http://lp09.desy.de

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Novel Accelerator Technologies

Mark Hogan

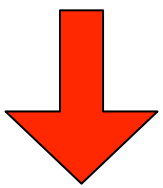
SLAC National Accelerator Laboratory

XXIV International Symposium on
Lepton and Photon Interactions at High Energies
August 17-22, 2009
Hamburg, Germany

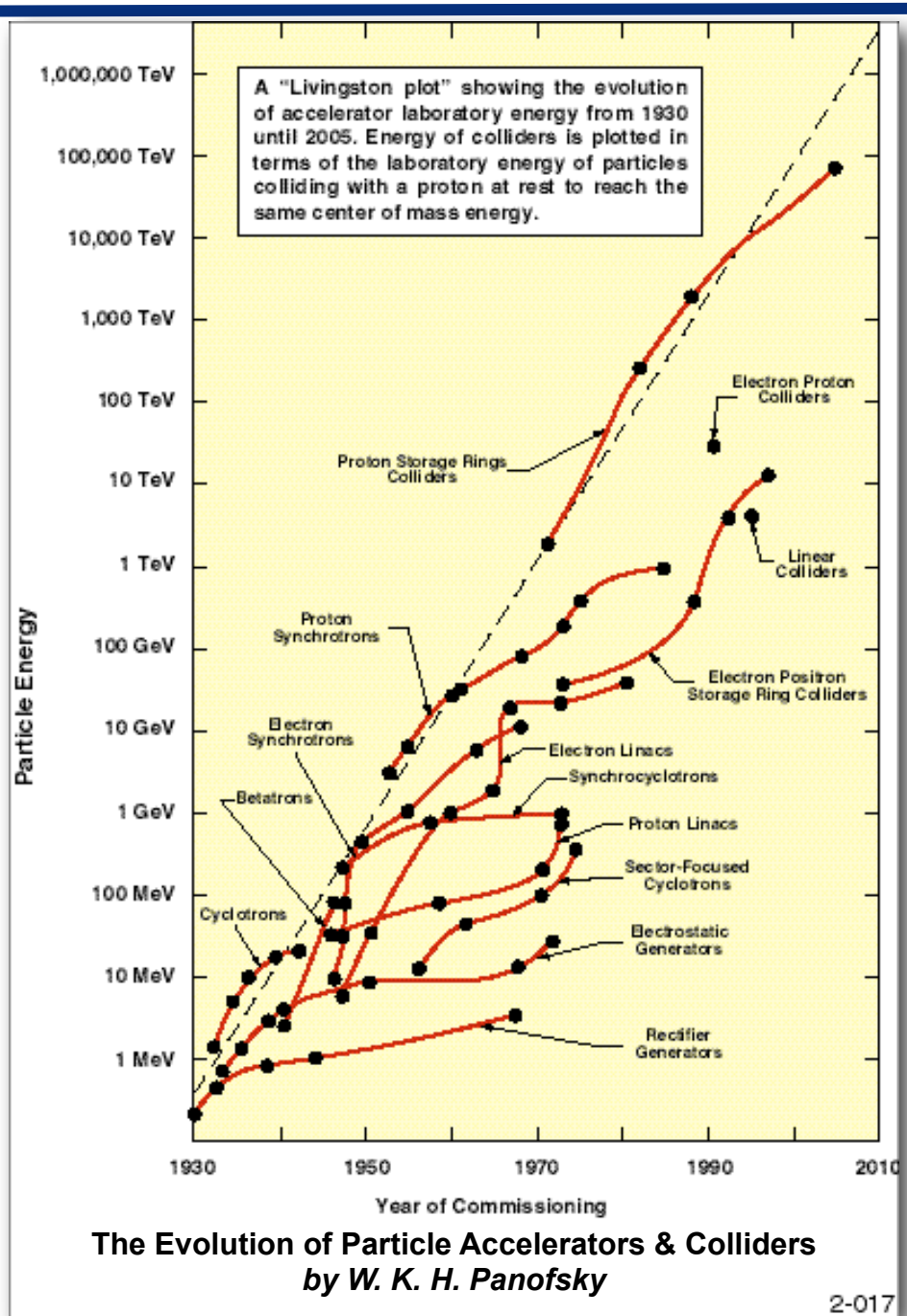
Photo: iStockphoto LP

Accelerators and Particle Physics

* Particle physics addresses fundamental questions that are often answered at the energy frontier
* The Livingston curve shows the exponential growth in CM energy that has come from new accelerator physics & technology



* This growth has been followed by profound discoveries - CP violation in K's, two ν's, J, quarks, ψ, τ, gluons & QCD, W, Z, top quark..



The Evolution of Particle Accelerators & Colliders
by W. K. H. Panofsky

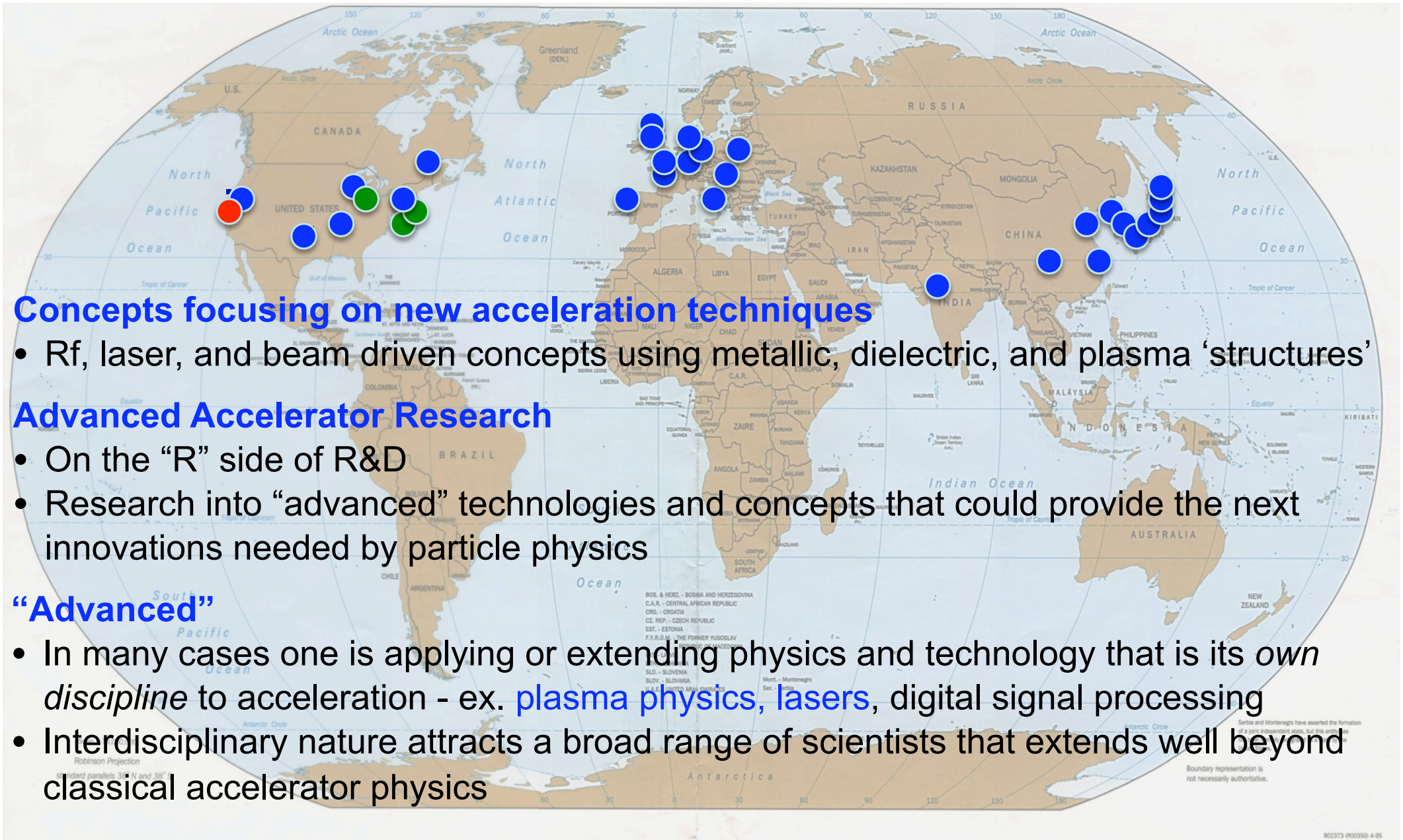
Linear Collider Status

* Strong international development program on linear collider over last 30 years
  - Designs based on 'reasonable' extrapolations of existing technology: ILC (1.3 GHz SC) and CLIC (12 GHz NC)
* Any linear collider is a massive project: varying between ultra-huge (10's B$) and huge (~5 B$) in US accounting
  - Access to funding will be influenced by political processes and is inherently uncertain
  - Given uncertainty, community must investigate new concepts and new approaches

Marx panel 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."

Advanced Accelerators are a Worldwide Effort



Concepts focusing on new acceleration techniques

- Rf, laser, and beam driven concepts using metallic, dielectric, and plasma 'structures'

Advanced Accelerator Research

- On the "R" side of R&D
- Research into "advanced" technologies and concepts that could provide the next innovations needed by particle physics

"Advanced"

- In many cases one is applying or extending physics and technology that is its *own discipline* to acceleration - ex. plasma physics, lasers, digital signal processing
- Interdisciplinary nature attracts a broad range of scientists that extends well beyond classical accelerator physics

● Laser Wake Expts ● Electron Wake Expts ● e-/e+ hi γ Wake Expts

High Gradient Acceleration

* Largest cost driver for a linear collider is the acceleration
  - ILC geometric gradient is ~20 MV/m → 50km for 1 TeV
* Size of facility is costly → higher acceleration gradients
  - High gradient acceleration requires high peak power and structures that can sustain high fields
    - Beams and lasers can be generated with high peak power
    - Dielectrics and plasmas can withstand high fields
* Many paths towards high gradient acceleration
  - RF source driven microwave structures
  - Beam-driven microwave structures

  } ~100 MeV/m

  - Laser-driven dielectric structures
  - Beam-driven dielectric structures

  } ~1 GeV/m

  - Laser-driven plasmas
  - Beam-driven plasmas

  } ~10 GeV/m

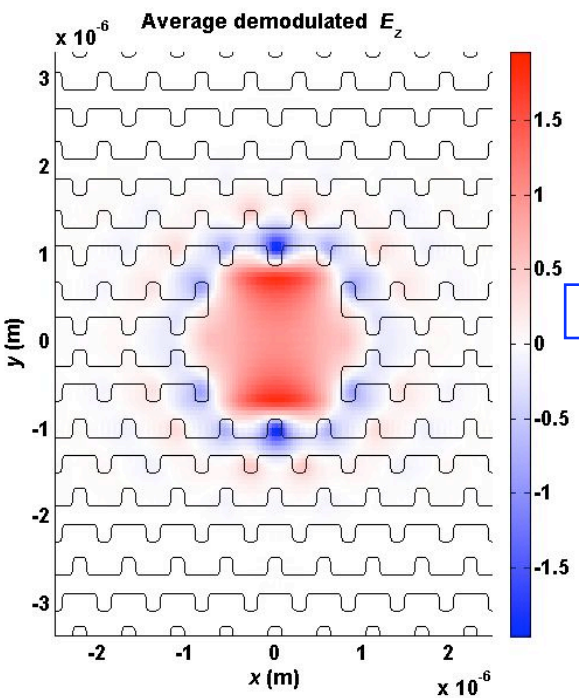
Laser Powered Dielectric Structures

* High Gradient Acceleration is Possible
  - Lasers produce very large electric fields >>>35 MV/m
  - Dielectrics have excellent short-pulse breakdown resistance >1 GV/m
  - Net accelerating gradients of 0.4-0.8 GV/m are expected to be possible, based on material damage threshold data
* High Efficiency Acceleration is Possible
  - Efficient lasers (>30%) are commercially available and are getting better (DARPA/SHEDS)
  - We have designed coupling structures that tightly couple laser to the beam
  - Power recirculation is possible to further enhance efficiency
* Large-scale private industry R&D can be leveraged
  - Fiber lasers, optics, and PCF fiber ⇔ telecomm, cutting/welding/engraving
  - Silicon structures ⇔ chip industry
* Other (non-HEP) applications
  - Short wavelength acceleration naturally leads to attosecond bunches and point-like radiation sources → Basic Energy Sciences
  - Structure Fabrication is by inexpensive mass-scale industrial manufacturing methods → Commercial Devices

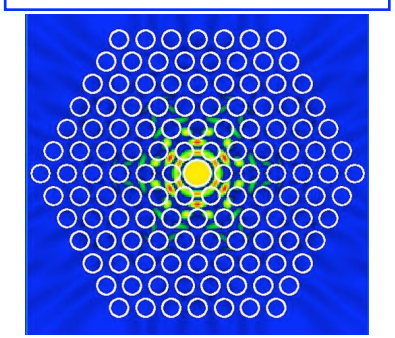
DLA Structure Design

* Create laser powered structures with a confined synchronous mode with large accelerating field
  - Design so that accelerating mode is confined; others radiate strongly
* All dimensions scale with wavelength → ~micron size apertures, ~100 attosecond (10^{-16} s) bunch lengths!
  - Structure and coupler design work at Stanford, SLAC, UCLA

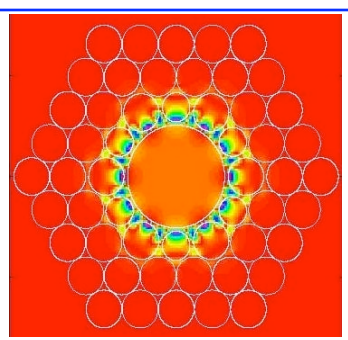
Photonic Crystal "Woodpile"
Silicon, λ=2200nm,
E_z=400 MV/m



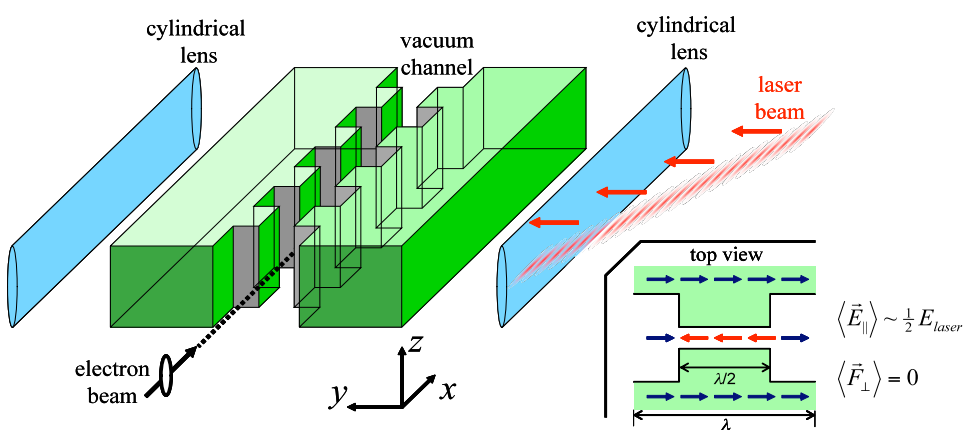
Photonic Crystal Fiber
Silica, λ=1890 nm,
E_z=400 MV/m



Silica, λ=1890nm, E_z=130 MV/m



Transmission Grating Structure
Silica, λ=800nm,
E_z=830 MV/m

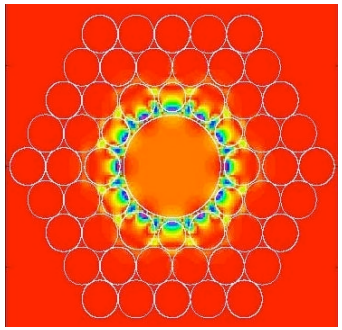
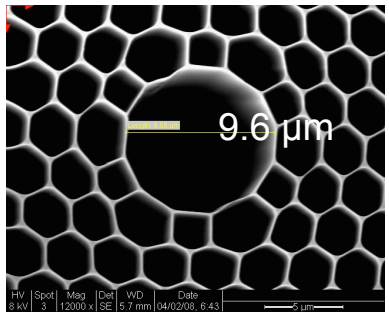


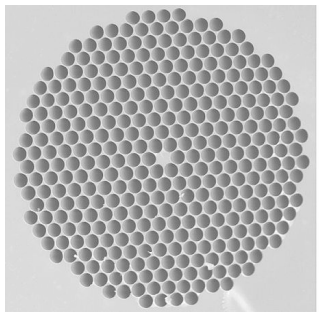
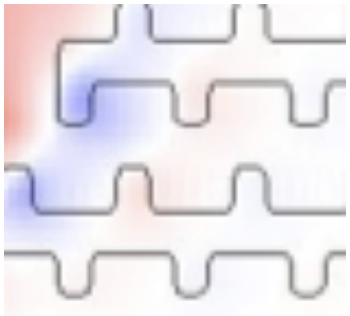
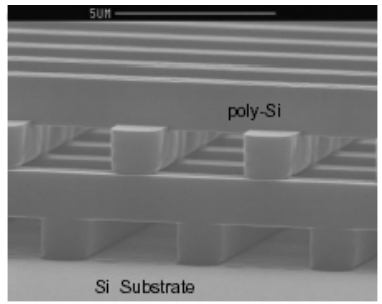
T. Plettner et al, Phys. Rev. ST Accel. Beams 4, 051301 (2006)

Accelerating gradients based on measured damage threshold of Si

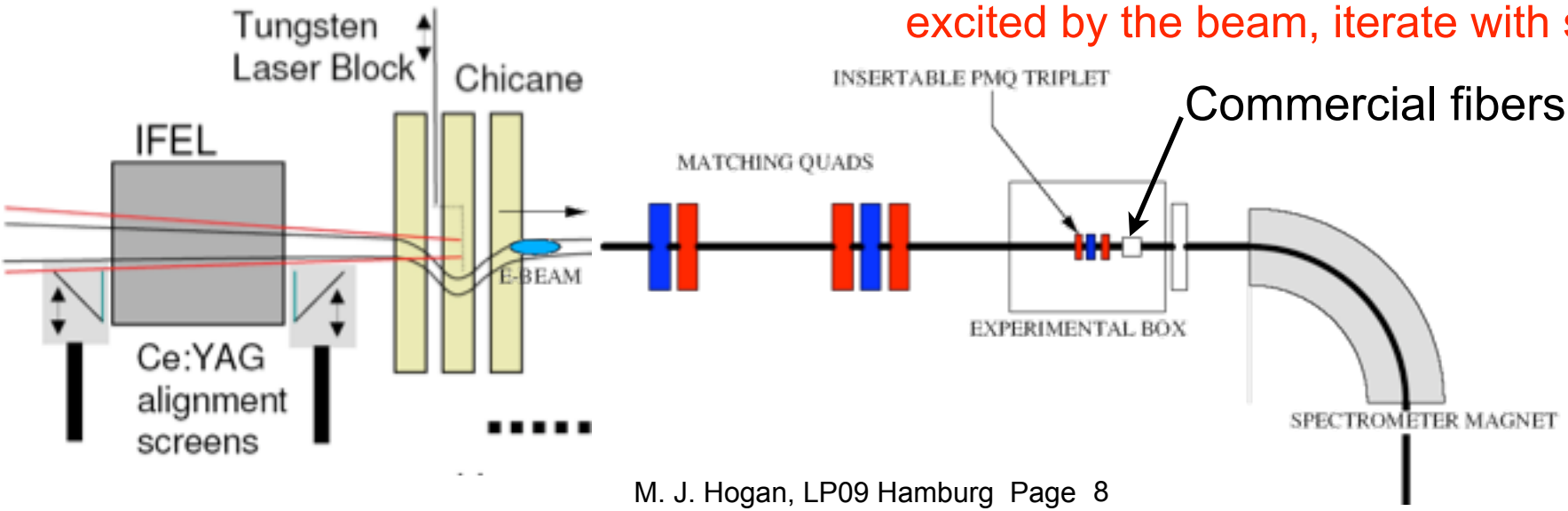
DLA Structure Fabrication and Testing

* Combination of commercial products and custom lithography (Stanford Nanofabrication Facility)
* All dimensions scale with wavelength – micron size apertures, attosecond (10^{-18} s) bunch lengths!
  - Structure fabrication and testing at UCLA & SLAC

  - Structures currently being tested 'in reverse'
  - Generate attosecond bunch trains, squeeze into aperture, measure which modes are excited by the beam, iterate with simulations

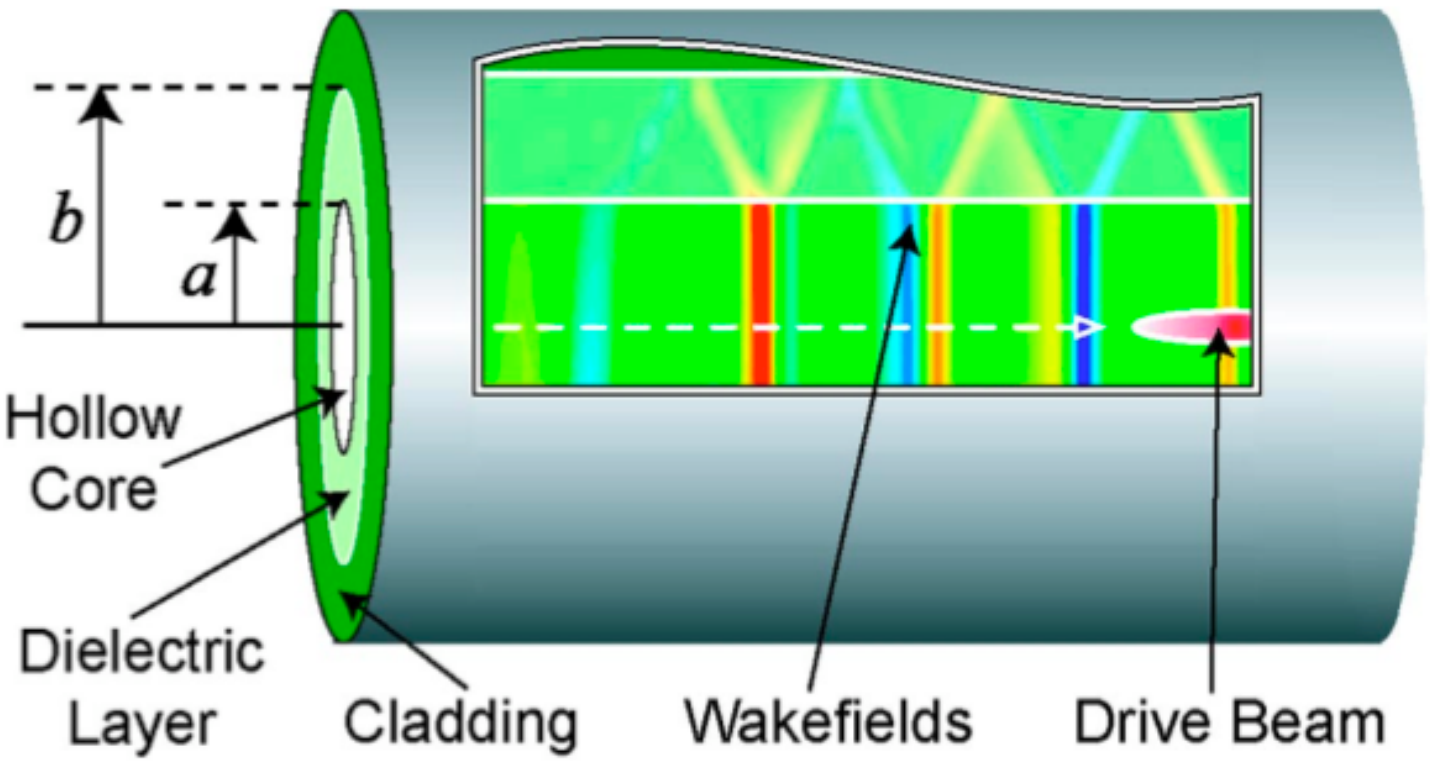


Laser Powered Dielectric Structures Outlook

* What we can expect in the near future:
  - Within 1 year:
    - Demonstrate the first near-IR structures with interaction distances of 100-1000λ .
    - Design compact input couplers and design integrate multiple accelerator structures
  - Within 3 years:
    - Stage multiple structures to achieve higher integrated energy gains
    - For fibers & woodpiles: fabricate the first integrated structures
    - Develop permanent-magnet focusing elements and beam transport techniques
    - Test coupler and accelerator components at high average laser power
    - Work with industry and university collaborators to phase-lock multiple fiber lasers
  - Within 5 years:
    - Develop large-scale integrated accelerator modules achieving 30-100 MeV gains
    - Demonstrate significant energy gain 100-1000 MeV from a DLA at 10 Hz

Beam Driven Dielectric Wakefield Accelerator (DWA)

A "drive" beam excites wake-fields in the tube, while a subsequent witness beam (not shown) would be accelerated by the Ez component of the reflected wakefields (bands of color).

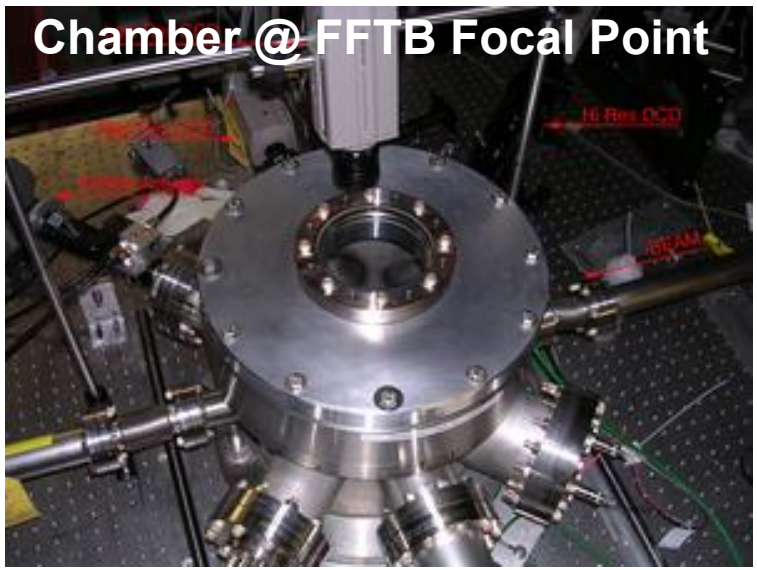


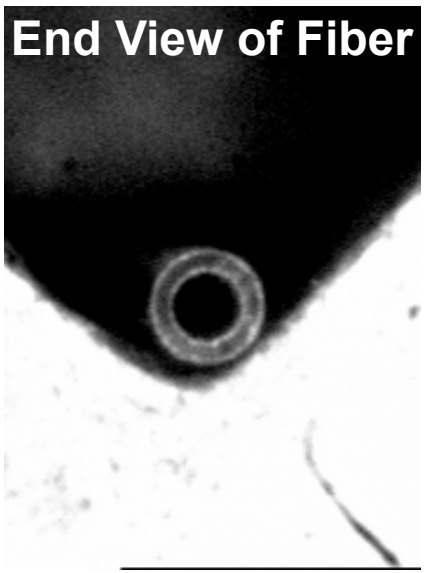
$$eE_{z,\mathrm{dec}} = eE_{r,\mathrm{surf}}\frac{\sqrt{\varepsilon-1}}{\varepsilon}$$

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

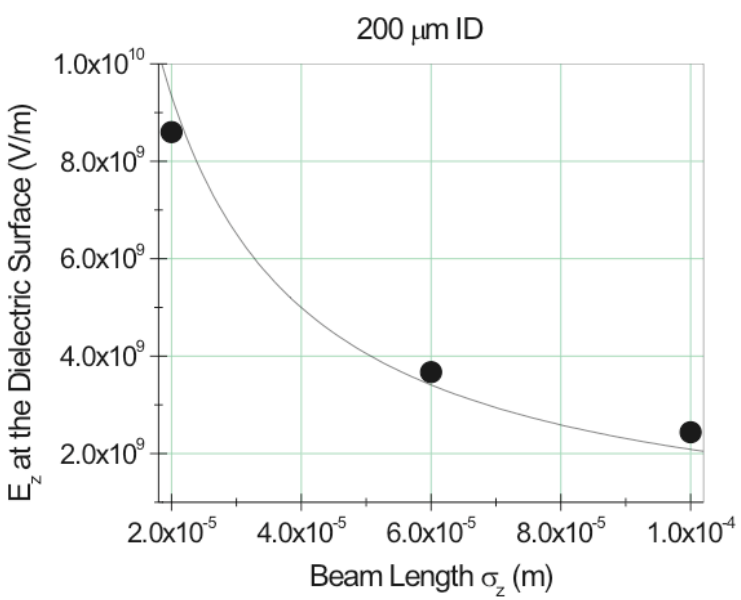
For large wakes want high charge, short bunches and narrow tubes,
e.g. 2E10 e-, σ_z=20μm, Si with 200μm ID get 85GV/m surface fields!

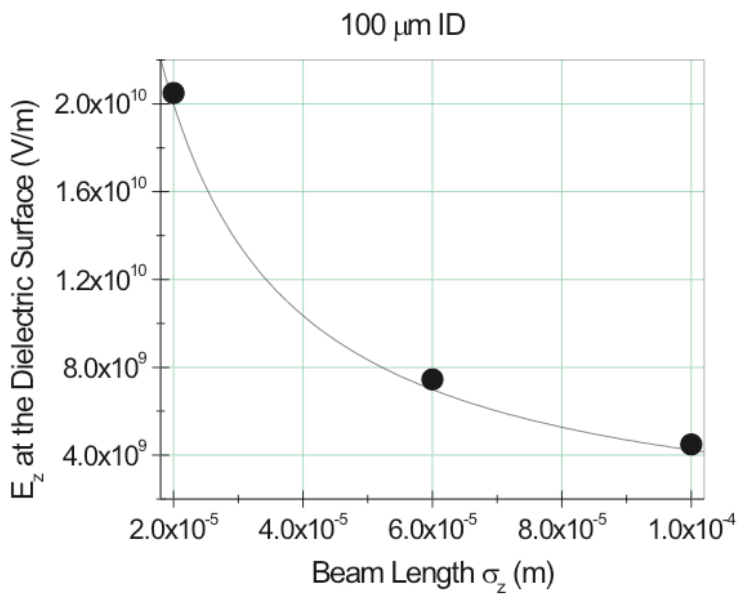
Recent Measurements Have Focused on Damage Threshold of Fused Silica





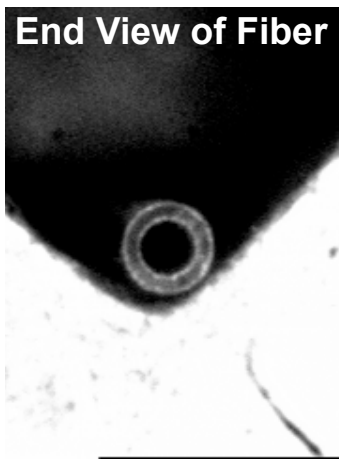
Study Breakdown As a Function of Bunch Length and Fiber Diameter

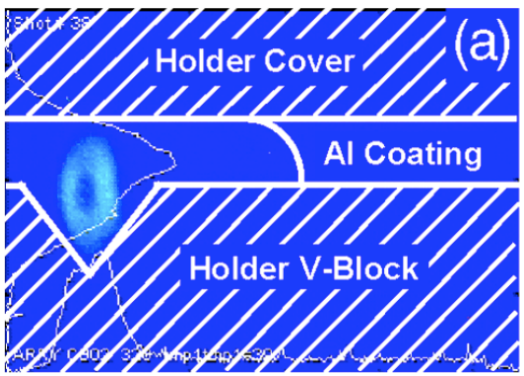


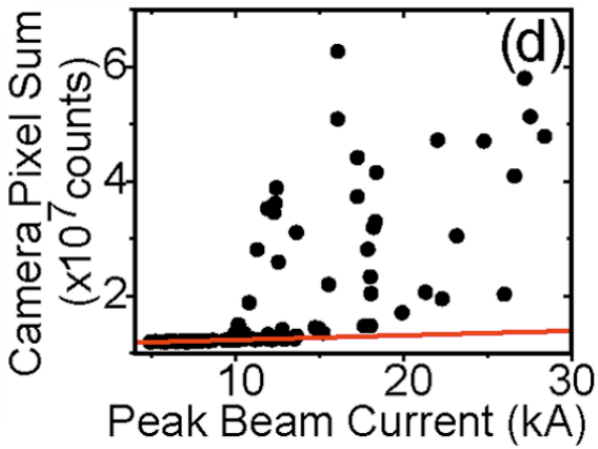


Initial Measurements Indicate High Damage Threshold, but also Yield Surprises

* Breakdown in capillary when I_{peak} > 10 kAmps
* Corresponding breakdown threshold:
  - ~14 GV/m on the dielectric surface and ~6 GV/m on axis





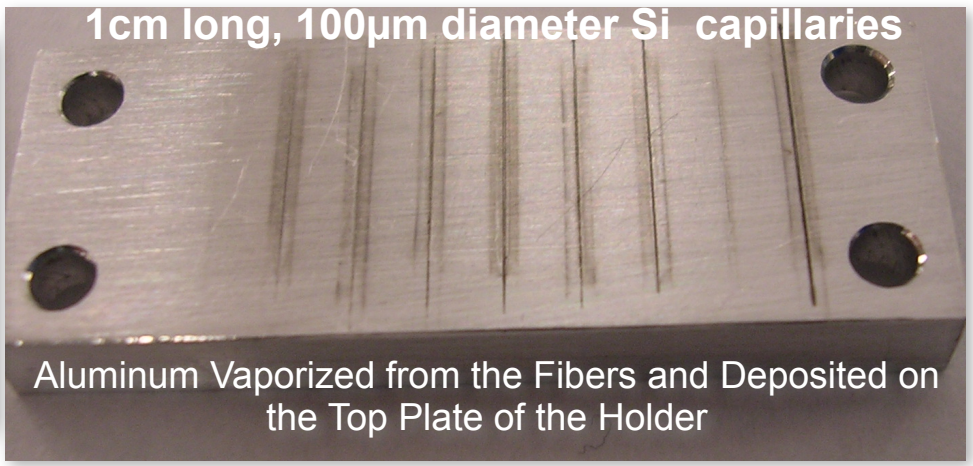


M.C. Thompson et al Phys. Rev. Lett. ***100****, 21480 (2008)*

* Aluminum cladding vaporized! Fused silica substantially intact.

Next steps for beam driven DWA:

- Requires specialized facilities (FACET early 2011)
- Replace metallic outer layer with dielectric
- Compare CVD-diamond fibers with Si
- Increase tube length ~meter and measure change to beam energy spectrum



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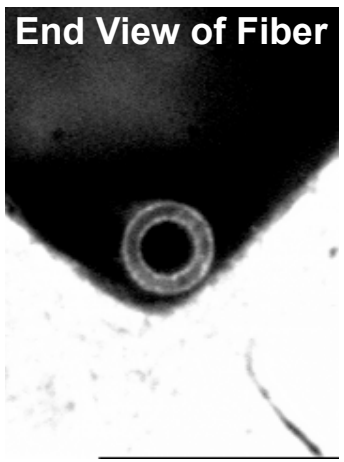

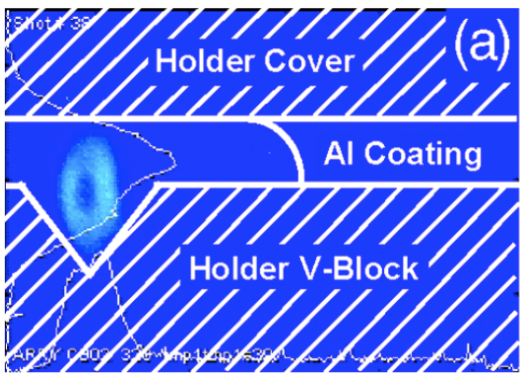

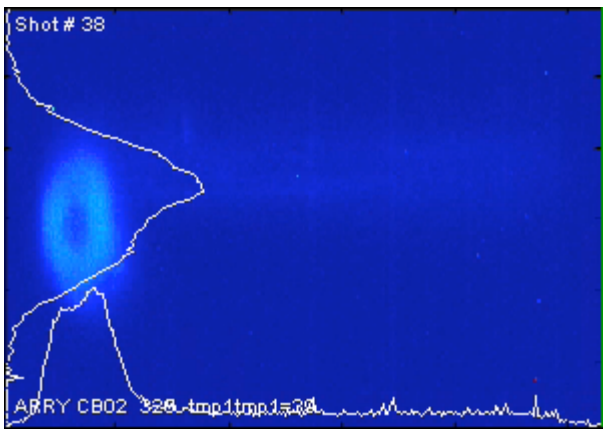

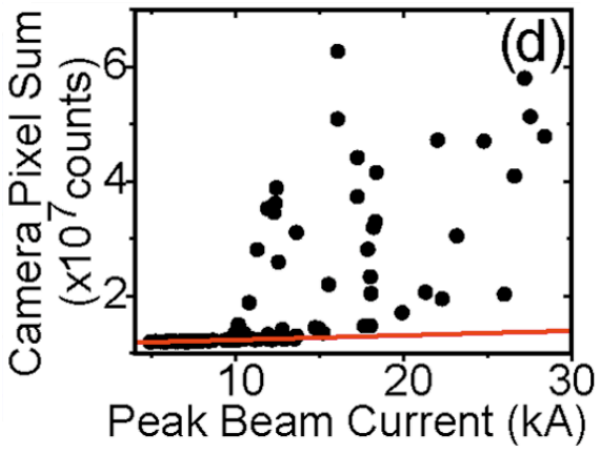

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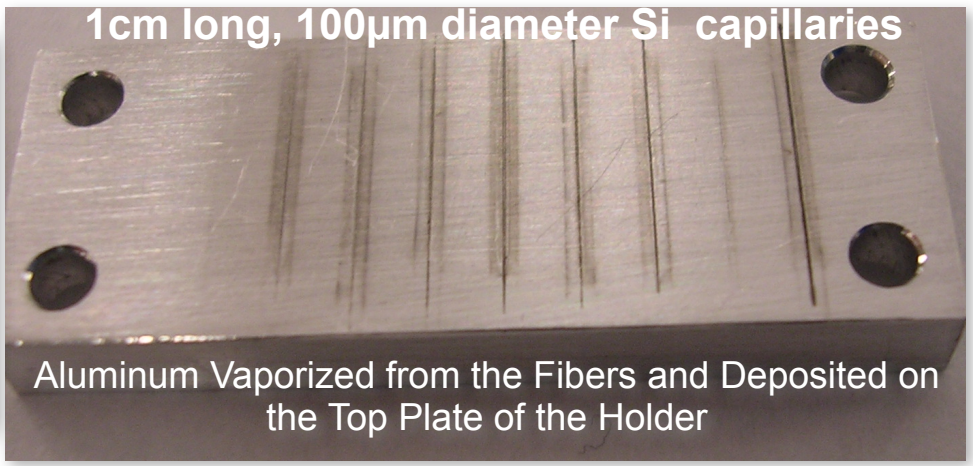
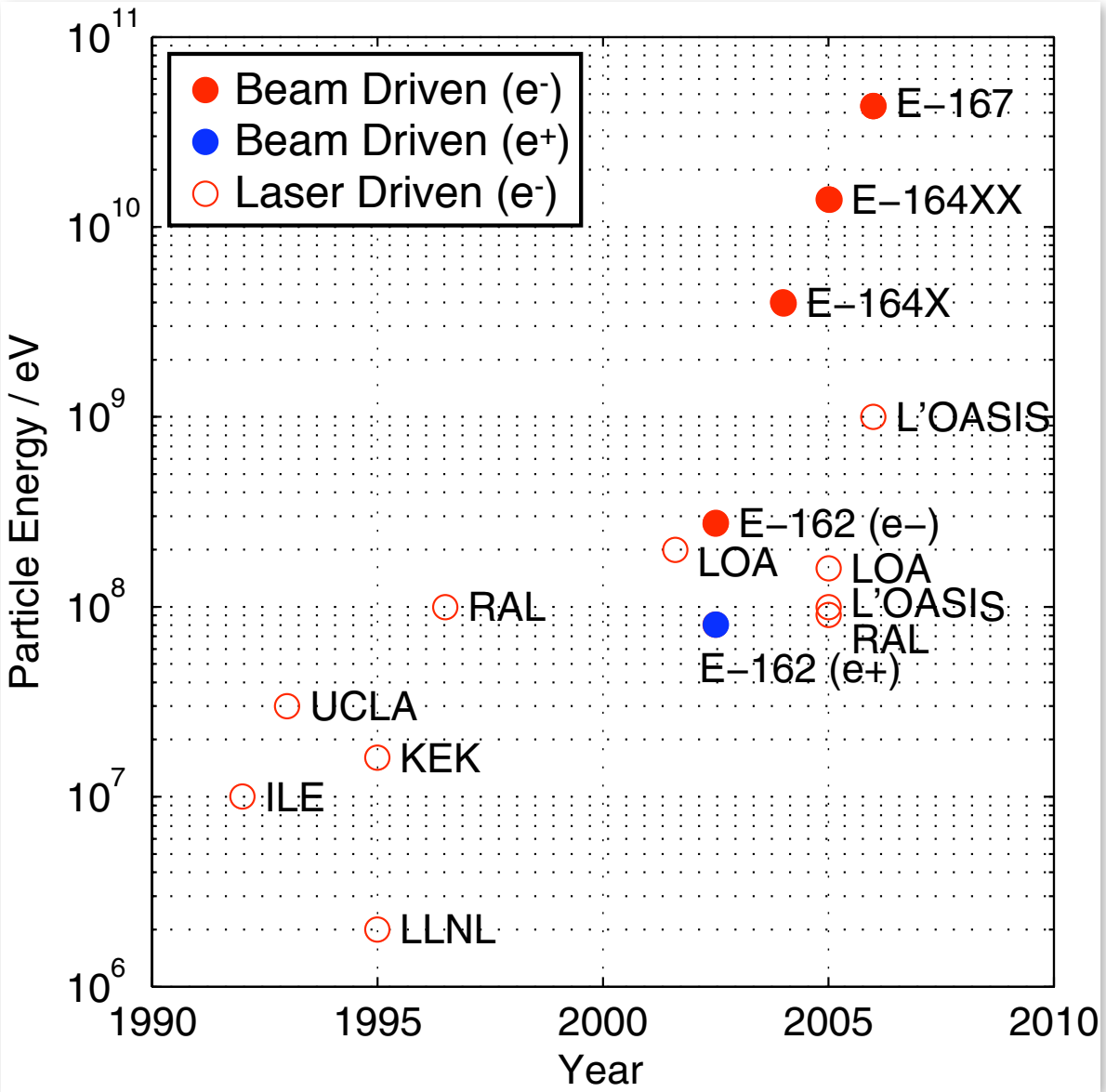


Plasma Accelerators Showing Great Promise



Laser Driven Plasma Accelerators:

Large Gradients:
- Accelerating Gradients > 100GeV/m (measured)
- Narrow Energy Spread Bunches
- Interaction Length limited to cm's

Specialized Facilities:
- Multi-TW lasers
- Plasma Channels/Capillaries

Beam Driven Plasma Accelerators:

Large Gradients:
- Accelerating Gradients > 50 GeV/m (measured!)
- Focusing Gradients > MT/m
- Interaction Length ~ meters

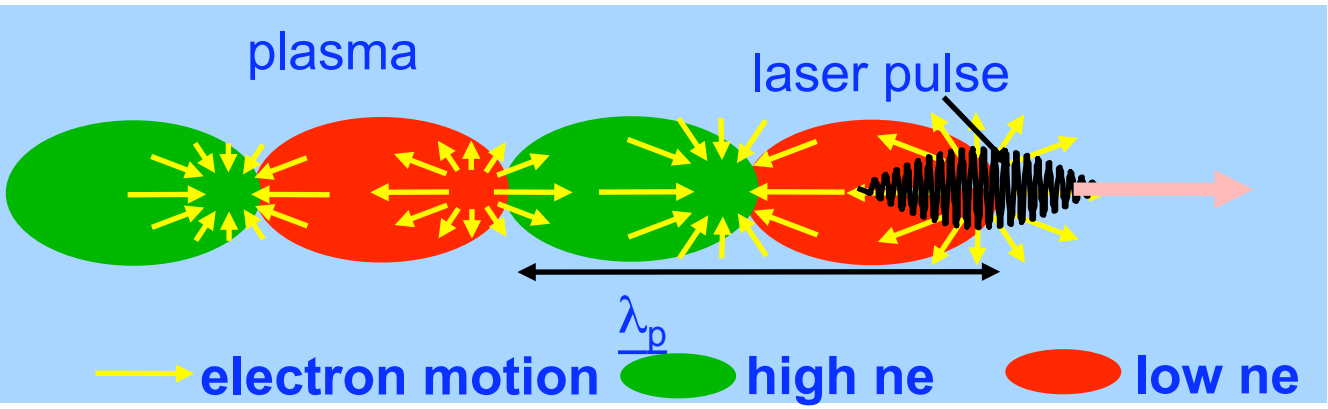
Unique SLAC Facilities:
- FFTB < 2006, FACET > 2011
- High Beam Energy
- Short Bunch Length
- High Peak Current
- Power Density
- e- & e+

LWFA: T. Tajima and J. M. Dawson
Phys. Rev. Lett. 43, 267 - 270 (1979)

PWFA: P. Chen et al
Phys. Rev. Lett. 54, 693 - 696 (1985)

Laser Driven Excitation of Plasma Waves: Laser Wakefield Accelerator (LWFA)

Standard regime (LWFA): pulse duration matches plasma period
Radiation pressure of intense laser pulse excites plasma wave (wakefield)



Ultrahigh axial electric fields
=> Compact electron accelerators

Plasma wakefields
E_z > 10 GV/m, fast waves

(Conventional RF accelerators
E_z ~ 10 MV/m)

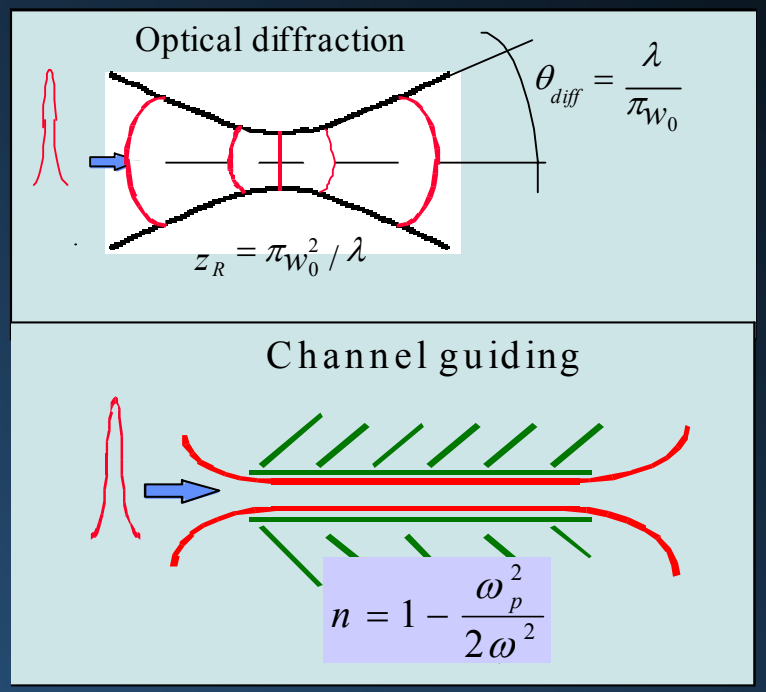
Wakefield Accelerator Physics: Scalings

- Electric field of plasma wave (n = density):
  $E_{WB} \sim n^{1/2} \sim 100$ GV/m for $n \sim 10^{18}$ cm^{-3}
- Laser Pulse length ~ plasma wavelength λ_p
  $L \sim \lambda_p \sim n^{-1/2} \sim 30\ \mu$m (100 fs) for $n \sim 10^{18}$ cm^{-3}
- Laser intensity: wake potential ~ ponderomotive potential
  $E_{wake} \sim a^2 E_{WB}$, (a^2 = normalized intensity)
  $E_{wake} \geq E_{WB}$ ---> $a^2 \geq 1$ ---> $I \geq 10^{18}$ W/cm^2
- Laser Power and Energy (~ 10 μm spot)
  $P \geq 10$ TW (≥ 1 J)

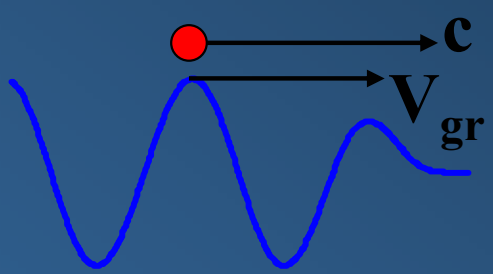
Tajima, Dawson (79); Gorbunov, Kirsanov (87); Sprangle, Esarey *et al.* (88)

Three Factors Limiting Energy Gain

- **Diffraction:** order mm!
  (but overcome w/ channels or relativistic self-focusing)



- **Dephasing:**



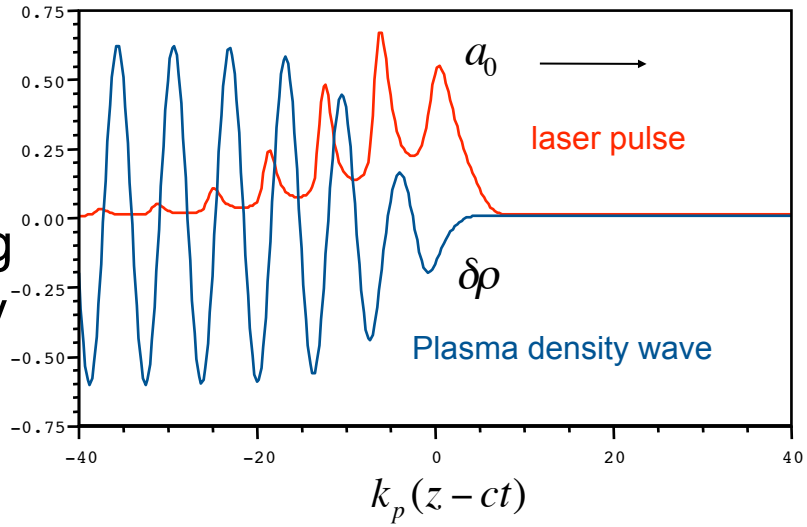
L_{dph} order 10 cm x $10^{16}/n_o$

- **Depletion:** For small intensity ($a_0 < 1$) >> L_{dph}
  For relativistic intensities (a_0 >~ 1), L_{dph}~ L_{depl}

State-of-the-Art Prior to 2004: Self-Modulated Laser Wakefield Accelerator (SM-LWFA)

Self-modulated regime:

- Laser pulse duration > plasma period
- Laser power > critical power for self-guiding
- High-phase velocity plasma waves by
  - Raman forward scattering
  - Self-modulation instability

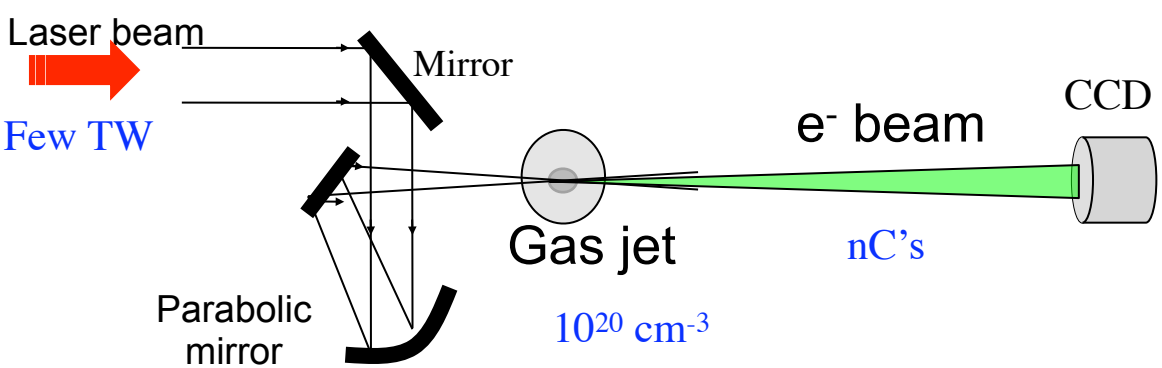


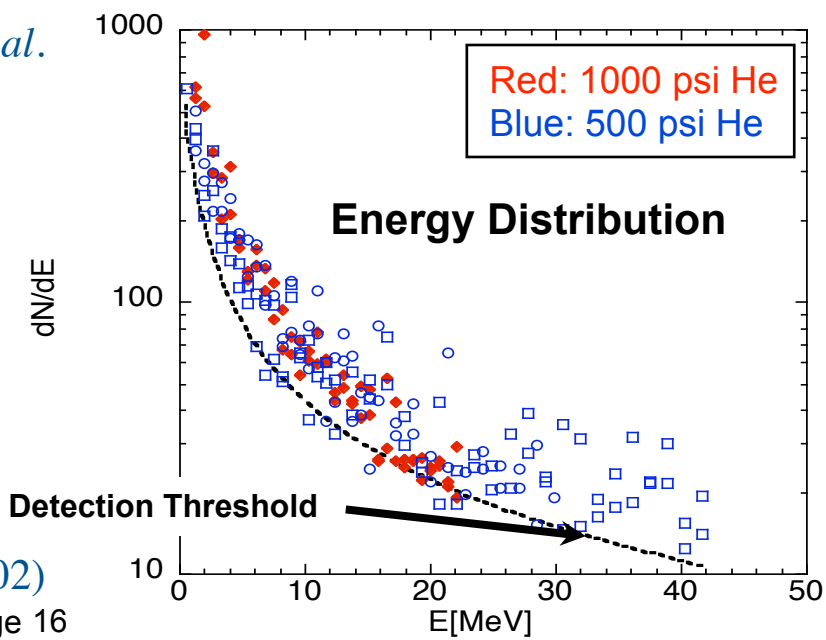
Sprangle *et al*. (92); Antonsen, Mora (92); Andreev *et al*. (92); Esarey *et al*. (94); Mori *et al*. (94)

SM-LWFA experiments routinely produce electrons with:

1-100 MeV (100% energy spread), multi-nC, ~100 fs, ~10 mrad divergence

Modena *et al*. (95); Nakajima *et al*. (95); Umstadter *et al*. (96); Ting *et al*. (97); Gahn *et al*. (99); Leemans *et al*. (01); Malka *et al*. (01)





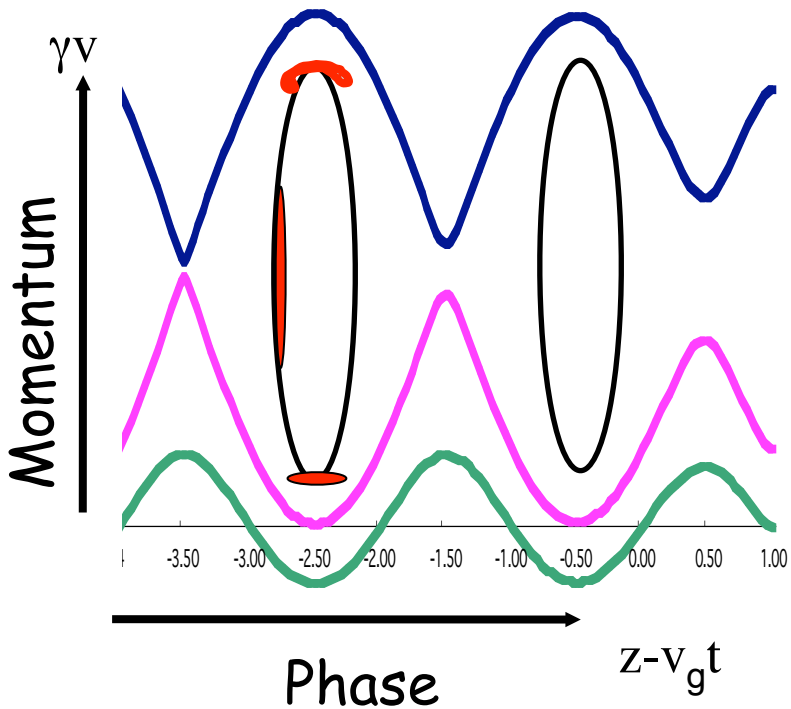
Leemans *et al*. (02)

LWFA: Production of a Monoenergetic Beam

1. Excitation of wake (e.g., self-modulation of laser)
2. Onset of self-trapping (e.g., wavebreaking)
3. Termination of trapping (e.g., beam loading)
4. Acceleration

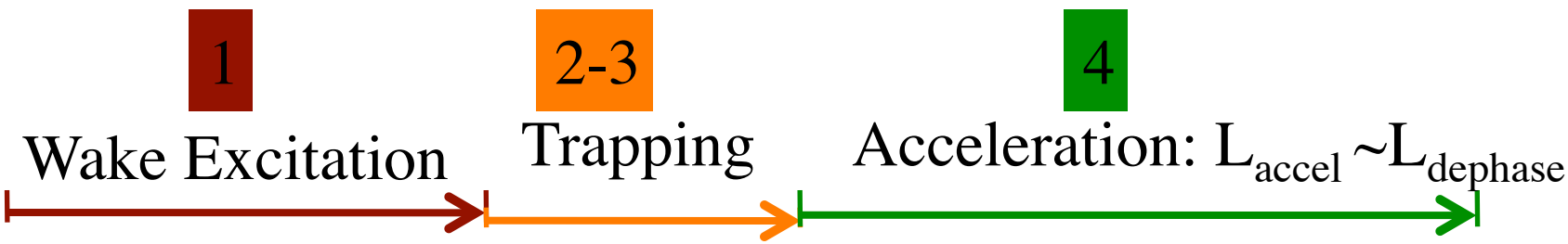
If > dephasing length: large energy spread

If ≈ dephasing length: monoenergetic



- Dephasing distance:

$$L_{dph} \approx \left(\lambda_p^3 / \lambda^2\right) \propto n_e^{-3/2}$$



Breakthrough Results: High Quality Bunches

30 Sep 2004 issue of *nature*:

Three groups report production of high quality e-bunches

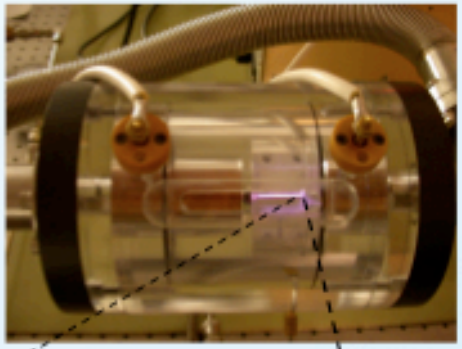
- Approach 1: Plasma channel
- LBNL/USA: Geddes et al.
  - Plasma Channel: 1-4x10^{19} cm^{-3}
  - Laser: 8-9 TW, 8.5 μm, 55 fs
  - E-bunch: 2×10^{9} (0.3 nC), 86 MeV, ΔE/E=1-2%, 3 mrad
- Approach 2: No channel, larger spot size
- RAL/IC/UK: Mangles et al.
  - No Channel: 2×10^{19} cm^{-3}
  - Laser: 12 TW, 40 fs, 0.5 J, 2.5×10^{18} W/cm^2, 25 μm
  - E-bunch: 1.4×10^{8} (22 pC), 70 MeV, ΔE/E=3%, 87 mrad
- LOA/France: Faure et al.
  - No Channel: 0.5-2x10^{19} cm^{-3}
  - Laser: 30 TW, 30 fs, 1 J, 18 μm
  - E-bunch: 3×10^{9} (0.5 nC), 170 MeV, ΔE/E=24%,10 mrad
- Channel allows higher e-energy with lower laser power

Experimental demonstration: 1 GeV high-quality beam via laser-plasma accelerator

40 TW,
38 fs,
1.5J,
10 Hz
25 micron spot
10^{18} W/cm^2

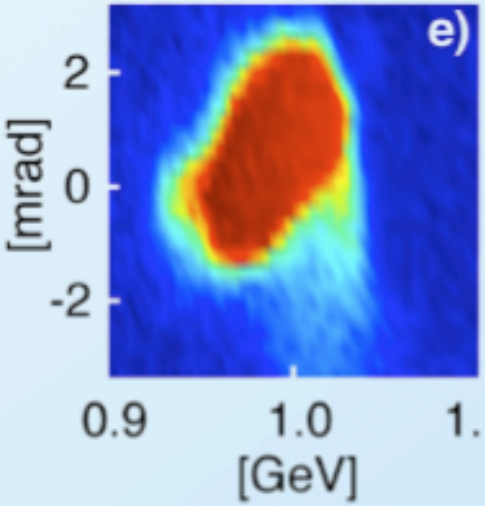
LBNL
Ti:Al_2O_3
laser

H-discharge capillary technology:
plasma channel production (1-4x10^{18} cm^{-3})



3 cm

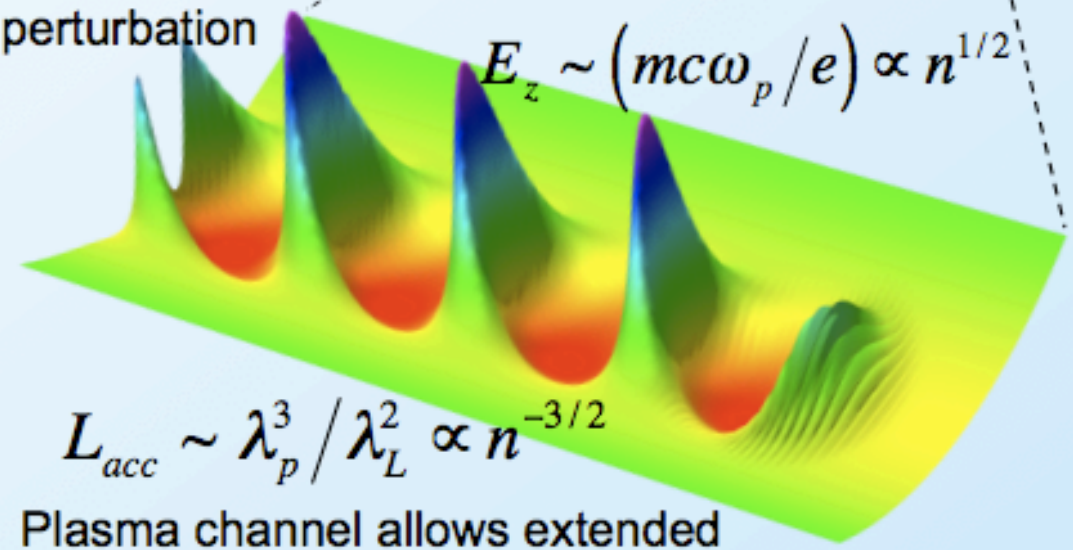
electron
beam



Beam energy =1.0 GeV
Charge= Q~30 pC
1.6 mrad rms divergence
2.5% rms energy spread

Leemans *et al.*, Nature Phys. (2006).
Nakamura *et al.*, Phys. Plasmas (2007).

Electron density perturbation



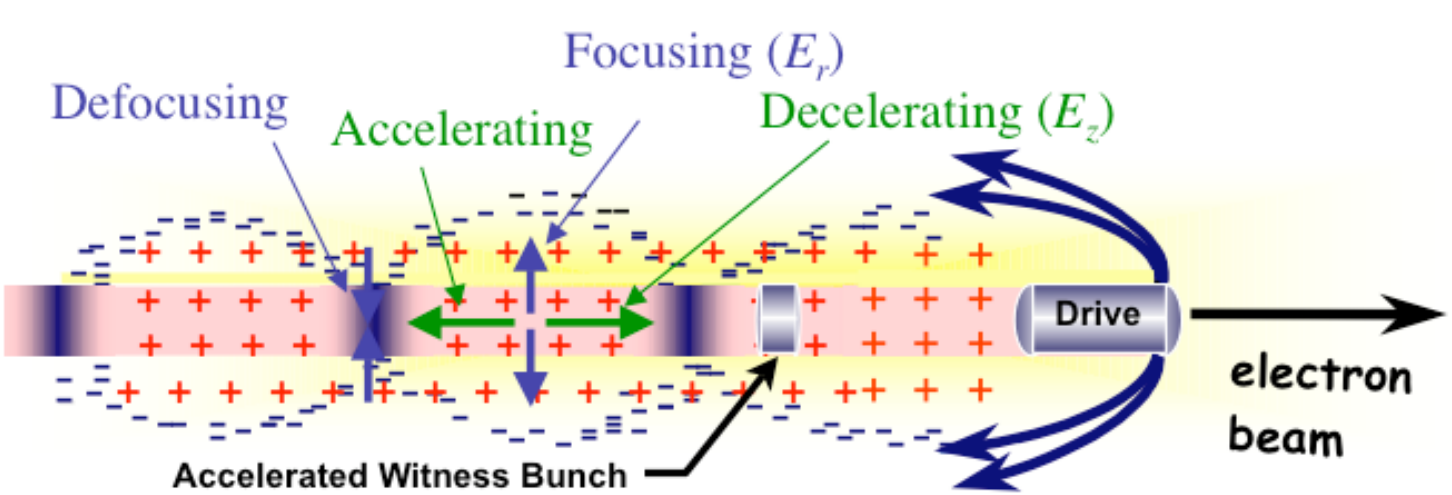
$$E_z \sim \left(mc\omega_p/e\right) \propto n^{1/2}$$

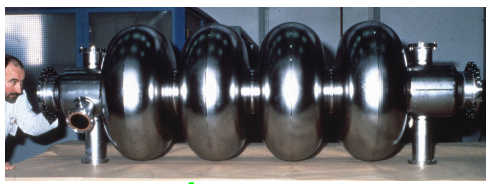
$$L_{acc} \sim \lambda_p^3/\lambda_L^2 \propto n^{-3/2}$$

Plasma channel allows extended laser-plasma interaction length

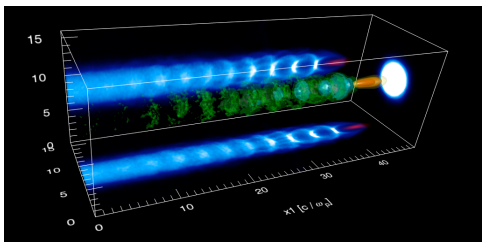
Next Step:
- 10 GeV module
- 40 J in ~ 40-100 fs laser pulse
- BELLA Project: 1 PW, 1 Hz laser

The Beam Driven Plasma Wakefield Accelerator





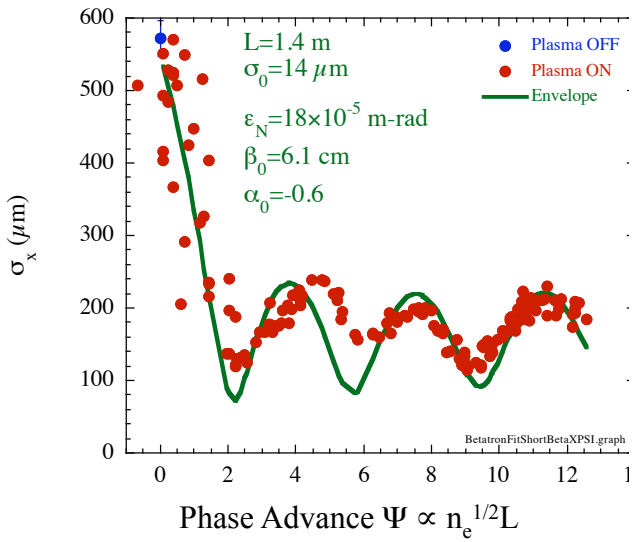
~1m
~100μm



* Two-beam, co-linear, plasma-based accelerator
* Plasma wave/wake excited by relativistic particle bunch
* Deceleration, acceleration, focusing by plasma
* Accelerating field/gradient scales as $n_e^{1/2}$
* Typical: $n_e \approx 10^{17}$ cm^{-3}, $\lambda_p \approx 100$ μm, G>MT/m, E>10 GV/m
* High-gradient, high-efficiency energy transformer

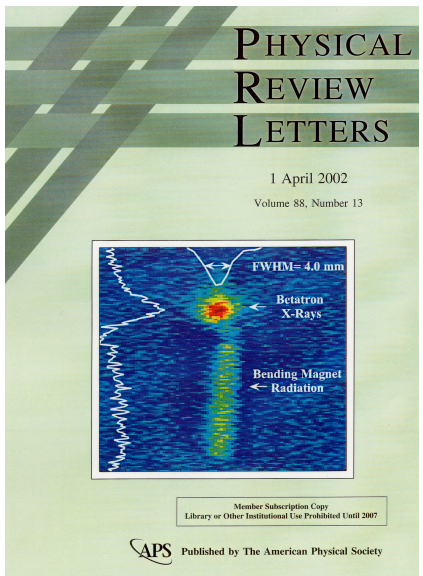
SLAC/UCLA/USC Experiments @ FFTB
Studied all aspects of beam-plasma interaction

Focusing & Matching e⁻



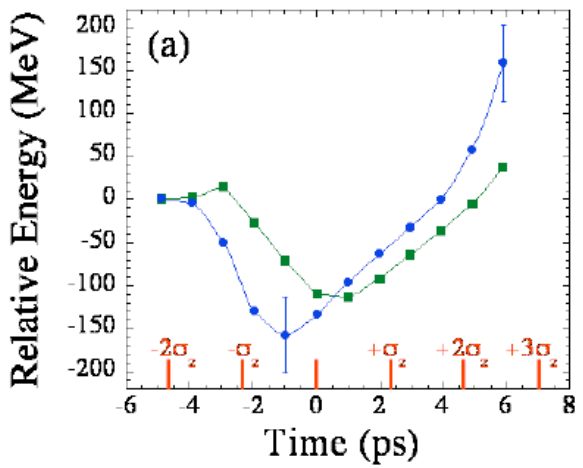
Phys. Rev. Lett. **93**, 014802 (2004)

X-ray Generation



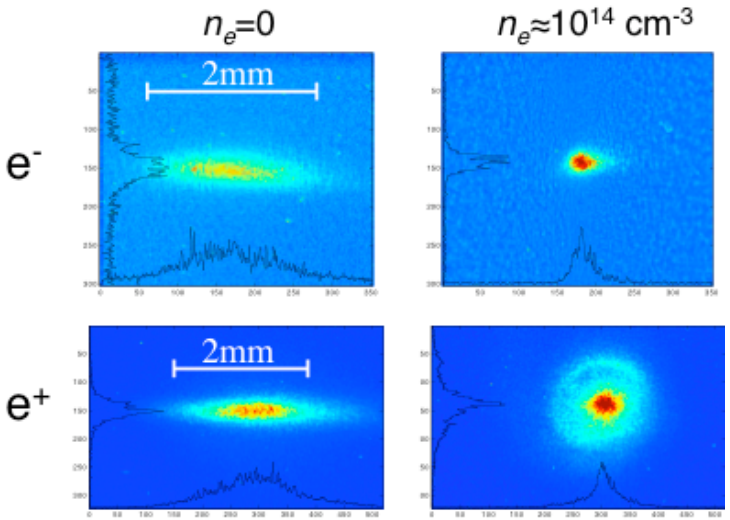
Phys. Rev. Lett. **88**, 135004 (2002)

Wakefield Acceleration e⁻



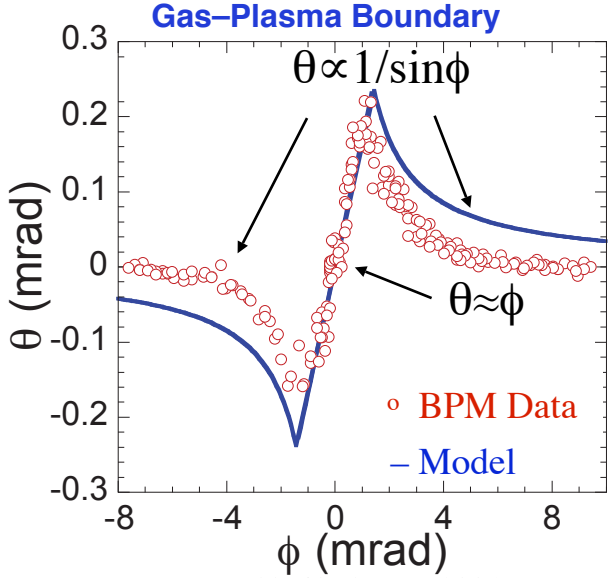
Phys. Rev. Lett. **93**, 014802 (2004)

Focusing & Halo Formation e⁺



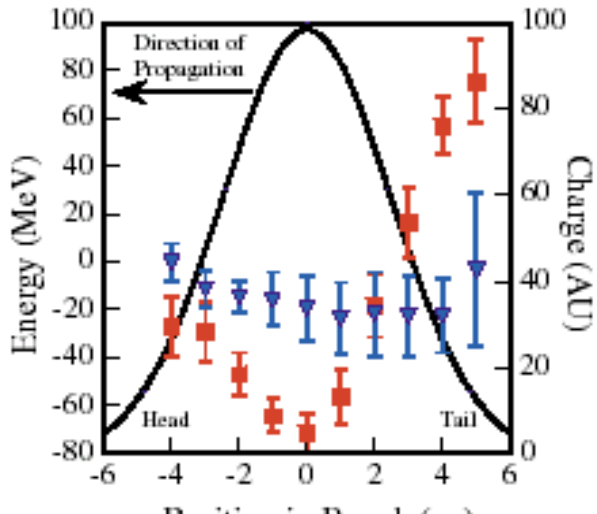
Phys. Rev. Lett. ***101***, *055001 (2008)*

Electron Beam Refraction at the Gas–Plasma Boundary



Nature **411**, 43 (3 May 2001)

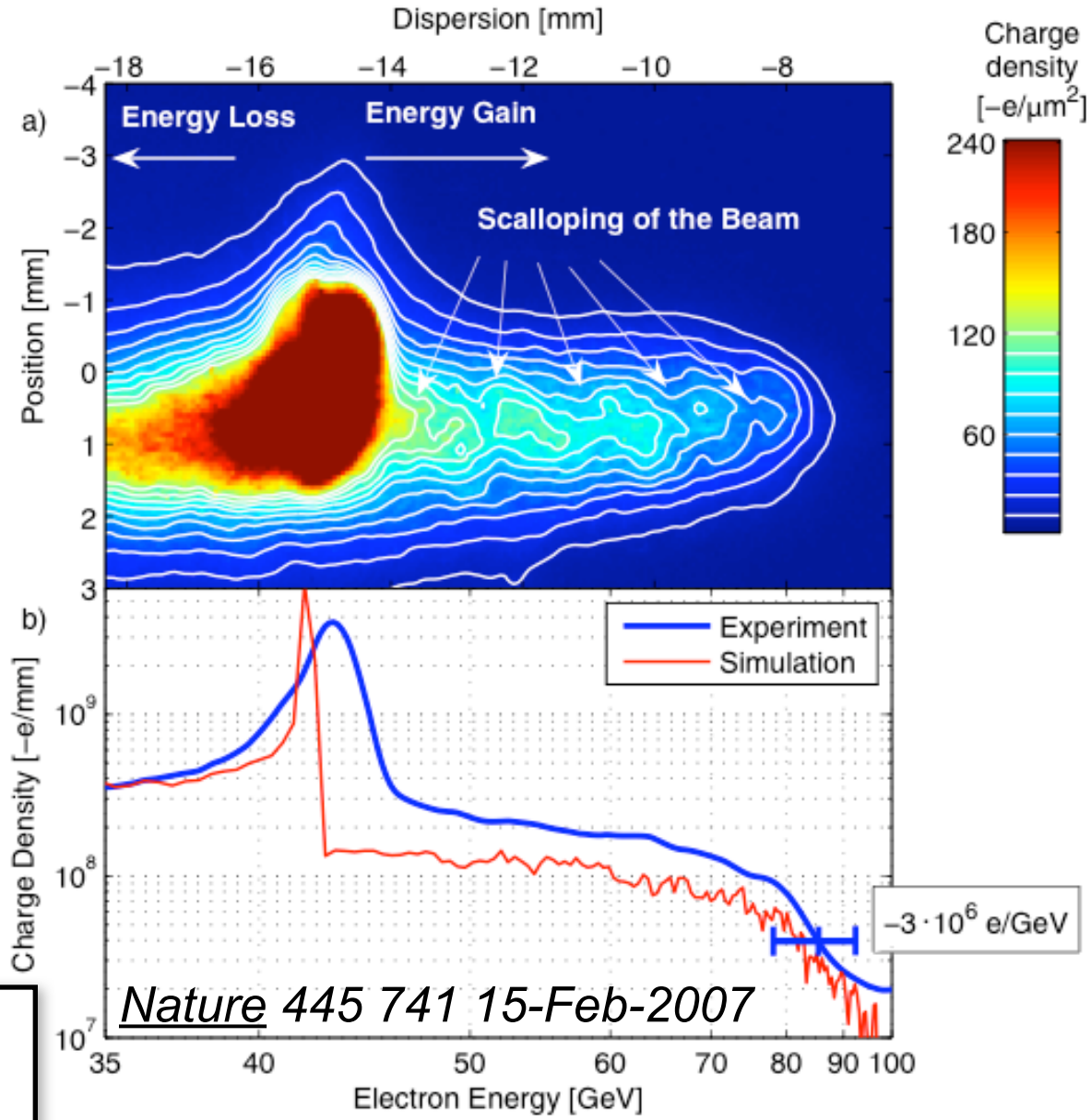
Wakefield Acceleration e⁺



Phys. Rev. Lett. **90**, 214801 (2003)

E-167: Energy Doubling with a Plasma Wakefield Accelerator in the FFTB

* Acceleration gradients of ~50 GV/m (3000 x SLAC)
  - Doubled energy of 45 GeV beam in 1 meter plasma
  - Record Energy Gain
  - Highest energy electrons ever produced at SLAC
  - Significant advance in demonstrating the potential of plasma accelerators



Next Step:
- 25 GeV stage
- Two Bunches, 6x10^{16} e$^-$/cm^3
- FACET Project: 2km of SLAC Linac

Discovery Potential Depends on More than Energy

* Luminosity is critical in a linear collider
  - Physics studies have been based on ~1x10^{34} cm^{-2}sec^{-1}

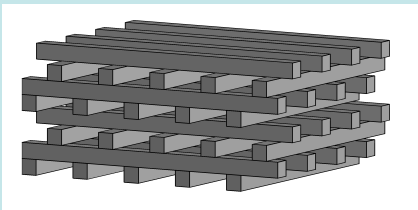
$$L = \frac{f_{rep}}{4\pi}\frac{N^2}{\sigma_x\sigma_y} \quad \Rightarrow \quad L = \frac{P_{beam}}{4\pi E_{beam}}\frac{N}{\sigma_x\sigma_y}H_D \sim \frac{P_{beam}}{E_{beam}}\frac{n_\gamma}{\sigma_y}H_D$$

* Need large beam powers, large bunch charges, and small spot sizes
  - For example, conventional parameters at 1 TeV:
    - 20 MW beam power, 10^{10} e$^+$/e$^-$ per bunch, frep = 10 kHz, and σ_x/σ_y= 140 / 3 nm → 1x10^{34} cm^{-2}sec^{-1} within 1% of cms energy
* All parameters pushed beyond state-of-the-art
  - Develop/adopt new concepts to allow rebalance of parameters
* SLAC Workshop July 2009
  - Concept focused groups tasked with proposing complete parameter sets for TeV collider (straw man level)

First pass at 'self-consistent' numbers for a TeV DLA linear collider

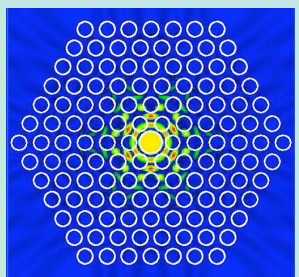
Structure Candidates for High-Gradient Accelerators

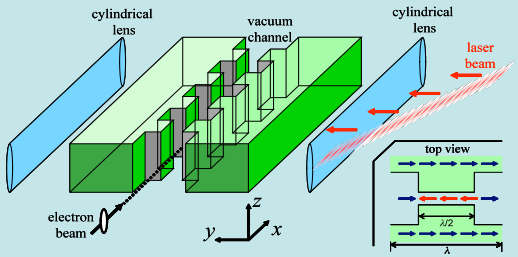
Maximum gradients based on measured material damage threshold data



Photonic Crystal "Woodpile"
Silicon, λ=2200nm,
E_z=400 MV/m

Photonic Crystal Fiber
Silica, λ=1890 nm,
E_z=400 MV/m





Transmission Grating Structure
Silica, λ=800nm,
E_z=830 MV/m

Luminosity from a laser-driven linear collider must come from **high bunch repetition rate** and **smaller spot sizes,** which naturally follow from the small emittances required

		"ILC"	Woodpile	PCF Fiber	Grating
E_cms	GeV	1000	1000	1000	1000
Bunch Charge	e	2.0E+10	1.8E+04	3.8E+04	1.0E+04
# bunches/train	#	2820	136	159	375
train repetition rate	MHz	4.0E-06	25	5	10
final bunch length	psec	1.00	1.00	1.00	1.00
design wavelength	micron	230609.58	2.20	1.89	0.80
Invariant Emittances	micron	10/0.04	1e-04/1e-04	1e-04/1e-04	1e-04/1e-04
I. P. Spot Size	nm	554/3.5	0.5/0.5	0.5/0.5	0.5/0.5
Enh Lumi/ top1%	**/cm^2/s**	**2.32E+34**	**2.45E+34**	**2.88E+34**	**2.29E+34**
Beam Power	MW	36.2	4.9	2.4	3.0
Linac Wall-Plug Power	MW	~200	98	48	60
Gradient	MeV/m	30	400	400	830
Total Linac Length	km	47	2.5	2.5	1.2

Beam pulse format is (for example)

(136 microbunches of 1.8x10⁴ e⁻ in 1 psec) x 25MHz

➔Storage-ring like beam format ➔ *reduced event pileup*

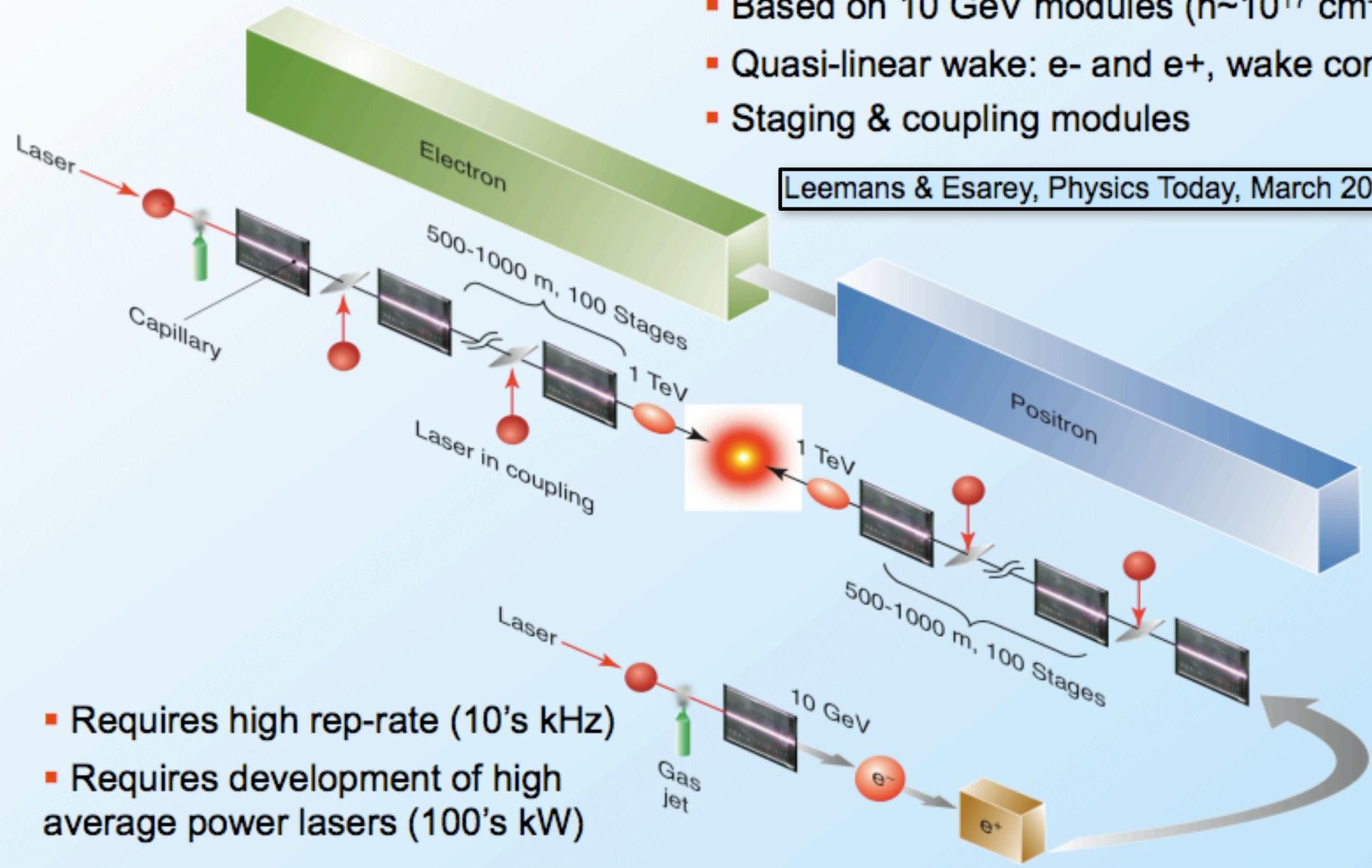
➔High beam rep rate=> *high bandwidth position stabilization is possible*

Parallel R&D needed in laser technology, sources, diagnostics etc...

Conceptual LWFA Linear Collider

- Based on 10 GeV modules ($n \sim 10^{17}$ cm^{-3})
- Quasi-linear wake: e- and e+, wake control
- Staging & coupling modules

Leemans & Esarey, Physics Today, March 2009



- Requires high rep-rate (10's kHz)
- Requires development of high average power lasers (100's kW)

Conceptual LWFA TeV Collider Parameters

Plasma density scalings:

Stage density scalings:

$$E_0 \propto n^{1/2}$$
$$L_{\text{stage}} \propto n^{-3/2}$$
$$W_{\text{stage}} \propto n^{-1}$$
$$U_L \propto n^{-3/2}$$
$$N_b \propto n^{-1/2}$$

Collider density scalings (for fixed luminosity):

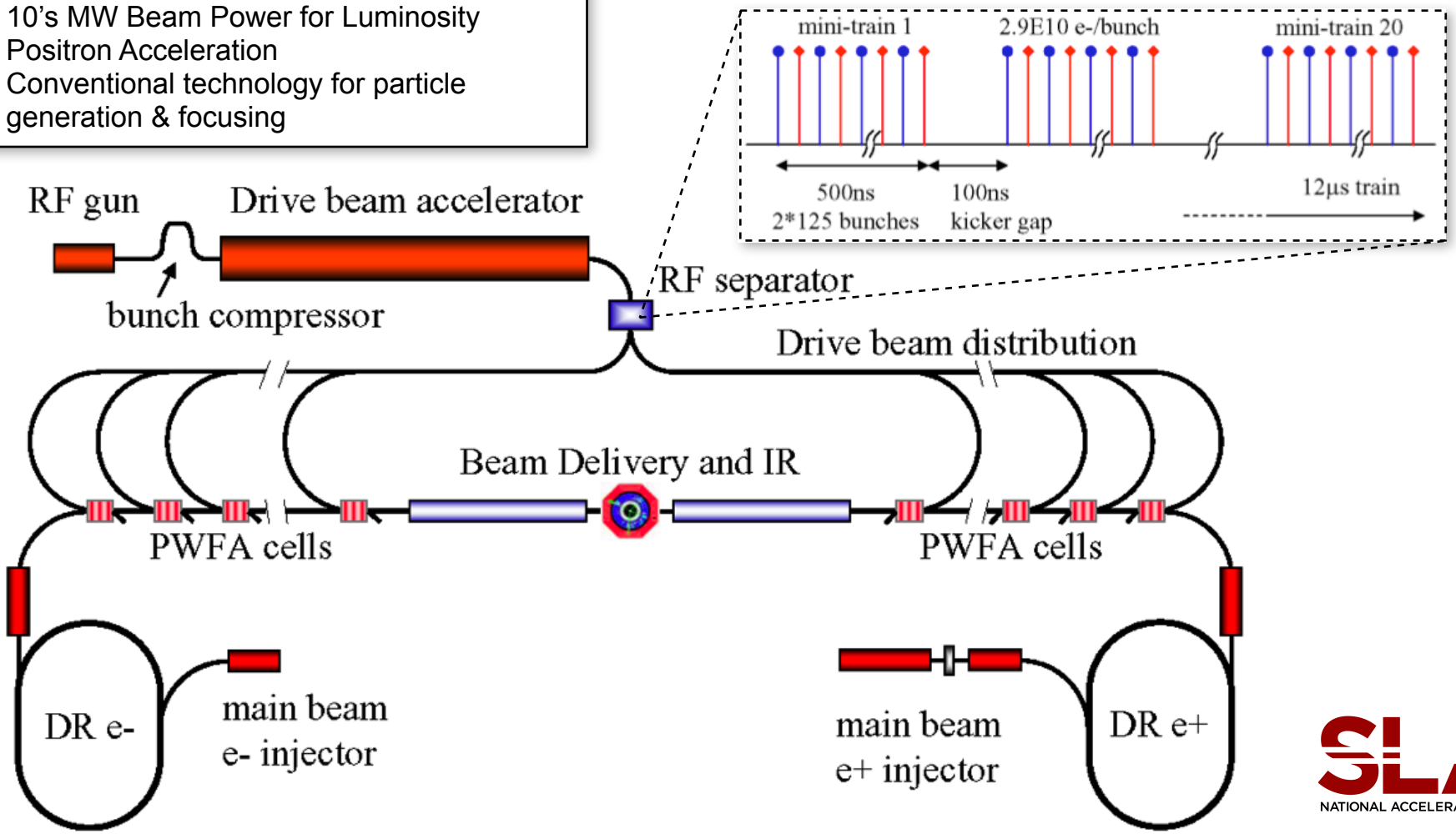
$$f \propto n$$
$$N_{\text{stage}} \propto n$$
$$P_b \propto n^{1/2}$$
$$P_{\text{laser}} \propto n^{-1/2}$$

Schroeder et al., AAC08

Plasma number density, n_0	10^{17} cm^{-3}
Energy, center of mass, E_{cm}	1 TeV
Beam energy, γmc^2	0.5 TeV
Number per bunch, N	4×10^9
Collision rate, f	15 kHz
Beam Power, $P_b = fN\gamma mc^2$	4.8 MW
Luminosity, $\mathscr{L}$	2×10^{34} s^{-1} cm^{-2}
Bunch length, σ_z	1 μm
Horizontal rms beam size at IP, σ_x	0.1 μm
Vertical rms beam size at IP, σ_y	1 nm
Horizontal normalized emittance, ε_{nx}	1 mm-mrad
Vertical normalized emittance, ε_{ny}	0.01 mm-mrad
Beamstrahlung parameter, Υ	35
Plasma wavelength, λ_p	105 μm
Energy gain per stage, W_{stage}	10 GeV
Single stage laser-plasma interaction length	0.9 m
Drive laser coupling distance between stages	0.5 m
Laser energy per stage	40 J
Laser wavelength	1 μm
Initial normalized laser intensity, a_0	1.5
Average laser power per stage	600 kW
Number of stages	50
Main linac length	70 m
Efficiency (wall-plug to beam)	5%
Total wall-plug power	190 MW

PWFA-LC 'Warm' Option

- TeV CM Energy
- 10's MW Beam Power for Luminosity
- Positron Acceleration
- Conventional technology for particle generation & focusing



Lots of room or optimization:

- Drive linac energy (length, # and size of turnarounds, compression, CSR, synchrotron losses, cost)
- Number of stages
- Beam time structure for highest efficiency, energy spread, plasma uniformity

PWFA-LC main parameters

Luminosity	3.5×10^{34} cm^{-2}s^{-1}
Luminosity in 1% of energy	1.3×10^{34} cm^{-2}s^{-1}
Main beam: bunch population, bunches per train, rate	1×10^{10}, 125, 100 Hz
Total power of two main beams	20 MW
Main beam emittances, $\gamma\varepsilon_x$, $\gamma\varepsilon_y$	2, 0.05 mm-mrad
Main beam sizes at Interaction Point, x, y, z	140 nm, 3.2 nm, 10 μm
Plasma accelerating gradient, plasma cell length, and density	25 GV/m, 1 m, 1×10^{17}cm^{-3}
Power transfer efficiency drive beam=>plasma =>main beam	35%
Drive beam: energy, peak current and active pulse length	25 GeV, 2.3 A, 10 μs
Average power of the drive beam	58 MW
Efficiency: Wall plug=>RF=>drive beam	50% × 90% = 45%
Overall efficiency and wall plug power for acceleration	15.7%, 127 MW
Site power estimate (with 40MW for other subsystems)	170 MW

PWFA-LC 'Cold' Option

* Same DB Energy = 25 GeV
* Same DB Charge = 3e10
* Same Linac Bunch Charge and Total Bunches per second
* DB bunch spacing = 150 ns (split bunches between linacs)
* DB current = 32 mA
* DB gradient = 31.5 MV/m (ILC) so ~ 1km DB Linac
* Pulse structure: 4 ms pulses at 30 Hz (12% duty)
* Linac bunch spacing = 9 us
* Turn-Around spacing = 150 ns (Each Linac 1 km)
* DB Accelerator Cost < 500 M$
* Fits on SLAC Site?

DB = Drive Beam

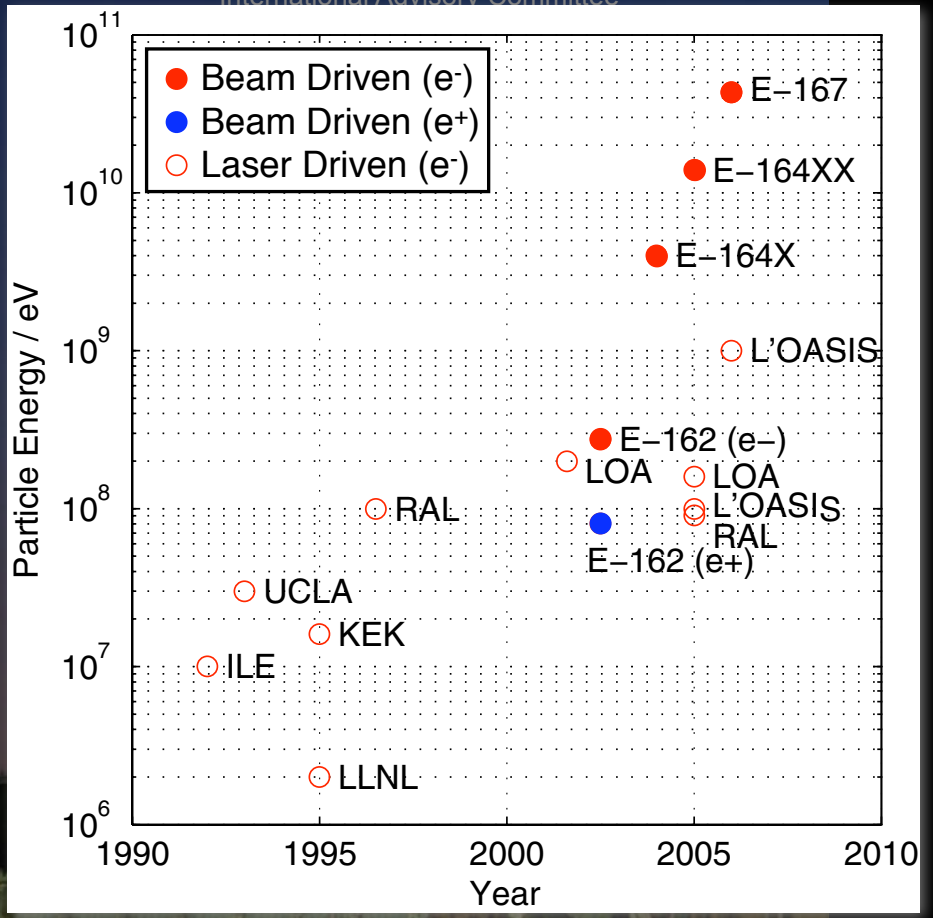
Conclusions:

http://lp09.desy.de

Exciting time for advanced accelerators!

International Advisory Committee

- **Plasma accelerators rapidly moving from infancy to energies of interest to High Energy Physics**
- **Still much work to do before any of these technologies are providing beams for doing physics**
- **Continued progress requires investment in 2nd generation facilities:**
- **DLA: Small, short, bunched beams**
- **LWFA: PW Laser Systems, meter scale plasmas, staging & controlled injection**
- **PWFA & DWA: Two bunches, High Energy, High peak current, well focused e- & e+**



- **Need to consider ALL subsystems, not just gradient/linac (sources, FF, beam delivery) if want to do physics AND have large impact on collider cost**
- **Good science, strong collaborations between university-laboratory groups and forefront facilities are the key ingredients to a successful advanced accelerator research program**
- **Second-generation research will bring these three elements together to significantly advance the field of Advanced Accelerators towards a practical technology for HEP.**