E163: Laser Acceleration of Electrons at the NLCTA

ARDB

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Work supported by Department of Energy contracts DE-AC02-76SF00515 (SLAC) and DE-FG03-97ER41043-II (LEAP).

E163: Laser Acceleration at the NLCTA

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Work supported by Department of Energy contracts DE-AC02-76SF00515 (SLAC) and DE-FG03-97ER41043-II (LEAP).

Motivation for Dielectric Structure Based Laser Acceleration

For HEP machines: Gradient and power efficiency are paramount

•Dielectrics have significantly higher damage threshold than metals, so higher gradients are potentially possible (typically GV/m vs 100 MV/m)

• Structures are all solid-state, so nonlinearities and shot-to-shot reproducibility problems inherent in plasma accelerators are avoided

• Power sources and structure fabrication techniques enjoy wide markets, rapid R&D by industry (DPSS lasers: ↑0.22 B$/yr vs. ↓0.060M$/yr for power tubes)

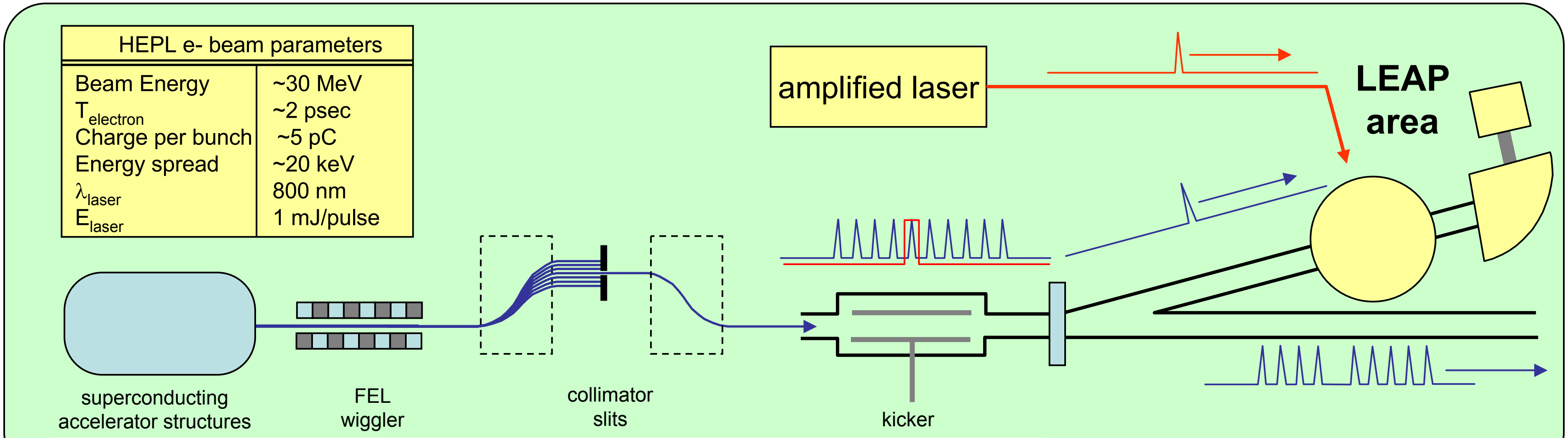
For radiation sources: Short bunches and peak power are paramount

• Short wavelength acceleration naturally leads to short bunches (~100 attosecond) and short radiation pulses if used to generate radiation

• May one day lead to fully-integrated power source/accelerator systems on a single substrate➔an all solid-state accelerator

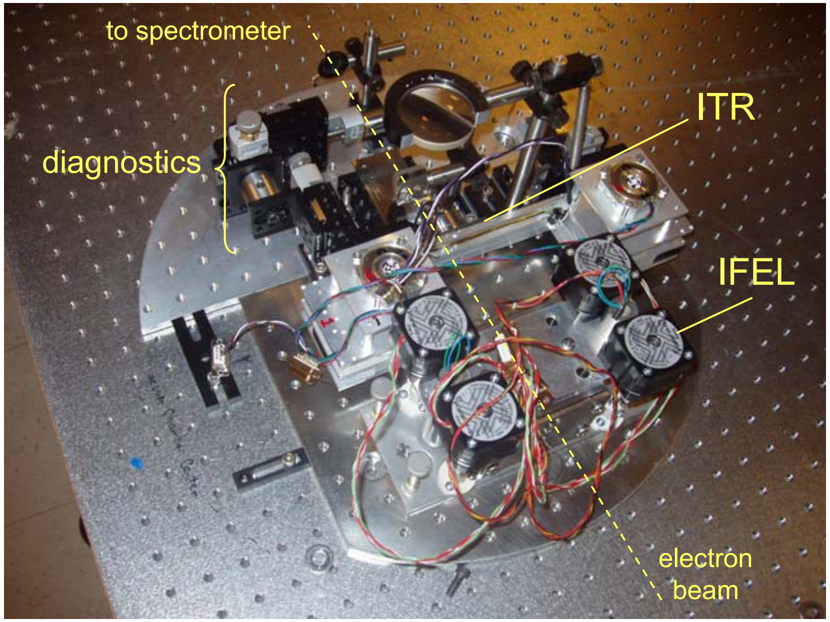
Experimental Results

Apparatus for Laser-Driven Dielectric-Structure Accelerator Demonstration

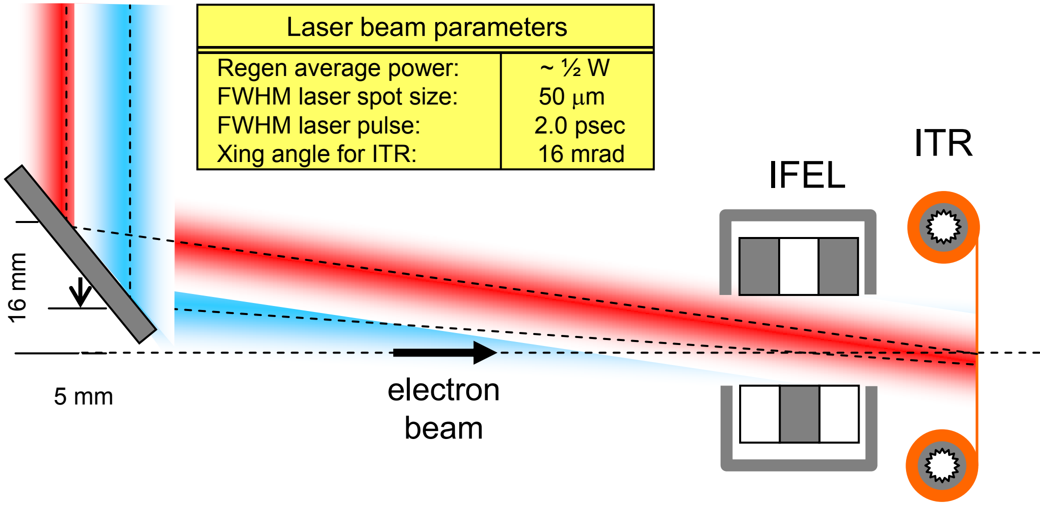


HEPL e- beam parameters	
Beam Energy	~30 MeV
$T_{electron}$	~2 psec
Charge per bunch	~5 pC
Energy spread	~20 keV
λ_{laser}	800 nm
E_{laser}	1 mJ/pulse

HEPL Superconducting Accelerator on Stanford Campus



IFEL-ITR laser beam alignment



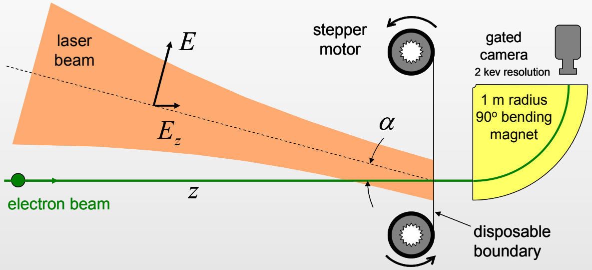
Laser beam parameters	
Regen average power:	~ ½ W
FWHM laser spot size:	50 μm
FWHM laser pulse:	2.0 psec
Xing angle for ITR:	16 mrad

First observation of Laser-Driven Particle Acceleration of Relativistic Electrons in a semi-infinite vacuum space*

Stanford
Linear
Accelerator
Center

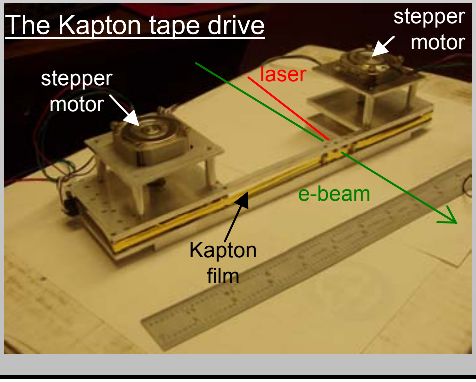
The experiment

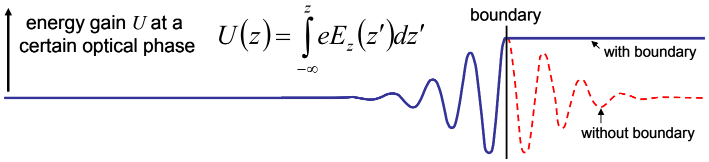
- single linearly polarized laser beam
- visible - near IR wavelength (800 nm)
- 30 MeV electron beam
- 2 psec pulse duration of laser and e-beam
- e-beam runs through a very thin disposable boundary that terminates the laser field



The disposable boundary

- 8μm thick kapton tape with a 1μm thick reflective gold film
- tape is moved to a new position for each laser shot. This allows for operation above the laser damage threshold. During the 2 psec laser pulse the gold surface remains reflective and only starts to degrade after 10 psec, Well after the passage of the e-beam.
- No significant e-beam degradation from the tape was observed





properties

- transverse electric field almost cancels transverse magnetic field force → no significant transverse forces

$$|F_\perp| << |F_\parallel|$$

- acceleration gradient proportional to laser E- field

$$G \propto E_z$$

- total energy gain proportional to path integral of longitudinal electric field

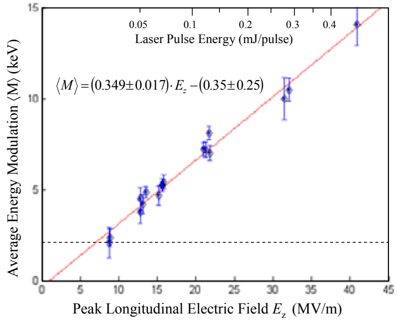
$$U = \int_{z1}^{z2} eE_z(z)dz$$

- optical phase slippage → necessity of a field- terminating boundary for nonzero energy gain. (The Lawson-Woodward Theorem)

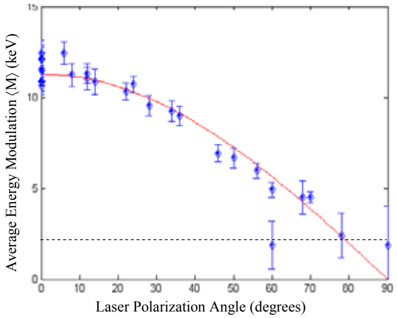
$$\int_{-\infty}^{+\infty} eE_z(z)dz = 0$$

- no optical pre-bunching: electron beam samples all optical phases of the laser: Interaction manifests as energy modulation

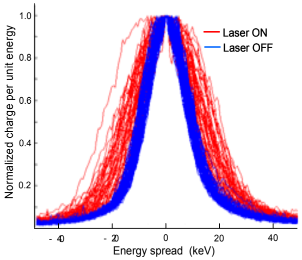
Laser electric field dependence



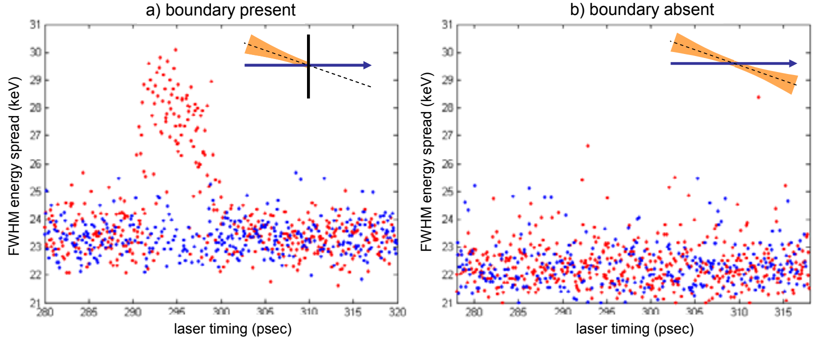
Laser polarization dependence



Observed energy modulation of the electron beam



Confirmation of the Lawson-Woodward Theorem


a) boundary present

b) boundary absent

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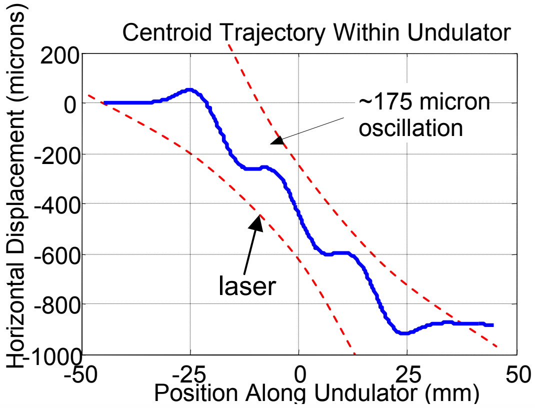
*Supported by DOEW grants DE-FG03-97ER41276 and DE-AC02-76SF00515.

First Demonstration of Harmonic Inverse FEL Interaction

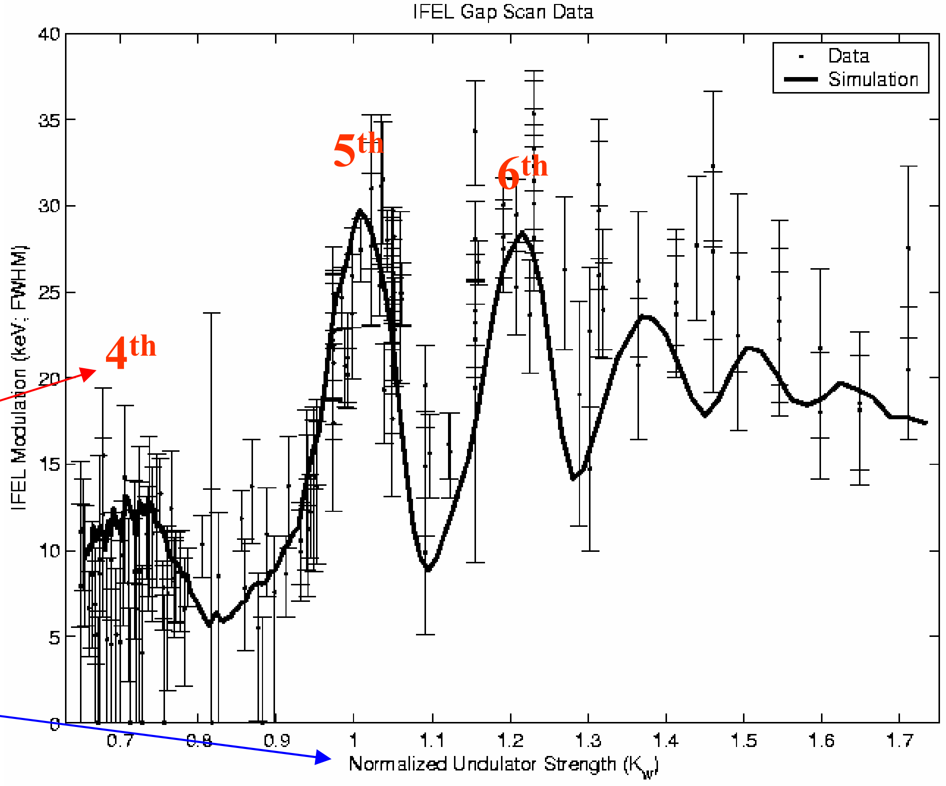


- 3 period, 1.8 cm period planar undulator with adjustable gap (B=0.3 – 1.1 Tesla)

- Laser Introduced off-axis (angle=15 mrad) with undulator de-tuned to give electrons net angle motion to coincide with laser. This increases even harmonics of interaction and simplifies laser introduction. Laser angle also needed for ITR experiment.

- Took ~150 runs at different gap heights to form plot. Compared to simulation. Observe 4th, 5th, and 6th harmonic peaks. Note: beam energy at HEPL 30 MeV; design value (for E-163) is 60 MeV, giving a starting harmonic of 4.

$$n = \frac{\lambda_w}{2\lambda_L\gamma^2}\left(1+\frac{K_w^2}{2}\right)$$

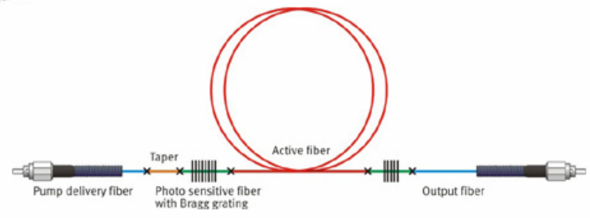


Development of Enabling Technologies

Efficient laser power is currently available

CRYSTAL FIBRE

High Power Fiber Laser Sub Assembly - BCU·150·01·Yb



Specifications		
Pump interface	Fiber:	400 µm / NA 0.22 pure silica core optical fiber
	Cable:	Steel reinforced cable
	Connector:	LD-80, angle polished. Includes mode stripping
Technology	Slope efficiency:	› 75%
	Single mode:	Yes
	Active fiber length:	‹ 2 meters (975 nm) / ‹ 6 m (915 m)
	Active fiber mode field diameter:	20 ± 2 µm
	Pump absorption @ 915 nm:	~ 3 dB/m
	Pump absorption @ 976 nm:	~ 9 dB/m
Output	Laser wavelength:	1073 ± 1 nm
	Emission bandwidth:	‹ 0.2 nm
	Output beam diameter:	20 ± 2 µm
	Output beam NA:	~ 0.05
	Output beam quality M²:	‹ 1.2
	Tested output power:	150 W
	Cable:	Steel reinforced cable
	Connector:	LD-80 , angle polished

nLIGHT PHOTONICS

Preliminary Data Sheet | **NL-SAG**

300W (cw), η_e=50%, λ=780-1000 nm

High Power Stacks

nLight Photonics' high power stacked bar module provides state-of-the-art power levels in a compact package. Starting with high power diode 1 cm bars, multiple modules are stacked to provide extremely high output power. These modules are water cooled to maximize output power without sacrificing the lifetime of the diode.

Optical	
Center Wavelength (Range)	780-1000nm
CW Output Power	300W (6 plates)
Center Wavelength Tolerance	±3.0nm
Array Length	1cm
Emitter Area	150 x 1µm
Number of Emitters	19 x 6
Emitter Size	150µm
Electrical	
Total Conversion Efficiency	50%
Threshold Current	10A
Operationg Current	60A
Operating Voltage	< 12V
Series Resistance	0.04Ω
Operating Temperature	10°C to 40°C
Fluid Flow Rate	300 ml/min/plate
Inlet to Outlet presure drop	30 psi
Deionized Water Resistivity	.5 – 2Mohm-cm
Filter	< 20µm

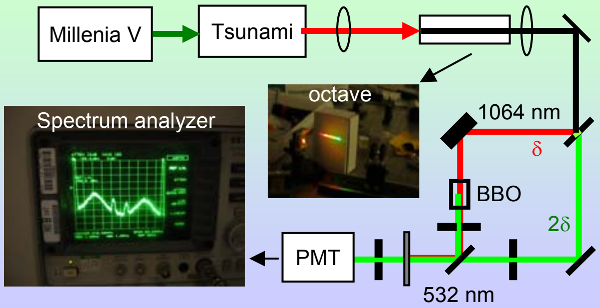
η_{tot}=(90%)(75%)(50%)=**34% wall plug-to-light**

Optical Phase Locking of Modelocked Lasers

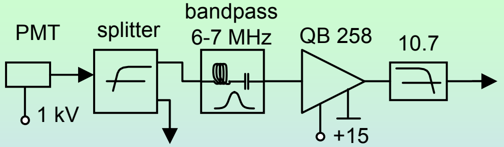
Present accomplishments

- observed the comb offset from a commercial Ti:Sapphire modelocked laser
- isolated a comb offset error signal
- manipulated the comb offset with an electronic signal
- constructed and tested a balanced cross-correlator
- we are presently switching to a 1 mm Yb:glass fiber modelocked laser

Comb offset detection experiment

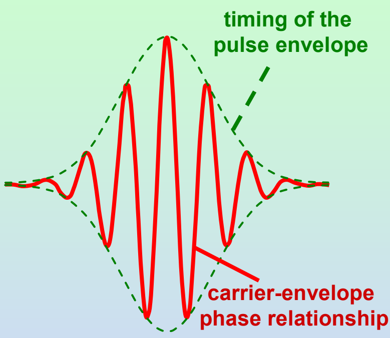


Beatnote detection circuitry



Two parameters for the control of the optical phase for modelocked lasers

Pulse envelope timing and carrier-to-envelope phase



Timing detection and control to within a fraction of an optical cycle

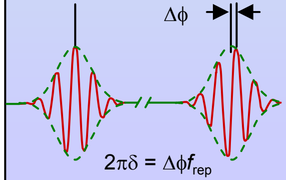
(1 opt. cycle ~ 3 fsec)

Balanced cross correlator technique (40° of optical phase)

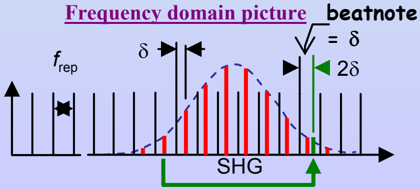
Frequency comb stabilization techniques

Requires one octave of bandwidth.

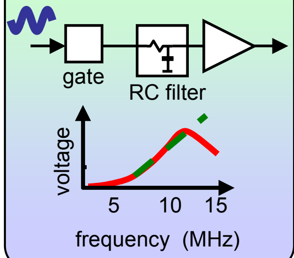
Time domain picture



Frequency domain picture



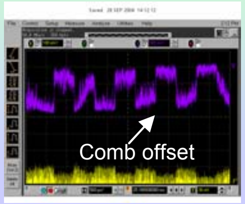
Comb Self referencing technique



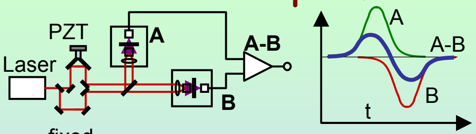
Comb offset control

Error signal into AOM controls pump power and dispersion of laser

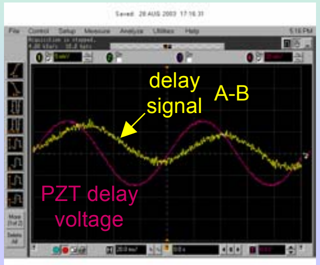
AOM signal:
1.0 kHz, 0.2V square wave



The balanced cross-correlator experiment



fixed delay



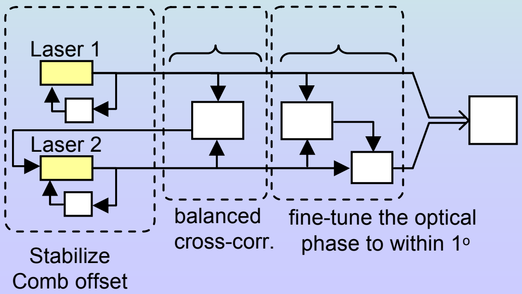
PZT delay

V_{pp} = 60 mV
t = 240 attosec

Future objectives

repeat these measurements with the fiber laser

- feedback the comb error signal and stabilize the comb offset of a single laser
- construct a second identical fiber laser
- synchronize the pulse envelopes of the lasers to sub-fsec with the balanced cross-corr. technique
- eliminate residual phase jitter with an external interferometer unit controlling a variable path delay (e.g. a PZT)



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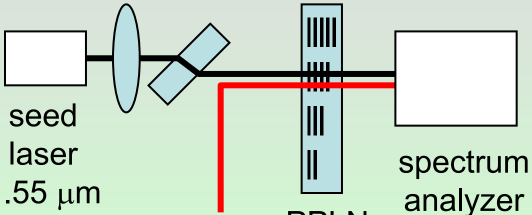
† Supported by DOEW grants DE-FG03-97ER41276 and DE-AC02-76SF00515.

Enabling Technologies for Laser Accelerators

generation of 1,5 mm radiation

OPA arrangement



Long term objective:
to utilize degenerate OPA as an efficient means for producing 2mm radiation from 1mm lasers

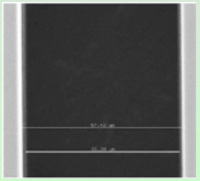
Sam Wong, Stanford

Silicon micromachining

Advantages of Si

- advanced micromachining technology
- possibility for integrated electronic circuits
- optically transparent 1.5-10 μm
- abundant and inexpensive
- high index of refraction
- good heat conductor
- radiation resistant

Optical quality surfaces



mm-deep trenches

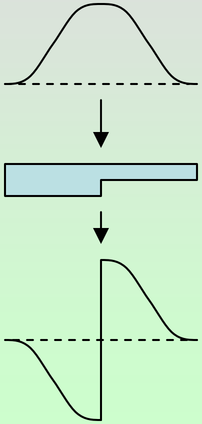
Sharp point features

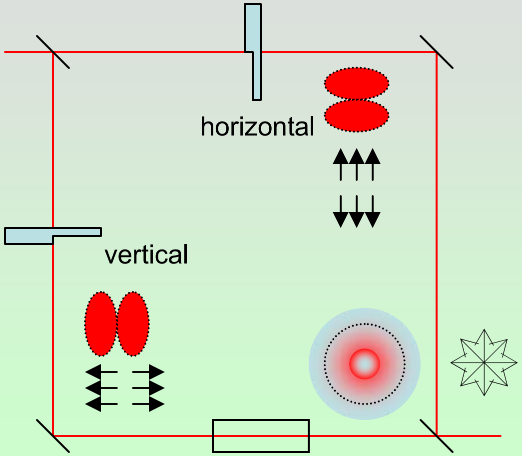
Challenges

- limited geometry freedom with existing anisotropic etching techniques
- semiconductor:→ lower bandgap energy, easier multiphoton absorbtion
wer laser damage threshold

Byer Group, Stanford

Generation of radially polarized modes





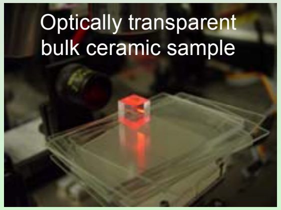
Variable path delay

Patrick Lu, Stanford

Ceramics micromachining

Advantages of ceramics

- possibility for magnetic and optical materials from compatible substrates
- macroscopically amorphous: no restricted geometry limitations
- potentially higher degree of purity and less defect sites
- enhanced flexibility in mixing of different materials
- do not require expensive crystal growth step
- typical substrates like YAG: larger bad gap
  - → also transparent at visible wavelengths
  - → higher laser damage threshold
  - → higher melting points



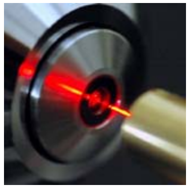
Optically transparent bulk ceramic sample

50 μm spacing pattern Imprinted with a Silicon preform

Challenges

- optical ceramics fabrication technology is a relatively new topic
- micromachining technology on ceramics
ot been developed.

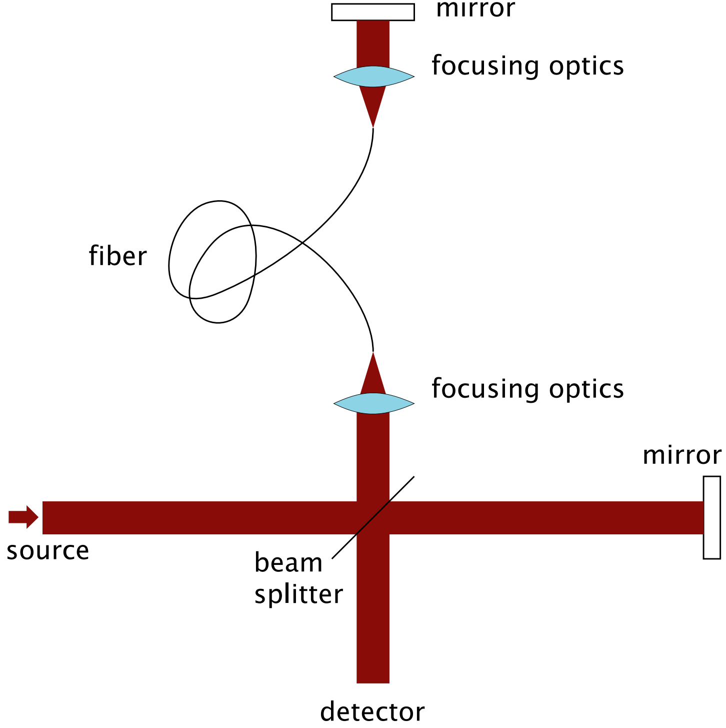
Romain Gaume, Stanford



Measurements with Photonic Band Gap Fibers

- Coupling of electron beam and laser into the same fiber
  - Explore coupling with sufficient free space
- Measurement of the transmission bandwidth
- Coupling of radially polarized light (TEM^*_{01}) into the fiber
  - Creation of an accelerating mode
- Measurement of mode profiles
  - Far field intensity distribution
  - Distribution at the exit of the fiber
- Temperature dependency of phase velocity
  - Measurement using interferometer
- Vibration sensitivity

⇝ Address technical issues on the road to a photonic band gap fiber accelerator

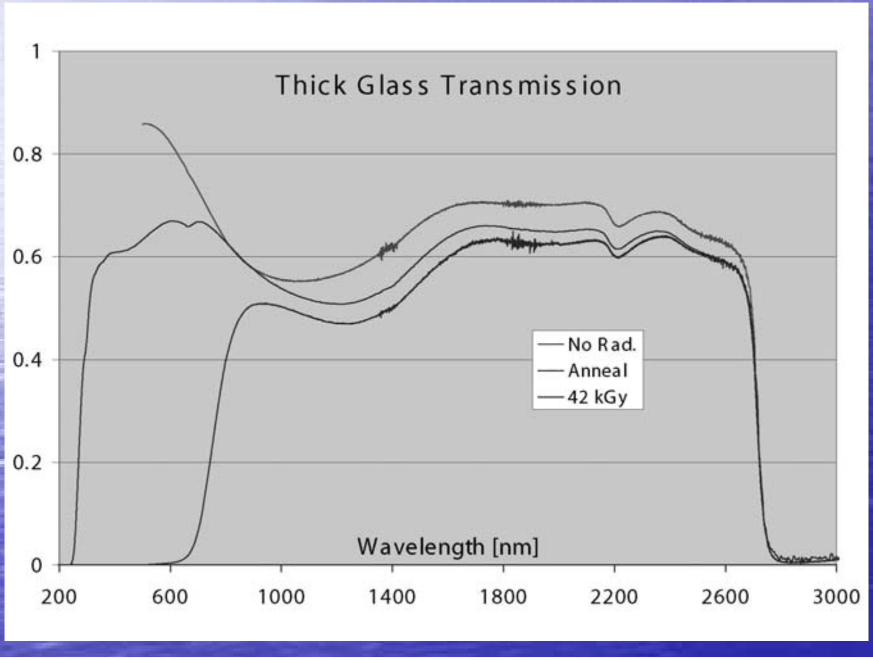


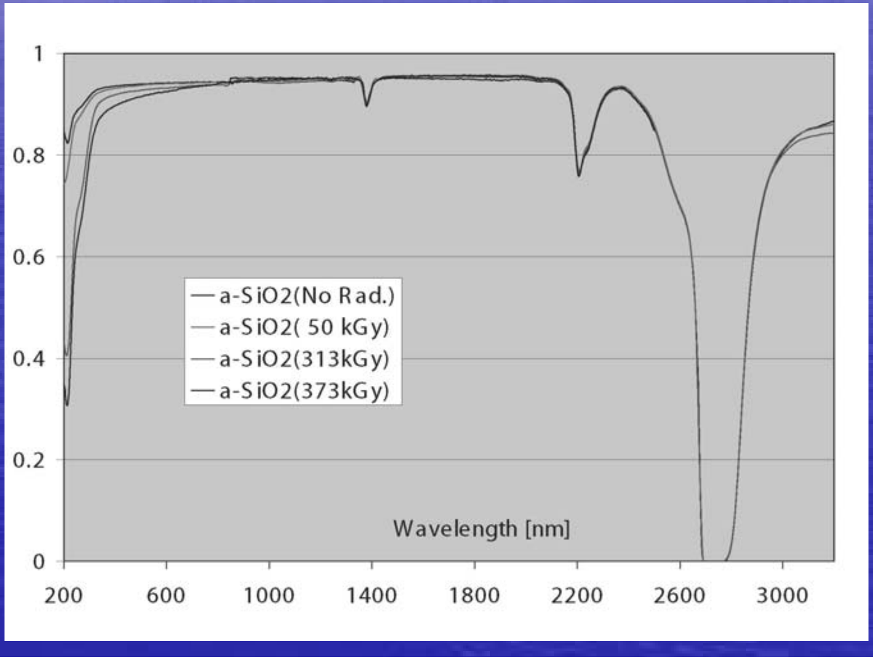
Planned interferometer to measure phase velocity stability

Radiation Hardness of Optical Materials

- Co^{60} γs on ½-in Borosilicate glass(left) and Silica (right).
- Much water and many low energy valence states.

- Heraeus uses Flame Hydrolysis of $SiCl_4$.
- Suprasil300 impurities + water ≤1ppm (μg/g).
- Polished samples from IMRA: 3,6,12,24,48mm.





IMRA

IMRA America, Inc.
Ann Arbor, MI

- Materials samples
- **Collaboration to draw first made-to-order PBG accelerator fiber**

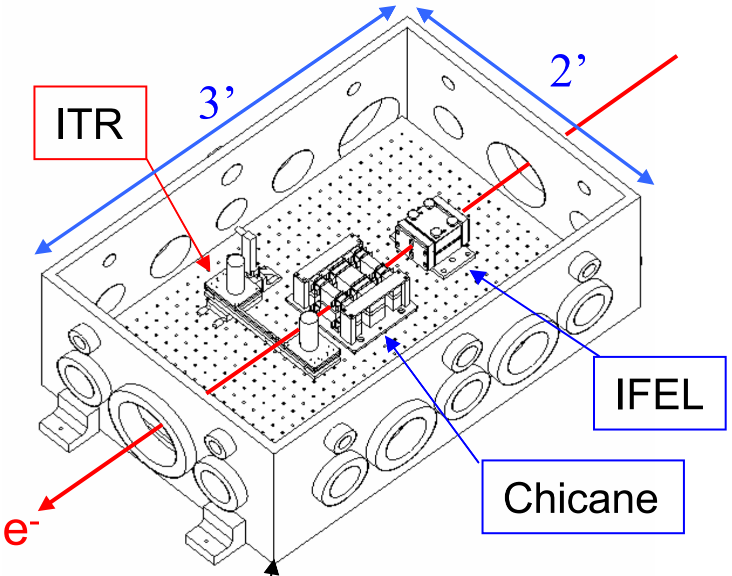
CRYSTAL FIBRE

Crystal Fibre
Birkerød, Denmark

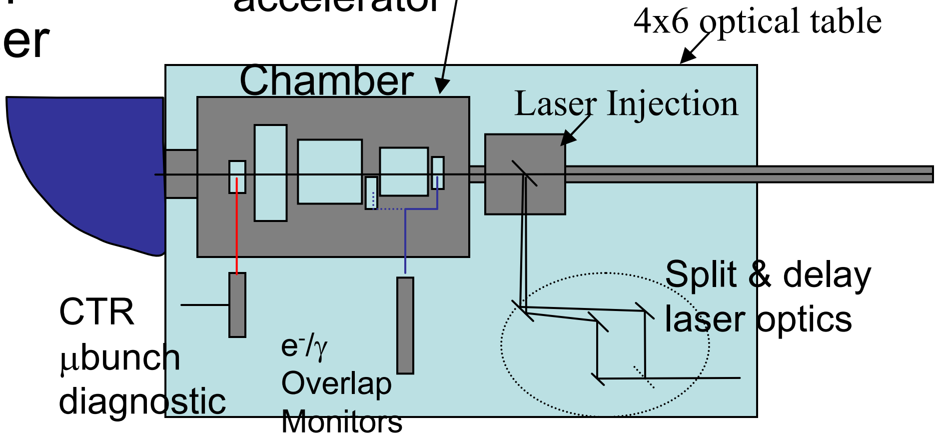
- Fiber samples

E-163 Experiments

- New large chamber to accommodate range of experiments & their diagnostics
- Components inside chamber mounted on thermally-stabilized kinematically-supported breadboard
- Chamber sits on a larger optical table; will have focusing optics and diagnostics
- Microbunching hardware: IFEL plus chicane. Already fabricated.
- Permanent magnet Quadrupole Triplet for focusing into small apertures of laser structures



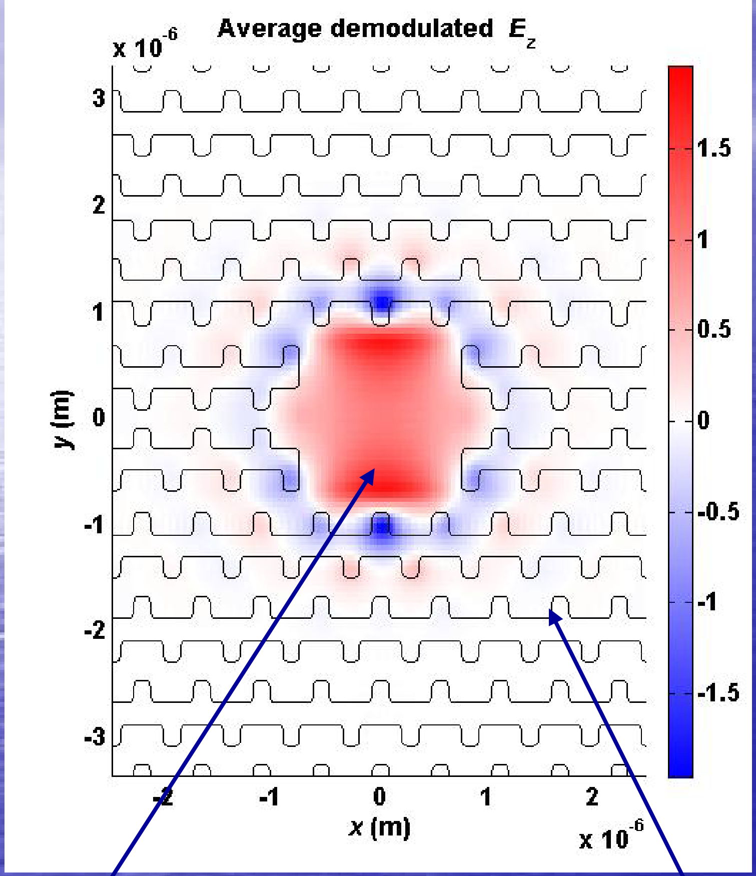
CAD of chamber with bunching hardware and tape boundary accelerator



Microstructure Development

Planar photonic accelerator structures

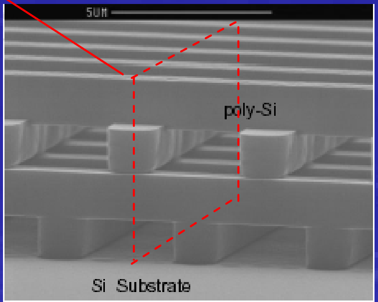
- Found accelerating mode in planar photonic bandgap structure
- Developed method of optical focusing for particle guiding over ~1m; examined longer-range beam dynamics
- Simulated several coupling techniques
- Current work:
  - Exploring fabrication techniques
  - Simulating effects of fabrication error
  - Developing efficient coupling



Vacuum defect/beam path

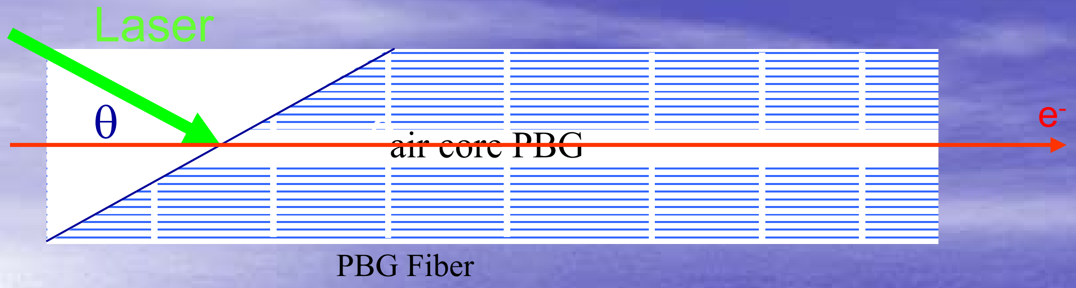
silicon

Structure contour shown for $z = 0$; field normalized to $E_{acc} = 1$



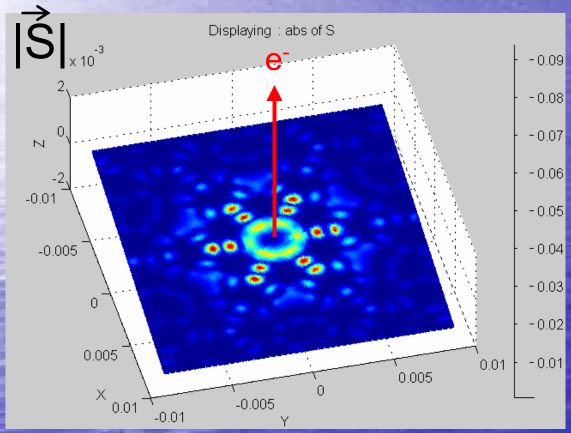
S. Y. Lin *et. al.*, Nature **394**, 251 (1998)

Free Space Coupler: Fiber Cleave

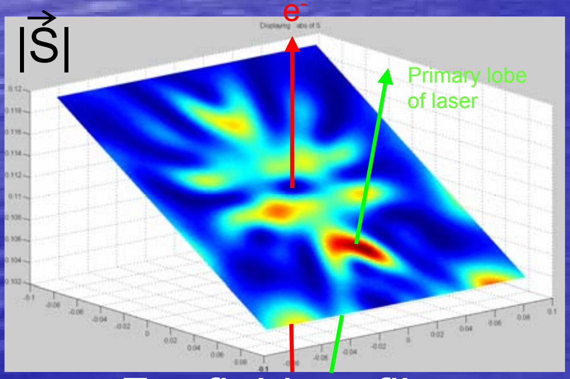


- Ease of fabrication
- Coupling efficiency controlled by angle θ

Solve reciprocal problem:

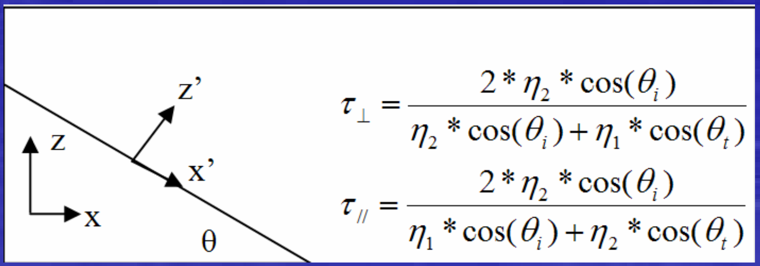


Near field



Far field profile

1. Load field profiles from MIT Photonic Bands code, assuming infinite waveguide in propagating direction
2. Add phase factor E=E*exp(i*k*z);
3. E and H fields along x and z direction decomposed into x’ and z’ direction
4. Apply Fresnel’s coefficient at the air-dielectric interface to calculate transmitted field
5. E and H fields composed back to x and z
6. Calculate point sources and radiate into farfield (custom Matlab vector diffraction code)

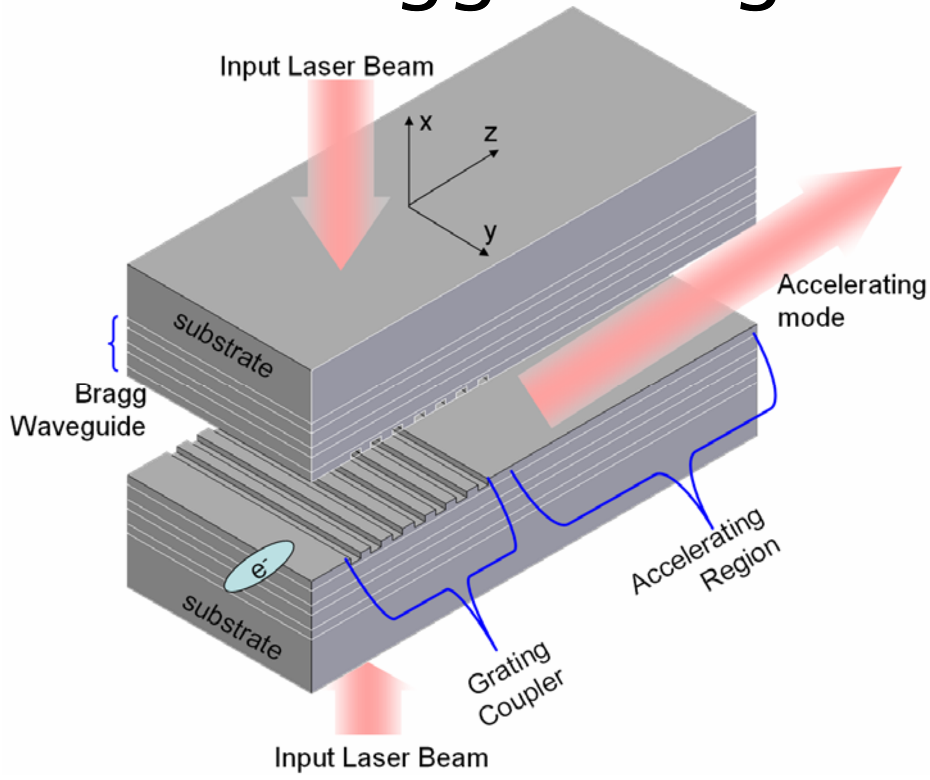


$$\tau_{\perp} = \frac{2 * \eta_2 * \cos(\theta_i)}{\eta_2 * \cos(\theta_i) + \eta_1 * \cos(\theta_t)}$$

$$\tau_{//} = \frac{2 * \eta_2 * \cos(\theta_i)}{\eta_1 * \cos(\theta_i) + \eta_2 * \cos(\theta_t)}$$

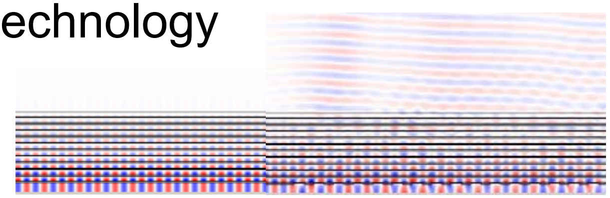
Planar Bragg waveguide structure

Zhiyu Zhang, ARDA

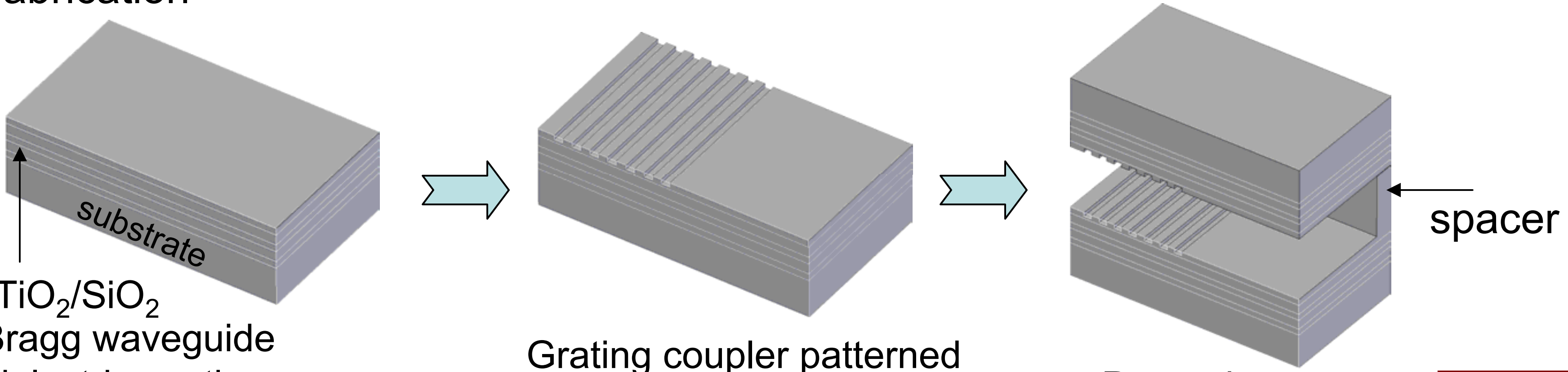


Optical all-dielectric planar accelerator structure

- Accelerating mode guided by the Bragg waveguide
- Grating coupler couples laser light from the side and converts it to accelerating mode
- Waveguide and coupler can be fabricated with micro-processing technology



Fabrication



TiO_2/SiO_2 Bragg waveguide dielectric coating

Grating coupler patterned by ebeam lithography or focused ion beam

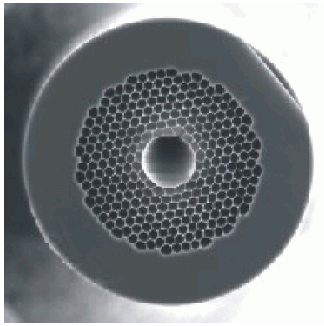
Patterning spacer and bonding

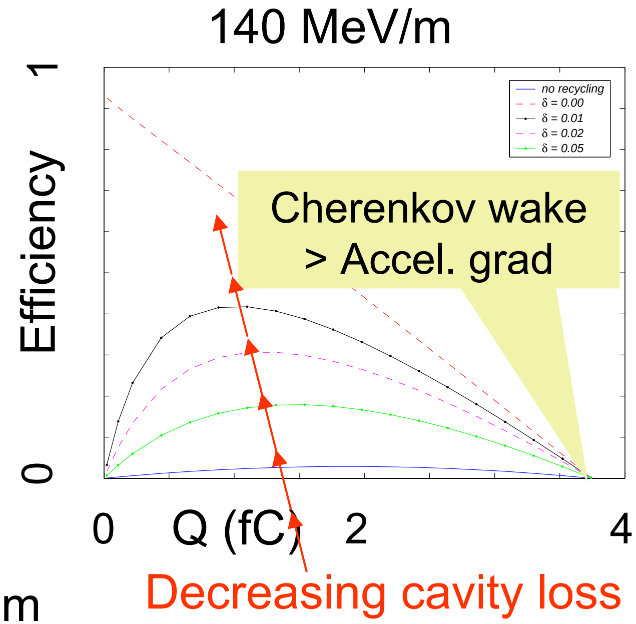
Designed for Nd:YAG

Laser Accelerator Efficiency

What efficiency can be achieved & what are the implications?

High efficiency => near field structures with R ~ λ.



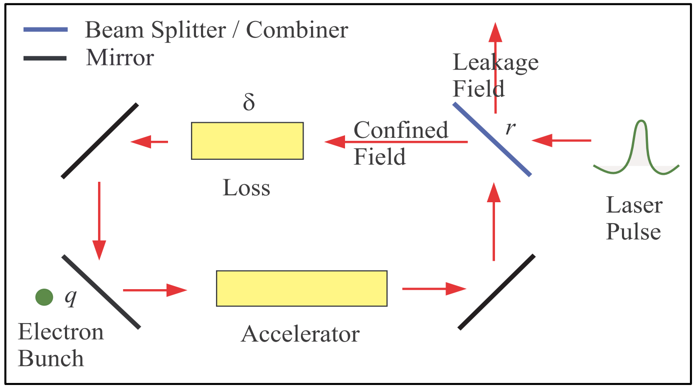


Consequence is small charge/bunch
(calculations for a reasonable example structure)

Increase efficiency by incorporating the accelerator in an optical cavity with coupling matched to the beam

Results of Efficiency Analysis

- Luminosity of a laser driven linear collider must come from spot size and repetition rate
- Higher charge/bunch applications will need open structures. Efficiency could be increased with an optical cavity.



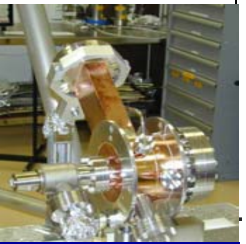
E-163 Progress and Plans

Status: June 2005

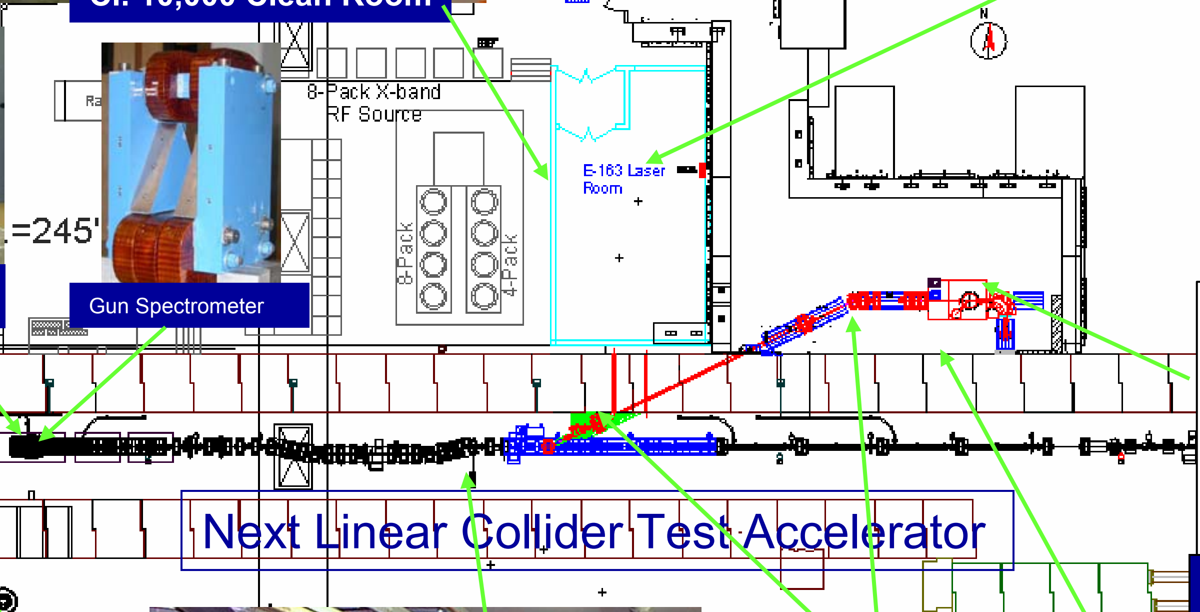
Cl. 10,000 Clean Room

Counting Room
(b. 225)

Ti:Sapphire Laser System

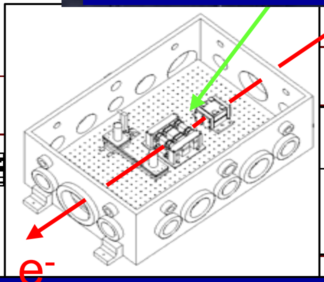


RF PhotoInjector



Gun Spectrometer

Optical Microbuncher



New Expt. Chamber

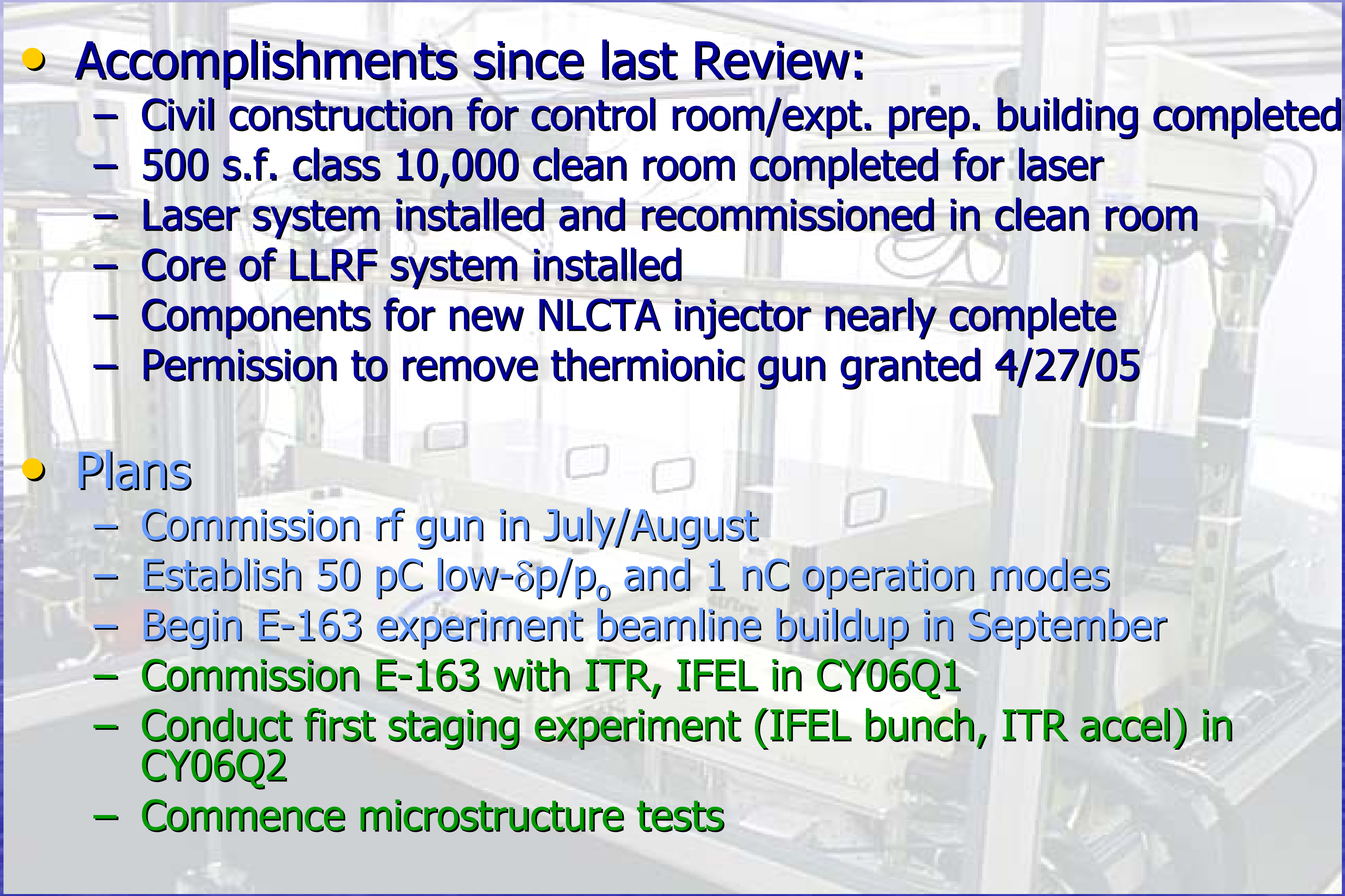
RF System

NLCTA; T'Gun Removed

Beamline quads

60 MeV Experimental Hall

E-163 Accomplishments and Plans

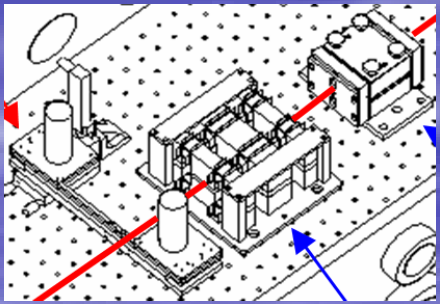


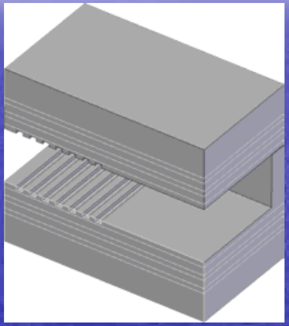
- **Accomplishments since last Review:**
  - Civil construction for control room/expt. prep. building completed
  - 500 s.f. class 10,000 clean room completed for laser
  - Laser system installed and recommissioned in clean room
  - Core of LLRF system installed
  - Components for new NLCTA injector nearly complete
  - Permission to remove thermionic gun granted 4/27/05

- Plans
  - Commission rf gun in July/August
  - Establish 50 pC low-$\delta p/p_o$ and 1 nC operation modes
  - Begin E-163 experiment beamline buildup in September
  - Commission E-163 with ITR, IFEL in CY06Q1
  - Conduct first staging experiment (IFEL bunch, ITR accel) in CY06Q2
  - Commence microstructure tests

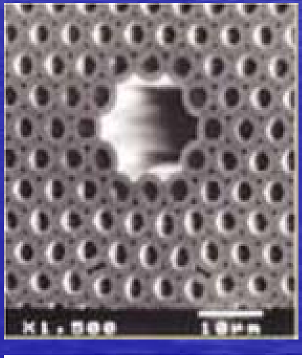
Roadmap

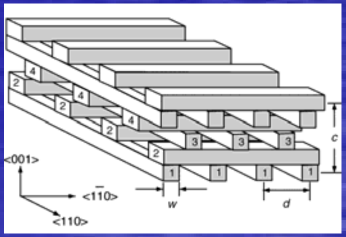
- Next 2 Years
  - Complete Inverse Transition Radiation Experiment
    - Boundary condition (in-)dependence
    - Angular dependence
  - Commission optical buncher (IFEL and chicane)
  - Conduct acceleration experiment (IFEL buncher, ITR accelerator)
  - Install Nd:YAG laser and test planar Bragg waveguide structure
  - Test PBG fiber structures (free-space TM_{01}^{*} end-coupled)
  - Continue degenerate OPA development (wavelength doubler)
  - Investigate engineering issues: thermal, vibration, and tolerance
  - Phase lock two lasers





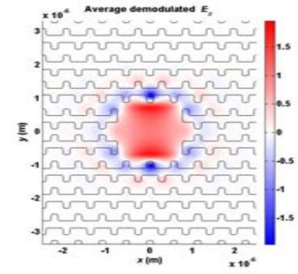
- 3-5 Years
  - Develop structures specifically for radiation generation
    - As antennae for beam diagnostics
    - As sources of ps- and ultimately fs-duration radiation
  - Test woodpile- and collonade-type structures (lithographic process)
  - Continue to push gradient & efficiency (low-Q, small aperture)
  - Develop structures for light source use (high-Q, large aperture)
  - Develop waveguiding power coupler
  - Investigation laser pulse recirculation
  - Develop a full accelerator "unit" (couplers+structure, environmental controls, diagnostics, possibly focusing)
  - Engineer and test structures using the high-efficiency lasers



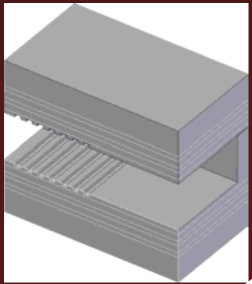


STANFORD LINEAR ACCELERATOR CENTER
ESTABLISHED 1962
D.O.E.

Stanford University

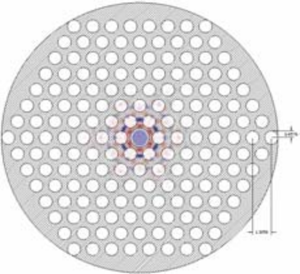


3D Photonic Crystal



Planar Bragg Waveguide (ARDA)

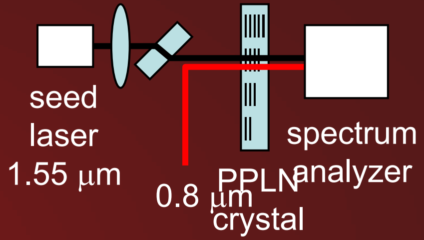
Stanford University
Partner Companies
Center for Integrated Systems



Photonic Crystal Fiber

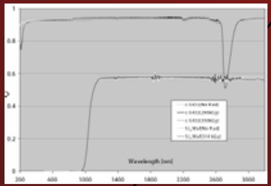
Structure Testing at the NLCTA (E-163)

Laser Acceleration

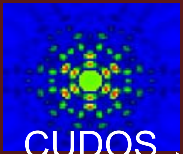


Efficient Wavelength Doubling

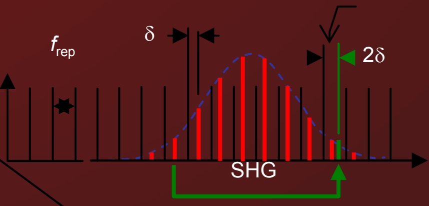
SPRC
STANFORD PHOTONICS RESEARCH CENTER



Rad-hard optical materials



CUDOS



Laser Phase Locking

The University of Sydney
Australia

IMRA

CRYSTAL FIBRE