An Optical-Scale Period Undulator for Hard X-Ray Production from Compact Devices?

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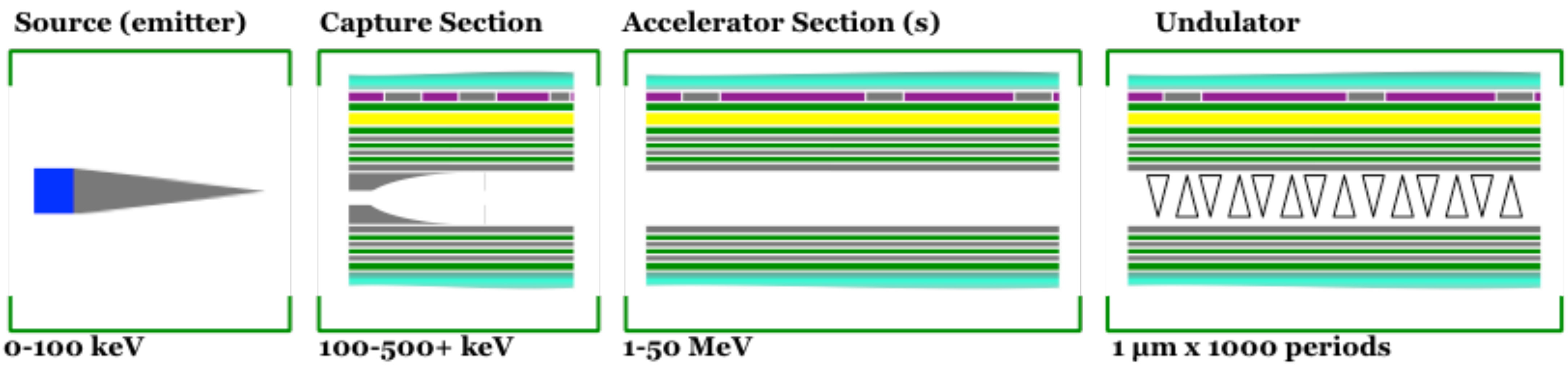
PBPL

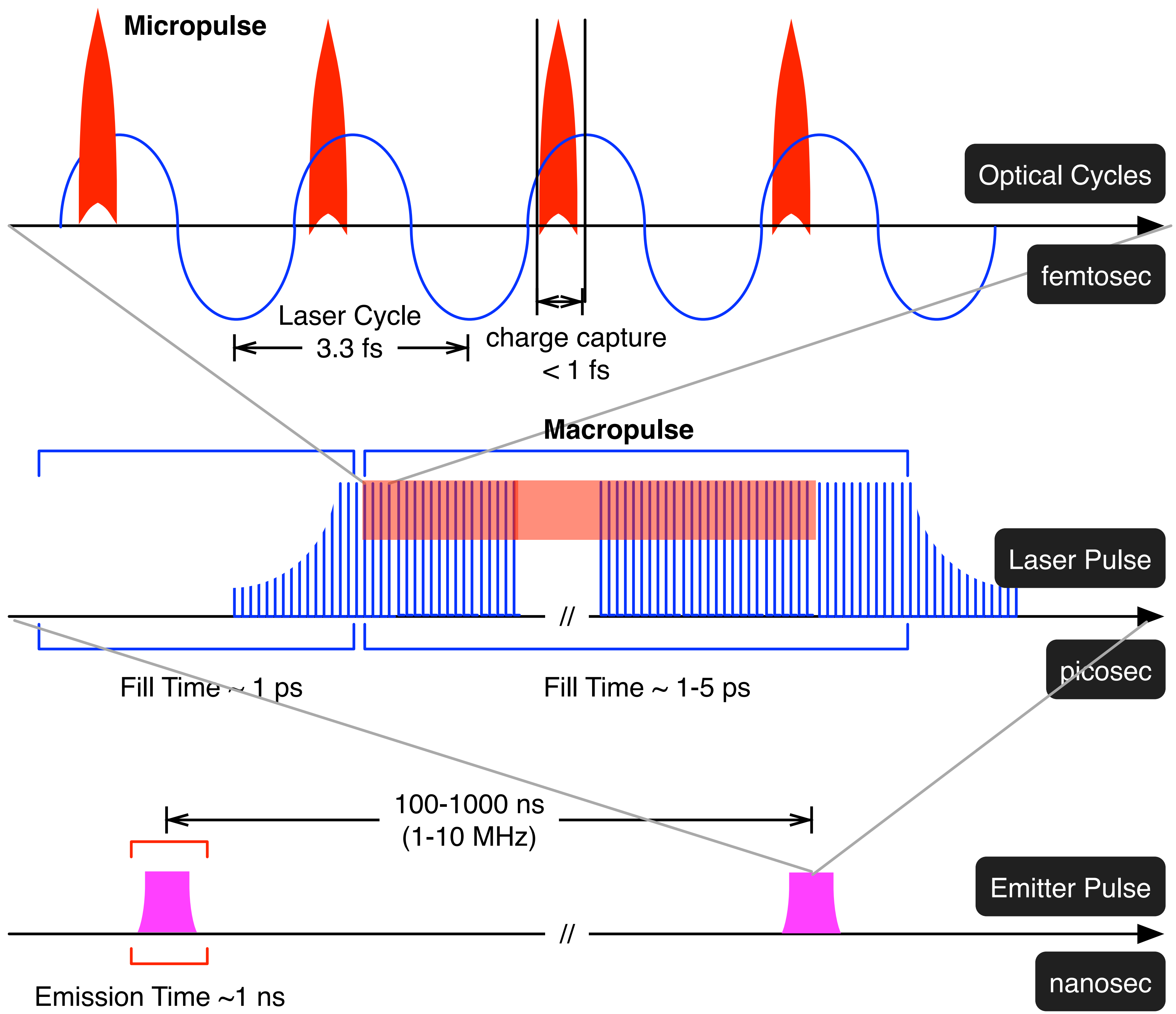
FLS 2012

A laser-powered dielectric accelerator can provide relativistic electron beams and x-rays in a chip-scale device

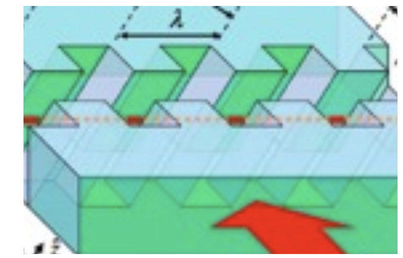


+ laser(s)

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

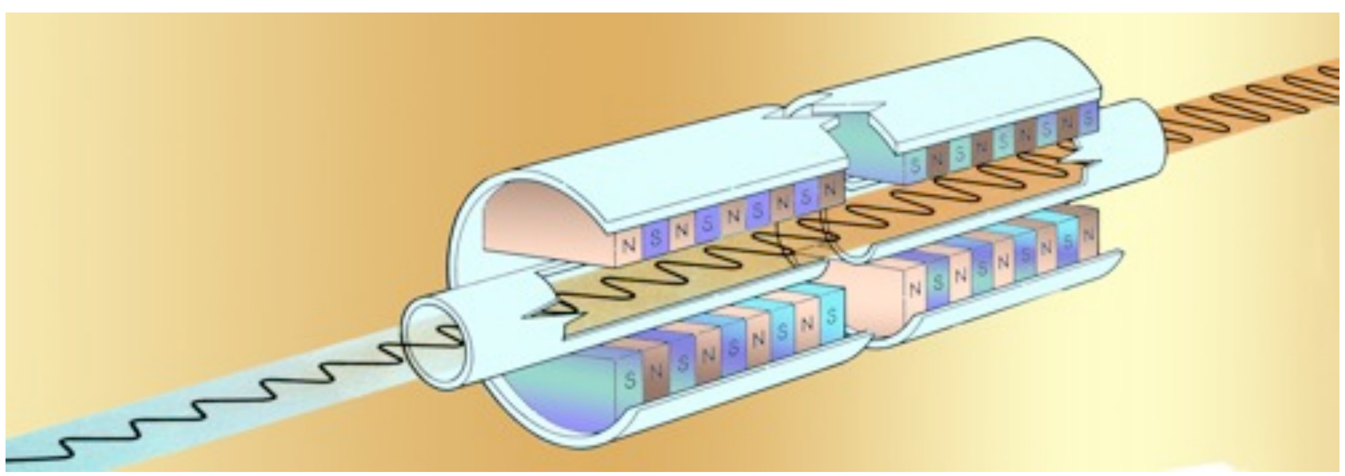


Undulator technology has significant impact on the FEL design.

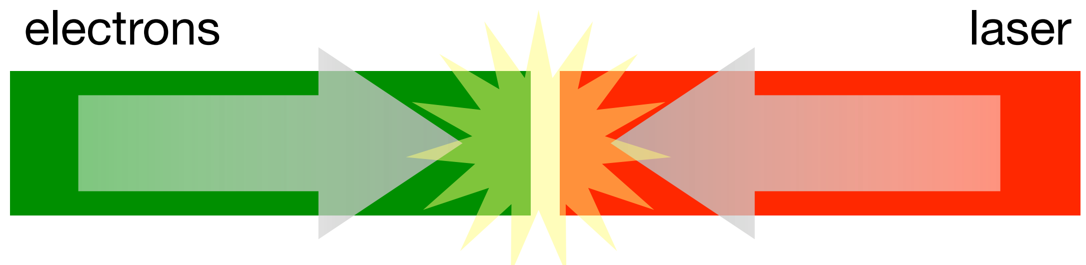
    

	PM	Micro/Pulsed	RF	Laser	Opt. Struct.
Period	>1 cm	0.1 - 1 mm	**0.1-1 cm**	1-20µm	1-100+µm
Parameter	1-10	**<1**	~1	~1	<0.01
Gap	5 mm	1 mm	**1+ cm**	open	1 µm
Status	Mature	some SC work	stalled	ICS like	paper

Ultra-short period undulators



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

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

Our baseline parameters:

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

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

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

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

In general, we take

$$L_R = L_L$$

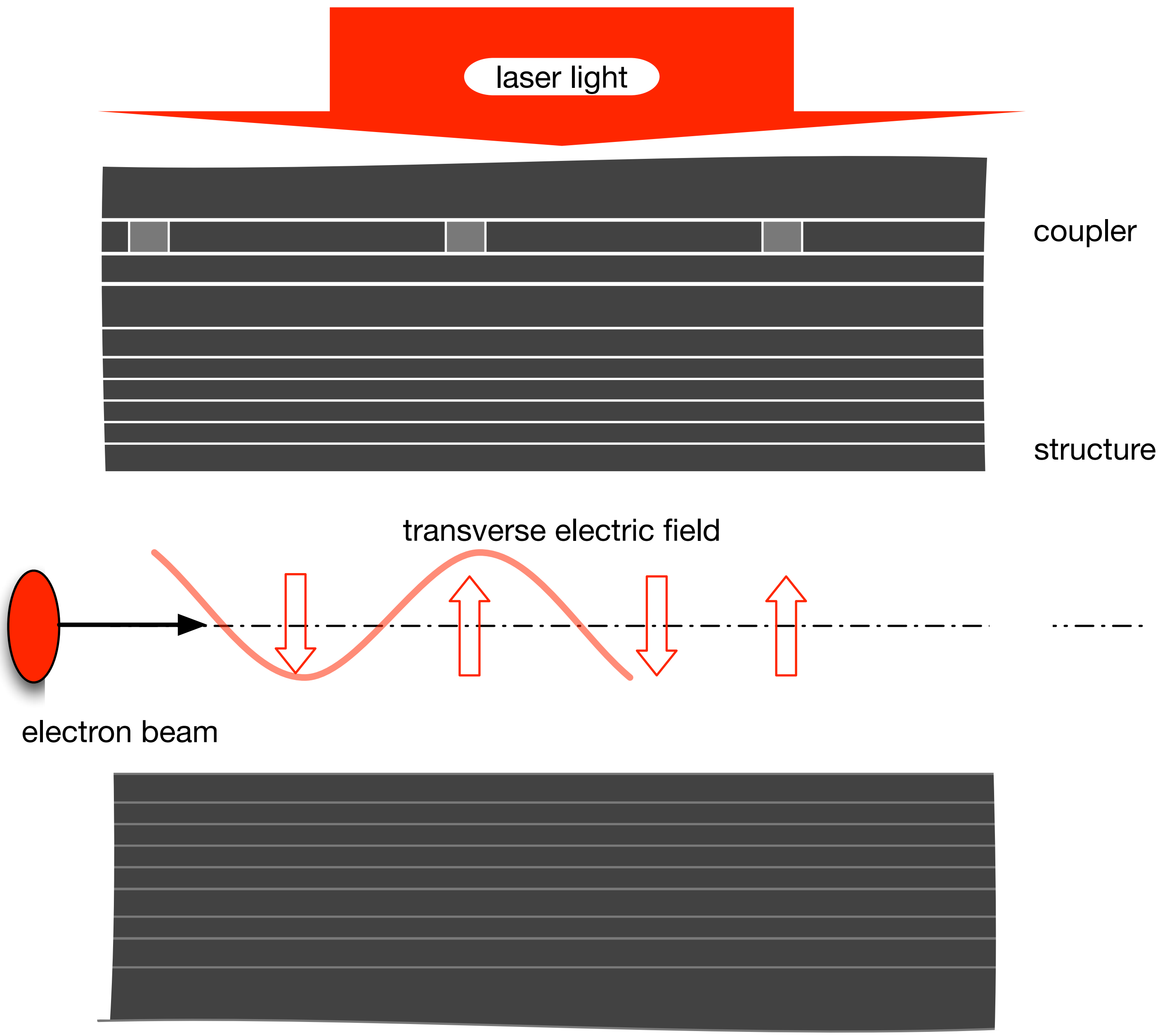
For our example case:

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

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.



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

very short (λ_u), very small (K), low (γ)

Small period means small K:

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

Focusing is an additional issue:

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

RF & Laser based undulators offer advantages but demand very high peak power and are under-developed

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

RF waveguide undulators can work

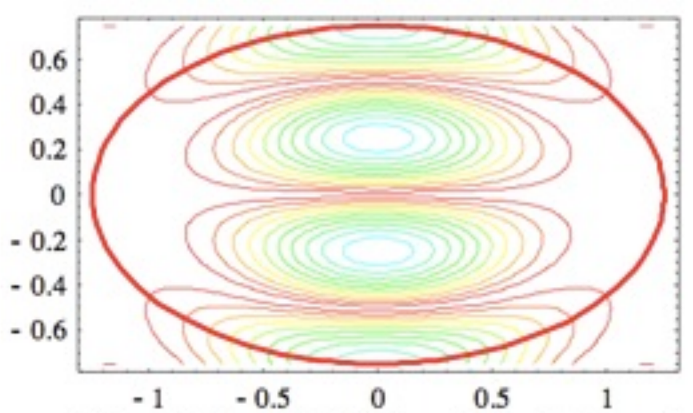
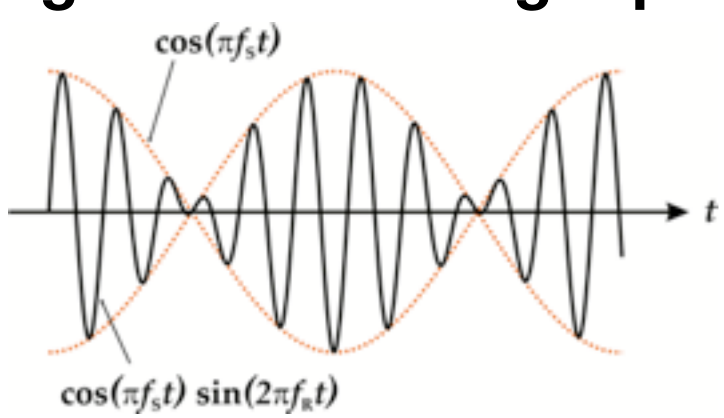


Figure 5. Electric field lines for the sTE_{12} mode.

Beating can create larger periods



800nm + 1µm = 20µm

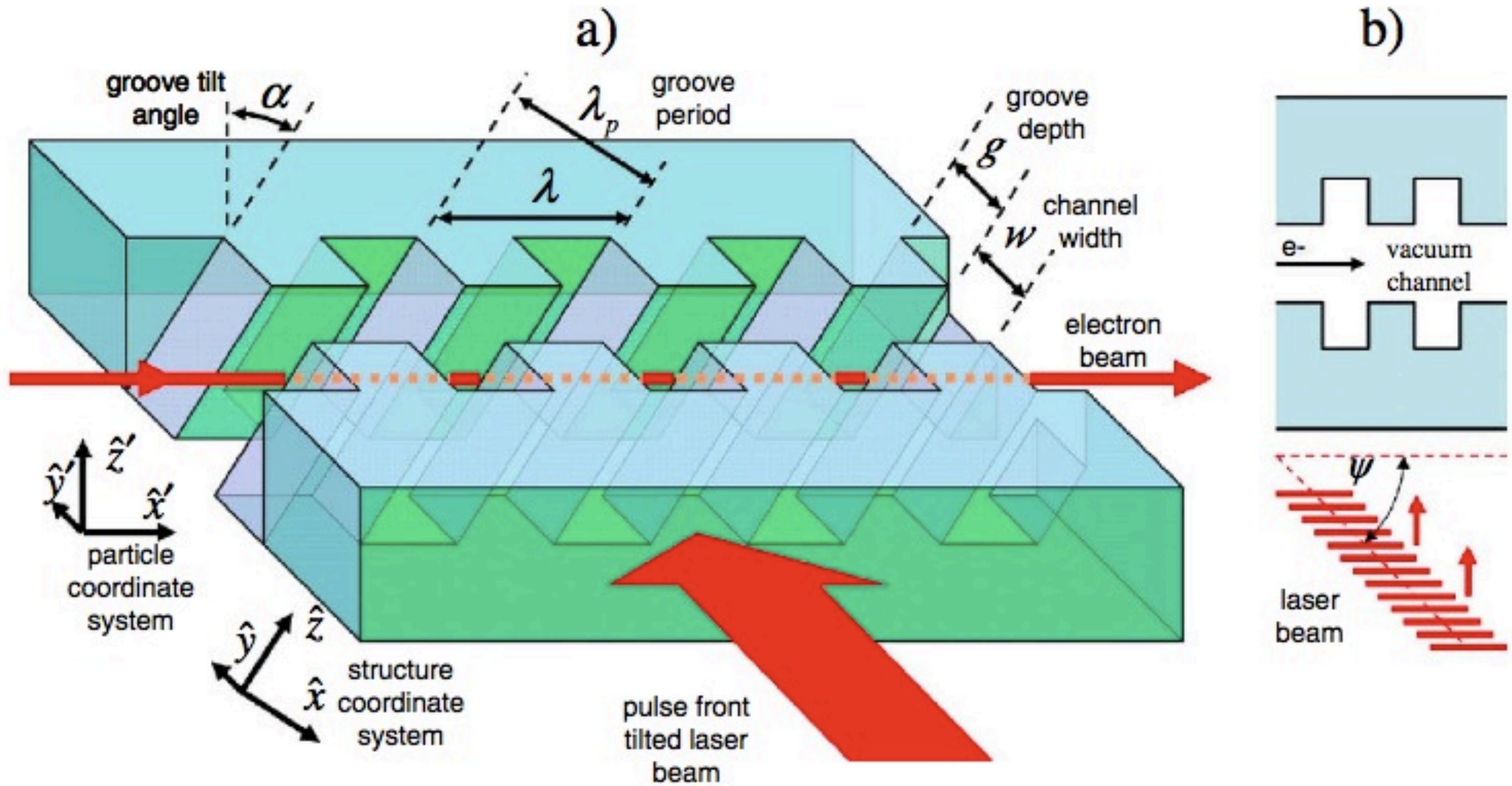
Bad:
betatron motion
power loss along waveguide
modes and cutoffs

Uniformity is very stringent:

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

Laser Undulator Issues:
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

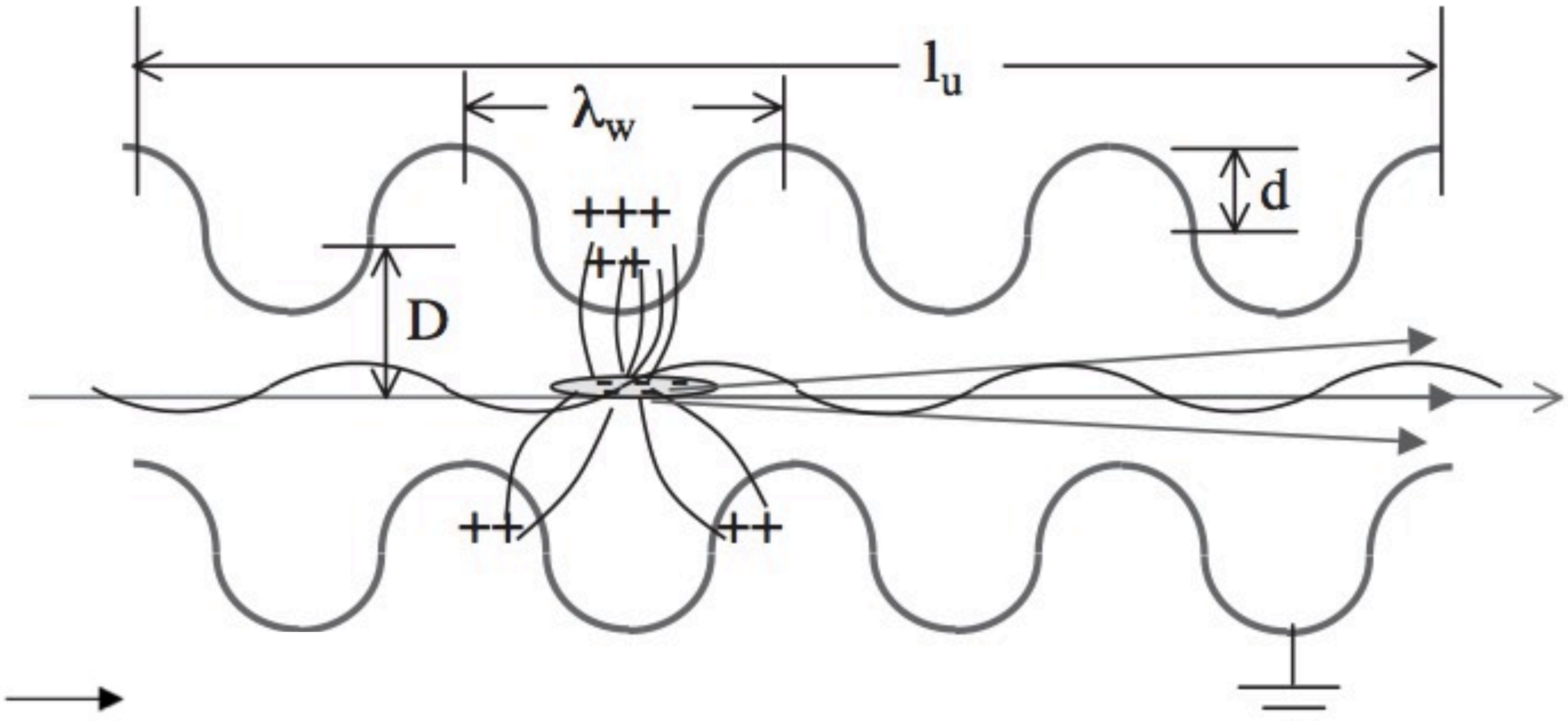


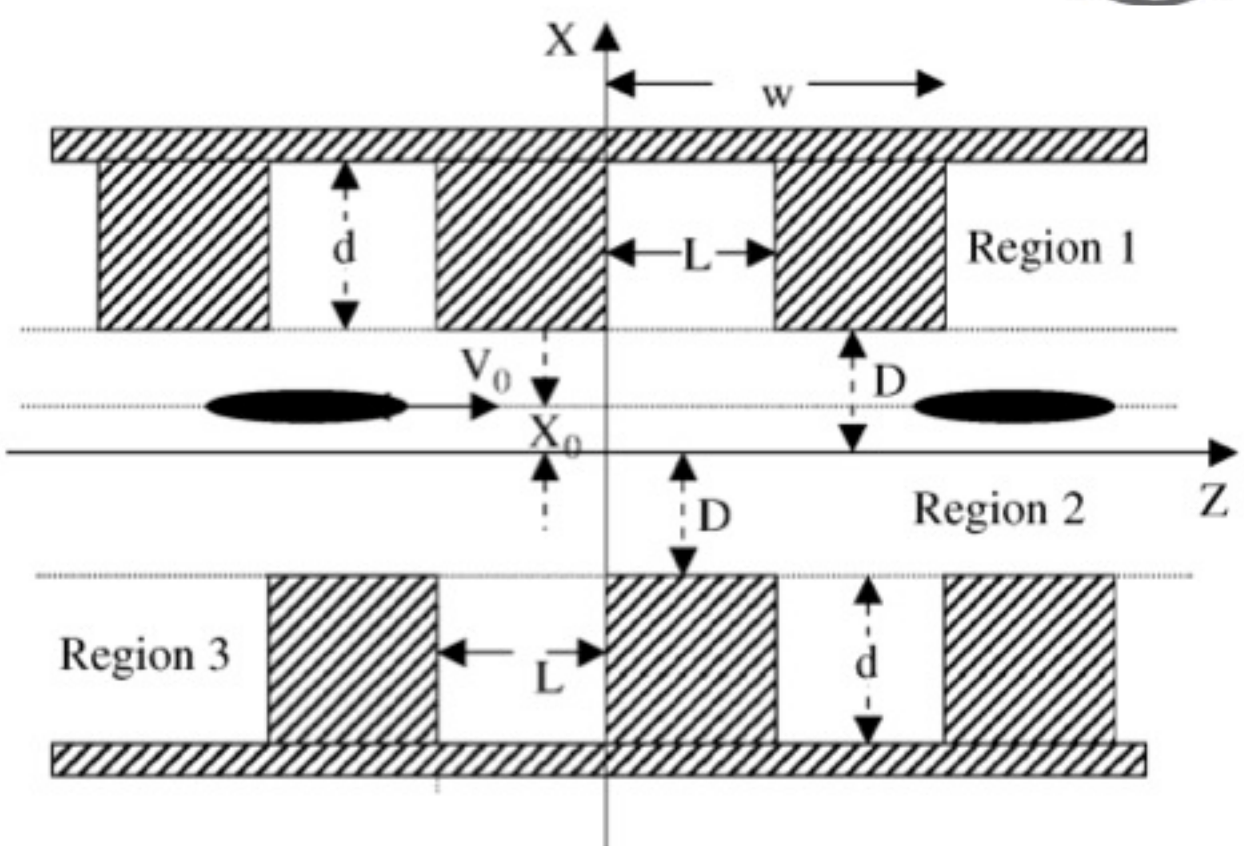
Plettner and Byer, Phys. Rev. ST Accel. Beams 11, 030704 (2008)

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

A resonant optical structure

might make a

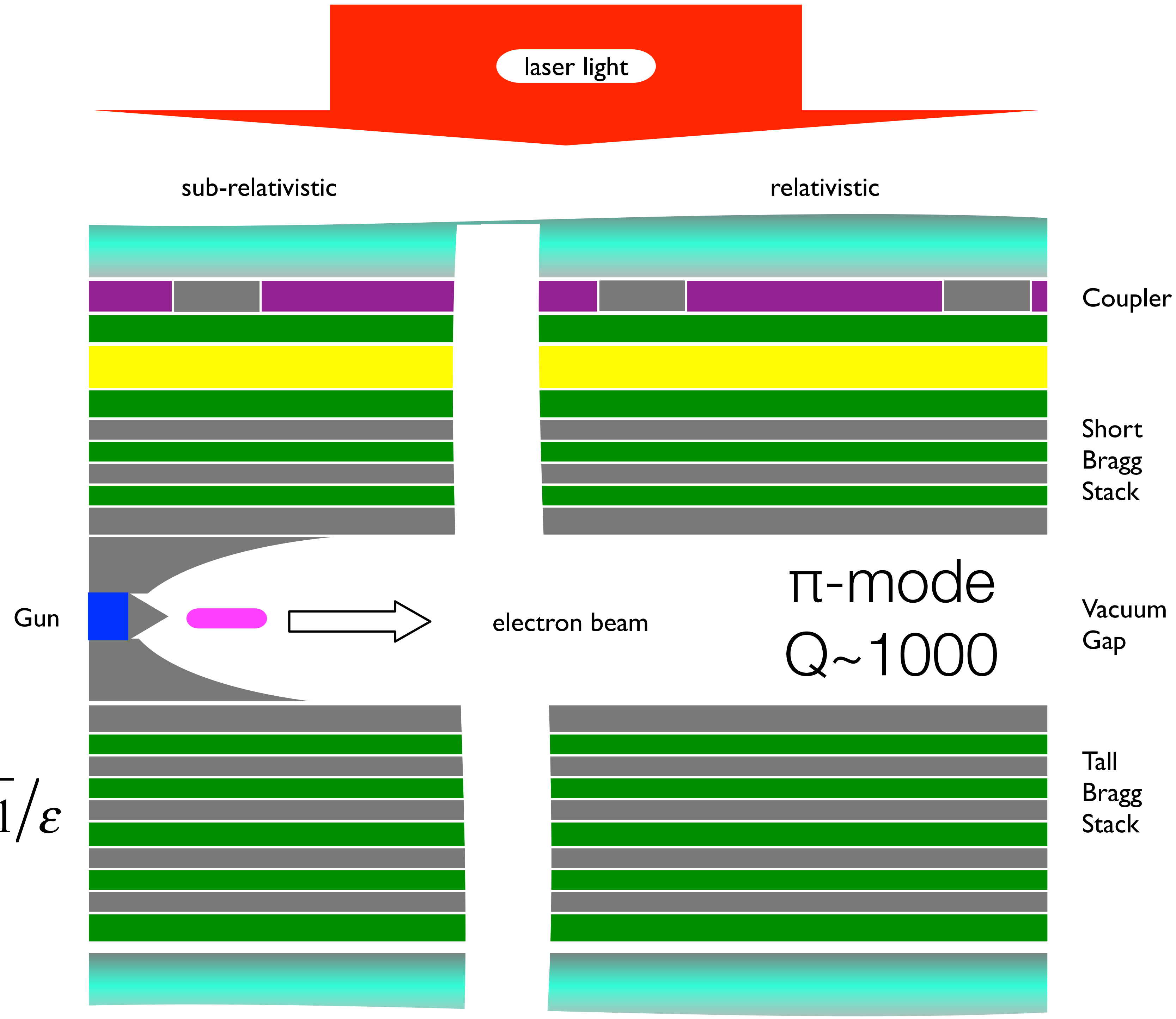
good undulator

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

Micro
Accelerator
Platform

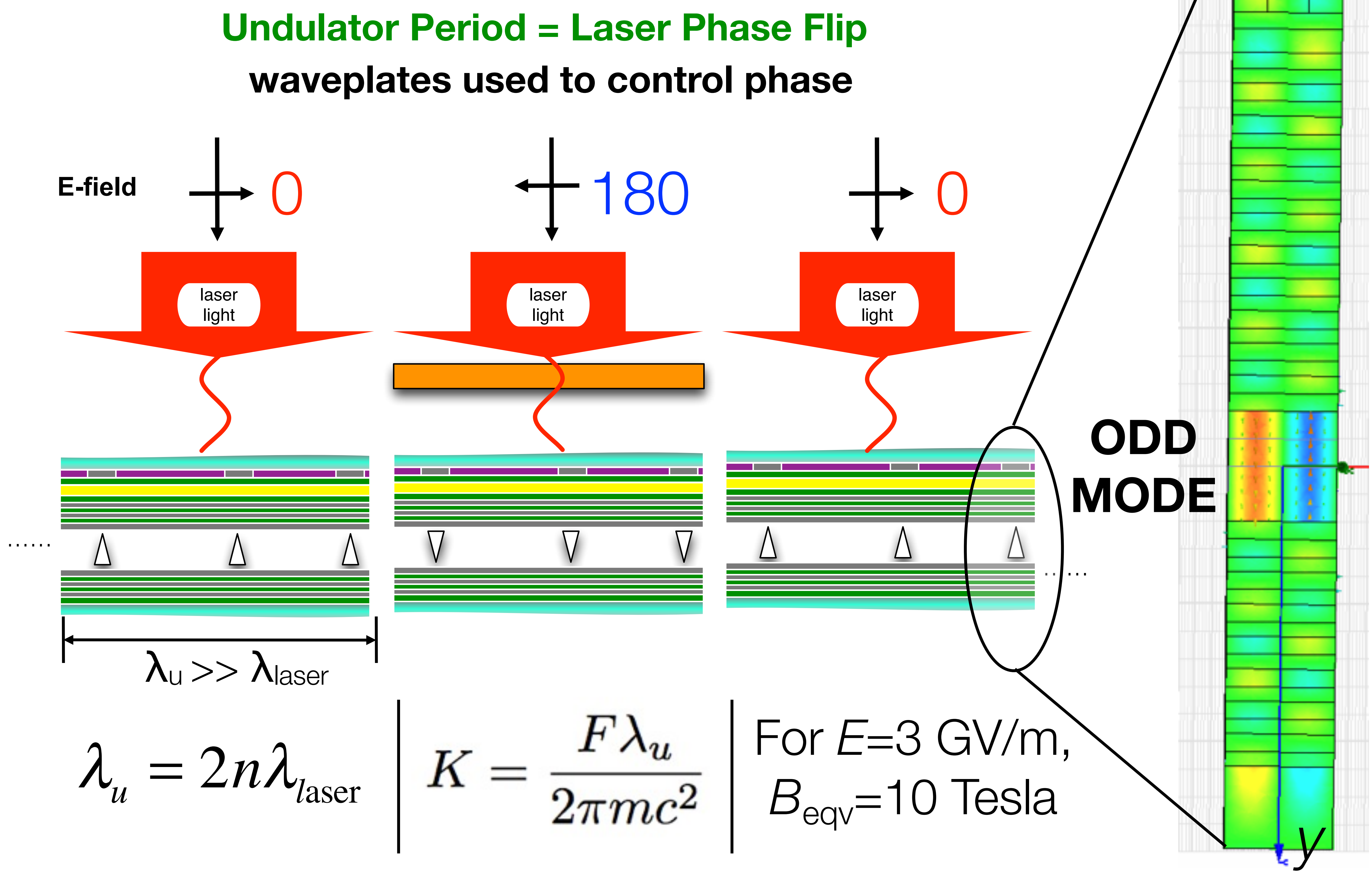
For gap *a* and dielectric *b-a* idealized resonance:

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



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

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



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

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

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

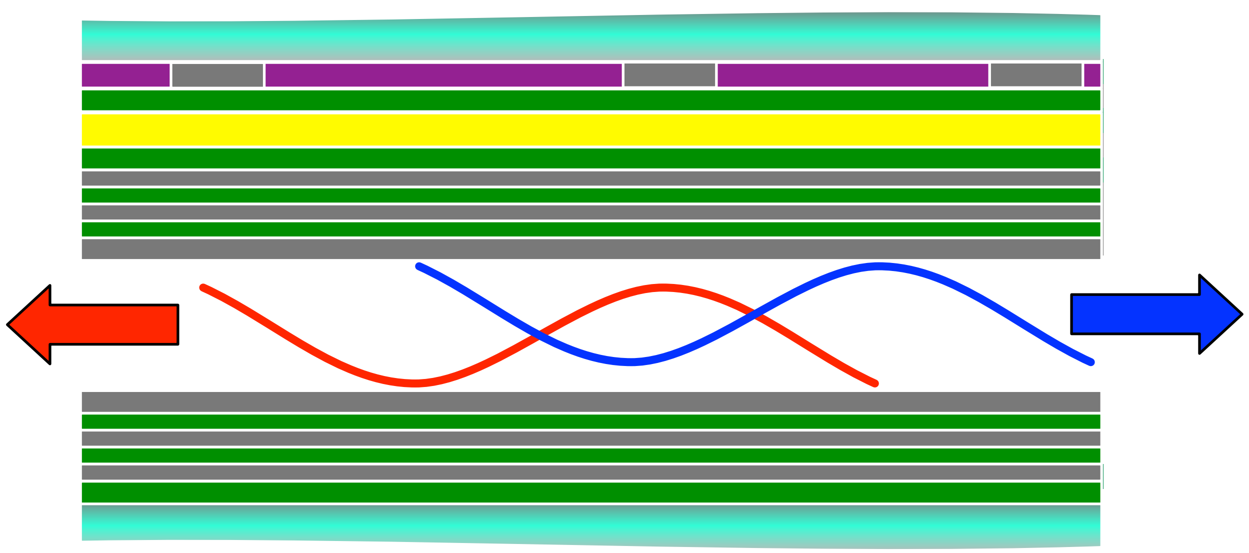
The equations of motion are simple, and are a series of alternating deflections

The fields (TEM) in the gap:

$$E_y = \frac{E_m}{2}\left[\exp(-jk_z z) - \exp(jk_z z)\right]\exp(j\omega t - \phi) \quad (1)$$

$$H_x = \frac{E_m}{2\eta}\mu\left[\exp(-jk_z z) + \exp(jk_z z)\right]\exp(j\omega t - \phi) \quad (2)$$

co and counter propagating waves



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co and counter propagating waves

The forces are then:

$$F_E(t) = qE_y = q\frac{E_m}{2}\left[\exp(-jk_z ct) - \exp(jk_z ct)\right]\exp(j\omega t - \phi)$$

$$F_B(t) = qv\mu_0 H_x = qv\frac{E_m}{2}\left[\exp(-jk_z ct) - \exp(jk_z ct)\right]\exp(j\omega t - \phi)$$

where:

$$k_z = \omega/c \qquad \eta = \sqrt{\mu_0/\varepsilon_0}$$

bunch length << laser wavelength

At the peak phase, the deflection forces simplify

$$F_E(t) = q\frac{E_m}{2}\left[1 - \exp(2j\omega t)\right]$$

$$F_B(t) \approx q\frac{E_m}{2}\left[1 + \exp(2j\omega t)\right]$$

Thus:

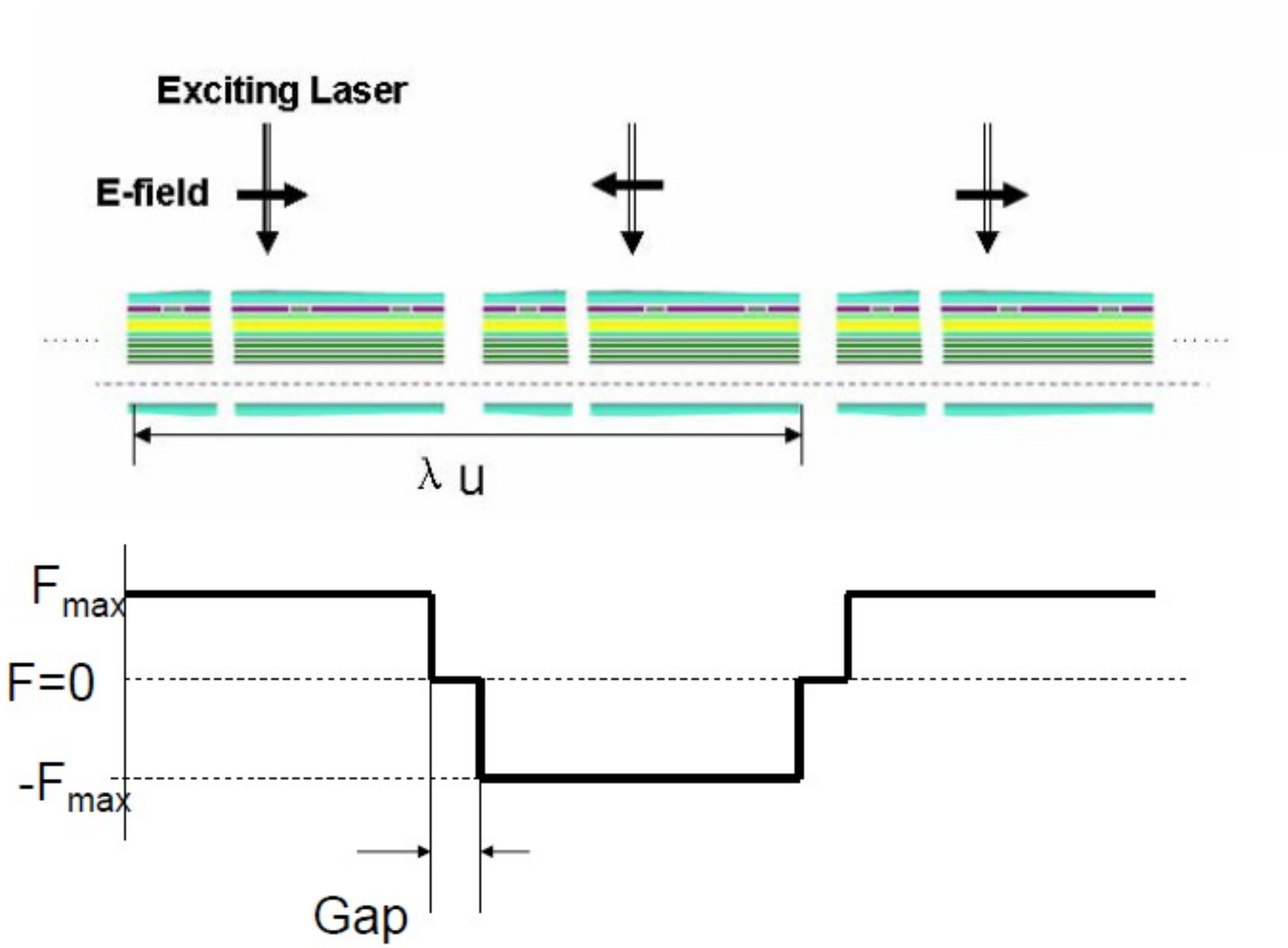
$$F_y(t) = F_E + F_B = qE_m \qquad \phi = \pi/2$$

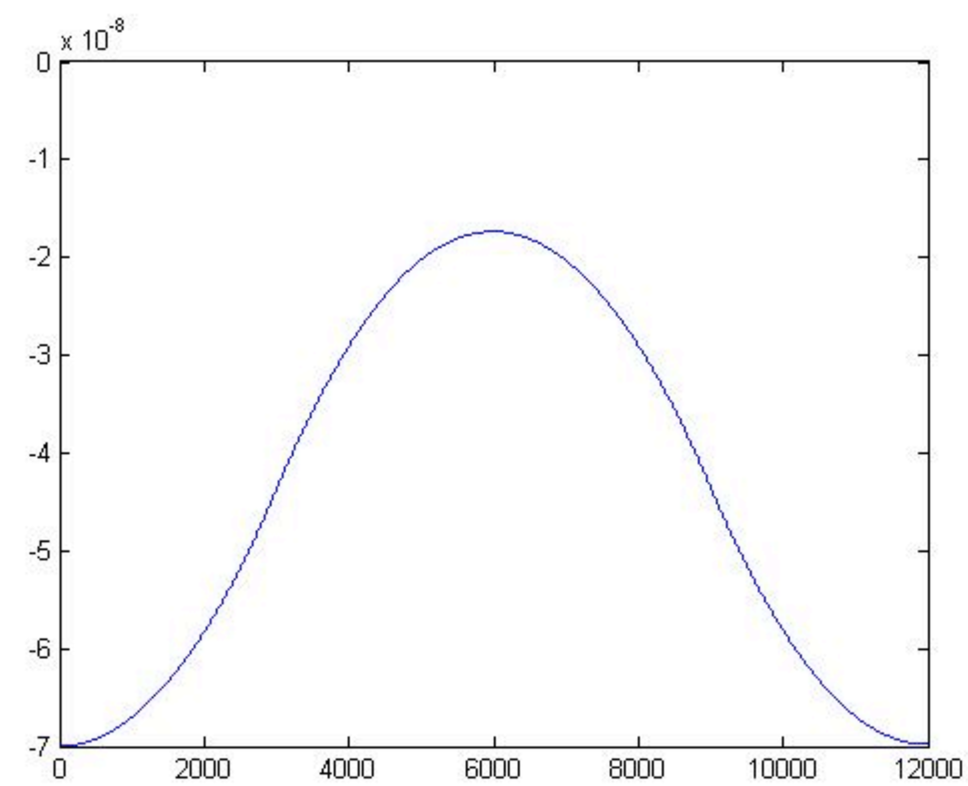
$$F_y(t) = -qE_m \qquad \phi = 3\pi/2$$

Also:

$$\lambda_u = 2n\lambda_{\mathrm{EM}} \qquad K = \frac{F\lambda_u}{2\pi mc^2}$$

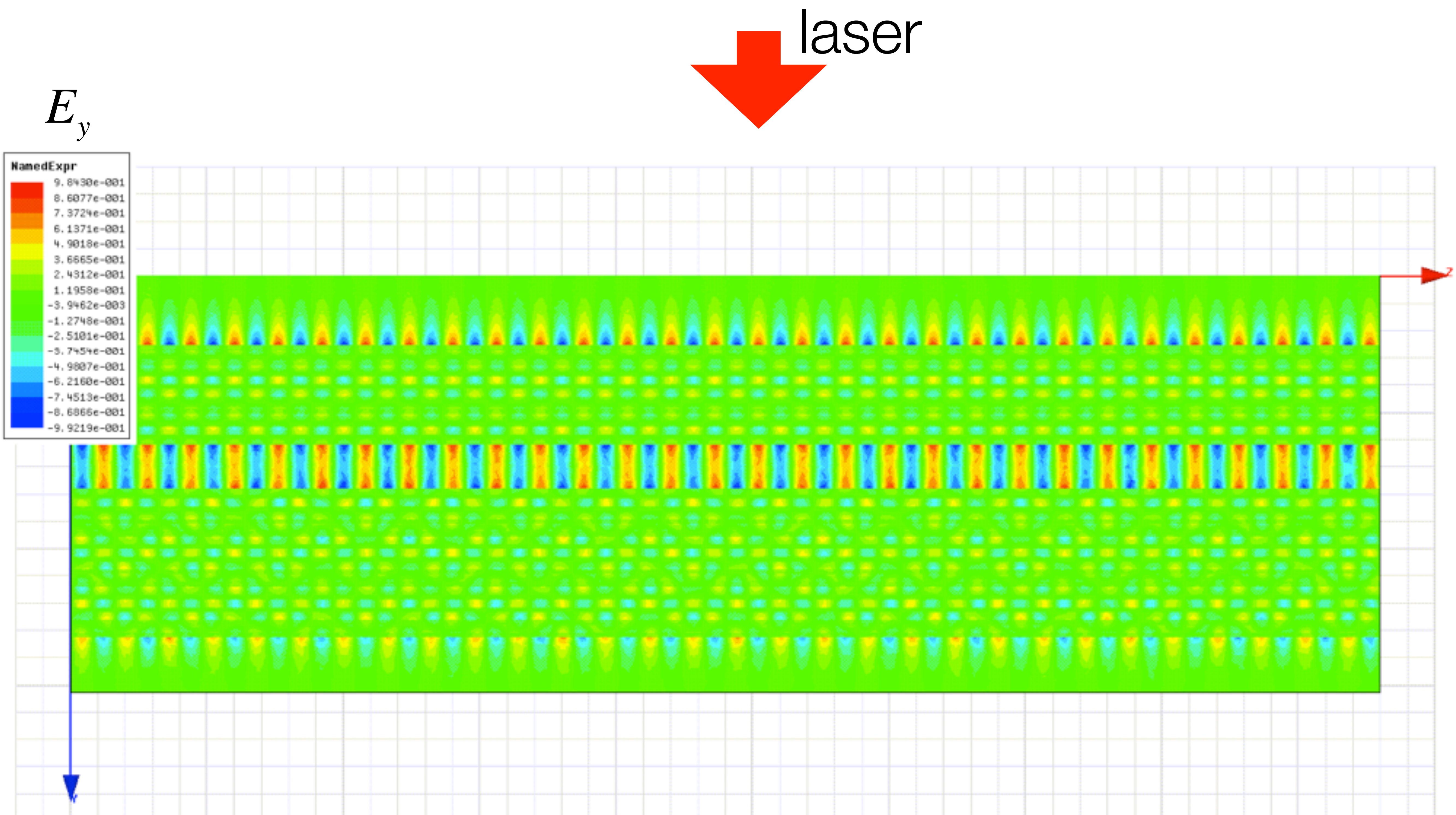
The trajectory is straightforward and limited by the structure walls (and the FEL function)



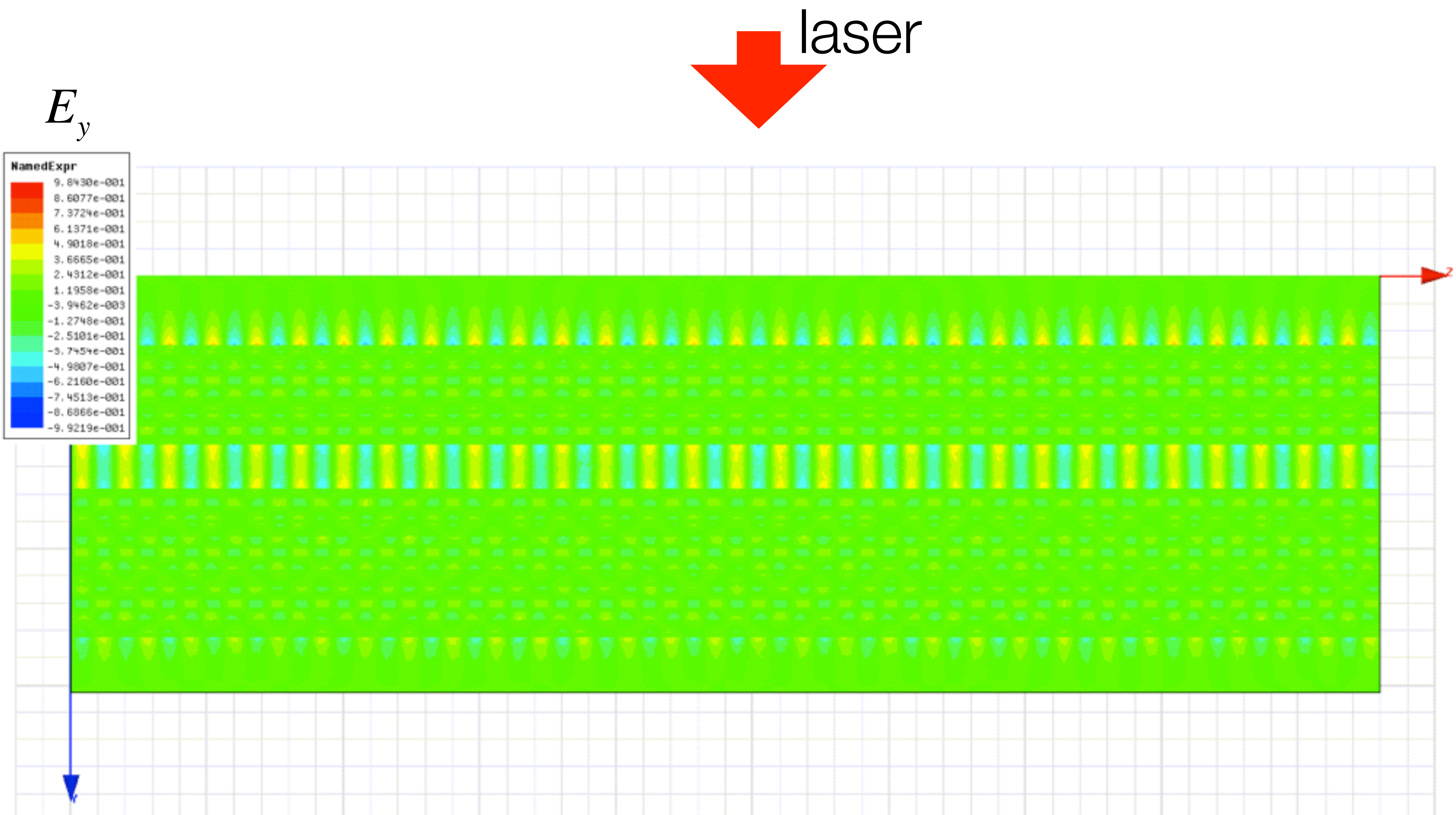


Good mode quality has been found

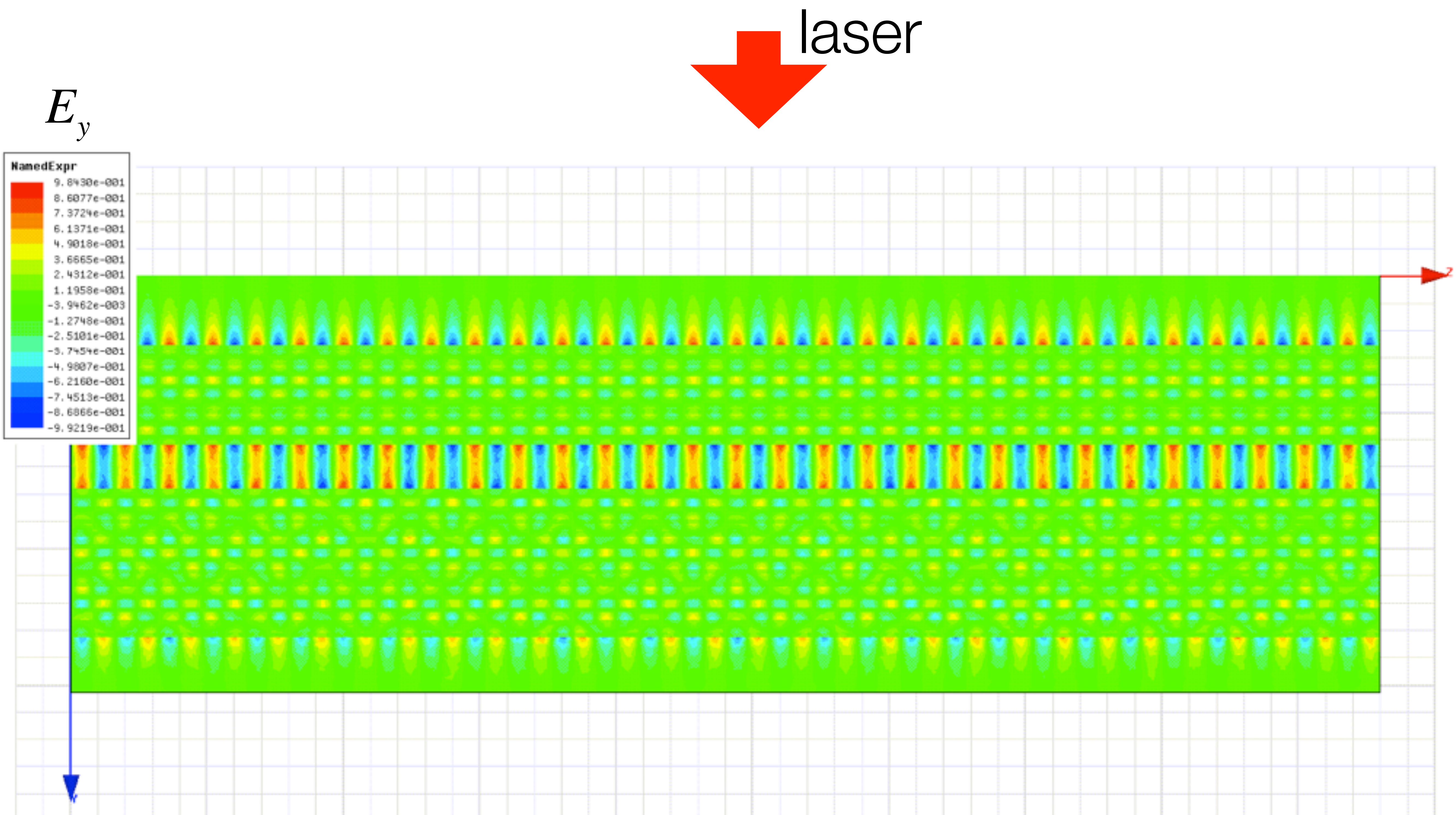
$\phi = \pi/2$



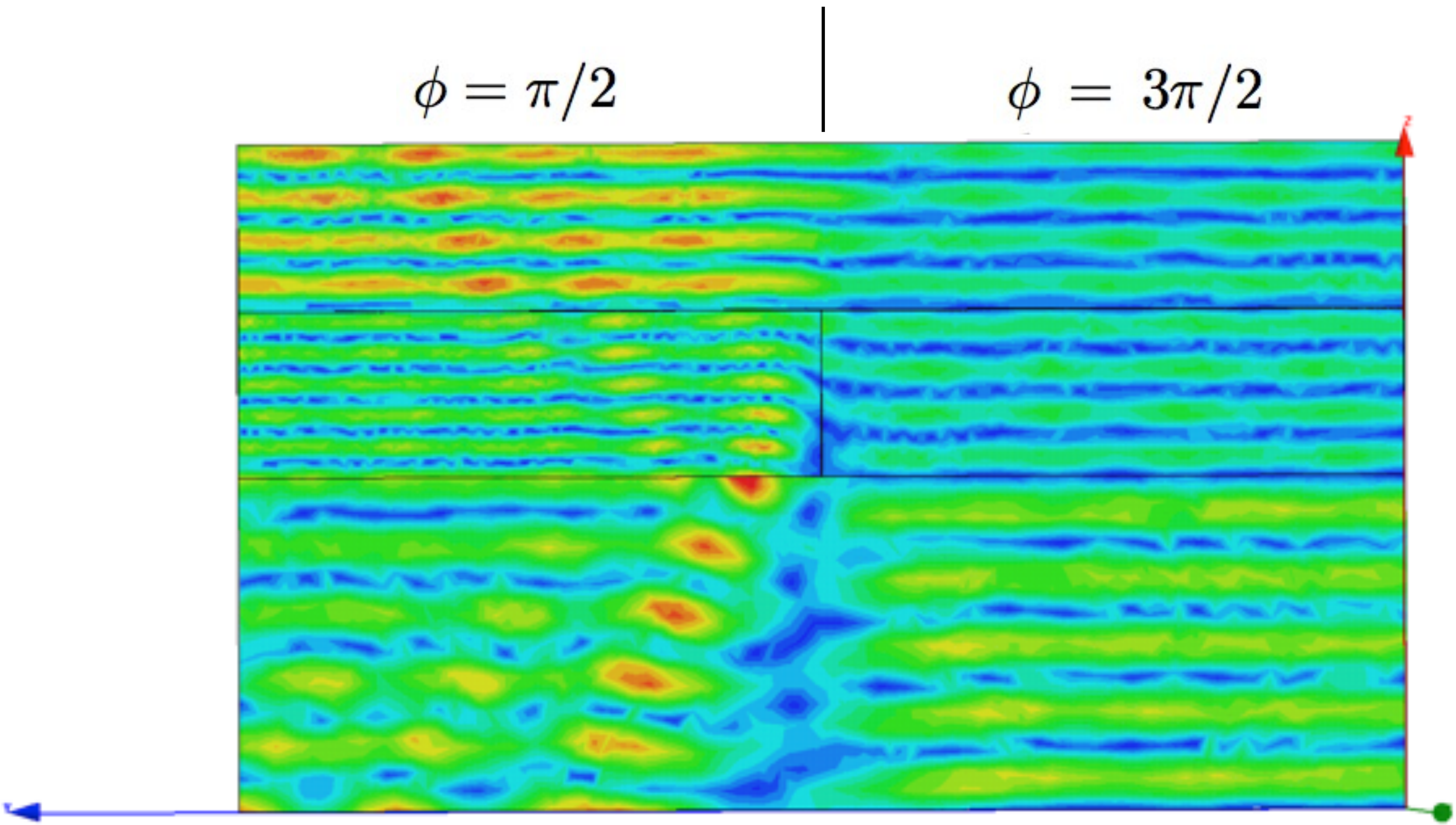
Good mode quality has been found $\phi = 0$



Good mode quality has been found $\phi = 3\pi/2$



...but phase flips are hard



These optical undulator structures may only work in two regimes

1 optical period	**> 20 optical period**
Even mode	Odd mode
Very low undulator parameter	Requires Phase Flip
Still a resonator	Low undulator parameter
	Resonator might have issues between half periods

two color operation is a possible solution

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

Parameter	Value	Alt. Value
Wavelength	6 nm	
Beam energy	50 MeV	75 MeV
Emittance (norm.)	0.06 µm (doh!)	
Current	2000 A	
Charge	160 fC (whew! ~10^6 e^-)	
Undulator parameter	0.11	0.23
Undulator period	120 µm	250 µm
Saturation length	125 mm	105 mm

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

low energy
+
optical undulator
=
QFEL

high energy
+
conventional undulator
=
FEL but long

... but compromises must be made

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 hard x-ray light source powered entirely by lasers and on a laptop scale might be a conventional FEL

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

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

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

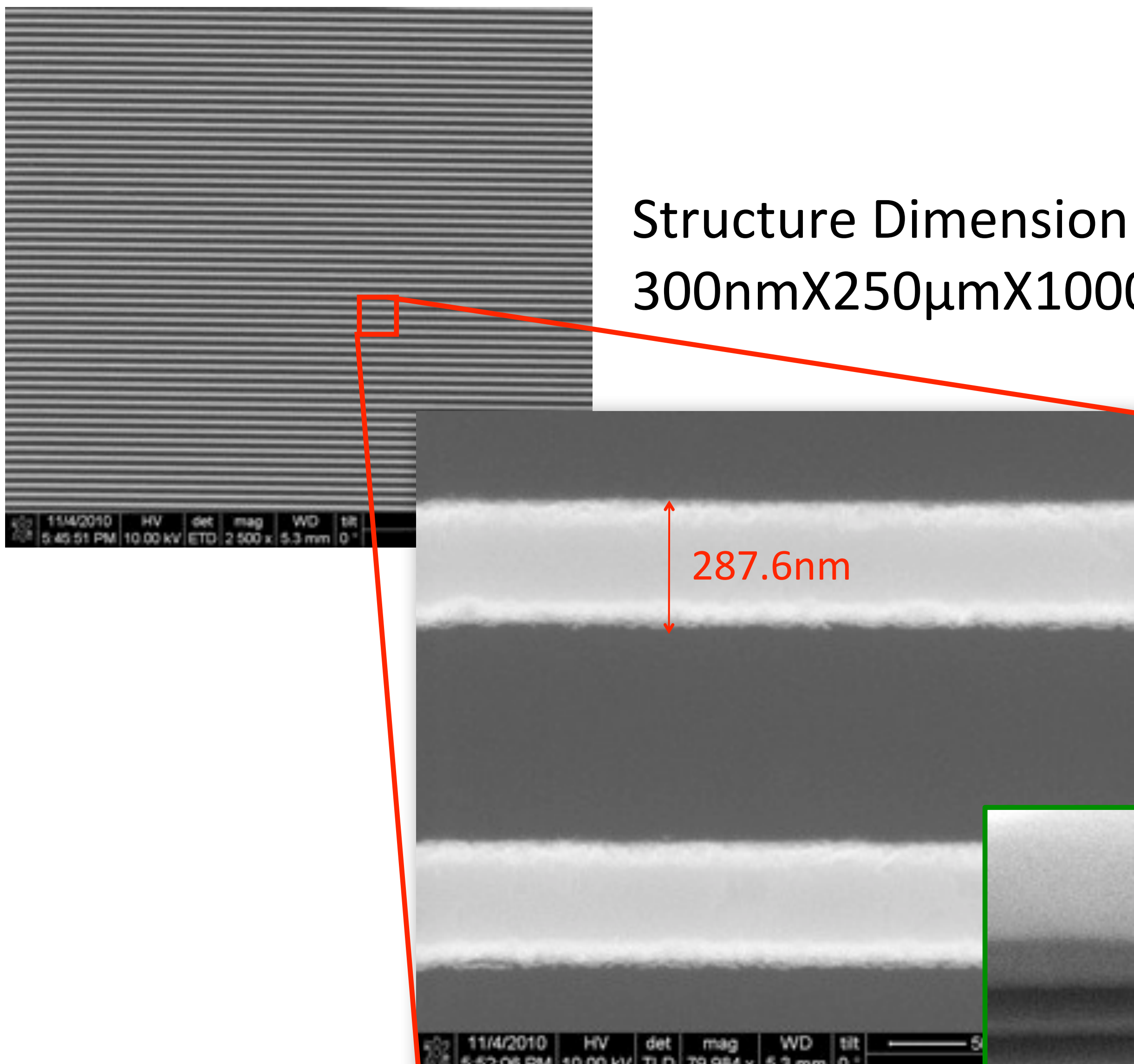
Parameter	**Optical Und.**	**Conventional**
FEL Wavelength	~0.1 Å	
Beam energy	10s MeV	100s MeV
Emittance (norm.)	0.06 μm	
Current	2000 A	
Charge	1 fC (whew! ~10^4 e^-)	
FEL Parameter (ρ)	**10^{-5}**	**10^{-3}**
Undulator parameter	**10^{-3}**	~1
Undulator period	1-20 μm	1 cm
Saturation length	~10 cm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

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

one photon emitted recoils > FEL bandwidth, ρ

Dielectric Laser Accelerators are becoming a reality. Optical-scale undulators should follow.

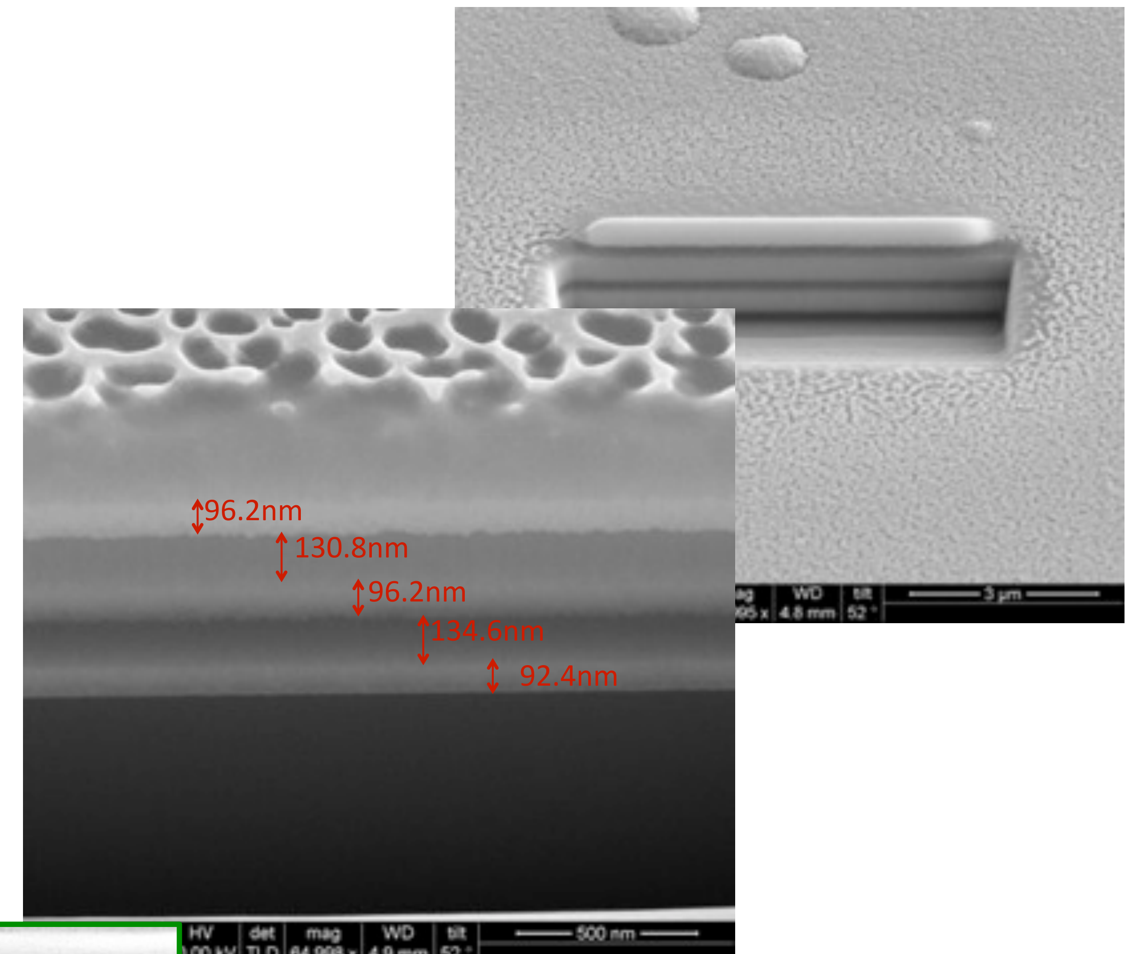
Full scale coupler



Structure Dimension:
300nmX250μmX1000

+

DBR



DBR+Coupler