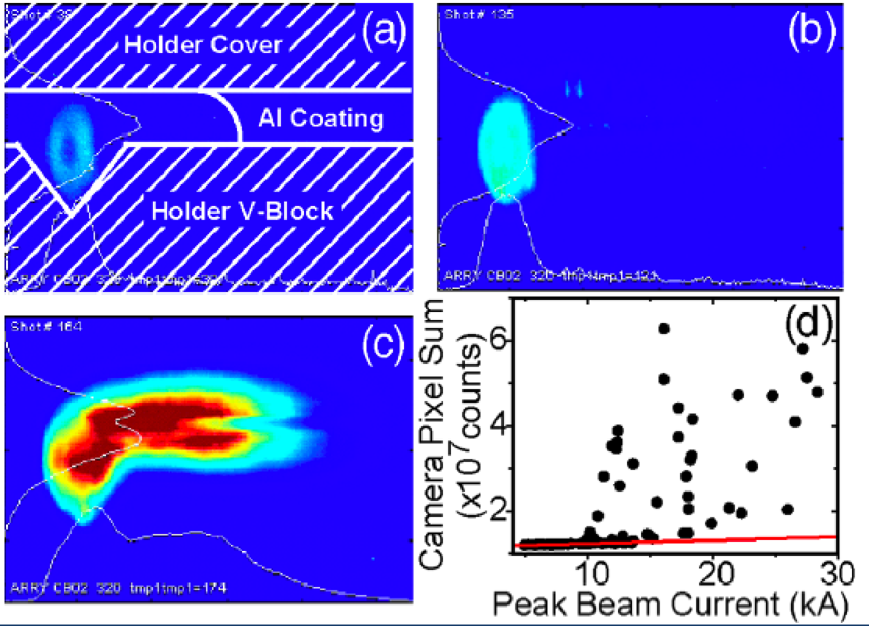
T481 Methods and Results



CAD rendering of the capillary tube mounting



Fiber viewed end on with a microscope. Unpolished at left and polished at right.



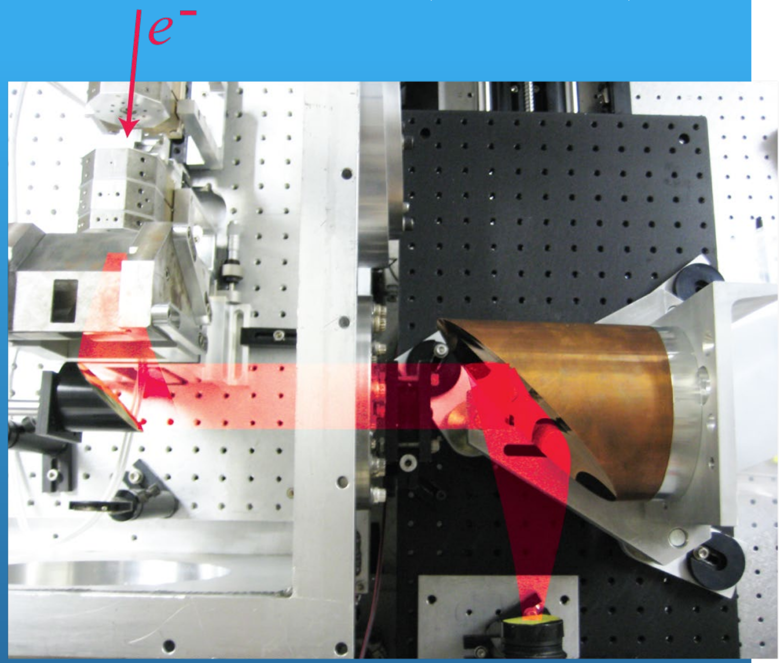
- Multiple tube assemblies
- Scanning of bunch lengths for wake amplitude variation
- *Vaporization of Al cladding… dielectric cladding needed*
- Observed breakdown threshold (field from simulations)
- Correlations to post-mortem inspection

♦5.5 GV/m deceleration field (sim.)
♦13.8 GV/m surface field!

M. Thompson, et al., *PRL* 100, 214801 (2008)

Coherent Cerenkov Radiation (CCR)

- For direct mode/field measurement – on to CCR
- FFTB closed 2006, FACET appears 2010
- Use UCLA Neptune for CCR
- Chicane-compress to 200 μm, 0.3 nC beam focused with PMQs: σ_r~100 μm (a=250 μm)
- *Single-mode* operation
  - Two tubes, different *b*, THz frequencies



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

Physics of narrow band CCR production

- CCR train created at $v_\phi \sim c$
- CCR propagates at $v_g \sim c$
- Length of pulse in DWA

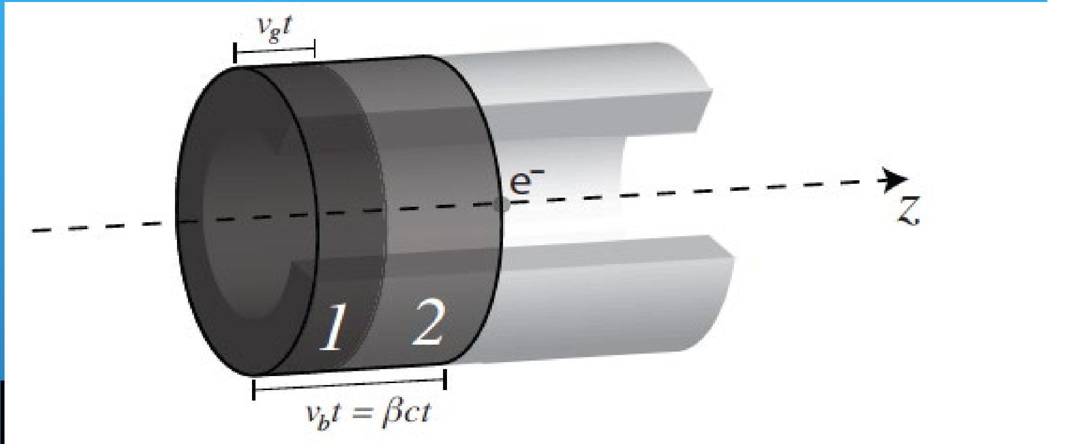
$$L_{DWA} = L\left(1-\beta_g\right)$$

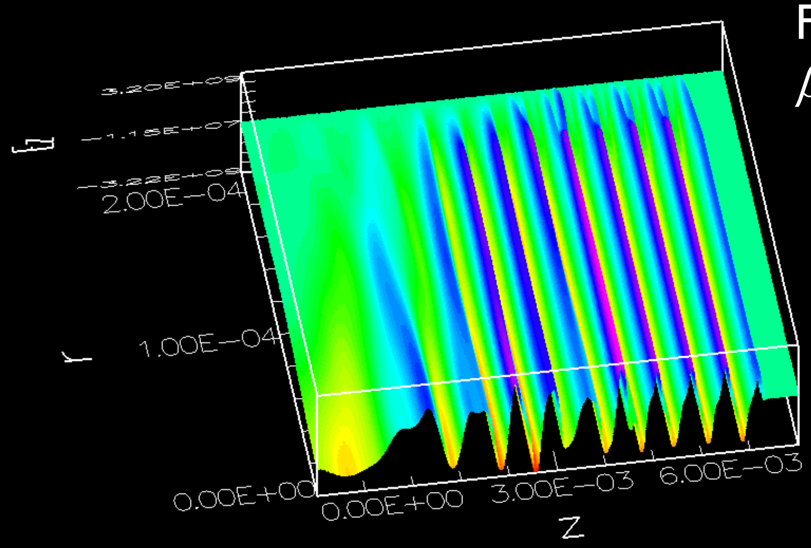
- Taking into account time to empty DWA, CCR wave train has length

$$L_{CCR} = L\frac{\left(1-\beta_g\right)}{\beta_g}$$

- Very narrow BW for apps!

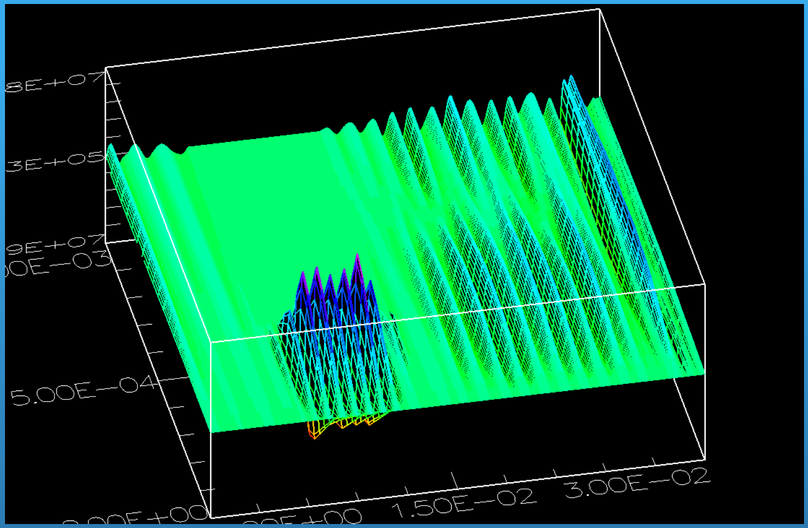
$$BW = \frac{\beta_g}{1-\beta_g}\left(\frac{L}{\lambda}\right)$$





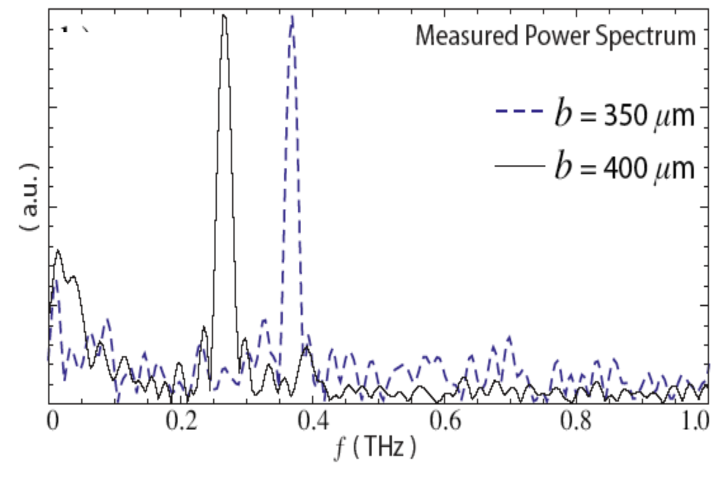
FACET case
β_g~0.25

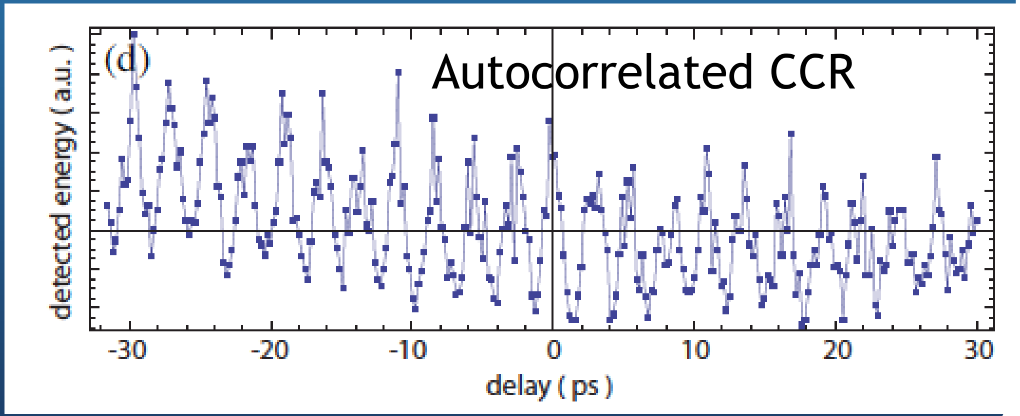
Narrow band, *low-loss* THz produced



Impedance matching reduces strong reflection

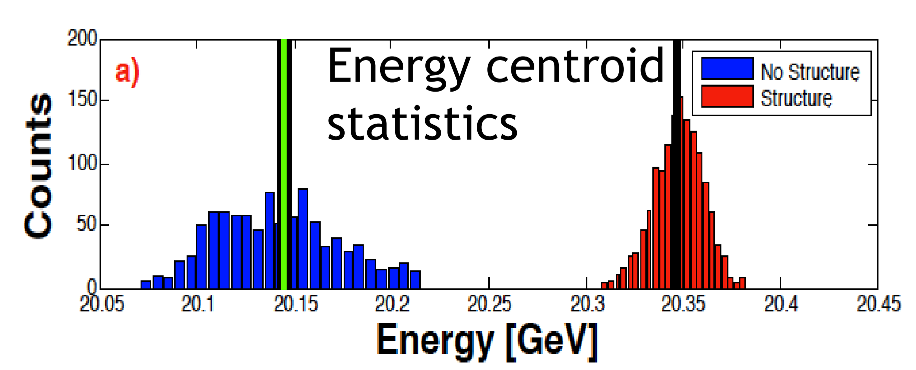
- Optimized launcher employed
- BW measurement limited
- Negligible damping observed
  - Valid at ~MV/m fields
  - Revisit at GV/m…
- 10 uJ collected (~50% transport efficiency)

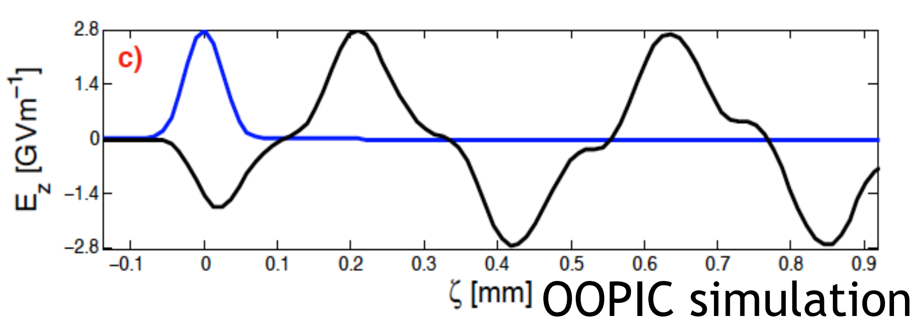




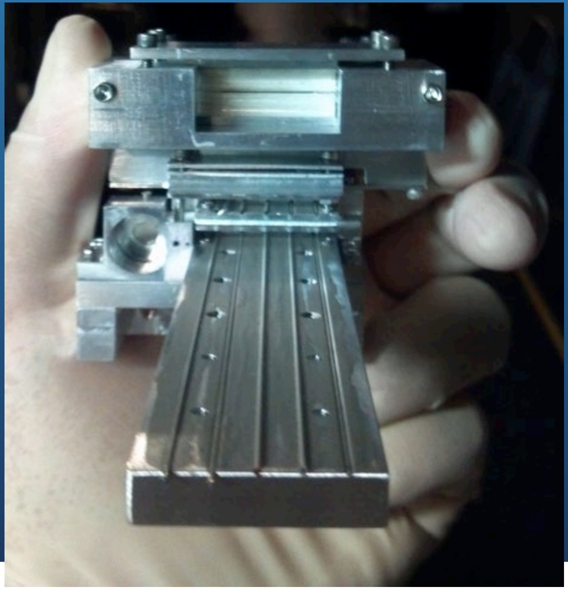
Pushing the frontier in DWA gradients: E201 at SLAC FACET

- Recover FFTB capabilities
- 3 nC, ~30x30 um beams
- 15 cm long structures
- >2 GeV/m deceleration
  - 2.8 GV/m peak wake
- *0.9 J deposited in CCR*





Energy changed by over 300 MeV in 15 cm

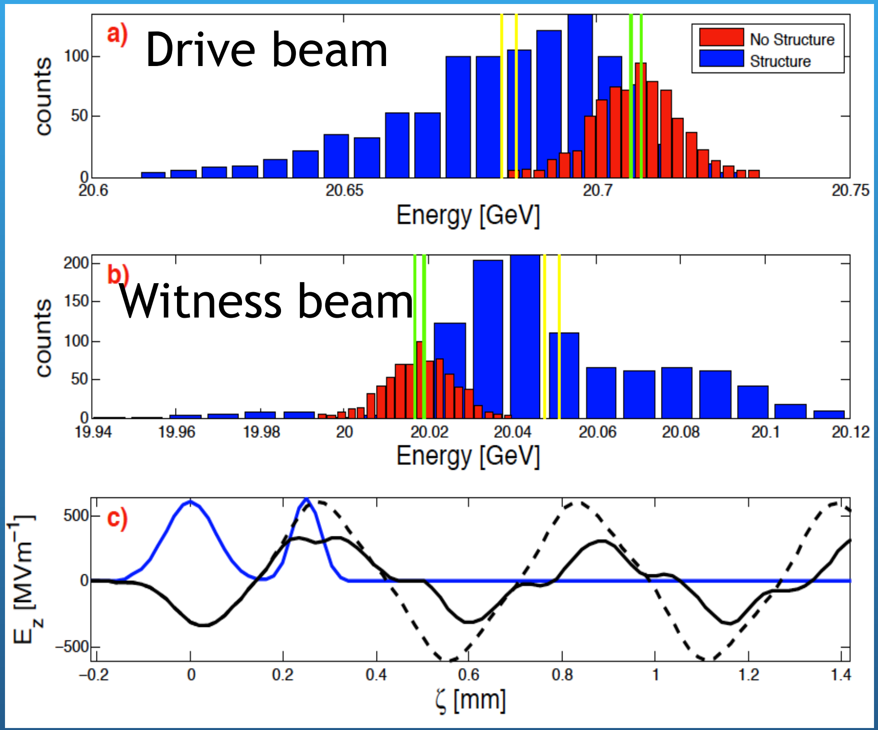


SiO_2 300 μm ID, 400 μm OD tubes

Acceleration with "witness" beam

- Shared charge between drive (1.6 nC) and witness (0.9 nC)
- 10 cm stuctures
- Lower gradients (640 MV/m)
- Loaded gradient 320 MV/m
- Efficiency of energy transfer to witness measured at 76%!
  - Consistent with gradient measurement

$$\eta = 1 - \frac{u_{EM,\mathrm{Load}}}{u_{EM,wave}} \propto 1 - \frac{E^2_{\mathrm{Load}}}{E^2_{\mathrm{wave}}} = 0.75$$

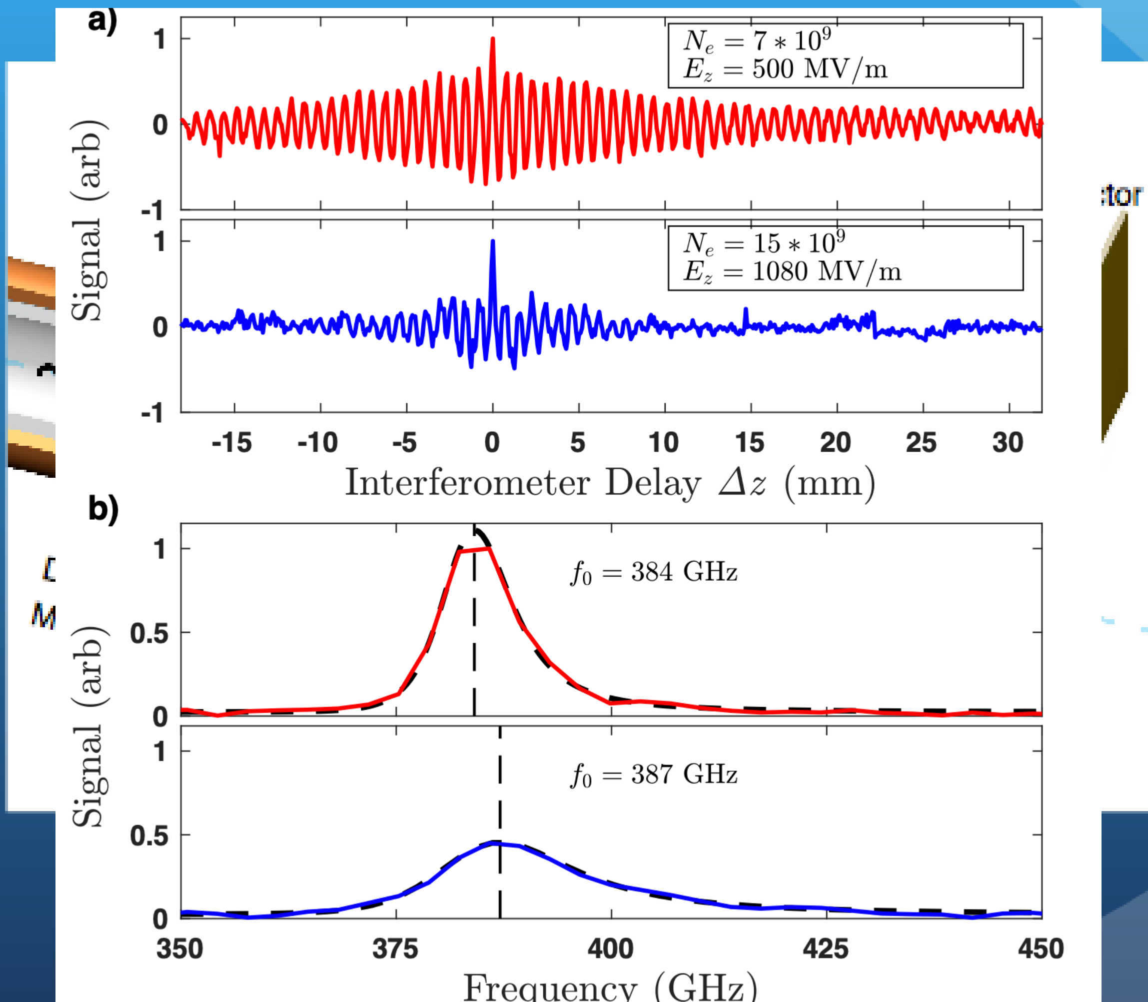


Theoretical prediction for wakefields

See B.O'Shea, *et al.*

Discovery of high-field damping

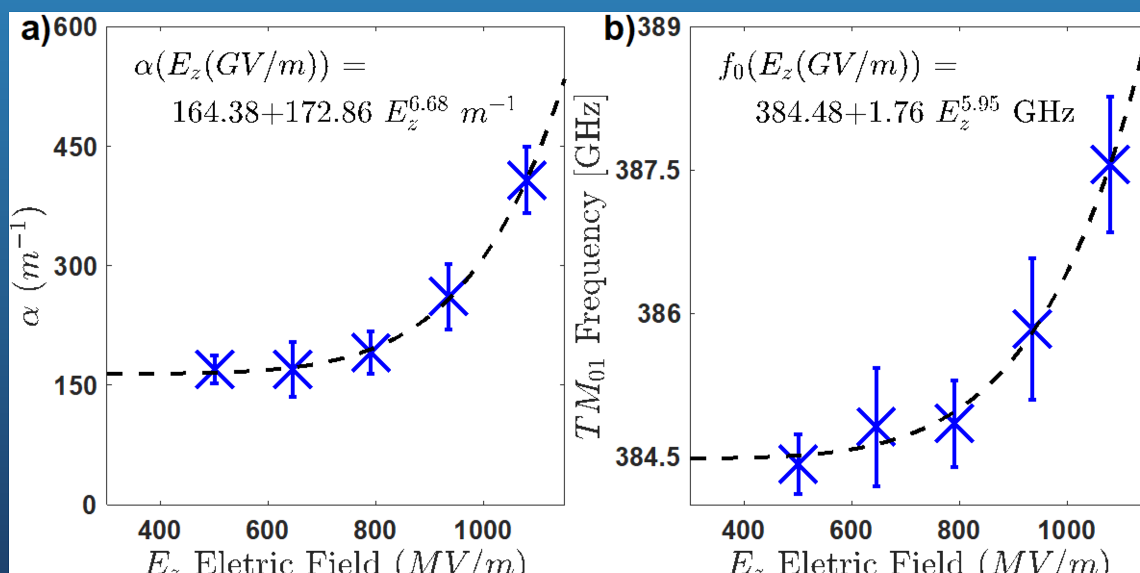
- CCR measurements at FACET show anomaly at >1 GV/m



Physical mechanism: high-field induced conductivity

- Systematic study yields onset of high field effects above ***800 MV/m*** **acceleration gradient**
  - Ponderomotive energy at THz $\sim E^2\lambda^2$ above keV,
  - impact ionization efficients

- Higher band-gap material offers improvement, …



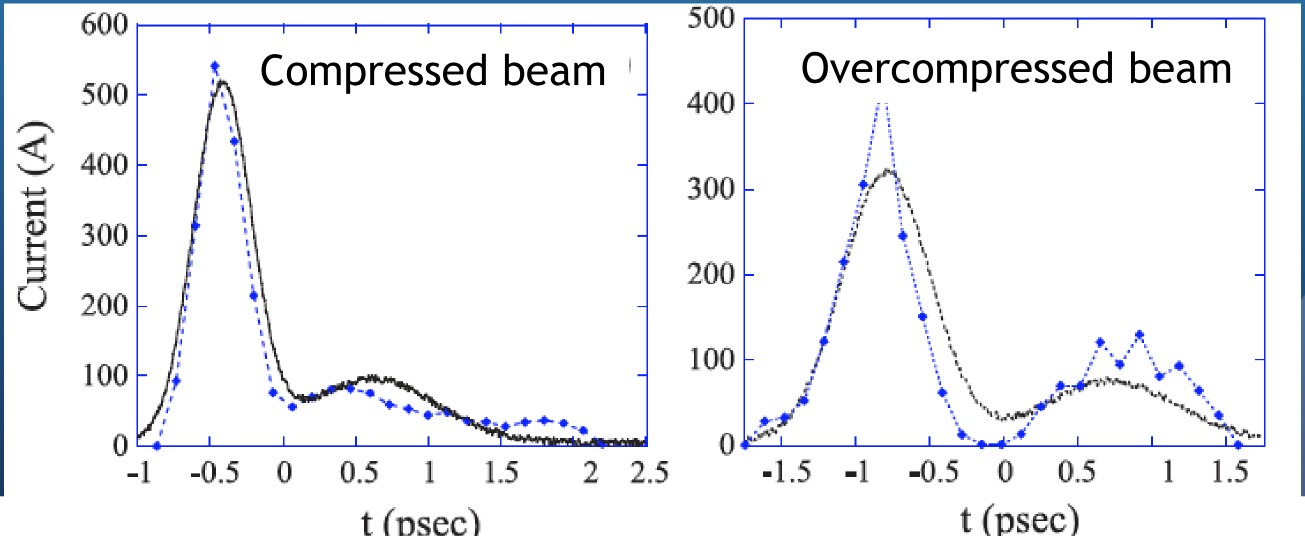
B. O'Shea, et al., Nature Comm. 7, 12763 (2016)

Temporal analysis of THz autocorrelation

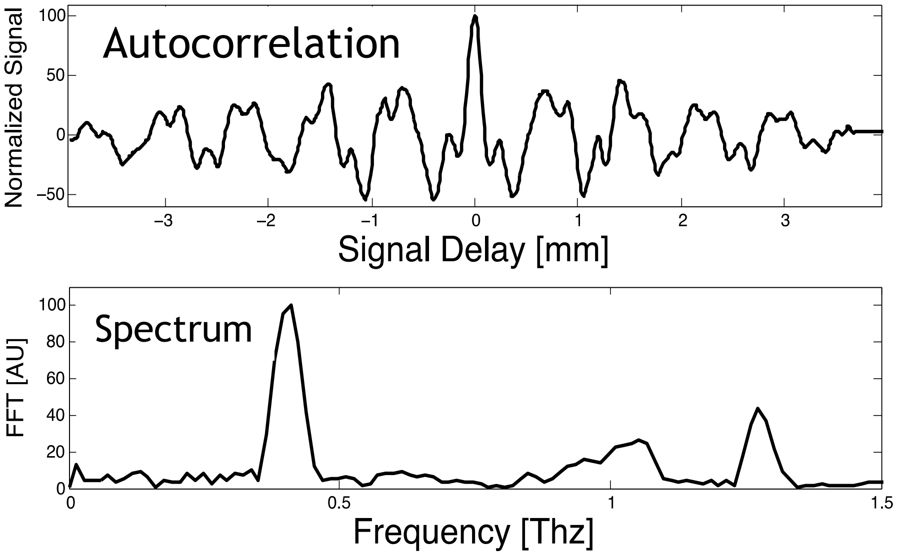
- With appropriate knowledge of spectrum from autocorrelation, one can retrieve phase
- Robust Kramers-Kronig algorithm uses minimal phase assumption

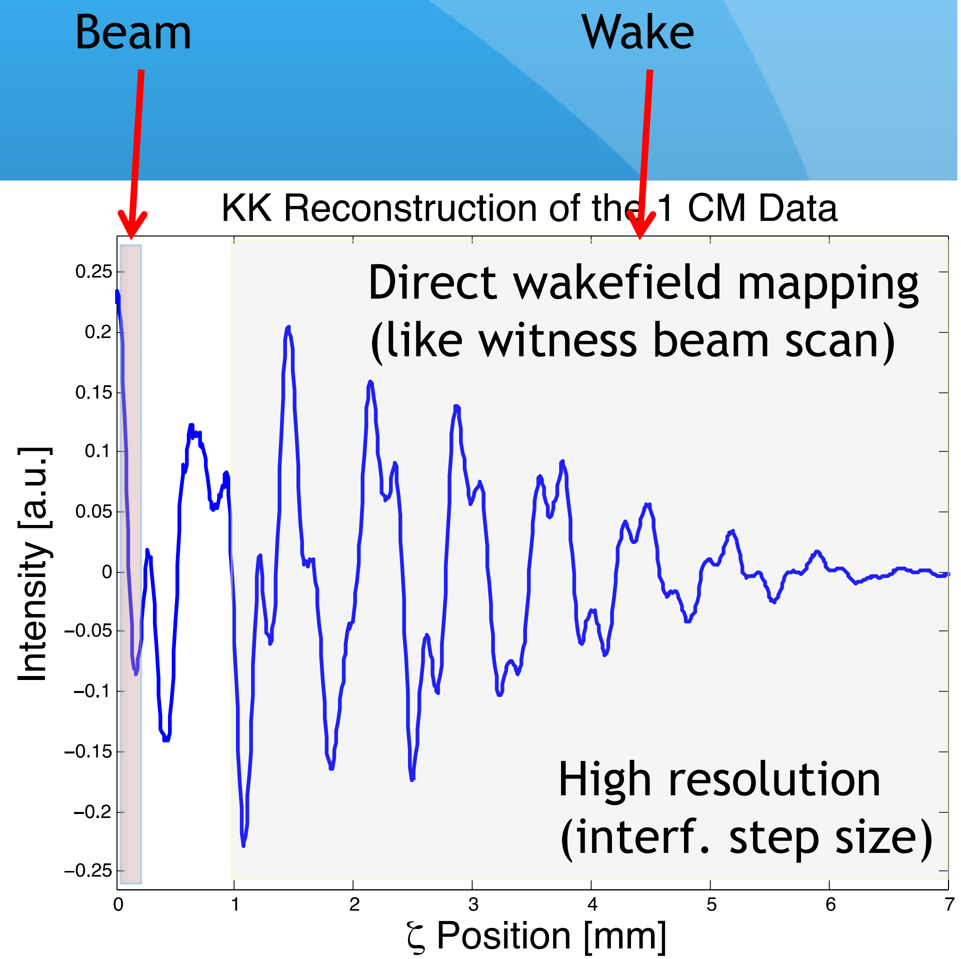
$$\psi(\omega) = -\frac{2\omega}{\pi} P \int_0^\infty dx \, \frac{\ln[\rho(x)/\rho(\omega)]}{x^2 - \omega^2}$$

- Measured CTR and start-to-end simulated signal compared in bunch compression expt.



Coherent THz-based wakefield map





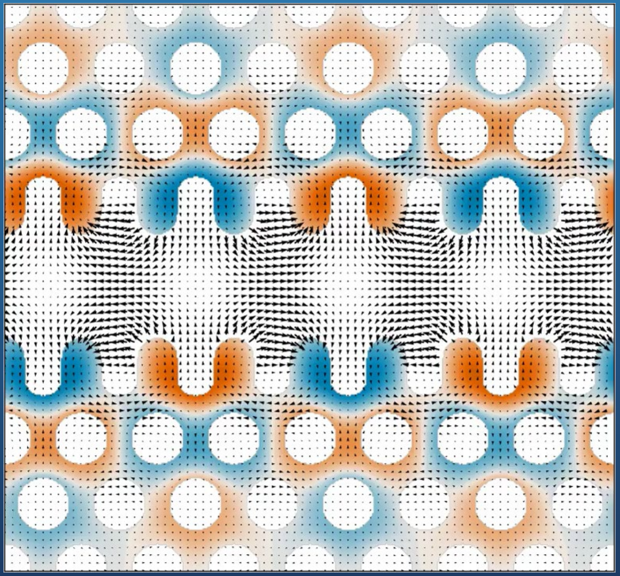
- TM_{01}(400GHz), and TM_{02} (1.2 THz) visible
- 1 cm structure should produce THz pulse >2 cm
- *Strong damping seen directly in time domain*

Key diagnostic for DWA in use

Lowering E-field inside of dielectric

- Dielectric boundary parallel to z produces worst case, tangential E is continuous — maximized
- Shield with modulated boundary, support mode with *normal* entry of field lines. Diminish E by ε^{-1}

Note not only modulation, but photonic confinement, Cartesian symmetry…



Cartesian symmetry in DWA

- Slab symmetry lowers longitudinal, wakes

$$E_{z,n} = E_{0,n} e^{-[x^2/w_{x,n}^2(\zeta)] - ik[x^2/R_n(\zeta)]} \exp[ik_n\zeta + \psi_n(z)]$$

$$E_0 \sim \sigma_x^{-1}$$

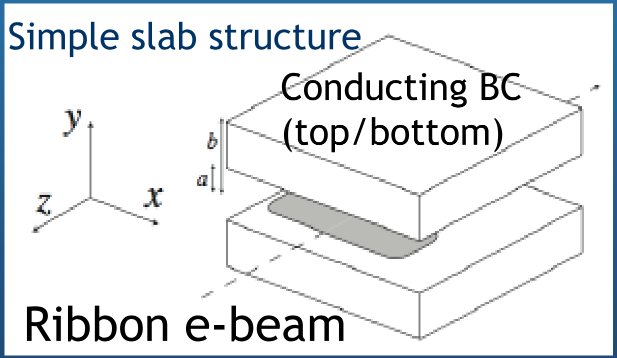
- Slab symmetry mitigates transverse wakes

$$F_{x,n} \equiv qW_{x,n} = q(E_{x,n} - B_{y,n}) = iE_0 \frac{2x}{k_n w_{x,n}^2(\zeta)} e^{-x^2/2\sigma_x^2} \exp[ik_n\zeta + \psi(z)],$$

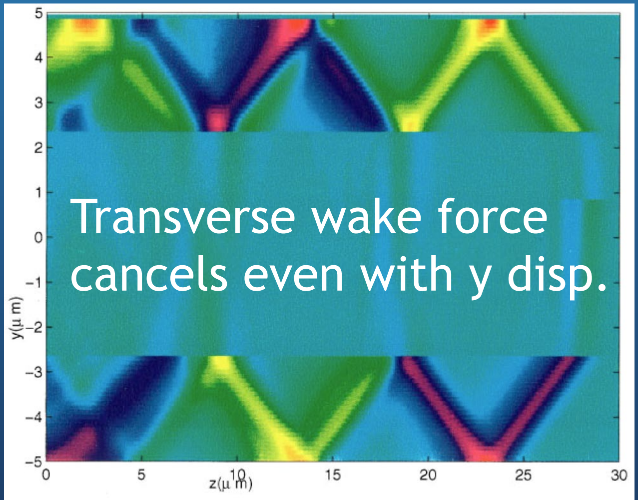
$$\sim \sigma_x^{-2}$$

Faster than E_z

- Permits *higher Q flat* beam acceleration
- Higher power at shorter λ

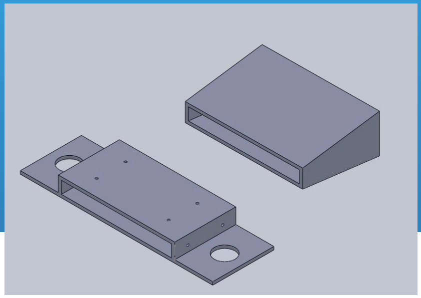


Slab symmetry

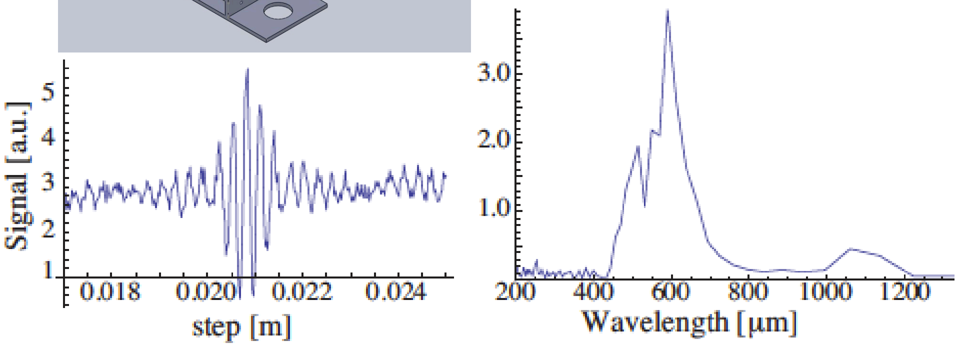


Wakefields in slab structures: results

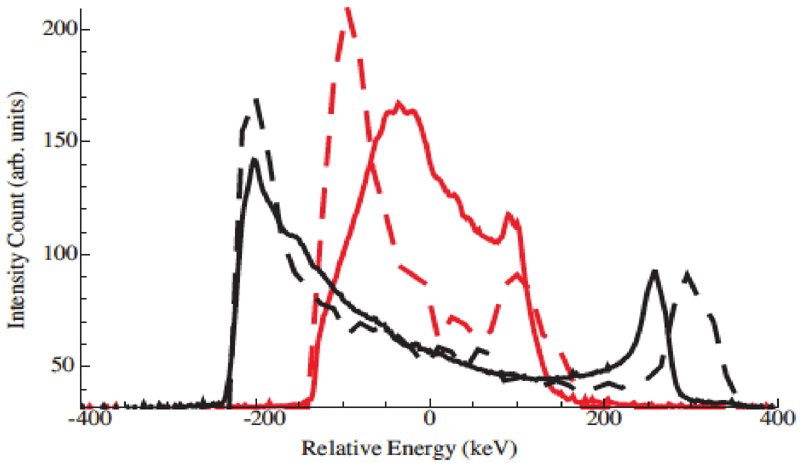
- 1st observation of *slab-symmetric* dielectric structure wakes @ATF
  - *Key* for DLAs and DWAs: mitigates wakes, space-charge, beam loading
  - Novel modes; Longitudinal Section Mode (unconfined in *x*)



CCR slab launcher



CCR signal and FFT

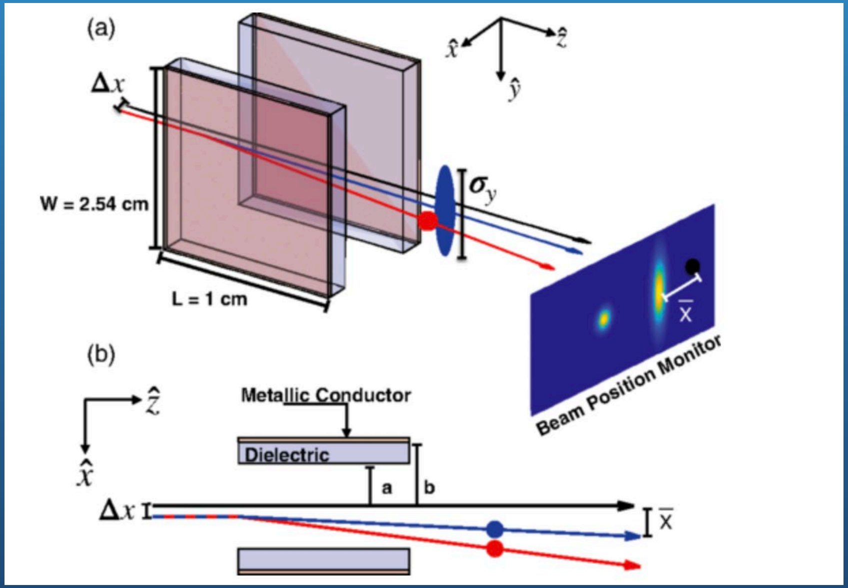


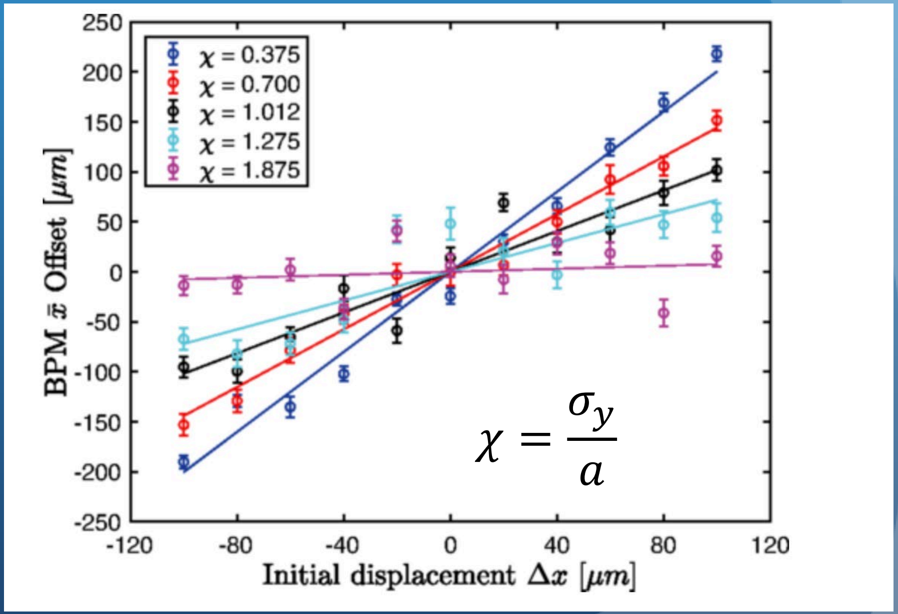
Observed (solid) and simulated (dashed) momentum spectra

G. Andonian, et al., *PRL*108, 244801 (2012)

Diminished transverse kick with flat beams in slab structures

- Narrow gap (250 um) slab structure used at FACET
- Beam tuned to have high aspect ratio
- Structure displaced in x (gap dim.) and spectrum, wake-field kick observed



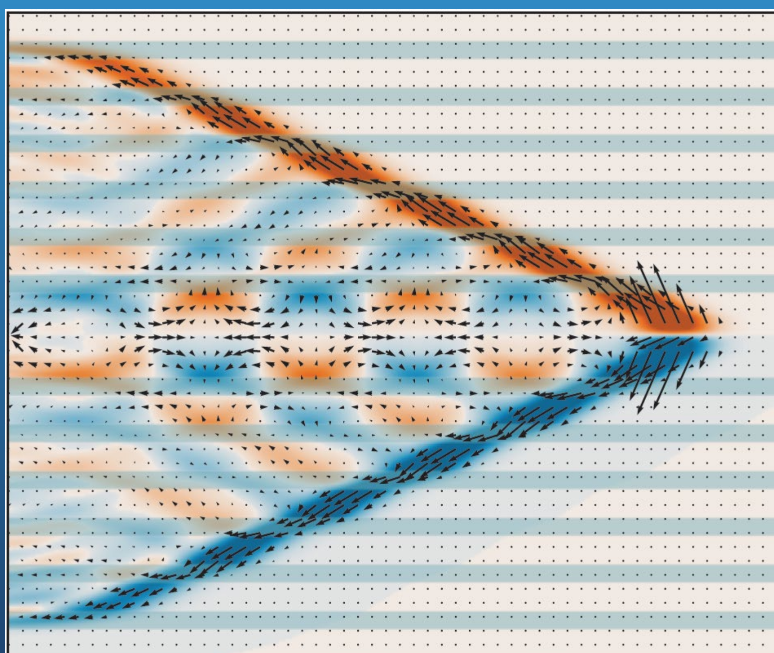


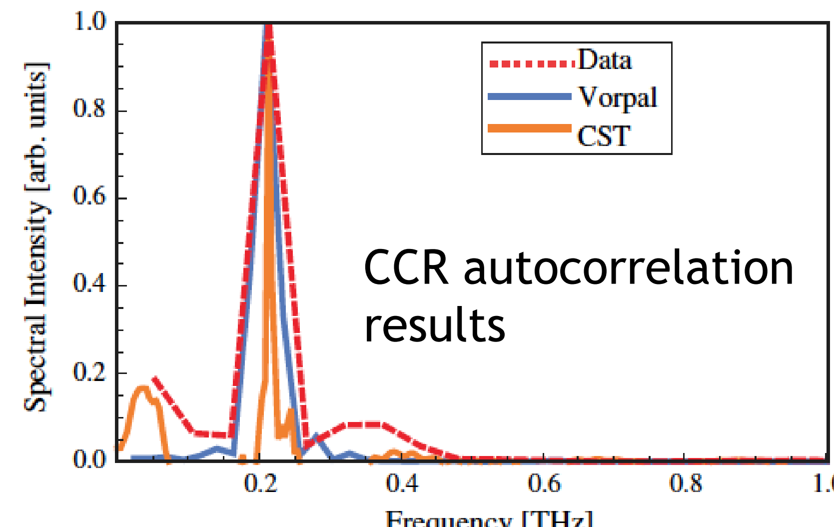
B. O'Shea, et al, Phys. Rev. Lett. **124**, 104801 (2020)

Suppresion of dipole kick for wide beam

Bragg slab wakefield experiment demonstrates confinement w/o metal

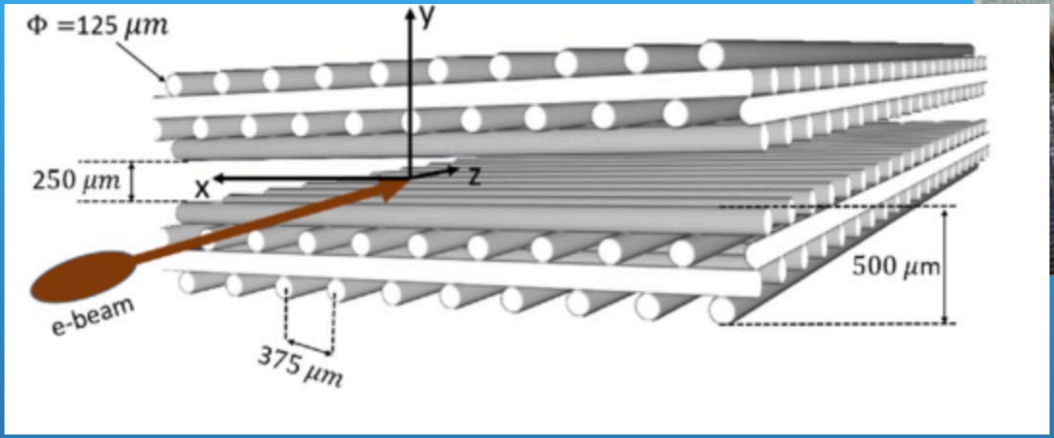
Simple 2D photonic structure (1st of its kind) with 3D effects observed
Quartz (also matching layer) + ZTA (<loss)

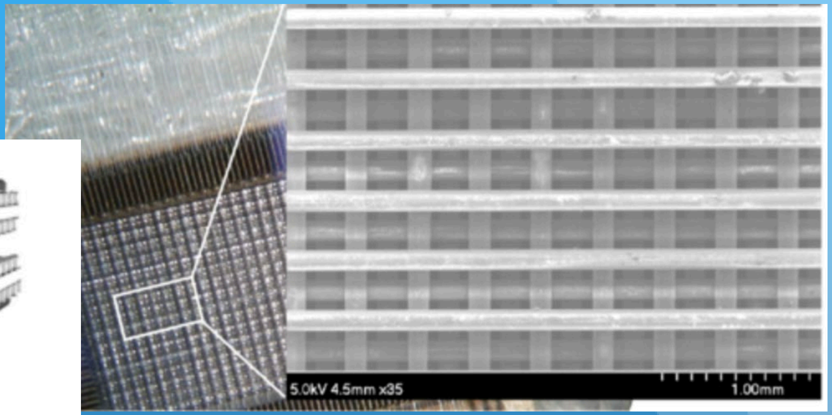




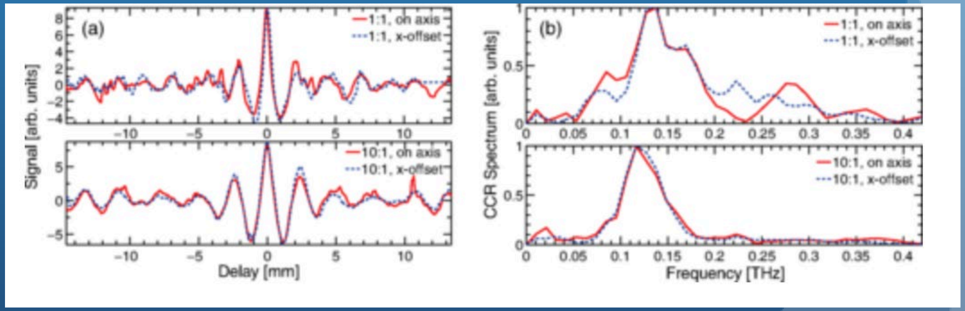
G. Andonian, et. al *Phys. Rev. Lett*. 113, 26480 (2014)

3D Photonic DWA Structure: Woodpile





- Similar construction with the Bragg. Uses 3D photonic lattice, termed "woodpile"
- THz wakefield experiment carried out at BNL-ATF
  - 125 micron OD rod structure

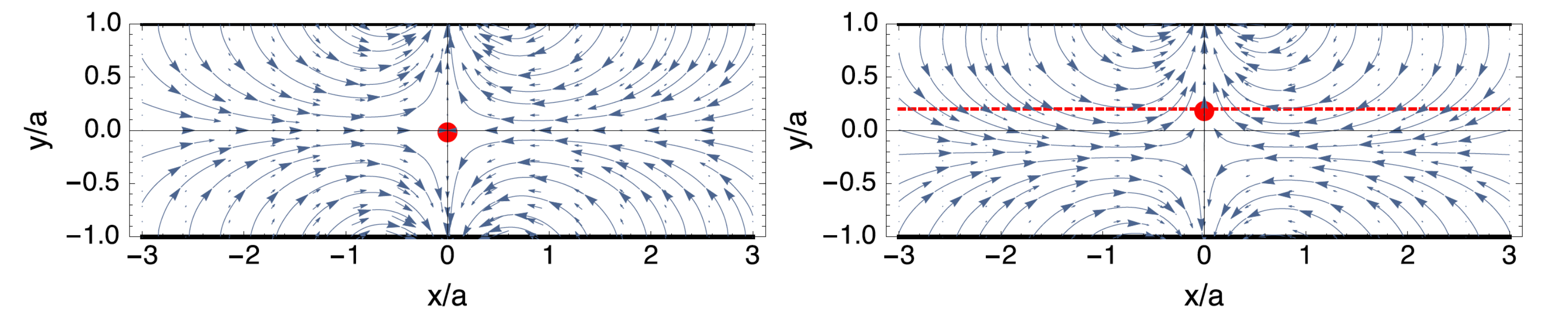


Rich Fourier spectrum of modes

P.D. Hoang, et al. Phys. Rev. Lett. **120**, 164801 (2018)

Slab structures support new modes

- Predictions of Baturin, et al., allow new modes to be easily identified
  - Dipole, quadrupole, *skew* quadrupole
  - Panofsky-Wenzel states that transverse wakes grow in *t*
  - Strong focusing instabilities induced in wide dimension

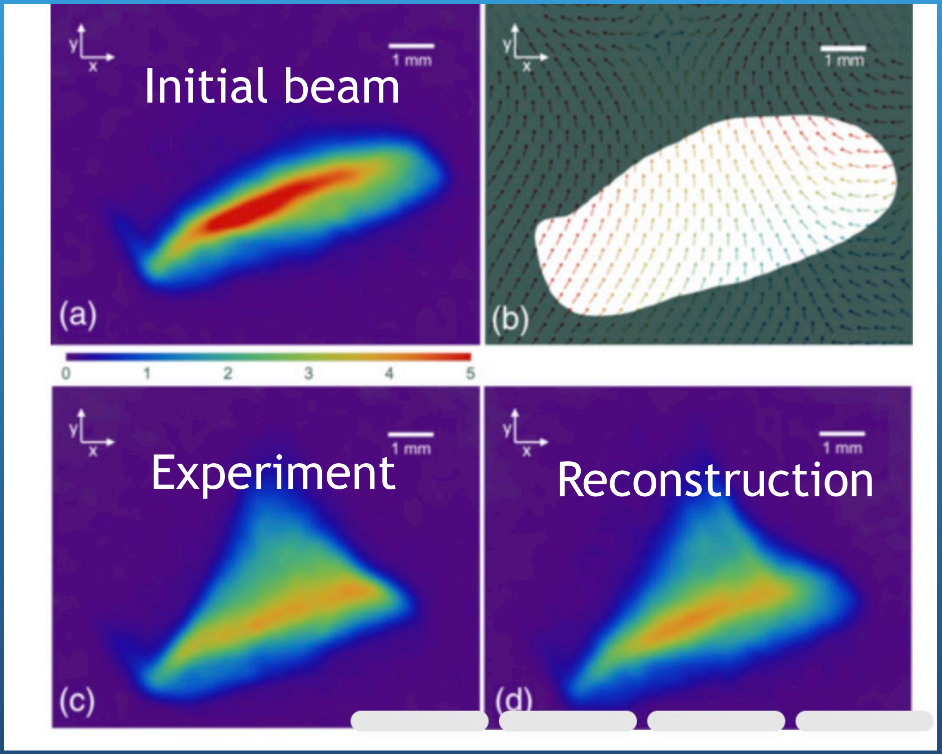


  - Unified, simple model of multipoles (for pencil beam)

S. S. Baturin, G. Andonian, and J. B. Rosenzweig *Phys. Rev. Accel. Beams* **21**, 121302 (2018)

Skew wakefields observed at AWA

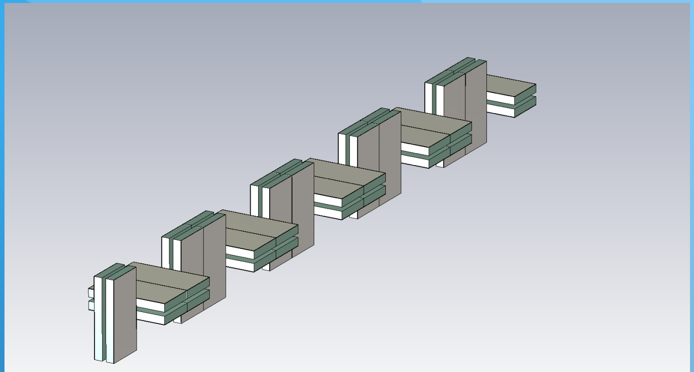
- Flat beams with tilts in slab structures
- New reconstruction of *transverse* wakes from images



W. Lynn, et al., Phys. Rev. Lett. 132, 165001 (2024)

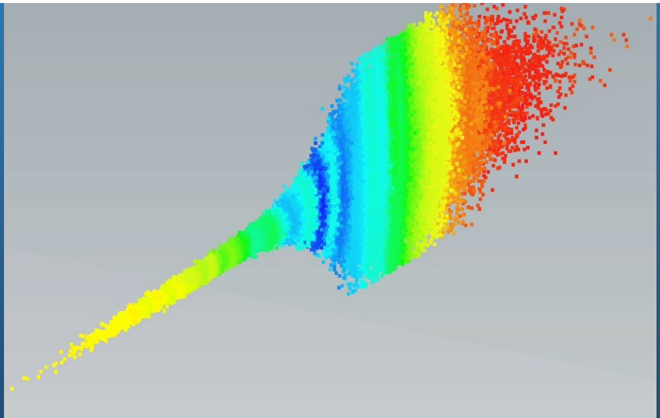
Vice to a virtue: alternating symmetry slab DWA

- Use pencil beam to excite strong time-dependent, alternating gradient focusing fields



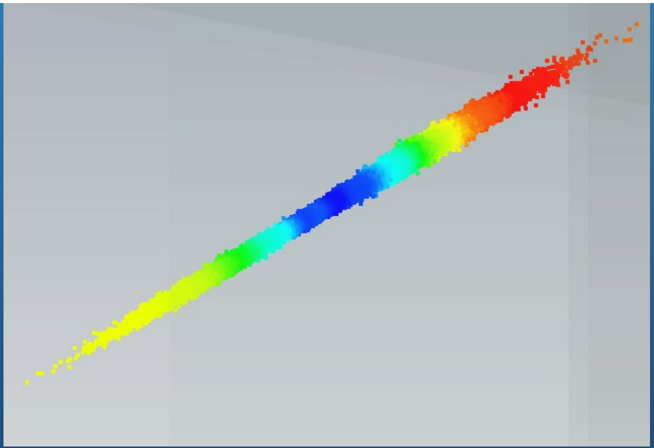
Alternating symmetry slab DWA

Final transverse spatial distribution (simple slab)



Quadrupole instability grows head to tail

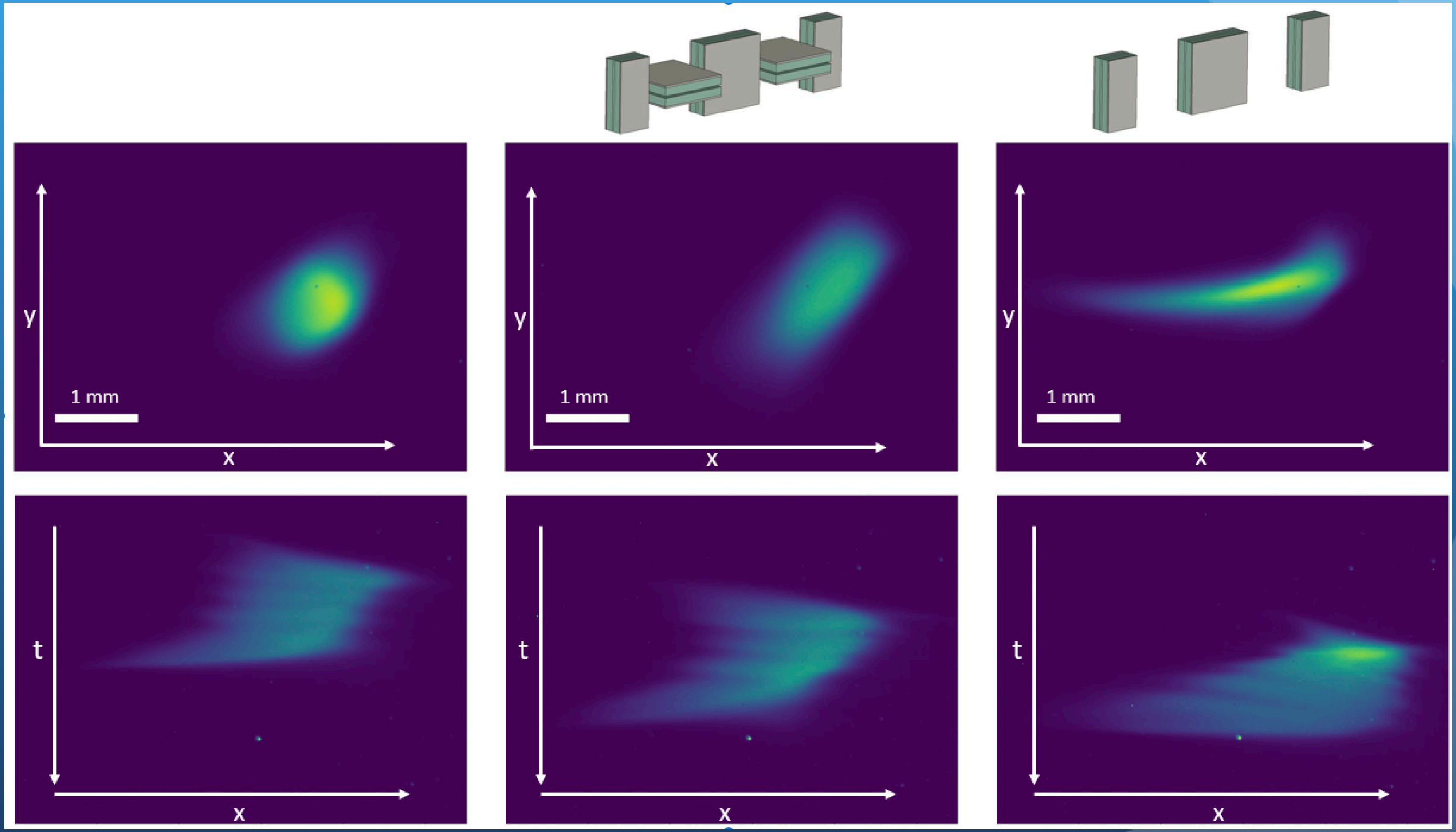
Final transverse spatial distribution propagation in alternating slabs



Second order stability in simulation

Current experimental testing at AWA

- New results now under analysis – a preliminary peek



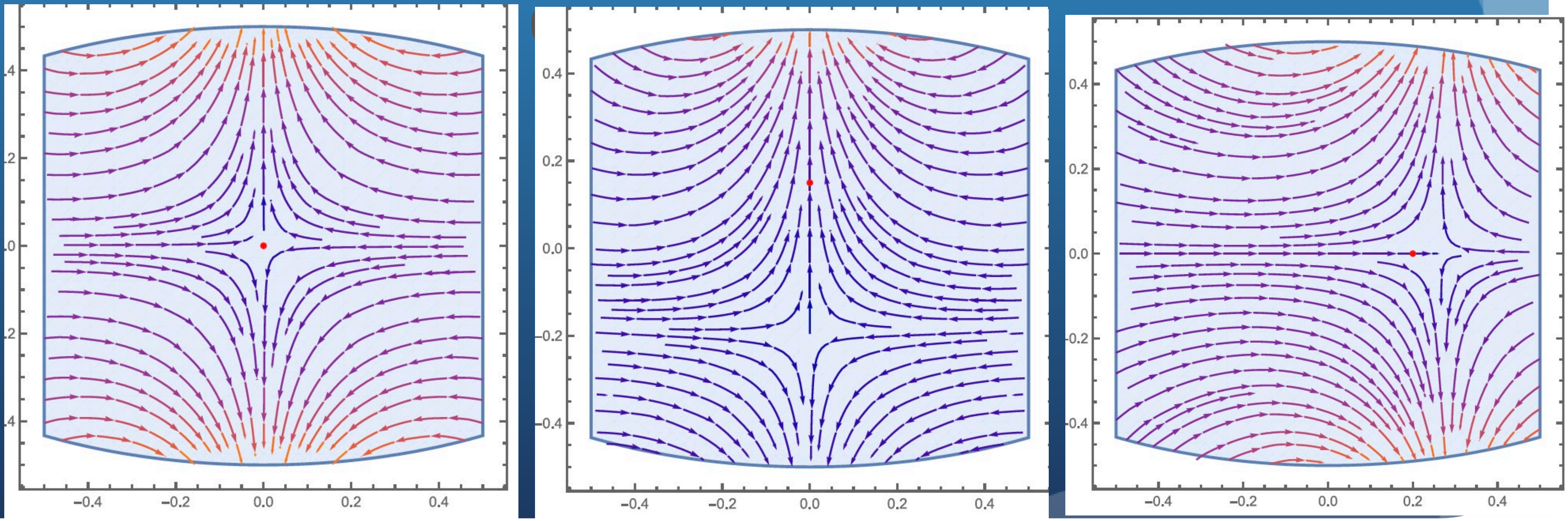
What to do with this? Fix BBU

- Provide time dependent second order focusing - stability
- Obtain a *new path* to BNS damping

C. Li, et al., PRSTAB 17, 091302 (2014)

    - Overcome ~300 MeV/m limit identified a decade ago
    - Must have a defined origin in both dimensions (elliptical)
- For flexibility one may consider two-beam noncollinear
    - Stabilize both drive and witness systems

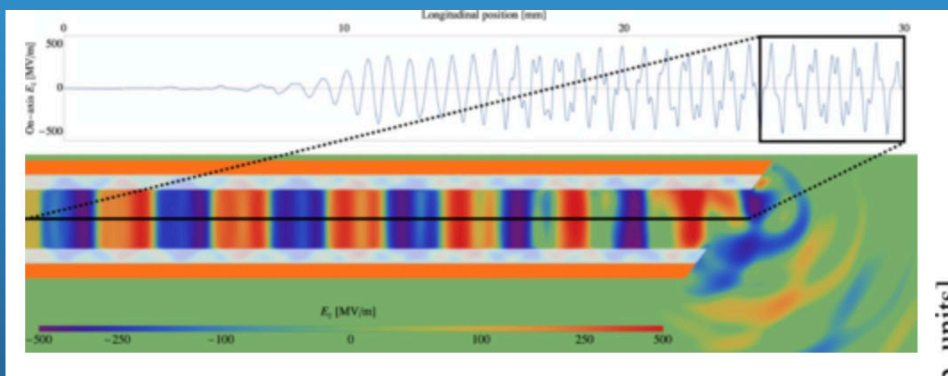
Phys. Rev. ST



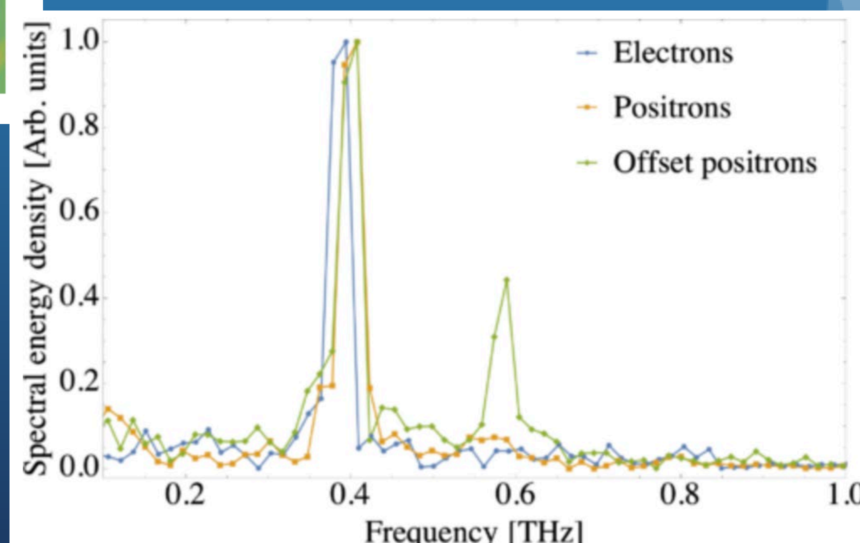
What about *positron* wakes?

- Moderately high field tests at FACET (500 MV/m accel)
  - Field emission into gap from positron space charge?

- Probe with difference in CCR signal between e+ and e-



- <u>No dependence on species</u>



N. Majernik, et al., Phys. Rev. Research 4, 023065 (2022)

Discussion and outlook

- Dielectric wakefield acceleration provides at path to near 1 GeV/m acceleration for electrons and positrons
- Much is known of the various structures, physical effects and experimental methods
- For a near-term Higgs factory, one may address the problem of positron stability
- New insight into focusing and BBU control
- Wide parameter space for collider design
- There is much to do – EuPRAXIA may play a role
  - Infrastructure for DWA directly overlaps with PWFA>