ICFA Mini-Workshop on Novel Concepts for Linear Accelerators and Colliders

Laser-Driven Dielectric Structures and Linacs

(Working group 2)

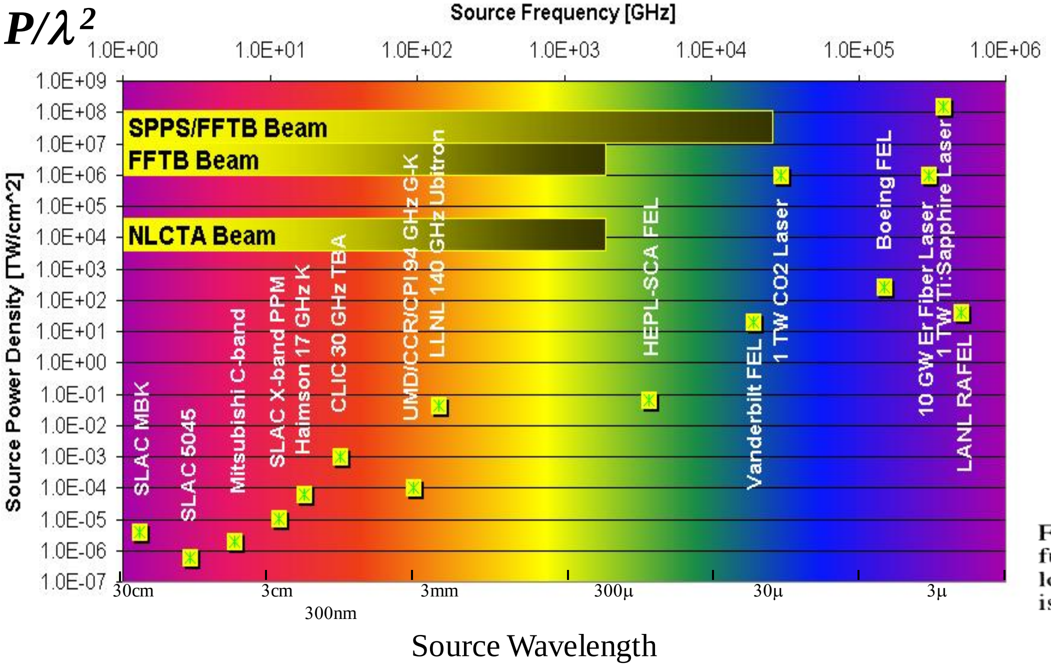
E. R. Colby

SLAC National Accelerator Laboratory
July 8th, 2009

Outline

1) Overview of technology
2) Critical issues and requirements on other subsystems
3) First cut at a parameter list for a 1 TeV x 2e34 collider

The Possibility of High Gradient



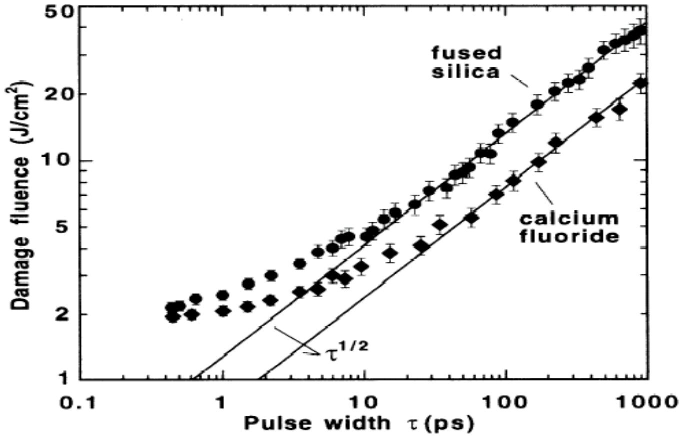
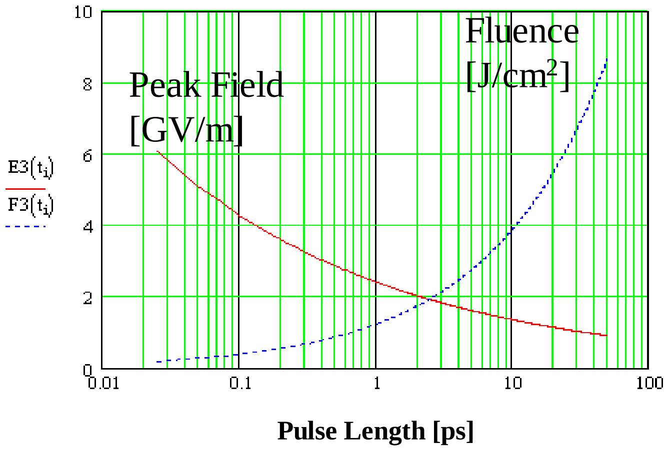


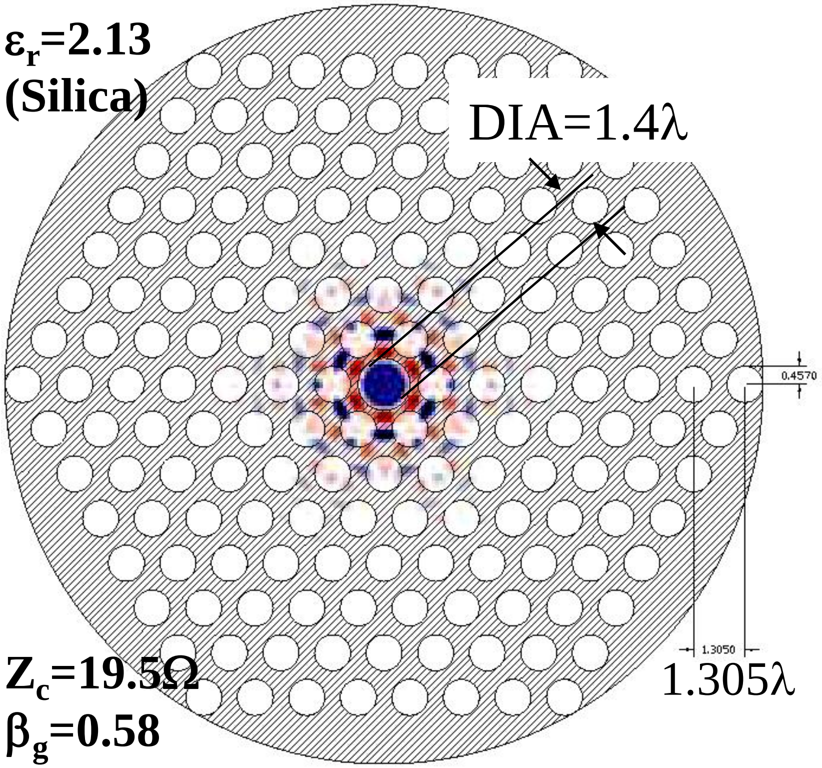
FIG. 1. Observed values of damage threshold at 1053 nm for fused silica (●) and CaF$_2$ (◆). Solid lines are $\tau^{1/2}$ fits to long pulse results. Estimated uncertainty in the absolute fluence is ±15%.

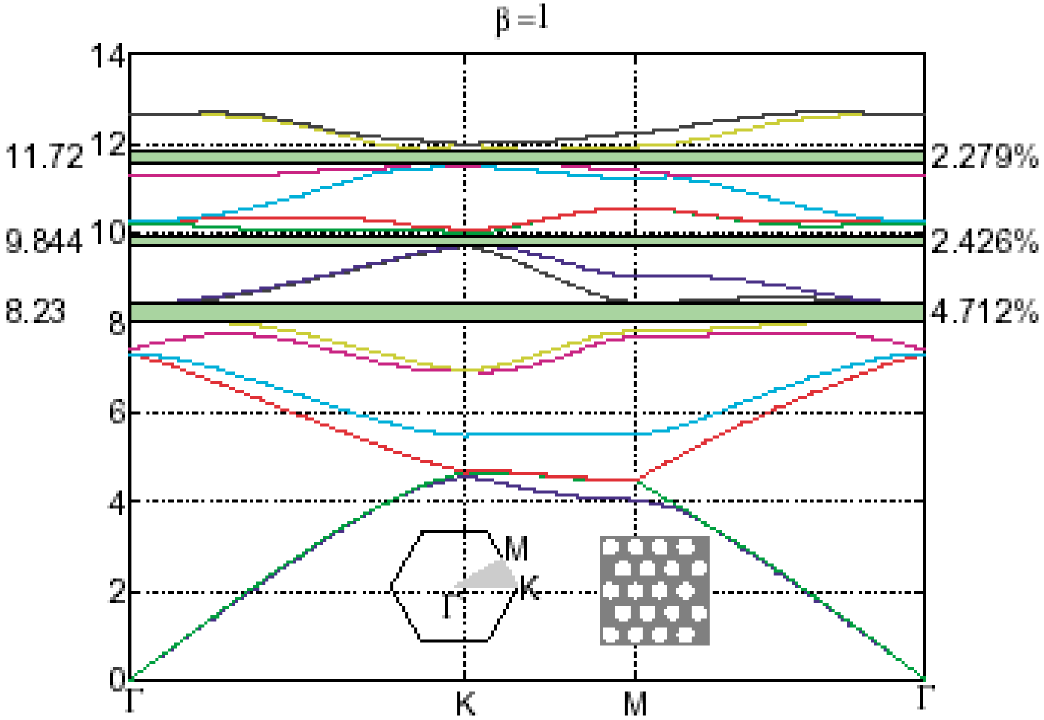
B. C. Stuart, *et al*, "Laser-Induced Damage in Dielectrics with Nanosecond to Subpicosecond Pulses," *Phys. Rev. Lett.*, **74**, p.2248ff (1995).



Question #1: How can lasers be used to *efficiently* accelerate particle beams?

“Lin” PBG Fiber





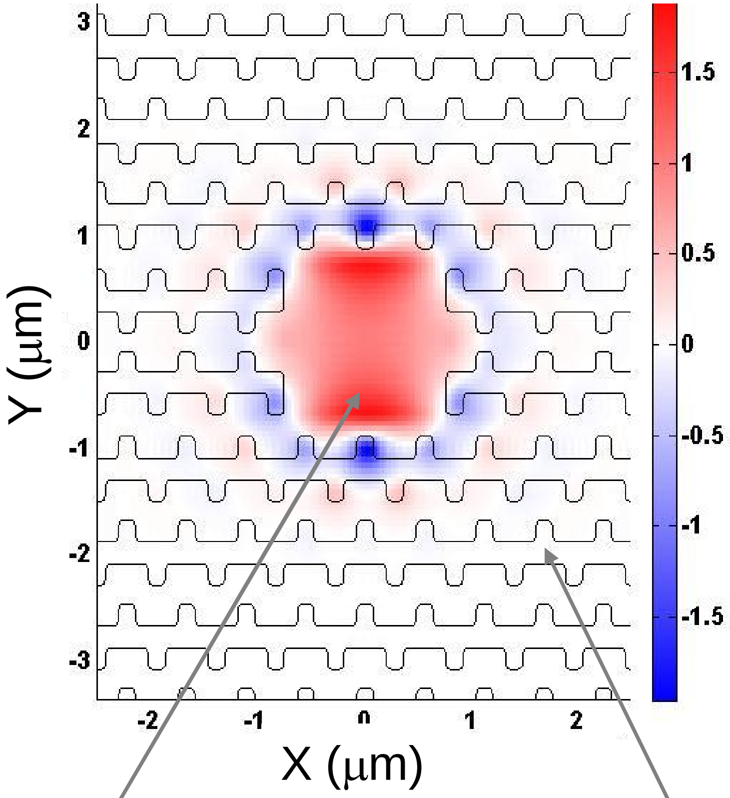
X. (Eddie) Lin, “Photonic Band Gap Fiber Accelerator”, *Phys. Rev. ST-AB*, **4**, 051301, (2001).

- Can be designed to support a single, confined, synchronous mode
- All other modes at all other frequencies radiate strongly

$$Z_c = \frac{\left|E_{\mathrm{acc}}\right|^2 \lambda^2}{2P}$$

Planar Photonic Accelerator Structures

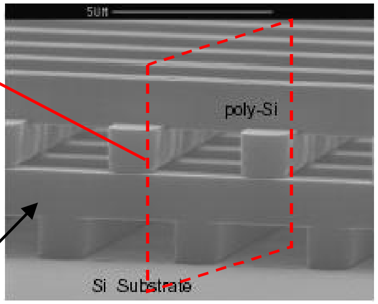
Synchronous (β=1) Accelerating Field



Vacuum defect
beam path is into the page

silicon

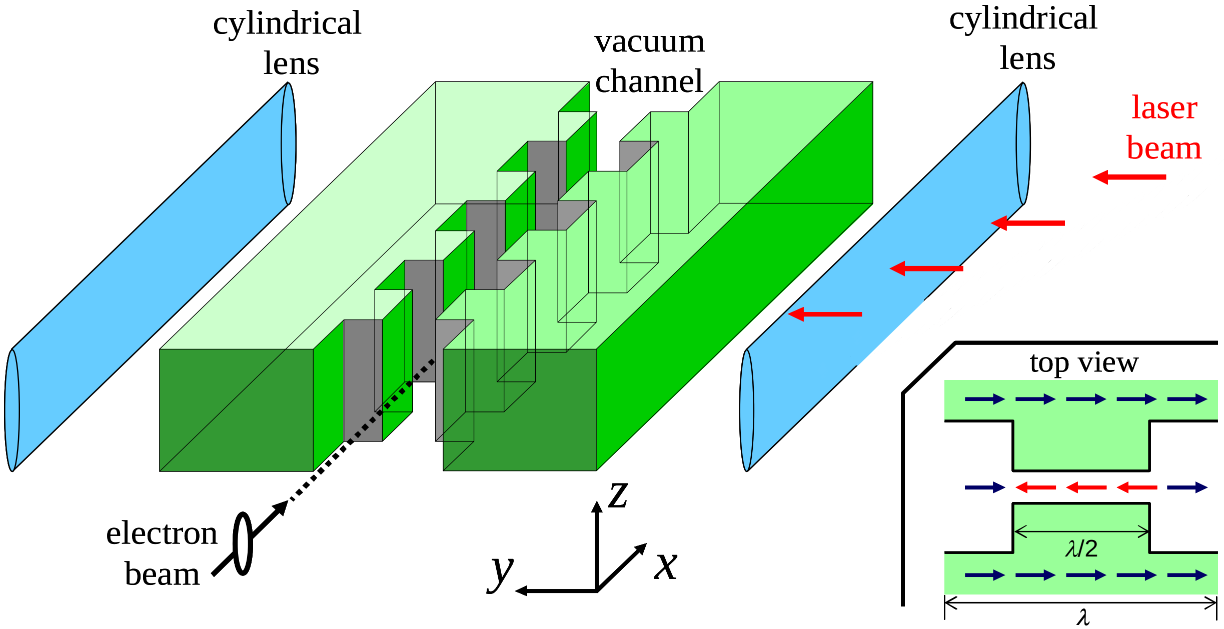
- Accelerating mode in planar photonic bandgap structure has been located and optimized
- Developed method of optical focusing for particle guiding over ~1m; examined longer-range beam dynamics
- Simulated several coupling techniques
- Numerical Tolerance Studies: Non-resonant nature of structure relaxes tolerances of critical dimensions (CDs) to ~λ/100 or larger



S. Y. Lin *et. al.*, Nature **394**, 251 (1998)

This “woodpile” structure is made by stacking gratings etched in silicon wafers, then etching away the substrate.

The Transmission Grating Accelerator



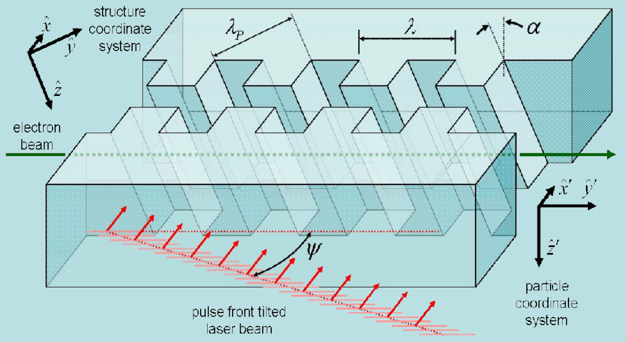
$\left\langle \vec{E}_{\parallel} \right\rangle \sim \frac{1}{2} E_{laser}$

$\left\langle \vec{F}_{\perp} \right\rangle = 0$

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

Silica, λ=800nm, E_z=830 MV/m

Simple Variant: Fast Deflector

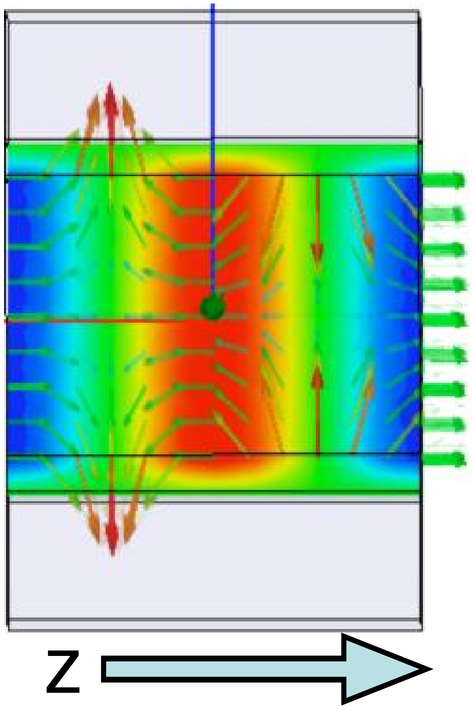


T. Plettner, *submitted to Phys. Rev. ST Accel. Beams*

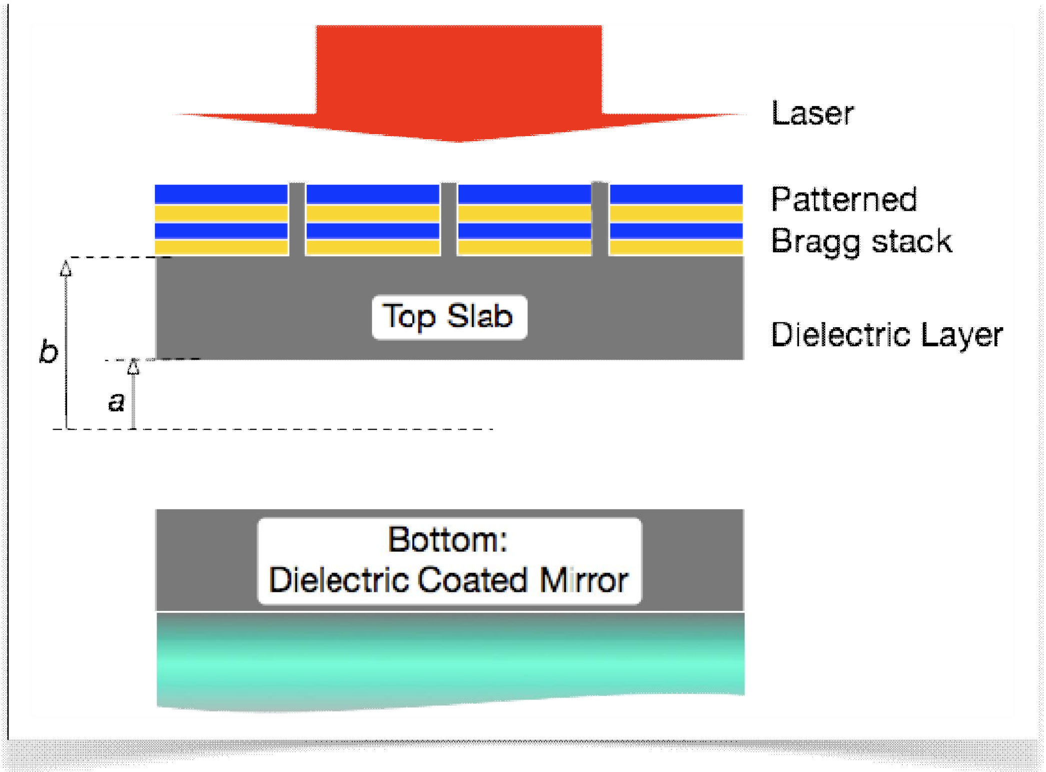
UCLA is designing, fabricating and testing a slab-symmetric, laser-driven, dielectric micro accelerator

Periodic modulation in z is necessary to have an accelerating mode: a standing wave with $k_z = \omega/\beta c$.

resonant structure with good E_z fields



one period



Device schematic;
structure variation in *x* not shown
Typical values (λ=1μm)
a ~ 0.1 μm
b ~ 0.3 μm
number of periods ~ 1000
overall length ~ 1 mm

Gil Travish, UCLA

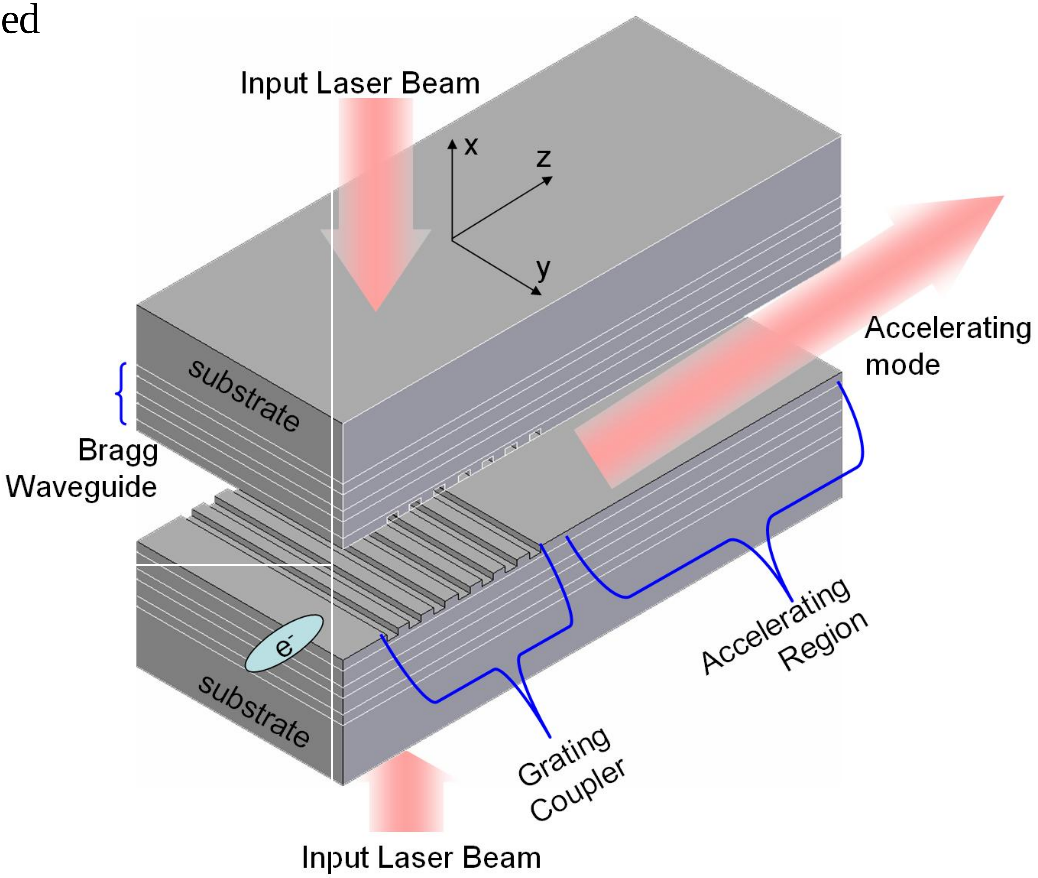
Optical Accelerator Structures under Study

Bragg Planar Dielectric Structure

- Accelerating mode guided by two-sided Bragg multi-layer waveguide

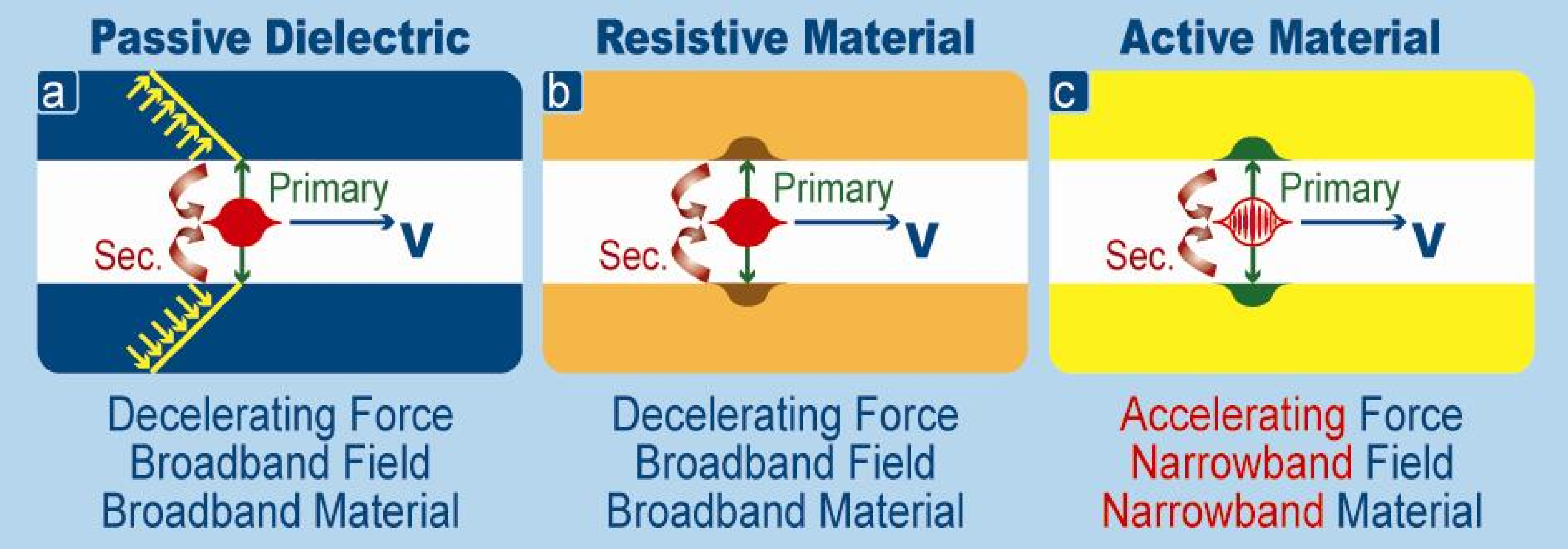
- Grating couples laser from side and converts it to accel mode

- Have TiO_2-SiO_2 multi-layer wafers fabricated by ZC&R Coatings Inc; etching of gratings and spacer fab are next steps



S. Tantawi & J. Guo, SLAC

Essence of the PASER



L. Schächter, Phys. Rev. E 53, p. 6427, 1996

Outline

1) Overview of technology
2) Critical issues and requirements on other subsystems
3) First cut at a parameter list for a 1 TeV x 2e34 collider

Critical Issue #1a: Efficiency!
#1b: Gradient!

Efficiency optimization: Single-Pass and Recirculating

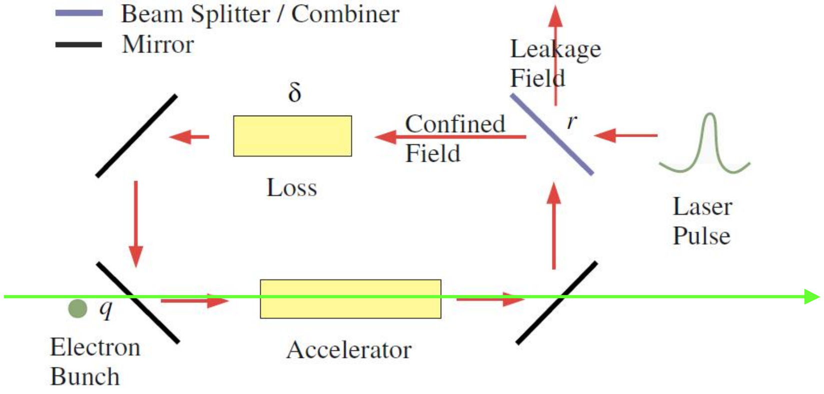
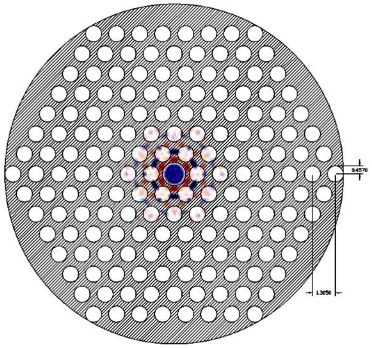


FIG. 1. (Color) The intracavity coupled, laser-driven linear accelerator pumped by the external laser.

1098-4402/05/8(3)/031301(9) 031301-1 © 2005 The American Physical Society

A Lin-type Photonic crystal fiber is taken for the example here.



Y. C. NEIL NA, R. H. SIEMANN, AND R. L. BYER Phys. Rev. ST Accel. Beams **8**, 031301 (2005)

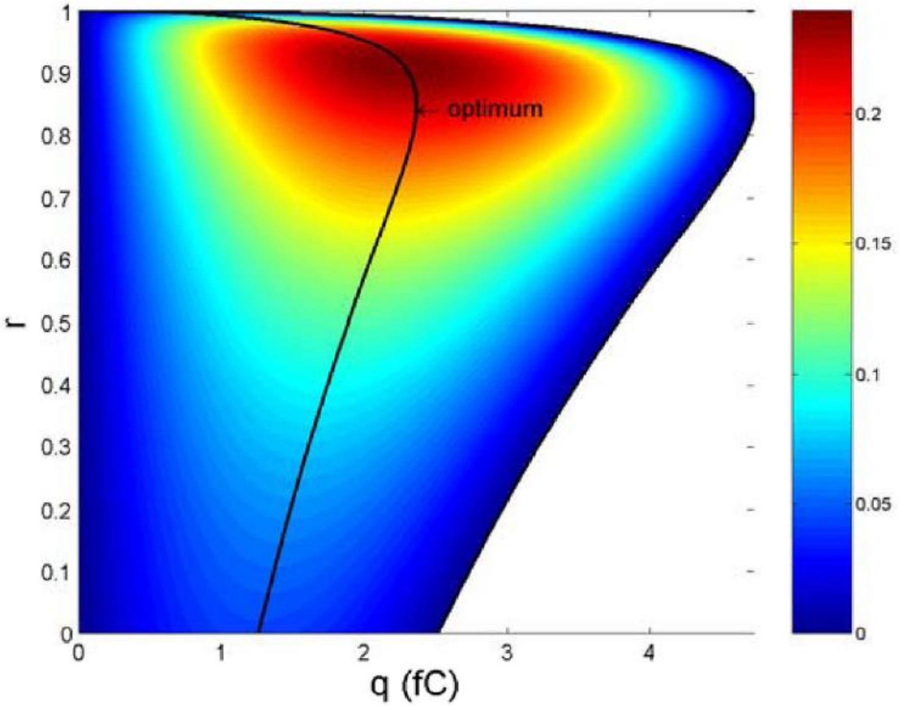
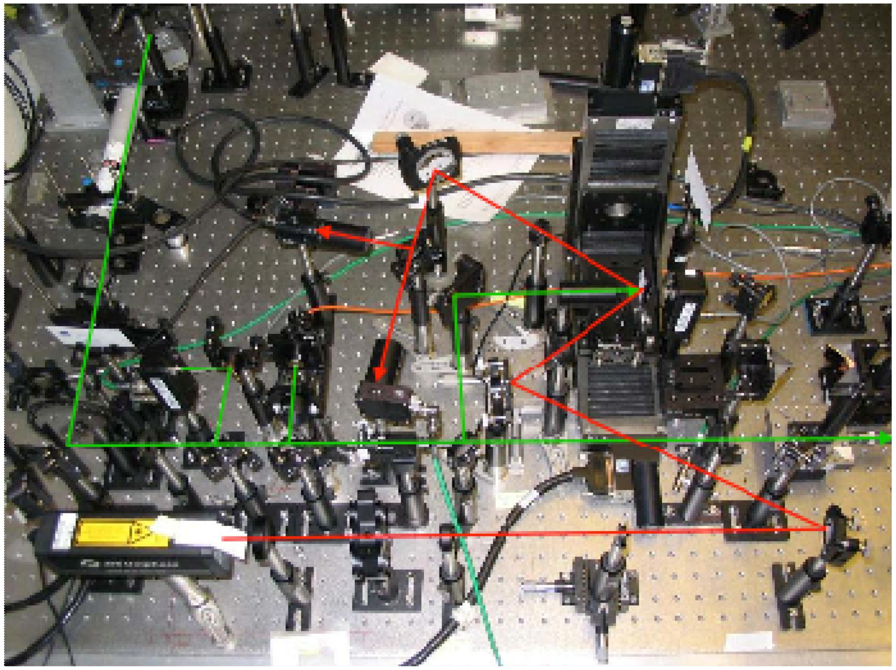
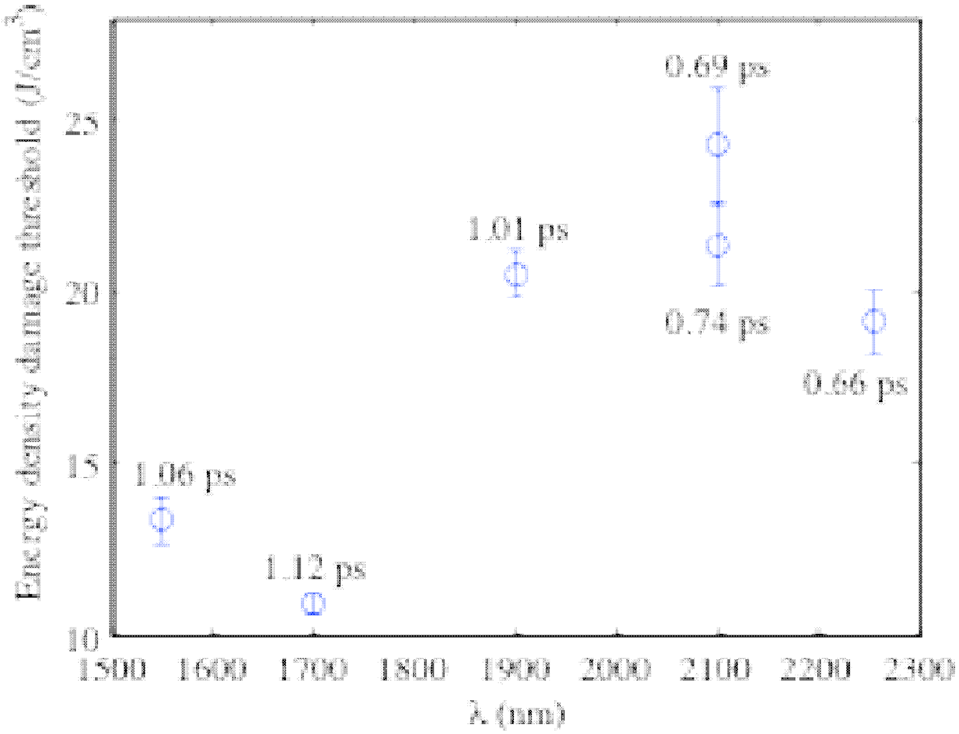


FIG. 3. (Color) Energy efficiency as a function of reflectivity and charge for $\delta = 0.05$. The blank part is where $\eta < 0$, and the hard black line gives the maximum efficiency for a given reflectivity. The optimum case is chosen as indicated in the figure.

Gradient: Damage Threshold Measurements

- Pump-Probe Apparatus developed for measuring the damage threshold of materials in the 1-3 micron range.
- Silicon promising, but gradients > 1 GeV/m in NIR unlikely



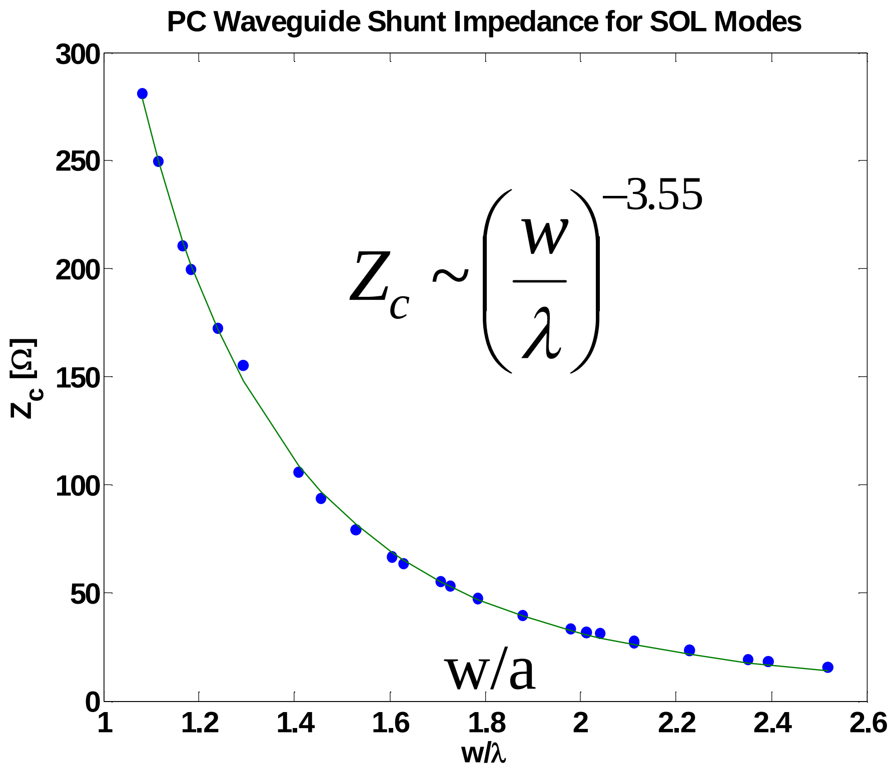


Proc. SPIE **6720**, 67201M-1

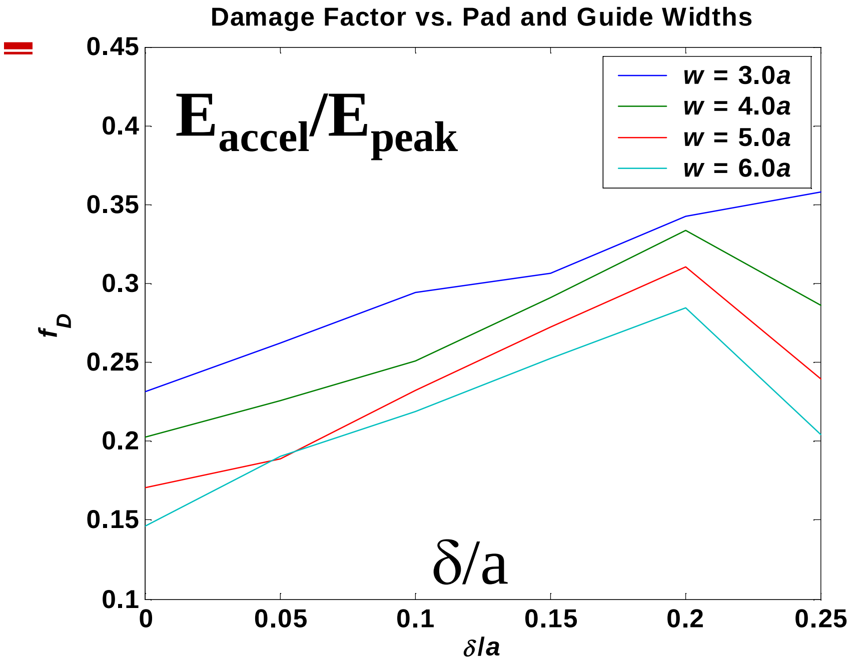
B. Cowan, Tech-X

Critical Issue #2: Aperture!

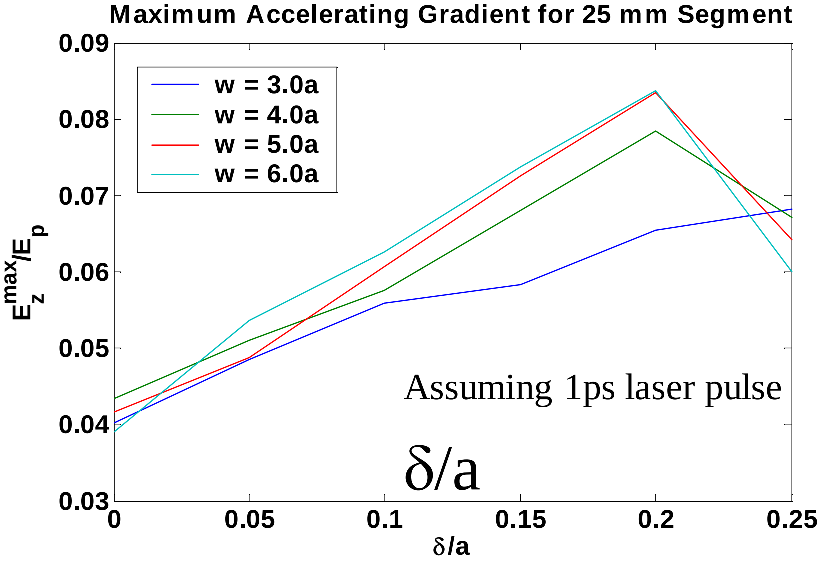
Impedance and Gradient Optimization



$$Z_c \sim \left(\frac{w}{\lambda}\right)^{-3.55}$$



E_{accel}/E_{peak}



Assuming 1ps laser pulse

Ben Cowan, Tech-X

Question #2: What is the best wavelength?

Question #2: What is the best wavelength?

- Question #2 (in more useful form): What is the best wavelength given:

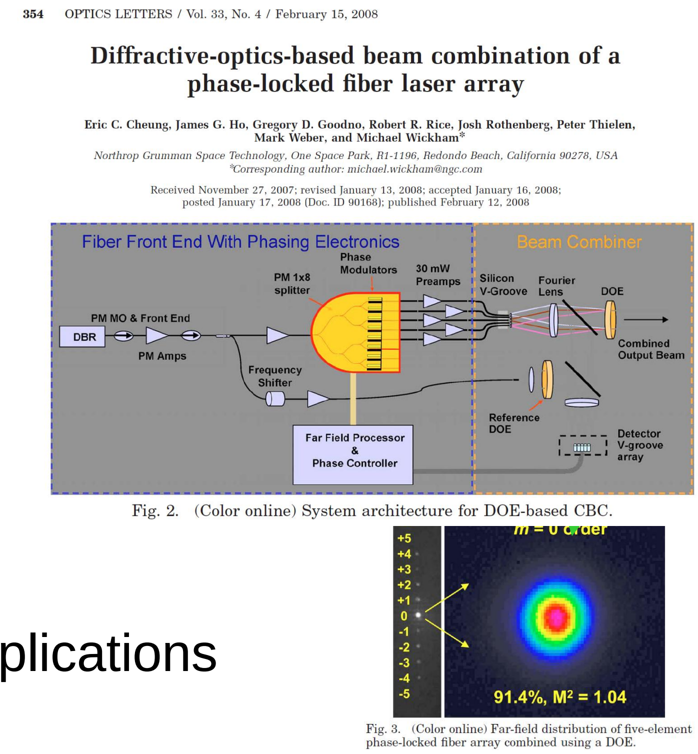
The geometric limitations of present and future fabrication techniques,

Expectations for highly efficient power production in (e.g.) within 10-years,

The breakdown behavior of suitable materials?

Progress in Laser Technology

- Efficient pump diodes for CW operation
  - DARPA SHEDs program (→80% wall-plug-to-light, CW)
  - JDS Uniphase has demonstrated >76% efficiency CW from room-temperature diode bars
- Efficient materials
  - Yb:KGdWO$_4$ disk lasers (marketed and R&D)
  - High-dopant concentration ceramic lasers (R&D)
  - Yb-fiber (1.1 μ)
  - Th-fiber (1.75-2.1 μ)
  - Ho-fiber (2.1, 2.8 μ)
  - DOE SBIR program
- Carrier Phase Locking (NIST)
  - Self-referencing demonstrated in 1999
  - 5 fiber lasers optically phase-locked
- PCF use in commercial high-average power applications



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Diffractive-optics-based beam combination of a phase-locked fiber laser array

Eric C. Cheung, James G. Ho, Gregory D. Goodno, Robert R. Rice, Josh Rothenberg, Peter Thielen, Mark Weber, and Michael Wickham*

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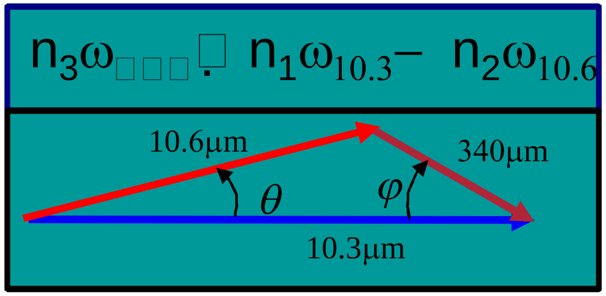
Fig. 2. (Color online) System architecture for DOE-based CBC.

Fig. 3. (Color online) Far-field distribution of five-element phase-locked fiber array combined using a DOE.

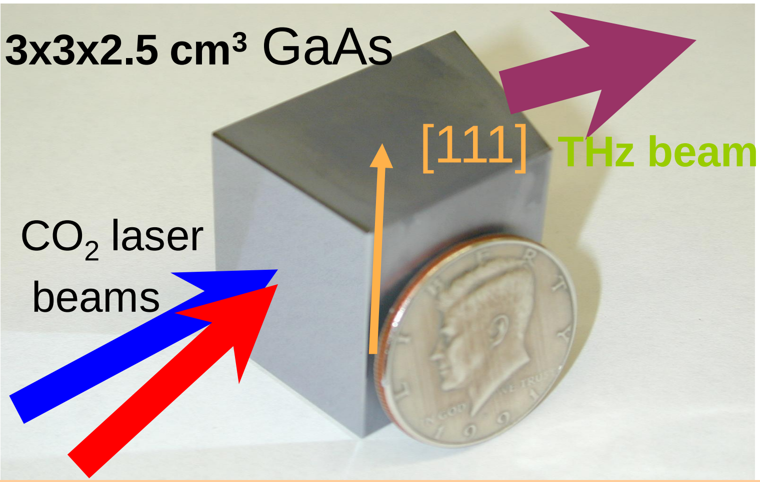
Narrow-Band, High-Power THz DFG Source

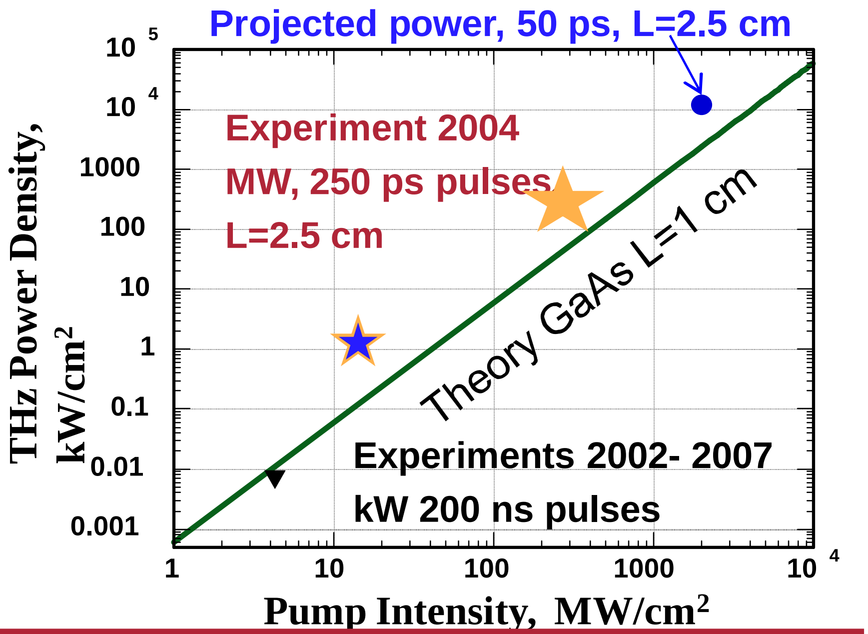
Noncollinear Frequency Generation in a nonlinear GaAs Crystal using 2 CO_2 laser lines

Phase Matching



$n_3\omega_{\square\square\square}\square\ n_1\omega_{10.3} - n_2\omega_{10.6}$





2 MW at 340 μm 0.5 mJ in a 250 ps pulse

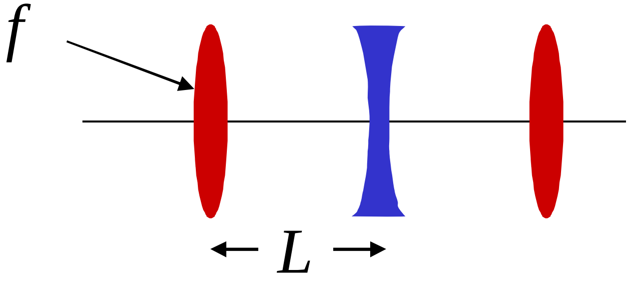
2 kW tunable 0.5-2 THz pulse(0.4 mJ - 200 ns).

1. MW power THz pulses using Difference Frequency Generation (DFG) of CO_2 laser lines in GaAs in a single-shot experiment. **JAP, 98, 026101, 2005**
2. kW power THz pulses using DFG of CO_2 laser pulses in GaAs at a 1 Hz pulse repetition frequency. **JOSA B, 24, 2509-2516, 2007**

Sergei Tochitsky, UCLA

Question #3: How can beam be transported through such a small aperture?

Emittance and Beam Transport



If a is the beam hole radius, the acceptance is

$$A = \frac{a^2}{\beta_{\max}} = n\frac{\varepsilon_I}{\gamma}$$

$n \equiv$ clearance = 25 for 5σ beam

$\varphi \equiv$ phase advance/half-cell

$$\beta_{\max} = 2f\frac{1+\sin\varphi}{\cos\varphi}$$

For a quad of length l and gradient G

$$f = \frac{\gamma mc}{eGl}$$

$$\varepsilon_I = \frac{a^2}{n}\frac{eGl}{2mc}\frac{\cos\varphi}{1+\sin\varphi}$$

Example

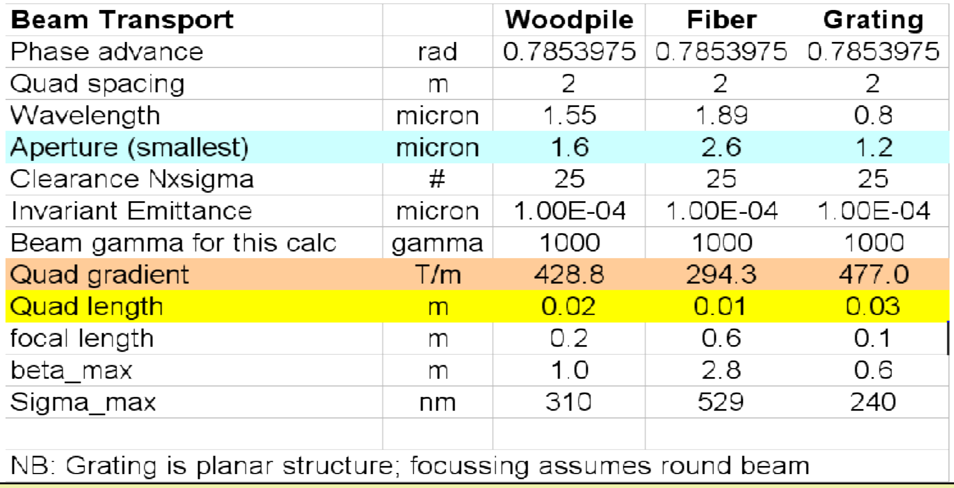
$$G = 2.5kT/m; l = 1.0cm; \gamma = 2\times10^4 \Rightarrow f = 1.36m$$

$$\varphi = 45^o \Rightarrow L = 1.93m$$

$$a = 1.2\lambda = 2.4\mu m; n = 25 \Rightarrow \boxed{\varepsilon_I = 7\times10^{-4}\pi \text{ mm-mr}}$$

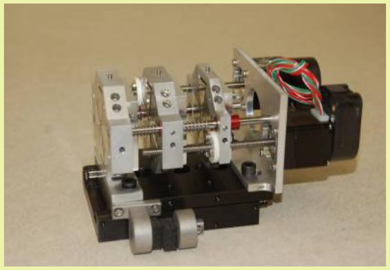
Beam Transport

- FODO lattice solution
  - Modest quad strengths (400-650 T/m, NB: aperture is <1 mm!)
- Permanent magnet focusing elements are adequate
  - 500 T/m quad triplet already designed and in fabrication
- Laser-driven focusing elements also considered
  - Tremendous strength possible: 800,000 T/m !
  - Dynamic aperture studies completed for woodpile lattice

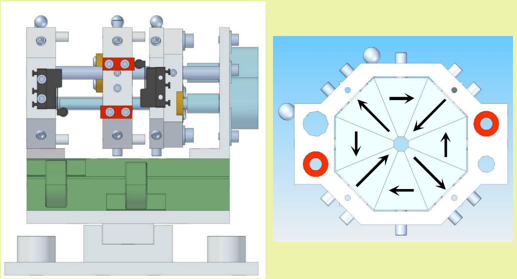


Beam Transport		Woodpile	Fiber	Grating
Phase advance	rad	0.7853975	0.7853975	0.7853975
Quad spacing	m	2	2	2
Wavelength	micron	1.55	1.89	0.8
Aperture (smallest)	micron	1.6	2.6	1.2
Clearance Nxsigma	#	25	25	25
Invariant Emittance	micron	1.00E-04	1.00E-04	1.00E-04
Beam gamma for this calc	gamma	1000	1000	1000
Quad gradient	T/m	428.8	294.3	477.0
Quad length	m	0.02	0.01	0.03
focal length	m	0.2	0.6	0.1
beta_max	m	1.0	2.8	0.6
Sigma_max	nm	310	529	240

NB: Grating is planar structure; focussing assumes round beam



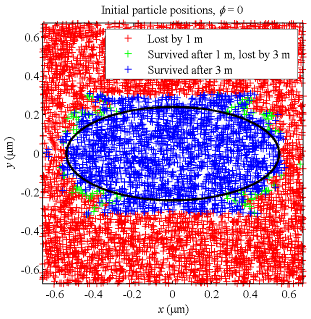
First-Generation PMQ Triplet
NdFeB/Iron Pole tips G=250 T/m



Second-Generation PMQ Triplet
NdFeB Halbach Design G=500 T/m

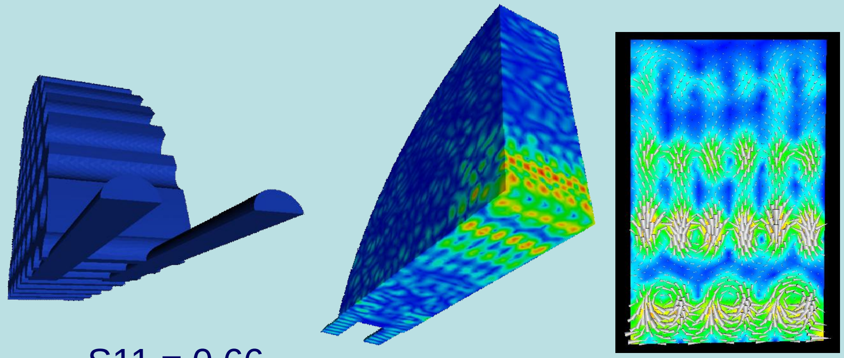
Long-transport channel studies of beam propagation stability in laser-driven focusing lattices

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

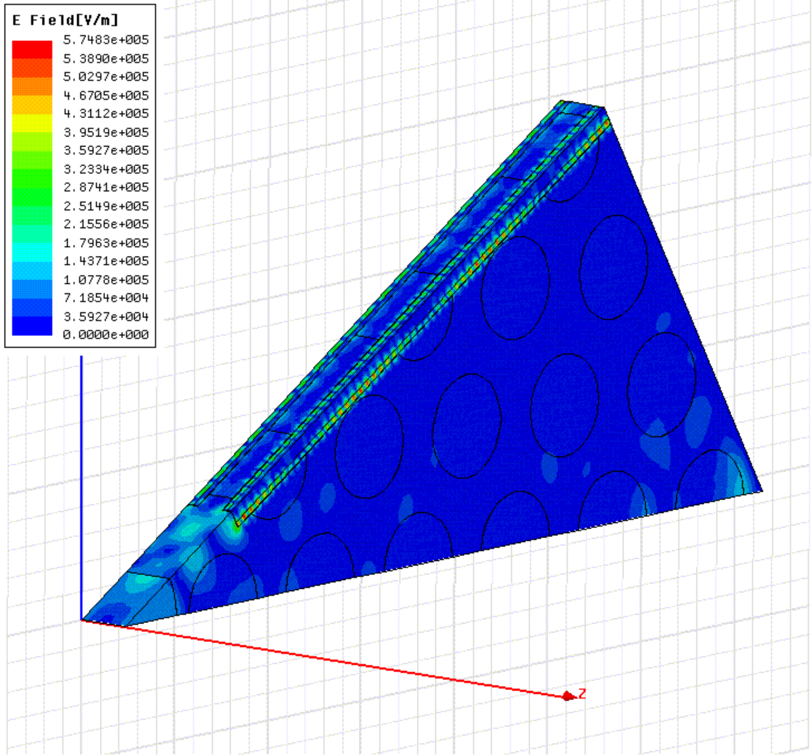


Question #4: How can efficient coupling between the power source and structure be achieved?

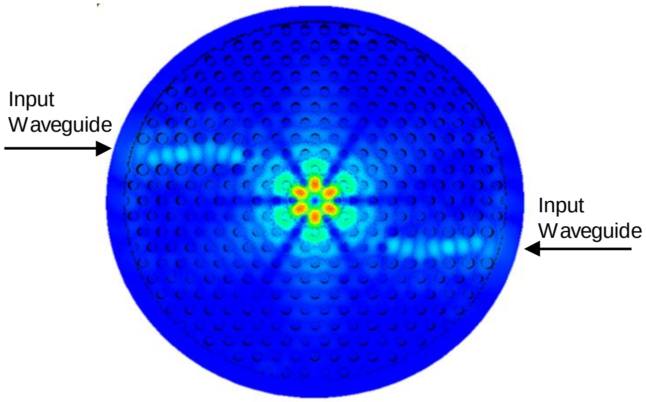
Example: Compact Fiber Couplers



Single-mode fiber coupler for TM mode (metal WG)



Single-mode fiber coupler for TM mode (dielectric WG)



“Shoulder coupler” for TE mode

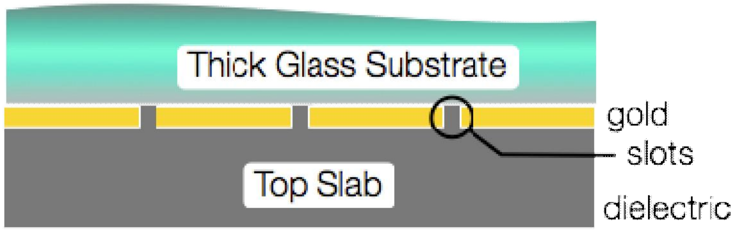
C. Ng, SLAC

J. England, SLAC

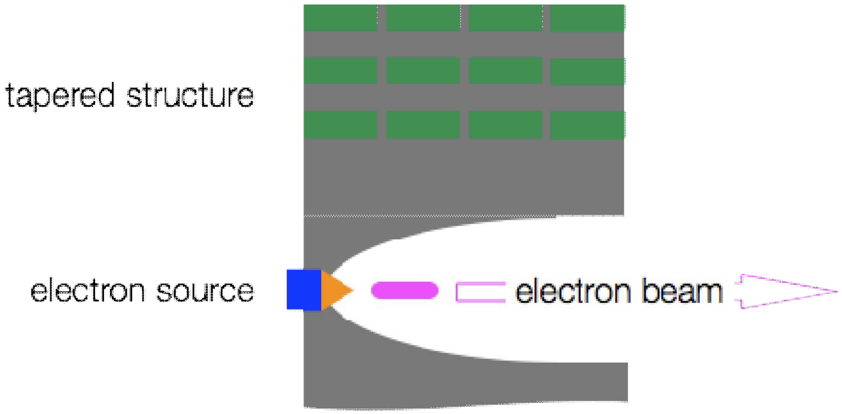
Question #5: Can electron and positron sources can be made to provide suitable beams?

We are taking a three-pronged approach and deferring some issues typically of concern in HEP accelerators

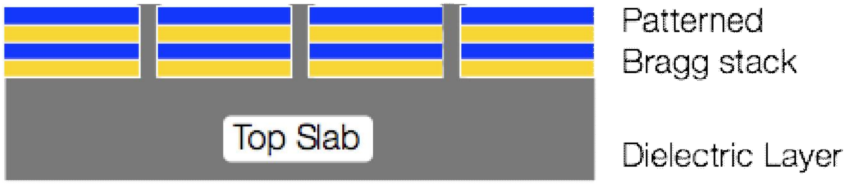
❶ Metallic Cold Test



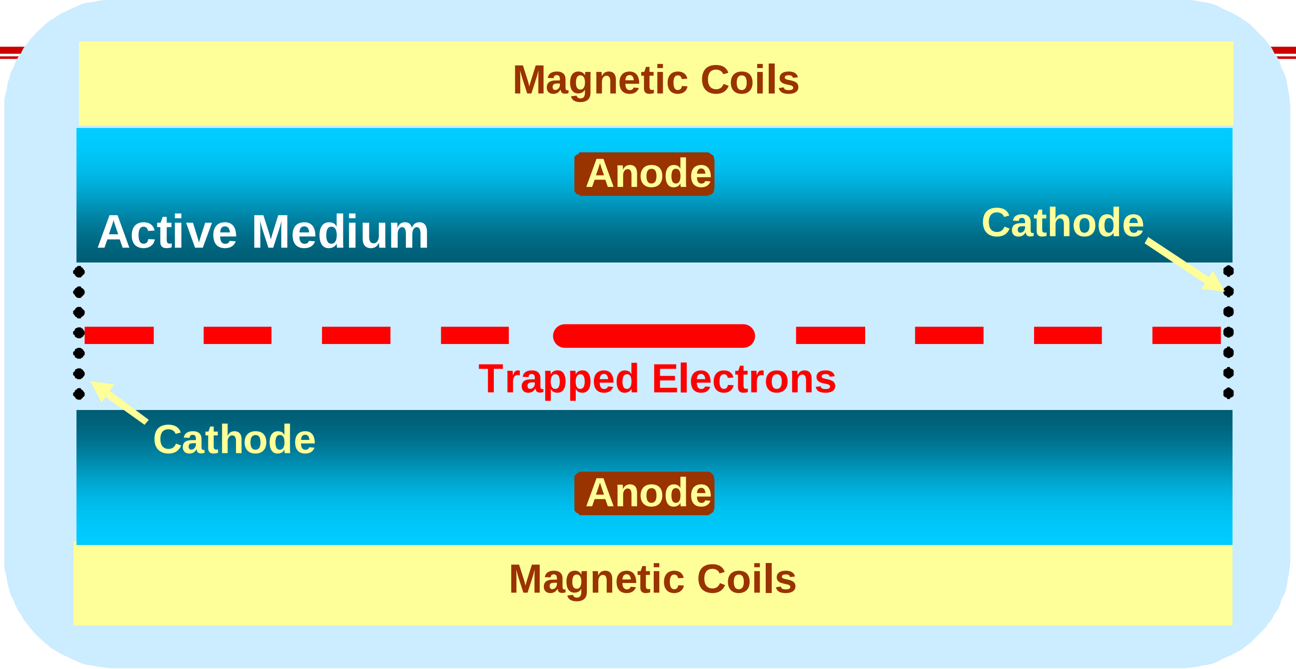
❷ Integrated “gun”



❸ All-dielectric structure



Penning-Trap Optical injector: basic concept



- *Trapped electrons*
- *Active medium*
- *Electrons become bunched ,they extract energy from the medium therefore, the decay-rate of energy stored in the medium in enhanced.*
- *Electrons that become bunched, escape the trap – optical injector*

Schächter; PRL, 102, 034801 (2009).

Question #6: What does the final focus optics look like?

First-Pass Luminosity Calculation

$$P_b = (nN)\, f_r \gamma m c^2$$

$$N_\gamma = 2.12 \frac{\alpha r_e (nN)}{\sigma_x + \sigma_y}$$

$$L \propto \frac{N_\gamma P_b}{\gamma \sigma_y \left(1 + \sigma_y / \sigma_x\right)}$$

$$\xi_1 = \frac{2 r_e^2 N \gamma}{\alpha \sigma_z \left(\sigma_x + \sigma_y\right)}$$

E_{CM} = 500 GeV	**Laser**	**JLC/NLC**
N	5×10^6	9.5×10^9
f_c	50MHz	11.4kHz
P_b (MW)	10	4.5
σ_x/σ_y (nm)	0.5/0.5	330/5
N_γ	0.22	1.1
σ_z (µm)	120	300
σ_z/c (psec)	0.4	1
ξ_1	0.045	0.11
L	**1×10^{34}**	**5.1×10^{33}**

- Optical bunching within the short macropulses must be destroyed, otherwise beamstrahlung is unacceptably high. Can do this after acceleration with small R_{56}.

R. Siemann, ARDB

Outline

1) Overview of technology
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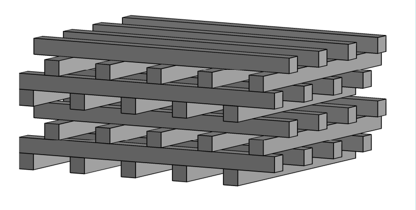
Sample Parameters for a 1 TeV x 2e34 Collider

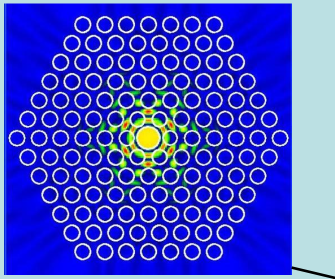
Structure Candidates for High-Gradient Accelerators

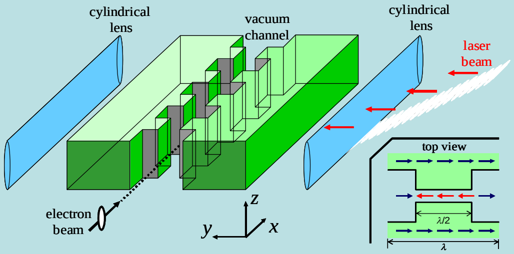
Maximum gradients based on measured material damage threshold data



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

Beam pulse format is (for example)

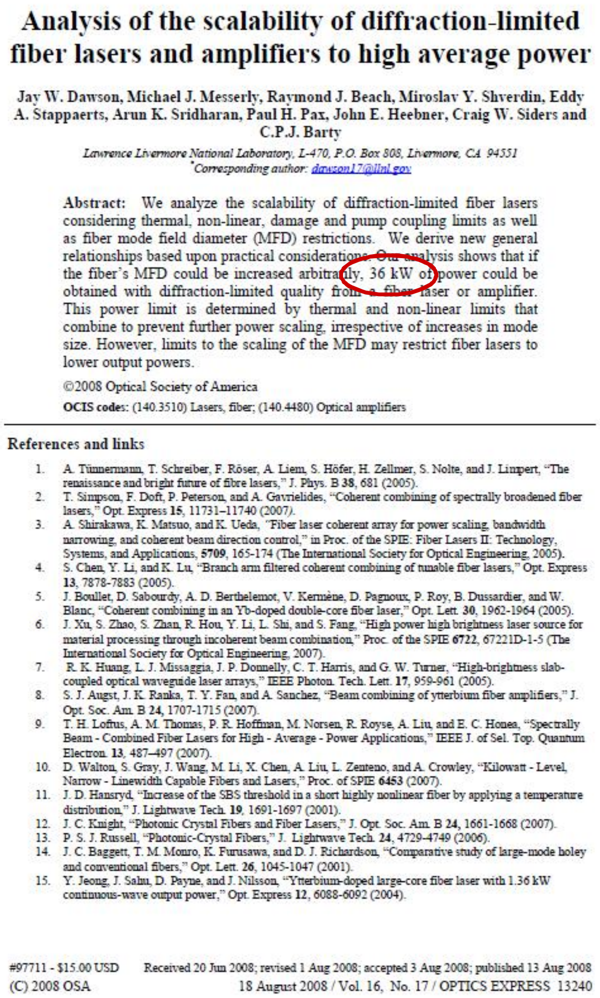
(136 microbunches of $1.8x10^4$ e^- in 1 psec) x 25MHz

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

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

		"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

Average Power Handling Capacity of Fibers



Analysis of the scalability of diffraction-limited fiber lasers and amplifiers to high average power

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Abstract: We analyze the scalability of diffraction-limited fiber lasers considering thermal, non-linear, damage and pump coupling limits as well as fiber mode field diameter (MFD) restrictions. We derive new general relationships based upon practical considerations. Our analysis shows that if the fiber's MFD could be increased arbitrarily, 36 kW of power could be obtained with diffraction-limited quality from a fiber laser or amplifier. This power limit is determined by thermal and non-linear limits that combine to prevent further power scaling, irrespective of increases in mode size. However, limits to the scaling of the MFD may restrict fiber lasers to lower output powers.

OCIS codes: (140.3510) Lasers, fiber; (140.4480) Optical amplifiers

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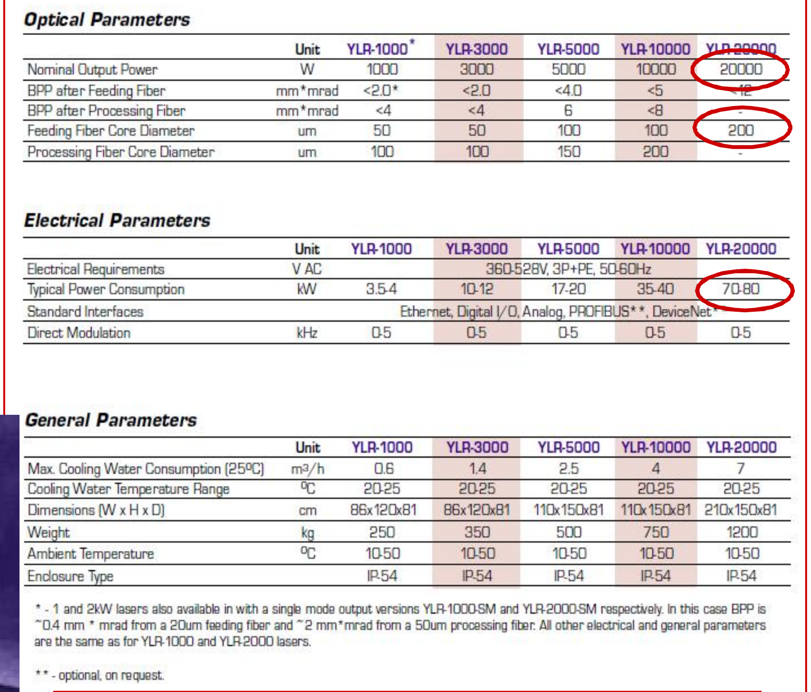
Typical Specifications



Optical Parameters

	Unit	YLR-1000*	YLR-3000	YLR-5000	YLR-10000	YLR-20000
Nominal Output Power	W	1000	3000	5000	10000	20000
BPP after Feeding Fiber	mm*mrad	<2.0*	<2.0	<4.0	<5	<12
BPP after Processing Fiber	mm*mrad	<4	<4	6	<8	-
Feeding Fiber Core Diameter	um	50	50	100	100	200
Processing Fiber Core Diameter	um	100	100	150	200	-

Electrical Parameters

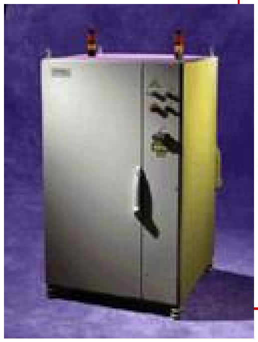
	Unit	YLR-1000	YLR-3000	YLR-5000	YLR-10000	YLR-20000
Electrical Requirements	V AC		360-528V, 3P+PE, 50-60Hz			
Typical Power Consumption	kW	3.5-4	10-12	17-20	35-40	70-80
Standard Interfaces		Ethernet, Digital I/O, Analog, PROFIBUS**, DeviceNet**				
Direct Modulation	kHz	0-5	0-5	0-5	0-5	0-5

General Parameters

	Unit	YLR-1000	YLR-3000	YLR-5000	YLR-10000	YLR-20000
Max. Cooling Water Consumption (25ºC)	m³/h	0.6	1.4	2.5	4	7
Cooling Water Temperature Range	ºC	20-25	20-25	20-25	20-25	20-25
Dimensions (W x H x D)	cm	86x120x81	86x120x81	110x150x81	110x150x81	210x150x81
Weight	kg	250	350	500	750	1200
Ambient Temperature	ºC	10-50	10-50	10-50	10-50	10-50
Enclosure Type		IP-54	IP-54	IP-54	IP-54	IP-54

* - 1 and 2kW lasers also available in with a single mode output versions YLR-1000-SM and YLR-2000-SM respectively. In this case BPP is ~0.4 mm * mrad from a 20um feeding fiber and ~2 mm*mrad from a 50um processing fiber. All other electrical and general parameters are the same as for YLR-1000 and YLR-2000 lasers.

** - optional, on request.



http://www.ipgphotonics.com/documents/documents/HP_Broshure.pdf

Some Questions – 1/3

- Power Source
  - What is the maximum efficiency of **mode-locked,** phase-locked fiber, crystal, and ceramic lasers?
  - How can sections ~100 meters apart maintain ~1°⇔~50 attosecond temporal alignment?
- Particle (Injector) Source
  - Can a compact, economical source of electrons be made?
  - How can positrons with the required qualities be produced?

Some Questions – 2/3

- Structure
  - What is the damage threshold for structure materials?
  - What are the nonlinearity-imposed field limits?
  - What are the thermal limitations for these structures?
  - What is the best way to couple power from lasers into the structures?
  - What emittance degradation do the accelerating fields cause?
  - What emittance degradation do wakefields cause?
  - How is structure alignment accomplished?
  - How long do optical materials retain good properties in a harsh radiation environment?

Some Questions – 3/3

- Beam Transport and Emittance Preservation
  - How is transport focusing provided, and how is it diagnosed?
  - How are focusing elements held in alignment with the structures?
- Final Focusing
  - How best to destroy the optical bunch structure (to mitigate beamstrahlung)?
  - How do you focus and stably collide sub-nm class IP spots?