Present Limits and Future Prospects for Dielectric Acceleration

Eric R. Colby*
SLAC
Advanced Accelerator Research Department

Prepared with generous assistance from:

The E163 Collaboration
Jay Hirshfield, Yale
Gennady Shvets, UT-Austin
The FACET Collaboration
Jamie Rosenzweig, UCLA
Ben Cowan, Tech-X
Wei Gai, ANL
Levi Schächter, IIT

* ecolby@slac.stanford.edu

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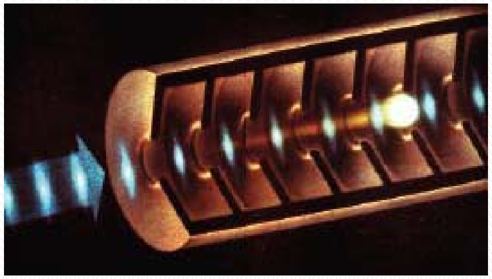
Overview

- What is meant by "dielectric acceleration" and why is it worth pursuing?
- Current work on dielectric-based accelerator concepts at microwave, terahertz, and optical frequencies
- Outline e^+e^- collider configurations and parameters
- Discuss limitations and open questions
- Future Prospects

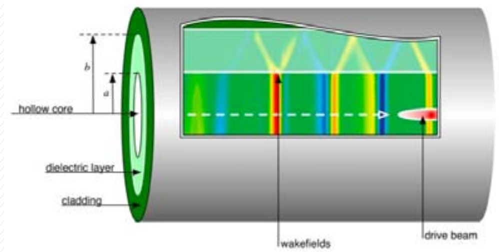
What is dielectric acceleration?

- Conventional (conducting) case:
  - EM wave guiding is enforced by outside metal wall
  - Phase velocity synchronism is enforced by periodic loading (metal irises)
  - Tend to be high-Q resonators requiring long low-power pulses
  - Limited (at present) to ~150 MV/m (short structures)

- Dielectric case:
  - Guiding is by either metal wall or Bragg reflector
  - Synchronism is enforced by manipulating the effective index
  - Tend to be low-Q structures requiring short high-power pulses
  - Potentially capable of sustaining >1 GV/m gradients



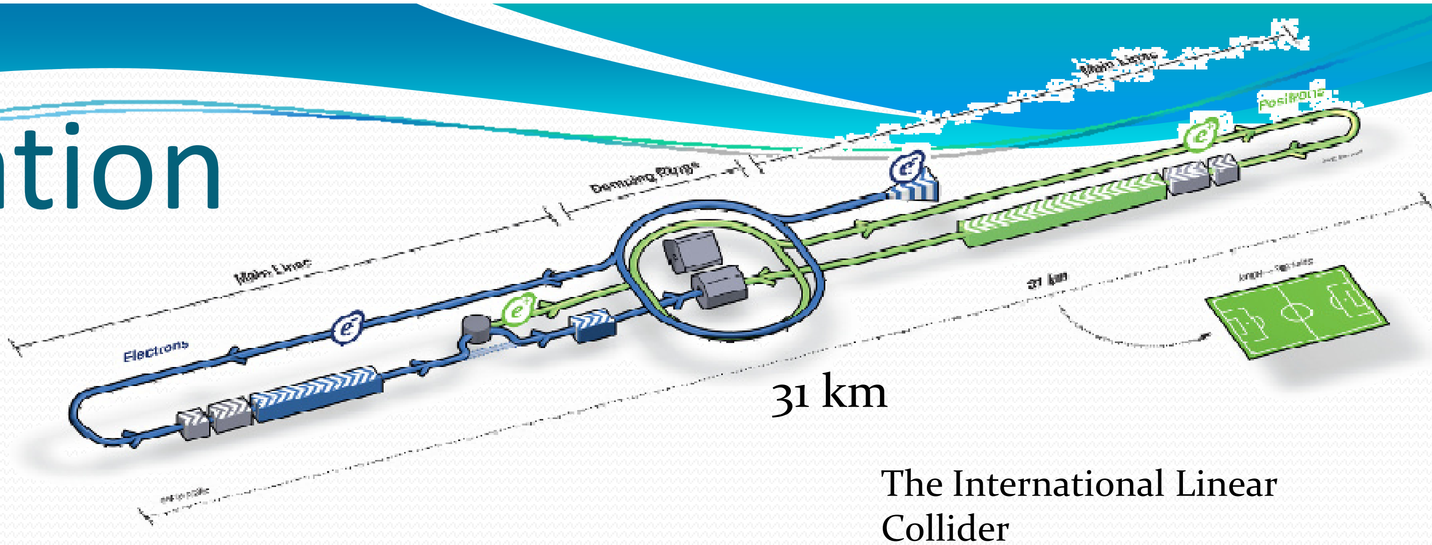
Conventional Iris-Loaded Structure



Dielectric-Lined Waveguide

Bragg Waveguide

Motivation



The International Linear Collider

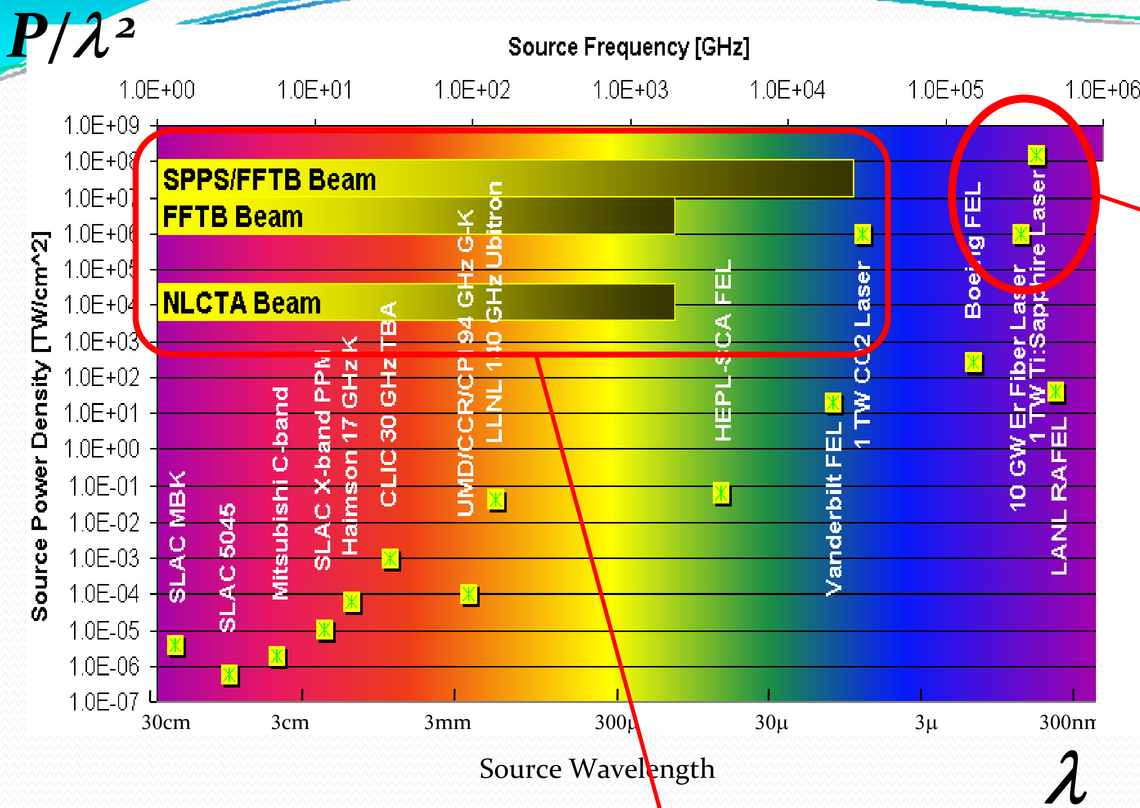
31.5 MV/m – the ILC design gradient (superconducting)
150 MV/m – maximum achieved in a **metallic** structure (75 years)

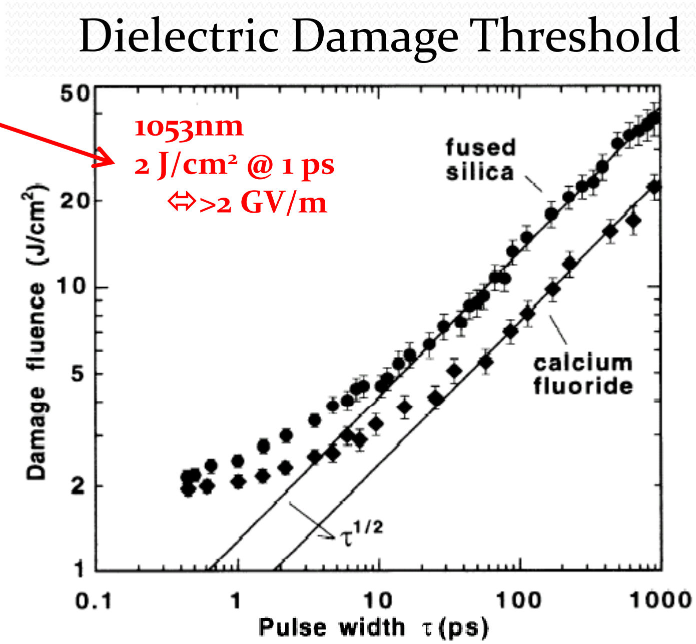
*~1,000 MV/m – gradient expectation for **dielectric** acceleration*
13,800 MV/m – maximum achieved in a **dielectric** structure (25 years)

*~10,000 MV/m – gradient expectation for high-quality **plasma** acceleration*
50,000 MV/m –maximum gradient achieved in **plasma** over ~1 meter
>200,000 MV/m—maximum gradient achieved in **plasma** over ~1 mm

Marx panel (a HEPAP subpanel) recommendation -- July 2006
"A major challenge for the accelerator science community is to identify and develop new concepts for future energy frontier accelerators that will be able to provide the exploration tools needed for HEP within a feasible cost to society. The future of accelerator-based HEP will be limited unless new ideas and new accelerator directions are developed to address the demands of beam energy and luminosity and consequently the management of beam power, energy recovery, accelerator power, size, and cost."

Dielectric Breakdown Resistance





B. C. Stuart, *et al*, *Phys. Rev. Lett.*, **74**, p.2248ff, (1995).

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

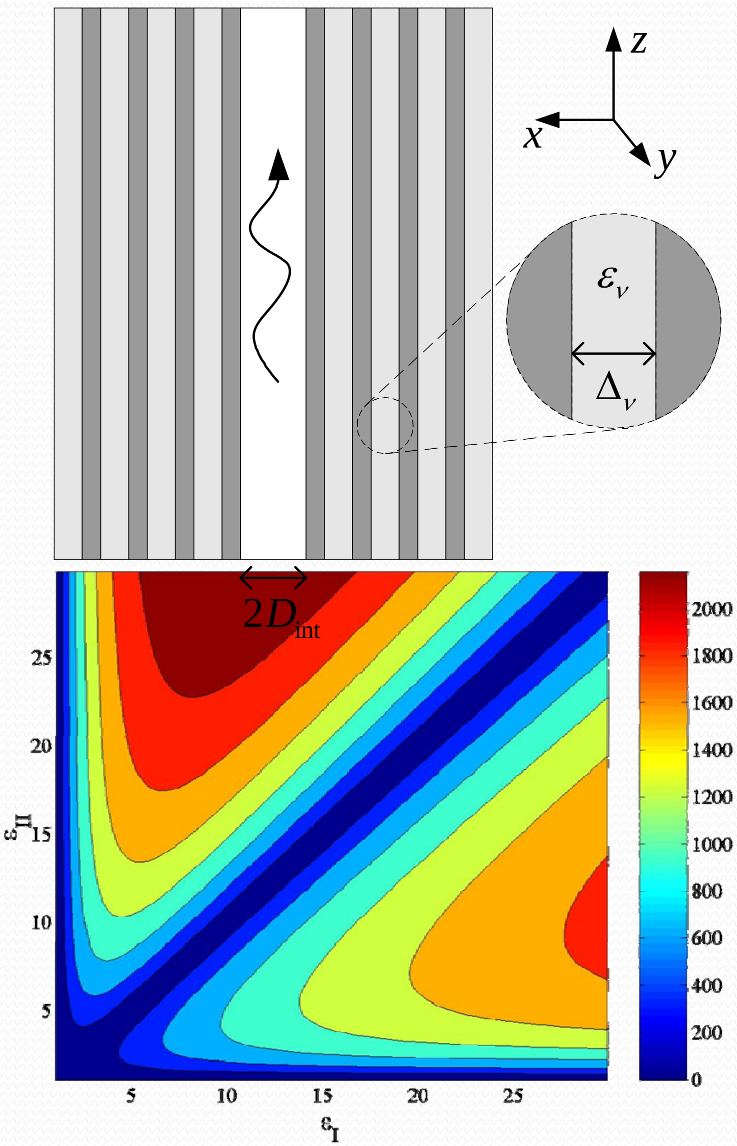
Breakdown Limits on Gigavolt-per-Meter Electron-Beam-Driven Wakefields in Dielectric Structures

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]

$\boxed{13.8 \pm 0.7 \text{ GV/m.}}$

Fused silica, THz range, ~psec exposure

Narrowband boundary conditions can be designed to mitigate instabilities—Bragg Fiber

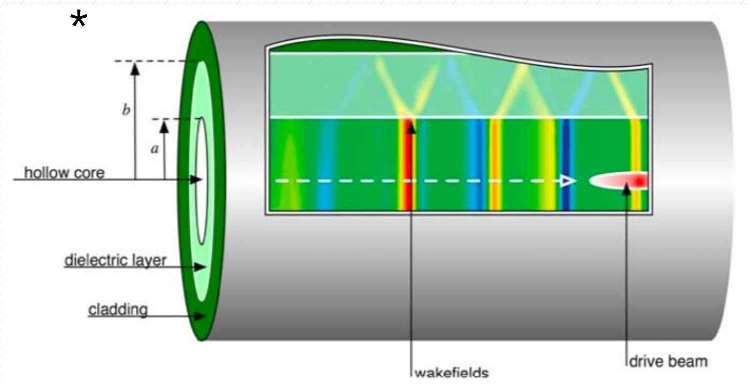


- With the exception of the first (matching) layer, each layer: $\lambda / 4\sqrt{\varepsilon - 1}$
- Interaction impedance peaks for large contrast. Optimal materials.
- Harness developments in the communication and semiconductor industry: e.g. solid state laser wall-plug to light efficiency.
- At optical wavelengths, dielectrics sustain higher electric fields than metals and have smaller loss.

A. Mizrahi and L. Schächter, *Optical Bragg Accelerator*, Phys. Rev. E, **70**, 016505 (2004).

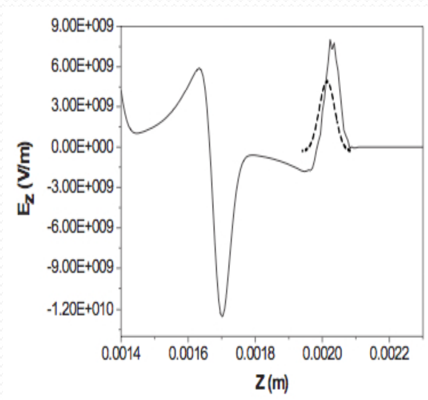
Driving a Dielectric Wakefield Accelerator

(Common to both Microwave and Terahertz cases)



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

E_z on-axis (OOPIC)



- Electron bunch (β ≈ 1) drives ***Cerenkov wake*** in cylindrical dielectric structure
  - Dependent on structure properties
  - Multimode excitation
  - Can be resonantly driven by a pulse train
- Wakefields accelerate trailing bunch
  - Mode wavelengths (quasi-optical)

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

  - Peak decelerating field

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

  - Transformer ratio (unshaped beam)

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

J. Rosenzweig, UCLA.

Progress Developing Microwave Two-Beam Structures

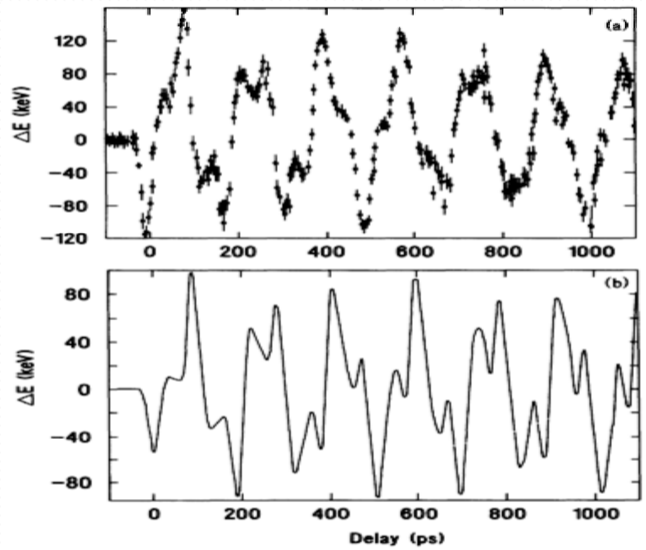
- Proof-of-principle experiments
  (H. Figueroa, *et al, PRL,* 60, 2144–2147 (1988))
  - ANL AATF
- Mode superposition
  (J. Power, *et al*. and S. Shchelkunov, *et al.*)
  - ANL AWA, BNL
- Transformer ratio improvement
  (J. Power, *et al.*)
  - Beam shaping

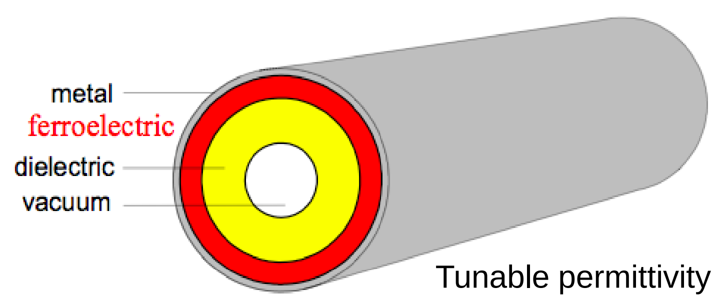
$$R = \frac{E_{z,accel}}{E_{z,decel}}$$

- Tunable permittivity structures
  - For external feeding

  (A. Kanareykin, *et al.*)

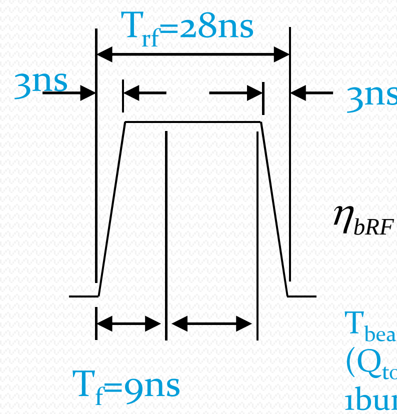
ΔE vs. witness delay





Demonstrated gradients limited to <100 MV/m by available drive beams
The FACET facility will enable significant extension of results in both gradient and frequency

High-Gradient DWA Accelerator Module



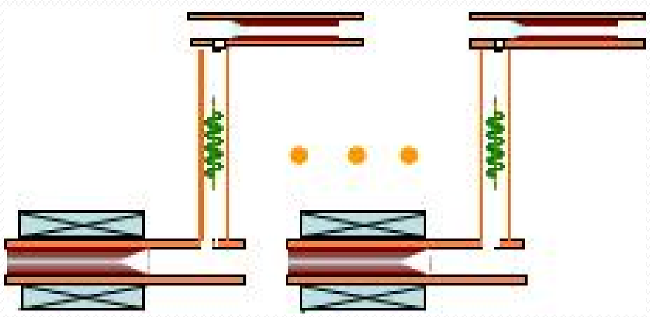
Competitive rf-beam efficiency for the short pulse TBA

$$\eta_{bRF} = \frac{I_{beam} E_{load} L_s}{P_{rf}} \times \frac{T_{beam}}{T_{rf}} = 26\%$$

T_{beam}=16ns=416rf cycles → 4160bunches (Q_{total}=2080nC),
1bunch/2 rf periods, 0.5nC/bunch

3GeV module (15m)

(38 DWPE & 38 DLA→ fill factor=76%)



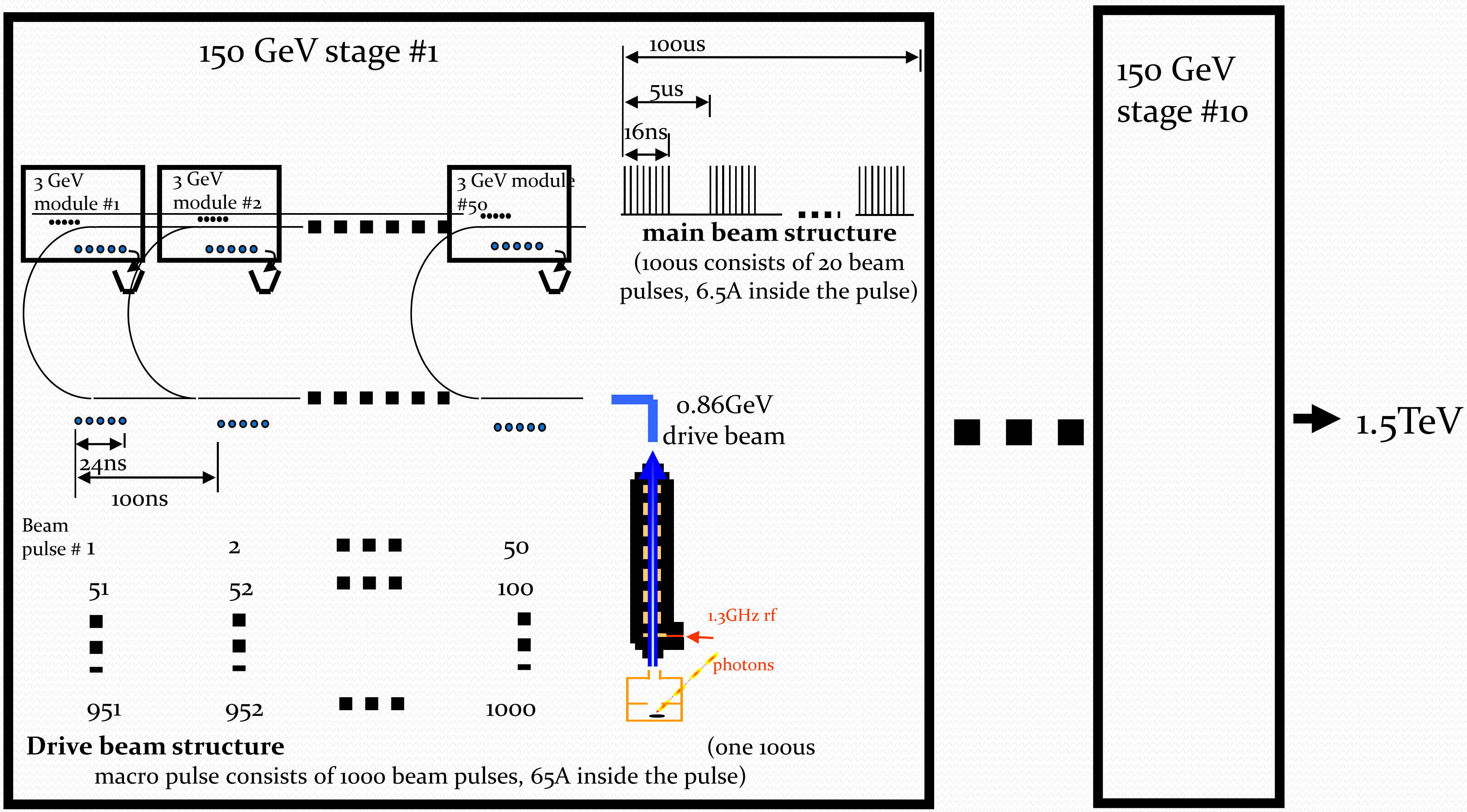
1.33GW output/Dielectric PETS;
5% rf transportation loss;
E_{load} =267MV/m (I_b=6.5A);

Drive beam becomes 80MeV, main beam gain 3GeV

	AWA Short Pulse (1.5TeV,e+)
Average drive beam current	80 mA
Average drive beam power	68.8 MW
Average rf power to main linac	60MW
Average main beam current	10.4 uA
Average main beam power	15.6 MW

W. Gai, ANL.

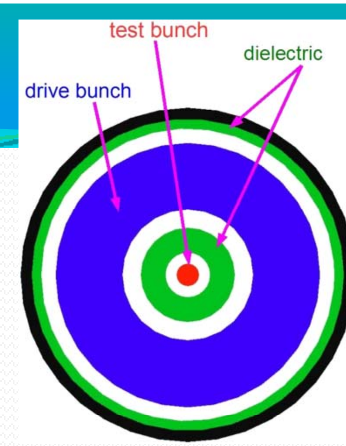
ANL 26GHz 3TeV Dielectric-based Short Pulse Two Beam Linear Collider (conceptual layout of one side of a 3TeV e^+e^- collider)

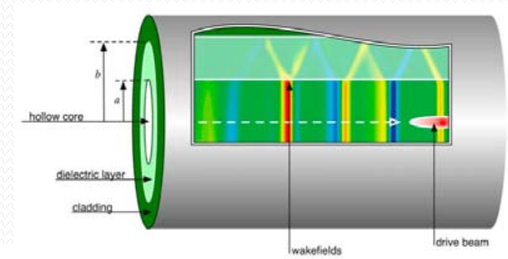


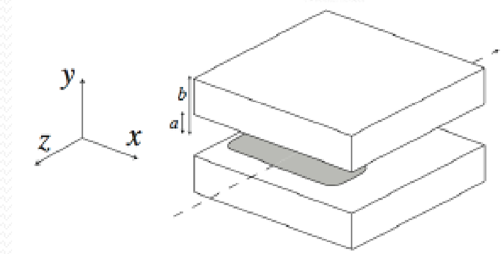
W. Gai, ANL.

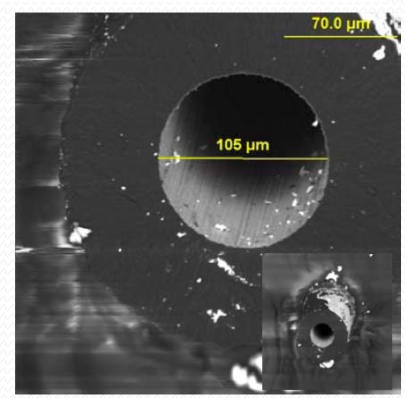
DWA Variations

- Coaxial two-beam DWA
  - High transformer ratios (~10!)
  - Sotnikov, *et al*, *PRST-AB,* **12**, 061302 (2009).
- Terahertz Structures
  - Collinear DWA
    - Scaled to λ~300μm
  - Slab structure collinear DWA
    - Suppressed transverse wakes
    - Reduced gradient, but larger bunch charge
    - A. Tremaine, *et* al, *Phys. Rev. E,* **56**, 7204 (1997)
  - Other Materials
    - CVD Diamond (doped for low SEY)
      - Euclid Techlabs LLC
    - Silicon, GaAs







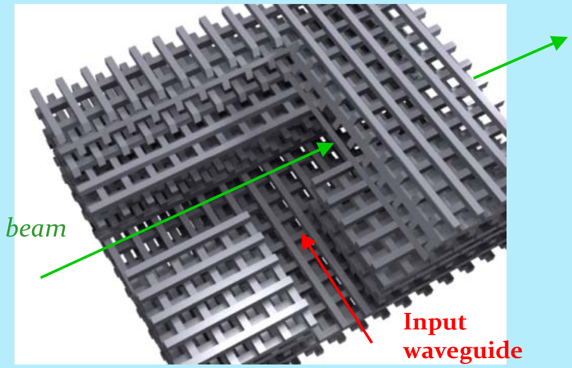


CVD deposited diamond

Laser-Driven Dielectric Accelerators

Structure Candidates for High-Gradient Accelerators

Projected maximum gradients based on measured material damage threshold data



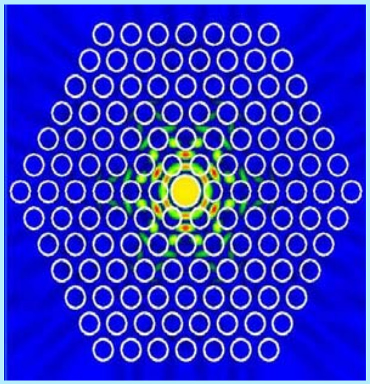
Photonic Crystal "Woodpile"

Silicon, λ=2200nm, E_z=400 MV/m

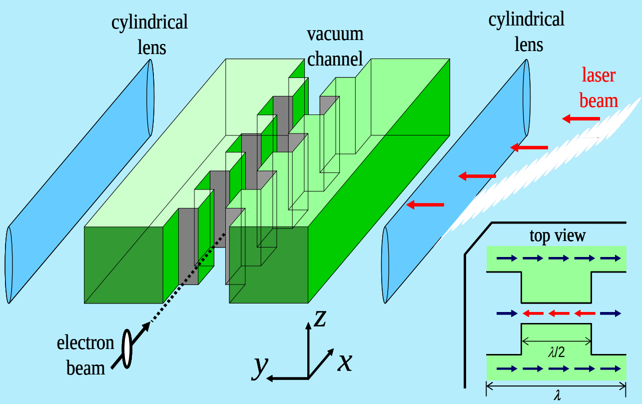
B. Cowan, *et al*, *PRST-AB*, **11**, 011301 (2008).

Photonic Crystal Fiber

Silica, λ=1890 nm, E_z=400 MV/m



X. Lin, *PRST-AB*, **4**, 051301 (2001).



Transmission Grating Structure

Silica, λ=800nm, E_z=830 MV/m

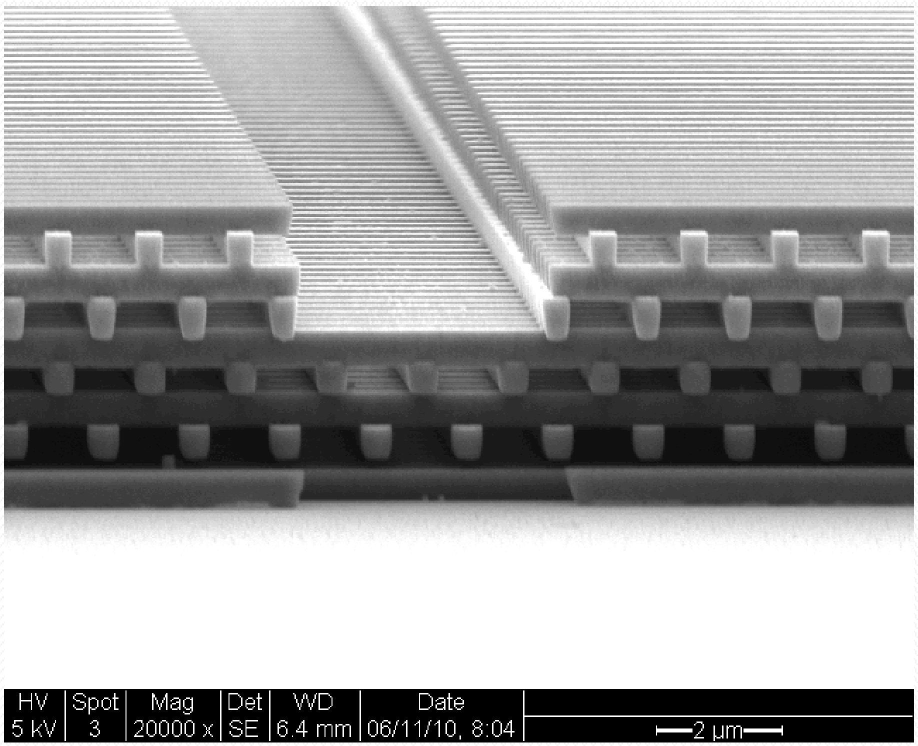
T. Plettner, *et al*, *PRST-AB*, **9**, 111301 (2006).

Wave Guiding Structures

Phase Mask Structure

3D Photonic Crystal: Woodpile Structures in Silicon

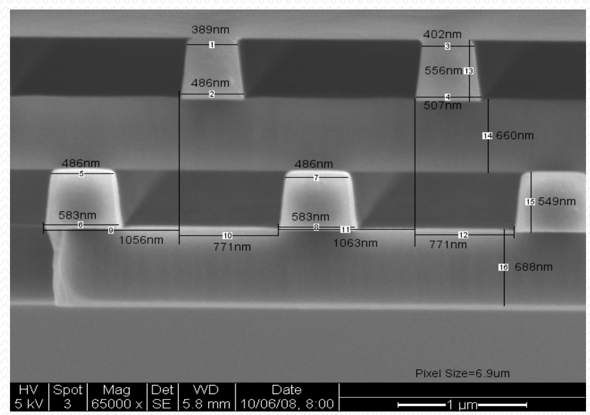
Silicon woodpile structure produced at the Stanford Nanofabrication Facility (SNF)



Designed for acceleration at λ~4 µm

Detailed Tolerance Studies of CDs

Process Version	Rod width base	Rod width top	Taper Angle	Layer Thickness	Alignment Offset	Period
3	389	486	9.89624641	556	142.5	1834
3	402	507	10.69429961	660	146	1827
3	486	583	10.01988665	549	161.5	1834
3	486	583	10.01988665	688	102.5	1808
3	311	441	9.575247964	516		2013
3	280	391	11.1759075	658		1721
3	379	509	11.04285784	559		
3	348	485	10.49147701	702		
2	438	556	13.12686302	506	412.5	1844
2	419	506	9.755861898	681	400	1838
2	469	525	5.75140209	556	522	1813
2	450	544	9.595956437	545	516	1857
2	384	455	7.092112957	643		1870
2	366	446	6.301068652	580		1832
2	446	527	5.850496153	527		
2	464	518	8.737992324			
1	434	529	10.43182293	542		1818
1	503	669	15.86761887	516		1789
1	483	649	15.86761887	584		
1	480	690	19.90374954	580		
average	420.85	529.95	10.55991867	586.7368421	300.375	1835.571
std	62.16808709	76.49594072	3.503712238	64.14206637	179.4061135	62.12112
version 3 mean	390.4285714	500	10.34633323	598	138.125	1839.5
version 3 std	74.27062003	65.09649431	0.57608771	73.11243787	25.14416765	95.24022
version 2 mean	429.5	509.625	8.276469191	576.8571429	462.625	1842.333
version 2 std	37.27887184	39.6157887	2.542079837	63.49128174	65.34188932	19.84607



Best achieved:

Width Variation:

<40 nm RMS (~λ/125)

Layer Thickness:

<65 nm RMS (~λ/75)

Layer Alignment:

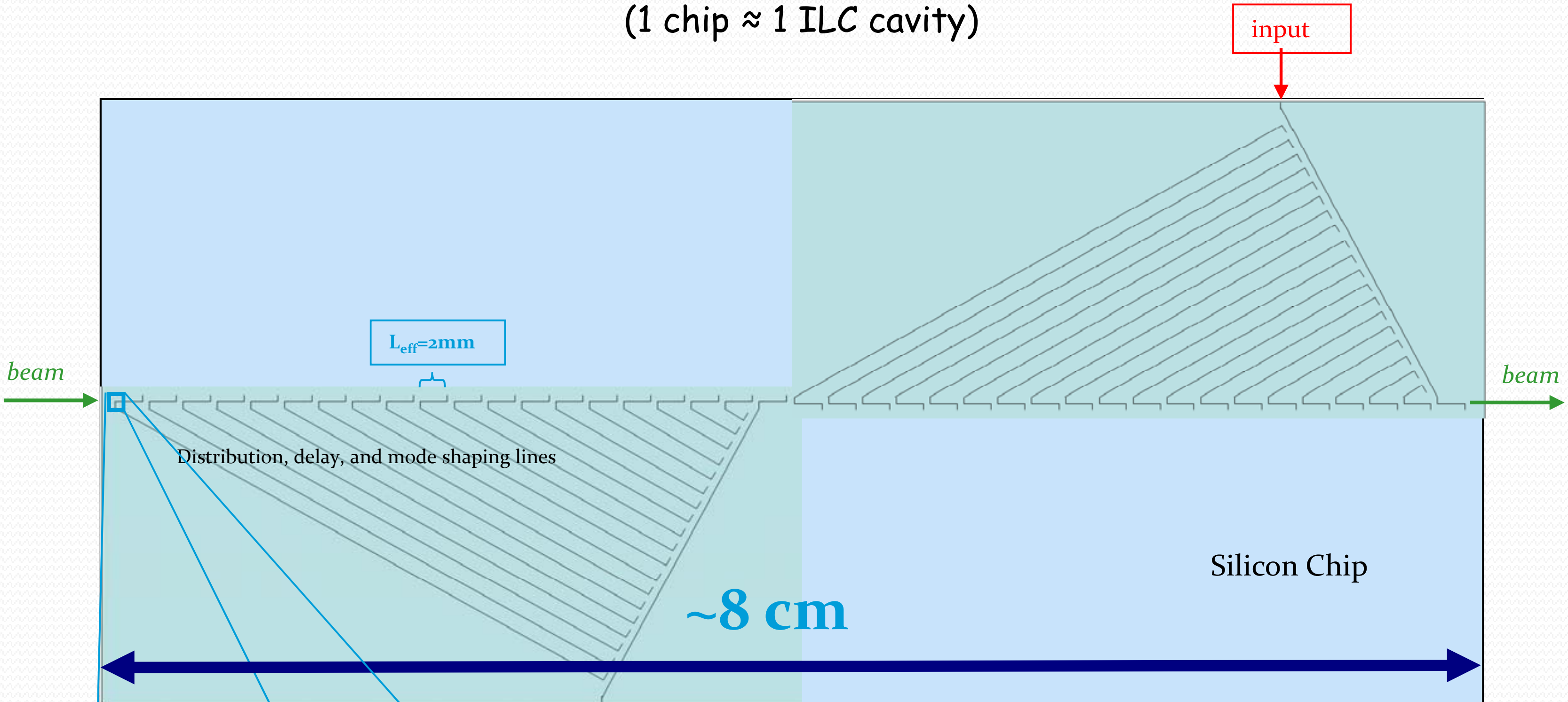
<65 nm RMS (~λ/75)

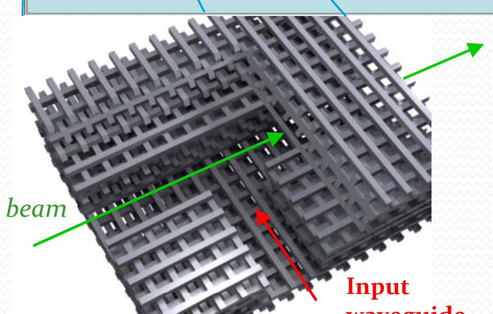
Measurement Technique Granularity: 7nm

C. McGuinness, *et al*, *J. Mod. Opt.*, **56**, 18 & 19 p. 2142ff, (2009).

The next level of integration:
A Single-Pulse 32 MeV-Gain Woodpile Accelerator Chip

(1 chip ≈ 1 ILC cavity)



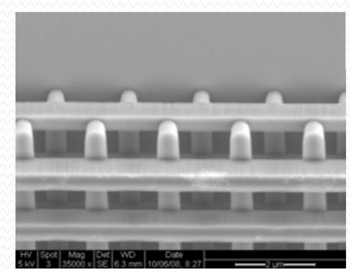


Cutaway sketch of coupler region

Image courtesy of B. Cowan, Tech-X.

Fiber coupled input

λ=2 μm
20 μJ/pulse
1 ps laser pulse



4-layer Structure Fabrication (completed at SNF)

Image courtesy of C. McGuinness, Stanford.

Strong coupling impedance comes at a price

Strong coupling to $E_\perp$ ➔ $r<\gamma\lambda$; Strong coupling to $\mathbf{E}_{//}$ ➔ $\mathbf{r\sim\lambda}$

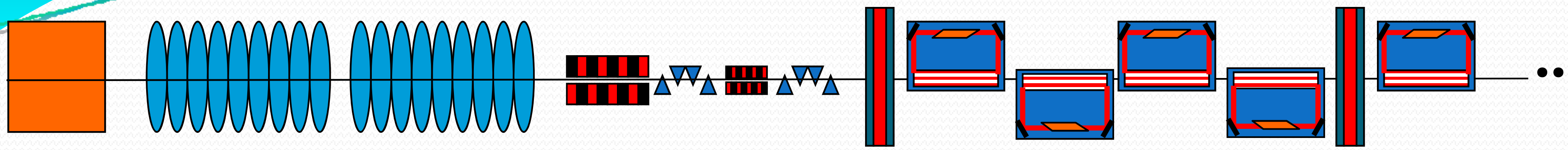
- Structure aperture ➔ ~λ
  - *Terahertz: has been achieved with CVD diamond deposition and capillary drawing*
  - *Optical: Has been achieved with semiconductor and fiber drawing technology*
- Optimum beam loading requires bunch charge ➔
  - *Terahertz: ~picoCoulombs per bunch*
  - *Optical: ~femtoCoulombs per bunch*
- Beam transmission requires very small emittances ➔ ~nm
  - *Possible with metal tip emission sources*
  - *Naturally leads to reduction in IP spot sizes*
- Narrow energy spread ➔ Bunch length ~λ/100
  - *Terahertz: Bunching by conventional means to ~λ/30 already achieved*
  - *Optical: Single-stage bunching at ~410as (~λ/8) demonstrated*
- Beam current ~1-10 μA requires high repetition rates ➔
  - *Terahertz: klystron-based power sources imply low rep rate and long pulse trains*
  - *Optical: lasers operating in the ~10-100 MHz are commercially available*
- BBU→Alignment tolerances ➔ ~λ/100
  - *Single-mode structures with no confined deflecting modes*
  - *Terahertz: Moderately high rep rate ➔ effective position stabilization feedback*
  - *Optical: Very high repetition rate ➔ very broadband position stabilization feedback*

Present Status of Optical Structures

- Dominant effort to date has been on designing and making **structures** that can support high gradient and scale to high energy (efficiently transfer power, preserve beam quality)
  - Wave guiding
  - Phase mask and swept-laser methods
- **Demonstrations** of "large-aperture" but inefficient acceleration concepts ($r \gg \lambda$) at $\lambda = 10\ \mu m$ and $0.8\ \mu m$ have been done
- Facilities and **accelerator techniques** for working in the picosecond-micron-pC domain **have matured**
- Research on suitable electron **sources** is underway
  - Laser-triggered field emission sources
  - Laser-triggered ferro-electric sources
- Work to experimentally **quantify structure limitations** is underway (damage threshold, dephasing, thermal, etc.)

Image credit: Gennady Shvets, UT Austin

Laser-Driven Dielectric Accelerator LC Cartoon



CW Injector

Warm rf gun   Cold Preaccelerator   Optical Buncher

433 MHz x 6E03 e⁻/macropulse (145 μpulse/macropulse)

$\varepsilon_N \sim 10^{-10}$ m (but note $Q/\varepsilon_N << 1$ nC/μm)

Laser Accelerator

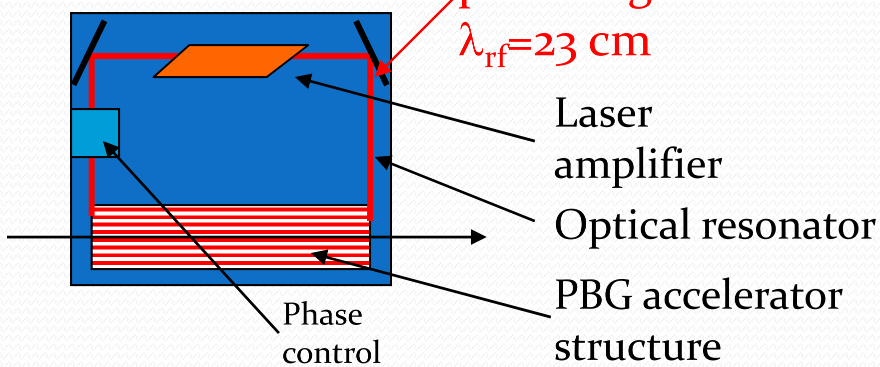
λ=2-4 μ, G~1 GeV/m

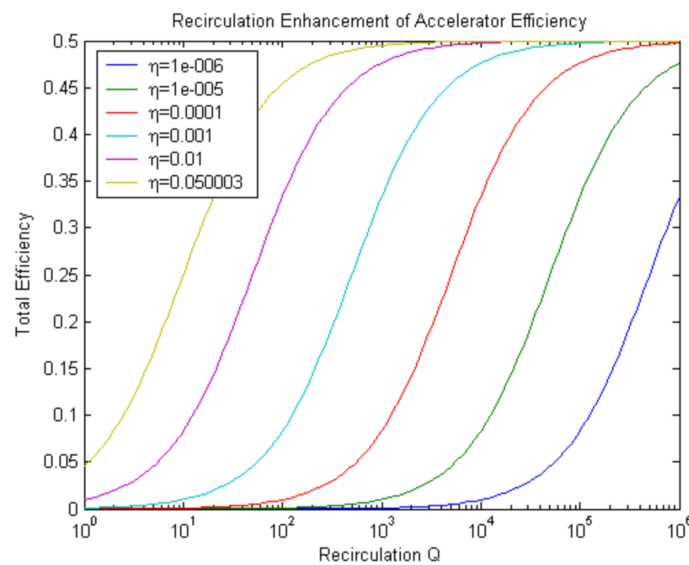
Photonic Band Gap Fiber structures embedded in optical resonant rings

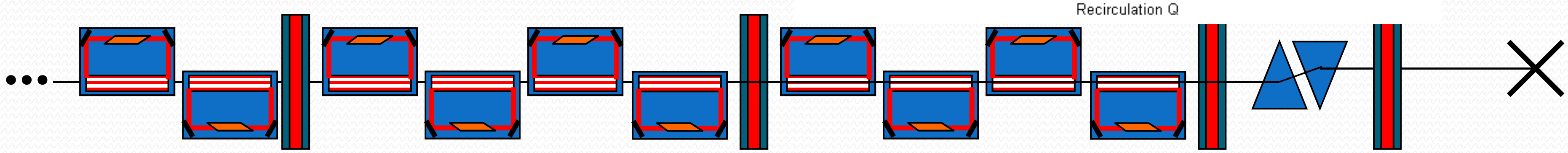
Permanent Magnet Quads (B'~2.5 kT/m)

An Acceleration Unit

Resonant ring path length: λ_{rf}=23 cm







Optical Debuncher   **Final Focus**   **I.P.**

Strawman 3 TeV Collider Parameters

		RF Source	RF Source ==> Beam Driven			Laser-Driven	
		"ILC"	"CLIC"	Microwave	Terahertz	Grating	Waveguide
E_cms	**GeV**	**3000**	**3000**	**3000**	**3000**	**3000**	**3000**
Bunch Charge	e	2.0E+10	3.7E+09	3.1E+09	1.1E+08	6.5E+03	3.5E+03
# bunches/train	#	1700	500	4160	4160	145	145
train repetition rate	Hz	4	50	5	120	50 MHz	125 MHz
design wavelength	micron	230610	24983	11530	300	4	2
Invariant Emittances	micron	10/0.04	0.7/0.02	0.3/0.02	0.008/0.001	1e-04/1e-04	1e-04/1e-04
I. P. Spot Size	nm	185/1.7	49/1.2	33/1.1	8/0.2	0.1/0.1	0.1/0.1
Enh Lumi	**/cm^2/s**	**1E+39**	**9E+38**	**9E+38**	**9E+38**	**1E+39**	**9E+38**
Beam Power	MW	32.7	22.2	15.6	13.2	11.3	15.2
Beamstrahlung Power	MW	14.1	7.4	6.3	1.2	0.0	0.0
Beamstrahlung Loss	%	43.1	33.4	40.2	8.9	0.1	0.3
Gradient	MV/m	31.5	100	270	2000	1000	500
Linac Length	km	95	30	11	2	3	6

cm ⟵|⟶ micron

For illustrative purposes only!

Limitations and Questions

- Physics Issues
  - Deflecting-mode-driven instabilities are severe, requiring small bunch charge and innovations in focusing and damping
  - Two-beam short-pulse accelerators require efficient broadband mode convertors
  - *What process ultimately limits the achievable gradient?*
- Material Issues
  - Degradation with high field and radiation exposure
  - Charging and multipactoring
  - Nonlinear polarizability and Raman scattering
  - *What materials have the best combination of attributes?*
- Particle Source Issues
  - *How can electron and positron sources with the required properties be made?*
- Power Source Issues
  - Drive beam stability and power transfer structure design
  - Efficient production of the drive beam
  - *How can compact, cost-effective drive sources be built?*
- Fabrication Issues
  - *How can the required tolerances be achieved for THz and optical structures?*
  - *How can the required alignment tolerances be achieved?*

Future Prospects

- Dielectrics offer higher damage resistance than metals and a natural way to provide synchronism with $\beta<1$ particles
- Frequency-selective boundary conditions are possible, allowing destructive HOMs to radiate out of the accelerator
- Higher frequency methods will require smaller bunch charges and increased repetition rates, providing experimental advantages of reduced beamstrahlung background and event pileup
- In contrast to higher-gradient plasma wakefield techniques, dielectric acceleration is **linear**, the structure is **solid-state**, and the technique is inherently more **stable**
- High power structure and beam tests are planned or underway for microwave, terahertz, and optical technologies and clear evidence as to the suitability of each technique should be available in the next few years