Light sources based on optical-scale accelerators

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Input from...
Claudio Pellegrini, Sven Reiche, Chris Seers, Chris McGuinness, Eric Colby, Joel England, Josh McNeur

Material stolen from... lots of people including C. Brau, J. Jarvis, T. Plettner

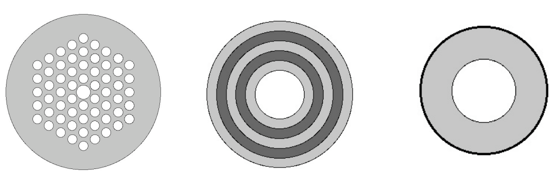
I want to thank the organizers for the opportunity

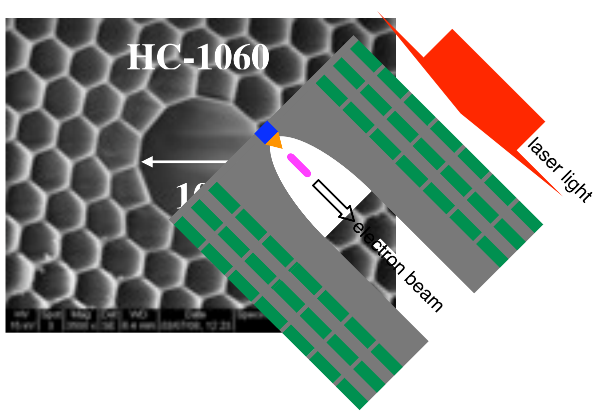
Eric

Bruce

Me

< 10 days





non-functional technology

talk length = f(t)

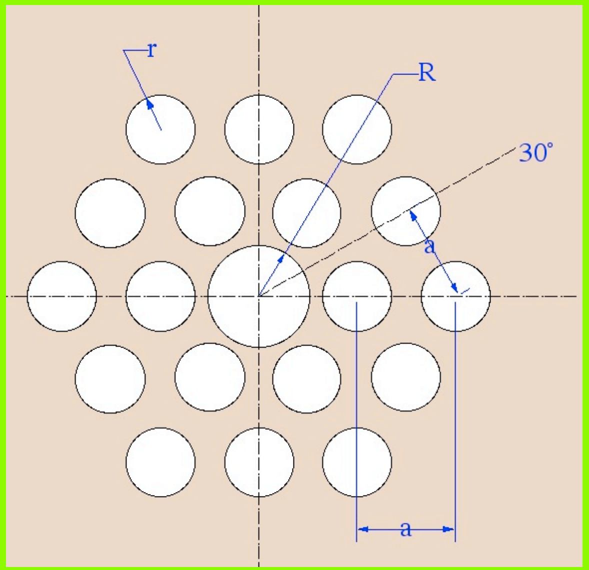
Make a light source!

Can you build an iPad sized light source?

Should you build it?

Optical-scale dielectric-structures promise GeV/m gradients and naturally short bunches

+ very short pulses
+ very high repetition rate
+/- low charge
- no track record
- limited R&D work
! The red-headed stepchild of AA



Tolerances:
PWFA: ~300nm
LWFA: ~30nm
MAP: ~10nm

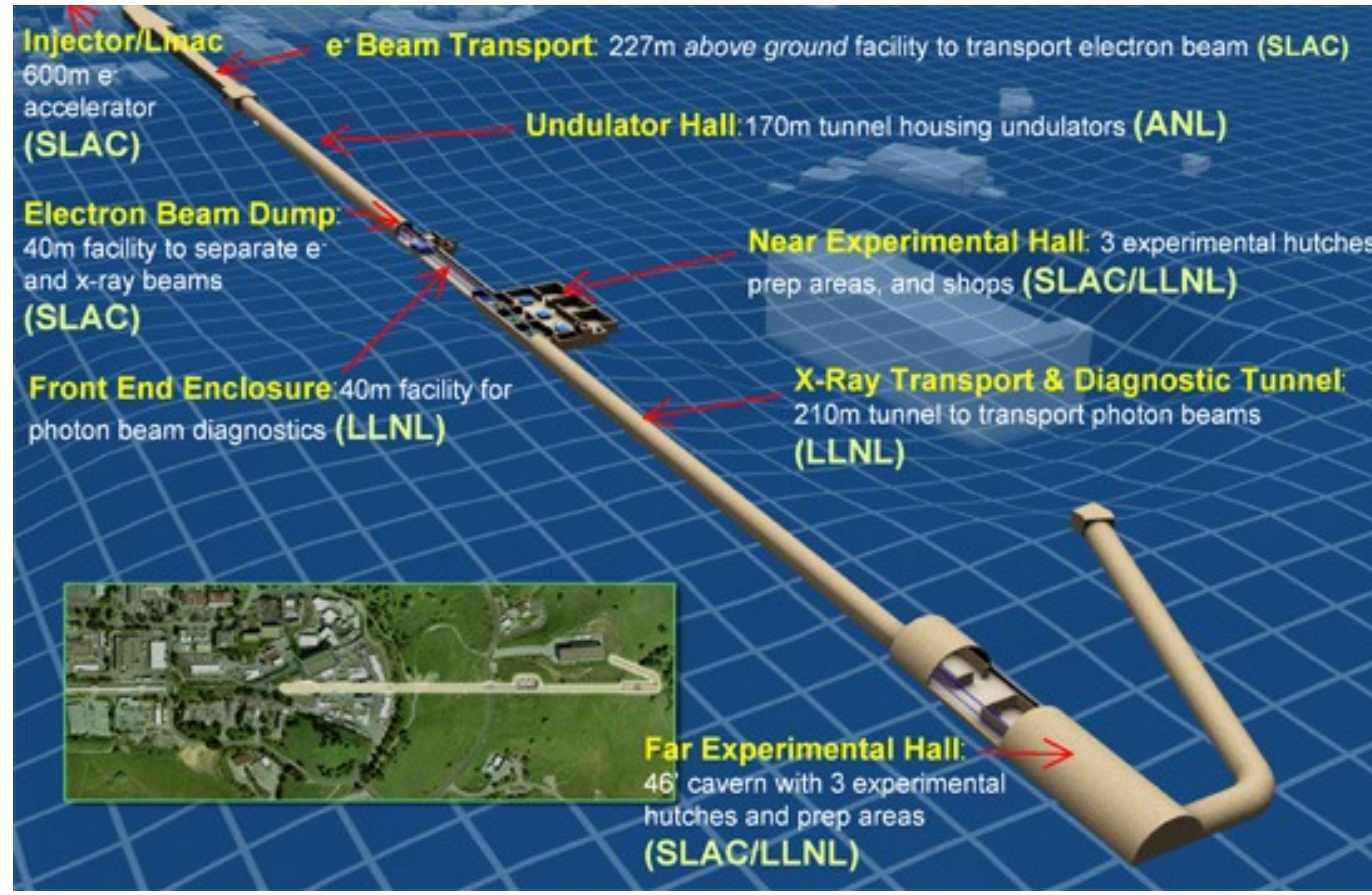
Gradients x10-x100 metal
Structural control of fields
Many possible geometries
Scalable fabrication

Basically, an FEL or ICS source has an injector, accelerator, radiator, and x-ray beamline.

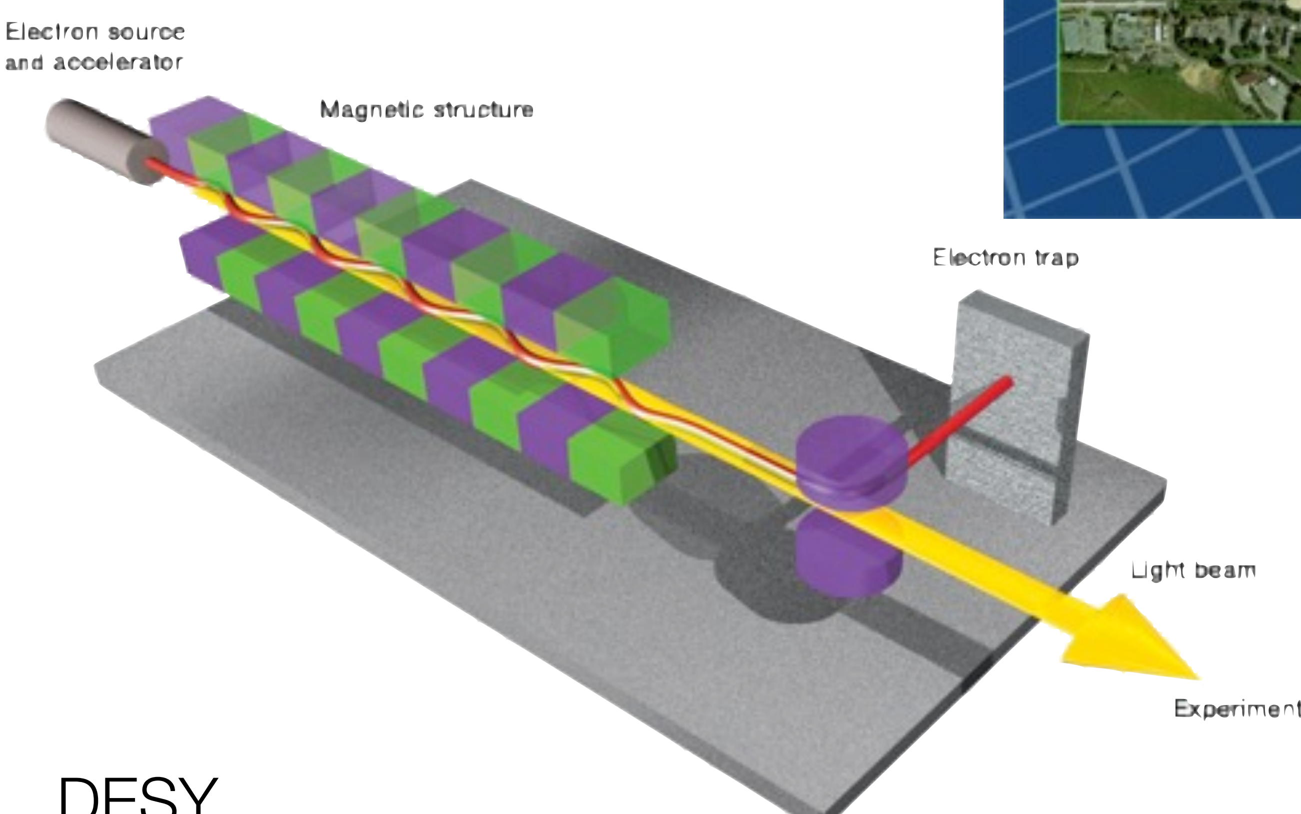
$$\rho = \frac{1}{2\gamma}\left[\left(\frac{\lambda_u f_c a_w}{2\pi}\right)^2 \frac{I}{I_A \sigma_x \sigma_y}\right]^{\frac{1}{3}}$$

$$L_g = \frac{\lambda_u}{4\sqrt{3}\pi\rho}$$

$$P_{sat} = 1.6\rho P_{beam} = 1.6\frac{mc^2}{e}\rho\gamma I$$



SLAC- LCLS



DESY

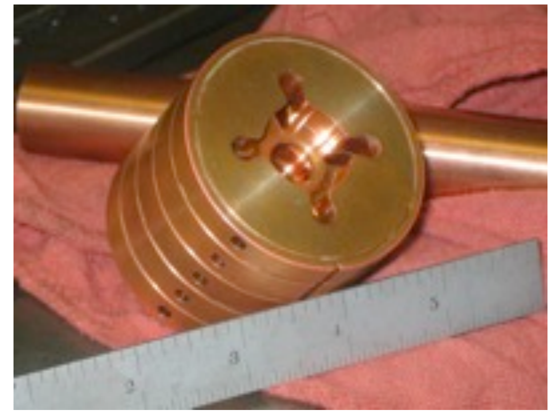
Energy spread limit

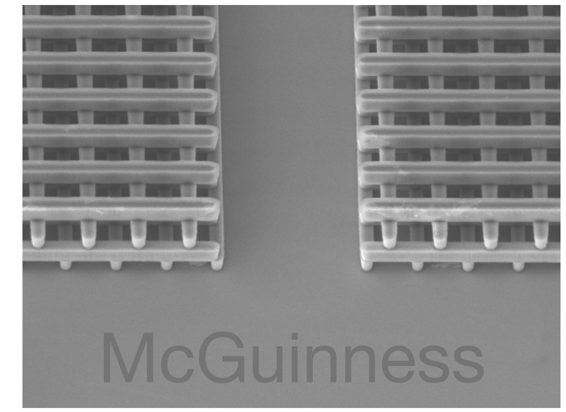
$$\frac{\sigma_\gamma}{\gamma} << \rho$$

Space charge limit

$$k_p = \sqrt{\frac{4\pi I}{\gamma I_A A}} << 2k_u\rho\gamma$$

The choice of accelerator technology impacts the possible light source configurations...





	RF	Optical
Gradient	10-100 MeV/m	**1-10 GeV/m**
Energy gain per period	1 MeV	**1 keV**
Repetition Rate	100 Hz	**10-100 MHz**
Charge per Bunch	0.1 - 1+ nC	0.01-1 pC
Bunch Length	1-100 ps	1-100 fs

key: charge and time scale; not gradient

... the undulator technology has at least as much impact on the FEL design.

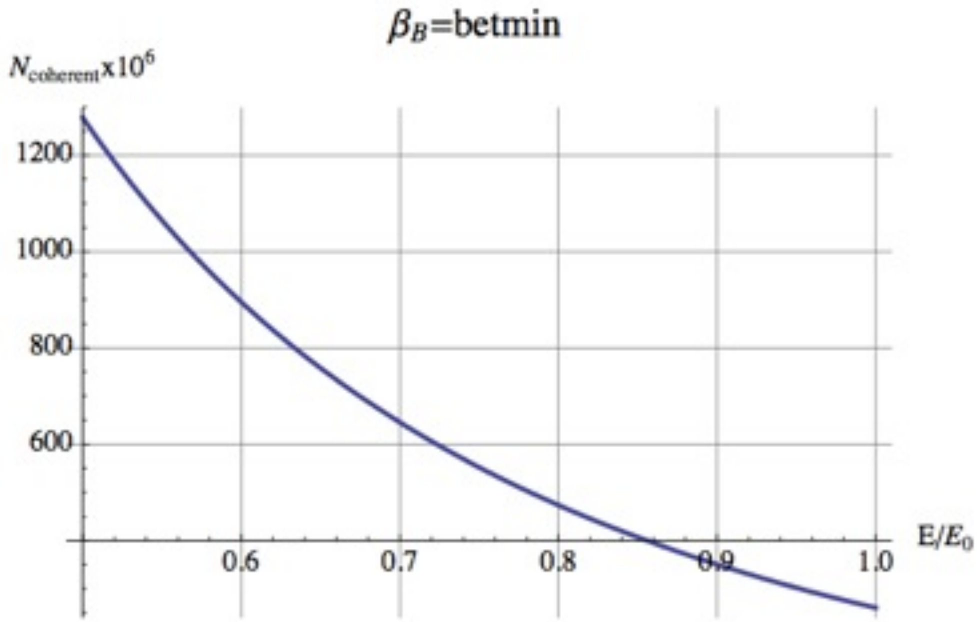
	PM	Micro/Pulsed	RF	Optical
Period	>1 cm	0.1 - 1 mm	**0.1-1 cm**	1-20μm
Parameter	1-10	**<1**	~1	~1
Gap	5 mm	1 mm	**1+ cm**	20-100μm?
Status	Mature	some SC work	stalled	paper

Focusing is an addition issue:

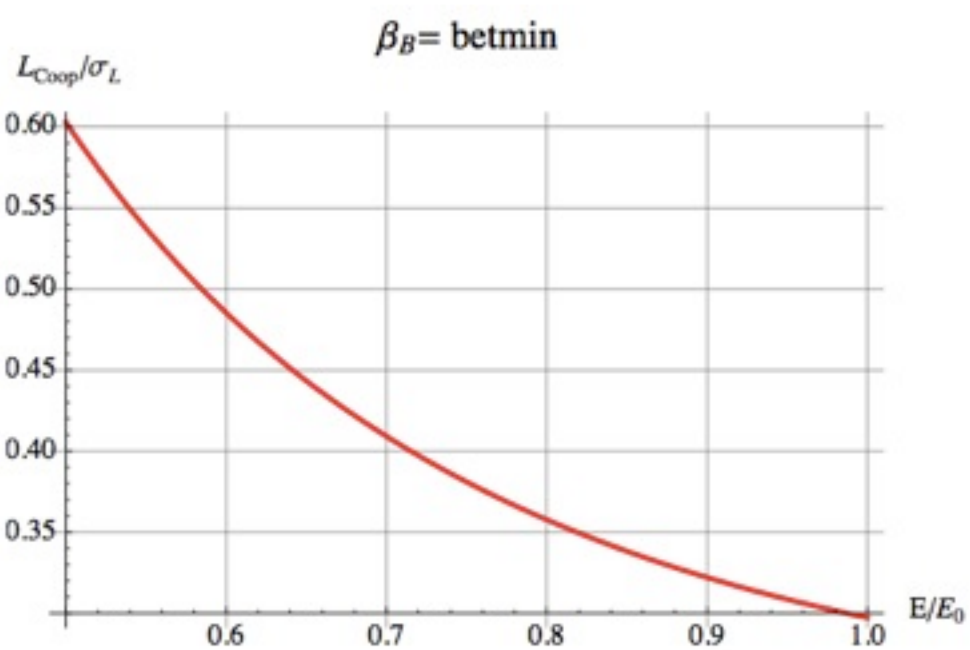
$$\beta_{opt} \approx 3\sqrt{\frac{\varepsilon_n}{\gamma}\frac{4\pi}{\lambda}L_g}$$

An example of a soft x-ray FEL-based source reveals the need for new undulator approaches

10^6 electrons; 10^8 photons



$L_{coop}/\sigma_L<1$: 1-2 spikes



Parameter	**Value**
Wavelength	6 nm
Beam energy	25.5 MeV
Energy spread	10^{-4}
Emittance (norm.)	0.06 µm (doh!)
Charge	1 pC (whew!)
Peak current	750 A
Undulator parameter	1
Undulator period	20 µm
Focusing betafunction	~ 3 mm
Gain length	500 µm
FEL parameter	~3 x 10^{-3}
Saturation length	6 mm (LOL)
x-ray flux per bunch	~5 x 10^8

Pellegrini and Travish

A laser undulator for the 20μm case requires guiding or LLNL class lasers

Magic 20μm laser
(similar for 10μm case)
for a_u=1
need
E_L= 35J
P_L ~ 1TW

Beating lasers
800 nm + 1μm
for a_u=1
need
E_L= 8J x 2
P_L < 1TW

$$\boxed{Z_R = \frac{\pi w_0^2}{\lambda_L} \simeq 2L_U = 12\text{mm}}$$

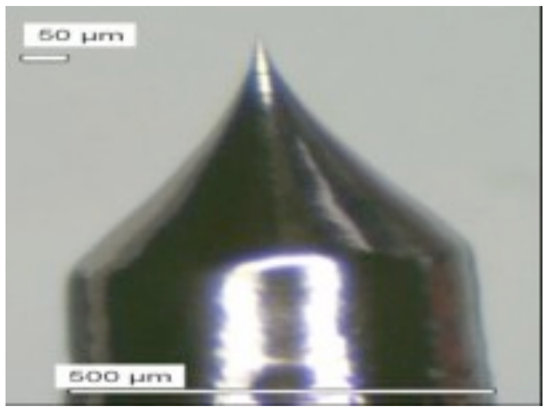
$w_0 \sim 330\,\mu m$

$w_0 \sim 70\,\mu m$

A hard x-ray FEL source using optical period undulator would be too low energy to function well

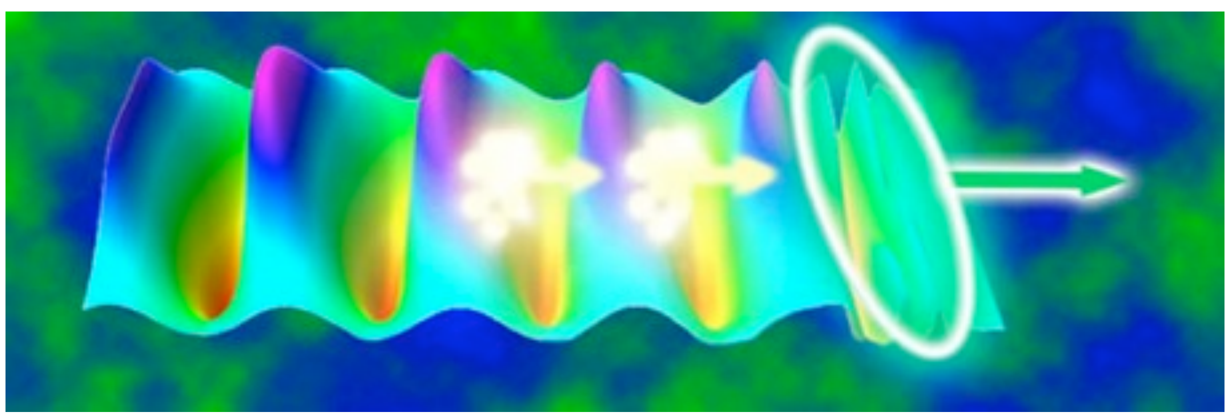
An ICS-based hard x-ray source could produce tolerable fluxes if laser guiding works

We need to develop four critical technologies to make the iPad sized Light Source

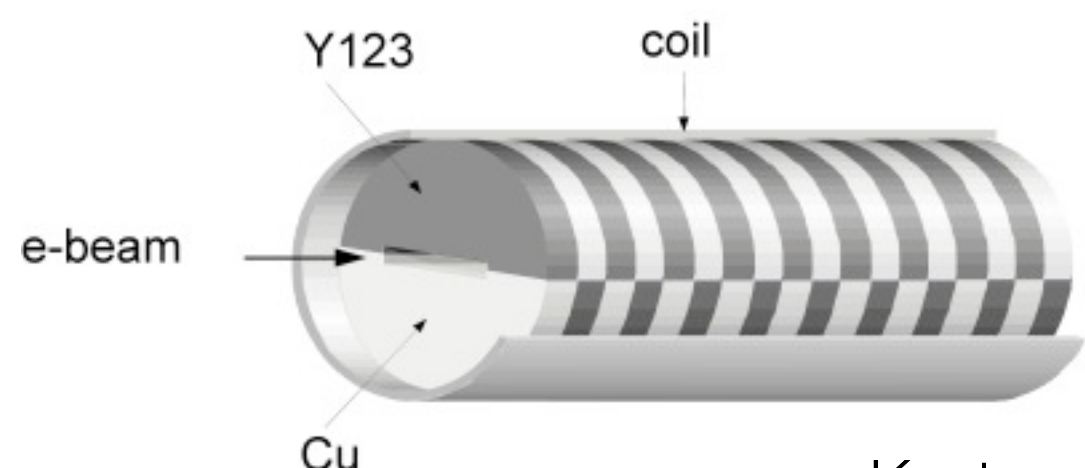


PSI

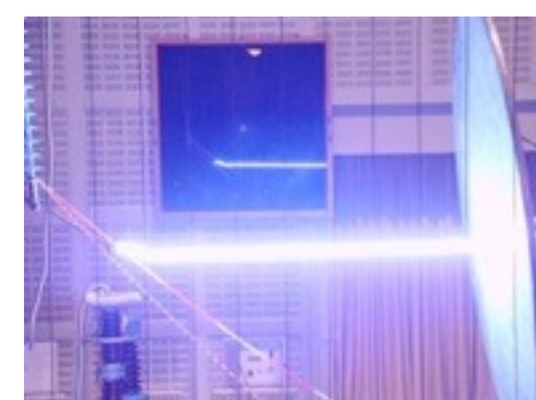
1. Ultra low emittance injectors
2. Optical-scale accelerators
3. Micron-period undulators
4. Laser guiding



LBNL



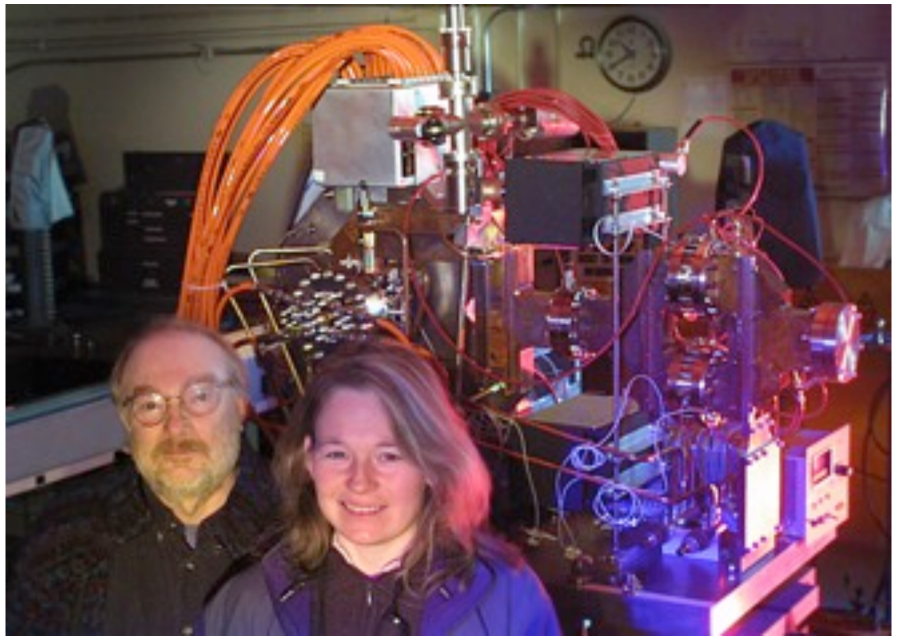
Kyoto



Teramobile

Low charge, high brightness injectors

Conventional RF photoinjectors are a viable source of low-charge, low-emittance beams



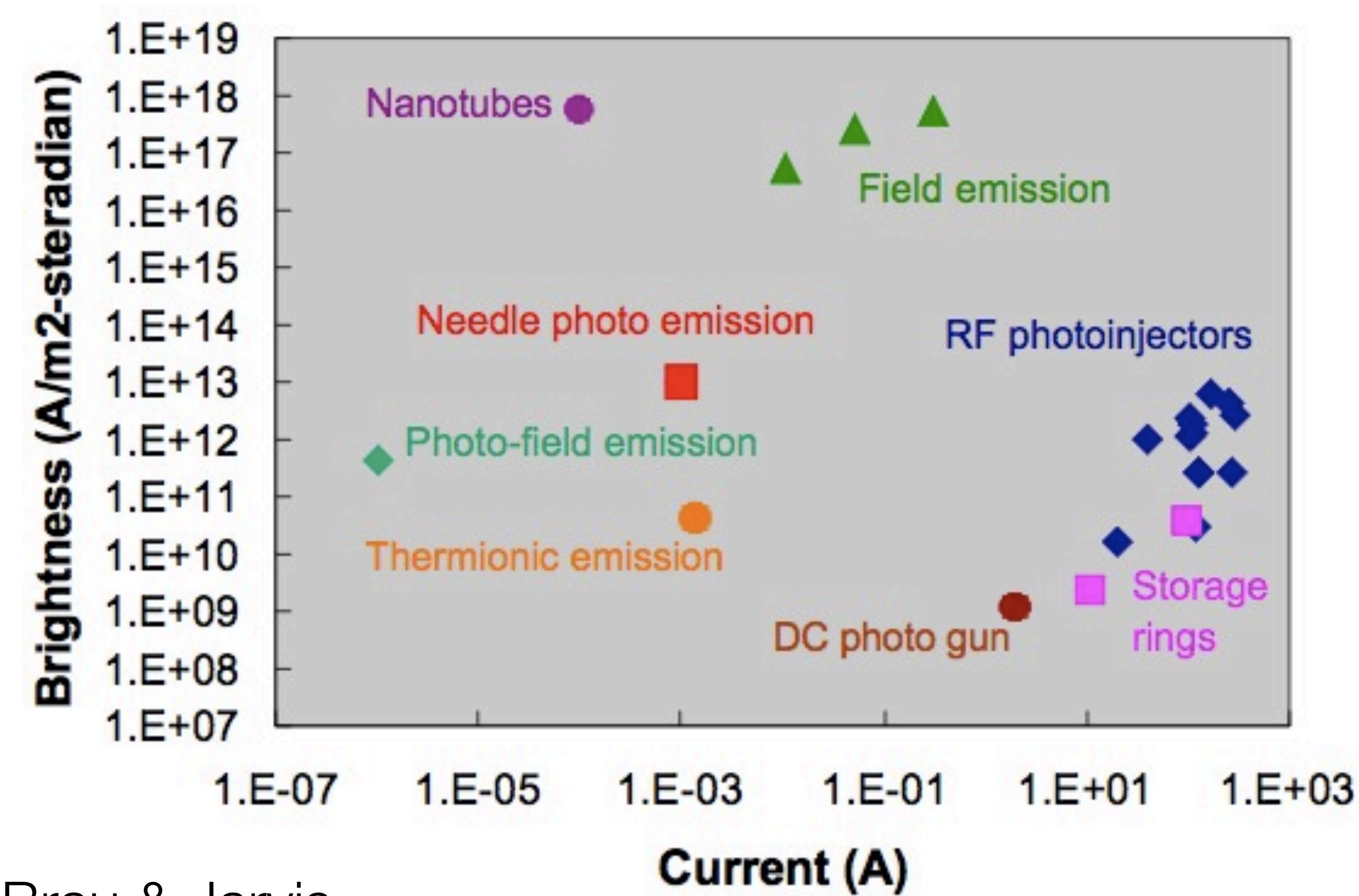
LCLS injector
@ 20 pC
achieved
0.13μm emittance

At ~1 pC, we need <0.01μm (10 nm) emittances

What's the problem?

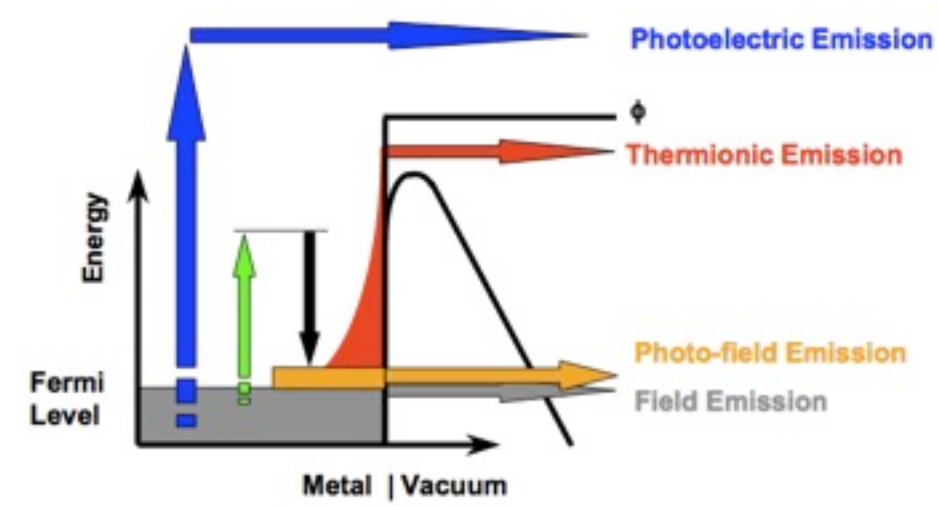
- Preservation of nm emittances
- Laser technology (MHz repetition rates)
- Injection into optical structures

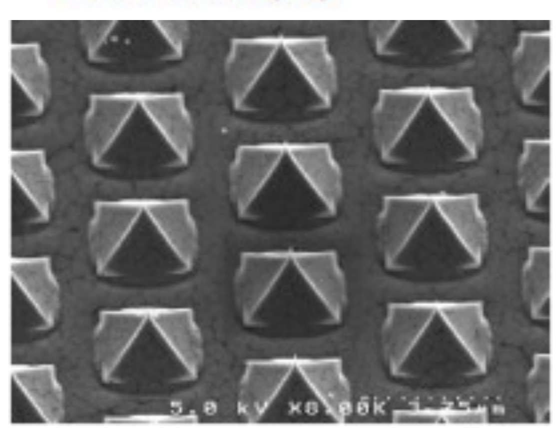
Electron microscopes achieve the requisite emittances, albeit at very low current

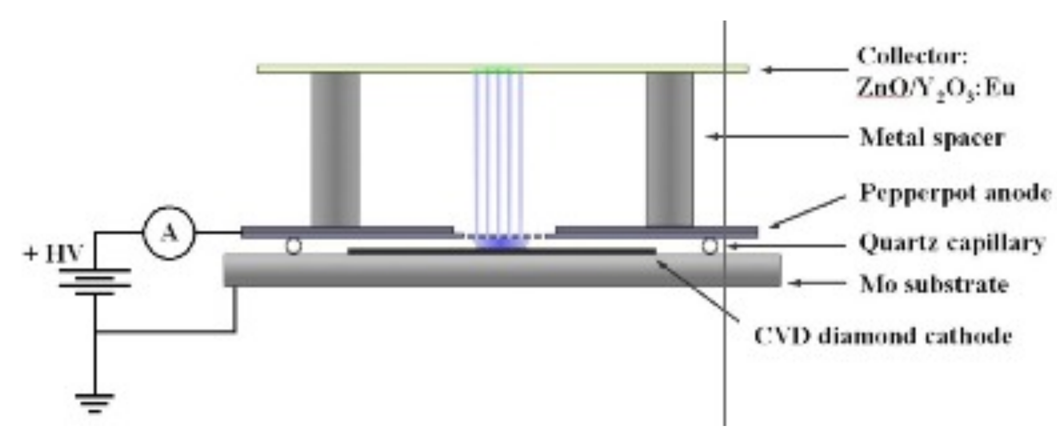


Brau & Jarvis

Field and photo-assisted field emission work well



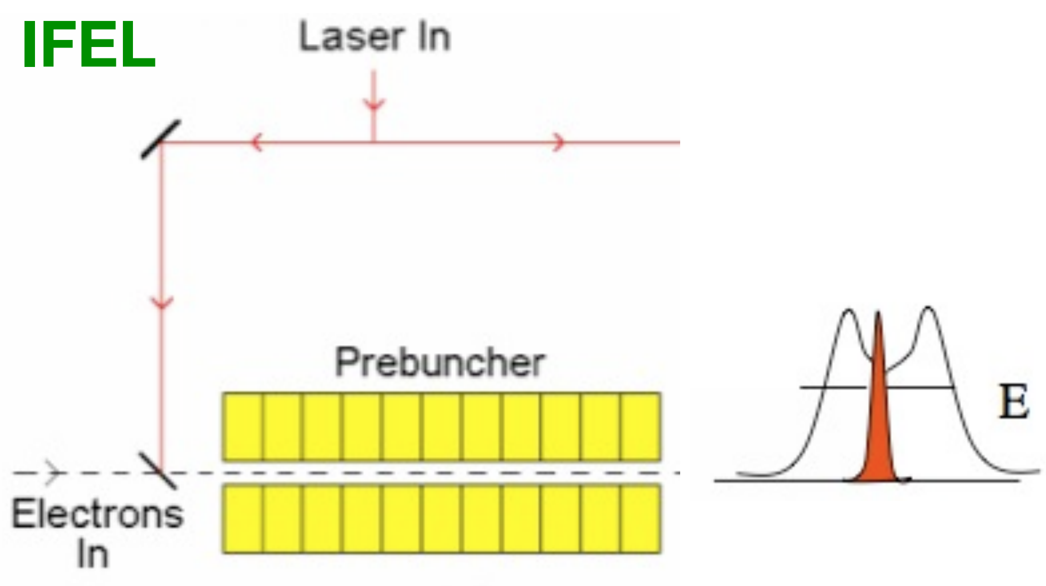




Needle cathode work is showing the way

Injection into a sub-micron aperture and a sub-ps bucket is a concern

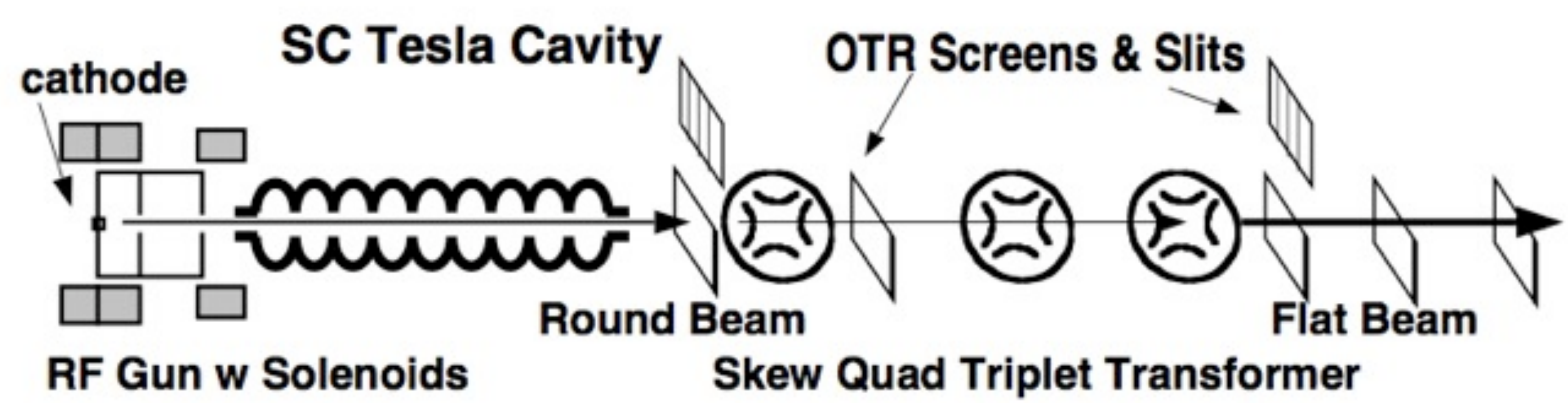
IFEL



E. Colby

Final focus type
Asymmetric emittances
IFEL pre-bunching
Dielectric Injector

Flat beam

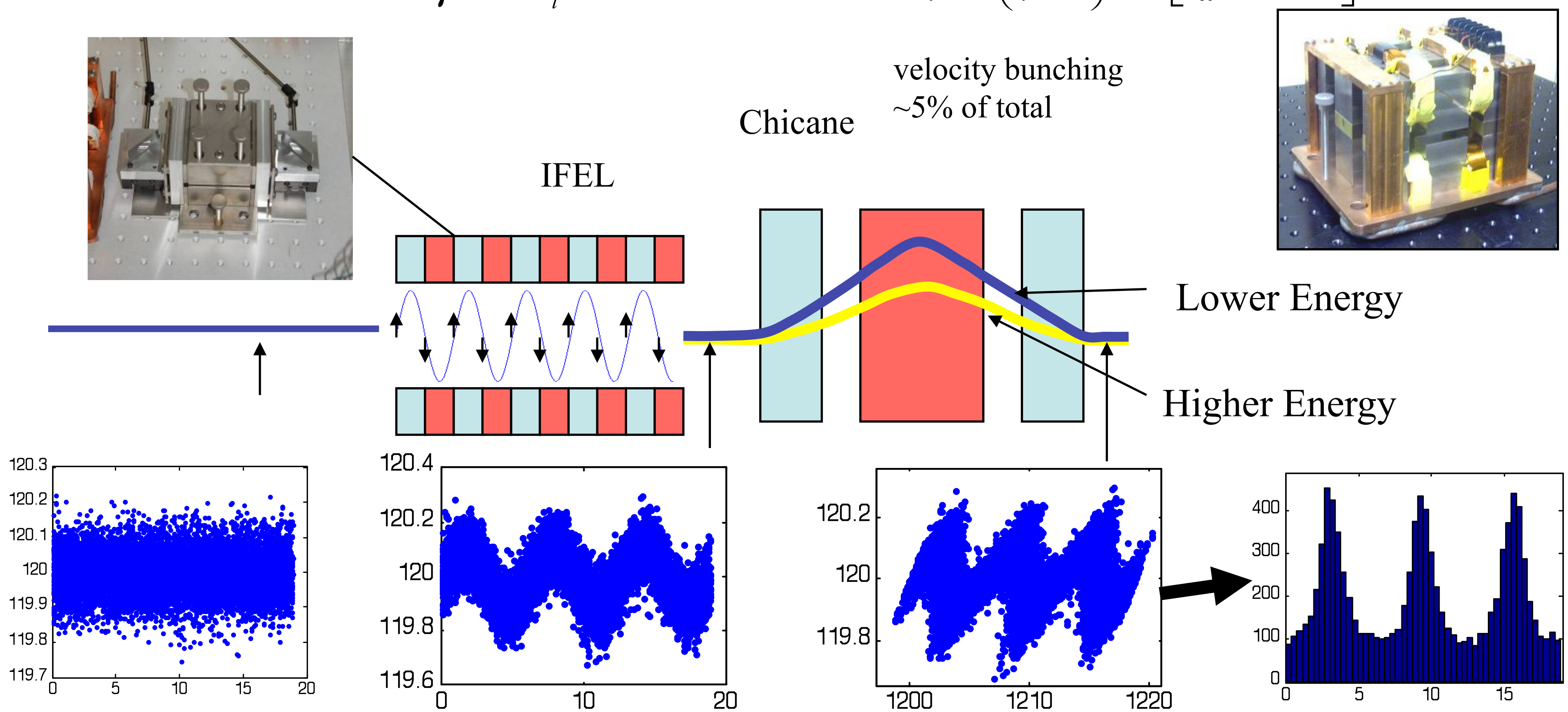


$$\frac{\varepsilon_y}{\varepsilon_x} \approx 50$$

D. Edwards, *et al*., XX Linac Conference, (2000)

Longitudinal manipulation (bunching) of the beam on the attosecond level has been shown

$$\Delta\gamma = \frac{\pi N K_r K_w}{\gamma}\frac{\lambda_w}{\lambda_l}\cos(k_l z_0) \qquad R_{56} = \frac{L}{\gamma^2} + \left(\frac{q}{\gamma mc}\right)^2 \int_{-\infty}^{\infty}\left[\int_{-\infty}^{z} B(z')dz'\right]^2 dz$$



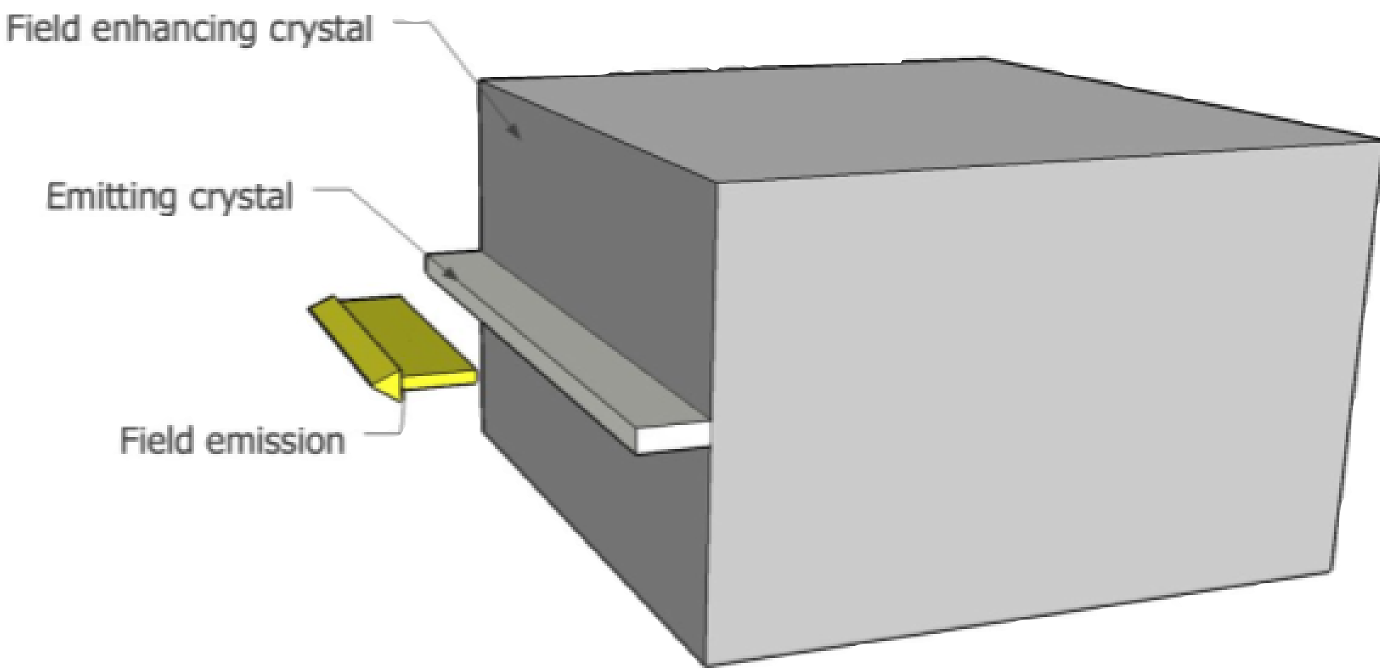
σ_γ $\qquad \gamma_i \rightarrow \gamma_i + \eta \sin k_l z \qquad z_i \rightarrow z_i + R_{56}\gamma_i$

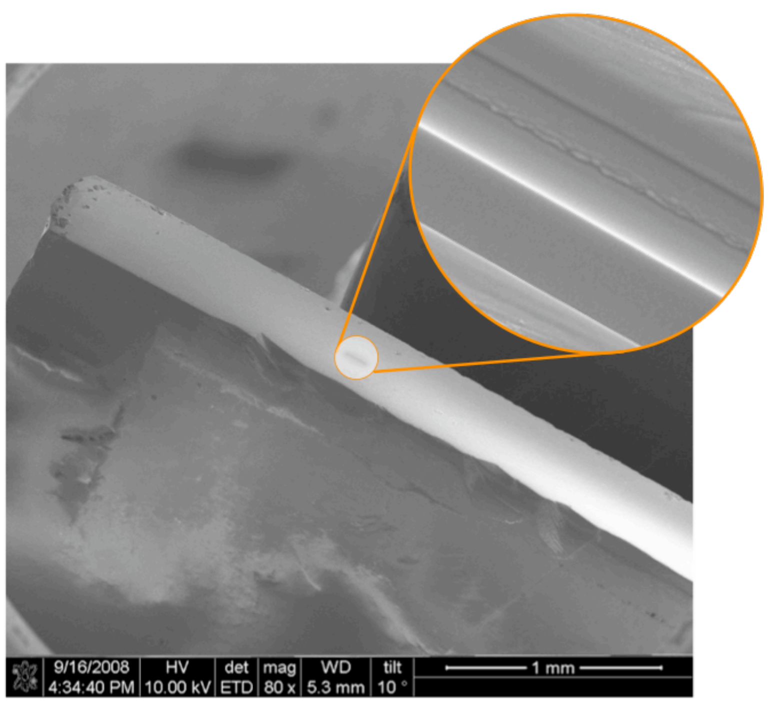
bunch'o math

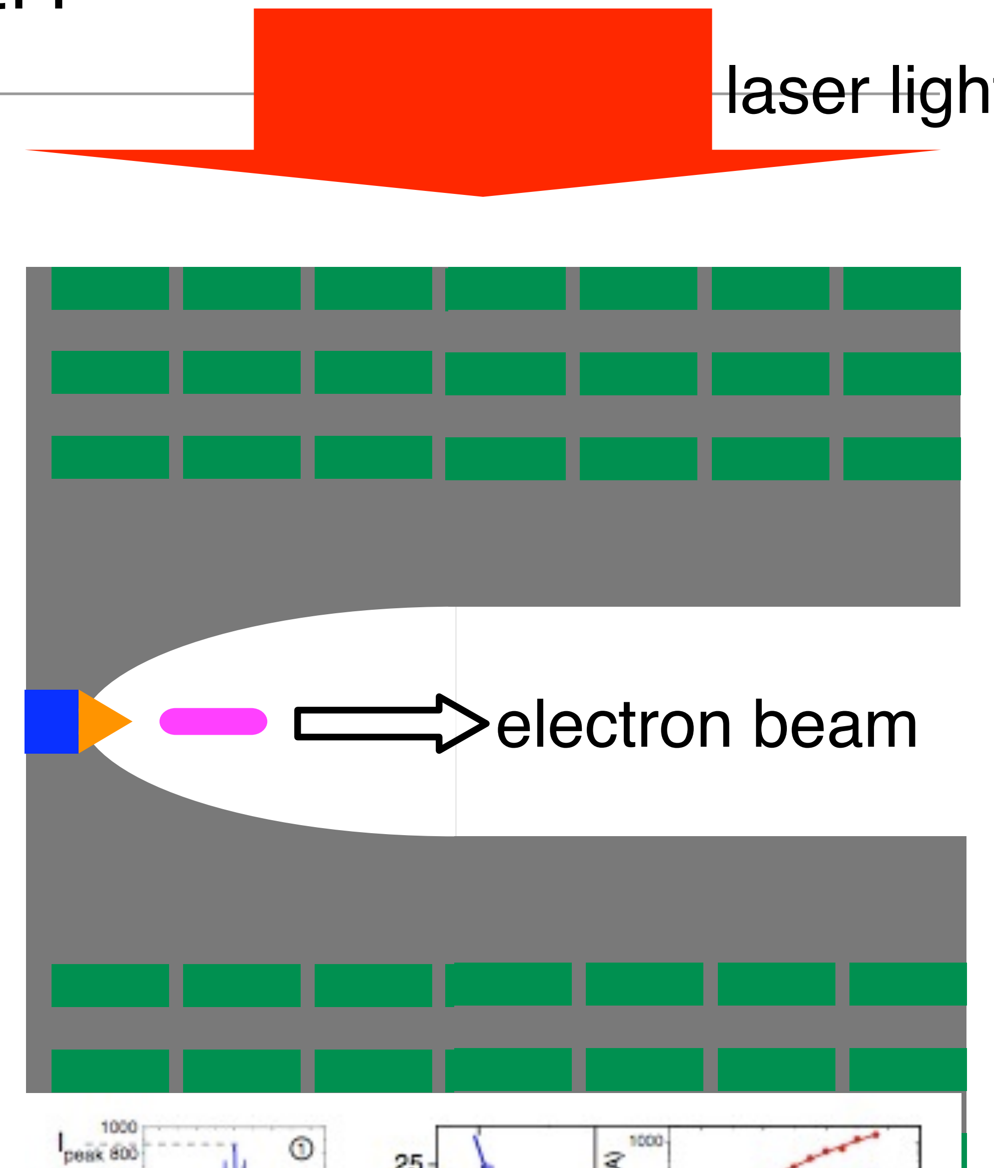
$$\rho(z) = \rho_0\left[1 + 2\sum_{n=1}^{\infty} J_n\left(nk_l R_{56}\frac{\eta}{\gamma_0}\right)\exp\left[-\frac{1}{2}\left(nk_l R_{56}\frac{\sigma_\gamma}{\gamma_0}\right)^2\right]\cos(nk_l z)\right]$$

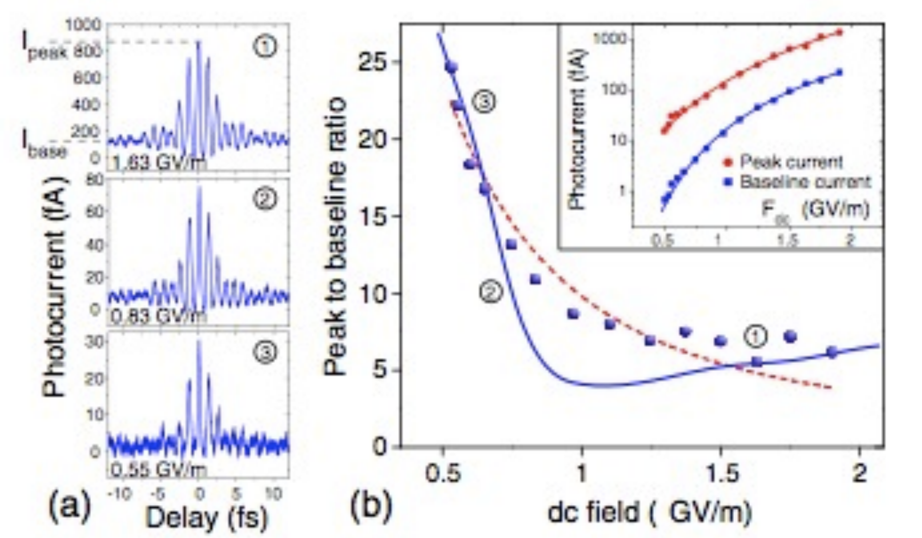
C. Sears

Integrating the injector and optical scale accelerator may be the best path





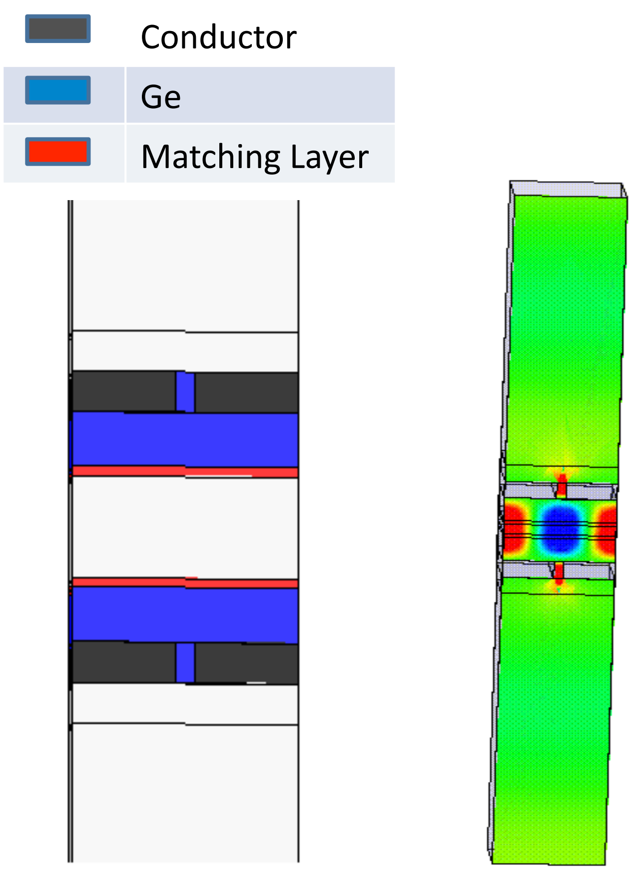




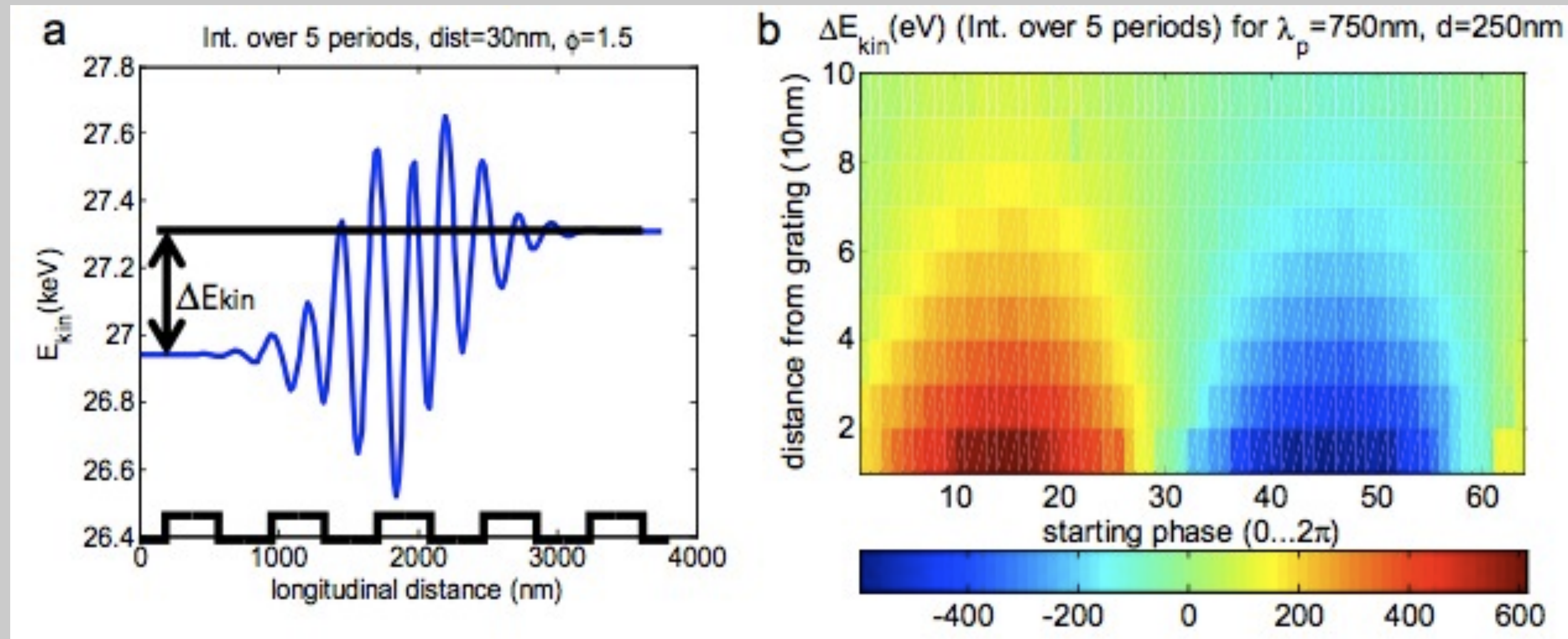
Ultrafast Electron Pulses from
Peter Hommelhoff, Catherine Kealhofe
PRL **97,** 247402 (2006)

Creating low beta optical-scale structures is hard. Really hard.

low ß MAP



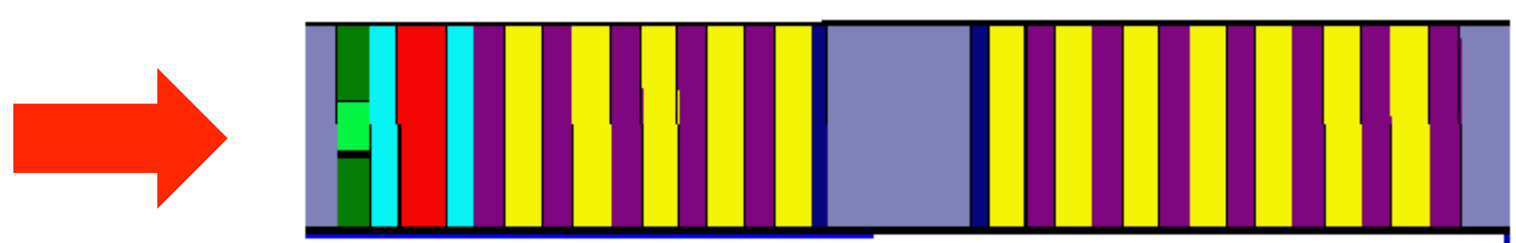
100 MeV/m @ 30nm from grating



John Breuer, Christopher M. S. Sears, Tomas Plettner, and Peter Hommelhoff

Color	Height (nm)	Width (nm)	Material
	90	120	SiO_2
	60	120	HfO_2
	240	100	MgF_2
	240	170	SiO_2
	240	105	HfO_2
	240	130	SiO_2
	240	59	Ge

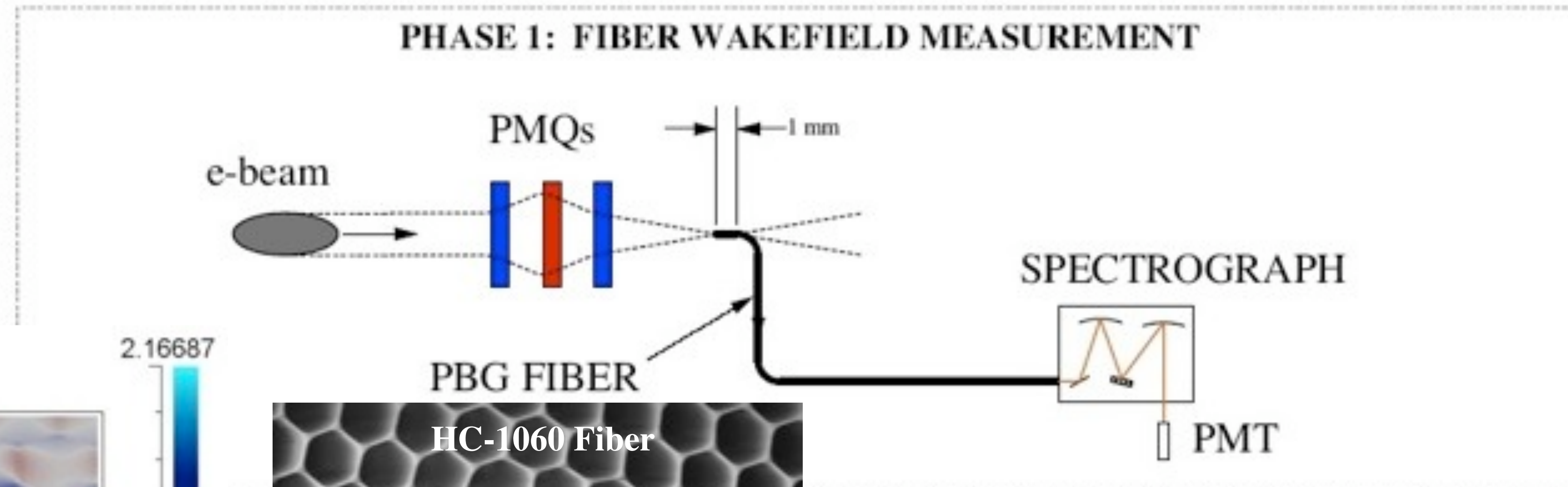
All dielectric design needs work

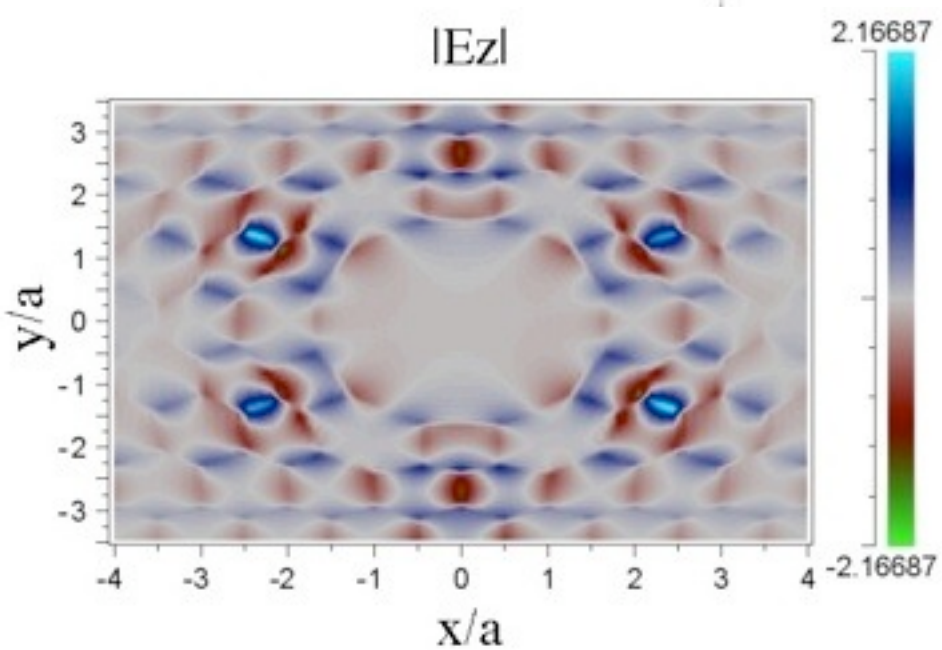


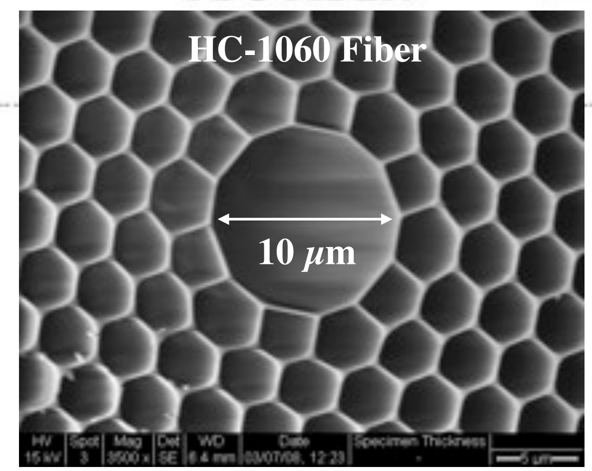
Optical-scale accelerator structures

Here at SLAC, the E-163 AARD team is producing a set of laser-driven dielectric micro-accelerators

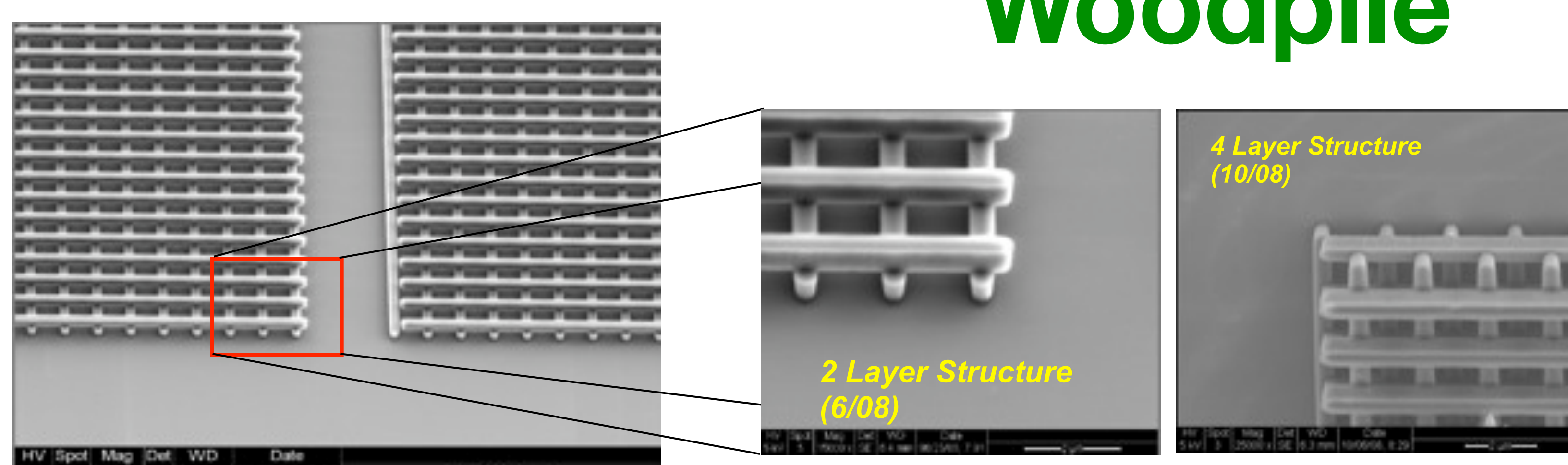
PBG



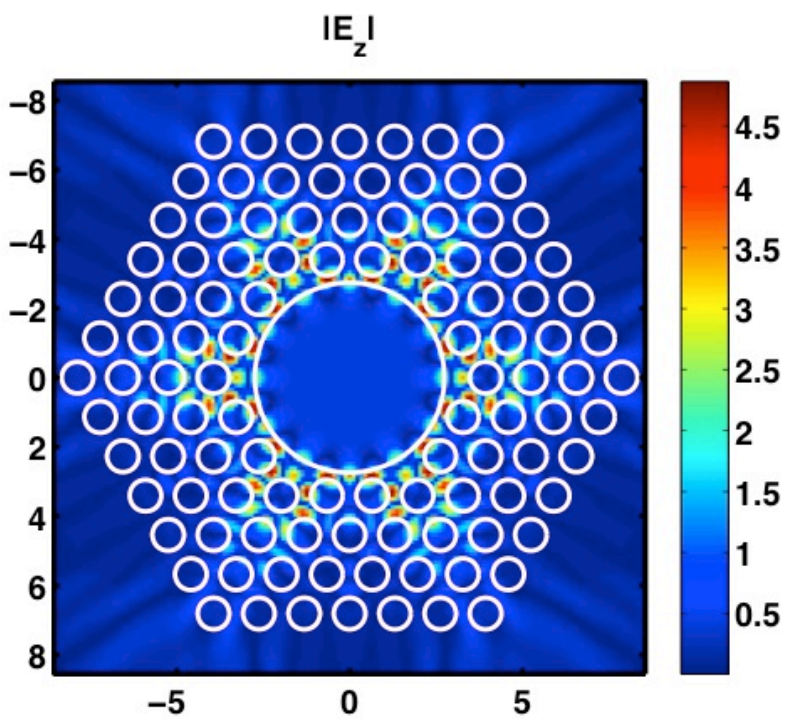


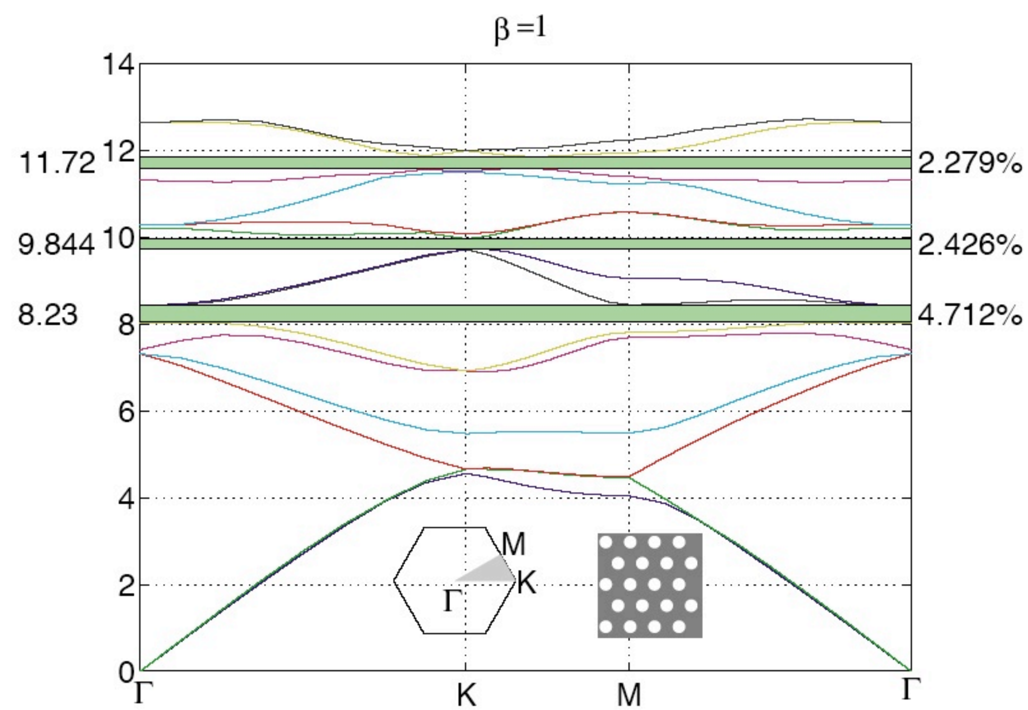


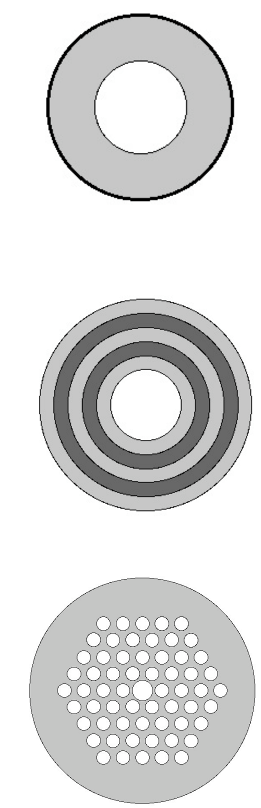
Woodpile



PBG-fiber-based structures afford large apertures and scalability to HEP-length structures

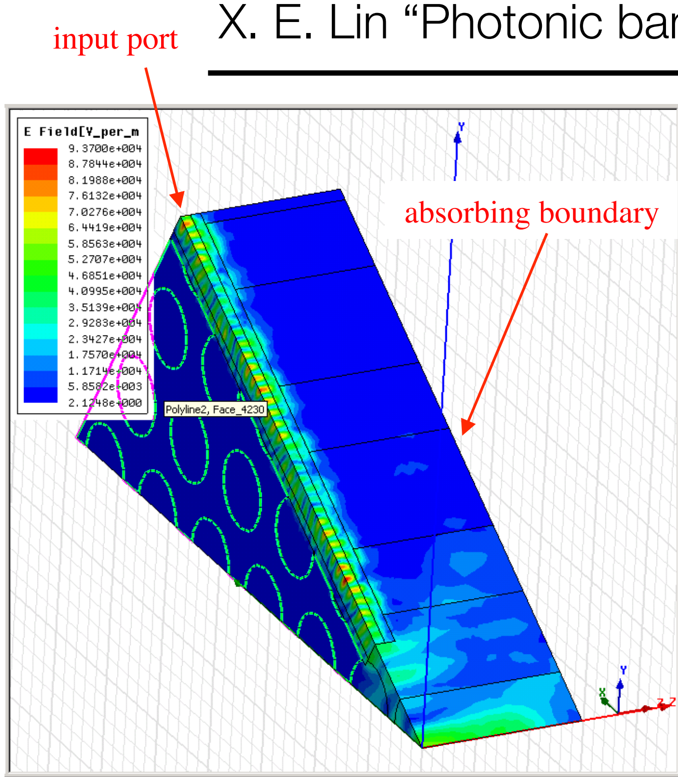






X. E. Lin “Photonic bandgap fiber accelerator,” PRSTAB 4, 051301 (2001)

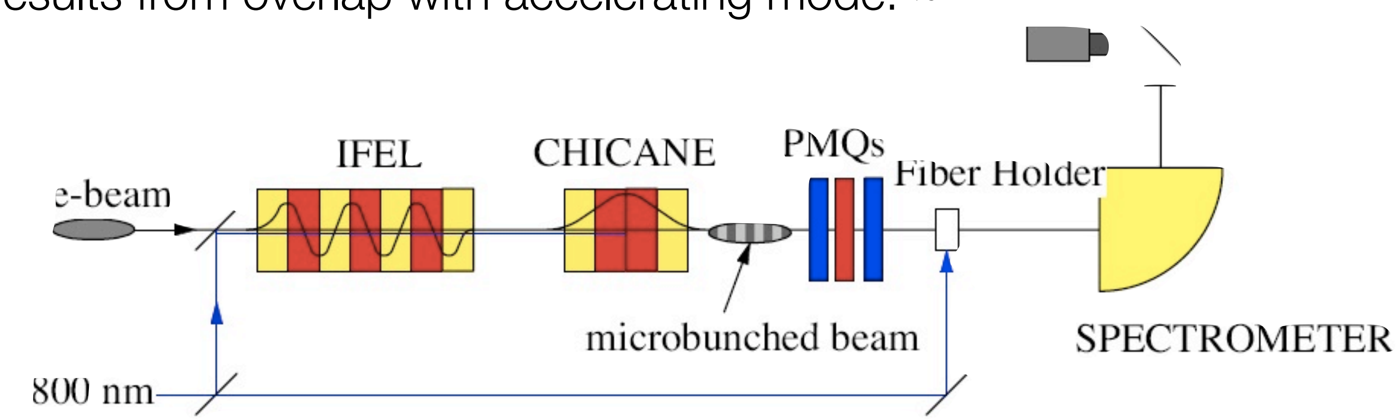
~2.5 GV/m



HFSS: custom dielectric waveguide coupler

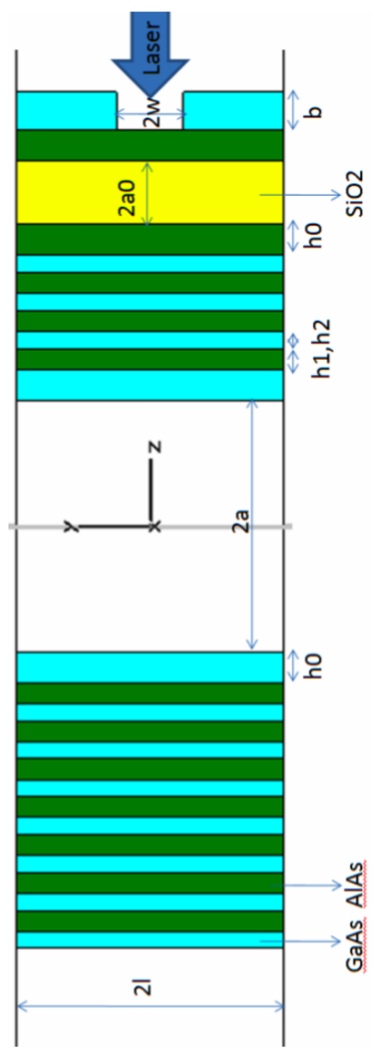
Efficient coupling to the accelerating mode of a PBG fiber is complicated by various issues:

- ➡overmoded: coupling to other modes drains away input power
- ➡extra modes are lossy and difficult to simulate
- ➡initial simulation results from overlap with accelerating mode: ~ 12%

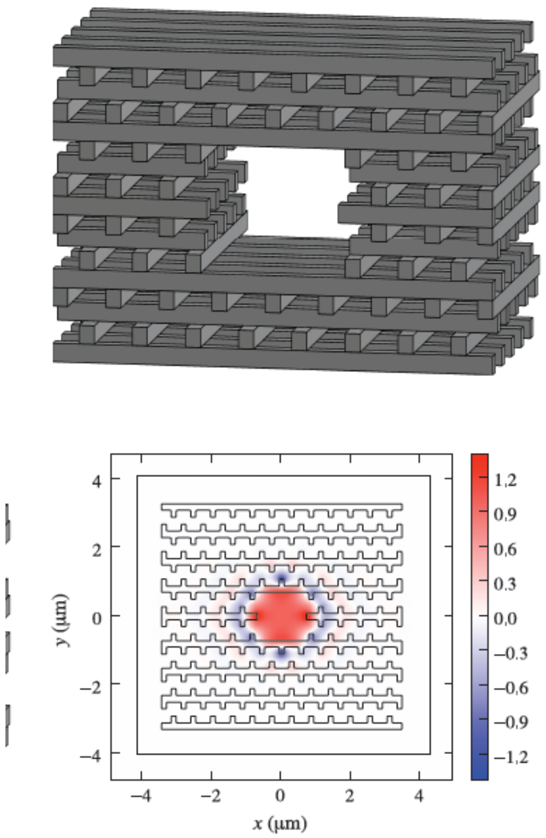


Planar structures offer beam dynamics advantages as well as ease of coupling power

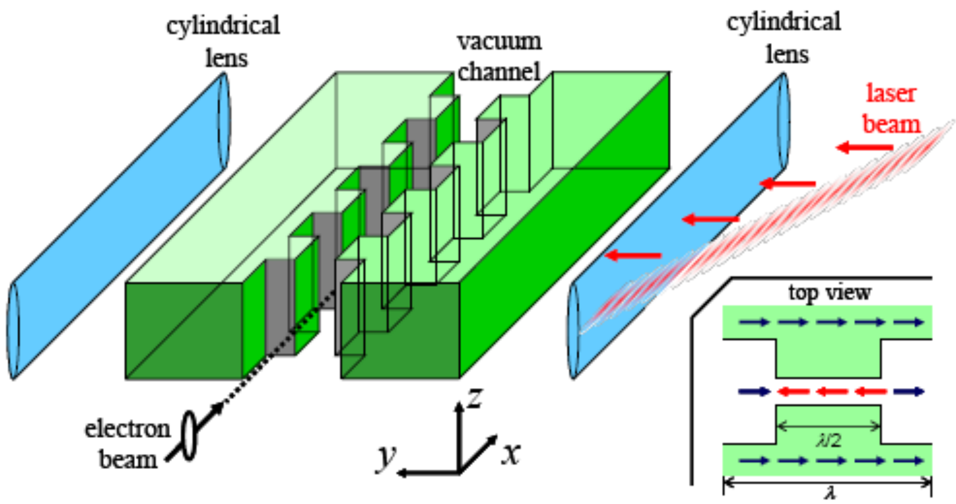
MAP



Logpile

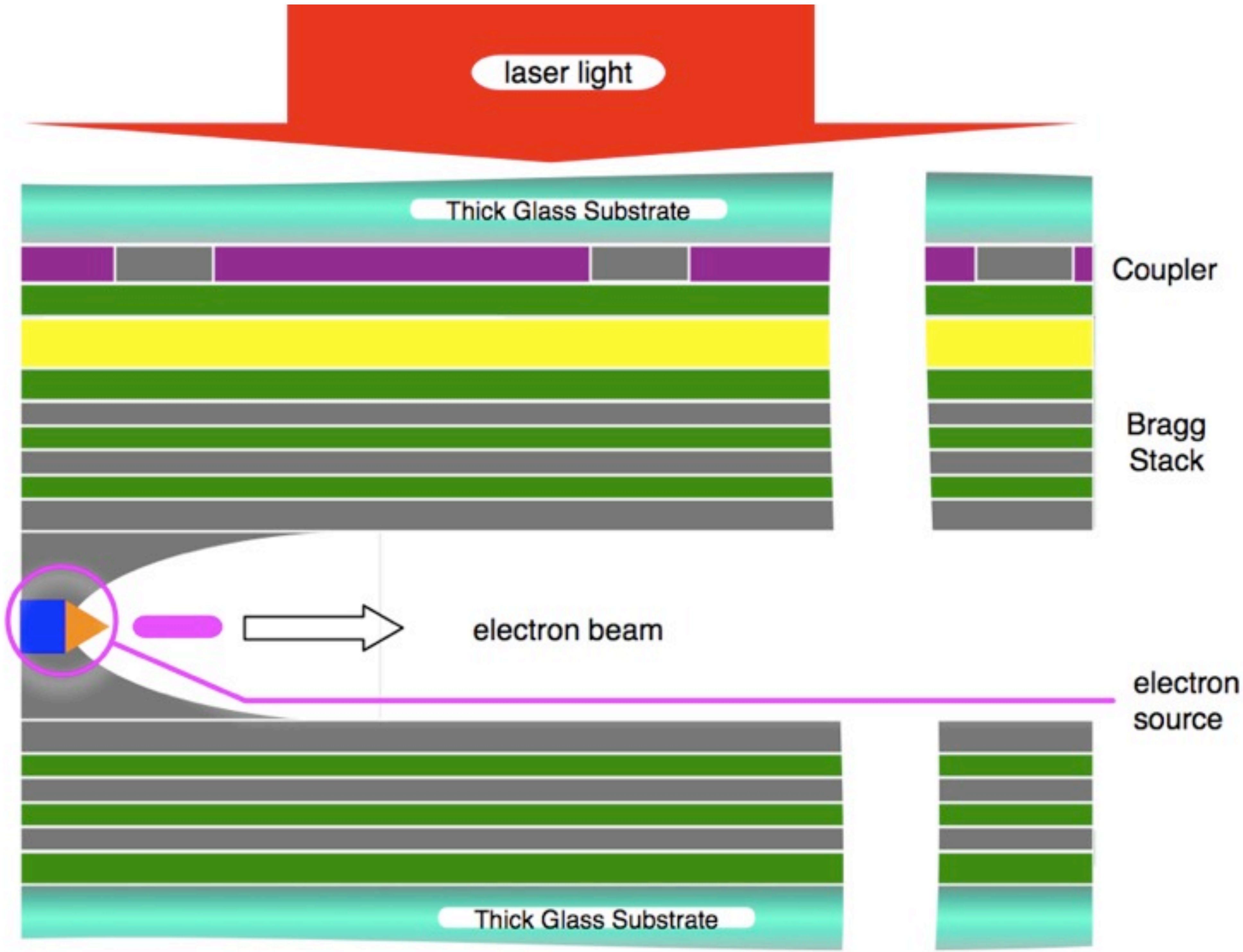


Grating

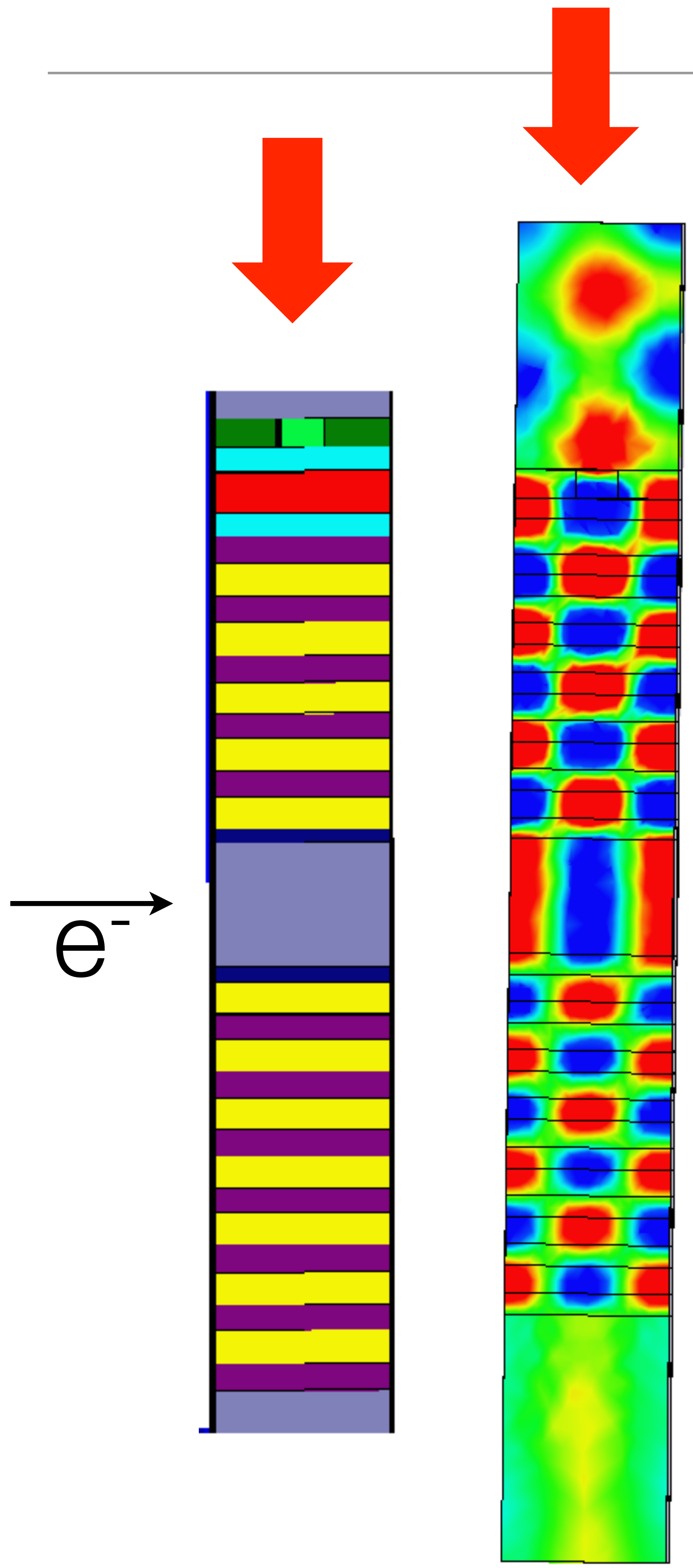


Flat beam LS: modes? coherence? undulator?

The MAP structure consists of a diffractive optic coupling structure and a partial reflector



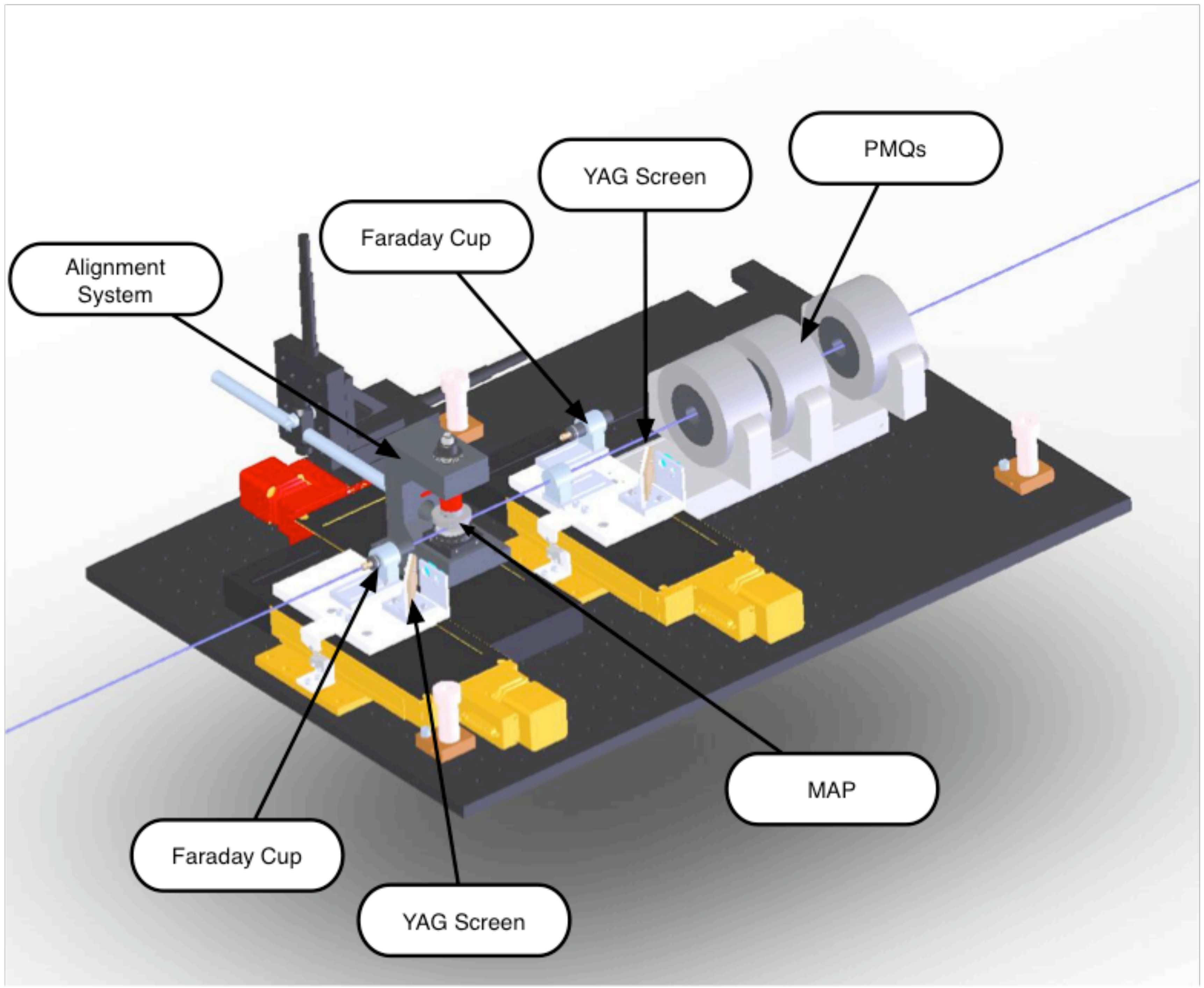
The Micro Accelerator Platform (MAP) is undergoing intense simulation and fabrication study



relativistic structure nearing fabrication-ready design

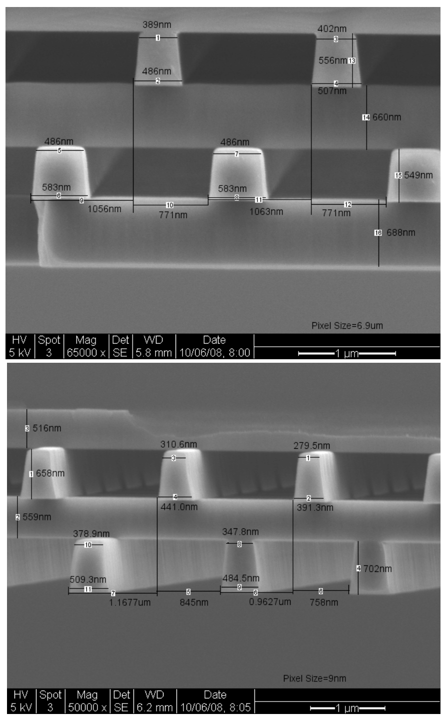
Color	Height (nm)	Width (nm)	Material
(dark green)	300	142	SiO_2
(light green)	200	142	HfO_2
(cyan)	800	120	MgF_2
(red)	800	170	SiO_2
(purple)	800	105	HfO_2
(yellow)	800	130	SiO_2
(blue)	800	105	HfO_2

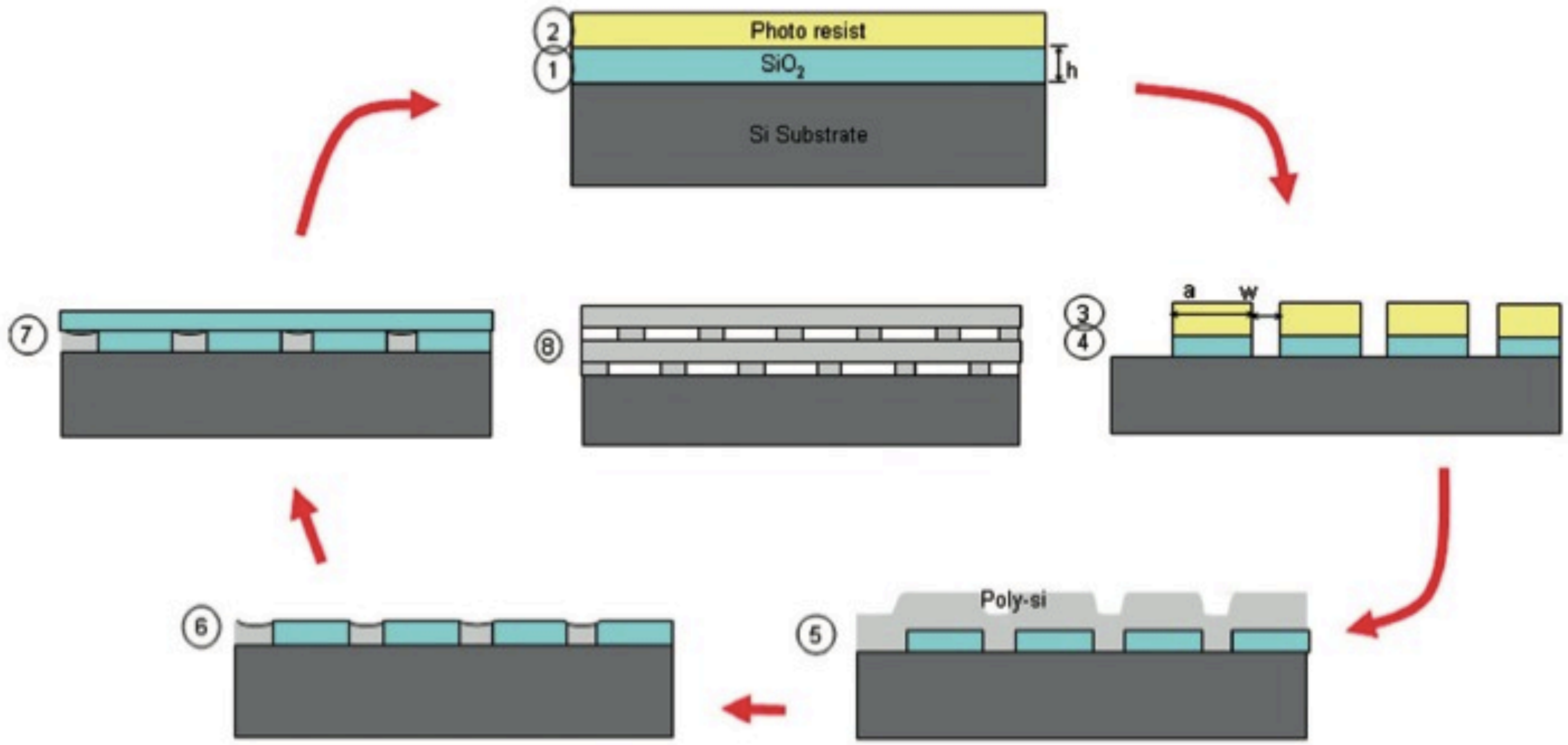
We are planning a ß=1 MAP beam de/acceleration experiment here at E163



SBIR collaboration with radiabeam TECHNOLOGIES

The log-pile structure is being fabricated and offers an intermediate gradient solution





Gradient
- 221 MeV/m @ 1.55μm

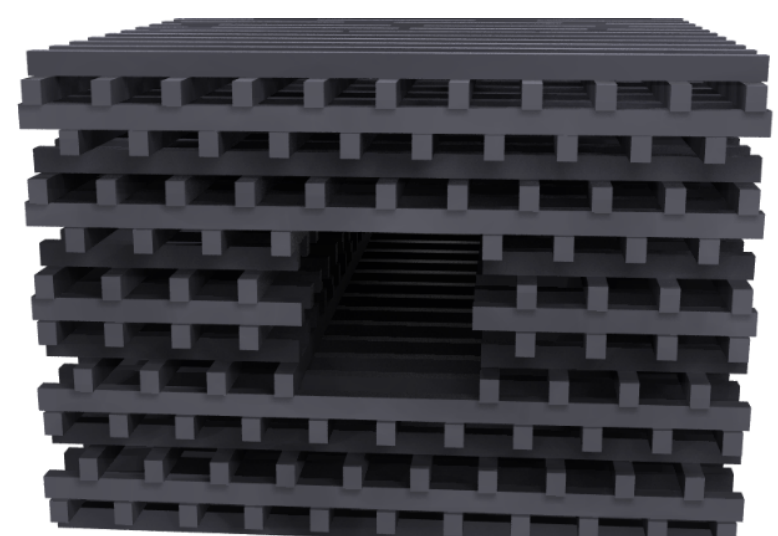
Fabrication
- Amenable to higher damage thresholds

Tunability

Coupling

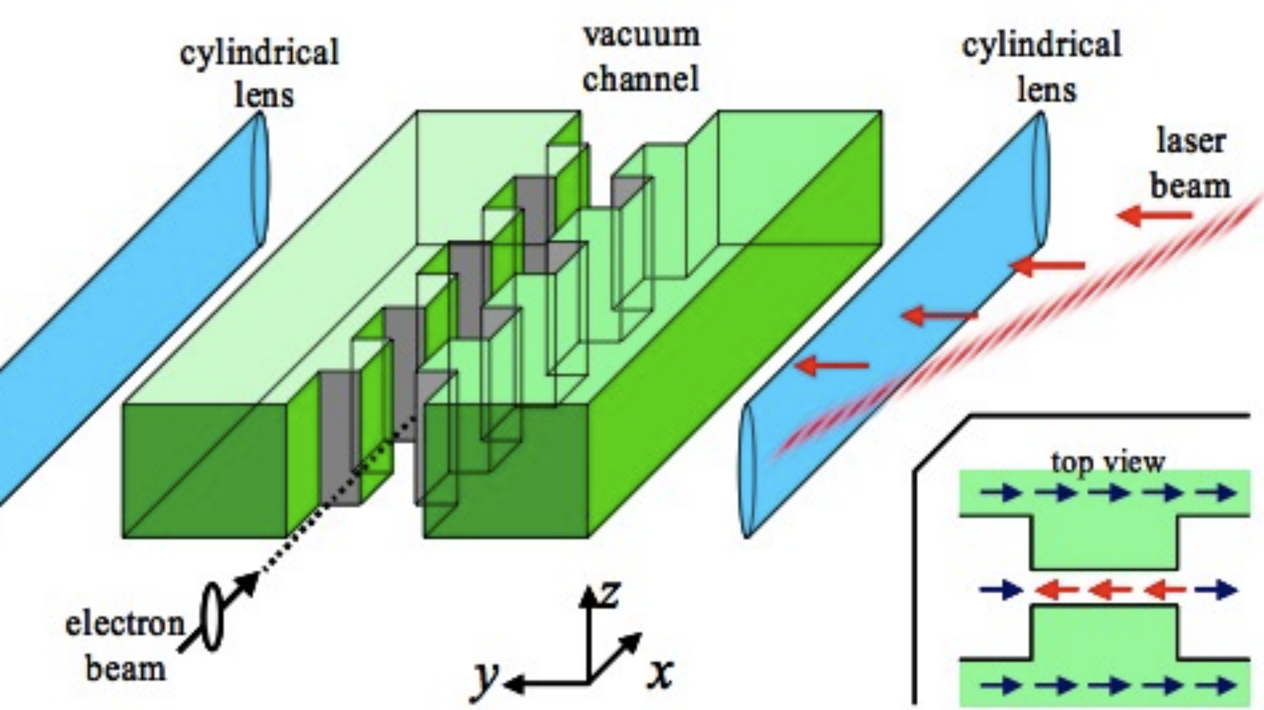
Impedence

C. McGuinness



The Stanford grating structure is non-resonant and might support >10GeV/m

Materials near beam = easy to make the fields; bad for wakefields
= 10 fs pulses; but complex coupling and synchronization



Plettner, et al., PAC 2007

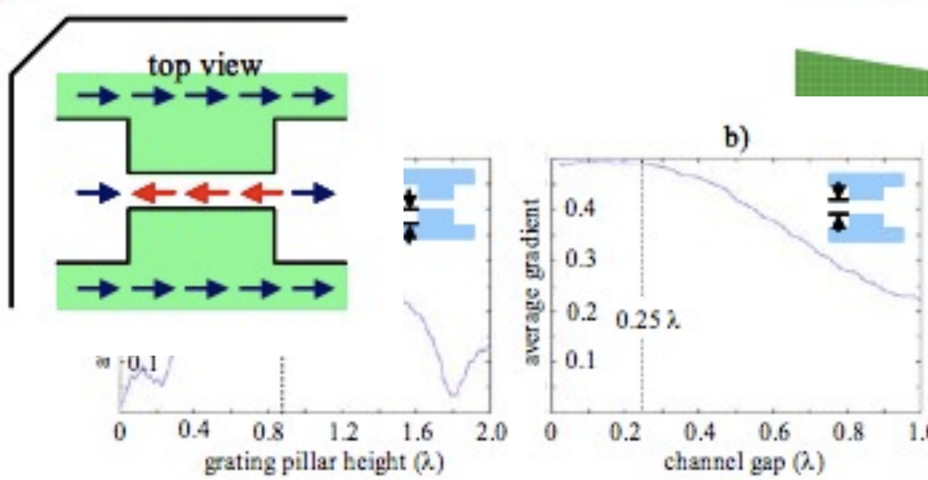
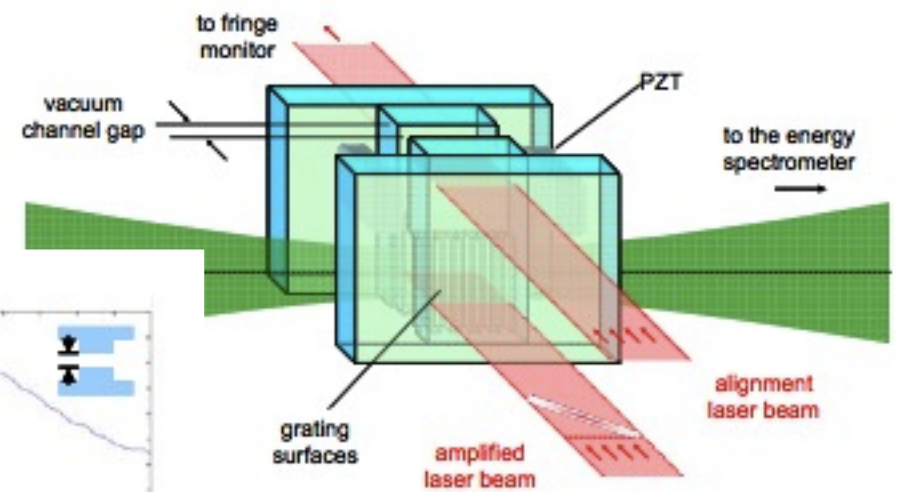


Figure 2: Average gradient as a function of the vacuum channel grating groove depth (a) and width (b).



gh efficiency acceleration requires a
h high fluence and efficiency:

Power efficiency improves with decreasing stored energy

$$P_{ac} \propto \frac{G\lambda^2}{\eta} E_{cm}$$

E_{cm} – Collider's center-of-mass energy
G – Accelerator Gradient
λ – Acceleration field wavelength
η – power source efficiency

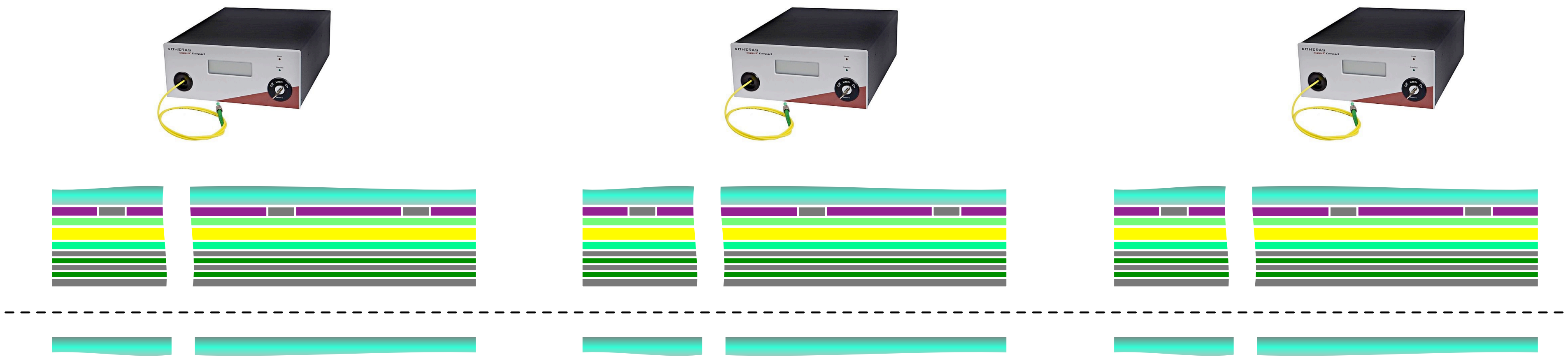
$$E_{cm} \propto \left\{\frac{\eta \cdot P_{ac}}{\lambda^2}\right\} \frac{1}{G}$$

SOURCE FLUENCE

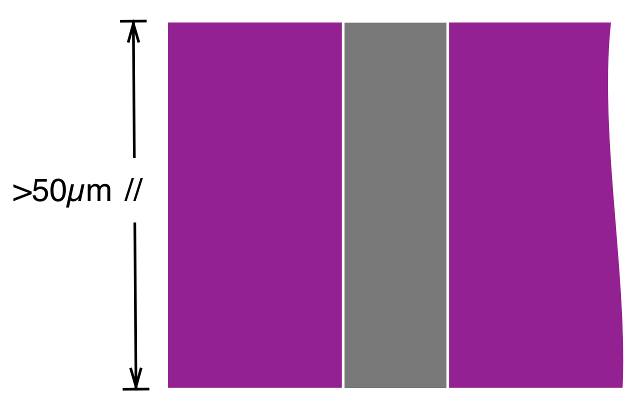
These planar structures are modular and scalable

easy power coupling

“easy” to scale & stage



flat beams
low wakefields



Breaking News Alert
The New York Times
Tue, February 23, 2010 -- 3:08 PM ET

Toyota Executive Says Recall Might 'Not Totally' Solve Accelerator Problems

He doesn’t know the half of it!

Example: focusing issues in the MAP

Alternating Phase Focusing

periodically modulating the position of the coupling slot

$$\phi_s = \phi_0 + \phi_m \sin(k_p z)$$

Initial analysis

$$\langle y''_{sec} \rangle = \left\{ \frac{\alpha_{rf} k_z^2}{\gamma^3 \beta^2} sin(\phi) \left(1 - \frac{\phi_m^2}{4}\right) - \frac{{\alpha_{rf}}^2 k_z^4}{\gamma^6 \beta^4} \frac{\phi_m^2}{2k_p^2} cos^2(\phi) \right\} \langle y_{sec} \rangle$$

$$\langle \phi'' \rangle = \frac{{\alpha_{rf}}^2 k_z^4 {\phi_m}^2}{2\gamma^6 \beta^4 {k_p}^2} \cos(\phi) \left[sin\phi_0 - sin(\phi)\right] + \frac{\alpha_{rf} k_z^2}{\gamma^3 \beta^2} \left[\cos(\phi) - cos\,\phi_0\right]$$

bucket depth is impossibly limited

ϕ_m (radians)	$\frac{k_p}{k_z}$	Long. Acceptance (radians)	Bucket Depth (eV)
.785	.035	.667	6.15
.785	.03	.8	11.5
.785	.025	.94	22.1
.785	.02	1.1	44.1
.75	.035	.68	6.7
.8	.035	.74	8.75
.85	.035	.78	11
.9	.035	.84	13

Ultra-short period undulators

RF & Laser based undulators offer advantages but demand excellent uniformity and are undeveloped

Good:
large aperture
high fields
smooth bore (wakefields)
tunable

Bad:
betatron motion
power loss along waveguide
modes and cutoffs

Ugly:

$$\frac{\delta a_U}{a_U} << \rho$$

RF waveguide undulators can work

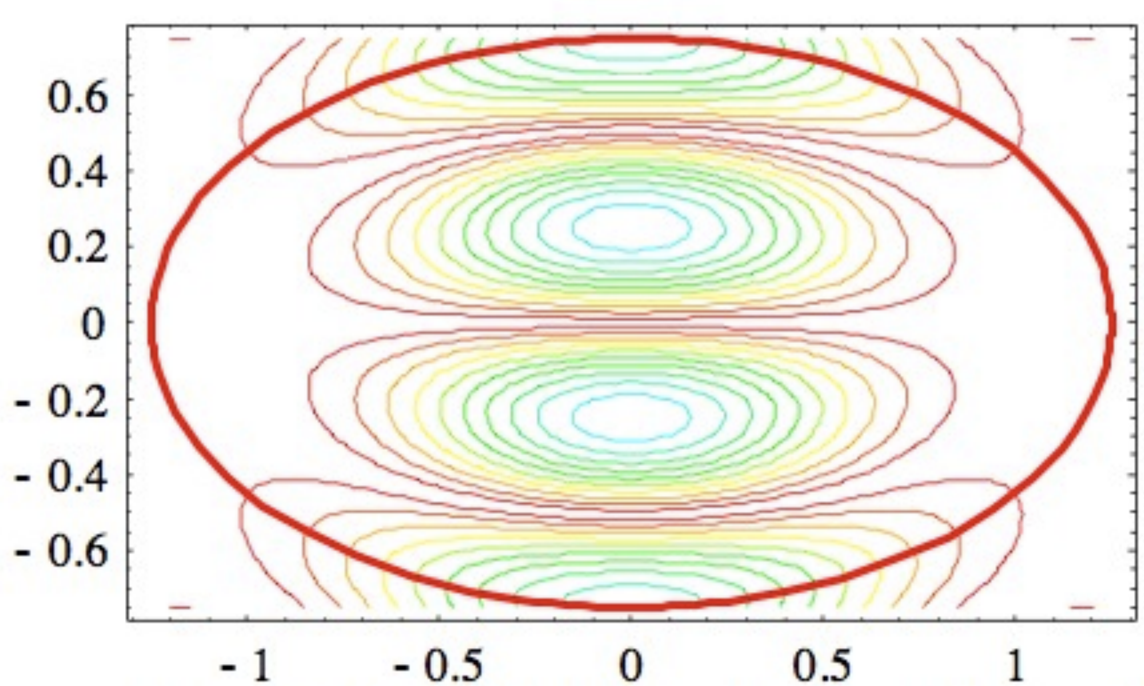
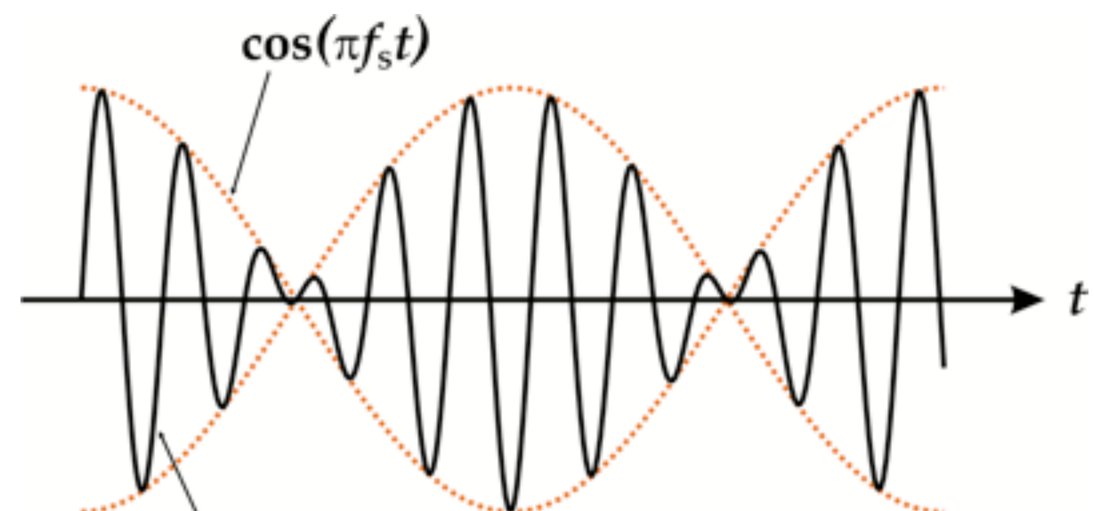


Figure 5. Electric field lines for the sTE_{12} mode.

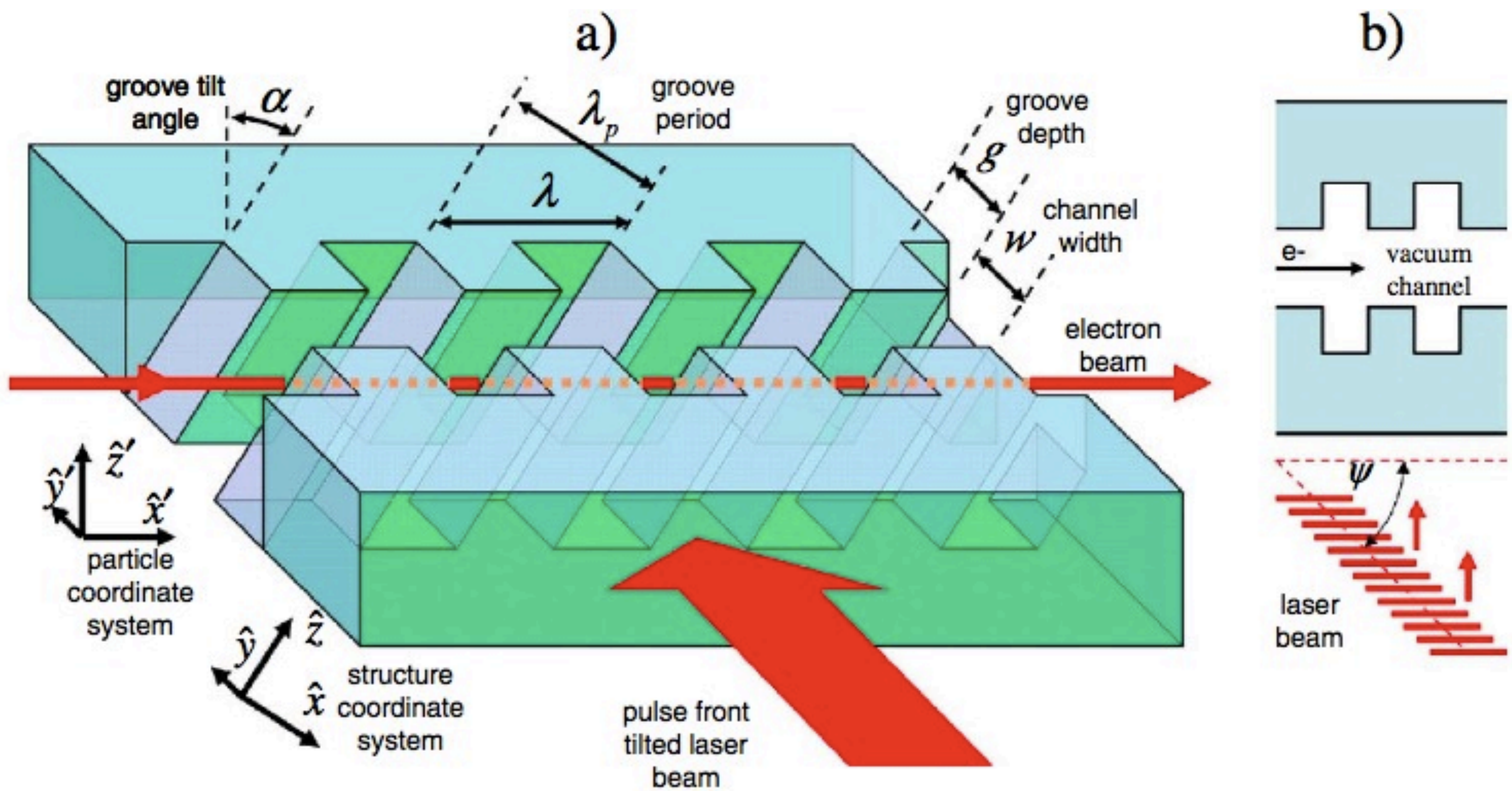
Beating can create larger periods



Issues: $\cos(\pi f_s t)\,\sin(2\pi f_R t)$ 800nm + 1µm = 20µm

Readily available laser technology
Efficient path to longer periods
Better than OPO/OPA?
Ripples ok?

A grating based undulator can produce an intermediate-period device

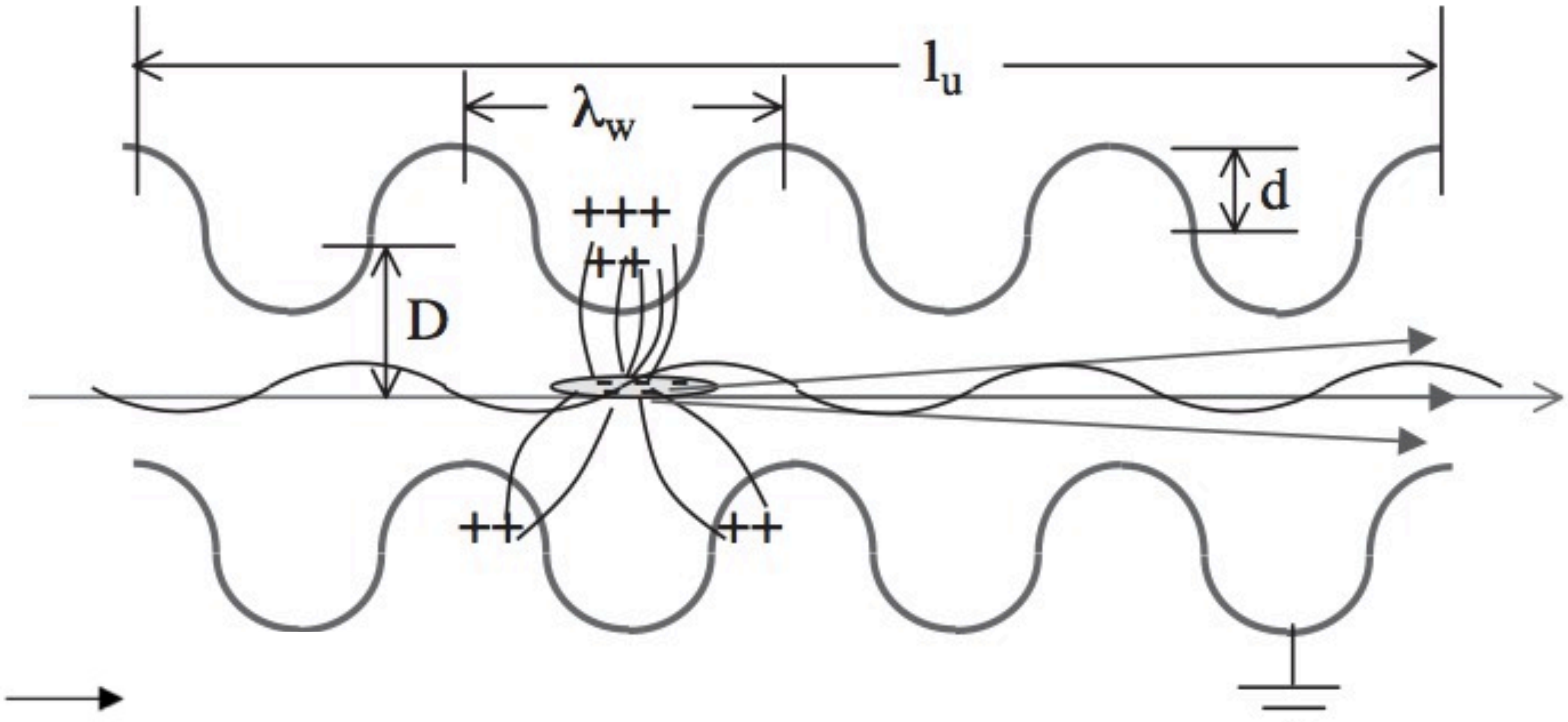


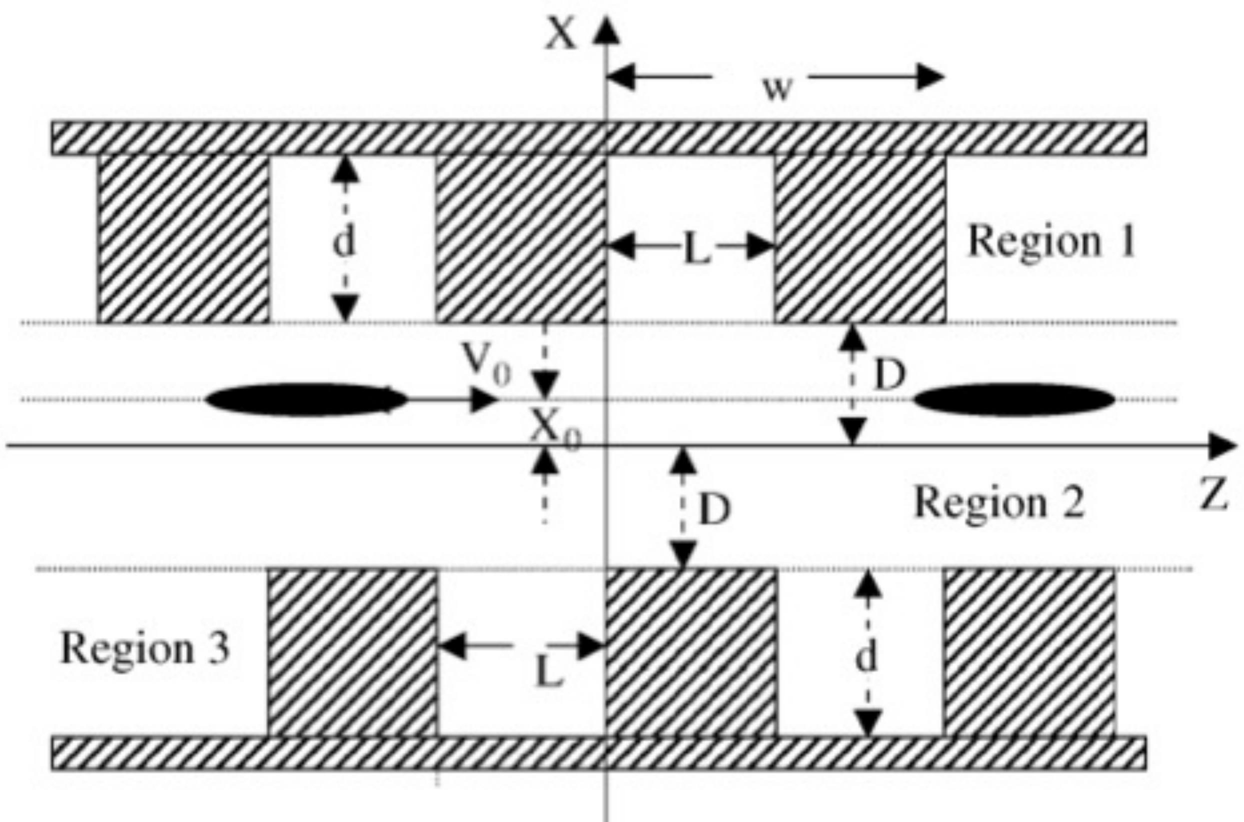
Plettner and Byer, Phys. Rev. ST Accel. Beams 11, 030704 (2008)

Barriers:
Smith Purcell parasitic radiation
Attosecond pulses and synchronization
Low fields?
Period limit? (300μm)

Beam powered devices have also been considered: Image charge undulator (Wakefield)

Issues:
Another beam?
Advantage over RF?
Energy loss?
Acronym challenged (ICU)

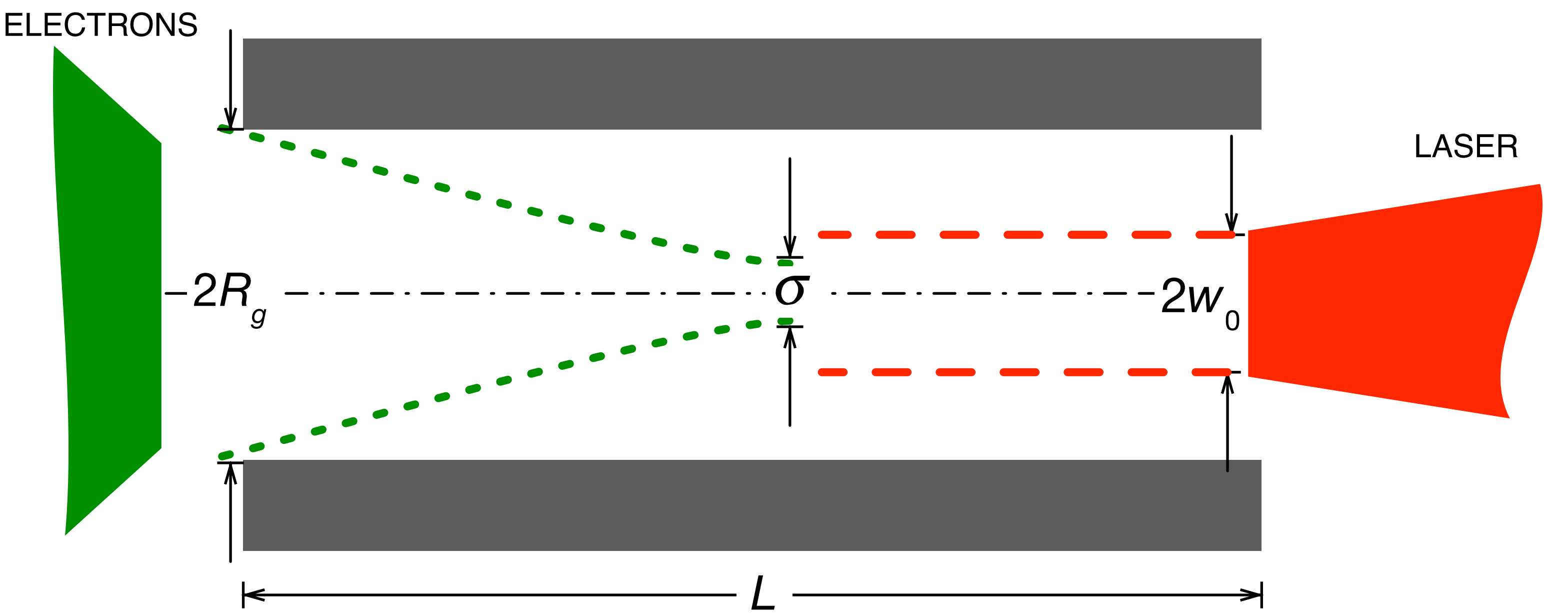


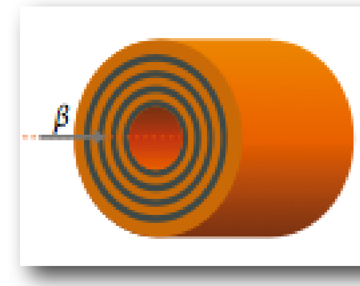


Y. Zhang et al., NIM A 507 (2003) 459–463

Laser guiding and laser technology

Guiding of the laser reduces the effects of diffraction and the Gouy phase shift





Propagating the electron beam through the tube is necessary:

$$\sigma = \sqrt{\frac{\varepsilon_n \beta}{\gamma}} = \sqrt{\frac{\varepsilon_n L}{\gamma}}$$

Electron beam transmission will be very challenging at low energies. There are many additional considerations such as vacuum, breakdown, plasma formation, etc.

In practice, the fiber (waveguide) will be overmoded

$$R_g \gg \lambda \approx 1 \mu m$$

On the other hand, a very small bore is required to obtain significant enhancement from guiding. We take

$$2R_g = 20\ \mu m$$

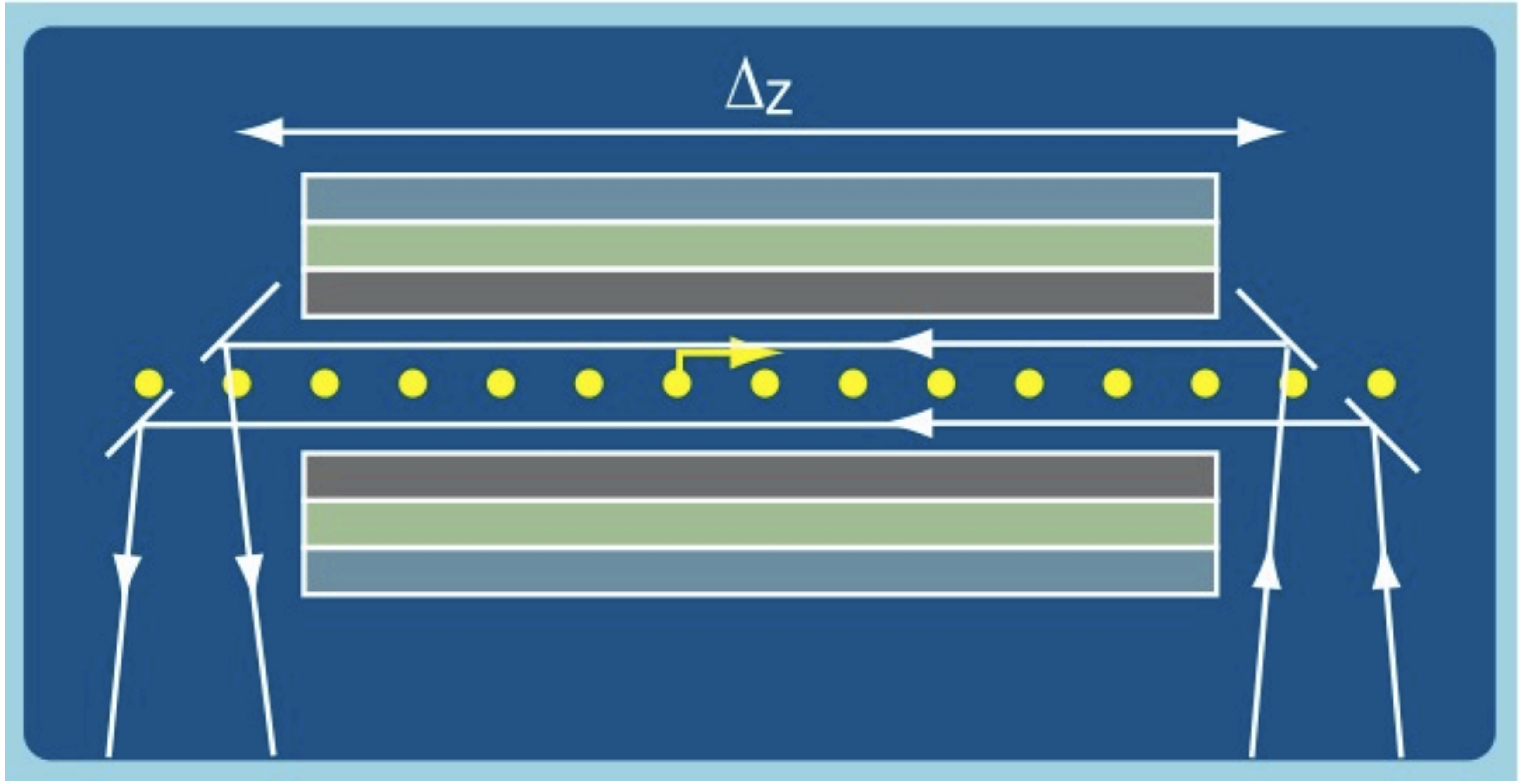
The naive flux enhancement factor is simply

$$\left(\frac{2w_0}{2R_g}\right)^2 = 4$$

The brightness is enhanced further as the bandwidth may be reduced.

Planar Bragg guiding...

Claim:
energy out is
2 OOM over
free space,
but only
10^{-6} photons per
electron

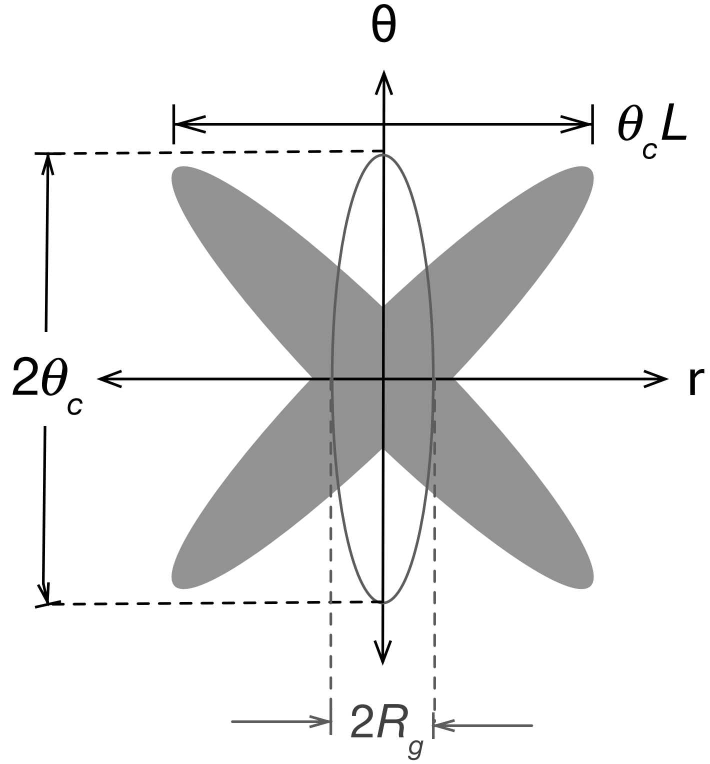


Vadim Karagodsky, David Schieber, and Levi Schächter PRL 104, 024801 (2010)

Bragg waveguide setup. The electrons interact with a counterpropagating laser and emit x-ray radiation. The laser mode of interest has a TEM form inside the vacuum core. The mode is confined to a submicron cross section, enabling strong interaction not at the expense of interaction length.

Guiding of the (soft) x-rays is also possible

Unguided



Equivalent phase space area:

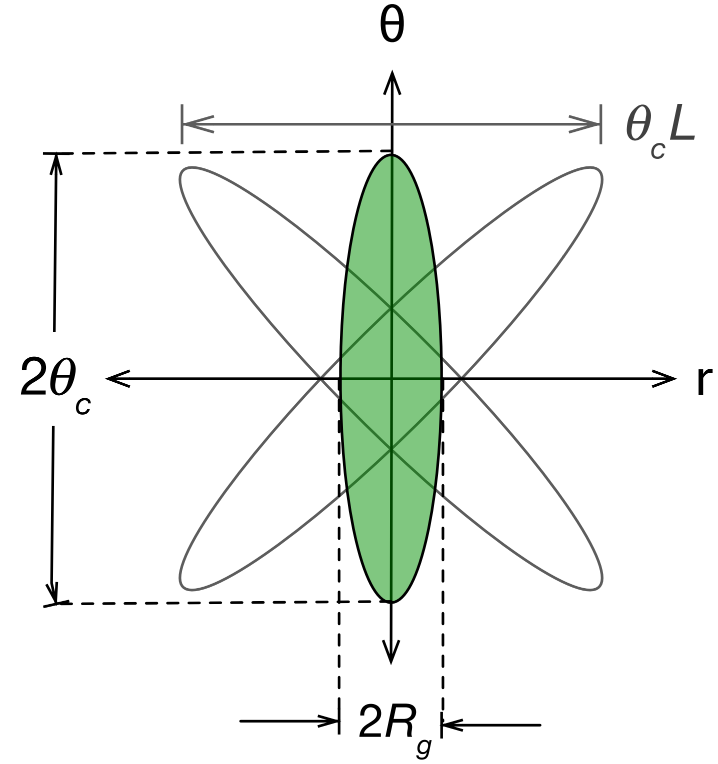
$$2\theta_c^2 L$$

assuming

$$\theta_c L \gg 2R_g$$

(smallest ellipse is at least x2 bigger)

Guided



For the guided source, the phase space is at most

$$2\theta_c 2R_g$$

The phase space reduction factor is

$$\frac{2\theta_c^2 L}{4\theta_c R_g} = \frac{\theta_c L}{2R_g} = \frac{1}{N_{zz}}$$

Guiding in optical accelerator driven ICS is interesting:

- short pulse = higher damage threshold
- high rep rate = less laser energy per pulse
- fields in guide ~ fields in accelerator

Conclusions

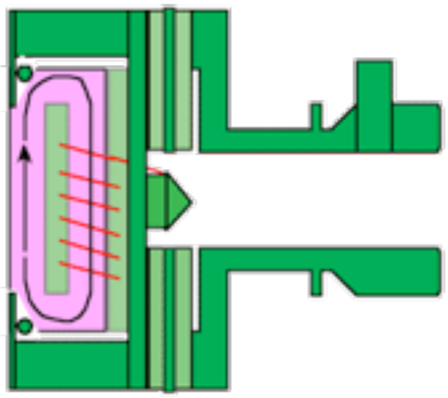
A soft x-ray light source powered entirely by lasers and on a laptop scale seems possible

Parameter	Value
Wavelength	6 nm
Beam energy	25.5 MeV
Emittance (norm.)	0.06 μm (doh!)
Charge	1 pC (whew!)
Undulator parameter	1
Undulator period	20 μm
FEL parameter	~3 x 10^{-3}
Saturation length	6 mm (LOL)
x-ray flux per bunch	~5 x 10^{8}

Pellegrini and Travish

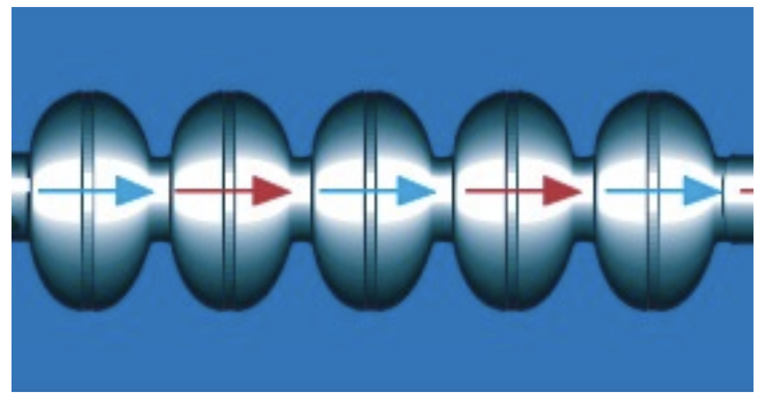
We have the opportunity to develop a suite of on-chip particle beam tools

guns



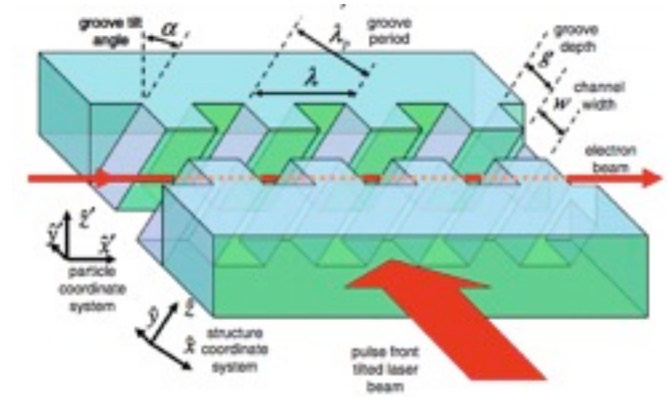
monolithic structures

sub-relativistic structures



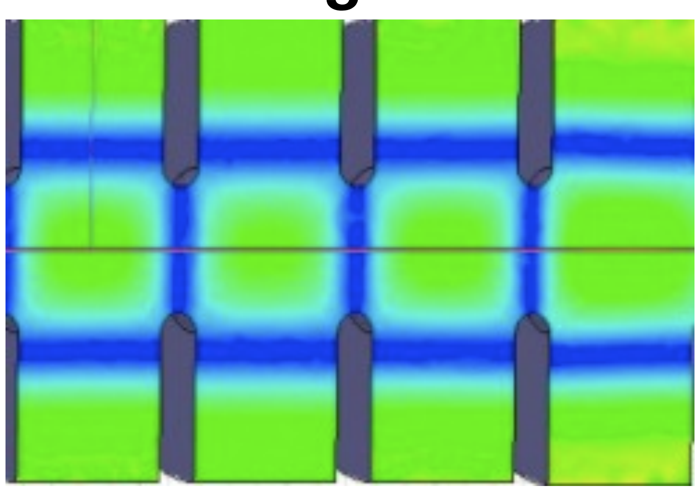
muons, protons, ions

undulators



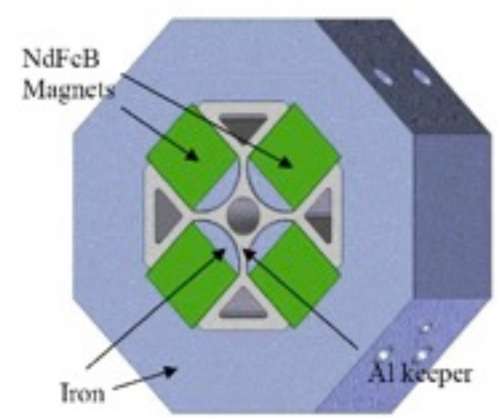
coherent THz/x-ray sources
IFEL accelerator

deflecting cavities



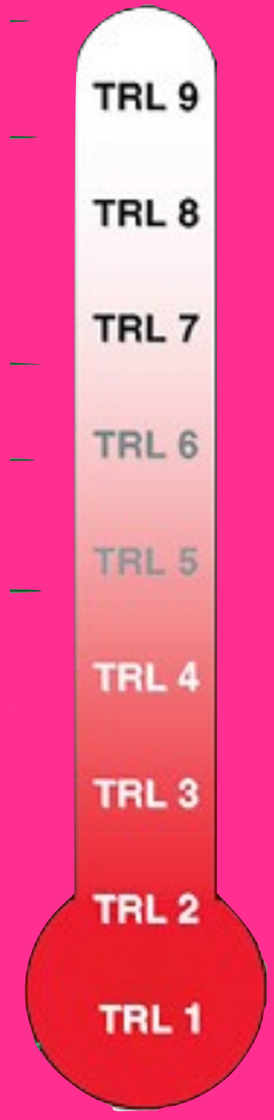
ultra-fast sources

focusing



ICS Gamma-Ray Source

all using laser-driven dielectric structure



Technical development level will decide which optical scale structure is of interest

Very low charge is good for very short time scales

Killer app for optical structure based light source still needs to be identified

prediction

A laser “add-on box” to up-convert to x-rays and based on an optical-scale accelerator will be available in 10 years