E-163 and Laser Acceleration

Eric R. Colby
AARD & *E163 Spokesman*

Work supported by Department of Energy contracts DE-AC03-76SF00515 (SLAC) and DE-FG03-97ER41043-III (LEAP).

E-163 At-a-Glance

Who we are

SLAC→PPA→ARD→AARD→E163

PIs: Robert H. Siemann (50%), SLAC & Robert L. Byer, Stanford University

Staff Physicists
Eric R. Colby (100%), Spokesman
Robert J. Noble (30%)
James E. Spencer (ret.)

Engineering Physicist
Dieter Walz (ASD, 10%)

Graduate Students
Chris McGuinness
Chris Sears [grad June 08]
Umut Eser

Postdoctoral RA
Joel England (100%)
Rasmus Ischebeck (50%) [now at PSI]

E163 Collaborators
Tomas Plettner (Stanford University)
Jamie Rosenzweig (UCLA)
Sami Tantawi (ATR)
Cho Ng (ACD)

What we do

Develop laser-driven dielectric accelerators into a useful accelerator technology by:

* Developing and testing candidate dielectric laser accelerator structures
* Developing facilities and diagnostic techniques necessary to address the unique technical challenges of laser acceleration

Publications

20 since May 2007:

* 6 Refereed papers (all in *Physical Review*)
* 14+ Conference papers (6 at PAC2007, 4+ at AAC2008, 4 at others)

Graduate Theses since May 2007

* **Chris Sears**, Ph.D., Stanford, “PRODUCTION, CHARACTERIZATION, AND ACCELERATION OF OPTICAL MICROBUNCHES”, June 2008.

Refereed Publications since May 2007

- **Production and characterization of attosecond electron bunch trains,** C.M.S. Sears, E. Colby, R. Ischebeck, C. McGuinness, J. Nelson, R. Noble, J. Spencer, R.H. Siemann, D. Walz, R.L. Byer, T. Plettner, *Phys. Rev. ST Accel. Beams* 11, 061301 (2008)
- **Three-dimensional dielectric photonic crystal structures for laser-driven acceleration**, Benjamin M. Cowan, *Physical Review Special Topics – Accelerators and Beams* **11**, 011301 (2008).
- **Proposed dielectric microstructure laser-driven undulator**, T. Plettner, R.L. Byer, *Physical. Review. Special Topics – Accelerators and Beams* 11, 030704 (2008)

- **Generation and measurement of relativistic electron bunches characterized by a linearly ramped current profile**, R.J. England, J.B. Rosenzweig, and G. Travish *PRL* 100, 214802 (May 28, 2008).
- **Experimental Generation and Characterization of Uniformly Filled Ellipsoidal Electron-Beam Distributions**, P. Musumeci, J. T. Moody, R. J. England, J. B. Rosenzweig, and T. Tran, *Phys. Rev. Lett*. **100**, 244801 (2008)

- **Essay: Accelerators, Beams and *Physical Review Special Topics – Accelerators and Beams*,** R. H. Siemann**,** Founding Editor**,** *Physical Review Special Topics – Accelerators and Beams* **11**, 050003 (2008)

Community Service Since May 2007

Eric Colby

2007 Particle Accelerator Conference Program Committee Member
LBNL -- 2007 Director's Review of Accelerator & Fusion Research Department
FNAL -- A-Zero Photoinjector Program Committee, 2001-- present
LCLS -- Gun Test Facility Task Force Co-leader, 2006 – present
DOE SBIR Proposal Reviewer, 2001 – present
DOE HENP Grant Renewal Reviewer, 2001 – present
PRST-AB, IEEE Trans. Plasma Science, PRE, and Physics of Plasmas paper referee
Panofsky Fellowship Selection Committee Member, 2006 – present
Member, Accelerator Research Associate Committee, PPA Division
Member, DOE Office of Independent Oversight Action Item C-2 Response Committee
Radiation Safety Committee Member 2008 – present

Joel England

Member of the Advanced Instrumentation Seminar Committee

Rasmus Ischebeck (frmr.)

2006 Advanced Accelerator Concepts Workshop Organizing Committee Member and Working Group Leader
LCLS Design Reviewer, 2006

Robert Noble

Chair, Accelerator Research Associate Committee, PPA Division
Referee for *Physics of Plasma* Journal

Stephanie Santo (frmr.)

Assistant to the Editor, *Physical Review Special Topics - Accelerators and Beams*, 2003 – 2007
AARD Safety Committee Member, 2004 –2008

Robert Siemann

Founding Editor, *Physical Review Special Topics - Accelerators and Beams*, 1998 – 2007
Chair, Accelerator Systems Advisory Committee of the Spallation Neutron Source, 1998 – 2006
DOE Tevatron Operations Review, March 2006

James Spencer (ret.)

DOE SBIR Proposal Reviewer, 2006
Physical Review and Physical Review Letters paper referee
Member, ARD Research Associate Committee
Judge, Santa Cruz County and Santa Clara Science Fairs
Member, Accelerator Research Associate Committee, PPA Division
Member, ETF Committee that assessed SLAC's commitment to education and outreach with the idea of proposing a broader, more unified program
Member, SULI selection committee

E-163: Relevance to the DOE Mission

Motivation

* **High gradient** (>0.5 GeV/m) and high wall-plug power efficiency are possible

➔ **HIGH ENERGY PHYSICS**

* Short wavelength acceleration naturally leads to **attosecond bunches** and point-like radiation sources

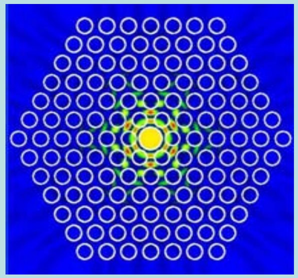
➔ **BASIC ENERGY SCIENCES**

* Lasers are a **large-market technology** with rapid R&D by industry (DPSS lasers: ↑0.22 B$/yr vs. ↓0.060B$/yr for microwave power tubes)
* Structure Fabrication is by **inexpensive mass-scale** industrial manufacturing methods

➔ **COMMERCIAL DEVICES**

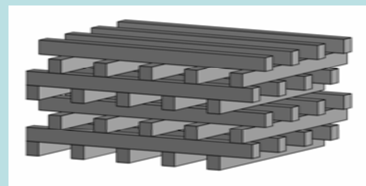
Structure Candidates for High-Gradient Accelerators

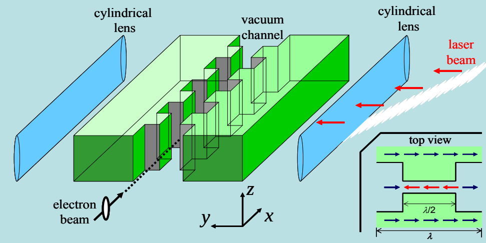
Maximum gradients based on measured material damage threshold data



Photonic Crystal Fiber
Silica, λ=1053nm,
E_z=790 MV/m

Photonic Crystal "Woodpile"
Silicon, λ=1550nm,
E_z=240 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)

(193 microbunches of $1x10^4$ e^- in 1 psec) x 200MHz

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

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

		ILC Nom	Fiber
E_cms	GeV	1000	1000
Bunch charge	e	2.0E+10	1.0E+04
# bunches/train	#	2820	193
train repetition rate	MHz	5.0E-06	200
final bunch length	psec	1.00	1.00
design wavelength	micron	1.55	1.55
Invariant Emittances	micron	10/0.04	1e-4/1e-4
I.P. Spot Size - X	nm	554/3.5	0.5/0.5
Geometric Luminosity	**/cm^2/s**	**2.32E+34**	**2.39E+34**
Beam Power	MW	45.2	62.0
Gradient	MeV/m	30	790
Active Linac Length	m	33333	1266

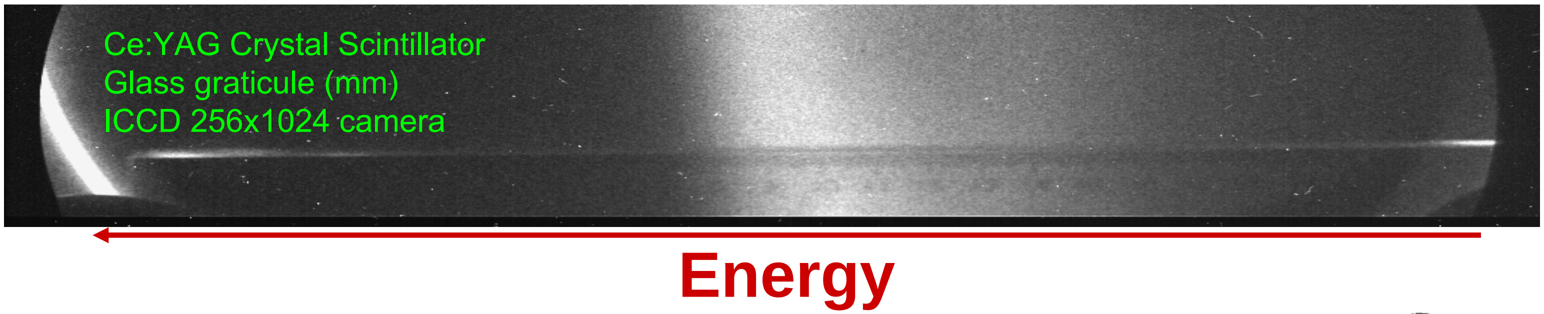
E-163: Laser Acceleration at the NLCTA

E-163 Scientific Goal: Investigate physical and technical issues of laser acceleration using dielectric structures

Build a test facility with high-quality electron and laser beams for advanced accelerator R&D

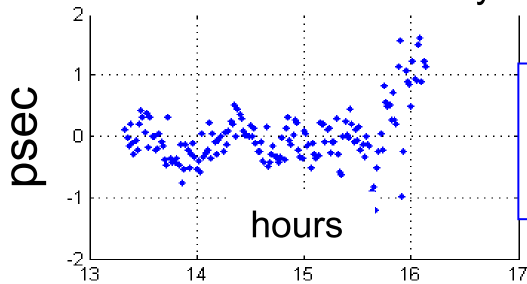
- Endorsed by EPAC and approved by the SLAC director in July 2002
- Test facility construction completed December 2006
- Accelerator Readiness Review completed December 18th, 2006
- Director's and DOE Site Office approval to begin operations granted March 1st, 2007
- E163 Beamline commissioning begun March 8th, 2007

First beam to high resolution spectrometer of E163 beamline on March 16th, 2007!



Timing stability and very narrow energy spread have been demonstrated

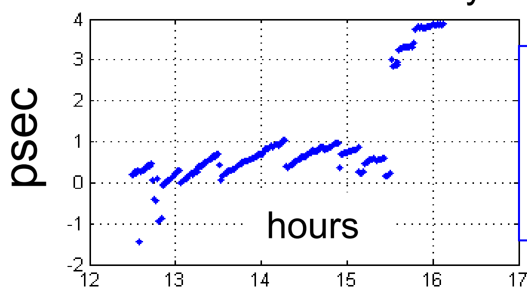
Gun RF Phase Stability



Gun (s-band)

σ_ϕ=0.46ps
over 3 hours

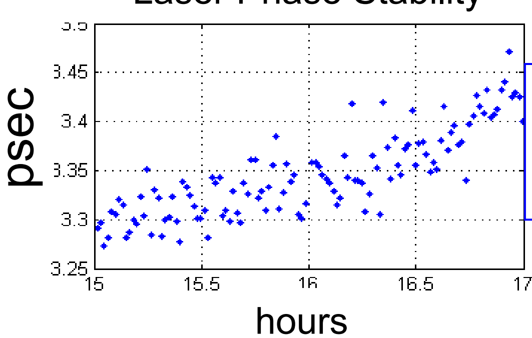
X-band Phase Stability



Accelerator (x-band)

σ_ϕ=1.2ps
over 3.5 hours

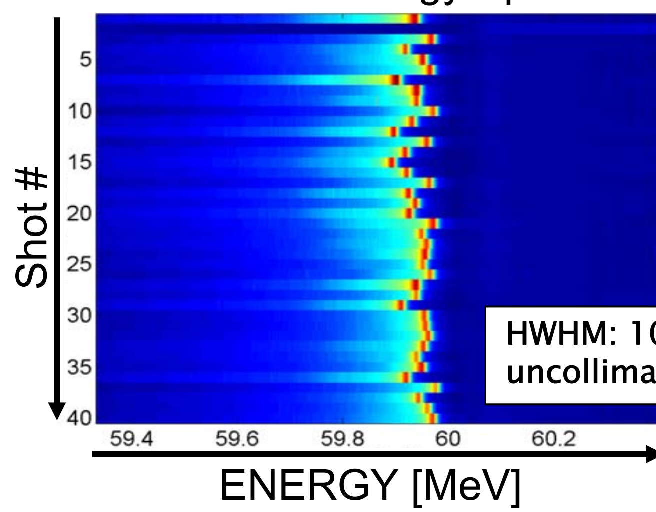
Laser Phase Stability



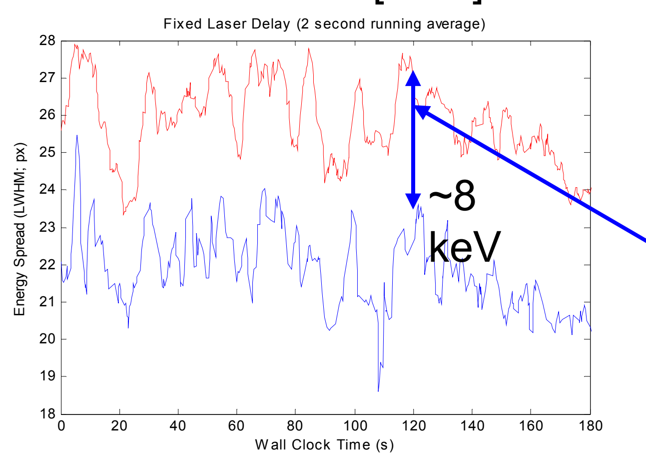
Laser

σ_ϕ=0.044 ps
over 2 hours

Electron Beam Energy Spectrum



HWHM: 10keV ⇔ 1.7×10^{-4}
uncollimated



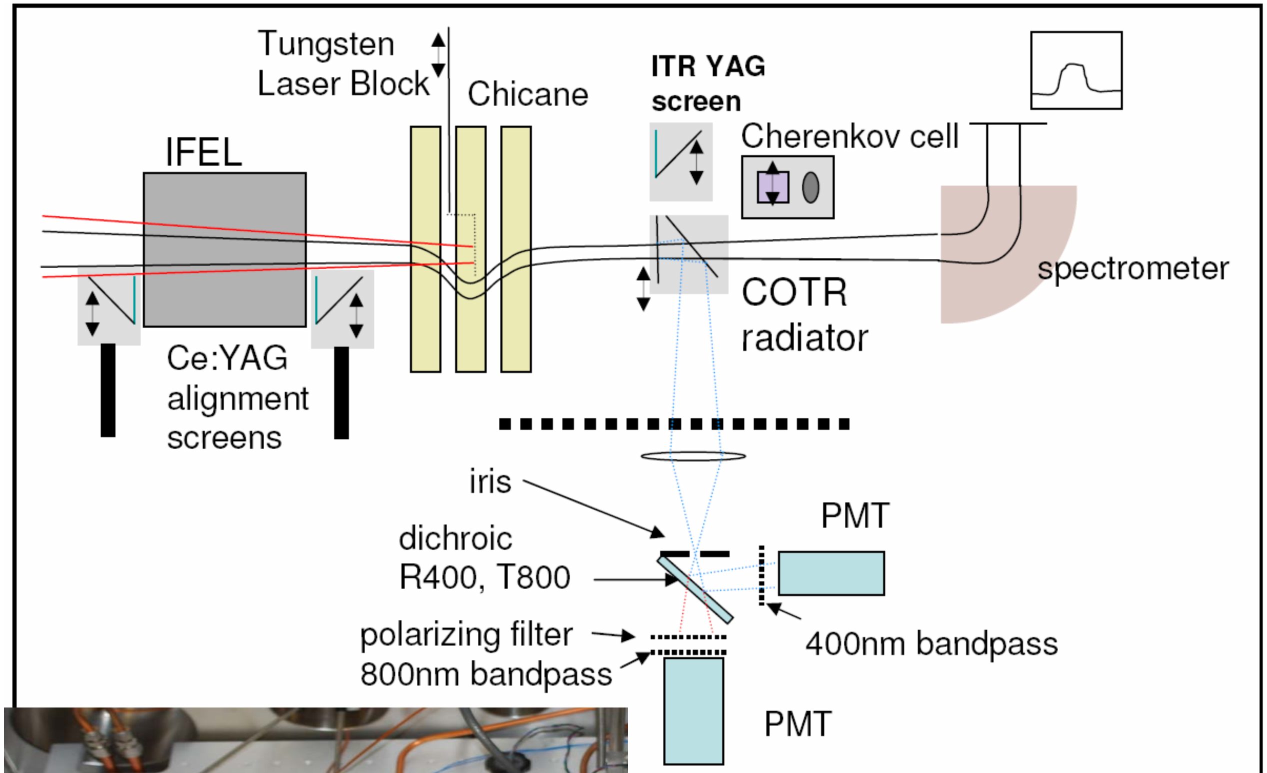
Interaction Strength remains essentially constant over 3 minute period

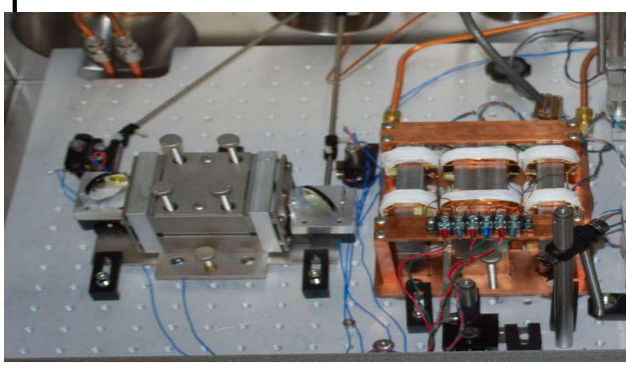
E163 Capabilities

* Electron Beam
  - 60 MeV, 5 pC, $\delta p/p \leq 10^{-4}$, e~1.5x1.5 μ, $\sigma_t \sim 0.5$ psec
  - Beamline & laser pulse optimized for very low energy spread, short pulse operation
* Laser Beams
  - 10 GW-class Ti:Sapphire system (800nm, 2 mJ)
    - KDP/BBO Tripler for photocathode (266nm, 0.1 mJ)
  - Active and passive stabilization techniques
  - 5 GW-class Ti:Sapphire system (800nm, 1 mJ)
    - 100 MW-class OPA (1000-3000 nm, 80-20 μJ)
* Precision Diagnostics
  - Picosecond-class direct timing diagnostics
  - Femto-second class indirect timing diagnostics
  - Picocoulomb-class beam diagnostics
    - BPMS, Profile screens, Cerenkov Radiator, Spectrometer
  - A range of laser diagnostics, including autocorrelators, crosscorrelators, profilometers, etc.

You'll visit the E-163 Facility on your tour this afternoon

Attosecond Bunching Experiment Schematic

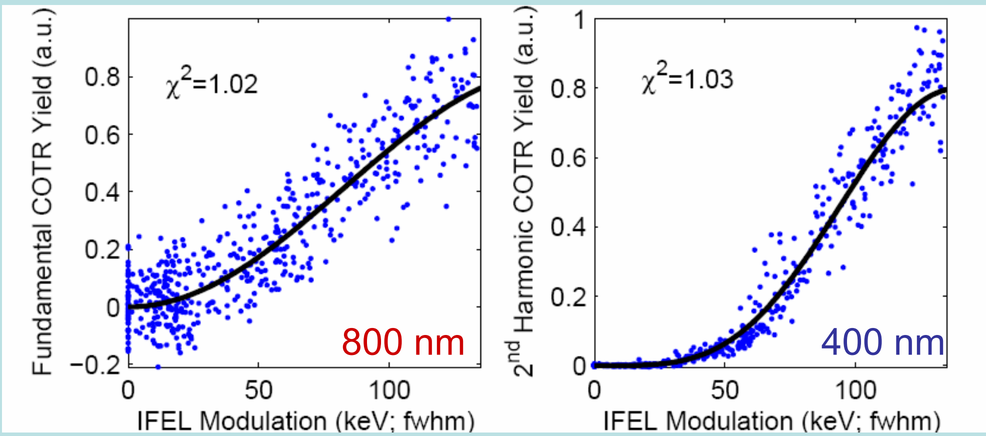




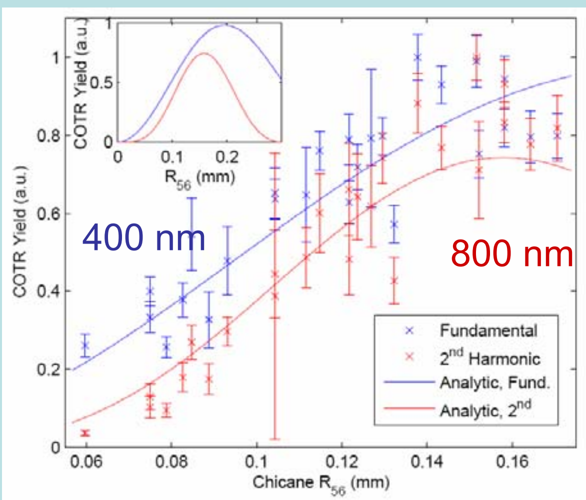
Experimental Parameters:

- Electron beam
  - $\gamma=127$
  - Q~5-10 pC
  - $\Delta\gamma/\gamma=0.05\%$
  - Energy Collimated
  - $\varepsilon_N=1.5\ \pi\ \mu$
- IFEL:
  - ¼+3+¼ period
  - 0.3 mJ/pulse laser
  - 100 micron focus
  - z_0=10 cm (after center of und.)
  - 2 ps FWHM
  - Gap 8mm
- Chicane 20 cm after undulator
- Pellicle (Al on mylar) COTR foil

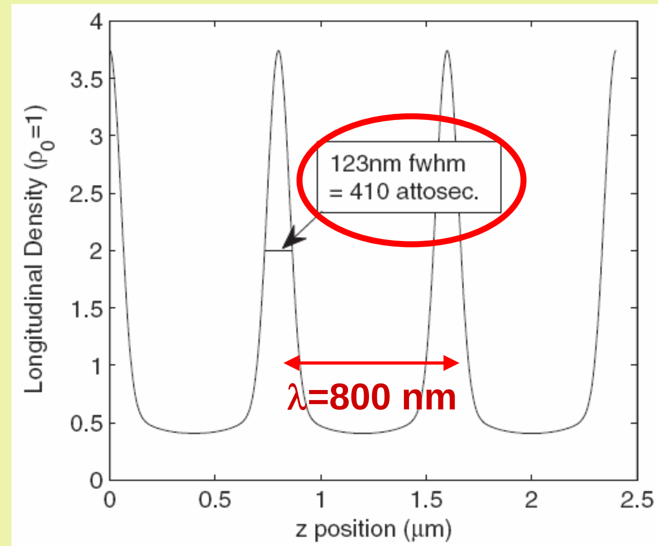
Attosecond Bunch Train Generation



First- and Second-Harmonic COTR Output as a function of Energy Modulation Depth ("bunching voltage")



Left: First- and Second-Harmonic COTR output as a function of temporal dispersion (R_{56})

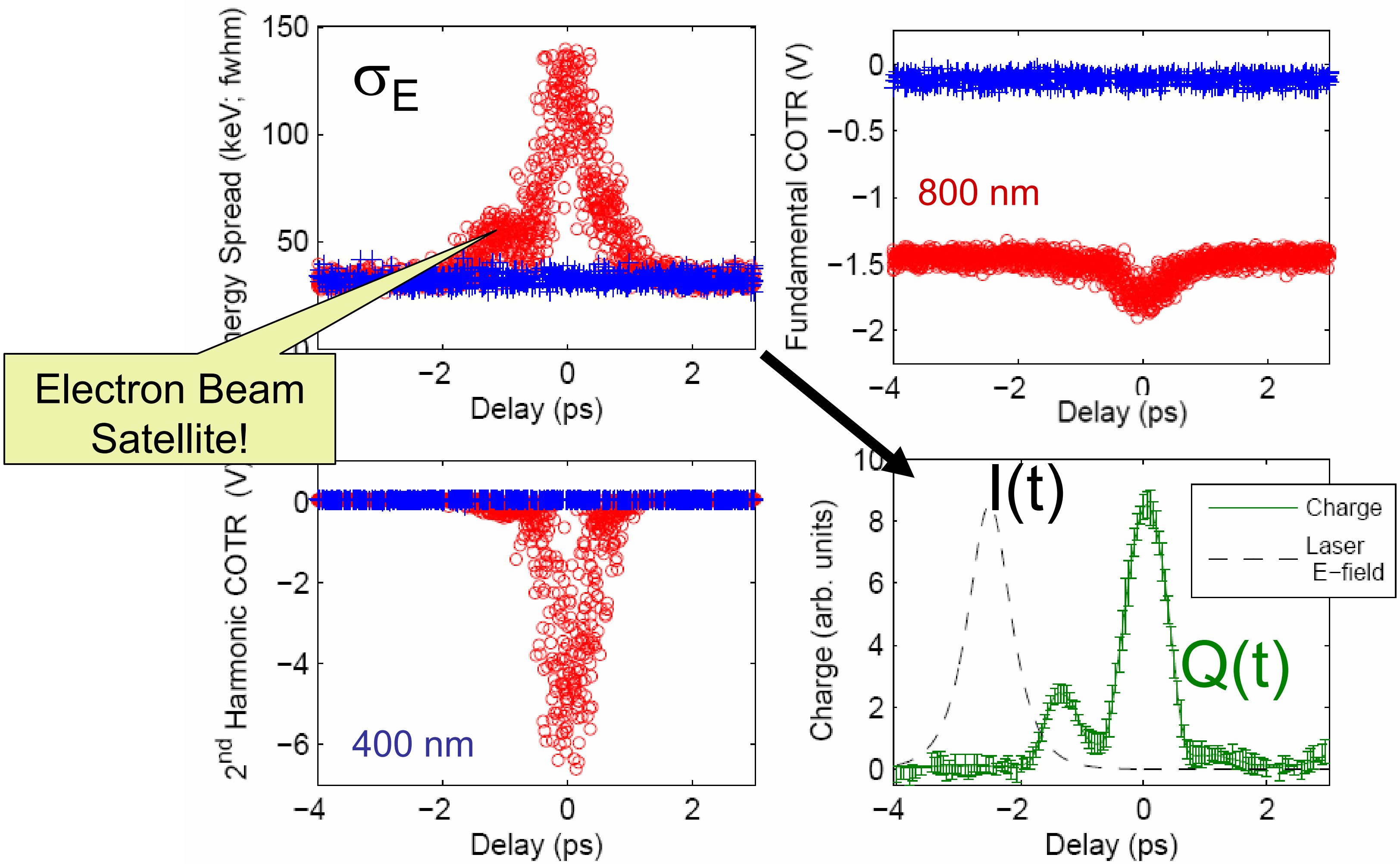


Inferred Electron Pulse Train Structure

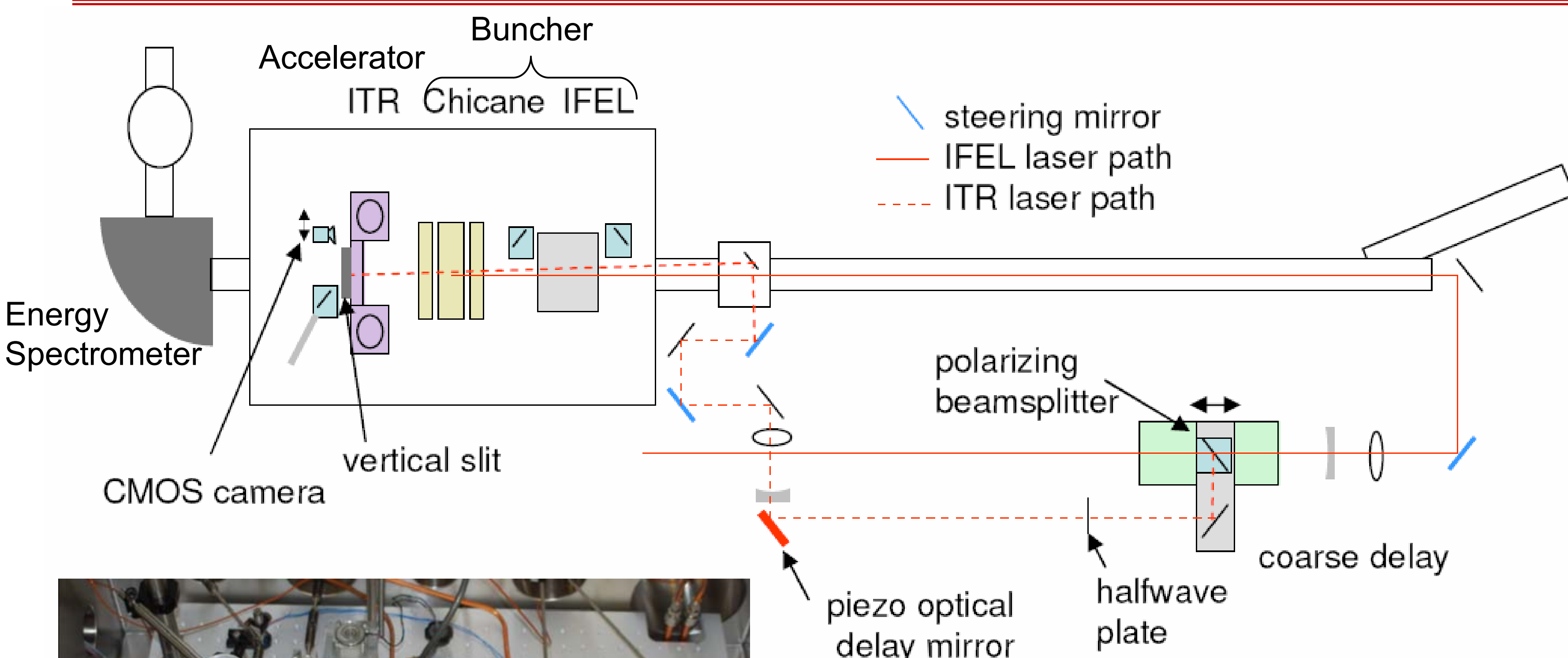
Bunching parameters: b_1**=0.52,** b_2**=0.39**

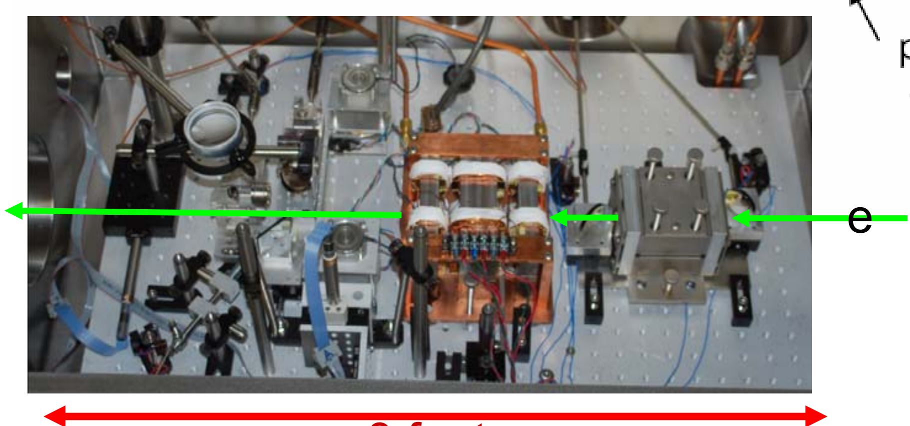
C. M. Sears, *et al*, "Production and Characterization of Attosecond Electron Bunch Trains", *Phys. Rev. ST-AB*, **11**, 061301, (2008).

Inferred Electron Beam Satellite Pulse



Staged Laser Acceleration Experiment

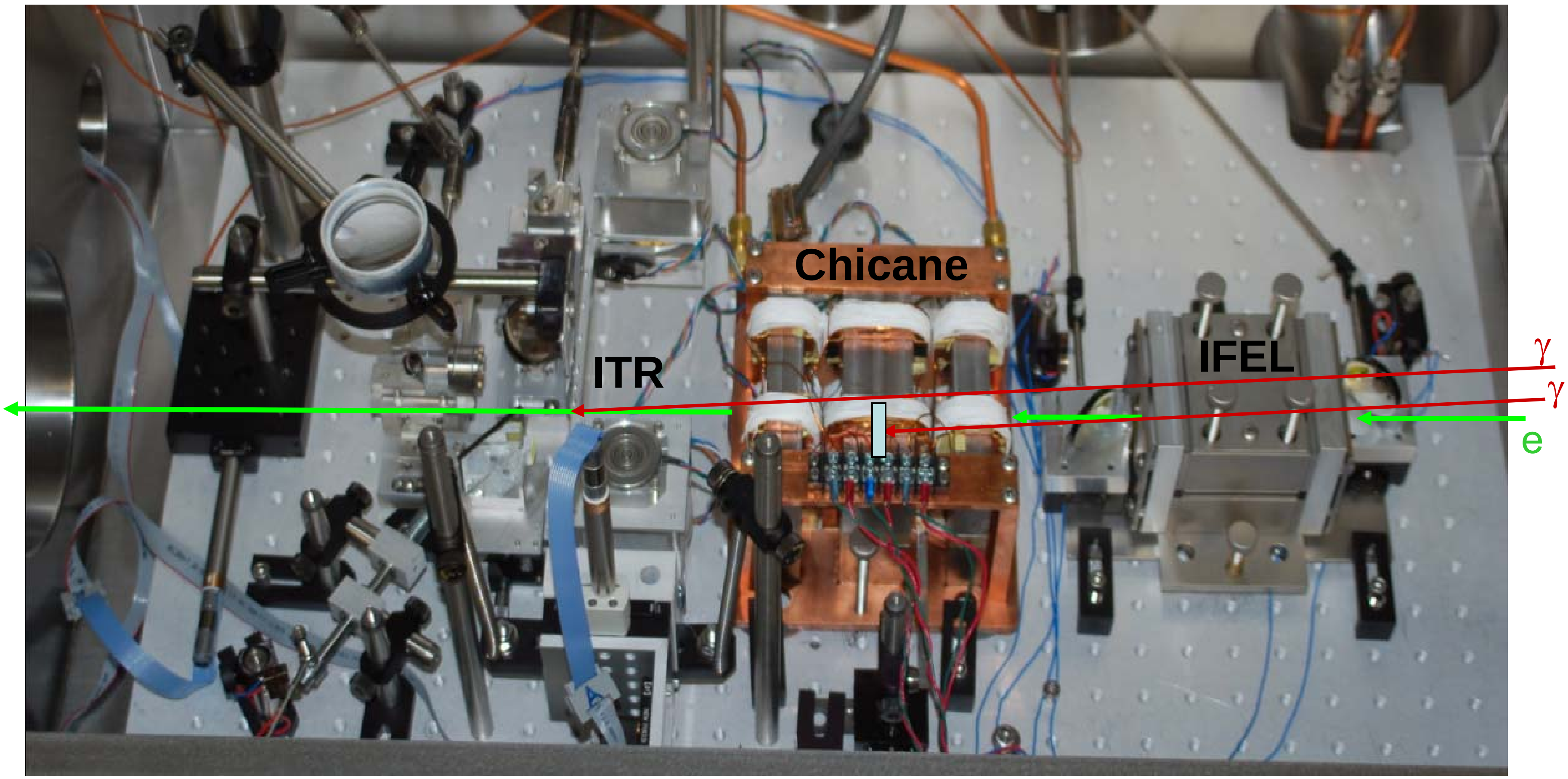




Total Mach-Zender Interferometer path length: ~19 feet = 7.2x10^6 λ !!

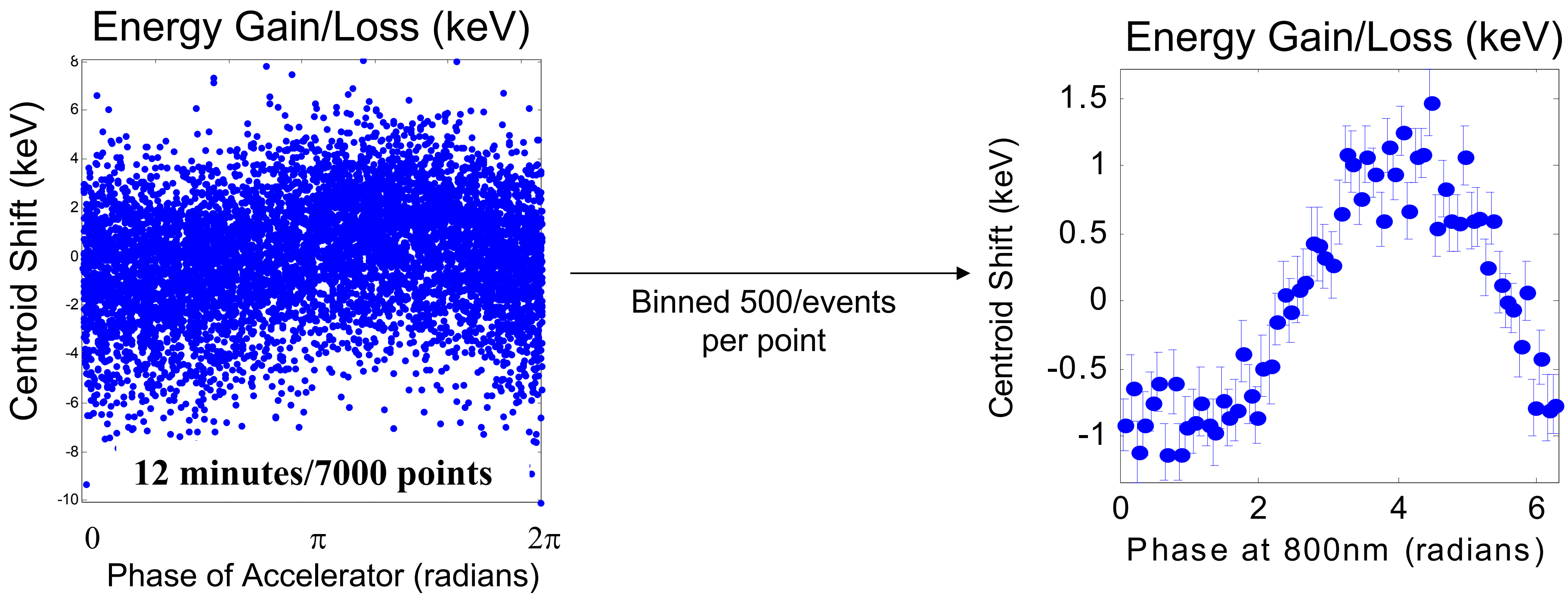
All-passive stabilization used (high-mass, high-rigidity mounts, protection from air currents)

Staging Experiment



3 feet

Demonstration of Staged Laser Acceleration



C. M. Sears, "Production, Characterization, and Acceleration of Optical Microbunches", Ph. D. Thesis, Stanford University, June (2008).

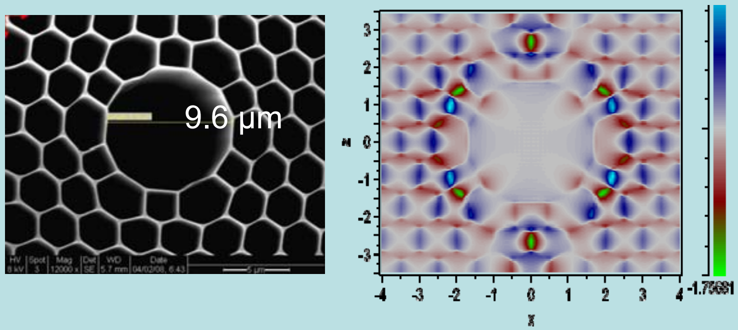
The first demonstration of staged particle acceleration with visible light!

Effective averaged gradient: 6 MeV/m (poor, due to the ITR process used for acceleration stage)

In Progress Now:

First Tests on an Extended Micro-accelerator Structure

(Excitation of Resonant Wakefield in a commercial PBG fiber)

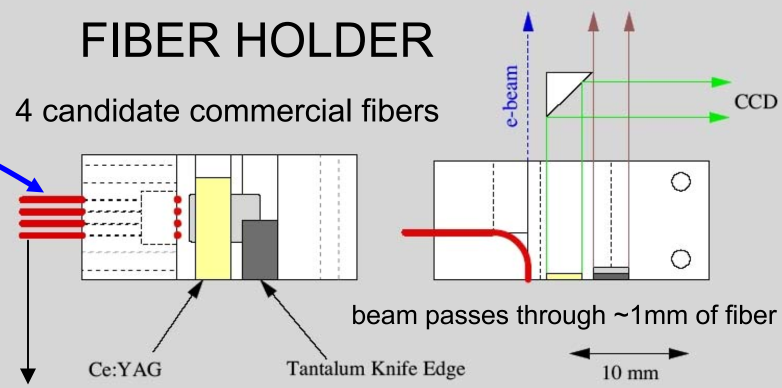


Left: SEM scan of HC-1060 fiber core
Right: Accelerating Mode fields for λ=1.09µ

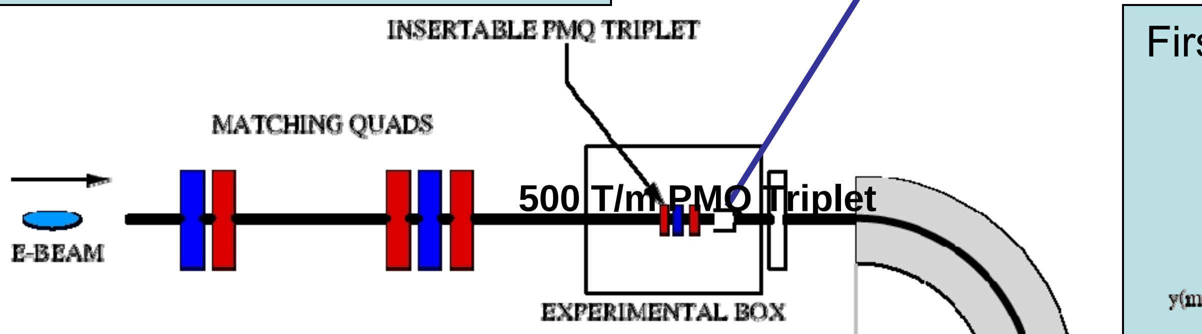
Test Structure length: 1200λ (1 mm)

FIBER HOLDER

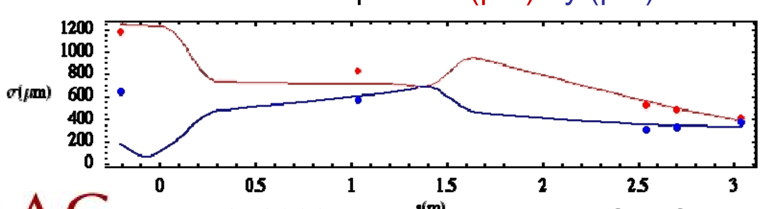
4 candidate commercial fibers



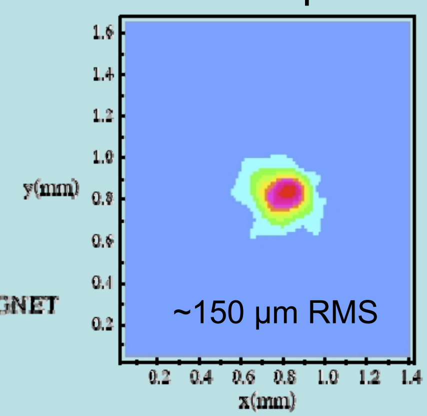
fibers exit chamber for spectrographic analysis



beam envelopes: σx (µm) σy (µm)



First Challenge: Preparing a small spot



2D Photonic Band Gap Structure Designs

Goals:

1. Design fibers to confine v_{phase} = c defect modes within their bandgaps
2. Understand how to optimize accelerating mode properties: Z_C, v_{group}, E_{acc}/E_{max} ,…

Codes:

1. RSOFT – commercial photonic fiber code using Fourier transforms
2. CUDOS – Fourier-Bessel expansion from Univ of Sydney

Accelerating Modes in Photonic Band Gap Fibers

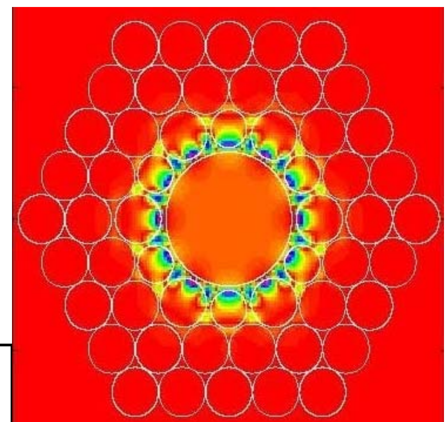
- Accelerating modes identified as special type of defect mode called "surface modes" : dispersion relation crosses the v_{phase}=c line and high field intensity at defect edge.
- Tunable by changing details of defect boundary.
- Mode sensitivities with defect radius R, material index n, and lattice spacing a:

$$d\lambda/dR = -0.1,\ \ (d\lambda/\lambda)/(dn/n) = 2,\ \ d\lambda/da = 1.$$

Example: For 1% acceleration phase stability over 1000 λ, the relative variation in fiber parameters must be held to: $\Delta R/R \sim 10^{-4}$, $\Delta n/n \sim 5\times10^{-6}$, $\Delta a/a \sim 10^{-5}$

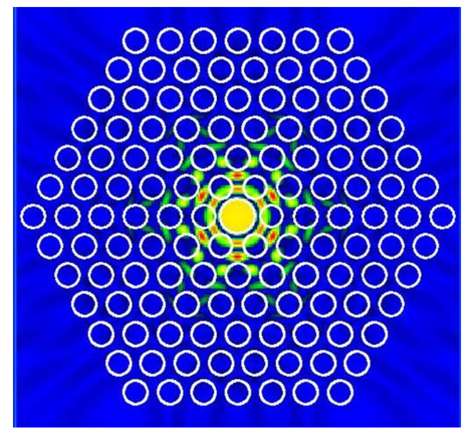
Silica, λ=1890nm, E_z=130 MV/m

E_z of 1.89 μm accel. mode in Crystal Fibre HC-1550-02



Large Aperture

Silica, λ=1053nm, E_z=790 MV/m

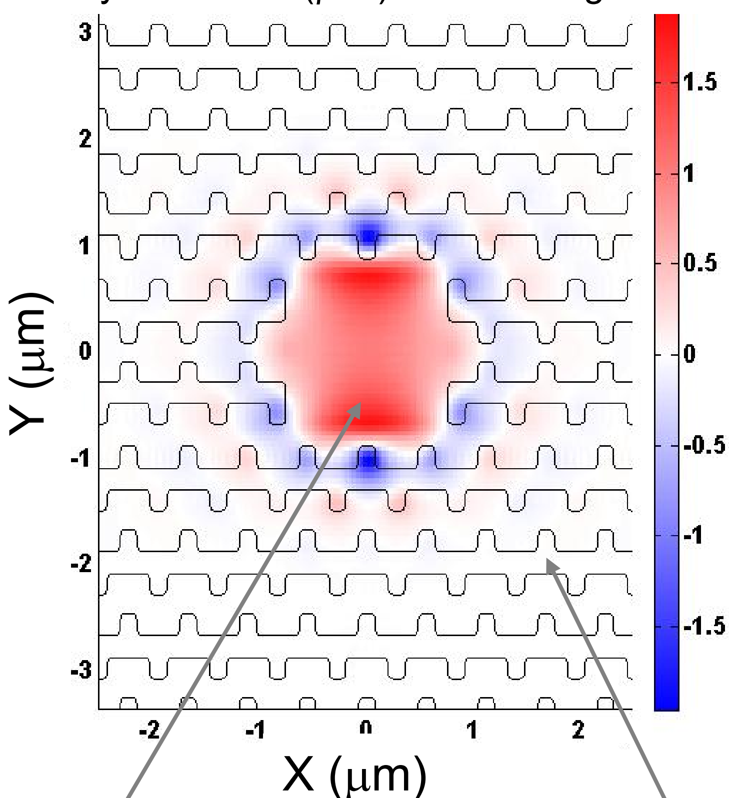


High Efficiency
High Gradient

R_{inner}(μm)	λ(μm)	E_{acc}/E_{max}	Z_C(Ω)	Loss (db/mm)
5.00	1.8946	0.0493	0.136	0.227
5.10	1.8872	0.0660	0.250	0.035
5.20	1.8767	0.0788	0.371	0.029

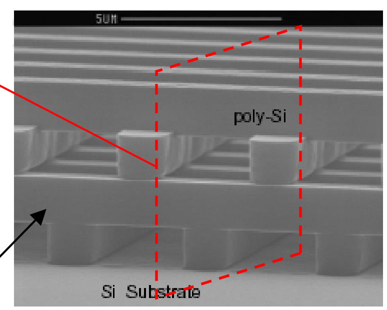
Planar Photonic Accelerator Structures

Synchronous (β=1) Accelerating Field



Vacuum defect
beam path is into the page

silicon

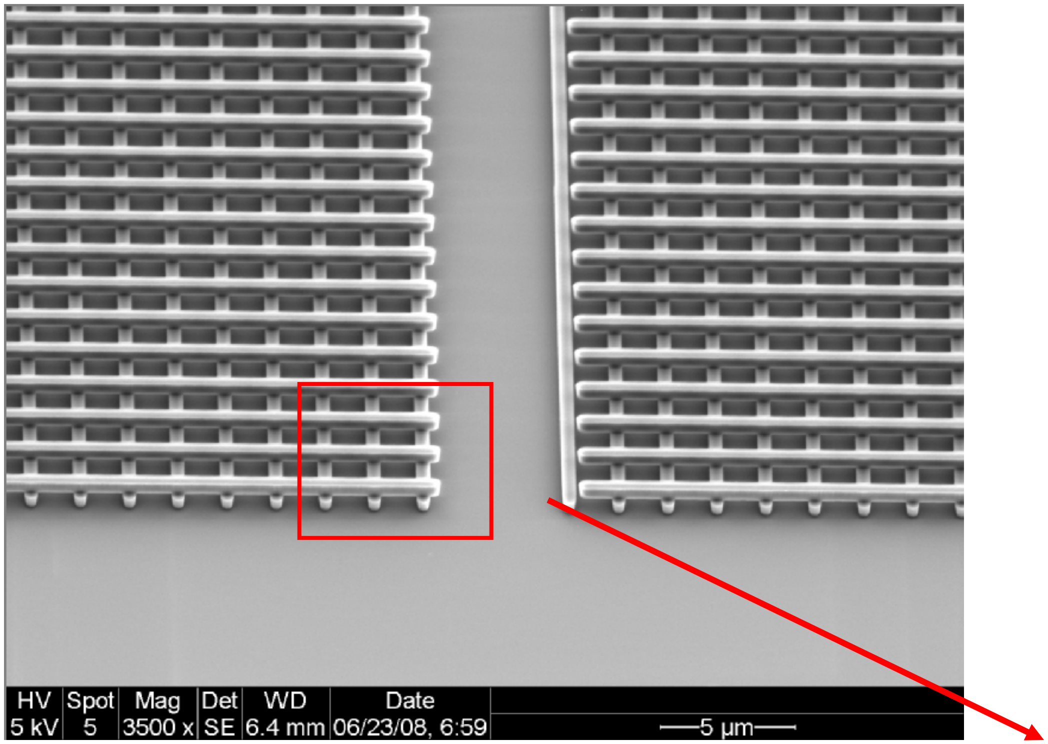


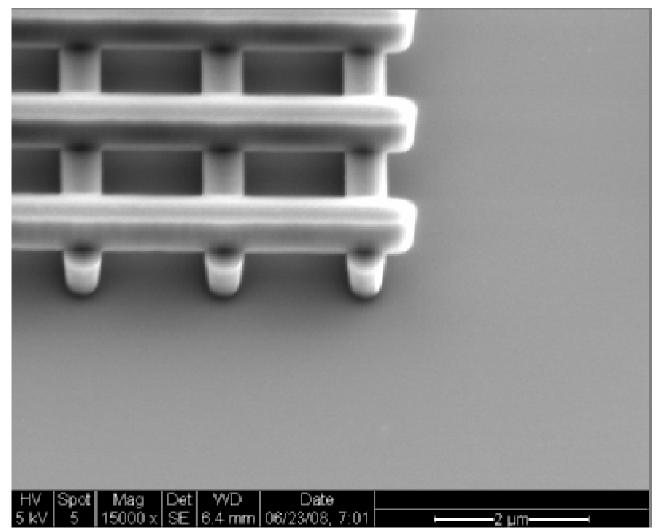
S. Y. Lin *et. al.*, Nature **394**, 251 (1998)

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

* 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

Fabrication of Woodpile Structures in Silicon





Silicon woodpile structure produced at Stanford's Center for Integrated Systems (CIS)

Laser Acceleration R&D Roadmap

LEAP

1. Demonstrate the physics of laser acceleration in dielectric structures
2. Develop experimental techniques for handling and diagnosing picoCoulomb beams on picosecond timescales
3. Develop simple lithographic structures and test with beam

E163

Phase I. Characterize laser/electron energy exchange in vacuum

Phase II. Demonstrate optical bunching and acceleration

Phase III. Test multicell lithographically produced structures

Now and Future

1. Demonstrate carrier-phase lock of ultrafast lasers
2. Continue development of highly efficient DPSS-pumped broadband mode- and carrier-locked lasers
3. Devise power-efficient lithographic structures with compact power couplers
4. Develop appropriate electron sources and beam transport methods

Damage Threshold Improvement

In 3-4 years: Build a 1 GeV demonstration module from the most promising technology