High Frequency, High Gradient Dielectric Wakefield Acceleration Experiments at SLAC and BNL

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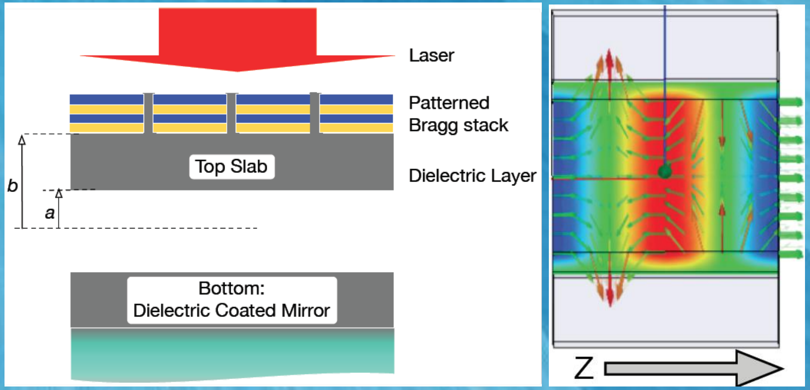
Scaling the accelerator in size

- *Lasers* produce copious power (~J, >TW)
  - Scale in λ by 4 orders of magnitude
  - $\lambda < 1\ \mu$m gives *challenges* in beam dynamics
  - Reinvent resonant structure using *dielectric* (E163, UCLA)
  - GV/m fields possible, breakdown limited…

Resonant dielectric laser-excited structure (with HFSS simulated fields)

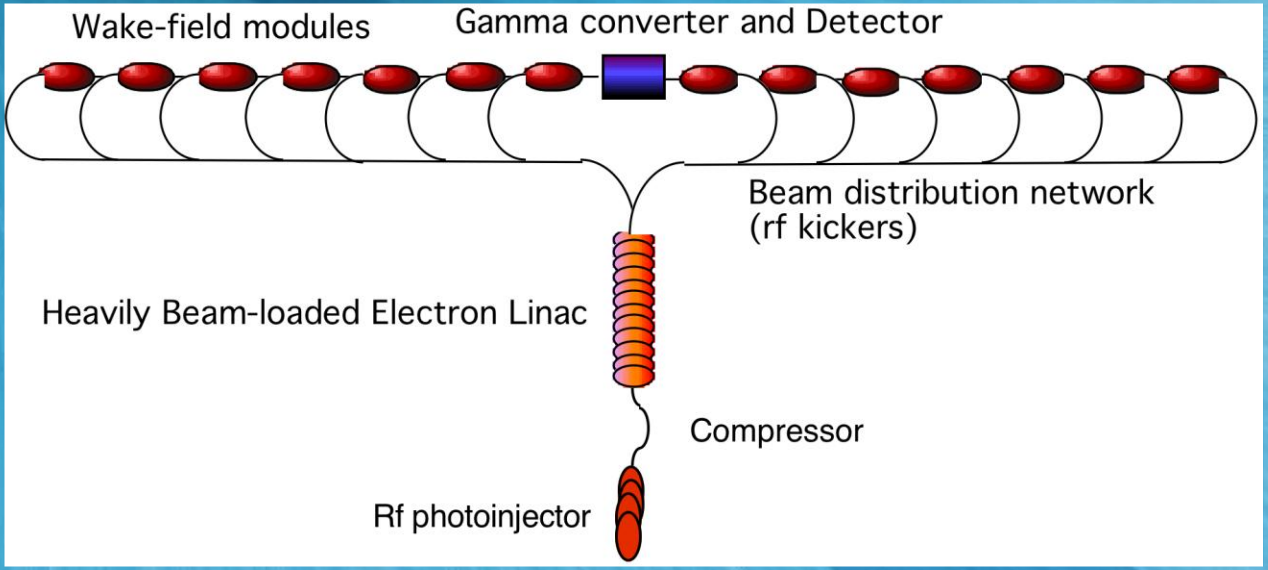


- GV/m allows major reduction in size, cost
- To jump to GV/m, mm-THz may be better:
  - Beam dynamics, breakdown scaling
  - Must have new source…

Promising paradigm for high field accelerators: wakefields

- Coherent radiation from bunched, *v~c,* e^- beam
  - *Any slow-wave* environment
  - Powers exotic schemes: plasma, dielectrics
- Resonant or non-resonant (*short pulse)* operation
- High average power beams can be produced
  - Tens of MW, beats lasers…
- Intense beams needed by many fields
  - X-ray FEL
  - X-rays from Compton scattering
  - THz sources

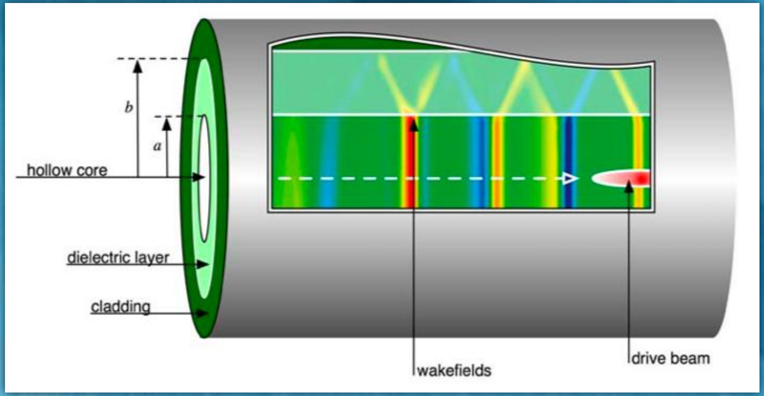
Schematic of wakefield-based collider



J. Rosenzweig, *et al., Nucl. Instrum. Methods A* ***410 532 (1998).***
(concept borrowed from W. Gai…)

- Similar to original CLIC scheme
- Study for plasma wakefield accelerator
  - $\gamma\gamma$ due to charge asymmetry in PWFA
  - Not a problem for DWA…

The dielectric wakefield accelerator



Coherent *Cerenkov* scaling

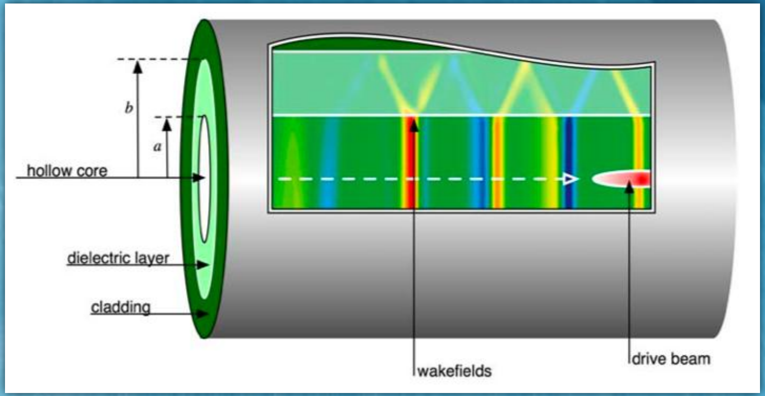
$$\frac{dU}{dz} \propto k_{\max}^2 \propto \sigma_z^{-2}$$

$$\frac{dU}{dz} \propto \int (n-1) k\, dk \propto k_{\max}^2$$

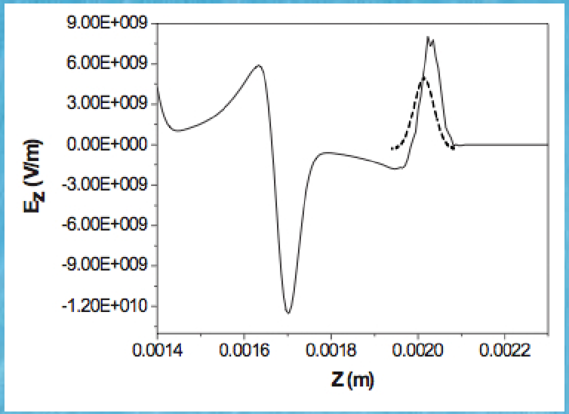
- High accelerating gradients: GV/m level
  - Dielectric based, low loss, short pulse
  - Higher gradient than optical?
  - Unlike plasma, charged particles in beam path…
- Use wakefield collider schemes
  - CLIC style modular system
  - *Afterburner* (energy multiplier) possible for existing accelerators
- Spin-offs
  - High power THz radiation source (e.g. E. Chiadroni)

Dielectric Wakefield Accelerator

Overview



- Design Parameters a,b σ_z ε



Ez on-axis, OOPIC

- Electron bunch (β ≈ 1) drives wake in cylindrical dielectric structure
  - Dependent on structure properties
  - Generally multi-mode excitation
- Wakefields accelerate trailing bunch
  - Mode wavelengths (quasi-optical

$$\lambda_n \approx \frac{4(b-a)}{n}\sqrt{\varepsilon-1}$$

  - Peak decelerating field

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

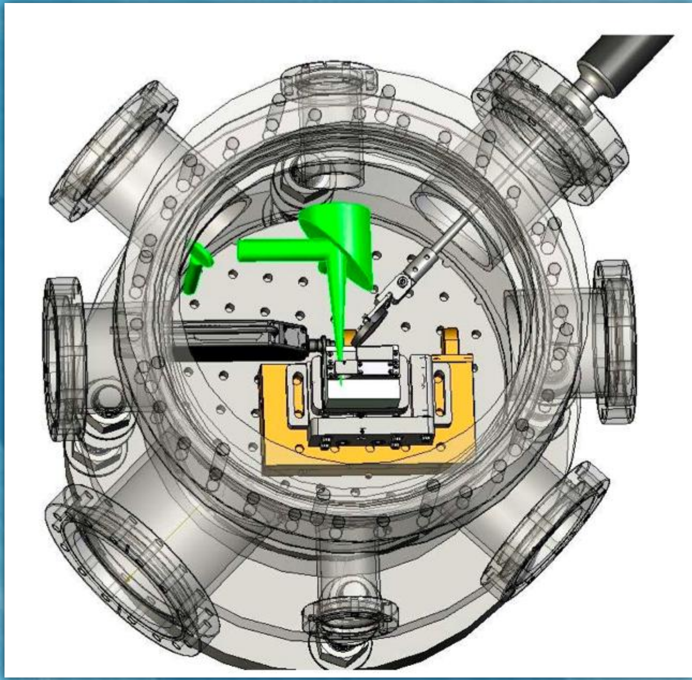
Extremely good beam needed

  - Transformer ratio (unshaped beam)

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

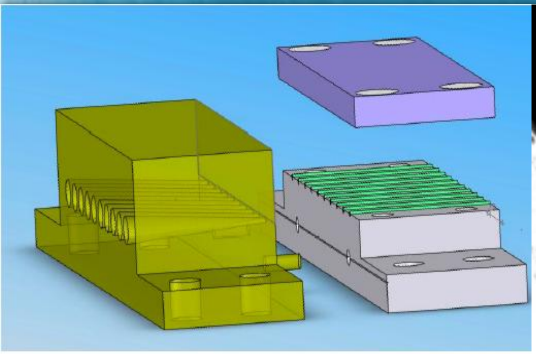
T-481: Test-beam exploration of breakdown threshold

- 1st ultra-short, high charge beams
- Beyond pioneering work at ANL…
  - Much shorter pulses, small radial size
  - Higher gradients…
- Leverage off E167 PWFA
- Goal: breakdown studies
  - Al-clad fused SiO_2 fibers
    - ID 100/200 μm, OD 325 μm, L=1 cm
  - Avalanche v. tunneling ionization
  - Beam parameters indicated $E_z \leq$12GV/m can be excited
    - 3 nC, $\sigma_z \geq$ 20 μm, 28.5 GeV
- 48 hr FFTB run

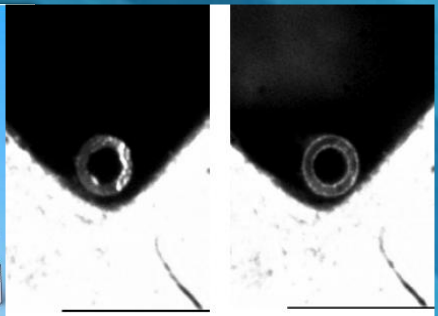


T-481 "octopus" chamber

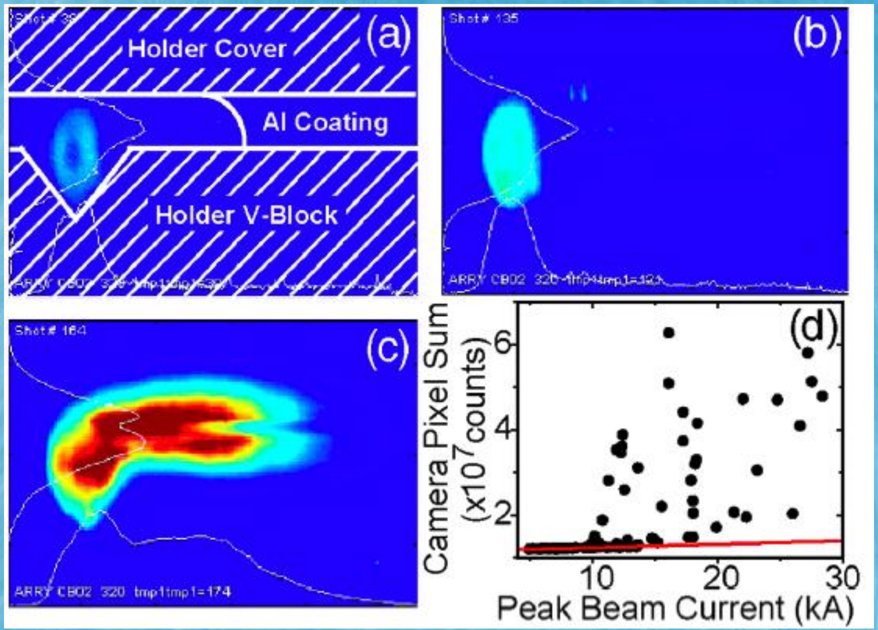
Methods and Results



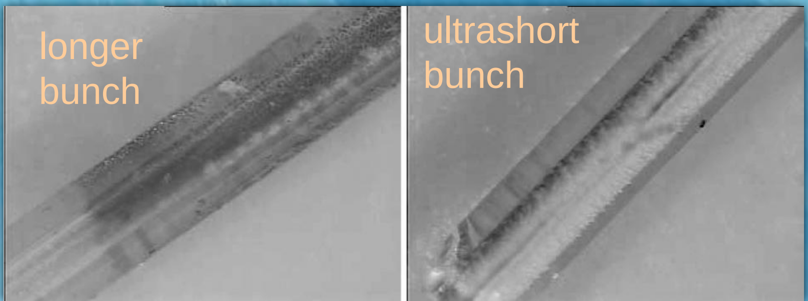
CAD rendering of the capillary tube mounting



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 more robust
- Observed breakdown threshold (field from simulations)
  - 13.8 GV/m surface field
  - 5.5 GV/m deceleration field
  - Multi-mode effect?
- Correlations to post-mortem inspection



Methods and Results

PRL 100, 214801 (2008) PHYSICAL REVIEW LETTERS week ending 30 MAY 2008

Breakdown Limits on Gigavolt-per-Meter Electron-Beam-Driven Wakefields in Dielectric Structures

M. C. Thompson,[1,2,*] H. Badakov,[1] A. M. Cook,[1] J. B. Rosenzweig,[1] R. Tikhoplav,[1] G. Travish,[1] I. Blumenfeld,[3] M. J. Hogan,[3] R. Ischebeck,[3] N. Kirby,[3] R. Siemann,[3] D. Walz,[3] P. Muggli,[4] A. Scott,[5] and R. B. Yoder[6]

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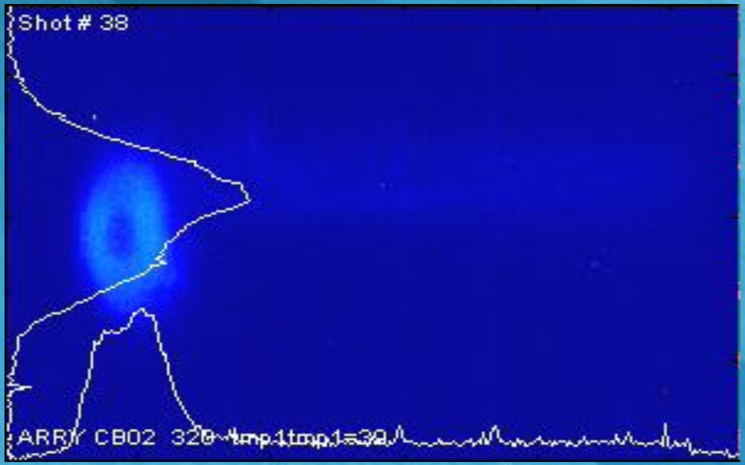
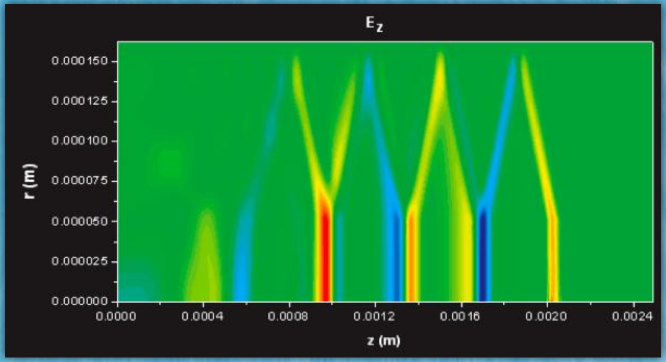
First measurements of the breakdown threshold in a dielectric subjected to GV/m wakefields produced by short (30–330 fs), 28.5 GeV electron bunches have been made. Fused silica tubes of 100 μm inner diameter were exposed to a range of bunch lengths, allowing surface dielectric fields up to 27 GV/m to be generated. The onset of breakdown, detected through light emission from the tube ends, is observed to occur when the peak electric field at the dielectric surface reaches 13.8 ± 0.7 GV/m. The correlation of structure damage to beam-induced breakdown is established using an array of postexposure inspection techniques.

Beam Observations and Analysis



View end of dielectric tube;
frames sorted by increasing peak current

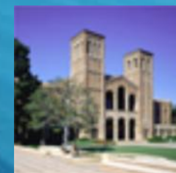
Breakdown determined by benchmarked OOPIC simulations



Breakdown limit:
5.5 GV/m decel. field

Multi-mode excitation – short, separated pulses — gives better breakdown dynamics

~~E169~~ Collaboration



UCLA

H. Badakov[α], M. Berry[β], I. Blumenfeld[β], A. Cook[α], F.-J. Decker[β], M. Hogan[β], R. Ischebeck[β], R. Iverson[β], A. Kanareykin[ε], N. Kirby[β], P. Muggli[γ], J.B. Rosenzweig[α], R. Siemann[β], M.C. Thompson[δ], R. Tikhoplav[α], G. Travish[α], R. Yoder[ζ], D. Walz[β]

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[β]*Stanford Linear Accelerator Center*

[γ]*University of Southern California*

[δ]*Lawrence Livermore National Laboratory*

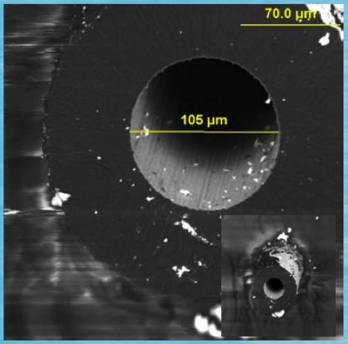
[ζ]*Manhattanville College*

[ε]*Euclid TechLabs, LLC*

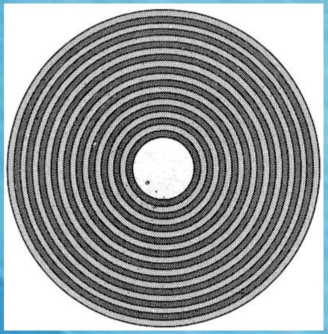
Collaboration spokespersons

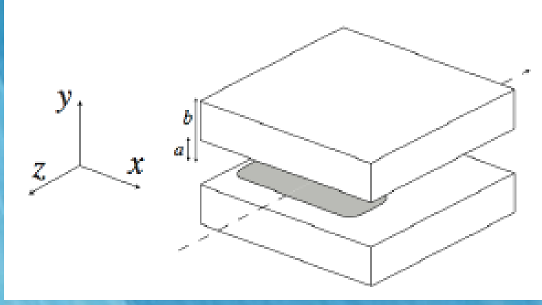
E169 at FACET: overview

- Research GV/m acceleration scheme in DWA
- Goals
  - **Explore breakdown issues in detail**
  - **Determine usable field envelope**
  - ~~**Coherent Cerenkov radiation measurements**~~ (Already explored At UCLA)
  - **Explore alternate materials**
  - **Explore alternate designs and cladding**
    - **Slab structure (permits higher *Q*, low wakes)**
    - **Radial and longitudinal periodicity…**
  - **Varying tube dimensions**
    - Impedance change
    - Breakdown dependence on wake pulse length
- Awaits FACET construction
  - Reapproval needed
  - Add AWA group to collaboration



CVD deposited diamond

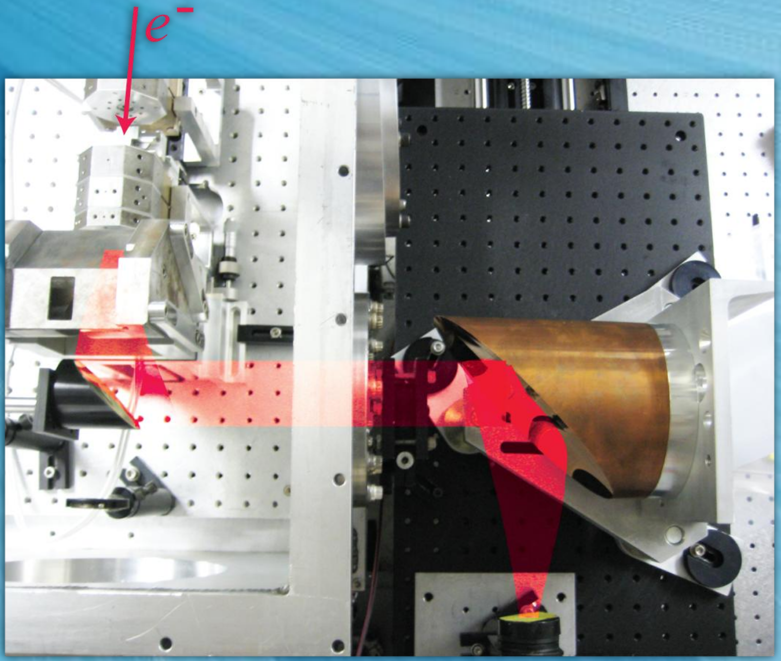

Bragg fiber



Slab dielectric structure (like optical)

Observation of THz Coherent Cerenkov Wakefields @ Neptune

- Chicane-compressed (200 μm) 0.3 nC beam
  - Focused with PMQ array to 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



Observation of THz Coherent Cerenkov Wakefields @ Neptune

- Chicane-compressed (200 μm) 0.3 nC beam
  - Focused with PMQ array to $\sigma_r \sim 100$ μm (a=250 μm)
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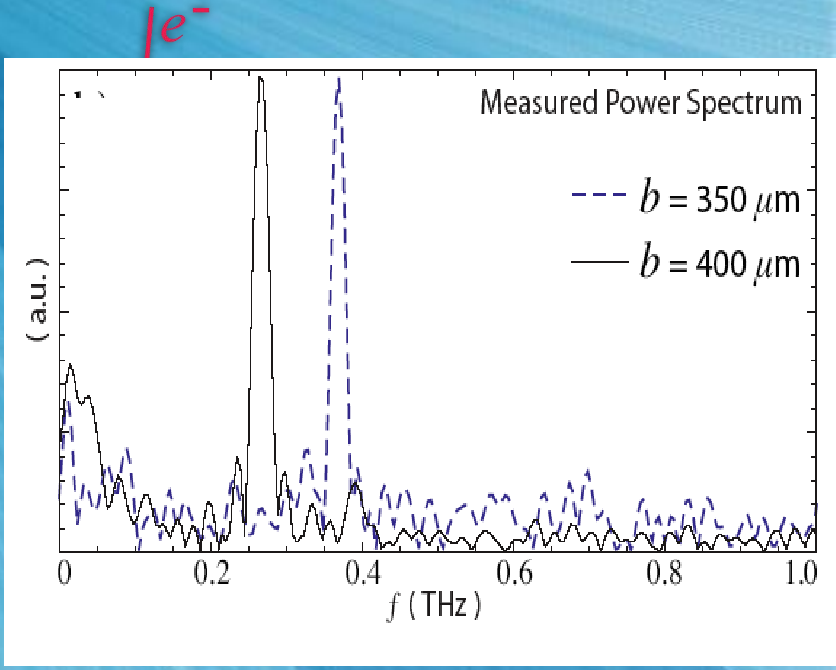
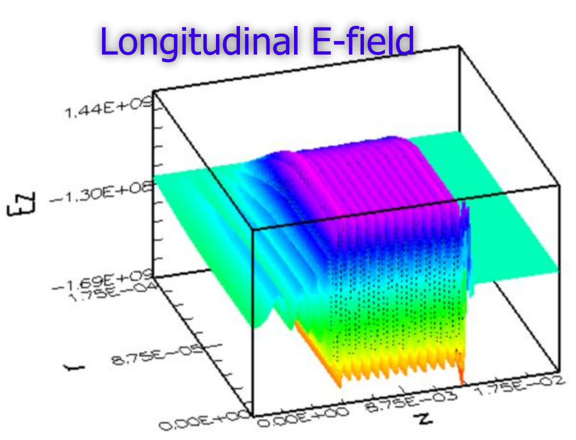


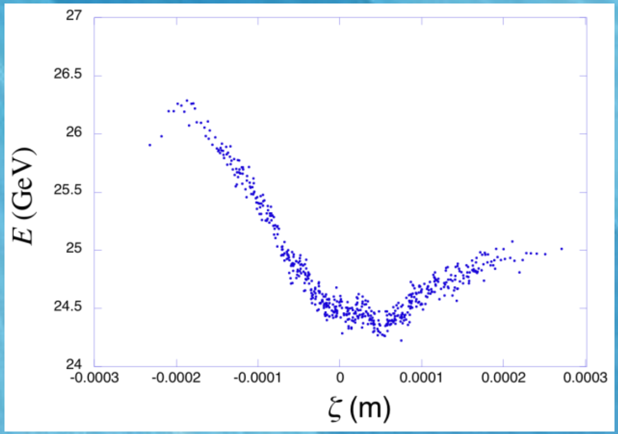
E-169 at FACET: Acceleration

- Observe acceleration
  - ✓ 10-33 cm tube length
  - ✓ longer bunch, acceleration of tail
  - ✓ “moderate” gradient, 1-3 GV/m
  - ✓ single mode operation
- Phase 3: Accelerated beam quality
  - ✓ Witness beam
  - ✓ Alignment, transverse wakes, BBU
  - ✓ Group velocity & EM exposure $t = L/(c - v_g)$
  - ✓ Positrons. Breakdown is different?

σ_z	50-150 μm
σ_r	< 10 μm
E_b	25 GeV
Q	3 - 5 nC

FACET beam parameters for E169: acceleration case





Momentum distribution after 33 cm (OOPIC)

E-169 at FACET: Acceleration

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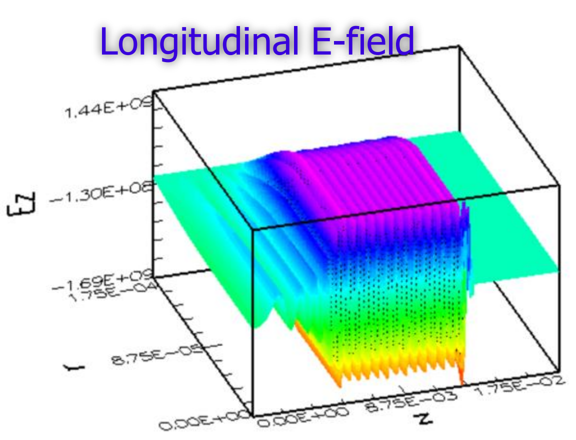
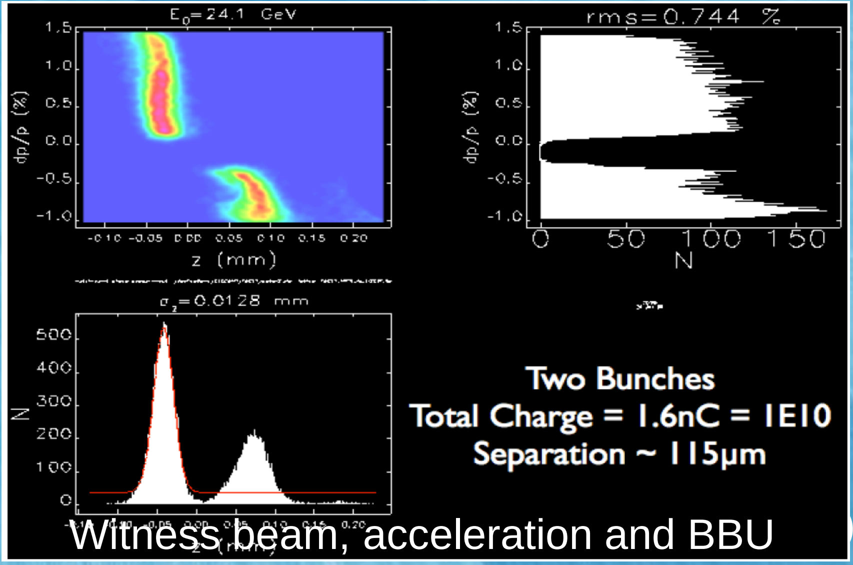
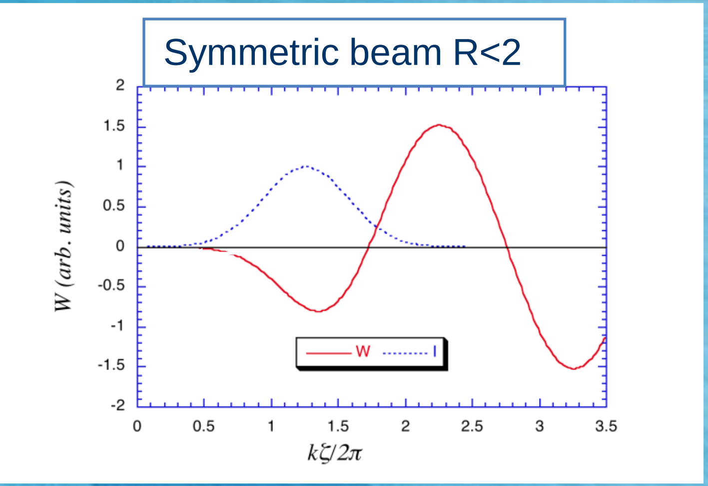


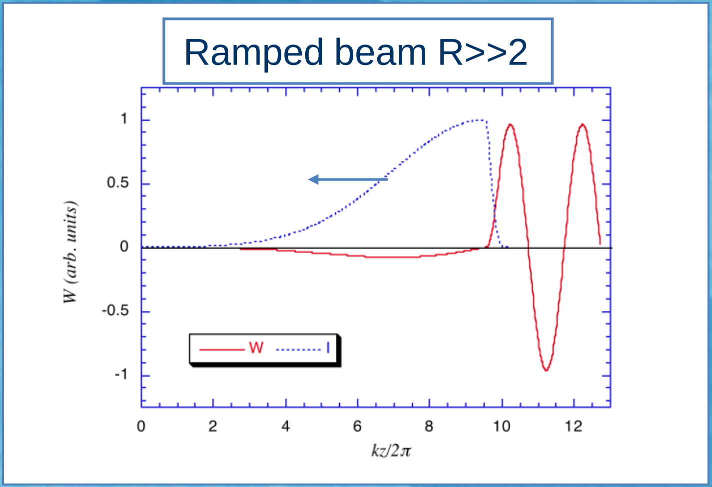


Witness beam, acceleration and BBU

A High Transformer Scenario using Dielectric Wakes

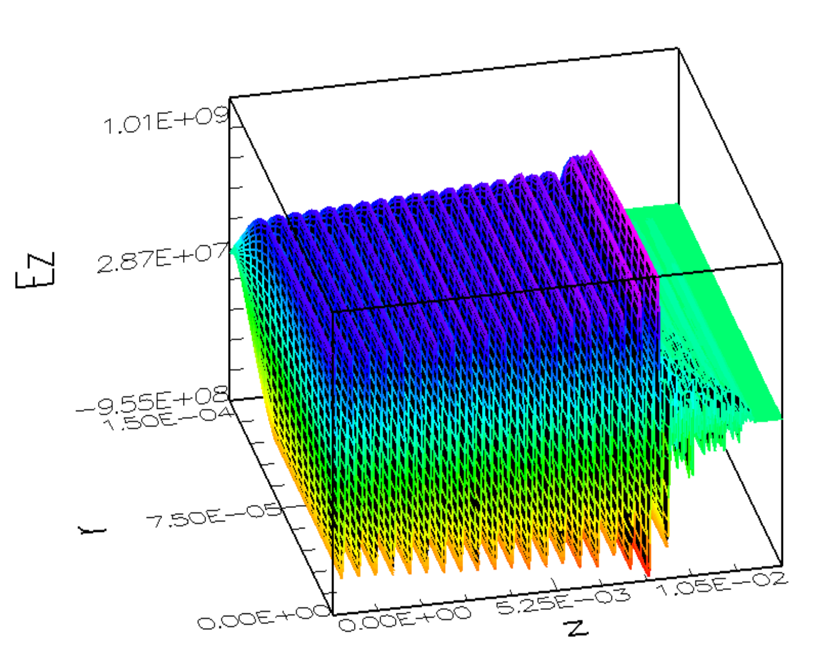
- How to reach high energy with DWAs?
- Enhanced transformer ratio with *ramped beam*
- Does this work with *multi-mode* DWA?
- Scenario: 500-1000 MeV ramped driver; 5-10 GeV FEL injector in <10 m





A FACET test for light source scenario

- Beam parameters: Q=3 nC, ramp L=2.5 mm, U=1 GeV
- Structure: a=100 μm, b=100 μm, ε=3.8
- Fundamental f=0.74 THz
- Performance: E_z>GV/m, R=9
  10 (10 GeV beam)
- Ramp achieved at UCLA. Possible at ATF, FACET?



Sag in wake due to multi-mode

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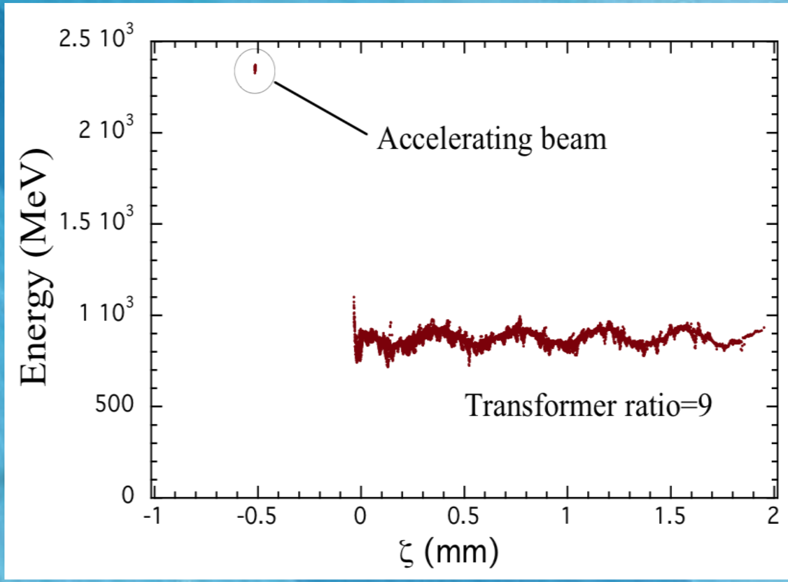

Longitudinal phase space after 1.3 m DWA (OOPIC)

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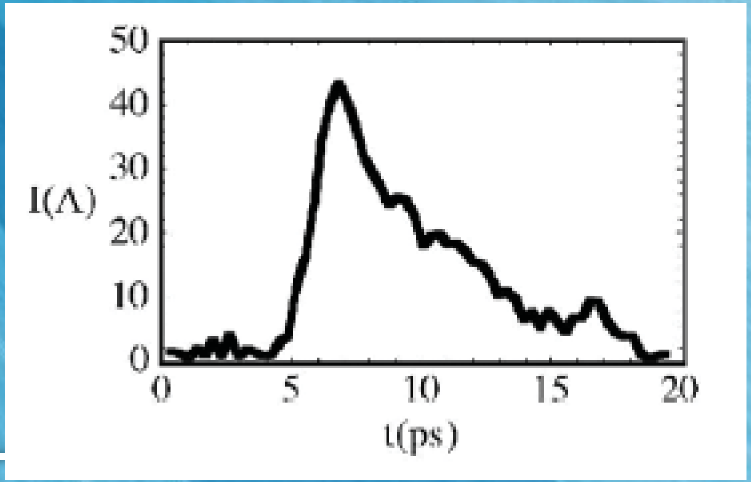
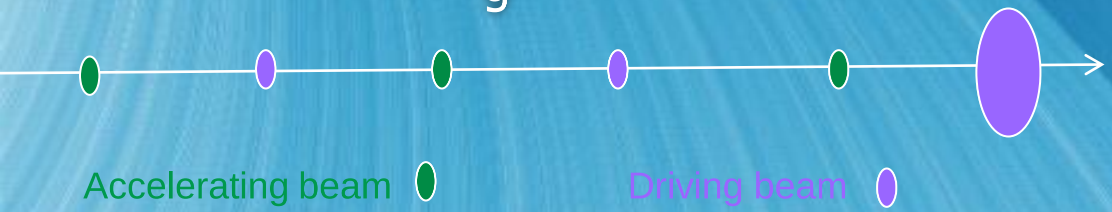


Ramped beam using sextupole-corrected dogleg compression

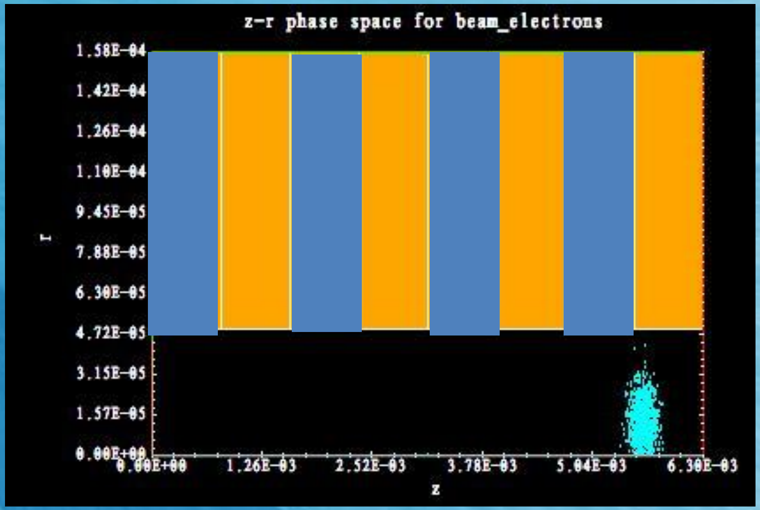
R. J. England, J. B. Rosenzweig, and G. Travish, PRL 100, 214802 (2008)

Multipulse operation: control of group velocity

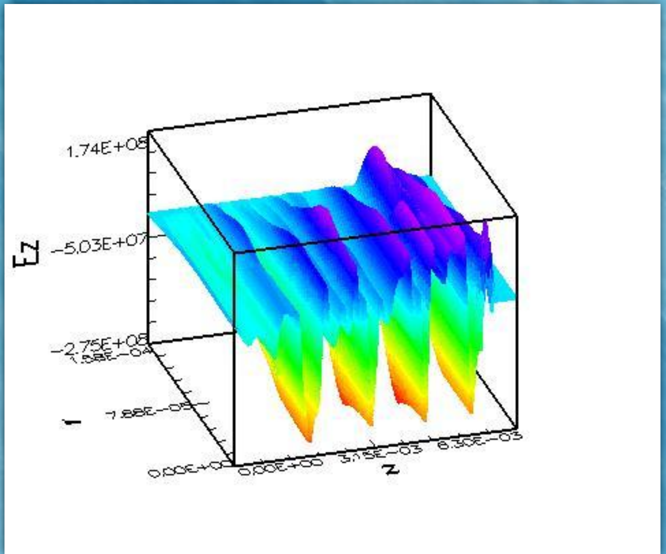
- *Multiple pulse beam-loaded operation* in linear collider, needs *low* v_g



- Low charge gives smaller (low ε), shorter beams
  - Can even replace large Q driver
- Use *periodic DWA* structure in $\sim\pi$-mode, resonant excitation



Example: SiO_2/diamond structure



Multipulse operation: control of group velocity

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Accelerating beam   Driving beam

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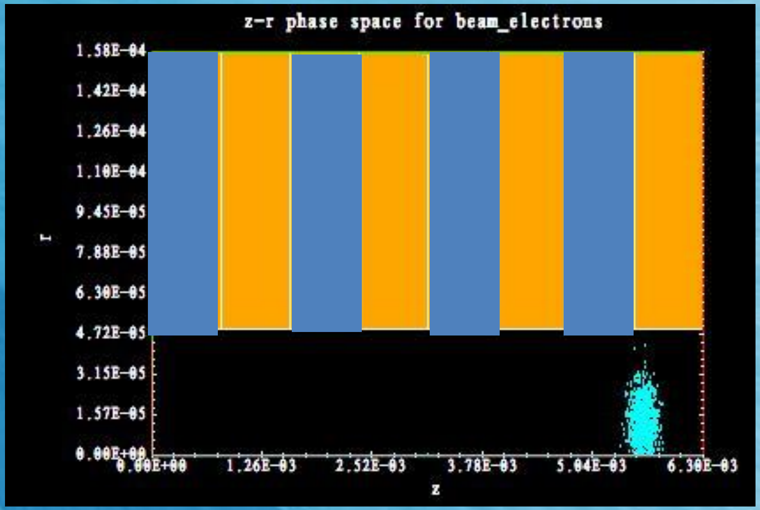

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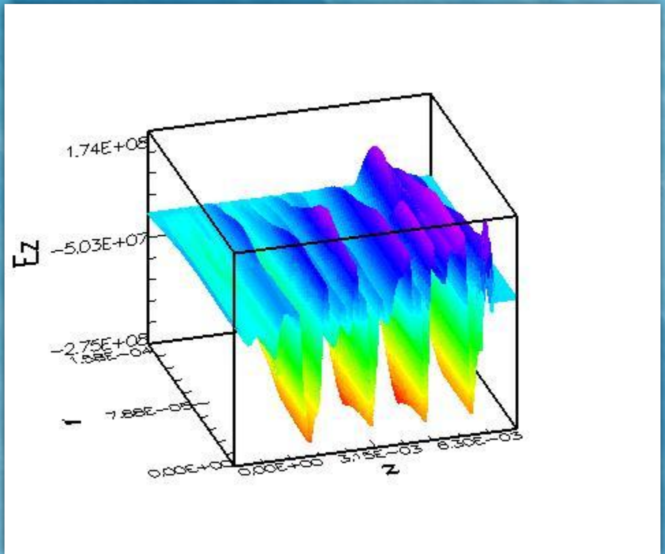
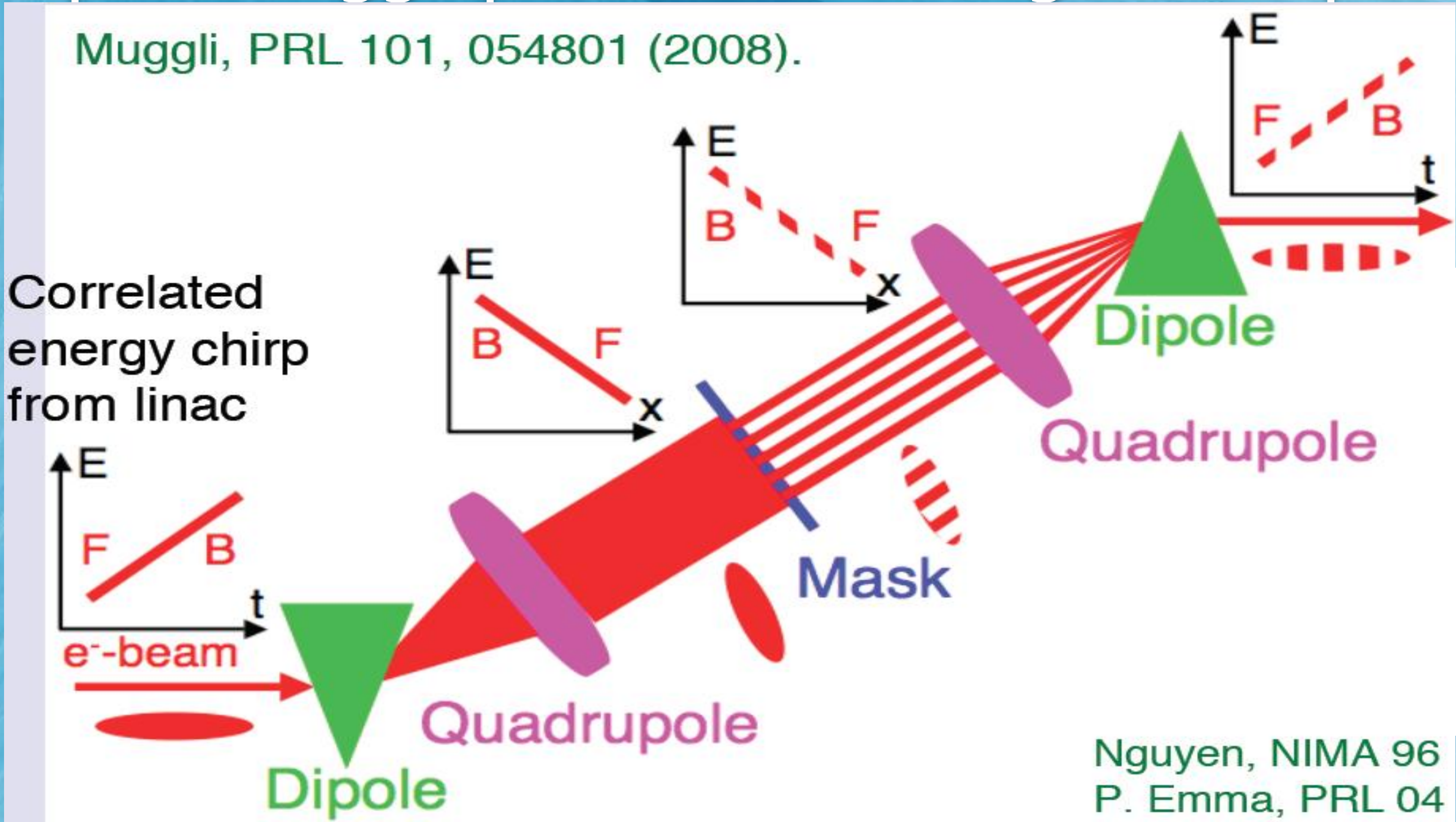


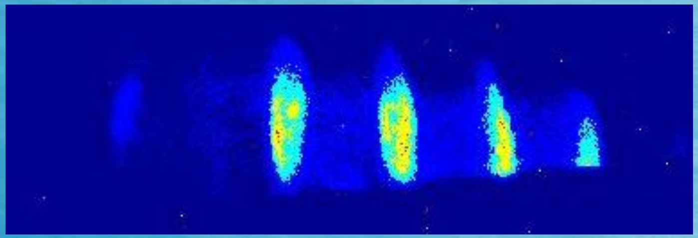
Initial multi-pulse experiment: uniform SiO_2 DWA at BNL ATF

- Exploit Muggli pulse train slicing technique

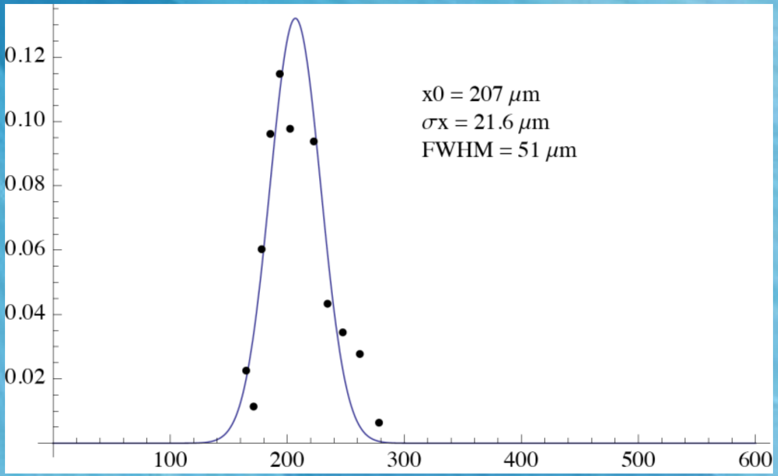


First results from BNL multi-pulse experiments

- Array of 1 cm tubes
  - Si02, diamond!
  - 325-660 μm λ
- Operation of pulse train with both chirp signs
  - Sextupole correction used
  - CTR autocorrelation
- Single bunch wakes observed
- Next: resonant wake excitation, CCR



4-drive + witness in spectrometer



CTR autocorrelation and FFT

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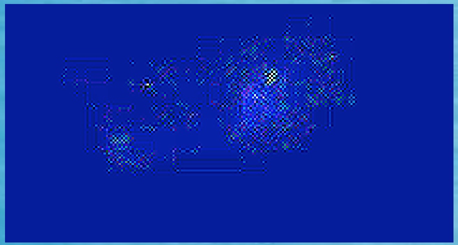
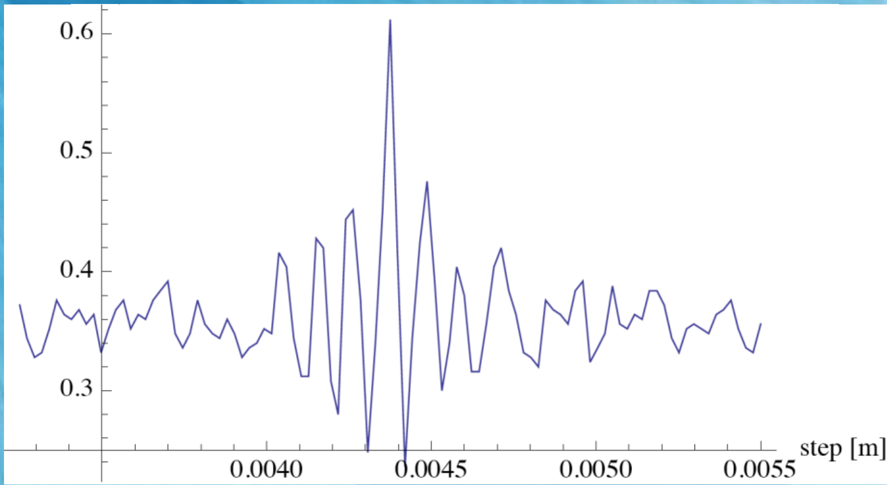


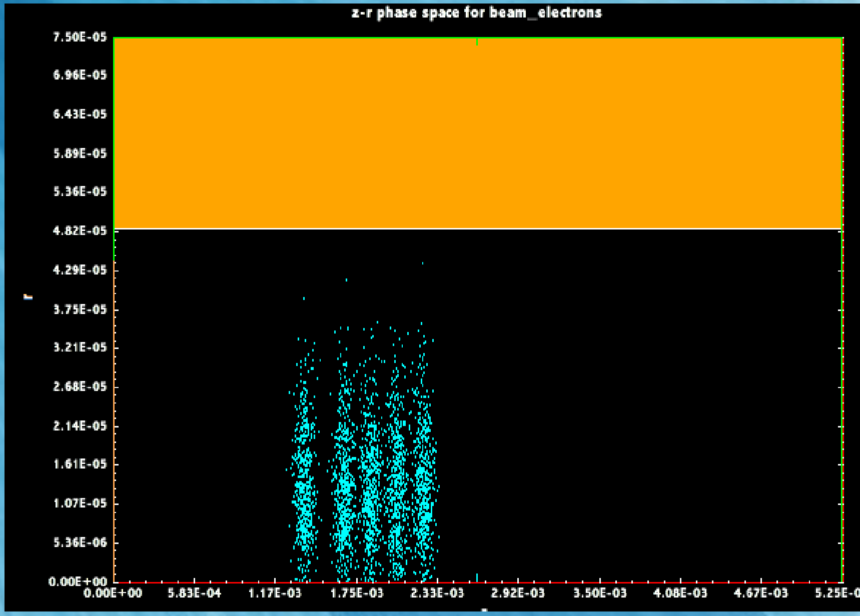
Single drive spectrum shows acceleration and deceleration



CTR autocorrelation and FFT

To a GV/m: multiple pulse DWA experiment at SPARC/X (LNF)

- Uses laser comb technique
- Bunch periodicity: 190 μm (0.63 ps)
  - 0.5 of BNL case
  - Scaled structure
- 125 pC/pulse @ 750 MeV
- 4 pulses + witness
- 1 GV/m, energy doubling in <70 cm



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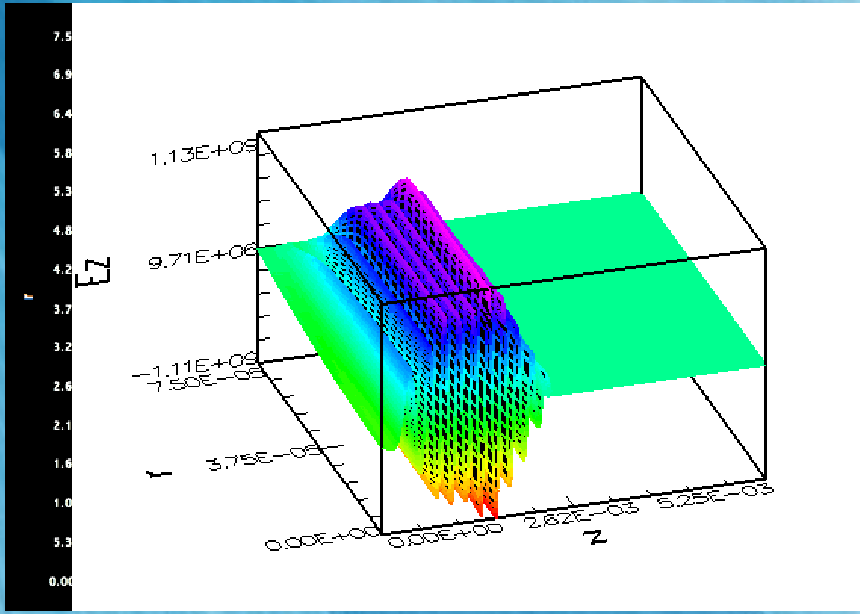

>1.1 GV/m wakes in scaled DWA@SPARX

Conclusions

- Very promising technical approach in DWA
  - Physics surprisingly forgiving thus far
  - Looks like an accelerator!
  - Many open questions still to resolve for GV/m
- Pushing towards applications
  - Linear collider: multi-pulse
  - FEL: booster for reaching hard X-rays in few m
- Expect rapid experimental progress
  - 1st ATF; then FACET, SPARC/X…