Photonic Bandgap Fiber Wakefield Experiment:

Focusing and Instrumentation for Dielectric Laser Accelerators

R. Joel England

E. R. Colby, C. McGuinness, J. Ng, R. Noble, T. Plettner, C. M. S. Sears, R. H. Siemann, J. E. Spencer, D. Walz

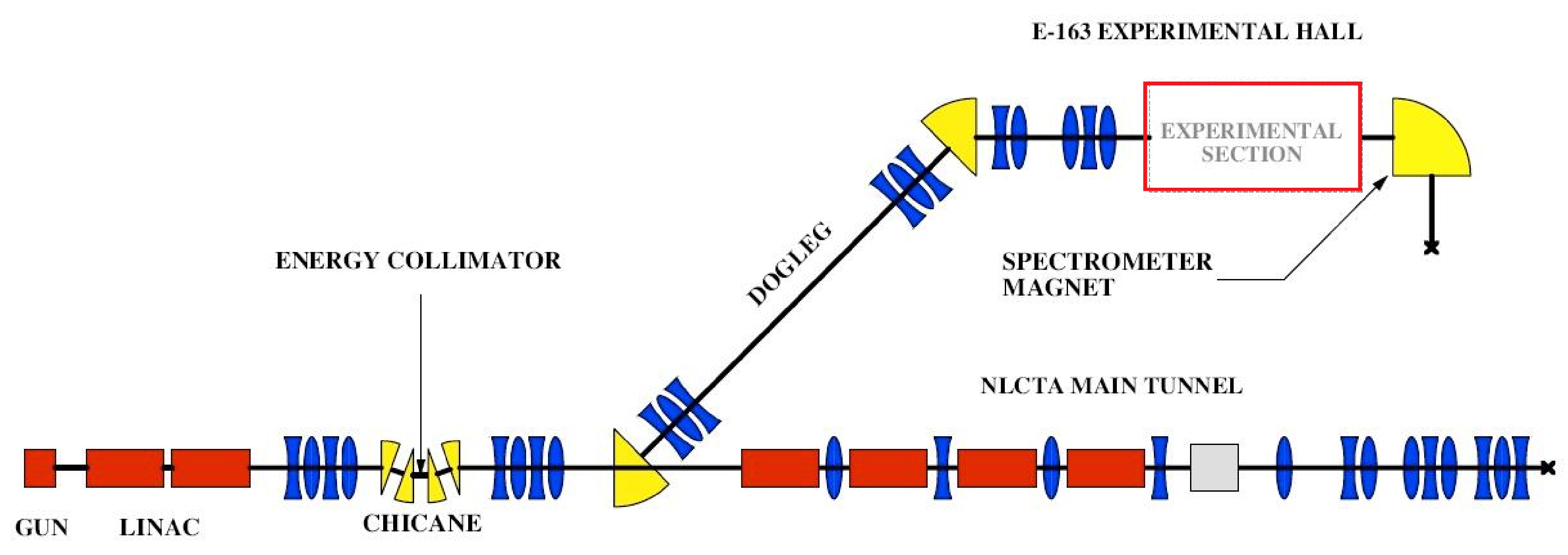
Advanced Accelerator Research Department

SLAC National Accelerator Laboratory

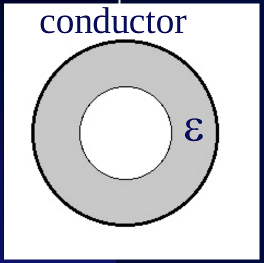
NLCTA E163 Test Beamline

E163: A facility for testing laser-driven accelerator structures.

Beam energy = 60MeV; σ_t = 1ps to 400 attosec; σ_E = 0.1%



Dielectric Fiber Accelerator



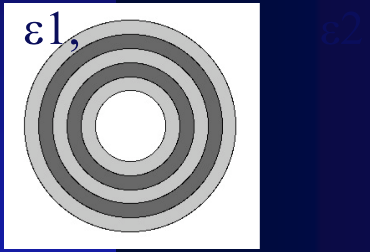
hollow dielectric-lined waveguide
aperture ~ 0.26 λ; E_z~ 2.5 GV/m

$DF\ ;\ \varepsilon/\sqrt{\varepsilon-1}=2$

Rosing & Gai, PRD **42**, 1829 (1990)

conductor lossy at optical wavelengths

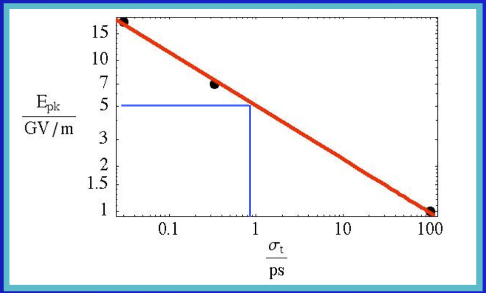
damage threshold for SiO_2 ~ 5GV/m @ 1ps



hollow Bragg waveguide
aperture ~ 0.3 λ; E_z ~ 2.5 GV/m

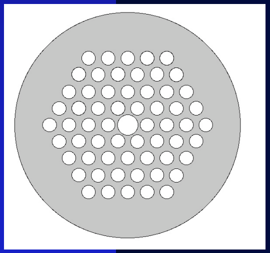
$DF\ ;\ \sqrt{1+(2\pi a/\lambda)^2}=2.1$

Mizrahi & Schachter, PRE **70**, 016505 (2004)



$$E_z = E_{pk}/DF$$

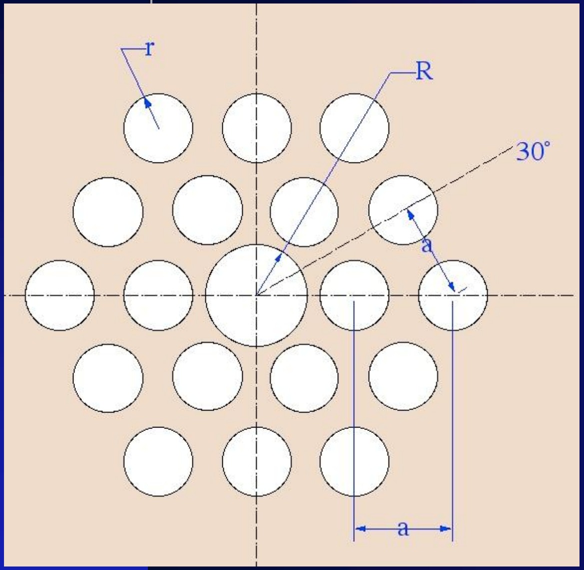
$$\sigma_t > (1 - v_g/c)L_{fiber}$$



PBG fiber with central defect
aperture ~ 0.68 λ; E_z ~ 2.5 GV/m

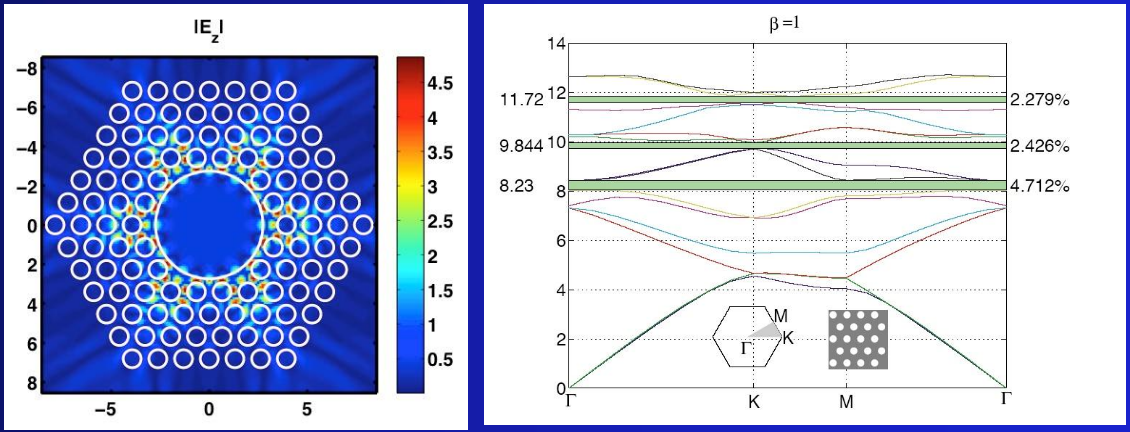
X. E. Lin, PRSTAB **4**, 051301 (2001)

Optimized PBG Fiber Geometry



$a = 0.35 \lambda$; $R = 0.52 a$

Rdefect (micron)	0.678	1.75	2.74
lambda (micron)	1.01	1.01	1.01
Cherenkov Z (ohm)	133.2	20.0	8.2
Cherenkov loss factor (V/C)	3.92E+22	5.88E+21	2.40E+21
Characteristic Z (ohm)	19	0.7	0.15
Loss factor (V/C)	3.26E+21	1.20E+20	2.57E+19
Damage Factor	2.1	8.0	15.6



X. E. Lin “Photonic bandgap fiber accelerator,” PRSTAB **4**, 051301 (2001)

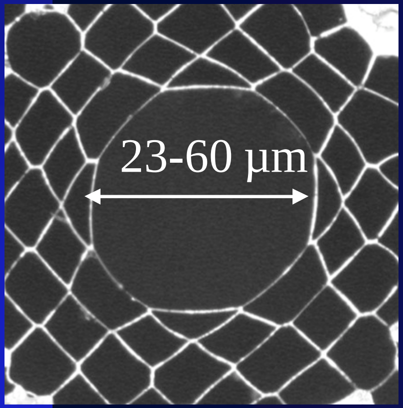
The Road to a Fiber-based Accelerator

- Manufacture/Prototyping
- Coupling
  - $e^{\pm}$ beam: focusing, emittance, microbunching
  - laser: mode-matching, coupling efficiency, phase stability
- Fiber Characterization
- Proof-of-Principle Acceleration + Staging

Manufacturability

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

Courtesy Crystal-Fibre, Inc.



A. Argyros, et al., Optics Express **18**, 5642 (2008)

Custom Fiber Manufacture

- prohibitively expensive for accel. prototyping
- SBIR or other funding for collaboration with industry (e.g. Incom, Inc. - Charlton, MA)

Pre-made Telecom Commercial Fibers

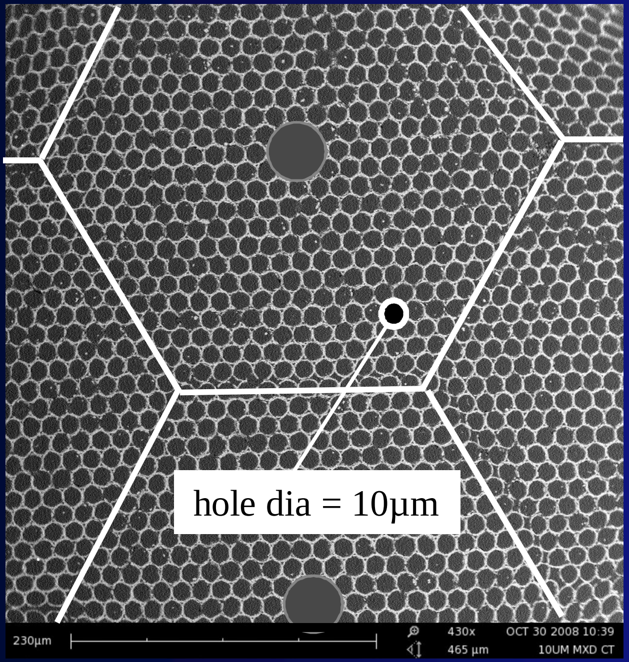
- PBG telecom fibers exist (~$500/m)
- Thorlabs + Crystal-Fibre, Inc.
- Not designed for accelerator applications

Polymethylmethacrylate (PMMA) Fibers

- U. Sydney (A. Argyros, et al)
- drawing process less expensive
- technique could be used for geometrical prototyping and tolerance testing

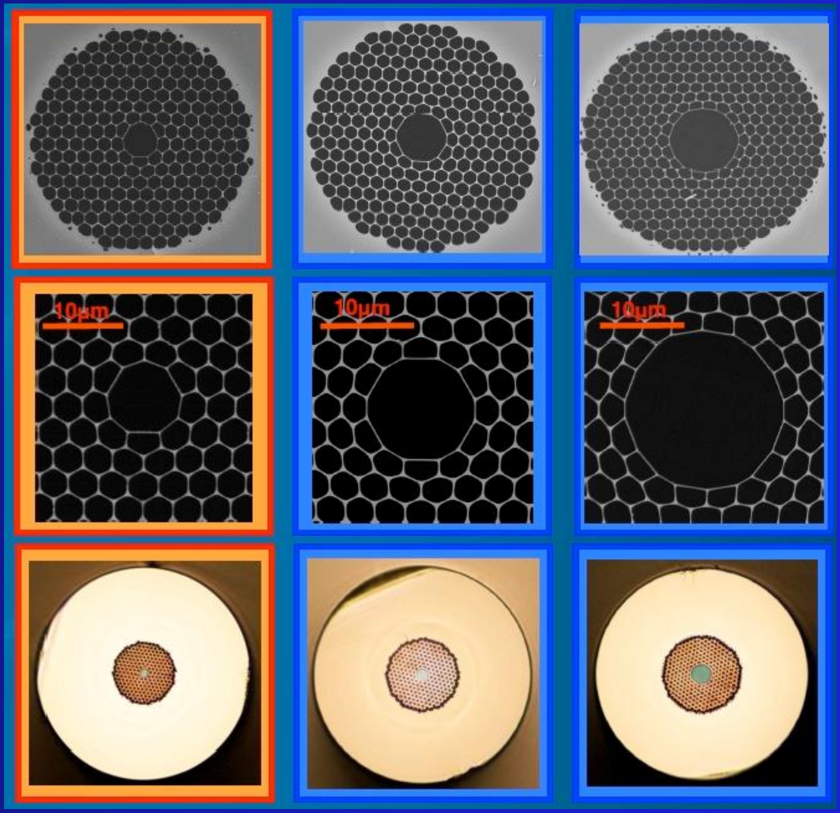
Manufacturability

matrix of 10µm holes, 1mm thick
Incom, Inc. SBIR proposal



courtesy J. E. Spencer, B. Noble

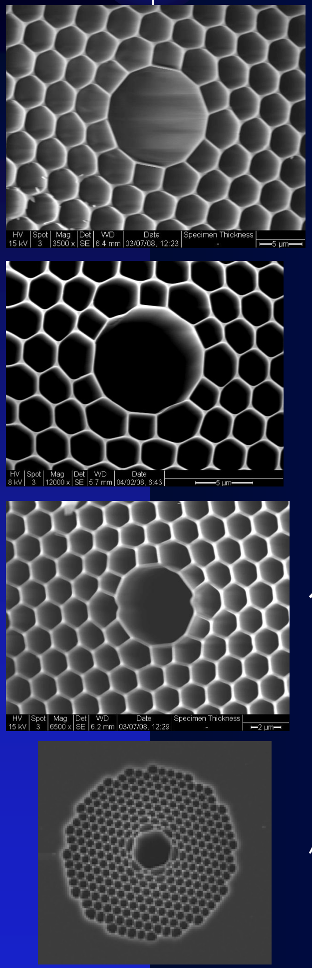
Air-core fibers from U. Southampton



courtesy Dave Richardson

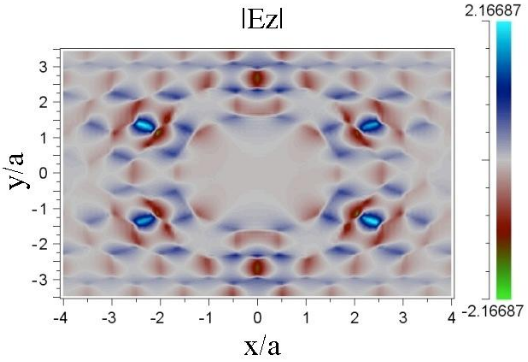
Commercial Fibers

fibers manufactured by Crystal-Fibre, Inc.



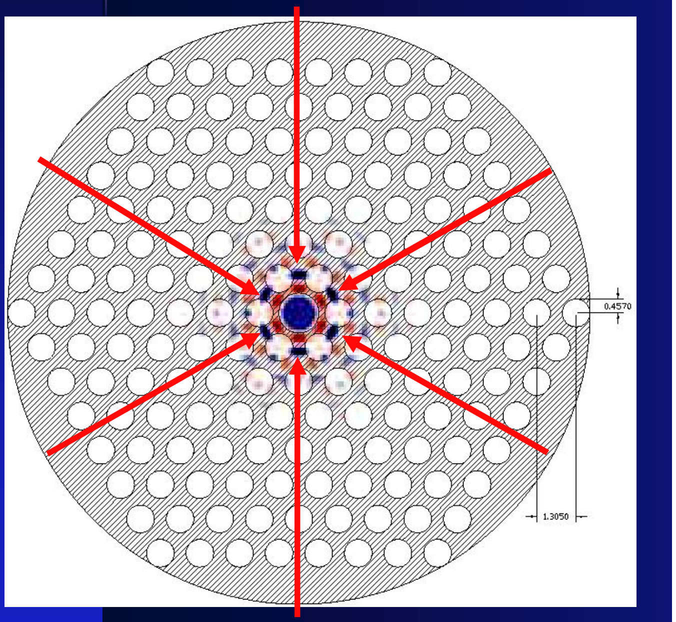
λ (telecom)	2R (defect) (μm)	a (pitch) (μm)	lattice dia. (μm)	cladding dia. (μm)
1550	10.9	3.8	70	120
1060	9.7	2.75	50	123
633	5.1	1.77	33.5	101
830	9.2/9.5	2.3	40	135

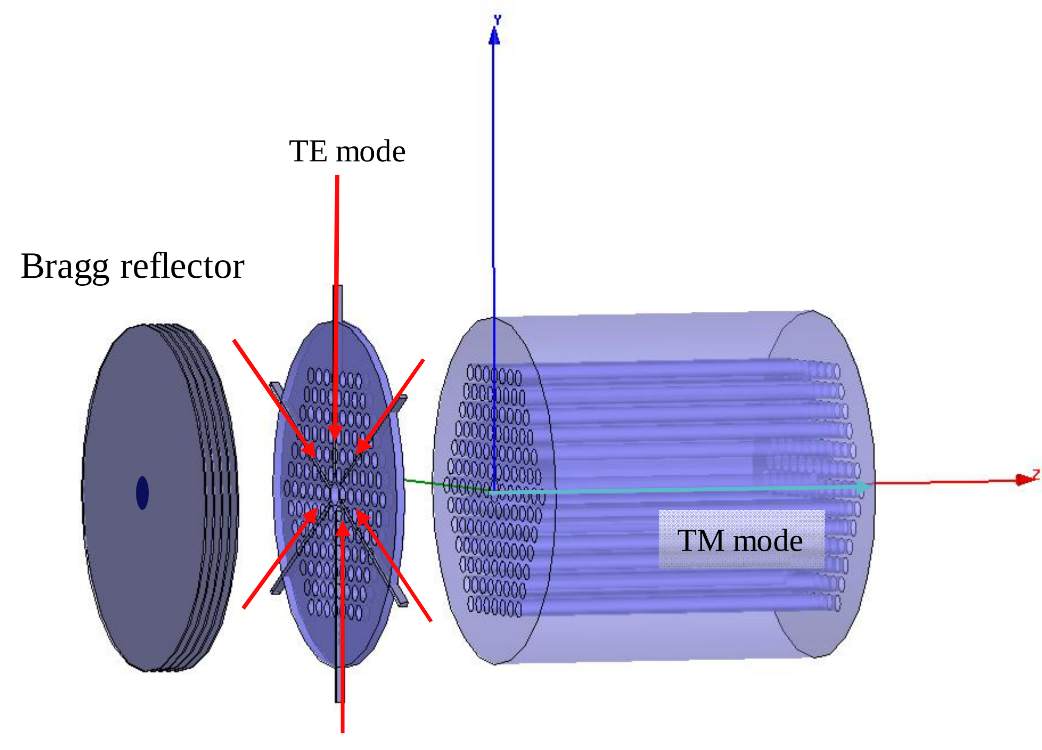
BANDSOLVE
simulation of accelerating mode
for HC-1060 fiber
maximum gradient ~ 30 MV/m



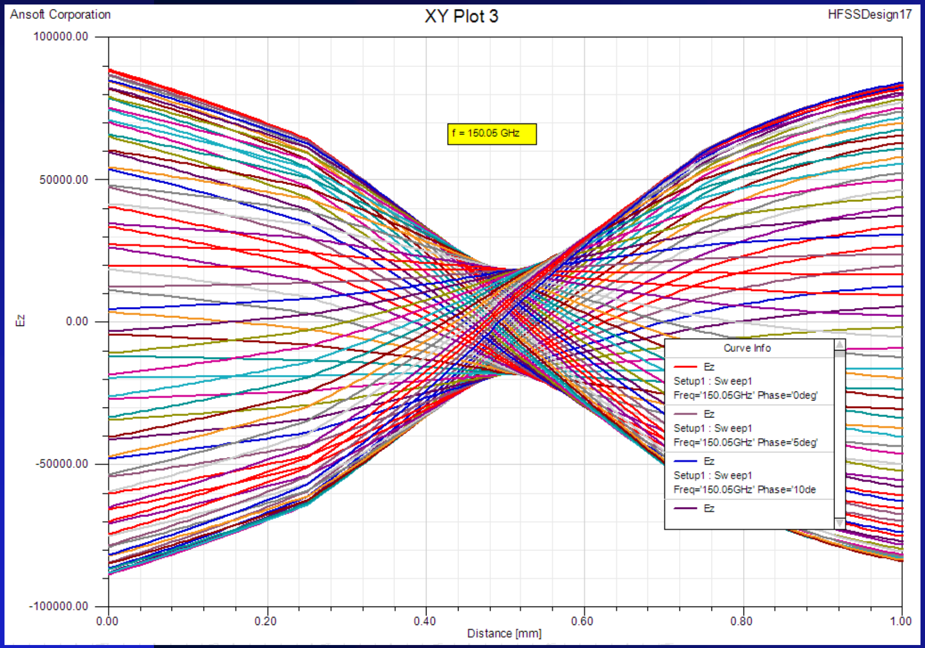
courtesy B. Noble

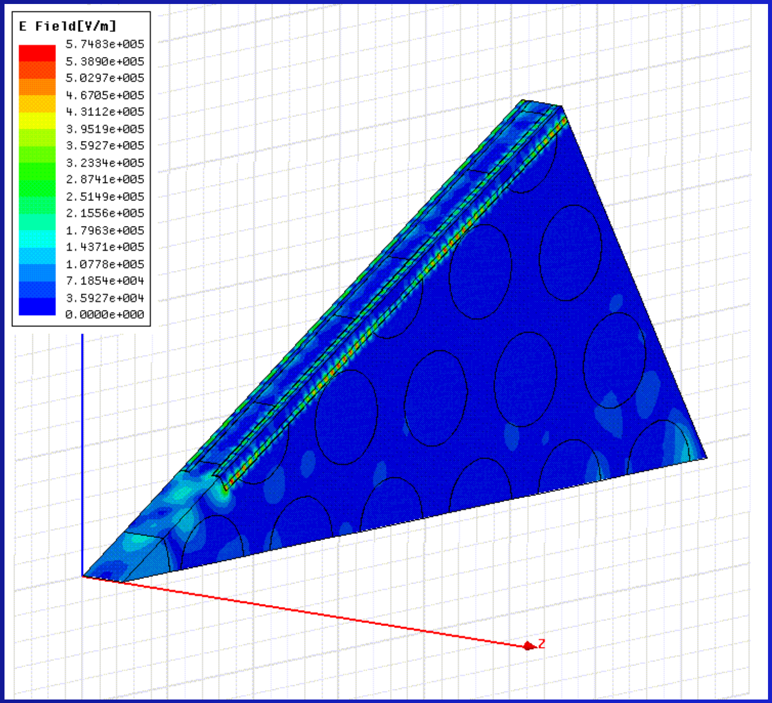
Laser Coupling



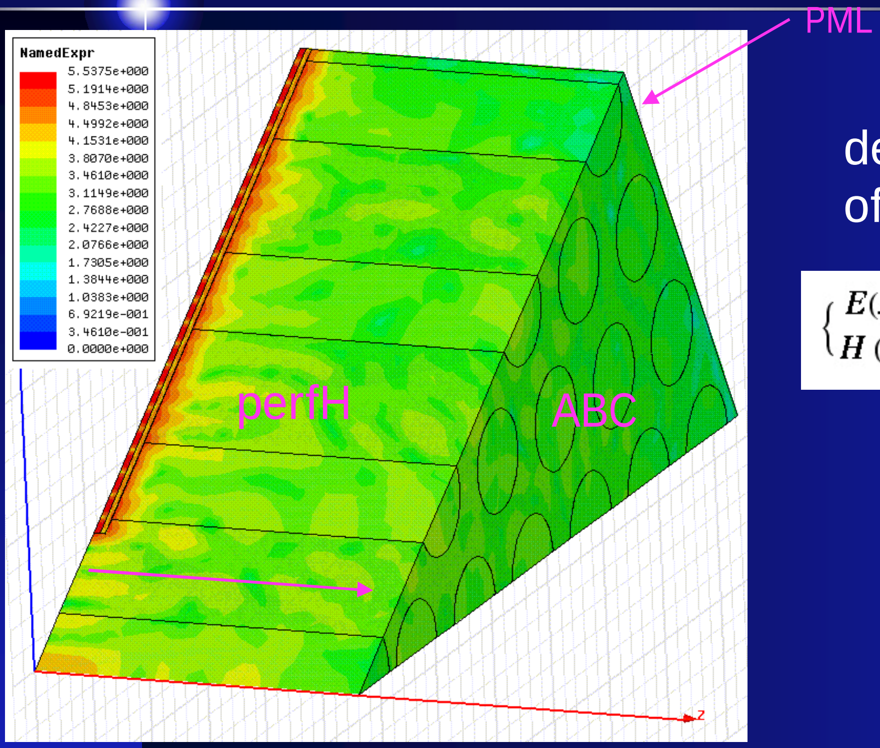


Coupler Studies





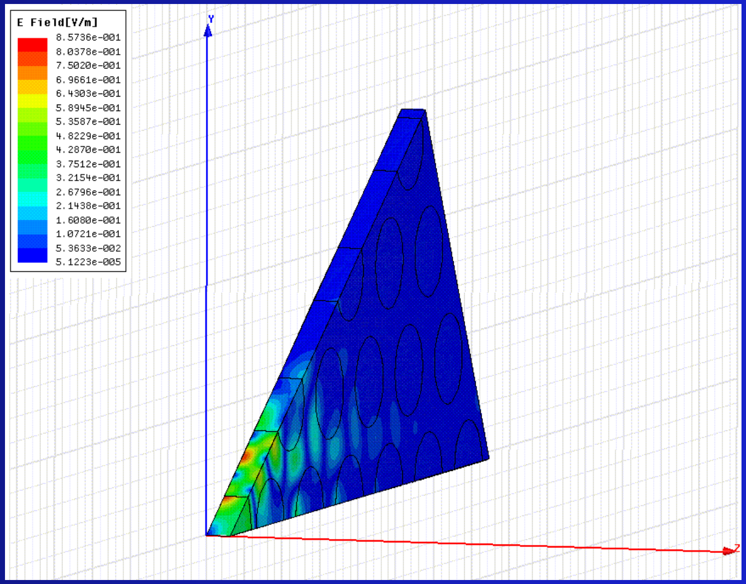
Coupler Studies



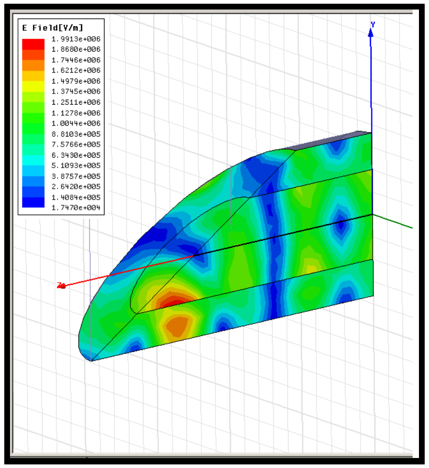
1/12 section of fiber
HFSS Simulation

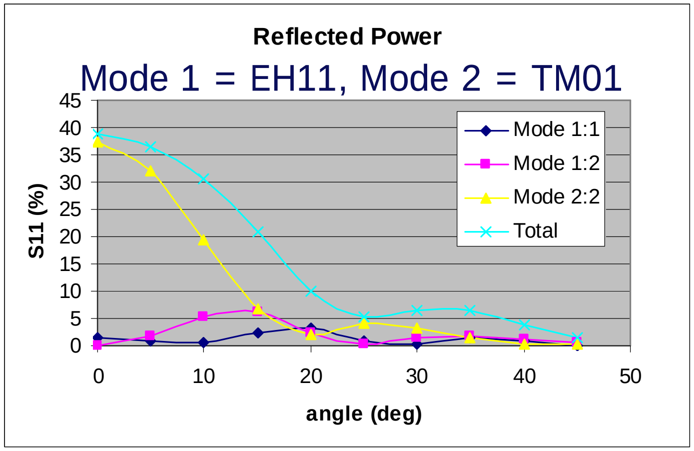
decompose excitation into normal modes of the waveguide (including Lin mode):

$$\begin{Bmatrix} E(x,y,z,t)\\ H(x,y,z,t)\end{Bmatrix} = \sum_n \left[a_n^+ \begin{Bmatrix}E_n(x,y)\\ H_n(x,y)\end{Bmatrix} e^{+ik_n z} + a_n^- \begin{Bmatrix}E_n^*(x,y)\\ -H_n^*(x,y)\end{Bmatrix} e^{-ik_n z}\right];$$



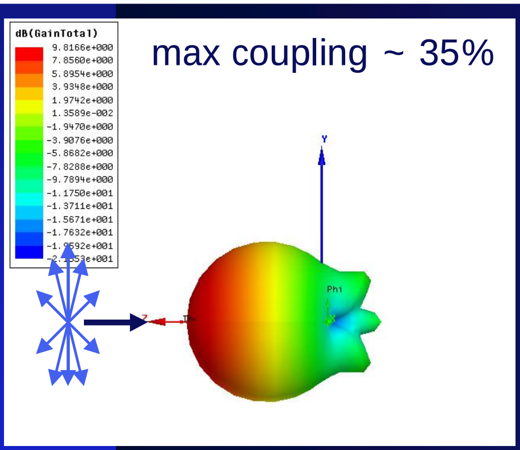
Laser Coupling from Free Space





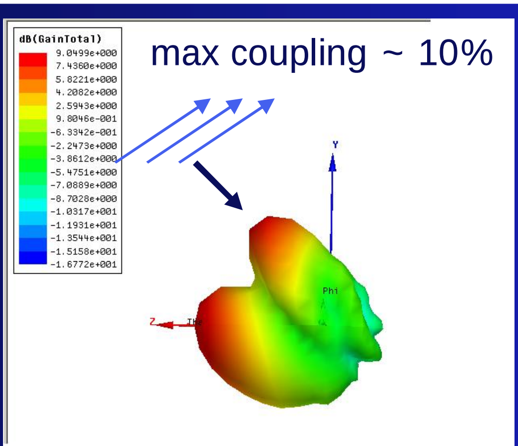
Coupling to fiber tip from free space:

- shorter term solution
- HFSS model of simple dielectric waveguide
- will extend to PBG lattice type fiber



max coupling ~ 35%

Cleave angle = 0 deg



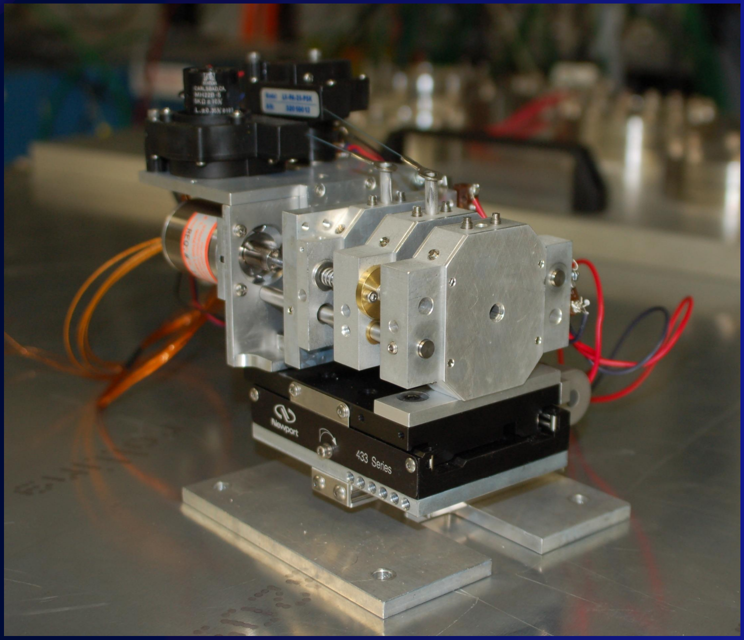
max coupling ~ 10%

Cleave angle = 45 deg

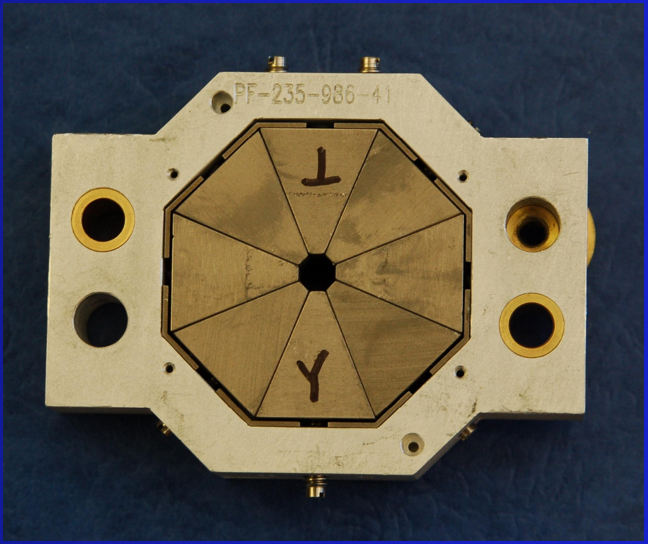
options:

- radially polarized laser on flat fiber tip
- linearly polarized laser on angled fiber tip

E-Beam Focusing

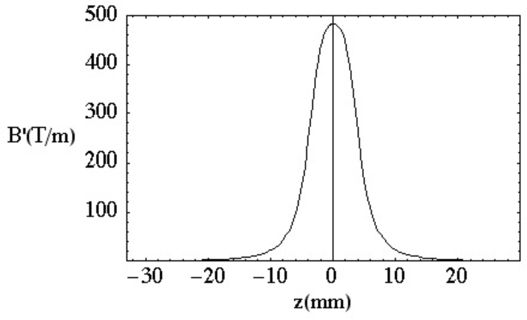


New Halbach Magnet Design
Field Gradient ~ 500 T/m
Aperture = 6 mm
Adjustable z positions of magnets.
String encoder readback of magnet positions.
On slider stage for insertion/removal of assembly.
Magnets aligned on titanium rods.

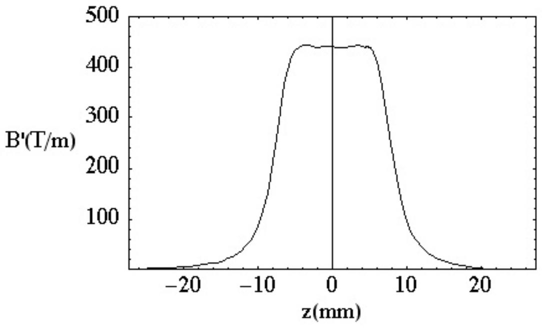


Permanent Magnet Quadrupoles

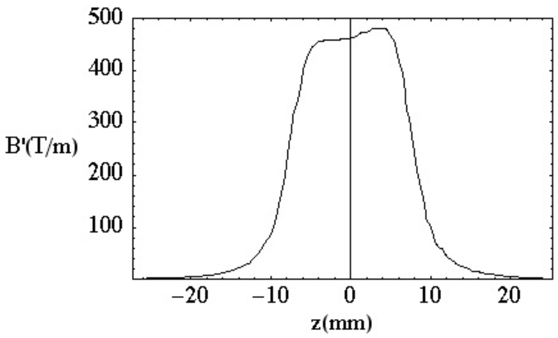
PMQ 1: B’ = 483.0 T/m



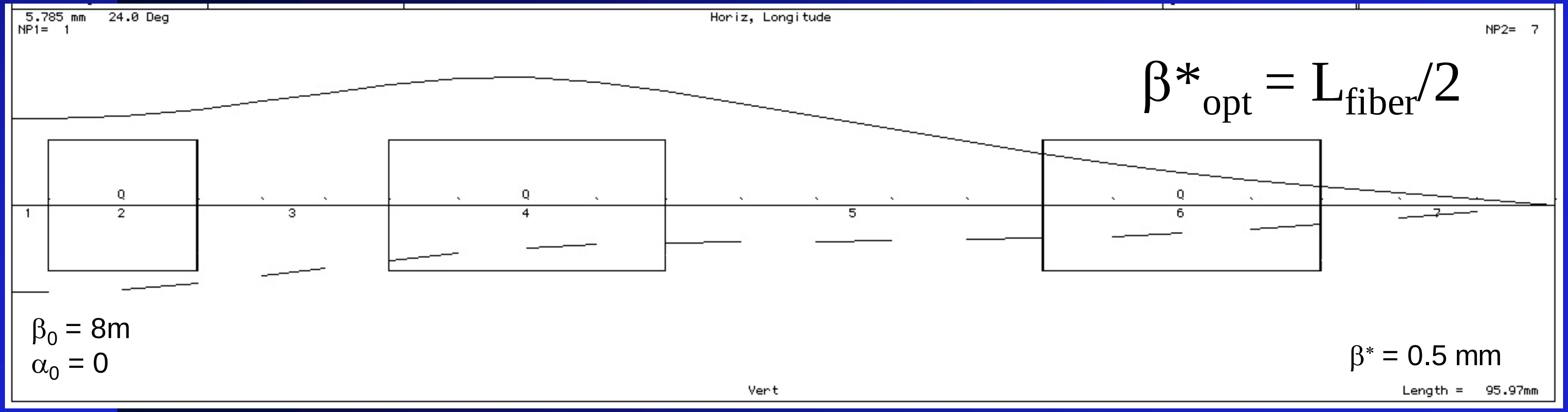
PMQ 2: B’ = 440.5 T/m



PMQ 3: B’ = 462.4 T/m



PowerTrace Simulation



$\beta^*_{opt} = L_{fiber}/2$

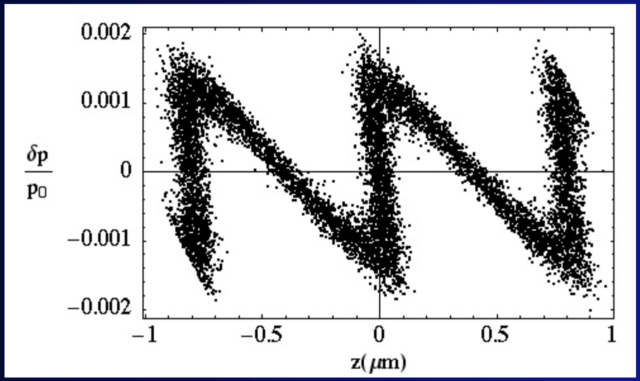
$\beta_0 = 8\text{m}$

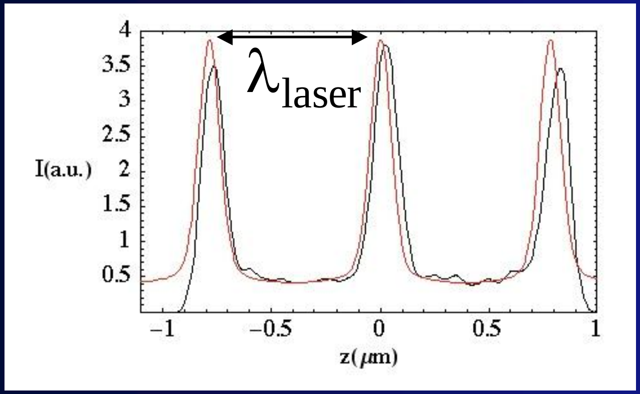
$\alpha_0 = 0$

$\beta^* = 0.5$ mm

Microbunch Washout

Initial Microbunched Beam





$$I(z) = I_0[1 + 2\sum_{n=1}^{\infty} b_n \cos(nk_L z)]$$

IFEL Interaction + Chicane Compression

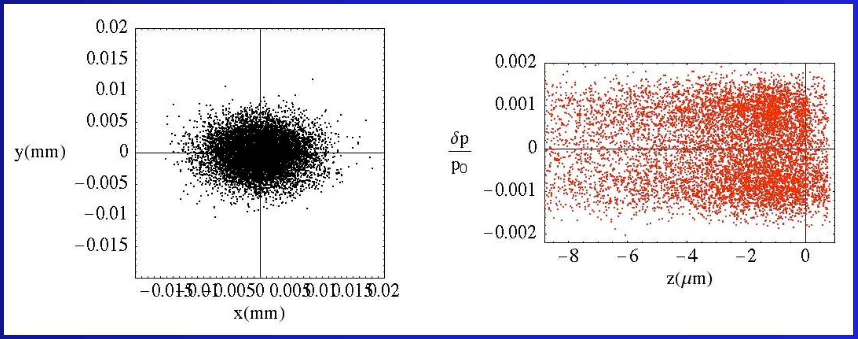
Technique recently demonstrated by C.M.S. Sears -> 400 attosec bunches

$$\delta_f = \delta_0 + \eta \sin(k_L z_0)$$

Dominant washout terms

$$z_f = z_0 + R_{56}[\delta_0 + \eta \sin(k_L z_0)] + T_{511} x_0^2 + T_{533} y_0^2$$

After PMQ Focus



Primary culprits are the T511 and T533 of the PMQs

Microbunch Washout

Possible Remedies

Radially Dependent Amplitude

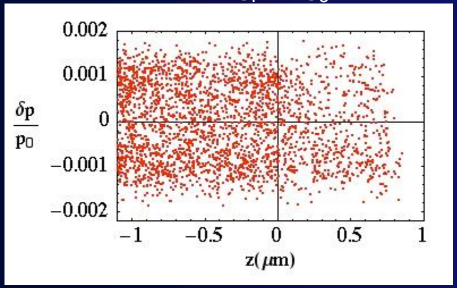
$$z_f = z_0 + R_{56}\{\delta_0 + \eta(x_0, y_0, z_0)\sin(k_L z_0)\} + T_{511}x_0{}^2 + T_{533}y_0{}^2$$

$$\eta(x_0, y_0, z_0) = \eta - \frac{T_{511}x_0{}^2 + T_{533}y_0{}^2}{R_{56}\sin(k_L z_0)}$$

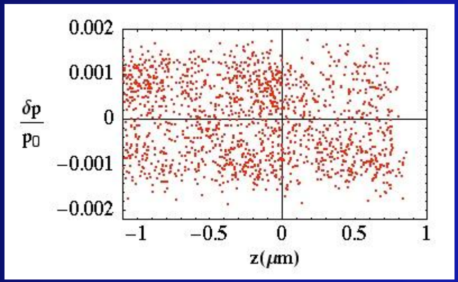
this requires the IFEL modulation to increase quadratically with radial distance

Collimation

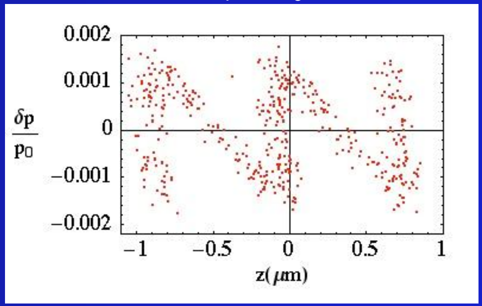
NO collimator
$Q_f = Q_0$



400 μm diameter collimator
$Q_f = Q_0/6$

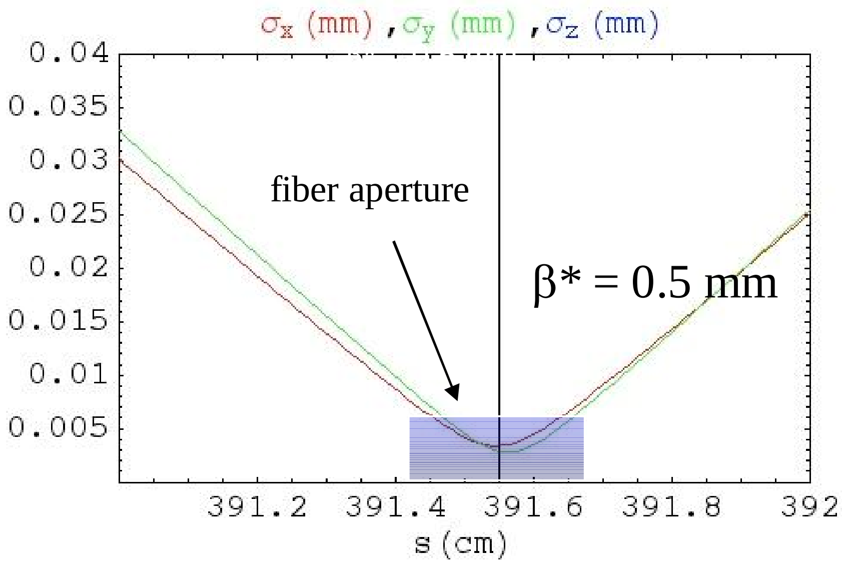


200 μm diameter collimator
$Q_f = Q_0/21.5$

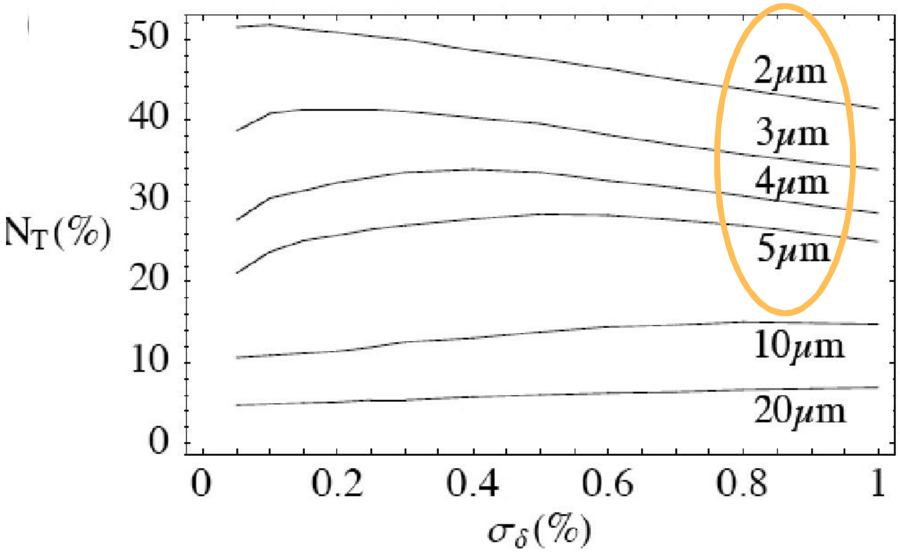


Emittance Requirements

ELEGANT simulation of focal waist

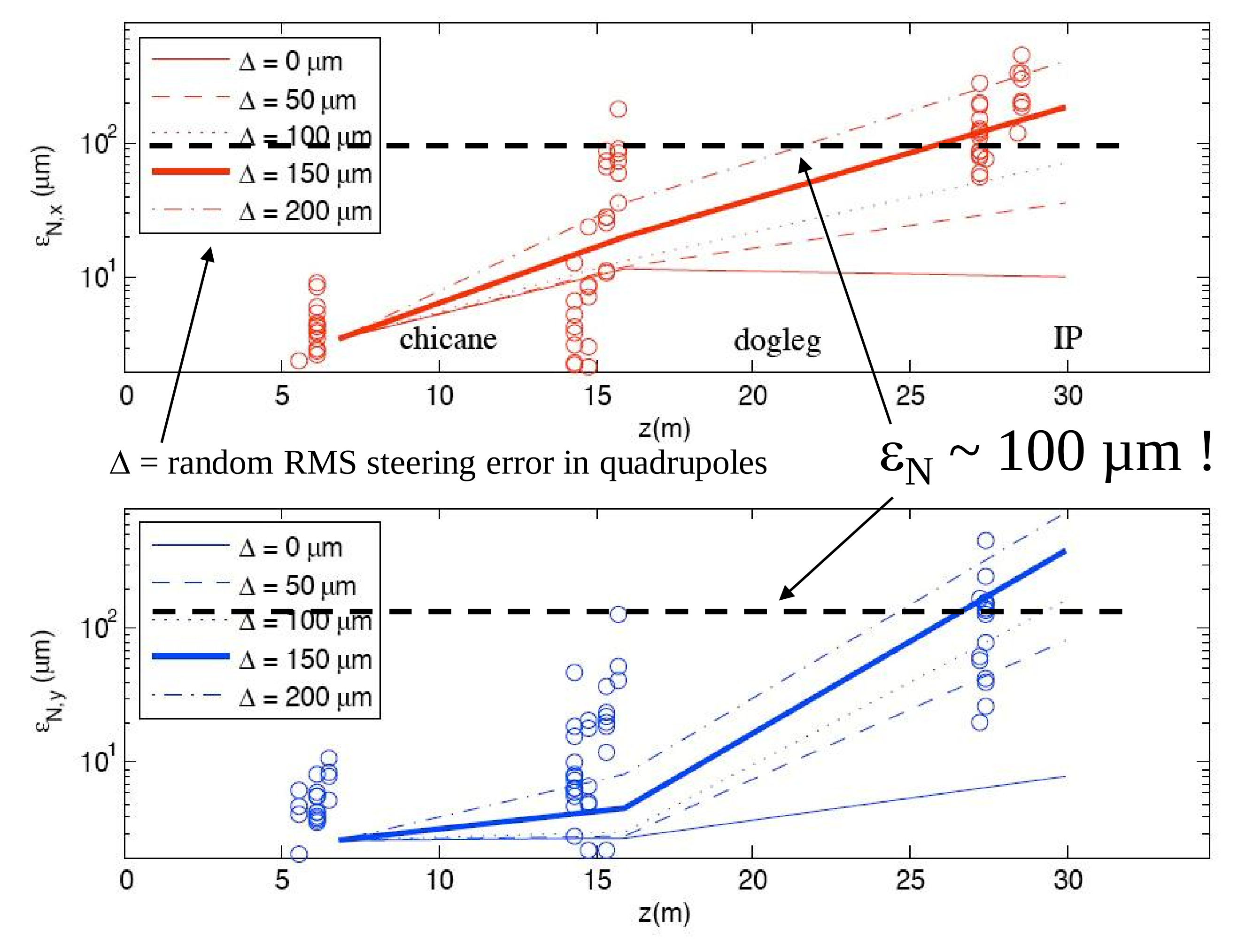


Transmission vs. Normalized Emittance



Emittance Preservation

Measured Emittance Growth in the NLCTA/E163 Beamline

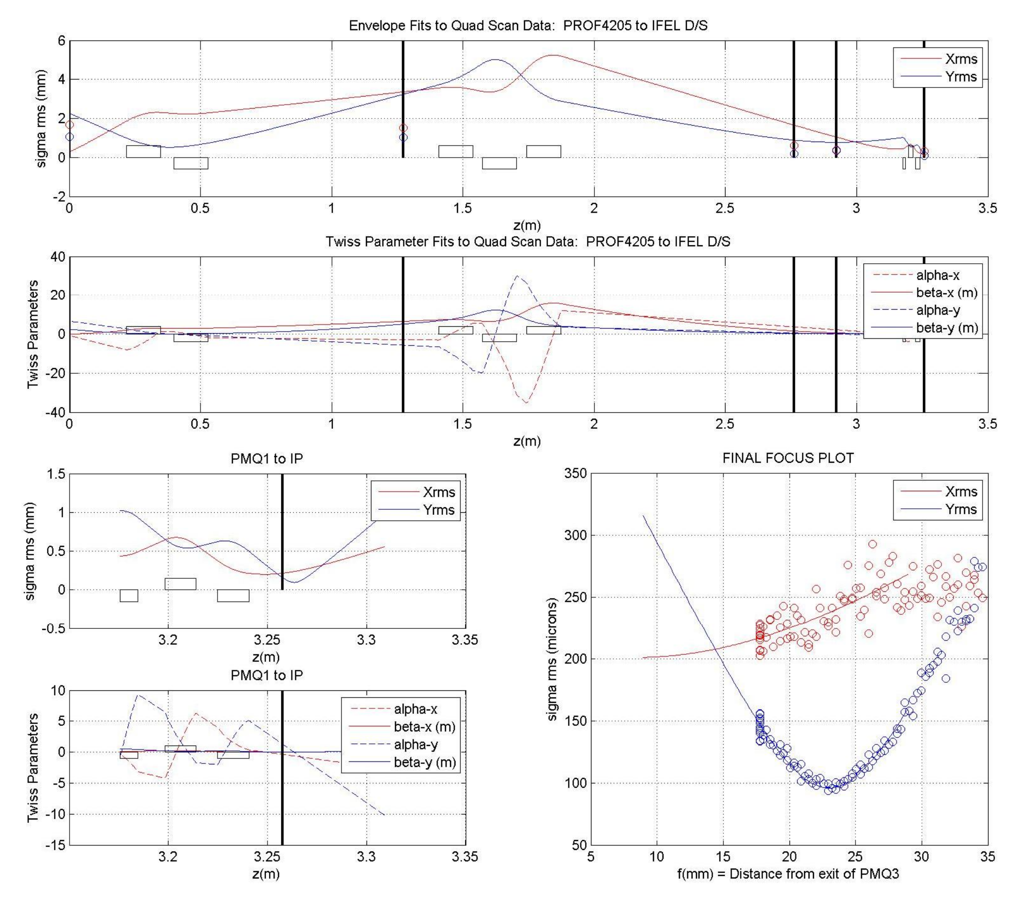


Δ = random RMS steering error in quadrupoles

$\varepsilon_N \sim 100\ \mu m$!

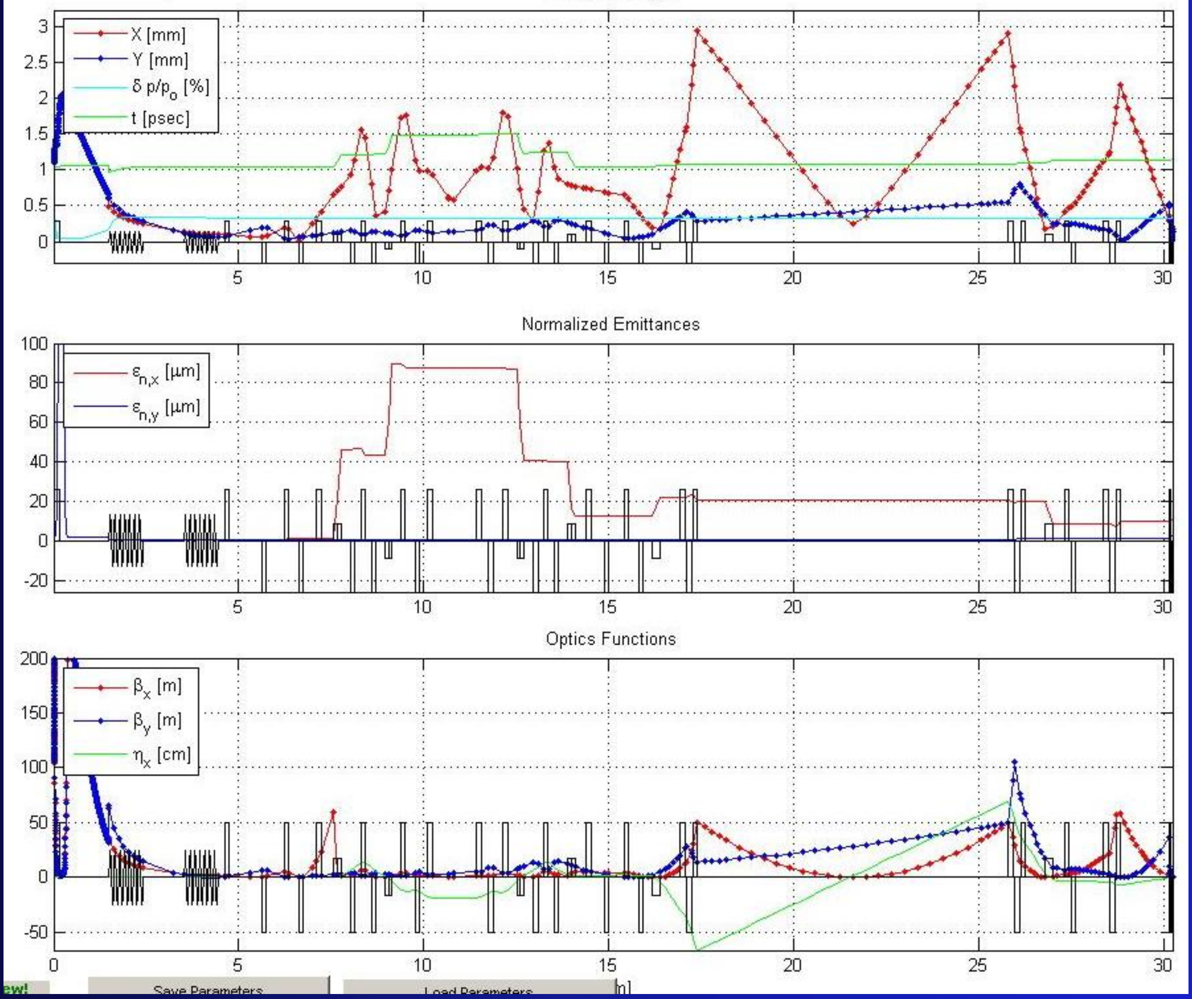
Improved Modeling Tools

Matlab-based



Improved Modeling Tools

ELEGANT-based



Improved Modeling Tools

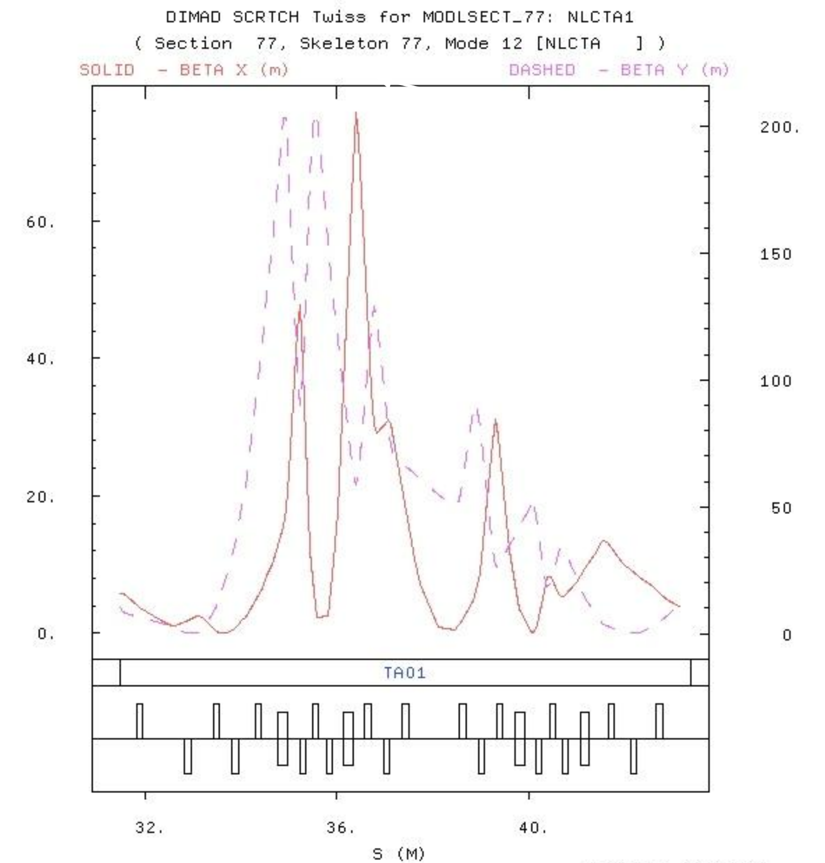
DIMAD-based: Built into the Control System

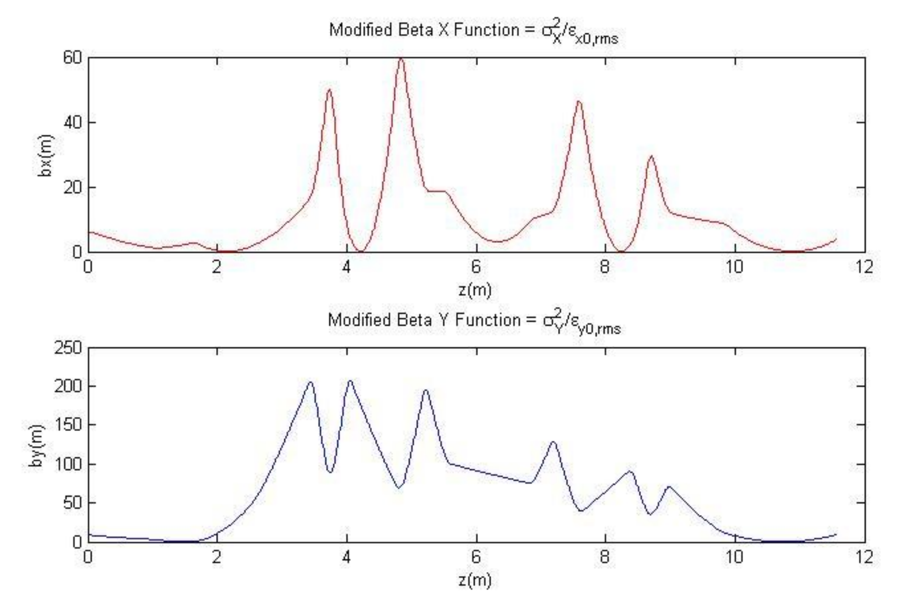
Alternate definitions of βx and βy

Matlab and ELEGANT models use $\beta_x(s) = \sigma_x^2(s) / \varepsilon_{x,rms}(s)$

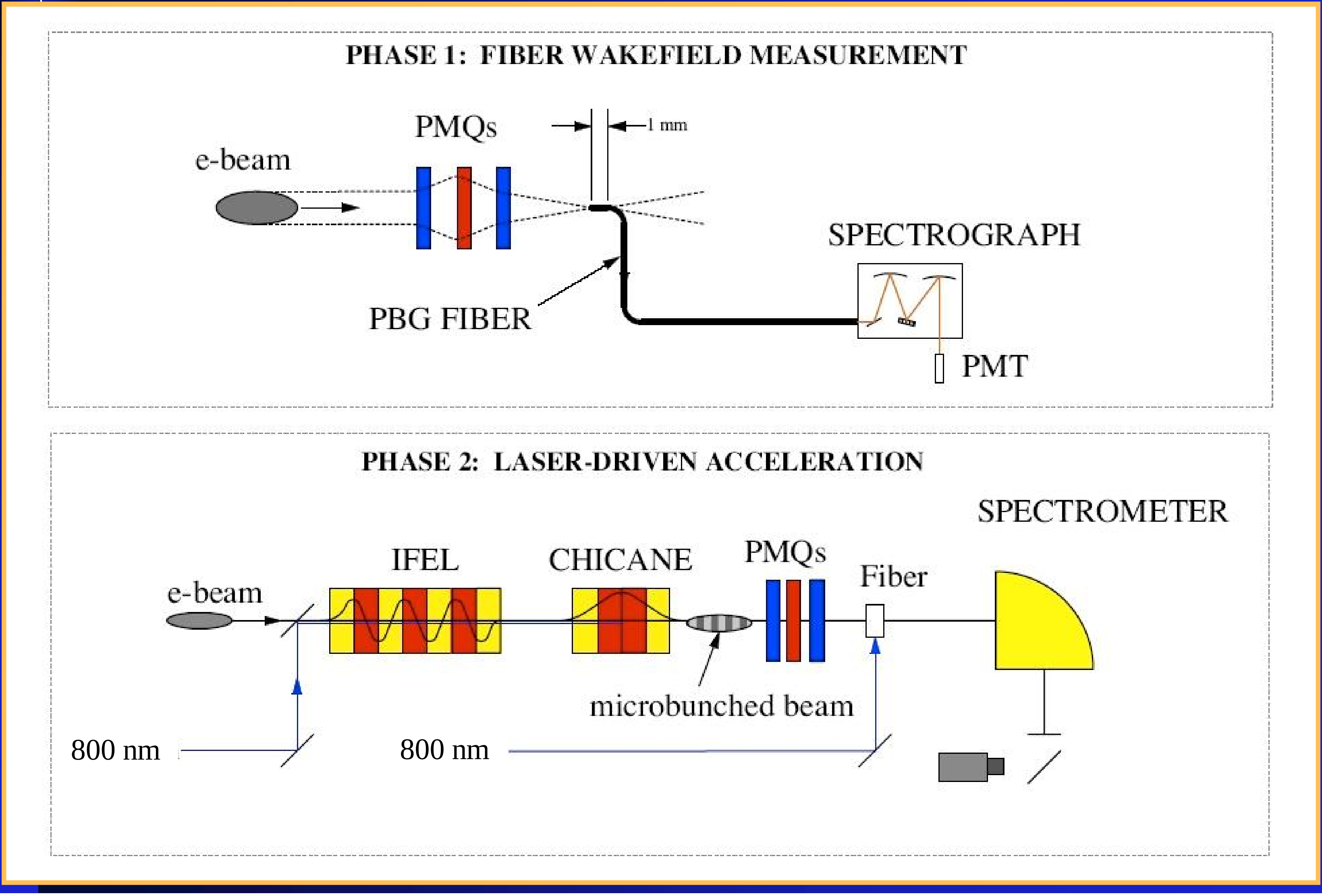
If we instead use $\beta_x(s) = \sigma_x^2(s) / \varepsilon_{x,initial}$ constant

then we (mostly) reproduce the SCP results:





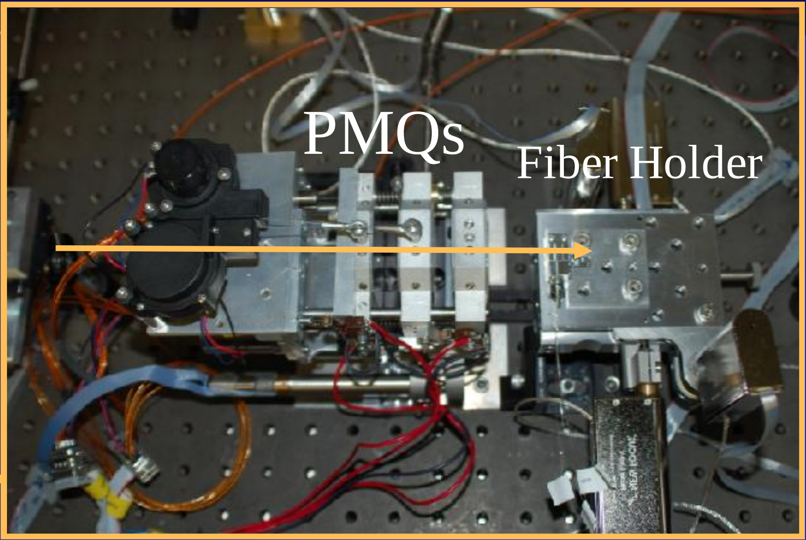
Experimental Plan

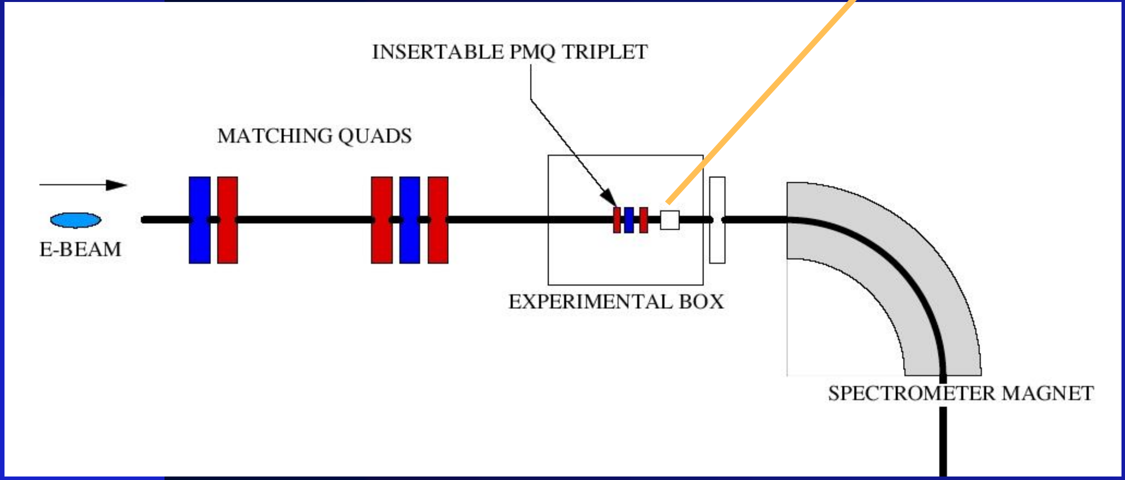


Phase 1: Experiment Layout

Required Beam Parameters

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





QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

Newport MS 260i Spectrograph

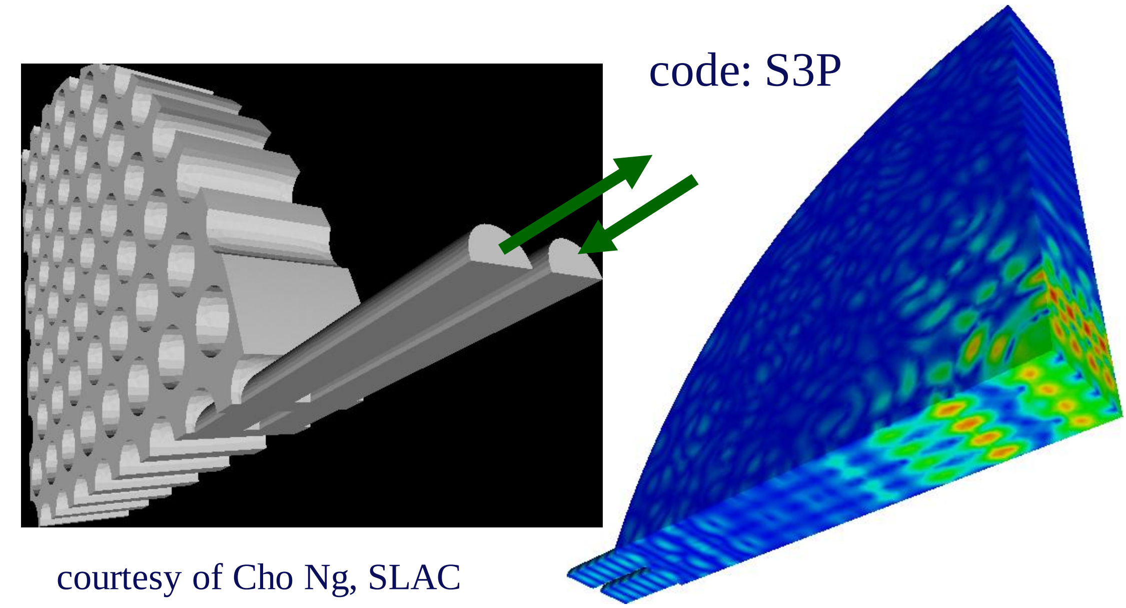
Summary

Issues to be addressed in developing PBG Fibers as Accelerators:

- Affordable (<$10k) manufacturing of Prototypes
- For injected test beam:
  - emittance
  - focusing and spot size
  - microbunch washout
- Laser coupling:
  - optimizing air-to-fiber coupling
  - developing high-efficiency advanced coupler designs
- Doing proof-of-principle experiments with single and then multiple stages of acceleration.

Backup Slides

Coupler Studies



code: S3P

courtesy of Cho Ng, SLAC

Advanced coupler design:
- in/out power couplers
- analogy to RF tw accelerator
- S_{11} = 0.1: power coupling can be close to 100%
- how to manufacture?

Motivation

S-Band RF

↓

X-Band RF

↓

Optical to IR

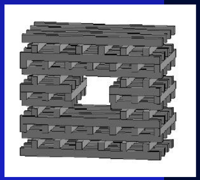
$$Gradient = \frac{\sqrt{P \cdot R_S}}{L} \propto f$$

smaller RF structures:

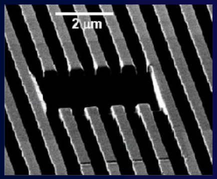
- higher gradient
- machining tolerances
- transverse wakefields
- breakdown ($E_z \leq 100$ MV/m)

laser-driven microstructures

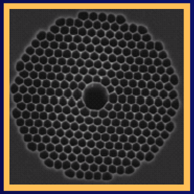
- lasers offer high rep rates, strong field gradients (>0.5 GV/m), commercial support
- dielectrics: high breakdown threshold (~4 GV/m)
- manufacturability
- coupling of beam/laser



3D “woodpile” structure



dielectric gratings



PBG Fibers

Photon Budget & SN Ratio

$$\Delta E_{\text{mode}} = kq^2 = \frac{e^2 c}{4}\,\frac{\beta_g}{1-\beta_g}\,\frac{Z_c L}{\lambda_0^2} \qquad \frac{\Delta E_{\text{mode}}}{\Delta E_{\text{Cherenkov}}} > 1 \;\Rightarrow\; \mathrm{Z_C}[\Omega] > \frac{120}{\lambda[nm]}$$

HC-1060 fiber: $\mathrm{Z_C} = 0.005\Omega\;;\;\frac{120}{\lambda[nm]} = 0.12\Omega$

$$k = 1.42\times 10^{18}\,J/C^2 m \rightarrow \Delta E_{\text{mode}} = 3.6\times 10^{-23}\,J/electron$$

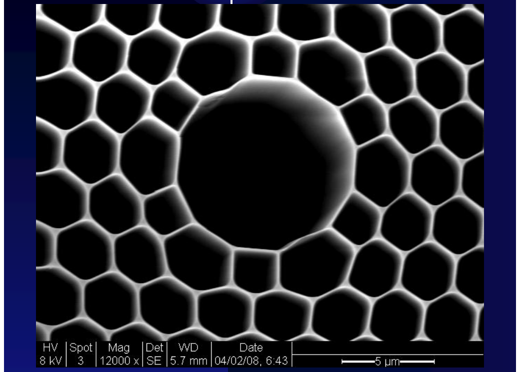
$$N_\gamma = \Delta E_{\text{mode}}\cdot\left(\frac{50\,pC}{e}\right)\frac{1}{h\omega} = 6162\,photons$$

$$N_{\text{detector}} = N_\gamma \eta_{transmission}\eta_{fiber}\eta_{spectrgraph} = 1150\,photons$$

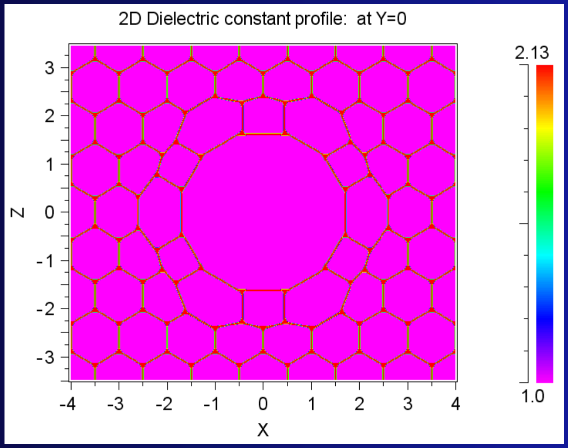
50% 98% 38%

- Cherenkov background cannot couple to the lattice modes at frequencies in the bandgap.
- Coupling to the defect modes would improve the signal.
- Coupling to the cladding: can be reduced through bend losses

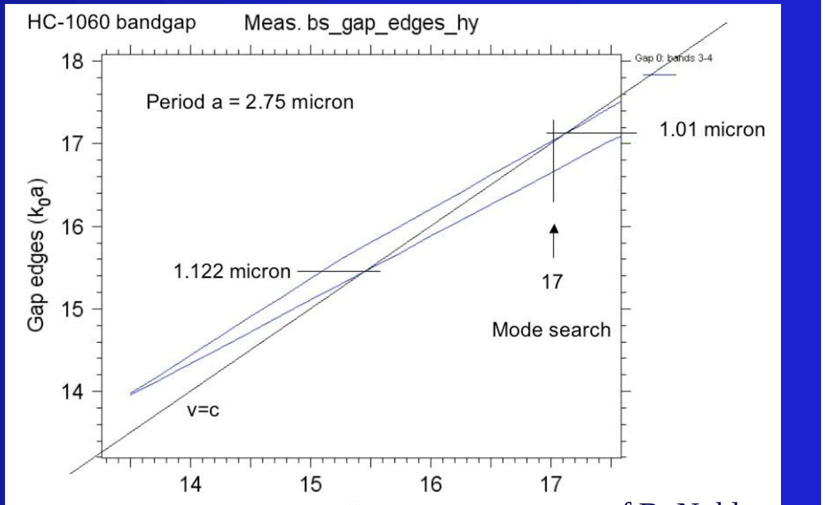
Search for Candidate Accel. Modes



HC-1060 SEM image

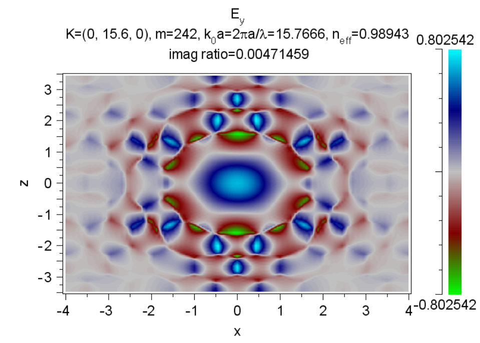


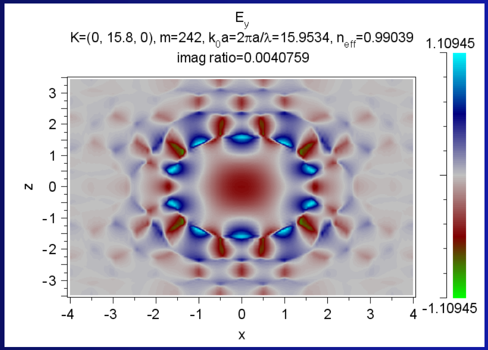
RSoft BandSolve Model

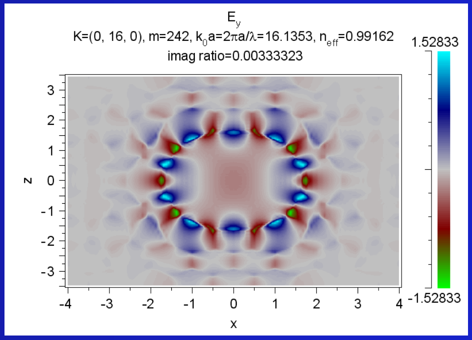


courtesy of B. Noble

toward SOL line







Schottky vs Cherenkov

$$\Delta E_{\text{mode}} = kq^2 = \frac{e^2 c}{4}\,\frac{\beta_g}{1-\beta_g}\,\frac{Z_c L}{\lambda_0^2}$$

$$\Delta E_{Cherenkov} = \int_{\lambda_0-\Delta\lambda}^{\lambda_0+\Delta\lambda} \frac{4\pi^2 r_e L m c^2}{f\lambda^3}\left(1-\frac{1}{\varepsilon}\right)d\lambda$$

$$\frac{\Delta E_{\text{mode}}}{\Delta E_{\text{Cherenkov}}} = \left[\frac{\varepsilon}{\varepsilon-1}\,\frac{f\varepsilon_0 c\beta_g/(1-\beta_g)}{4\pi(1+fL_{cladding}/L_{fiber})}\right]\frac{\lambda_0}{\Delta\lambda}Z_c$$

$v_g = 0.6;$

$\Delta\lambda = 0.48\ \text{nm};$

$\text{L}_{\text{fiber}} = 1\ \text{mm};$

$\text{L}_{\text{cladding}} = 164\ \mu\text{m};$

$\varepsilon = 2.13\ ;\ f = 10;$

$$\frac{\Delta E_{\text{mode}}}{\Delta E_{\text{Cherenkov}}} > 1 \quad \Rightarrow \quad \text{Z}_\text{C}[\Omega] > \frac{212}{\lambda[nm]}$$

HC-1550 fiber: $\text{Z}_\text{C} = 0.2\Omega\ ;\ \frac{212}{\lambda[nm]} = 0.13$

Lin Fiber: $\text{Z}_\text{C} = 19\Omega\ ;\ \frac{212}{\lambda[nm]} = 0.2$

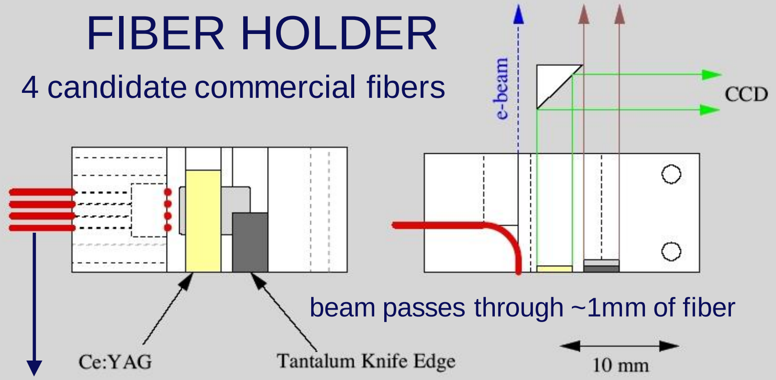
Experimental Layout

NLCTA: design parameters

Beam Charge	50 pC
Normalized Emittance	1-2 mm mrad
Energy	60 MeV
Bunch length	1 ps
Energy Spread	0.1 %

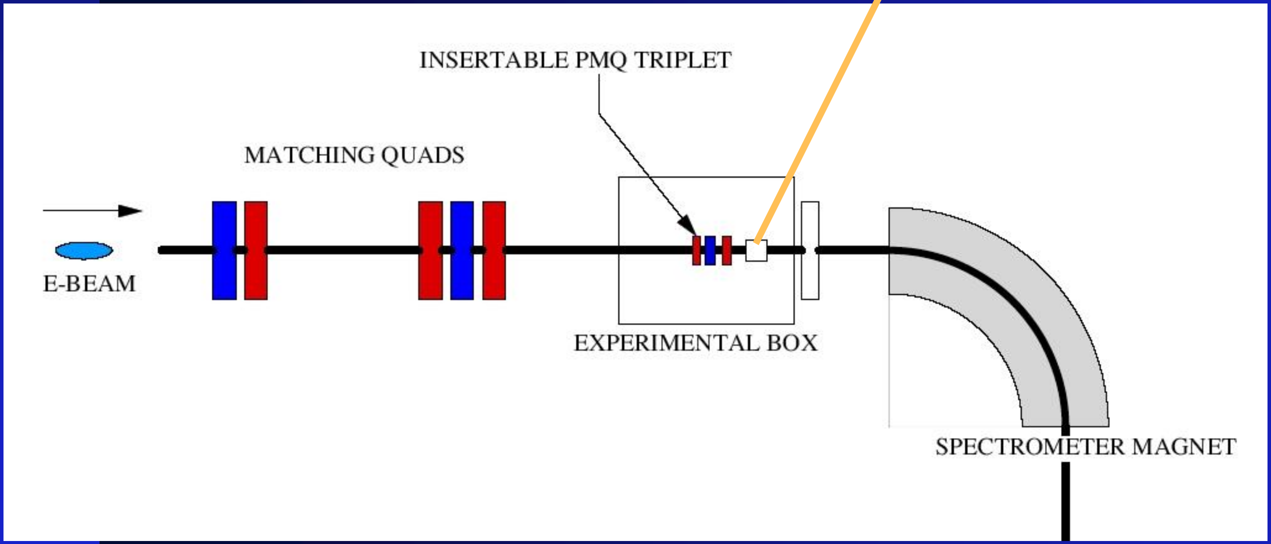
FIBER HOLDER

4 candidate commercial fibers



beam passes through ~1mm of fiber

fibers exit chamber for spectrographic analysis



Experimental Layout

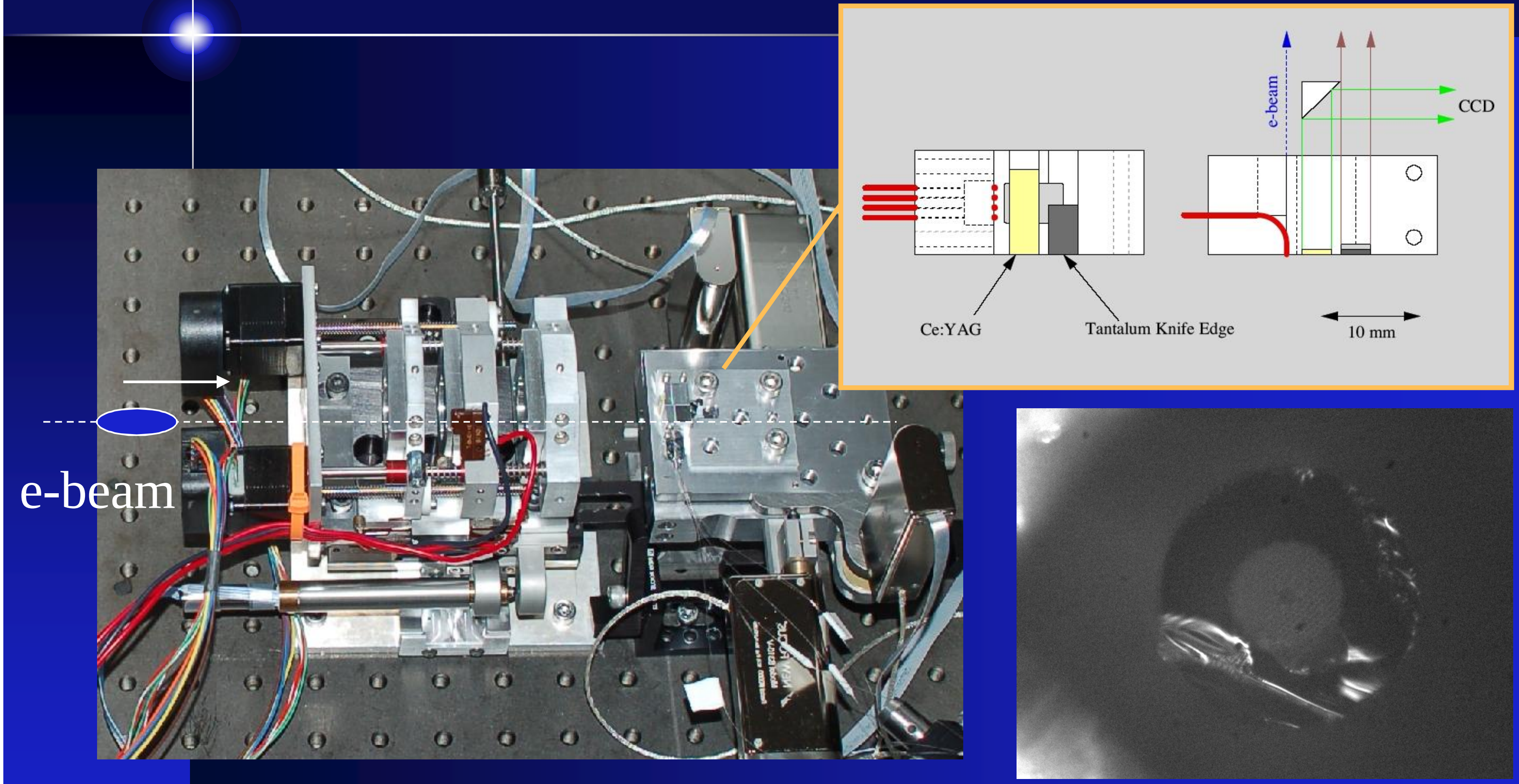
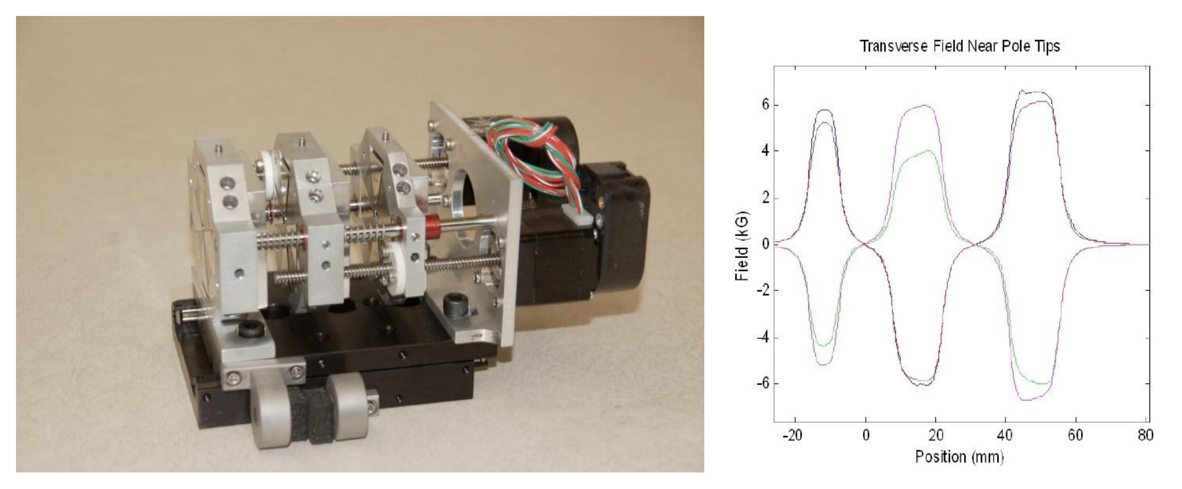


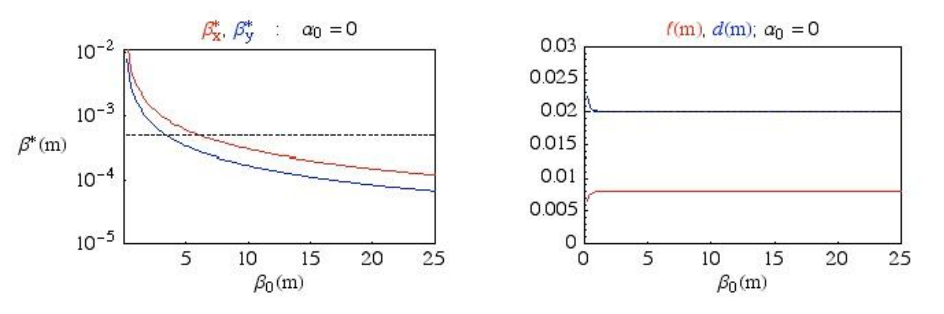
image of mounted fiber

Challenge: Small Spot Sizes



PMQ triplet with motorized gap spacing and focal position.
420, 560, 560 T/m field strengths
modified Halbach design

C.M. Sears, “Production, characterization, and acceleration of optical microbunches,” PhD dissertation, Stanford U. (2008)



Challenge: Small Spot Sizes

PowerTrace Simulation

QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

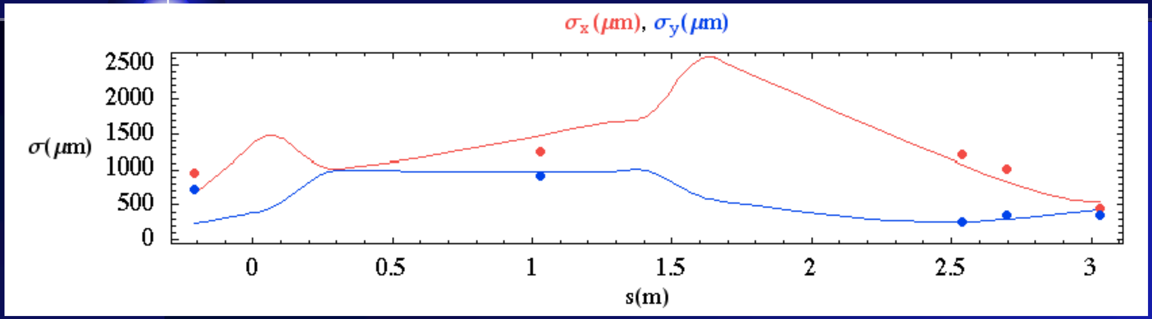
QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

ELEGANT simulation of the final focus transmission ~ 50% (for 1060 fiber with 10 µm defect)

$\beta x, \beta y \sim 0.5$ mm

$\sigma x, \sigma y \sim 3$ µm

Challenge: Small Spot Sizes



QuickTime™ and a
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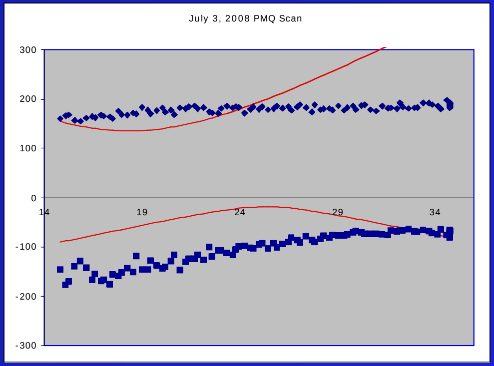

QuickTime™ and a
TIFF (LZW) decompressor
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Summary

optical to IR accelerating structures:

- offer high gradients (~ 1GeV/m),
- high rep rates, high damage threshold of dielectrics
- require micron-scale focusing, microbunching, and manufacturing

PBG fiber accelerators:

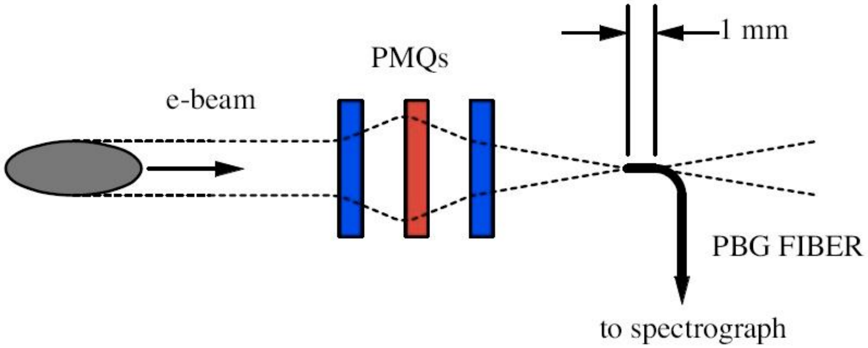
- permit large apertures
- commercial manufacturing capability;
- premade fibers are designed for telecom, not acceleration
- need to develop custom geometries: Lin fiber

E163

- near-term: focusing of e-beam through fiber cores + spectrally resolving fiber modes from the emitted wakefield radiation
- long-term: coupling of structure to drive laser and observing net acceleration of microbunched e-beam ---> multiple stages

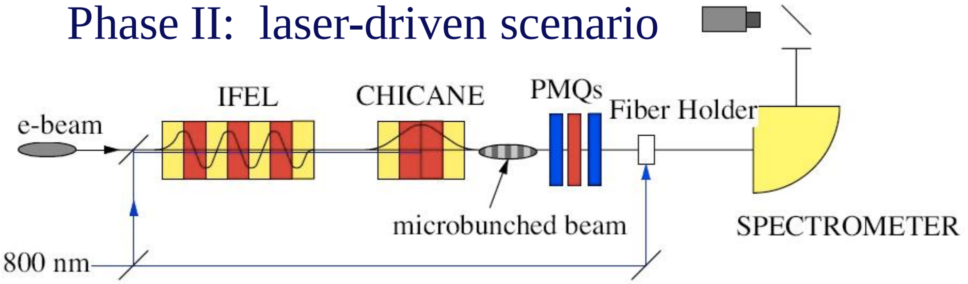
Experimental Plan

Phase I: Wakefield Excitation (no laser)



- tightly focus beam through fiber central defect (spot sizes < 10 µm)
- wakefield excitation of fiber modes
- resolve accelerator-like modes by spectral analysis

Phase II: laser-driven scenario



- few-100 attosec microbunched beam using IFEL + chicane
- laser coupled to the fiber accelerator mode
- measure net microbunch acceleration with magnetic spectrometer