Overview of dielectric wakefield accelerators

Prof. J.B. Rosenzweig

UCLA Dept. of Physics and Astronomy

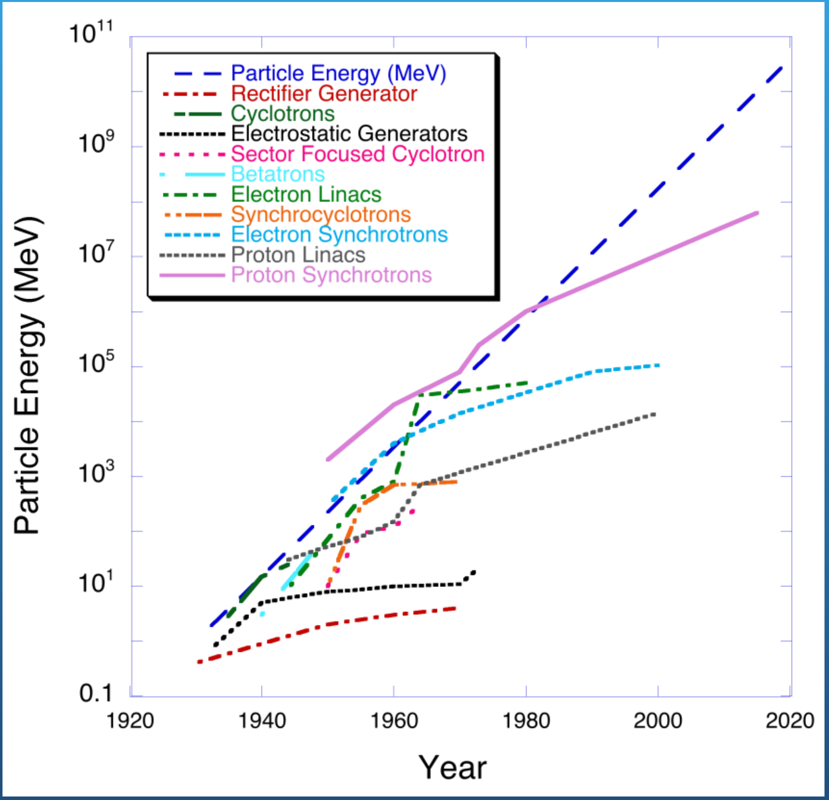
ANAR Workshop, CERN

April 25, 2017

How do we extend the exponential path of energy in colliders?

- Exponential growth in *t* in *available energy U*
  - Livingston plot: “Moore’s Law” for accelerators
- *Generational* history
- New generation will operate at much higher fields
  - **US GARD Panel***: regardless of technique GV/m for multi-TeV e+e-
  - Scale in wavelength…

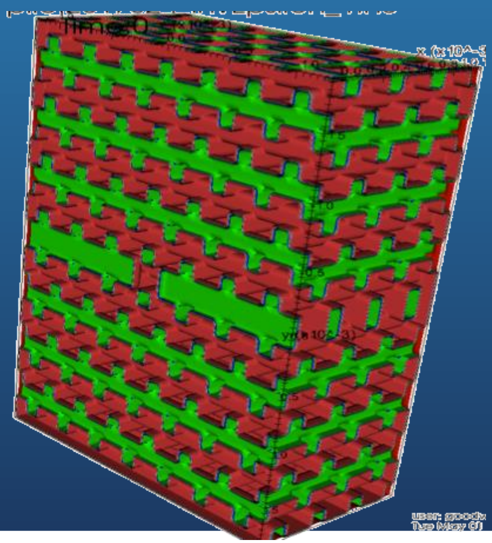
*Most DWA work is in US presently

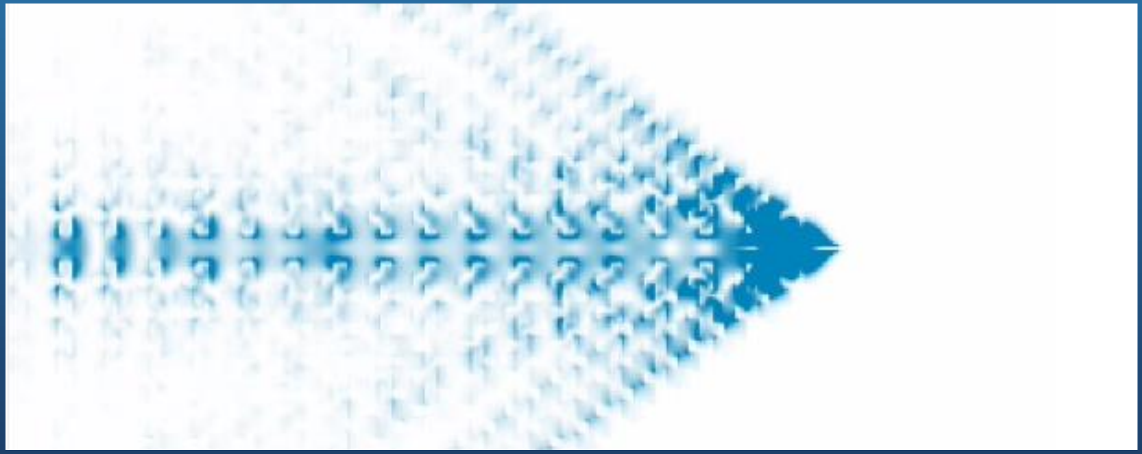


Moore’s law for HEP discovery

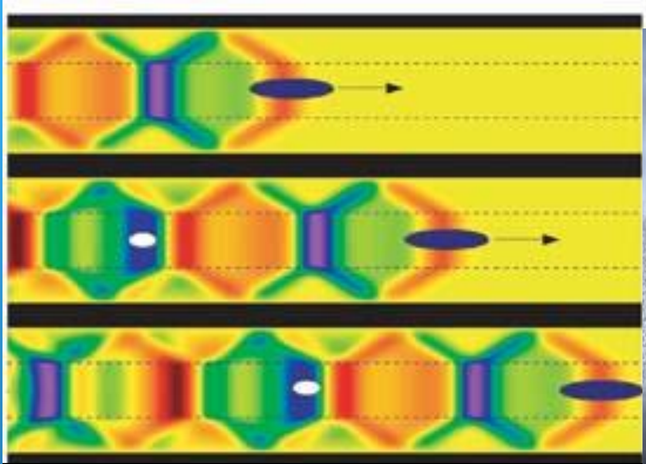
Shrinking the linear accelerator

- **Higher E** (>GV/m) increases stored energy density $u_{EM} \sim E^2$
- **Obvious solution: shorter λ** ($E \sim \lambda^{-1}$), preserves dU_{EM}/dz (total U_{EM})
- To jump from <50 MV/m to GV/m, means μwave ->THz
  - *Need* **smaller ε** (apertures)
  - **Small Q** (*beam loading*/eff. $Q \sim \lambda^2 E \sim \lambda$).
  - **Losses** -> dielectric at short λ -> no metal implies *photonics*
  - **Breakdown considerations** -> dielectric (then *plasma*)
  - **Sources**? **Lasers** extend to mid IR. What yields THz? ***Wakefields***…

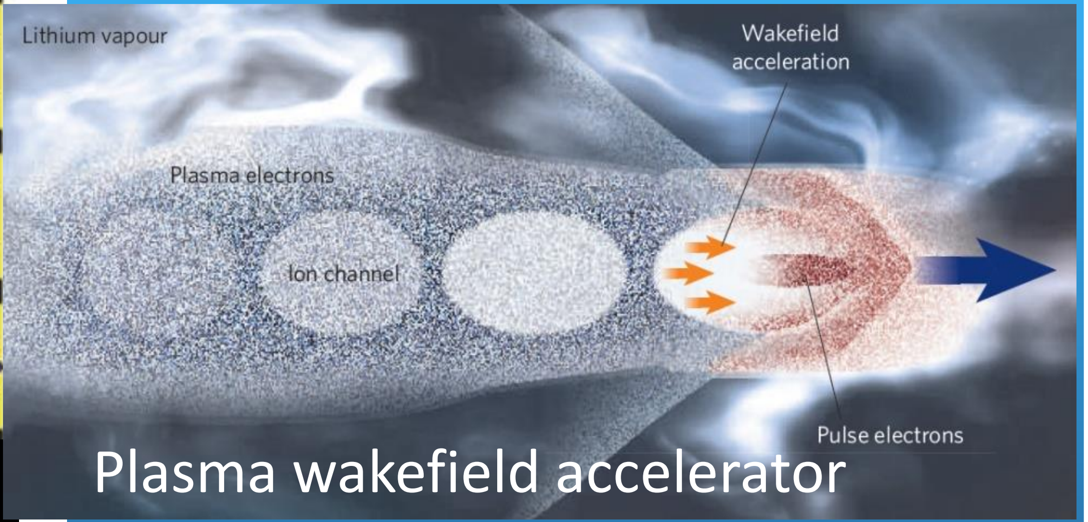




Wake-field acceleration overview



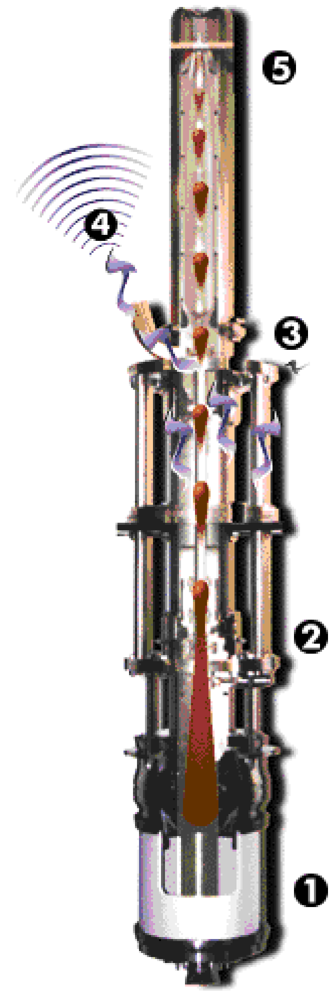
Wakefields in dielectric tube
Driving & accelerating beams



Plasma wakefield accelerator

- Electromagnetic waves excited by beam in slow-wave environment — *generalized Cerenkov radiation* in polarizable medium (e.g. dielectric, plasma)
- Synchronous wave energy excited at expense of electron beam — the beam is compact efficient power source
- Common theme for high average power sources (*e.g*. ICF); beams store a *lot* of energy

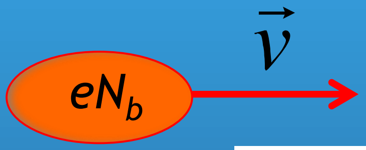
Aren’t all klystron-fed RF accelerators based on wakefields?



- Klystrons use high *I* electron beams as power source
- *Moderate energy* beams velocity-bunched by RF
- Bunches coherently radiate in resonant system
- Emitted waves transported to RF accelerator via wave-guide
  - Two beam accelerator (TBA)
- High rf/wall-plug efficiency >50%, but…
- Space charge opposes scaling to high frequency and power

Relativistic electron beams as radiation sources

- **Beams store significant directed energy** $U_b = eN_{e-}U_{e-}$



$$U_{e-} = g m_e c^2$$

Ex: FACET @ SLAC $U_{e-} = 20\ \text{GeV}\ \left(g = 4\times10^4\right)$ $eN_{e-} = 3\ \text{nC}$ U_b=60 J

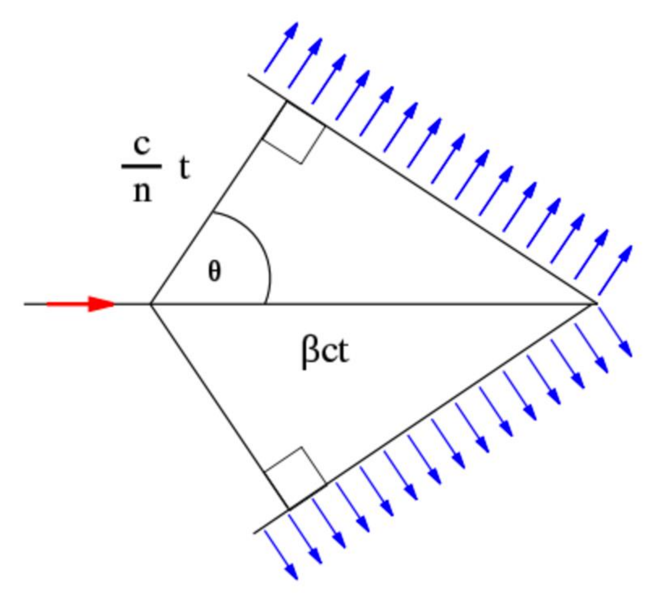
- Electrons can couple out large fraction of energy through prompt radiation mechanisms:
  - e.g. synchrotron, transition, **Cerenkov radiation**
- Directed energy naturally produced: e.g $g^{-1},\ q_c$
- Sub-ps time scales τ now routinely accessed (for e- only)
  - *Coherent radiation* pulses in/beyond *THz* spectral region

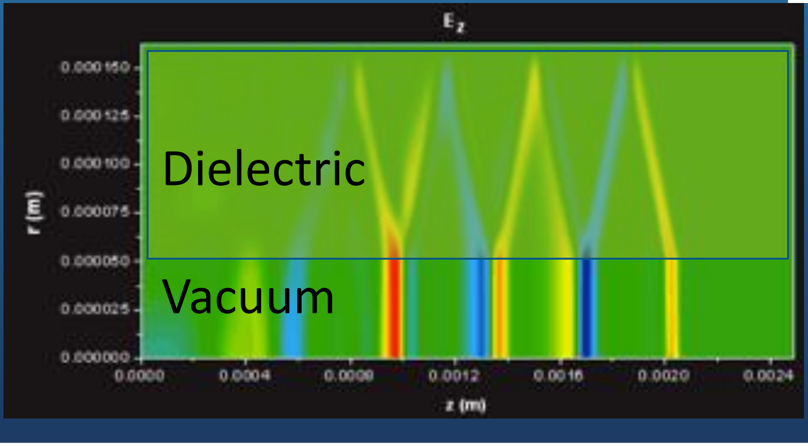
Cerenkov Radiation

- Cerenkov radiation produced by relativistic beam propagating in/near dielectrics
- Cerenkov angle $\cos\theta_c = (\beta n)^{-1}$
- Spectral response not flat $\frac{dI}{d\omega} \sim \omega \sim k$

and $\left.\frac{dU}{dz}\right|_{1\text{ e-}} \propto \int (n-1)\, k\, dk \propto k_{\max}^2$

- Confine mode with waveguide
  - *Wakefield* geometry





Wake-excited mode, showing Cerenkov angle in dielectric (OOPIC simulation)

Coherent radiation from e-beams

- Free electrons radiate coherently when they are organized with spatial structure below the radiation wavelength

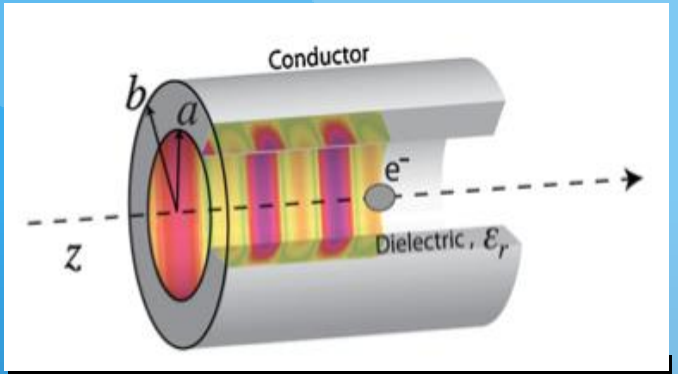
$$\frac{d^2 I}{d\omega d\Omega} = \left.\frac{d^2 I}{d\omega d\Omega}\right|_{1e-} \left| \sum_{i=1}^{N} \exp\left(i\vec{k} \cdot \vec{x}_i' \right) \right|^2$$

- For bunched beam

$$\left| F\left(\omega\left(k\right),\theta\right)\right|^2 \equiv \left| \sum_{i=1}^{N} \exp\left(i\vec{k} \cdot \vec{x}_i' \right) \right|^2 \cong N^2 \exp\left(-\left(k\sigma_z\right)^2 \right)$$

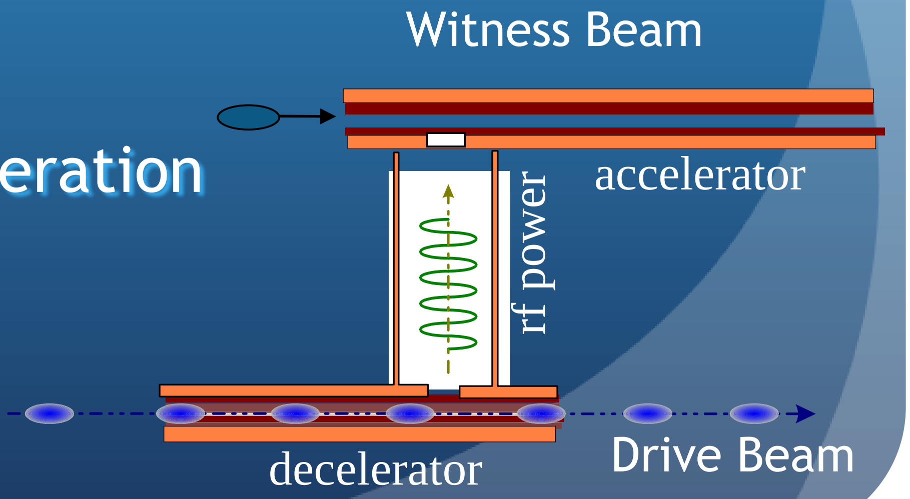
- **Radiated energy ~N^2, implies collective field ~N**
- *Coherent Cerenkov radiation* **gives $U \sim Nk^2_{max} \sim N/\sigma_z^2$**

Dielectric wakefield acceleration



Wakefields in dielectric tube

- Based on *coherent Cerenkov radiation* (CCR)
- Simplest DWA tube looks like a scaled THz linac
  - Collinear or two-beam accelerator (TBA) geometry
  - *More sophisticated structures possible/desired*
- *THz operation possible*
  - Single bunch or resonant operation
  - Unique THz source (nearly 1J!)
  - Over GV/m before breakdown



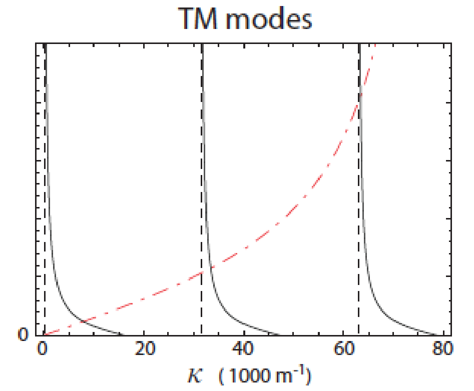
Dielectric TBA

Quasi-optical model: wavelength λ

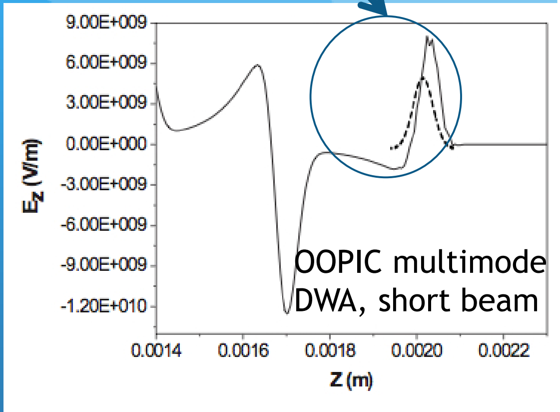
- Geometrically, the accelerating modes in

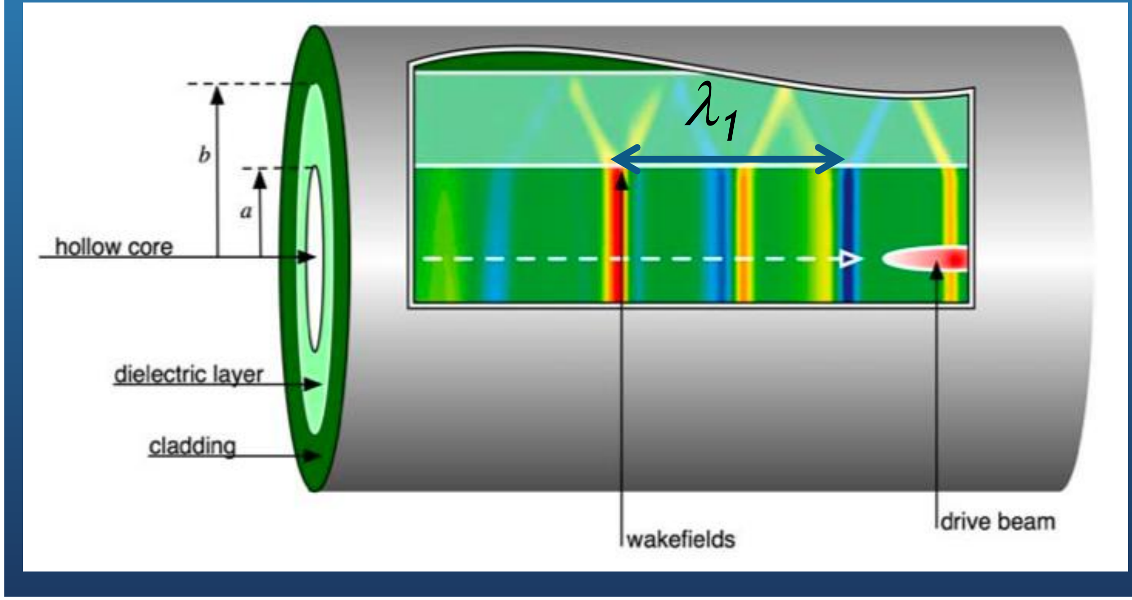
$$\lambda_n \approx \frac{4(b-a)}{n}\sqrt{\varepsilon-1}, \quad n=1,3,5\ldots$$

Compare to full wave analysis



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





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

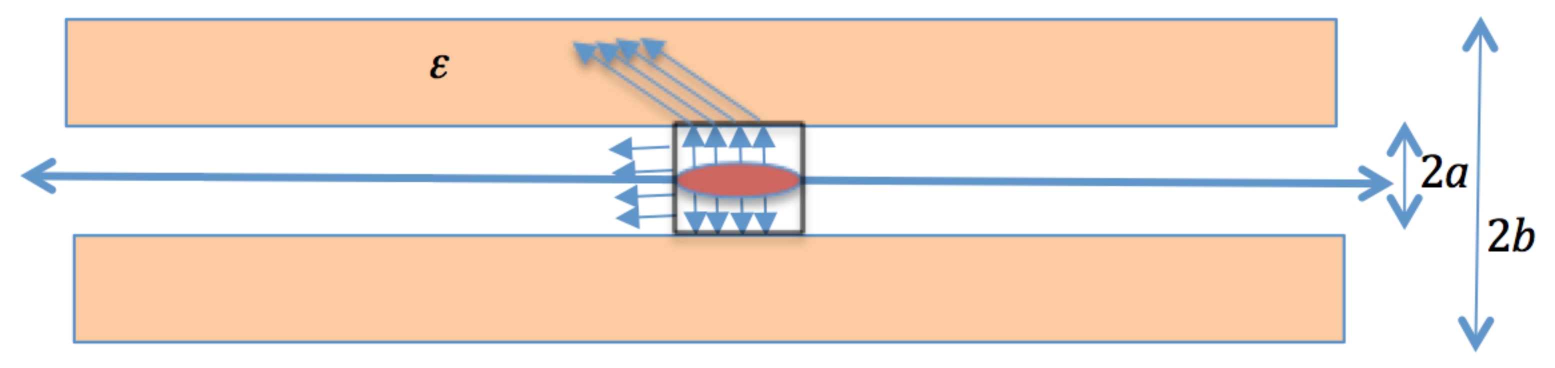
Angle given by Cerenkov:

$$\tan\theta_c = \sqrt{\varepsilon-1}, \quad n=1,3,5\ldots$$

$$\tan\theta_c = k_r / k_z \text{ checks}$$

"Even" forbidden by wave symmetry

Quasi-optical energy loss



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

See HW

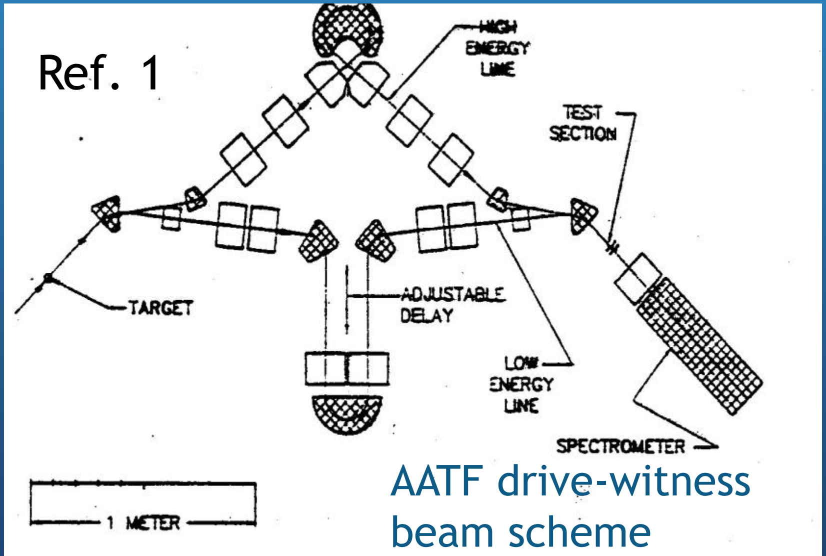
$$eE_{z,dec} » \frac{-4N_b r_e m_e c^2}{\overset{\text{é}}{\underset{\text{ë}}{a\text{ê}}}\sqrt{\frac{8p}{e-1}}\,es_z+\overset{\text{ù}}{\underset{\text{û}}{a\text{ú}}}}$$

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

- With $a µ / µ s_z$ we obtain *Cerenkov* scaling $eE_{z,dec} µ \frac{N_b}{s_z^2}$

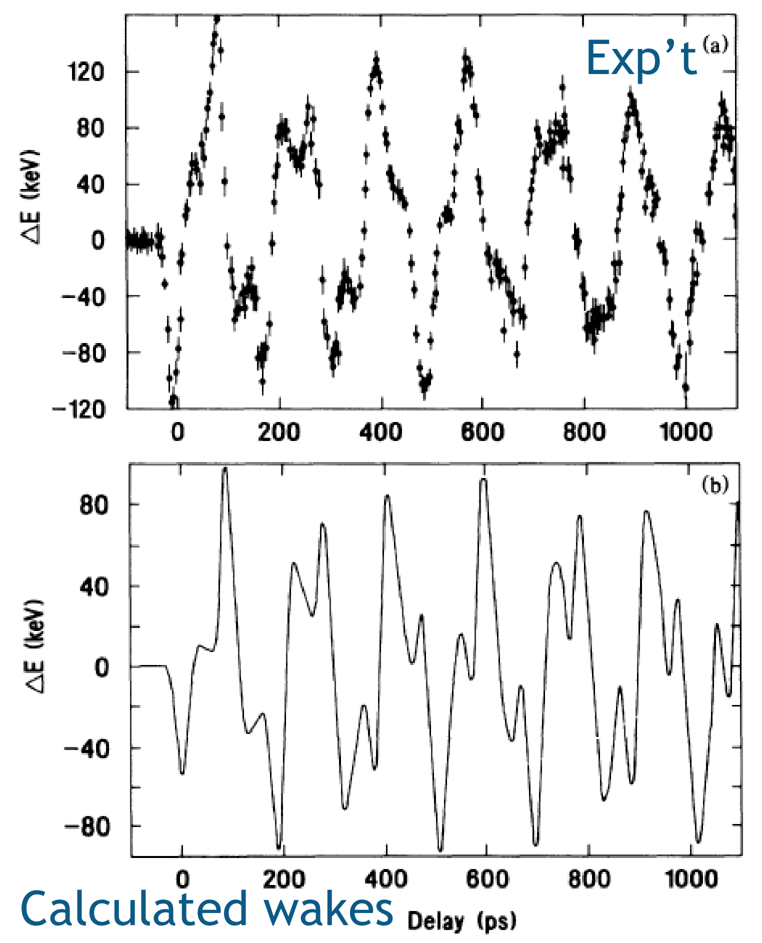
First *GHz* DWA experiment (ANL, 1988)

- Fundamental (THz) and harmonic observed with drive-scanning witness beam at AATF
- *Less than 1 MeV/m gradient*
- High charge; large *a*, σ_z=1 cm



Ref. 1

AATF drive-witness beam scheme



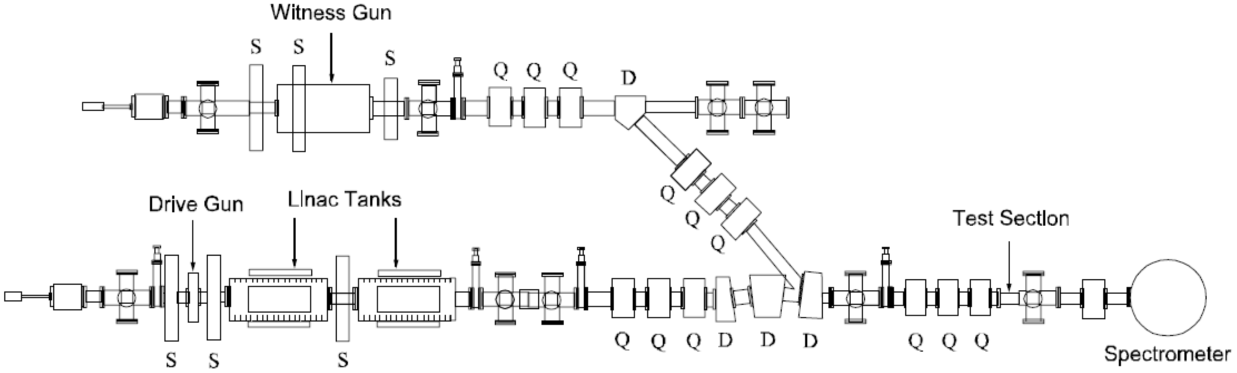
Exp't

Calculated wakes

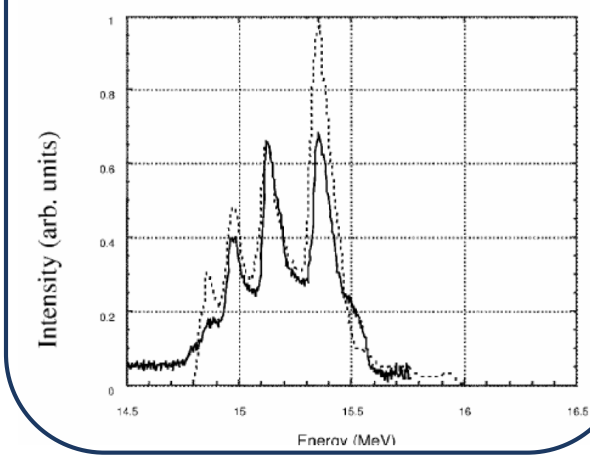
AATF gave way to Argonne Wakefield Accelerator (AWA)

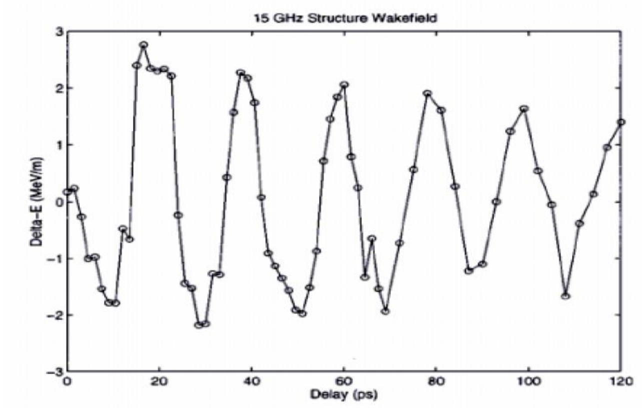
AWA - 2000

High Brightness Beams (two RF photoinjectors):
Drive Beam: 10-50 nC, 4-6 mm (rms), 1000 um, 14 MeV
Witness Beam: 1 nC, 10 ps (FWHM), 3.5 MeV



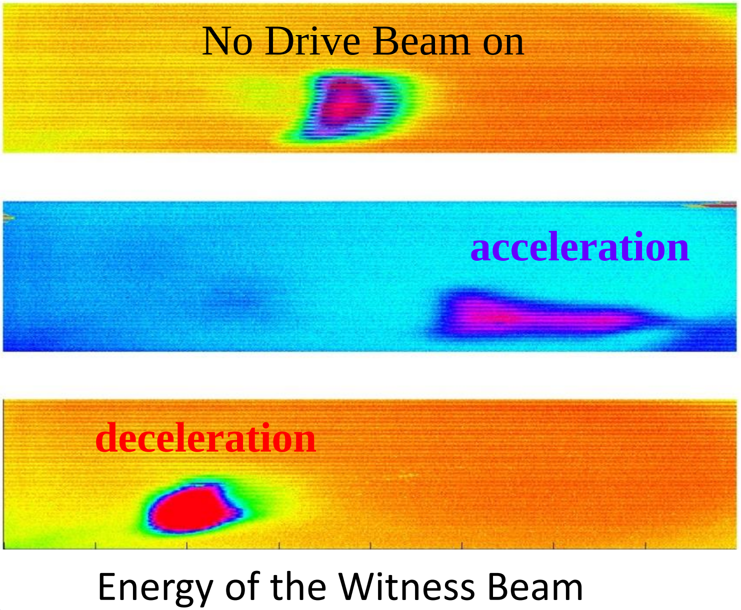
First Bunch Train
in collinear DWFA





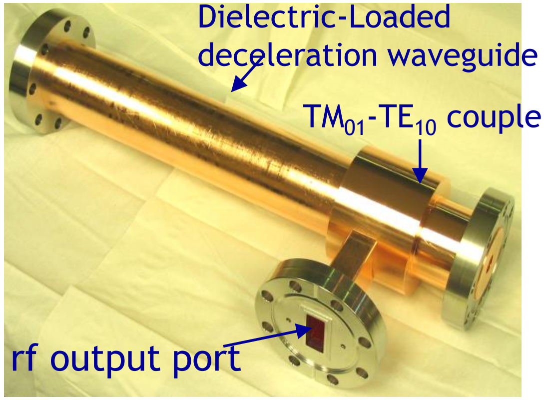
High Gradient (7 MV/m)
15.6 GHz collinear DWFA structure
PAC 1997

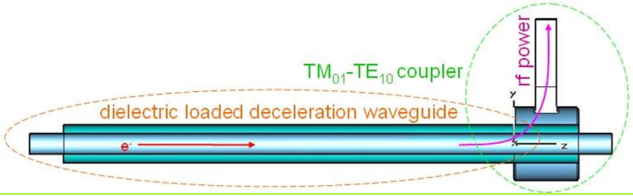
Demonstrated dielectric two-beam acceleration in first ever POP experiment

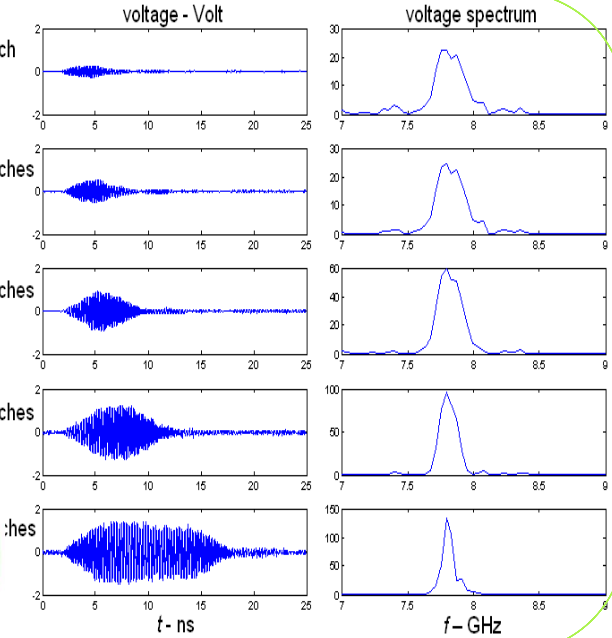


AWA RF pulsed power generation

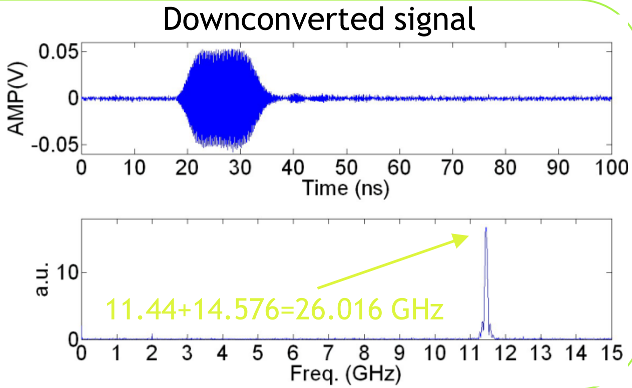
7.8 GHz
Power Extractor
30ns@1MW
10ns@44 MW







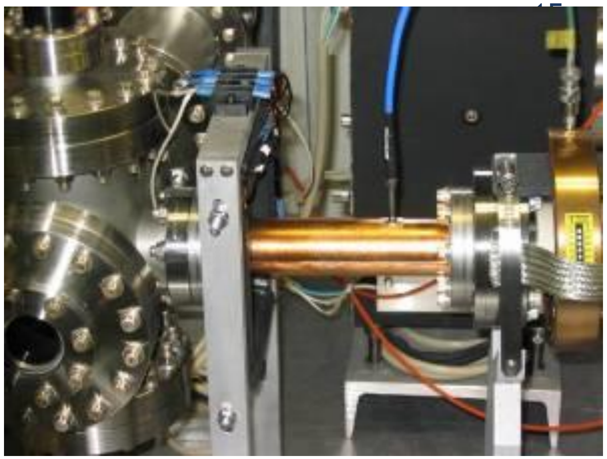
f = 26 GHz
Power Extractor
16ns@1MW
10ns@20MW



→ Power limited by drive beam

Increasing Accelerating Gradients in DWA

- Circa 2000: ~10 MV/m
- Structure #1 (Summer 2005): 21 MV/m
- Structure #2 (Winter 05/06): 43 MV/m
- Structure #3 (Summer 2006): 78 MV/m
- Structure #4 (Spring 2007): 100 MV/m`



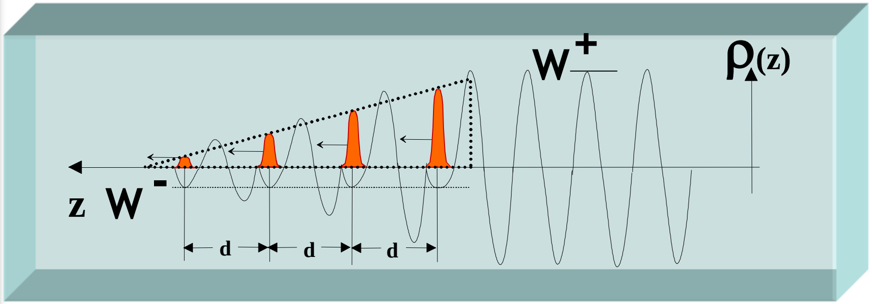
Gradient limited by the drive beam

SW Structure	#1 C10-102	#2 C10-23	#3 C5.5-28	#4 Q3.8-25.4
Material	Cordierite	Cordierite	Cordierite	Quartz
Dielectric constant	4.76	4.76	4.76	3.75
Freq. of TM01n	**14.1 GHz**	**14.1 GHz**	**9.4 GHz**	**8.6 GHz**
Inner radius	5 mm	5 mm	2.75 mm	1.9 mm
Outer radius	7.49 mm	7.49 mm	7.49 mm	7.49 mm
Length	102 mm	23 mm	28 mm	25.4 mm
Wakefield gradient	0.45 MV/m/nC	0.5 MV/m/nC	0.91 MV/m/nC	1.33 MV/m/nC
Maximum charge	**46 nC**	**86 nC**	**86 nC**	**75 nC**
Maximum gradient	**21 MV/m**	**43 MV/m**	**78 MV/m**	**100 MV/m**

Increasing DWA Transformer Ratio

$$\text{Transformer Ratio: } TR = \frac{E_{\max gain}}{E_{\max loss}} \quad \begin{matrix}\text{(Trailing bunch)}\\ \text{(driving bunch)}\end{matrix}$$

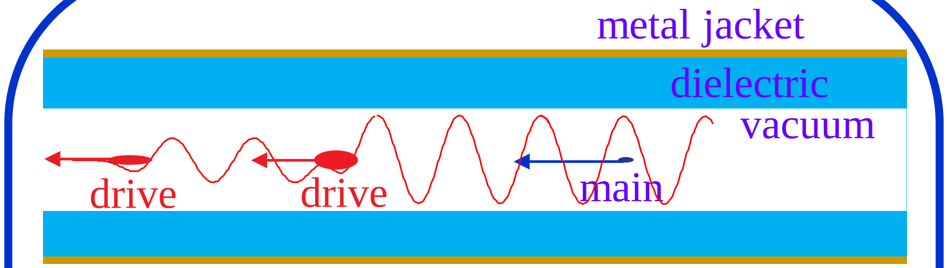
Demonstrated Ramped Bunch Train Generation …

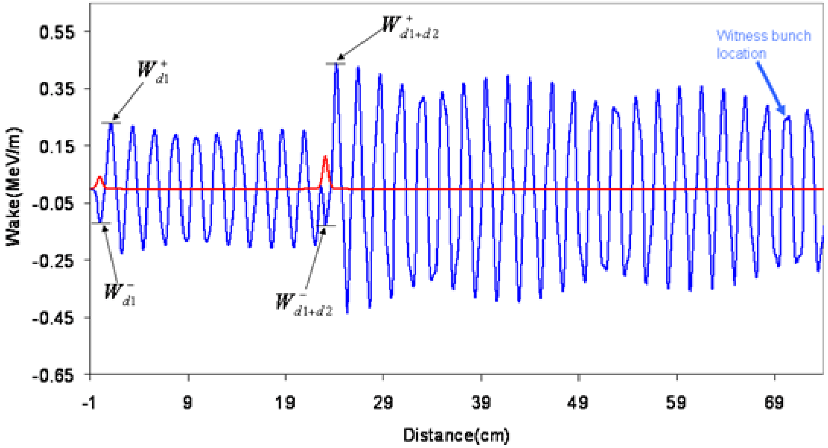


Experimental Progress

*First demonstration of R>2

**Highest demonstrated R =3.4



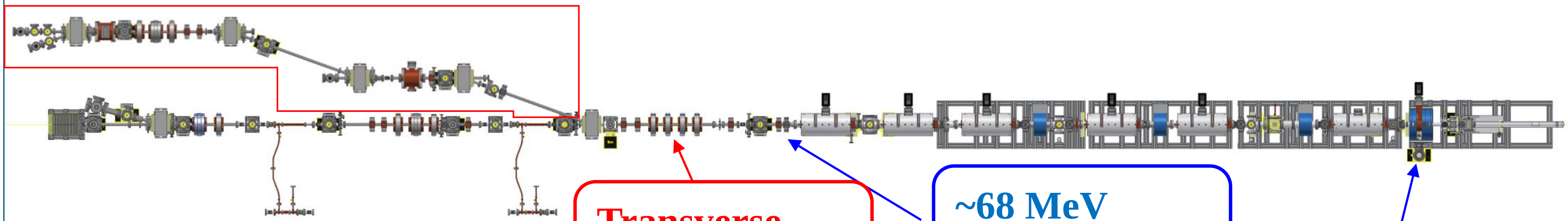


… and demonstrated highest enhanced transformer ratio **R=3.4**

Double dogleg EEX beam line at AWA

Argonne Wakefield Accelerator

Double dogleg EEX

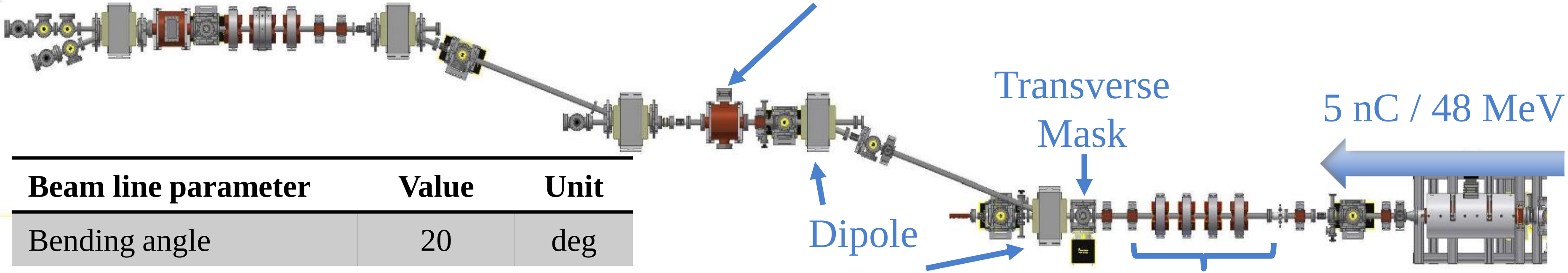


Experimental area

Transverse manipulation

~68 MeV
Chirp control

~8 MeV
Up to 100 nC



Transverse Deflecting cavity

Transverse Mask

5 nC / 48 MeV

Dipole magnet

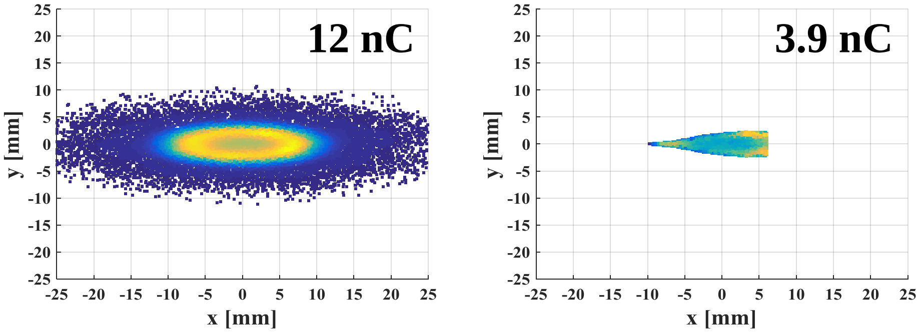
Quadrupole

Beam line parameter	Value	Unit
Bending angle	20	deg
Dipole-to-Dipole	2.0	m
Dipole-to-TDC	0.5	m
Power to TDC	1.2	MW

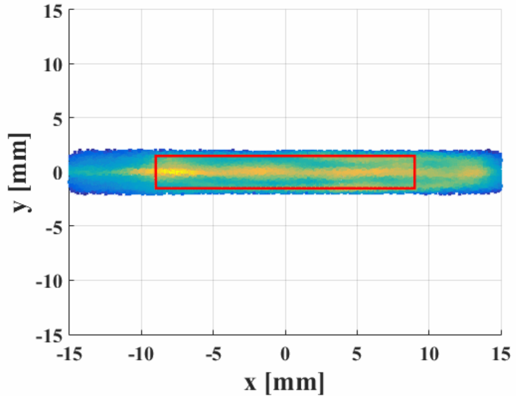
Future Experiment: High Transformer Ratio

Rectangular Dielectric Wakefield Structure

Mask

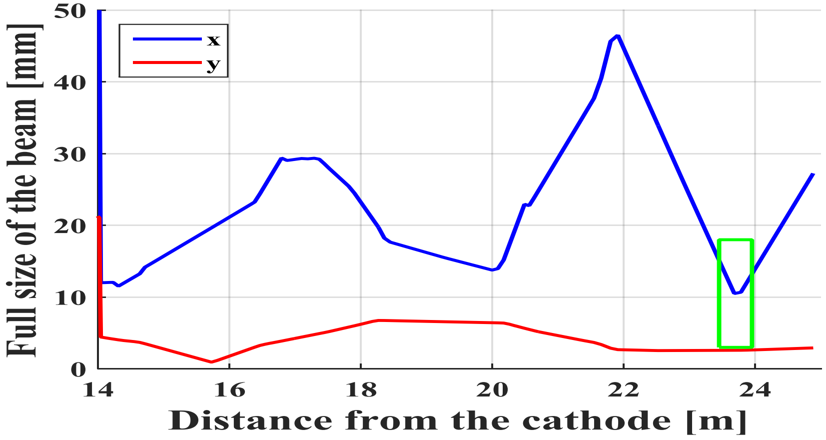


Beam transport through structure

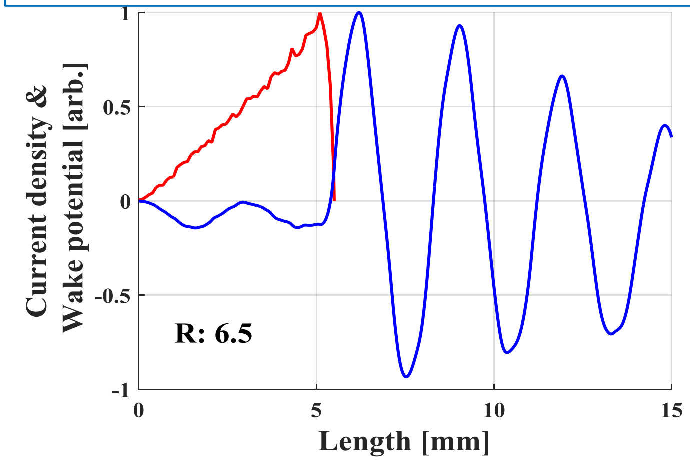


SIMULATION

Beam envelope



Longitudinal Bunch Shape & Transformer ratio

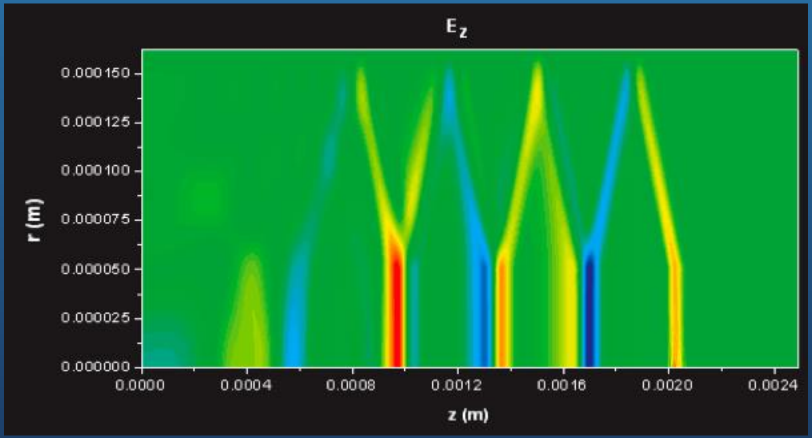


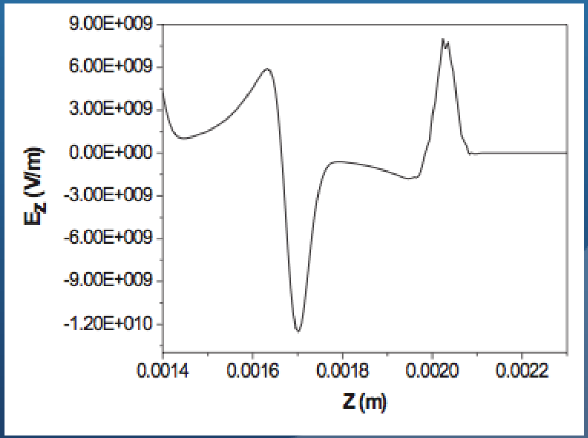
Euclid Techlabs LLC: Q. Gao, C.Jing, A.Kanareykin.

SLAC FFTB opens THz-GV/m DWA horizon

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

$eE_{z,dec}$ @7.9 GeV/m, $eE_{z,acc}$ @12 GeV/m!





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

1st THz, GV/m DWA with ultra-short, high charge beams

Leveraged by plasma wakefield at FFTB

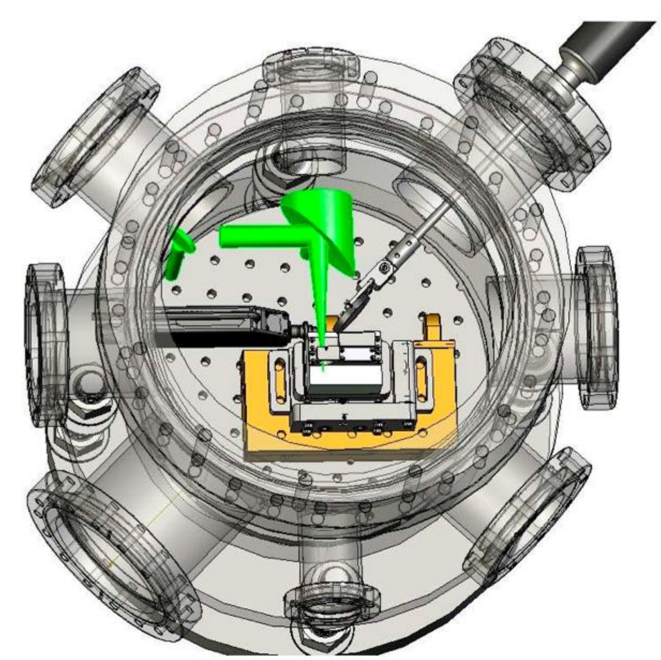
- Excellent beam 3 nC, $\sigma_z \geq 20$ μm, 28.5 GeV

Goal: THz breakdown studies

- Al-clad fused SiO_2 fibers
  - ID 100/200 μm, OD 325 μm, L=1 cm
- Prediction: E_z =12 GV/m (*much higher than optical-IR limit*)
- Avalanche v. *tunneling* ionization studies

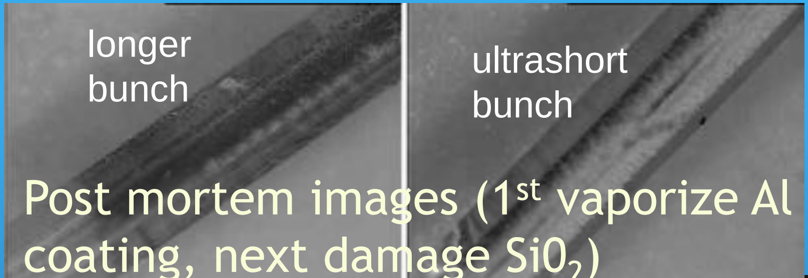
Keldysh parameter transition in THz

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

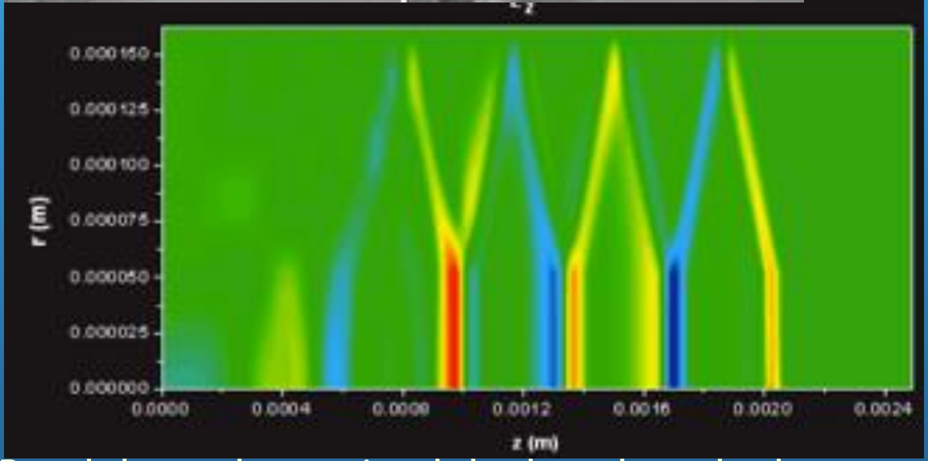


T-481 “octopus” chamber DWA holders, CCR collecting horn and transport, optical inspection

Breakdown threshold: many GV/m

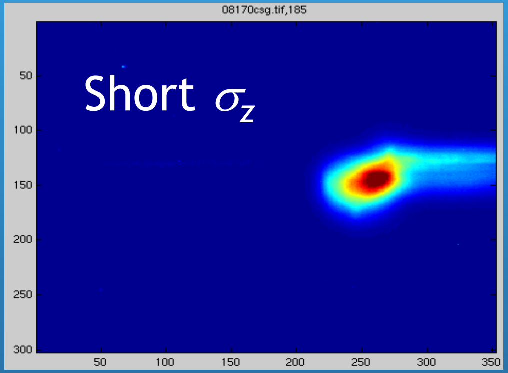


Post mortem images (1^{st} vaporize Al coating, next damage SiO_2)



Breakdown determined by benchmarked simulations (OOPIC)

Breakdown field dependence established by varying σ_z



Breakdown limit:
5.5 GV/m decelerating field (10 GV/m accel?)

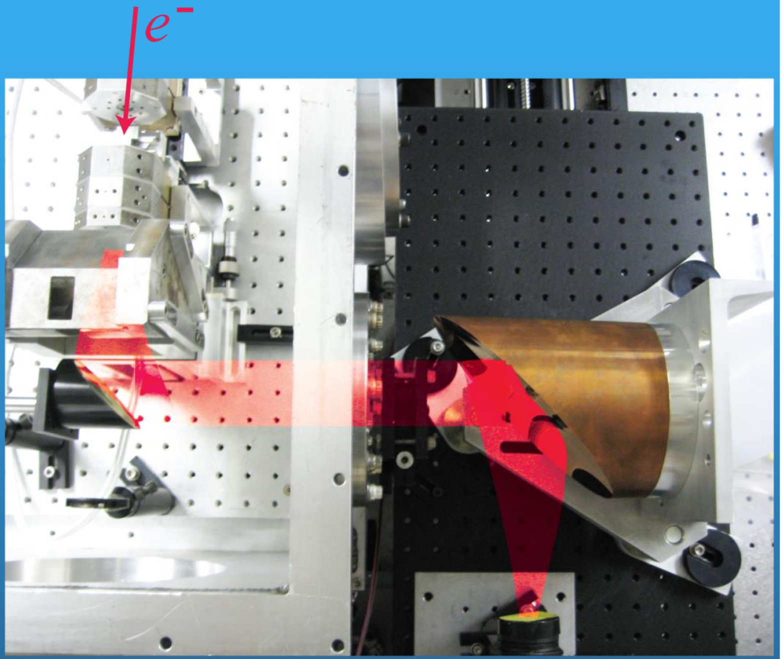
Multi-mode excitation – 100 fs, pulses separated by ps — gives better breakdown dynamics

Multi-GV/m Cerenkov-excited fields obtained in DWA

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

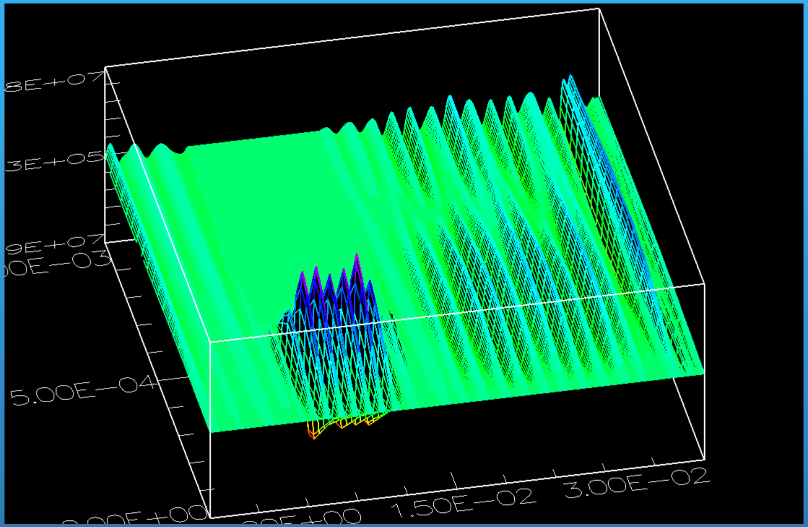
THz Coherent Cerenkov Radiation (CCR)

- No direct mode or field measurement – on to CCR
- FFTB closes 2006…
- Use UCLA Neptune for CCR
    - Compress 0.3 nC beam to 200 μm, focus with PMQs: σ_r~100 μm (a=250 μm)
- Single mode operation
    - Two tubes, different b, *different THz frequencies*



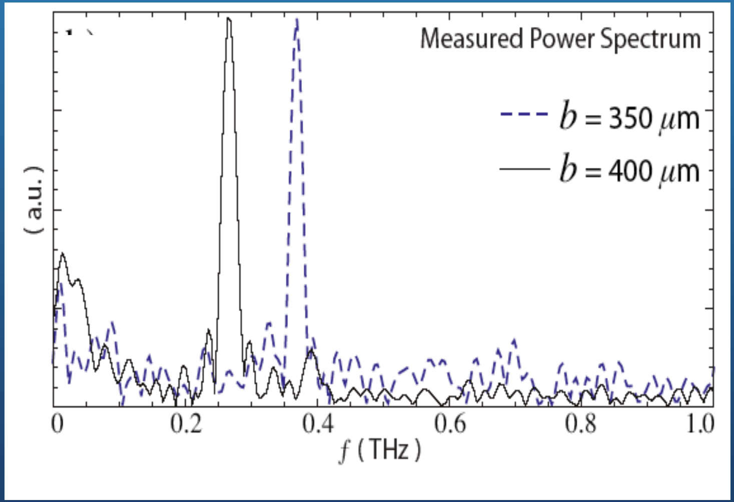
A. Cook, et al., Phys. Rev. Lett. 103, 095003 (2009)

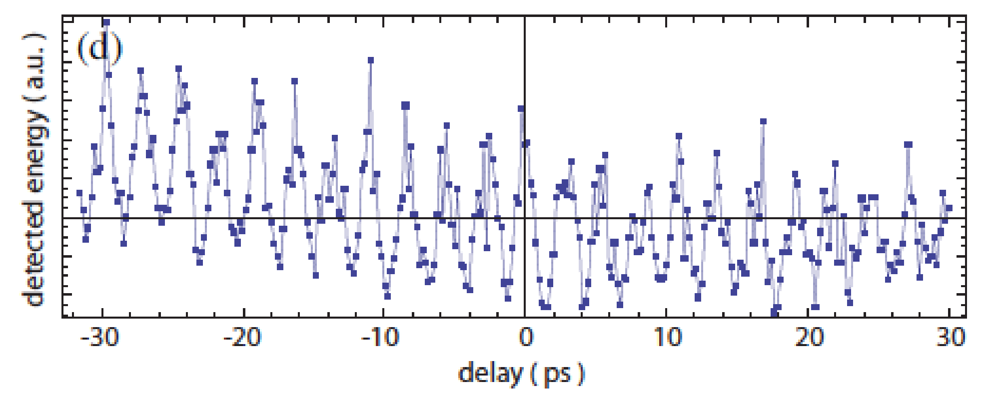
Narrow band, low loss THz produced



Impedance matching reduces strong reflection

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

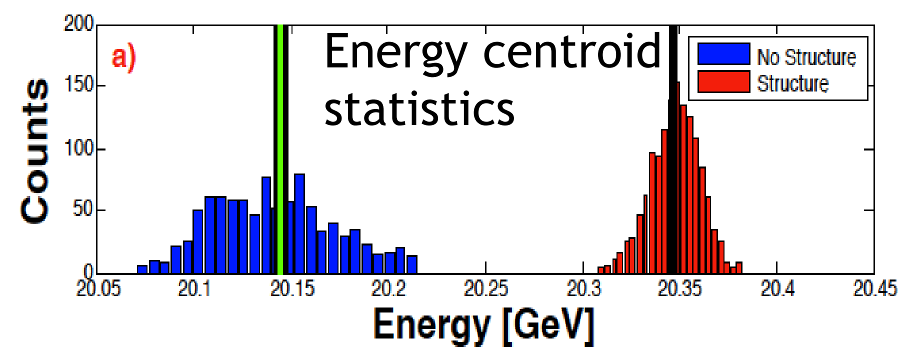




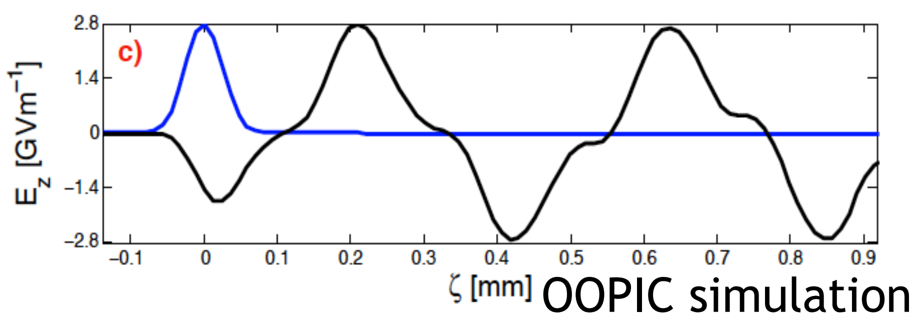
Autocorrelated CCR

Present frontier in DWA gradients: E201 at SLAC FACET

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



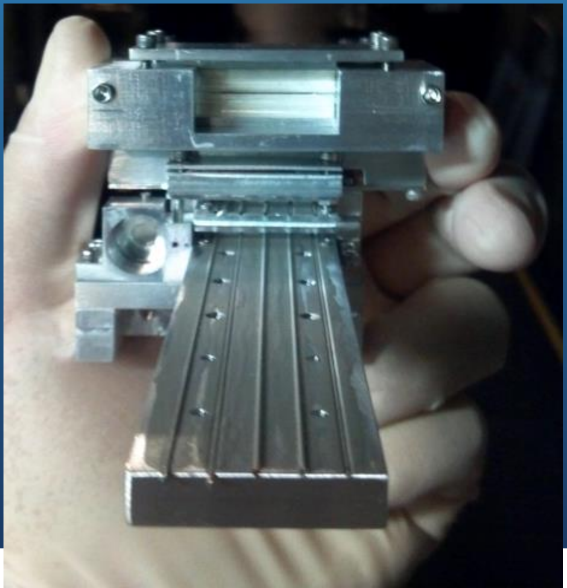
Energy centroid statistics



OOPIC simulation

Energy changed by over 200 MeV in 15 cm

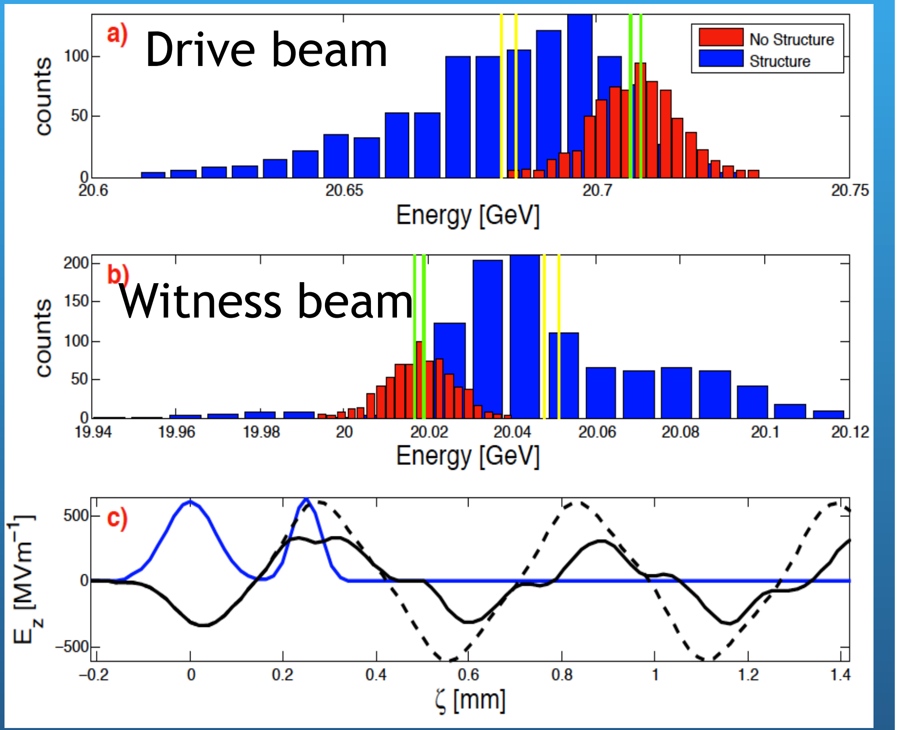
This is full beam deceleration ~1.35 GV/m



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

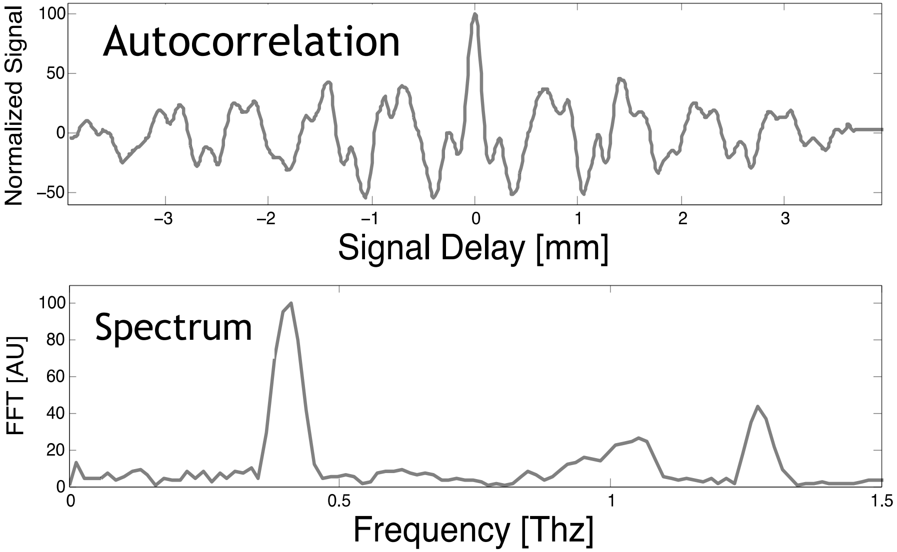


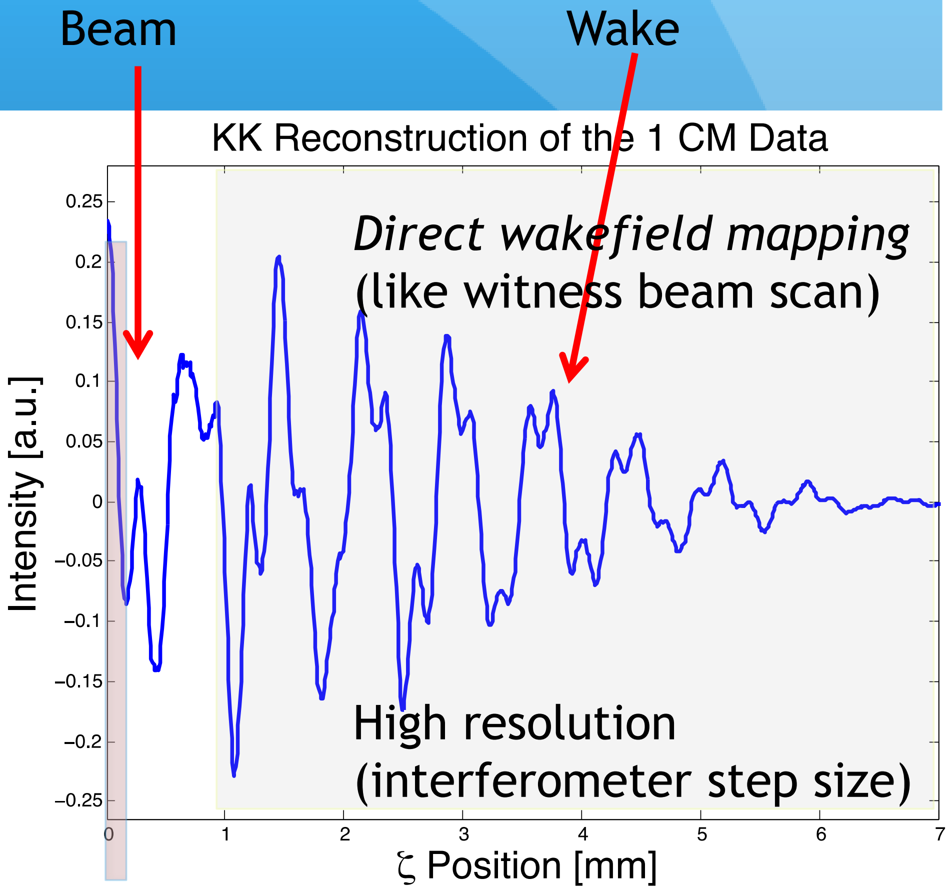
Theoretical prediction for wakefields

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

B.O’Shea, *et al., submitted to Nature Physics*

Coherent THz production (CCR): radiation source *and* wakefield map





Direct wakefield mapping (like witness beam scan)

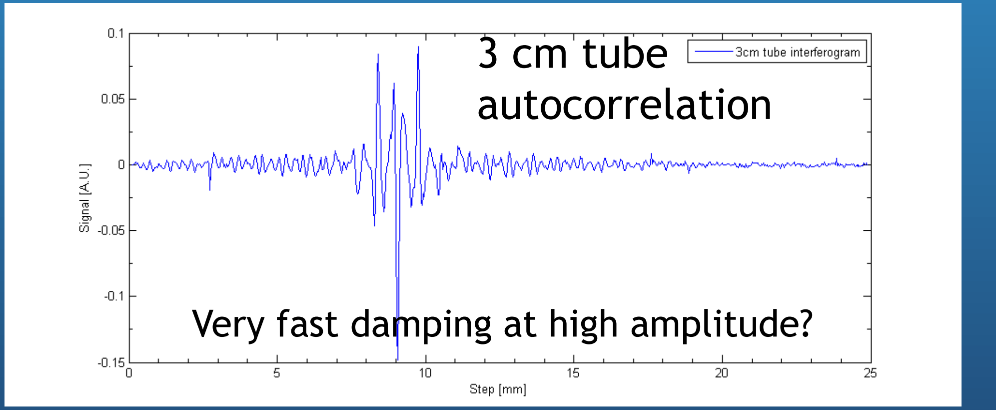
High resolution (interferometer step size)

- TM_{01}(400GHz), TM_{02} (1.2 THz) seen
- 1 cm structure *should* produce THz pulse >2 cm
- Kramers-Kronig wakefield phase reconstruction
- ***Strong damping observed***

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

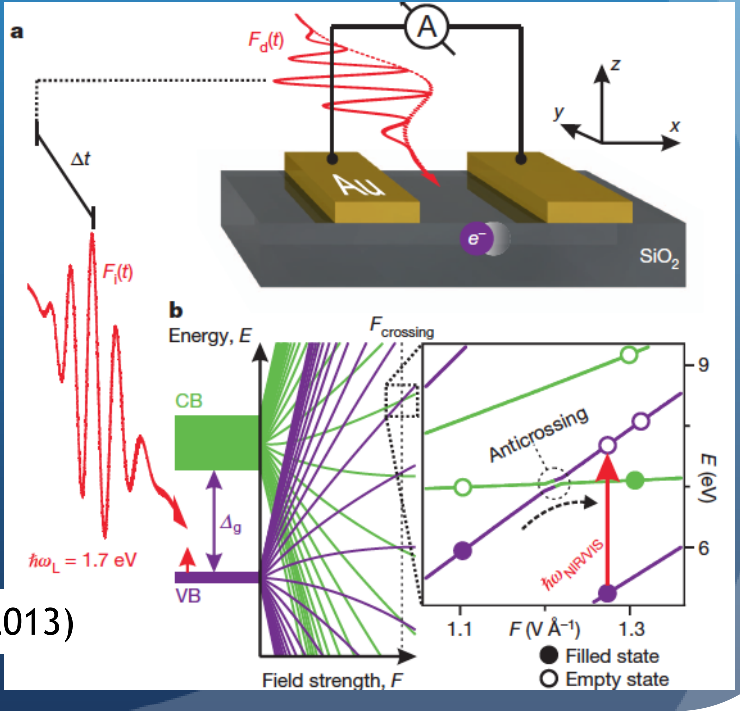
Mechanisms for wake damping

- Longer structures did not produce linearly increased length
- Introduced reversible (temporary) conductivity
- High field (>GV/m) induced conductivity from band distortions
  - “metallization” through non-adiabatic process (collisions)
- Conduction band electrons from EM *showers*
  - Test with “spoiler”



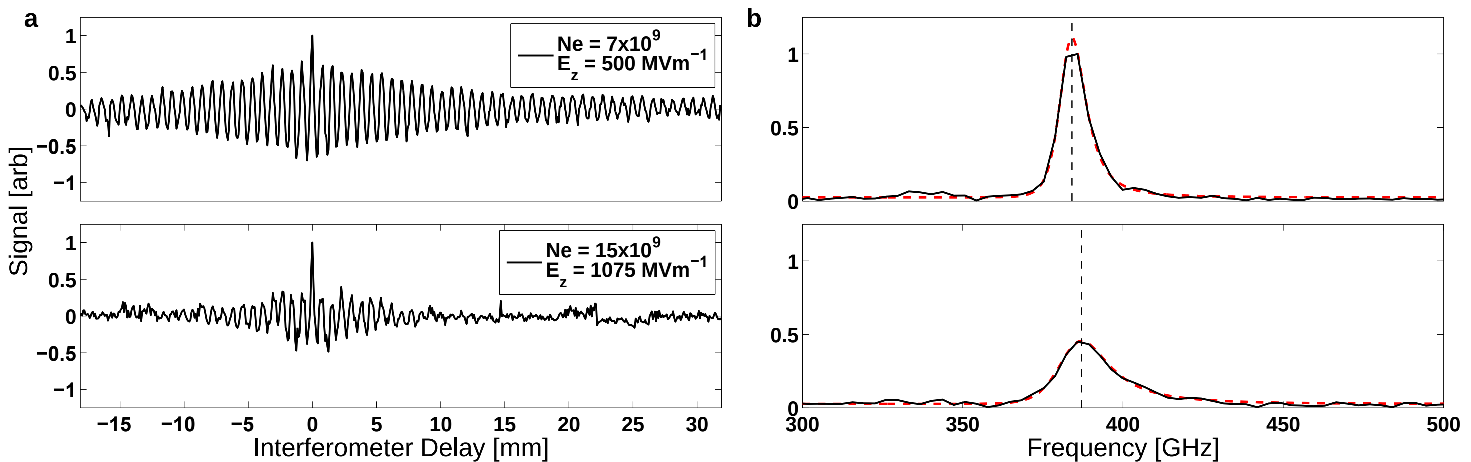
3 cm tube autocorrelation

Very fast damping at high amplitude?



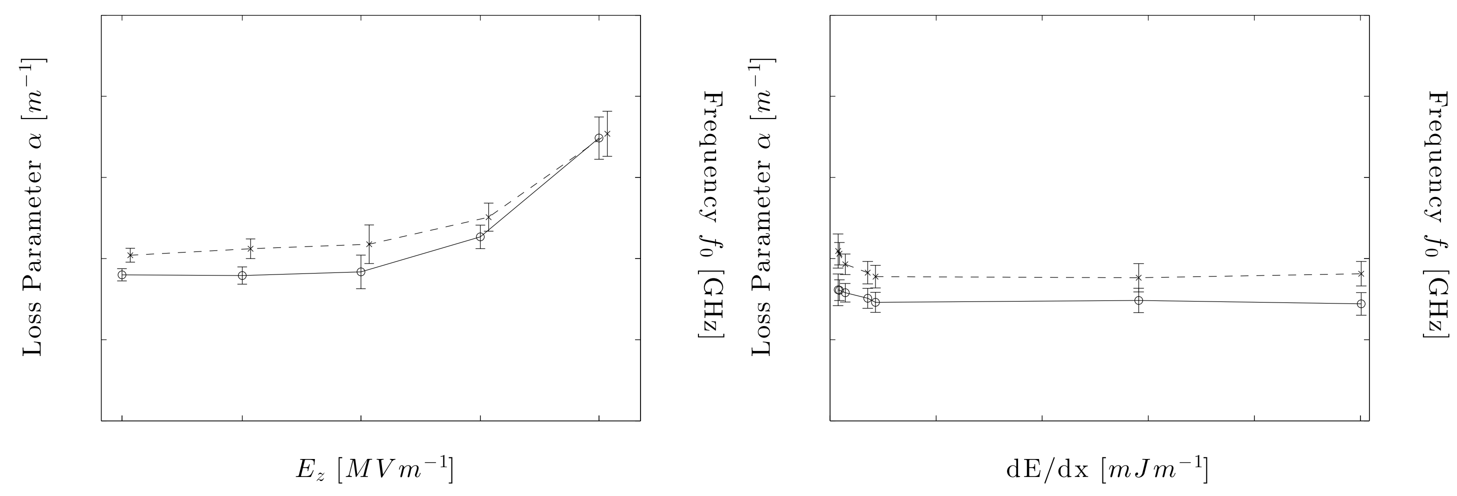
A. Schiffrin, et al., Nature Letters 493, 70 (2013)

Signal reconstruction and analysis



Autocorrelation reconstruction

Spectral broadening from damping



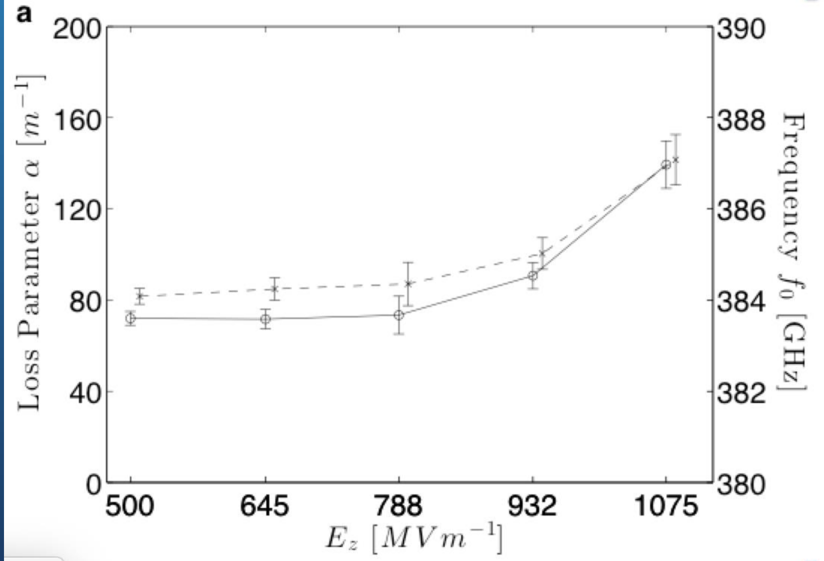
Threshold dependence on field

No dependence on enhanced dose

High field damping: conclusions and questions

- Experiments reproducible and clear
  - ~900 MV/m threshold found
  - Conductivity persistent after field drops below threshold
- Detailed comparison to theoretical model needed
- Implications for dielectric accelerator design
  - Field exclusion from dielectric
  - Material choice

Results contained in B. O'Shea et al, submitted to *Nature Photonics*

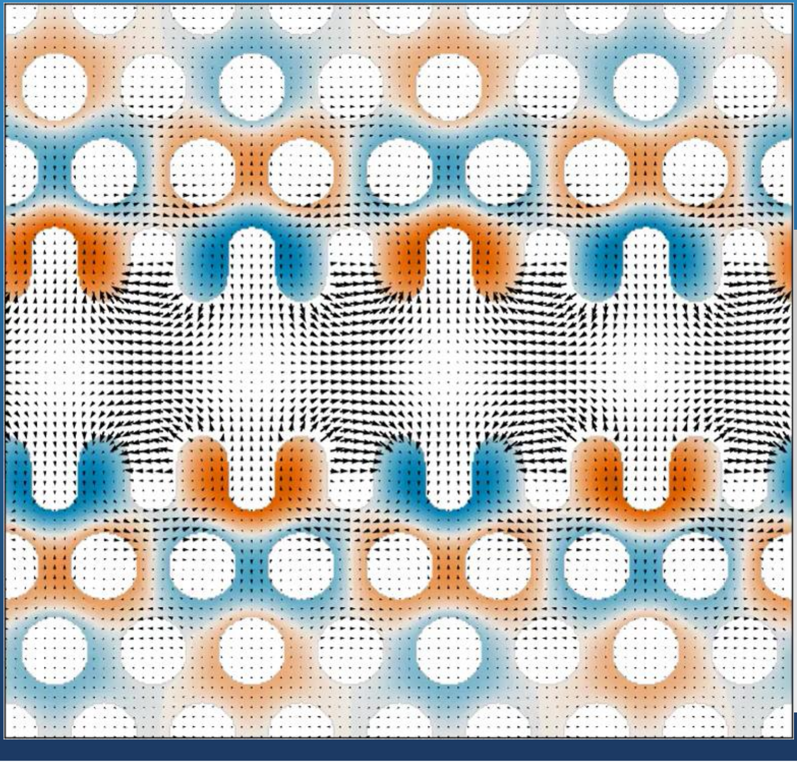


Lowering E-field inside of dielectric

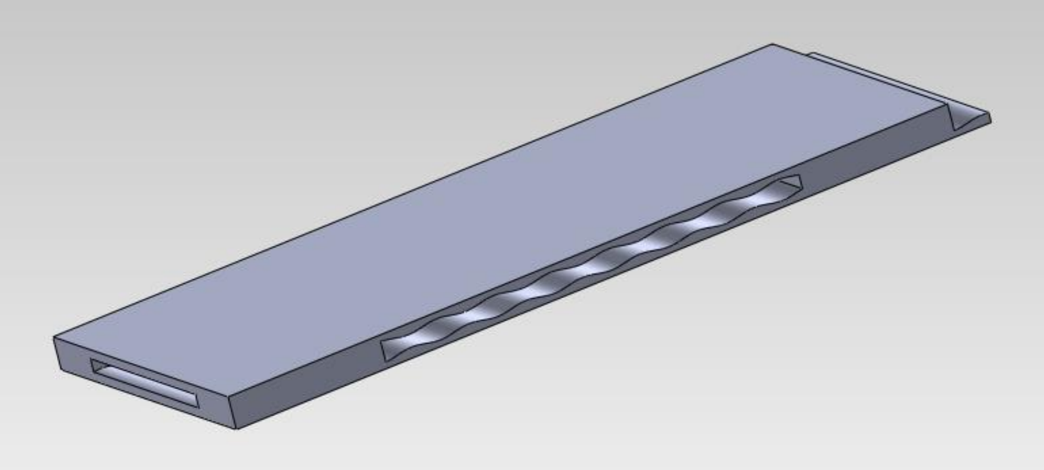
- Dielectric boundary parallel to z produces worst case, tangential *E* is continuous — and is *maximized*

- Shield with modulated boundary, support mode with *normal* entry of field lines. Diminish *E* by ε^{-1}

“GALAXIE” dielectric *laser* accelerator

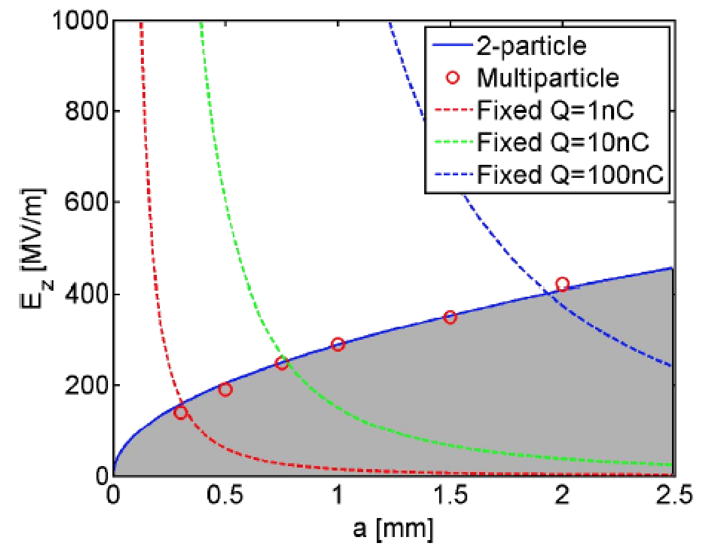


Note: not only modulation,
but *photonics*, and *slab symmetry*



Critical Aside: Transvserse Beam Breakup

- Cylindrical tubes have strong scaling in strength of transverse wakes $W_x \sim a^{-3}$
- Analysis by Li, et al. with BNS damping indicates discouranging limit on gradient (300 MeV/m @ 300 GHz)



$$E_z^{\max}[\mathrm{MV/m}] \approx 290 \times \sqrt{a[mm]}$$

Li, et al. Phys. Rev. ST Accel. Beams 17, 091302 (2014) 091302

- Possible solutions: time-dependent focusing, *slab-structures/flat beams…*

Slab Symmetry and Flat beams

- Slab symmetry/flat beams lower longitudinal, wakes

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

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

- Slab symmetry mitigates transverse wakes. Critical stability!

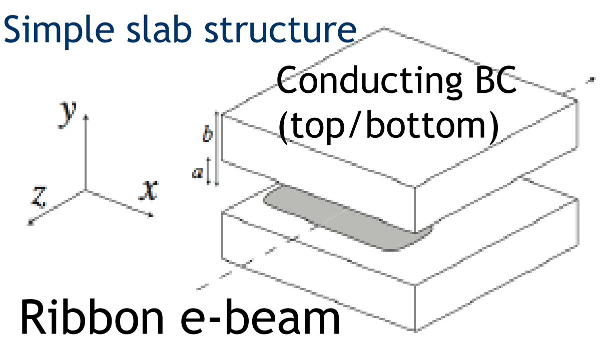
"Quadrupole" mode

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

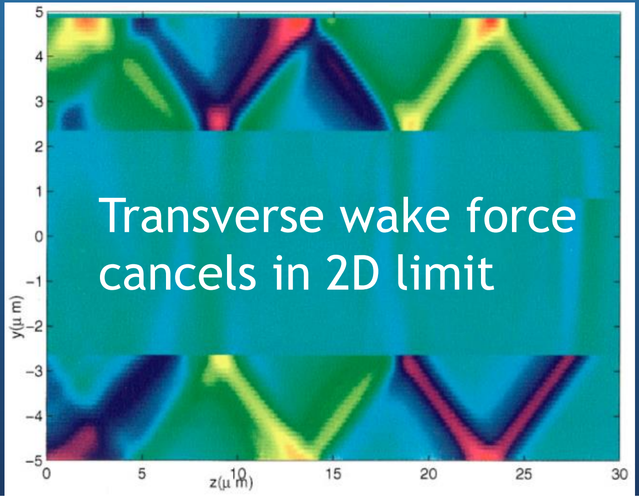
$$\sim s_x^{-2}$$

Faster than E_z

  - Permits *higher Q, flat* beam acceleration
  - Higher power available at shorter λ, essential for *laser driven dielectric accelerator* (DLA)



Slab symmetry

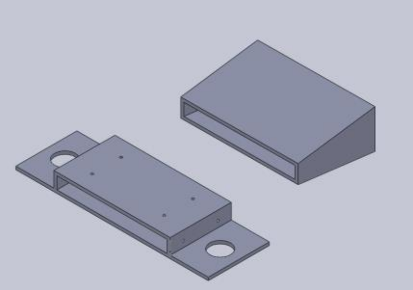


Transverse wake force cancels in 2D limit

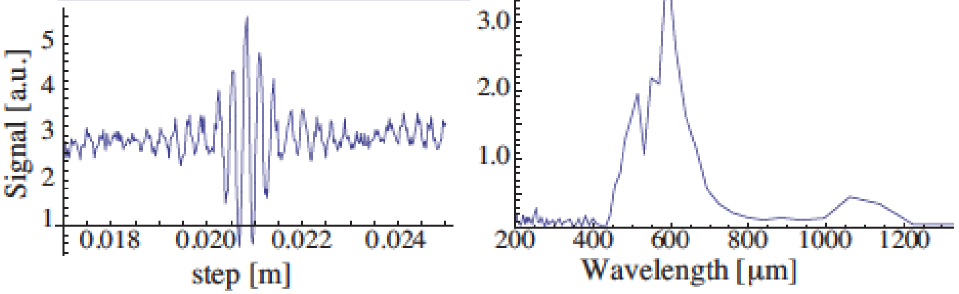
A. Tremaine, J. Rosenzweig, and P. Schoessow, Phys. Rev. E **56**, 7204 (1997)

Wakefields in slab structures: experiment

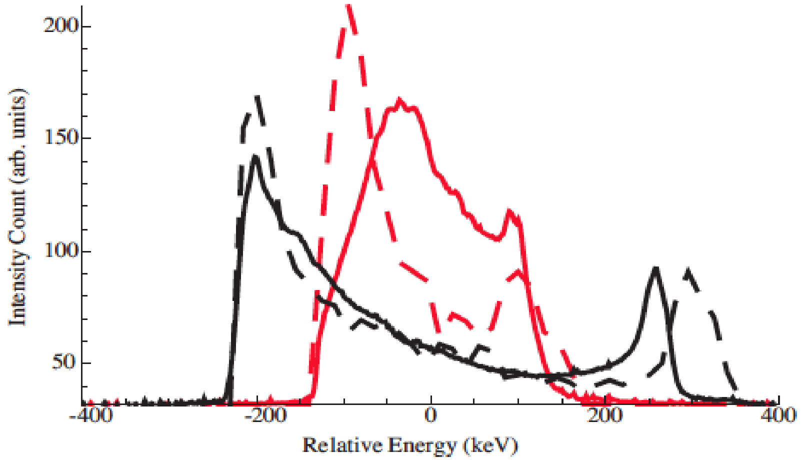
- 1st observation of *slab-symmetric* dielectric structure wakes @ATF
  - *Key* for THz DWAs: mitigates wakes, space-charge, beam loading
  - Novel modes; Longitudinal Section Mode (unconfined in *x*)



CCR slab launcher



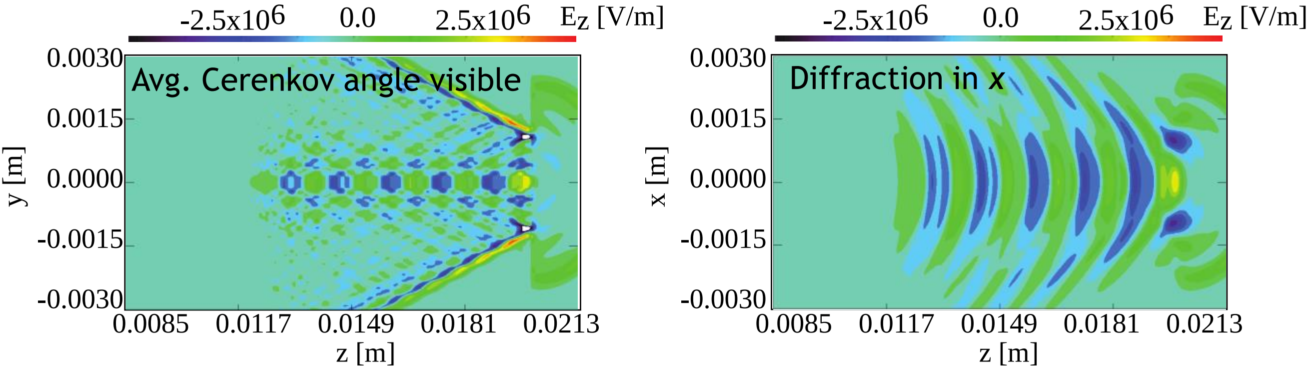
CCR signal and FFT

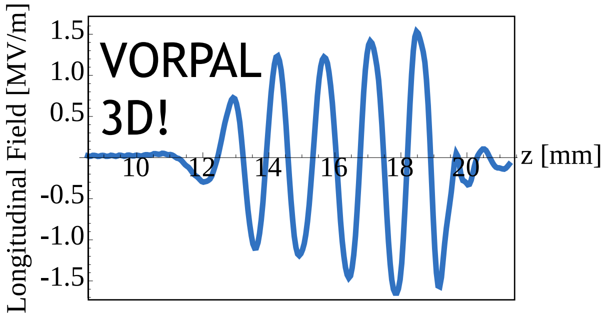


Observed (solid) and simulated (dashed) momentum spectra

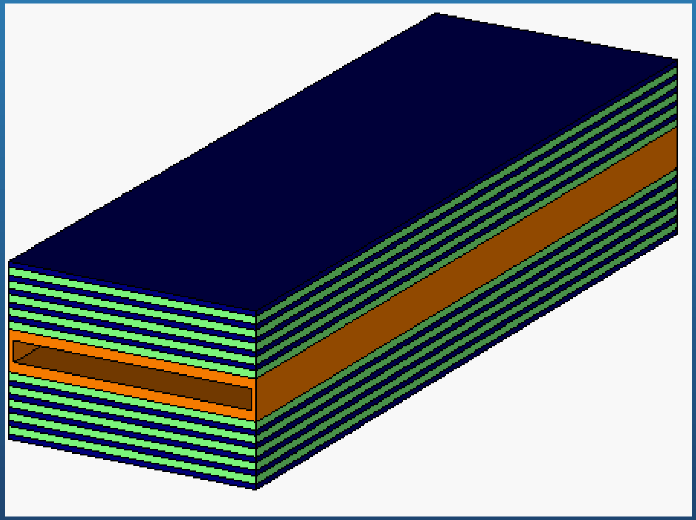
G. Andonian, et al., *PRL*108, 244801 (2012)

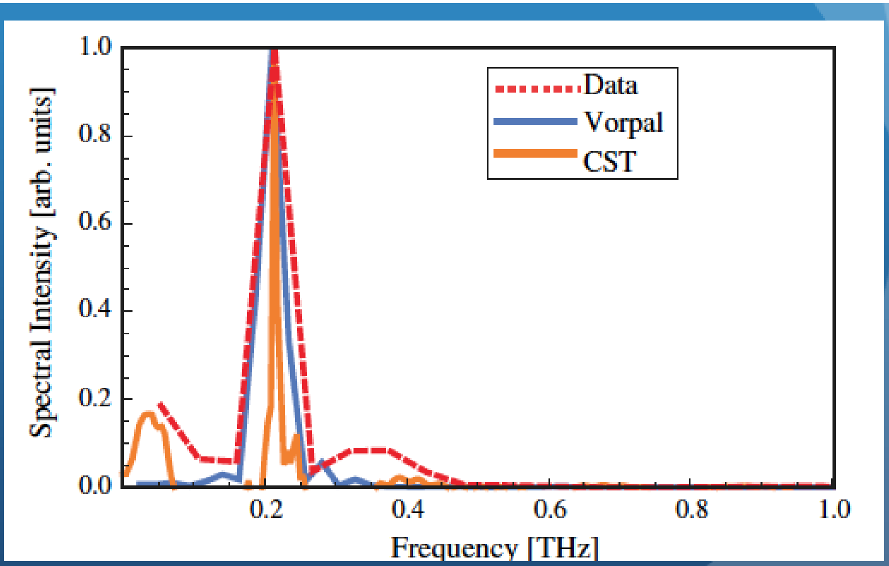
Photonic slab structure: Bragg mirror, *confinement without metal*





Bragg *eliminates metal* in IR-THz

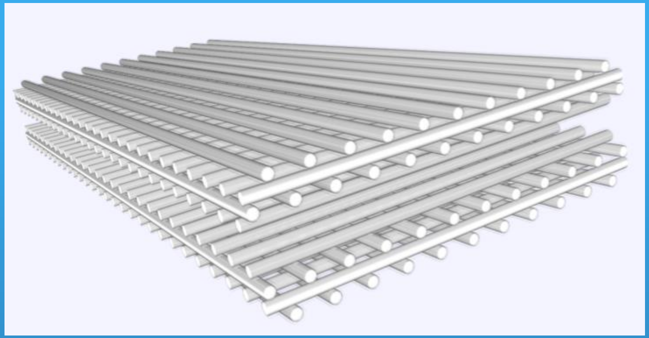




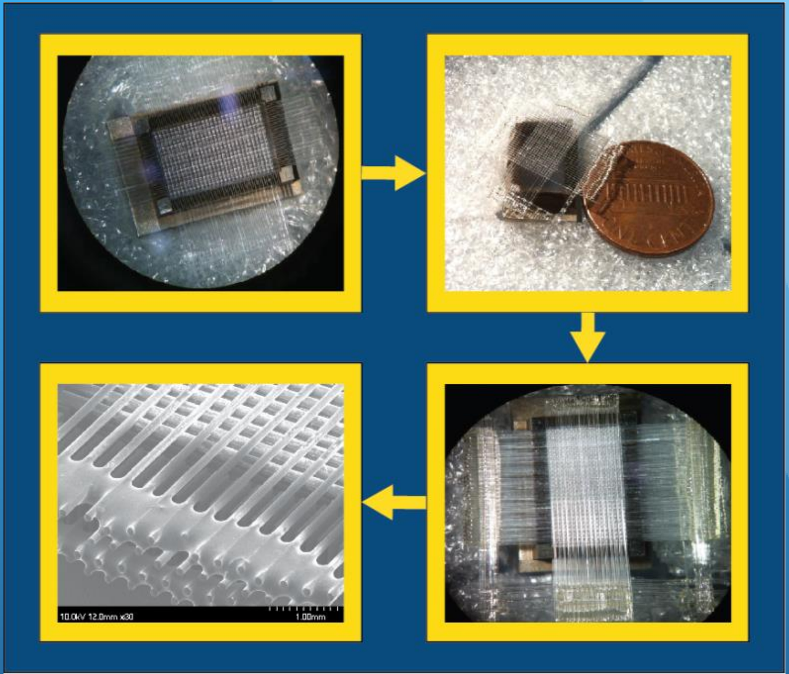
CCR autocorrelation results

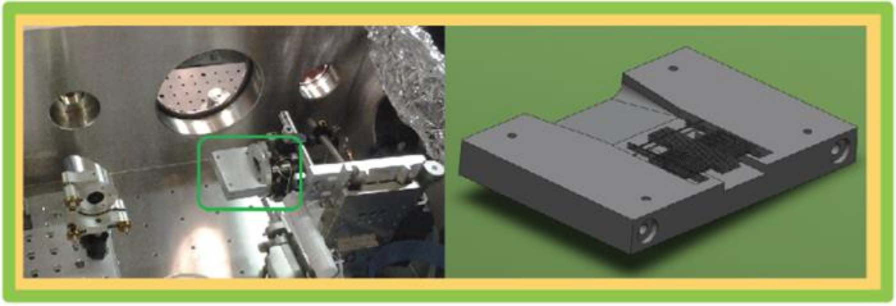
G. Andonian, et. al *Phys. Rev. Lett*. 113, 26480 (2014)

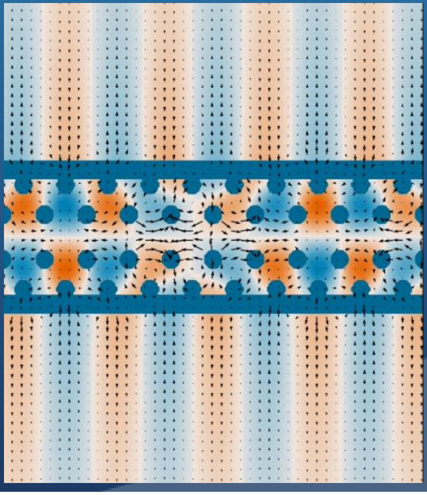
Woodpile 3D Photonic Structure



- Similar construction to Bragg. Uses 3D photonic lattice, termed “woodpile”
- Manually assembled at UCLA
  - 125um sapphire rods
- THz wakefield experiment carried out at BNL-ATF



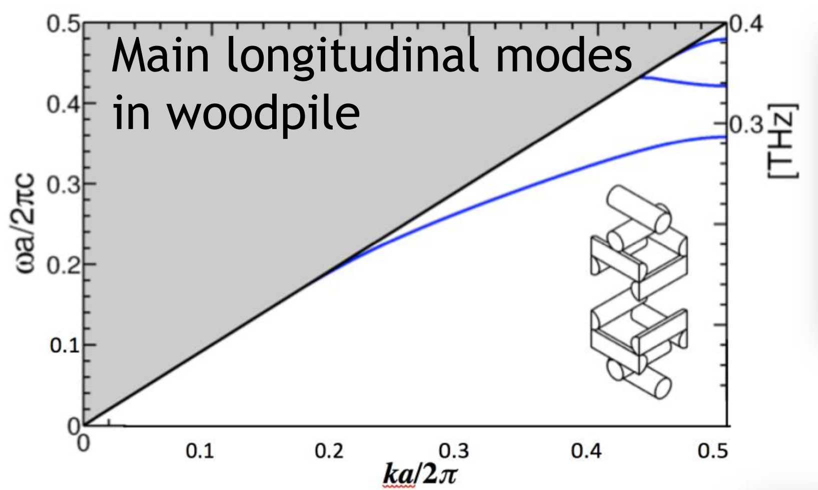




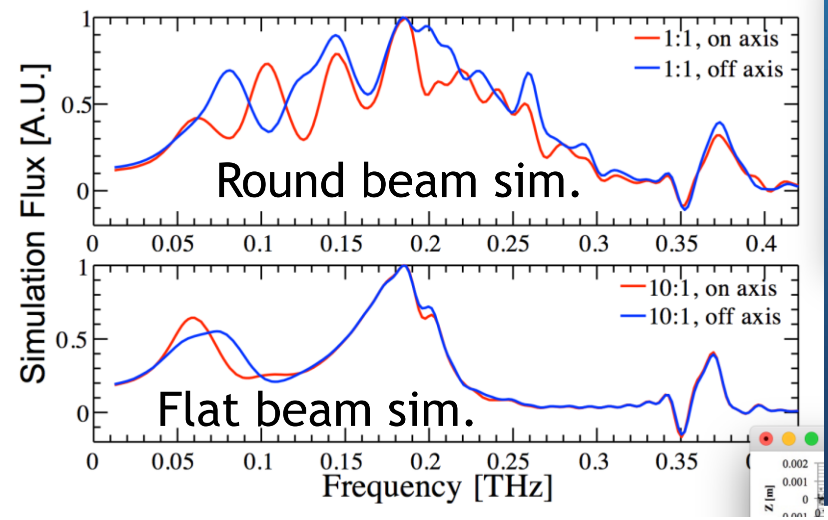
“Leaky” confinement (CST sim.)

Woodpile Beam-Structure Interaction

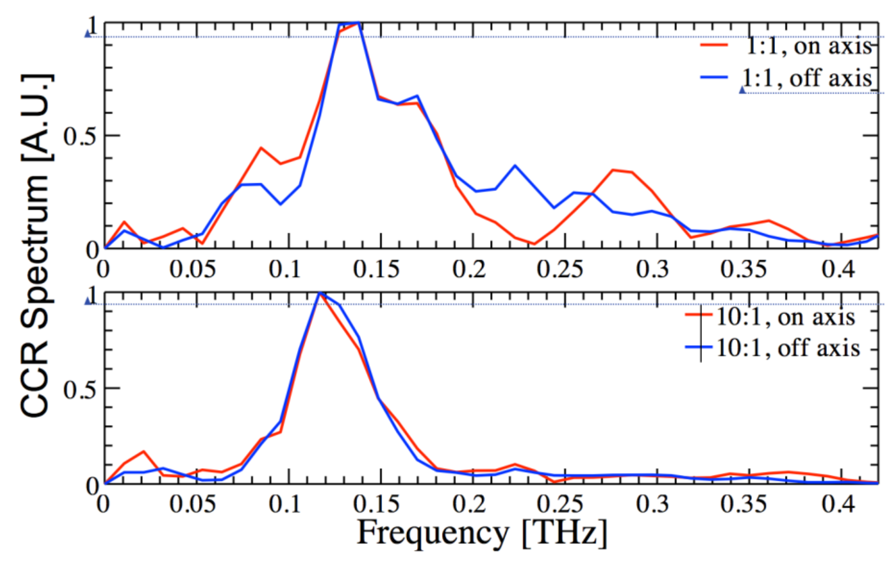
P. Hoang et al, **Experimental characterization of electron beam-driven wakefield modes in a dielectric woodpile Cartesian symmetric Structure,. Submitted to PRL**


Main longitudinal modes in woodpile

- Woodpile experiment shows:
  - 3D photonic confinement
  - Field exclusion geometry
  - Flat beam excitation (off-axis)


Round beam sim.

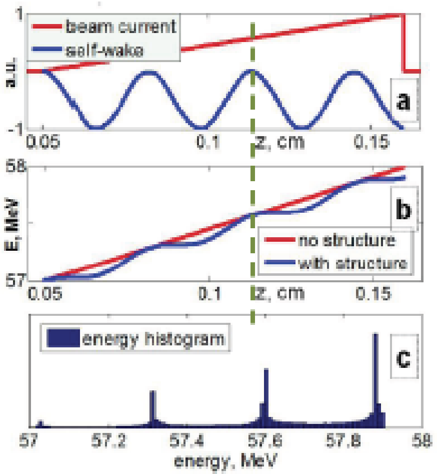
Flat beam sim.

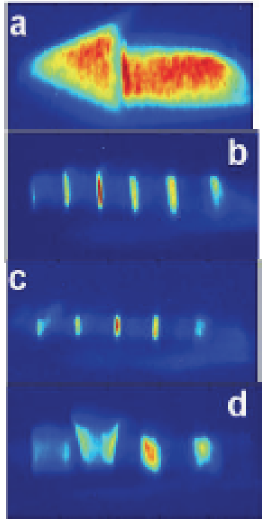


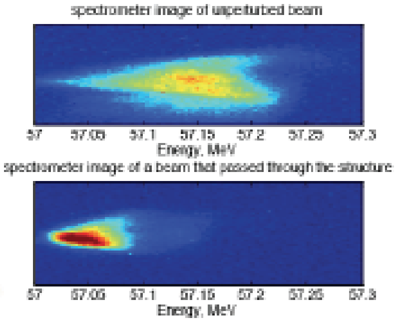
DWA: manipulations in phase space

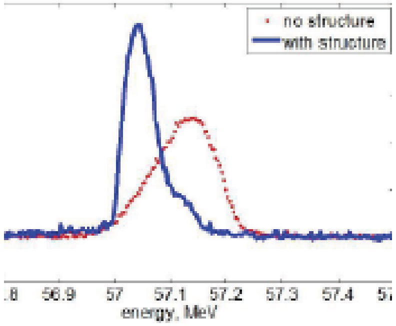
Energy Modulation & Chirp Suppression

- SiO_2, Au-sputtered, cylindrical
  - 1) 0.95THz, 1" long
  - 2) 0.76THz, 1" long
  - 3) 0.62THz, 2" long
- BNL ATF
  - 57MeV, 130pC
  - Triangular + rectangular bunch
  - Length variable with slits
- Results
  - Energy mod. for $\sigma_z > \lambda_{01}$
  - Chirp suppression for $\sigma_z < \lambda_{01}$
  - "Double" bunches when structure not optimal
- Applications
  - Bunch train (convert Energy mod to density mod with chicane)
  - Wakefield "silencer" for $\sigma_z < \lambda_{01}$
  - Reduce e-spread in passive medium





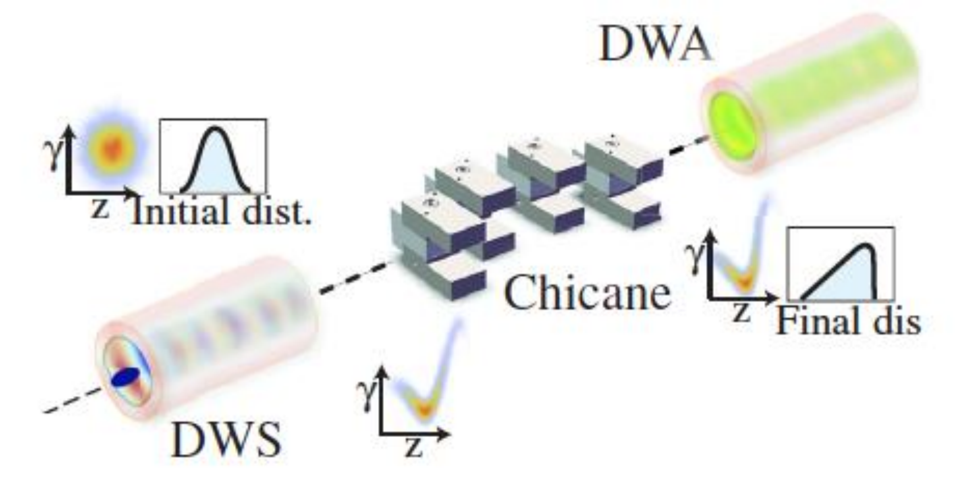


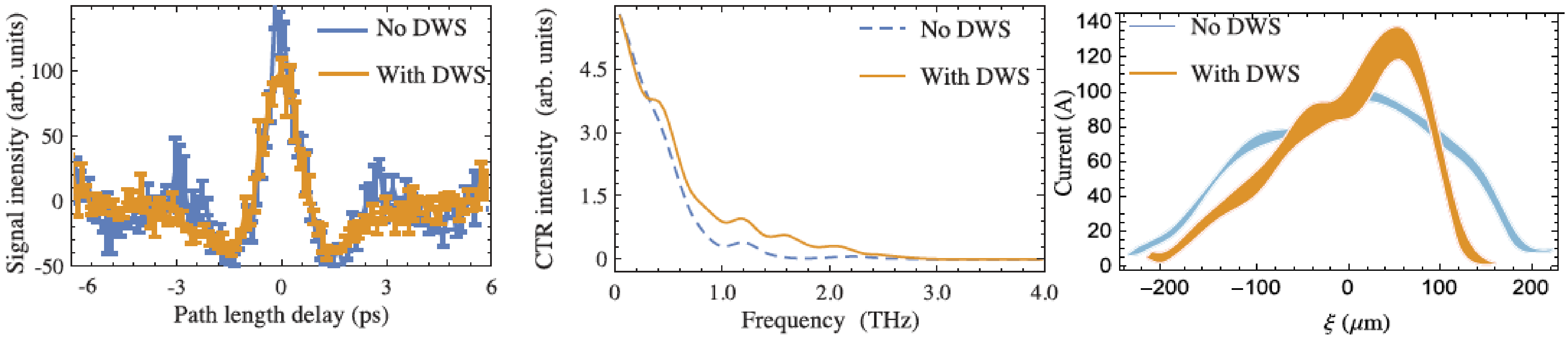


S. Antipov, *et al.*, *Phys. Rev. Lett.* **108**, 144801 (2012)

Ramped Beam Creation with DWA

- DWA energy modulation, chicane transport
- Triangular pulses in simple system

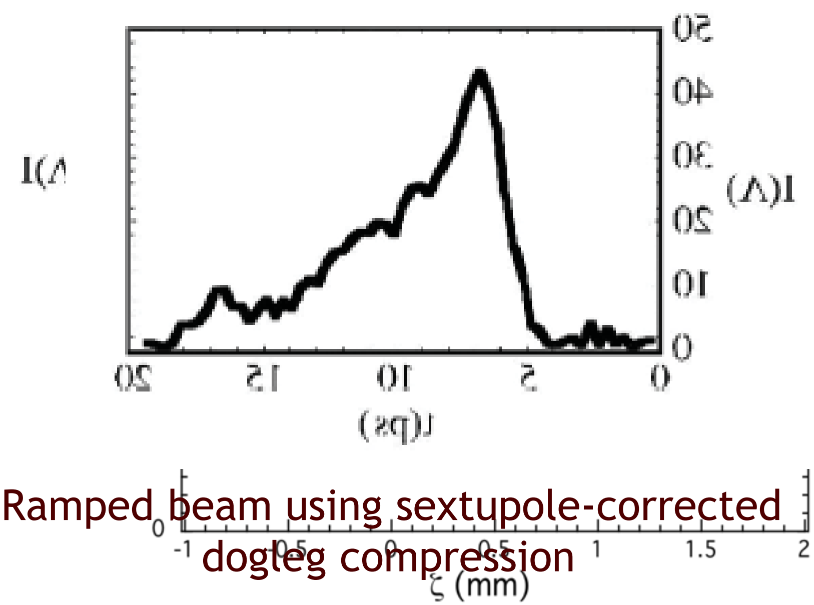




Kramers-Kronig reconstruction of ramped beam
G. Andonian, et al., PRL 118, 054802 (2017)

Stepping stone application: 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, ANL
- Enables *hard X-ray source* w/high average power, small footprint?



Ramped beam using sextupole-corrected dogleg compression

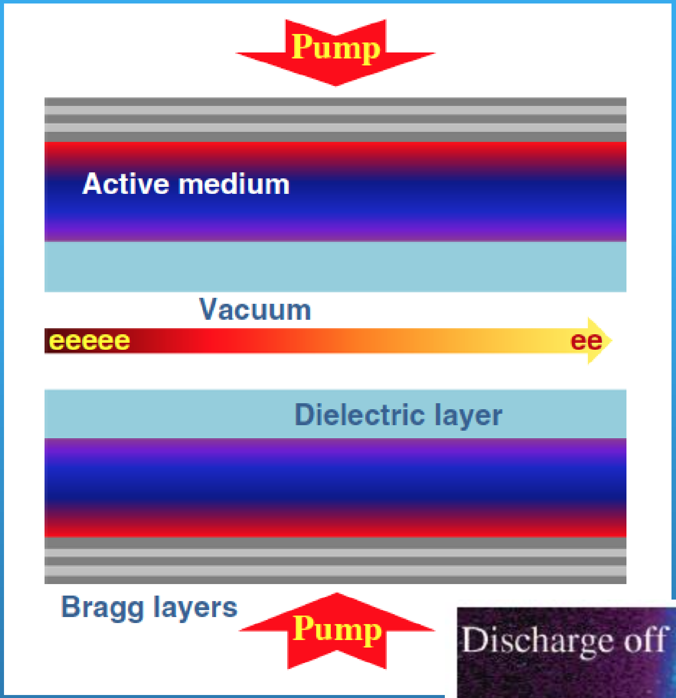
Longitudinal phase space after 1.3 m DWA (OOPIC)

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

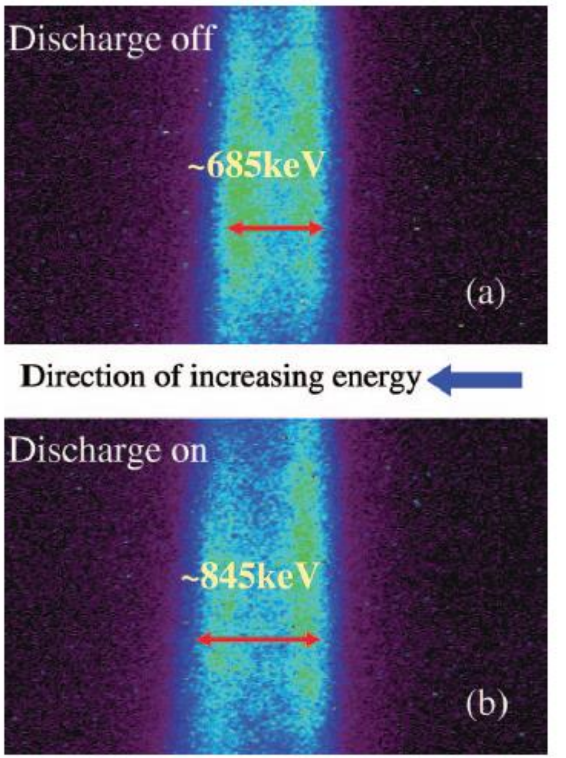
Longitudinal wakefields with ramped beam

Exotic ideas

- Nonlinear materials
  - Ferroelectrics
- Electromagnetic mode conversion?
  - THz from laser
- Particle acceleration through stimulated emission of radiation
  - PASER
  - Inverted medium triggered by beam wakefield



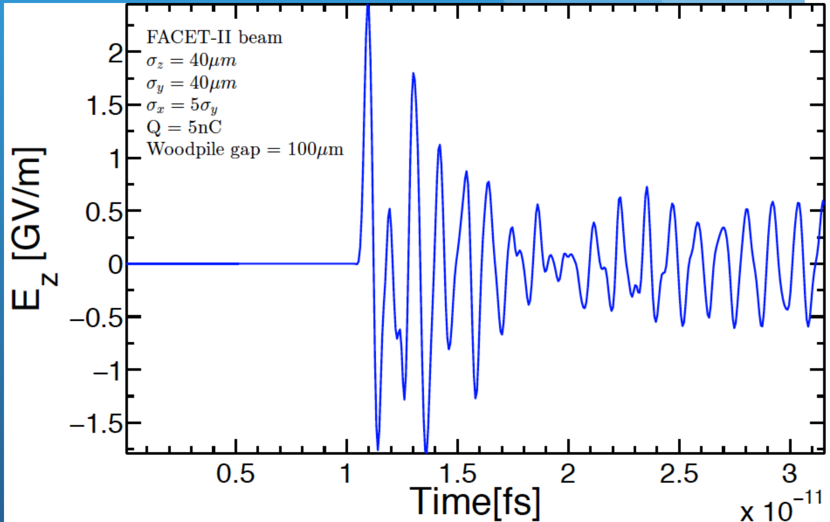
PASER
Proof of principle experiment



Status and future directions

- Proof-of-concept experiments have been performed
  - GHz to THz, up to 2.6 GV/m fields without breakdown
  - Pulse train excitation, transformer ratio
  - Longitudinal beam shaping
  - Materials
  - Photonic designs

- For the future (non-exclusive!)
  - Field exclusion, new materials
  - Long term driver & witness dynamics
    - Computation in 3D
  - Cartesian symmetry, flat beams
  - Facility use! AWA, ATF, FACET II, SPARC,…
  - Photonic design for mode shaping
  - Stepping stone projects (*e.g.* EUPRAXIA)



FACET II flat beam experimental sim. for GV/m fields