Novel Optical-Scale Acceleration Schemes (but mostly Dielectric Laser Accelerators)

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UCLA

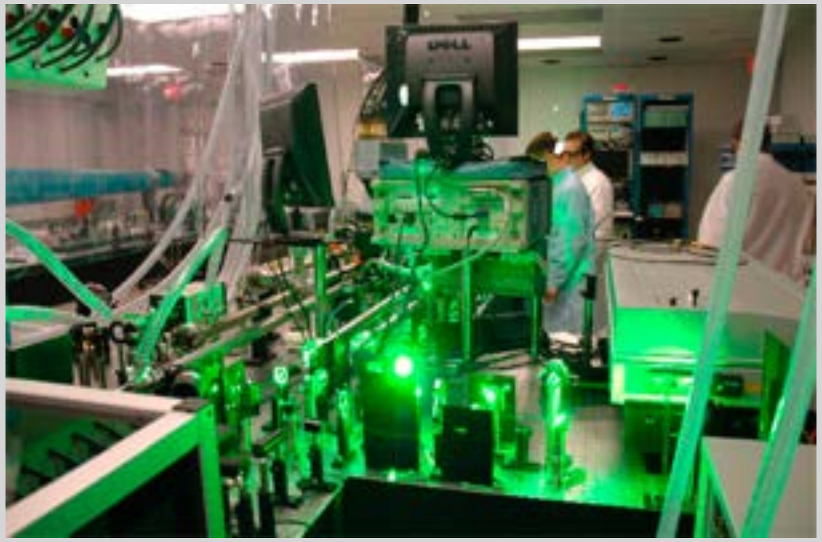
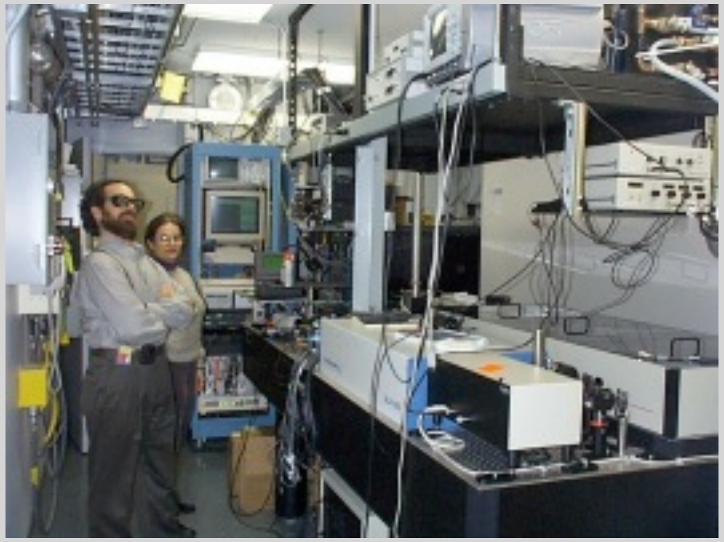
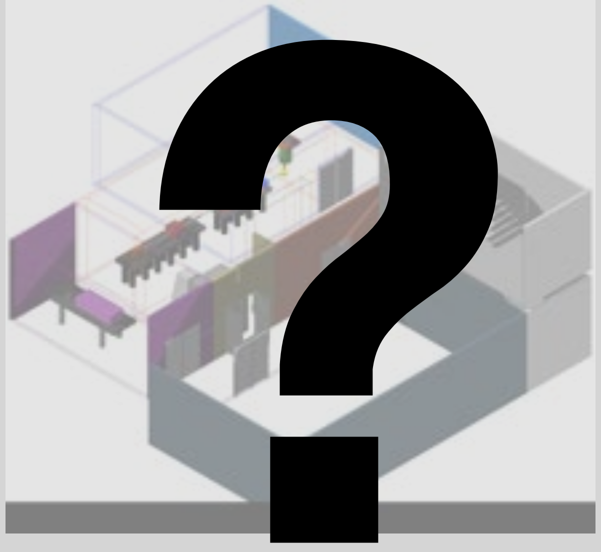
LA^{3}NET

School on Laser Applications at Accelerators

semester long course

1 hour

you

COST	SIZE	LASER	ACCELERATOR
$\$10^9$	XL		
$\$10^7$	M		
$\$10^5$	S		

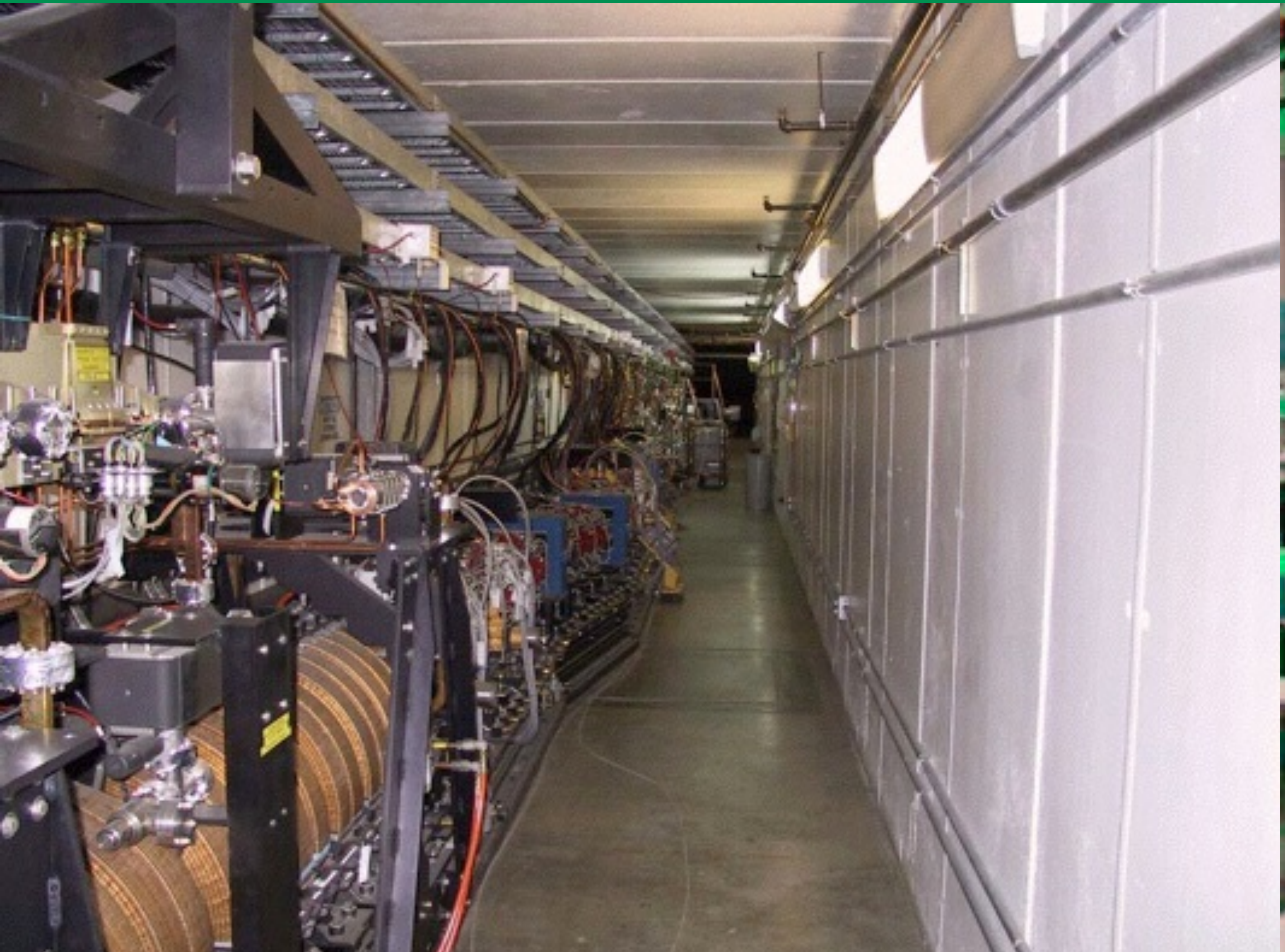
~ $$10^9$$

Accelerator (APS)

LASER (NIF)

~ $\$10^7$

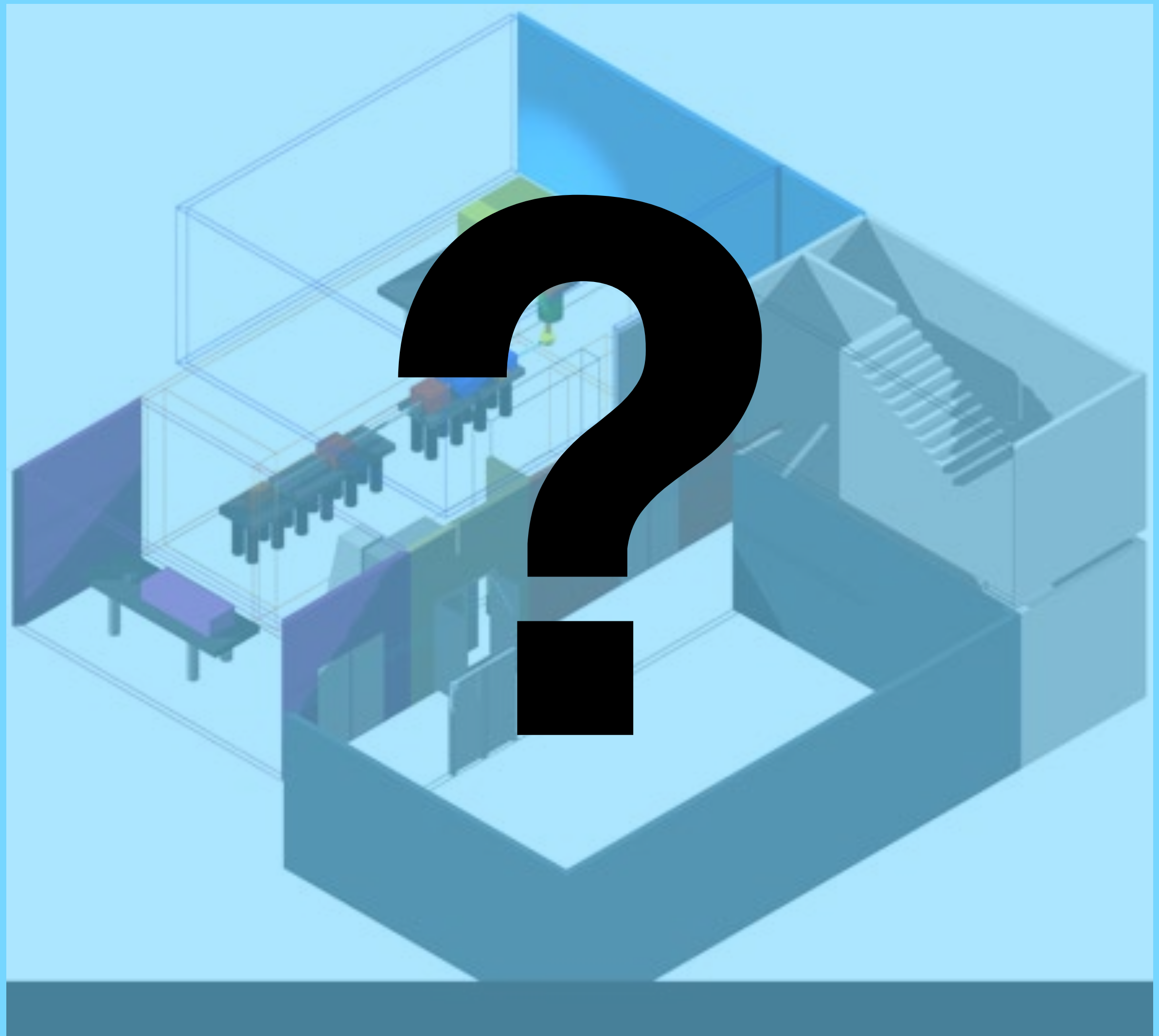
Accelerator (NLCTA)



LASER (100TW Falcon)

~ $$10^5$

Accelerator



LASER (T3)

Lasers are commonly found in research laboratories in all science disciplines

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UCLA Campus

~12

number of accelerators

400

number of class 3&4 lasers registered

>>1000 all lasers

Despite demand, accelerating structures have evolved slowly and gradients remain modest

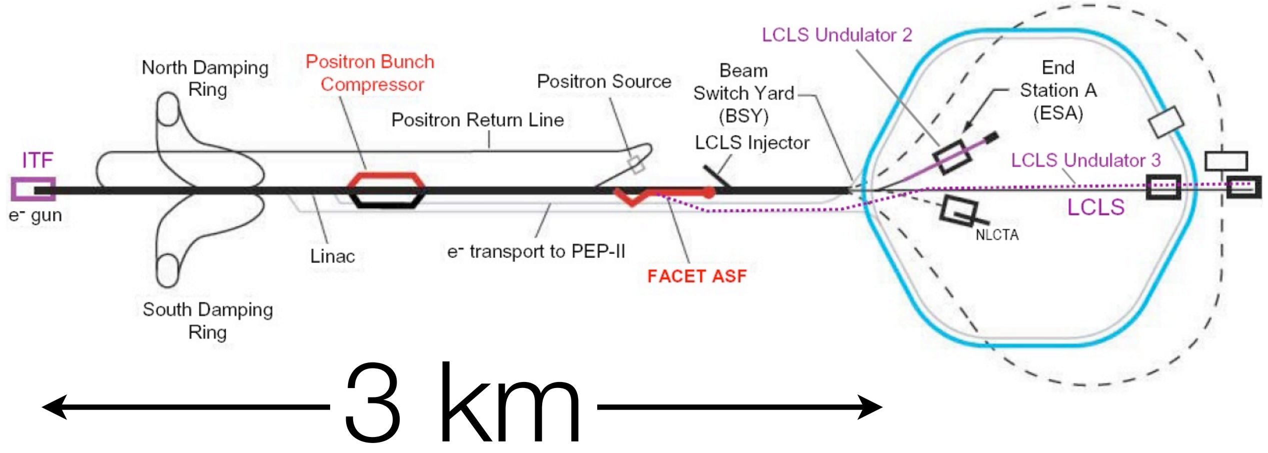
On the shoulders of giants

1950s
SLC
10 MV/m

→

1990s
NLC
90 MV/m

2000s
Laser and Plasma Wakefield
10s GV/m
BUT...

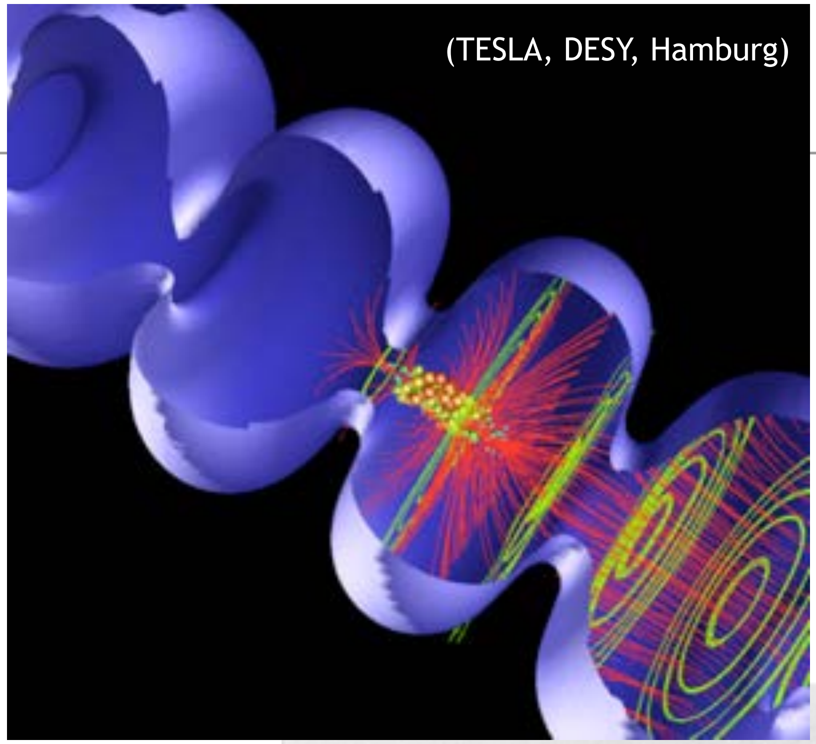


THE WORKHORSE FOR 50 YEARS

what happens if we shrink this all down by

1000 ?

We can't just increase the operating frequency and shrink the machines

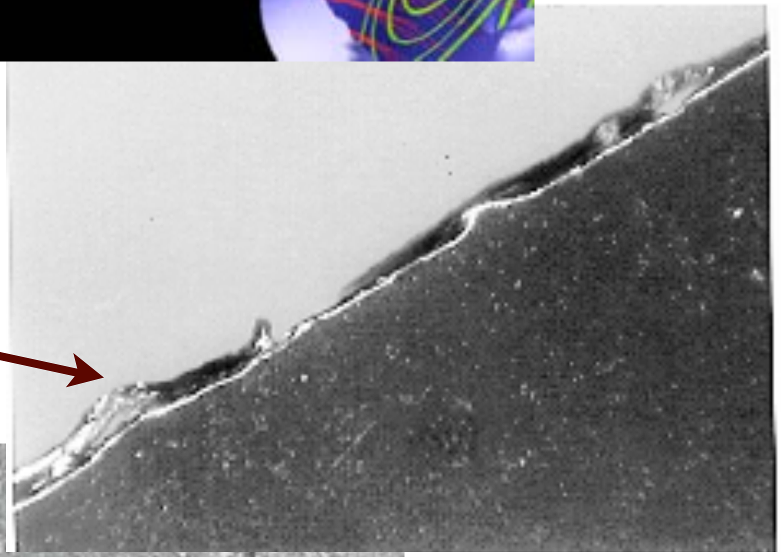

(TESLA, DESY, Hamburg)

Wakefields:

- Charged particles + small apertures = radiation
- Transverse wakefields ~ λ^{-3}
- Beams break up from their own wakes

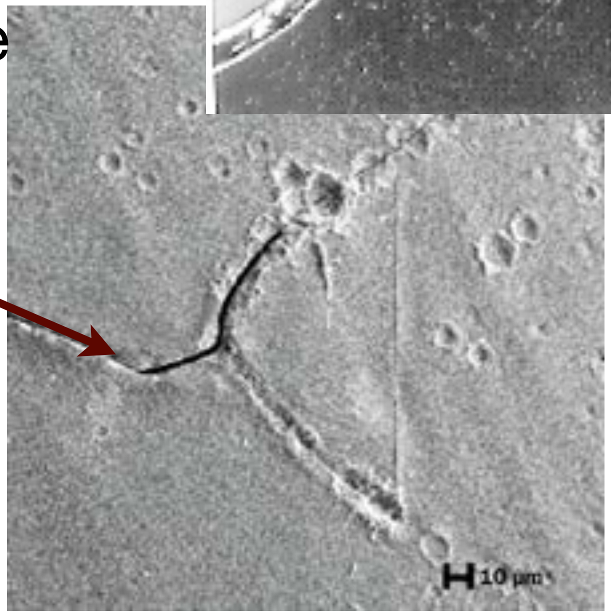
Machining:

- Surface roughness must be λ/500 or less
- Tolerances become too tight


(SLAC)

Breakdown:

- High energy density + small apertures + surface roughness = electric breakdown
- Structure damage ==> poor performance



(CLIC, CERN)

No sources:

- Lack of good technology for high power radiation with *f* > 34 GHz

What is a particle accelerator?

?

Why do we want them to be ______ ?
(small, high gradient, laser powered…)

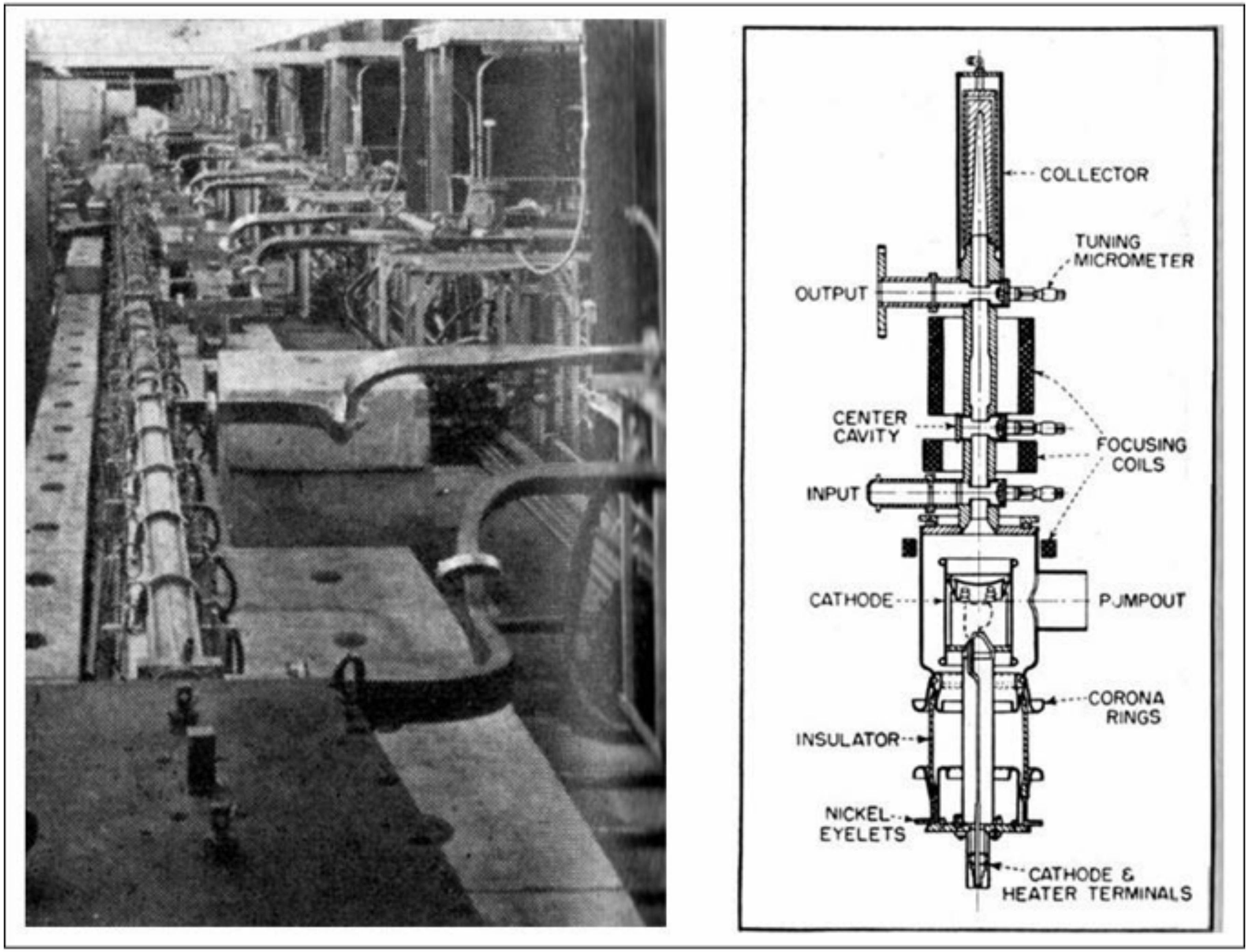
Can a technology support everything from colliders to medical treatment devices?

Why are you doing this to yourself (accelerators already work well)?

What does it take for a novel accelerator to be successful?

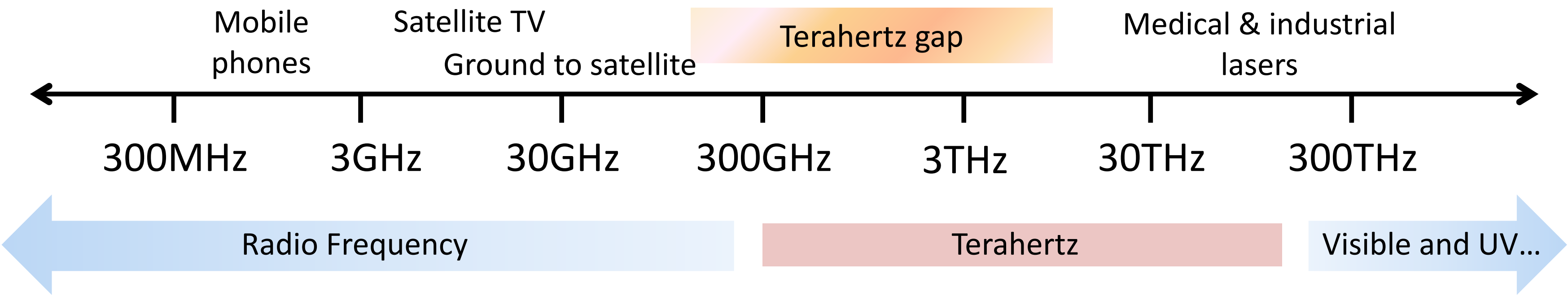
An accelerator structure transfers energy from one source to another (the beam)

!



Stanford Microwave Laboratory around 1953

Of available power sources at wavelengths shorter than microwaves, lasers are the most capable



Mobile phones

Satellite TV

Ground to satellite

Terahertz gap

Medical & industrial lasers

300MHz

3GHz

30GHz

300GHz

3THz

30THz

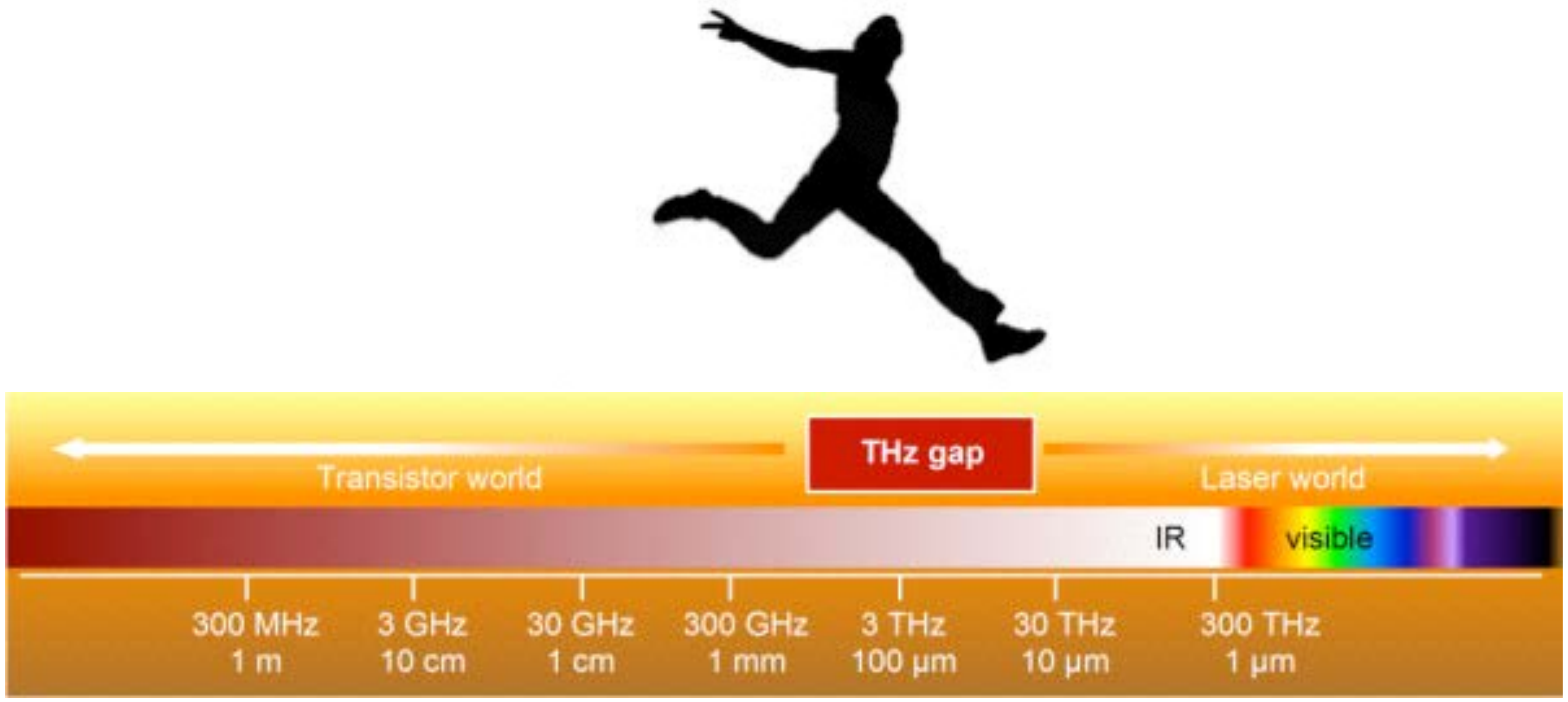
300THz

Radio Frequency

Terahertz

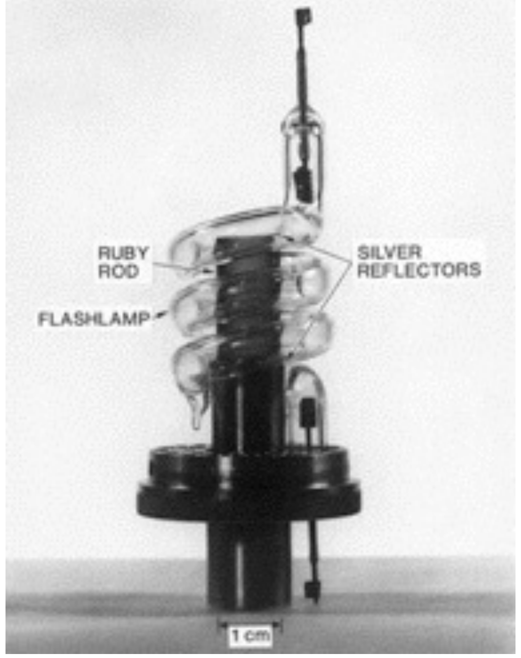
Visible and UV…

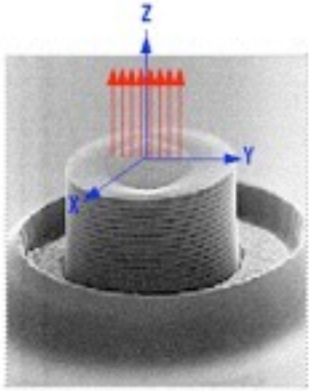
lack of sources, materials and fabrication technology force us to make a leap from Microwave to Optical



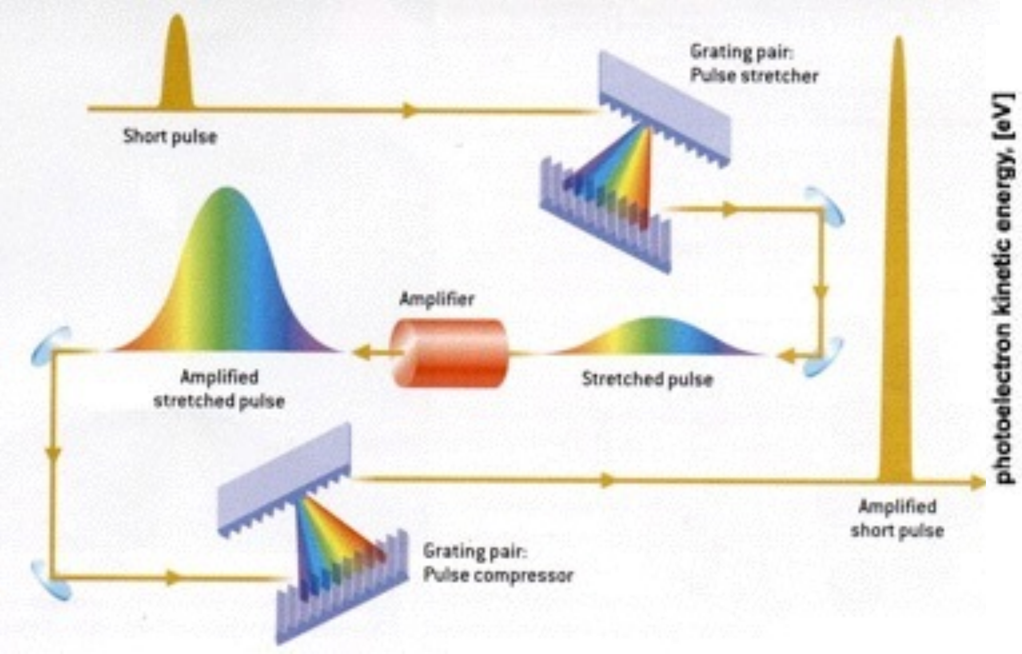
Lasers offer several features at once:
low cost, high power, ultra-fast, compact

SOLID STATE

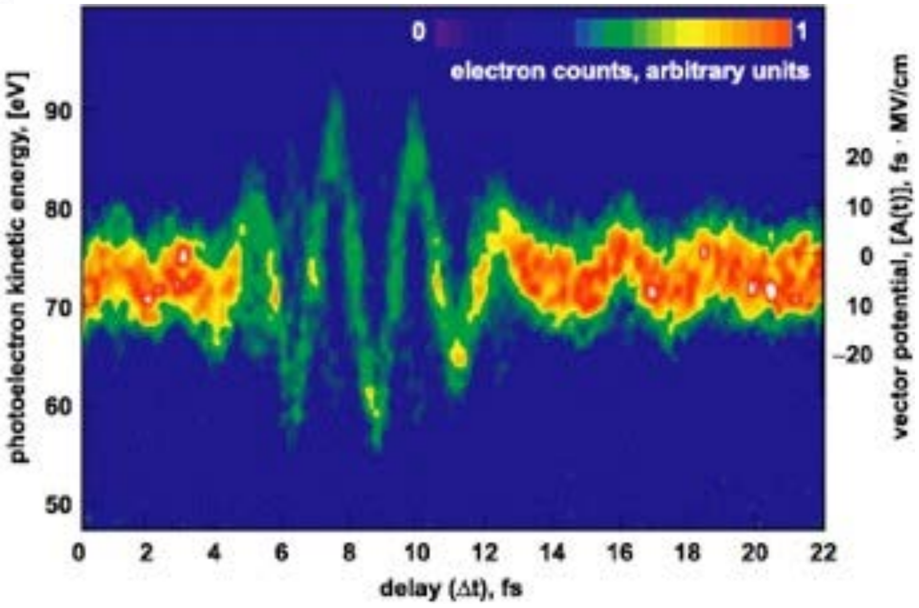




CPA



ULTRAFAST

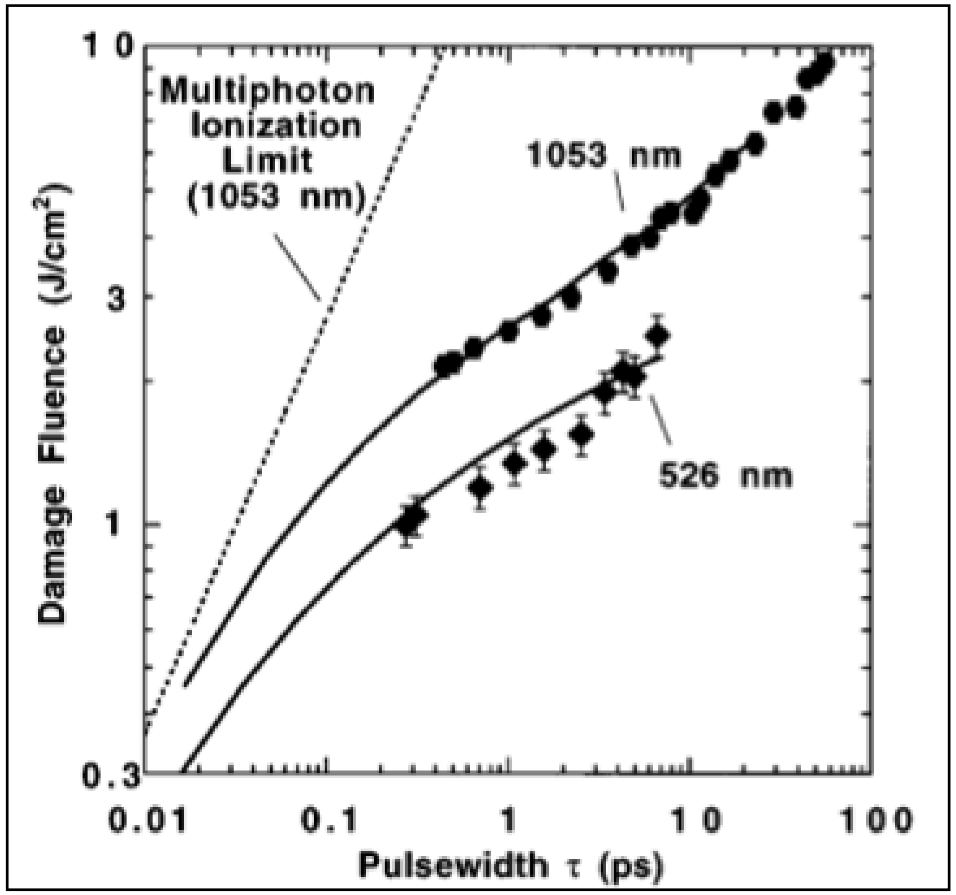


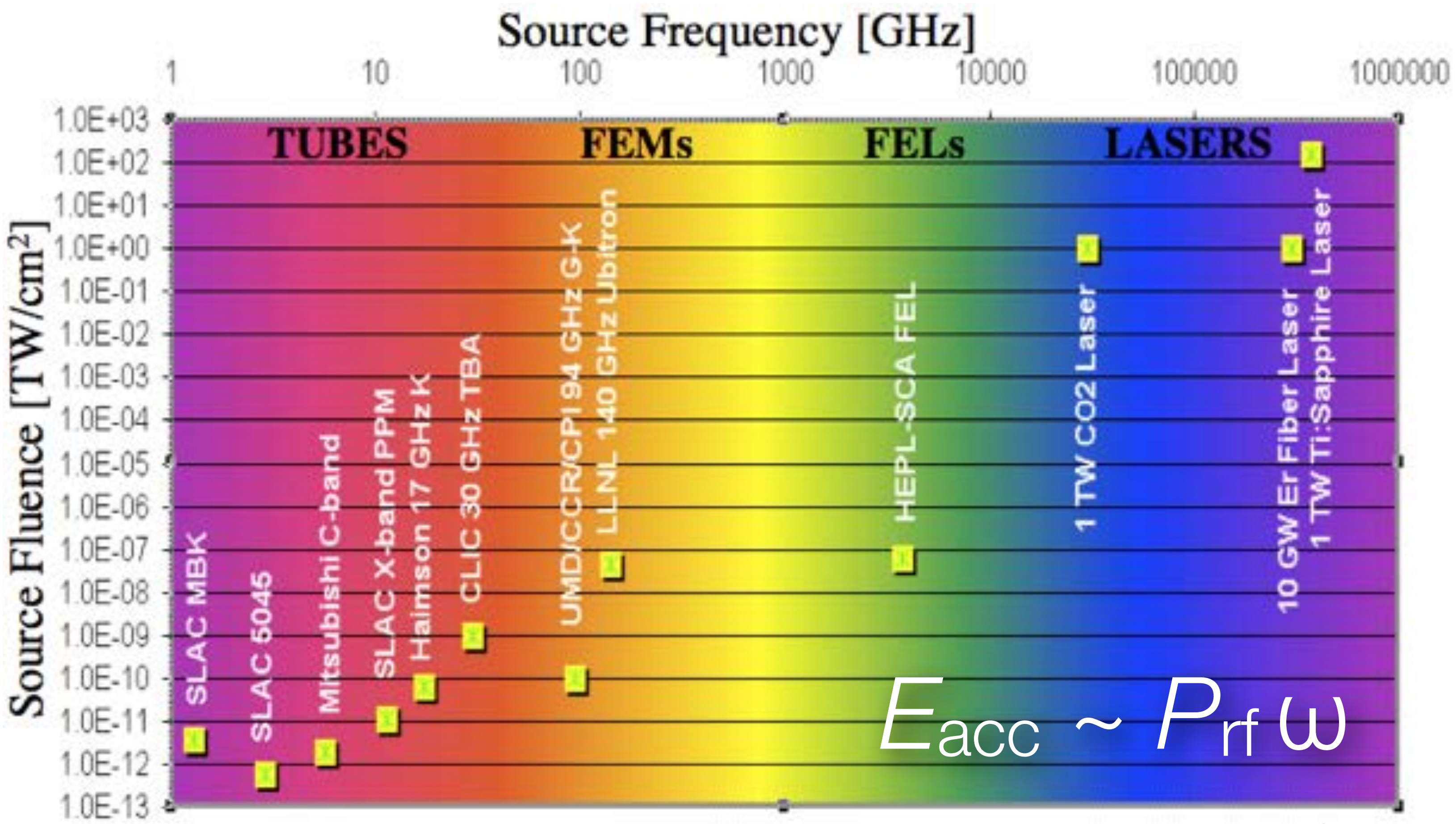
Breakdown and available power sources motivate operating regime and composition of new devices

Dielectric:
Breakdown

Optical:
THz Gap

Short Wavelength:
Gradient





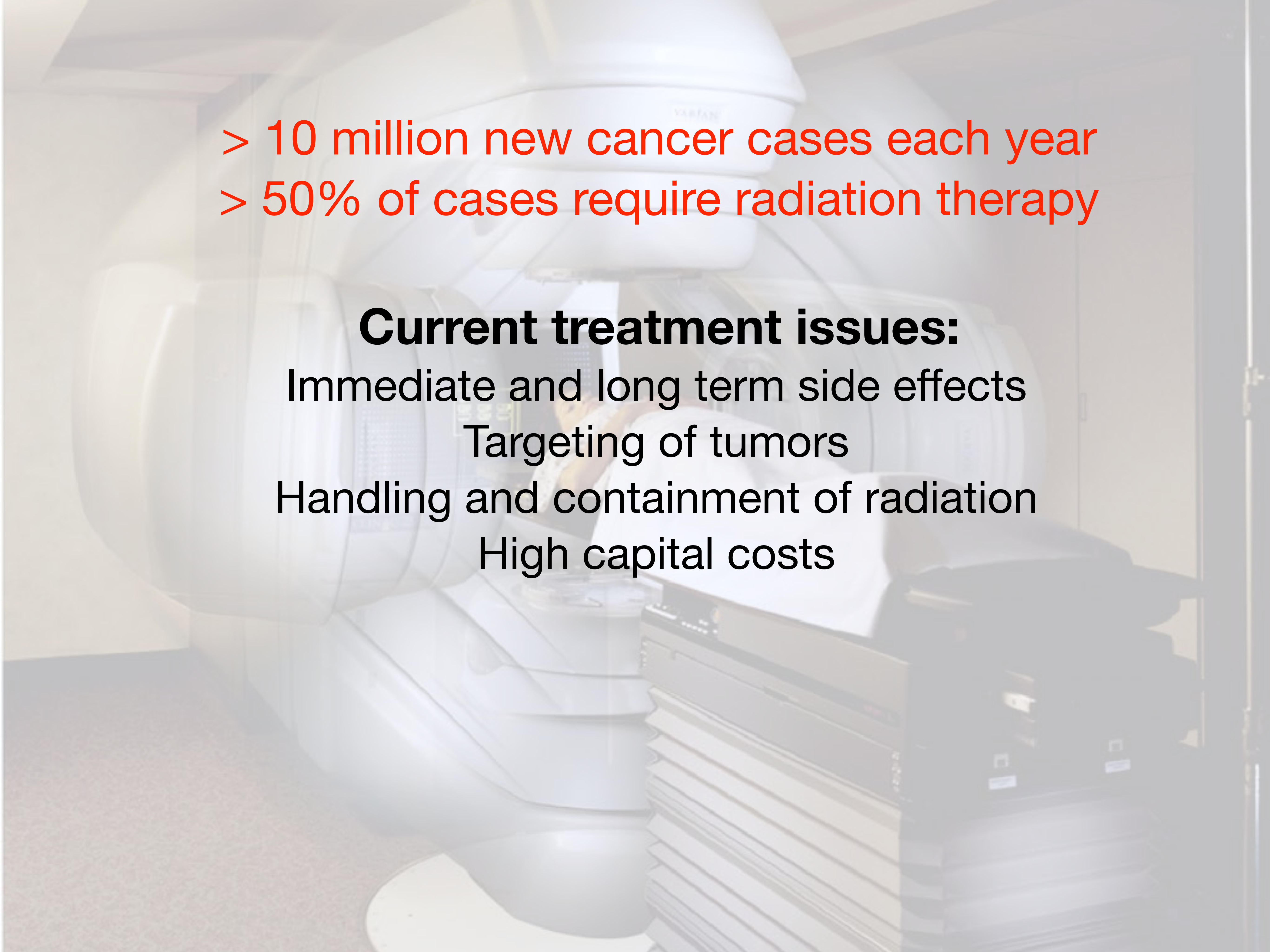
$E_{acc} \sim P_{rf}\,\omega$

E. Colby

fabrication methods & materials strongly support the optical scale

WE ARE TOOL BUILDERS

HEALTHCARE

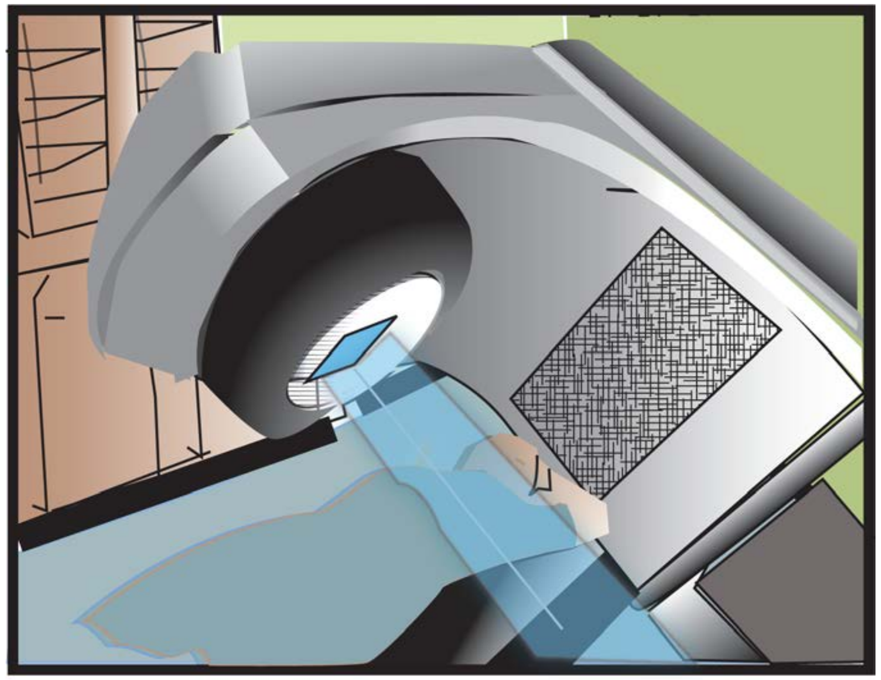


> 10 million new cancer cases each year
> 50% of cases require radiation therapy

Current treatment issues:

Immediate and long term side effects
Targeting of tumors
Handling and containment of radiation
High capital costs

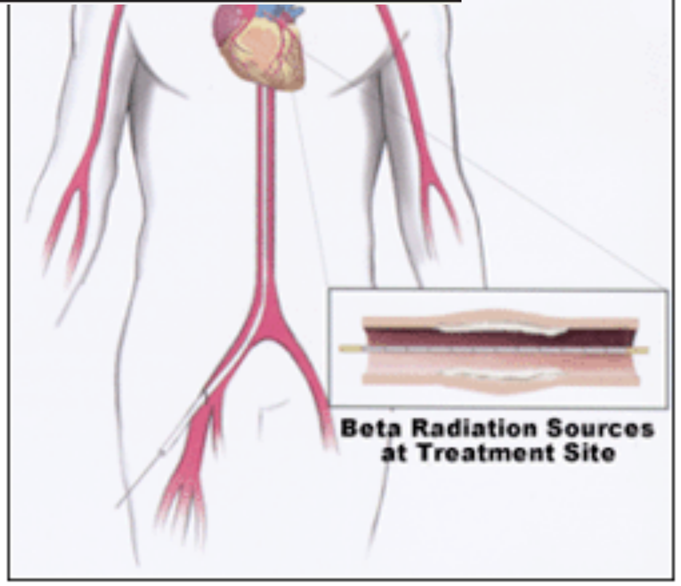
I have a dream… that one day, particle accelerators AND lasers can live side by side…



external beam

vs.

intra-op device



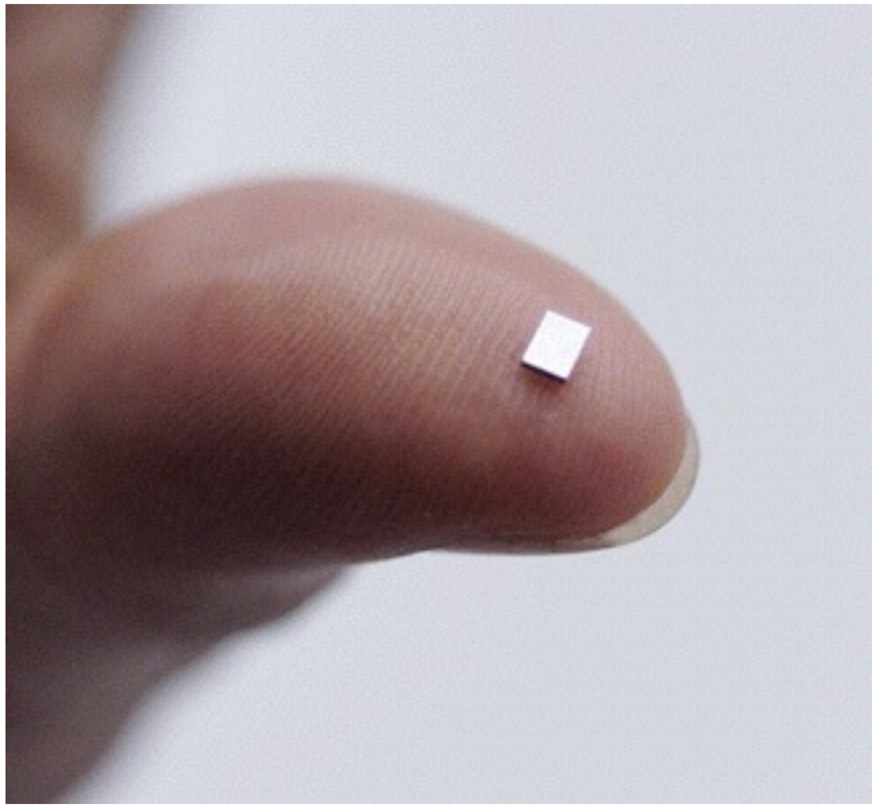
Bringing the source closer to the site allows electrons to deposit energy over a tumor depth

EBRT Machine

Big
Heavy
Expensive ($3-5M)
Microwave powered

MAP

Microchip sized
Endoscope tip
Disposable
Laser powered ($200k)

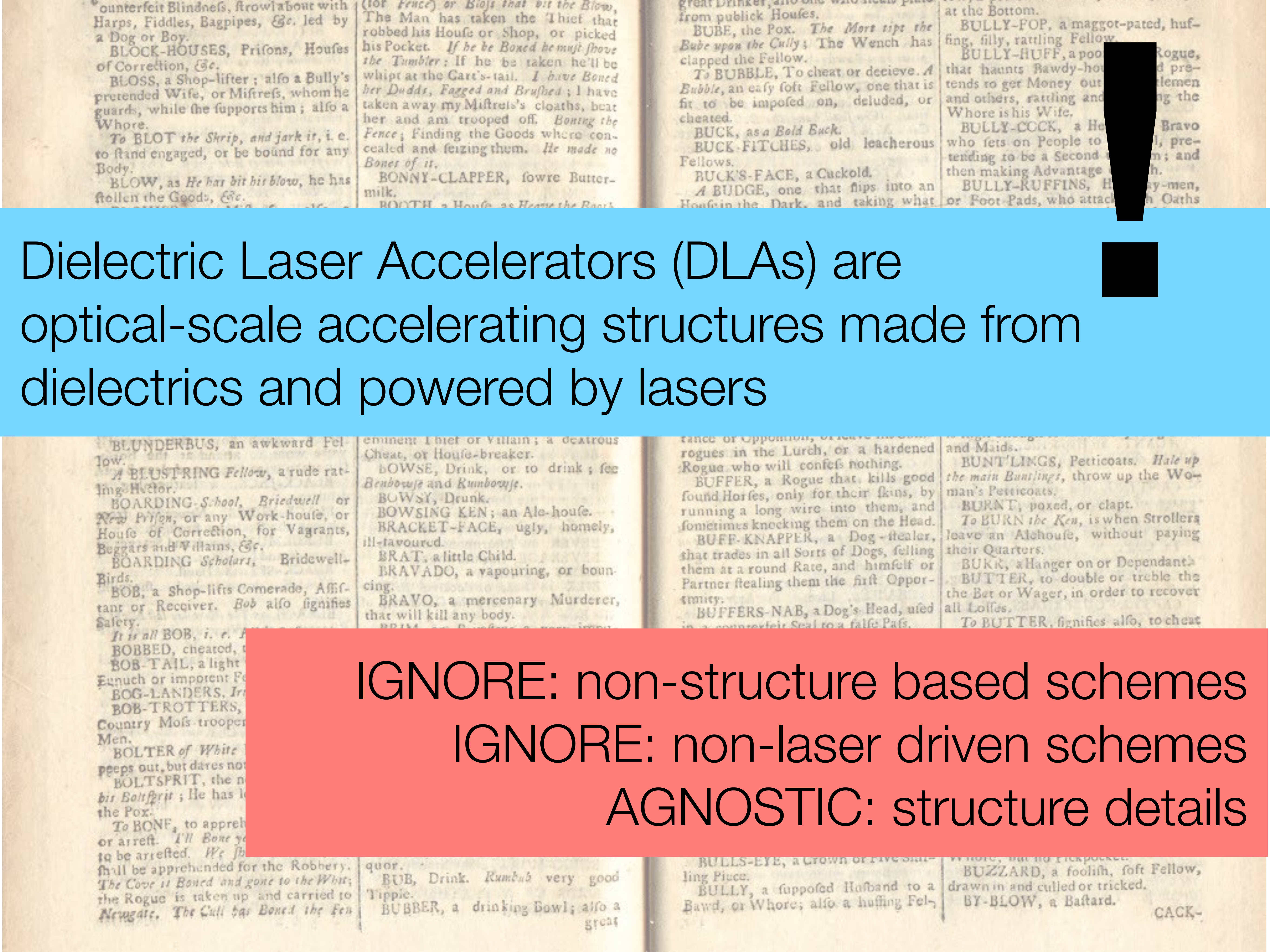


1-6 MeV electrons have ~1-3 cm range
minimal stopping power = minimal surrounding tissue damage

Dielectric Laser Accelerators (DLAs) are optical-scale accelerating structures made from dielectrics and powered by lasers

!

IGNORE: non-structure based schemes
IGNORE: non-laser driven schemes
AGNOSTIC: structure details



ounterfeit Blindneſs, ſtrowl about with Harps, Fiddles, Bagpipes, &c. led by a Dog or Boy.

BLOCK-HOUSES, Priſons, Houſes of Correction, &c.

BLOSS, a Shop-lifter; alſo a Bully's pretended Wife, or Miſtreſs, whom he guards, while ſhe ſupports him; alſo a Whore.

To BLOT *the Skrip, and jark it*, i. e. to ſtand engaged, or be bound for any Body.

BLOW, as *He has bit his blow*, he has ſtollen the Goods, &c.

BLUNDERBUS, an awkward Fellow.

A BLUSTRING *Fellow*, a rude ratling Hector.

BOARDING-*School*, *Briedwell* or *New Priſon*, or any Work-houſe, or Houſe of Correction, for Vagrants, Beggars and Villains, &c.

BOARDING *Scholars*, Bridewell-Birds.

BOB, a Shop-lifts Comerade, Aſſiſtant or Receiver. *Bob* alſo ſignifies Safety.

It is all BOB, i. e.

BOBBED, cheated,

BOB-TAIL, a light

Eunuch or impotent

BOG-LANDERS,

BOB-TROTTERS,

Country Moſs trooper

Men.

BOLTER *of White*

peeps out, but dares no

BOLTSPRIT, the

his Boltſprit; He has

the Pox.

To BONE, to appreh

or arreſt. *I'll Bone y*

to be arreſted. *We ſh*

ſhall be apprehended for the Robbery. *The Cove is Boned and gone to the Whit*; the Rogue is taken up and carried to *Newgate*. *The Cull has Boned the Fen*

(for *Fence*) *or Bos that bit the Blow*, The Man has taken the Thief that robbed his Houſe or Shop, or picked his Pocket. *If he be Boned he muſt ſhove the Tumbler*: If he be taken he'll be whipt at the Cart's-tail. *I have Boned her Dudds, Fagged and Bruſhed*; I have taken away my Miſtreſs's cloaths, beat her and am trooped off. *Boning the Fence*; Finding the Goods where concealed and ſeizing them. *He made no Bones of it.*

BONNY-CLAPPER, ſowre Butter-milk.

eminent Thief or Villain; a dextrous Cheat, or Houſe-breaker.

BOWSE, Drink, or to drink; ſee *Benbowſe* and *Rumbowſe*.

BOWSY, Drunk.

BOWSING KEN; an Ale-houſe.

BRACKET-FACE, ugly, homely, ill-favoured.

BRAT, a little Child.

BRAVADO, a vapouring, or bouncing.

BRAVO, a mercenary Murderer, that will kill any body.

quor.

BUB, Drink. *Rumbub* very good Tippie.

BUBBER, a drinking Bowl; alſo a great

great Drinker, alſo one who ſteals plate from publick Houſes.

BUBE, the Pox. *The Mort tipt the Bube upon the Cully*; The Wench has clapped the Fellow.

To BUBBLE, To cheat or deceive. *A Bubble*, an eaſy ſoft Fellow, one that is fit to be impoſed on, deluded, or cheated.

BUCK, *as a Bold Buck*.

BUCK-FITCHES, old leacherous Fellows.

BUCK'S-FACE, a Cuckold.

A BUDGE, one that ſlips into an Houſe in the Dark, and taking what

rogues in the Lurch, or a hardened Rogue who will confeſs nothing.

BUFFER, a Rogue that kills good ſound Horſes, only for their ſkins, by running a long wire into them, and ſometimes knocking them on the Head.

BUFF-KNAPPER, a Dog-ſtealer, that trades in all Sorts of Dogs, ſelling them at a round Rate, and himſelf or Partner ſtealing them the firſt Opportunity.

BUFFERS-NAB, a Dog's Head, uſed

ling Piece.

BULLY, a ſuppoſed Huſband to a Bawd, or Whore; alſo a huffing Fel-

at the Bottom.

BULLY-FOP, a maggot-pated, huffing, ſilly, rattling Fellow.

BULLY-HUFF, a poo Rogue, that haunts Bawdy-ho pretends to get Money out tlemen and others, rattling and the Whore is his Wife.

BULLY-COCK, a He Bravo who ſets on People to pretending to be a Second ; and then making Advantage

BULLY-RUFFINS, H y-men, or Foot-Pads, who attack Oaths

and Maids.

BUNTLINGS, Petticoats. *Hale up the main Buntlings*, throw up the Woman's Petticoats.

BURNT, poxed, or clapt.

To BURN *the Ken*, is when Strollers leave an Alehouſe, without paying their Quarters.

BURR, a Hanger on or Dependant.

BUTTER, to double or treble the Bet or Wager, in order to recover all Loſſes.

To BUTTER, ſignifies alſo, to cheat

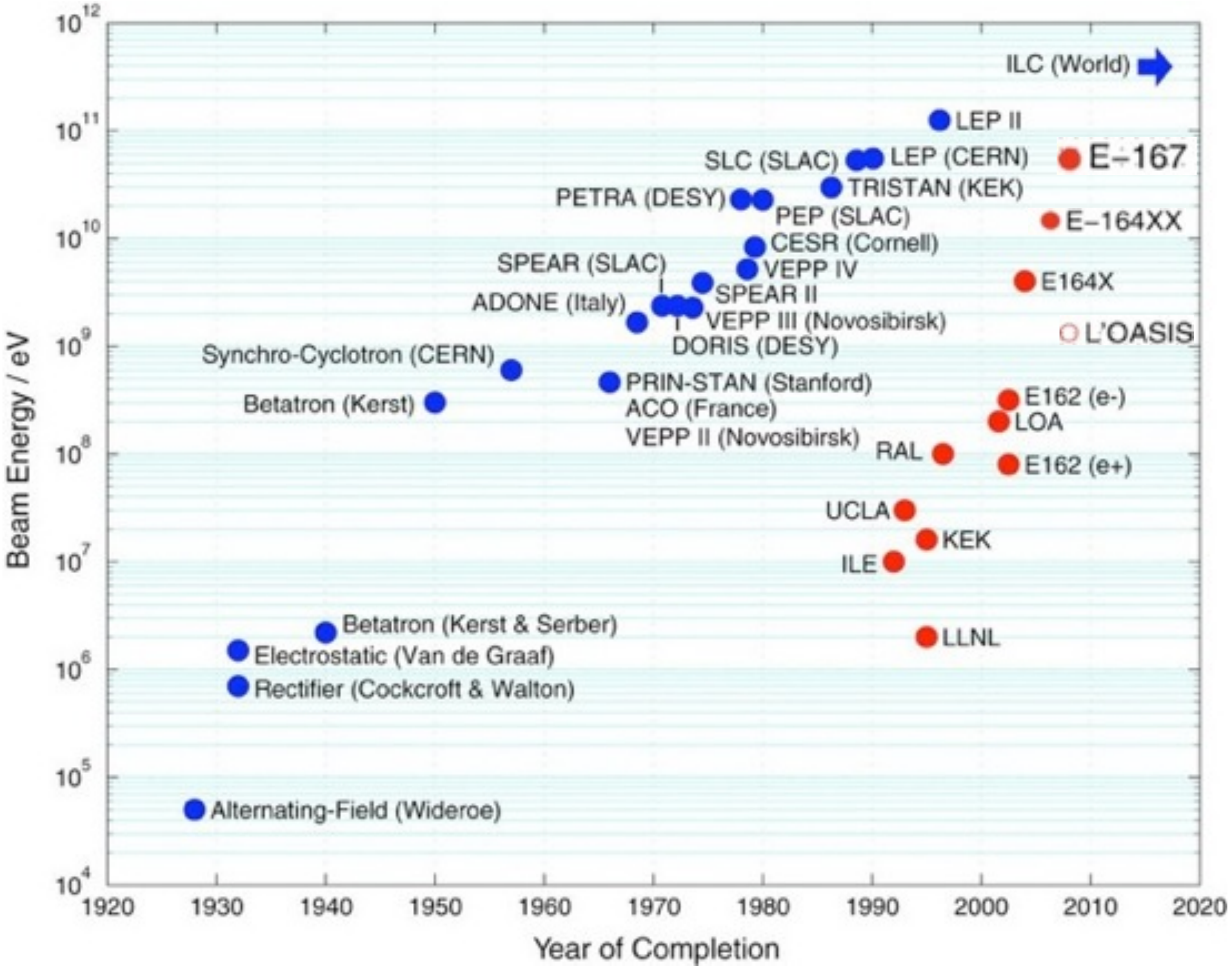
BUZZARD, a fooliſh, ſoft Fellow, drawn in and culled or tricked.

BY-BLOW, a Baſtard.

CACK-

Where do Dielectric Laser Accelerators fit?

What impact will advanced accelerators have?

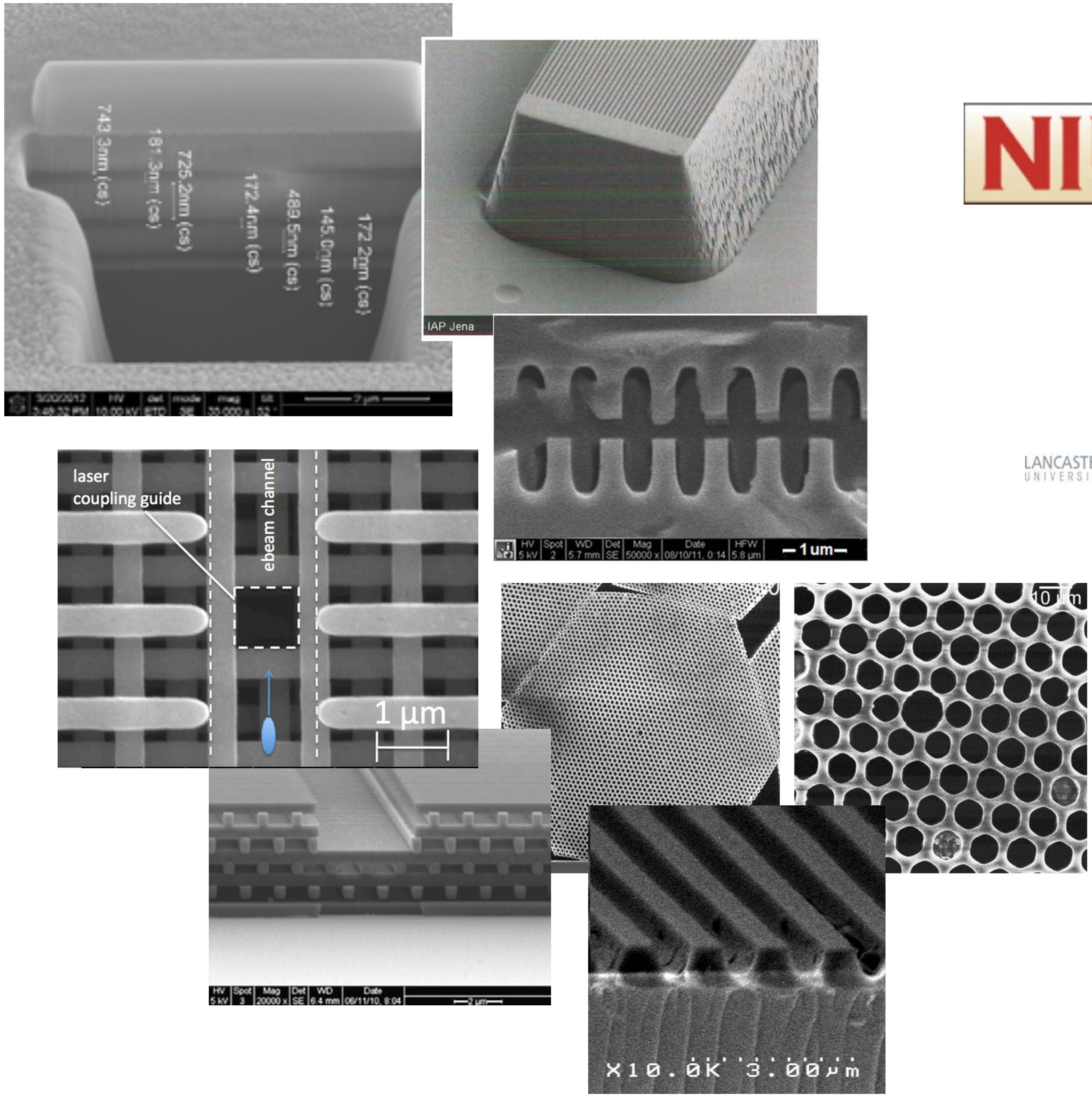


R. Ischebeck
M. Hogan

Can DLAs be used for colliders and factories?

What prevents a basement-lab light source?

Optical scale structures for particle acceleration have been and are being realized



NIU

Manhattanville
COLLEGE

The Cockcroft Institute
of Accelerator Science and Technology

MAX-PLANCK-INSTITUT
FÜR QUANTENOPTIK

radiabeam
TECHNOLOGIES

VANDERBILT

LANCASTER
UNIVERSITY

UNIVERSITY OF
LIVERPOOL

Technion
Israel Institute of Technology

PBPL

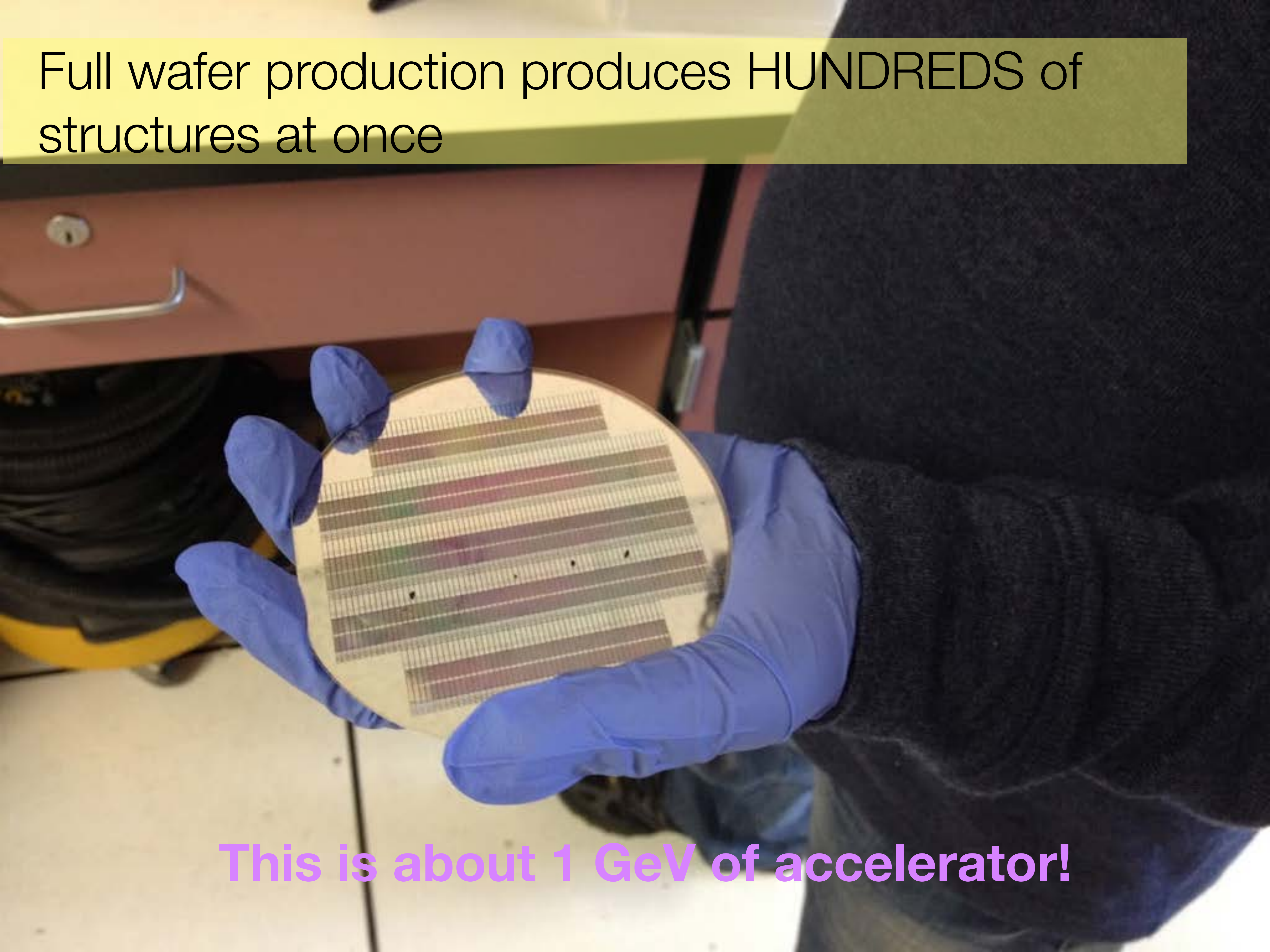
PURDUE
UNIVERSITY

SLAC
NATIONAL ACCELERATOR LABORATORY

TECH-X

PennState

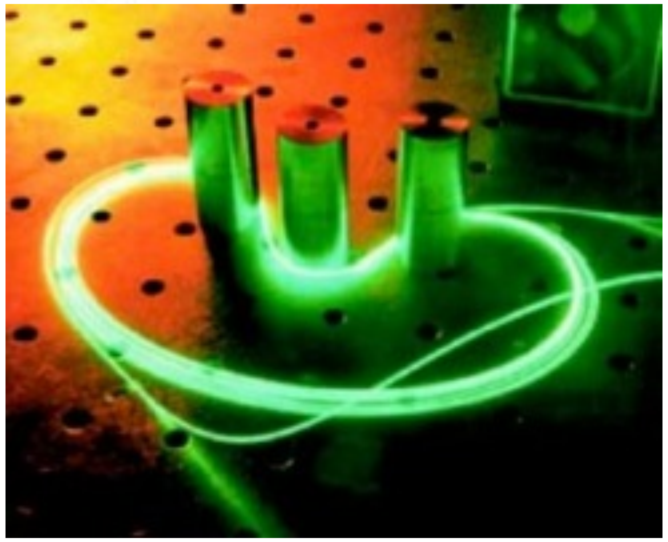
Full wafer production produces HUNDREDS of structures at once



This is about 1 GeV of accelerator!

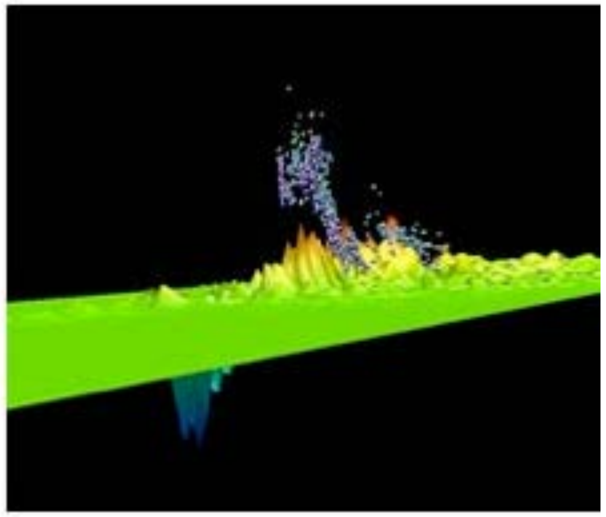
These Dielectric Laser Accelerators (DLAs) leverage key technical developments

LASERS



MICROFAB

SIMULATIONS



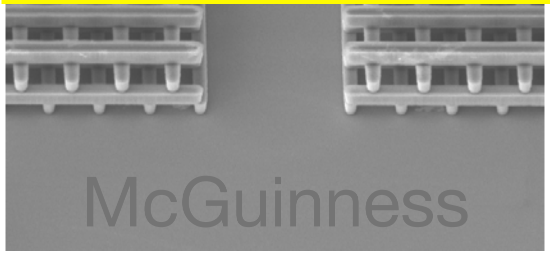
Technology match; not size or gradient specs

The choice of accelerator technology impacts the and nature of the beam produced

Breakdown limits metal:

$$E_s = 220(f[\mathrm{GHz}])^{1/3}\ \mathrm{MV/m}$$

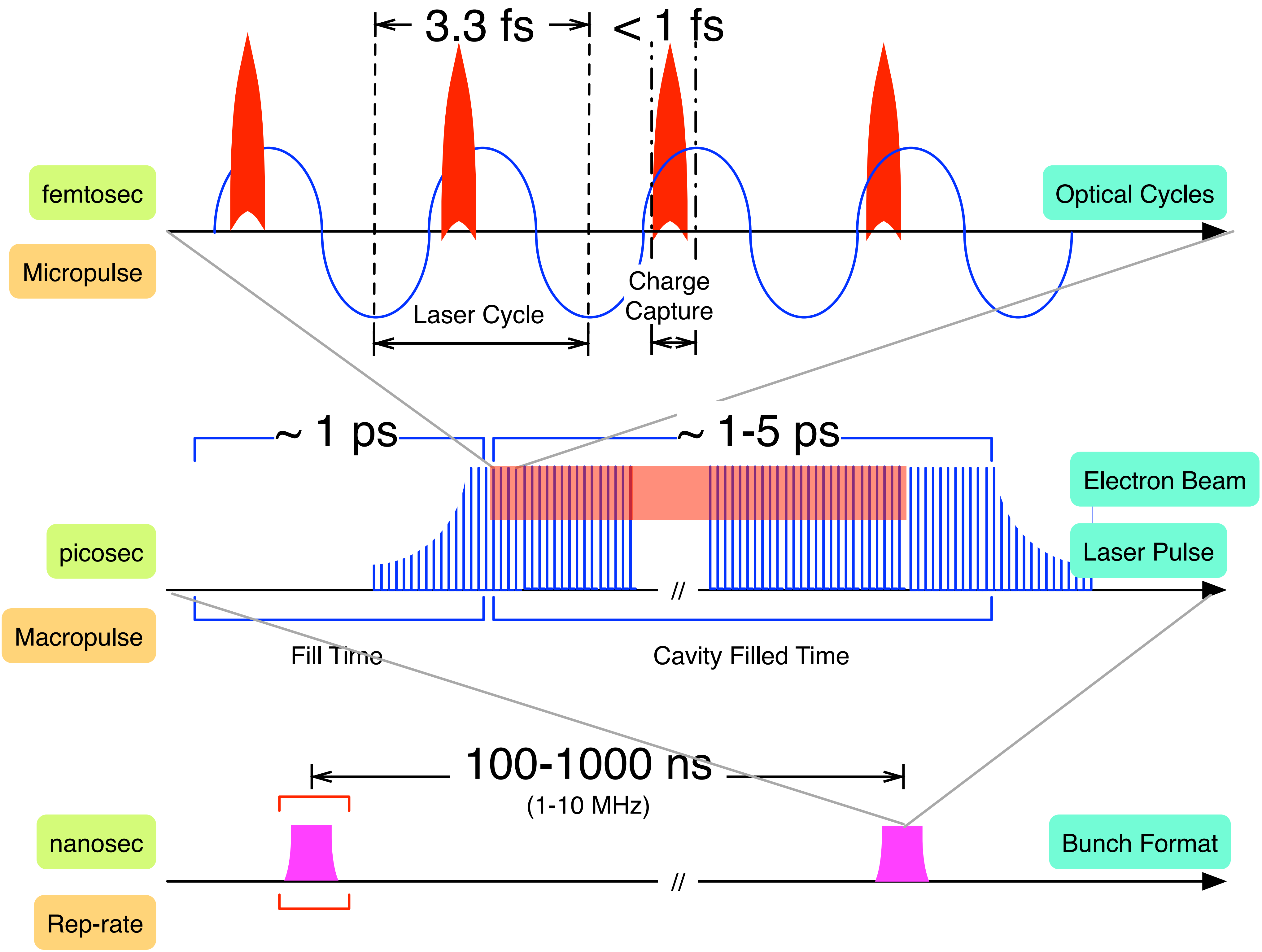
$E_{acc} \sim P_{rf}/\lambda$



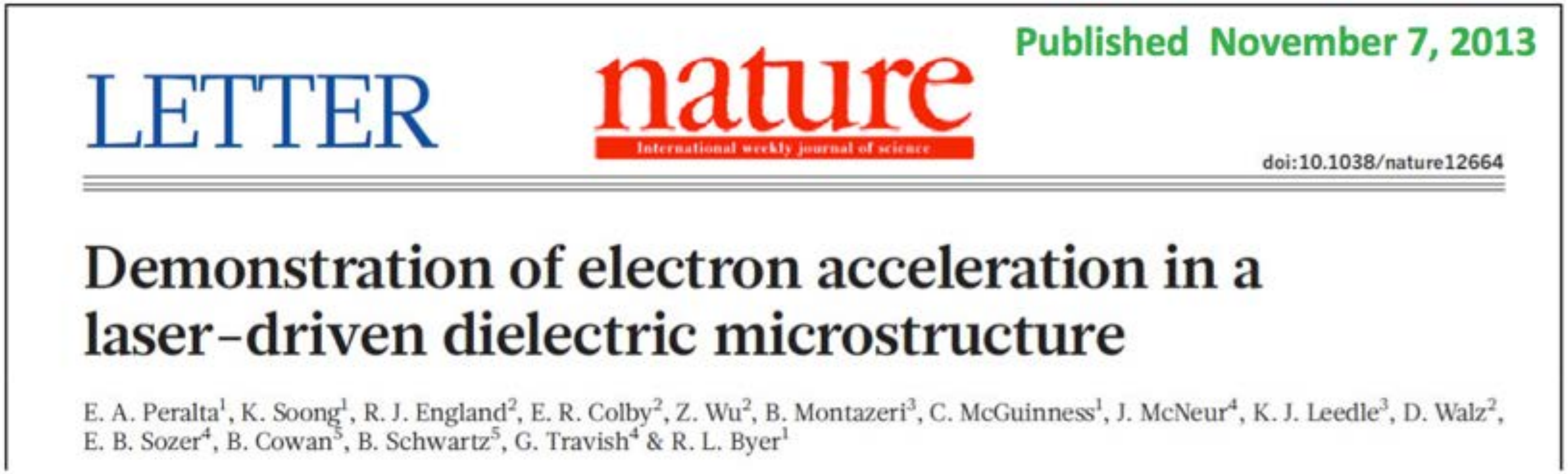
	RF	Optical
Gradient	10-100 MeV/m	**1-10 GeV/m**
Energy gain per period	1 MeV	**1 keV**
Repetition Rate	100 Hz	**10-100 MHz**
Charge per Bunch	0.01 - 1+ nC	0.01-1 pC
Bunch Length	1-100 ps	0.1-1 fs

key: charge and time scale; not gradient

Optical structures naturally have sub-fs time scales and favor high repetition rate operation



Recent results no longer make DLA-based schemes seen so far off



LETTER

nature

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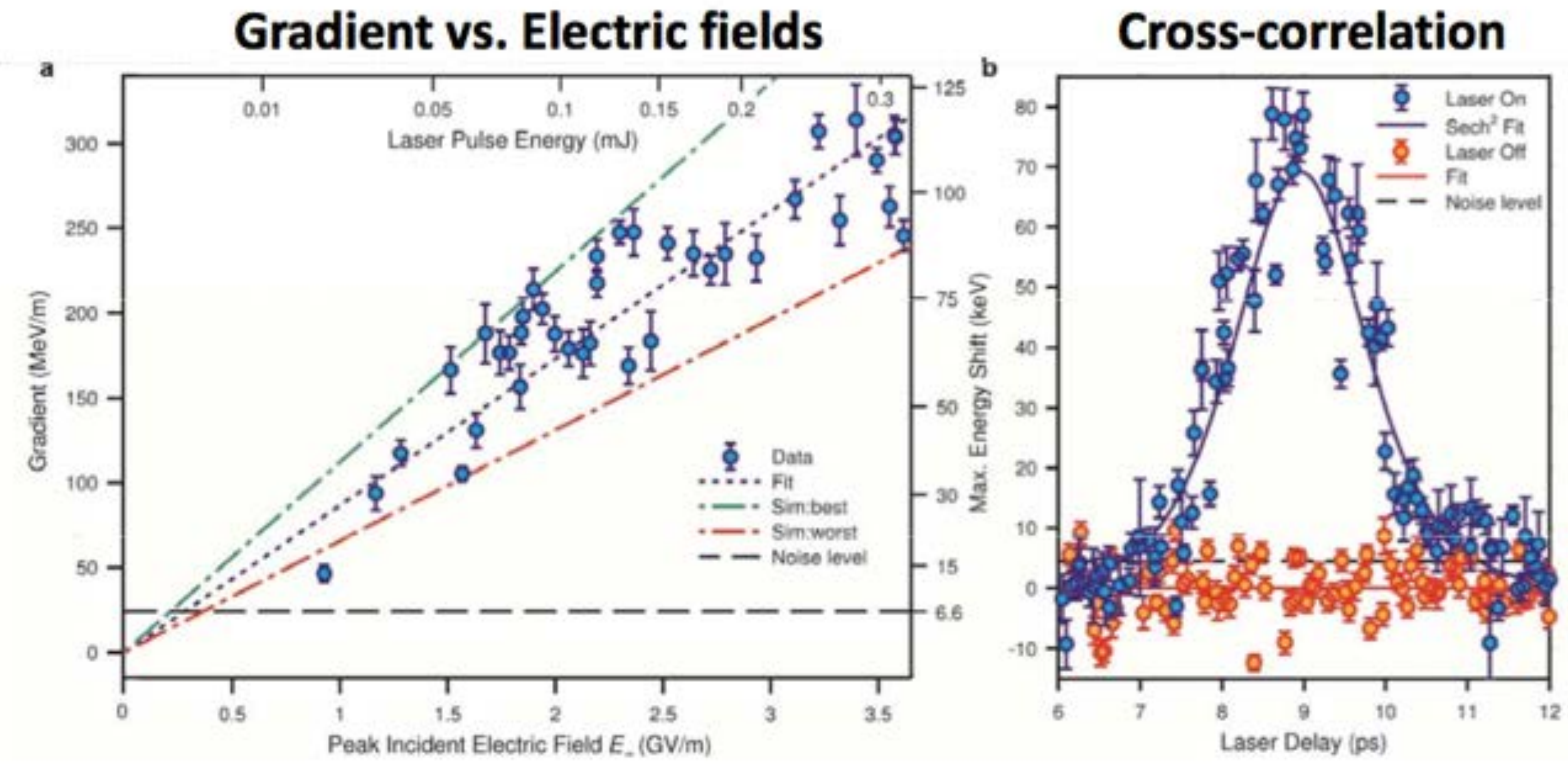
Demonstration of electron acceleration in a laser-driven dielectric microstructure

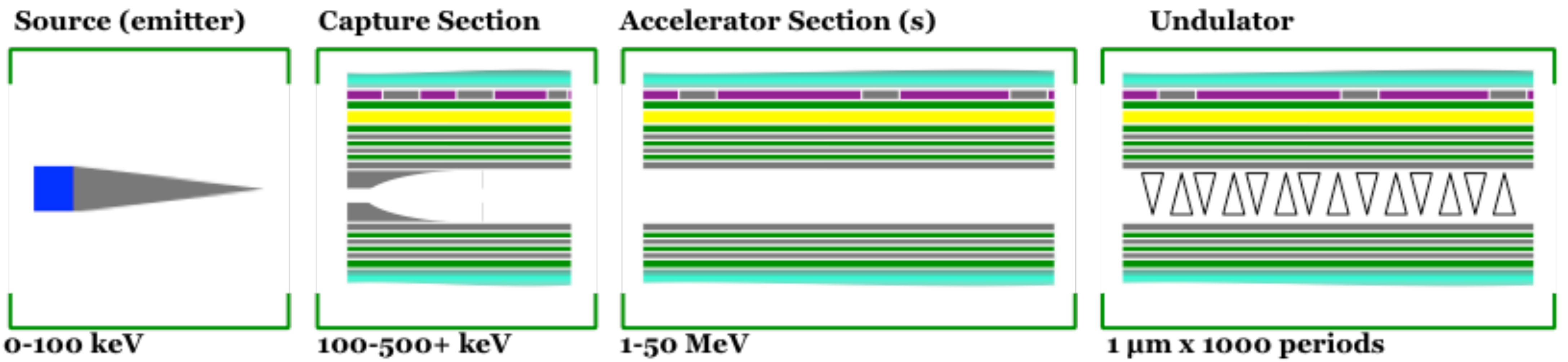
E. A. Peralta[1], K. Soong[1], R. J. England[2], E. R. Colby[2], Z. Wu[2], B. Montazeri[3], C. McGuinness[1], J. McNeur[4], K. J. Leedle[3], D. Walz[2], E. B. Sozer[4], B. Cowan[5], B. Schwartz[5], G. Travish[4] & R. L. Byer[1]



Gradient vs. Electric fields

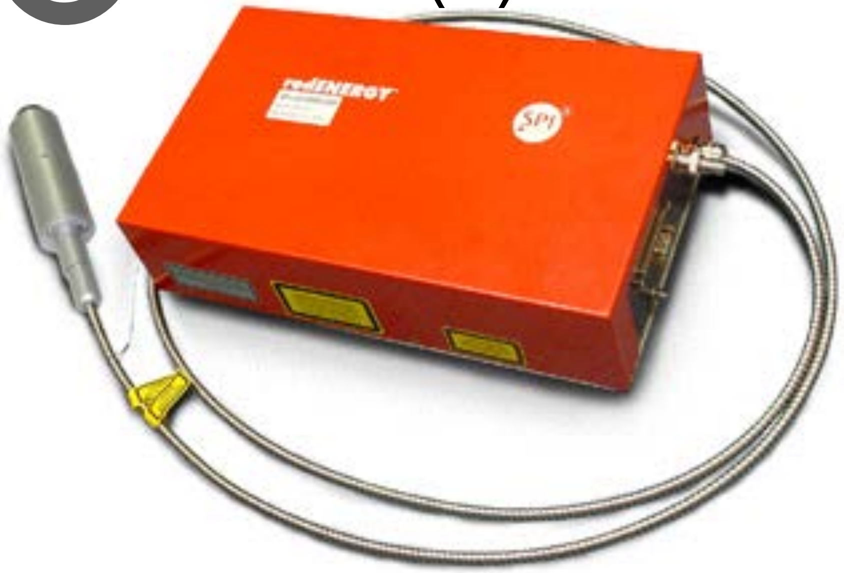
Cross-correlation

DLAs require an ecosystem of components and devices to produce usable beams



❶ ❷ ❸ ❹

❺ laser(s)



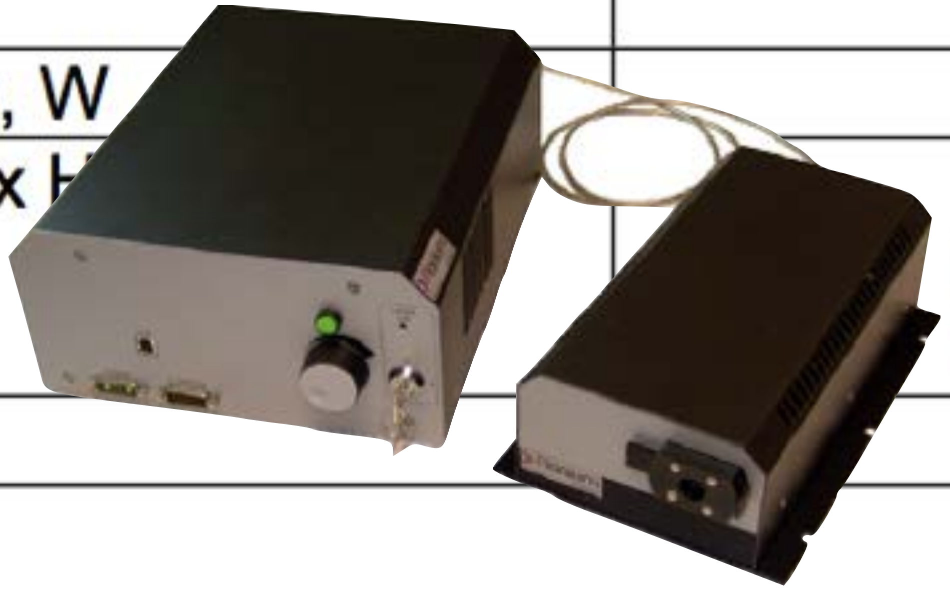
❻ other components (optics, diagnostics, etc.)

The Laser

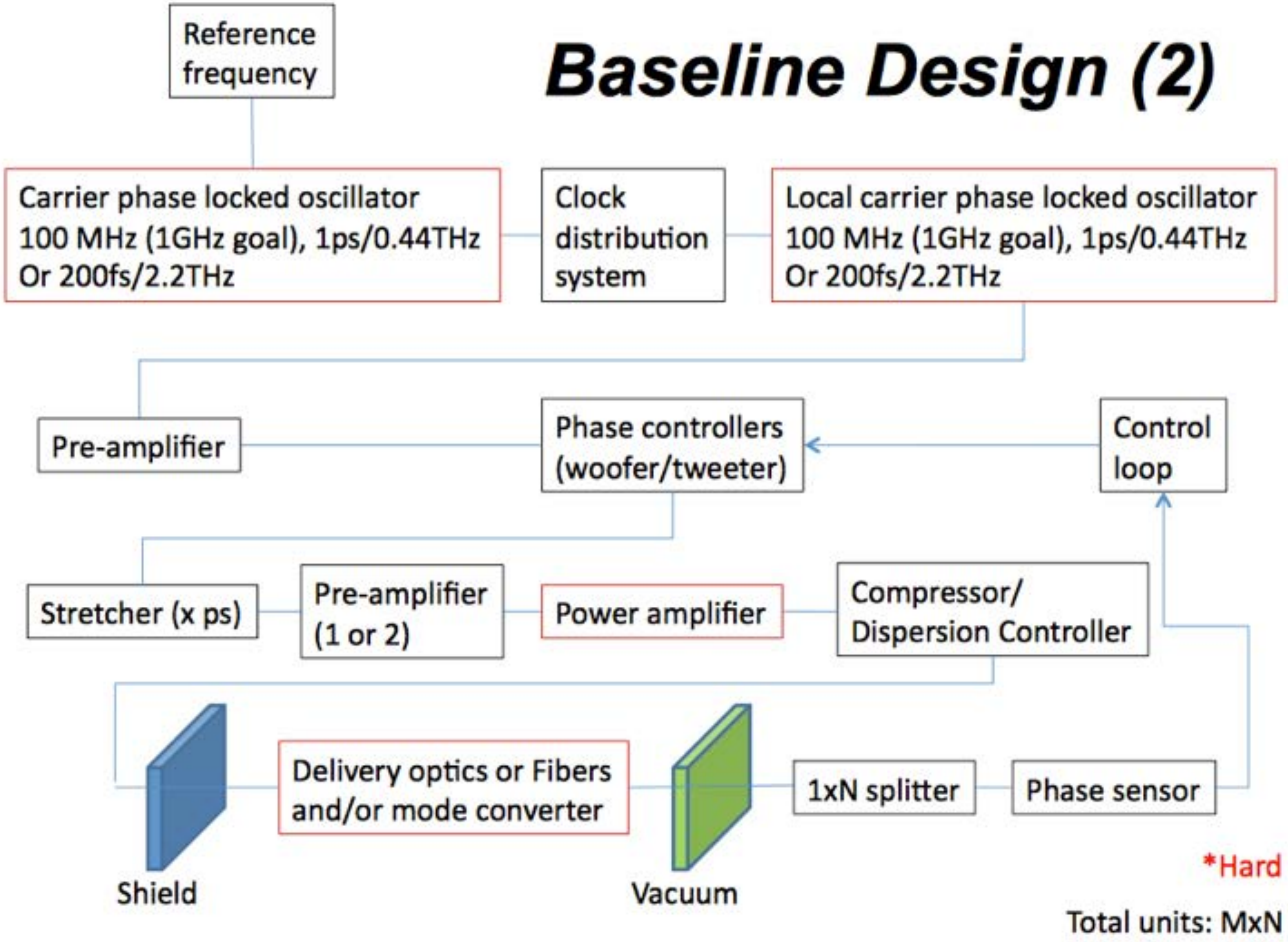
❺

Fiber lasers are ideally suited to DLAs because of their high repetition rates and moderate pulse lengths

Product characteristics	**FemtoPower1064-5s-pp**
Output wavelength, nm	1064
Average output power, W	5 (at 5 MHz)
Pulsewidth, ps	<1
Repetition rate, MHz	1 MHz – 20 MHz
Spectral width, nm	10
RMS amplitude noise, %	1
Long term power stability, %	2
Output beam quality, M^2	<1.5
Beam diameter, mm	1.5
Polarization	Linear
Power consumption, W	<100
Dimensions (W x L x H	
Laser	300x250x120
Optical Head	270x180x85
Weight (kg)	8



Of course a realistic system has to account for power distribution, reflections, etc.



Baseline Design (2)

Reference frequency

Carrier phase locked oscillator
100 MHz (1GHz goal), 1ps/0.44THz
Or 200fs/2.2THz

Clock distribution system

Local carrier phase locked oscillator
100 MHz (1GHz goal), 1ps/0.44THz
Or 200fs/2.2THz

Pre-amplifier

Phase controllers (woofer/tweeter)

Control loop

Stretcher (x ps)

Pre-amplifier (1 or 2)

Power amplifier

Compressor/ Dispersion Controller

Delivery optics or Fibers and/or mode converter

1xN splitter

Phase sensor

*Hard

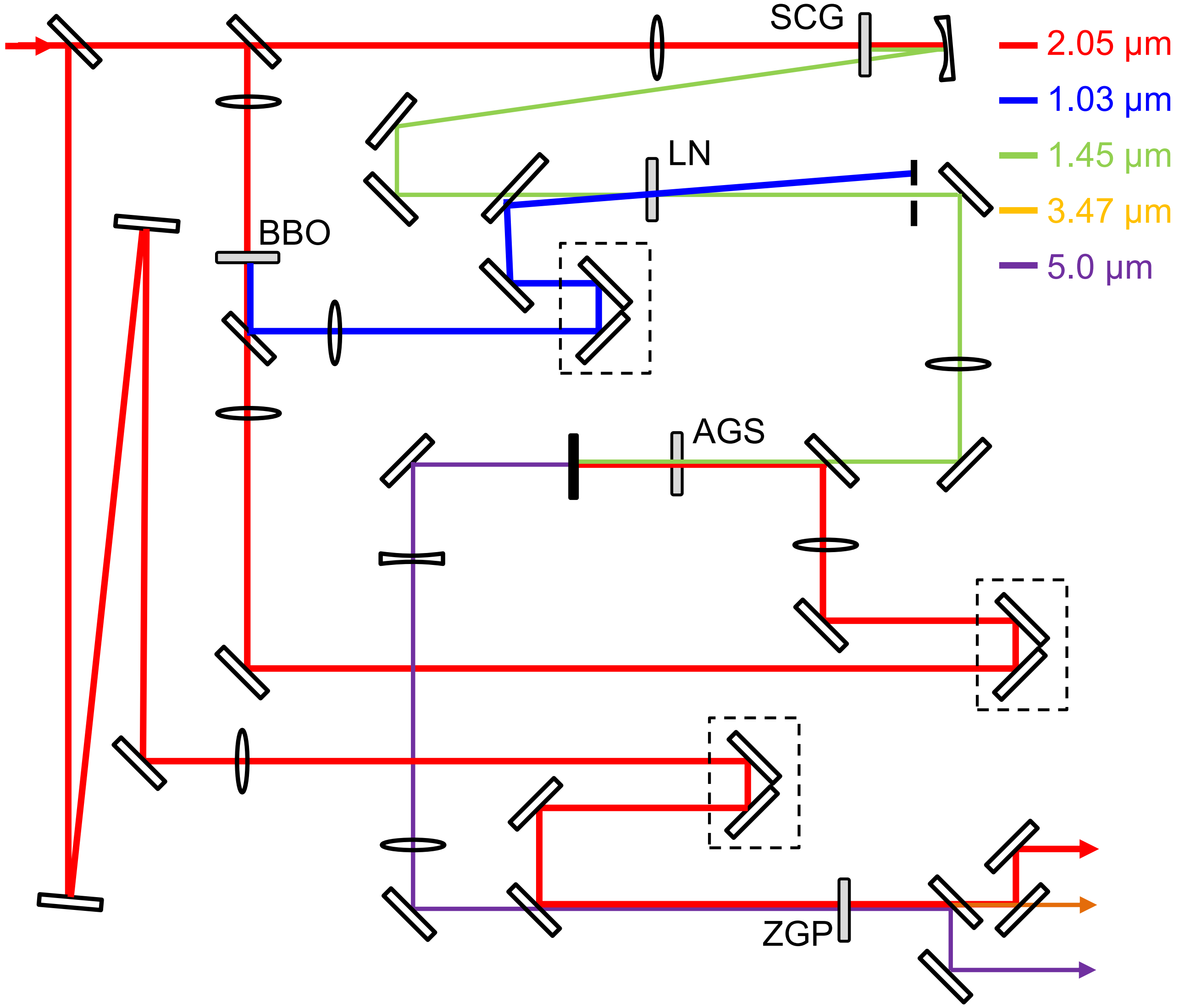
Total units: MxN

DLA-2011 Laser Working Group, Jay Dawson & Bob Byer

Wide availability, especially at test facilities, favors 800nm/1µm operating wavelengths, but…

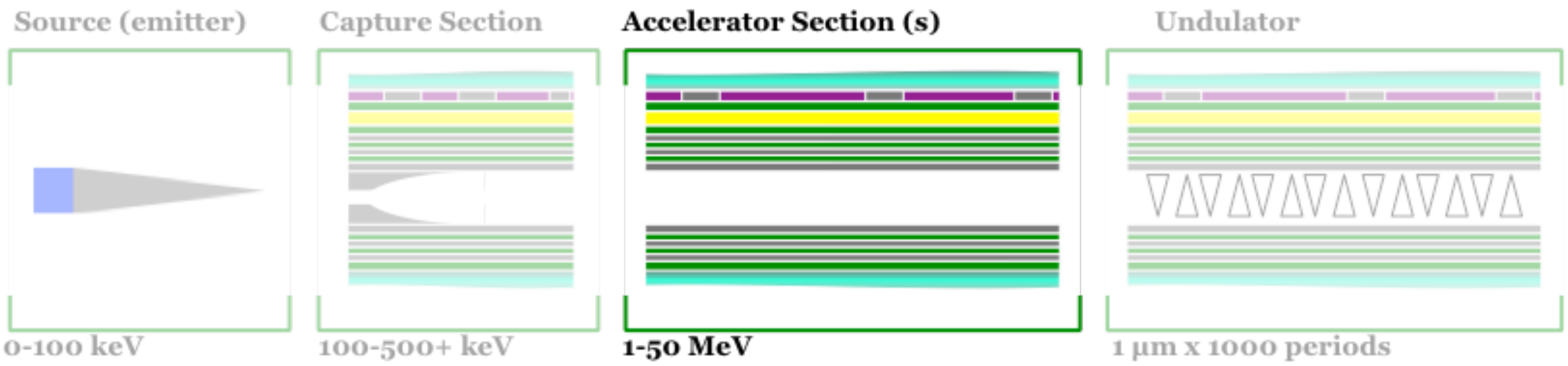
Material maximum fluence (~2J/cm^2 @ 100fs)
and structure geometry
imply **gradients < 10 GV/m (more like 1 GV/m)**

but you can
do better at 2µm
and even better
at 5µm (maybe)



I. Jovanovic
Carrier-envelope phase stabilized 5-µm OPA

Accelerator Module ❸



Source (emitter)

0-100 keV

Capture Section

100-500+ keV

Accelerator Section (s)

1-50 MeV

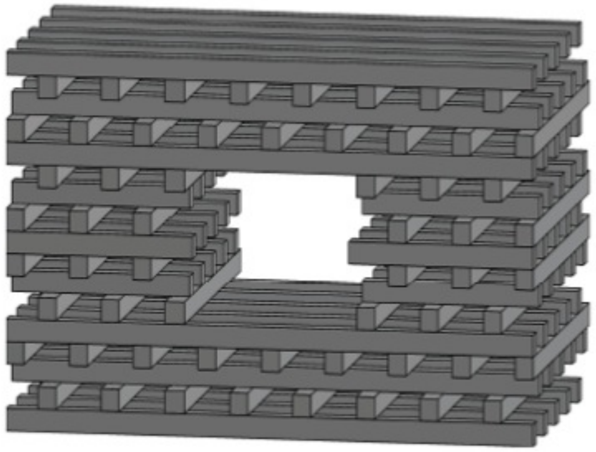
Undulator

1 µm x 1000 periods

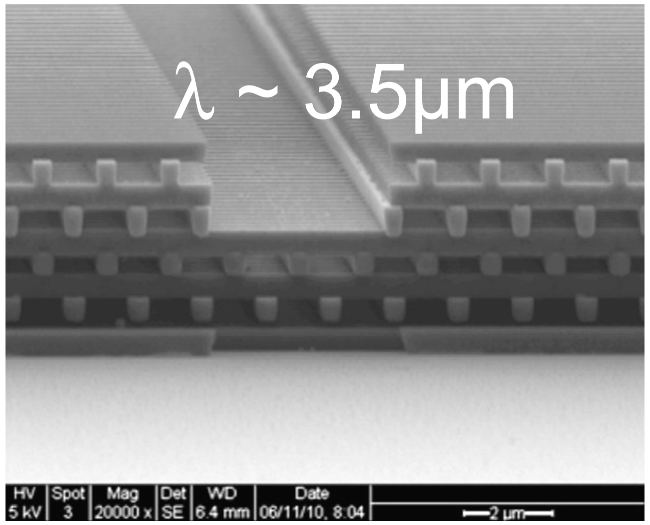
A variety of optical-scale dielectric structures are under consideration

3D

image courtesy B. Cowan

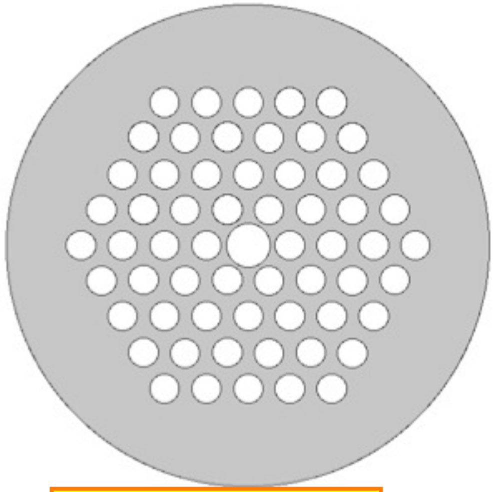


C. McGuinness

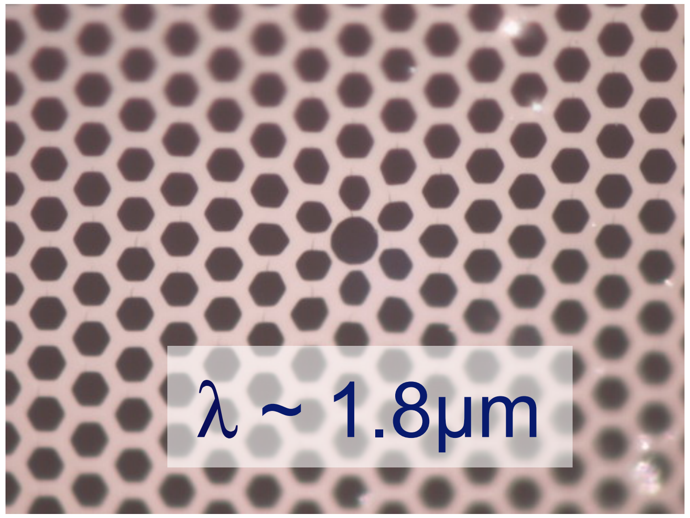


"woodpile" silicon photonic crystal (C. McGuinness)

2D



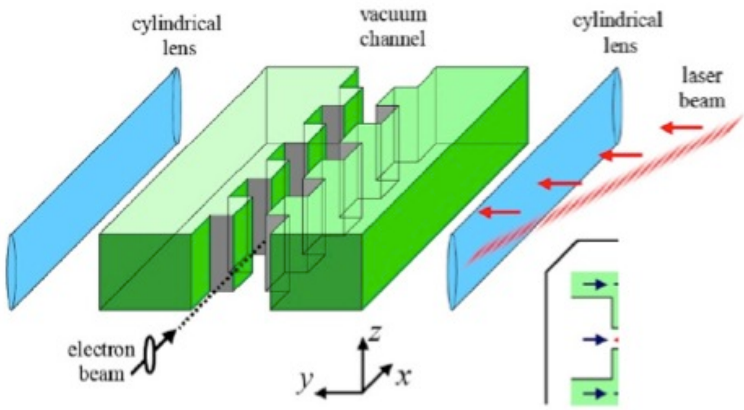
J. Spencer



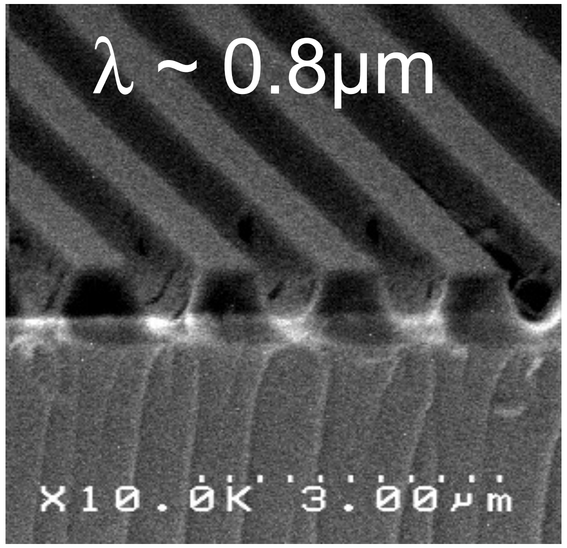
photonic crystal borosilicate fibers (J. Spencer/Incom Inc)

1D

img courtesy T. Plettner



E. Peralta

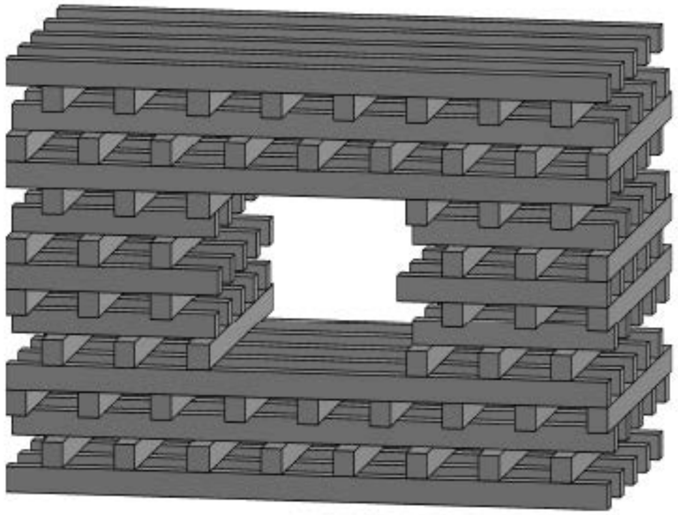


dual silica grating accelerator (E. Peralta)

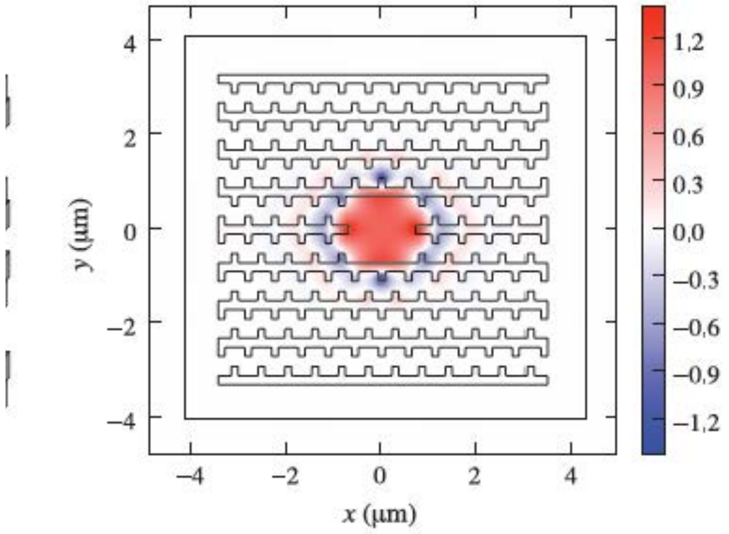
J. England

The woodpile structure offers intermediate gradients with monolithic fabrication possibilities

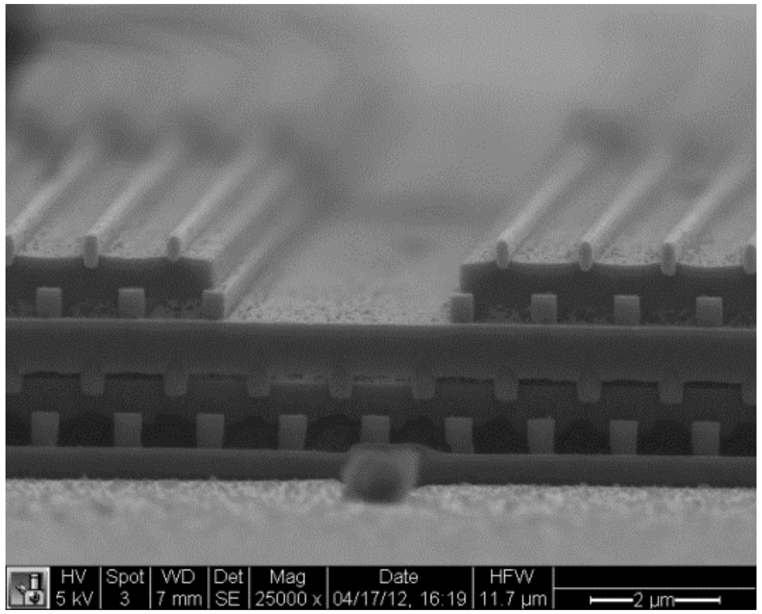
simulation of accelerating mode



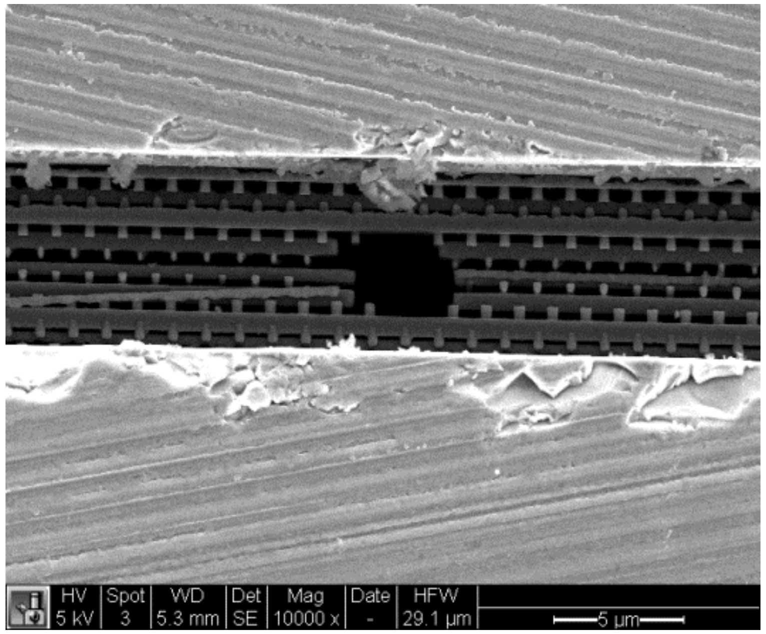
max gradient ~ 400 MV/m

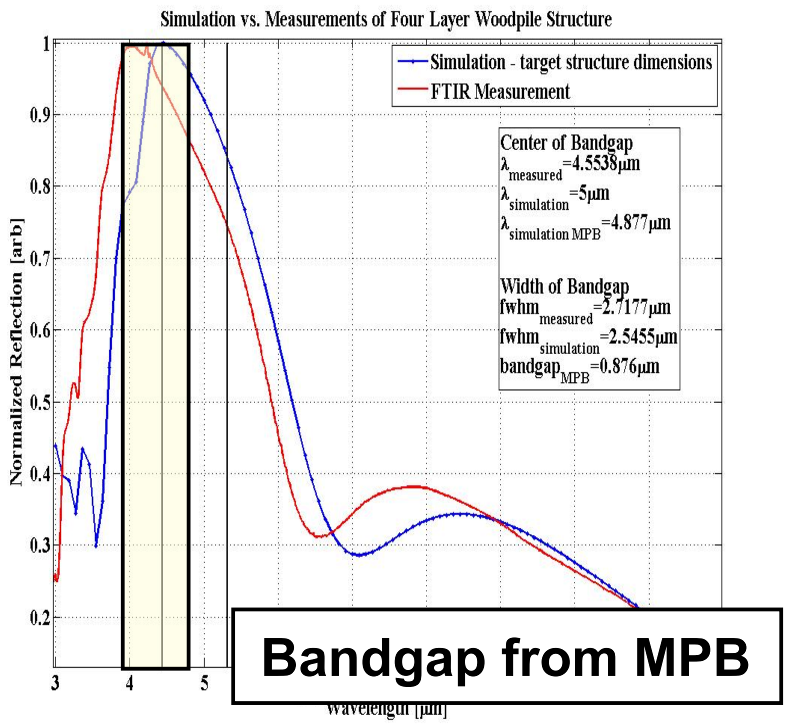


B. Cowan, Tech-X



images courtesy of C. McGuinness

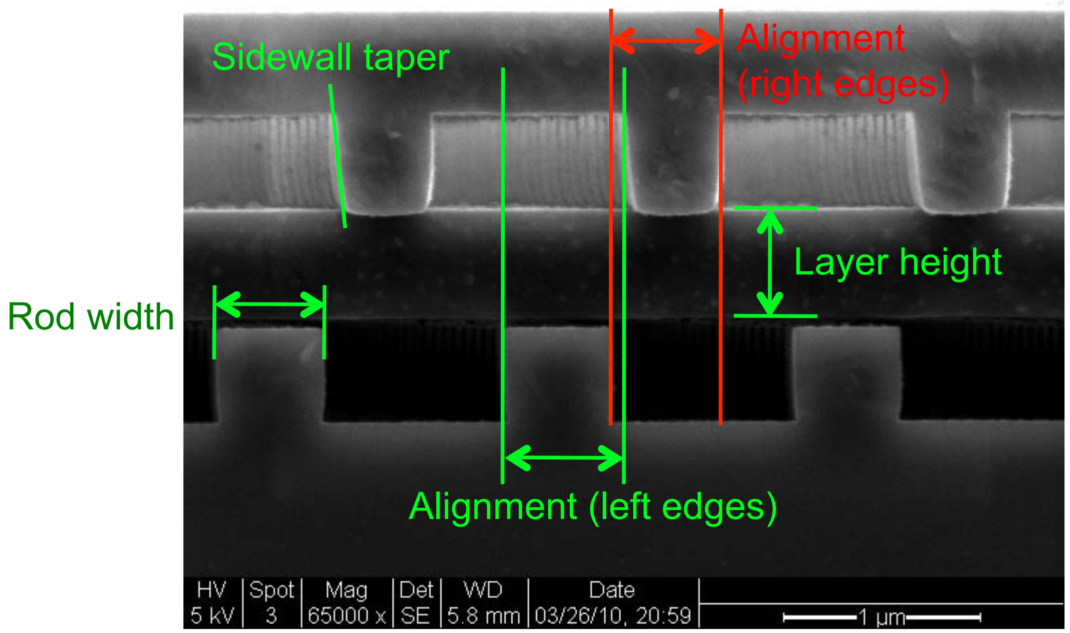




17-layer structure built with ~400nm "logs" by photolithography
Suitable for 3.5 μm wavelength drive laser (Ti:Saph laser + OPA)

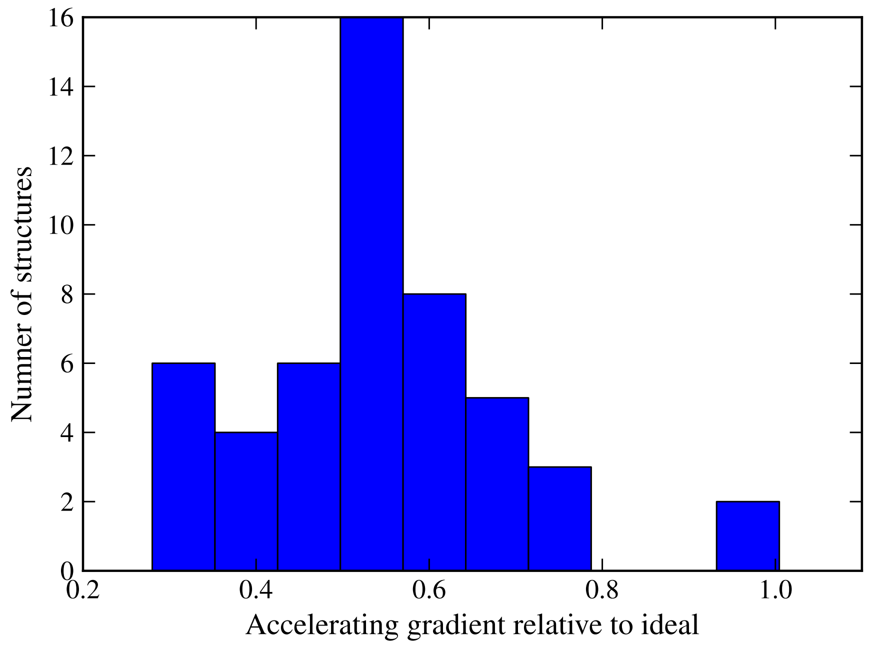
J. England

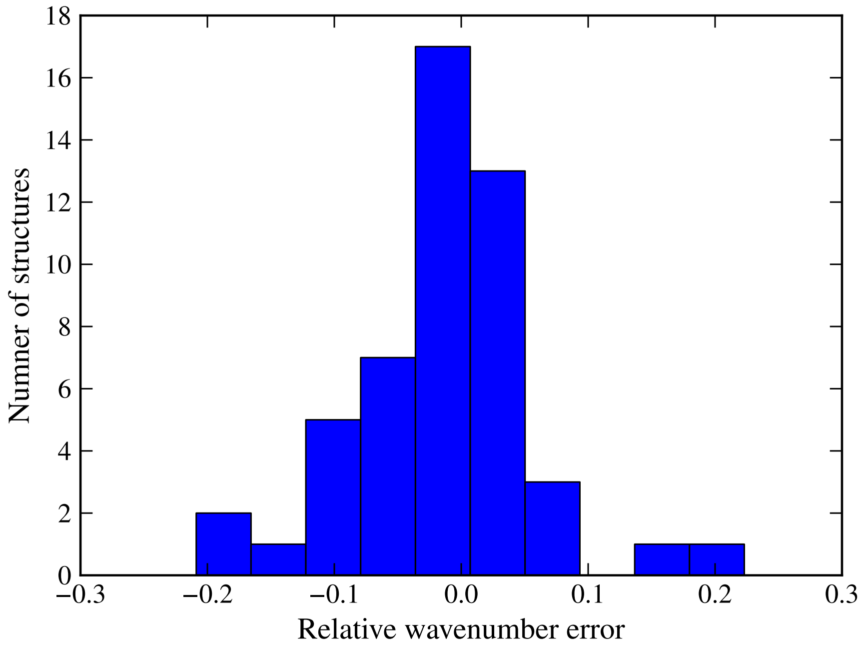
Realistic and rigorous error estimates can be performed using metrology from fabricated structures



Fabrication error parameters

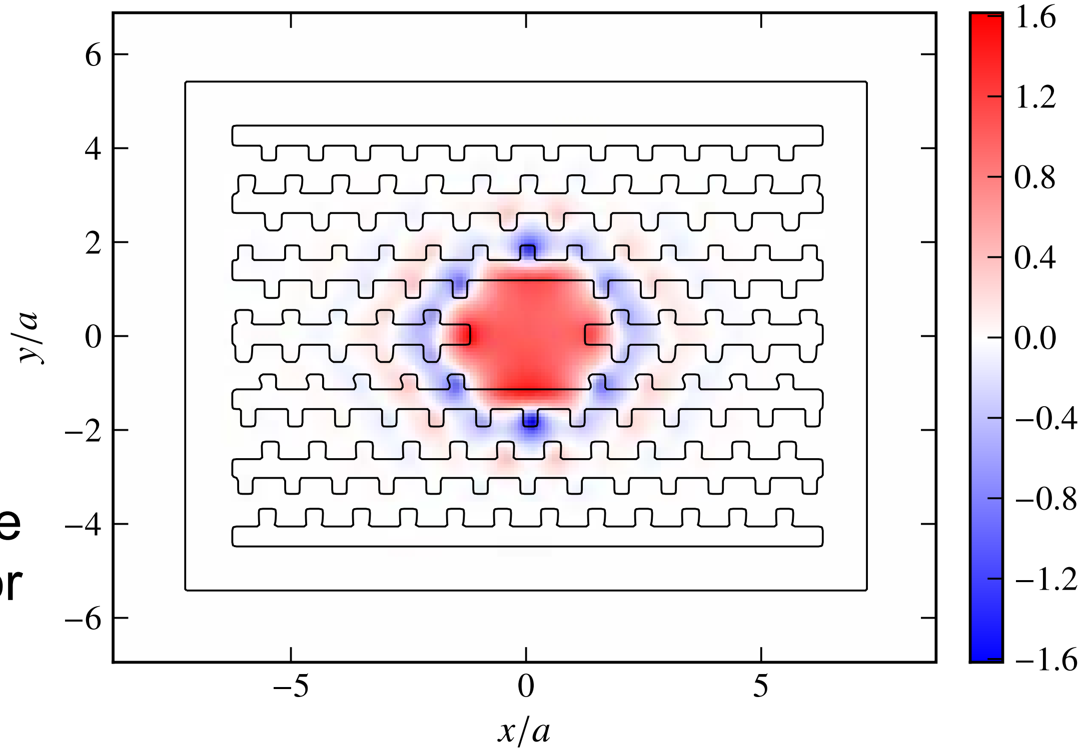
Accelerating gradients of structures with error





Phase velocity errors

Fields in structure with fabrication error



the benefit of simulations in the loop

B. Cowan

The fiber accelerator has been pulled and is undergoing testing

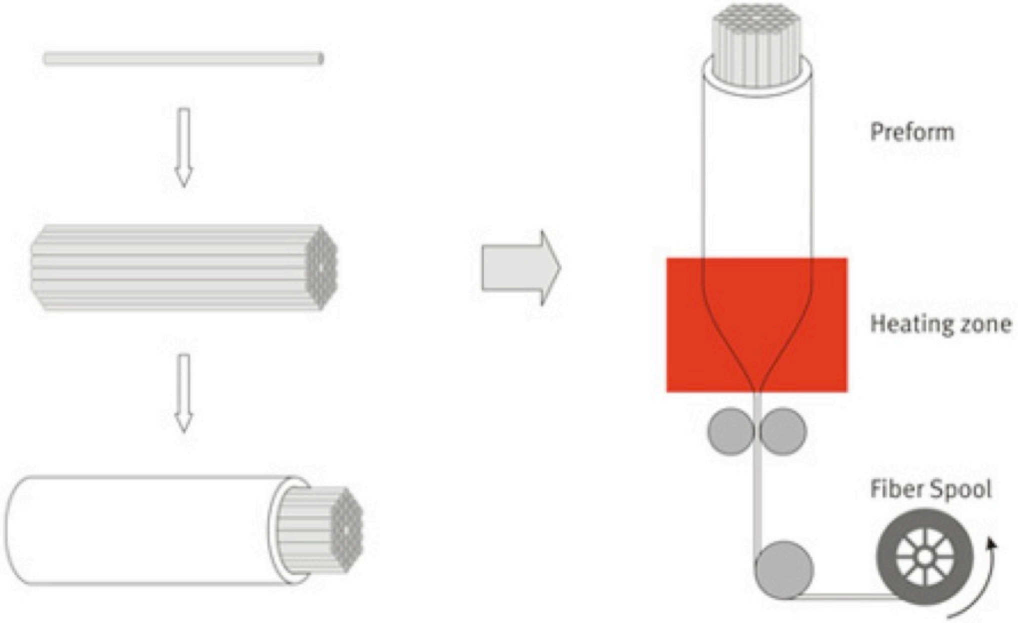
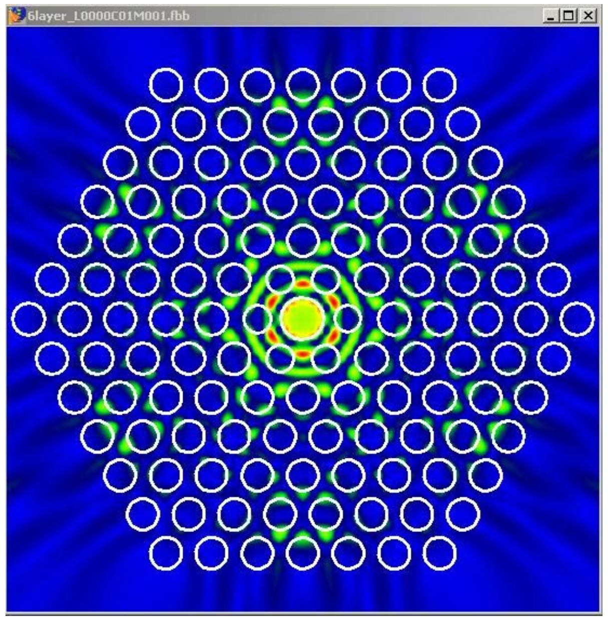


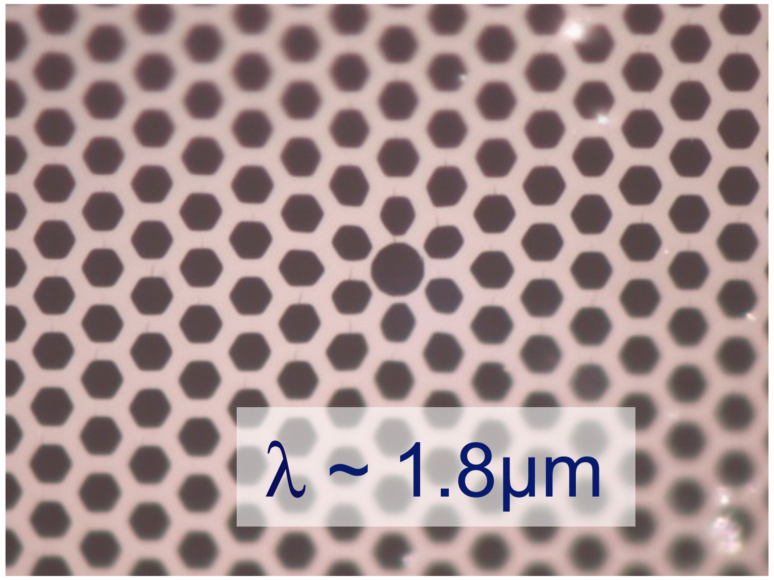
Image Attribution: Crystal-Fibre, Inc.

Example CUDOS mode

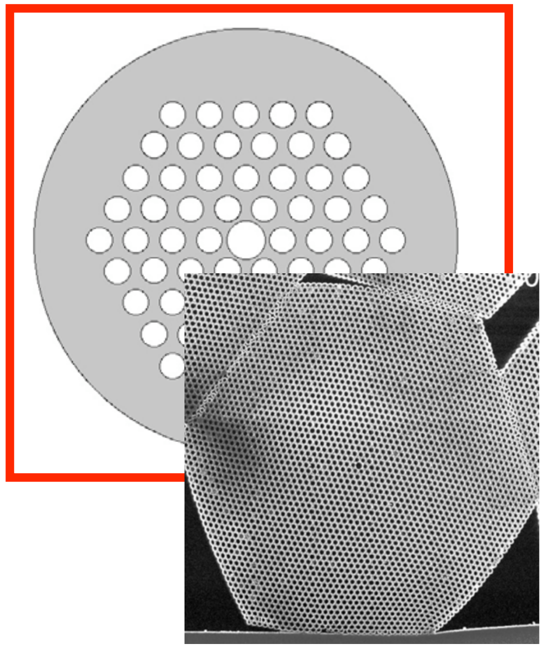


B. Noble, J. Spencer

central hole is beam channel and accelerating mode guide



borosilicate PBG fiber prototype, via SBIR with Incom Inc.



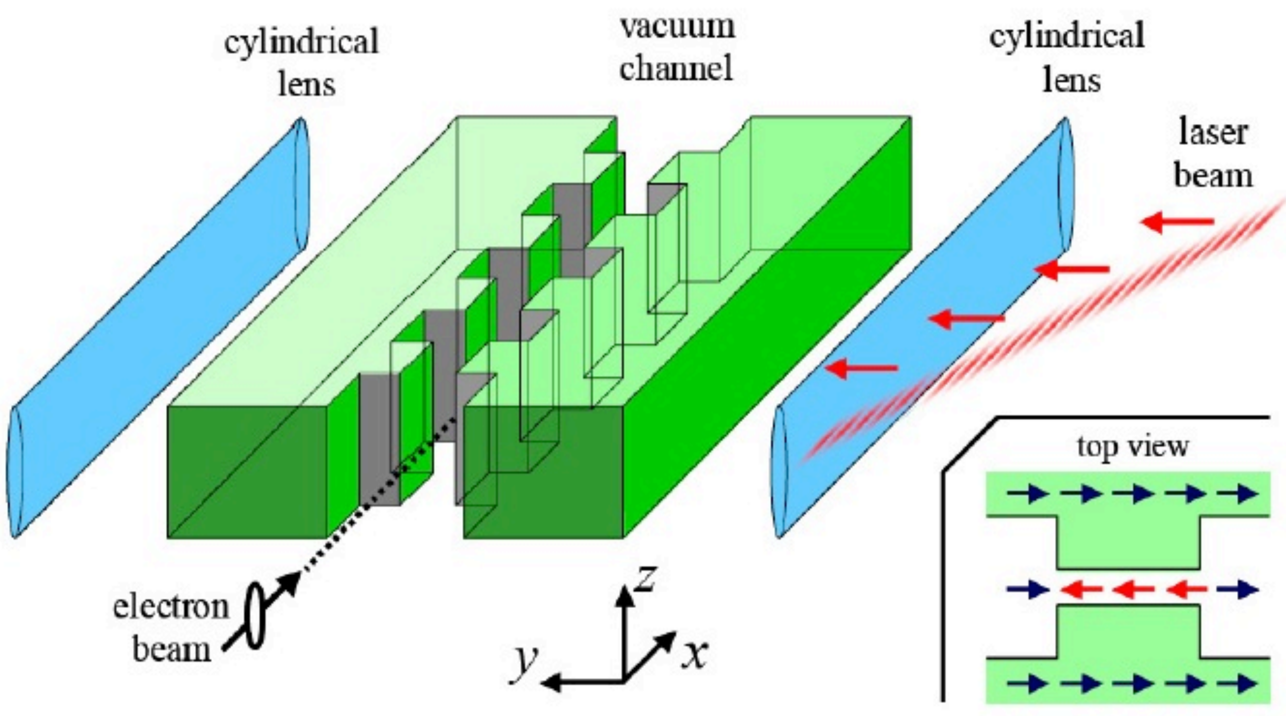
PBG fiber with central defect aperture ~ 0.68 λ; G_0 ~ 2.5 GV/m

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

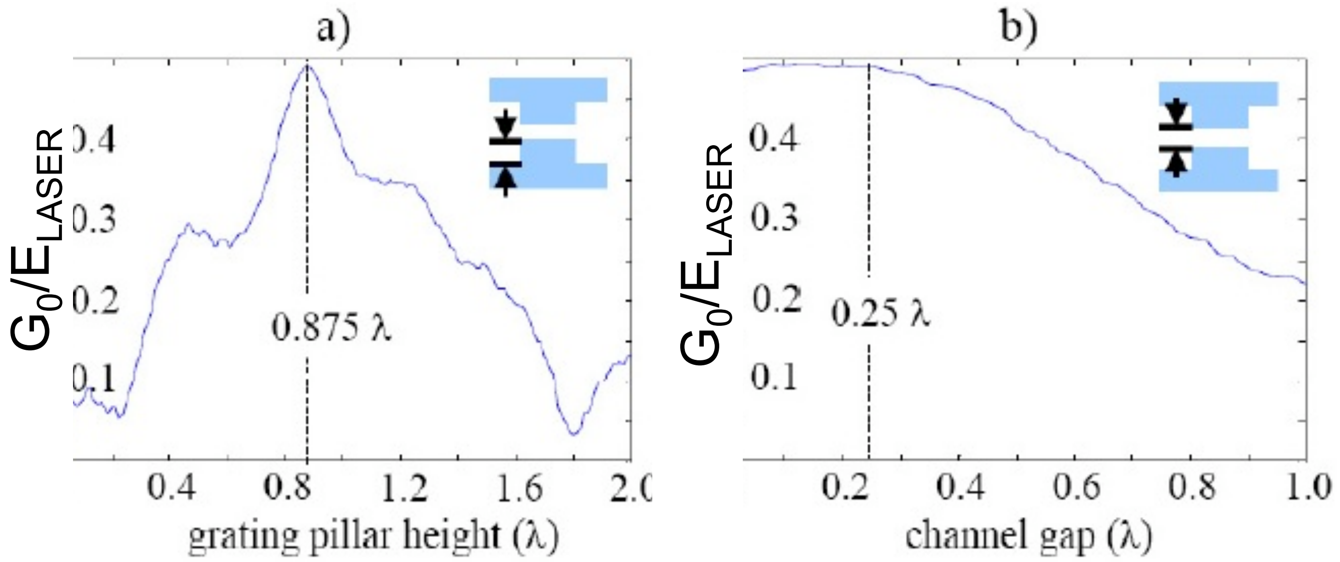
fabrication from optical communication world

J. England

The grating structure can offer very high gradients, planar geometry, easy coupling and simple fabrication



T. Plettner, et al. PRST-AB **9**, 111301 (2006).

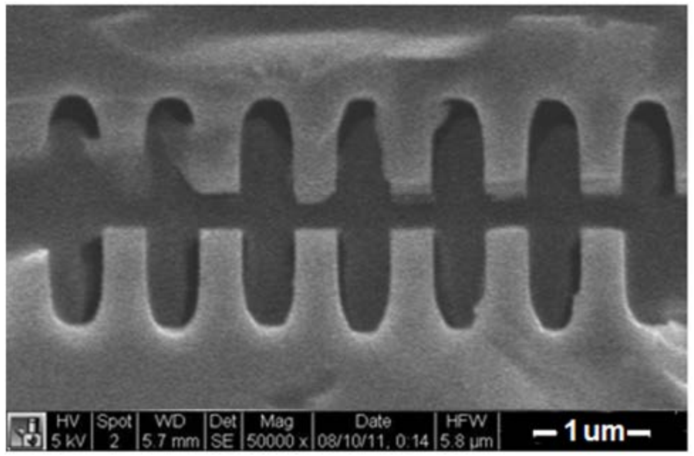


SiO_2 planar gratings with side-coupled laser and flat beam.

Periodic phase reset of the EM field results in a large accelerating gradient over many periods.

damage threshold for SiO_2 >3 GV/m @ 1ps

$G_{0,max}$ ~ 1GV/m



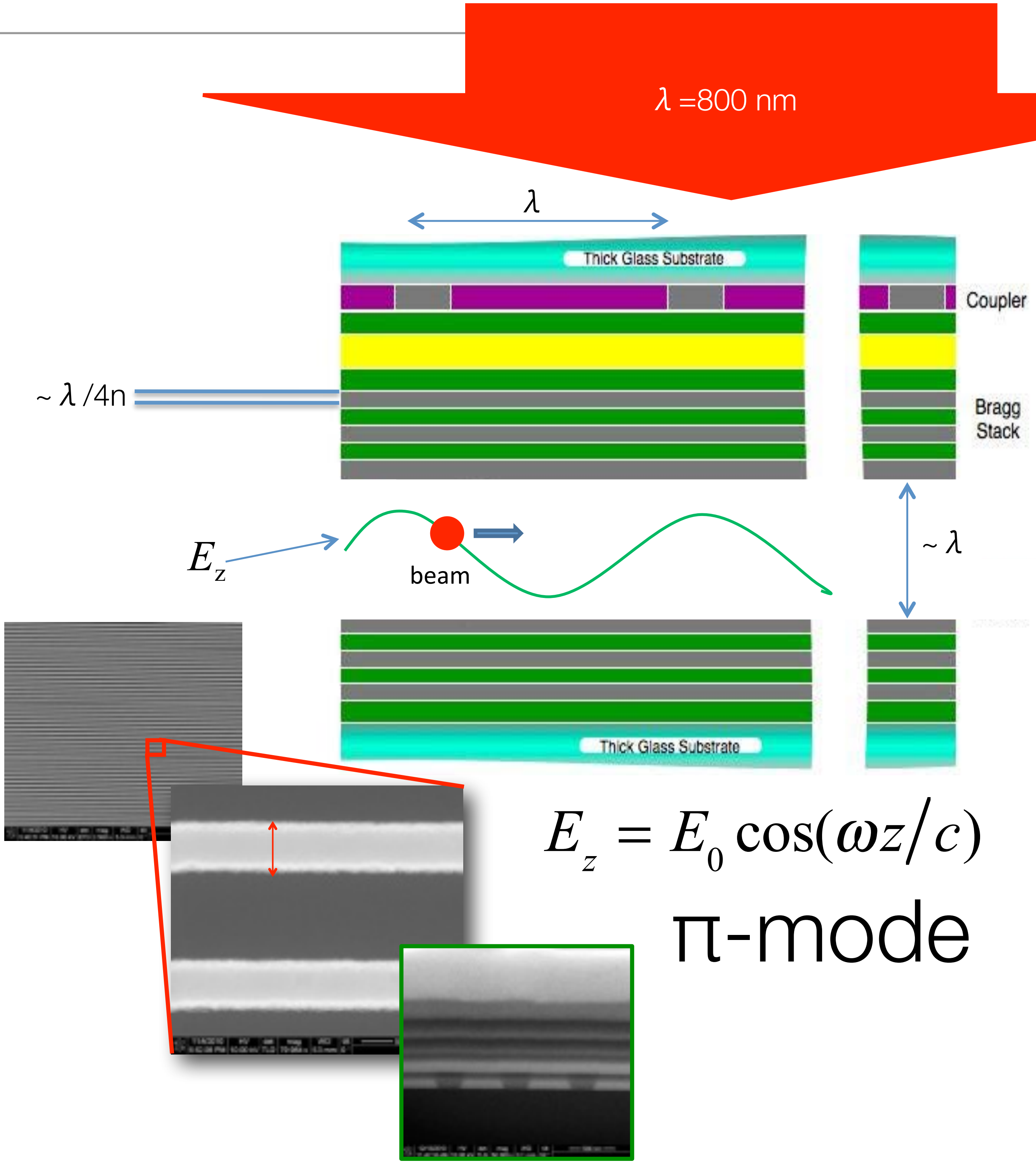
E. Peralta, recently fabricated prototype structure

J. England

The MAP is a moderate-Q structure which matches well with existing laser technology

Micro
Accelerator
Platform

Parameter	Value
Laser wavelength	800nm
Cell length	800nm
Effective gradient	~1 GeV/m
Quality factor Q	**800**
Power dissipation	<1% (0.75 MW)
Fill time	**0.5 ps**
Laser intensity	100 MW
Laser pulse length	~3-5 ps
Energy gain per unit cell	~1keV



$$E_z = E_0 \cos(\omega z/c)$$

π-mode

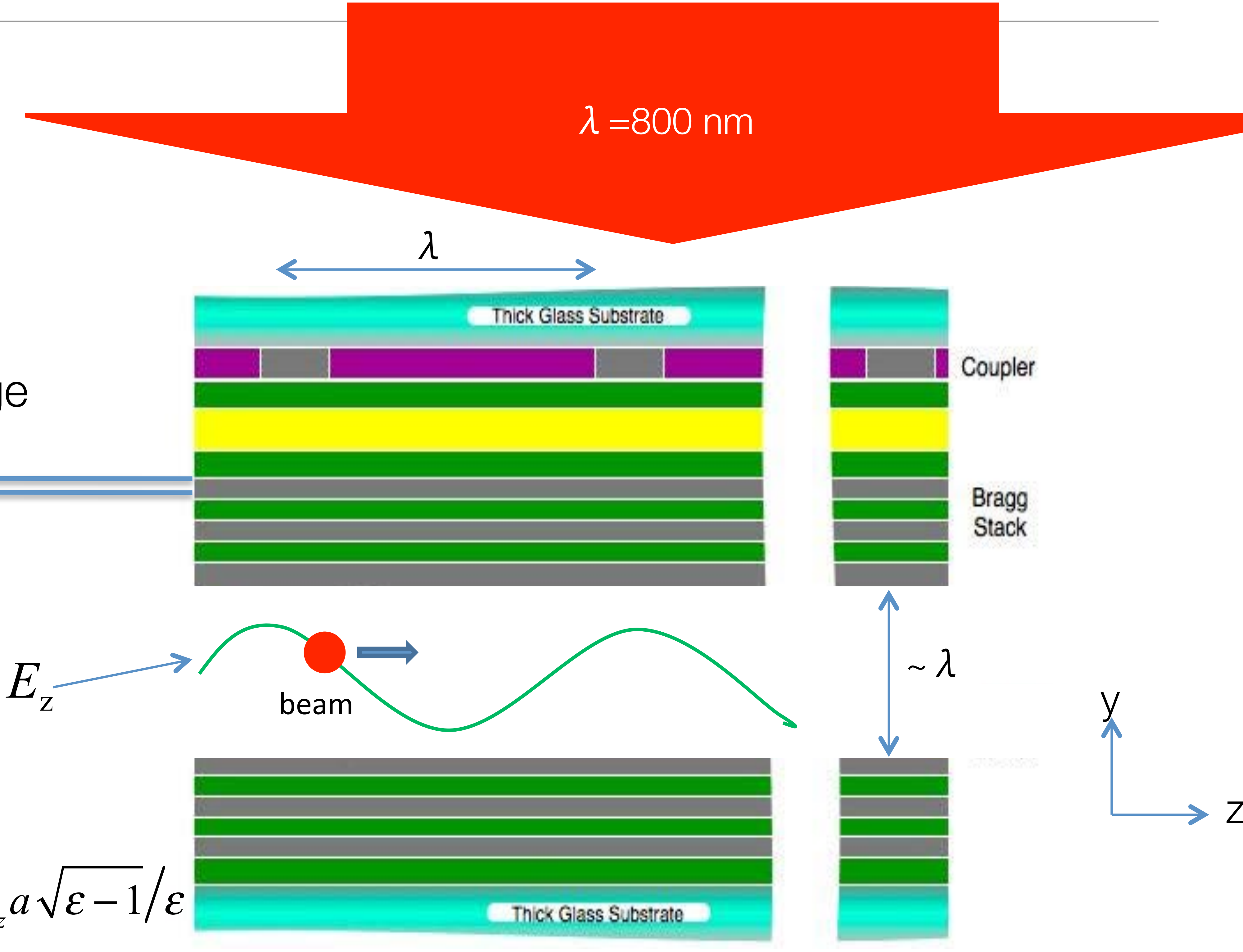
smooth walls reduce wakes

flat beams reduce space charge

The basic structure consists of a diffractive coupling structure and a **resonator**

Micro
Accelerator
Platform

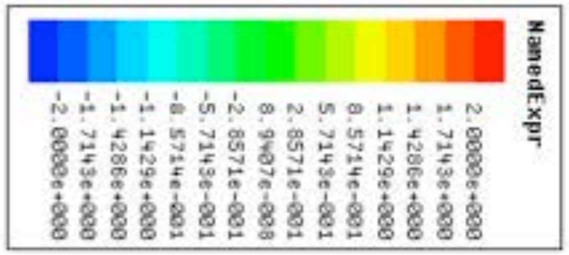
smooth walls
reduce wakes
flat beams
reduce space charge

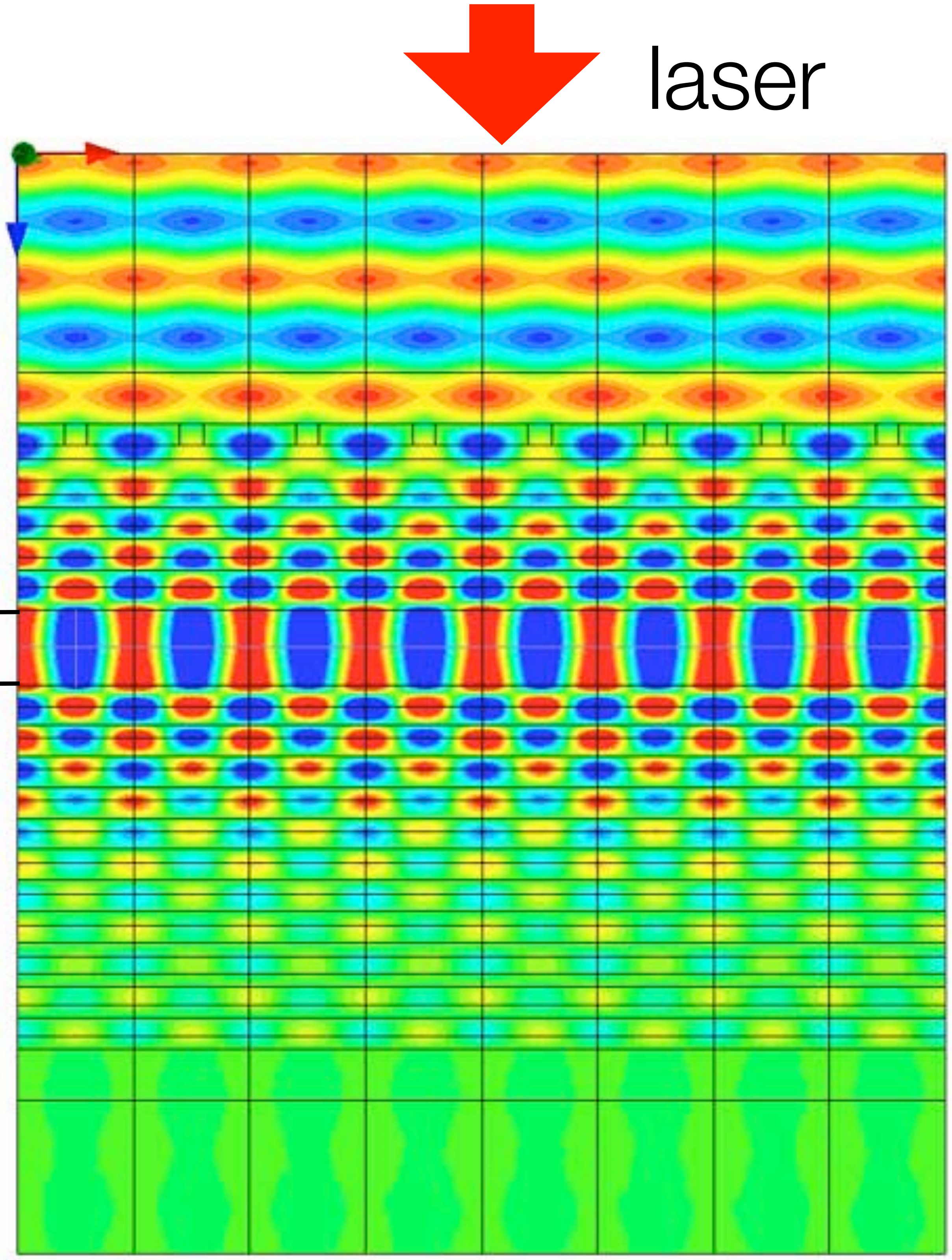


For gap *a* and dielectric *b-a* idealized resonance:

$$\cot\left[k_z\sqrt{\varepsilon-1}\left(b-a\right)\right]=k_z a\sqrt{\varepsilon-1}/\varepsilon$$

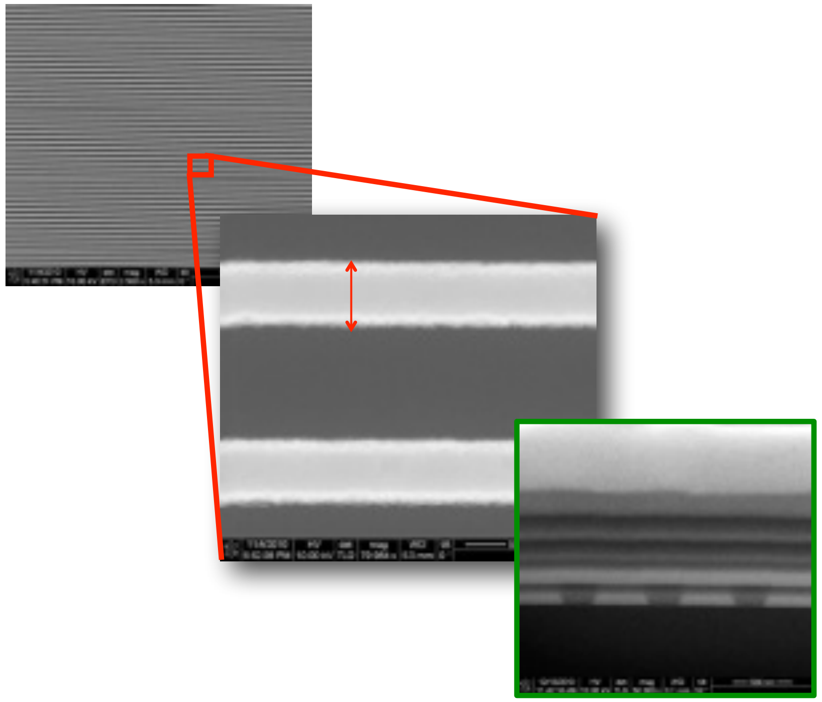
The design of the relativistic structure is mature and includes realistic material properties.





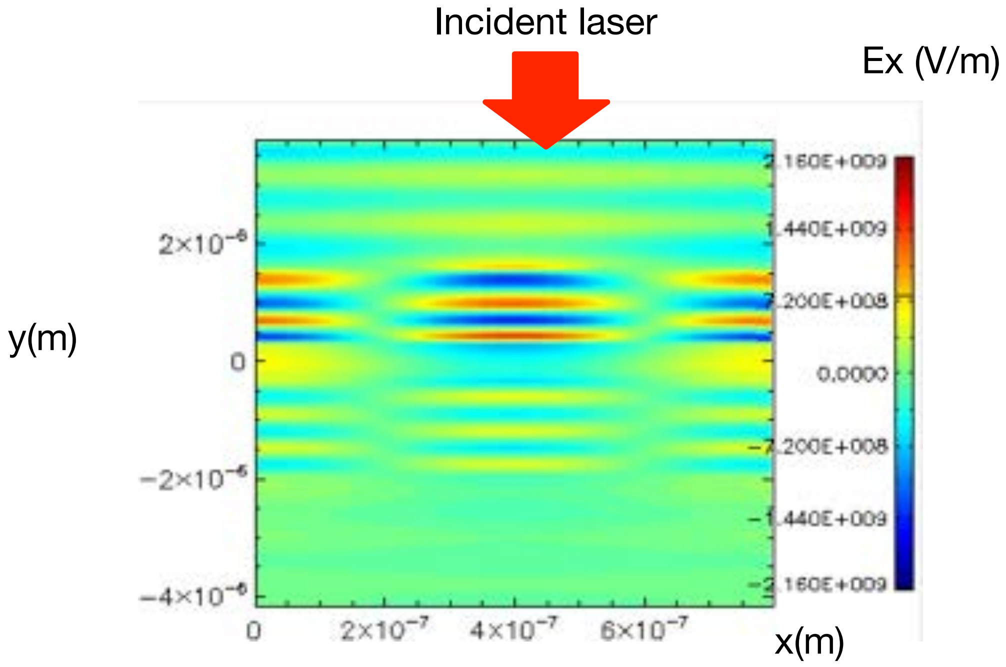
$$E_z = E_0 \cos(\omega z/c)$$

gap (1 optical wavelength)



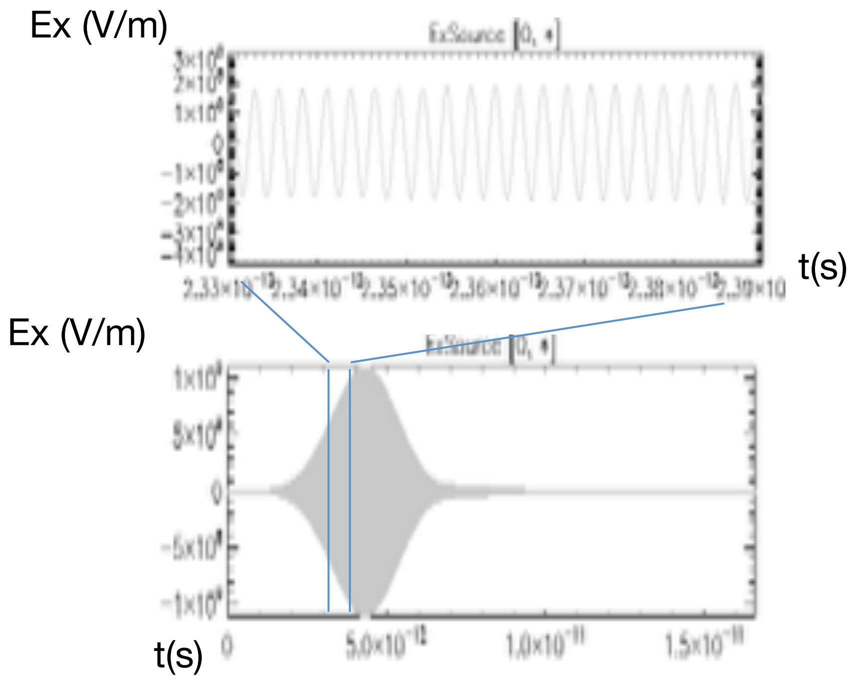
Simulations include acceleration, beam dynamics and material properties.

Resonant Fields (@ t = 7 ps)

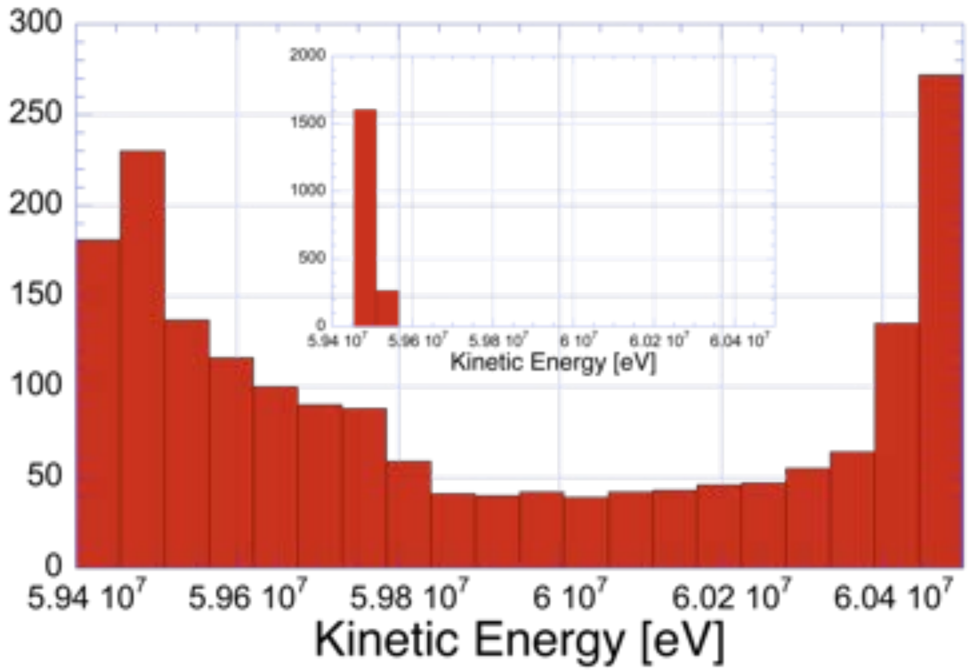


Input laser source

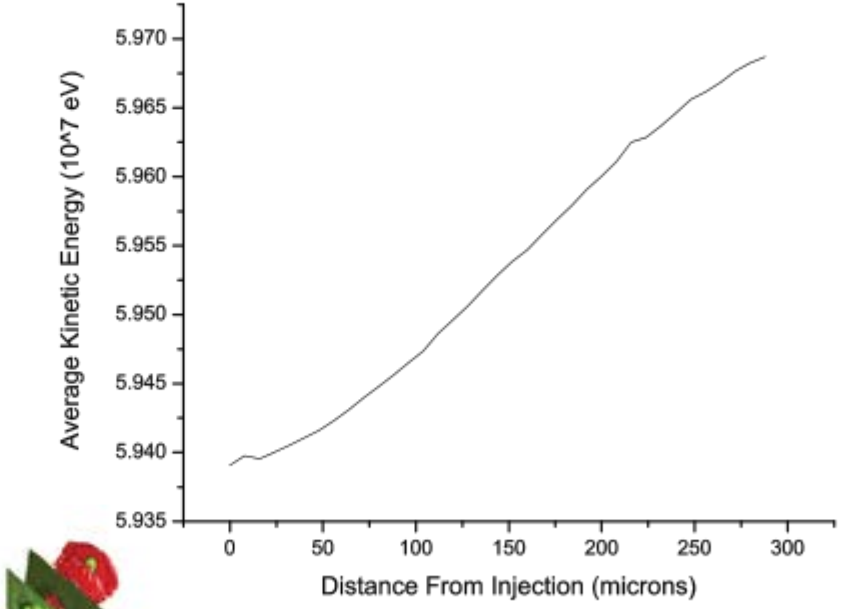
can correspond to actual $Ti:Al_2O_3$ laser



Energy Distributions



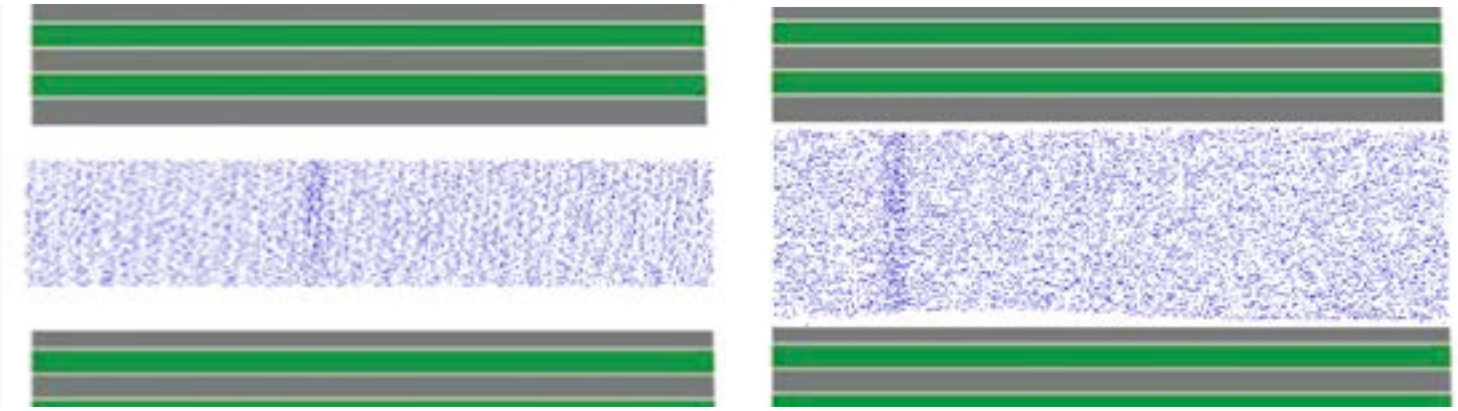
Energy Gain



VORPAL

Simulations have confirmed good beam dynamics in the as-designed structures

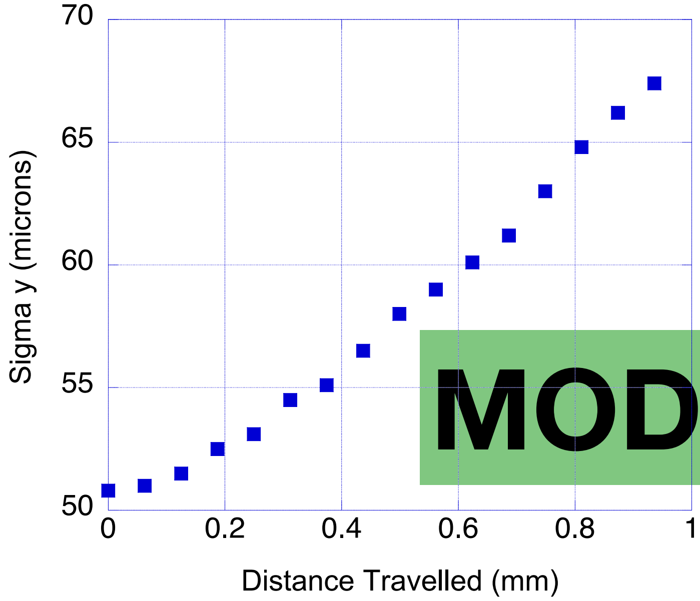
DEFOCUSING



MODEST

(1 mm later)

SPACE CHARGE



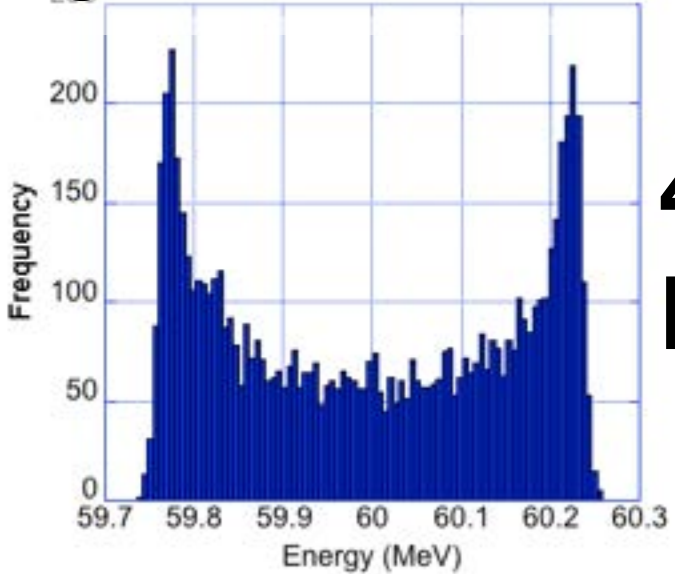
MODEST

WAKEFIELDS

10keV/m

NEGLIGIBLE

GRADIENT

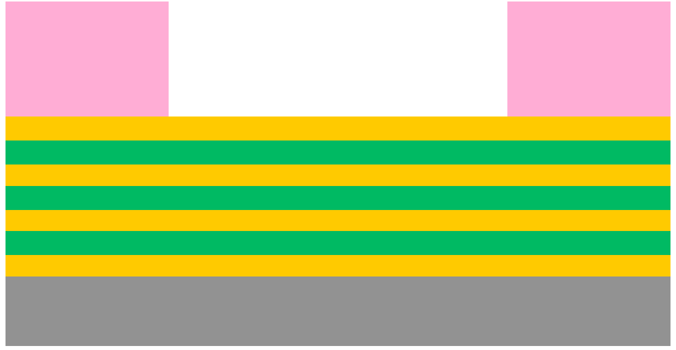


400 MeV/m

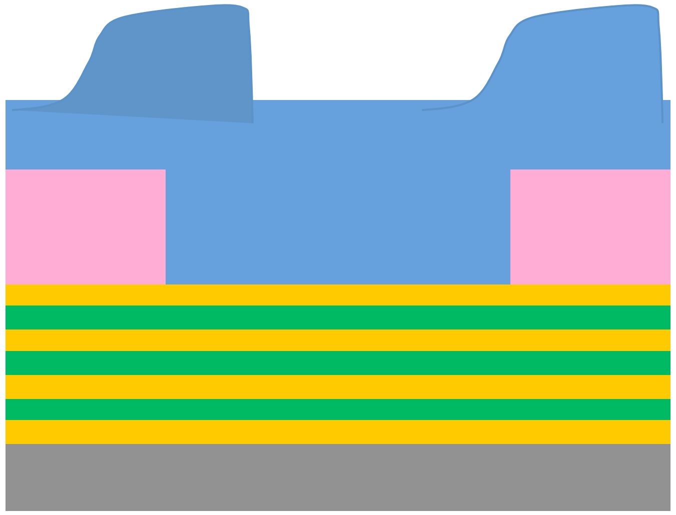
DETECTABLE

Fabrication involves a series of standard foundry processes, not unlike other optical structures

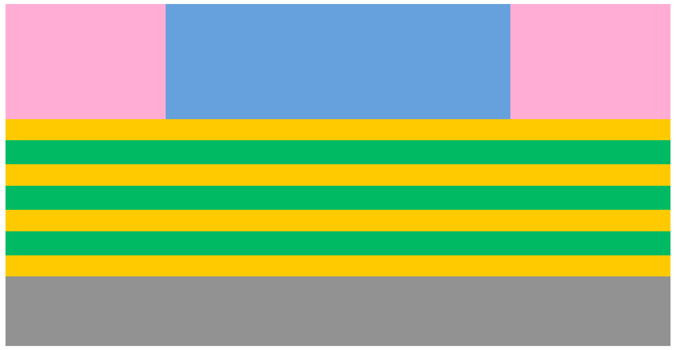
1. DBR deposition on substrate



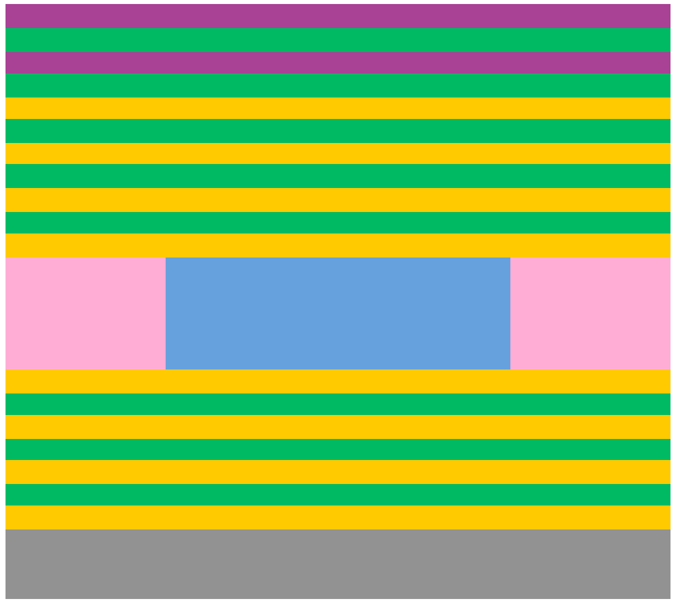
2. Patterned SiO_2 deposition for gap support



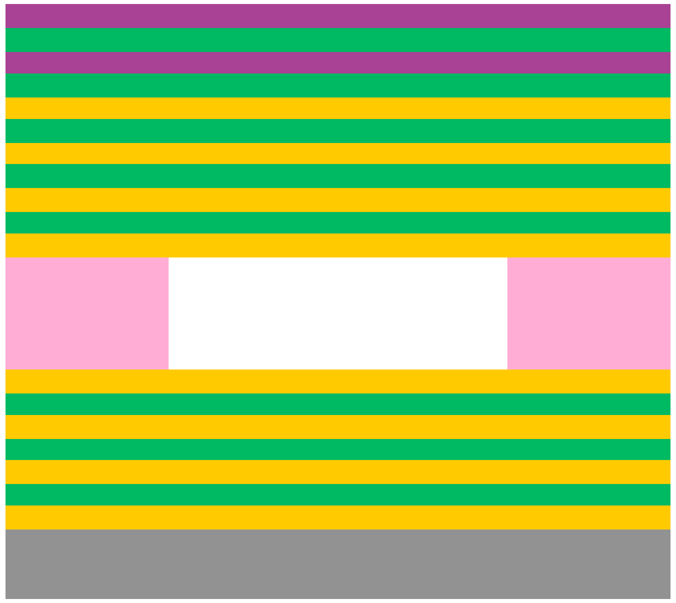
3. Fill material Si deposition



4. CMP to planarize and achieve the desired thickness

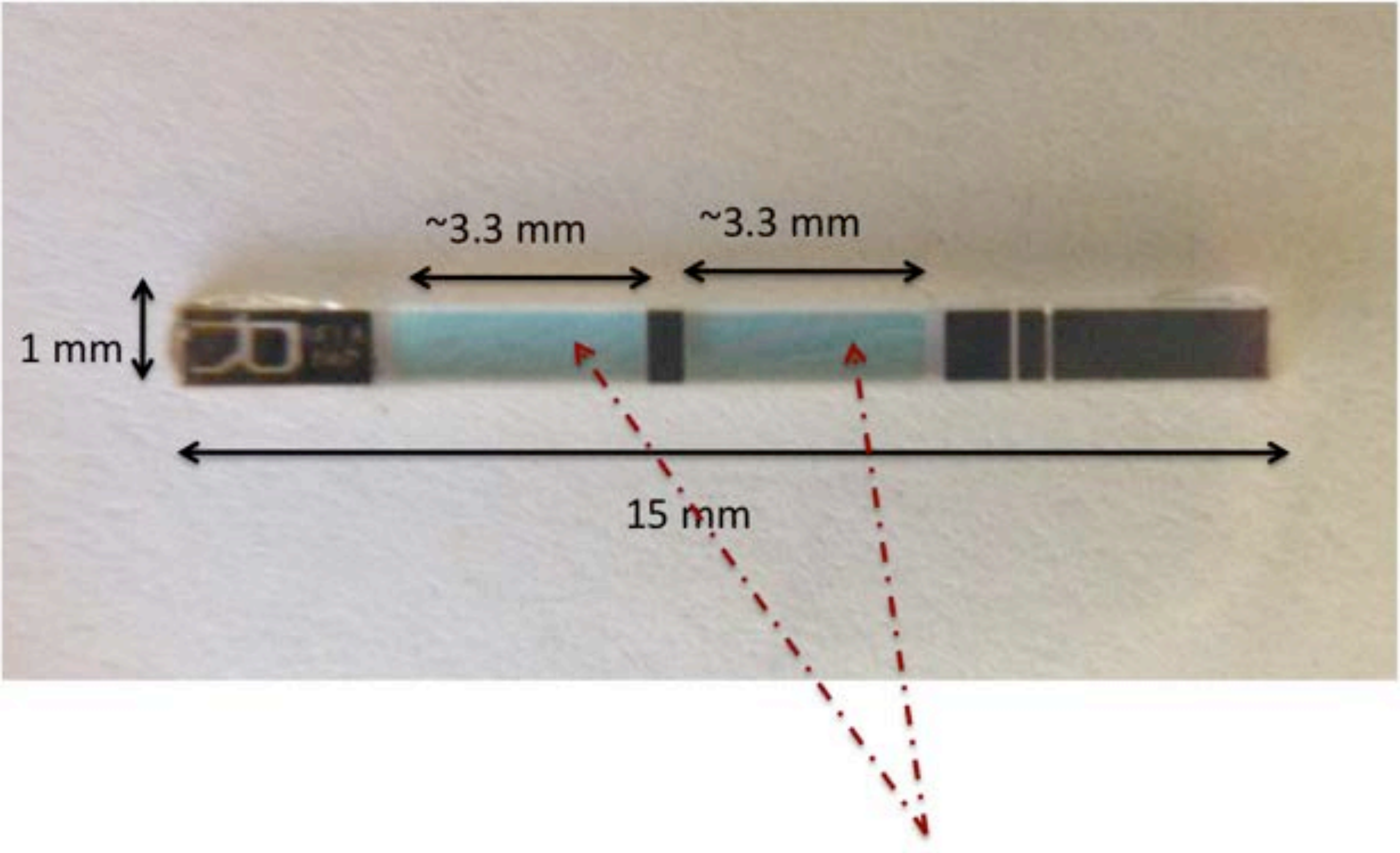


5. Top structure fabrication

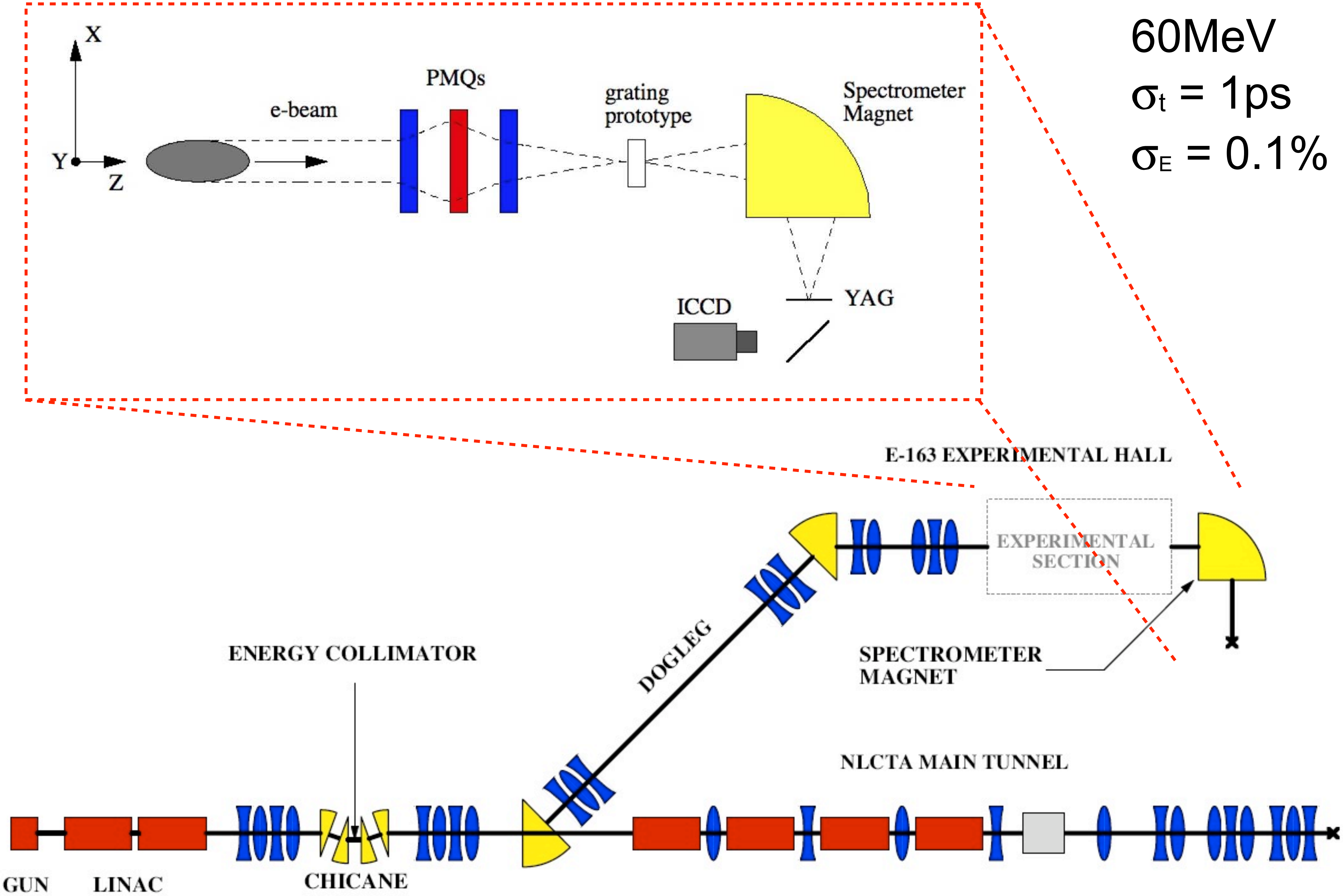


3. Wet etch filled Si to create vacuum gap

The final structure is short to match beam focal depth (β^*) and wide to allow for many test regions



The E163 at NLCTA (SLAC) provides a purpose built test bed for DLAs and a rich source of acronyms



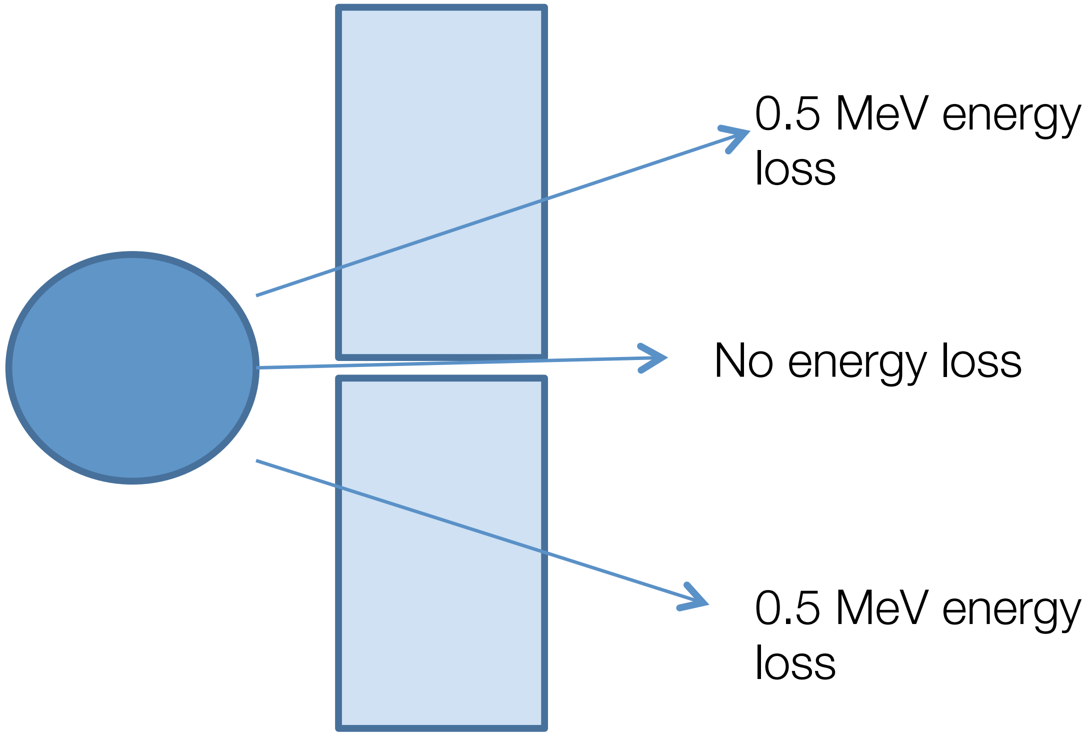
60MeV

σ_t = 1ps

σ_E = 0.1%

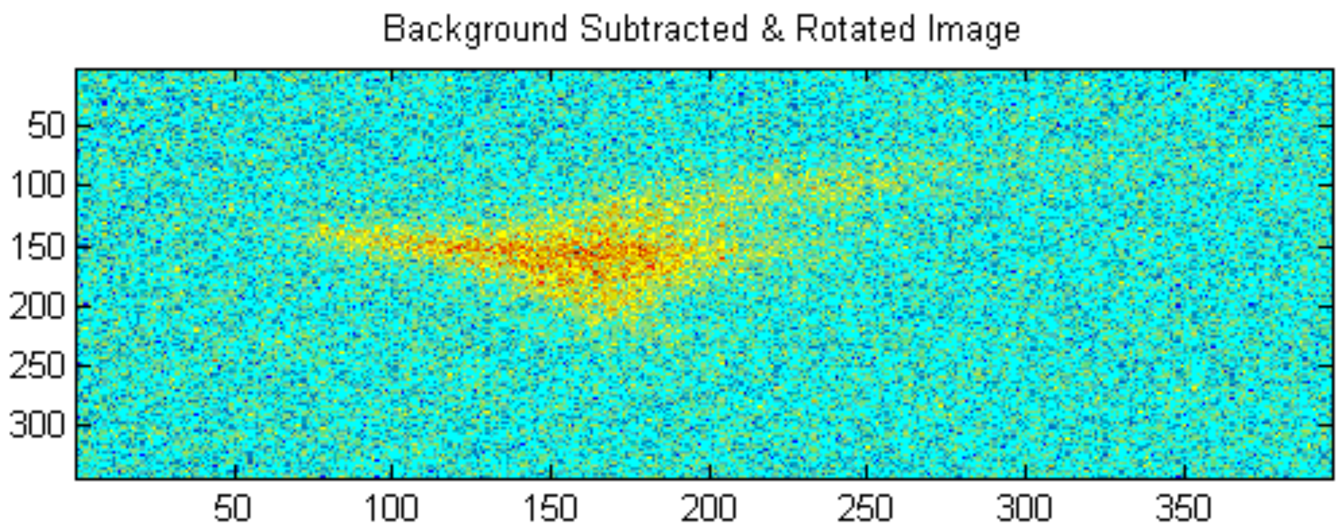
Observing beam transmission would seem to be a needle in a haystack problem

Property	Current Value at E163
Beam energy	60 MeV
Energy spread	20 KeV
Transverse emittance	2x10 um-rad
Spot size	40x40 um2
Charge	10 pC
Bunch length	1-5 ps
Rep rate	10 Hz

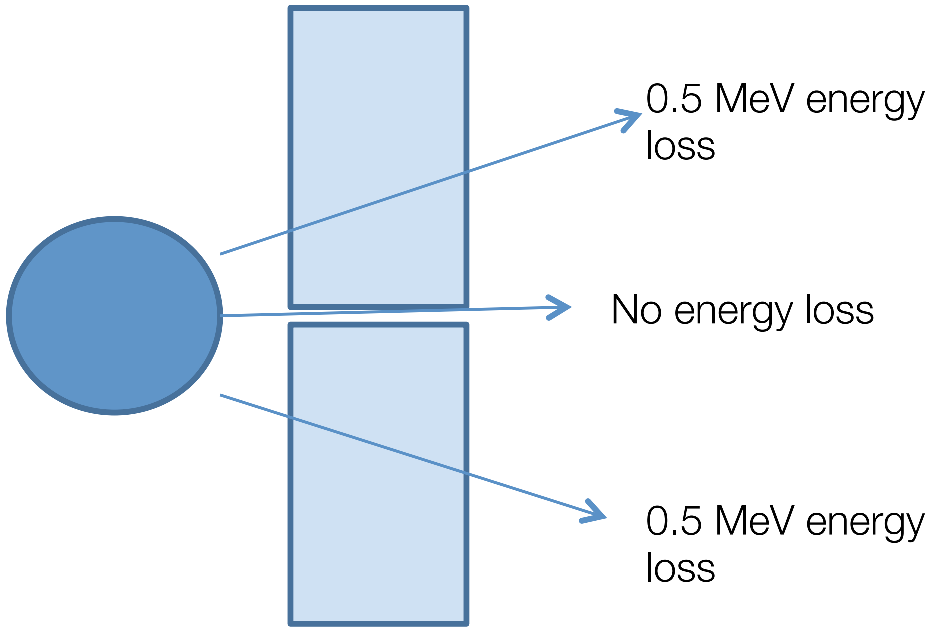


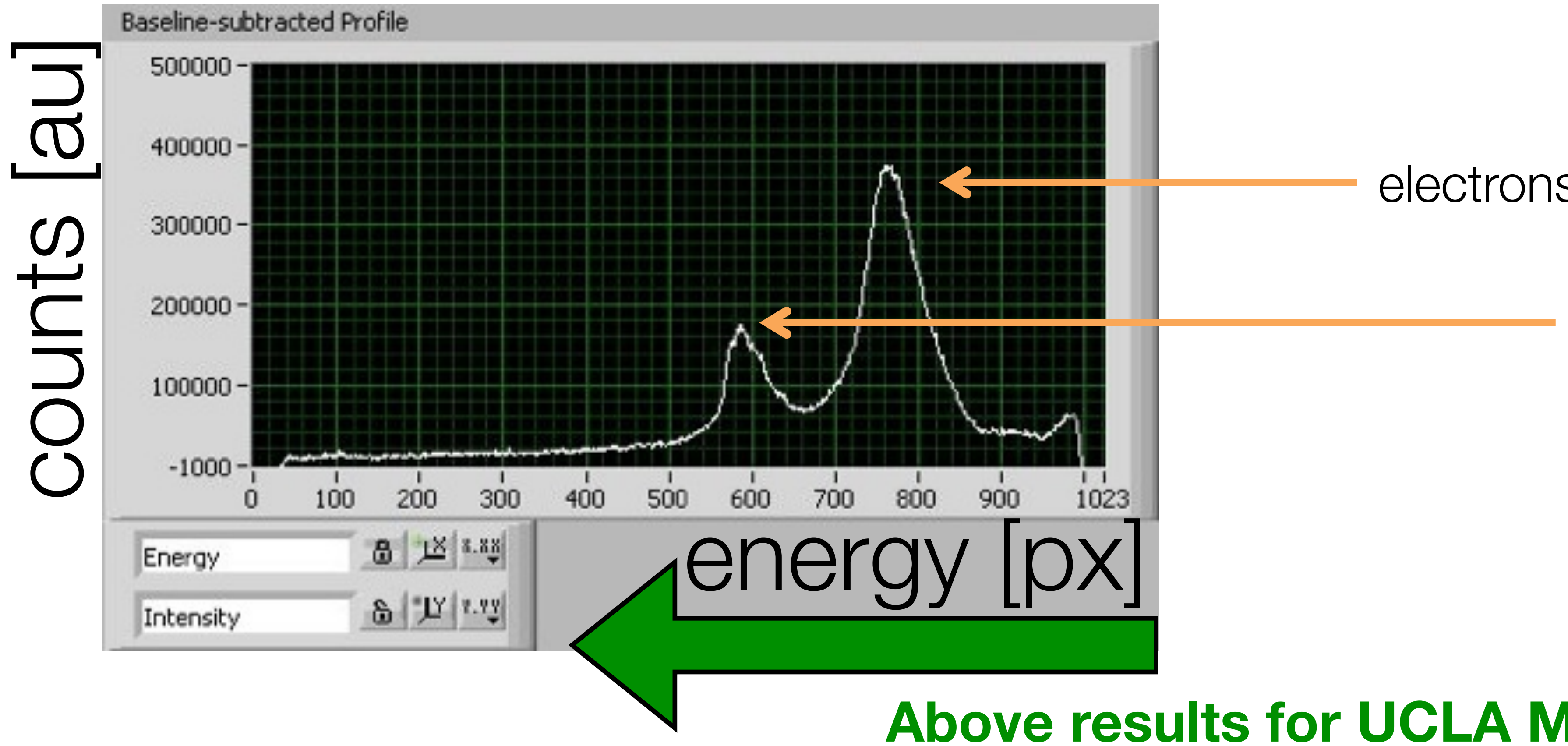
For ε_y = 24 μm-rad, σ_y=40 μm, and a gaussian charge distribution, we expect **0.005%** of the beam to get through the vacuum gap

Beam transmission through the optical-scale structure is challenging.



Spectrometer Image (higher energy to the left)





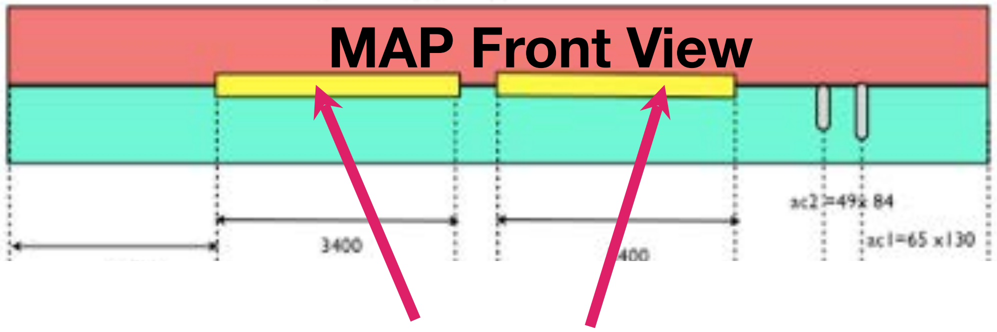
electrons w/ glass energy loss

electrons through slot

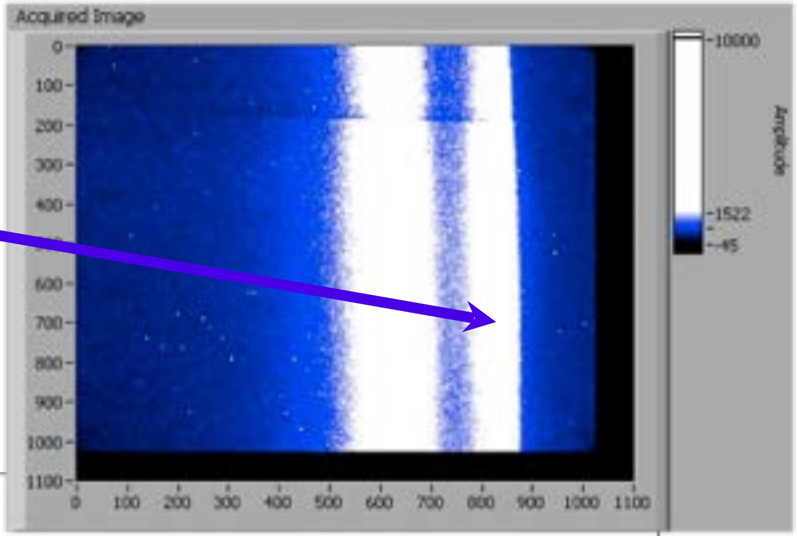
Above results for UCLA MAP
SLAC team has better results for grating

The MAP, a resonant DLA structure, has demonstrated acceleration at NLCTA

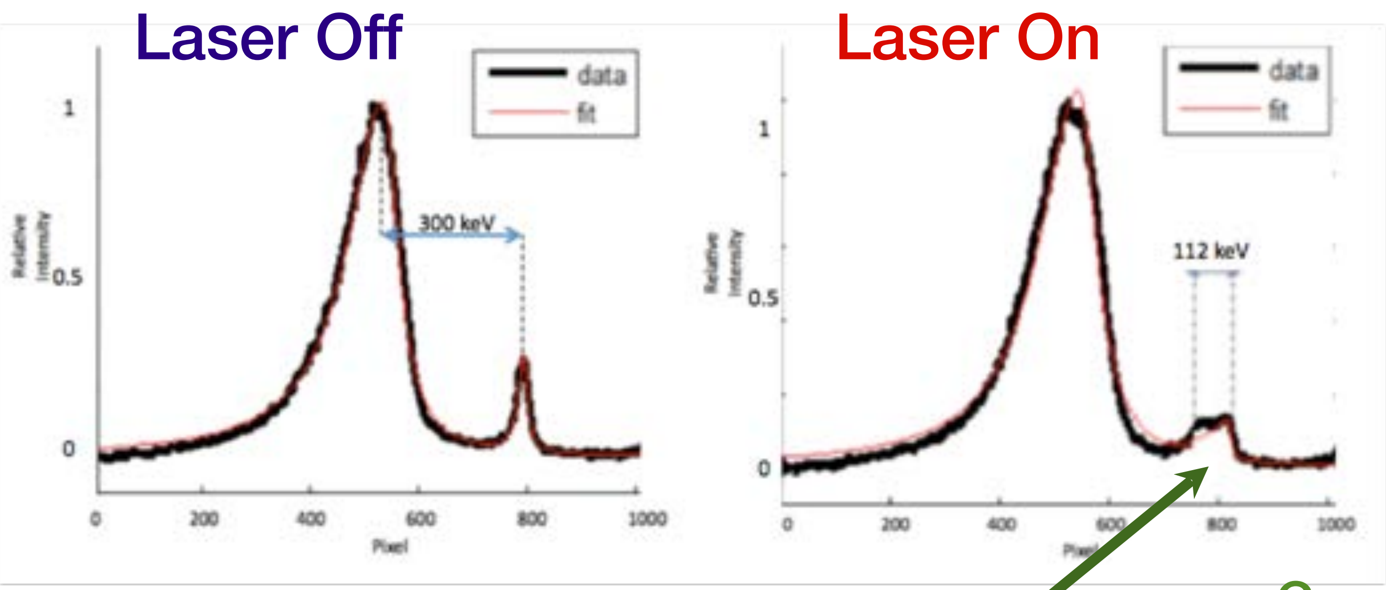
Micro
Accelerator
Platform



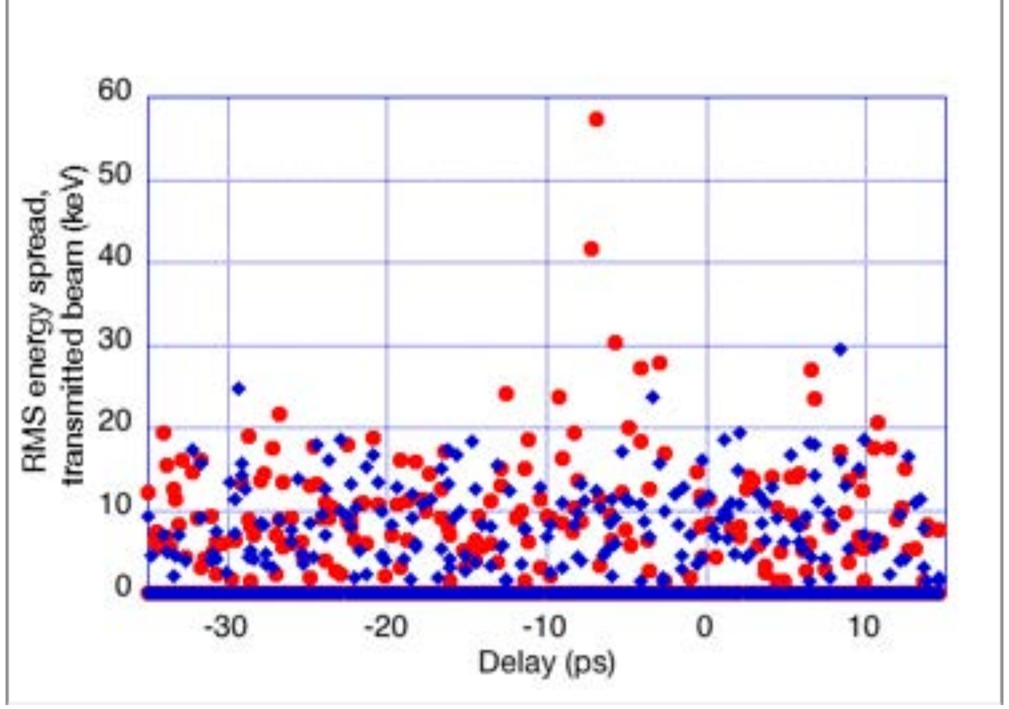
3 mm x 400 nm acceleration channels, with laser coupled through top face of slab



Spectrometer image:
Transmitted population
sees accelerating fields



Spreading of transmitted peak shows energy modulation of electrons traversing vacuum channel

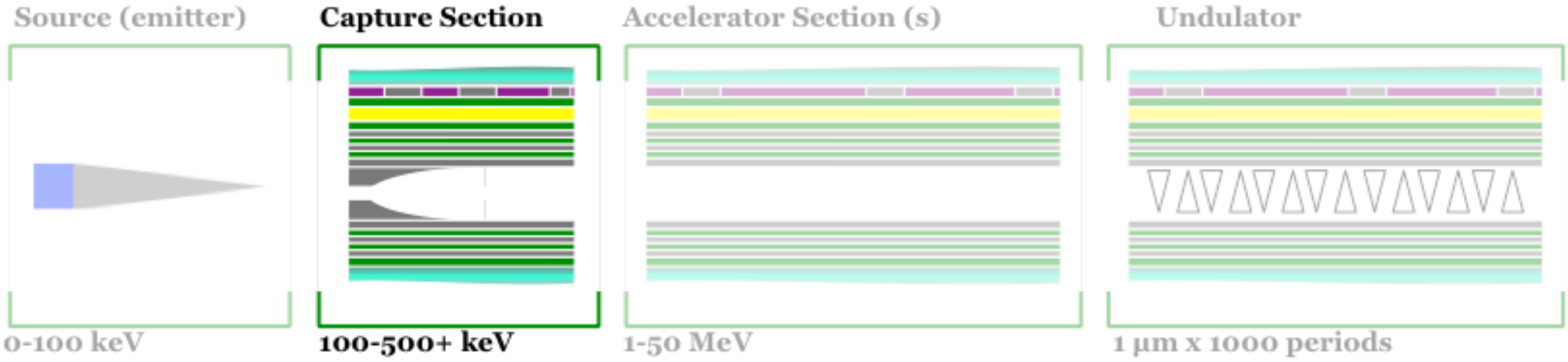


Correct laser+e-beam temporal overlap shows energy change; inferred gradient 28 MeV/m;
simulation predicts ~70 MeV/m for ideal structure

Performance was near expectations despite fabrication challenges

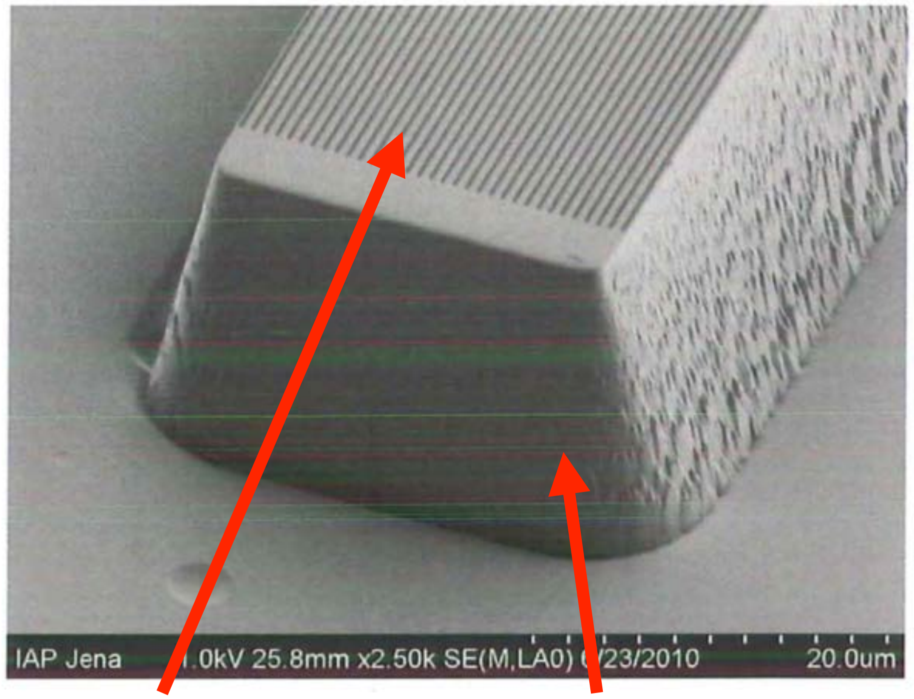
Capture Module

❷

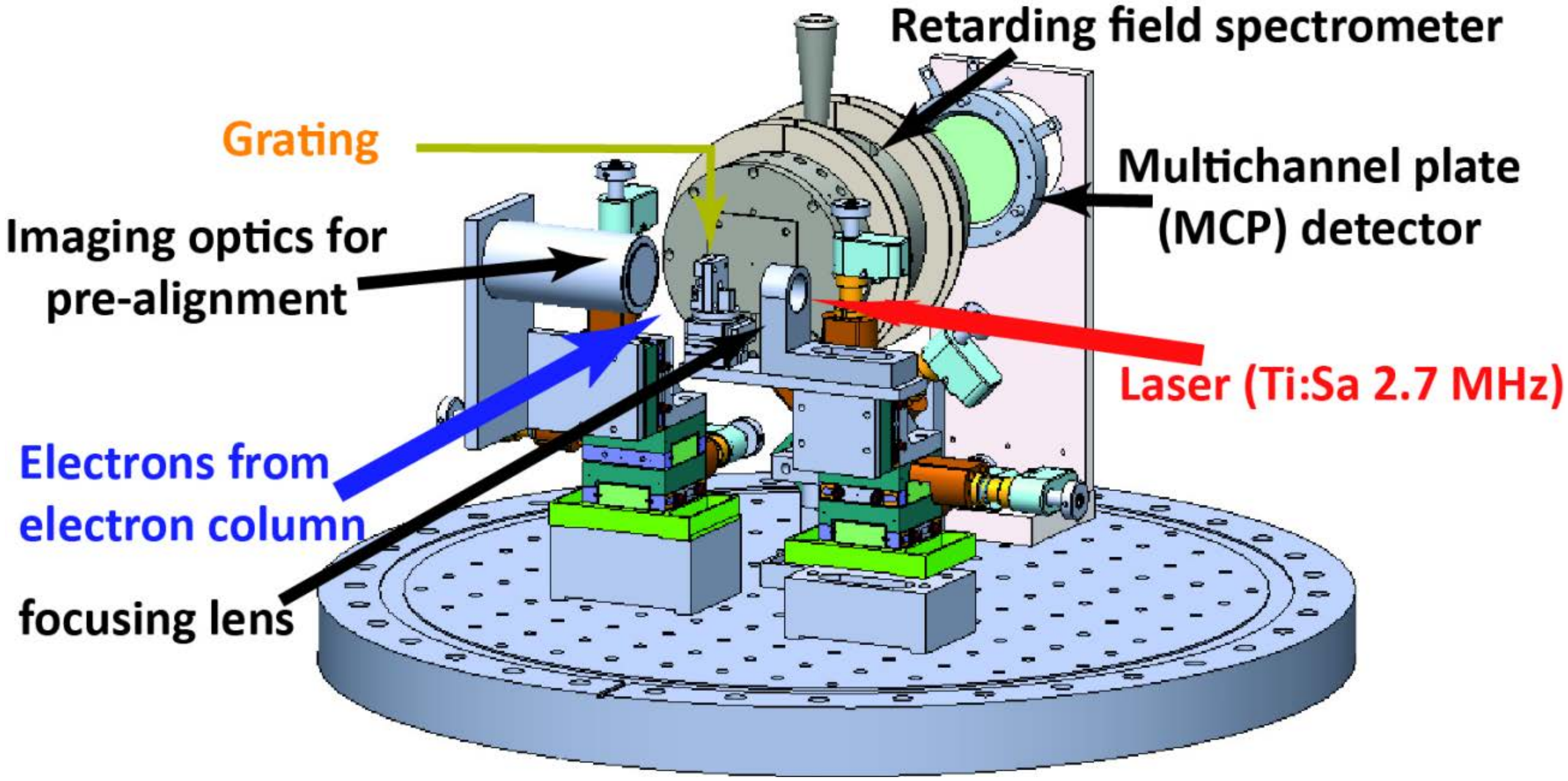


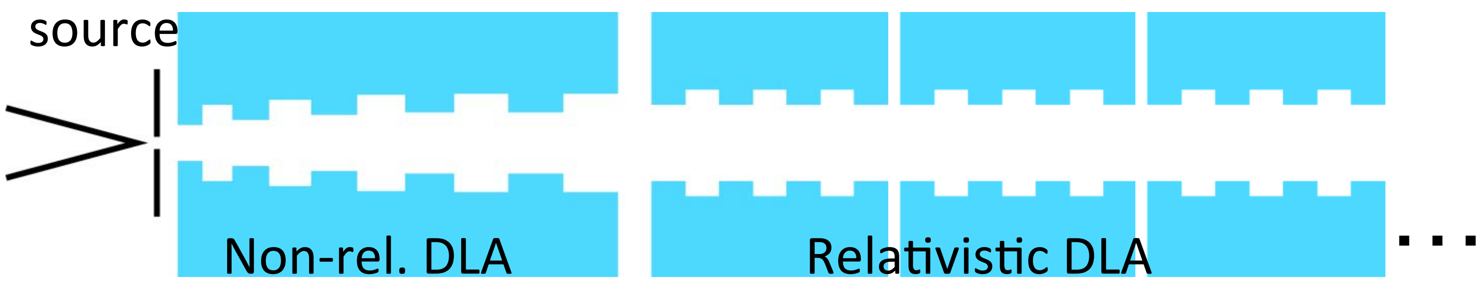
A non-relativistic grating structure has shown proof of concept for gun-to-DLA acceleration

Goal:
bridge between
30 keV electron gun &
relativistic DLA structures;
<20 mm long



Silica grating on mesa structure

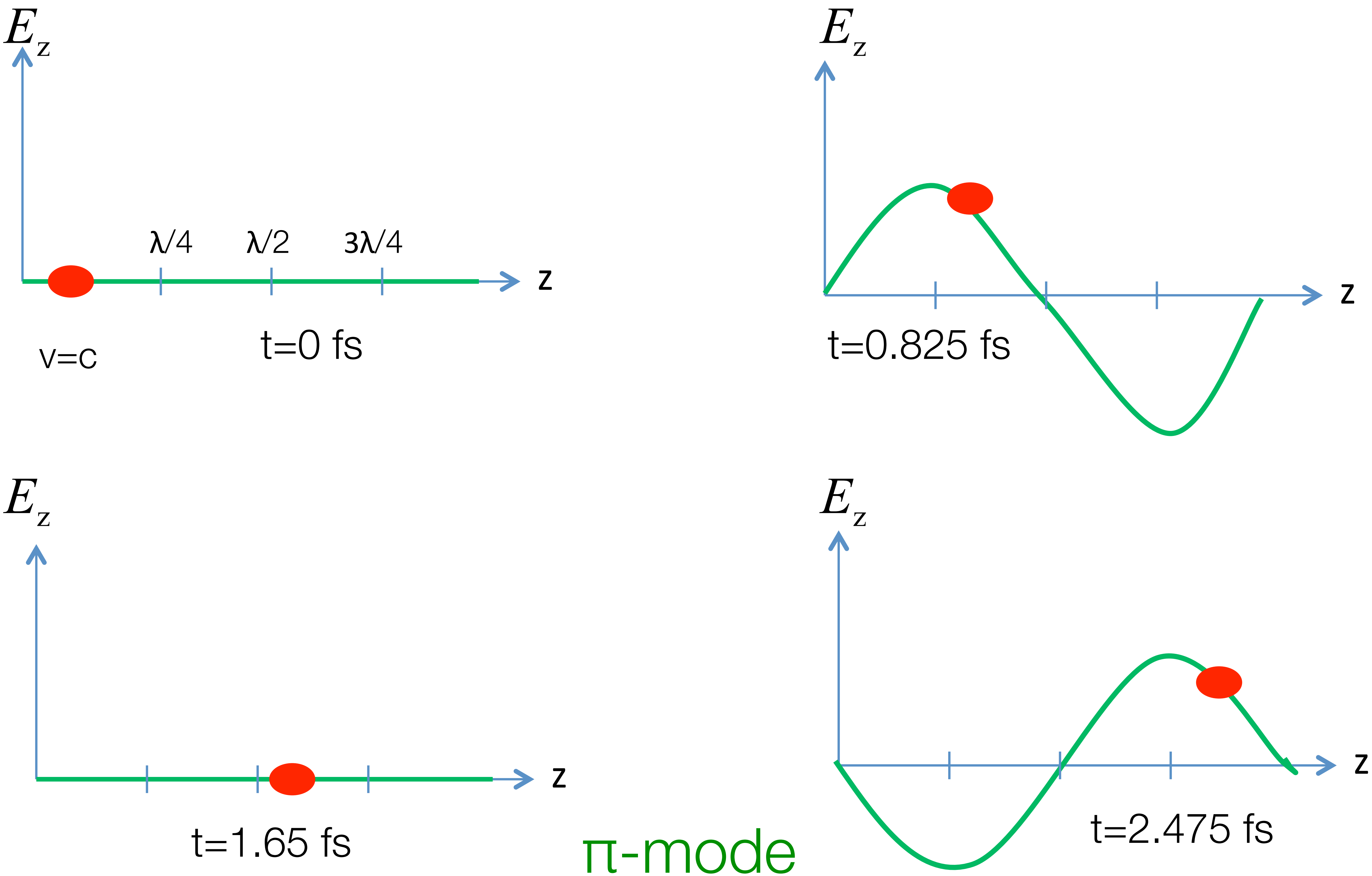




Achieved: single grating, 100 nJ, 100 nm distance
= 50 MeV/m, 280 eV gain

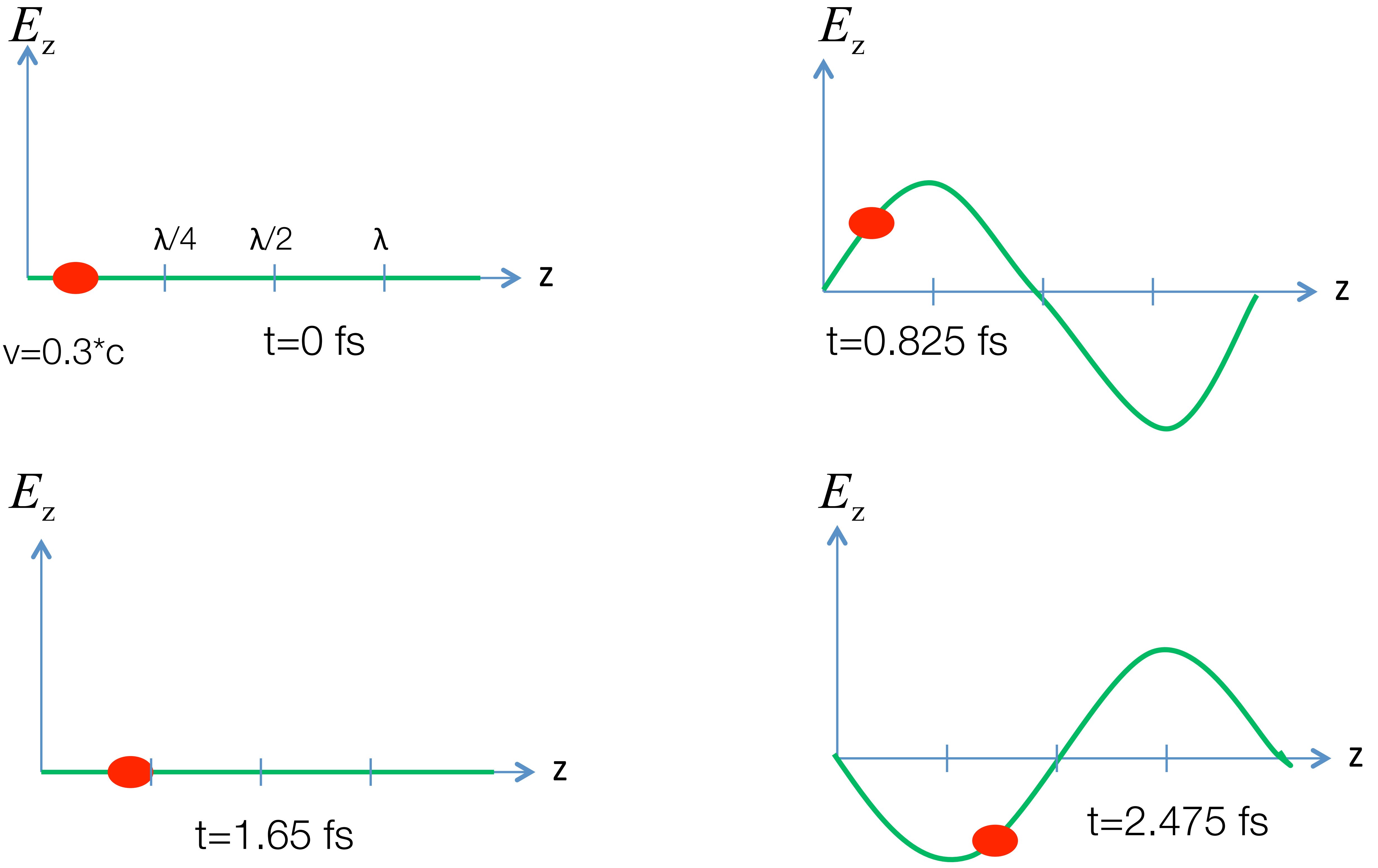
John Breuer & Peter Hommelhoff

Synchronous acceleration in a standing-wave relativistic structure is straightforward as $V_p=c$.

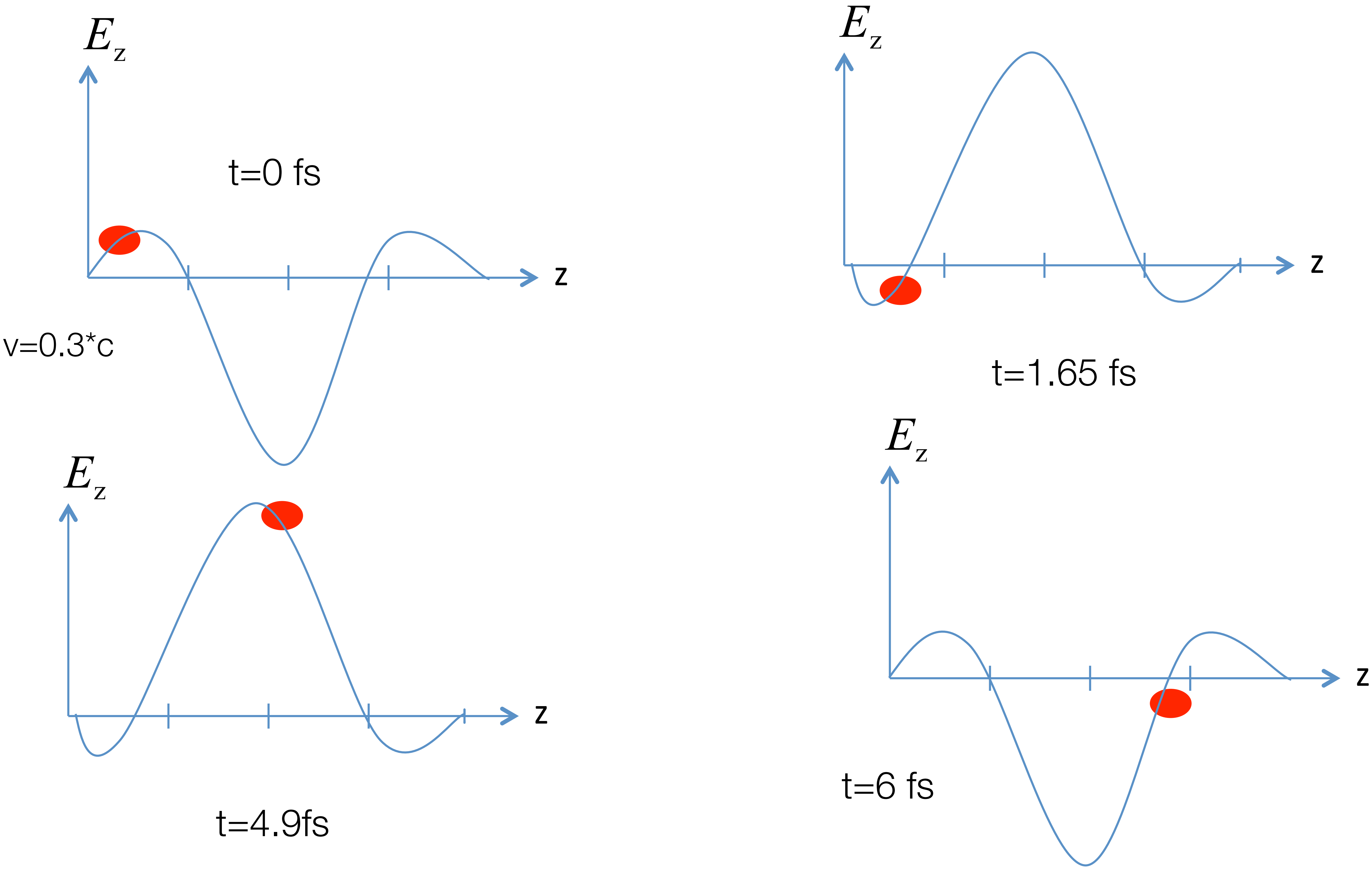


π-mode

At sub-relativistic velocities, the particle is no longer synchronous with a speed-of-light structure

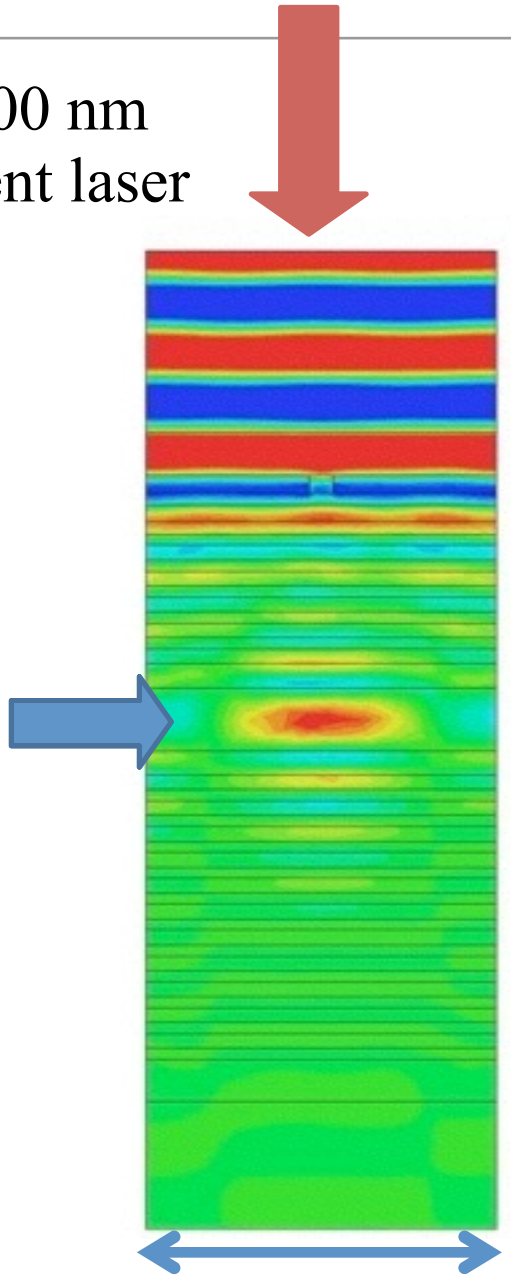


Asynchronous net-acceleration is possible with evanescing waves.



A sub-relativistic (low beta) MAP design relies on asynchronous acceleration.

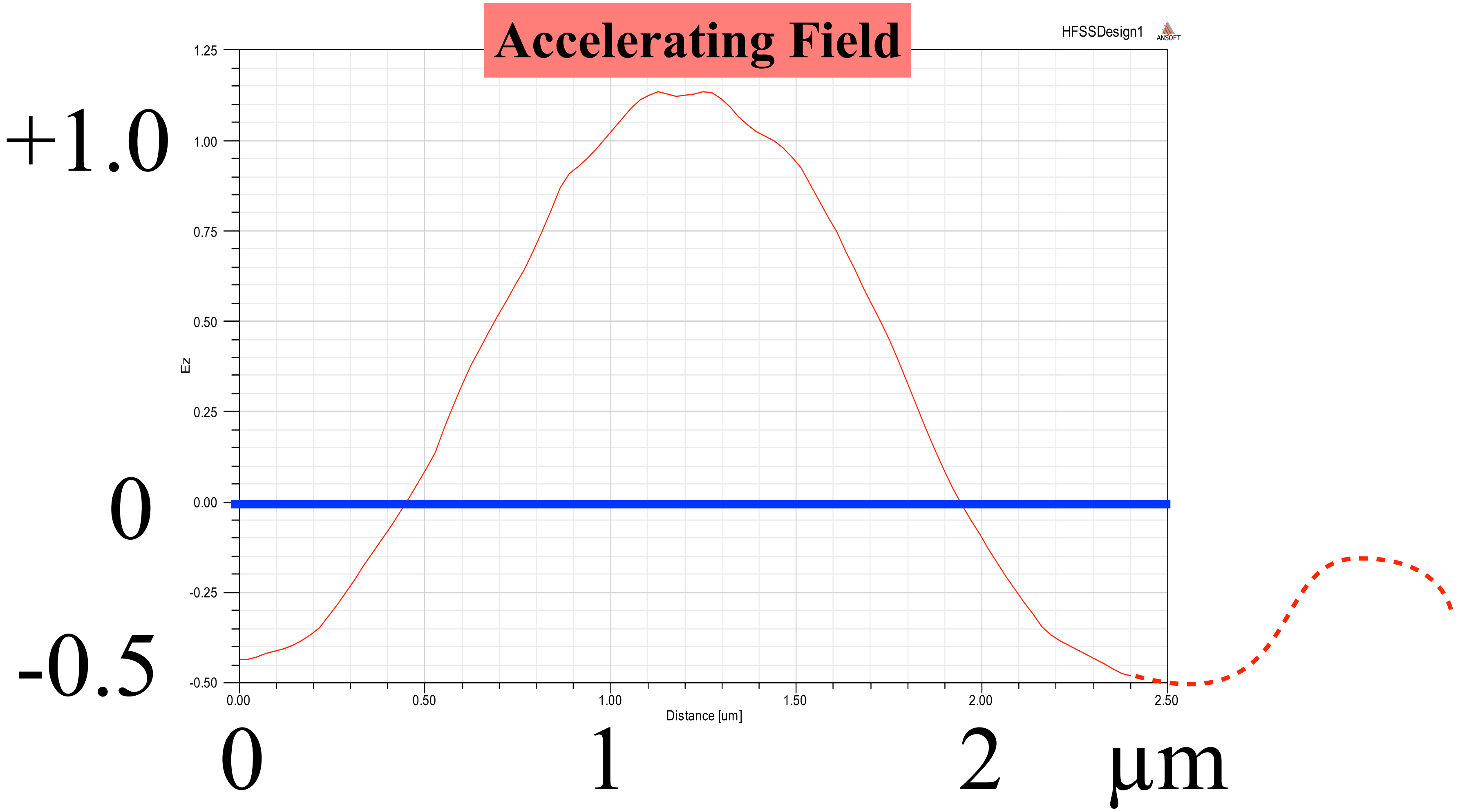
λ=800 nm
incident laser



β=0.3
e-beam

2.4 μm = 10βλ

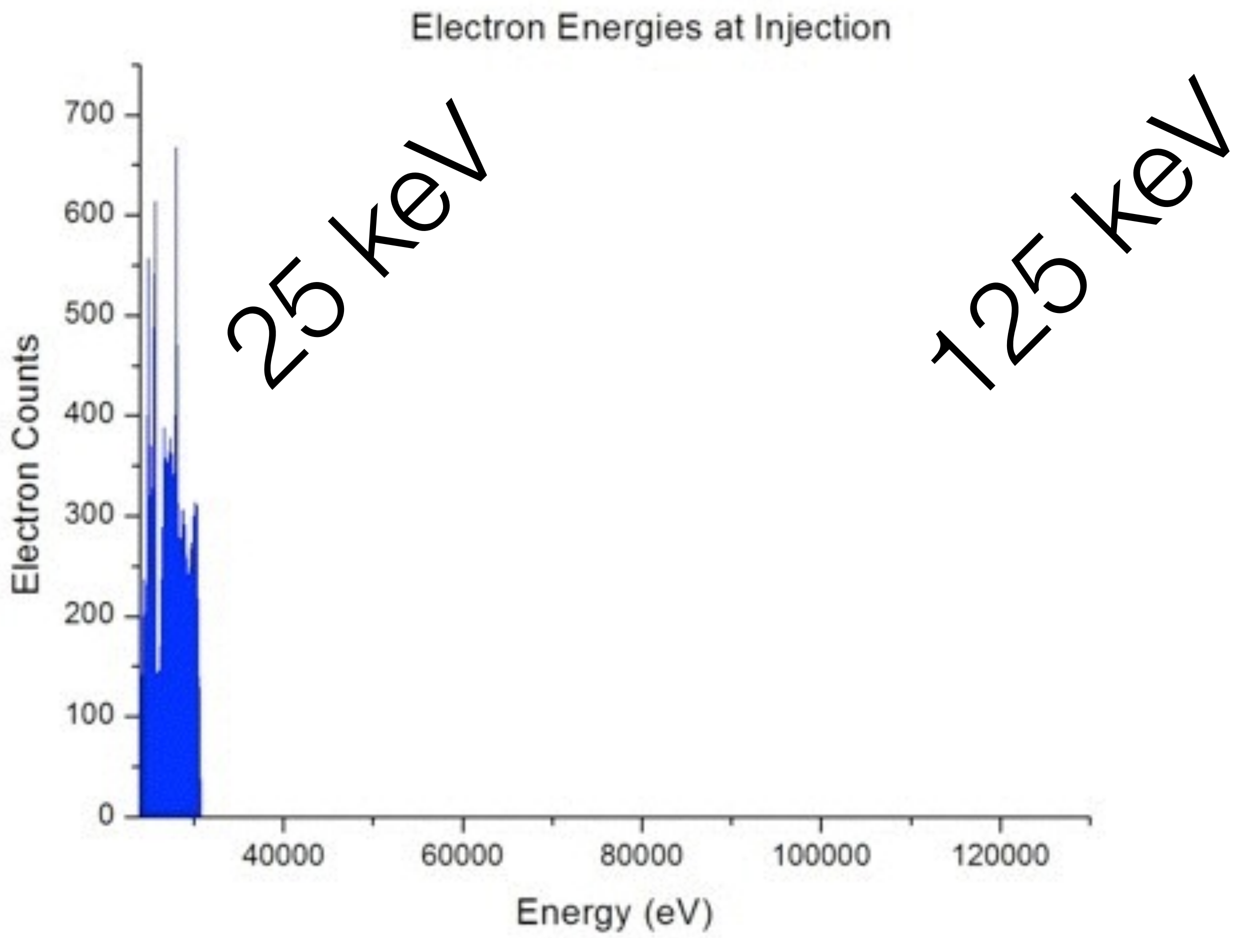
Accelerating Field

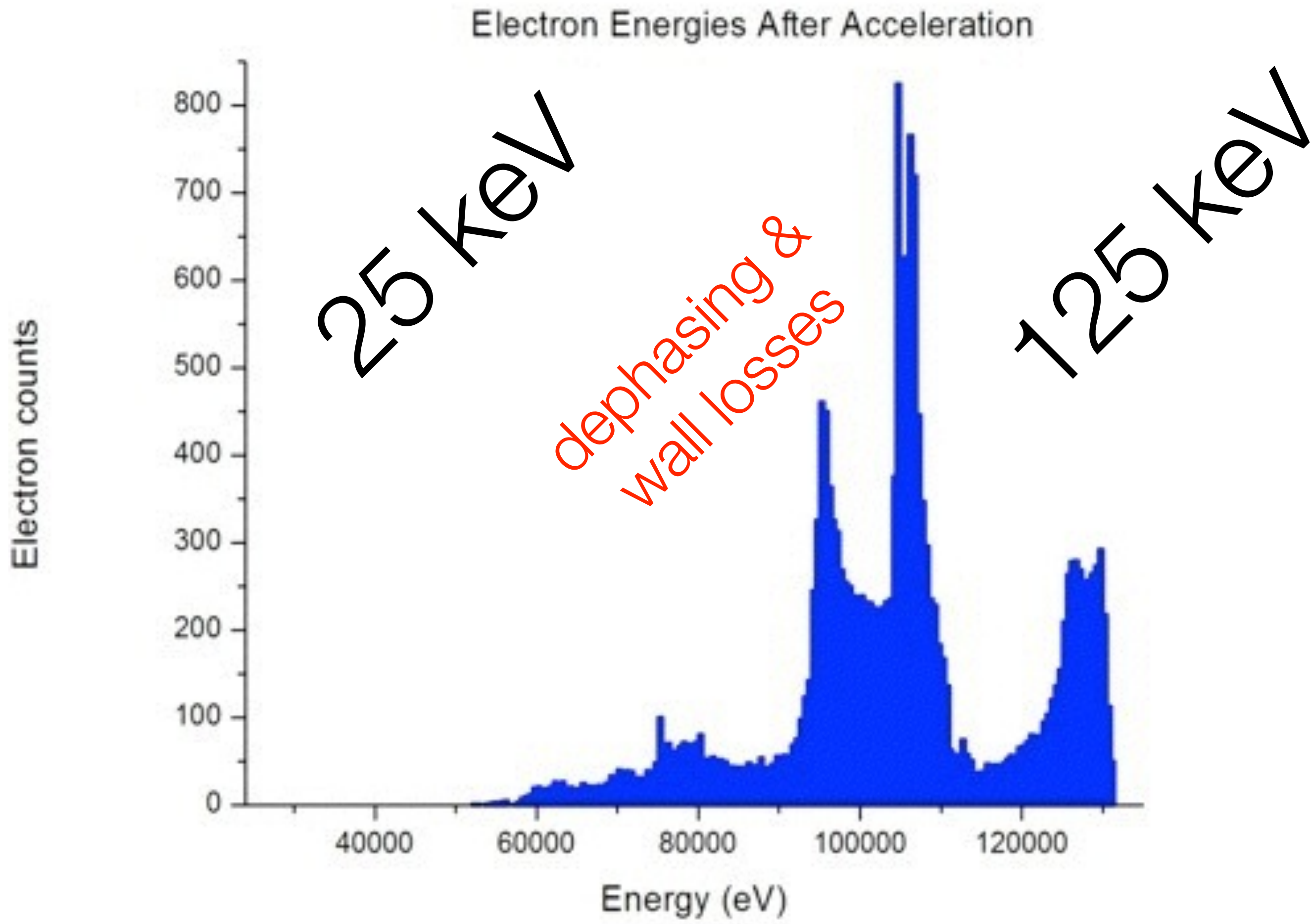


$$\int_{StructurePeriod} qE_z dz > 0$$

Electrons' energy gains outweigh losses, resulting in net acceleration

Simulations show energy gain for low-beta electrons to energies sufficient for the ß=1 structure



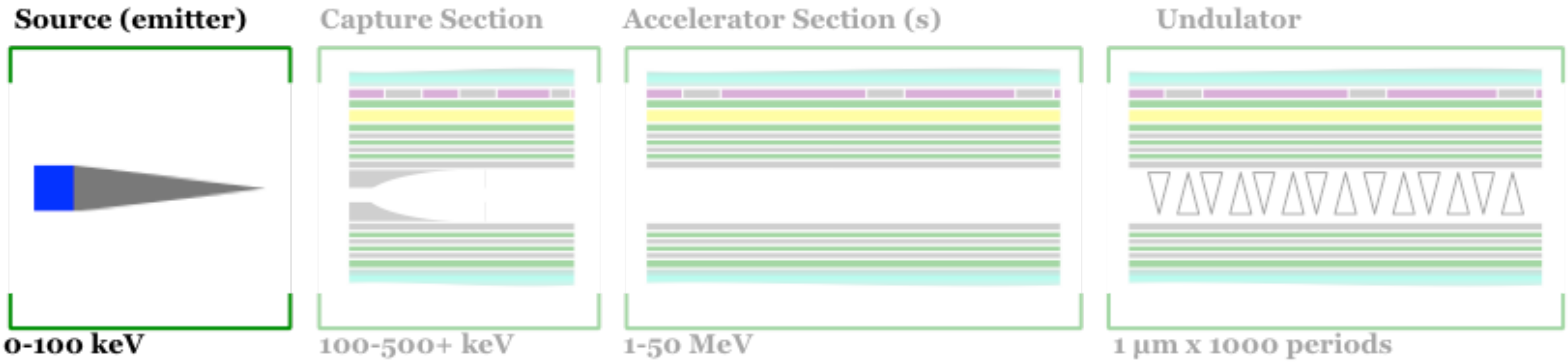


100 keV energy gain over
~250 microns

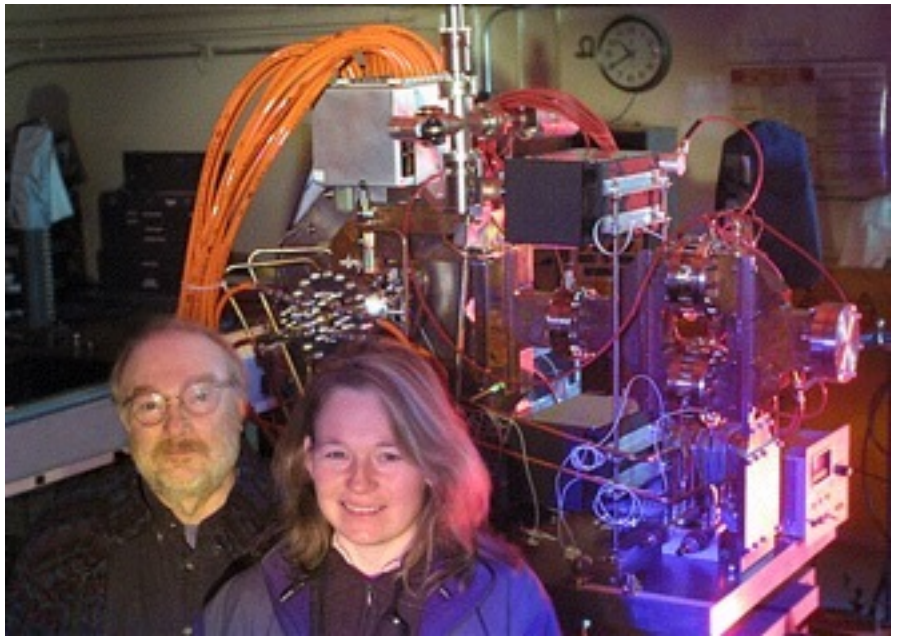
0.4 GeV/m
Accelerating Gradient

Gun Module

➊


Source (emitter)
Capture Section
Accelerator Section (s)
Undulator
0-100 keV
100-500+ keV
1-50 MeV
1 µm x 1000 periods

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



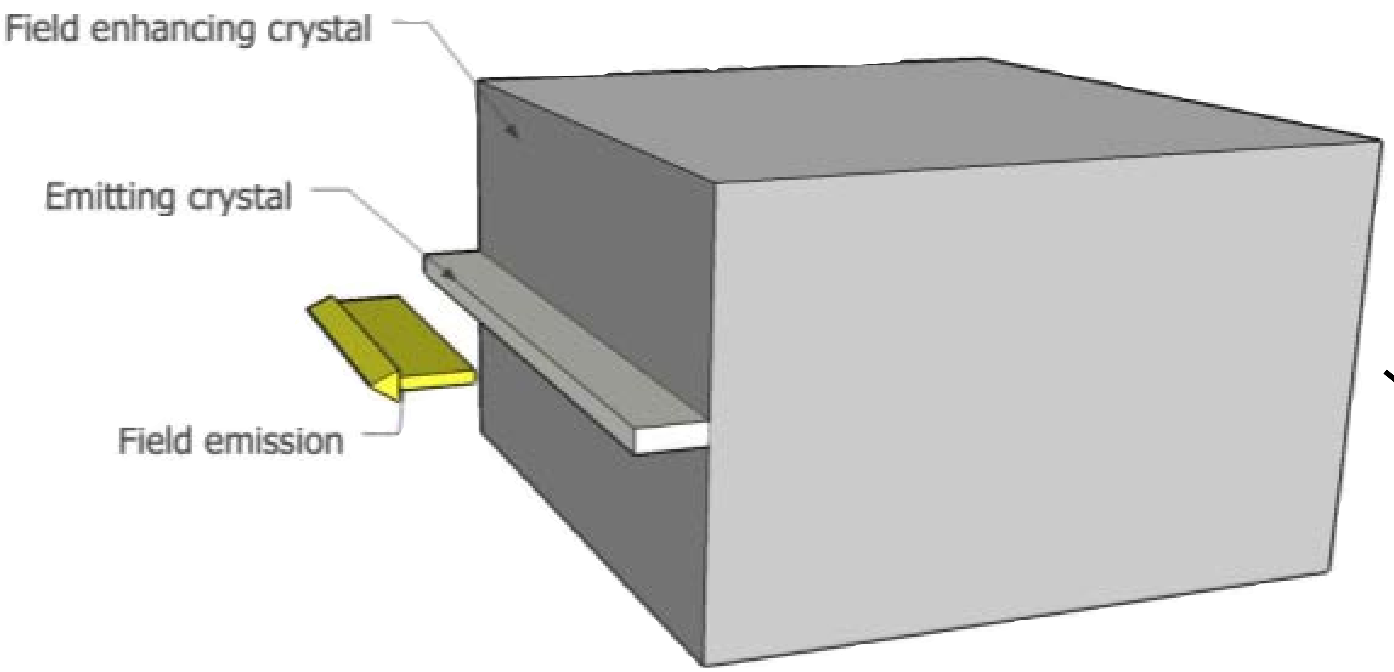
LCLS injector
@ 20 pC
achieved
0.13μm emittance

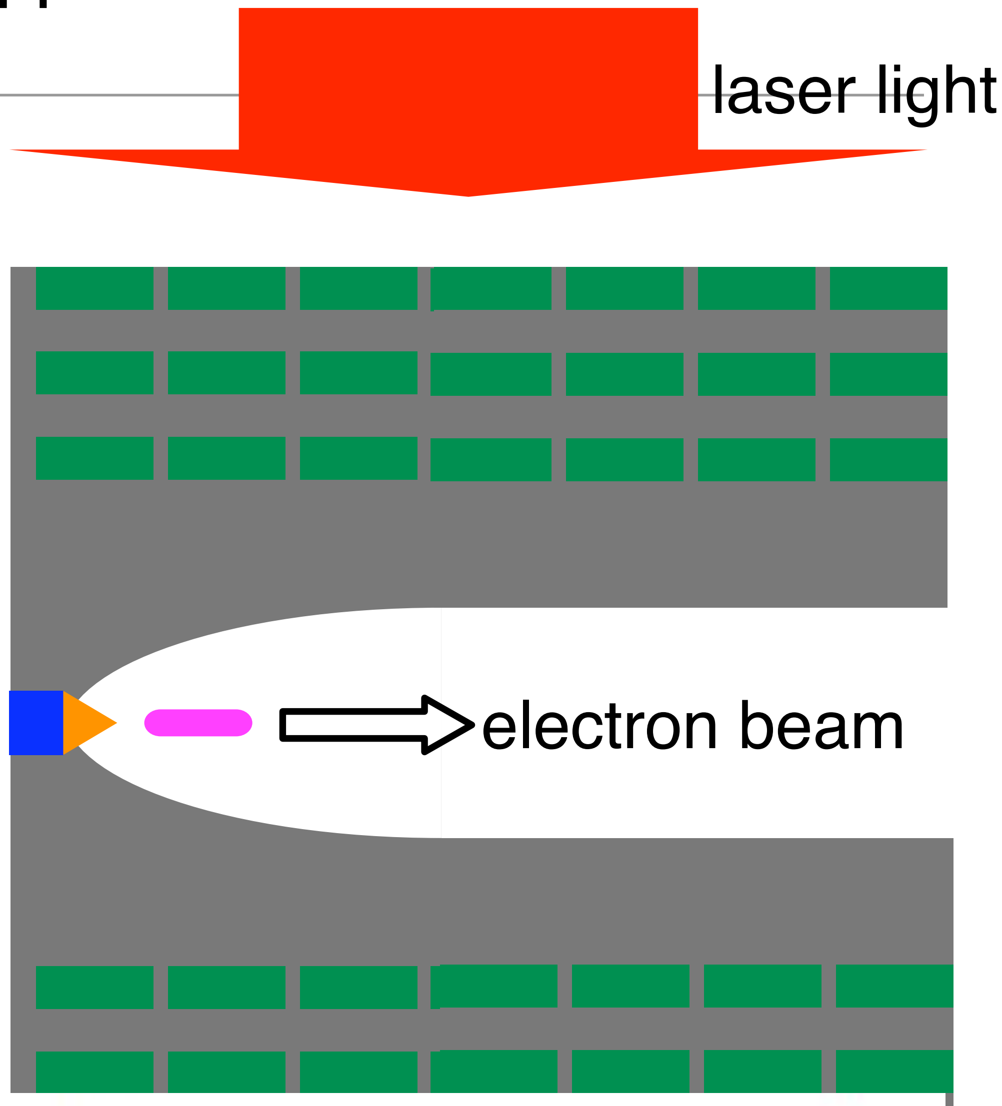
At ~1 pC, we need
<0.01μm (10 nm)
emittances

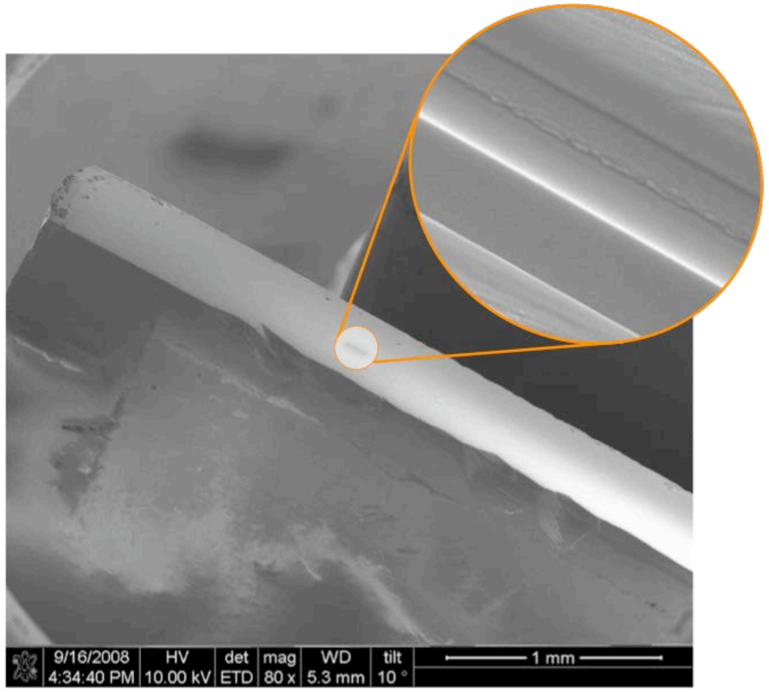
What's the problem?

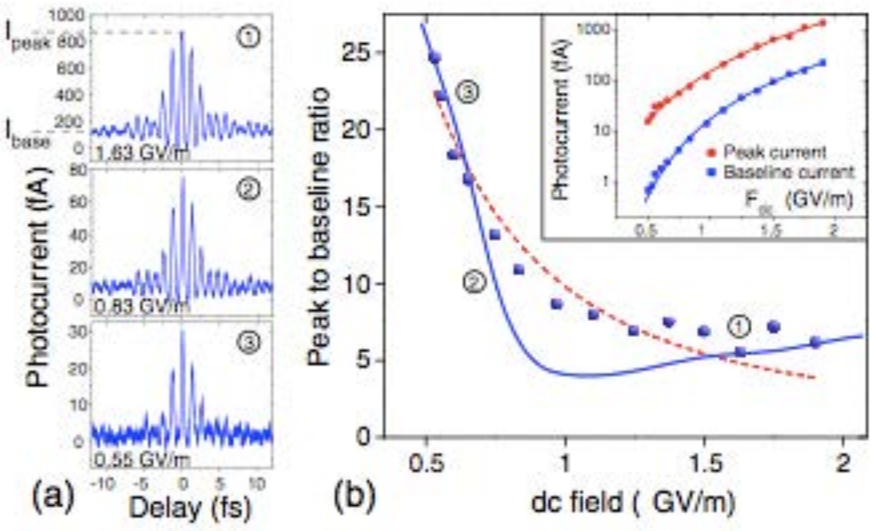
- Preservation of nm emittances
- Laser technology
  (MHz repetition rates)
- Injection into optical structures

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



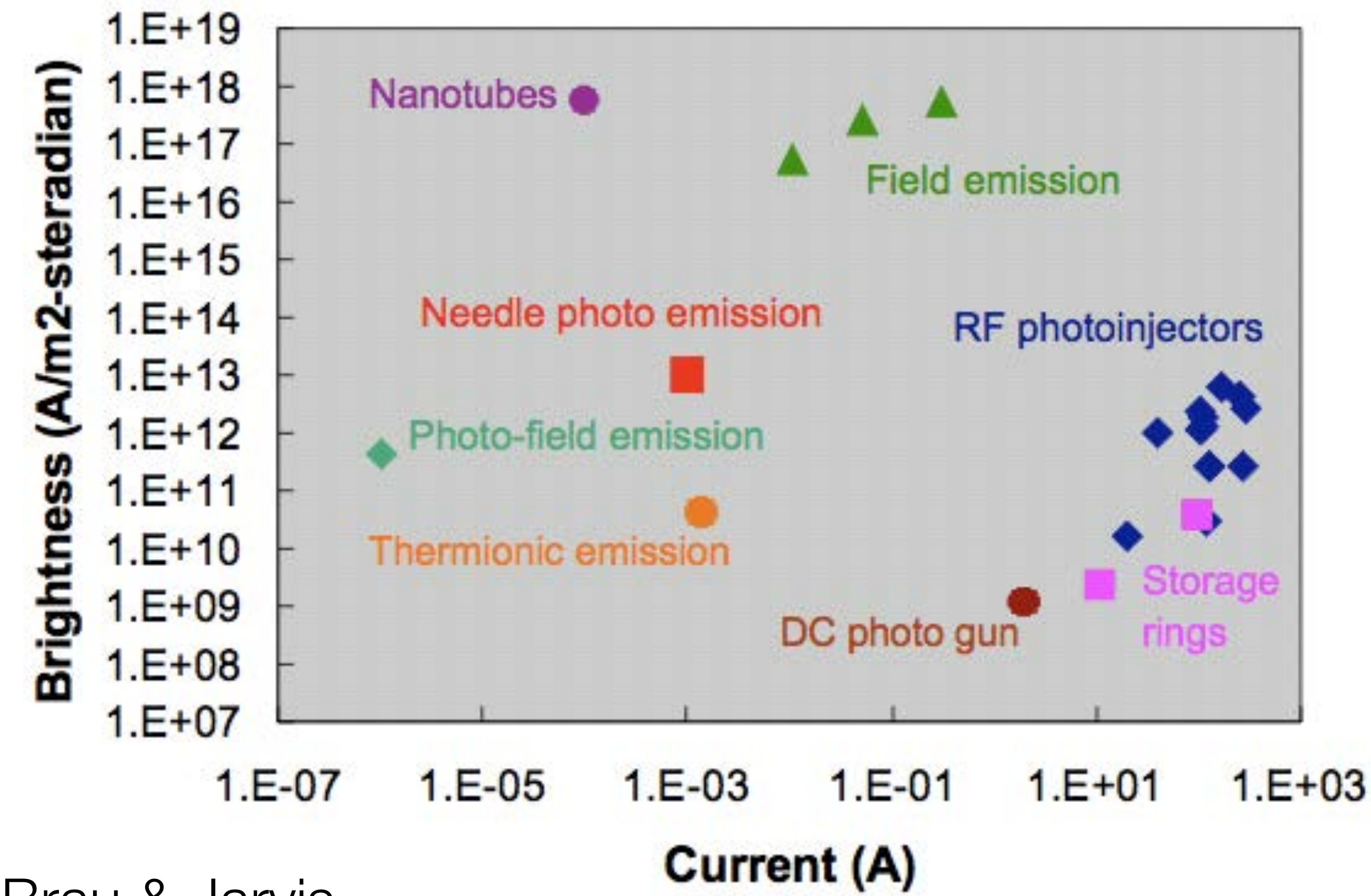






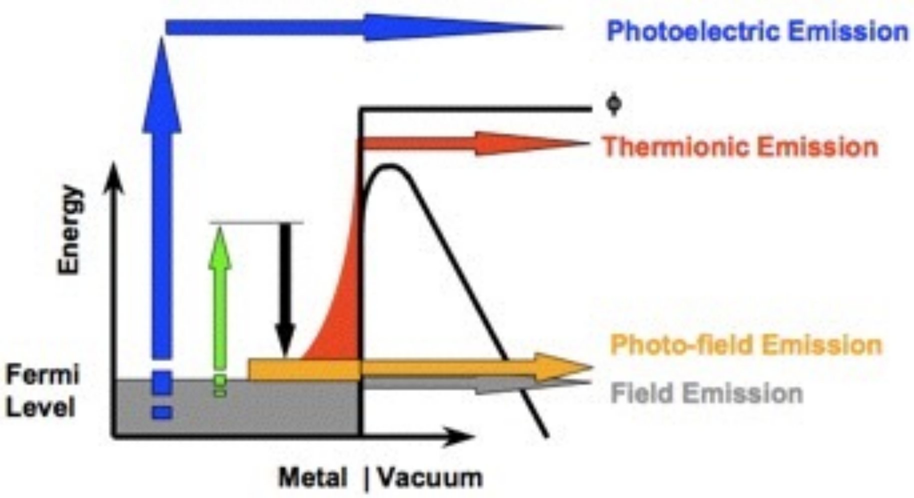
Ultrafast Electron Pulses from **es**
Peter Hommelhoff, Catherine Kealhofe
PRL **97,** 247402 (2006)

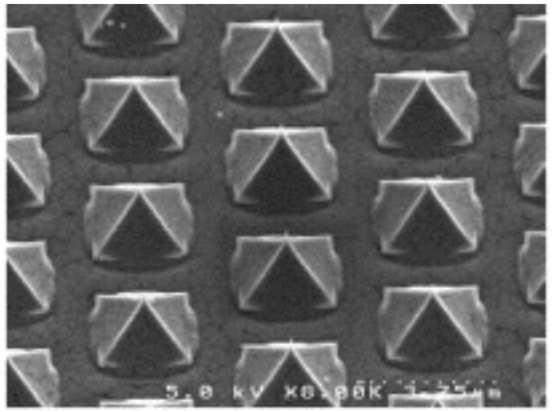
Electron microscopes achieve the requisite emittances, albeit at very low current

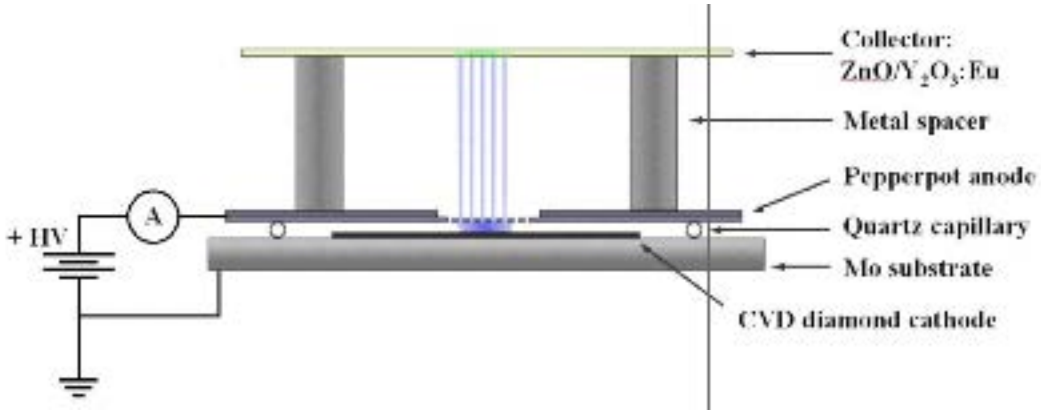


Brau & Jarvis

Field and photo-assisted field emission work well

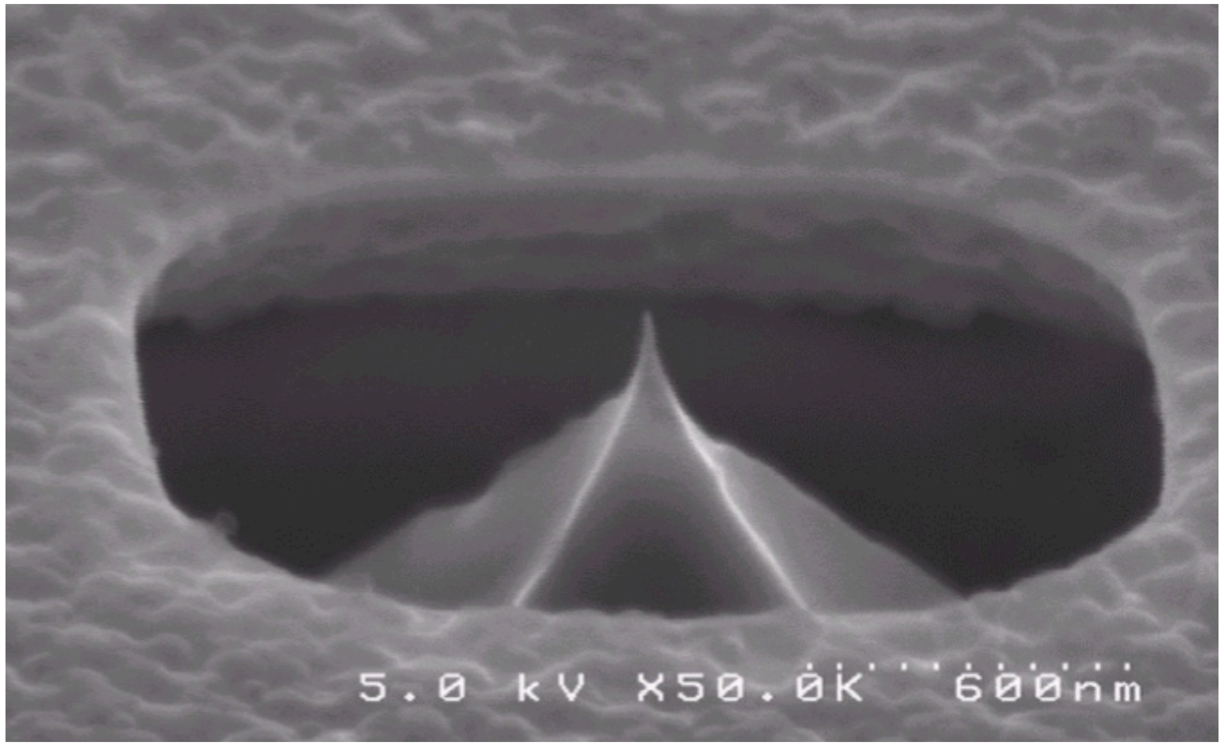


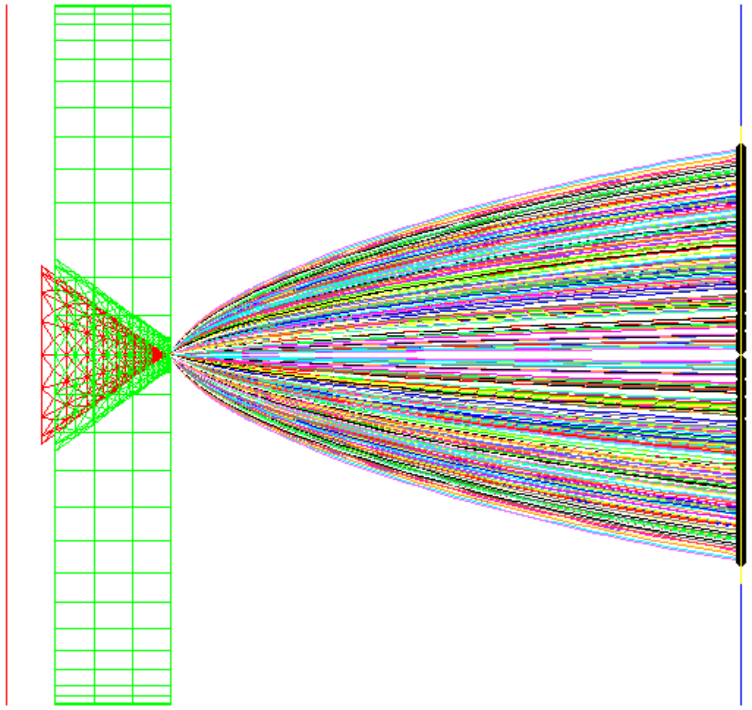




Needle cathode work is showing the way

Individual field emitters provide electron beams with exquisite brightness





Measured current ~ 15 μA

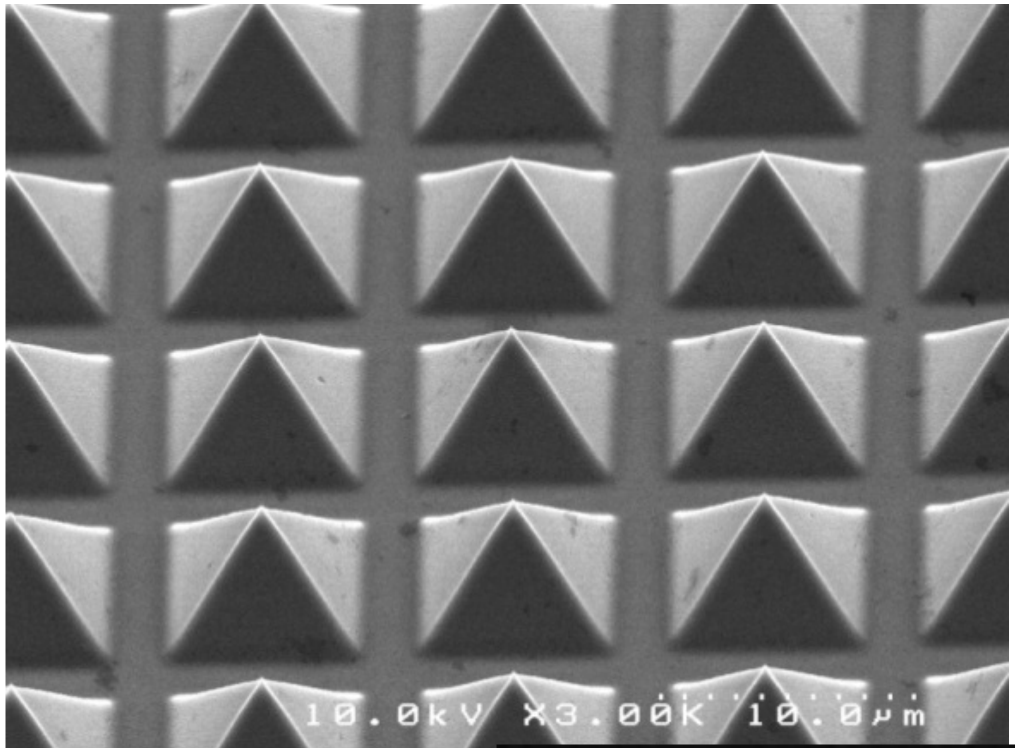
Simulations indicate normalized emittance ~ 1.3 nm

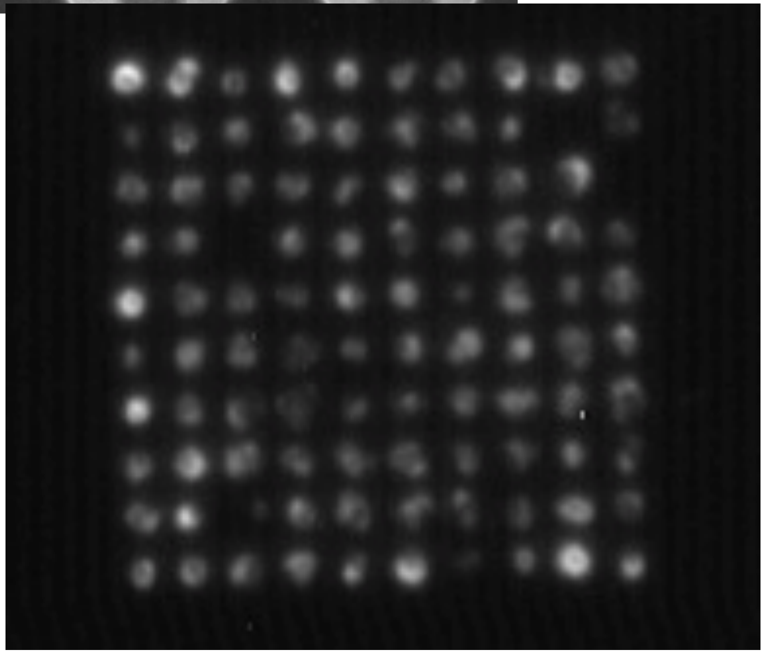
(Mostly spherical aberration)

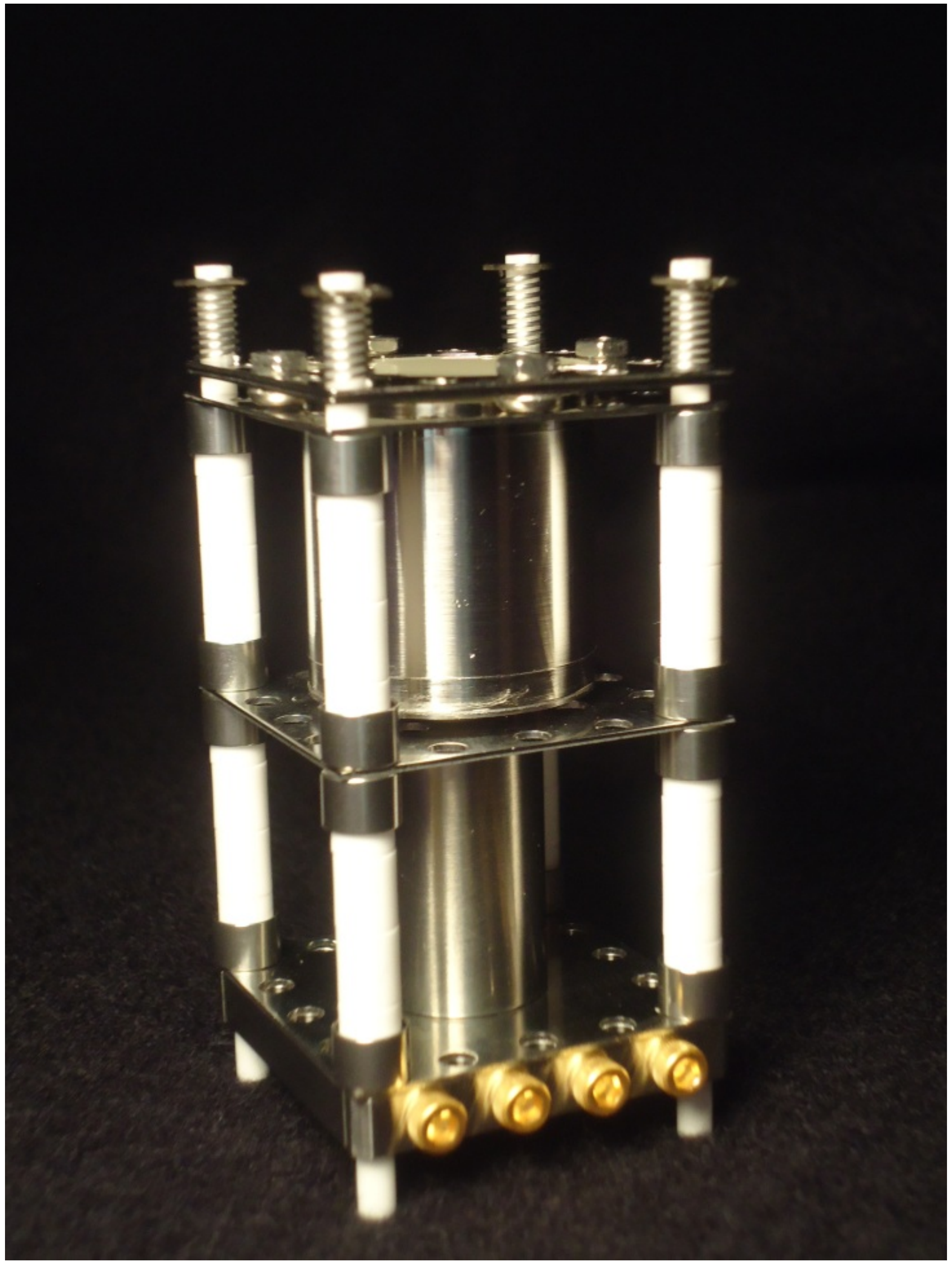
Heisenberg limit ~ 1 pm possible from ungated tip

C. Brau

Arrays of diamond emitters are being produced and tested for other applications





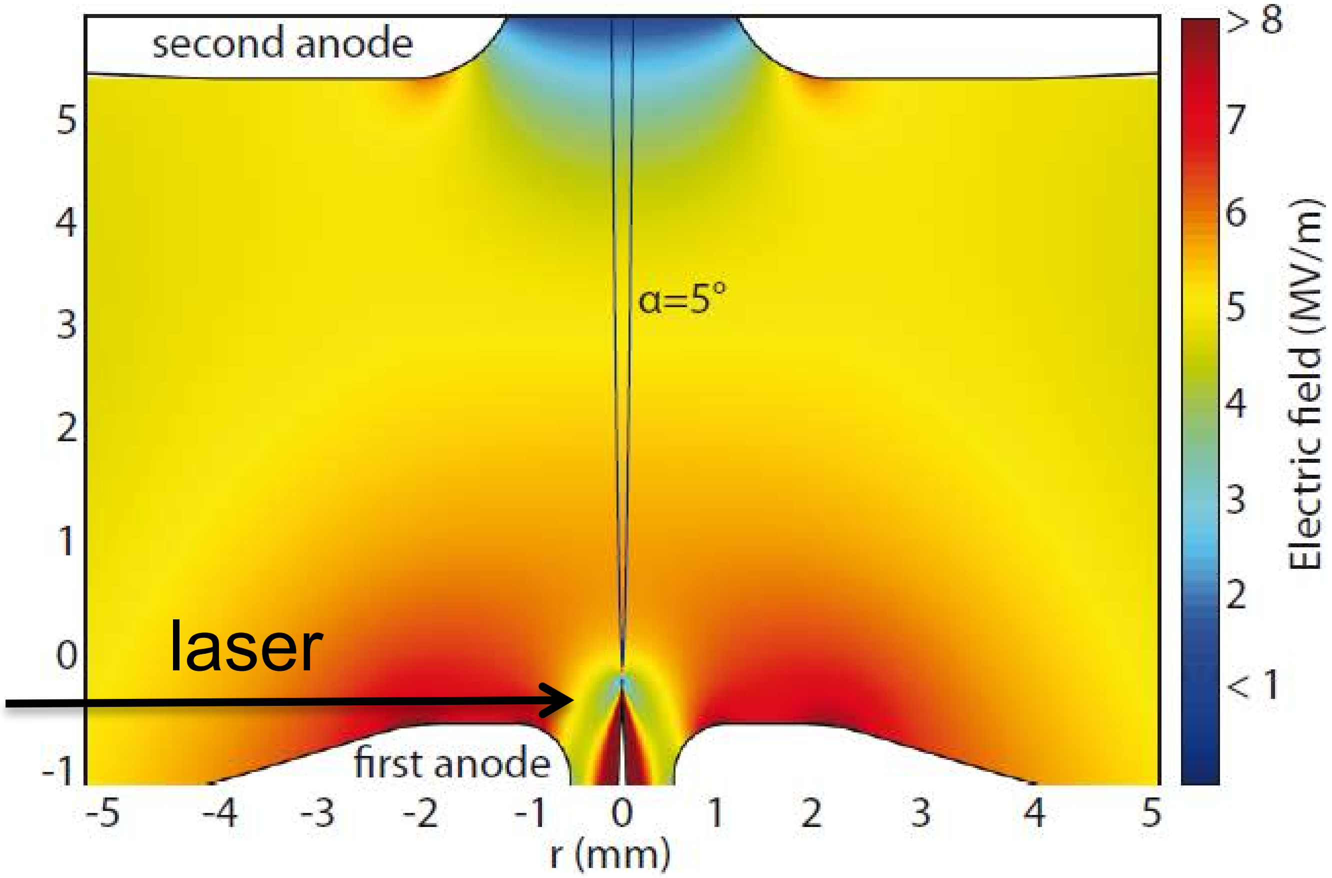


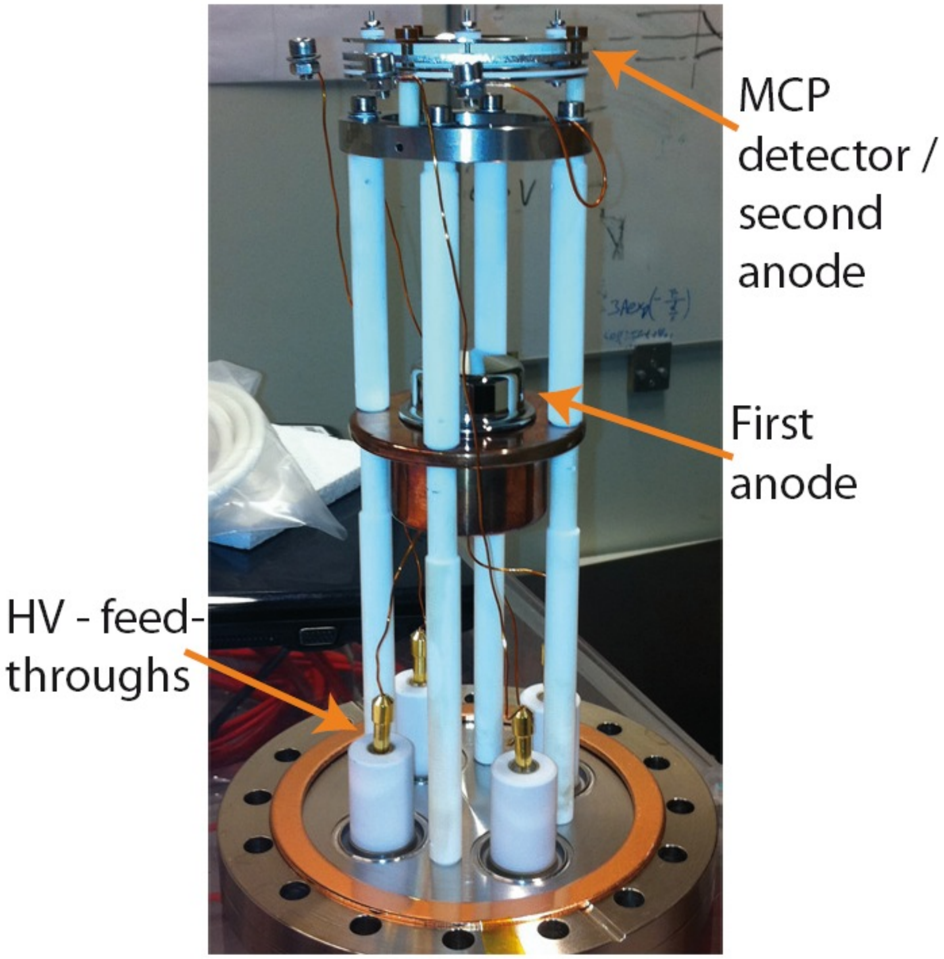
C. Brau

Highly controlled, needle cathode guns are being created with relevant beam parameters for DLAs

Dr. Peter Hommelhoff, Johannes Hoffrogge, (MPQ)

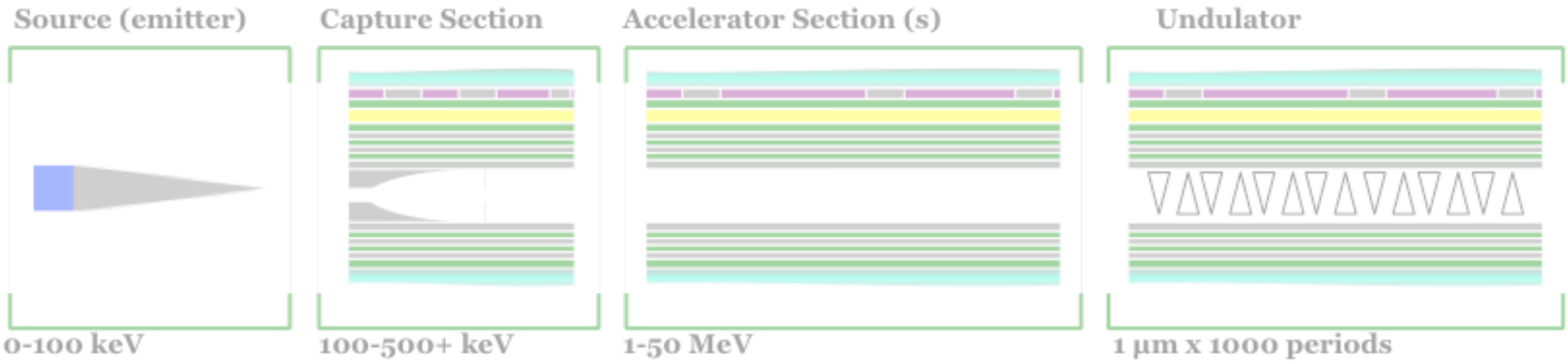
- Optimized 30 keV structure found with the help of FDTD eletric field simulations and particle tracking. Result:



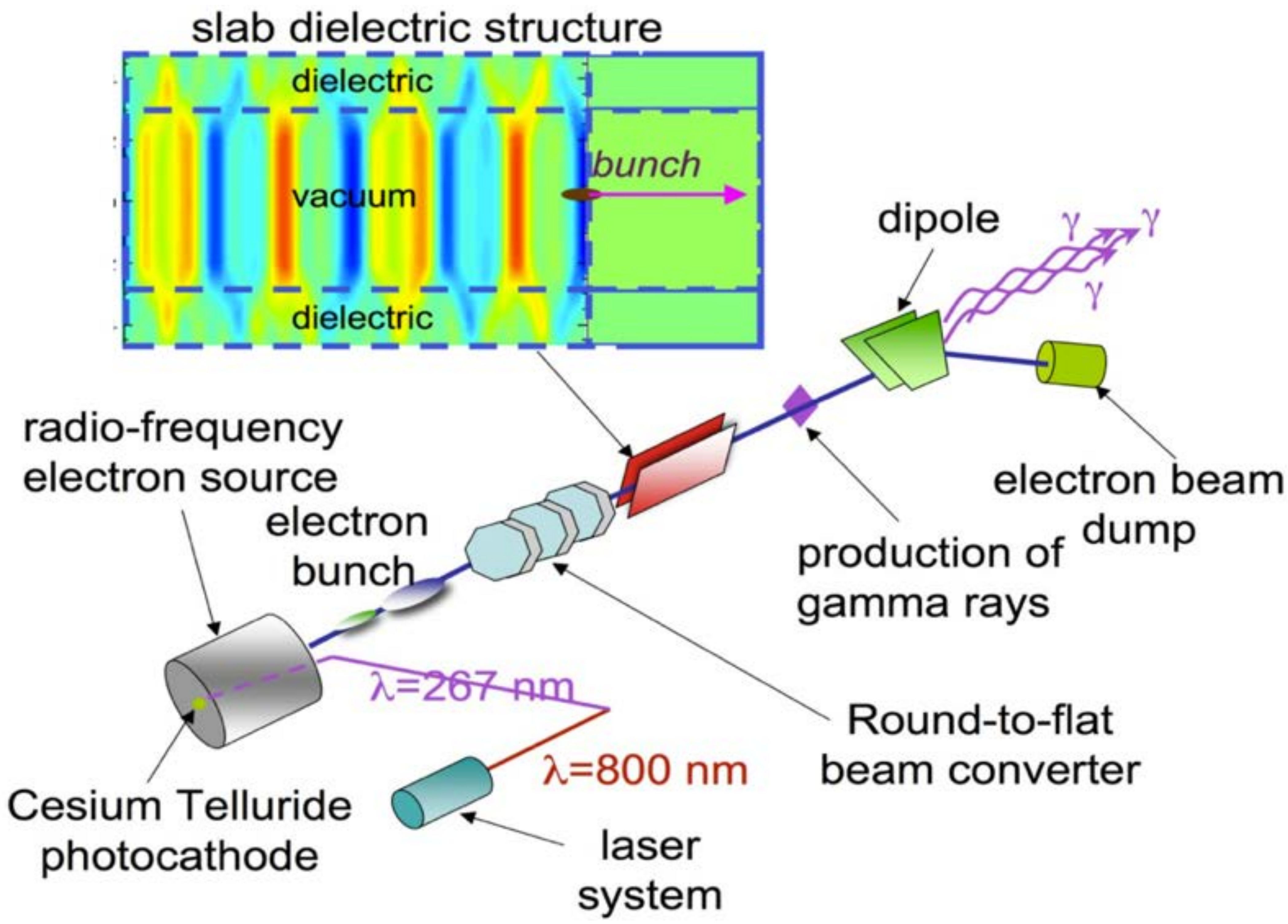


Tip pointing through one anode, with second anode a few mm away (left). With this geometry, the field on electrons' path never drops below ~4MV/m

Diagnostics & Optics ❻



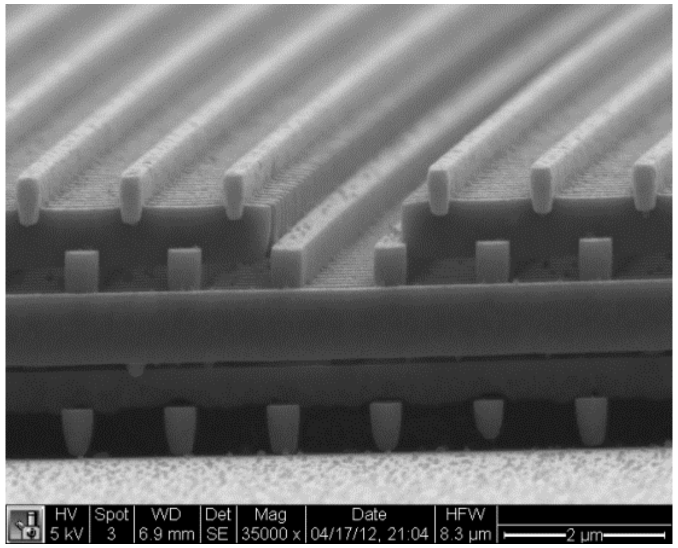
Beam manipulation including flat beam production is part of a wider effort to test novel structures

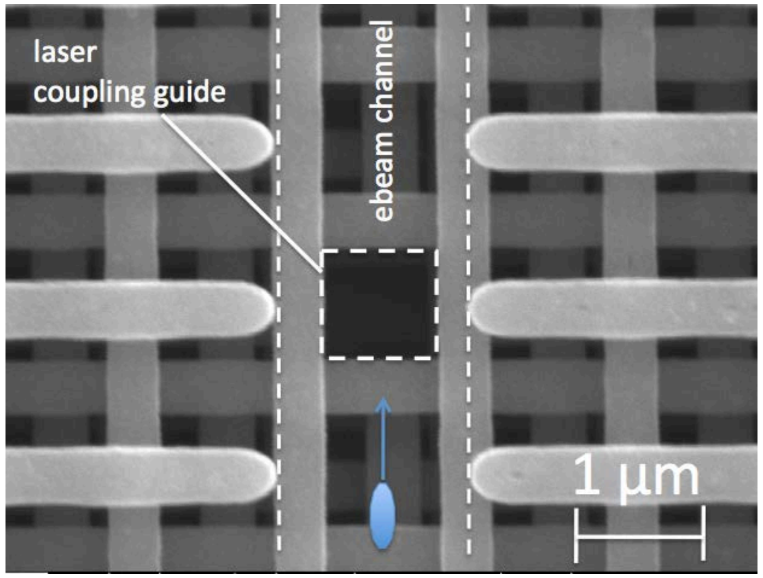


P. Piot & P. Stoltz

Optical-scale diagnostics, focusing elements, couplers and other components have been or are being built

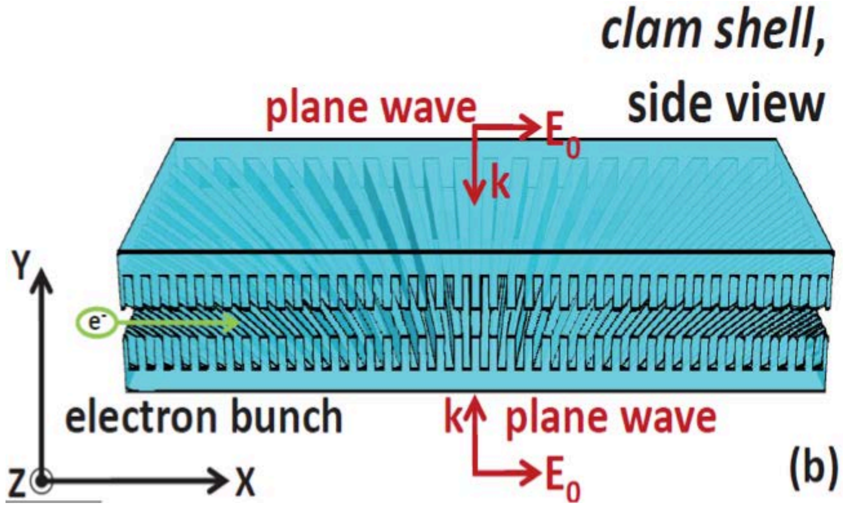
Efficient Coupler Designs



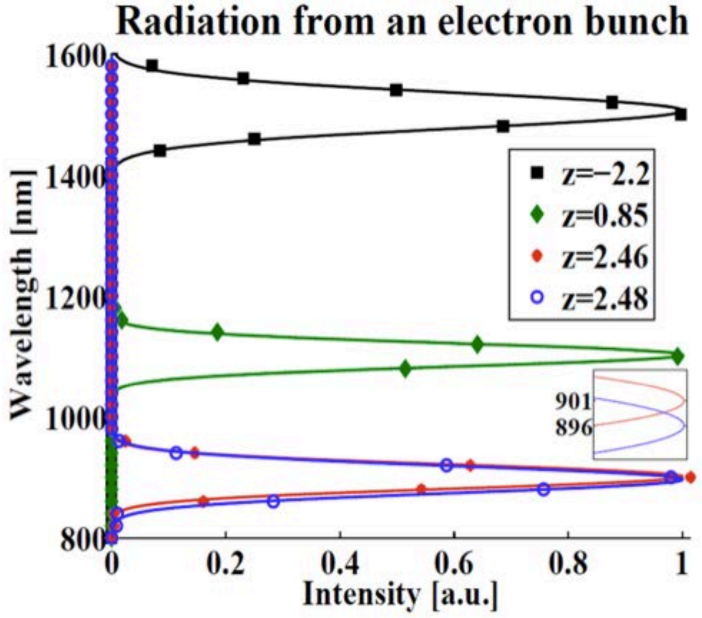


C. McGuinness. Z. Wu

BPMs



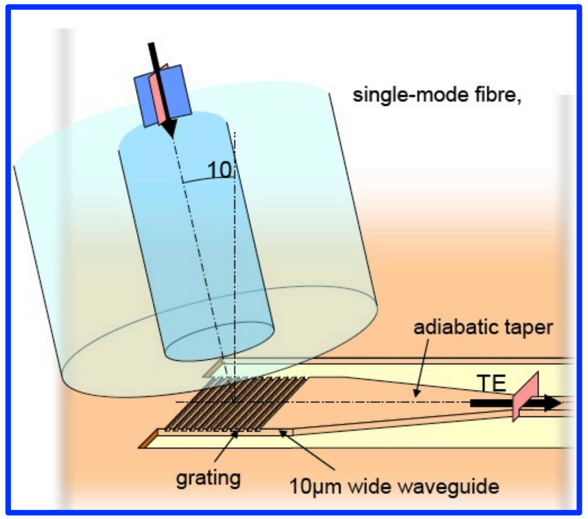
K. Soong

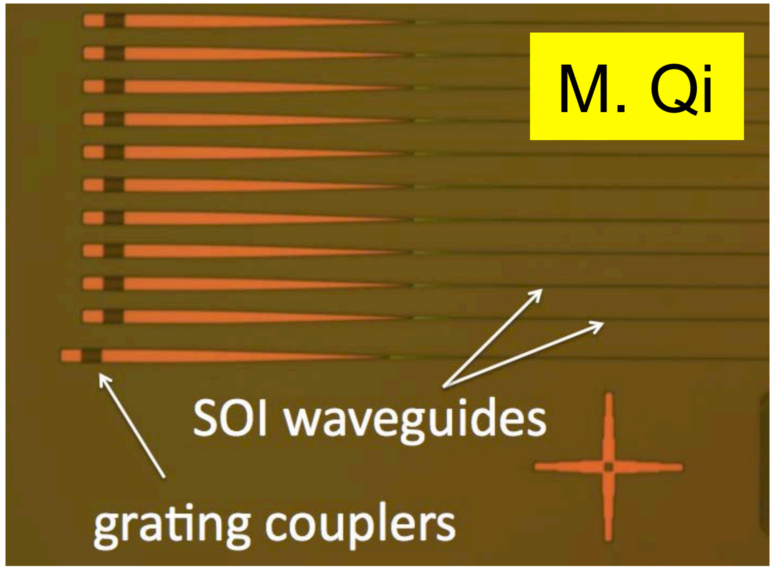


K. Soong, et al. *Optics Letters*, Vol. 37, Issue 5, pp. 975-977 (2012)

Fiber couplers Waveguide Networks

Taillaert, et al., JQE 38(7), p.949 (2002)



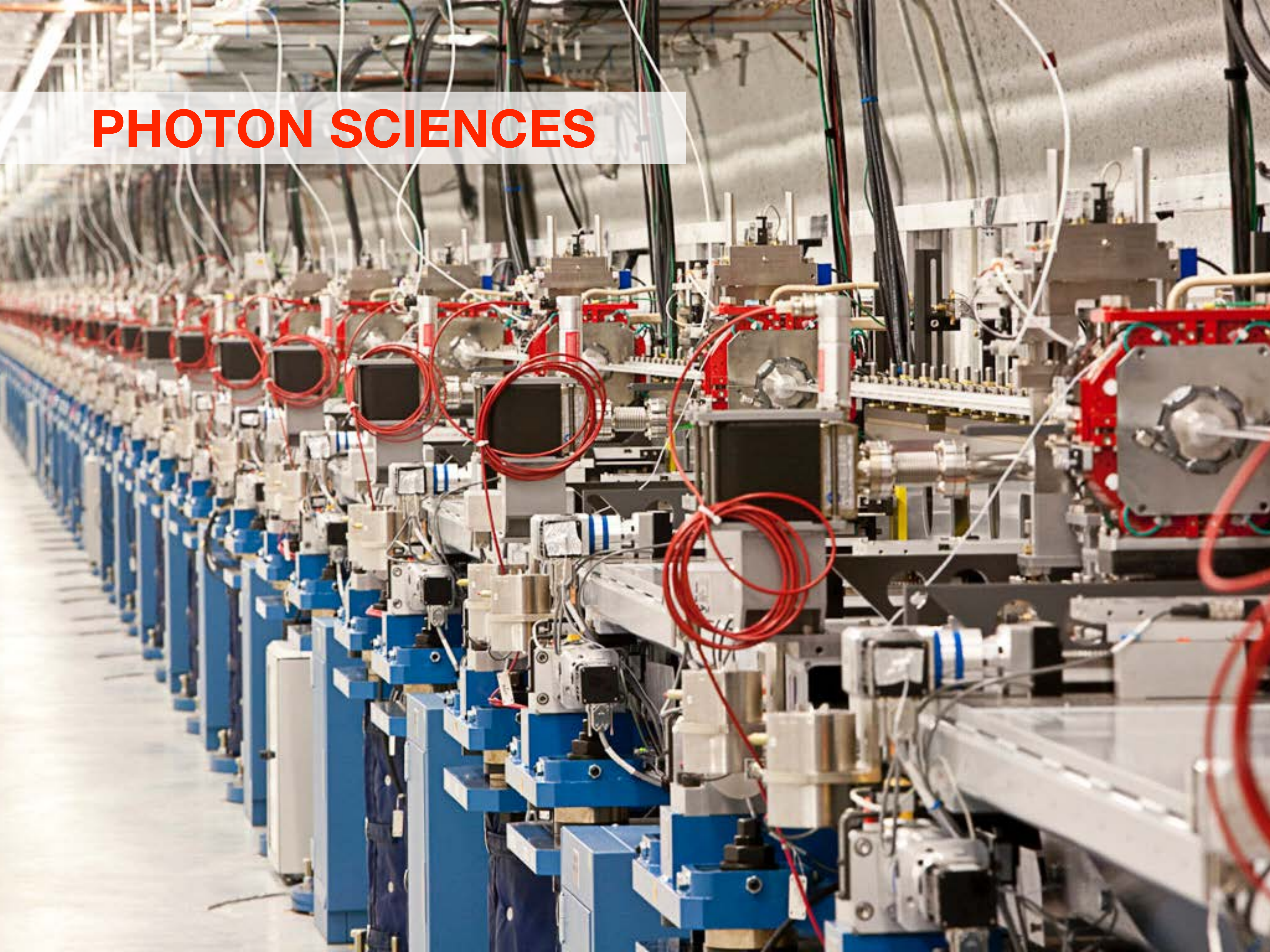


M. Qi

J. England

WE ARE TOOL BUILDERS

PHOTON SCIENCES



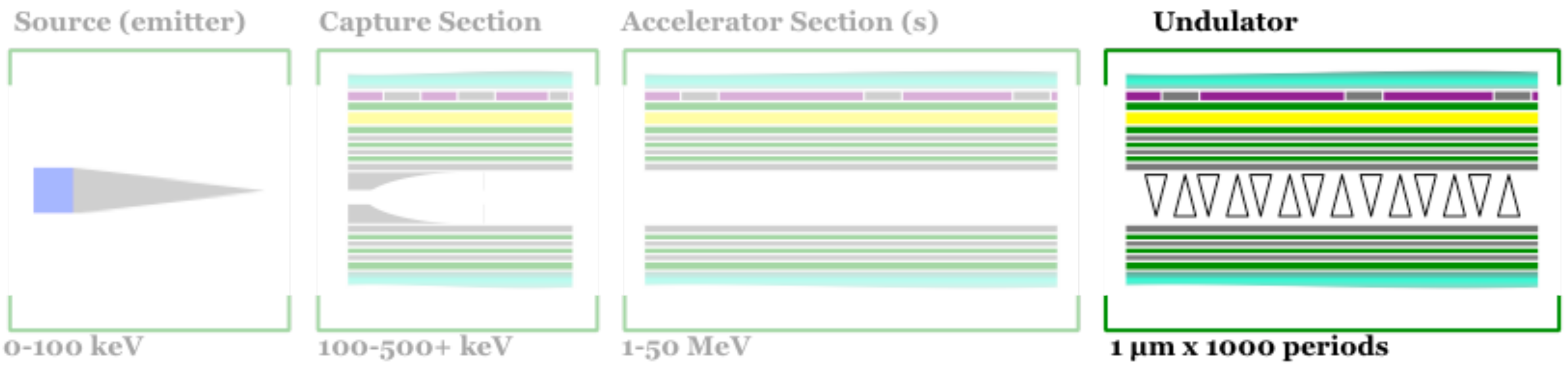
It is possible to have an all-laser-powered x-ray source using optical accelerator structures...

low energy	high energy
+	+
optical undulator	conventional undulator
=	=
QFEL	FEL but long

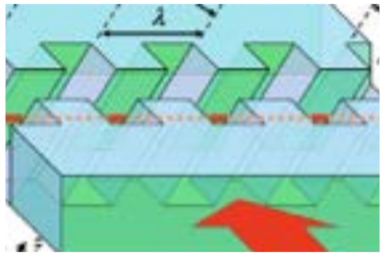
... but compromises must be made

Radiator Module

④

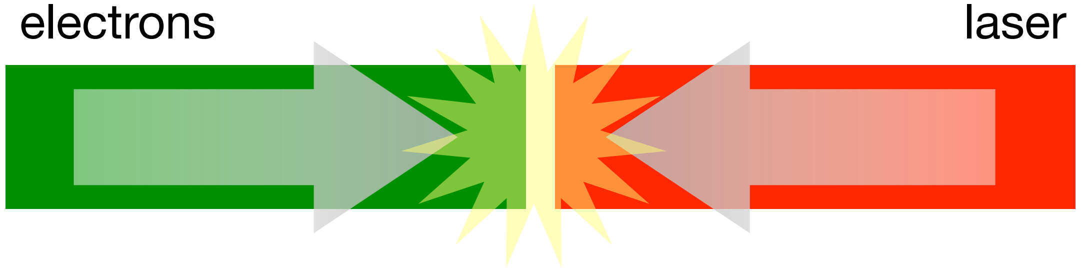


Undulator technology has significant impact on the FEL design



	PM	Opt. Struct.
Period	>1 cm	1-100+µm
Parameter	1-10	<<1
Gap	5 mm	1 µm
Status	mature	paper

This isn’t ICS where the laser spot and Gouy phase shift dominate



For free space, the “uniform” laser propagation length is set by the Rayleigh range

$$L_R = 2Z_R = 2\frac{\pi w_0^2}{\lambda}$$

In general, we take

$$L_R = L_L$$

Our baseline parameters:

$$\tau_L = 10\text{ ps} \Rightarrow \mathrm{L}_L = 3\text{ mm}$$

$$\lambda = 1\,\mu\text{m}$$

$$\varepsilon_n = 1\,\mu\text{m}$$

$$\mathrm{E}_b = 30\text{ MeV}$$

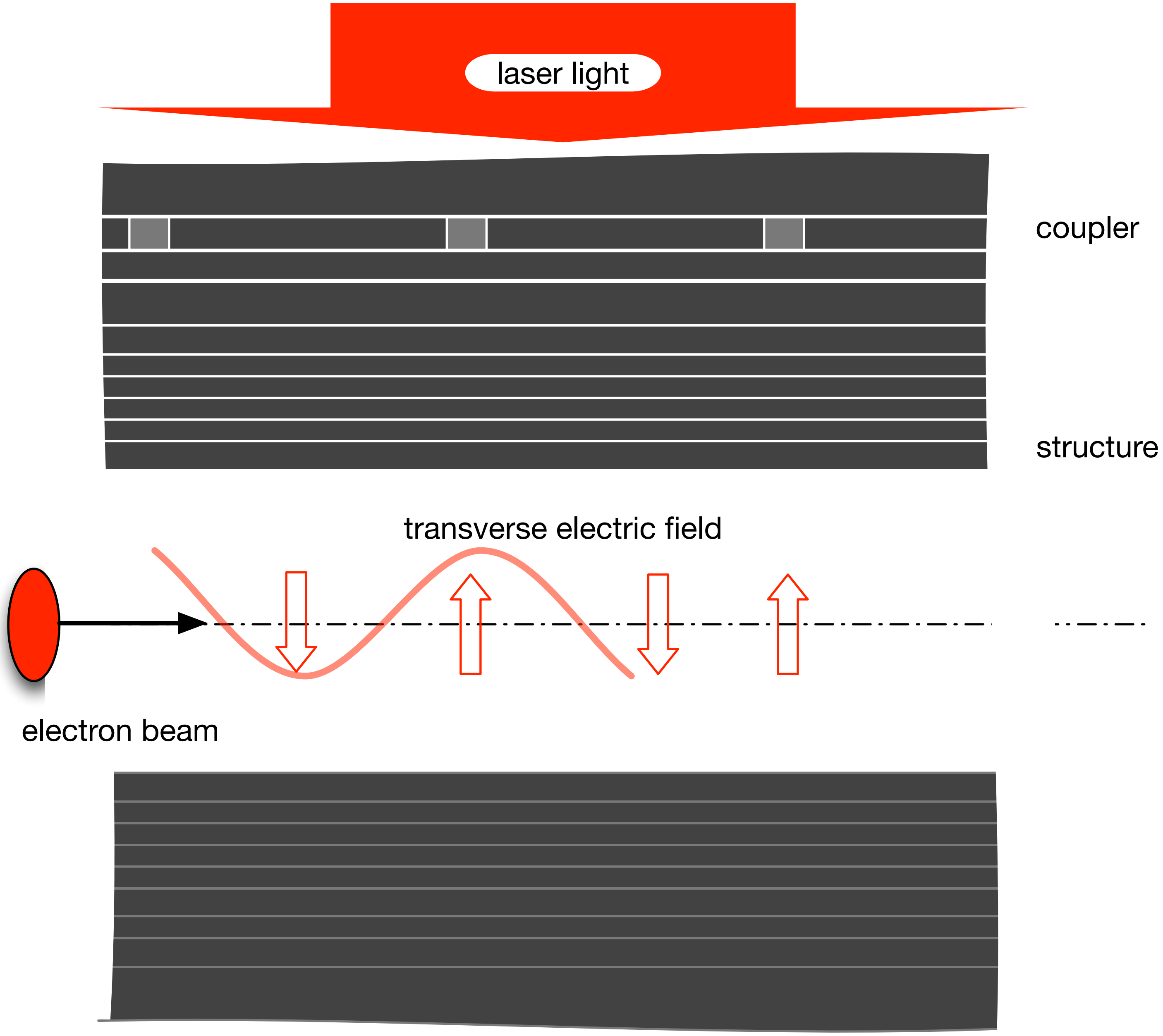
For our example case:

$$2w_0 \approx 40\,\mu\text{m}$$

So, the laser beam limits the spot size here:

$$\varepsilon = \varepsilon_n/\gamma \ll \lambda$$

Here the field is guided and forms a uniform, long undulator. FEL action is used.



very short

very small

$$\lambda_r = \frac{\lambda_u}{2\gamma^2}\left(1 + K^2\right)$$

low

Small period means small K:

$$K = \frac{F\lambda_u}{2\pi mc^2}$$

Focusing is an additional issue:

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

A iPad-scale soft x-ray light source powered entirely by lasers seems possible

Parameter	Value
Wavelength	6 nm
Beam energy	50 MeV
Emittance (norm.)	0.06 µm
Current	2000 A
Charge	160 fC
Undulator parameter	0.11
Undulator period	120 µm
Saturation length	125 mm
X-ray flux/bunch	~10

(wow!)

(resistive wall? wakes?)

(whew! ~10^6 e^-)

A hard x-ray light source powered entirely by lasers and on a tabletop scale would be a QFEL

Parameter	Value	
FEL Wavelength	~1 Å	
Beam energy	~110 MeV	
Emittance (norm.)	0.01 μm	(LOL!)
Current	2000 A	(resistive wall?wakes?)
Charge	1 fC	(whew! ~10^4 e^-)
FEL Parameter (ρ)	**10**	
Undulator parameter	**2 x 10**	
Undulator period	10 μm	
Saturation length	~5 cm	

$$\hbar\omega / E \sim 10^{-4}$$

The quantum regime of the FEL has positive implications for the spectrum; negative for the flux

---

Photon energy: $\hbar\omega$

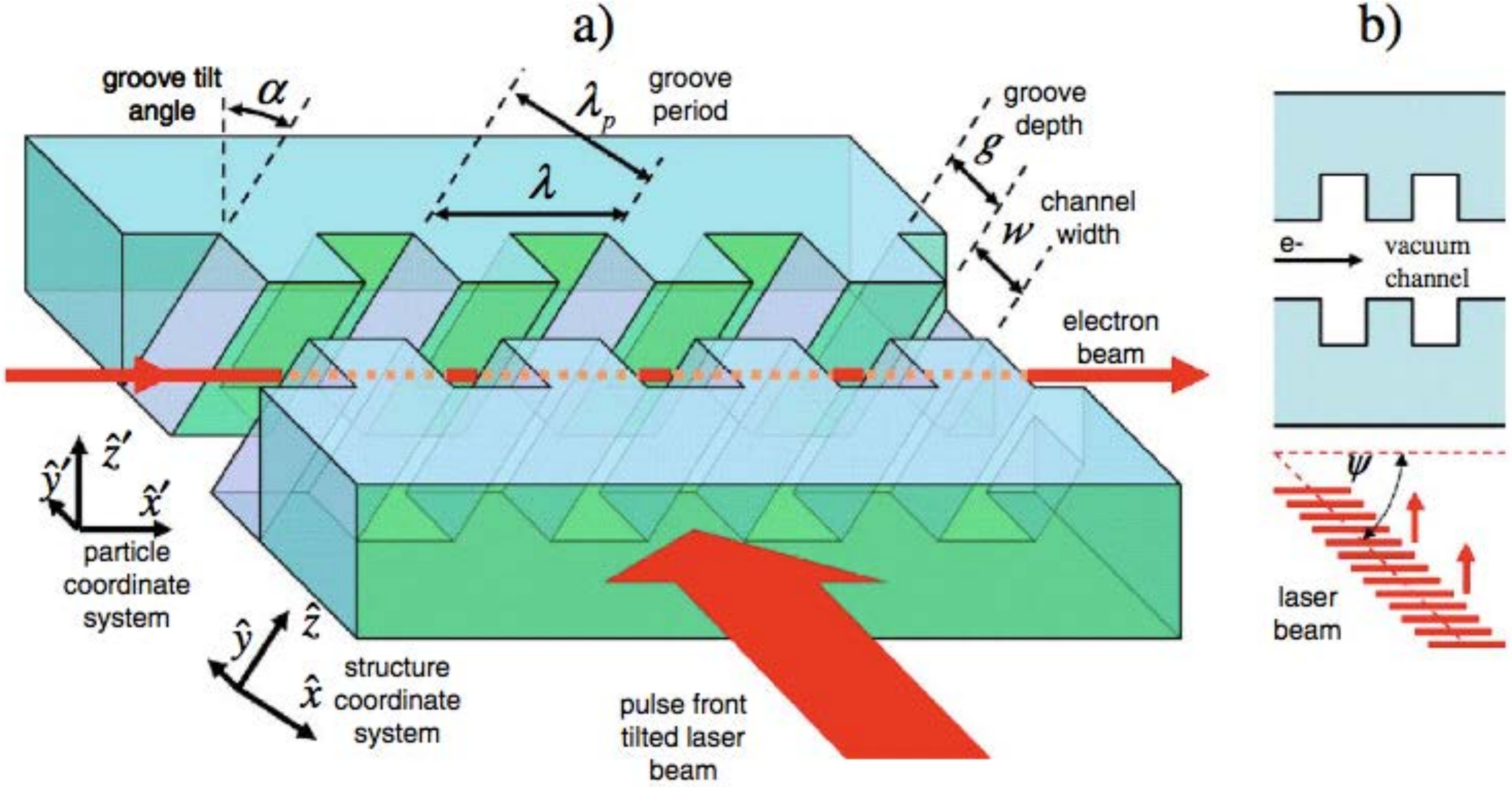
Beam energy: E

FEL bandwidth: $\Delta\omega/\omega \sim \rho$

When the recoil energy loss is greater than the FEL bandwidth, the quantum regime dominates and the emission spectral bandwidth is very narrow

$$\hbar\omega \,/\, E > \Delta\omega/\omega \sim \rho$$

A grating based undulator can produce an intermediate-period device

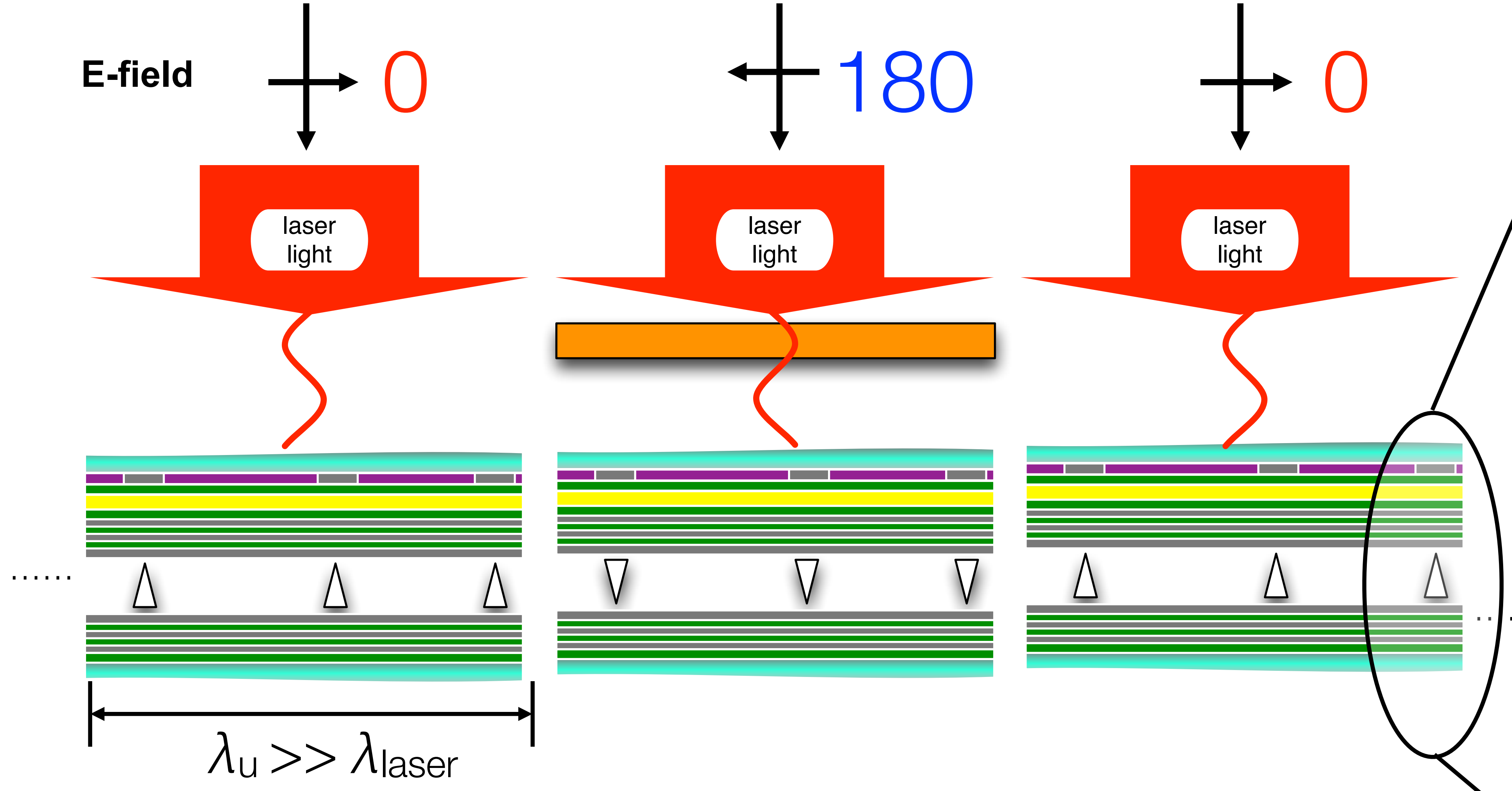


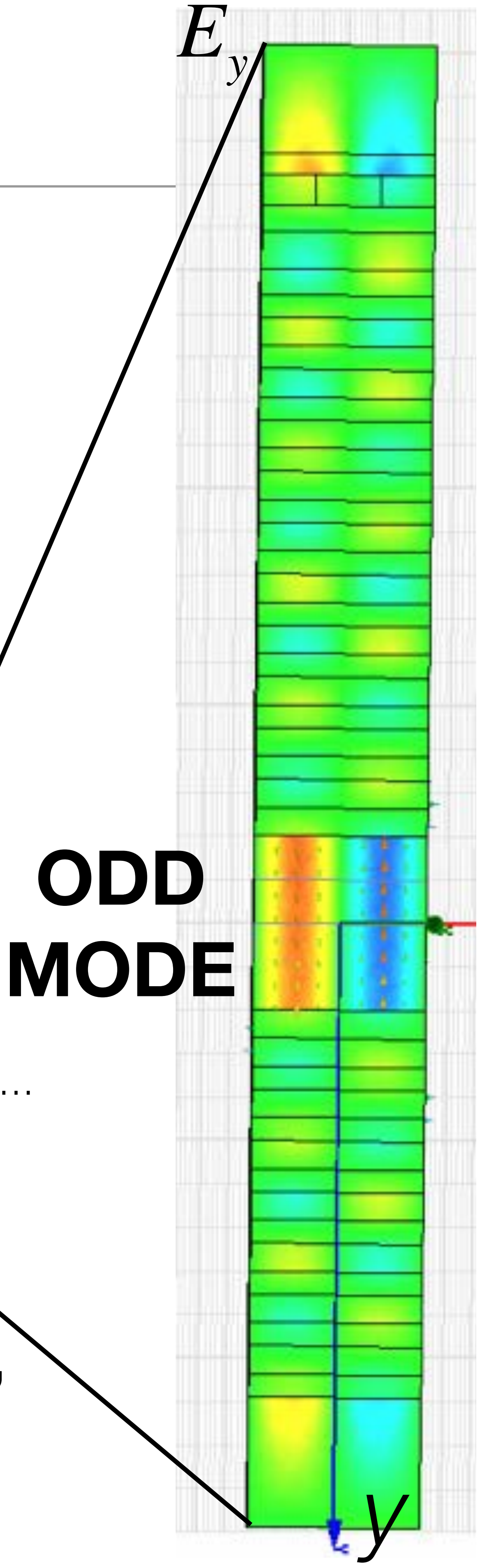
Plettner and Byer, Phys. Rev. ST Accel. Beams 11, 030704 (2008)

A MAP-based **undulator** structure has been designed

Undulator Period = Laser Phase Flip

waveplates used to control phase



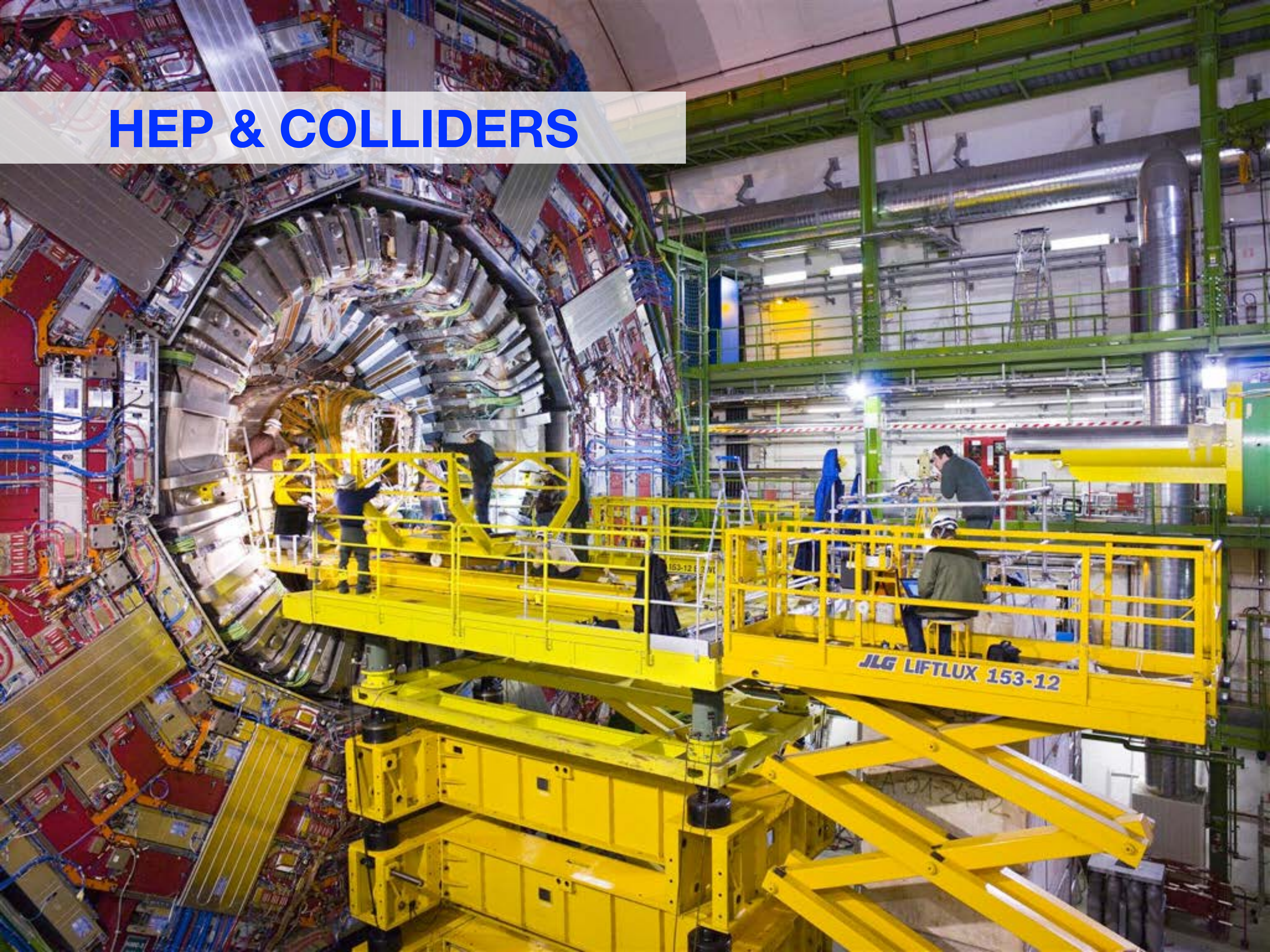


$$\lambda_u = 2n\lambda_{laser}$$

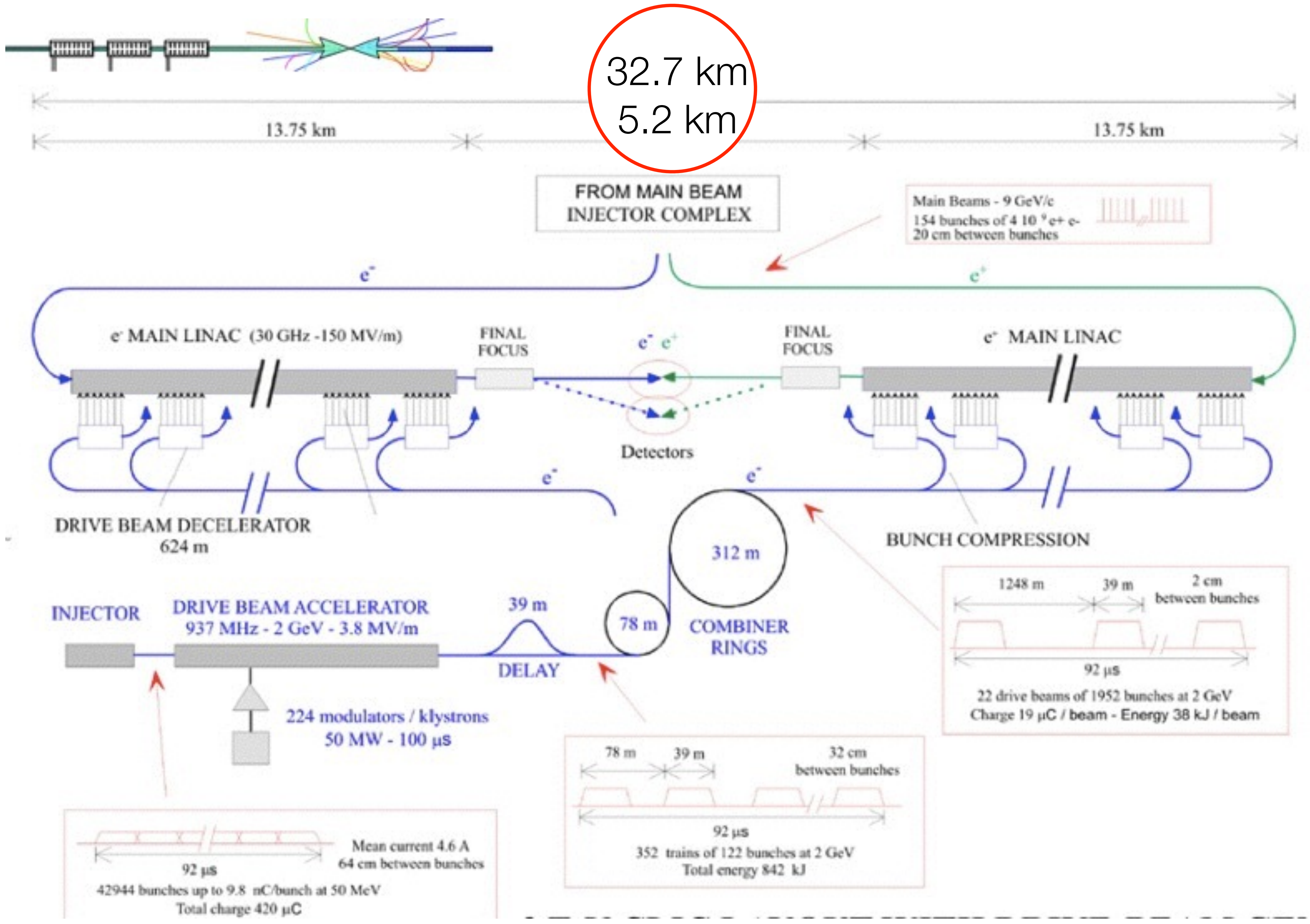
$$K = \frac{F\lambda_u}{2\pi mc^2}$$

For E=3 GV/m, B_{eqv}=10 Tesla

HEP & COLLIDERS



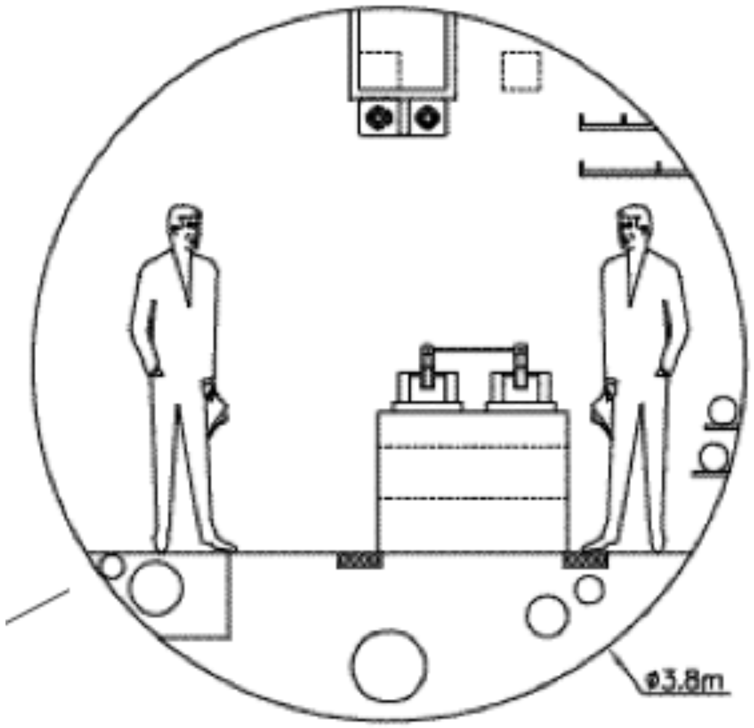
High gradient acceleration only does a little to change the demands



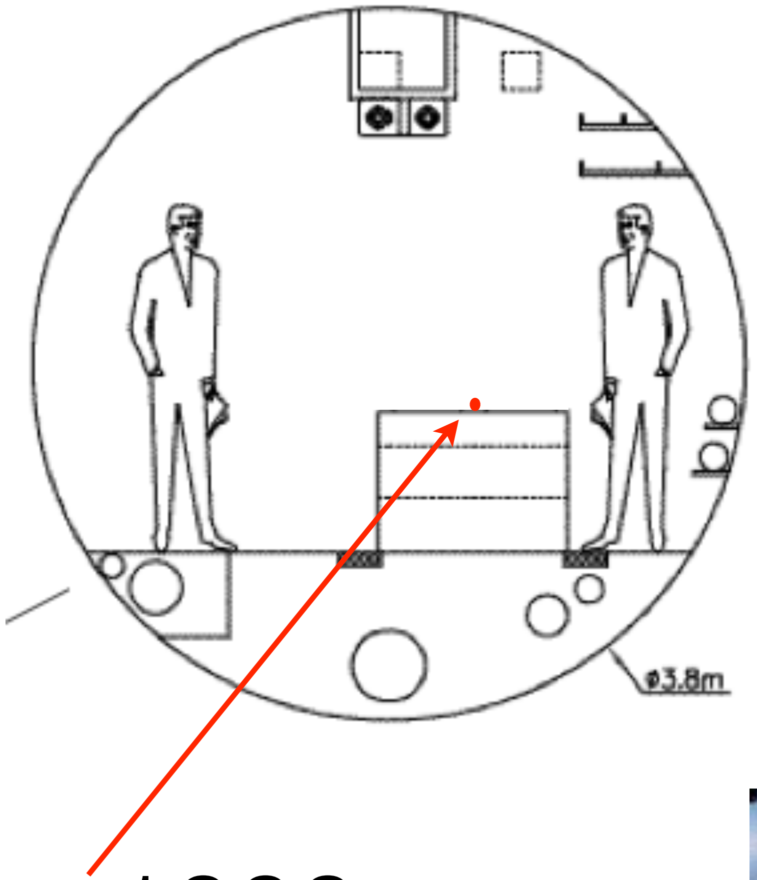
J.P.Delahaye

Conventional facilities designs may not transfer over and we have little experience with km optical scale structures

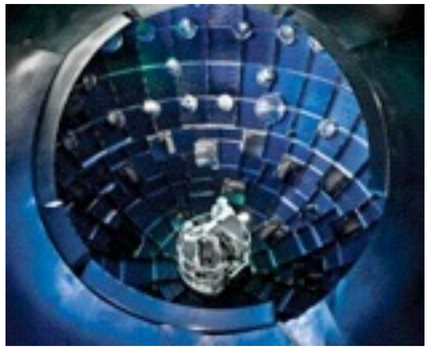
CLIC Tunnel



DLA Tunnel



DLA x 1000



NIF & LIGO may be useful guides

Beamstrahlung and beam disruption favors low charge per bunch...

For flat beams

$$D \approx 2r_e \frac{\sigma_z}{\gamma\sigma_x\sigma_y} N$$

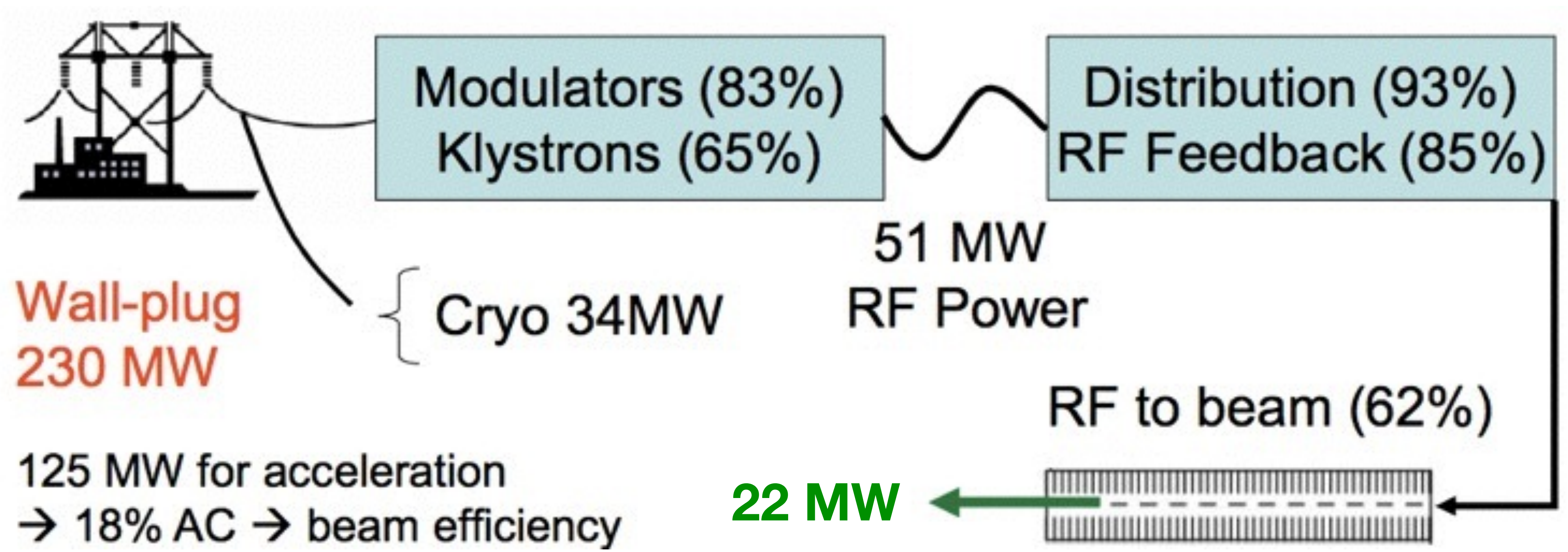
For D<<1, we can have luminosity enhancement

Reference beamstrahlung parameter:

$$\Upsilon_0 = \frac{r_e \lambda\!\!\!^{-}{}_c}{\sqrt{2\pi}} \frac{\Gamma}{\sigma_r \sigma_z} N$$

complicated interplay... but low N is generally favored

Efficiency is a concern in any collider.



Modulators (83%)
Klystrons (65%)

Distribution (93%)
RF Feedback (85%)

51 MW
RF Power

Wall-plug
230 MW

Cryo 34MW

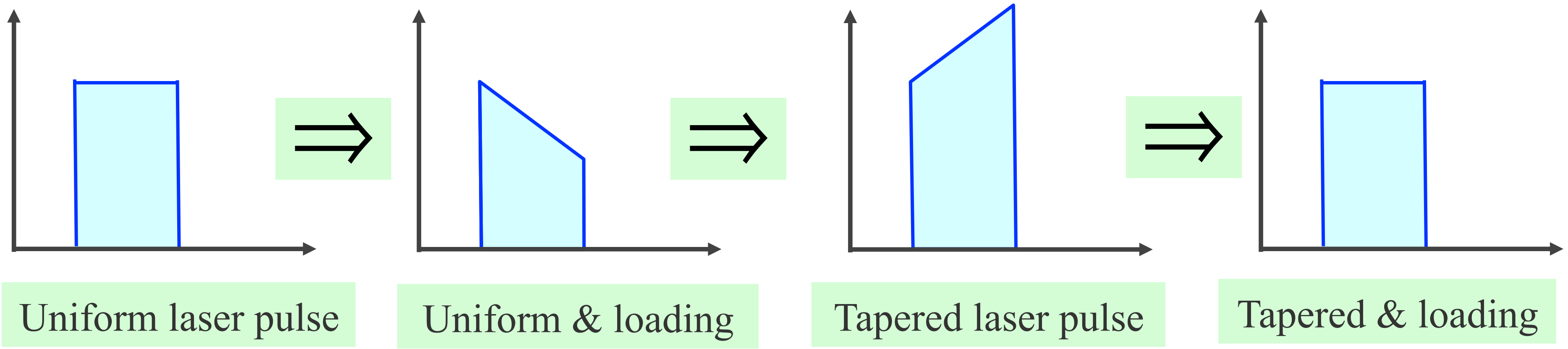
RF to beam (62%)

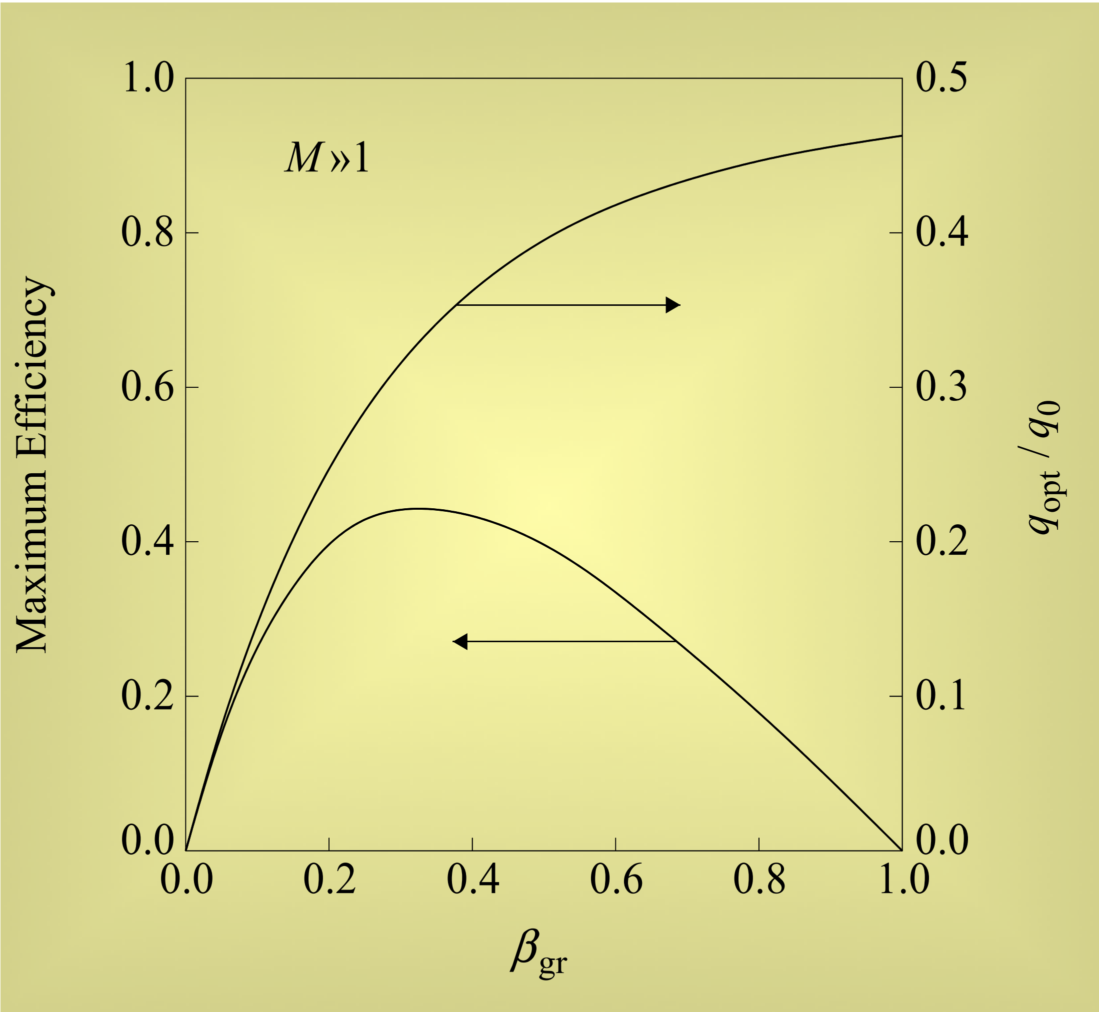
22 MW

125 MW for acceleration
→ 18% AC → beam efficiency

T. Raubenheimer

In a TW structure, beam loading is not sufficient to produce high efficiency


Uniform laser pulse ⇒ Uniform & loading ⇒ Tapered laser pulse ⇒ Tapered & loading



Still we have a problem: wake propagates at *c* whereas laser's envelope propagates at $c\beta_{gr}$.
Solution: $M\lambda=d$

In spite of splitting the macro-bunch, there still is 50% waste of laser energy ==>feedback loop.

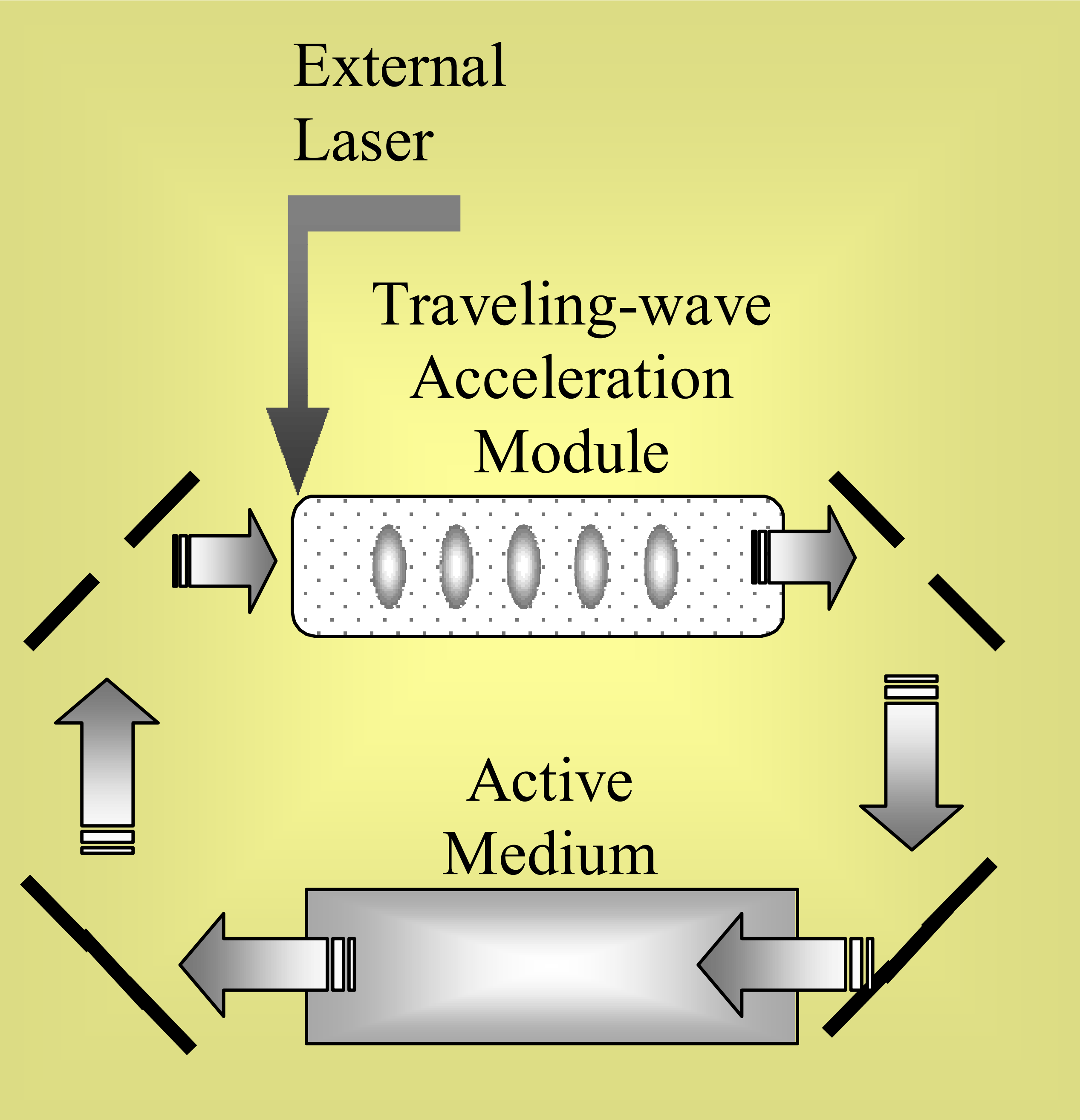
L. Schächter

It may be possible to use the wakefield from the bunch train to accelerate trailing bunches

Long train of bunches
→ Quasi-coherent wake
→ Feedback (filter + amplifier)

Conditions for self-consistent field:

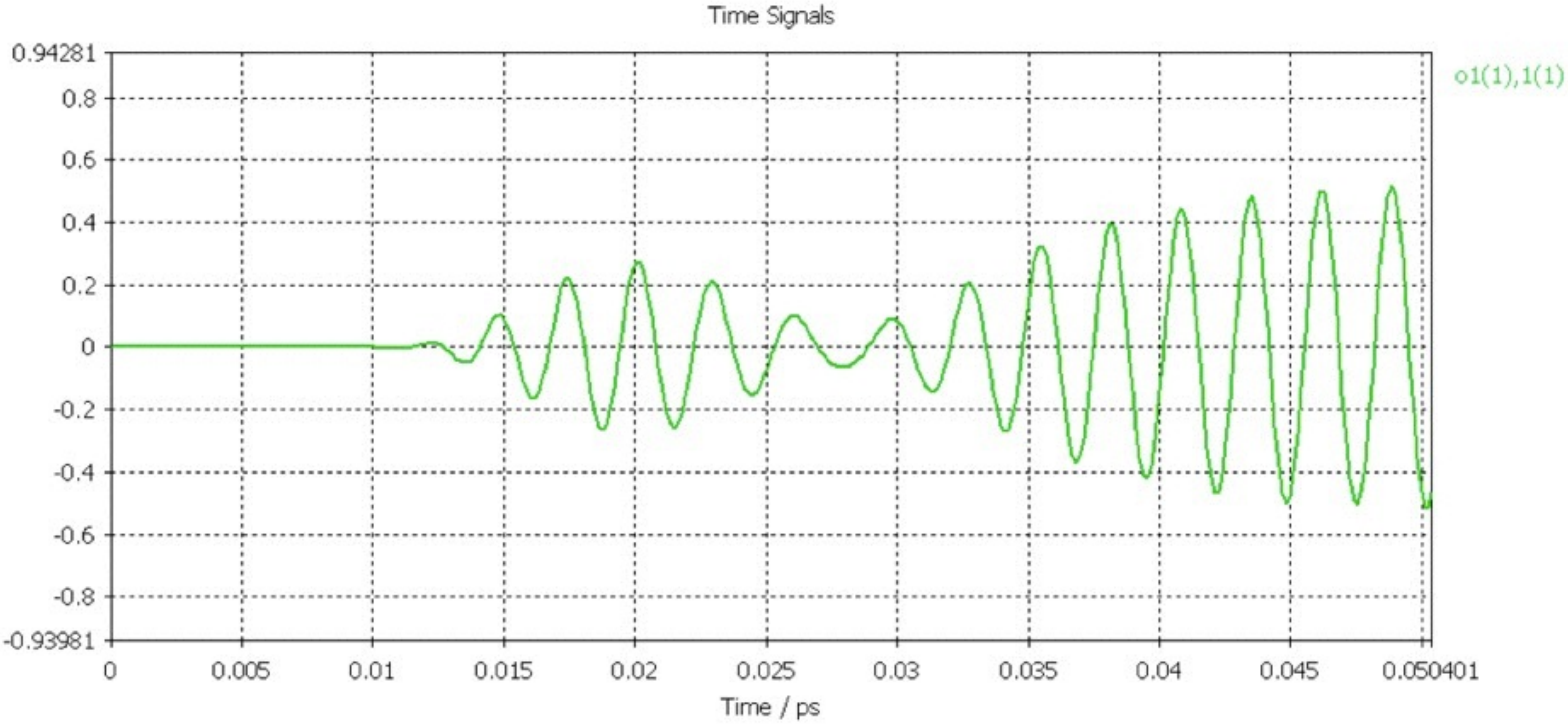
1. Amplifier compensates for all **radiation loss**
2. External laser compensates for **beam-loading**



L. Schächter

Preliminary studies of coupling show a path from low to >70% coupling efficiency.

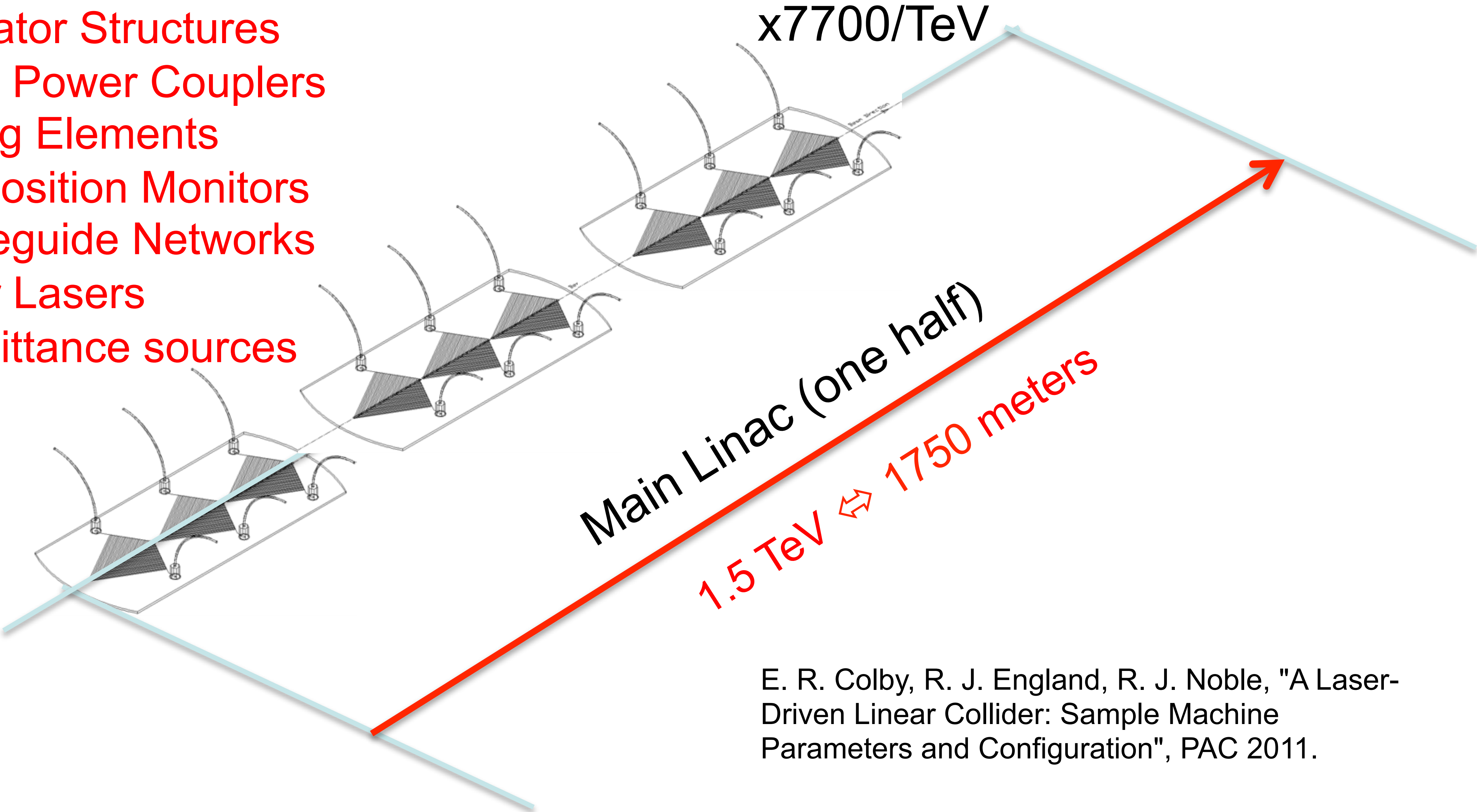
$$\text{Cavity Field/Incoming Field} = 1 - |S11|^2$$



Staging of DLAs has been conceptually considered; much work remains.

Train of Integrated Modules on Silicon Wafers

Accelerator Structures
Efficient Power Couplers
Focusing Elements
Beam Position Monitors
IR Waveguide Networks
IR Fiber Lasers
Low-emittance sources
...



E. R. Colby, R. J. England, R. J. Noble, "A Laser-Driven Linear Collider: Sample Machine Parameters and Configuration", PAC 2011.

The road to a viable DLA-based accelerator for applications is still long, and someone needs to pay.

reliable many-period acceleration

staging

tolerances & alignment

beam manipulation

injection

positrons

polarized beams

radiation damage

thermal management

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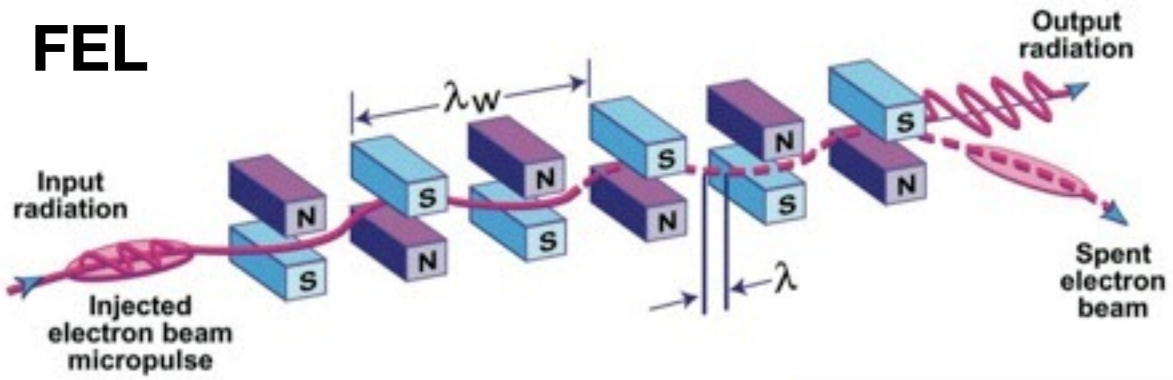
INDUSTRIAL & DEFENSE

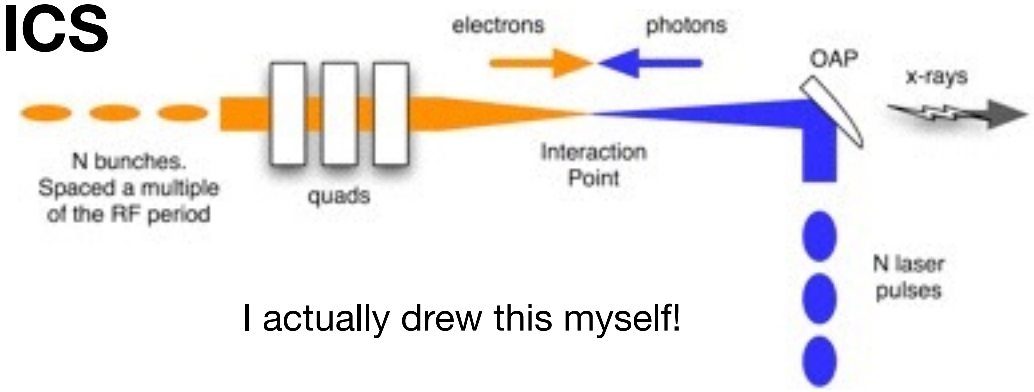
There are numerous applications where modest beam energies in a compact system are desired

FEL



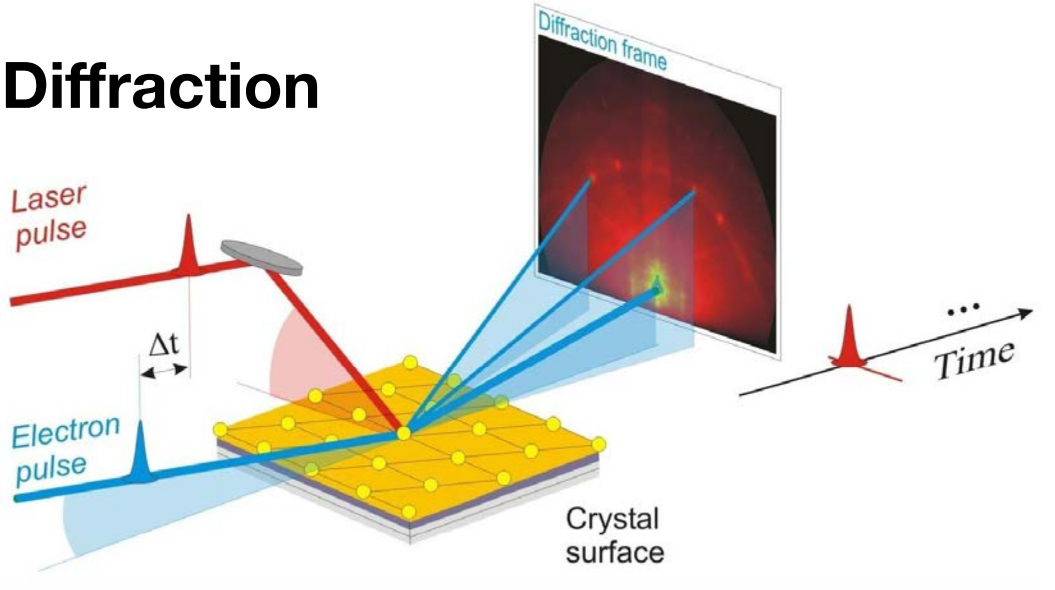
P. O'Shea et al.
Science (2001).

ICS



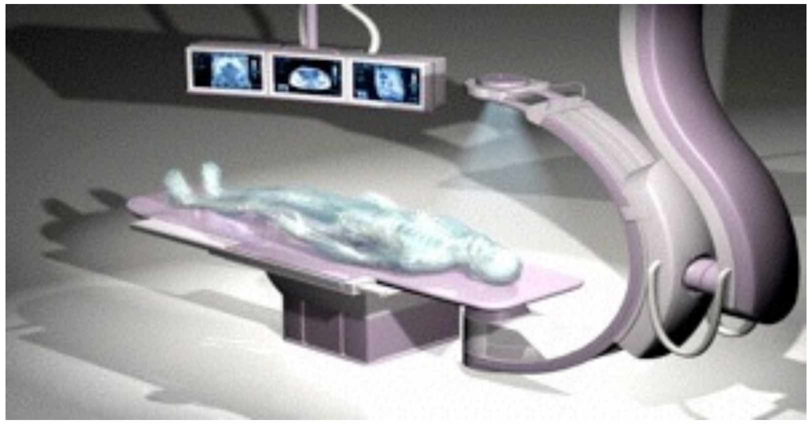
I actually drew this myself!

Diffraction



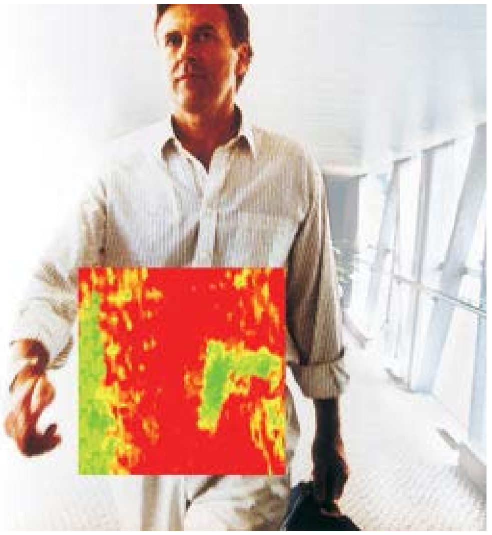
P. Musumeci (UCLA)

Diagnostic x-ray



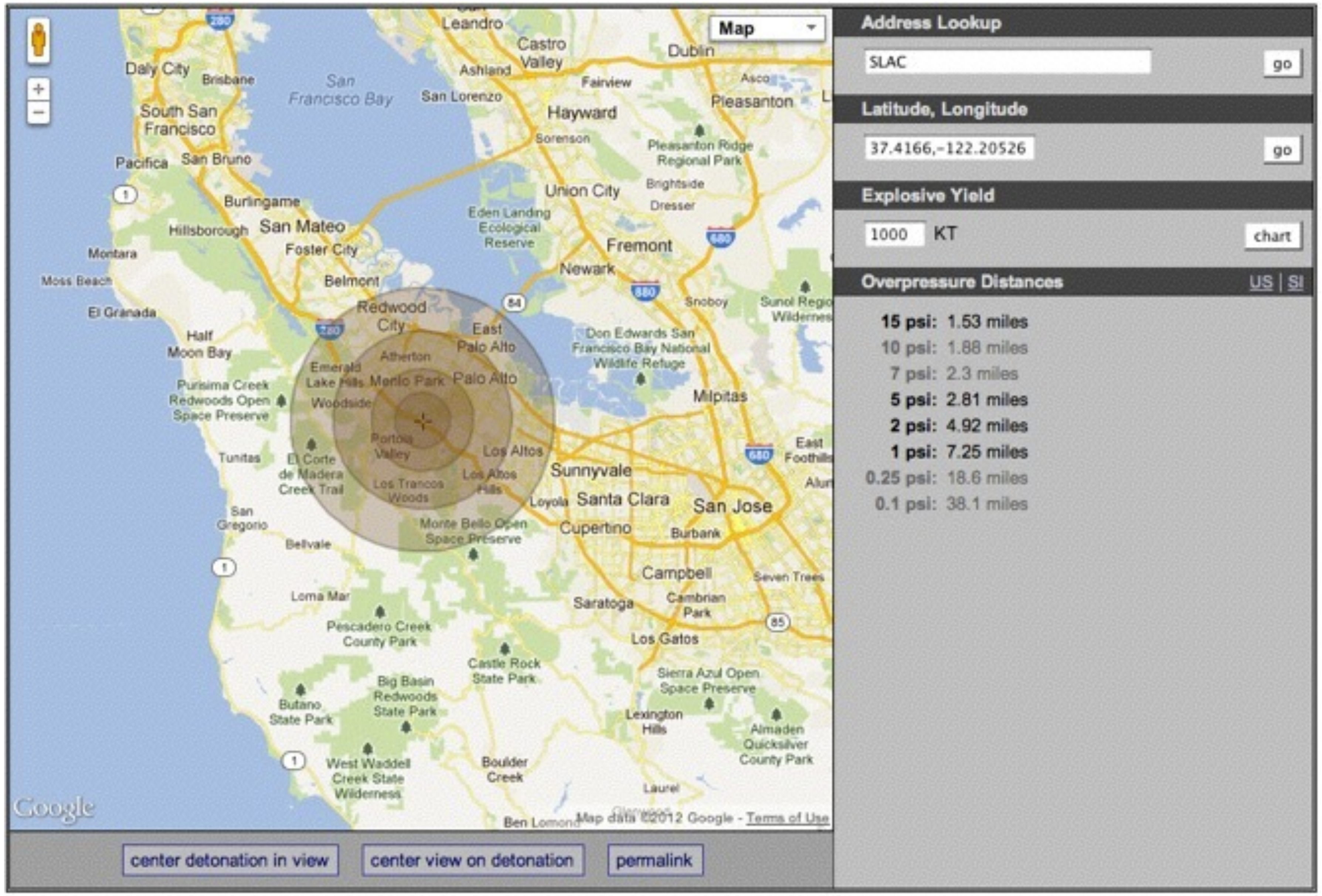
Random web image

THz



THzNetwork.org

“Evil doers” obtaining Special Nuclear Materials (SNR) is considered a high likelihood.



Address Lookup

SLAC

Latitude, Longitude

37.4166,-122.20526

Explosive Yield

1000 KT

Overpressure Distances

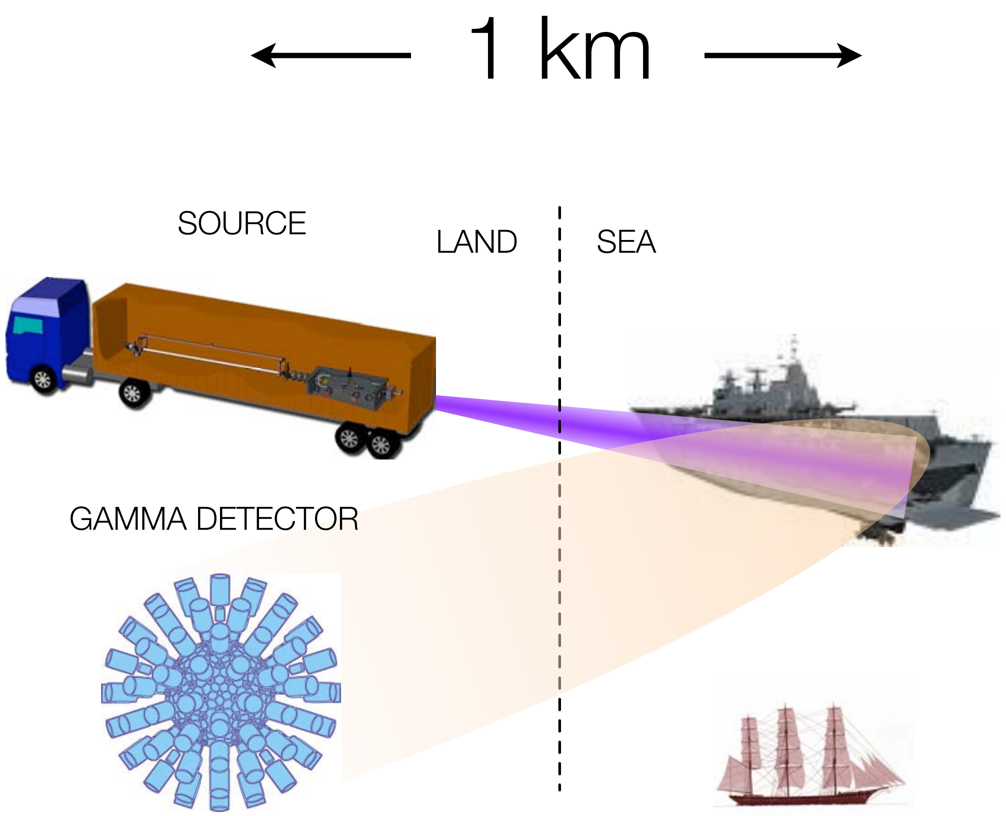
15 psi: 1.53 miles
10 psi: 1.88 miles
7 psi: 2.3 miles
5 psi: 2.81 miles
2 psi: 4.92 miles
1 psi: 7.25 miles
0.25 psi: 18.6 miles
0.1 psi: 38.1 miles

In this post-Cold War world, nuclear terrorism may be the single most catastrophic threat that any nation faces - we must do everything we can to ensure against its occurrence.

-- Joseph Krol, Associate Administrator, NNSA

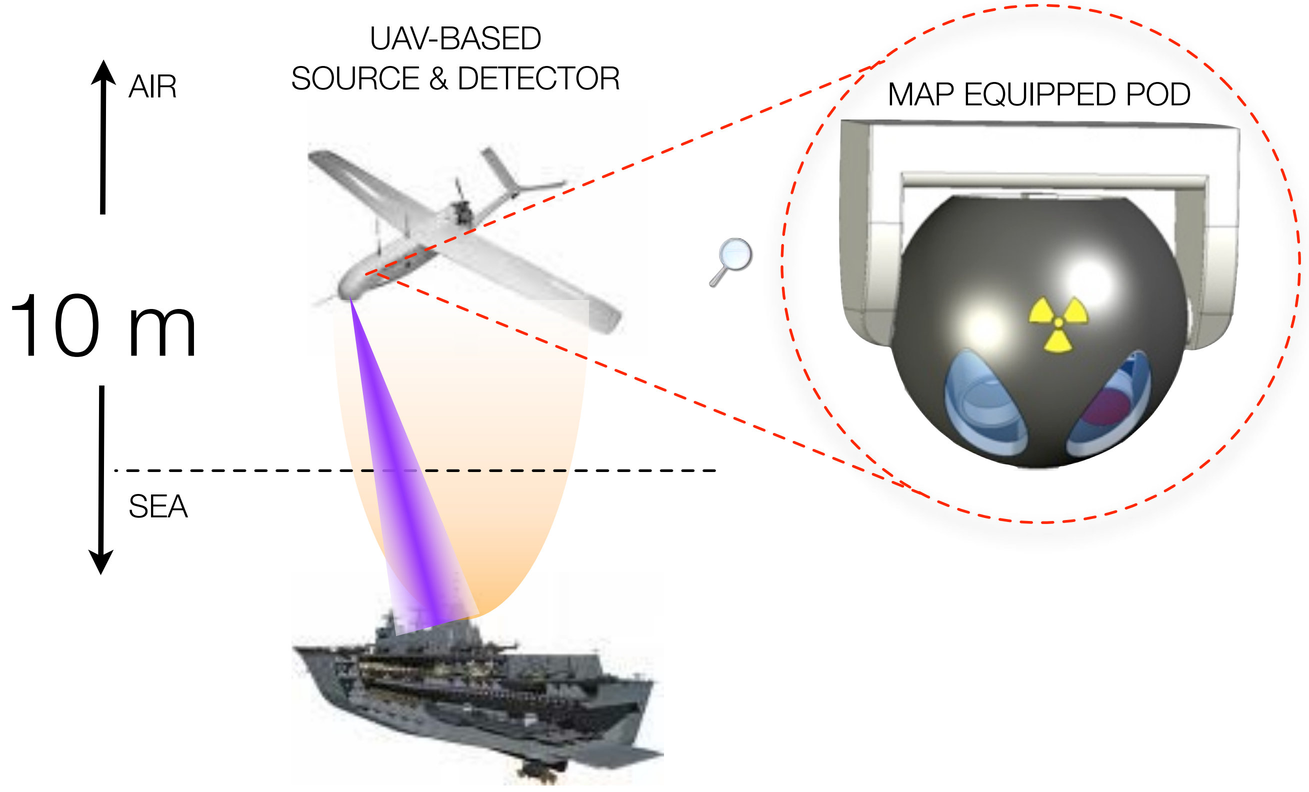
A reduction of 1000x in source flux required can be achieved by bringing the source to the target

need 10^{13} γ/s

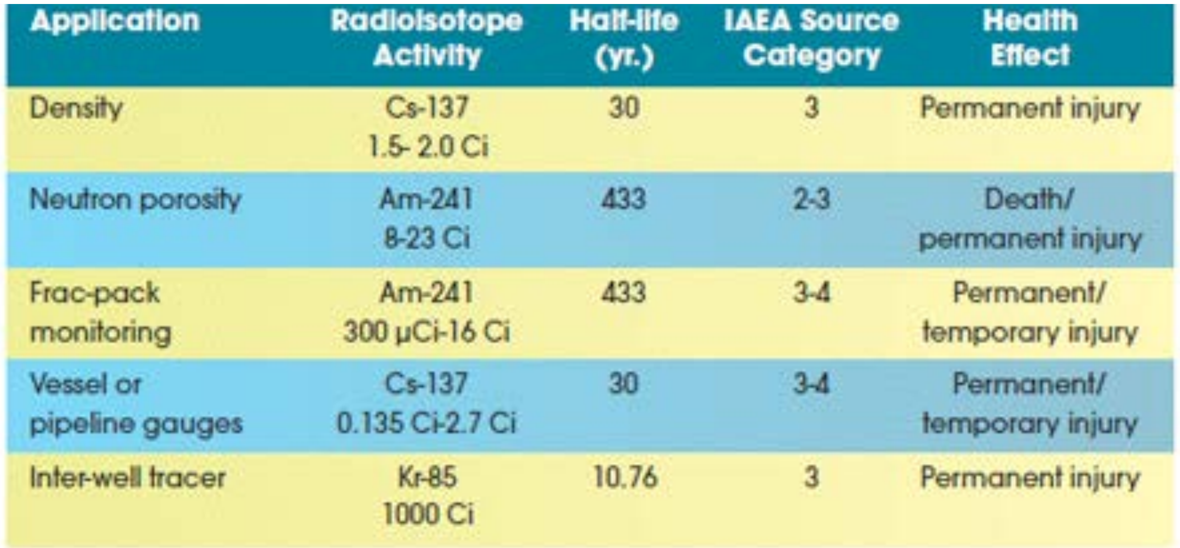


Producing 10 MeV gammas by ICS requires
~500 MeV electrons
(assuming green drive laser)

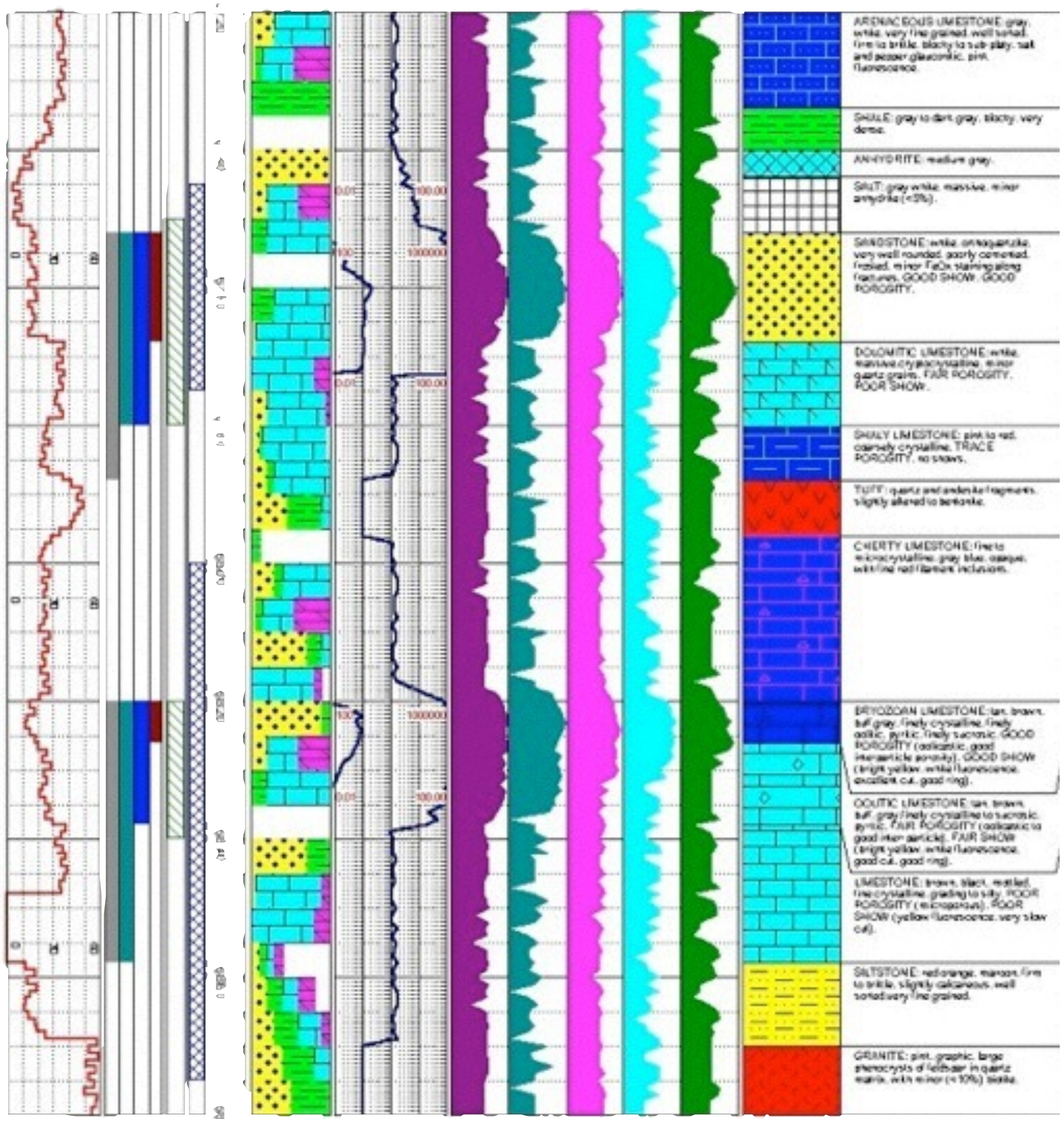
need 10^{10} γ/s



Oil well logging (densitrometry, lithology, etc.) uses radioactive sources with high proliferation hazard.

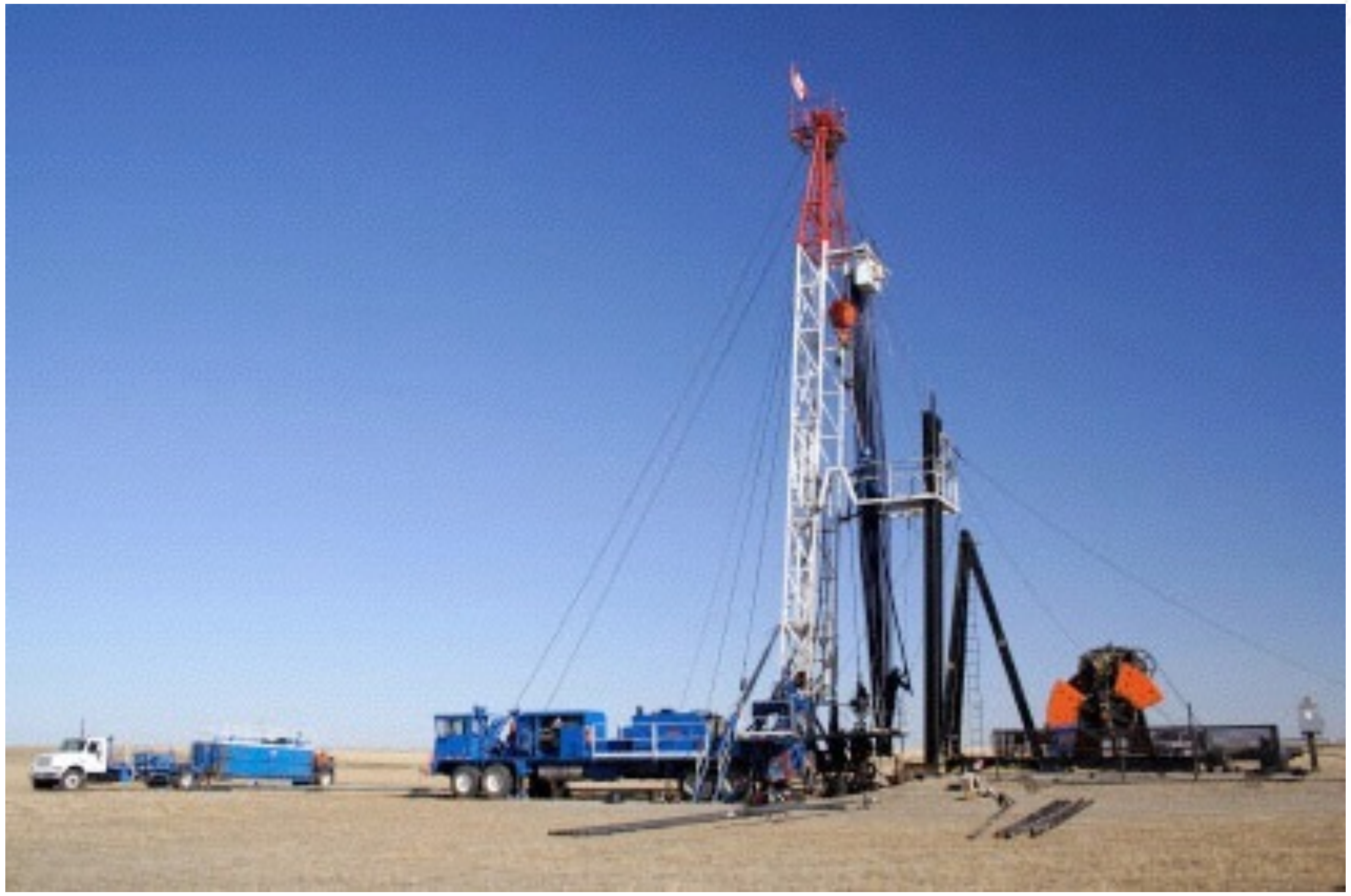


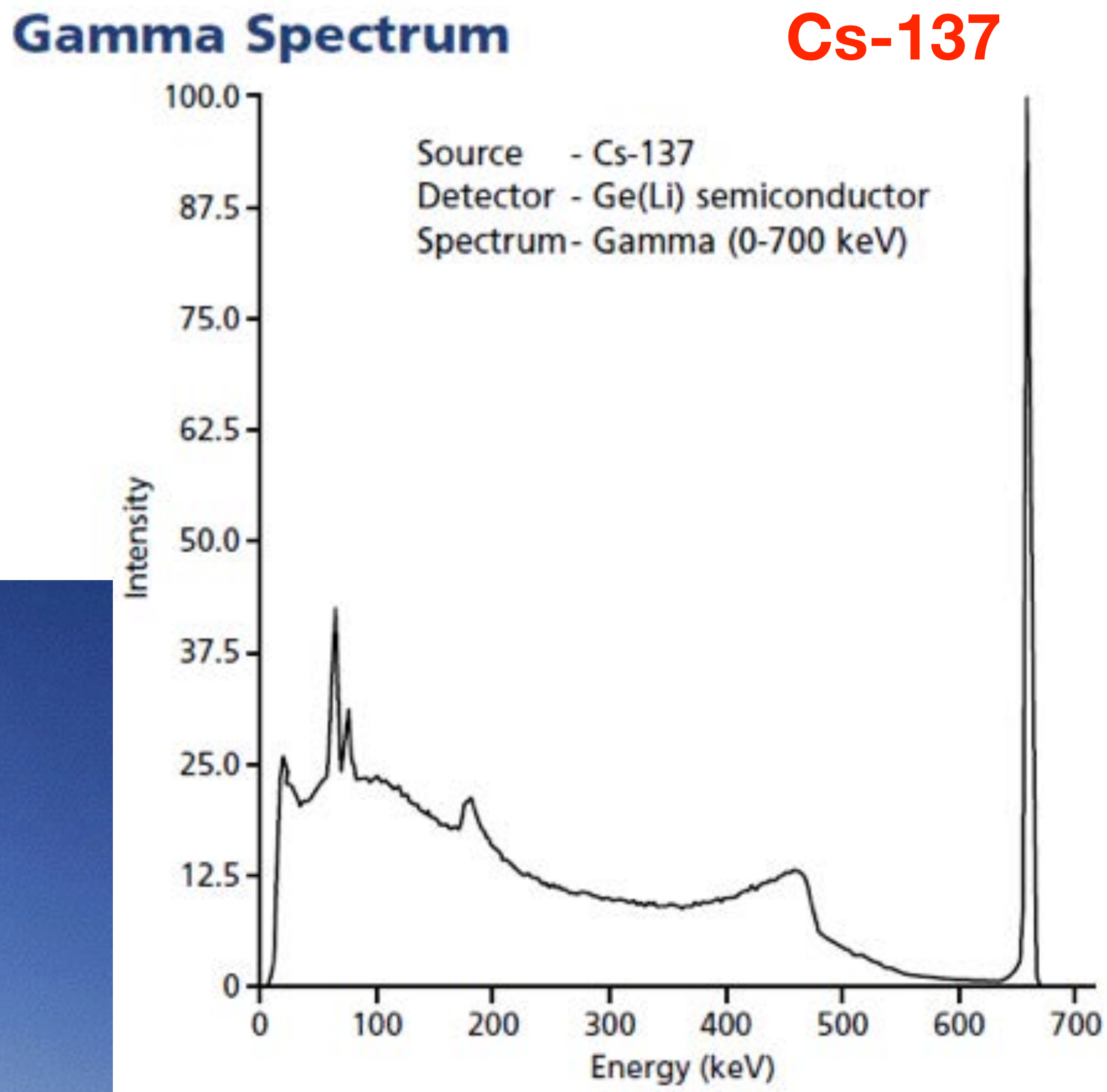
Application	Radioisotope Activity	Half-life (yr.)	IAEA Source Category	Health Effect
Density	Cs-137 1.5- 2.0 Ci	30	3	Permanent injury
Neutron porosity	Am-241 8-23 Ci	433	2-3	Death/ permanent injury
Frac-pack monitoring	Am-241 300 μCi-16 Ci	433	3-4	Permanent/ temporary injury
Vessel or pipeline gauges	Cs-137 0.135 Ci-2.7 Ci	30	3-4	Permanent/ temporary injury
Inter-well tracer	Kr-85 1000 Ci	10.76	3	Permanent injury



We seek to replace Cs-137 and related radionuclides in geological and industrial applications

Oil Well Logging





1. http://www.hightechsource.co.uk/Resources/Oil%20Well%20Logging.pdf
2. http://www.ieccorporation.com/ee_oil_well_logging.htm

Exotic schemes

Covering 100 TeV/m-10 GeV/m

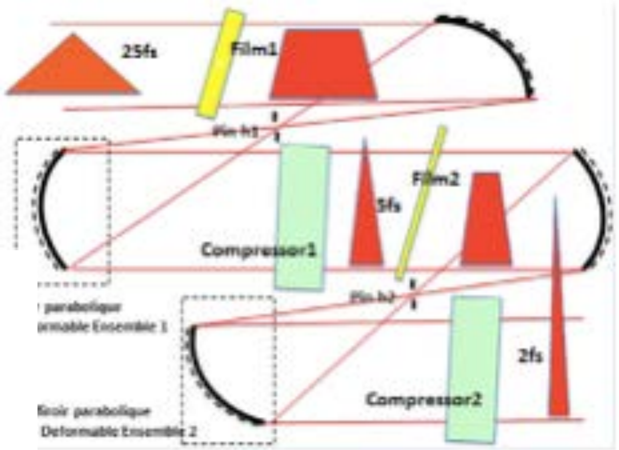
Summary of LWFA in Novel Media

T. Tajima, G. Mourou, and A. Chao

2-step Laser Conversion:

1PW Opt. Laser → 10PW Opt. Laser → 1EW X-ray Laser

30fs, 40J, 1eV 3fs, 30J, 1eV 0.3as, 0.3J, 10keV



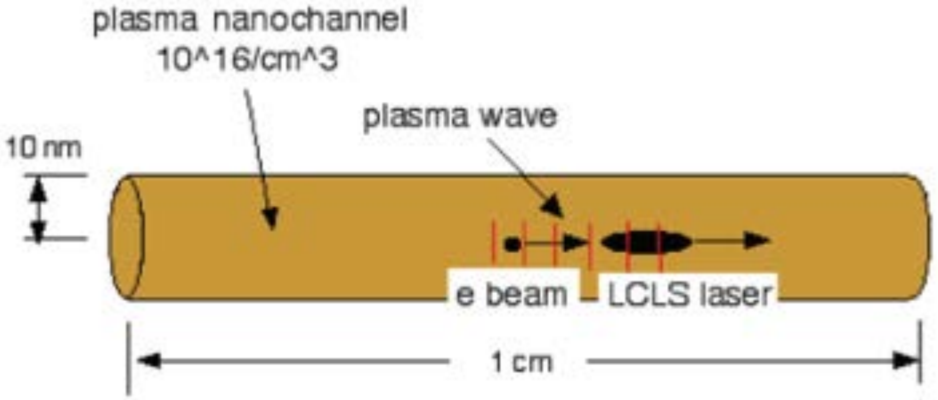
LWFA at solid density

10keV photon: $n_{cr} = 10^{29}$ /cc---- solid density $n = 10^{23}$/cc

wakefield energy gain $= 2mc^2 a_0^2 (n_{cr} / n) = a_0^2$ TeV

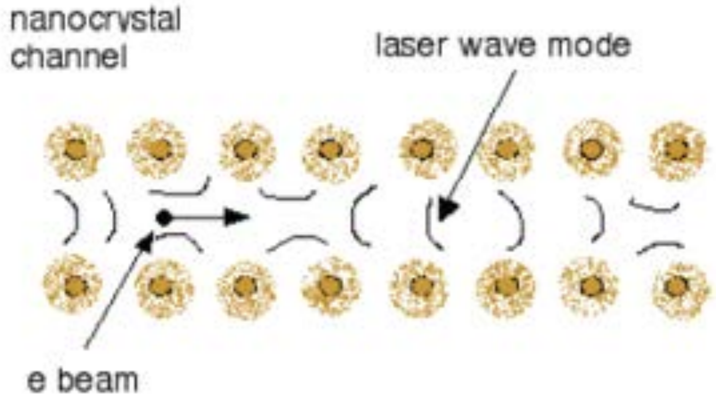
accelerating gradient $= a_0 (n / n_{18})^{1/2}$ 1GeV/cm = $300 a_0$GeV/cm

X-ray LWFA in crystal: accelerating gradient $300 a_X$ *GeV/cm, accelerating length 1-10m, energy gain per stage PeV; portable miniaccelerators*



Zeptosecond nano beams of electrons, protons (ions), muons (neutrinos), coherent γ-rays to very high energies over mm to m

Test of linear optics in crystal in LCLS proposed



Summary of "TeV/m Nano-Accelerator: Current Status of CNT-Channeling Acceleration Experiment"

Y. M. Shin[1,2], A. H. Lumpkin[2], J. C. Thangaraj[2], R. M. Thurman-Keup[2], P. Piot[1,2], and V. Shiltsev[2]
[1]Northern Illinois Center for Accelerator and Detector Development (NICADD), Department of Physics, Northern Illinois University
[2]Fermi National Accelerator Laboratory (FNAL)

Crystal Channeling Acceleration

→ **Plasma acceleration gradient:**

$$E_0 = \frac{m_e c \omega_p}{e} \approx 100[\frac{GeV}{m}] \cdot \sqrt{n_0[10^{18} cm^{-3}]}$$

Gas-State plasma with 10^{16} – 10^{18} cm^{-3}: 10 – 100 GeV/m

Solid-State (crystal) plasma with 10^{20} – 10^{23} cm^{-3}: 1 – 30 TeV/m

- **Critical Limits of Natural Crystals (Silicon, Germanium, etc)**
  - **(1) Angstrom-scale channel - Low particle transmission (low acceptance)**
  - **(2) High de-channeling rate**
  - **(3) High power requirement of driving sources (e.g. 3 GW of 40 keV x-ray)**
  - **(4) Low thermal damage threshold**

Carbon Nanostructures (CNTs)

(1) Readily controllable channel size (up to micron). The larger channel can

→ decrease de-channeling rates

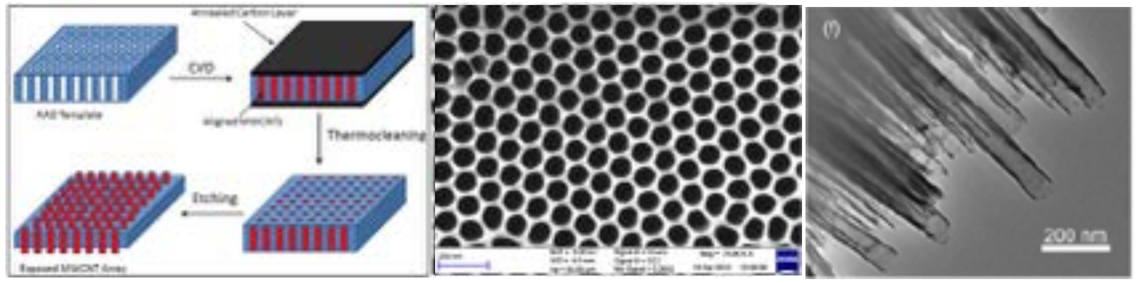
→ increase acceptance

→ mitigate power requirement of driving sources

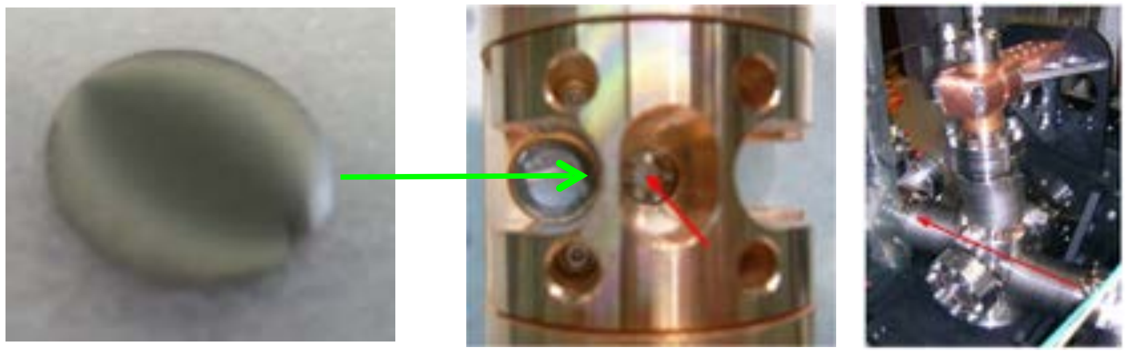
(2) Thermally and mechanically stronger than crystals

(3) Single-mode, Stable Acceleration)

AAO (Anodic Aluminum Oxide)-CNT

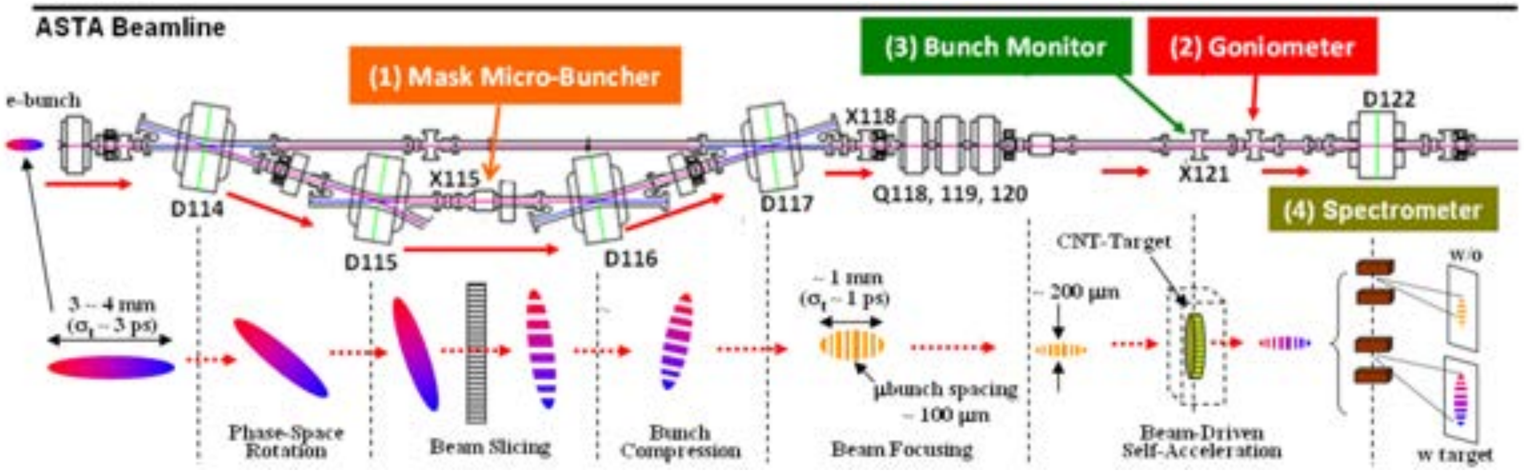


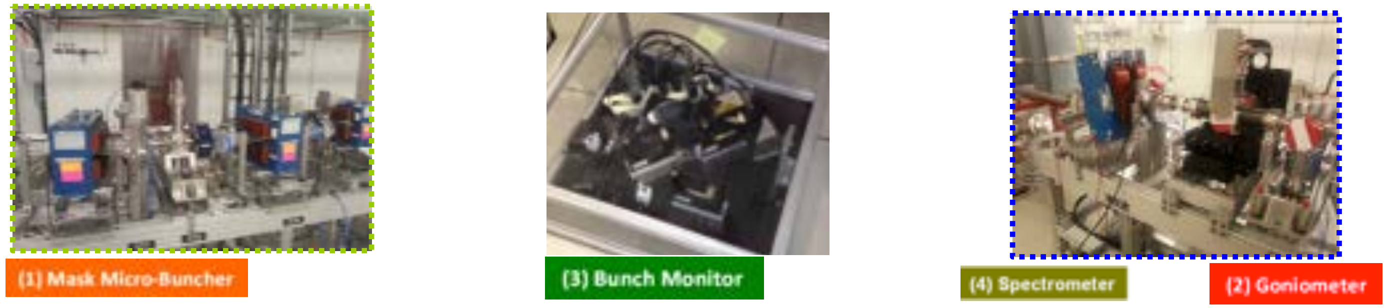
Membranes **2011**, *1*, 37-47; doi:10.3390/membranes1010037



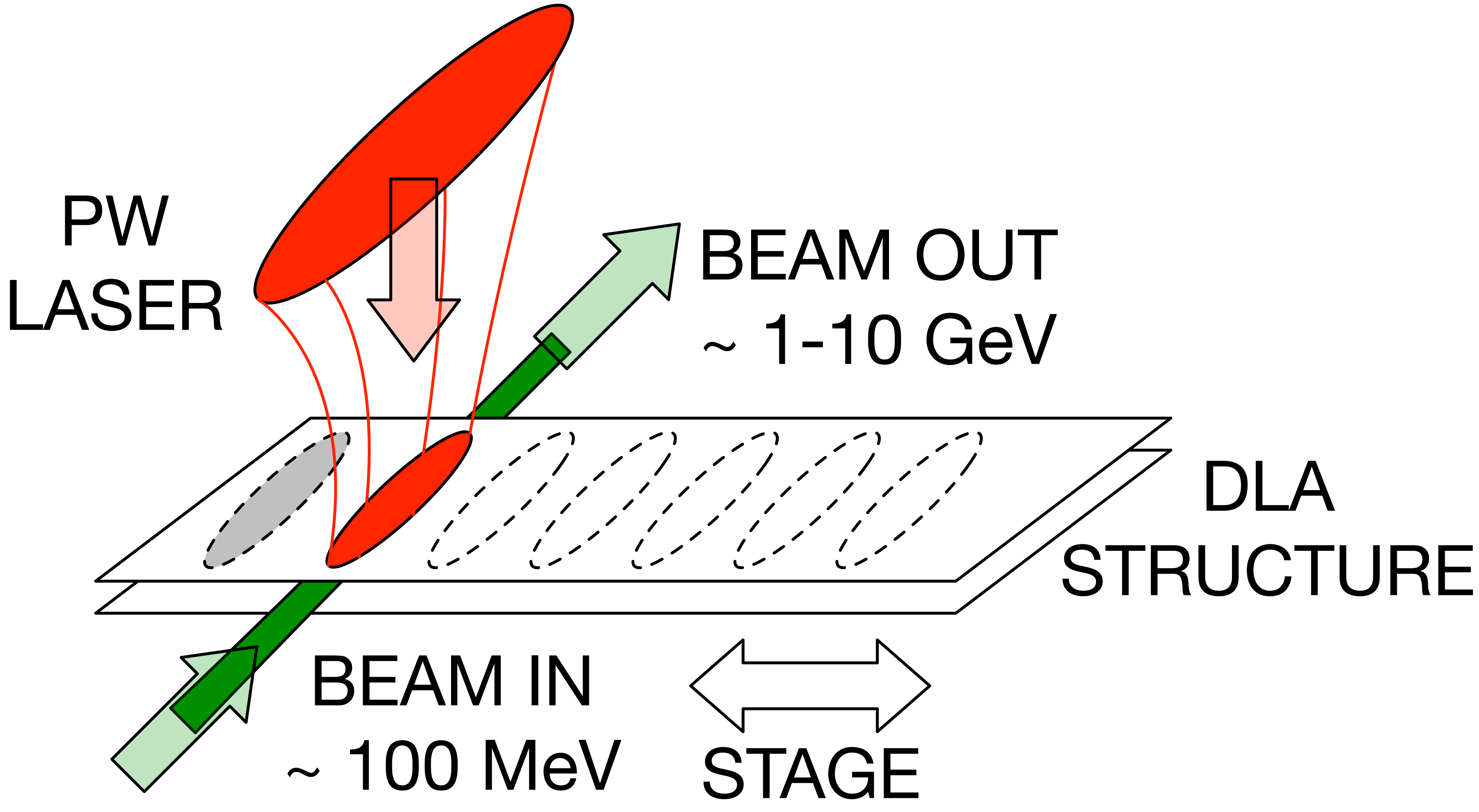
AAO-CNT samples are fabricated by NanoLab Inc., Waltham, MA

POC Experiment @ Fermilab-ASTA (Beam-Driven Self-Acceleration)





At PW laser powers, all interceding matter ablates or vaporizes, so the accelerator is single shot

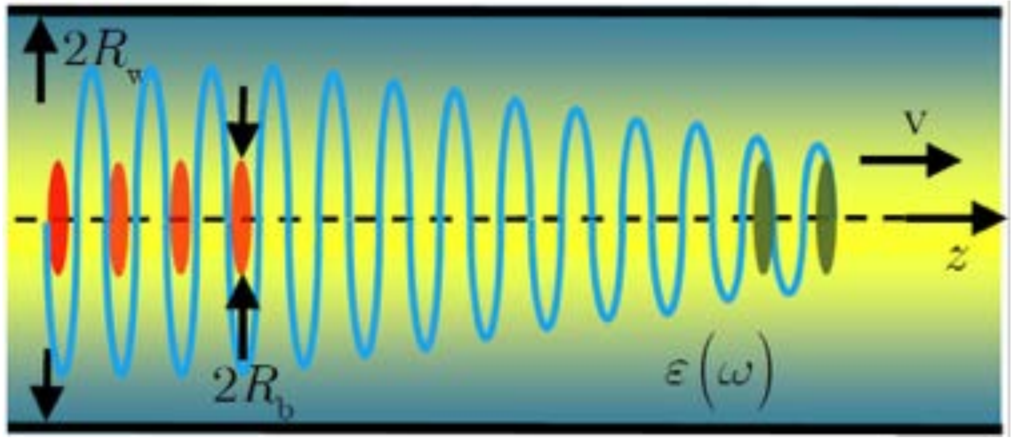


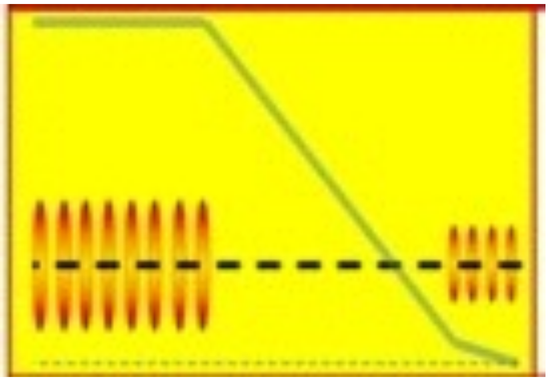
Ablation ~ps

Acceleration field ~100fs

Two-beam accelerator with active medium as the energy source

M. Voin, Z. Toroker, W.D. Kimura, P. Muggli, C. Joshi and L. Schächter





Driving beam is replaced by a trigger train of micro-bunches, which does not carry the energy, but rather generates a quasi-monochromatic Cerenkov-wake

This wake is amplified by active medium as spectrum of wake overlaps resonance of medium

Wake grows exponentially until medium is depleted; hence, field reaches saturation

At saturation, gradient (order of GV/m) is constant! Accelerated micro-bunches is positioned in this field region

With 10^4 electrons in a micro-bunch and 10^3 micro-bunches in a train, to satisfy luminosity goals requires $>10^{14}$ el. per sec; thus, rep-rate higher than 10 MHz would be necessary.

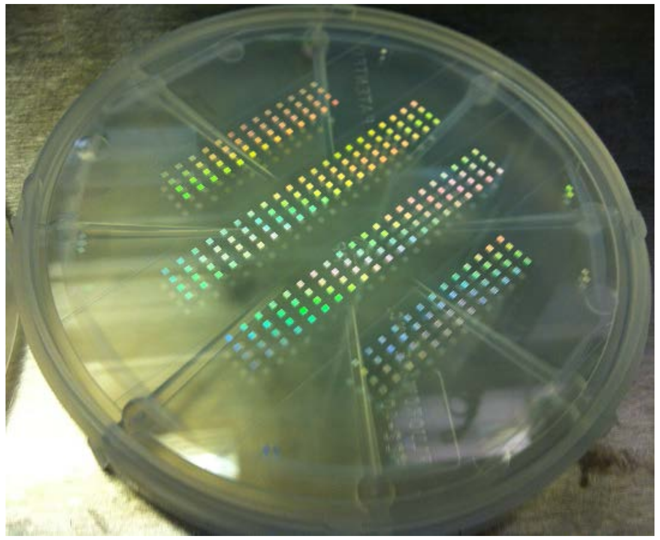
Saturation occurs in less than 1 nsec after trigger train, which is sufficient time to replenish drained medium

The Future

DLAs will show steady progress over the next few years, resulting in next generation prototype machines

Practical

bifurcation into small & extended devices
high flux & high average power
down-selecting specific technologies

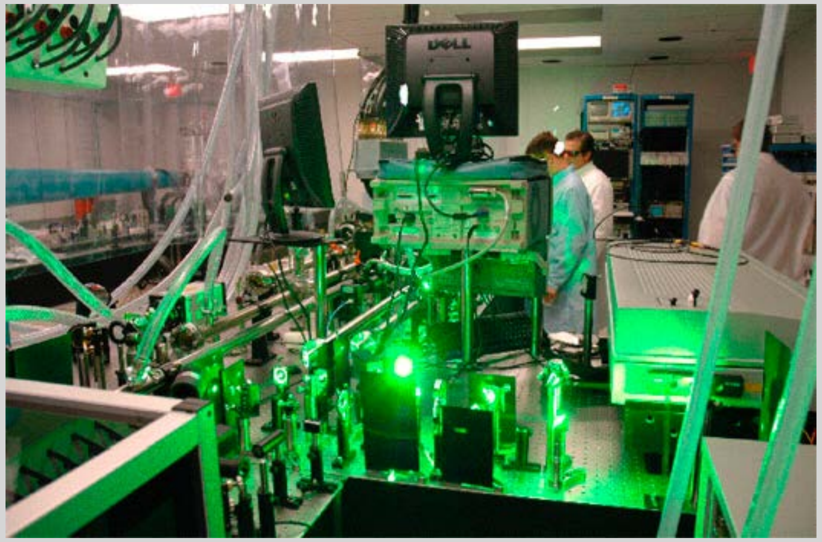
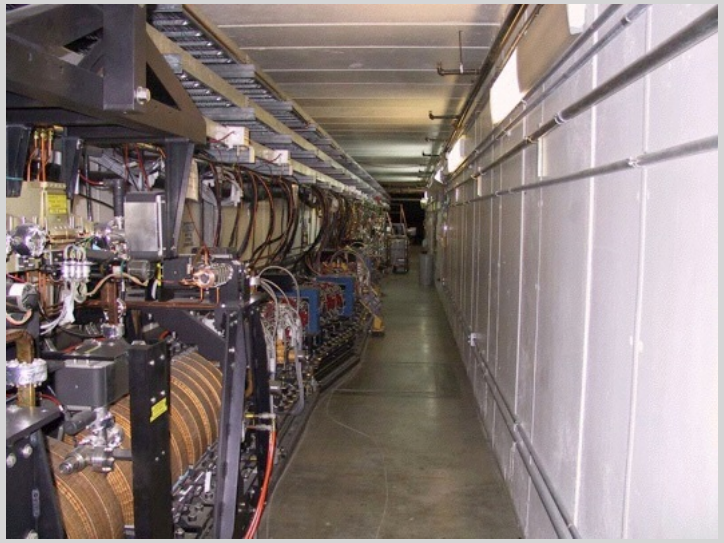
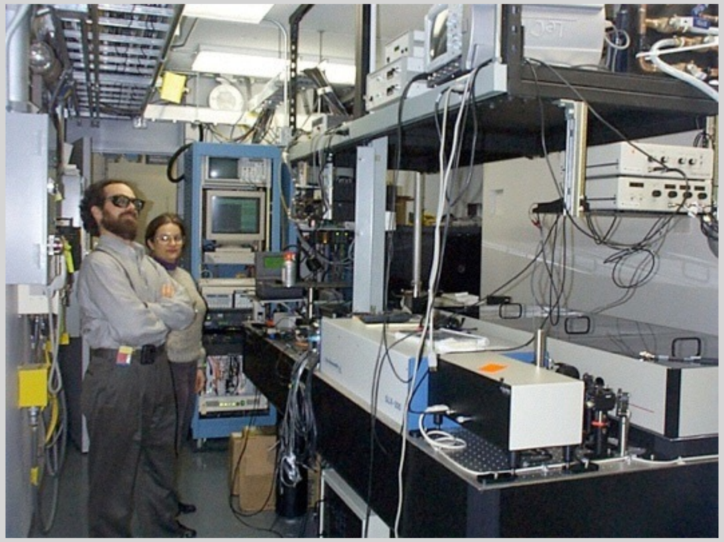
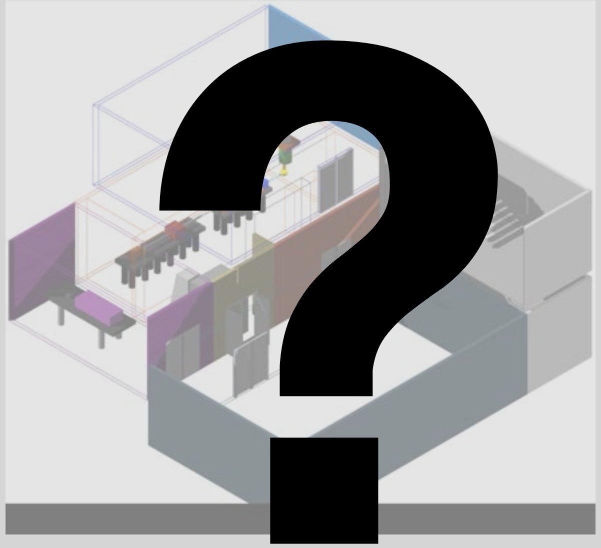


Technical

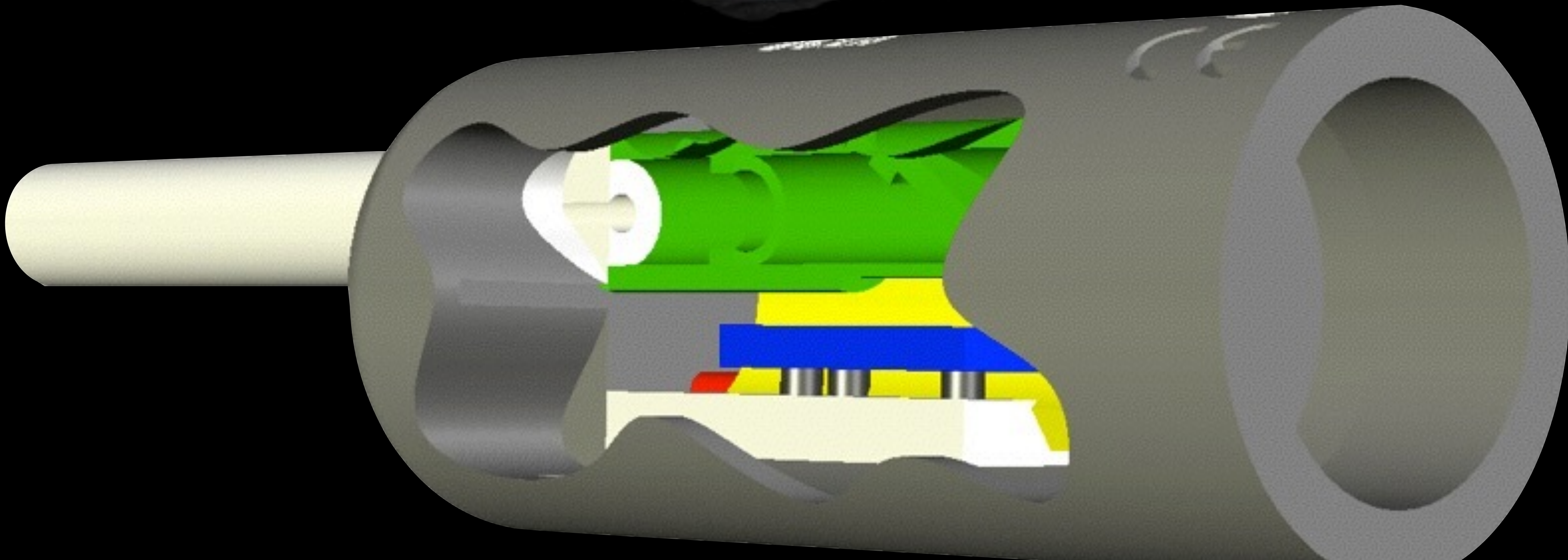
gun integration
fabrication consistency
improved breakdown
diagnostics
radiation damage
coupling

Beam Physics

real acceleration
staging
beam dynamics & focusing
beam loss
wakefields
flat beam production

COST	SIZE	LASER	ACCELERATOR
$\$10^9$	XL		
$\$10^7$	M		
$\$10^5$	S		

Optical scale accelerators will democratize accelerators in research, usher in attosecond sciences in basement labs, and couple accelerators to rapidly developing technologies.



This talk is a sampling of the efforts of many. Others no doubt should have been included.

Rodney Yoder
Joel England

Gang Liu
Kiran Hazra
Esin Sozer
Josh McNeur
Peter Stoltz
Ben Cowan
Robert Noble
Carsten Welsch
Peter Hommelhoff
Charlie Brau
Levi Schachter
John Breuer
Phillip Piot

Laser Applications for Accelerators – A Marie Curie Network

17 projects
23 Partner Institutions *(growing)*

www.liv.ac.uk/la3net

Salamanca Sandstone

=

SiO2 + other oxides

=