Experiment to Demonstrate Acceleration in Optical Photonic Bandgap Structures

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Stanford University

R. Laouar
Ecole Centrale de Lille

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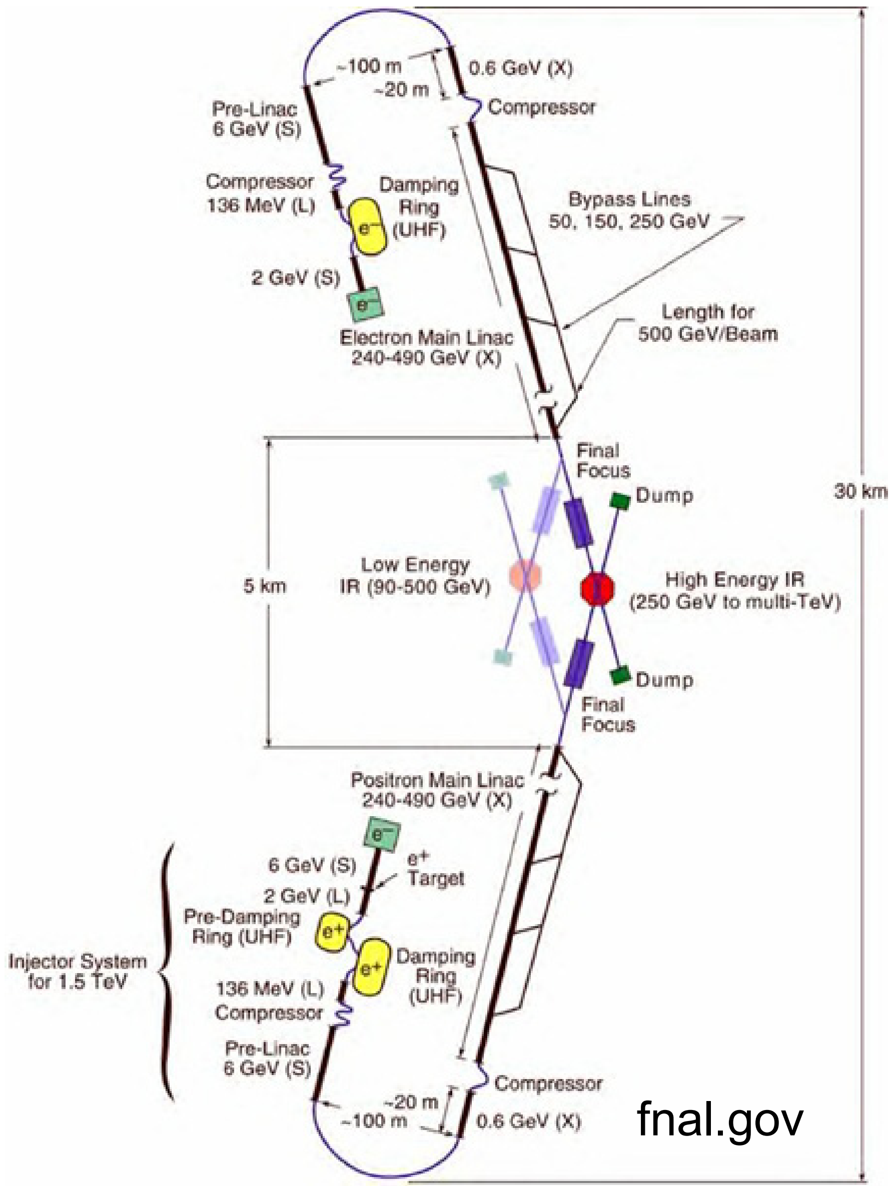
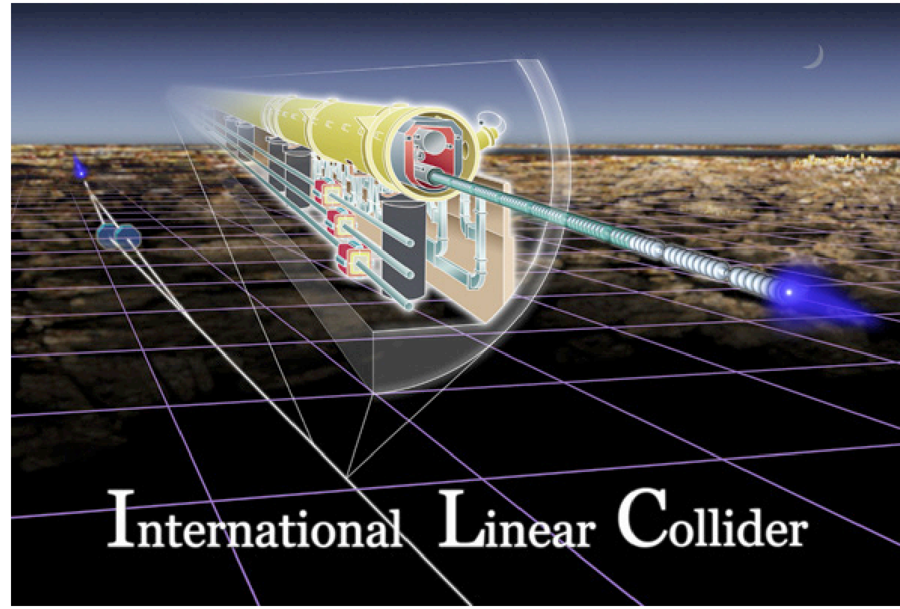


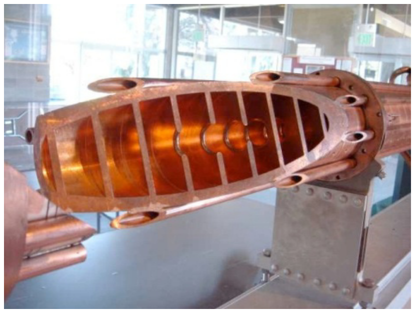
fnal.gov



Overall length: 30 km
Accelerating Gradient: 30 MV/m
Luminosity: 2×10^{34} $cm^{-2}s^{-1}$

Can new technologies improve upon gradient and reduce size/cost of accelerators?

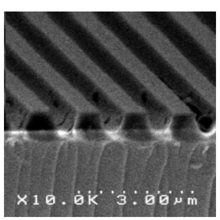
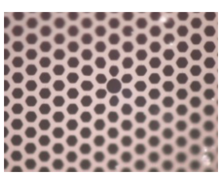
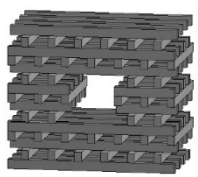
"DLA" = Dielectric Laser Acceleration



S-Band RF

X-Band RF

Optical to IR

1D	2D	3D
		
dielectric gratings	PBG Optical Fibers	silicon “woodpile” structure

smaller RF structures:

- higher gradient
- machining tolerances
- transverse wakefields
- breakdown ($E_z \leq 100$ MV/m)

laser-driven photonic crystal strutures

- lasers offer high rep rates, strong field gradients (>1 GV/m), commercial support
- dielectrics: high breakdown threshold (1-5 GV/m)
- fabrication amenable to mass production

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Collider Strawman Parameters

	Traditional RF	DLA
Source	Klystron (Microwaves)	Commercial μJ Class IR Laser
Wavelength	2-10 cm	1-10 μm
Bunch Length	1-5 ps	1-100 attosec
Bunch Charge	1-4 nC	1-10 fC
Required Emittance	0.1-1 μm	1-10 nm
Rep Rate	1-1000 Hz	1-10 MHz
Confinement of Mode	Metal Boundaries	Photonic Crystal (1D, 2D, 3D)
Material	Metal	Dielectric
Max Unloaded Gradient	30-100 MV/m	0.5-2 GV/m
Power Coupling Method	Critically-coupled Metal WG	Free-space /Silicon WG
Luminosity (cm^-2/s) *	1.70E+35	1.05E+36
Beamstrahlung E-loss (%) *	**53**	**4.4**
Wall Plug Power (MW) *	540	390

* For 10TeV c-o-m collider scenario, based on numbers from Report of ICFA-ICUIL 2010 Joint Task Force on Ultra-High Intensity Lasers, Ch. 1. RF numbers extrapolated from ILC parameters scaled to higher luminosity.

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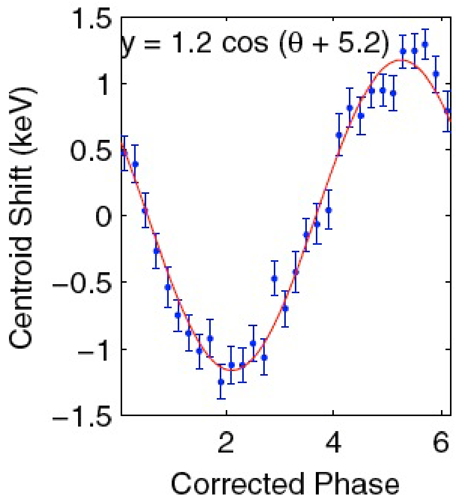
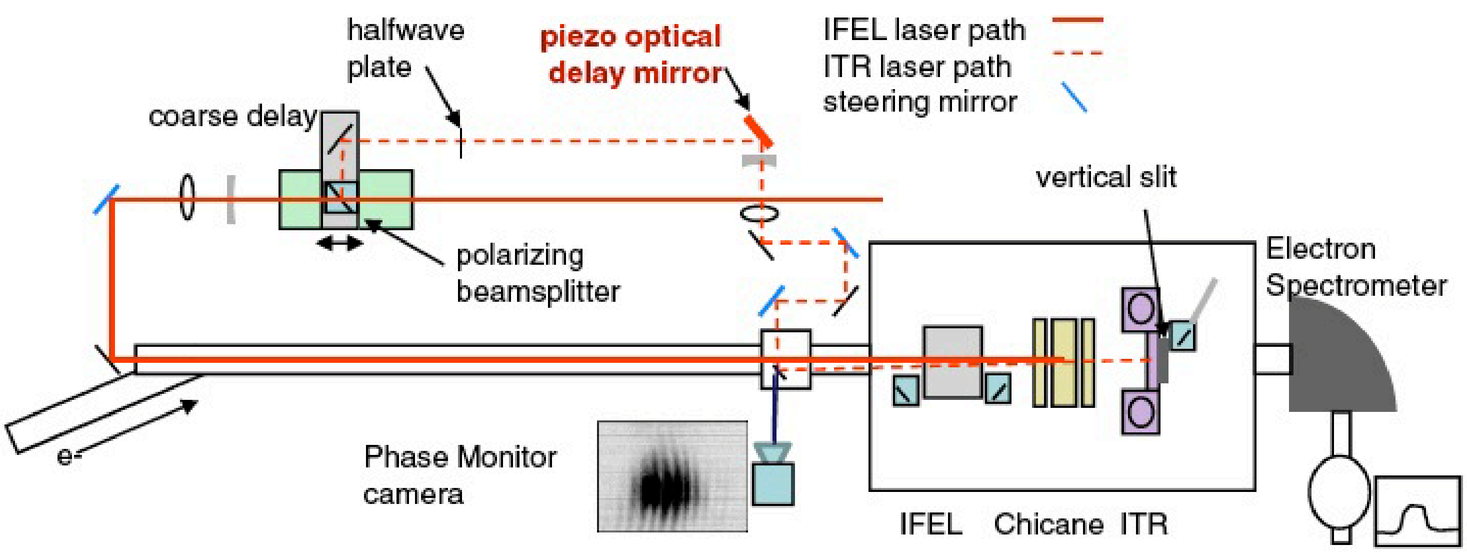
Microbunching



Net laser acceleration of 1.2 keV demonstrated for **400 attosec microbunches** using inverse transition radiation (ITR) at a metal foil.

C.M.S. Sears, et al. "Production and characterization of attosecond electron bunch trains," PRST-AB **11**, 061301 (2008)].

C.M.S. Sears, et al. "Phase stable net acceleration of electrons from a two-stage optical accelerator." PRST-AB **11**, 101301 (2008).



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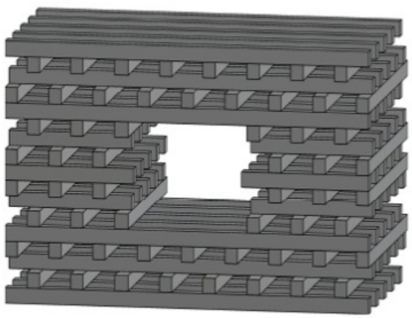
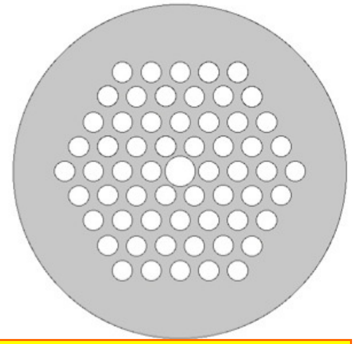
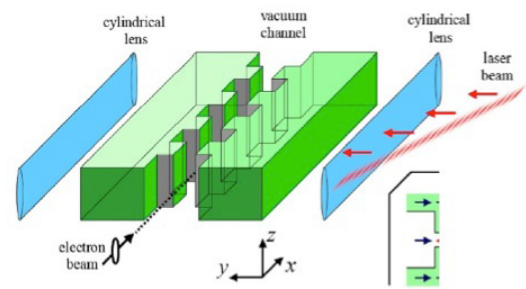
Structure Fabrication Studies

3D	2D	1D
image courtesy B. Cowan		img courtesy T. Plettner



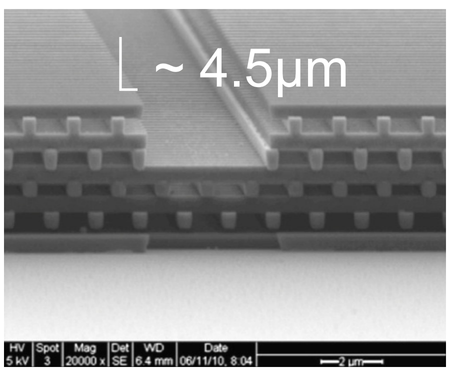


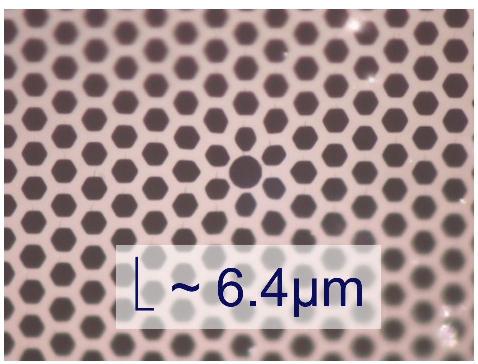


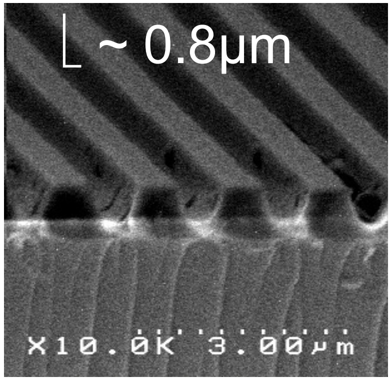
C. McGuinness, MOP133

J. Spencer, MOP136

E. Peralta, MOP096







"woodpile" silicon photonic crystal (C. McGuinness)

photonic crystal borosilicate fibers (J. Spencer/Incom Inc)

dual silica grating accelerator (E. Peralta)

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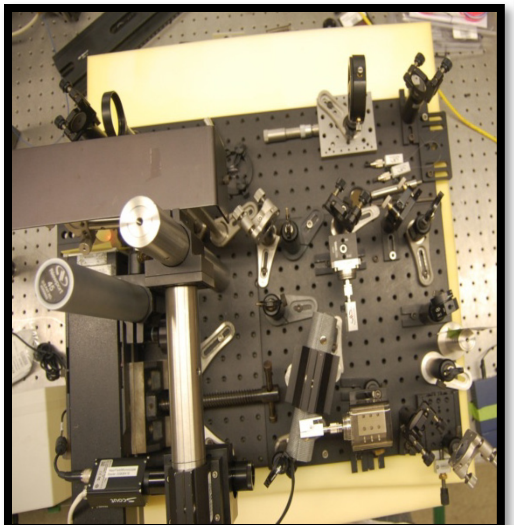
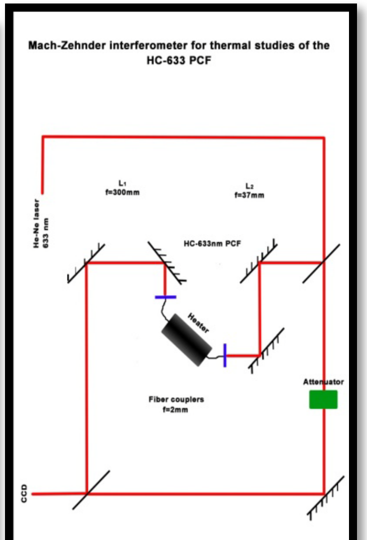
Benchtop Testing of Structures

Phase Stability of PBG Structures



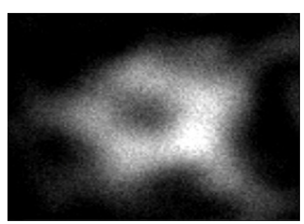


$$S = \frac{1}{\varphi}\frac{d\varphi}{dT} \approx \frac{N}{n_{eff} L . \Delta T / \lambda} = 9\,ppm/{}^\circ C$$

$\rightarrow 3^\circ$ phase / $^\circ$C for $L = 1000\lambda$

R. Laouar, TUP276

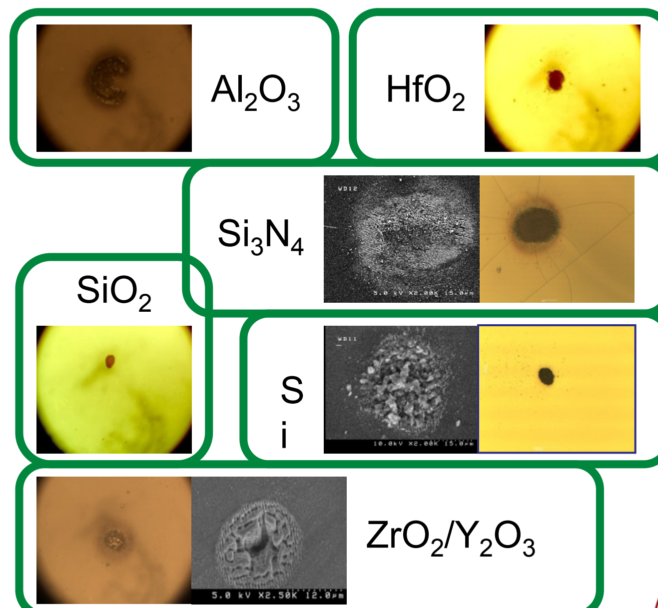
[633 nm HC fiber]



Damage Threshold of Dielectric Materials

2 J/cm^2 ~ E_{pk}=5 GV/m

Material	Thickness	Bandgap	F_{th} [J/cm^2]
Al_2O_3	1000μm	9.9eV	4.90$\pm$0.29
SiO_2 (Quartz)	1000μm	8.9eV	4.10$\pm$0.50
ZrO_2/Y_2O_3	15nm	5-7eV	3.97$\pm$0.16
HfO_2	<200nm	5.8eV	3.63$\pm$0.36
Si_3N_4	100nm	5.1eV	0.65$\pm$.05
Si	1000μm	1.1eV	0.14$\pm$.02



K. Soong, MOP095

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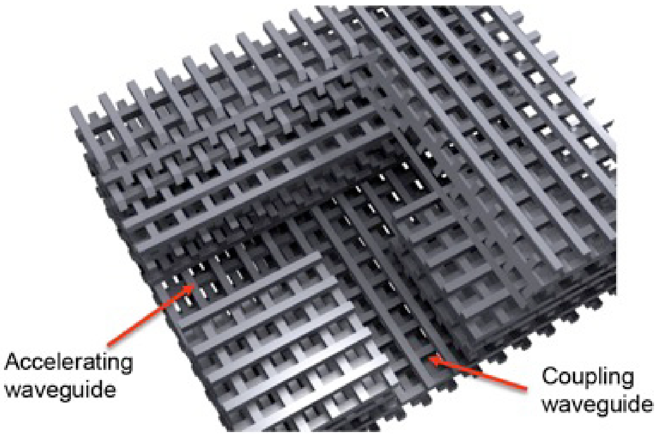
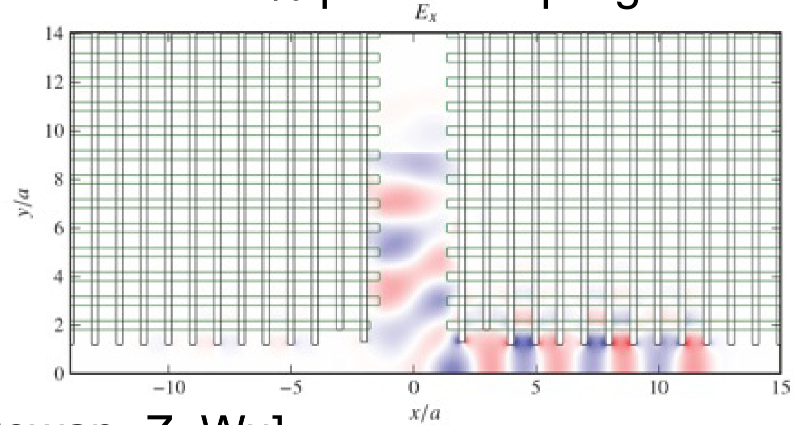
Laser Coupling to Structures

Transverse Coupling to Woodpile Structure



~90% power coupling

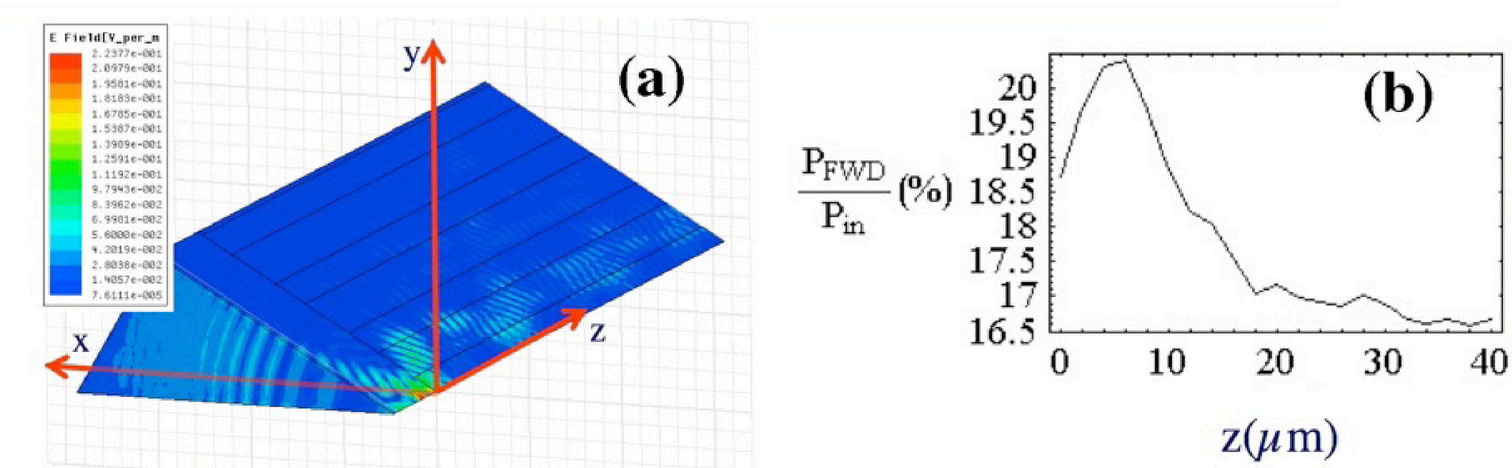


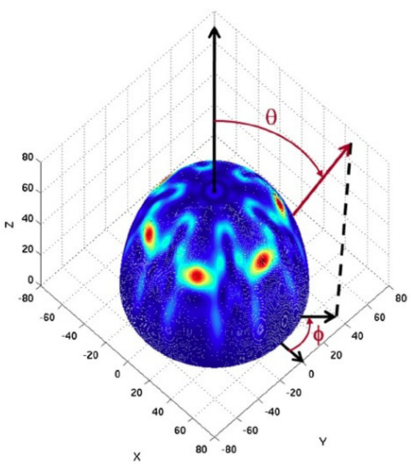
[courtesy B. Cowan, Z. Wu]

Coupling from transverse waveguide to accelerating mode of the woodpile structure.
~90% coupling from free space to silicon waveguide structures simulated recently; fabrication R&D of test couplers underway [Z. Wu, D. Xu]

Laser Coupling to Structures

Free-Space Coupling to Optimized PBG Fiber

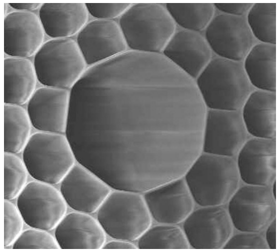


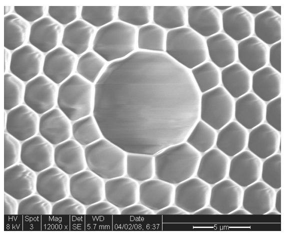


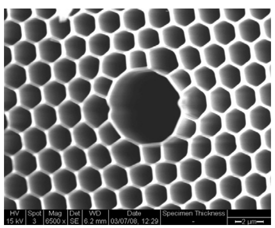
Above: free-space TEM01*-like mode end-coupled to the cleaved face of the fiber. Coupling to the desired fiber mode ~ 17%

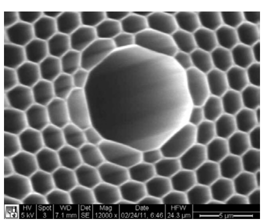
Left: Far-field radiation pattern from fiber
[C. Ng, et al. PR-STAB 13, 121301 (2010).]

Commercial Fibers





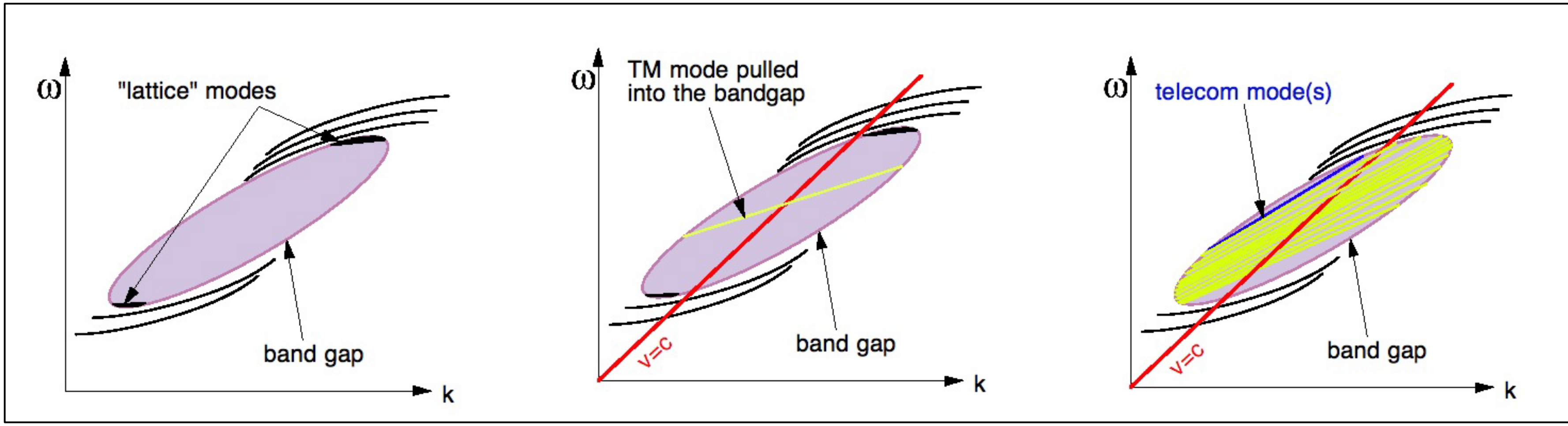


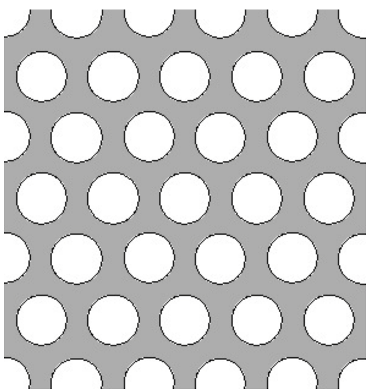


⌊ (nm)(telecom)	2R (defect) (μm)	a (pitch) (μm)	lattice dia. (μm)	cladding dia. (μm)
2000	14.5	4.4	90	155
1060	9.7	2.75	50	123
633	5.8	1.7	37	102
800	9.2	2.3	40	135

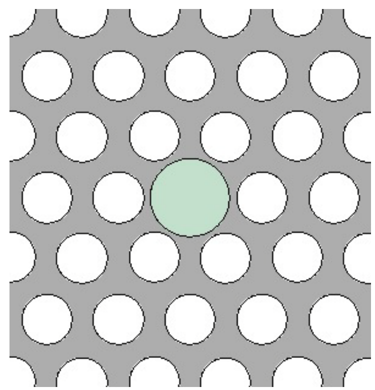
- NOT designed for accelerator use:
  - highly overmoded, poor characteristic impedances
- fibers manufactured by NKT Photonics
- 1060 fiber has geometry closest to optimized fiber (R/a = 1.76 vs.1.48 for Lin fiber)
- Useful as stand-in devices for testing and potential normal-gradient acceleration (~ 30 MV/m in 1060 fiber)

SOL Modes in PBG Structures

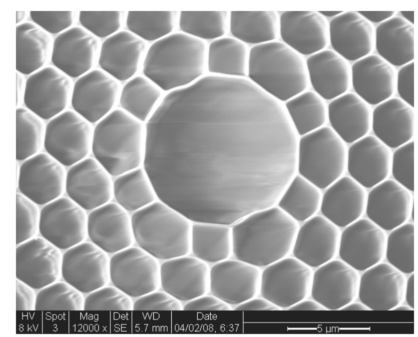




pure lattice



optimized accelerator structure



stand-in telecom fiber

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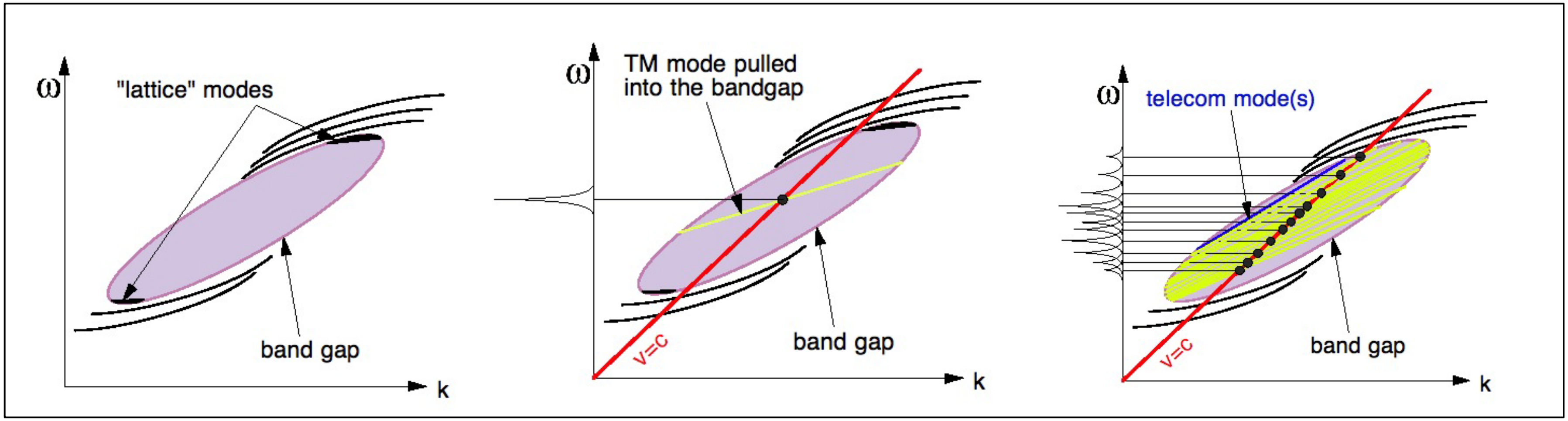
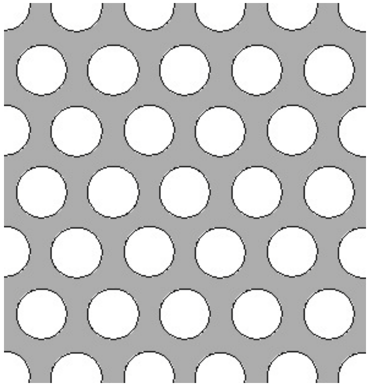
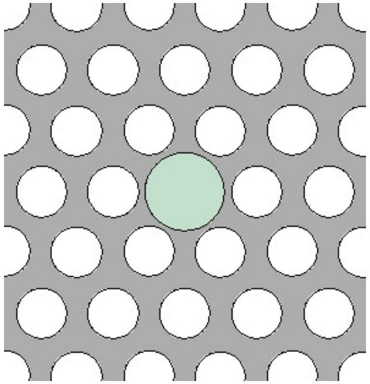
SOL Modes in PBG Structures

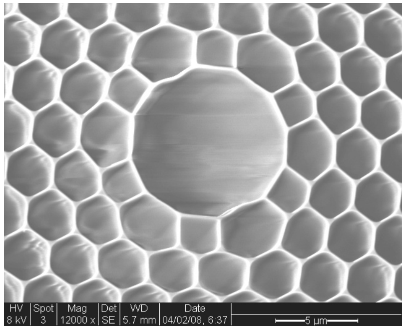




pure lattice



optimized accelerator structure



stand-in telecom fiber

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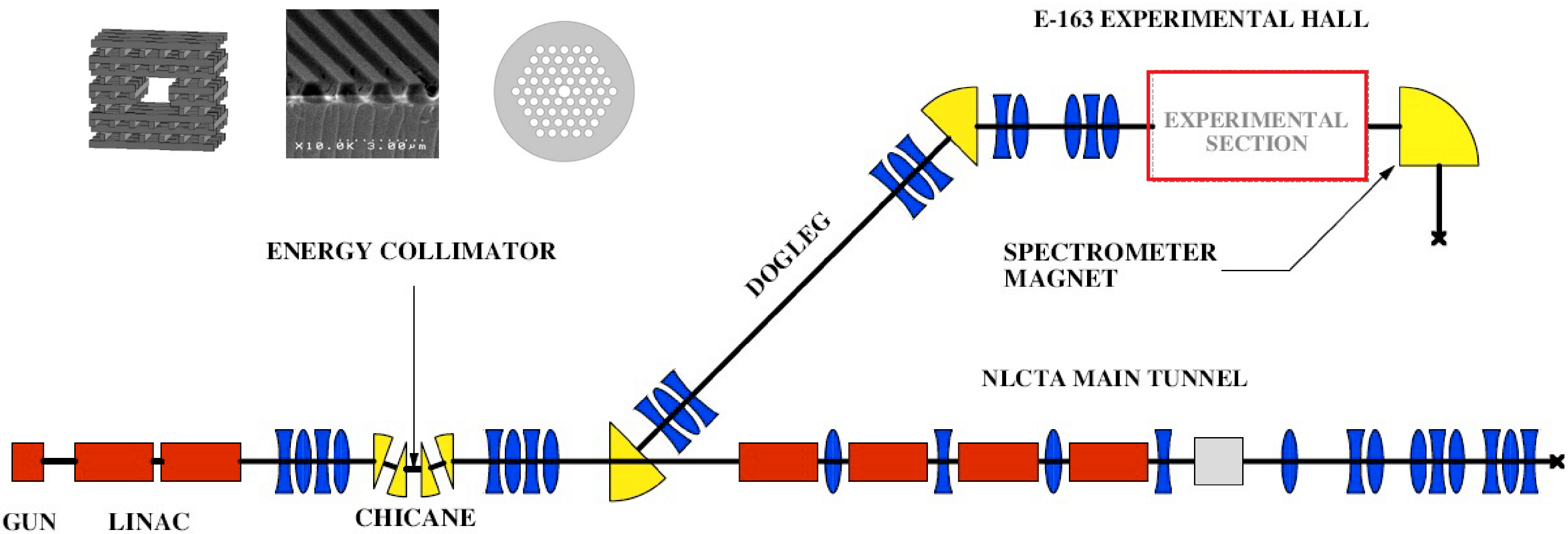
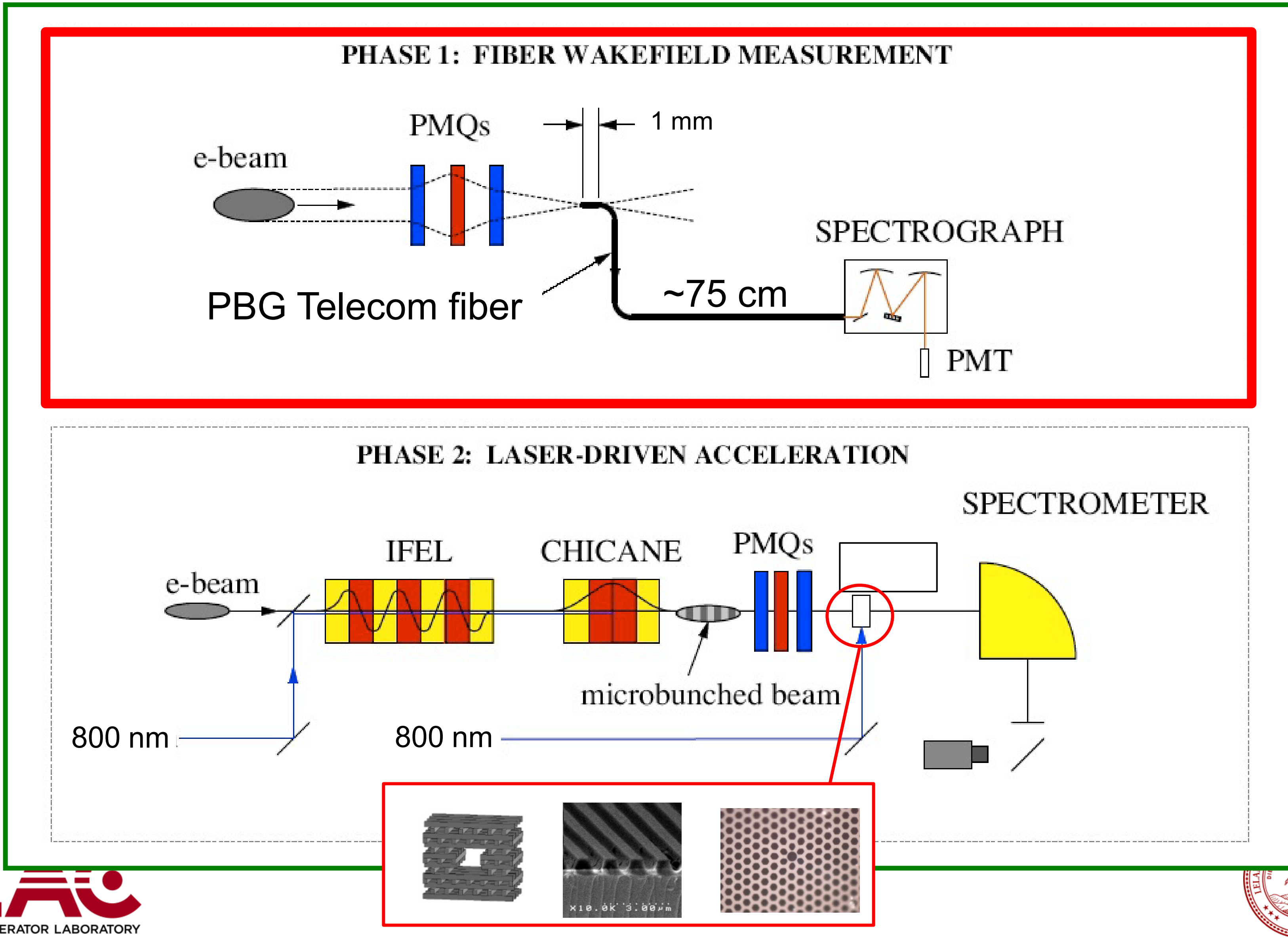
NLCTA-E163 Test Facility

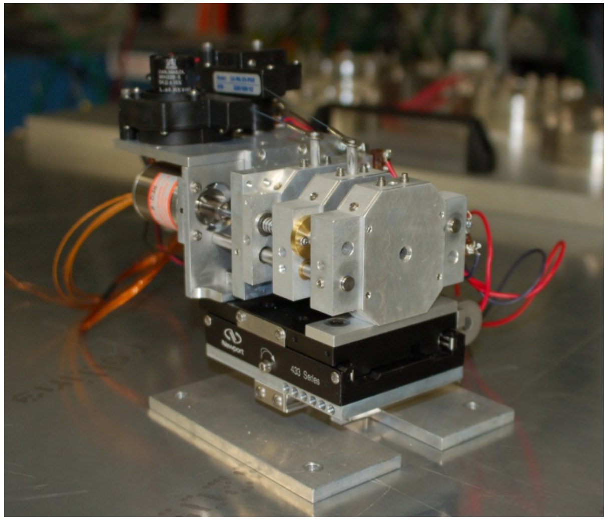
E163: A facility for testing laser-driven accelerator structures.
Beam energy = 60MeV; σ_t = 1ps to 400 attosec; σ_E = 0.1%



Experimental Plan

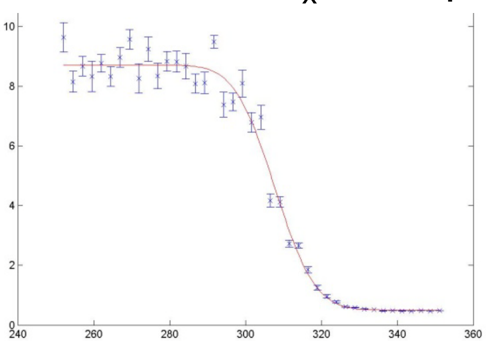


E163 Final Focus System

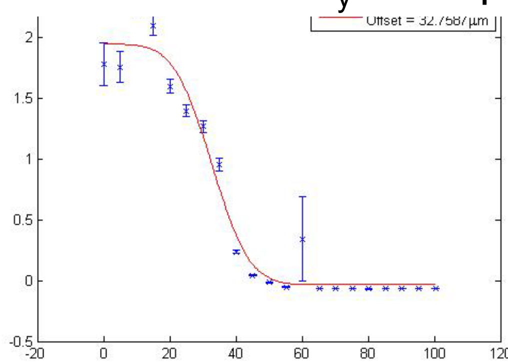


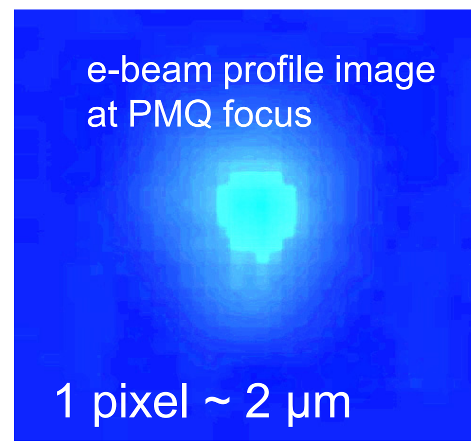
- High-gradient (420 T/m) NdFeb quadrupoles
- YAG profile monitor: res limit ~ 20 µm
- Tantalum knife edge: 1µm surface finish
- Knife Edge thickness = 0.5mm = $X_{rad}/6$
- Intercepted electrons filtered by downstream spectrometer
- Integrated spectrometer signal measured as a function of knife edge position (~40 nm res).

X: Extracted σ_x = 8.9 µm



Y: Extracted σ_y = 8.9 µm





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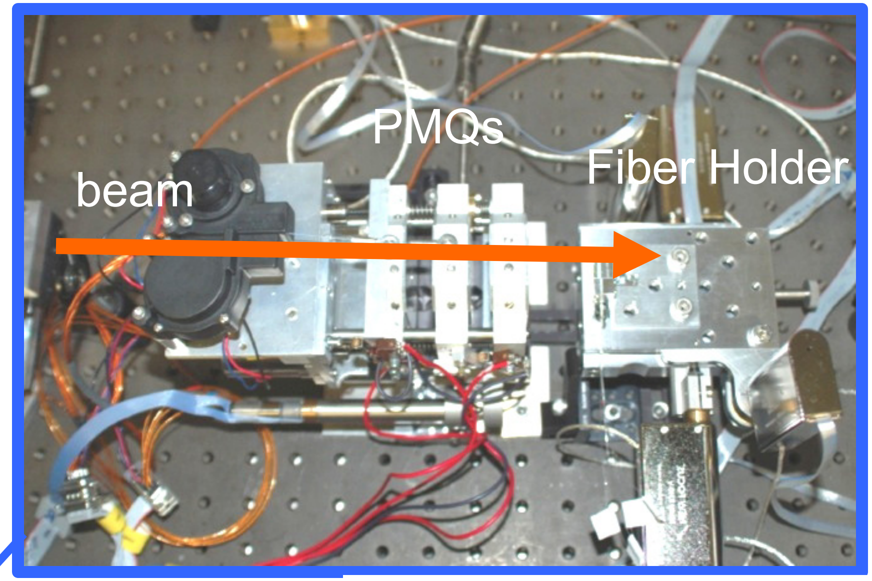
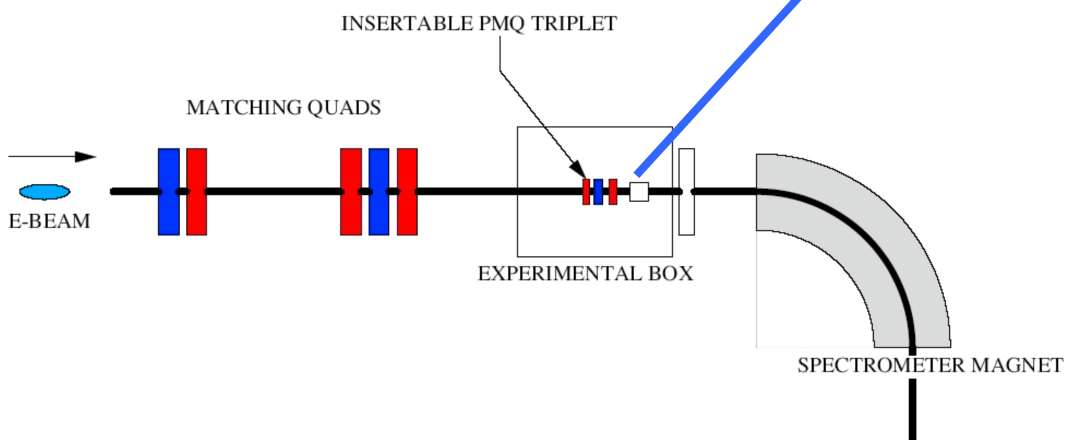
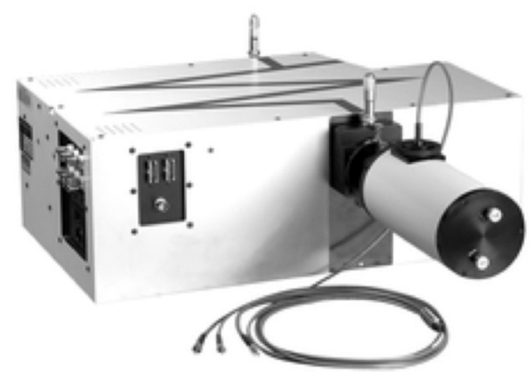
Fiber Experiment Layout

Required Beam Parameters

Beam Charge	50 pC
Normalized Emittance	**< 5 mm mrad**
Energy	60 MeV
Bunch length	1 ps
Energy Spread	0.1 %

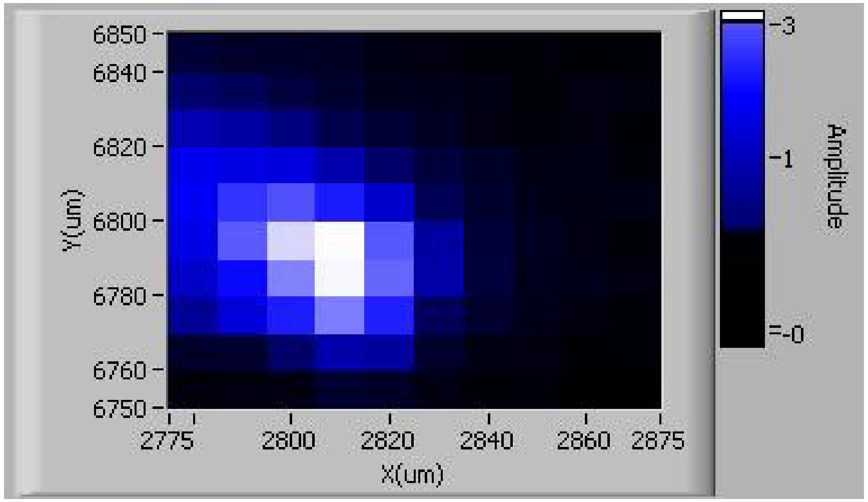






Newport MS 260i Spectrograph

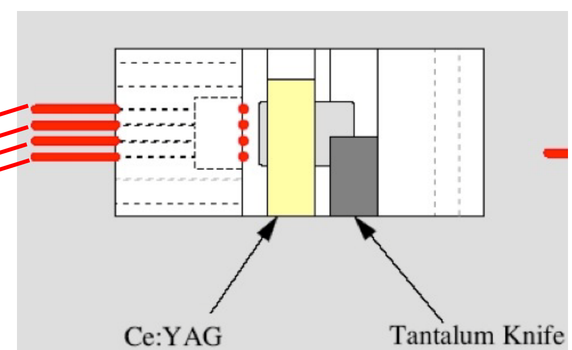
Fiber Signal Detection



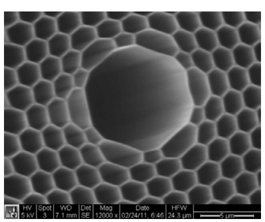
PMT Response vs. Fiber Position: HC-800 fiber

- PMT: Hamamatsu R5108; peak λ = 800nm
- No Spectrograph (yet): direct fiber to PMT
- Obtained signal and measured position of all 4 commercial fibers under study.
- Used filters and shutters to verify that the signal was really optical.
- Filter indicates that ~ 75% of PMT signal for the HC-800 fiber is at λ>600nm

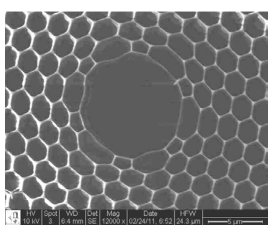
diagnostic block: beam direction into page



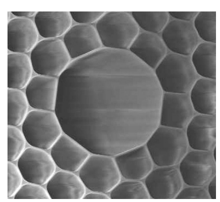
4 commercial fibers installed



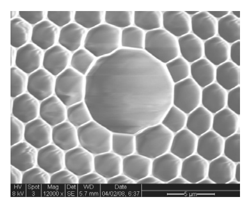
HC-800-1



HC-800-2

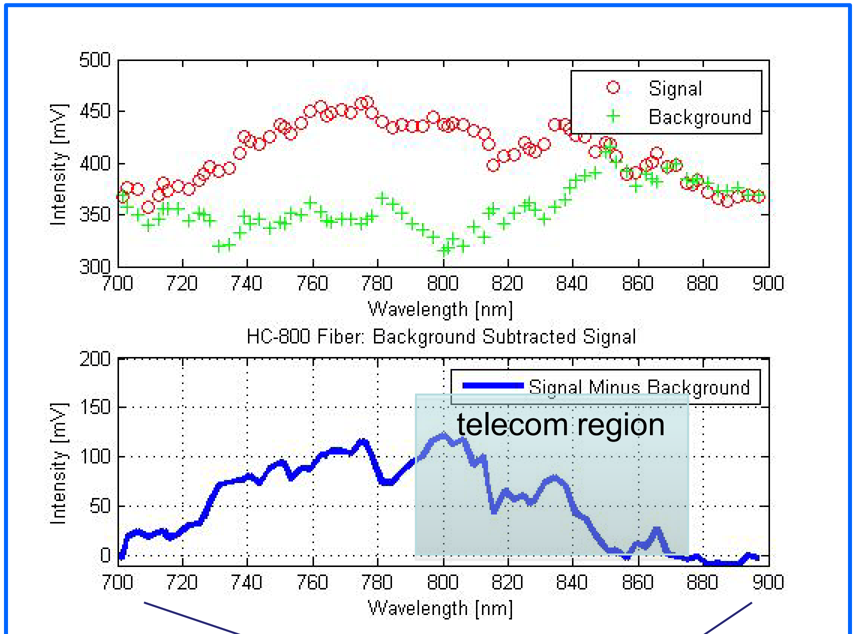


HC-2000

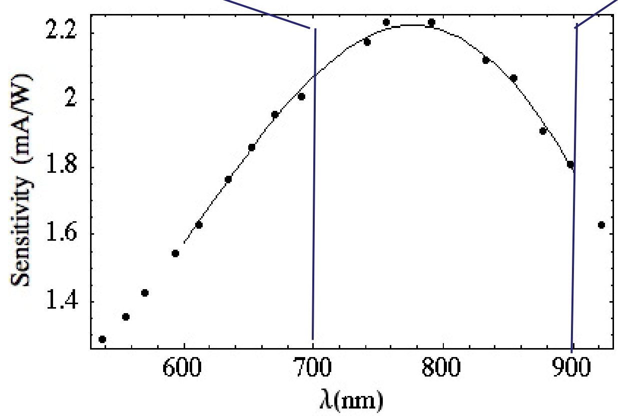


HC-1060

Spectrograph Measurement of 800nm PBG Commercial Fiber



Saw convincing signal on HC-800 fiber
Spectrograph Bandwidth: 60nm
Center wavelength varied randomly (78 values)
Shutter Opened/Closed @ 1Hz
Beam Rep Rate: 10 Hz
Total # Samples: 46,800
Rolling Averaged with 60nm window
Background signal: most likely x-rays



PMT (Hamamatsu R5108) peaks in this region
However, response is sufficiently flat within the data region that it does not significantly change the data.

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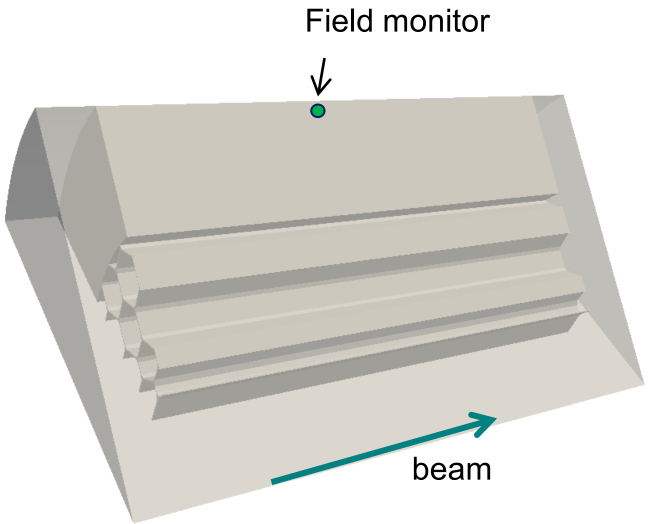
Wakefield Simulations

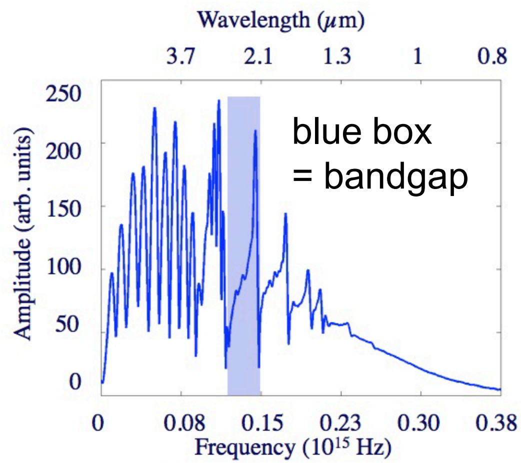


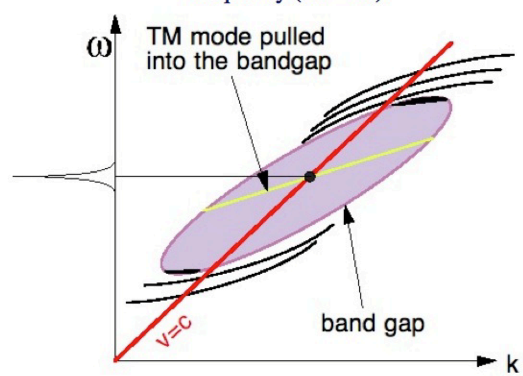
[courtesy Cho Ng]

ACE3P simulation of HC-800-1 fiber with axial current excitation. Time domain.

current pulse RMS duration = 0.2 ⌊/c
[scaled to actual design wavelength]

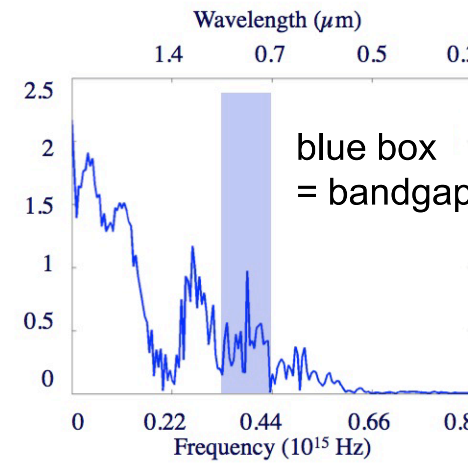
Optimized PBG Accelerator

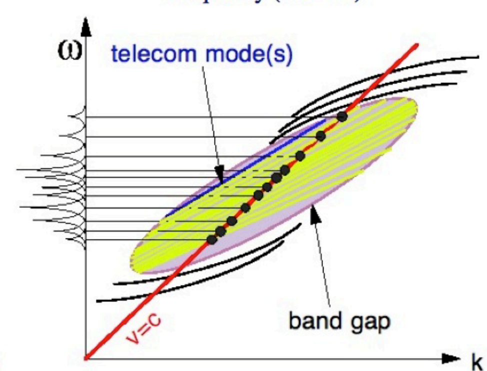




one mode excited

HC-800 Fiber Used in Experiment





many modes excited

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SOL Modes in the HC-800 Fiber

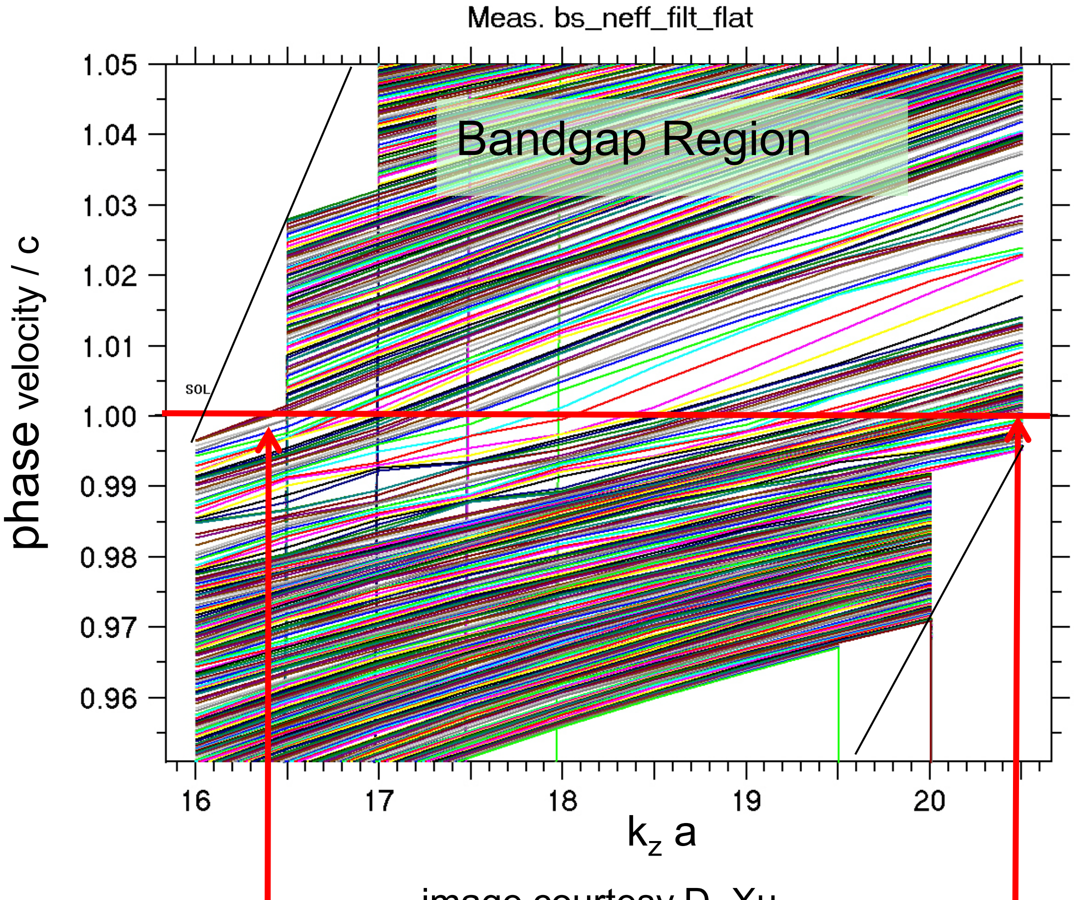
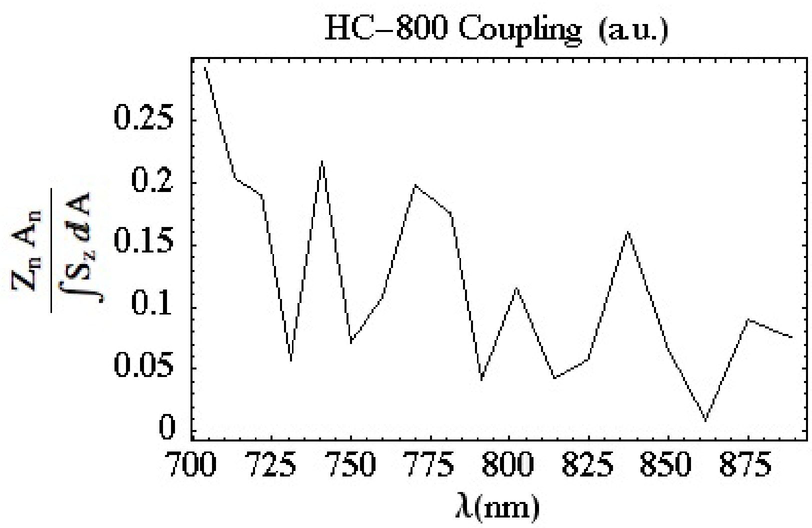


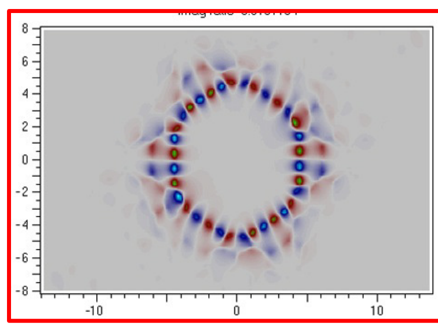
image courtesy D. Xu

⎣ = 862 nm ⎣ = 704 nm

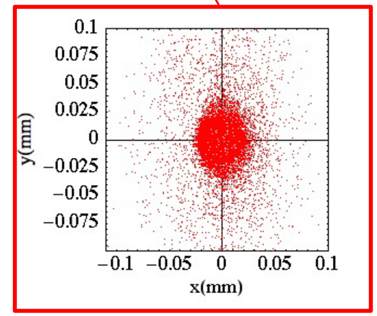
Beam Coupling in HC-800 Fiber for 18 Representative SOL TM Modes



$$A_n(\omega) \propto \int_V \mathbf{J}(\mathbf{r},\omega)\cdot \mathbf{E}_n\, d^3r \quad\rightarrow\quad q\,\mathbf{v}\cdot\tilde{\mathbf{E}}_n(\mathbf{r}_0)\,\delta(k_n - \omega/v)$$

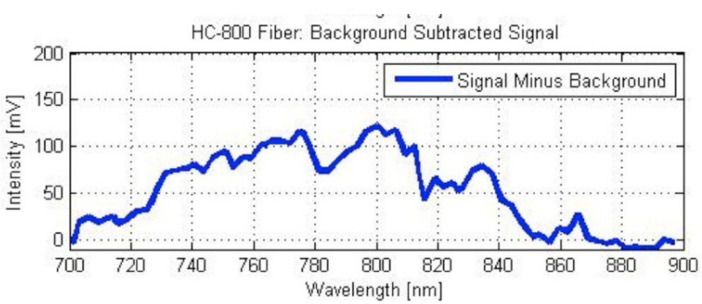


calculated mode E-field (BandSolve: D. Xu)



ELEGANT particle phase space model of beam

edges will get attenuated due to decreaseed confinement



- 18 representative modes selected
- Coupling to beam calculated from dot product of E field and simulated particle phase space at the IP
- PMT signal will be modified by the attenuation (dU/dz) of each mode, which is higher near edge of bandgap.

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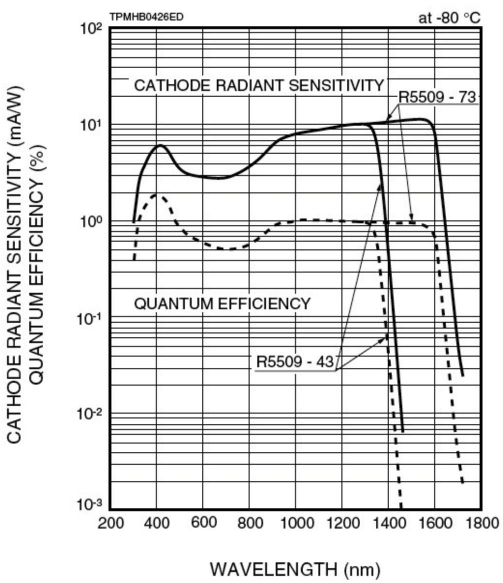
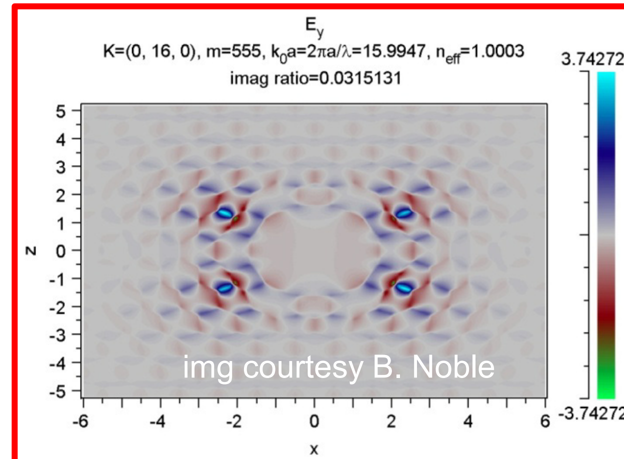
What's Next?

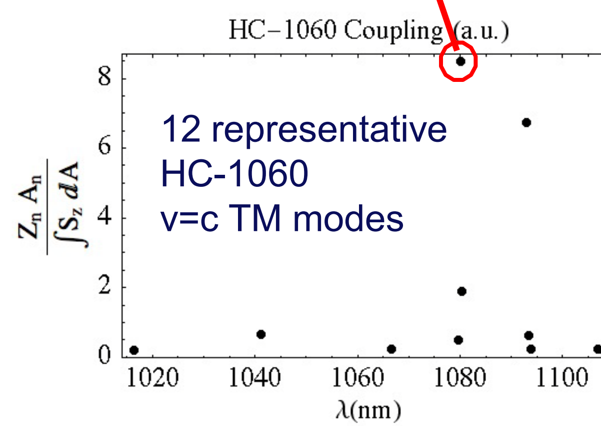
Cooled Hamamatsu R5509-73



- Extended spectral range of PMT should allow better detection of 1060 modes
- Improved shielding to reduce X-ray bkg / improve SNR
- Simulation of the 1060 fiber shows a strong TM mode which could potentially be used for acceleration.
- Estimated max G_0 ~ 30 MV/m

Predicted TM Accelerating Mode(s) in HC-1060 Fiber





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Summary

- First demonstration of SOL TM modes excited by an e-beam in the bandgap of a photonic crystal structure (800nm PBG fiber)
- 1060nm fiber expected strong SOL TM modes → possible accelerator structure
- Signal seen in 2000 and 1060 nm fibers but bandgap was not spectrally resolved.
- Relevant issues/challenges:
  - PMT sensitivity drops off above 900nm
  - Significant X-ray background
  - Resolution poor (60 nm bandwidth to get higher signal)
- Plans for next experimental run (and higher res capability)
  - New PMT: extends spectral range to 1700nm
  - Increased shielding at IP to reduce X-ray background
  - Signal processing: narrower or multiple gates to distinguish sig vs. bkg
- Plans for acceleration demonstration experiments:
  - 1060 fiber (if modes detected), Incom custom fiber, gratings, woodpile
  - Possibility of testing open half-structures (grating, woodpile)
  - E-modulation with long bunches → net acc. with microbunched e-beam