Wakefield Acceleration in Dielectric Structures

J.B. Rosenzweig

UCLA Dept. of Physics and Astronomy

ICFA Workshop on Novel Concepts for Linear Accelerators and Colliders

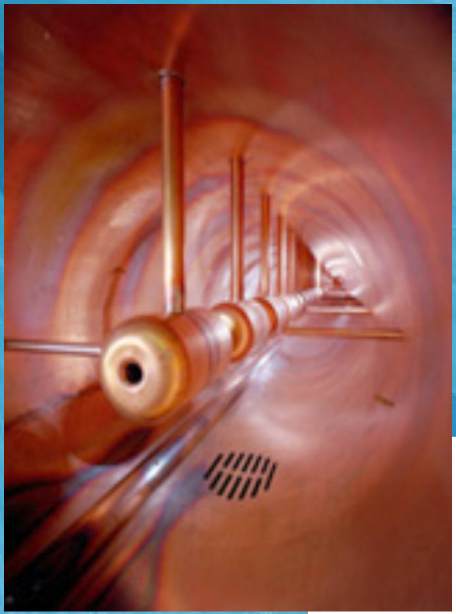
SLAC, July 8, 2009

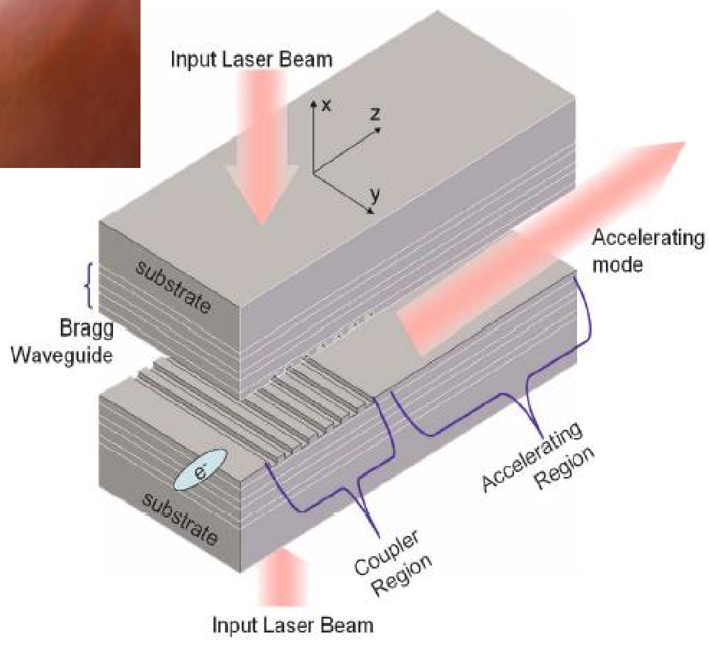
Future colliders: ultra-high fields in the accelerator

- High fields in violent accelerating systems

$$eE_z / mc\omega \sim 1$$

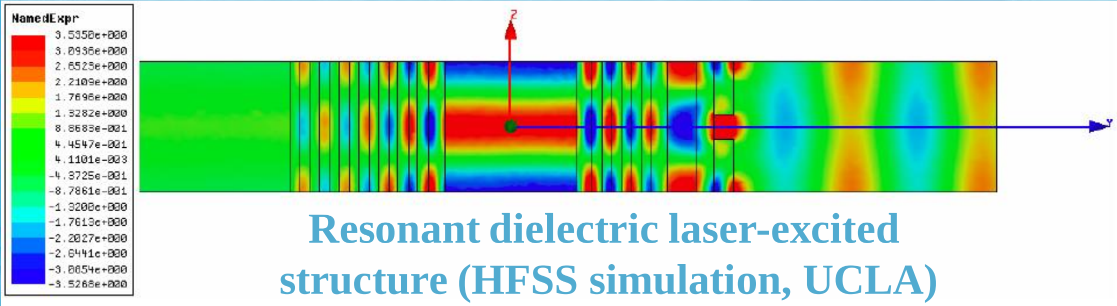
- High field implies short λ
  - Relativistic oscillations...
  - Limit peak power
  - Stored energy
- Challenges
  - Ultra-small beams
  - Structure breakdown
  - Pulsed heating
  - What sources < 1 cm?





Scaling the accelerator in size

- *Lasers* produce copious power (~J, >TW)
  - Scale in size by 4 orders of magnitude
  - λ < 1 μm gives *challenges* in beam dynamics
  - Reinvent resonant structure using *dielectric* (E163, UCLA)



Resonant dielectric laser-excited structure (HFSS simulation, UCLA)

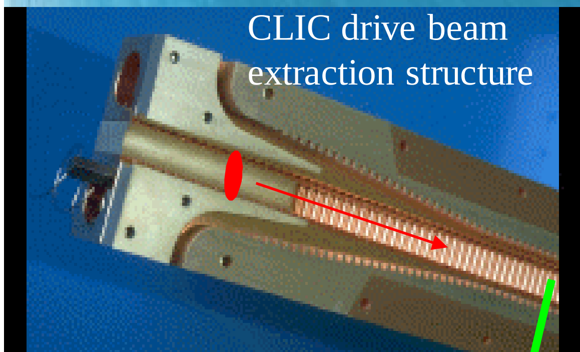
- To jump to GV/m, only *need* mm-THz
  - Must have new source…

Promising paradigm for high field accelerators: wakefields

- Coherent radiation from bunched, *v~c,* e^- beam
  - *Any impedance* environment
  - Powers more exotic schemes: plasma, dielectrics
- Non-resonant, *short pulse* operation possible
- Intense beams needed by other fields
  - X-ray FEL
  - X-rays from Compton scattering
  - THz sources

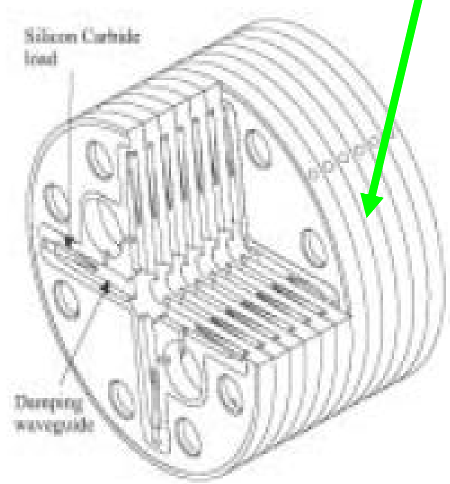
High gradients, high frequency, EM power from wakefields: CLIC @ CERN

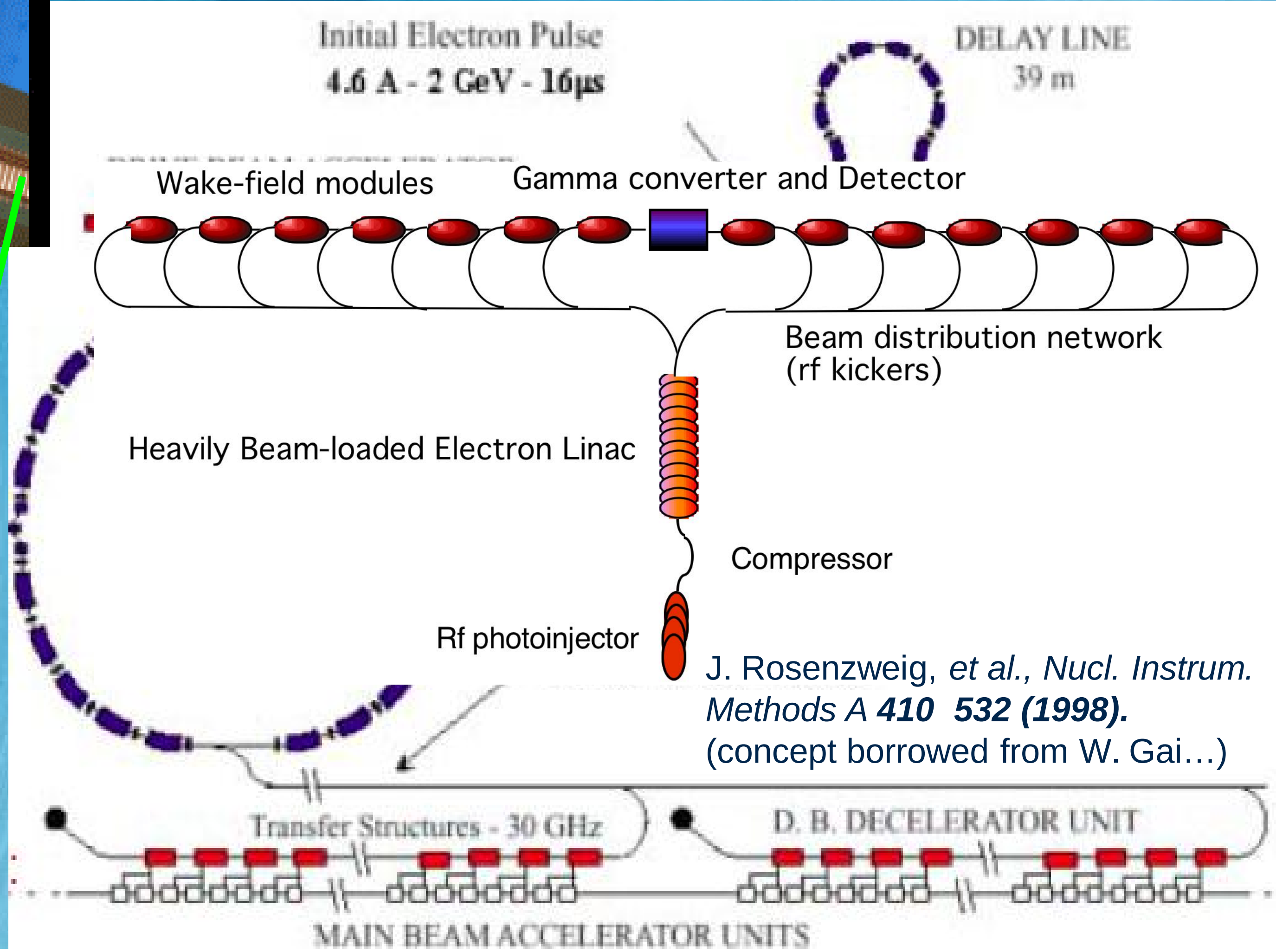
CLIC wakefield-powered resonant scheme



Power

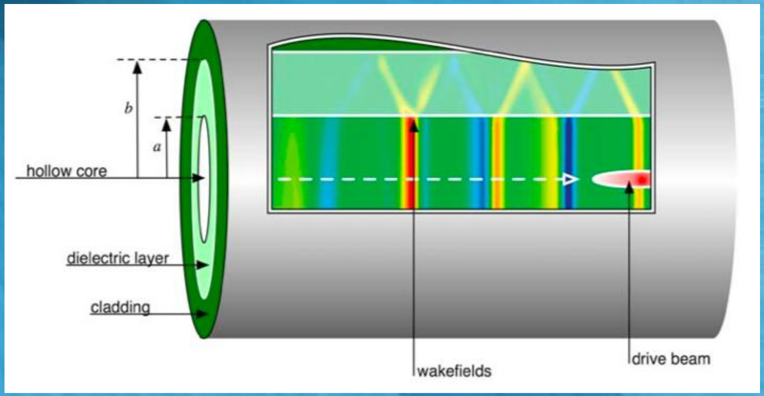
CLIC 30 GHz,
150 MV/m structures





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

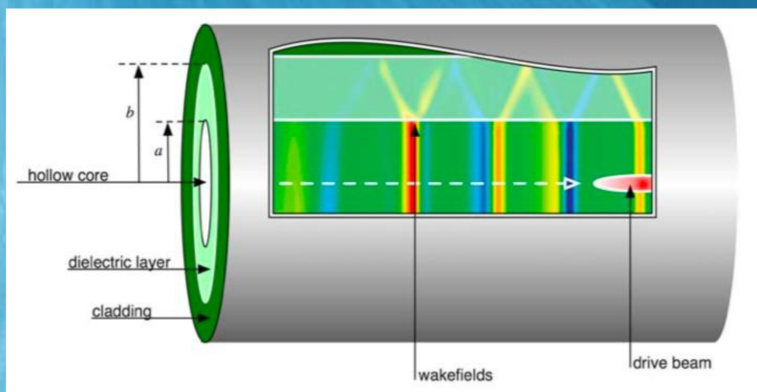
The dielectric wakefield accelerator



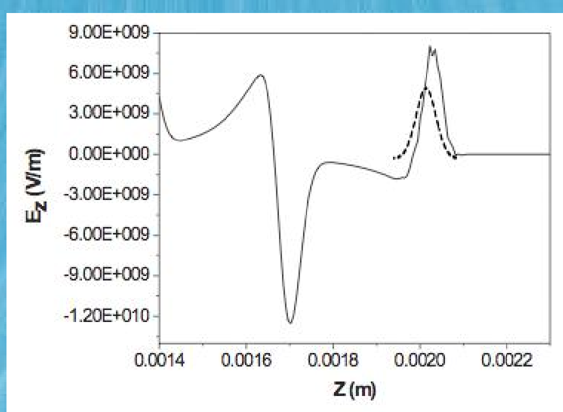
- Higher accelerating gradients: GV/m level
  - Dielectric based, low loss, short pulse
  - Higher gradient than optical? Different breakdown mechanism
  - No charged particles in beam path...
- Use wakefield collider schemes
  - CLIC style modular system
  - Afterburner possibility for existing accelerators
- Spin-offs
  - High power THz radiation source

Dielectric Wakefield Accelerator

Overview



- Design Parameters $a,b \quad \sigma_z \quad \varepsilon$



Ez on-axis, OOPIC

- Electron bunch (β ≈ 1) drives ***Cerenkov wake*** in cylindrical dielectric structure
  - Variations on structure features
  - Multimode excitation
- Wakefields accelerate trailing bunch
  - Mode wavelengths

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

  - Peak decelerating field

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

Extremely good beam needed

  - Transformer ratio (unshaped beam)

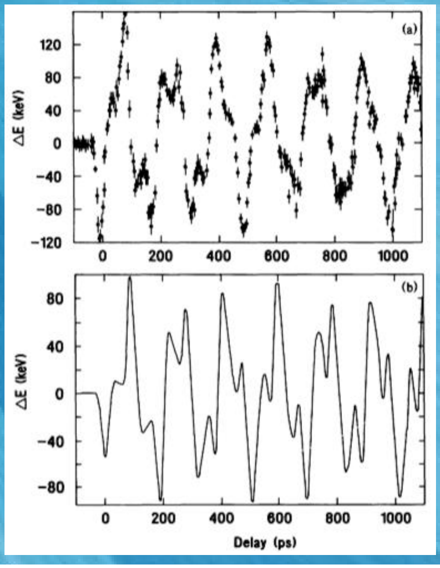
$$R = \frac{E_{z,acc}}{E_{z,dec}} \leq 2$$

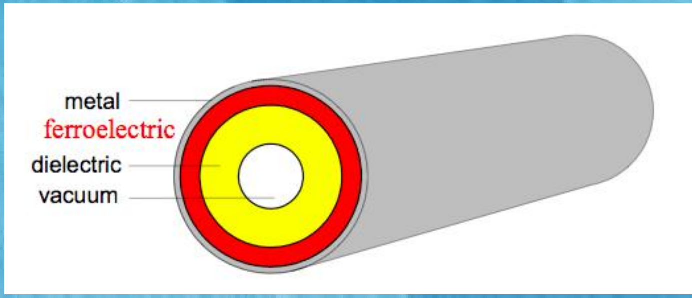
Experimental History

Argonne / BNL experiments

- Proof-of-principle experiments
  (W. Gai, *et al.*)
  - ANL AATF
- Mode superposition
  (J. Power, *et al.* and S. Shchelkunov, *et al.*)
  - ANL AWA, BNL
- Transformer ratio improvement
  (J. Power, *et al.*)
  - Beam shaping
- Tunable permittivity structures
  - For external feeding
  (A. Kanareykin, *et al.*)

ΔE vs. witness delay

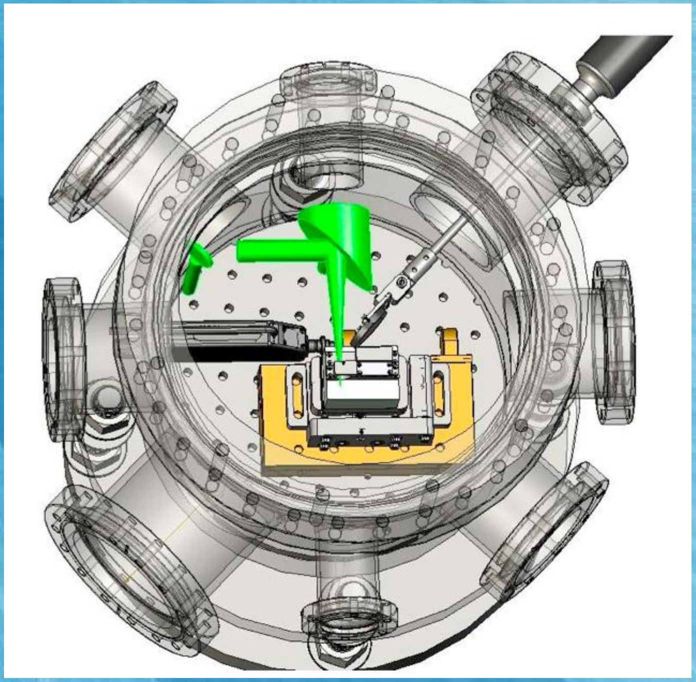




Gradients limited to <50 MV/m by available beam

T-481: Test-beam exploration of breakdown threshold

- Go beyond pioneering work at ANL
  - Much shorter pulses, small radial size
  - Higher gradients...
- Leverage off E167
- 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 indicate $E_z \leq 11$GV/m can be excited
    - 3 nC, $\sigma_z \geq 20$ μm, 28.5 GeV
- 48 hr FFTB run



T-481 “octopus” chamber

T481: 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

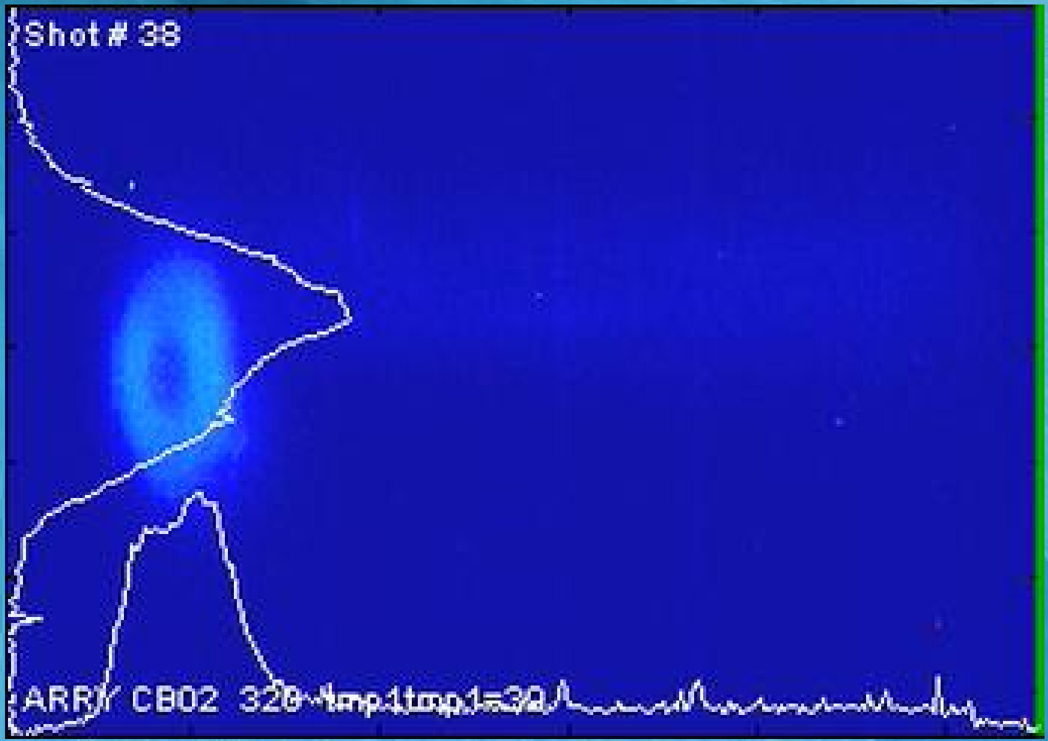
M. C. Thompson,[1,2,*] H. Badakov,[1] A. M. Cook,[1] J. B. Rosenzweig,[1] R. Tikhoplav,[1] G. Travish,[1] I. Blumenfeld,[3] M. J. Hogan,[3] R. Ischebeck,[3] N. Kirby,[3] R. Siemann,[3] D. Walz,[3] P. Muggli,[4] A. Scott,[5] and R. B. Yoder[6]

[1]*Department of Physics and Astronomy, University of California, Los Angeles, California 90095, USA*
[2]*Lawrence Livermore National Laboratory, Livermore, California 94551, USA*
[3]*Stanford Linear Accelerator Center, Menlo Park, California 94025, USA*
[4]*University of Southern California, Los Angeles, California 90089, USA*
[5]*University of California, Santa Barbara, California 93106, USA*
[6]*Manhattan College, Riverdale, New York 10471, USA*

(Received 20 January 2008; published 27 May 2008)

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.

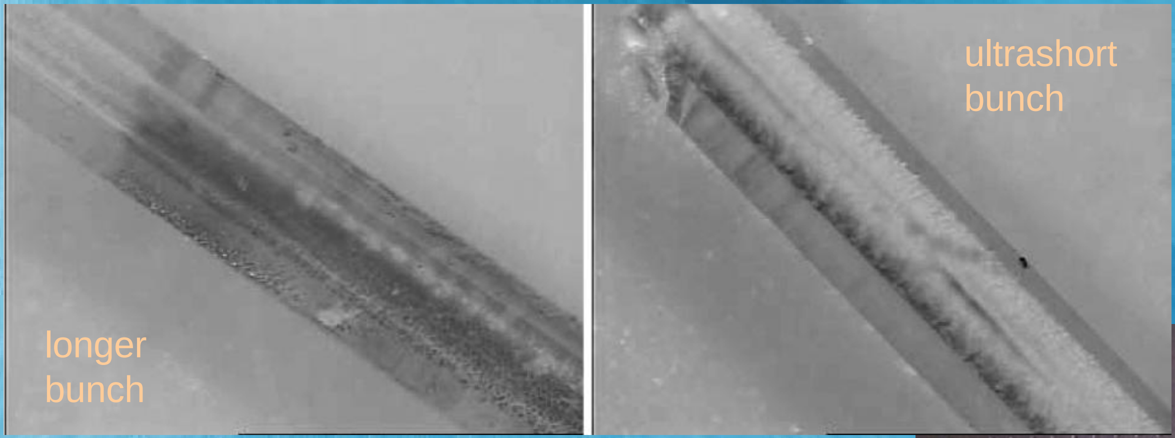
T481: Beam Observations



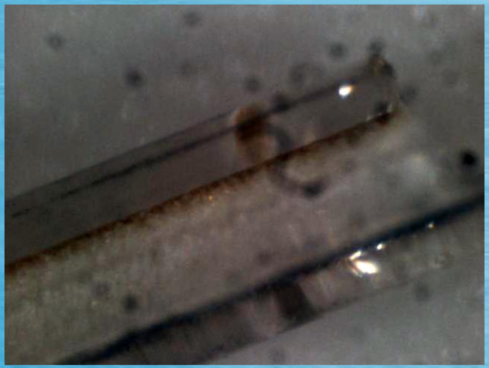
View end of dielectric tube;
frames sorted by increasing peak current

T-481: Inspection of Structure Damage

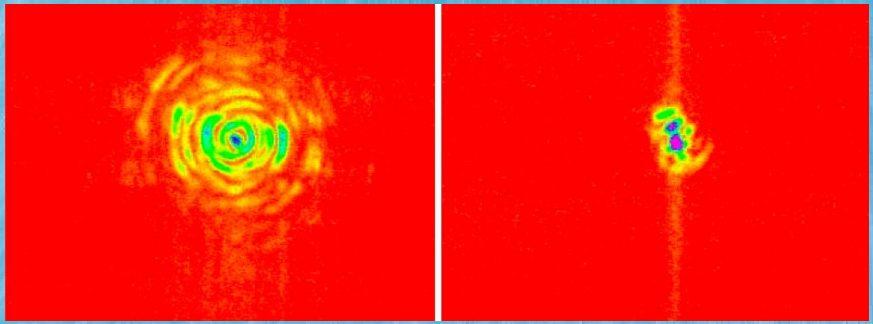
Damage consistent with beam-induced discharge



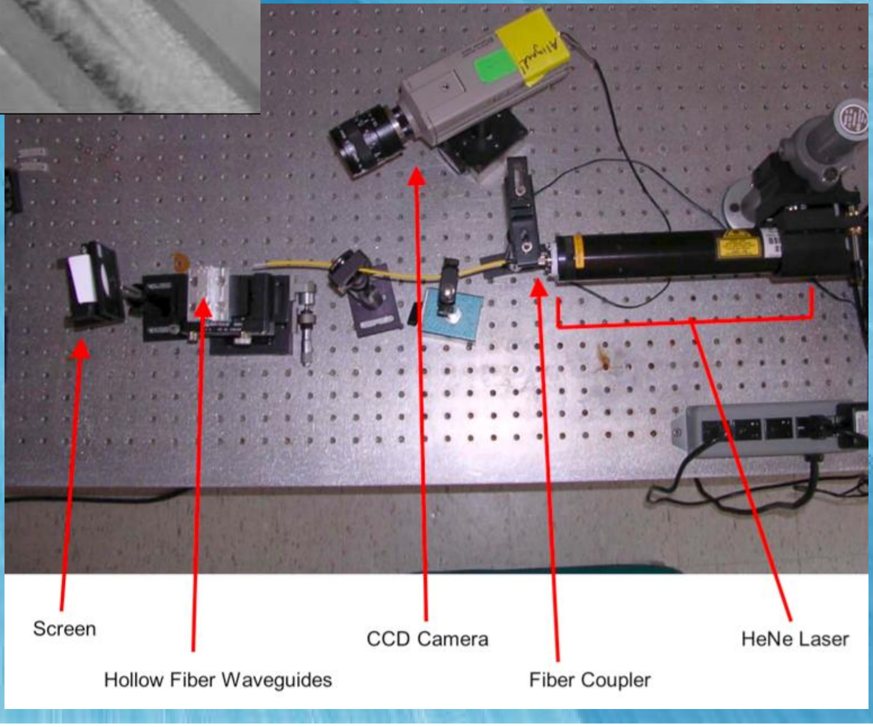
Aluminum vaporized from pulsed heating!



Bisected fiber

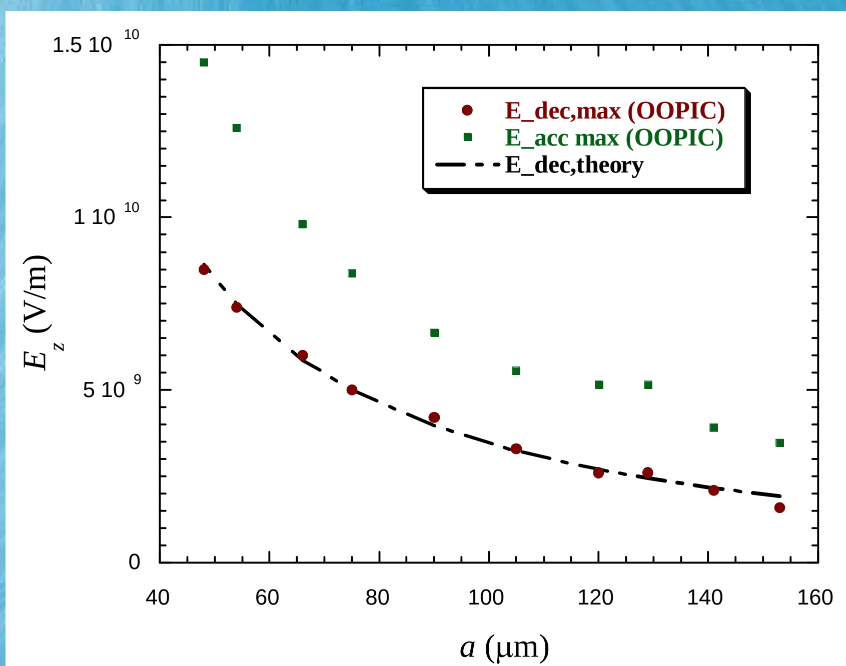


Laser transmission test

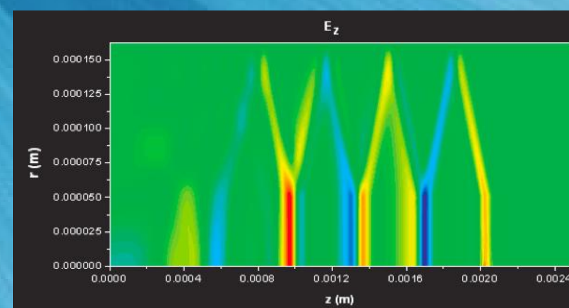


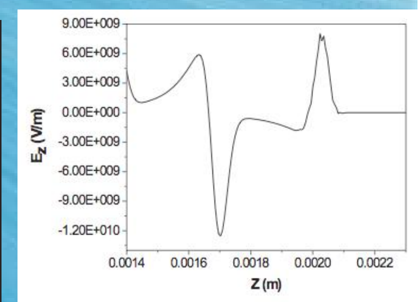
OOPIC Simulation Studies

- Parametric scans for design
- Heuristic model benchmarking
- Show pulse duration in multimode excitation… hint at mechanism
- Determine field levels in experiment: breakdown
  - Gives breakdown limit of 5.5 GV/m deceleration field



Example scan, comparison to heuristic model





Multi-mode excitation – short, separated pulse

Parameter	Value
Dielectric inner diameter ($2a$)	100 μm
Dielectric outer diameter ($2b$)	324 μm
Dielectric relative permittivity (ε)	$\sim$3
Number of e^- per bunch (N_b)	1.4×10^{10}
RMS bunch length (σ_z)	100 – 10 μm
RMS bunch radius (σ_r)	10 μm
Beam energy	28.5 GeV
Maximum radial field at dielectric surface	27 GV/m
Maximum decelerating field (vacuum)	11 GV/m
Maximum accelerating field (vacuum)	16 GV/m

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]

[α]*Department of Physics and Astronomy, University of California, Los Angeles*

[β]*Stanford Linear Accelerator Center*

[γ]*University of Southern California*

[δ]*Lawrence Livermore National Laboratory*

[ζ]*Manhattanville College*

[ε]*Euclid TechLabs, LLC*

Collaboration spokespersons

E-169 Motivation

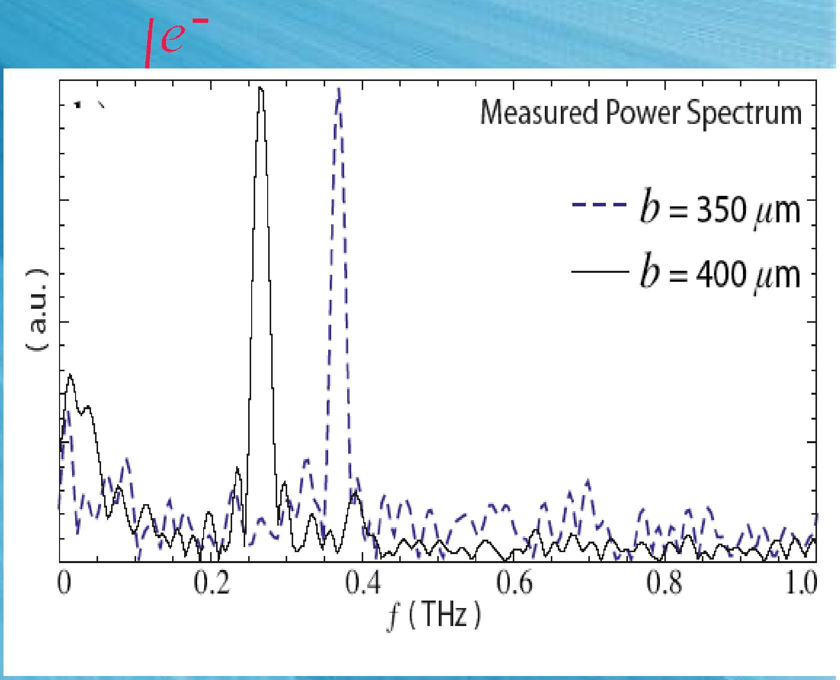
- Take advantage of unique experimental opportunity at SLAC
  - FACET: ultra-short intense beams
  - Advanced accelerators for high energy frontier
  - Very promising path: dielectric wakefields
- Extend successful T-481 investigations
  - Multi-GV/m dielectric wakes
  - Complete studies of transformational technique

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 Neptune
  - **Explore alternate materials**
  - **Explore alternate designs and cladding**
    - **Radial and longitudinal periodicity…**
  - **Varying tube dimensions**
    - Impedance change
    - Breakdown dependence on wake pulse length
- Approved experiment (EPAC, Jan. 2007)
- Awaits FACET construction

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
- Horn-launched quasi-optical transport
- Autocorrelation in Michelson interferometer



E-169: High-gradient Acceleration

Goals in 3 Phases

- Phase 1: Complete breakdown study (when does E169->E168!)
  - ✓ explore (a, b, σ_z) parameter space
  - ✓Alternate cladding
  - ✓Alternate materials (e.g. CVD diamond)
  - ✓Explore group velocity effect $T = L_d/(c - v_g) \leq \varepsilon L_d / c(\varepsilon - 1)$
- Coherent Cerenkov (CCR) measurement
  - ✓ Total energy gives field measure
  - ✓ Harmonics are sensitive σ_z diagnostic

$$U_C \approx \frac{eN_b E_{z,dec} L_d}{2}$$

$$U_n \approx \frac{\pi^2 n N_b{}^2 r_e m_e c^2 \sigma_z{}^2 L_d}{2a(b-a)^2\left[\sqrt{8\pi(\varepsilon-1)}\varepsilon\sigma_z + (\varepsilon-1)a\right]} \exp\left[-\left(\frac{n\pi\sigma_z}{2(b-a)\sqrt{\varepsilon-1}}\right)^2\right]$$

σ_z	≥ 20 μm
σ_r	< 10 μm
U	25 GeV
Q	3 - 5 nC

FACET beam parameters for E169: high gradient case

E-169 at FACET: Phase 2 & 3

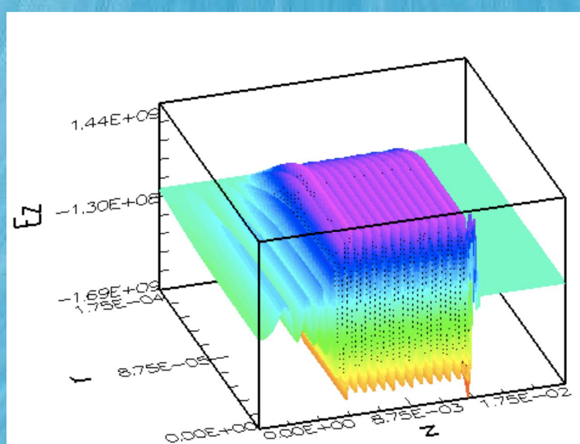
- Phase 2: Observe acceleration
  - ✓ 10-33 cm tube length
  - ✓ longer bunch, acceleration of tail
  - ✓ "moderate" gradient, 1-3 GV/m
  - ✓ single mode operation

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

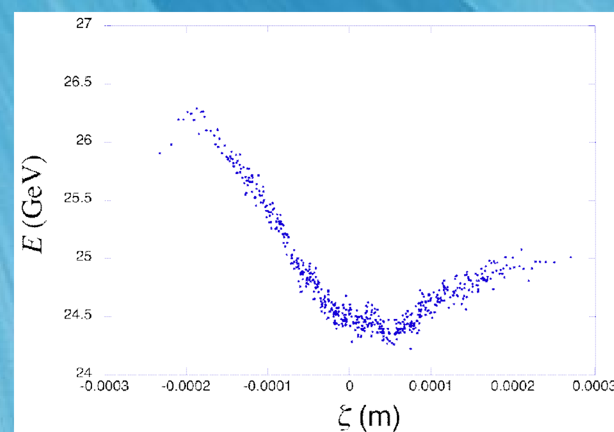
FACET beam parameters for E169: acceleration case

- Phase 3: Scale to 1 m length
  - ✓ Alignment, transverse wakes, BBU
  - ✓ Group velocity & EM exposure

*



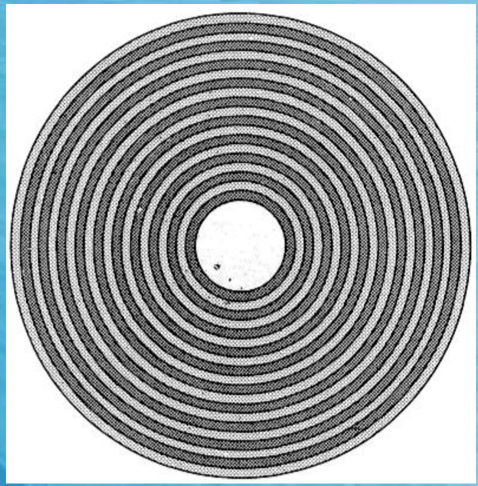
Longitudinal E-field



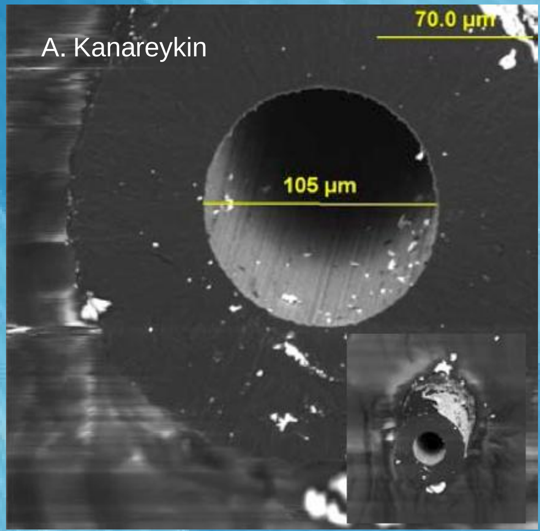
Momentum distribution after 33 cm (OOPIC)

Experimental Issues: Alternate DWA design, cladding, materials

- Aluminum cladding in T-481
  - ✓ Vaporized at moderate wake amplitudes
  - ✓ Low vaporization threshold; low pressure and thermal conductivity of environment
- Dielectric cladding
  - ✓ Lower refractive index provides internal reflection
  - ✓ Low power loss, damage resistant
- Bragg fiber?
  - Low HOM
- Alternate dielectric: CVD diamond
  - Ultra-high breakdown threshold
  - Doping gives low SEC
  - First structures from Euclid Tech.



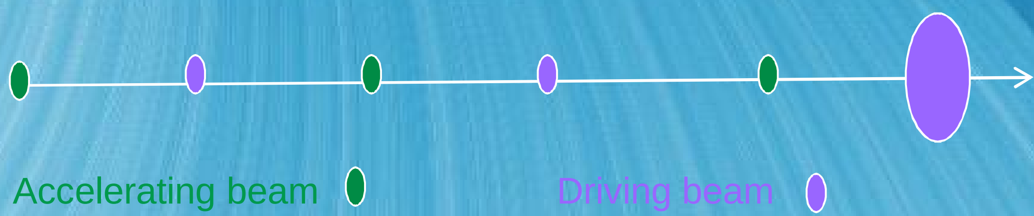
Bragg fiber

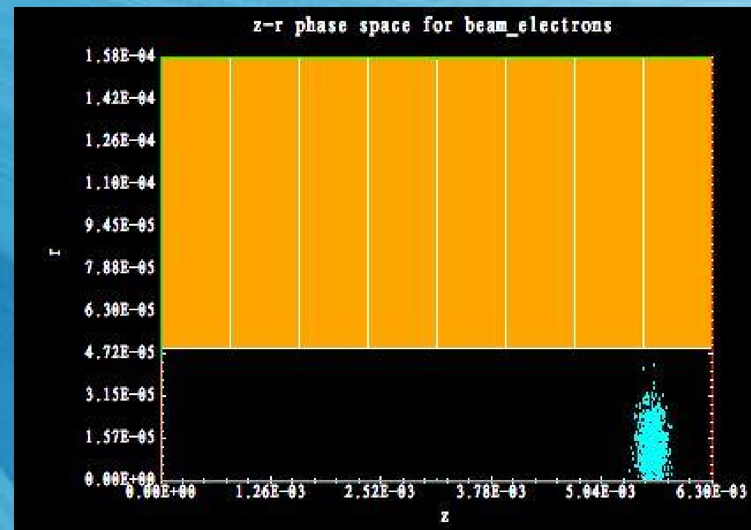


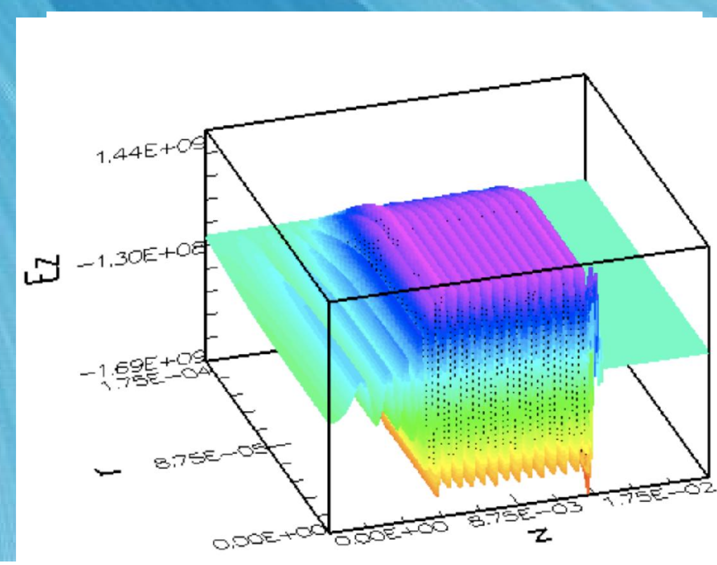
CVD deposited diamond

Control of group velocity with periodic structure

- For multiple pulse beam loaded operation in LC, may need *low* v_g





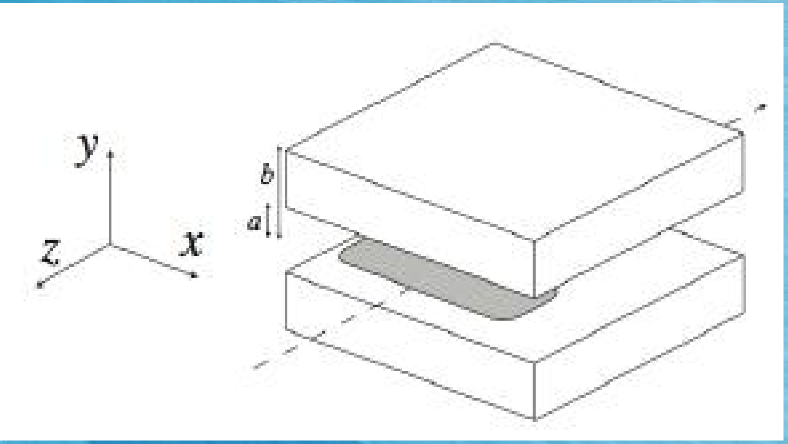


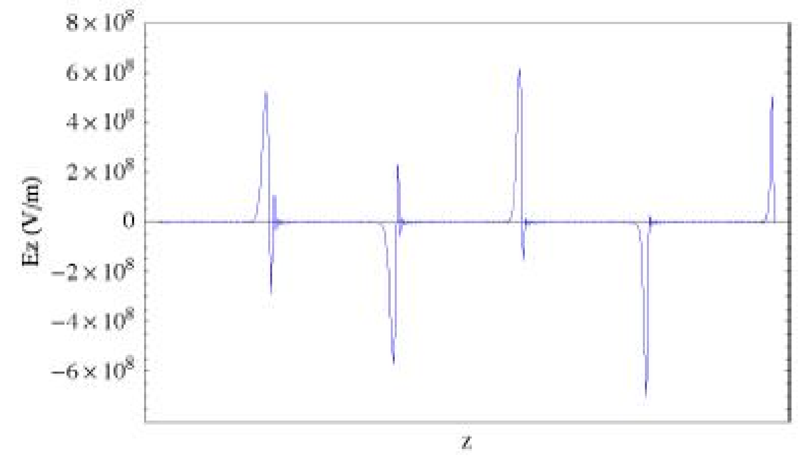
- Use periodic DWA structure in ~π-mode
- Example: simple SiO_2-diamond structure

Alternate geometry: slab

- Slab geometry suppresses transverse wakes*
  - Also connects to optical case
- Price: reduced wakefield
- Interesting tests at FACET
  - Slab example, >600 MV/m

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





Energy	σ_x	σ_z	σ_y	$2a$	$2b$	Q	ε
25 GeV	500 um	20 um	10 um	125 um	1100 um	3 nC	5.5

Towards a linear collider...

- *What have we learned?*
  - One might use gradients of 2-3 GV/m
    - Near to plasma w/o attendant challenges
  - Frequencies of interest are ~ few THz (?)
  - Need nC level drive bunch, <50 μm rms
- What do we need to learn?
  - Usable gradients, materials, aging
  - Structure design features (e.g. slab, v_g control)
  - Transverse wakes, beam loading
  - Full system considerations

Parameter list: a departure point

		ILC Nominal	DWA LC
E_cms	GeV	1000	1000
Bunch Charge	e	2.0E+10	5.0E+08
# bunches/train	#	2820	200
train repetition rate	kHz	5.0E-02	2.4
final bunch length	psec	1.00	0.08
design wavelength	micron	230609.58	300.00
Normalized emittances	micron	10/0.04	2e-02/6e-04
I. P. Spot Size	nm	554/3.5	25/0.5
Enh. Luminosity	**/cm^2/s**	**4.34E+34**	**1.14E+35**
Beam Power	MW	22.6	19.2
Wall-Plug Power	MW	104.0	76.9
Gradient	MeV/m	30	2500
Total Linac Length	km	33.3	0.4

Calculator from E. Colby

Based on multibunch trains
Other optimizations possible (slab structures)

Conclusions

- Very promising technical approach in DWA
  - Physics surprisingly forgiving thus far
  - Looks like an accelerator!
- FACET should provide critical test-bed
- Linear collider system presents new challenges
  - Unique problems of short λ, wakefields
  - Develop straw man now!