Opportunities of Dielectric Laser Accelerator on High-brightness Radiation

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Outline

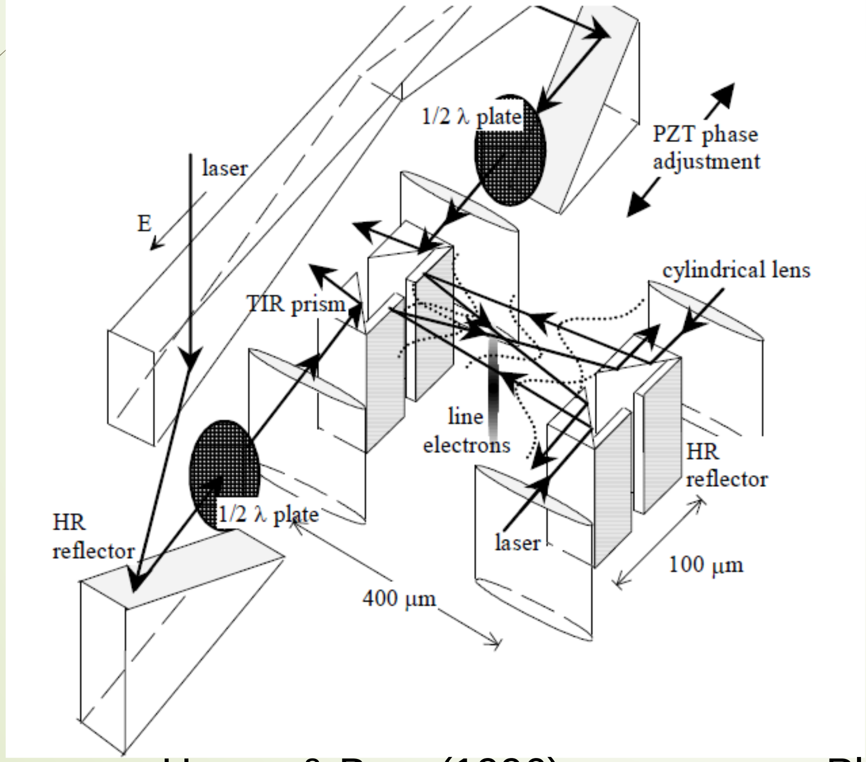
1. Dielectric laser accelerator (DLA)
2. Dielectric laser undulator
3. DLA-driven coherent undulator radiation
4. DLA-driven SASE XFEL
5. Conclusions

Dielectric laser accelerator (DLA) - accelerator on a chip (ACHIP)

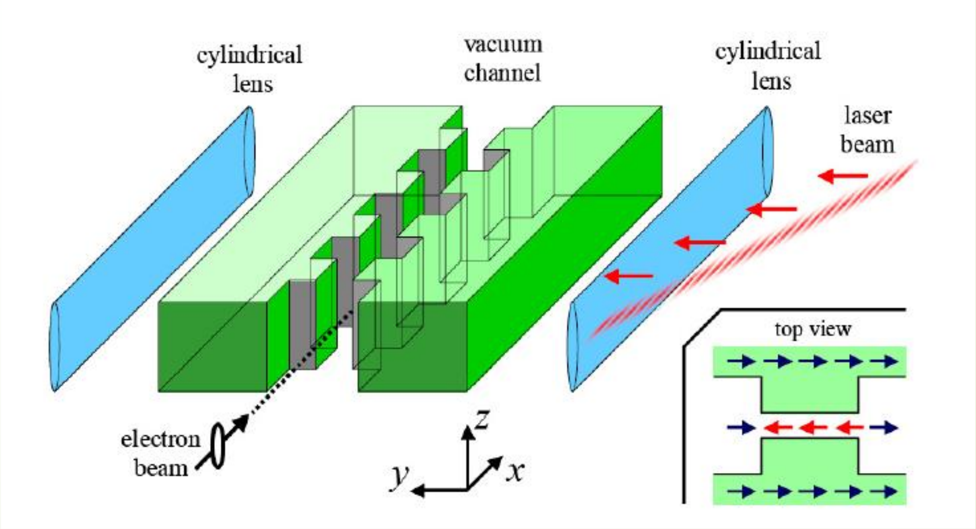
(laser wavelength ~ 1 μm)

$$E_{//} \approx \frac{-j}{k} \nabla_{\perp} E_{\perp} \sim 1 \text{ GV/m}$$

1. Solid state → **stable**
2. High damage field on dielectric and thus high acceleration gradient (up to ~ GeV/m)
3. Fabrication compatible to semiconductor lithographic patterning technique



Huang & Byer (1996)



Plettner, Lu, Byer, Phy. Rev. ST AB 9, 111301 (2006)

LETTER

doi:10.1038/nature12664

Demonstration of electron acceleration in a laser-driven dielectric microstructure

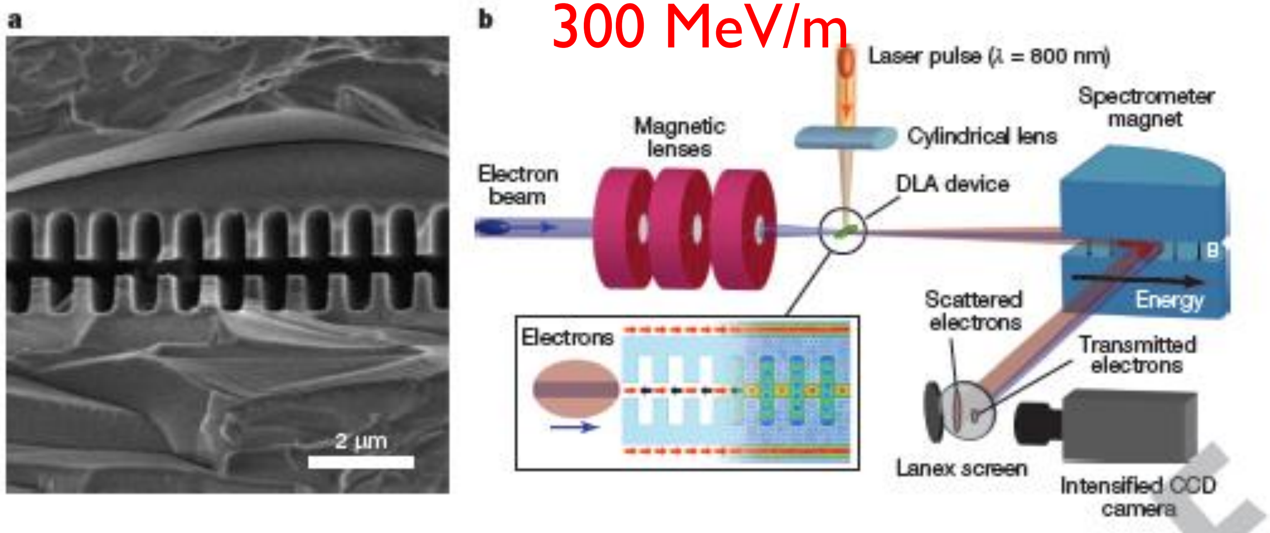
E. A. Peralta[1], K. Soong[1], R. J. England[2], E. R. Colby[2], Z. Wu[2], B. Montazeri[3], C. McGuinness[1], J. McNeur[4], K. J. Leedle[3], D. Walz[2], E. B. Sozer[4], B. Cowan[5], B. Schwartz[5], G. Travish[4] & R. L. Byer[1]

(extracted from SLAC website)

R. L. Byer

RESEARCH LETTER

300 MeV/m



Dielectric laser linac

Dielectric Laser Undulators
(λ_u >> λ_{laser} to operate with large γ)

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

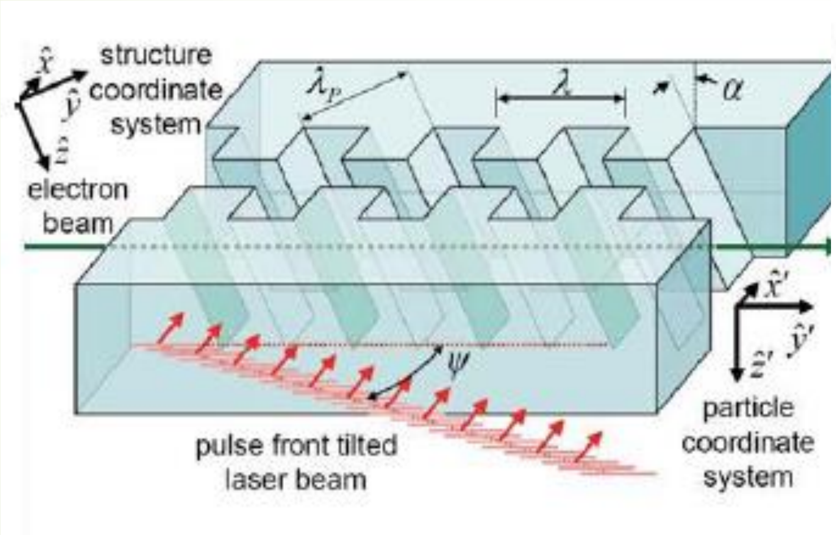
$$\lambda_u = \frac{\lambda}{\left| 1/\beta_e - 1/\beta_p \right|}$$

$$\lambda_u = 1 \sim 10^3\ \mu\mathrm{m},\ B_u \sim \frac{E_{laser}}{c} \sim 3.3\,\mathrm{T}$$

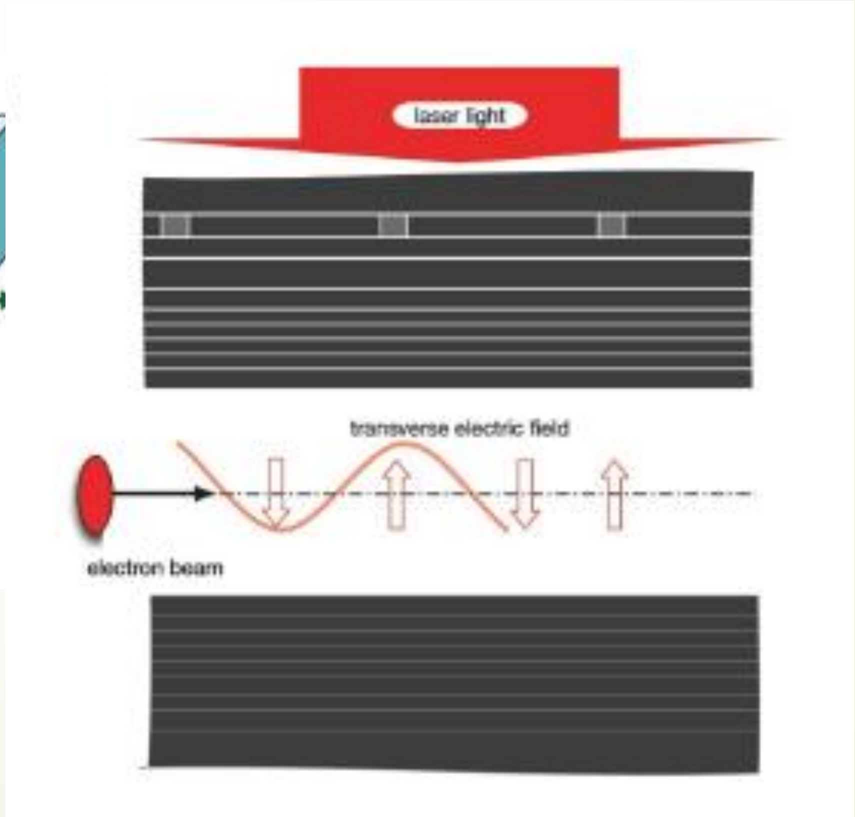
for E_{laser} ~ 1 GV/m

$\beta_e = v_e / c$: Electron velocity

$\beta_p = v_p / c$: Laser phase velocity

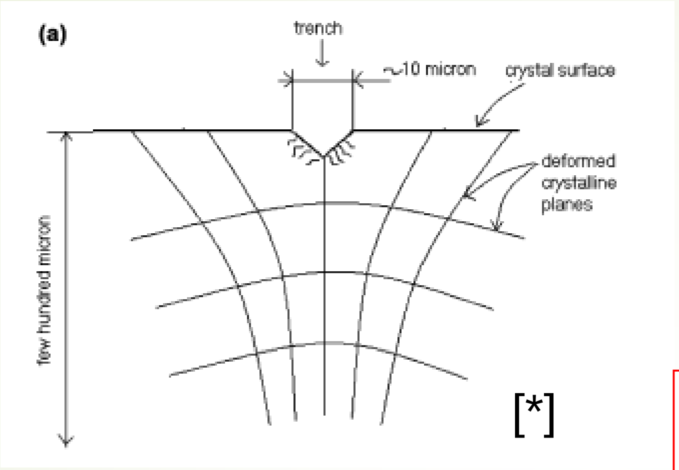


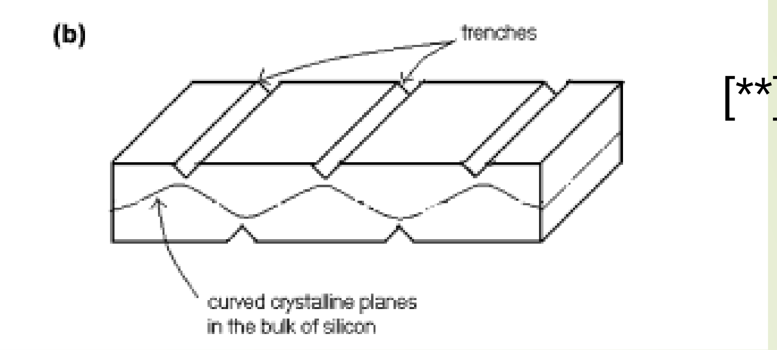
T. Plettner, R. L. Byer, Phys. Rev. ST Accel. Beams **11**, 030704 (2008).



G. Travish and R. B. Yoder, Proceedings SPIE 8079, (2011).

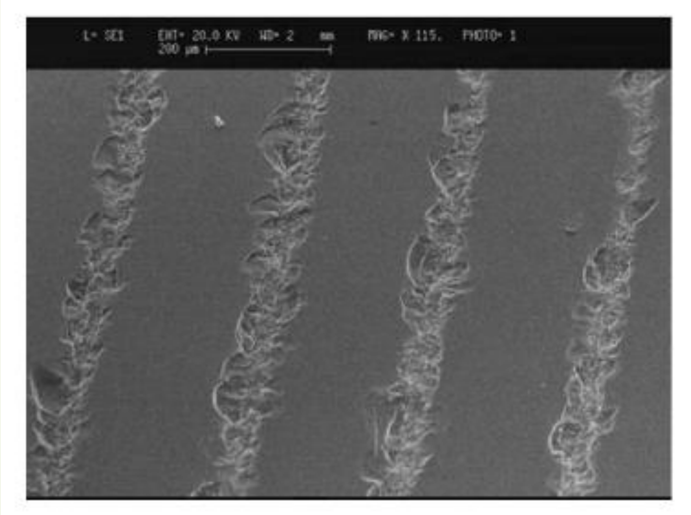
Micro-nano structured Crystal Undulators*,**

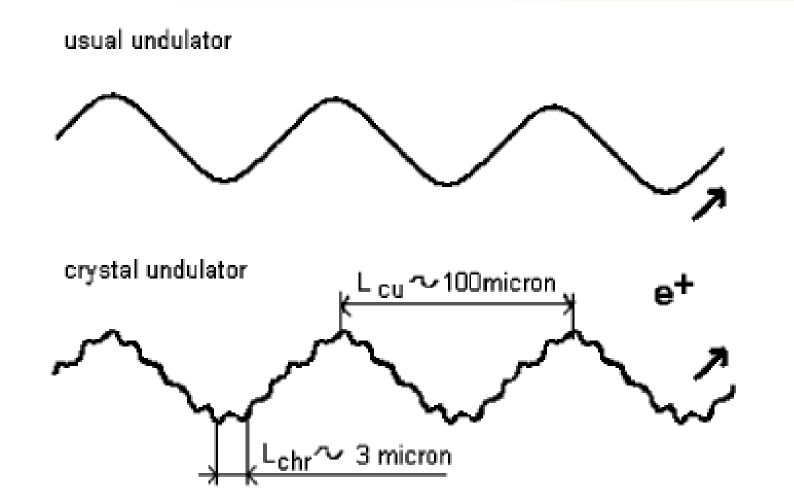




[**]

$$\lambda_u \sim 1-10^3\ \mu m, B_u = 10^2 \sim 10^3 T!$$





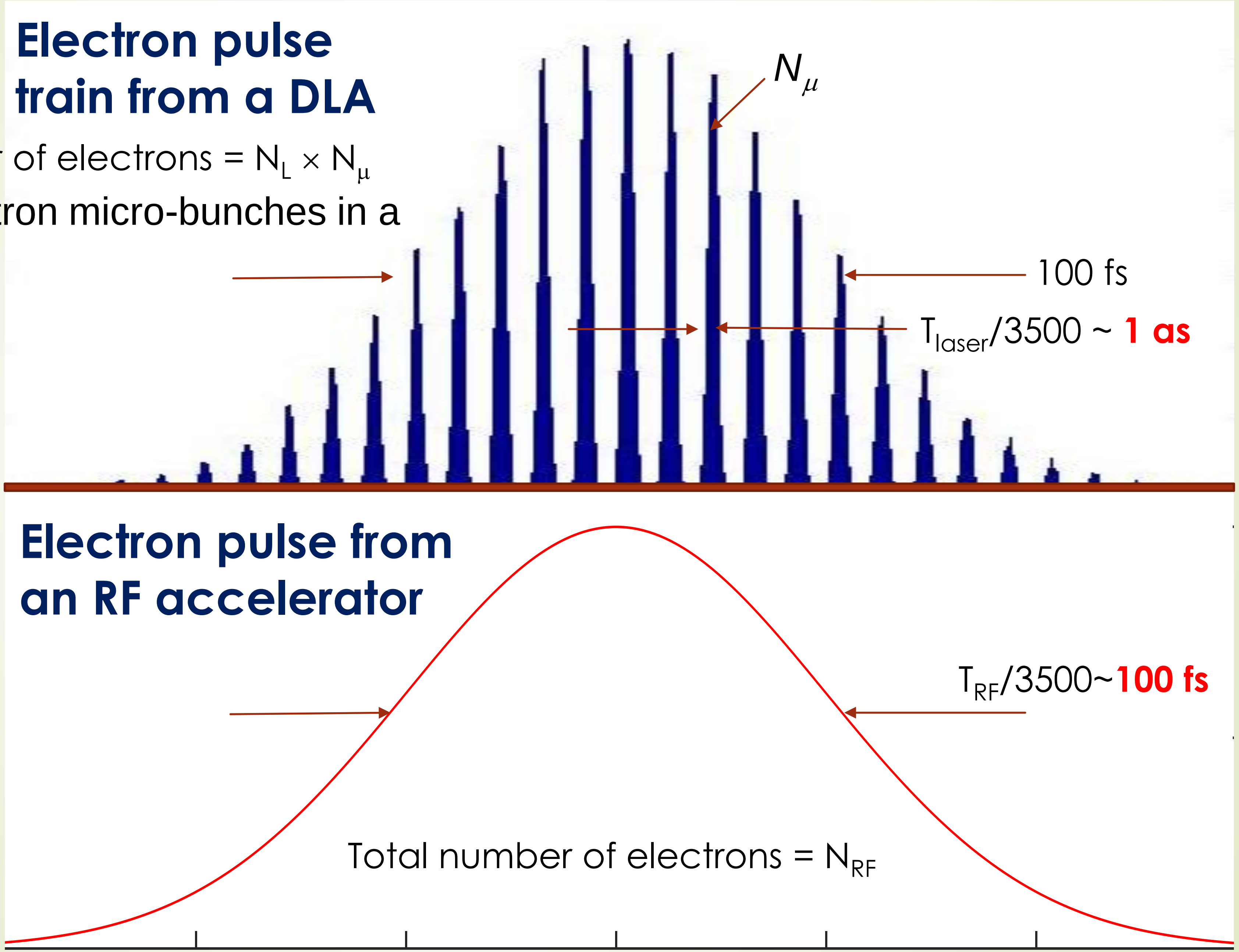
*A. G. Afonin et al., "crystal undulator experiment at HHEP," Nucl. Instr. And meth. In Phys. Res. B 234 , (2005) 122-127.

** S. Bellucci,et al., "Crystal undulator as a new compact source of radiation," PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS,VOLUME 7, 023501 (2004).

Pulse structures from DLA and RF Accelerator

Total number of electrons = $N_L \times N_\mu$

N_L: # of electron micro-bunches in a laser pulse



Short-bunch enhanced radiation

Total radiation Spectral Energy in one driver laser pulse $W_N = N_L[N_\mu + N_\mu(N_\mu - 1)b^2(\omega)]W_1$

$W_{1,N}$ radiation spectral energy of 1 & N electrons

$b(\omega)$: bunching factor, Fourier transform of the micro-bunch profile

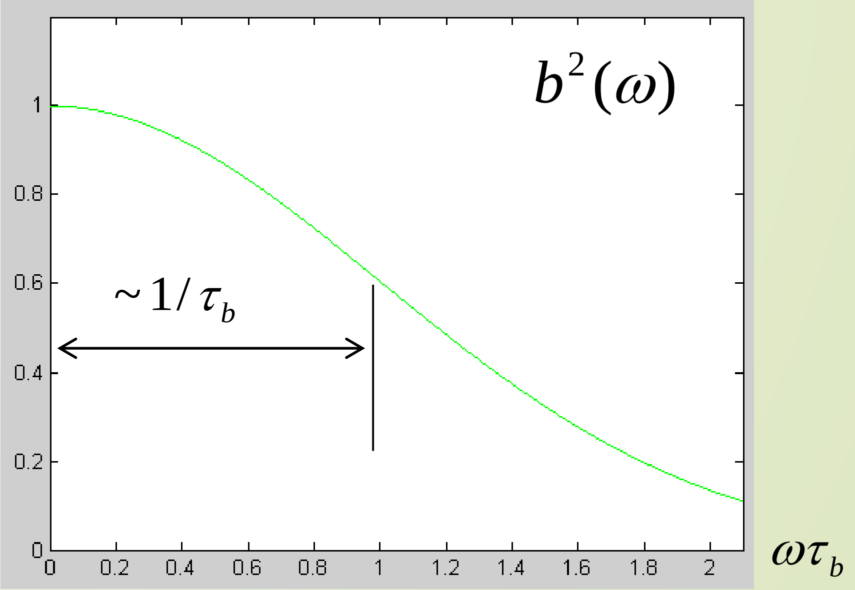
N_μ: # of electron in a DLA micro-bunch

N_L: # of electron micro-bunches in a driver-laser pulse

$N_L \times N_\mu$: total number of electrons in a driver laser pulse

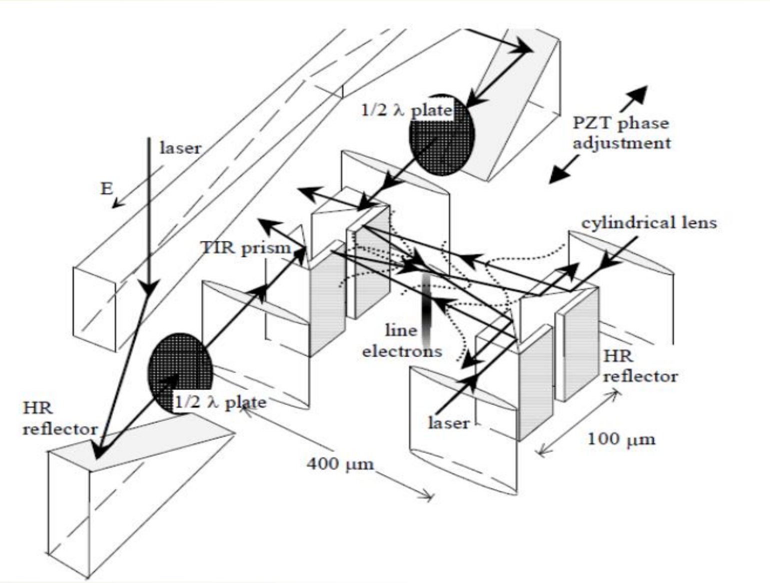
For Gaussian bunch $f(t) = \frac{\exp\left(-t^2/2\tau_b^2\right)}{\sqrt{2\pi}\tau_b}$

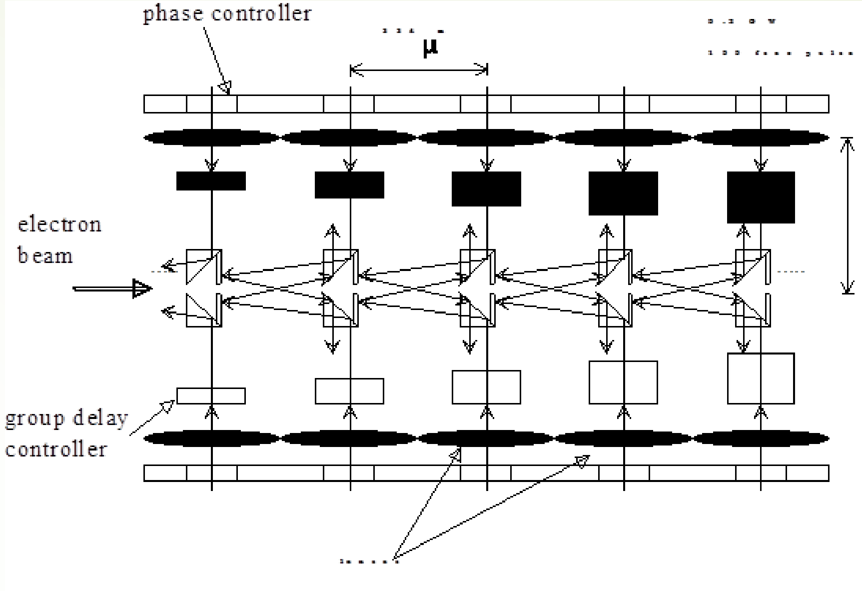
$$\Rightarrow \quad b(\omega) = \exp\left(-\frac{\omega^2\tau_b^2}{2}\right)$$



Scaling up DLA charges to $N_{RF} \times N_{\mu} \sim N_{RF}$

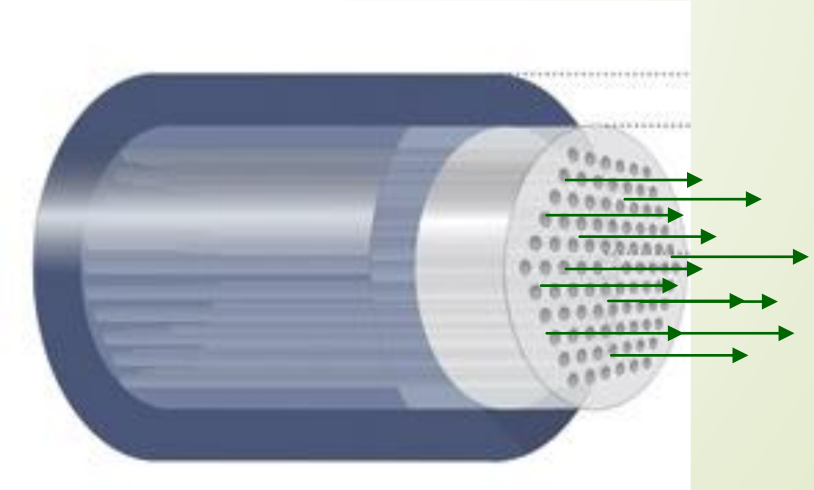
Flat beam DLA





Y.C. Huang and R.L. Byer, "A Proposed High-gradient, Laser-driven Linear Acceleration using Cylindrical Laser Focusing," *Appl. Phys. Lett.* **69** (15) Oct. 7, 1996.

Parallel-beam DLA



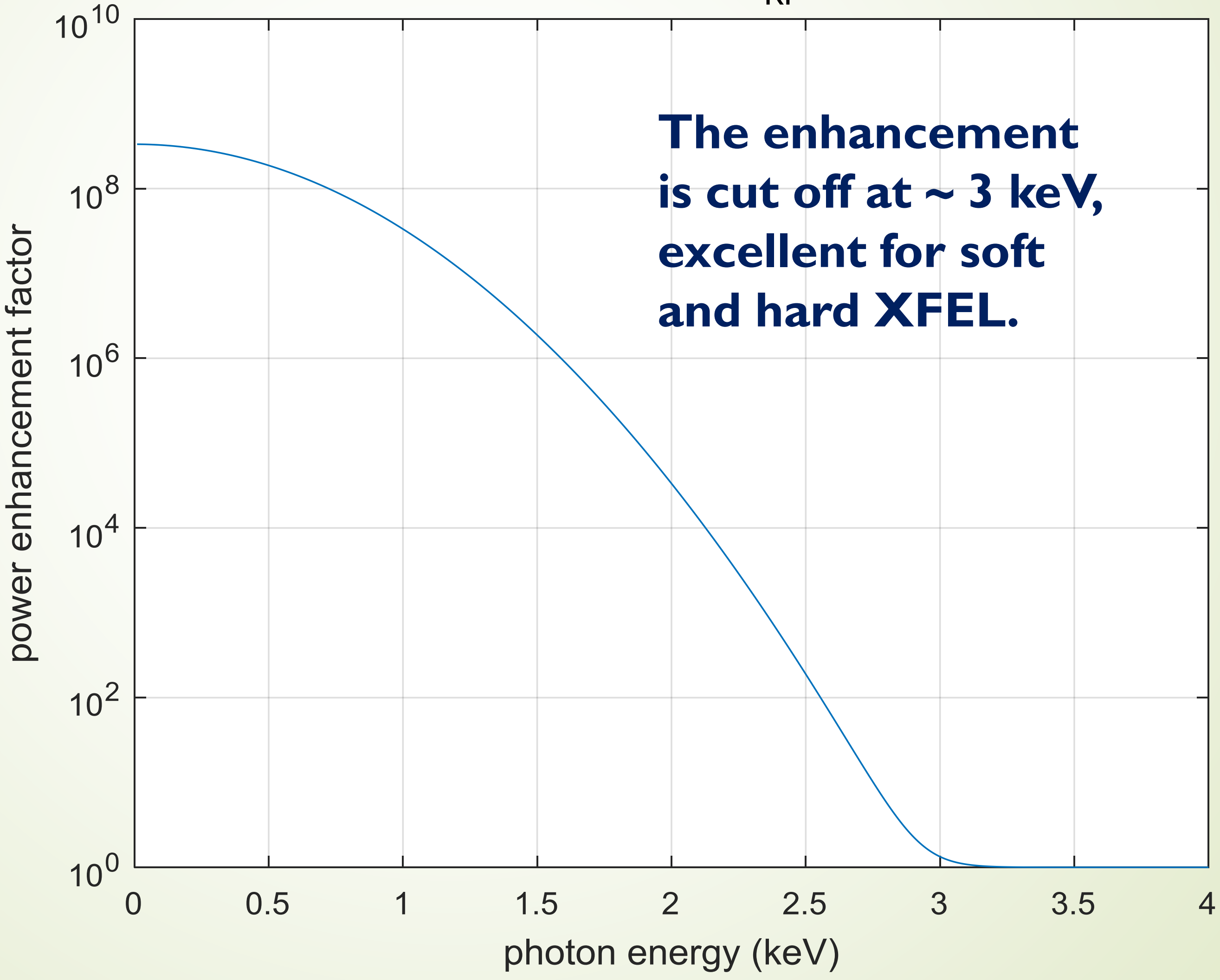
https://www.photonics.com/Article.aspx?AID=25277

DLA $P_{N,DLA} = N_L[N_\mu + N_\mu(N_\mu - 1)B^2(\omega)]P_1$

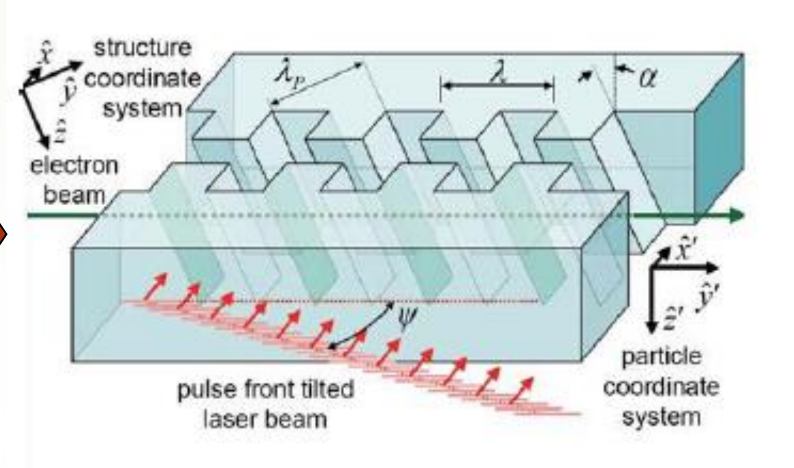
RF accelerator $P_{N,RF} = N_{RF} P_1$

$$\text{power enhancement factor} = \frac{P_{N,DLA}}{P_{N,RF}}$$

subject to $\mathbf{N_L} \times \mathbf{N_\mu} \sim \mathbf{N_{RF}}$ in the same 100-fs electron-pulse envelope for $N_{RF} = 10^{10}$



EUV Superradiant FEL @ 13.5 nm (important for lithography)



T. Plettner, R. L. Byer, Phys. Rev. ST Accel. Beams **11**, 030704 (2008).

10 cm

rms bunch length ~ 1 nm << 13.5 nm

Charge = 1 nC/10^4 = 0.1 pC

Gamma = 200 (100 MeV)

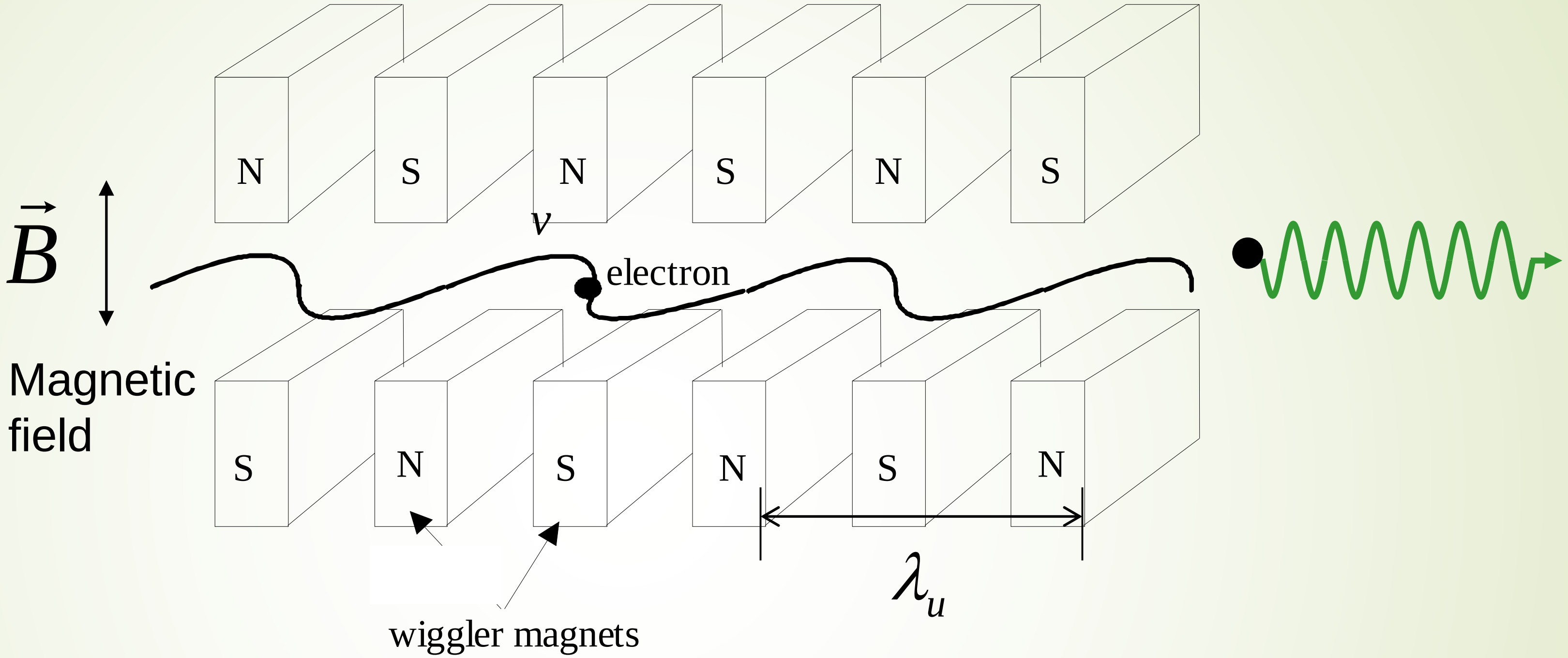
λ_u = 1.05 mm (N_u = 90)

B_{peak} = 3 T (subject to damage)

a_u = 0.23 (fundamental mode)

Chirped-pulse FEL (Y. C. Huang of NTHU, X.S. Liu of PKU, **Yuri Lurie of Ariel U.**)

Yen-Chieh Huang et al., "Isolated Few-cycle Radiation from Chirped-pulse Compression of Superradiant Free-electron Laser," Physical Review ST AB 18, 080701 (2015).



Radiation wavelength

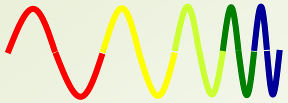
$$\lambda(z) = \frac{1+a_u^2}{2\gamma^2(z)}\lambda_u$$

where $a_u = 0.093 B_{rms}(\text{kgauss}) \times \lambda_u(\text{cm})$

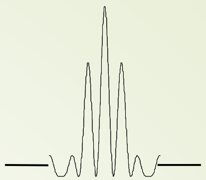
is called the *undulator parameter*

electron energy depletion ⇒ chirped radiation

Positive group velocity dispersion



$E(t)$ → **Dispersive element** $e^{j\phi(\omega)}$

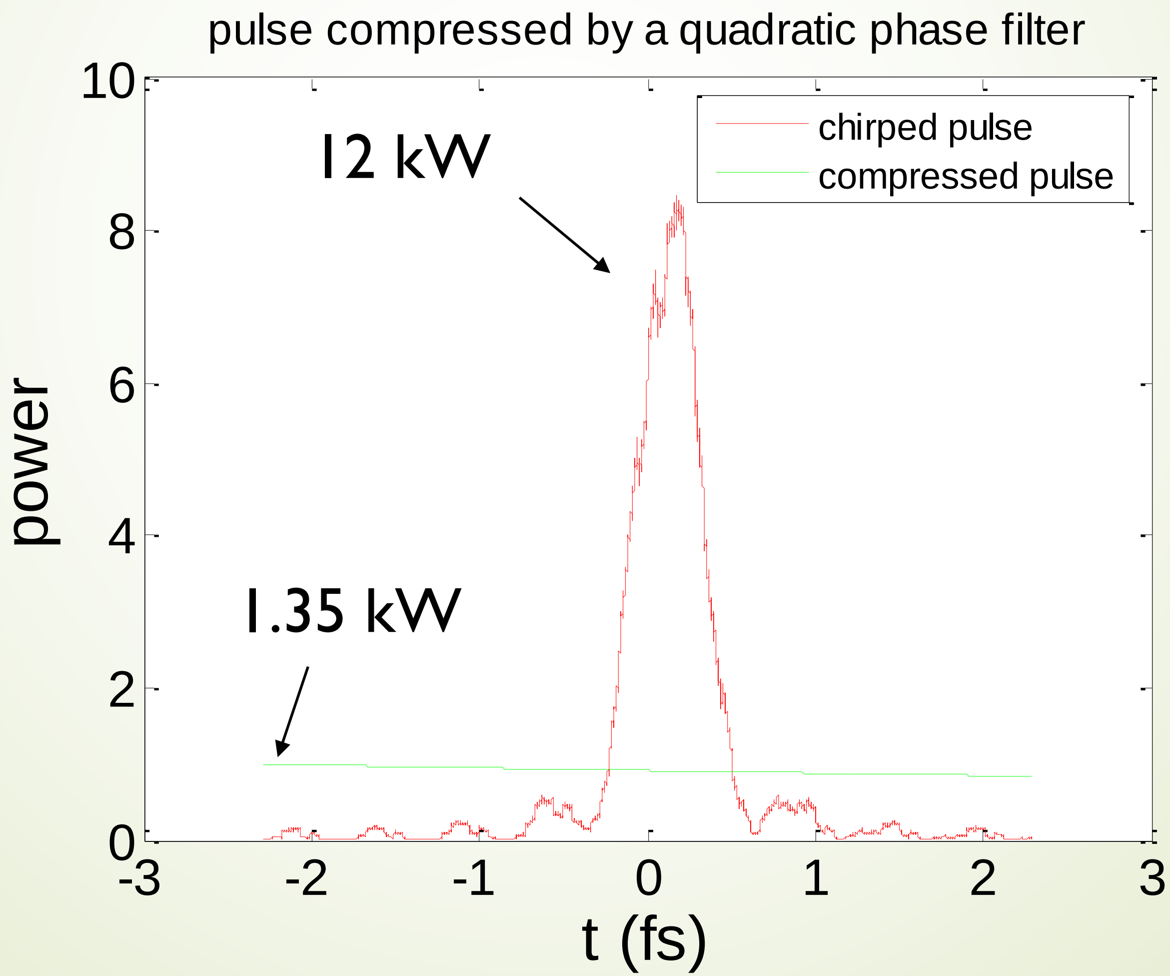


$E_c(t)$

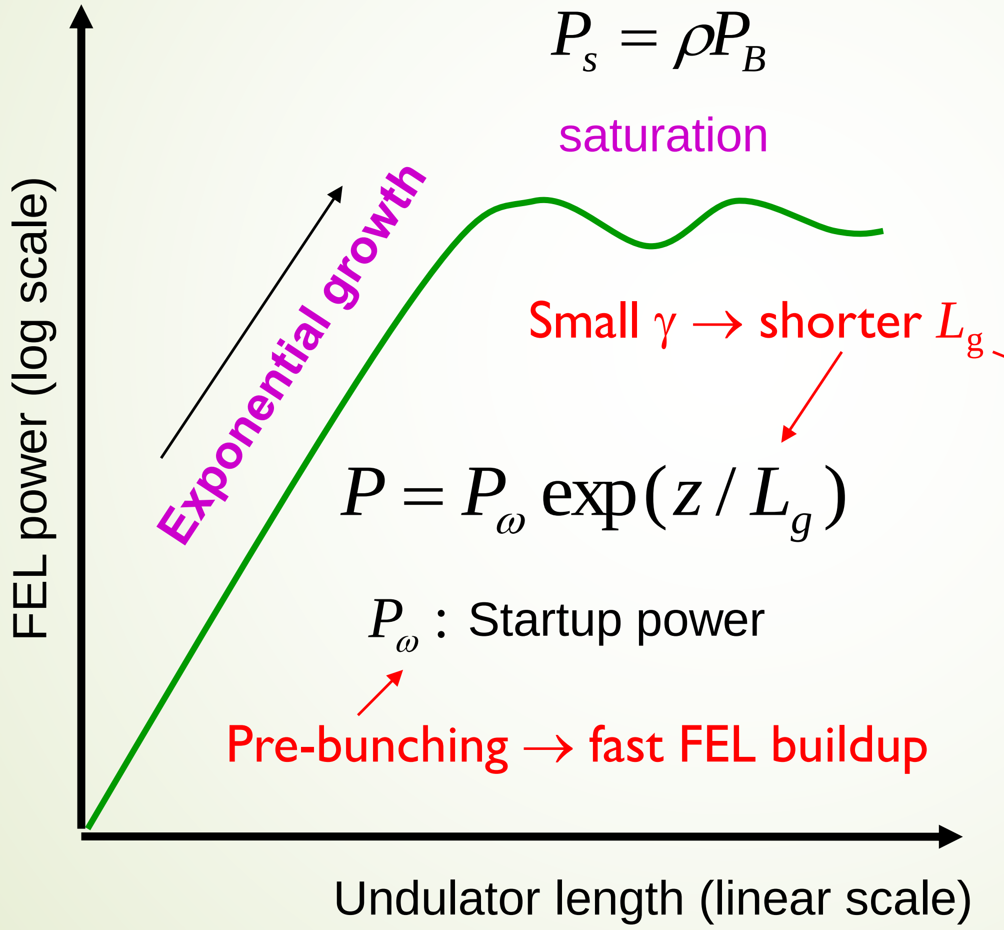
Chirped pulse

Compressed pulse

$$E(t) = \Im^{-1}[E_c(\omega) = E(\omega)e^{j\phi(\omega)}]$$



Typical SASE FEL Buildup Curve



Gain length (1-D theory)

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

Pierce parameter

$$\rho = 1.78\times10^{-5}\,\frac{A_u^{2/3}}{\gamma}\times \lambda_u^{2/3}[cm]\,n_e^{1/3}[cm^{-3}]$$

$A_u = a_u$ undulator parameter for helical undulator

Beam Power

$$P_B = IV_B$$

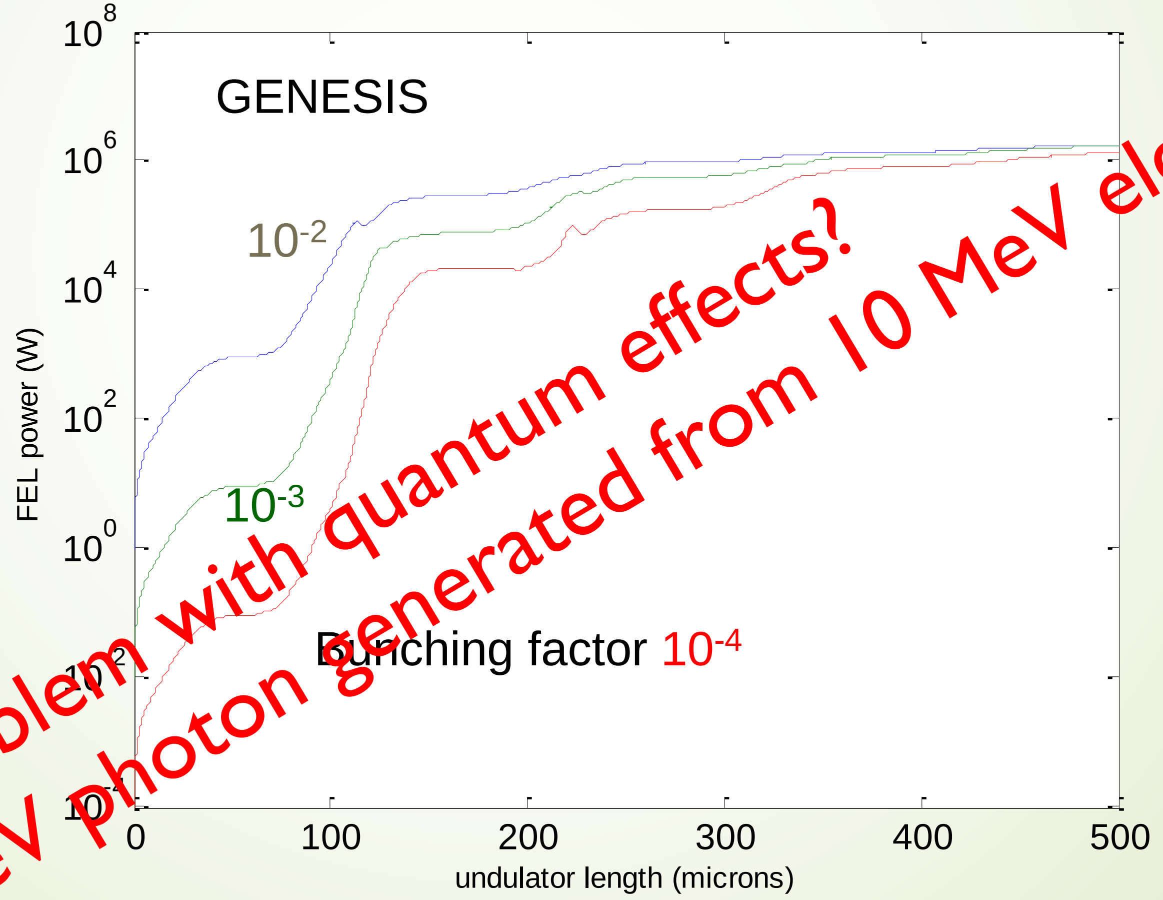
Low-γ XFEL

Beam energy (γ) = **22** , energy spread = 0.1%, peak current = 10 kA (100 fC/10 as)

normalized emittance = 1 nm-rad

Undulator period = 0.1 μm (eg. crystal undulator), undulator parameter (a_w) = 0.01 (rms B field = 10^3 T)

Radiation wavelength = =1 Å



Problem with quantum effects?

keV photon generated from 10 MeV electrons

Y. C. Huang presented in SLAC 2011 DLA Workshop

Quantum FEL

Pro: quantum noise added to startup power P_ω, usually small, could assist FEL buildup.

Con: (1) 1 photon from 1 electron $\rightarrow$ low efficiency

(2) Electron recoil induced energy spread << FEL gain bandwidth

Virtual photon (unndulator)

To stay in the gain bandwidth

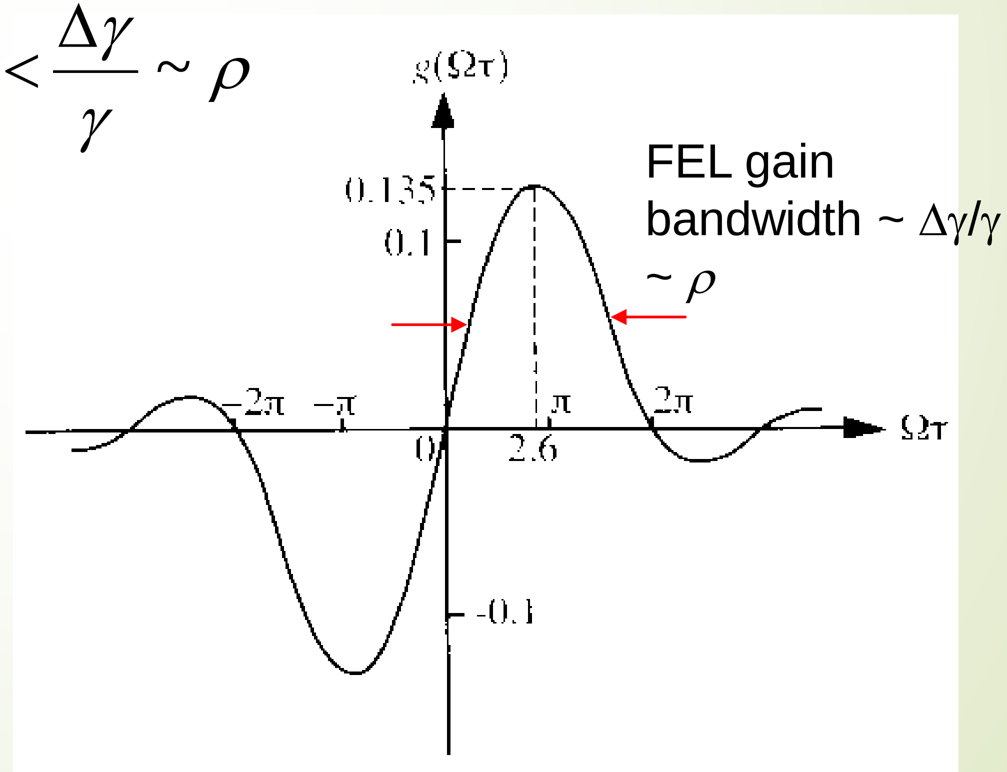
$$\frac{\hbar\omega}{\gamma mc^2} << \frac{\Delta\gamma}{\gamma} \sim \rho$$

Define quantum ρ parameter

$$\bar{\rho} = \rho(\gamma mc^2 / \hbar\omega)$$

Classic regime (γ large enough) $\bar{\rho} >> 1$

Quantum regime $\bar{\rho} \sim< 1$



Bonifacio, R., N. Piovella, M.M. Cola, L. Volpe, A. Schiavi, G.R.M. Robb, 2008, Optics Communications, **593**, 69.

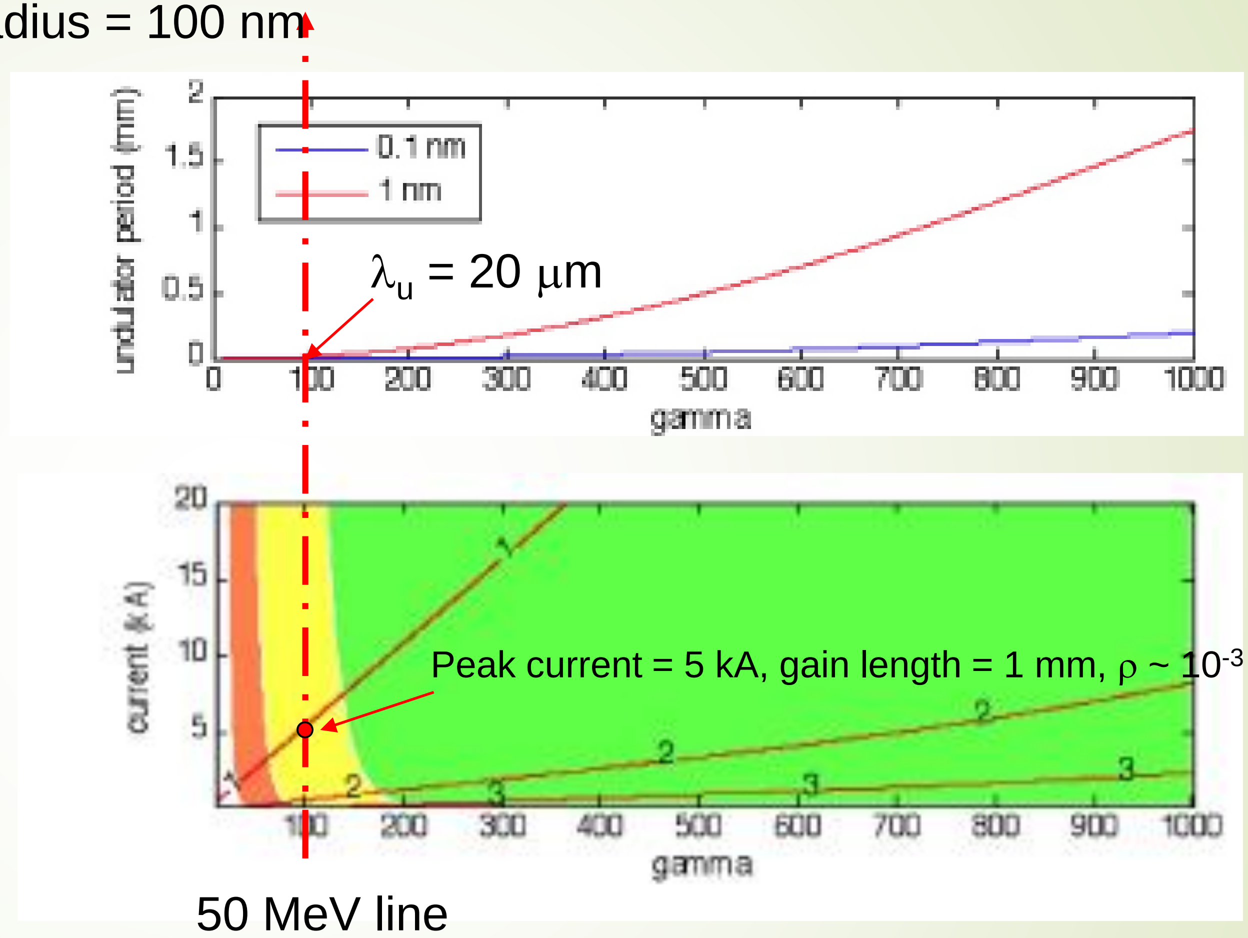
DLA-driven soft-x-ray FEL (laser undulator B_u ~ 3 T, λ_r = 1 nm)

Assume rms beam radius = 100 nm

$$\lambda_r = \lambda_u \frac{1+a_u^2}{2\gamma^2}$$

$$\bar{\rho} = \rho(\gamma mc/\hbar k)$$

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



Straight lines are gain-length contours in mm

- $\bar{\rho} < 1$
- $1 < \bar{\rho} < 10$

Quantum regime

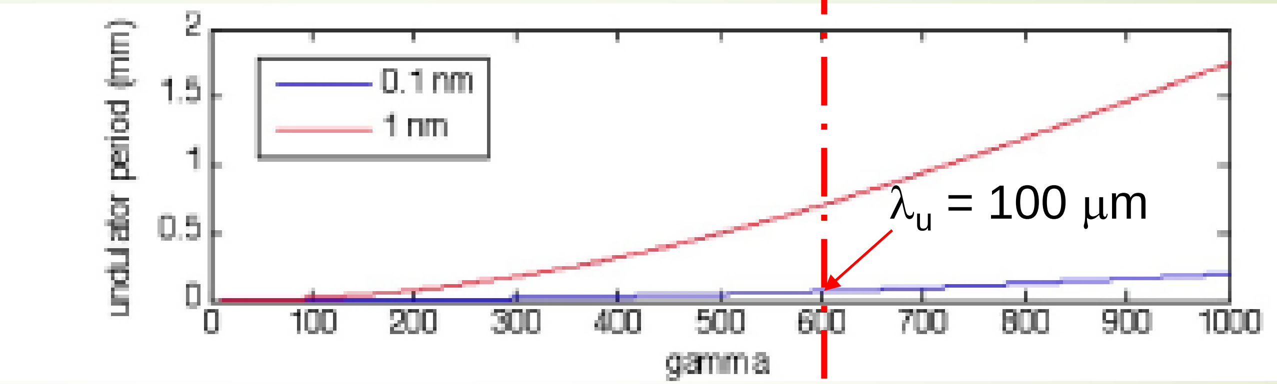
- $10 < \bar{\rho} < 100$
- $100 < \bar{\rho}$

Published in Review of Modern Physics, Oct. – Dec., 2014

DLA-driven hard-x-ray FEL (laser undulator $B_u \sim 3$ T, $\lambda_r = 1$ Å)

Assume rms beam radius = 100 nm

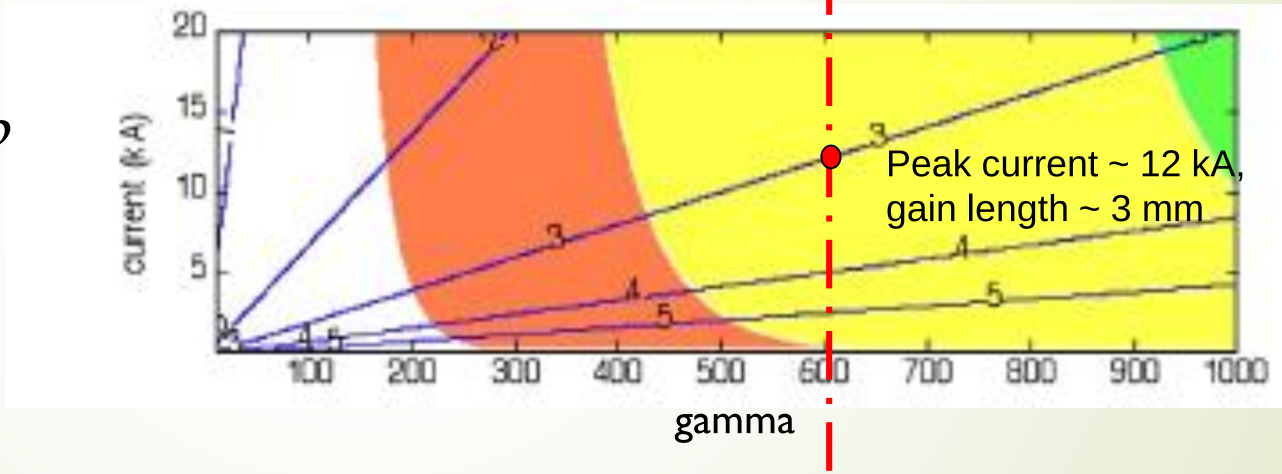
$$\lambda_r = \lambda_u \frac{1 + a_u^2}{2\gamma^2}$$



$$\bar{\rho} = \rho(\gamma mc / \hbar k)$$

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

Straight lines are gain-length contours in mm

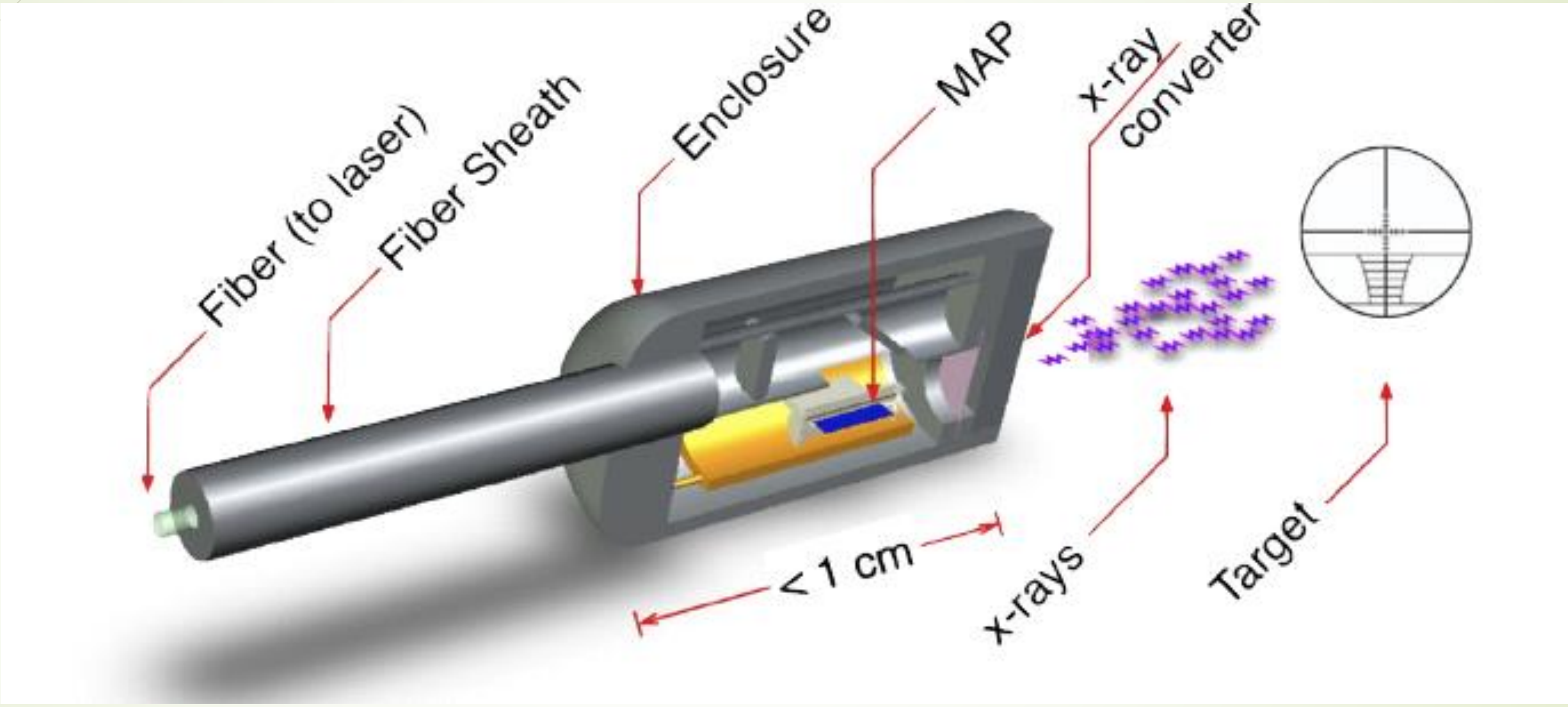


White	$\bar{\rho} < 1$
Orange	$1 < \bar{\rho} < 10$
Yellow	$10 < \bar{\rho} < 100$
Green	$100 < \bar{\rho}$

Quantum regime (white and orange)

Published in Review of Modern Physics, Oct. – Dec., 2014

Artist's rendering of a hand-held XFEL!!



Travish, G., and R.B. Yoder, 2011, "Laser-powered dielectric-structures for the production of high-brightness electron and x-ray beams", in Laser Acceleration of Electrons, Protons, and Ions; and Medical Applications of Laser-Generated Secondary Sources of Radiation and Particles, Prague, Czech Republic, edited by K. W. D. Ledingham *et al*, (SPIE, Bellingham, WA, 2011), Vol. 8079 of Proceedings of SPIE, p. 80790K

CONCLUSIONS

1. DLA is to provide stable acceleration gradient up to ~1 GV/m.

2. Dielectric undulator, having period of 0.1~1000 μm, is to offer undulator fields between 3-10^3 T.

3. Nano-bunches from DLA is well suited to generate EVU ~ x-ray superradiance.

4. Chirped undulator radiation from ultra-short electron bunches allows pulse compression to generate ultra-high peak power radiation.

5. Disadvantageous quantum effects can be avoided for low-energy-DLA driven XFEL.

6. Miniature XFEL is on the horizon.