

Do optical-scale structures make suitable accelerators for colliders?

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on behalf of the **MAP Team**

Particle Beam Physics Laboratory

*This talk is like is like an act of Congress:
it steals from everyone, gives back to few, and
may have unintended consequences.*

UCLA



NO.

The naysayers lined up to explain why our DLA accelerator could never work



-
-
-
- won't work
- won't work at low energies
- can't build it
- can't align it
- can't power it
- can't get beam into it
-
-

A few believers kept the DLA flame going...



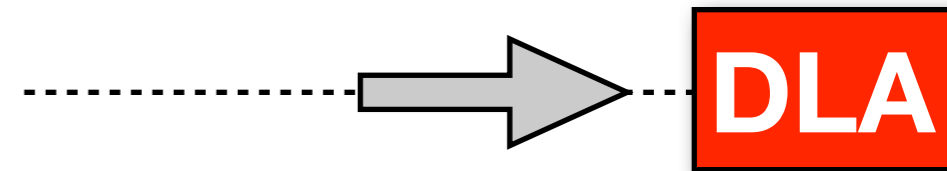
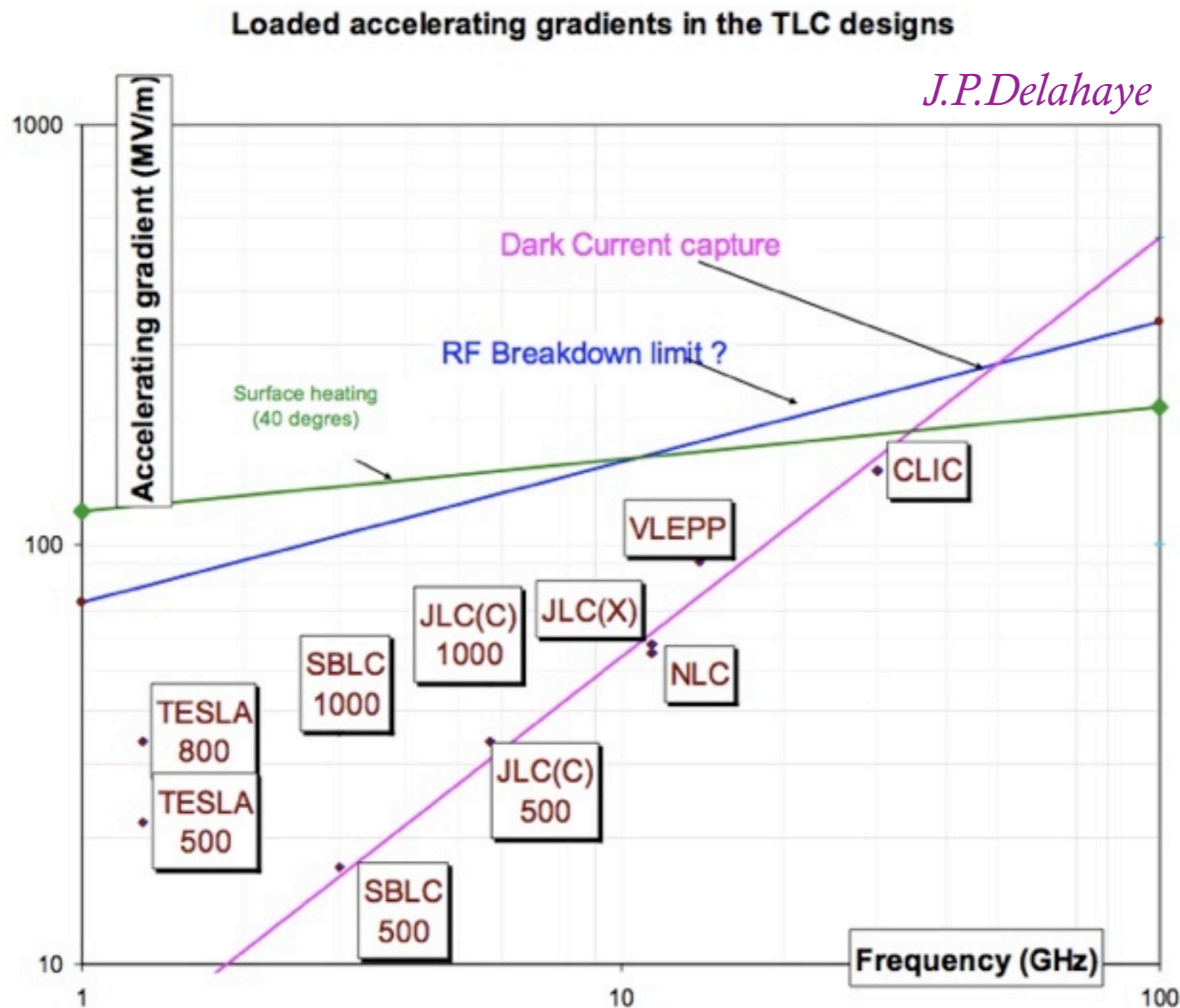
"WORTH ITS WEIGHT IN DIELECTRICS"

GETTING PAST NO

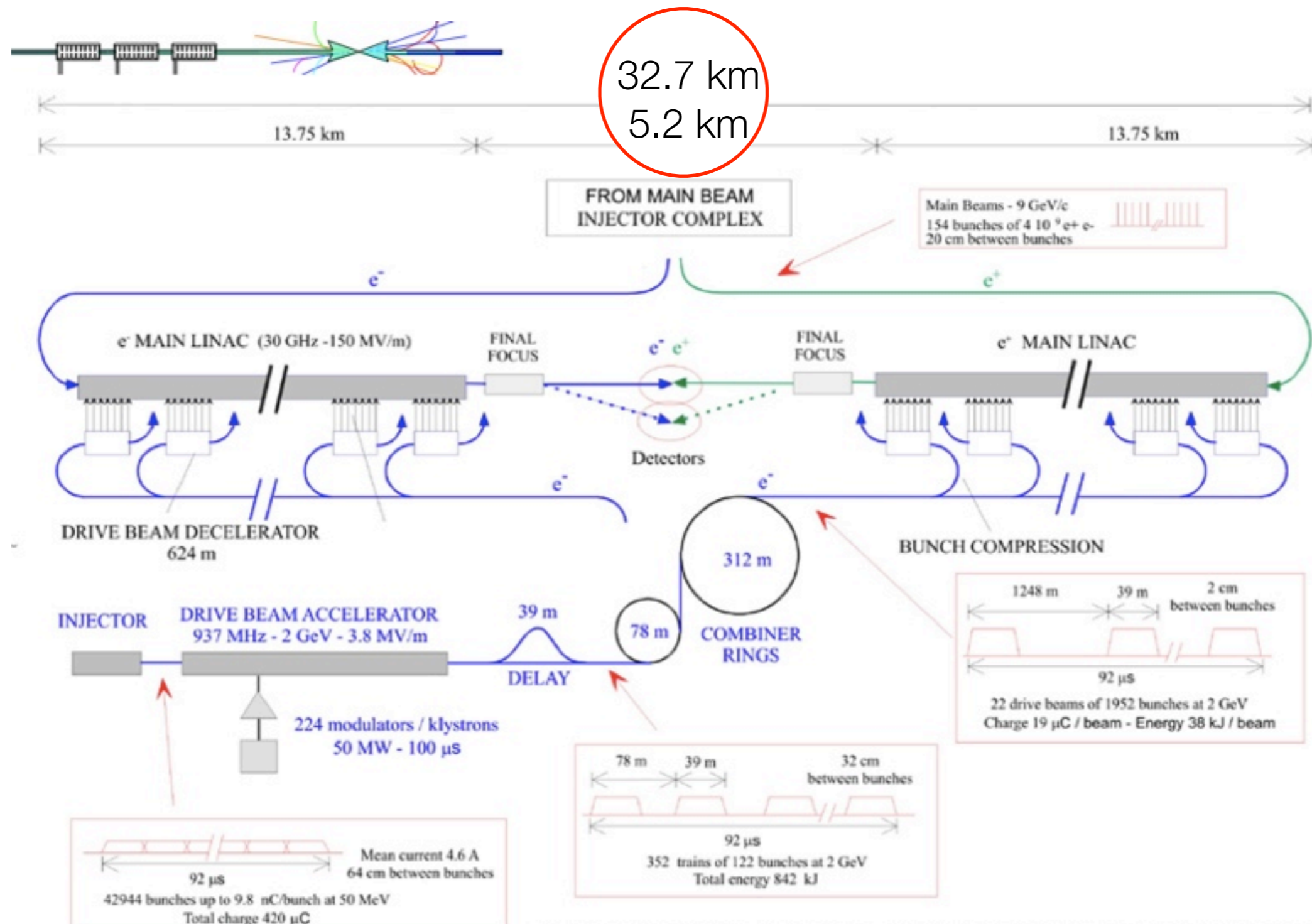
ACCELERATING IN
DIFFICULT SITUATIONS

OPTI CAL

A DLA-based collider requires a new operating regime



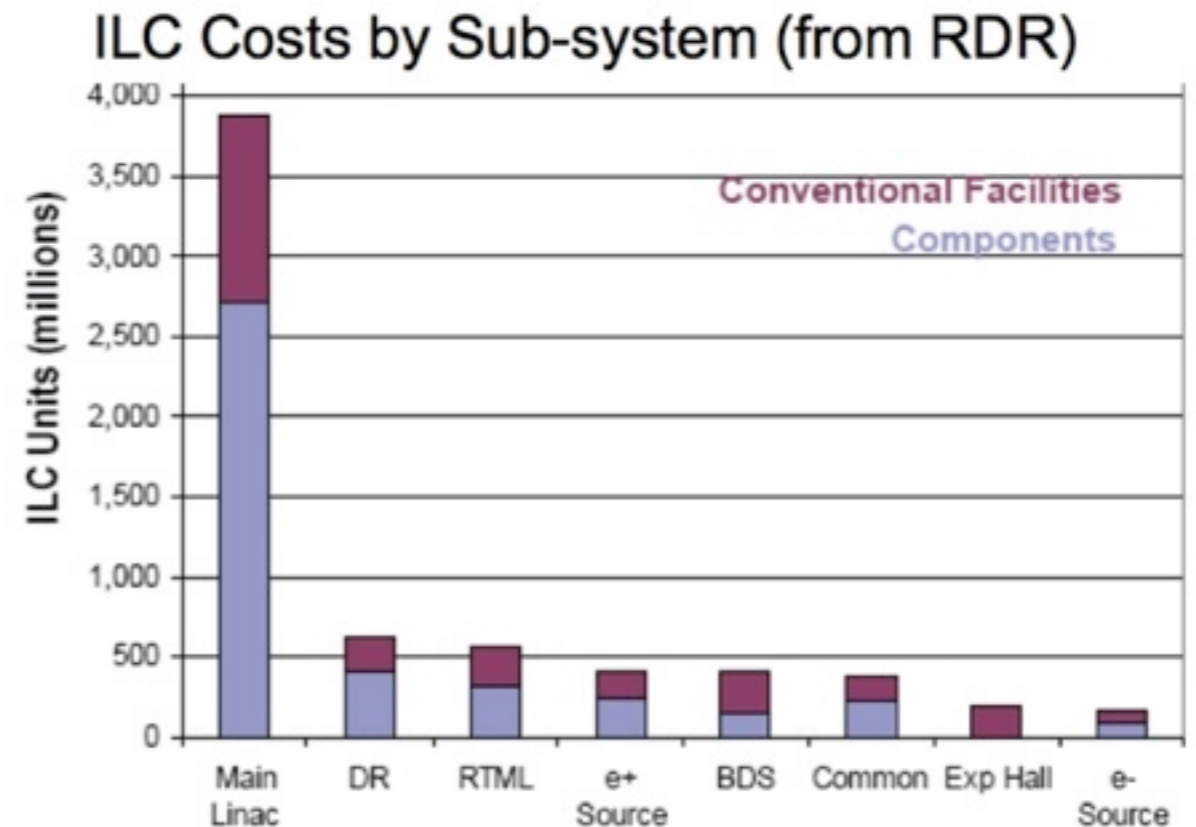
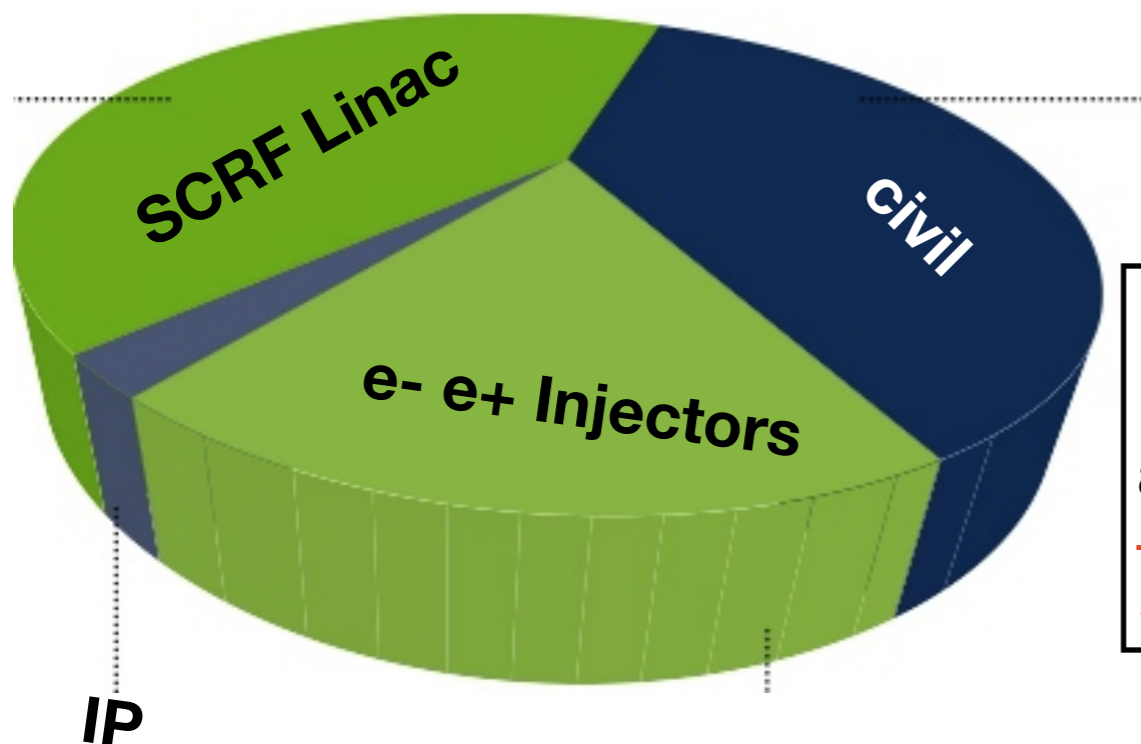
High gradient acceleration only does a little to change the demands



Collider costing models favor high gradients but demand high efficiency and low capital costs

Facility costs scale roughly with power consumption and facility size

ILC Breakdown (2007)



Largest cost driver for a linear collider is the acceleration

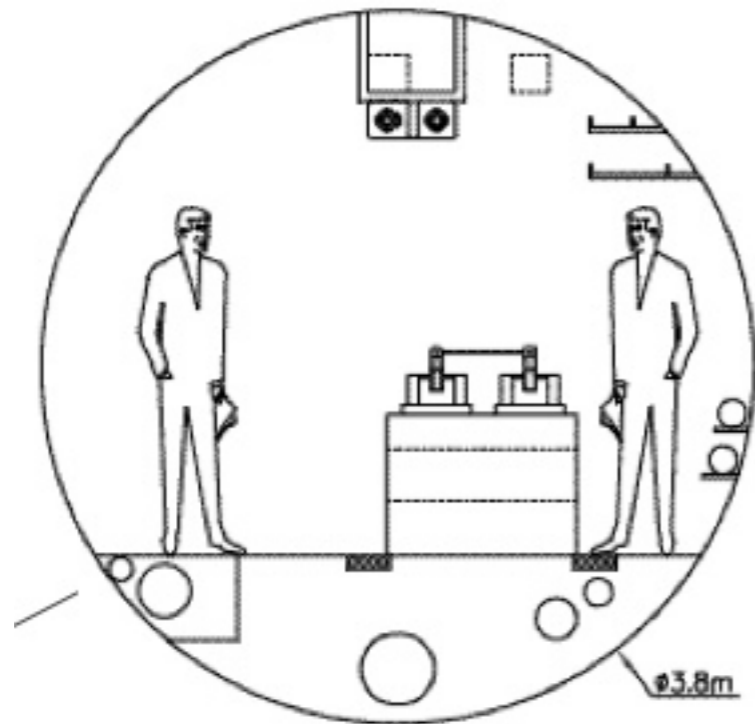
– ILC geometric gradient is ~20 MV/m -> 50km for 1 TeV

Size of facility is costly
⇒ higher gradients

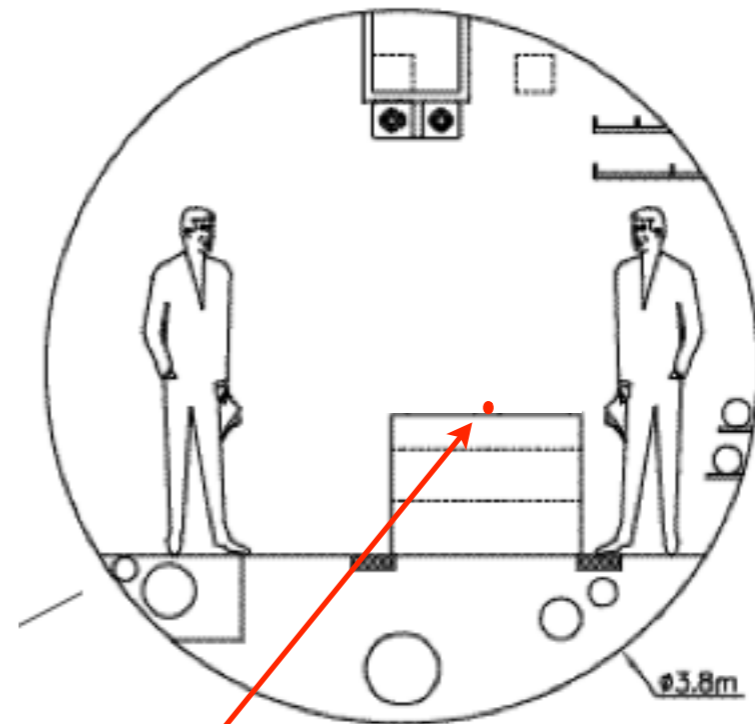
– High gradient acceleration requires high peak power and structures that can sustain high fields

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

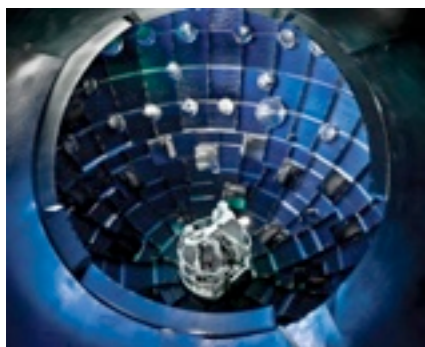
CLIC Tunnel



DLA Tunnel



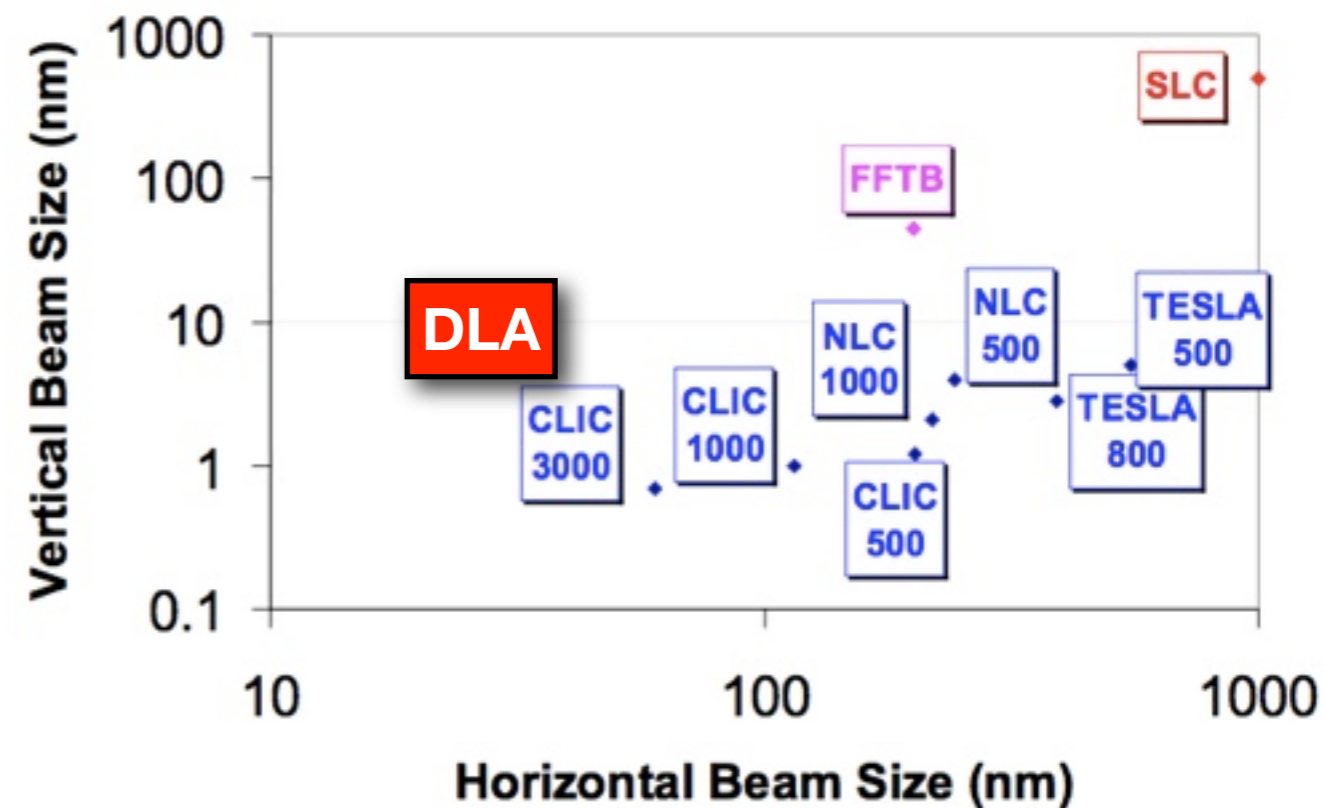
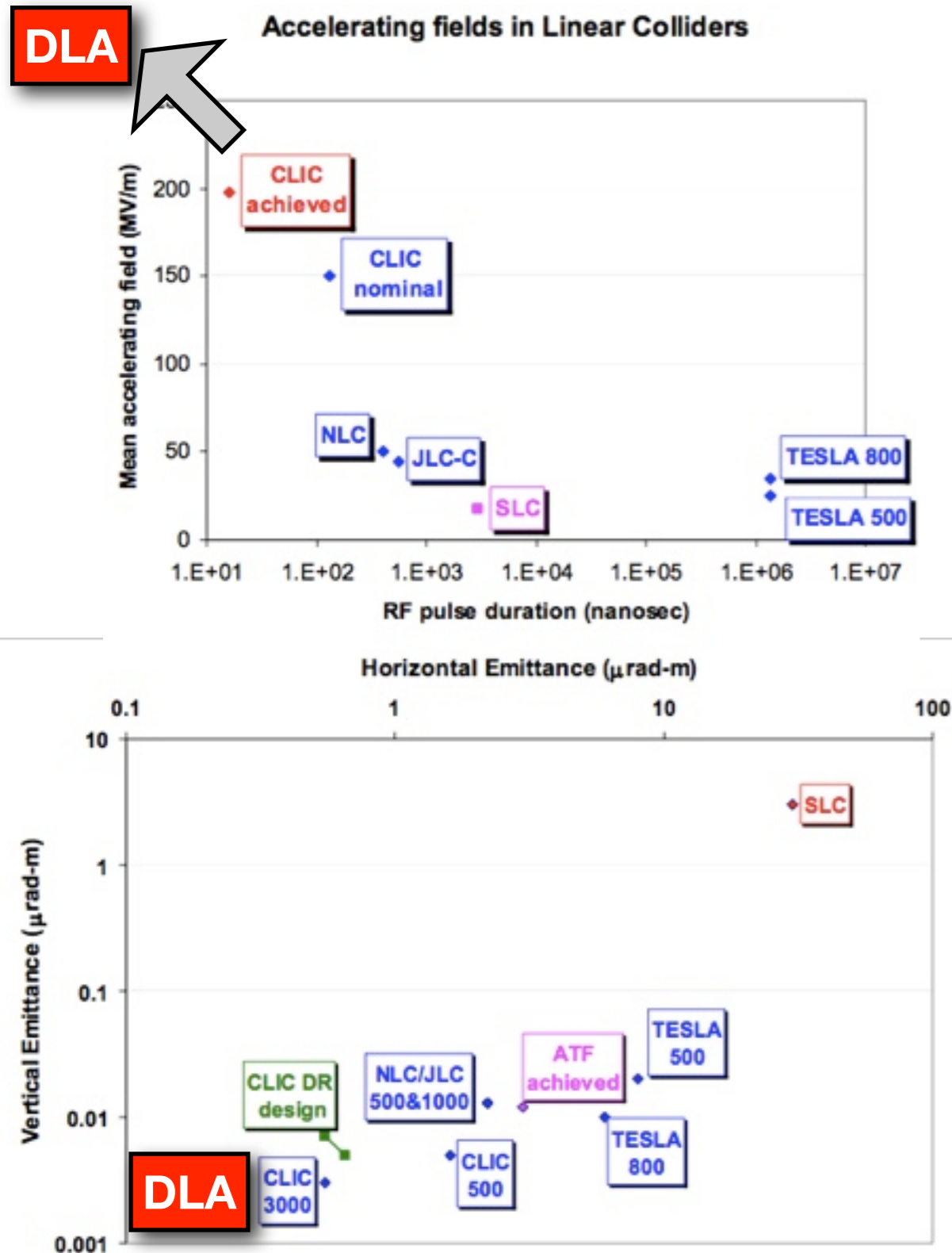
DLA x 1000



NIF & LIGO may be useful guides



On the other hand, “conventional” collider beam emittances and sizes match well with DLA



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

For flat beams

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

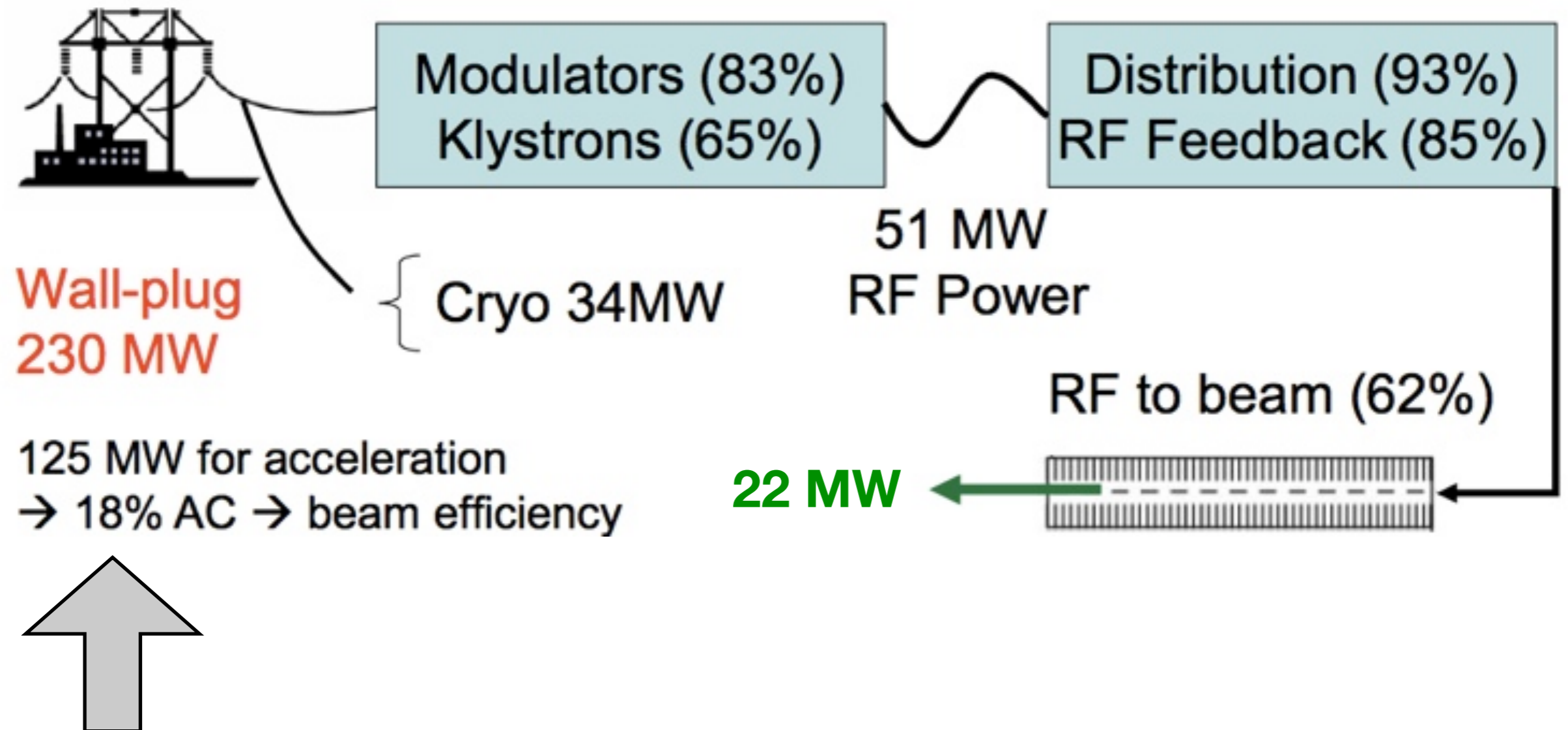
For $D \ll 1$, we can have luminosity enhancement

Reference beamstrahlung parameter:

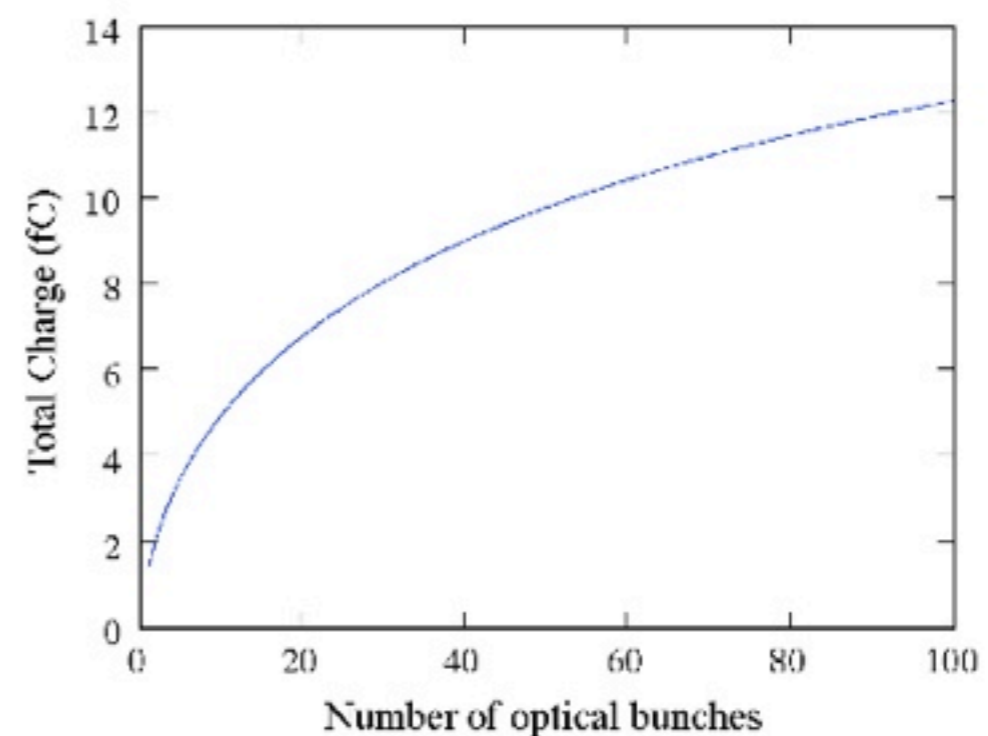
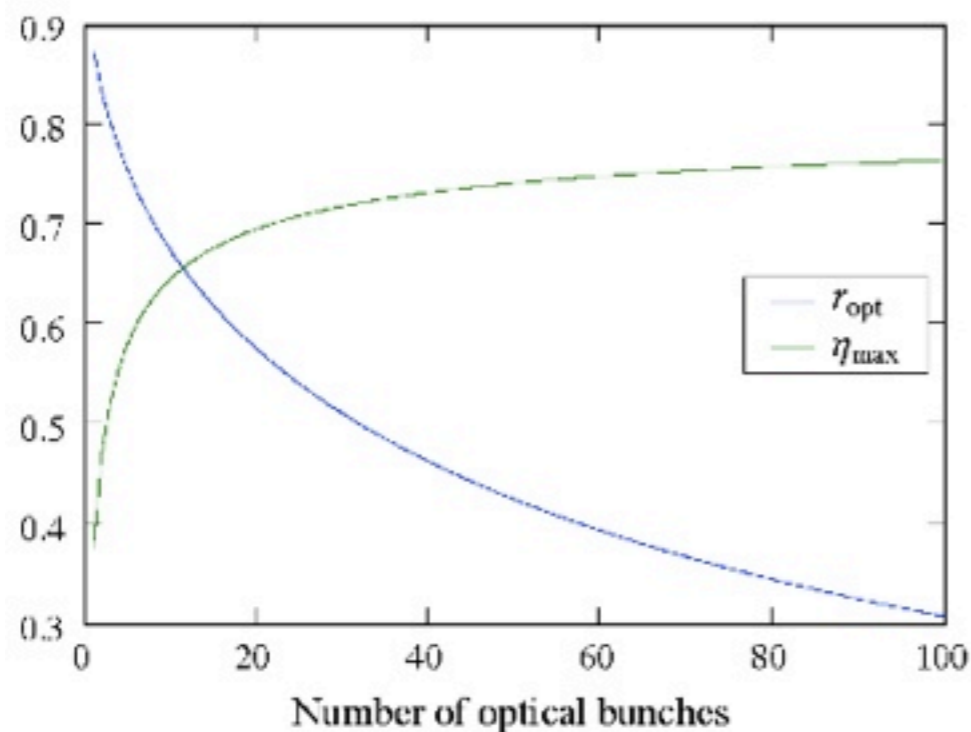
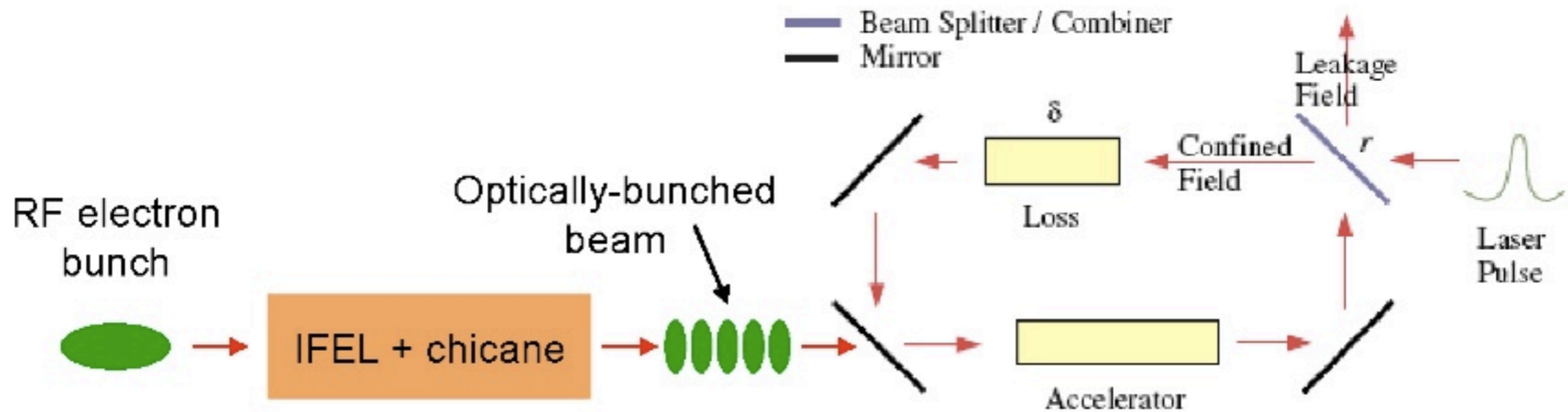
$$\Upsilon_0 = \frac{r_e \hat{\lambda}_c}{\sqrt{2\pi}} \frac{\Gamma}{\sigma_r \sigma_z} N$$

complicated interplay...
but low N is generally favored

Efficiency is a concern in any collider.



Efficiency and beam loading have been considered in optical structures.



Much more work needed

The DLA solves some critical problems.
New problems are introduced.

Generic Collider	High Gradient (CLIC)	DLA
Need high beam-energy	Higher Gradients	Very High Gradient
Need ultra-low emittance	-	Ultra low charge and short beams
Need nm beams & stability	-	Inherently nm scale
Beamstrahlung	-	Ultra low charge beams
Efficiency	Two Beam Accelerator	(smoke and) mirrors

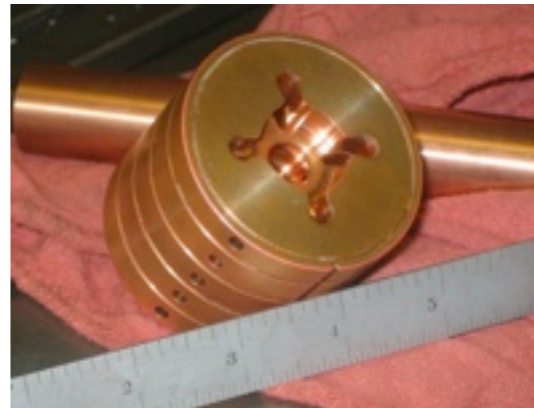
Potential DLA-based collider parameters match well to general collider goals

		ILC Nom.	DLA
E_cms	GeV	1000	1000
Bunch Charge	e	2.00E+10	1.00E+04
# bunches/train	#	2820	375
train repetition rate	MHz	5.00E-06	20
final bunch length	psec	1.00	1
design wavelength	micron	230609.58	0.8
Invariant Emittances	micron	10/0.04	1e-04/1e-04
I. P. Spot Size	nm	554/3.5	0.5/0.5
Enh Lumi/ top1%	/cm^2/s	4.34E+34	4.58E+34
Beam Power	MW	22.6	6.0
Wall-Plug Power	MW	104.0	120.1
Gradient	MeV/m	30	830
Total Linac Length	km	33.3	1.2

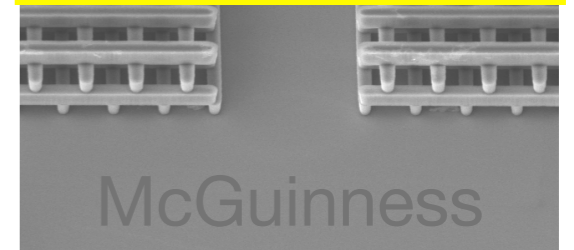
The choice of accelerator technology impacts the size and nature of the beam produced...

Breakdown limits metal:

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



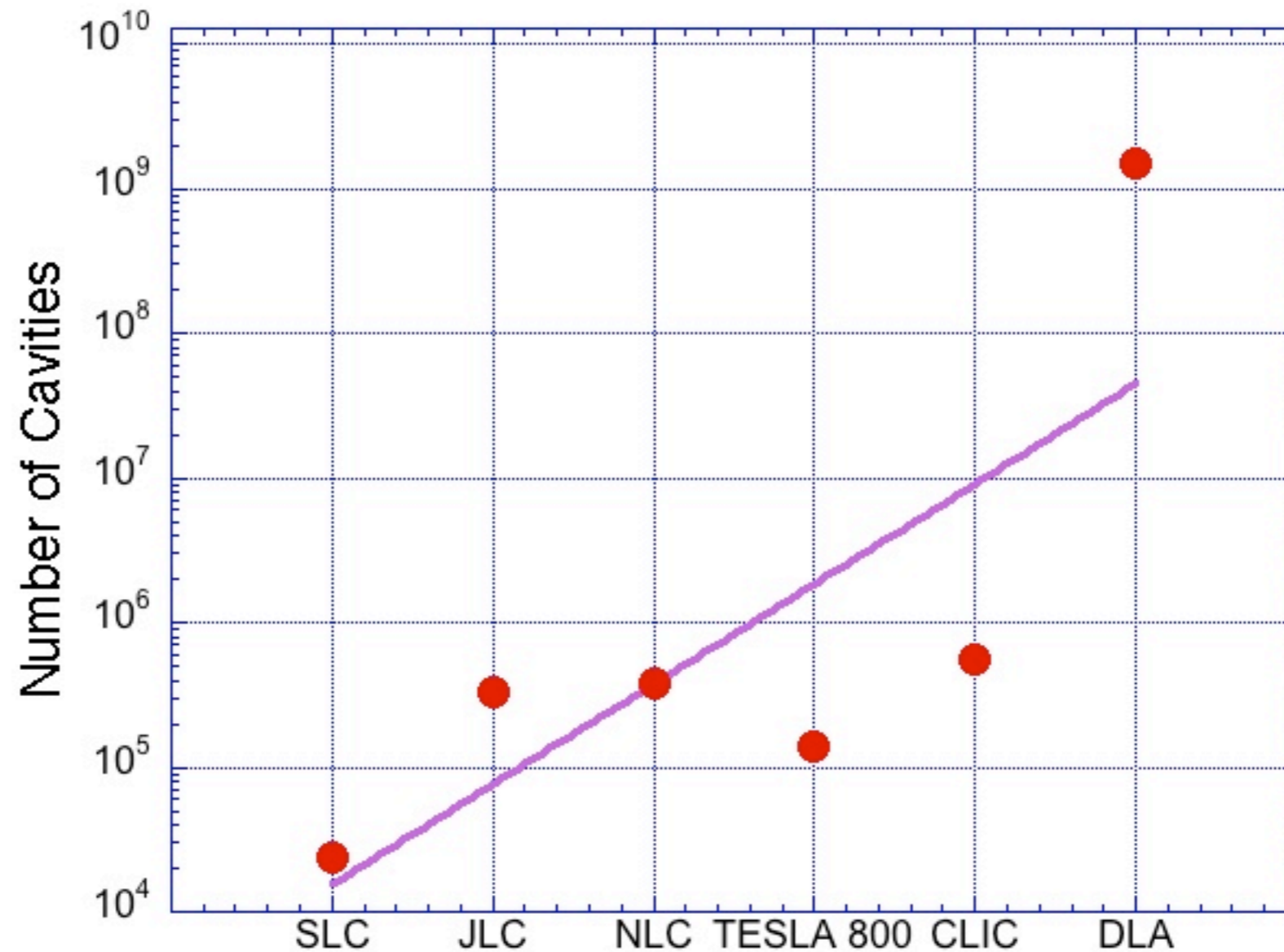
$$E_{\text{acc}} \sim P_{\text{rf}}/\lambda$$



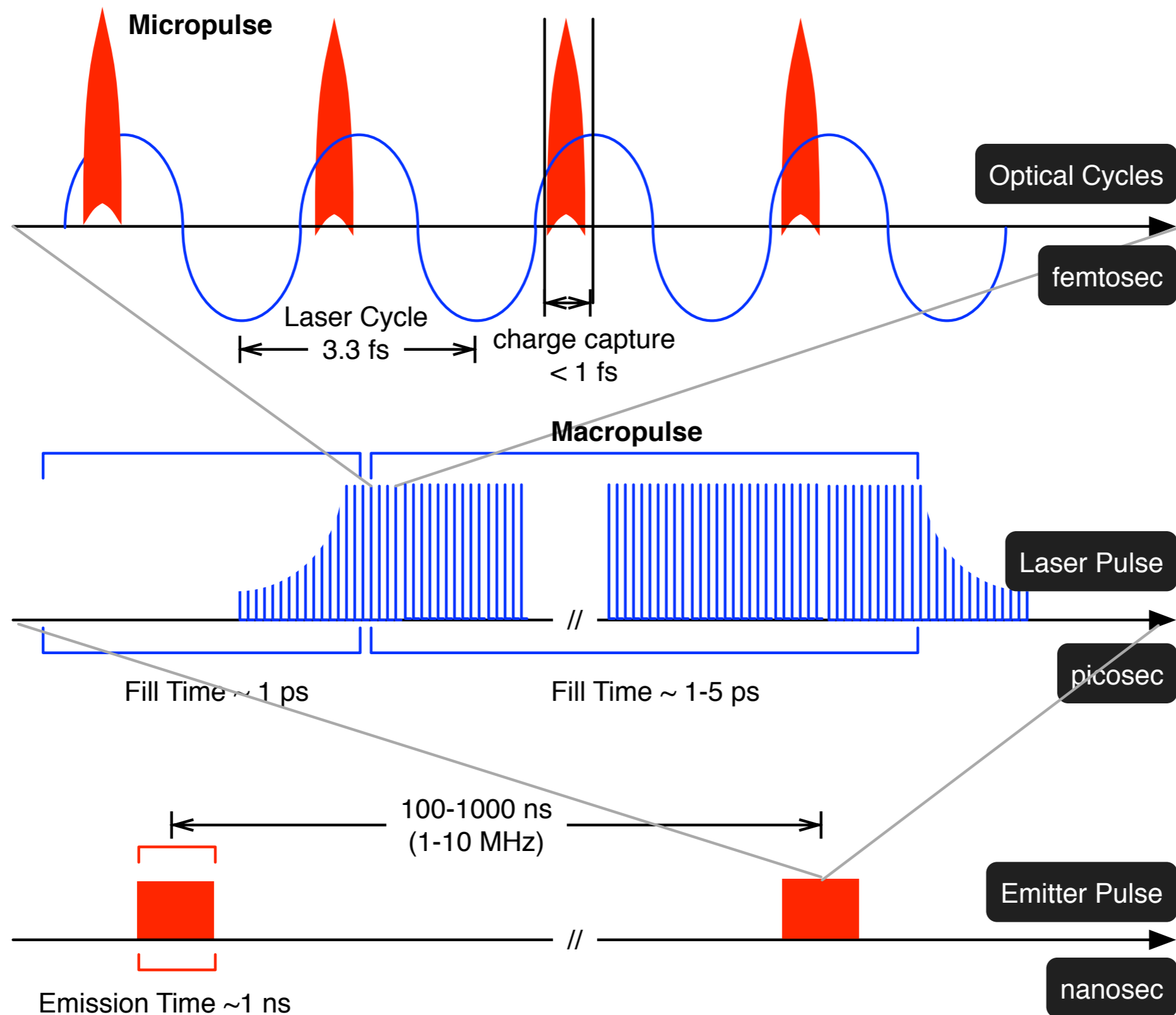
	RF	Optical
Gradient	10-100 MeV/m	1-10 GeV/m
Energy gain per period	1 MeV	1 keV
Repetition Rate	100 Hz	10-100 MHz
Charge per Bunch	0.1 - 1+ nC	10 - 100 fC
Bunch Length	1-100 ps	<1-10 fs

key: charge and time scale; not gradient

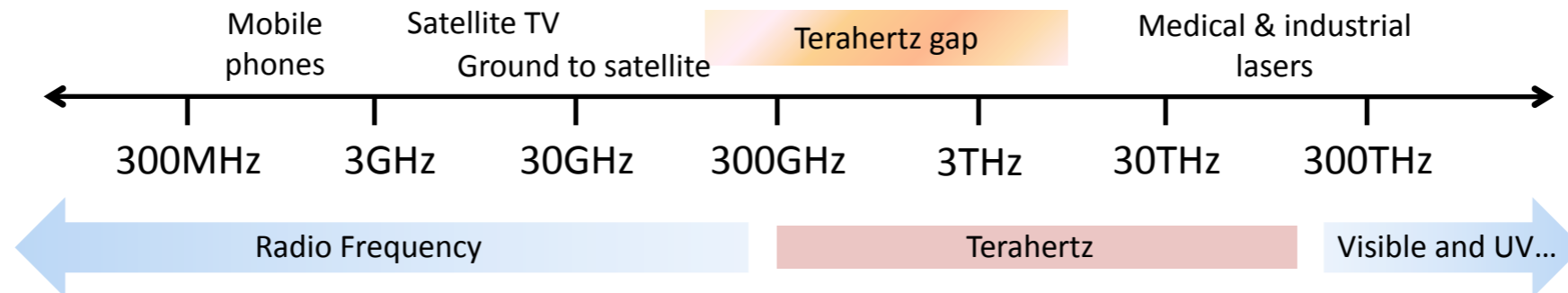
A Livingston-like plot of the number of cavities shows exponential growth over design iterations



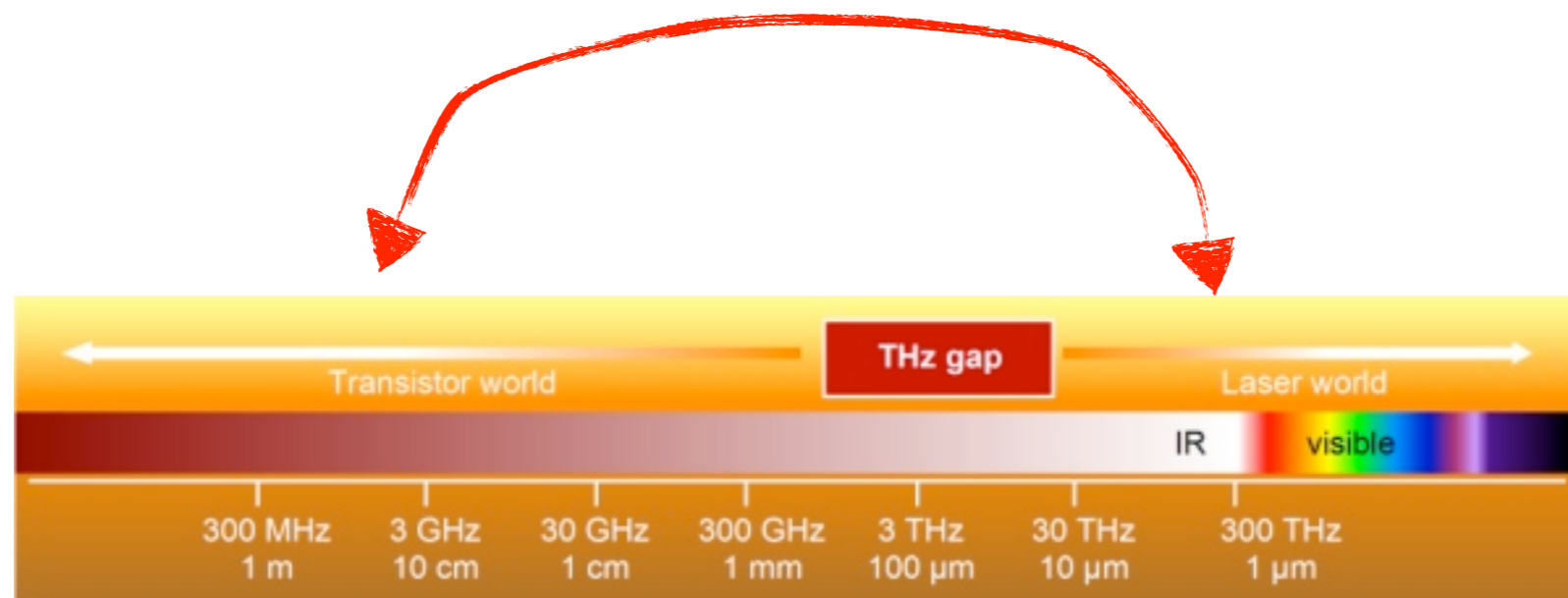
Optical structures naturally have sub-fs time structures and favor high rep. rate operation



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

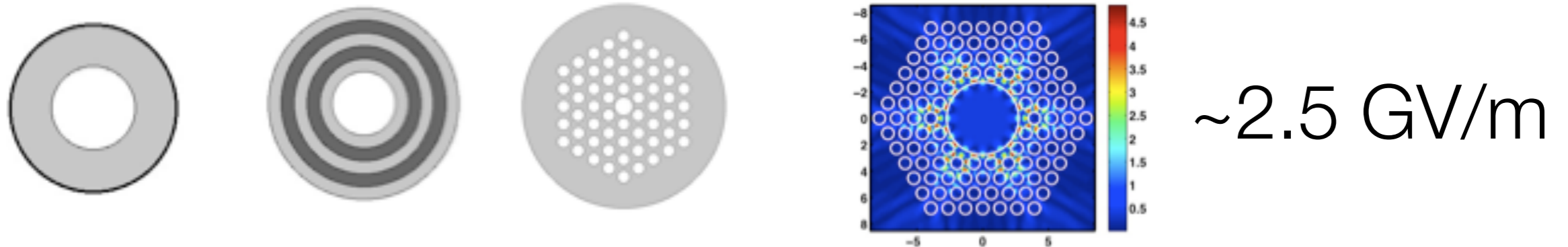


lack of sources, materials and fabrication technology
force us to make a leap from Microwave to Optical



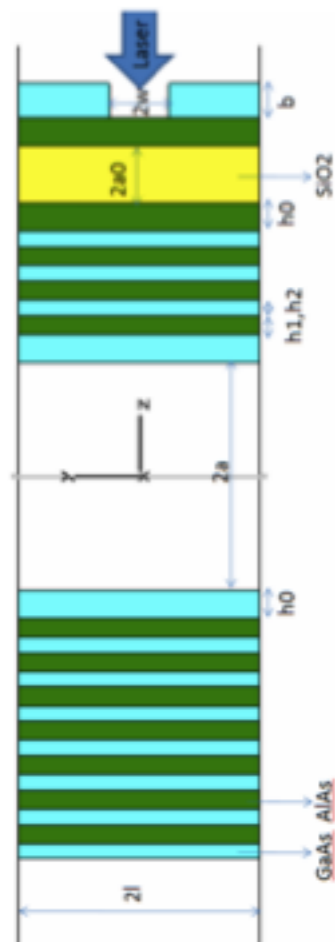
A variety of optical-scale dielectric structures are under consideration

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

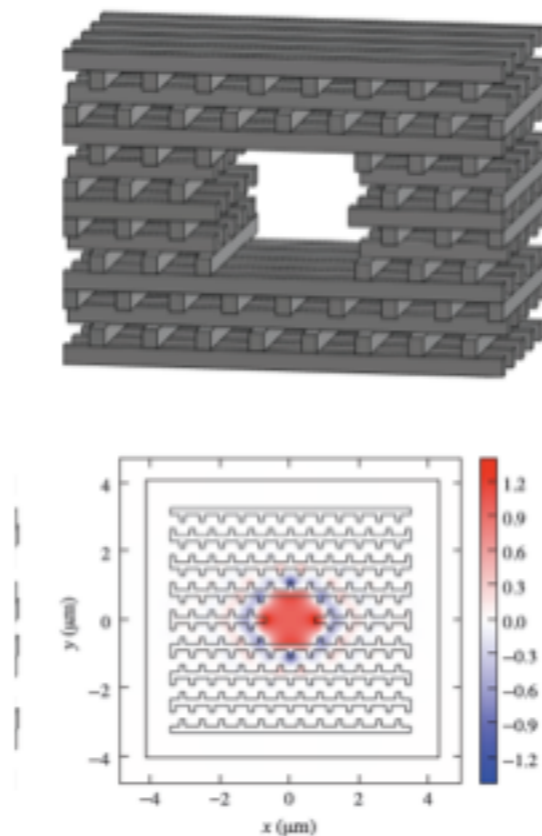


Planar structures offer beam dynamics advantages as well as ease of coupling power

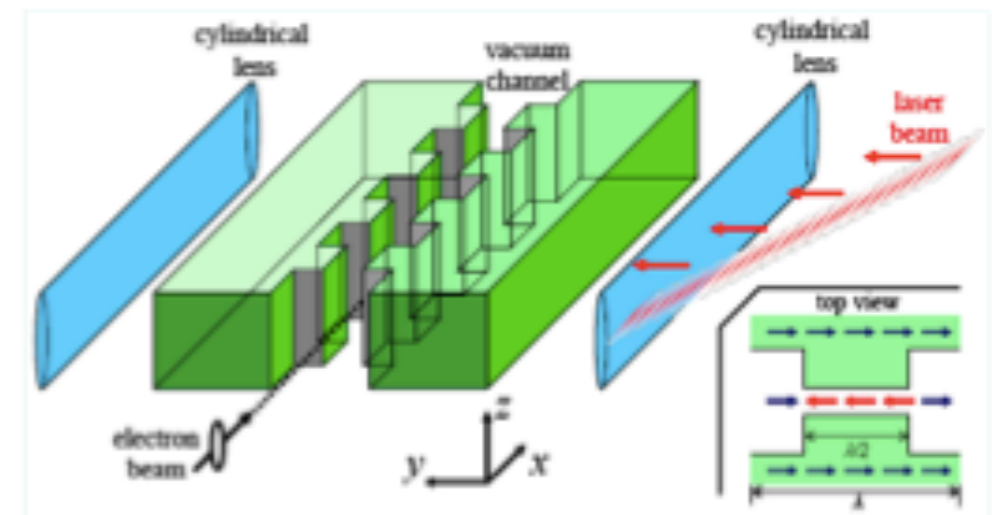
MAP



Logpile



Grating

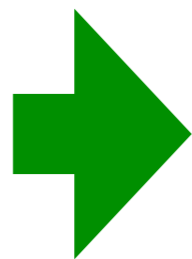


The MAP structure consists of a diffractive optic coupling structure and a **resonant cavity**

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

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

e-beam



gap (1 optical wavelength)

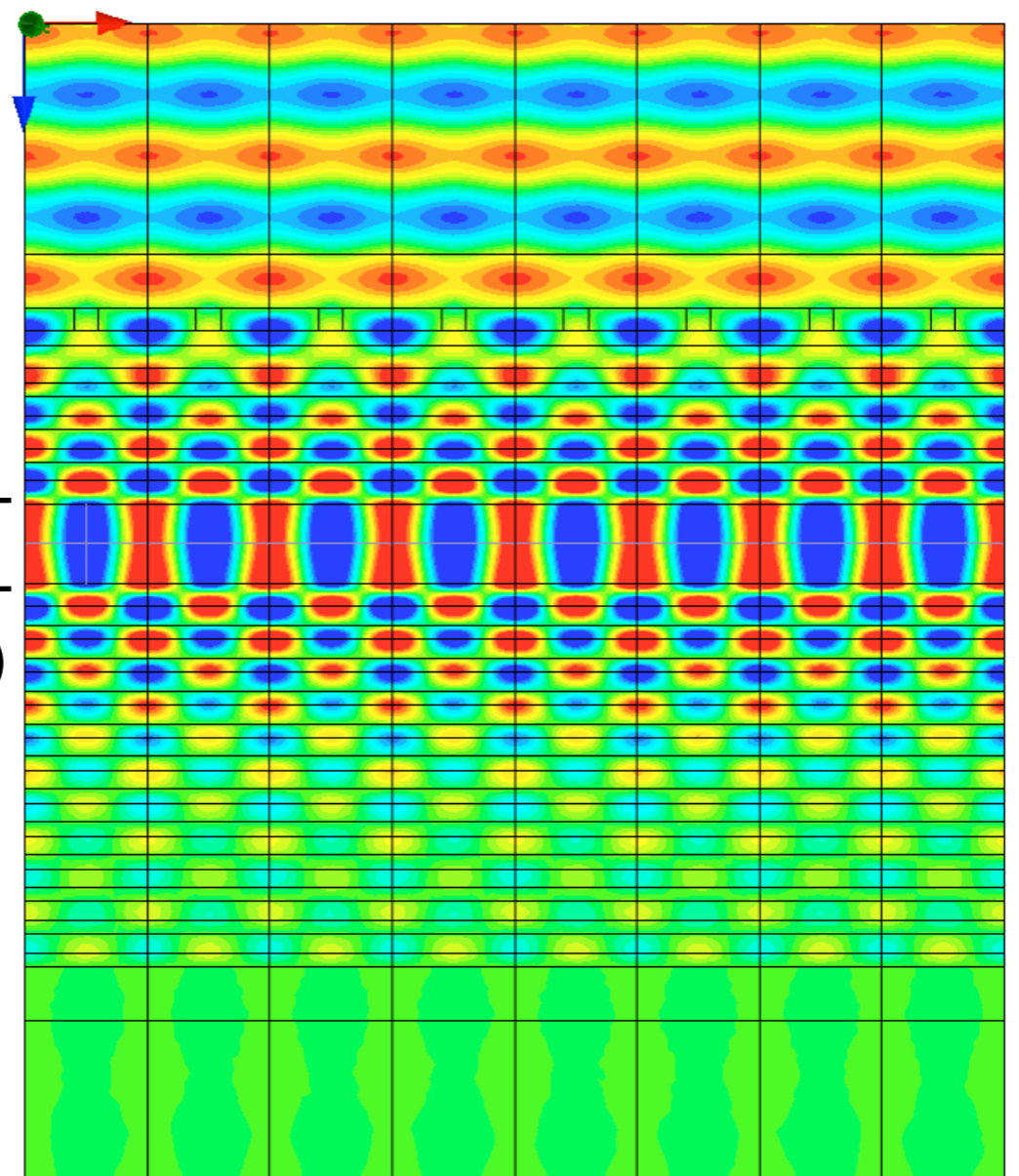
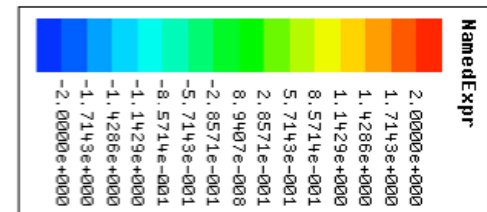
$$E_z = E_0 \cos(\omega z/c)$$

Tuning:
control “matching” layer
($b-a$).

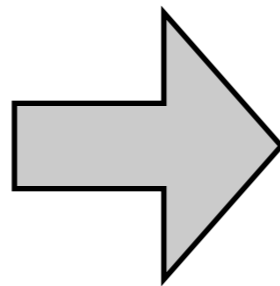
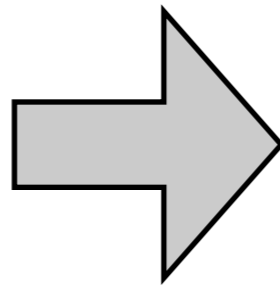
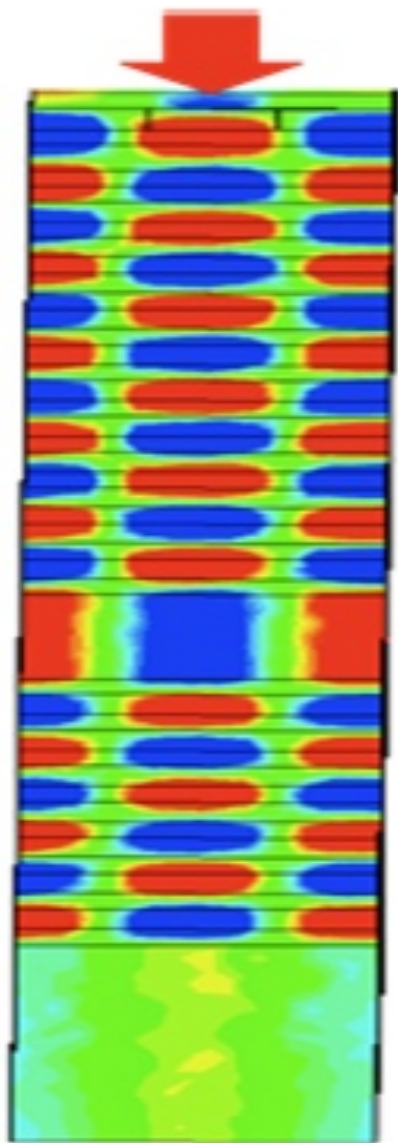
**Micro
Accelerator
Platform**



laser



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

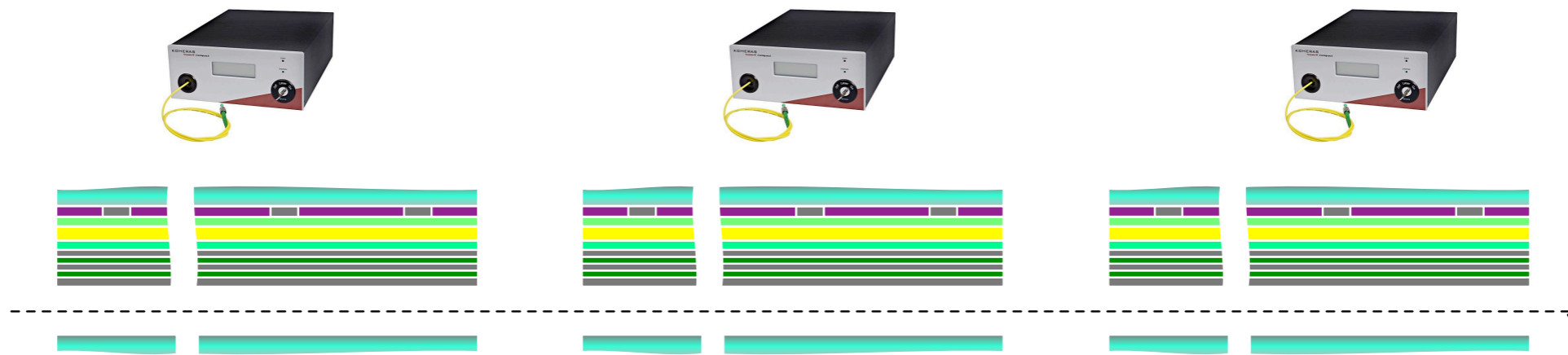


Parameter	Value
Laser wavelength	800nm
Cell length	800nm
Effective gradient	1.5 GeV/m
Quality factor Q	800
Effective shunt impedance R	2000 ohms
Effective shunt impedance per unit	2.0833 ohms
R/Q	2.5 ohms
R/Q per unit	0.0026 ohms
Transit factor	0.86
Stored energy	0.9 mJ
Power dissipation	<1% (0.75 MW)
Fill time	0.5 ps
Laser intensity	100 MW
Laser pulse length	1.8ps
Energy gain per unit cell	~2.5keV

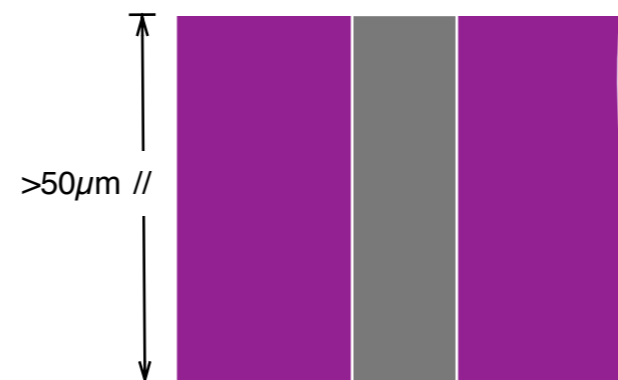
The laser-powered MAP can provide relativistic electron beams in an optical-scale device

easy power coupling

“easy” to scale & stage

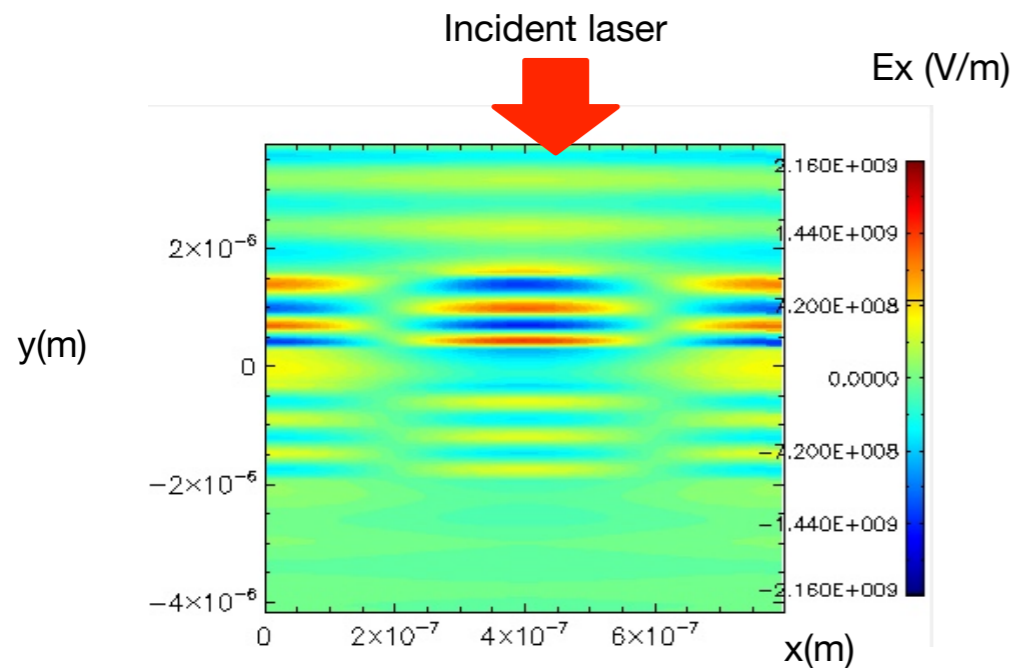


flat beams
low wakefields



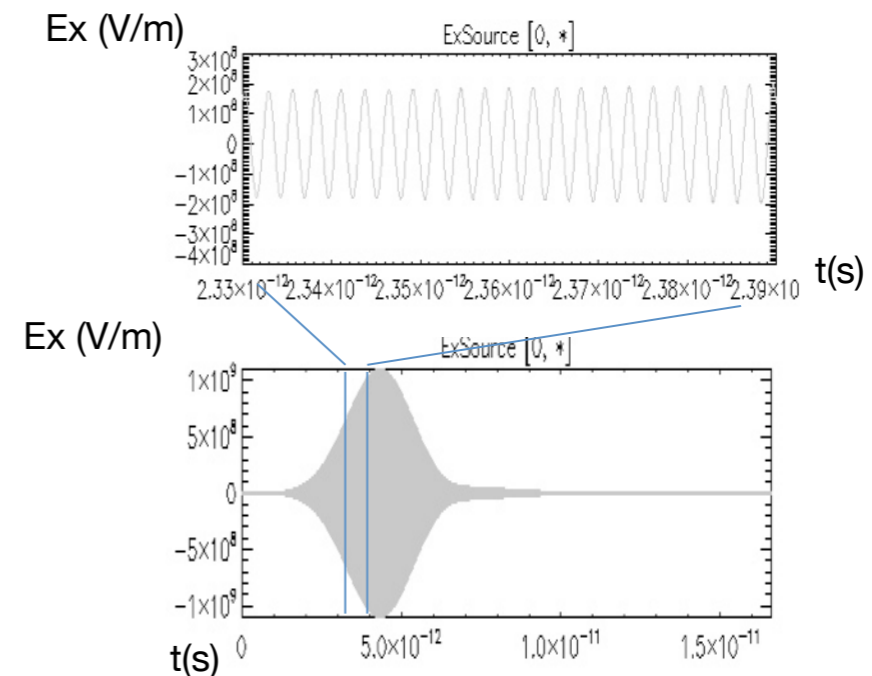
MAP simulations are now including acceleration, beam dynamics and material properties.

Resonant Fields (@ t = 7 ps)

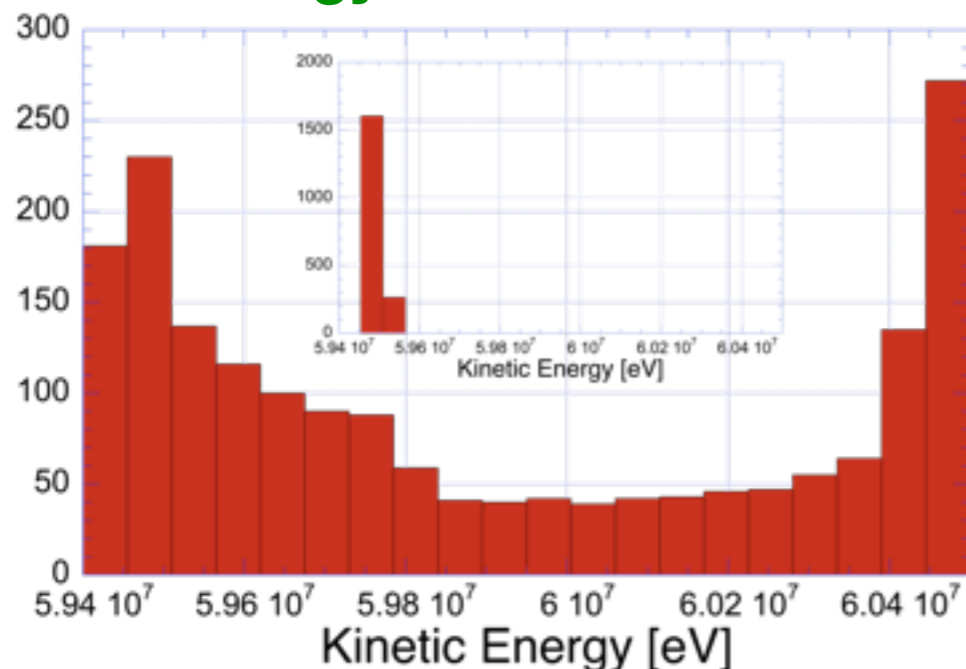


Input laser source

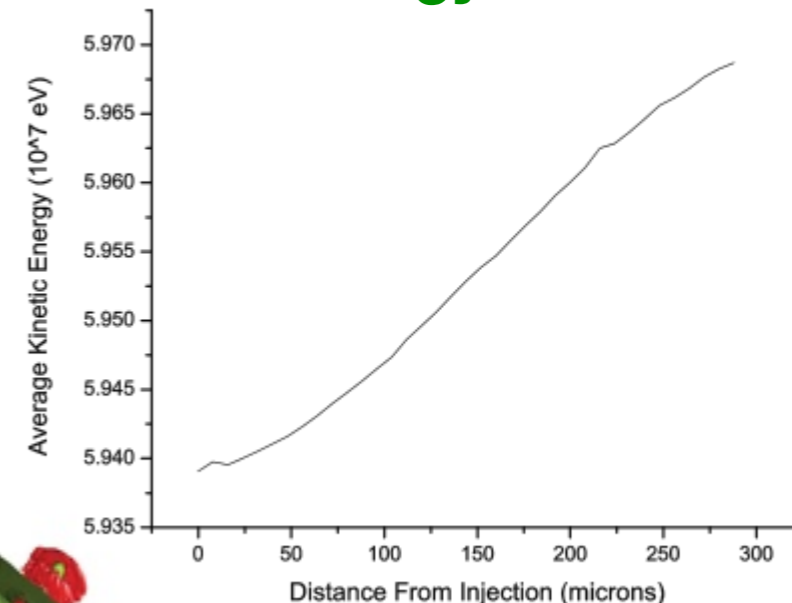
can correspond to actual Ti:Al₂O₃ laser



Energy Distributions

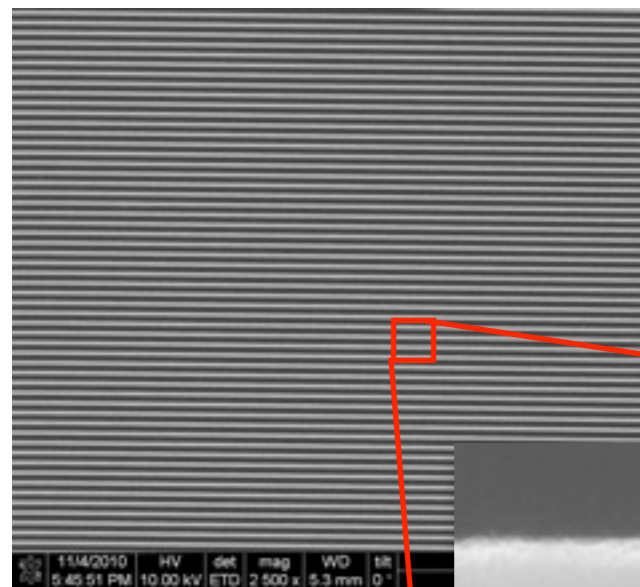


Energy Gain

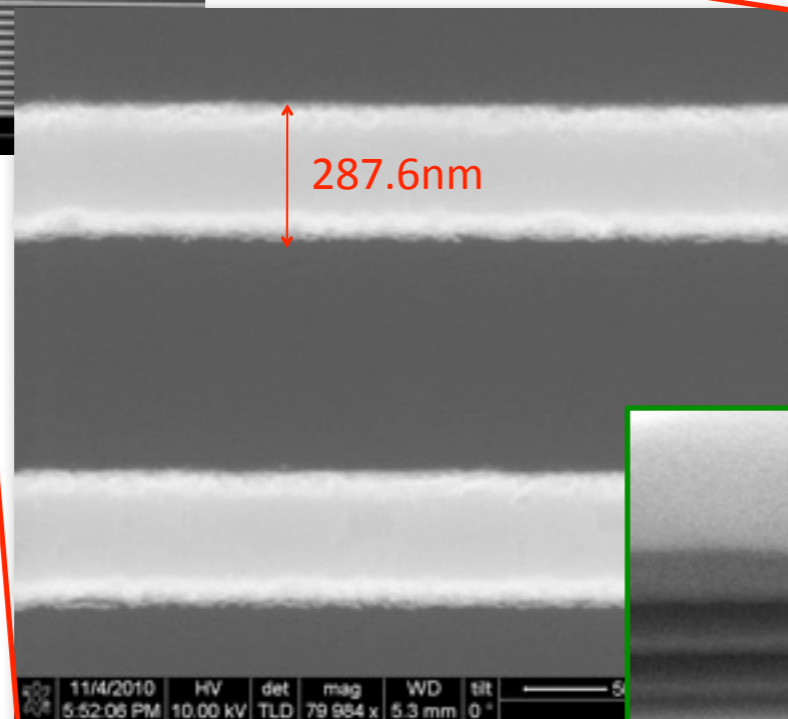


Thousand period structures—mm long and ~1 MeV gain—are now being produced.

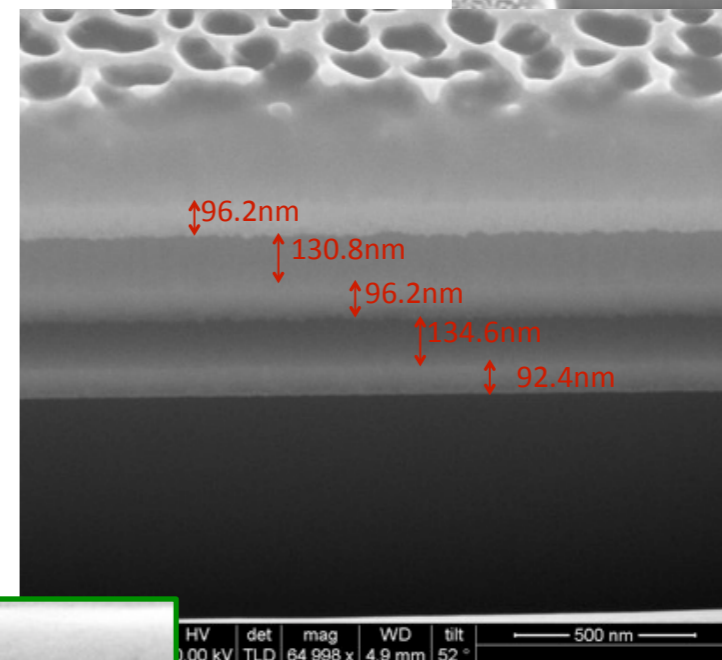
Full scale coupler



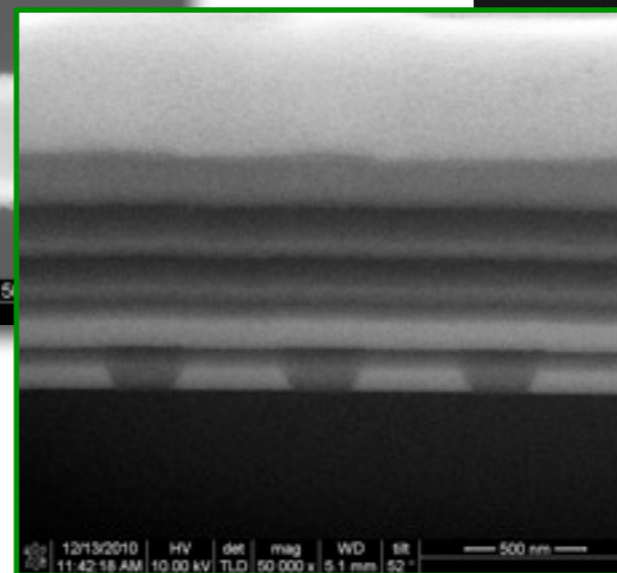
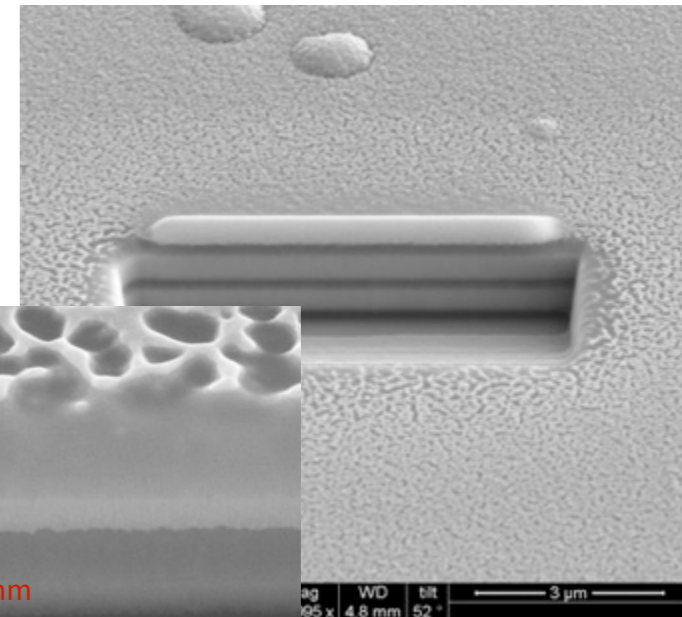
Structure Dimension:
300nmX250μmX1000



+



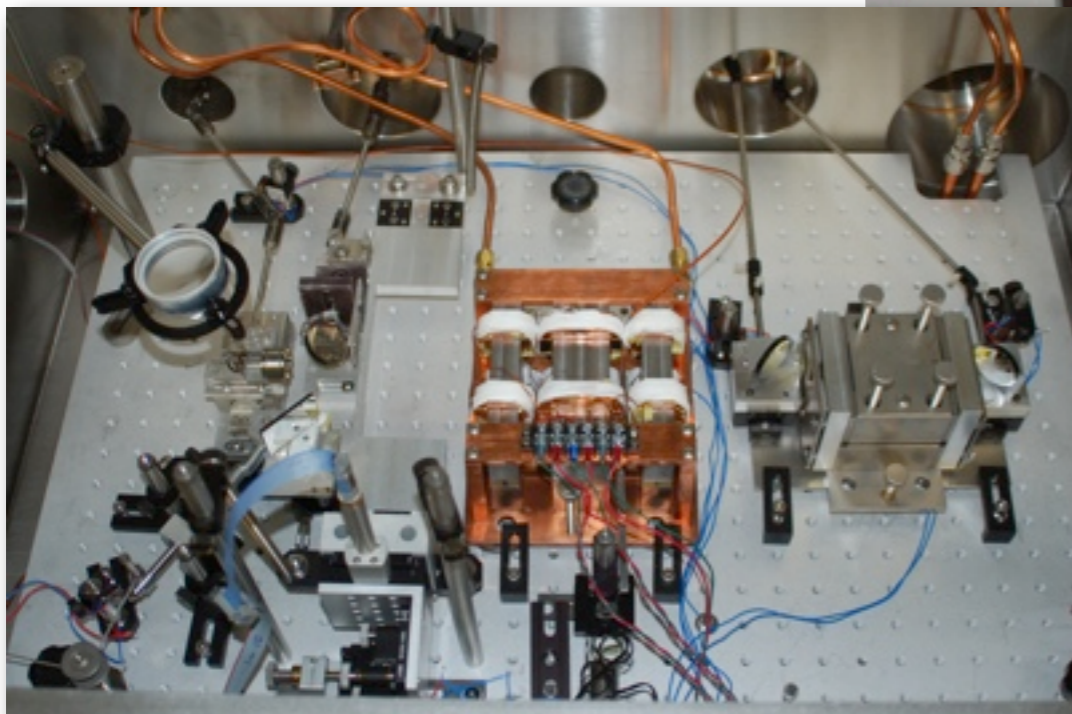
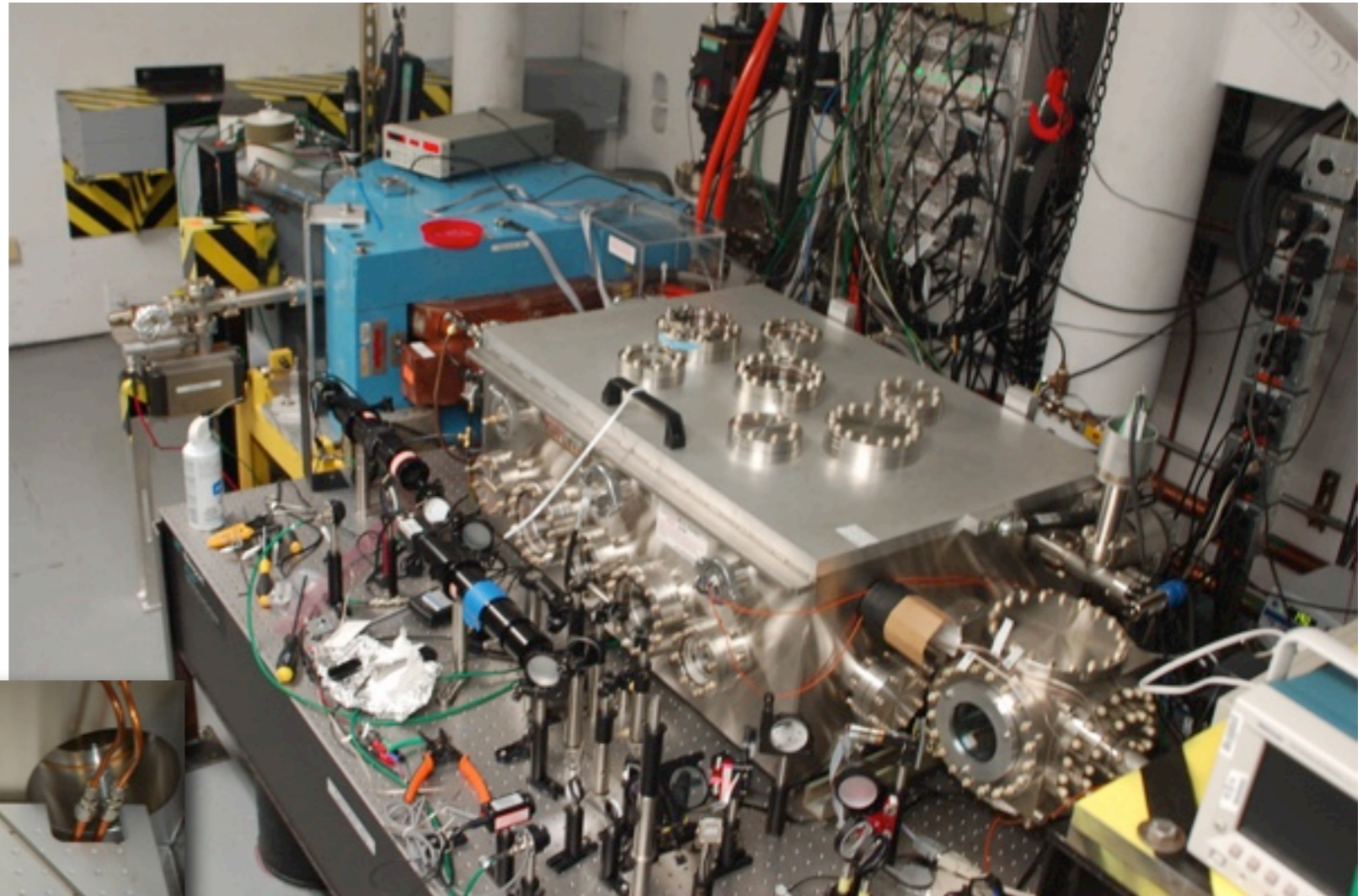
DBR



DBR+Coupler

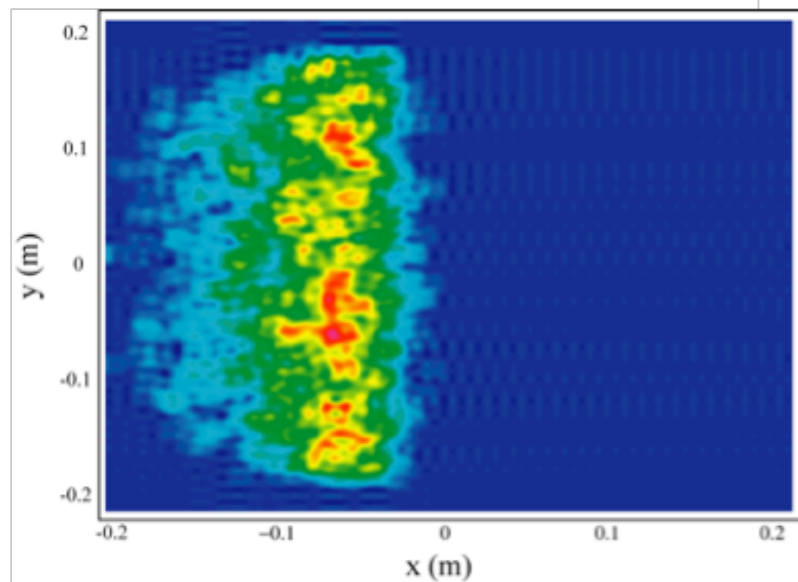
Beam testing has begun at SLAC's E163 facility which hosts a suite of micro accelerator tools.

 **AARD**

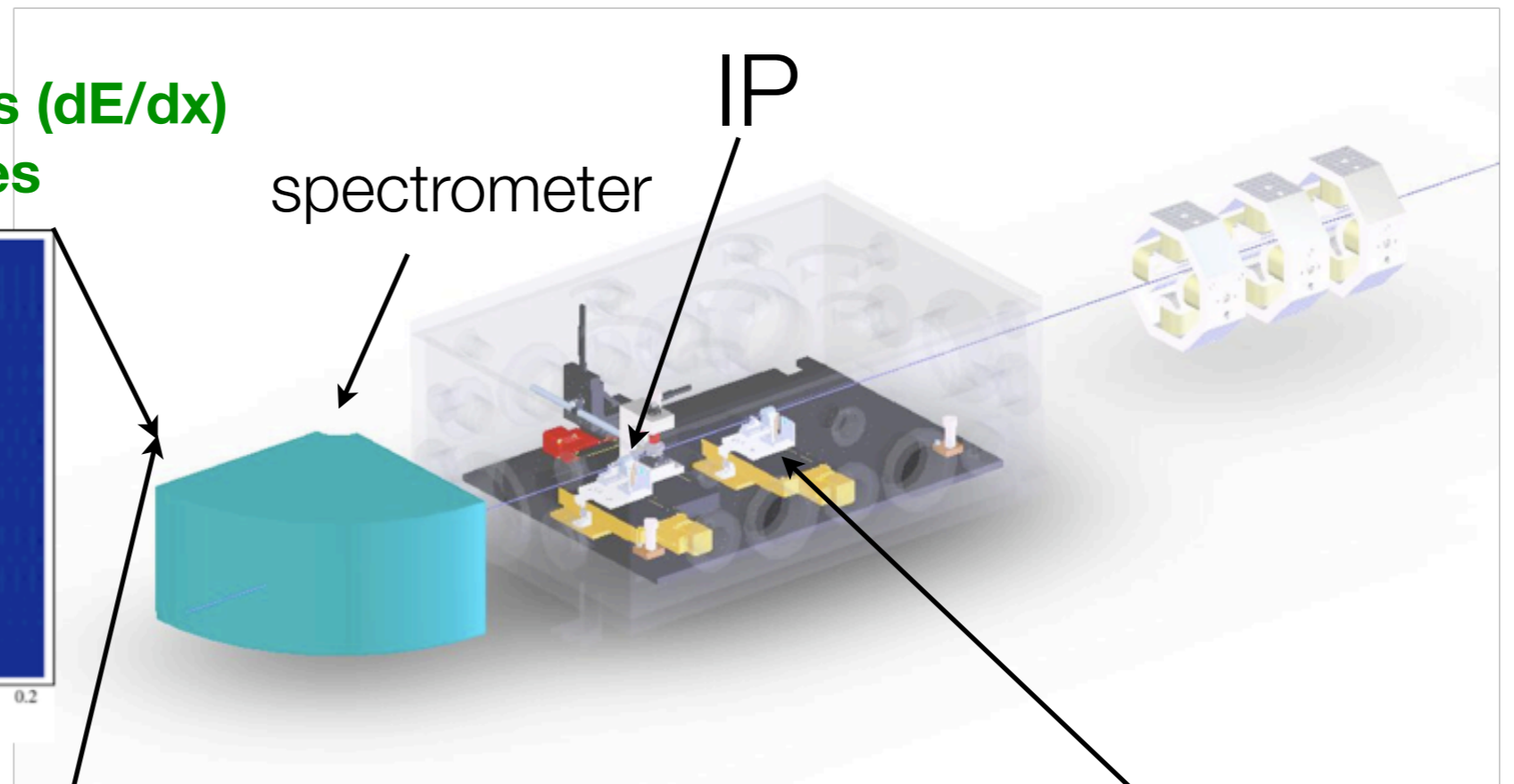
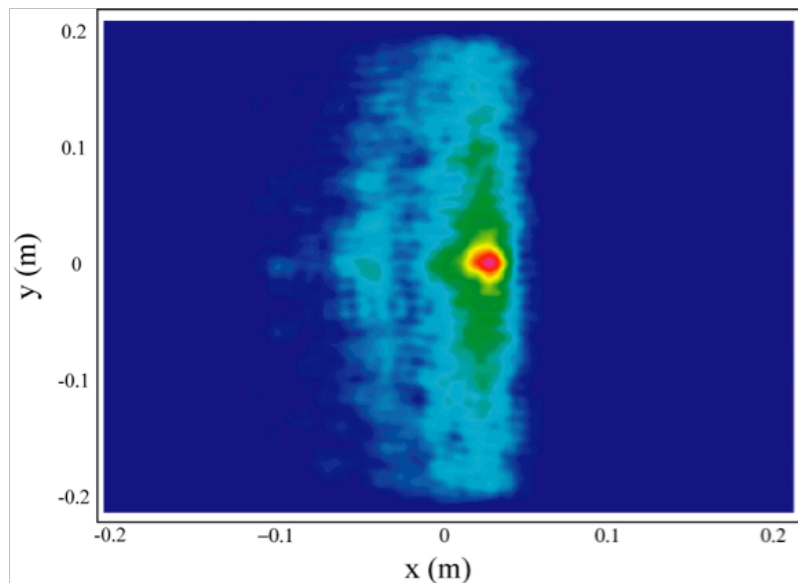


An energy spectrometer is capable of separating transmitted from scattered electrons

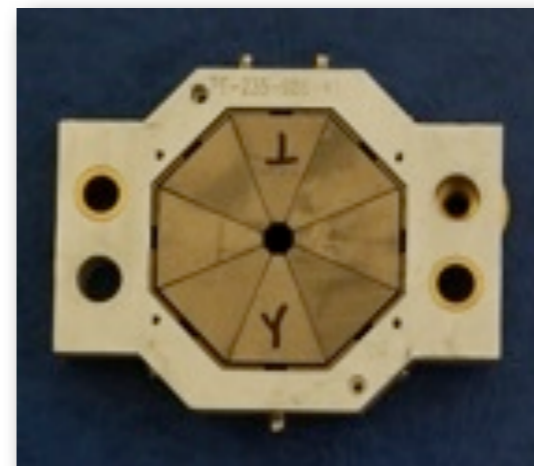
**structure causes energy loss (dE/dx)
to misaligned particles**



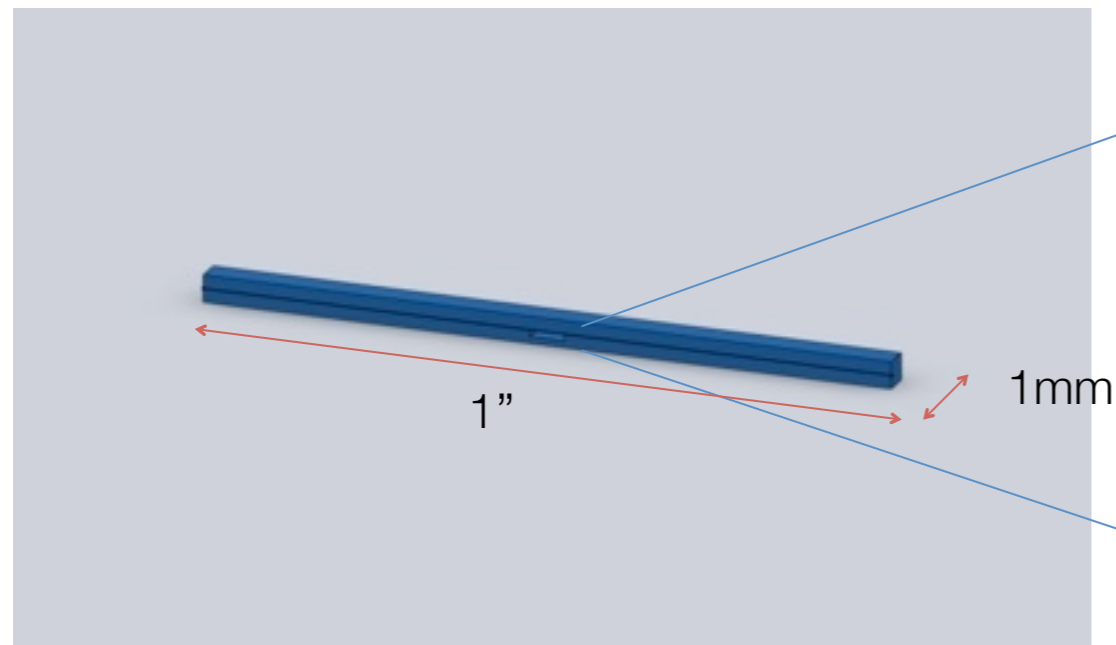
no structure at IP



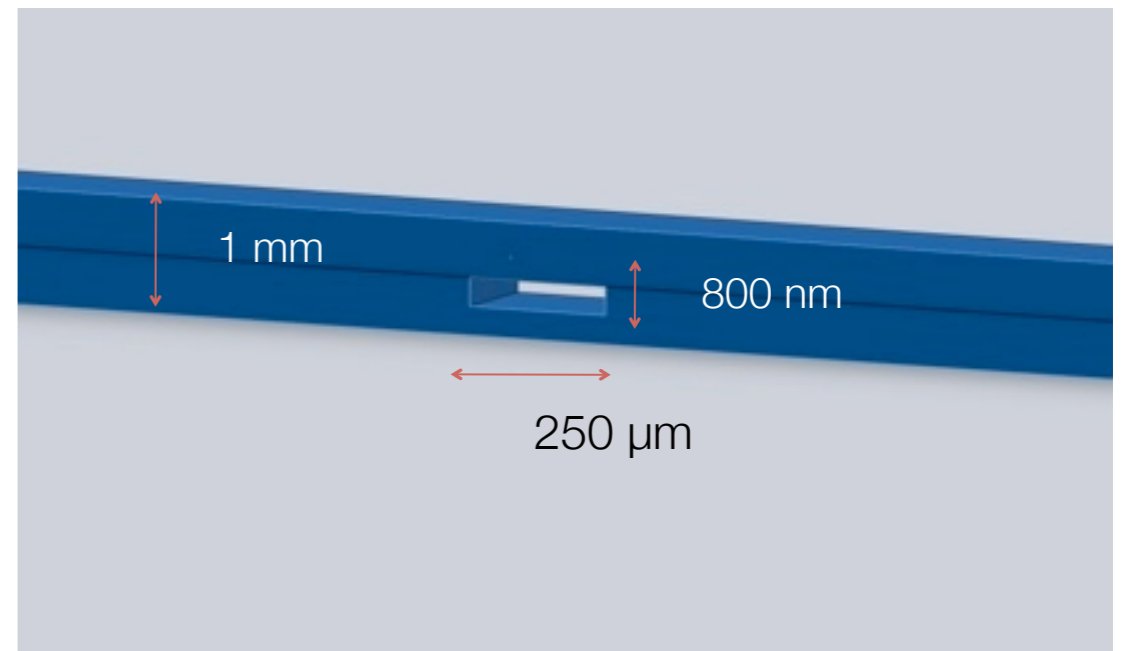
E-163 PMQs



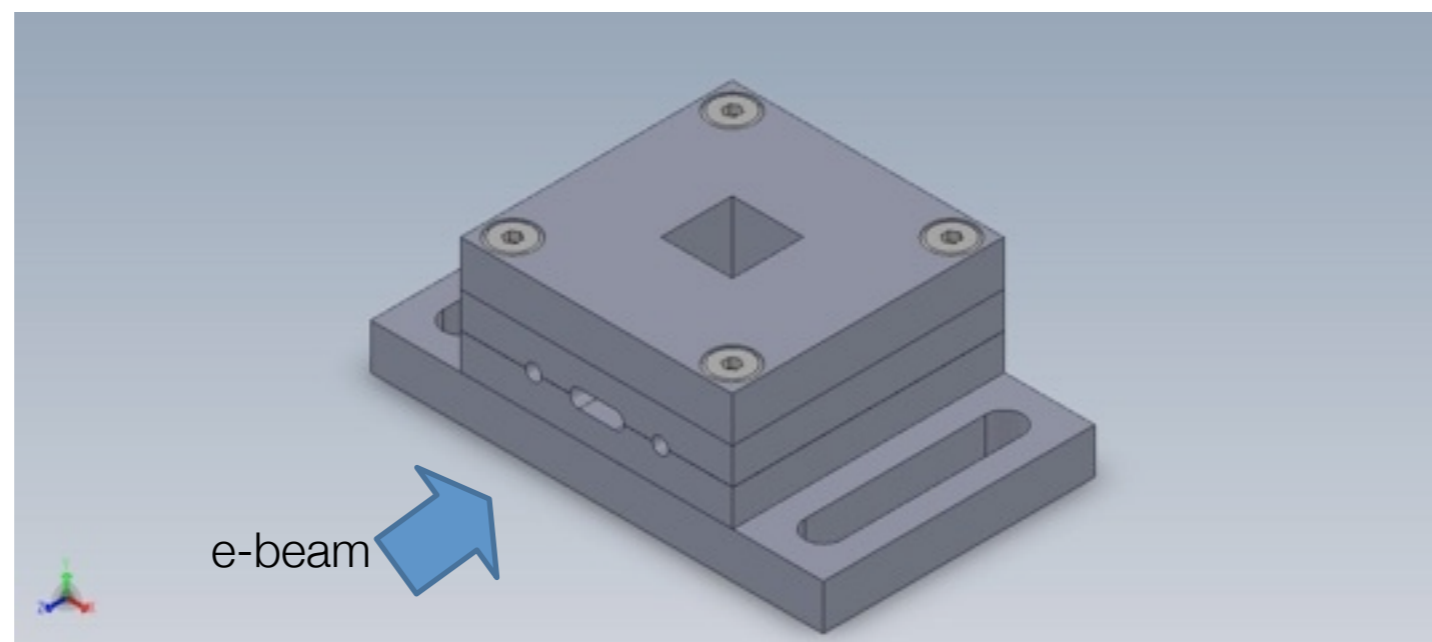
A “Dummy Structure” and mount was designed for beam transmission studies.



Glass dummy structure



Slot in dummy structure (not to scale)



Aluminum holder for glass structure

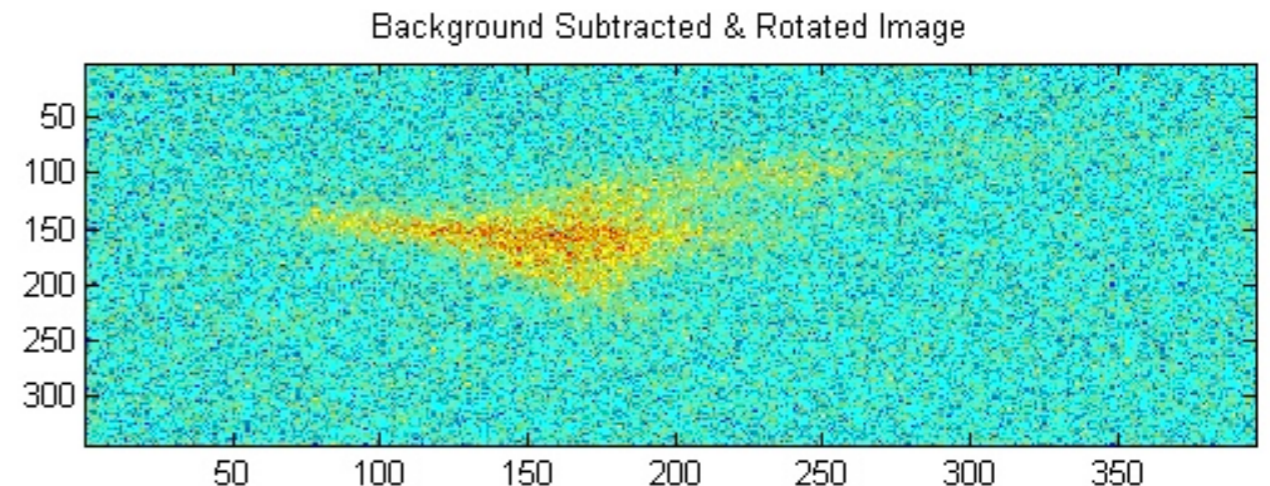
For the first time, beam was transmitted through the optical-scale structure!

Bunches from NLCTA Beamline

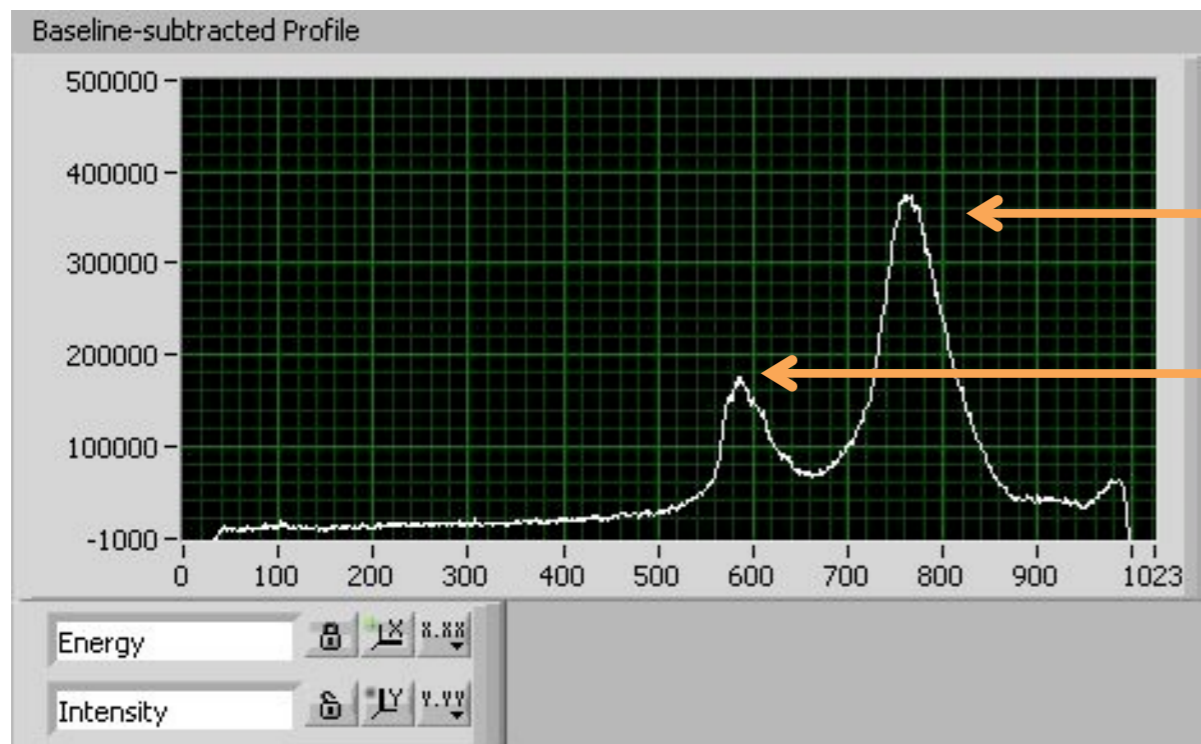
Spot size = $96 \times 83 \mu\text{m}^2$

$\epsilon_x = 43 \mu\text{m-rad}$

$\epsilon_y = 24 \mu\text{m-rad}$



Spectrometer Image (higher energy to the left)



electrons that lost energy while traveling through glass

electrons that made it through slot

► Theoretically, we expect peaks to be separated by **0.5 MeV**

► With calibration of 1.776 KeV/pixel, we find separation of **0.337 MeV**

Data analysis is ongoing

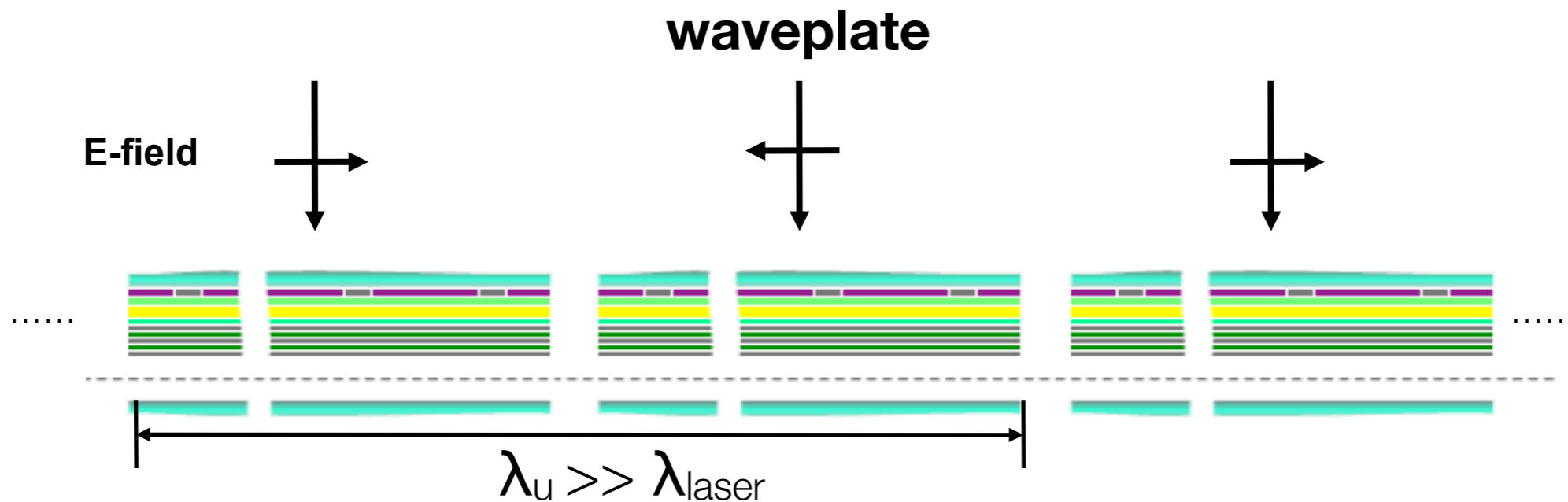
Just one more thing...
(three, really)



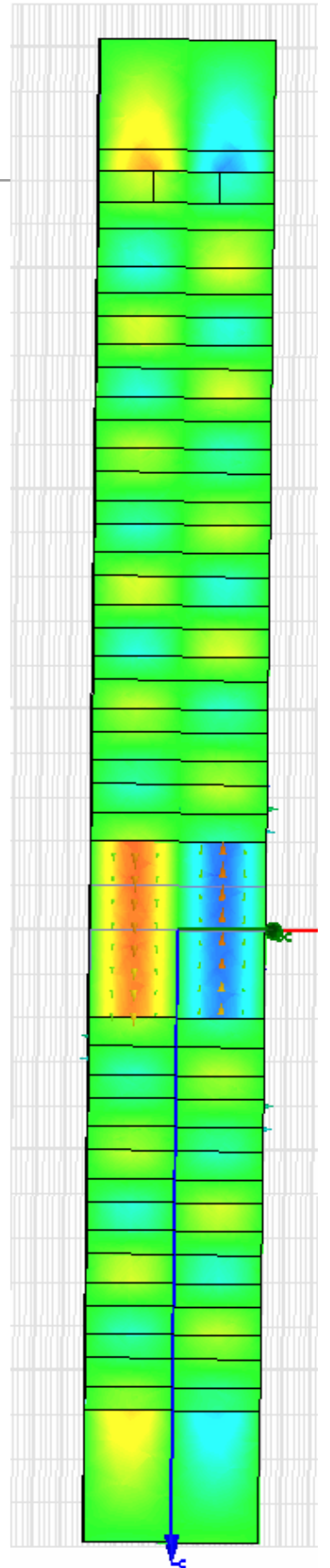
1. an all optical $\Upsilon\Upsilon$ collider?

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

Undulator Period = Laser Phase Flip



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



A hard x-ray light source powered entirely by lasers and on a laptop scale will be a **Quantum FEL**

Parameter	Optical Und.	Conventional
FEL Wavelength	~0.1 Å (10 keV)	
Beam energy	10s MeV	100s MeV
Emittance (norm.)	0.06 μm	
Current	2000 A	
Charge	1 fC (whew! ~10 ⁴ e ⁻)	
FEL Parameter (ρ)	10 ⁻⁵	10 ⁻³
Undulator parameter	10 ⁻³	~1
Undulator period	1-20 μm	1 cm
Saturation length	~10 cm	~1 m

because $\hbar\omega / E \approx 6 \times 10^{-4}$

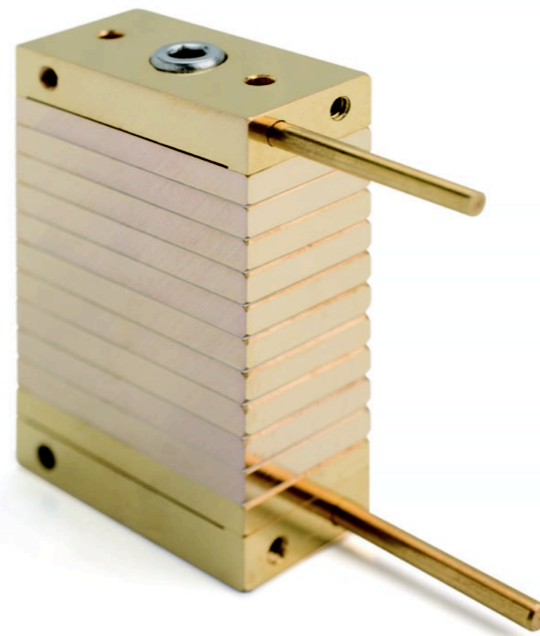
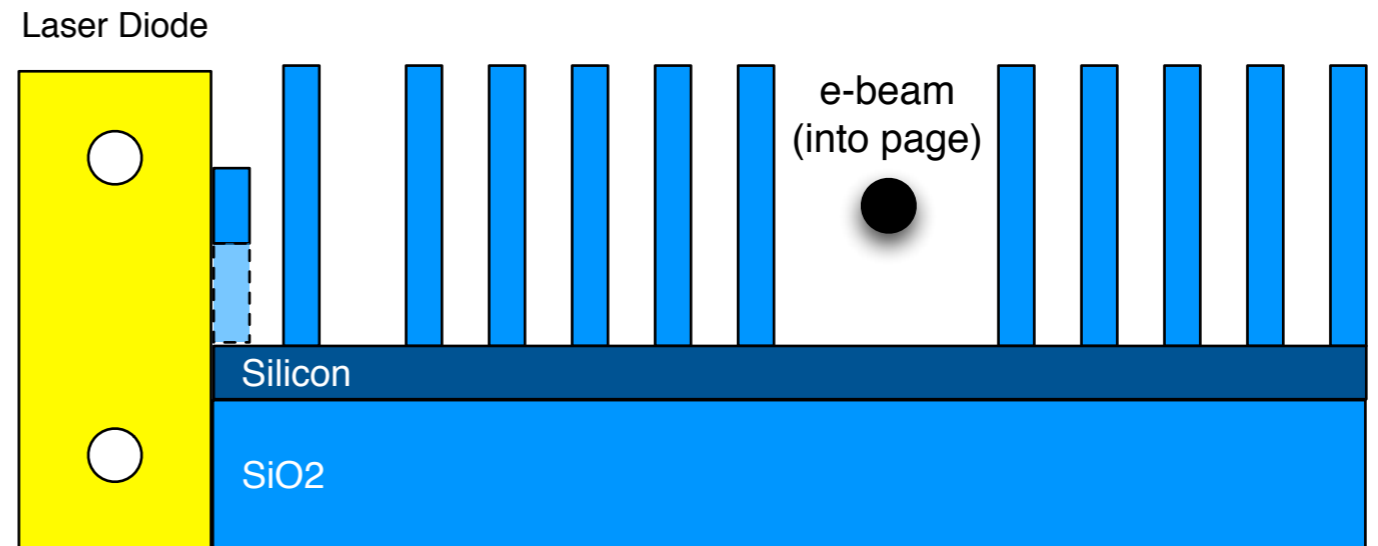
one photon emitted recoils > FEL bandwidth, ρ

2. a High-Q MAP

It may be possible to create a fully integrated optical accelerator and laser.

Vacuum slots cut into a monolithic structure allow for very low losses

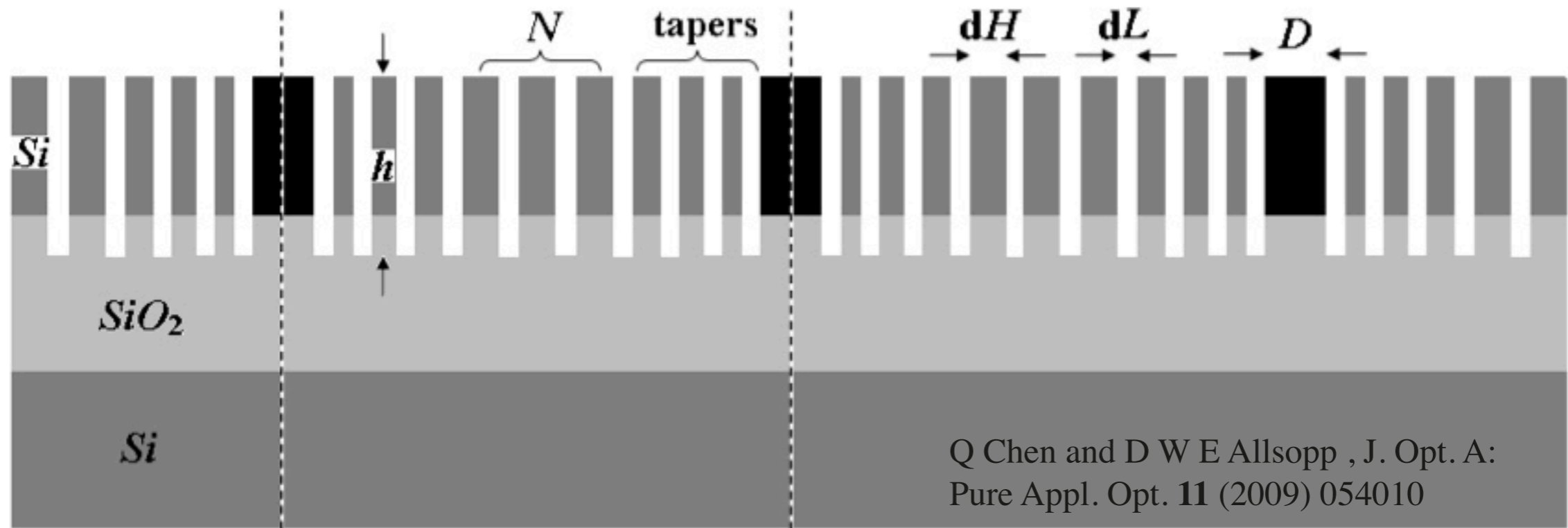
High Q = ns fill times & kw peak power needs



A diode laser naturally provides long pulses of moderate power

3. an ultra-low beta MAP

Using slow-light techniques, we may accelerate heavier particles such as protons and muons



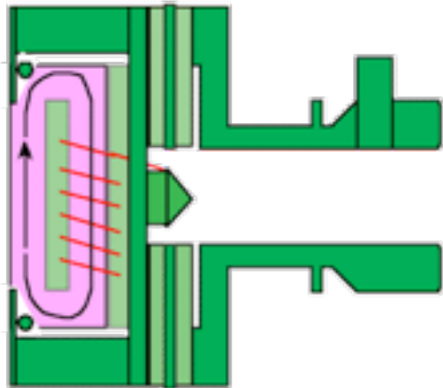
Coupled cavity WGs are a periodic chain of microcavities in which light propagation is realized by tunneling from one cavity to another

Group velocities of $c/100$ are possible.

A MAP based on these concepts is being designed for the acceleration of heavy charged particles

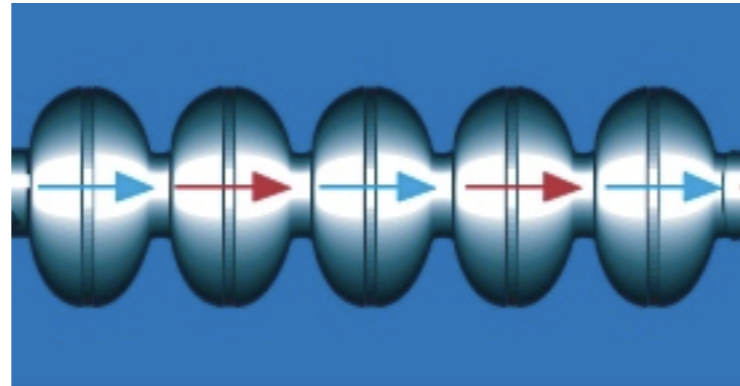
We have the opportunity to develop a suite of on-chip particle beam tools

guns



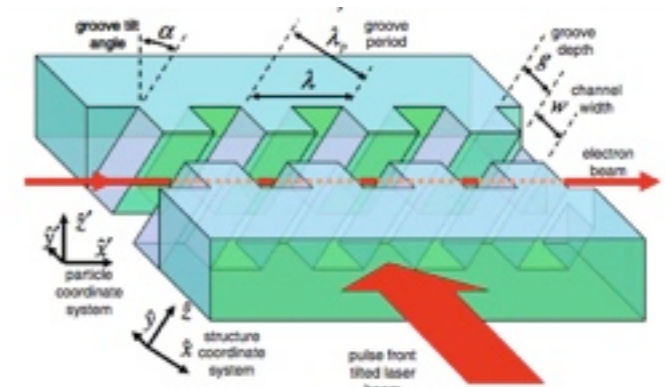
monolithic structures

sub-relativistic structures



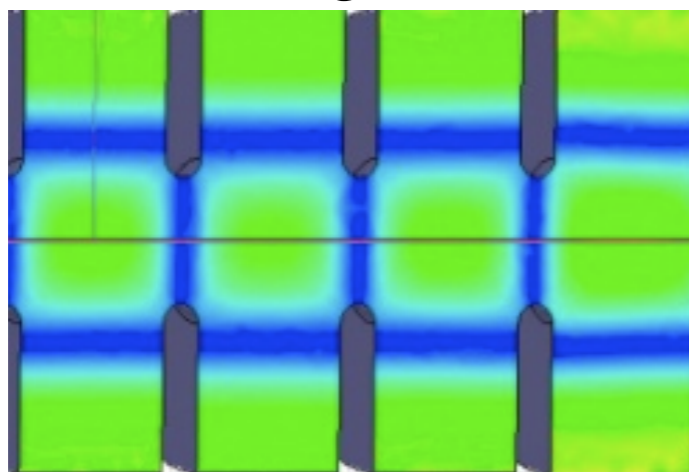
muons, protons, ions

undulators



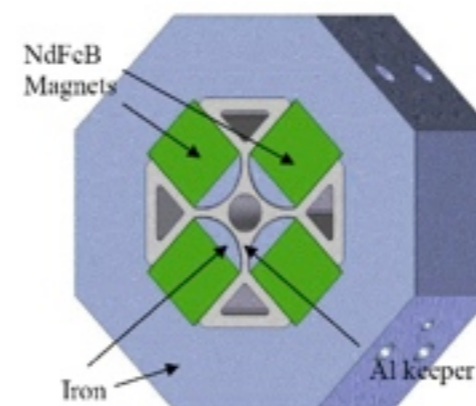
coherent THz/x-ray sources
IFEL accelerator

deflecting cavities



ultra-fast sources

focusing



ICS Gamma-Ray Source

all using laser-driven dielectric structure

Do optical-scale structures make suitable
accelerators for colliders?

YES

The road to a viable DLA-based accelerator for colliders is still long. Drivers (and funders) wanted.

reliable many-period acceleration
tolerances & alignment
beam manipulation
injection
positrons
polarized beams
radiation damage
thermal management

·
·
·

Acknowledgments

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DTRA

UCLA

DOE

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Josh McNeur (Grad - Simulations)

Esperanza Arab (Staff - Engineering)

Several past and present students...



UCLA

