2010 Advanced Accelerator Concepts Workshop

OVERVIEW OF LASER-DRIVEN STRUCTURES

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Prepared with generous assistance from:
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Image credit: Chris McGuinness, Stanford University

Outline

- Issues unique to laser-driven structures
- Motivation and Applications
- Structure Concepts
  - Waveguide-Based Concepts
  - Phase-Mask Concepts
- Key Questions

Issues Unique to Structure-Based Laser Acceleration

Compared to RF Accelerators

- Sources are typically freespace TEM, must match to guided TM
  - Power coupling requires special attention
- Accelerating fields are present for picoseconds, rather than microseconds
  - $\vec{k} \,//\, \vec{v}$: Waveguiding structures typically designed for high v_g~0.6 to limit envelope slippage
  - $\vec{k} \perp \vec{v}$: Phase mask and swept-laser methods
- Metals have higher loss and lower damage threshold at optical frequencies than dielectrics

Compared to Laser-Driven Plasma-Wakefield Accelerators

- No-threshold linear process; typically a_0~10^{-4} in solid-state structures
- Very strong coupling impedances
- E_{laser}~nJ to μJ ➔ P_{laser}~kW to MW (0.000000000001 PW to 0.000000001 PW)

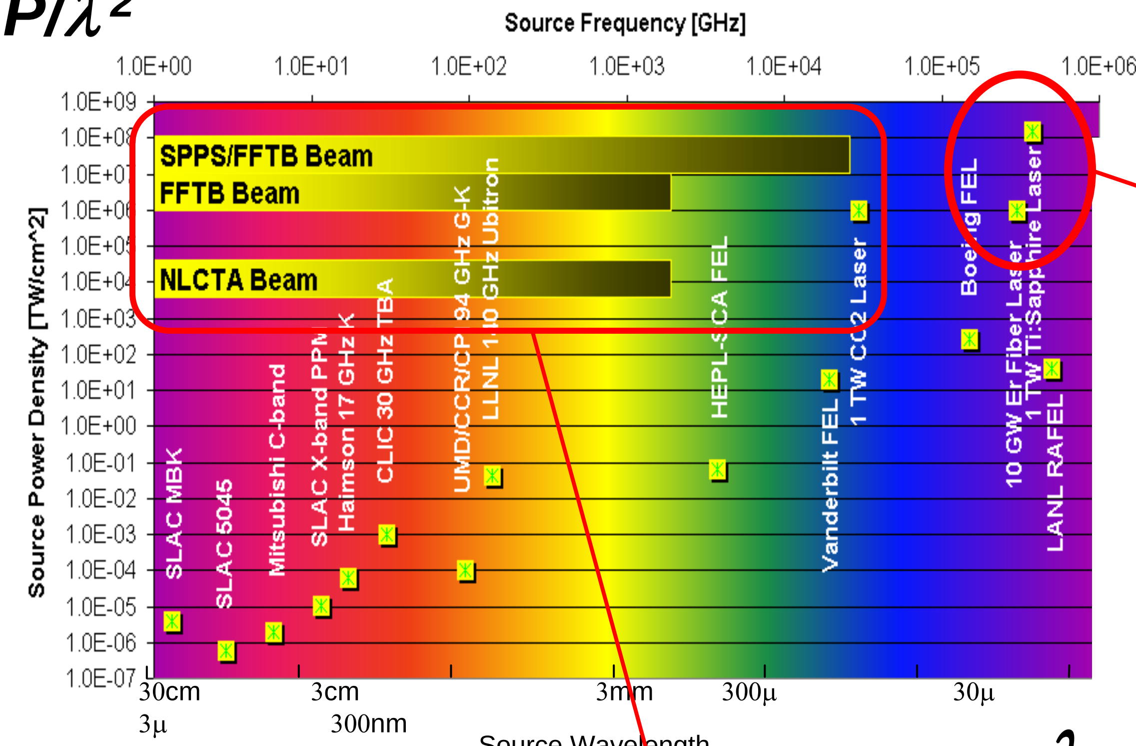
Strong coupling impedance comes at a price

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

- Structure aperture ➔ ~λ
  - *Has been achieved with semiconductor and fiber drawing technology*
- Optimum beamloading requires bunch charge ➔ ~fC
- Beam transmission requires emittances ➔ ~nm
  - *Possible with metal tip emission sources*
- Narrow energy spread ➔ Bunch length ~λ/100 ⇔ ~10s attoseconds
  - *Single-stage bunching at ~410as demonstrated*
- Beam current ~1-10 μA requires rep rates ➔ ~10-100 MHz
  - *~1 μJ/pulse at 1 MHz and ~100 nJ/pulse at 80 MHz commercially available now*
- BBU→Alignment tolerances ➔ $\sim\lambda/10$ or better
  - *Single-mode structures with no confined deflecting modes*
  - *High repetition rate* ➔ *broadband position stabilization feedback*

Motivation

P/λ²

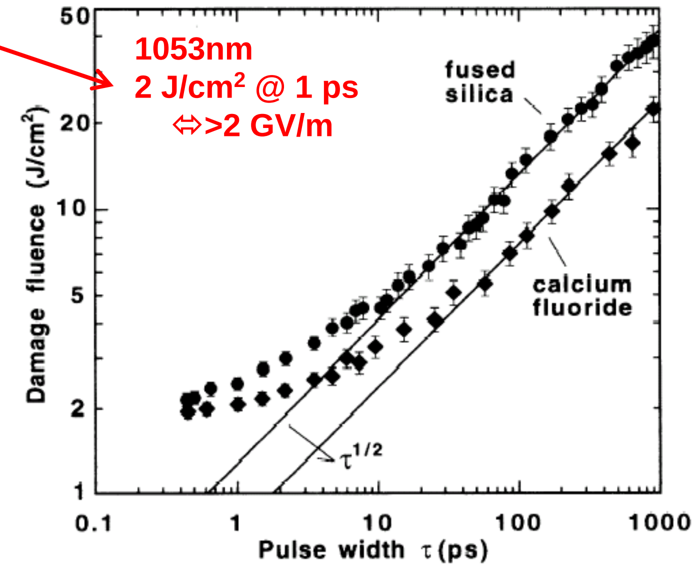


*28.5 GeV, 1e10 ppp, 1µ x 1µ x 600µ (20µ for SPPS) beam

**350 MeV, 1e10 ppp, 1µ x 1µ x 1 mm beam

λ

Dielectric Damage Threshold



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]

13.8 ± 0.7 GV/m.

Fused silica, THz range, ~psec exposure

Applications

- Linear Collider
  - Low charge/high rep rate operation has several significant advantages over conventional schemes:
    - Beamstrahlung power is greatly reduced, allowing
      - SVX to be moved in closer, permitting higher accuracy reconstruction
      - End-cap calorimeters to be brought in closer, capturing higher rapidity events
    - Event pileup is greatly reduced
    - High rep rate means feedback systems can operate very broadband, allowing effective cancellation of ground motion
- Attosecond Photon/Electron Sources
  - Photons and electrons are synchronized at the attosecond level
  - University-scale sources of GeV electrons and keV coherent photons
- Inexpensive, compact sources of electrons for medical and industrial applications
  - Accelerator on a chip

“Novel” Concepts: Progress of the last 50 years

- 1962 Koichi Shimoda, Professor of Physics, Univ. of Tokyo
- 1962 Adolf W. Lohmann, Head of the Optical Signal Processing Group, IBM Almaden Research

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- **Inverse Smith-Purcell Acceleration**

~0.05 MV/m, Bae *et al*, Tohuku U., 1987.

- **Inverse Cerenkov Acceleration**

31 MV/m, Kimura *et al*, BNL-ATF, 1995

- **Inverse Free Electron Laser**

~14 MV/m, Kimura *et al*, BNL-ATF, 2004.

- **Inverse Transition Radiation**

~40 MV/m, Plettner *et al*, Stanford, 2005.

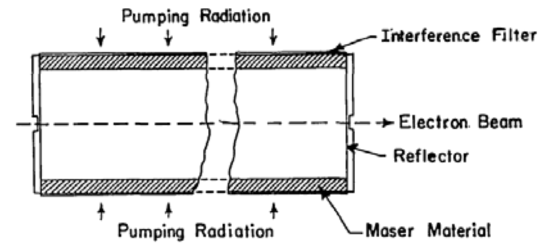
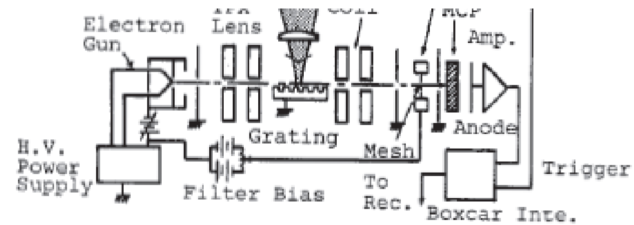
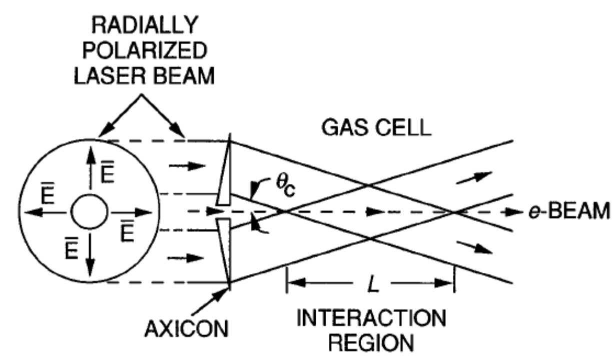


Fig. 1. Schematic diagram of an electron linear accelerator by optical maser.

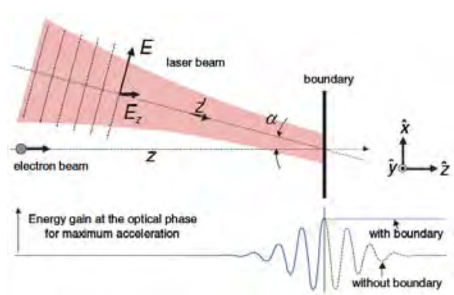
Applied Optics, **1** (1), p.33ff (1962).

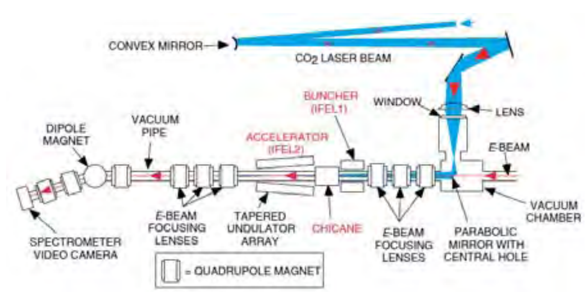


ISP, IEEE IEDM, p307ff, (1987).



ICA, PRL **74**(4), p.546ff (1995)





ITR, PRL **95**, 134801,(2005)   IFEL, PRL **92**(5), 054801-1, (2004)

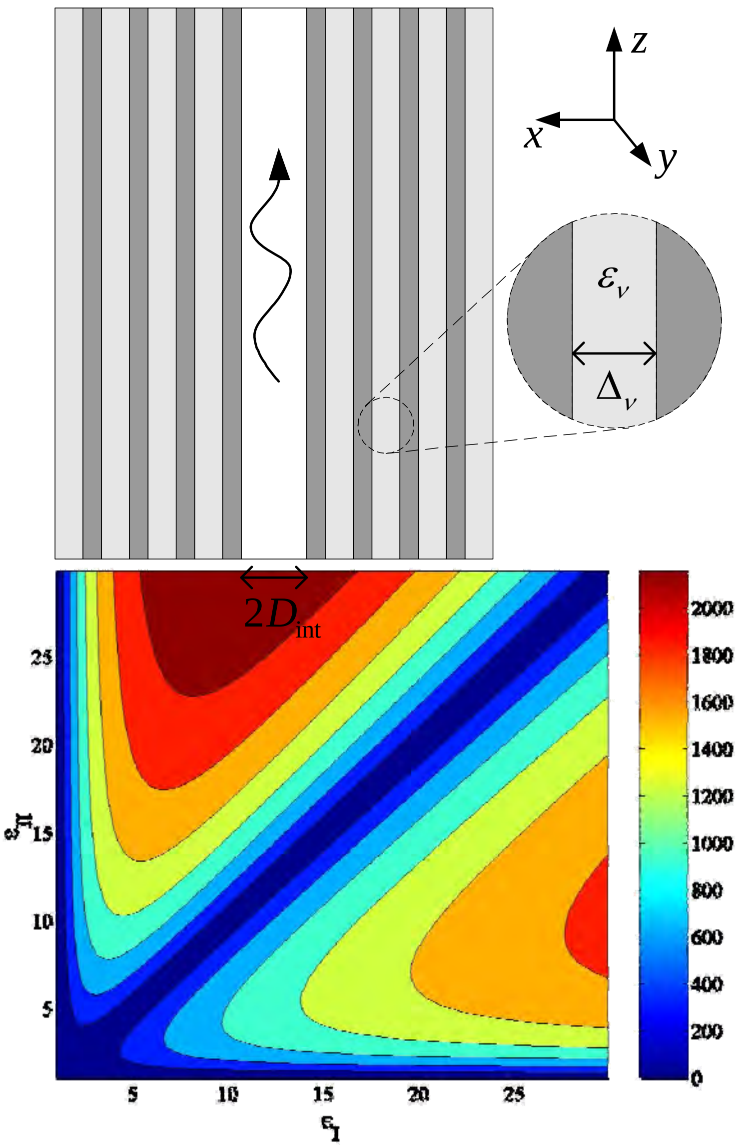
Present Status

- 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)
  - Waveguiding
  - Phase mask and swept-laser methods
- **Demonstrations** of “large-aperture” acceleration concepts ($r \gg \lambda$) at λ=10 μm and 0.8 μm have been done
- Facilities and **experimental 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

Technion – Israel Institute of Technology
Levi Schächter

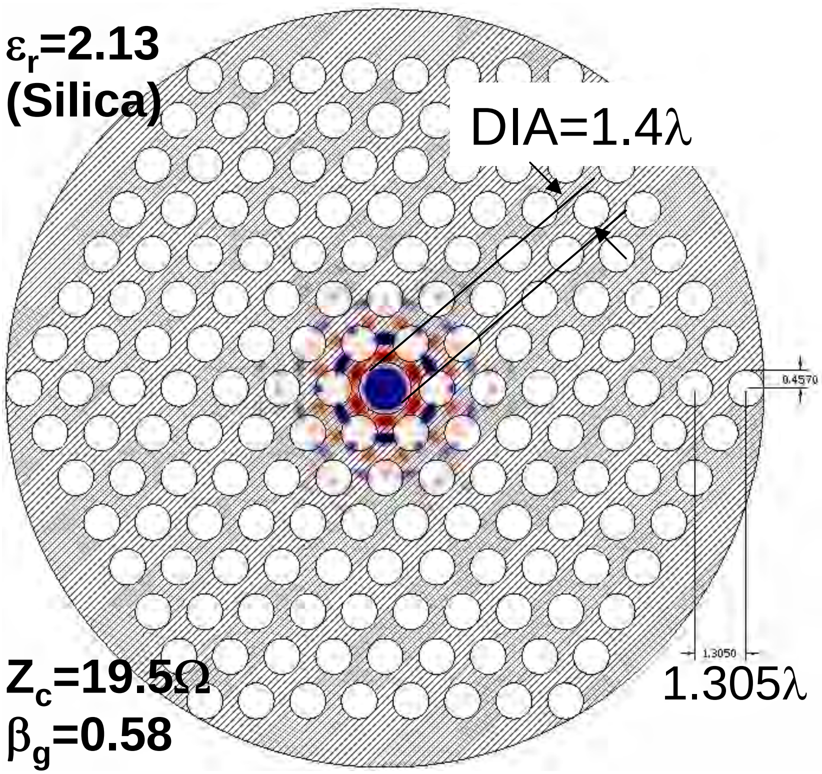
1D Photonic Xtal: Optical Bragg Acceleration Structure

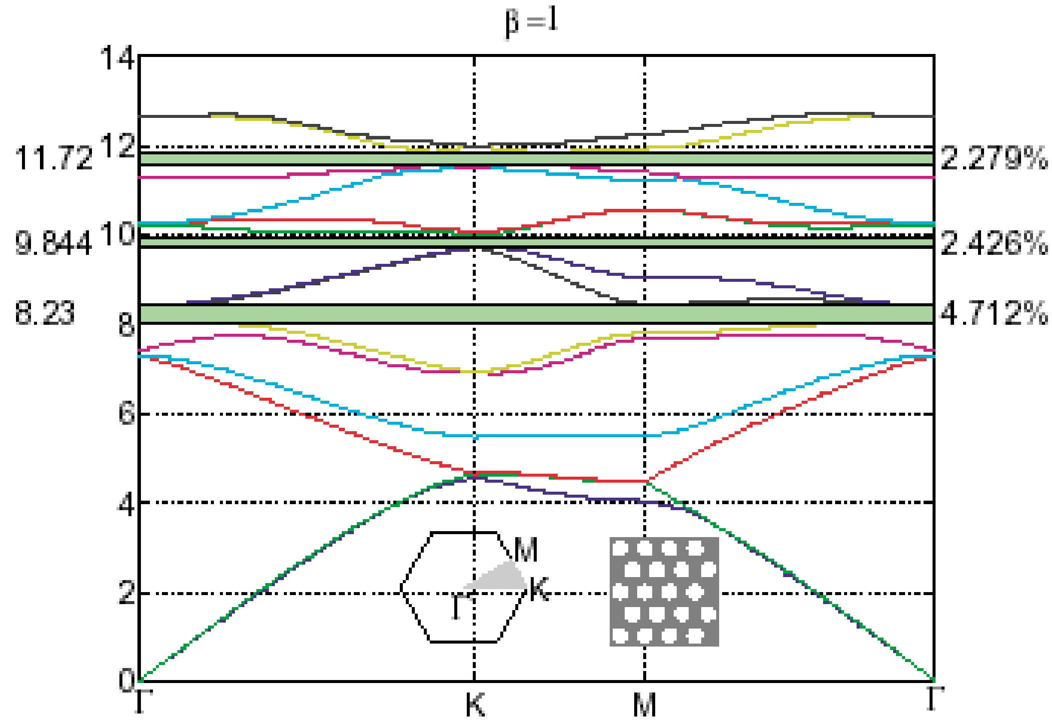


- Harness developments in the communication and semiconductor industry: e.g. solid state laser wall-plug to light efficiency.
- At optical wavelengths, dielectrics sustain higher electric fields than metals and have smaller loss.
- With the exception of the first (matching) layer, each layer: $\lambda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

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

2D Photonic Xtal: Fiber Structures



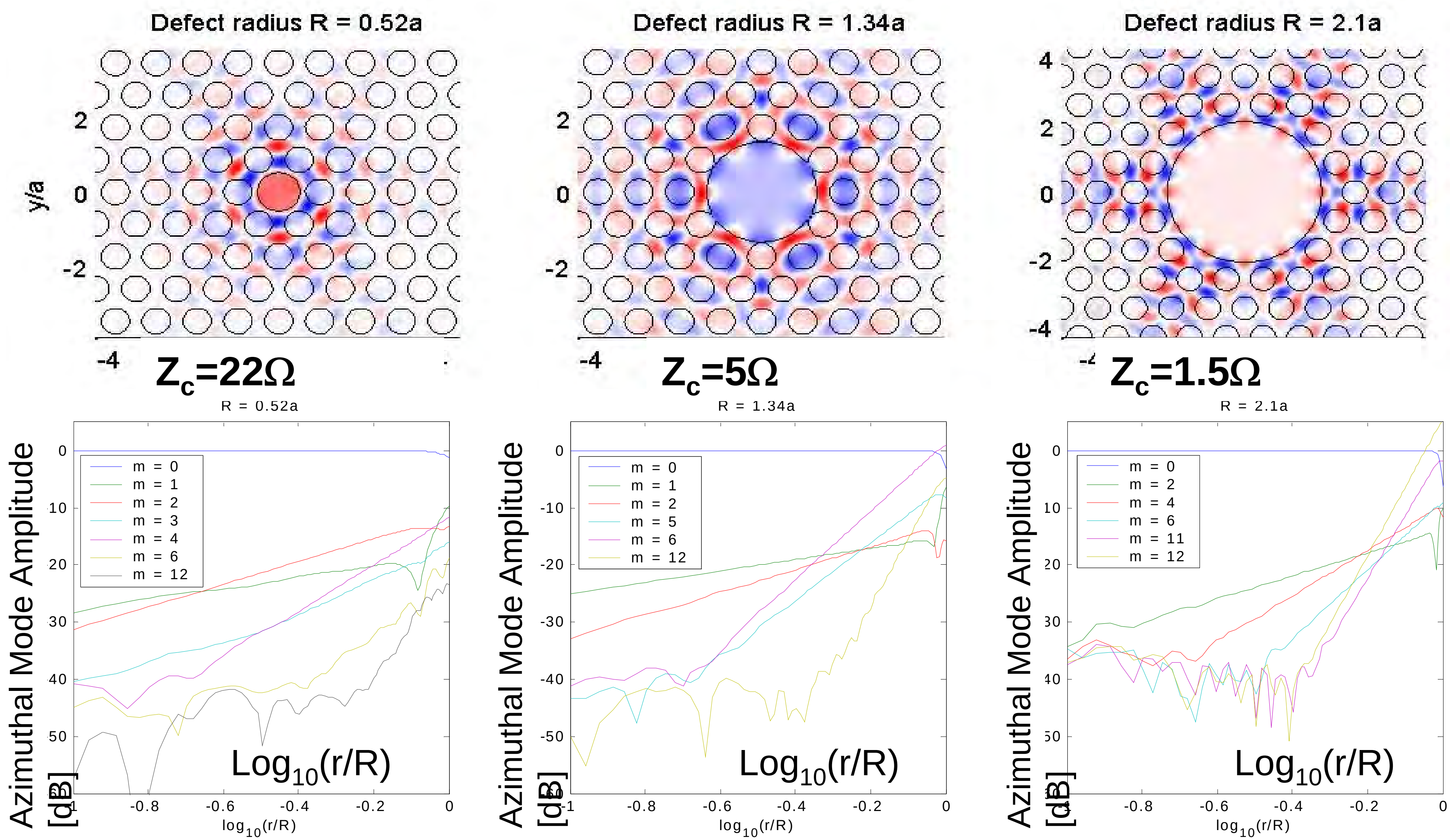


X. Lin, *Phys. Rev. ST-AB*, **4**, 051301, (2001).

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

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

Scaling of Coupling Impedance with Aperture
Example: photonic band gap fiber



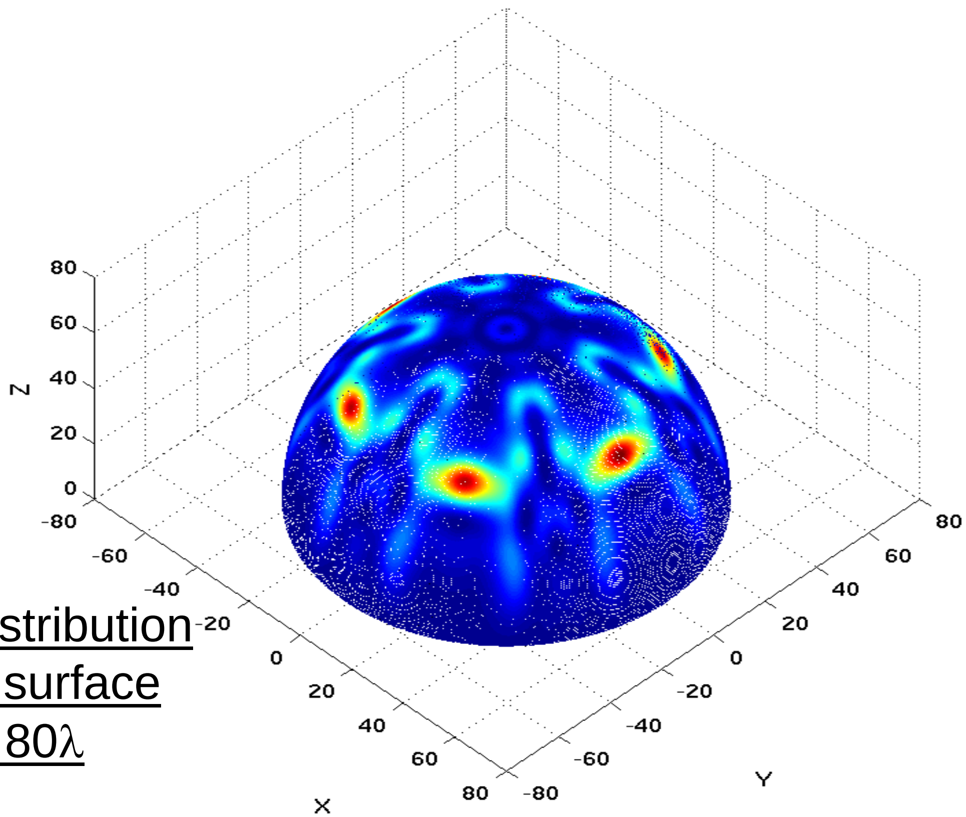
See Bob Noble's Talk, WG3, Thursday 4:15pm

Power Coupling from Laser to PC Fiber

- A Matlab program is used to determine far field pattern on forward hemisphere
- Six localized hot spots of Poynting flux are observed
- Hot spots are at 45º along longitudes and spaced at 60º from each other along a latitude
- All hot spots contain 75% power within 33% total area

See Cho Ng's Talk, WG3, Thursday 4:30pm

Far-field radiation pattern of PCF accelerating mode



Poynting flux distribution on hemisphere surface with radius $R = 80\lambda$

Single-bunch BBU-driven emittance growth is manageable

Misalignments

- Xq=Xa=50 nm
- X’o=0 rad, Xo=0 nn
- Grouping=10

Beam

- γ_o=1000
- σ=5/360λ
- Q=varies

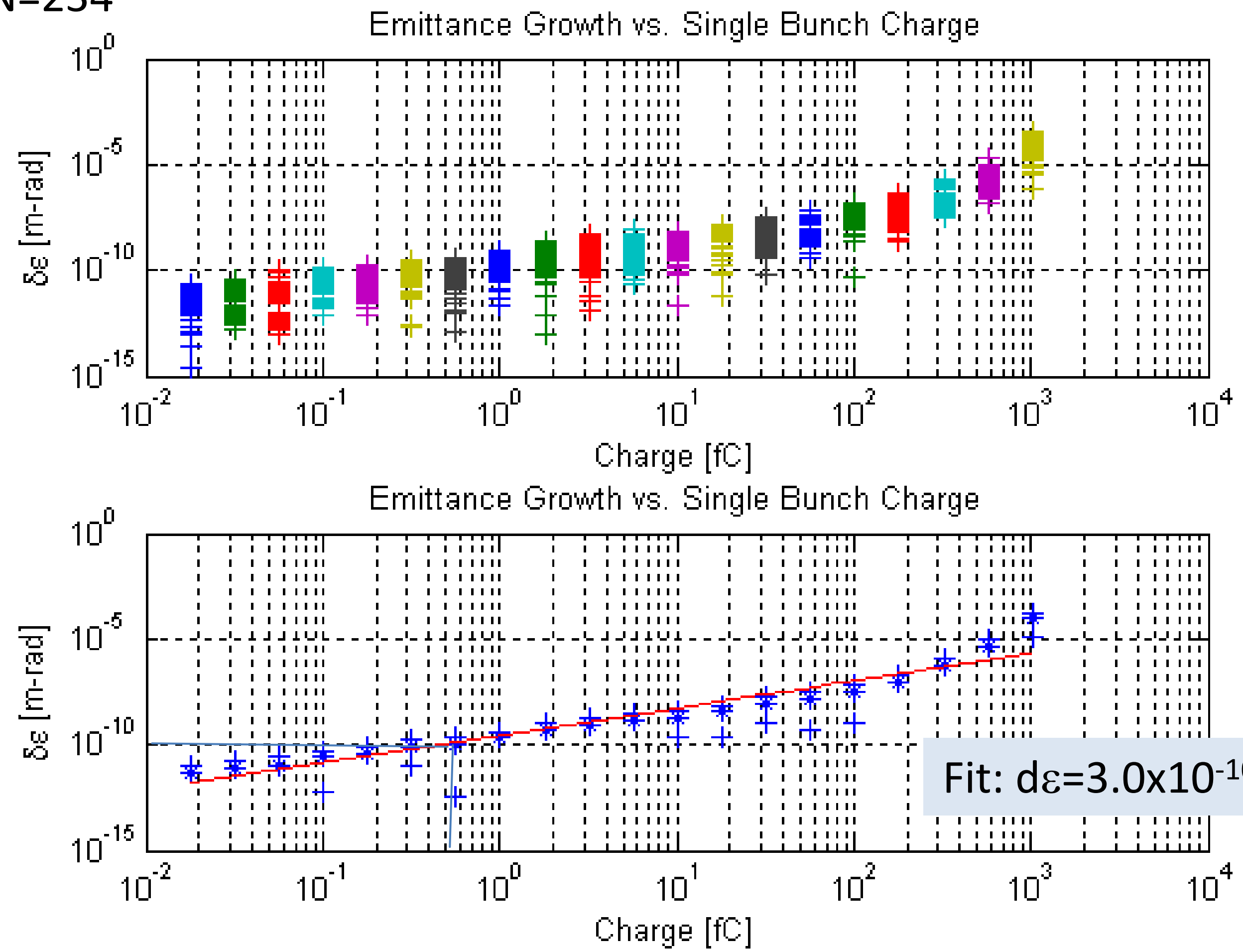
Accelerators

- L_s=1000λ
- R=5λ
- ε_r=2.31
- G=500 MV/m

Quad Lattice

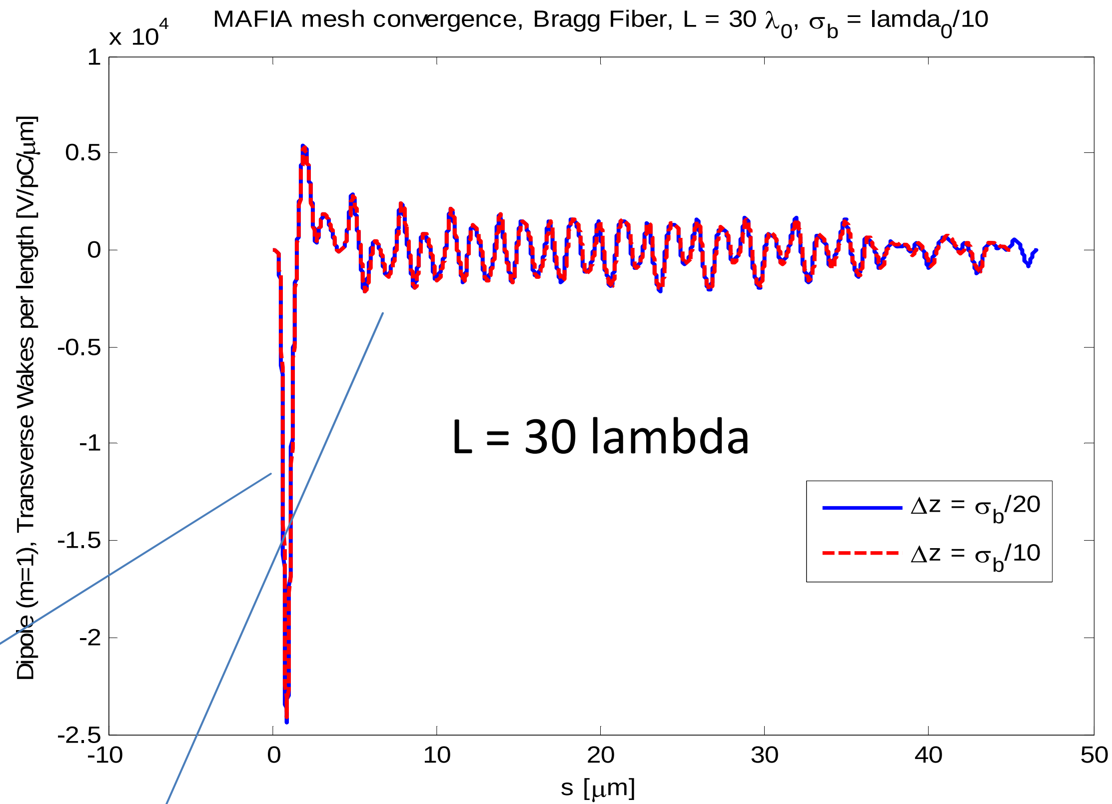
- L_{eff}=2.5 mm
- ψ=90°
- L_q=5 m
- K_q=600 T/m

N=234

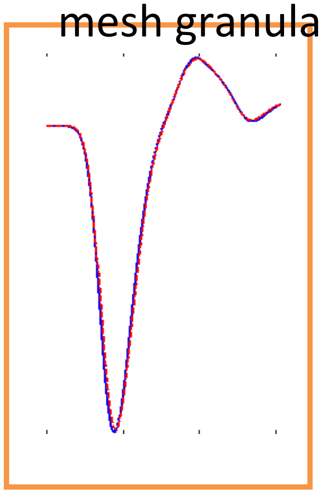


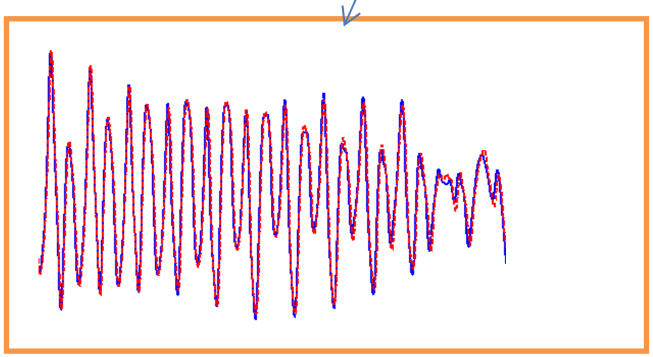
Fit: $d\varepsilon=3.0\times10^{-10}\,q^{1.28}$

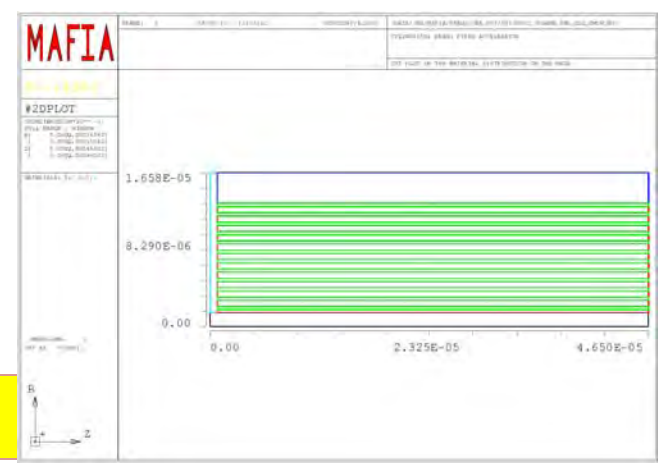
Calculation of Transverse Wakefield Effects (m=1)



Details of the wakefield calculation convergence with mesh granularity

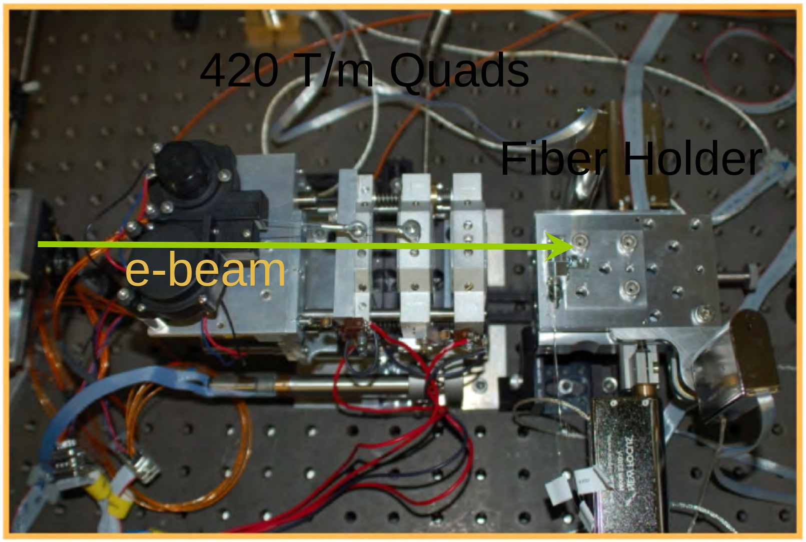




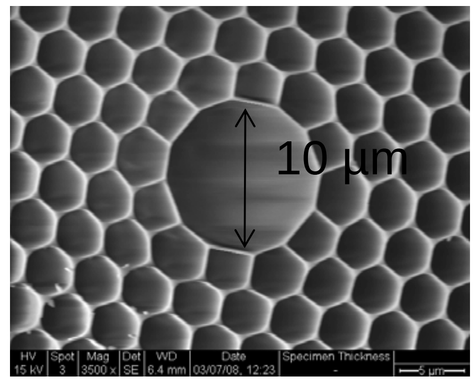


See Johnny Ng's Talk, WG3, Thursday 4:00pm

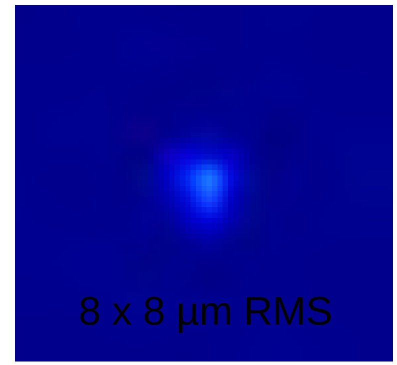
Beam Tests of Microstructures

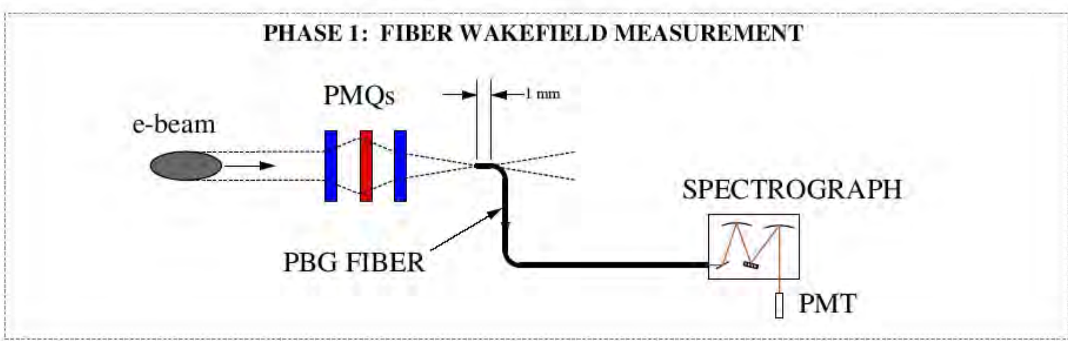


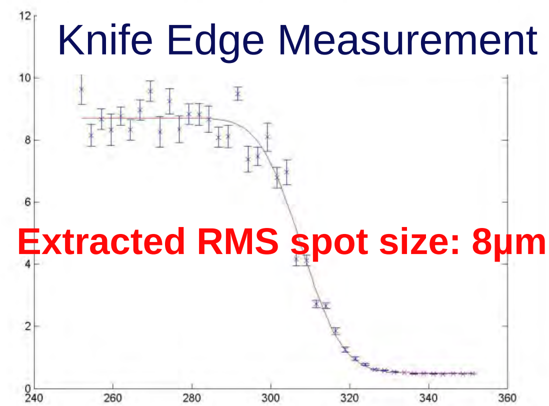
SEM image of HC-1550 fiber



e-beam profile image
at PMQ focus





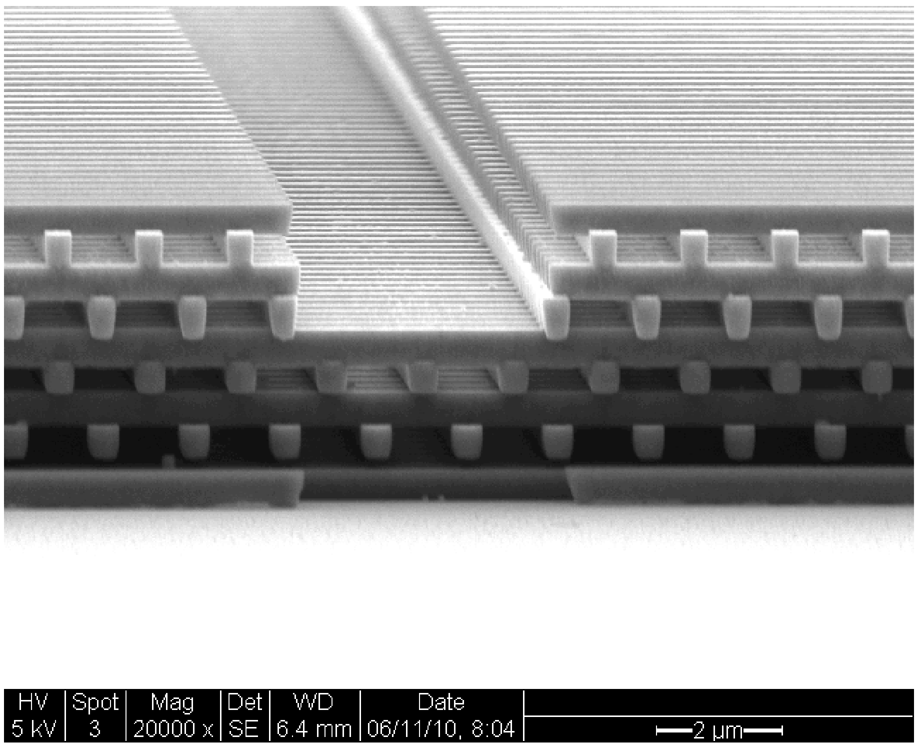


E163 Facility at SLAC

See Joel England's Talk, WG3, Friday 1:30pm

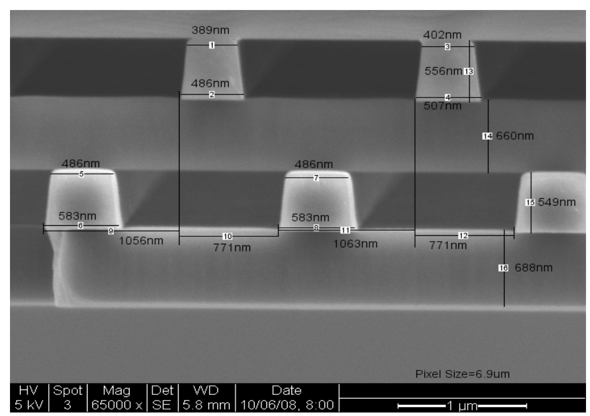
3D Photonic Xtal: Woodpile Structures in Silicon

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



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:

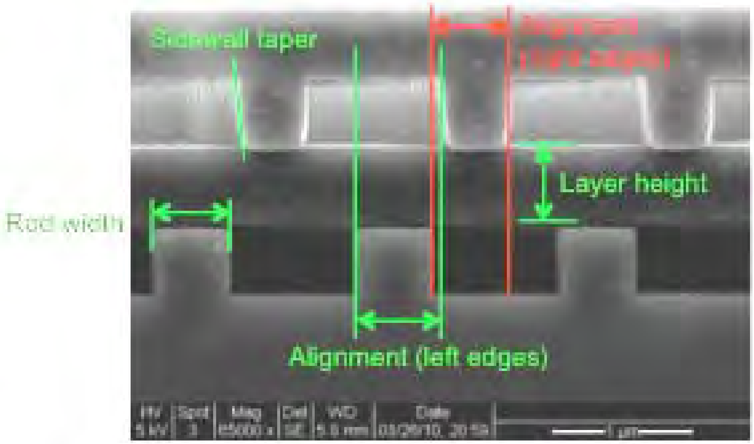
<65 nm RMS (~λ/75)

Measurement Technique Granularity: 7nm

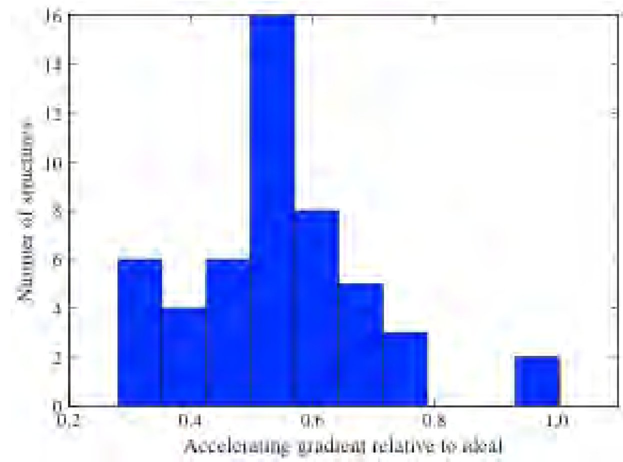
See Chris McGuinness's Talk, WG3, Friday 1:45pm

Rigorous studies of fabrication error underway

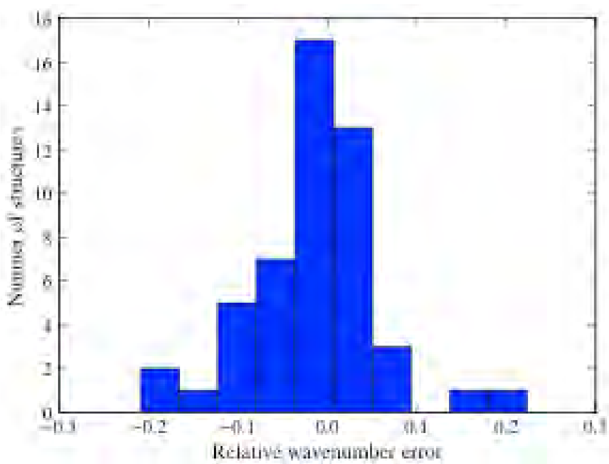
- Measured 4-layer woodpile test structures to quantify error
- Simulated structures with realistic error



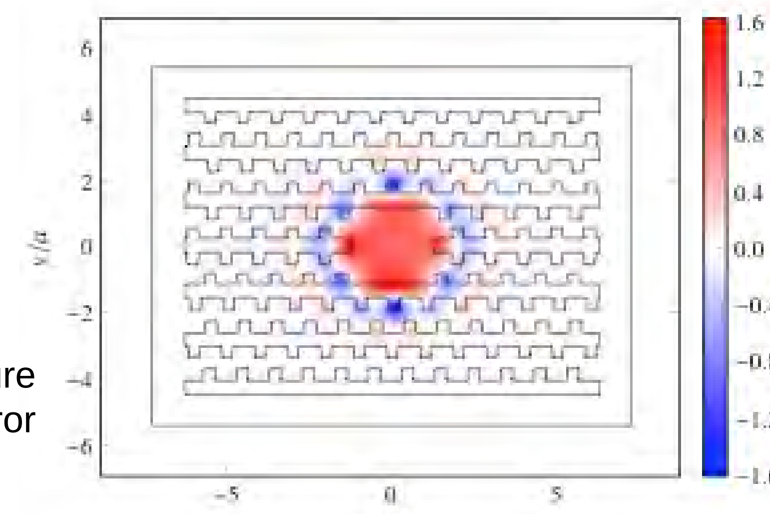
Fabrication error parameters



Accelerating gradients of structures with error



Phase velocity errors

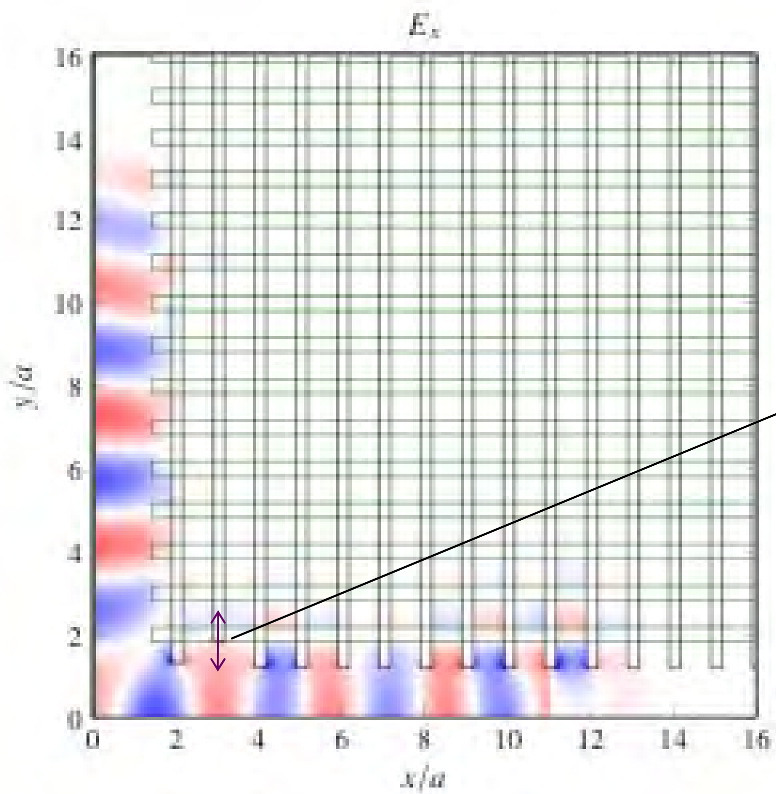


Fields in structure with fabrication error

See Ben Cowan's Talk, WG3, Friday 2:00pm

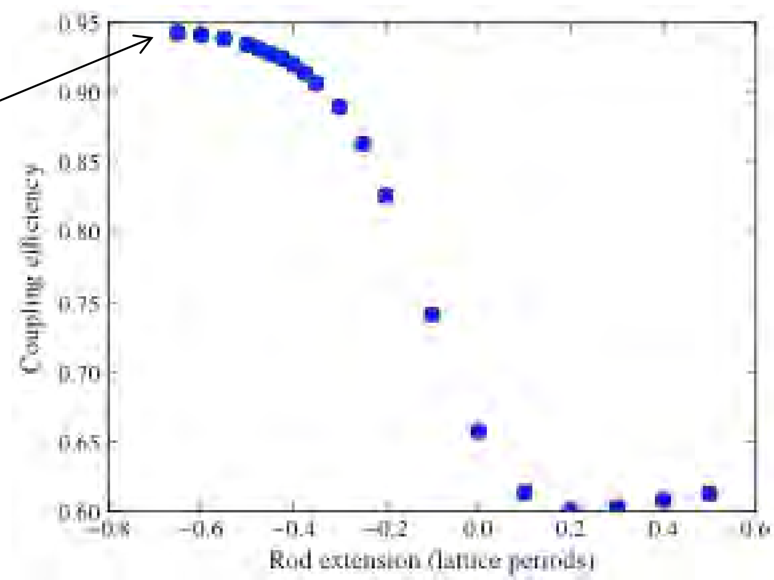
Optimization of Power Coupling

- Lithography enables detailed, precise control of features
- Accelerator components can be integrated – i.e. couplers



> 95% coupling efficiency in woodpile structure…

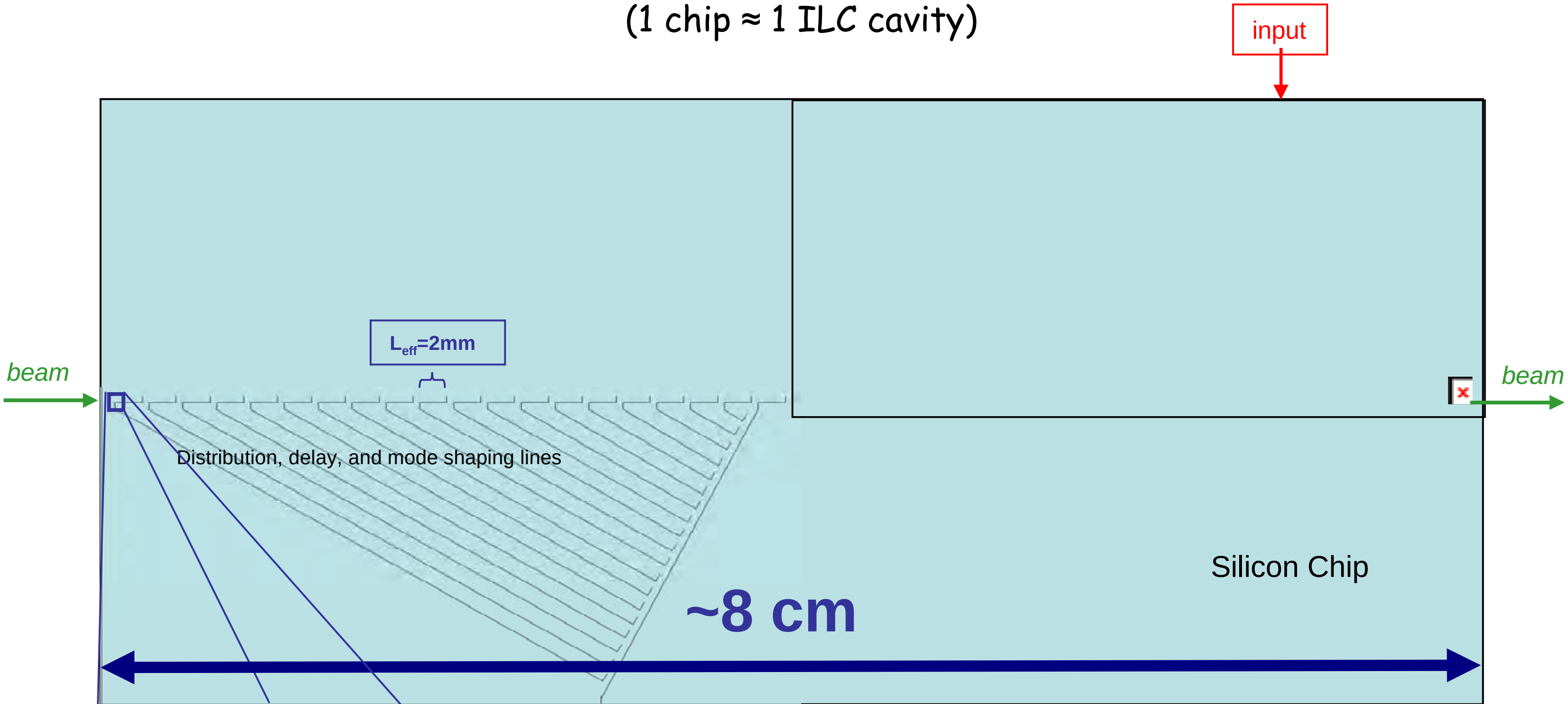
…obtained by adjusting individual rod positions – amenable to lithographic process

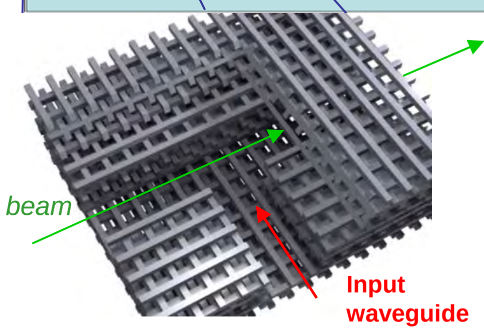


See Ben Cowan's Talk, WG3, Friday 2:00pm

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

(1 chip ≈ 1 ILC cavity)



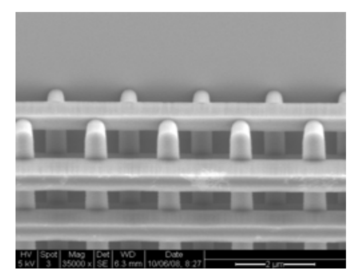


Cutaway sketch of coupler region

Image courtesy of B. Cowan, Tech-X.

Fiber coupled input

λ=2 μm
20 μJ/pulse
1 ps laser pulse



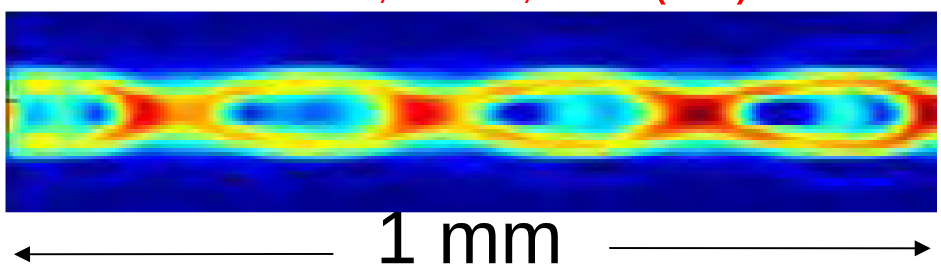
5μm 4-layer Structure Fabrication (completed at SNF)

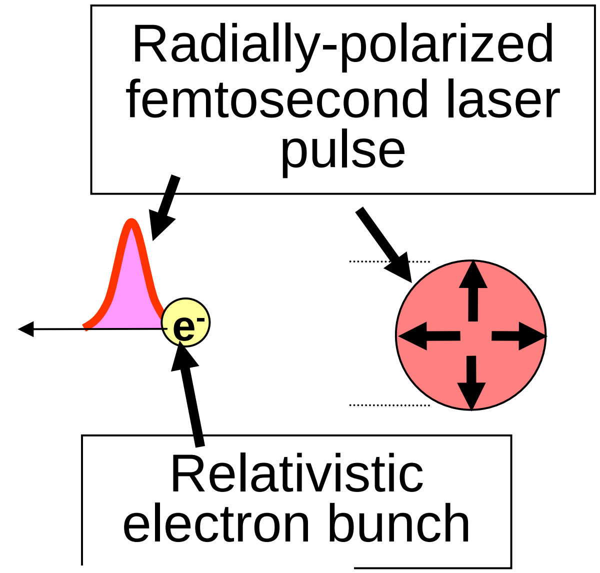
Image courtesy of C. McGuinness, Stanford.

Corrugated Plasma Waveguides

A structured plasma could phase-match direct acceleration of electrons

A. York et. al., PRL 100, 195001 (2008)





…and Univ. of MD has developed two techniques to make modulated plasma channels

Layer et al., Opt. Express 17, 4263-4267 (2009), Layer et al., PRL 99, 035001 (2007)

Accel. gradient scales linearly with laser field, and unlike LWFA has no minimum intensity threshold

Could be used with kHz systems for small scale, high rep rate accelerators – **1mJ** could drive **11MV/cm**

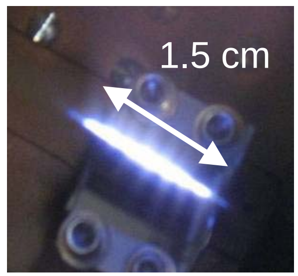
See Brian Layer's Talk, WG1, Wednesday 2:10pm

Slow Wave Guiding Micro-Structures: Two methods

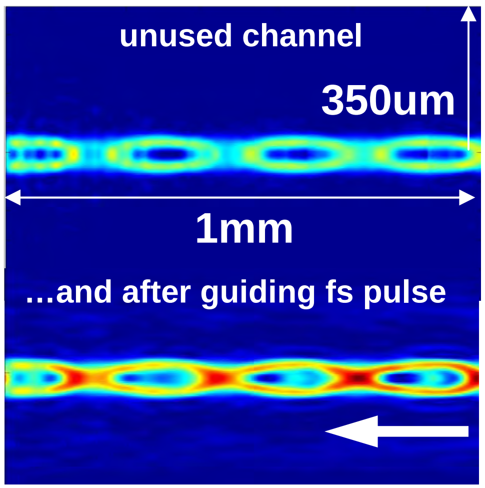
Ring Grating Imaged to Axicon Line Focus

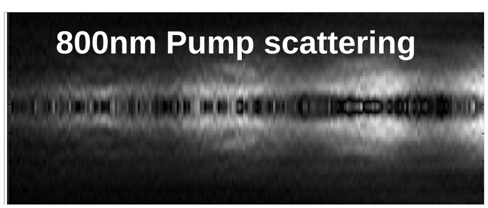
Argon plasma Channel w/ 300um period (fine RG)

Argon plasma channel w/ 2mm period (coarse RG)



Plasma density

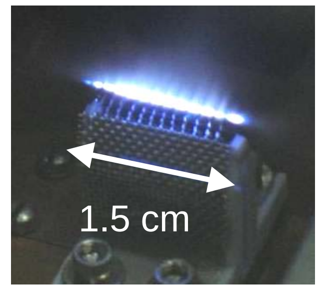




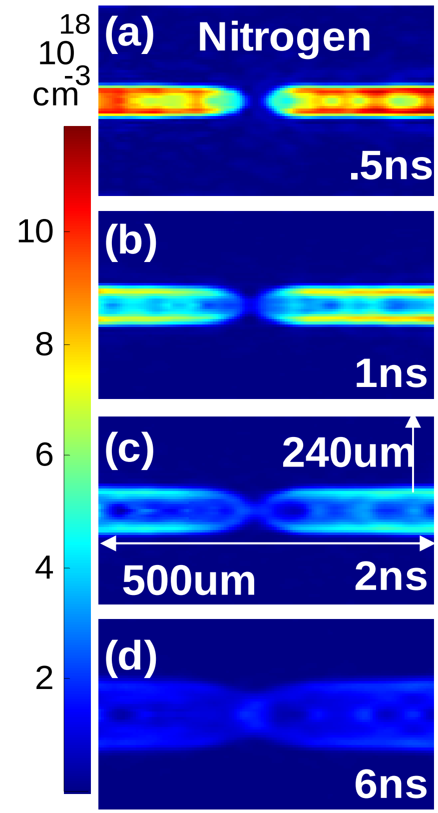
B.D. Layer *et. al.*, PRL 99, 035001 (2007)

Cluster Target Modulated w/ Wire Array

Flow blocked with 250um wires

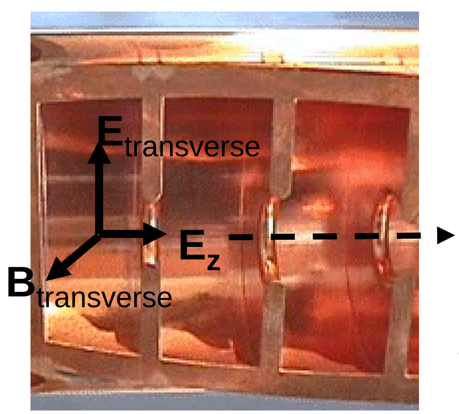


Flow blocked with 25um wire



•Gaps in cluster flow occur in “shadows” of wires and persist for full useful life of the waveguide

Compare to disk-loaded WG



‘slow-wave’ structure wave phase velocity < c

EM propagation & particle accel.

Direct Laser Acceleration (DLA) Challenges/Outlook

Current Experiment – proof-of-principle using LWFA to seed DLA

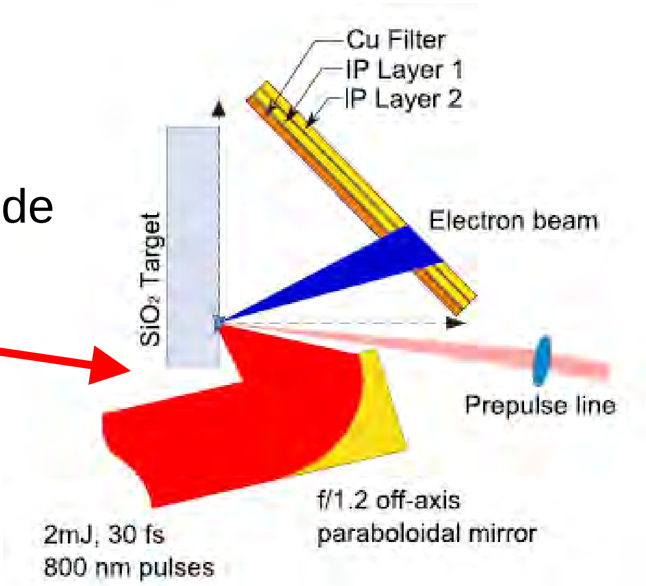
•Waveguides have already been demonstrated and tested

•Now generating intense, radially polarized, femtosecond pulses

•Need to achieve stable timing & pointing of seed bunch

Future Experiments –

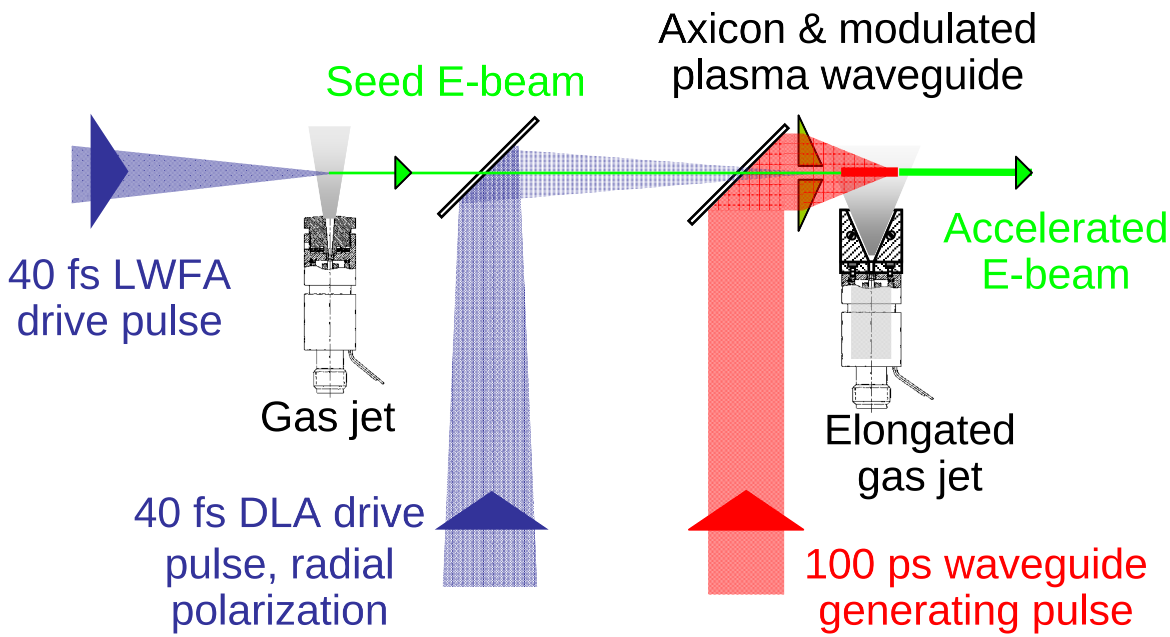
- Develop methods for seeding the structure
- Reduce laser energy required to make waveguide
- Experiments with solid targets* and clusters



*A.G. Mordovanakis et al PRL 103, 235001 (2009)

DLA proof-of-principle experimental layout

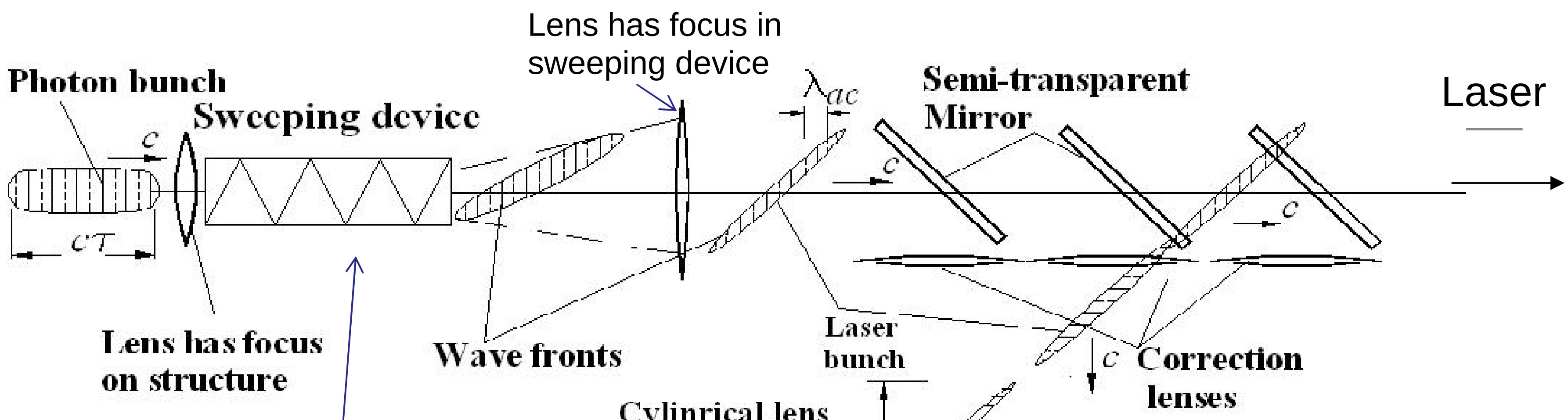
- **Demonstrate DLA acceleration mechanism – use extra gas jet + pulse to generate seed bunch**
- First jet – LWFA on a density downramp* to make a seed electron bunch
- Second jet – modulated plasma structure, DLA with radially polarized pulse



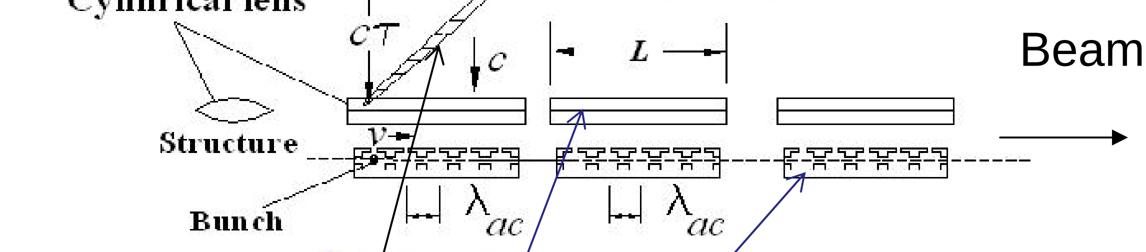
*C.G.R. Geddes et al PRL **100**, 215004 (2008)

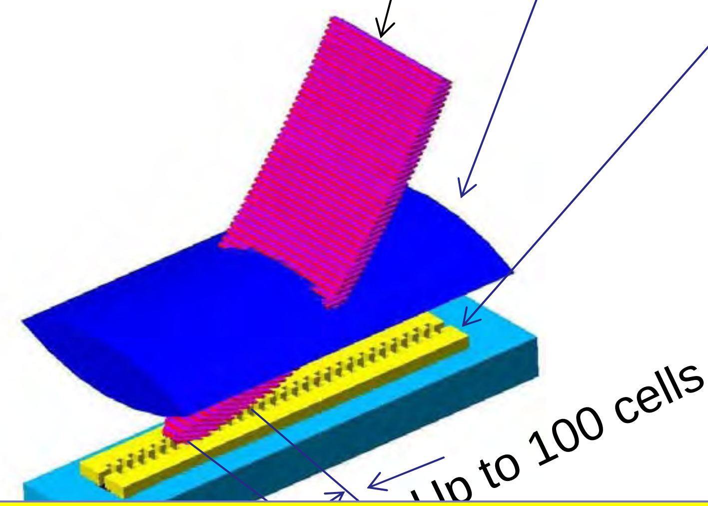
See Brian Layer's Talk, WG1, Wednesday 2:10pm

Non-Waveguide Concepts: Swept-Beam Foxhole Structure



Electro-optical device arranged by prisms with oppositely oriented optical axes; Driven by HV pulse



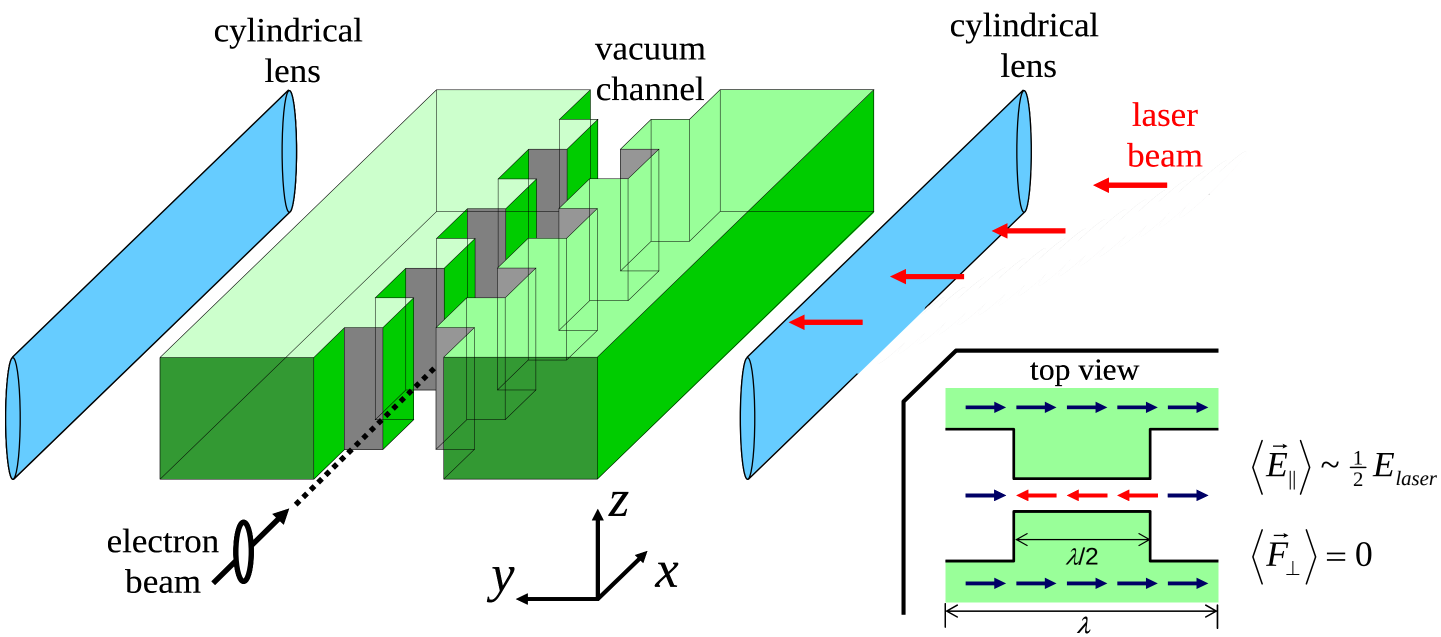


Quality factor ~10, so the field inside each cell can reach equilibrium

Transverse wake scales linearly, as it follows from its dimension:
Volt/Coulombs/meter

See Sasha Mikhailichenko's Talk, WG3, Friday 10:30am

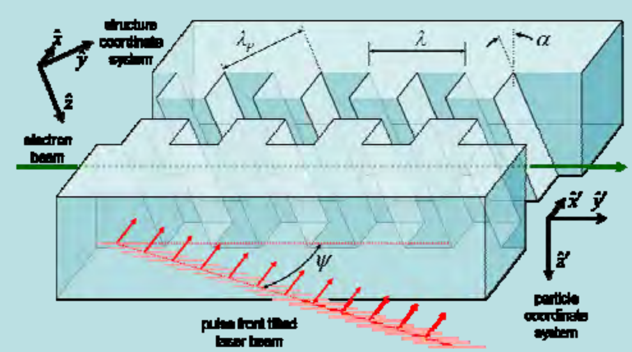
The Transmission Grating Accelerator



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*

The Micro Accelerator Platform is a fully integrated particle source using an optical-scale dielectric structure

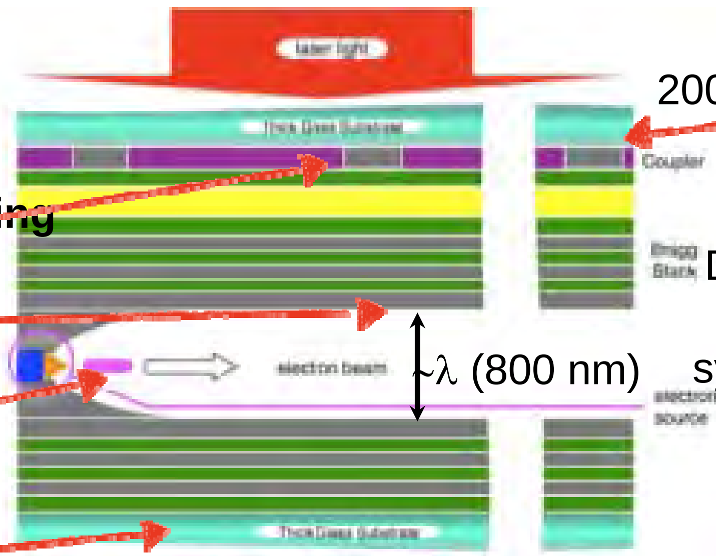
Features & Benefits:

Simple power coupling

Reduced wakes

Flat beams

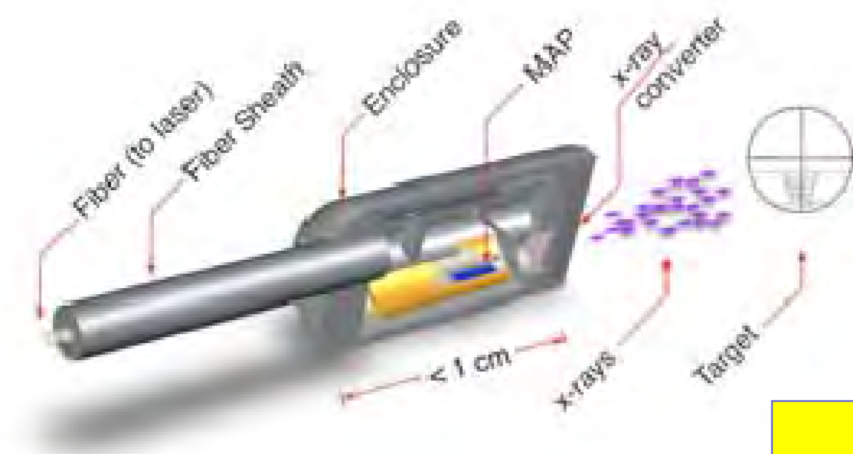
Chip-like fabrication

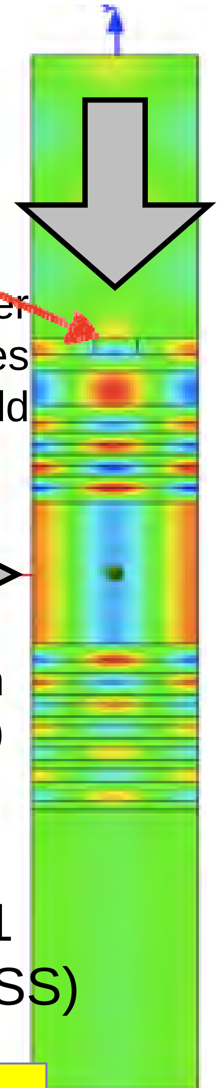


200 nm x 50 µm slots

~λ (800 nm)

Distributed grating coupler drives synchronous resonant field





laser

electrons

Gradient ~ 1 GV/m
(1 keV per period)

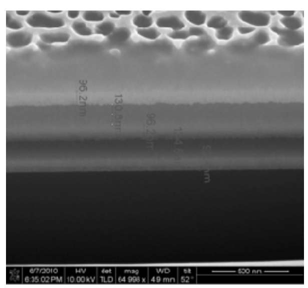
E_z over 1 period (HFSS)

See Rodney Yoder's Talk, WG3, Friday 11:00am

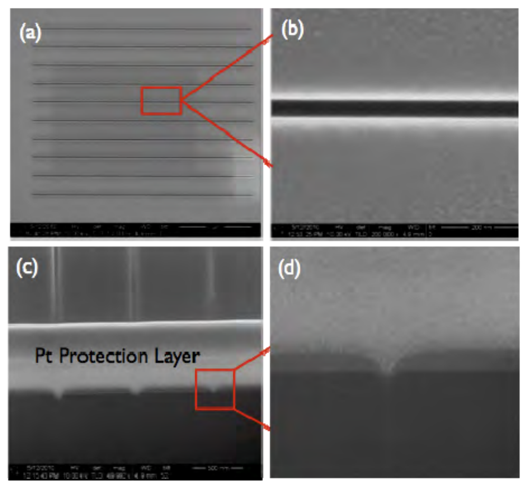
Structure design and material selection are complete; particle emitter under investigation

Materials must maximize transmission and contrast

Material	Transmission (%)	Absorption Coefficient	Index of Refraction (n)
TiO2	~85-90	6700cm^-1	~2
SiO2	~90	<1%	1.43
CaF2	90	<.08%	~1.43
MgF2	~95	<1 (x-coeff)	1.3-1.5
ZnSe	~70	.01 (x-coeff)	~2-4
SiOxNy	70	Lowest at 800nm	1.6-2
TiOx			1.8-2.3
HfO2		<2%	2.0

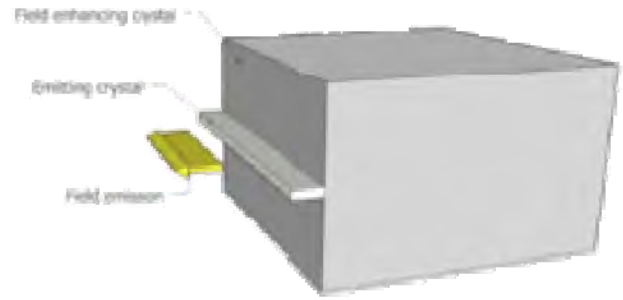


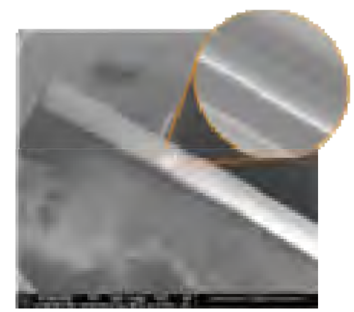
DBR



Coupler

Pyroelectric gun has been fabricated and is being tested experimentally

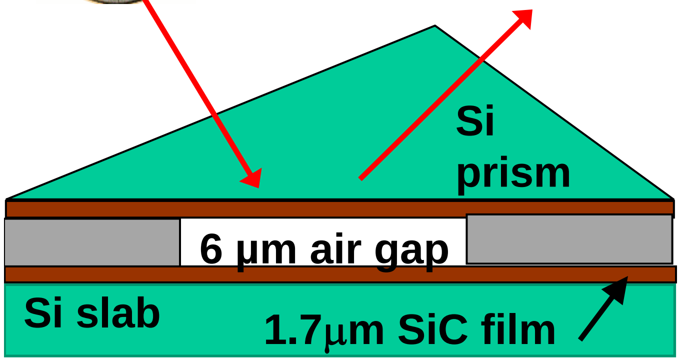


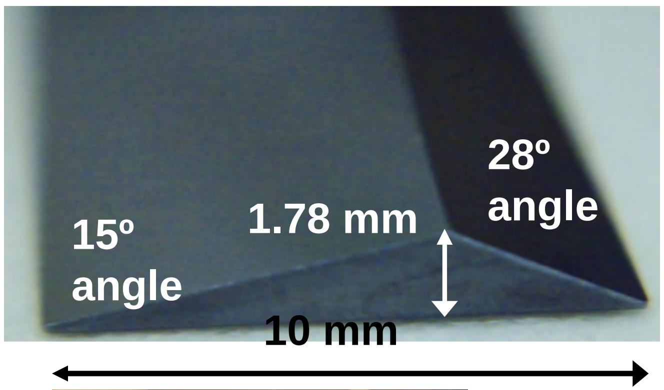


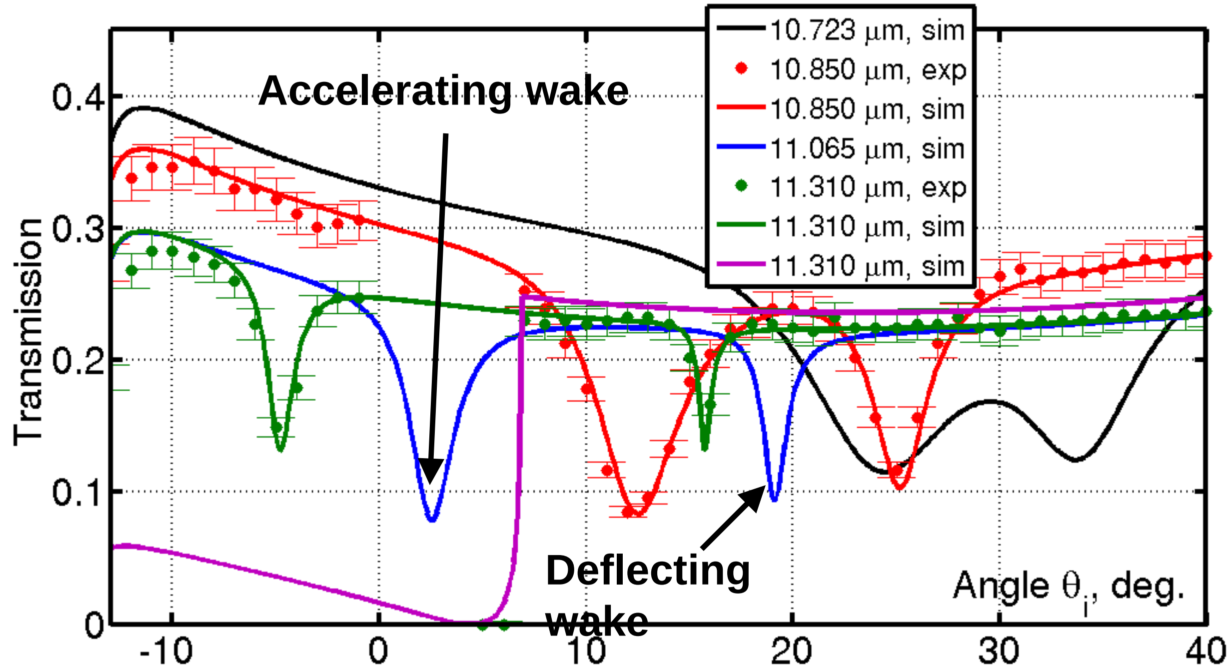
Pyroelectric crystal + field enhancement = Gun

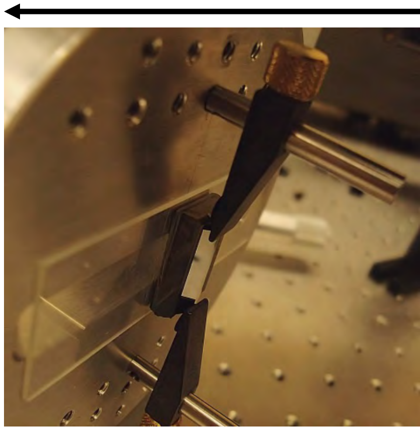
See Joshua McNeur's Talk, WG3, Friday 11:15am
And Jianyun Zhou's Talk, WG3, Friday 1:30pm

Surface Wave Accelerator and/or Asset for FACET









Top: schematic
Middle: photo of the Si prism with SiC film
Bottom: target assembly

- Both accelerating (good) and deflecting (parasitic) wakes are experimentally observed
- Ideal diagnostics for FACET's σ_z = 14μm beam

See Gennady Shvet's Talk, WG3, Wednesday 2:00pm

Polarization non-linearity

- *Breakdown & Nonlinearity*: In dielectrics at optical wavelengths breakdown threshold is *higher* than that required to excite nonlinear effects in the dielectrics.
- *Nonlinear Effects*: at high intensities, the laser field may affect the dielectric coefficient and therefore alter the laser pulse *phase* relative to the accelerated bunch.

$$\vec{P} = \varepsilon_0 \left[\chi^{(1)} \vec{E} + \chi^{(2)} \vec{E}\vec{E} + \chi^{(3)} \vec{E}\vec{E}\vec{E} + \ldots \right]$$

- *Third harmonic generation*
- *Four wave mixing*
- *Nonlinear refraction*

- *Second harmonic generation*
- *Sum-frequency generation*

Progress in Laser Technology

Efficient Diode Pumping

60 W/bar
55% now
78% electrical efficiency

nLIGHT

High power fiber lasers

NUFERN

ALABAMA LASER

20kW CW in 200μm core,
>25% electrical efficiency

Er:fiber
1.5μm
$840/W
Th:fiber
2μm
$900/W

Optical locking of multiple fiber lasers

354 OPTICS LETTERS / Vol. 33, No. 4 / February 15, 2008

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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Received November 27, 2007; revised January 13, 2008; accepted January 16, 2008;

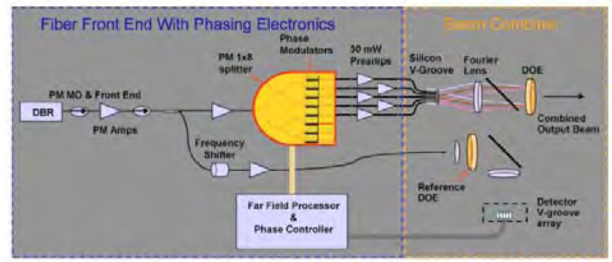


Fig. 2. (Color online) System architecture for DOE-based CBC.

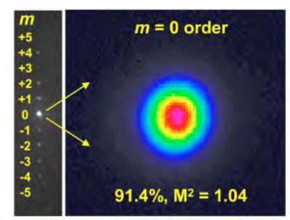


Fig. 3. (Color online) Far-field distribution of five-element phase-locked fiber array combined using a DOE.

Carrier-Envelope laser technology

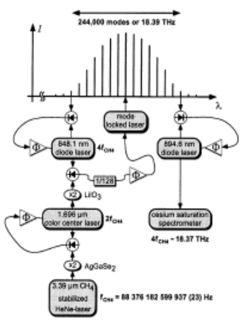


FIG. 1. Frequency chain that allows the comparison of the precisely known frequency of a methane stabilized He-Ne laser at 88.4 THz (3.39 μm) with the cesium D_1 transition at 335 THz (895 nm).

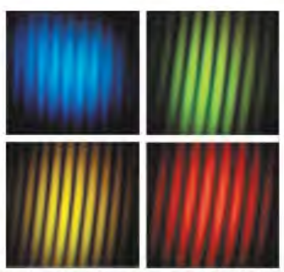
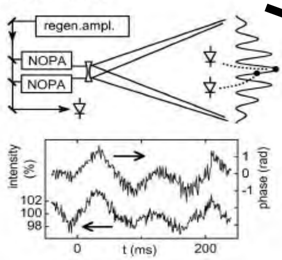


Fig. 2. Interference between two separate NOPAs for various center wavelengths.



CEP Accessory for Micra

Key questions for this workshop and beyond

- For the accelerating structures
  - What **accelerating gradients** will dielectric structures tolerate?
  - When do **nonlinear polarization** and **thermal** effects set in?
  - How can modulated plasma structures be made **reproducibly**?
  - How can **staging** to achieve large voltage gain be done economically?
- For the required sources
  - What source capabilities can be achieved?
  - How can bunched beams be prepared for injection?
  - Can polarized beams be transported?
  - How can a suitable positron source be made?
- For a laser-driven linac
  - How is alignment of stages achieved and maintained?
- For the diagnostics
  - How can attosecond-nanometer-fC class diagnostics be realized?

Image credit: Chris McGuinness, Stanford/Joel England, SLAC