FEL Winter School, NSRRC, Jan. 5-9 , 2026

「自由電子雷射研究新概念」

Photonic Chips for Electron Acceleration and Radiation

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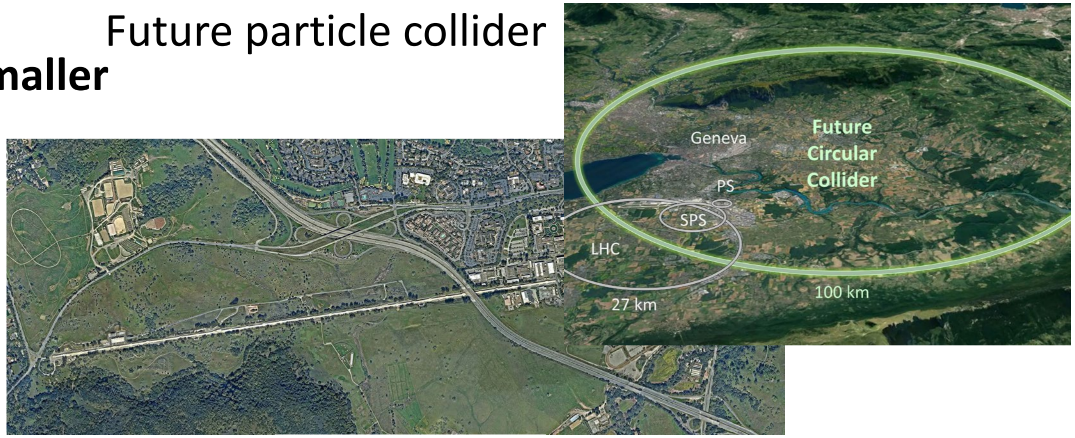
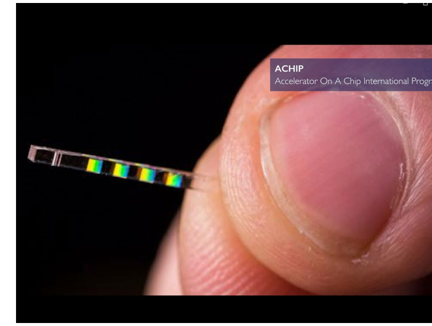
Motivation

1. **Smaller** Future particle collider



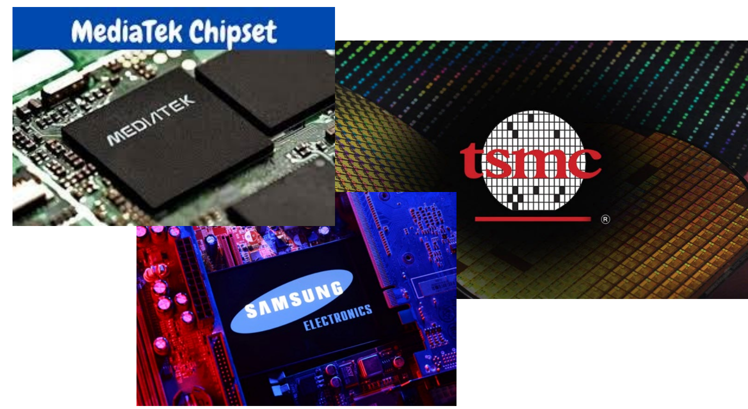


https://achip.stanford.edu/

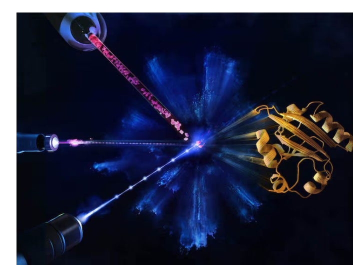
2-mile SLAC

2. **More Sustainable & economical**

https://www.xfel.eu/news_and_events/news/index_eng.html?openDirectAnchor=1143&two_columns=0



3. **Brighter**: brightness or brilliance = flux of particles/spatial-area/angular-area/energy-spread



OUTLINE

1. **Tutorial: Electron Acceleration = Inverse Electron Radiation**

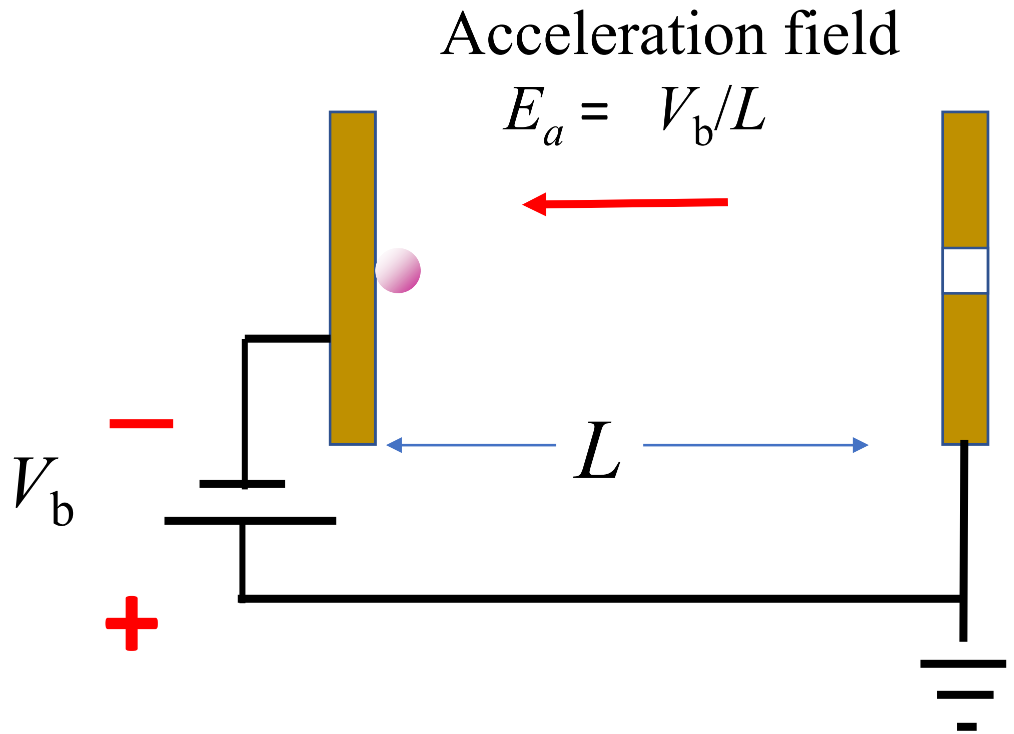
2. **Accelerator Chip: Dielectric Laser Accelerator (DLA)**

3. **Radiation Chip: Single-electron Free-electron Laser**

4. **Accelerator Chip + Radiation Chip: DLA-driven Coherent Undulator Radiation**

5. **Conclusions**

DC Accelerator

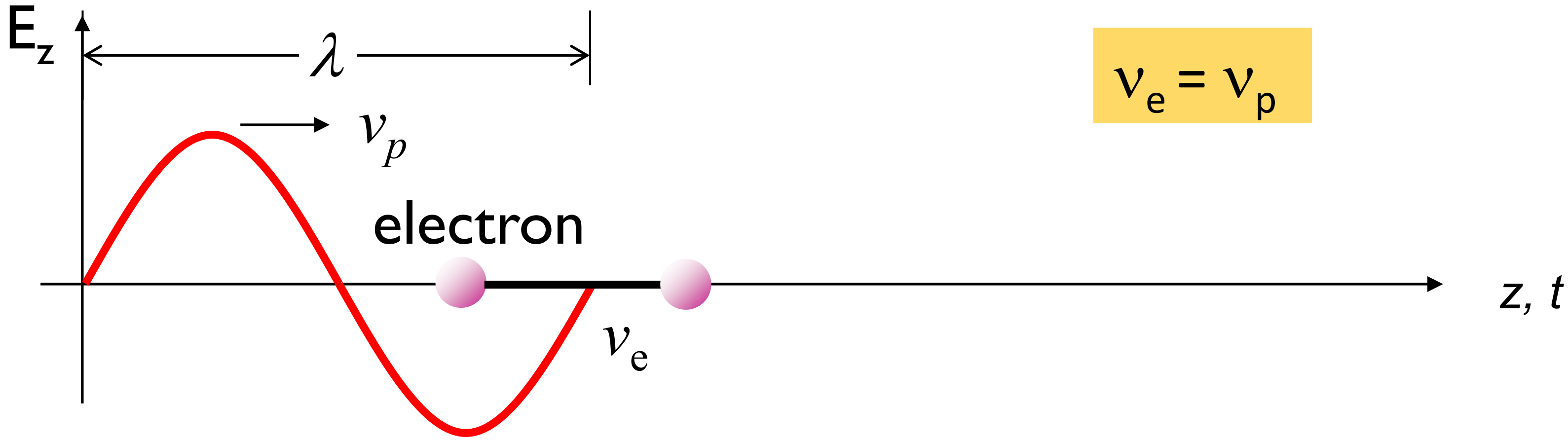


Energy gain: $\Delta W = eE_a \times L = eV_b$

Acceleration gradient: $E_g = \Delta W/(eL) = V_b/L$

RF Accelerator

Phase synchronization
Electron velocity = EM-wave phase velocity



$v_e = v_p$

$$E_z(R,t) = E_{z0}(x,y)\cos(\omega t - k_z z + \phi)$$

$$v_p = \omega / k_z$$

Power transfer – a phase sensitive process

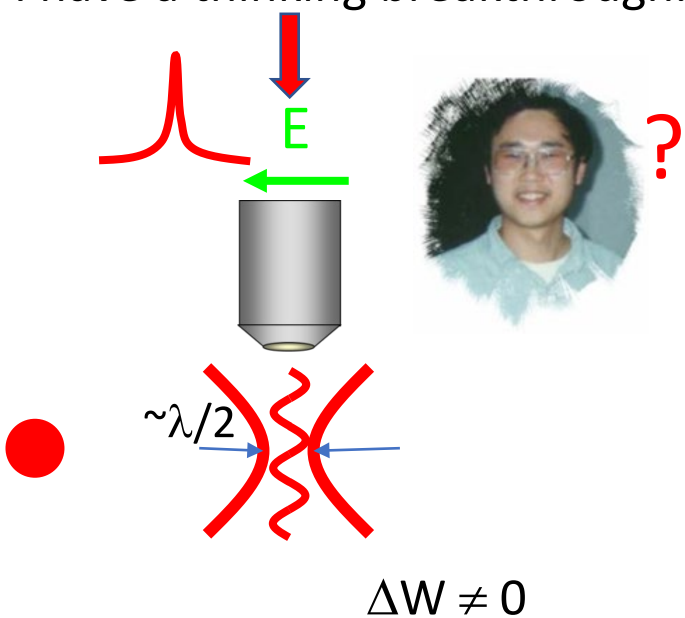
$$\frac{dK}{dt} = \vec{F}\cdot\vec{v} = e\vec{E}\cdot\vec{v} \propto \begin{cases} \vec{E}\cdot\vec{v} < 0 & \text{Acceleration} \\ \vec{E}\cdot\vec{v} > 0 & \text{Radiation} \end{cases}$$

K: electron kinetic energy

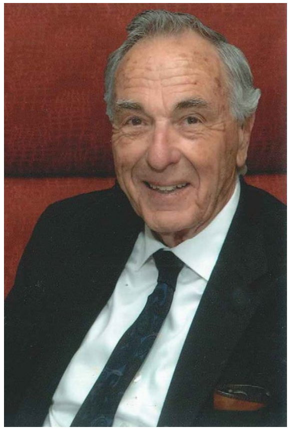
1995 Debate

Robert Byer

Byer: “I have a thinking breakthrough….”



Richard Pantell



Pantell: “read my paper…..”

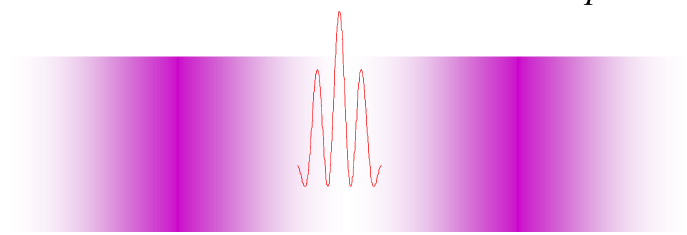
J. A. Edighoffer and R. H. Pantell, “Energy exahcnage between free electrons and light in vacuum,” J. App. Physics **50**, (1979) 6120-6122/

Lawson–Woodward theorem

“an electromagnetic plane wave can not provide a net acceleration to an ultra-relativistic charged particle in vacuum. ”

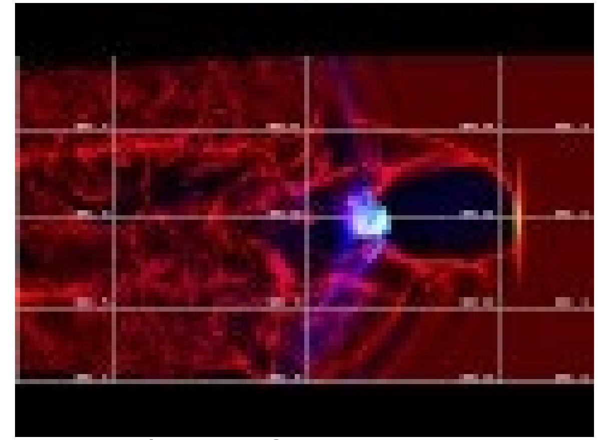
Laser/plasma Wakefield Accelerator

Short laser pulse $\tau_{laser} < \lambda_p / c$ λ_p ~ 20 μm



$E_a \sim 100\ \mathrm{GV/m}$

Density modulated plasma charges

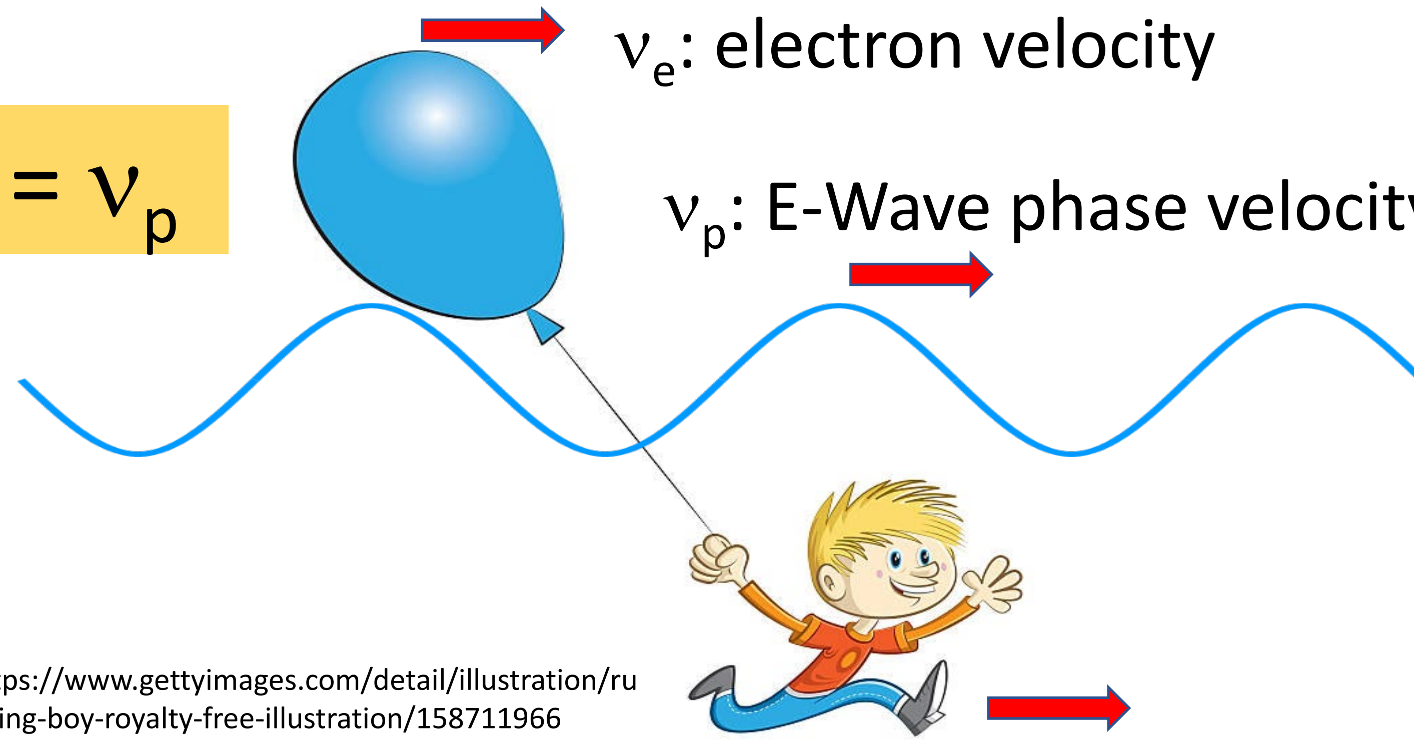


http://www.youtube.com/watch?v=MINxgmPVF6U

ν_e: electron velocity

$\nu_e = \nu_p$

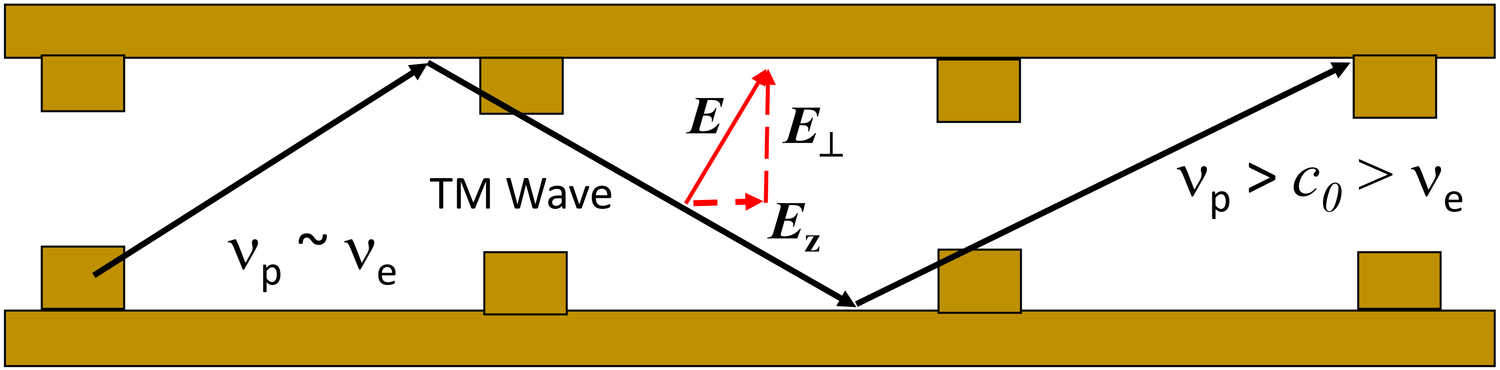
ν_p: E-Wave phase velocity

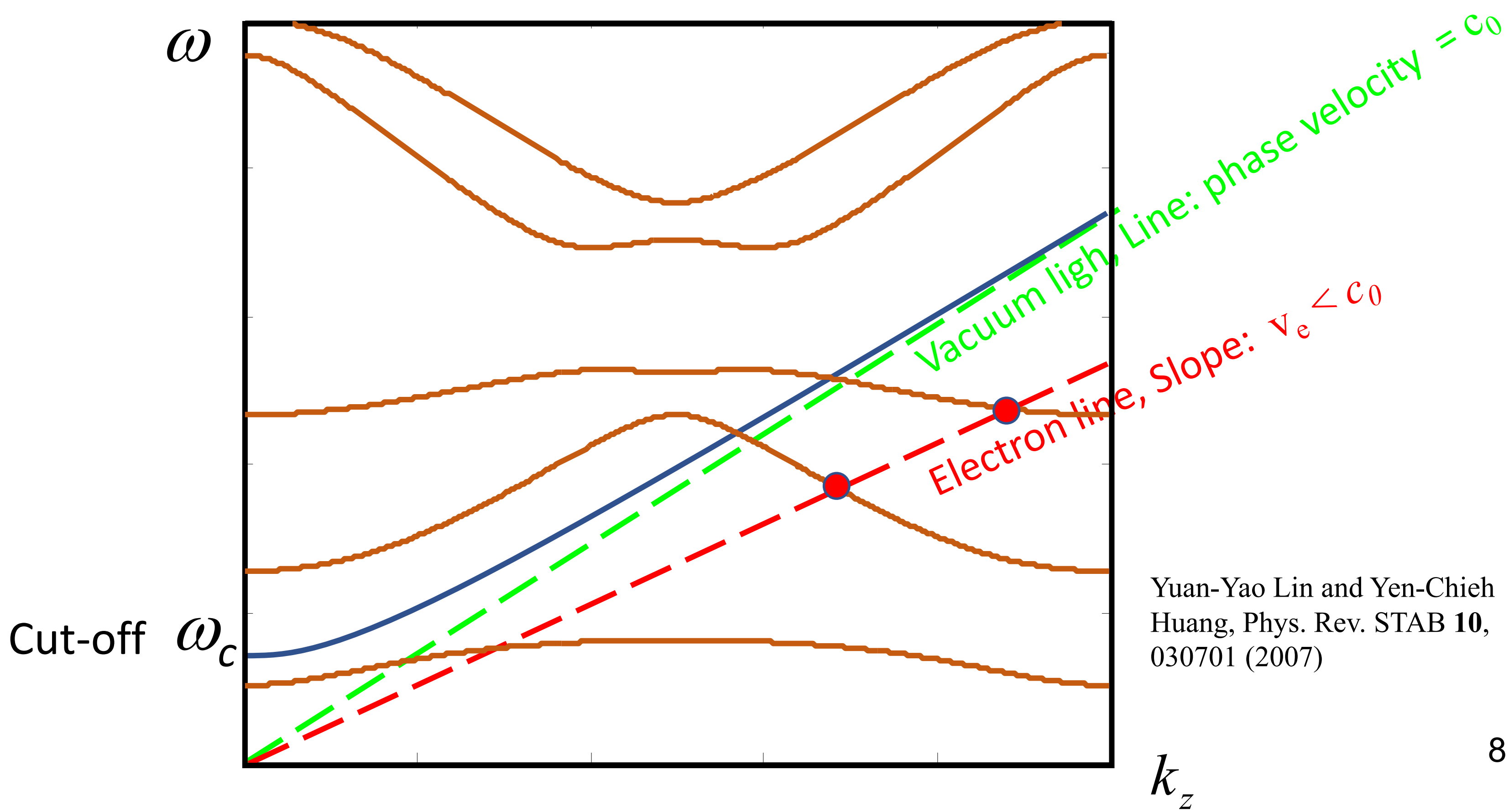


https://www.gettyimages.com/detail/illustration/running-boy-royalty-free-illustration/158711966

ν_g: pump-energy group velocity

Accelerator Structure

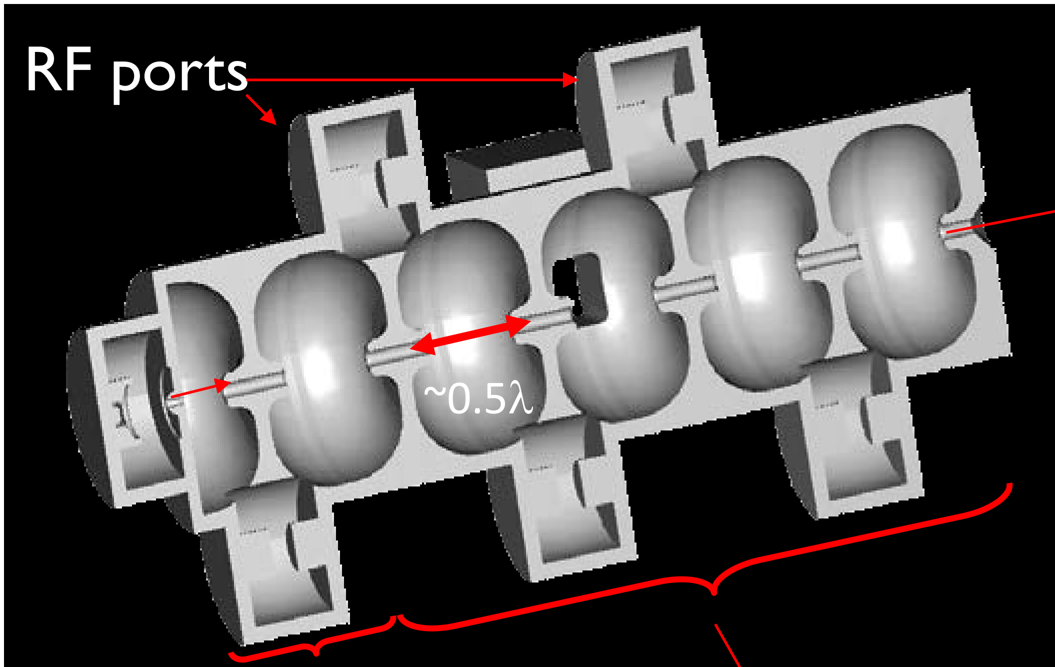




Yuan-Yao Lin and Yen-Chieh Huang, Phys. Rev. STAB **10**, 030701 (2007)

Cutaway view of a RF linear accelerator (linac)

(typical acceleration gradient ~10 MV/m)



Electron beam

http://www.comsol.com/blogs/hybrid-linac-mr-real-time-image-guided-radiotherapy/

Injector: A structure to increase electron velocity from ~ 0 to c_0

A structure to maintain $v_e = v_z \sim c_0$

Accelerator Chip: Dielectric Laser Accelerator (DLA)

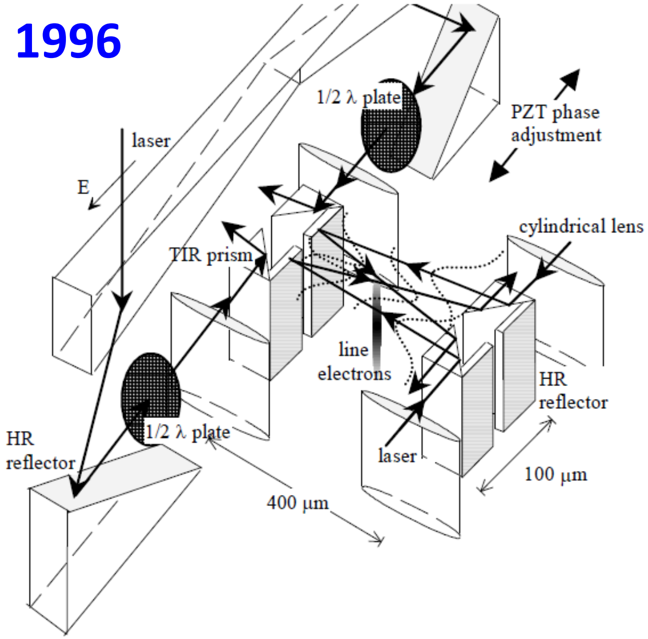
1. Dielectric → solid state → stable

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

2. Dielectric → high laser damage field and thus high acceleration gradient (up to 1-10 GeV/m @ sub-ps pulse width)

3. Economy: fabrication compatible with semiconductor lithographic patterning

DLA in 1996

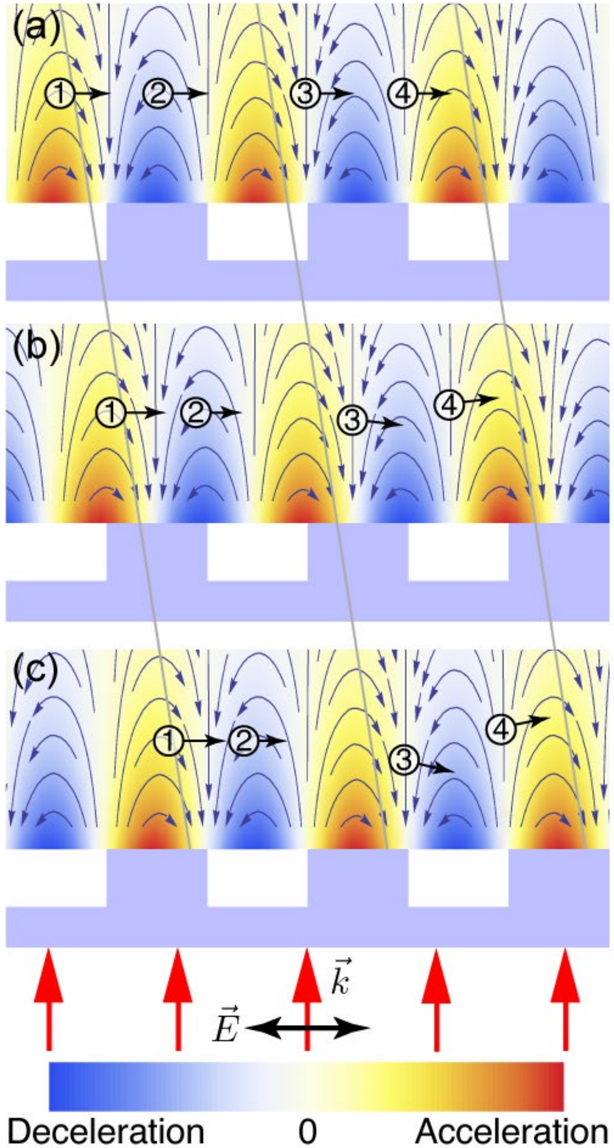


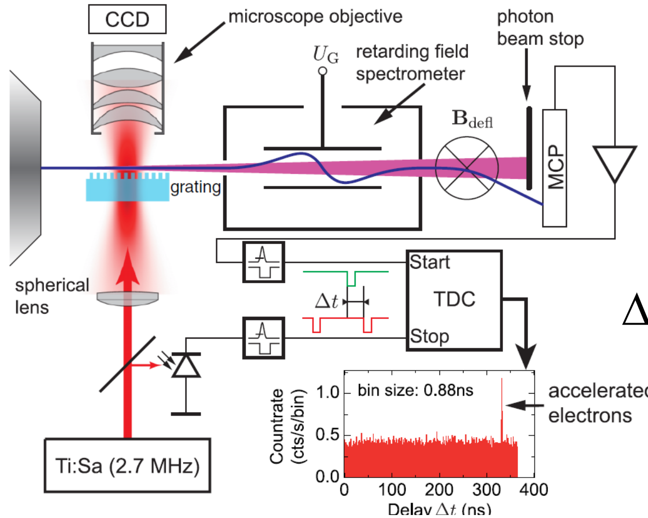
DLA in 2011

•Y.C. Huang, R.L. Byer, D. Zheng, and W. Tulloch, "A Proposed Structure for GeV per Meter Crossed-laser-beam Electron Linear Accelerator," *Appl. Phys. Lett.* 5, (1996) 10.
•Y.C. Huang and R.L. Byer, "A Proposed High-gradient, Laser-driven Linear Acceleration using Cylindrical Laser Focusing," *Appl. Phys. Lett.* **69** (15) (1996).

DLA in 2013

Acceleration of sub-relativistic electrons @ 25 MV/m





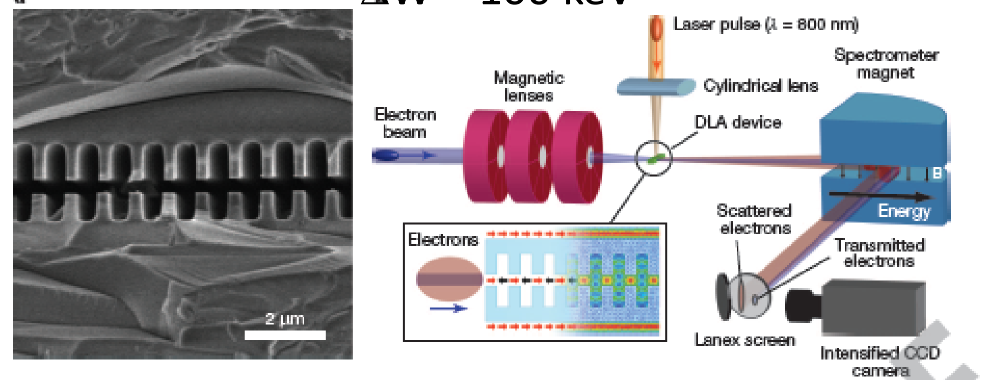
$\Delta W = 0.2 – 0.3$ keV

- John Breuer and Peter Hommelhoff, Phys. Rev. Lett. **111**, 134803 (2013).

Acceleration of 60-MeV electrons @ 300 MeV/m

ΔW ~ 100 keV

a

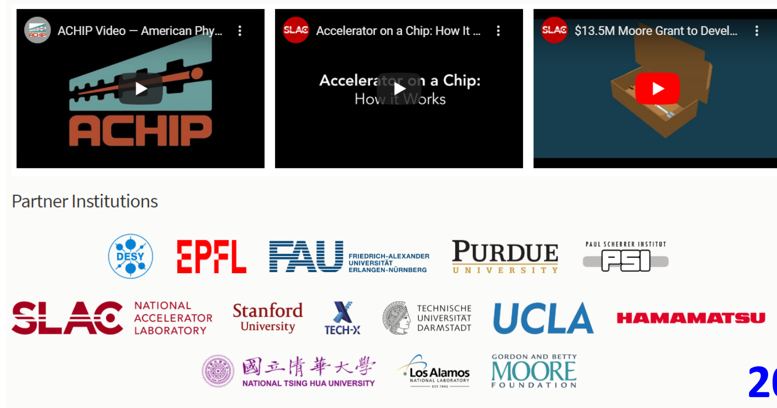


- E. Peralta, E., K. Soong, R. England *et al.*, “Demonstration of electron acceleration in a laser-driven dielectric microstructure,” *Nature* **503,** 91–94 (2013). https://doi.org/10.1038/nature12664

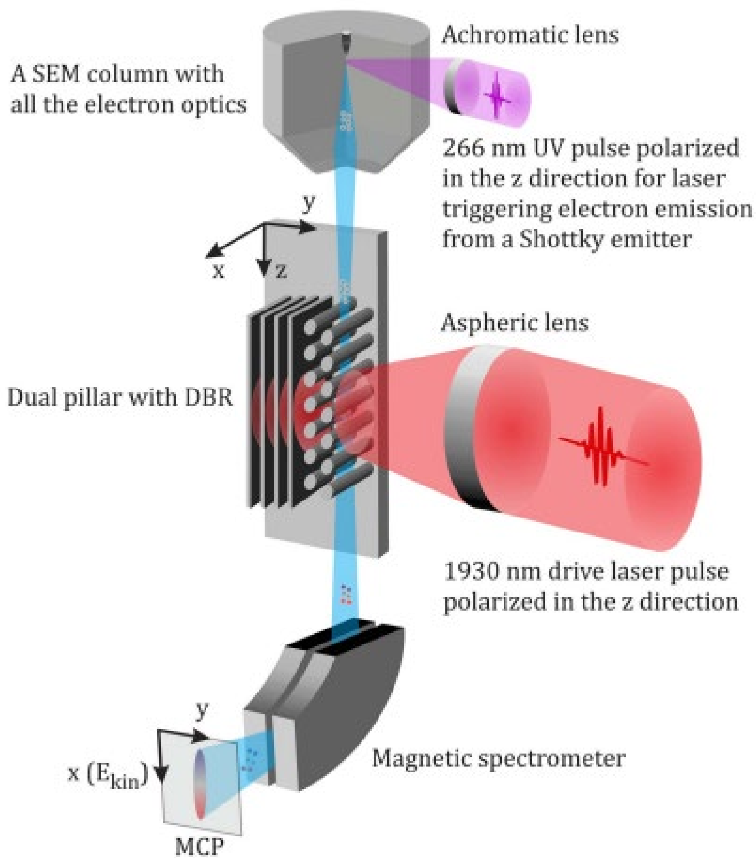
- John Breuer and Peter Hommelhoff, Phys. Rev. Lett. **111**, 134803 (2013).

DLA after 2016

The Moore Foundation funded 19.5M USD for DLA research



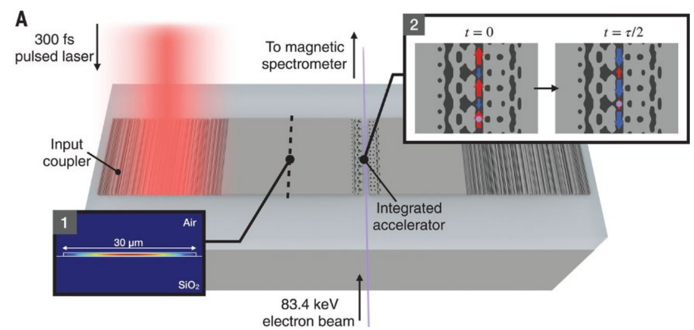
2019

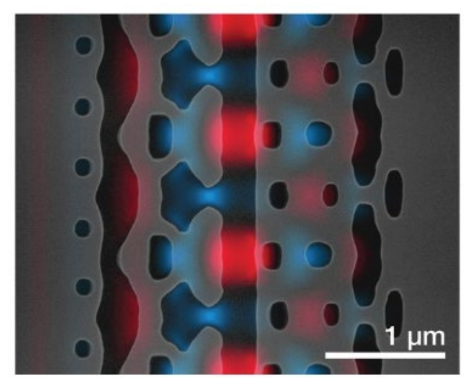


- Peyman Yousef… Peter Hommelhoff, *et al.*, Optics Letters **44,** 1520 (2019).

2020

Inverse-designed on-chip accelerator (30MV/m, ΔW ~ 0.9 KeV)

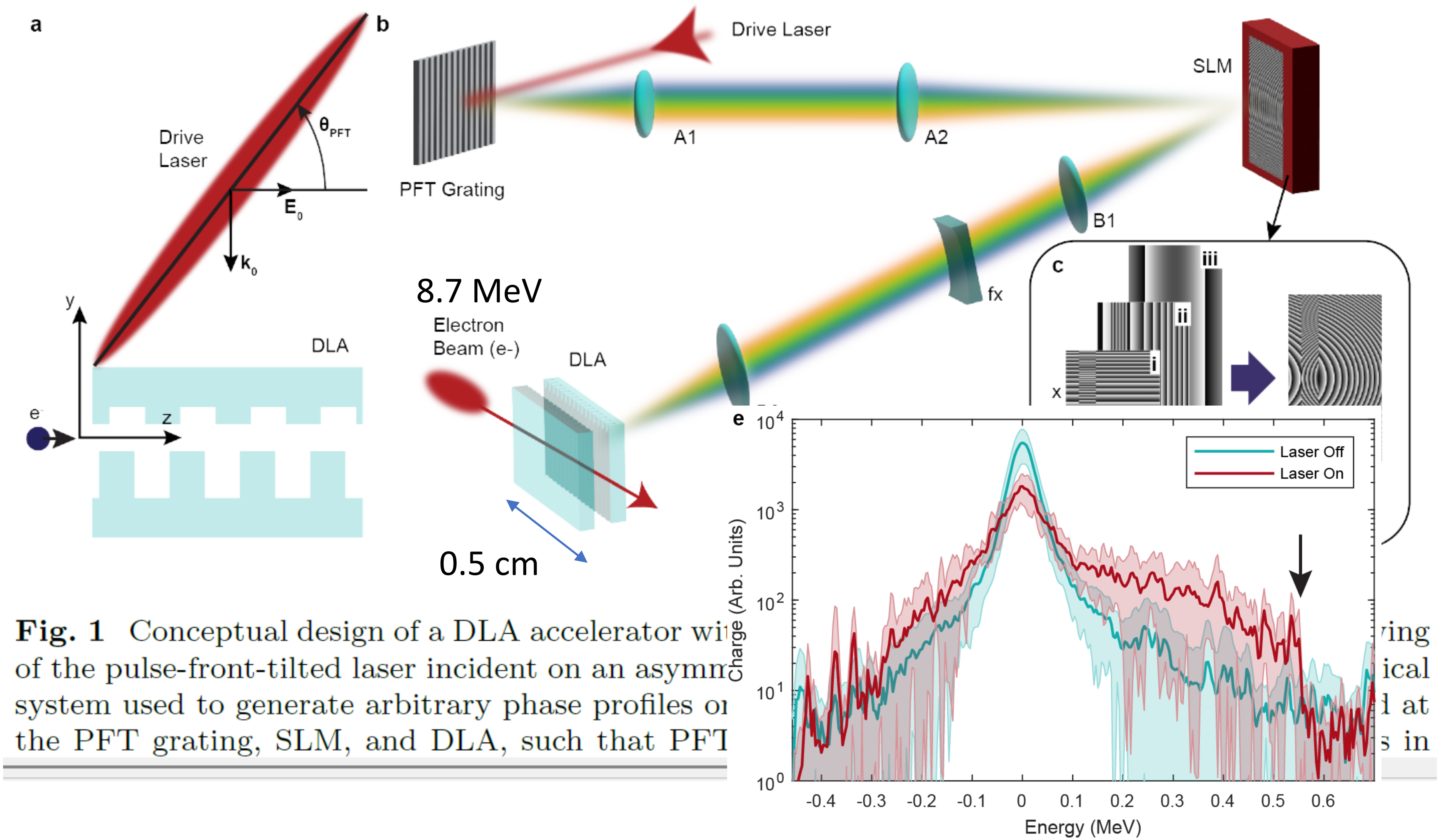




- Neil V. Sapra *et al.*, Science **367**, 79-83 (2020) DOI: 10.1126/science.aay5734

DLA in 2025 – ΔW ~ 0.55 MeV Energy Gain

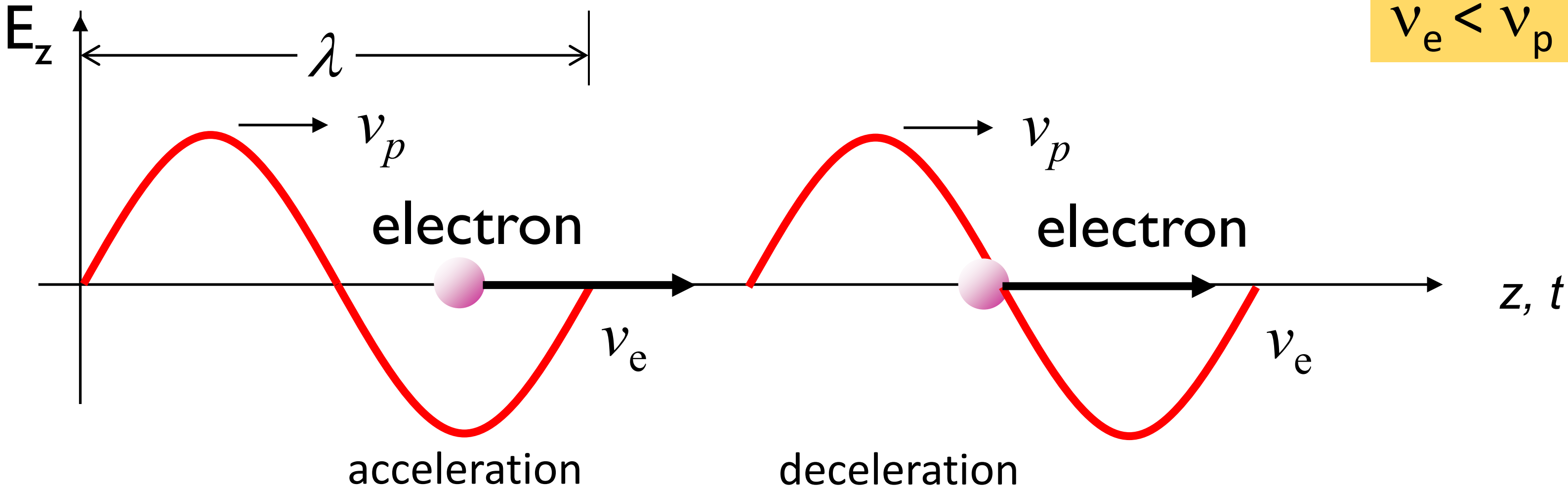
Sophie Crisp[1]*, R. Joel England[2] , Alexander Ody[1] , Pietro Musumeci[1] , “Dynamic control of laser driven electron acceleration in a photonic structure using programmable optical pulses,” arXiv:2509.08170, 9 Sep 2025. (UCLA)



Why is it so difficult?

Phase mismatch

$v_e < v_p$



Define coherence/dephasing length L_c, within which a particle gains energy

$$\omega t\Big|_{t=\frac{L_c}{v_e}} - k_z L_c = \pi \Rightarrow L_c = \frac{\lambda_z}{2\left(\frac{v_z}{v_e} - 1\right)} \propto \lambda$$

Short-λ acceleration is difficult!

THz Acceleration

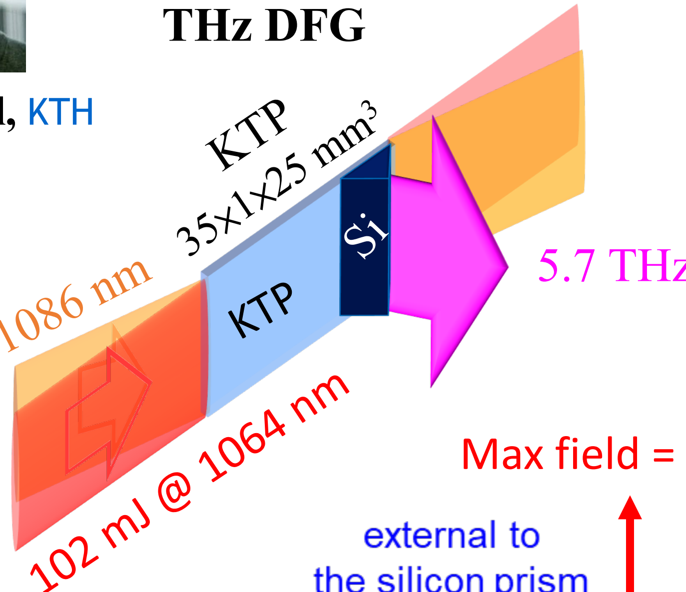
(TW-SE, SSF Contract # STP19-008…

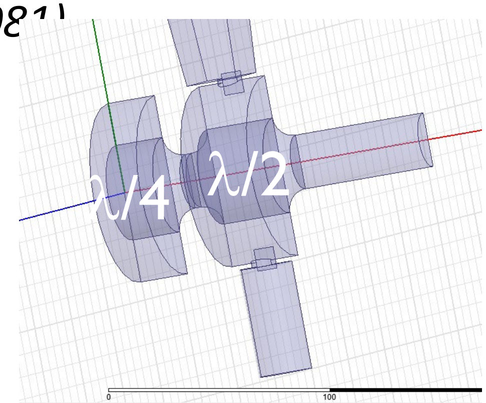
Ming-Hsiung Wu, NTHU

Fredrik Laurell, KTH

Jonas Weissenrieder, KTH

THz DFG

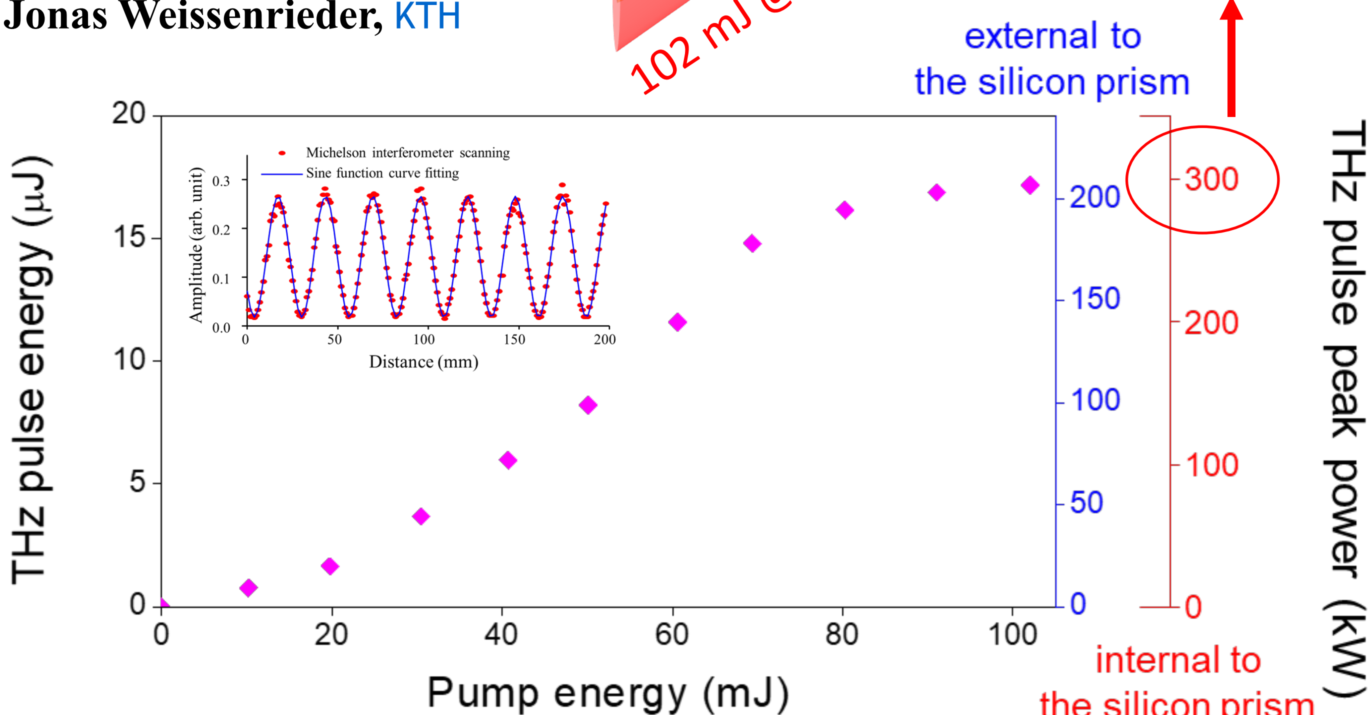


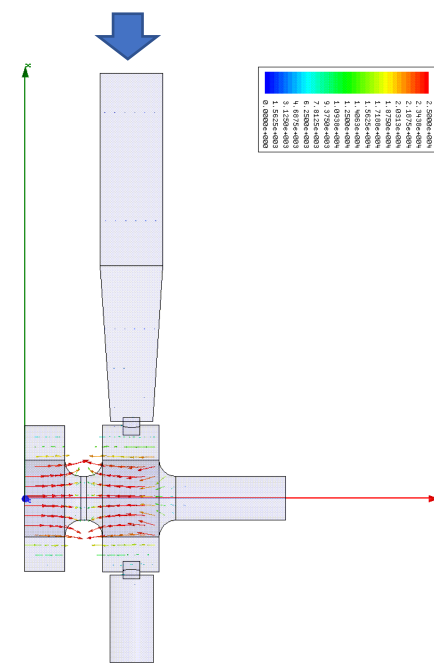


Cavity Q ~ 2000

Max field = 280 MV/m

THz input

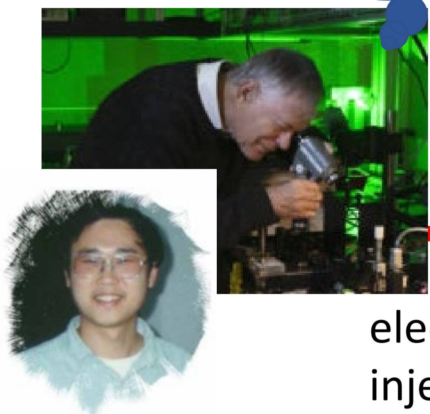


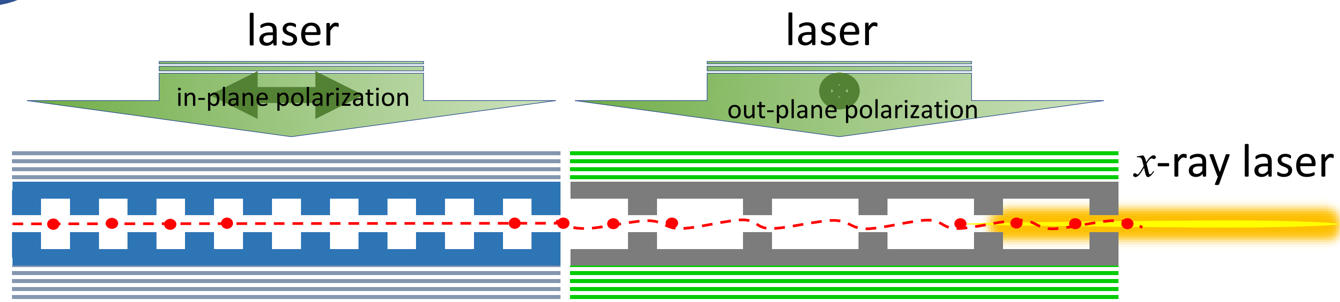


Radiation Chip driven by Accelerator Chip

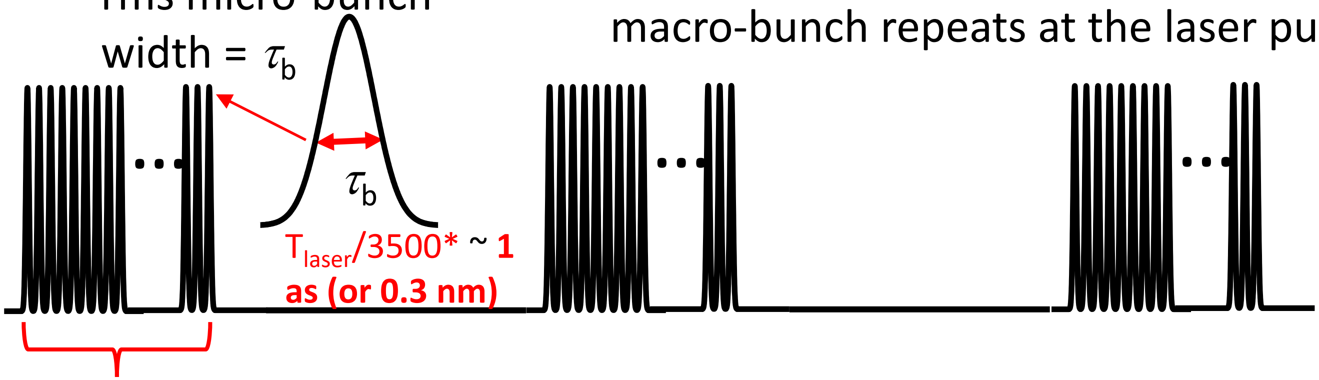
@ Ginzton Lab, Stanford

We had a dream… (1995-1996)





Electron Bunch Structure of a DLA



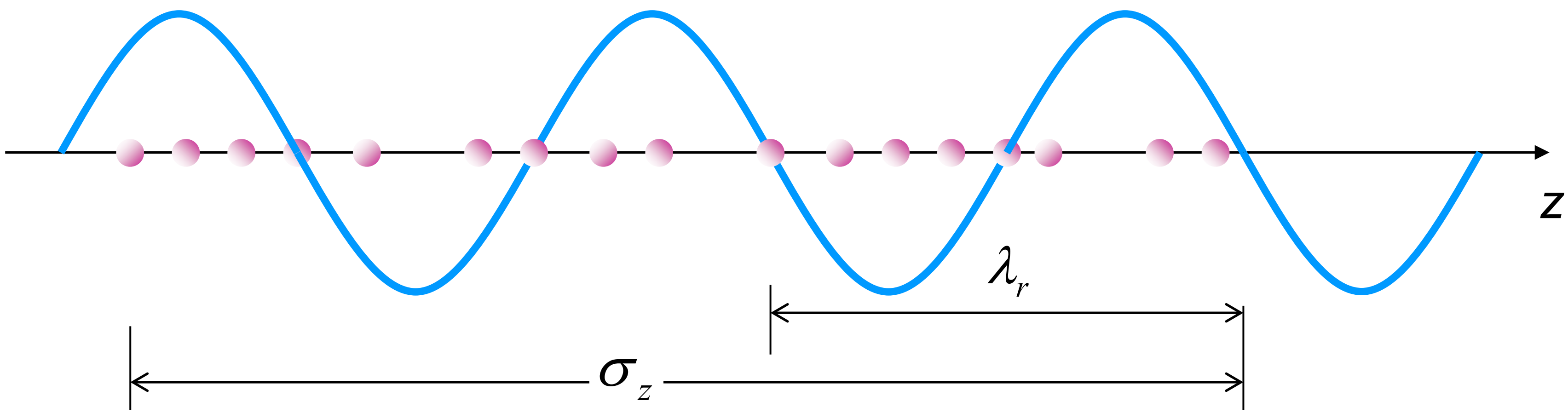
macro-bunch contains M_μ micro-bunches/optical cycles

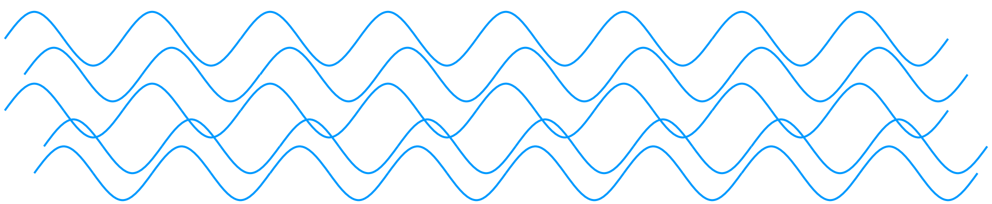
Total electron bunch rate $f_b = M_\mu f_{laser}$, f_{laser} = laser pulse rate

*The bunch-length scaling factor of 3500 is extrapolated from an RF accelerator (RFA)

Incoherent Radiation

Electron length: $\sigma_z >> \lambda_r, r_i$ is random





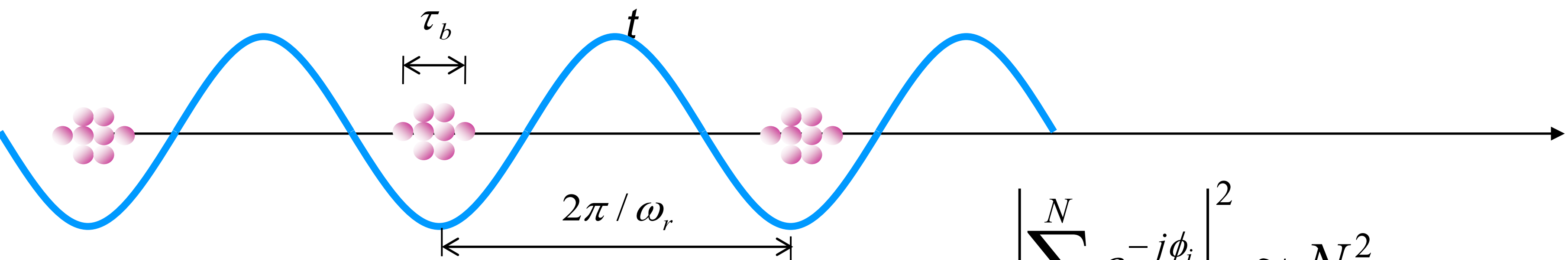
$$\left| \sum_{i=1}^{N} e^{-j\phi_i} \right|^2 \approx N$$

Total Spectral Energy $\left(\frac{dW}{d\omega} \right)_{inc,N} = N \left(\frac{dW}{d\omega} \right)_1 \propto \boxed{N}$ *N*: number of electrons

$\left(\frac{dW}{d\omega} \right)_1$ Radiation spectral energy of a single electron

Electron Superradiance

Harmonic Content of Bunched Electrons



$$\left| \sum_{i=1}^{N} e^{-j\phi_i} \right|^2 \approx N^2$$

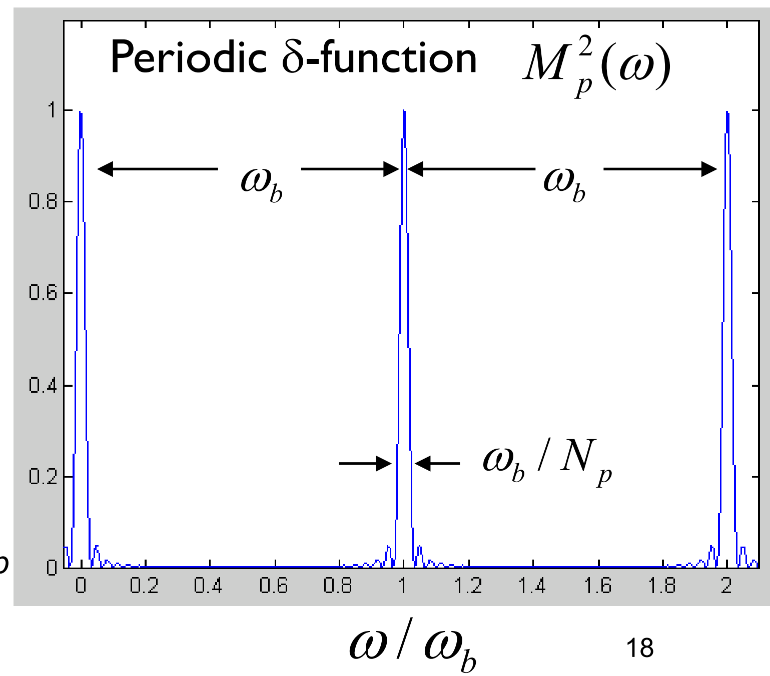
Spectral Energy

$$\left(\frac{dW}{d\omega} \right)_{SR} = \left(\frac{dW}{d\omega} \right)_1 \boxed{N_b^{\,2}} \boxed{\times N_p^2 M_p^2(\omega)}$$

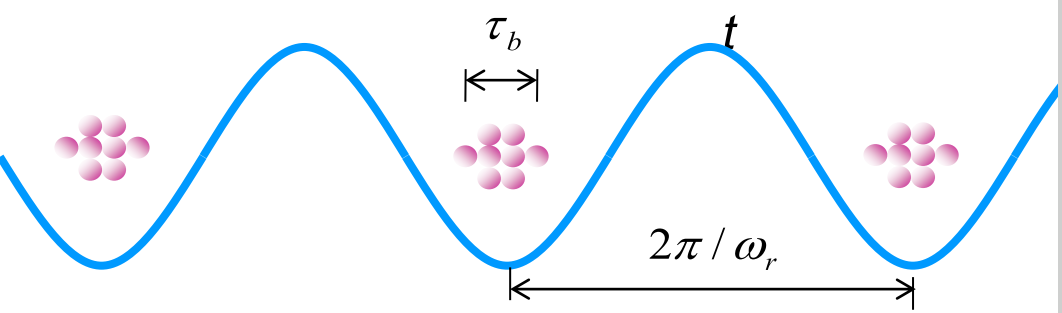
N_b: number of electrons in a bunch

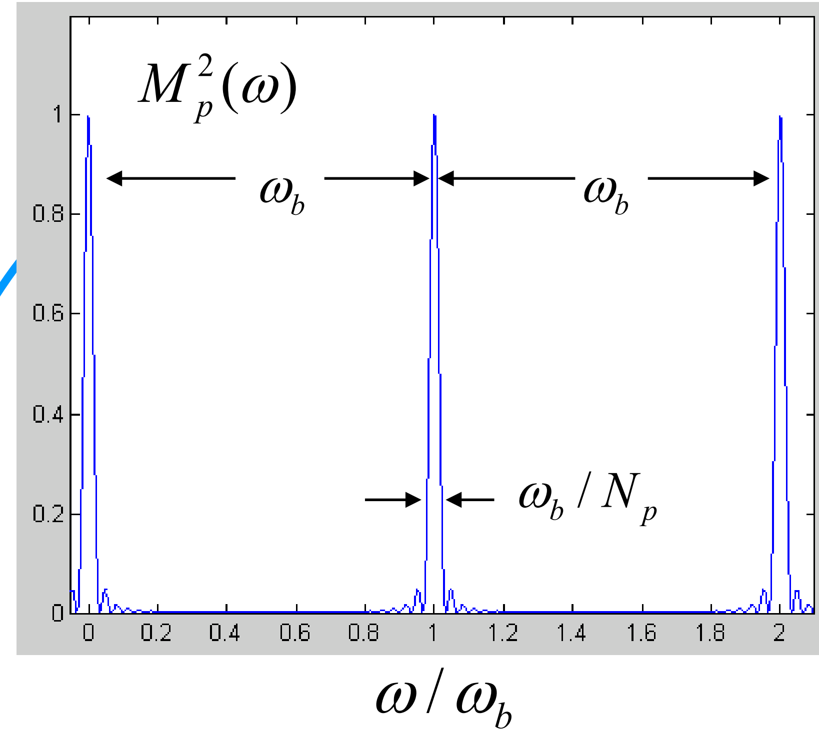
$$M_p(\omega) = \frac{\sin(N_p \pi \omega / \omega_b)}{N_p \sin(\pi \omega / \omega_b)}$$

Coherent sum of N_p bunches with bunching freq. ω_b

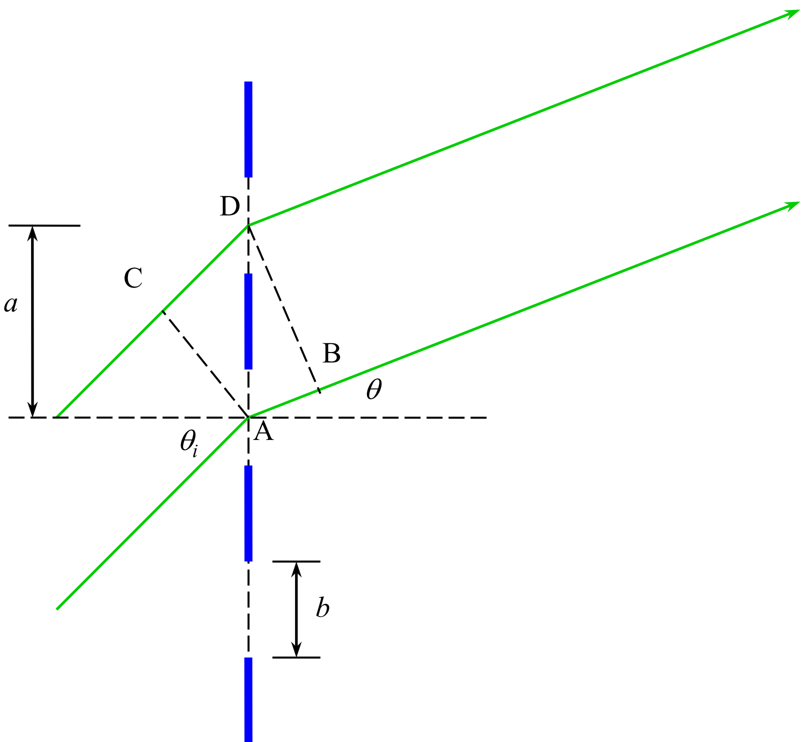


Multi-bunch radiation



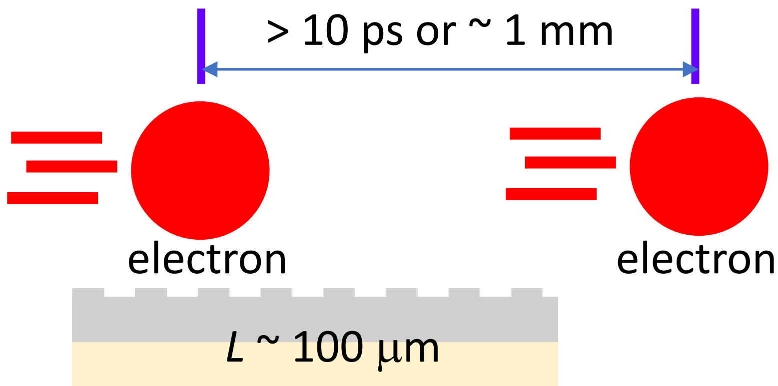


Analogy in grating diffraction



Today, a nano-Ampere current is being accelerated by a DLA…

Nano-Ampere over a micro-radiator



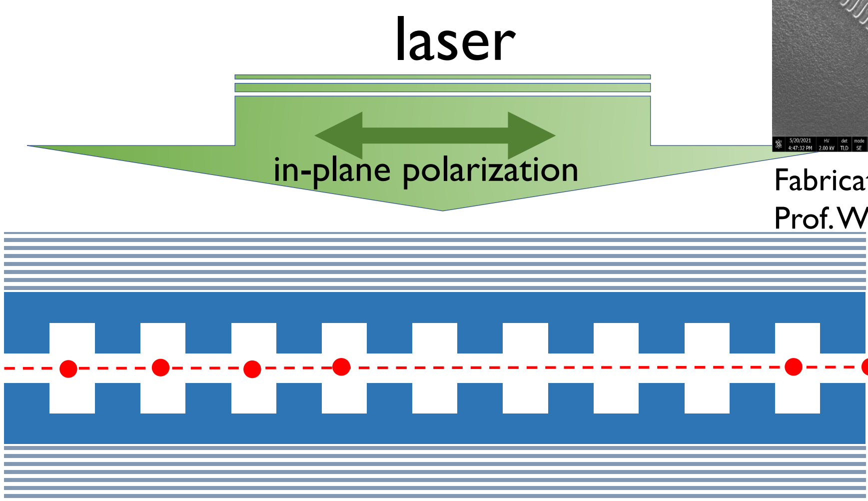
$$N_b \sim 1$$

$$\left(\frac{dW}{d\omega}\right)_{SR} = \left(\frac{dW}{d\omega}\right)_1 N_b^{\,2}$$

$$\times N_p^2 M_p^2(\omega)$$

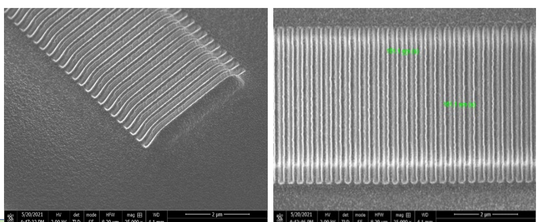
Nano-Ampere Source ≡ Single-electron Source for a micro-radiator

Single-electron Pulse Train

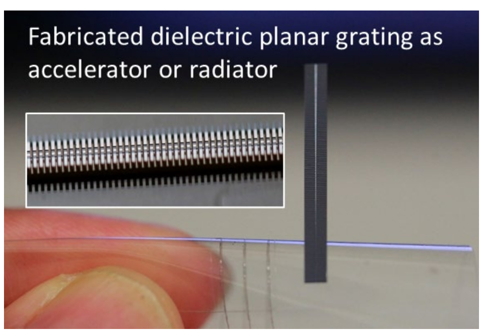


dielectric laser accelerator

→ periodic single electrons in a nano-channel (repeating @ drive laser freq.)



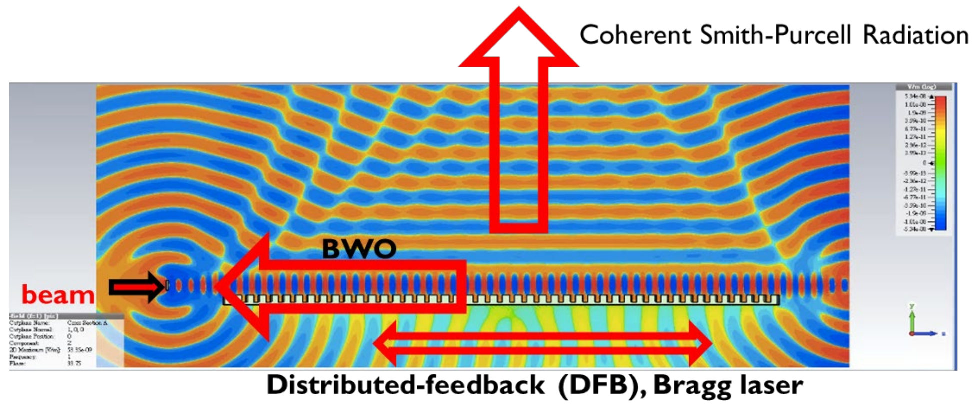
Fabricated structure on Si (courtesy of Prof. Wei-Chih Wang of NTHU)

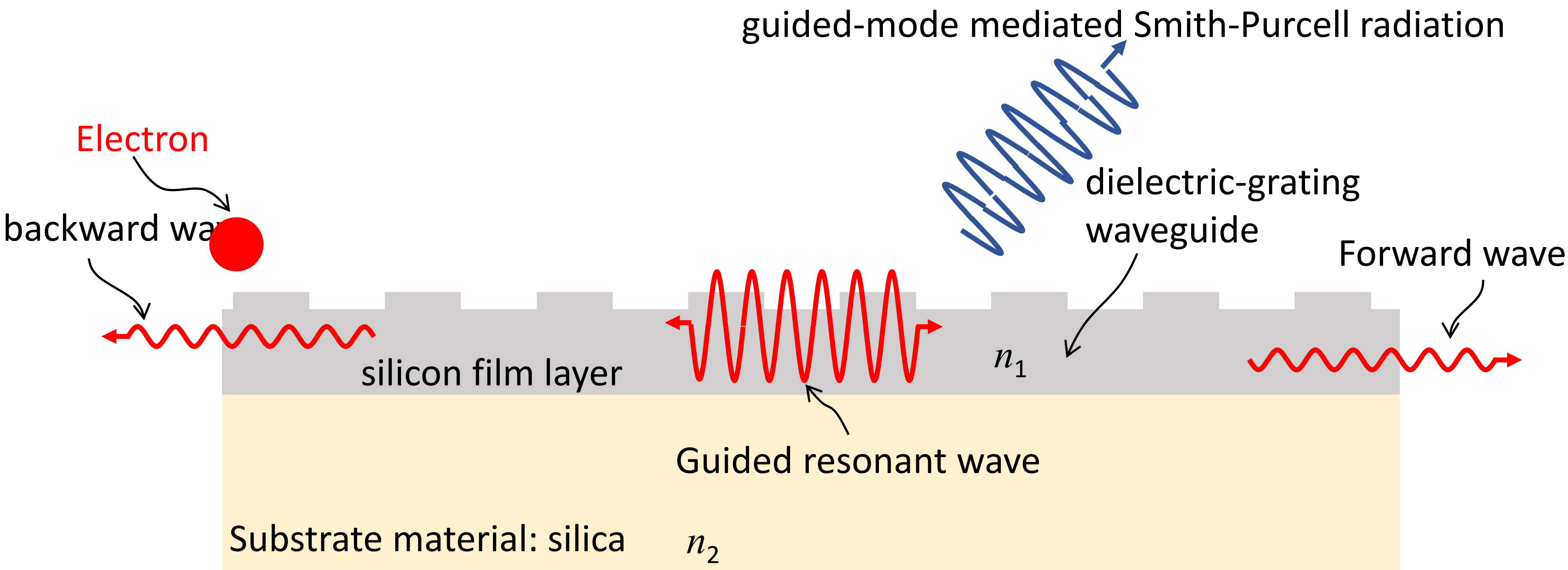


Single-electron FEL

TABLE I. The first-order design parameters for a 1.5-μm nano-chip FEL with a silicon ($n_f = 3.4$) grating waveguide on a glass substrate ($n_s = 1.5$).

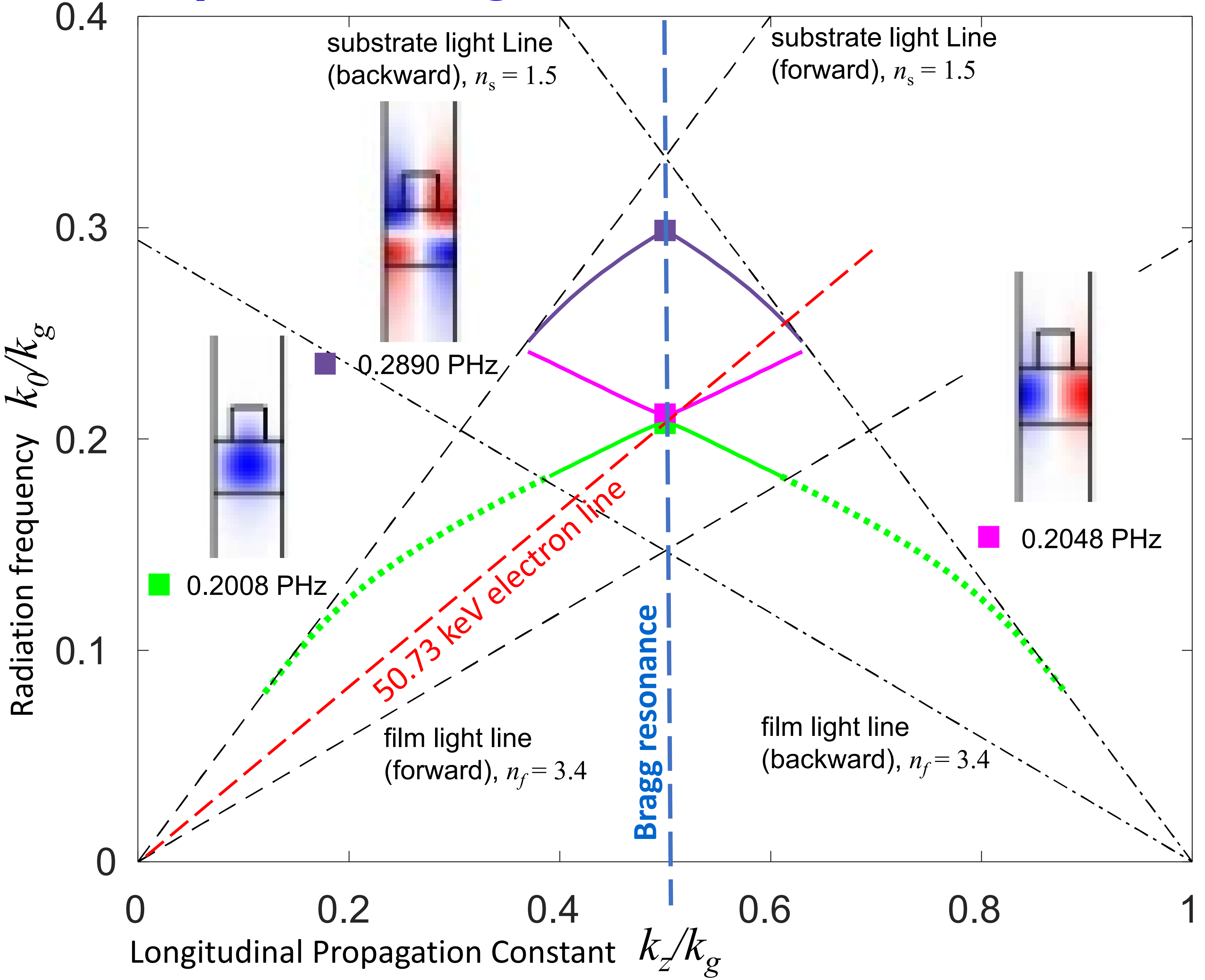
Design wavelength (μm)	Electron energy (keV)	Grating period Λ_g (nm)	Grating depth t_g (nm)	Film thickness t_f (nm)	Impact parameter l_{ip} (nm)
1.5	50	310	160	240	100





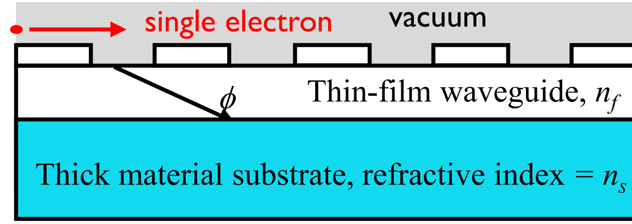
Dielectric-grating Waveguide – 1D photonic crystal

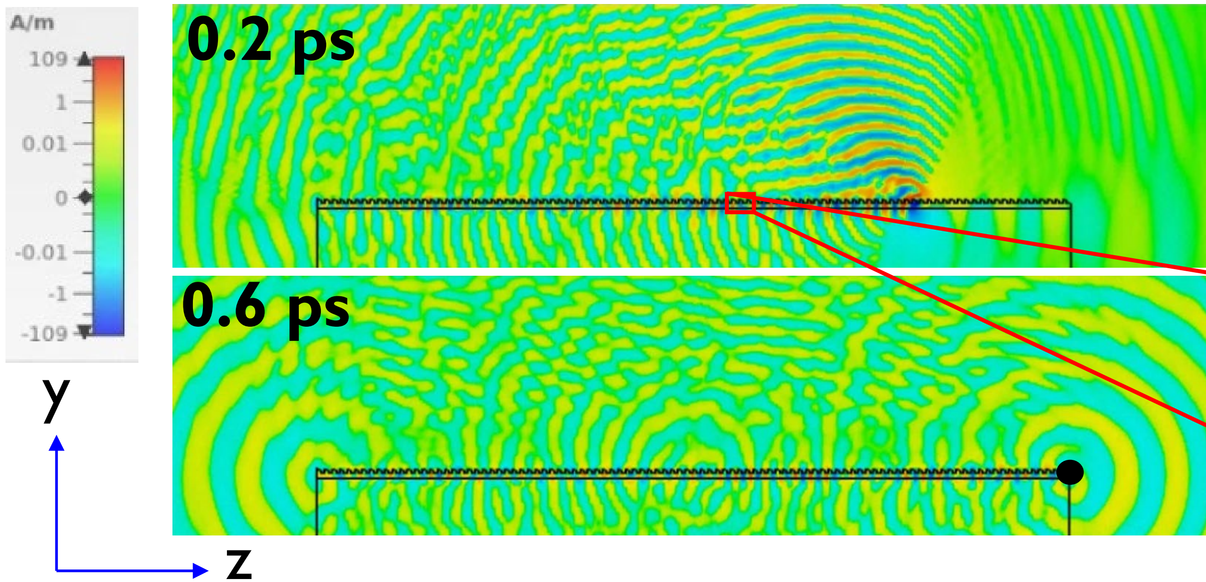
Dispersion Diagram



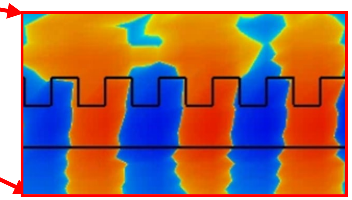
Grating-waveguide FEL driven by 1 electron

CST simulation

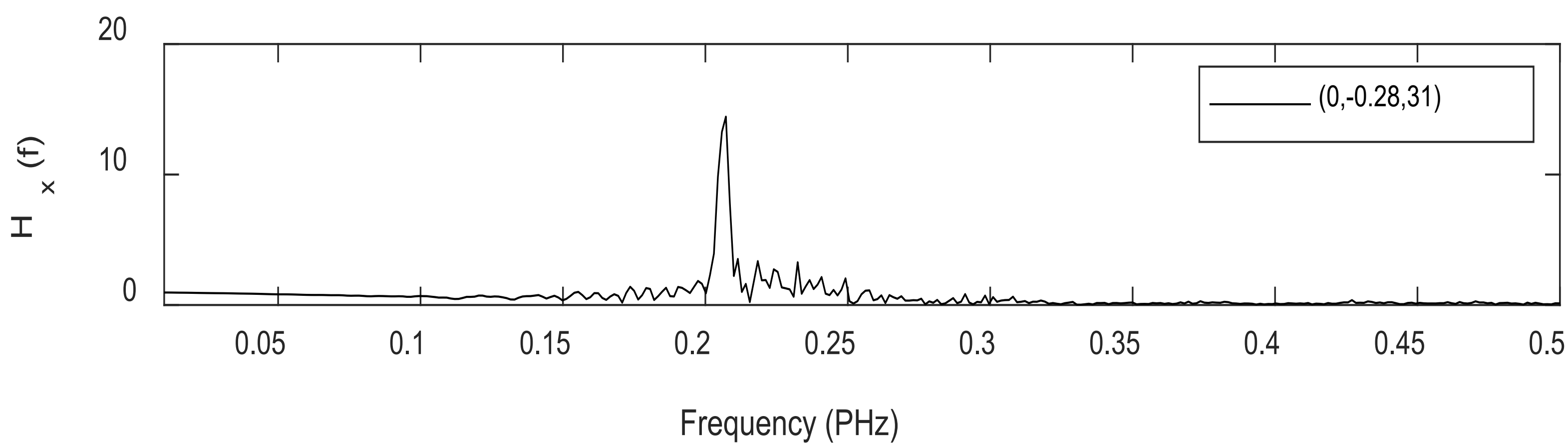




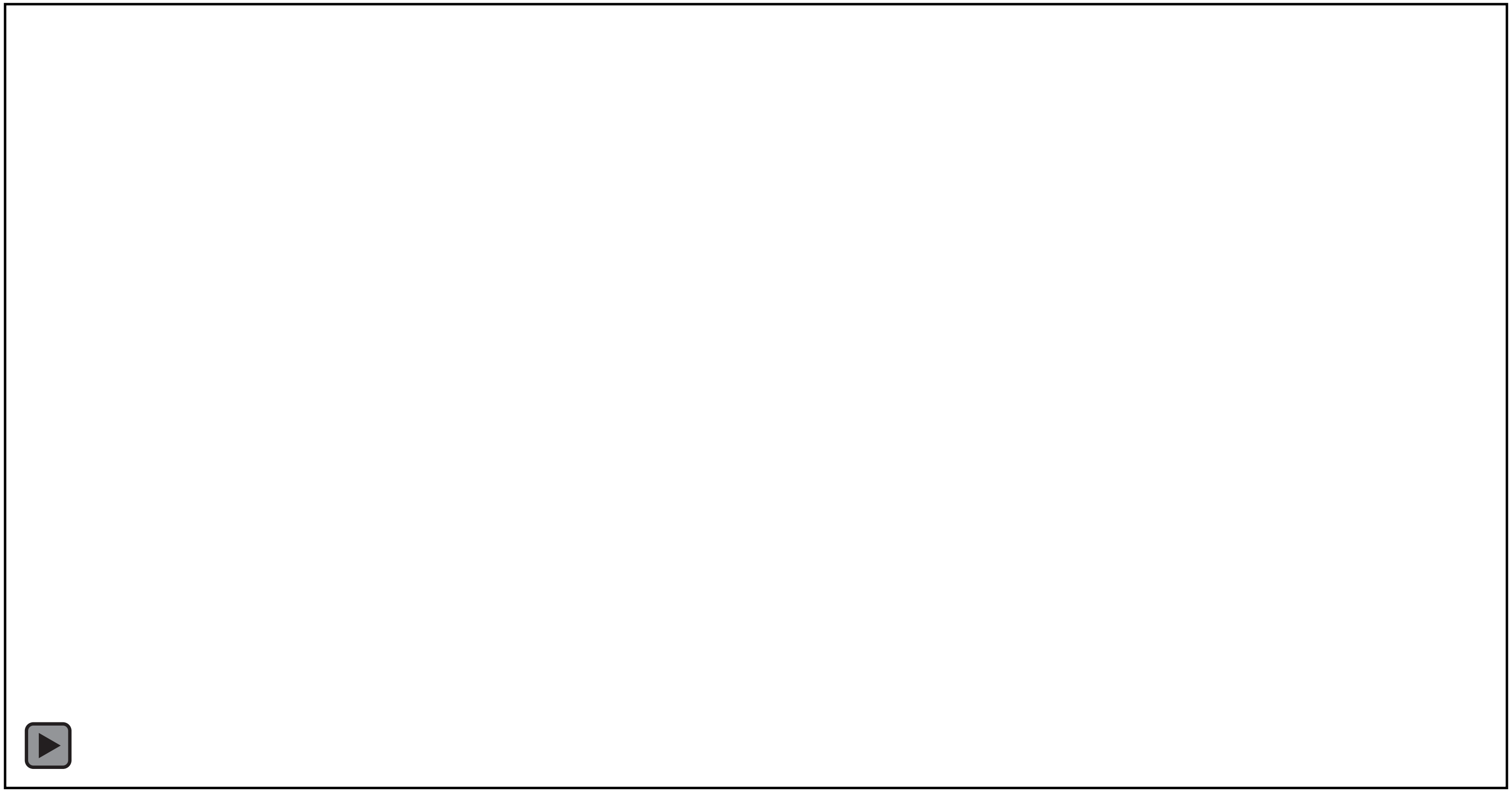
$$\Lambda_g = \frac{\lambda_z}{2}$$

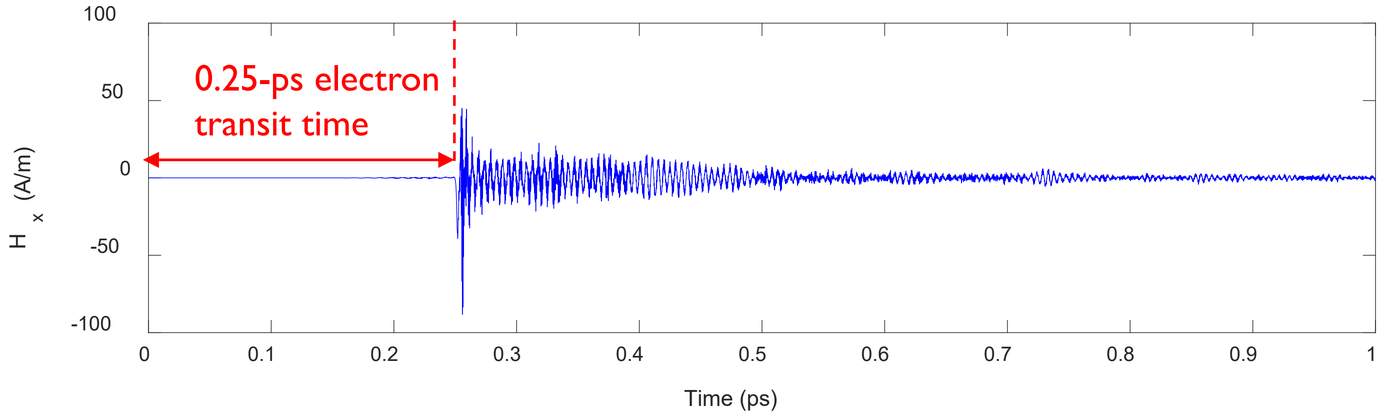


Bragg resonance



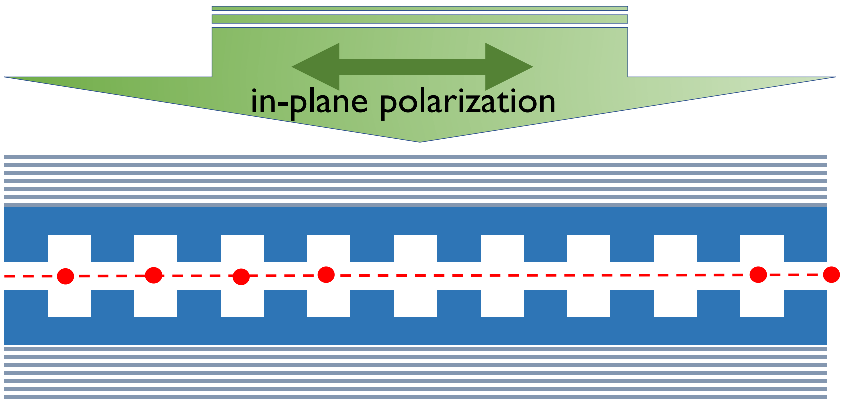
H_x Field Animation





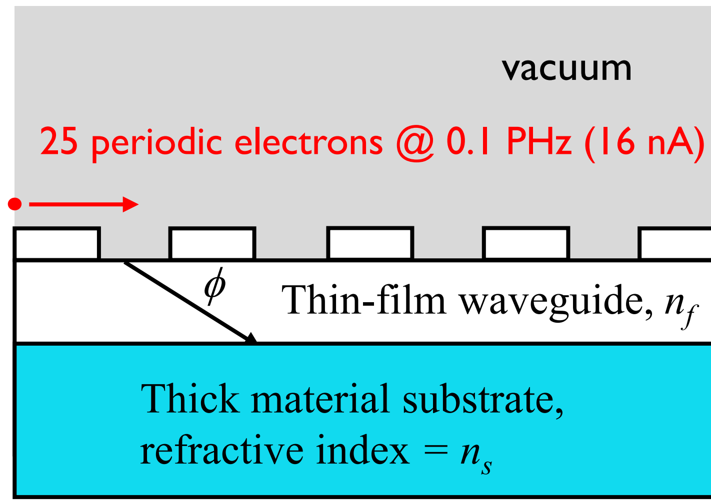
Grating-waveguide FEL driven by Periodic Single Electrons

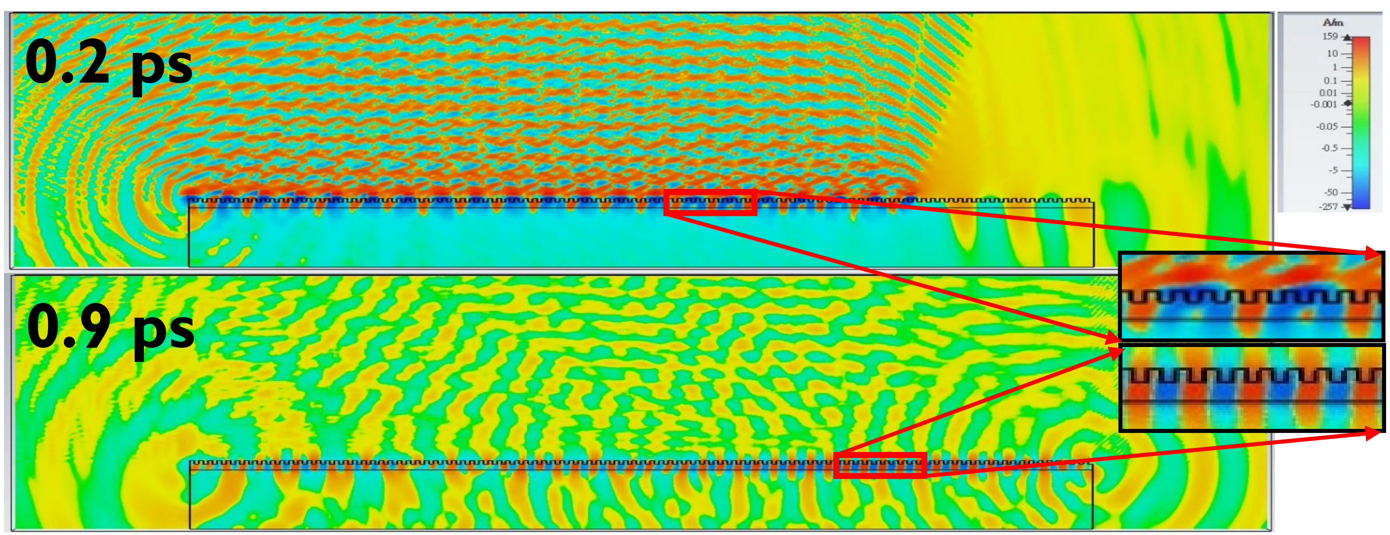
Laser at 3 μm



Dielectric laser accelerator
driven by a 3 μm (0.1 PHz) laser

FEL chip

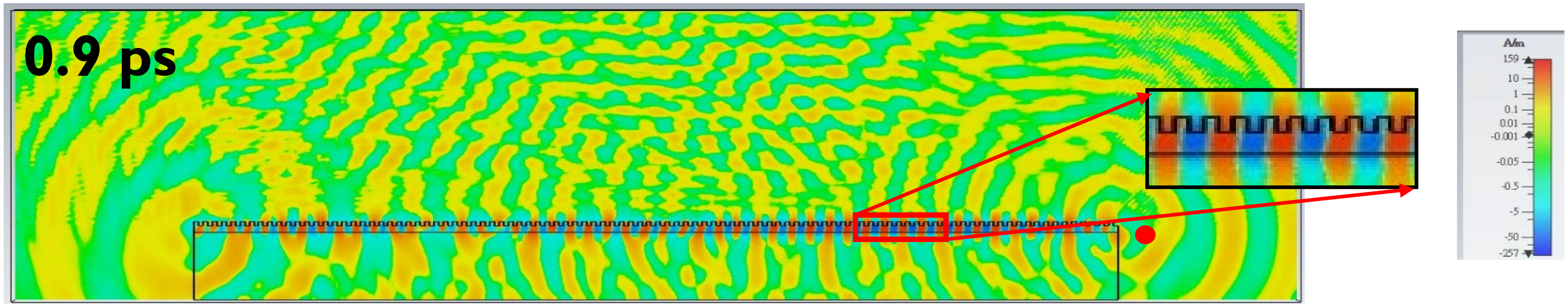


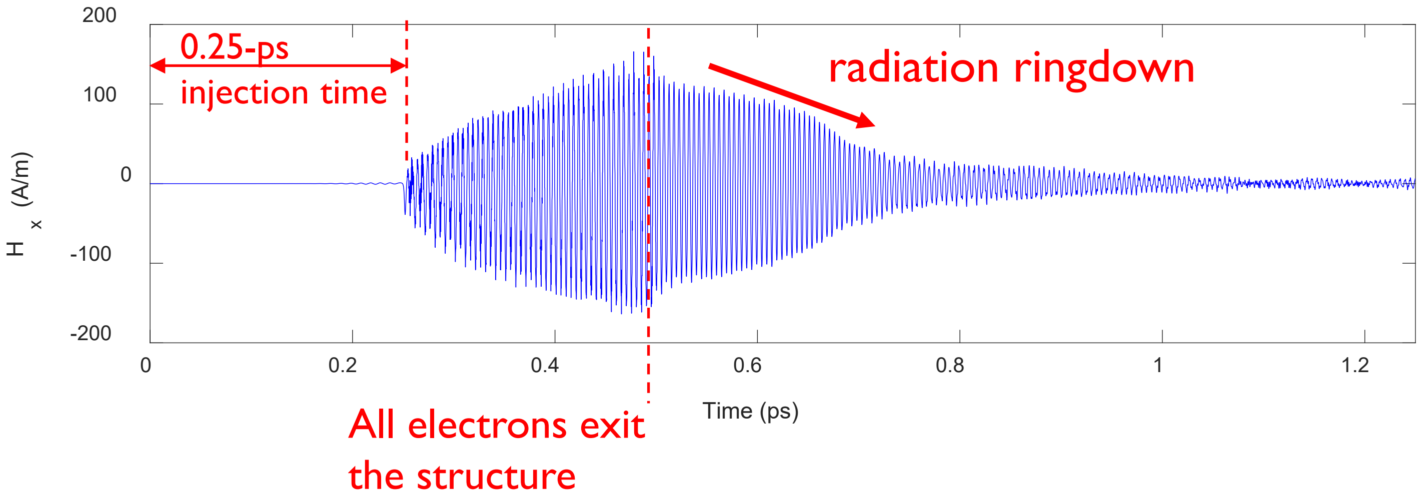


0.1-PHz
electron field

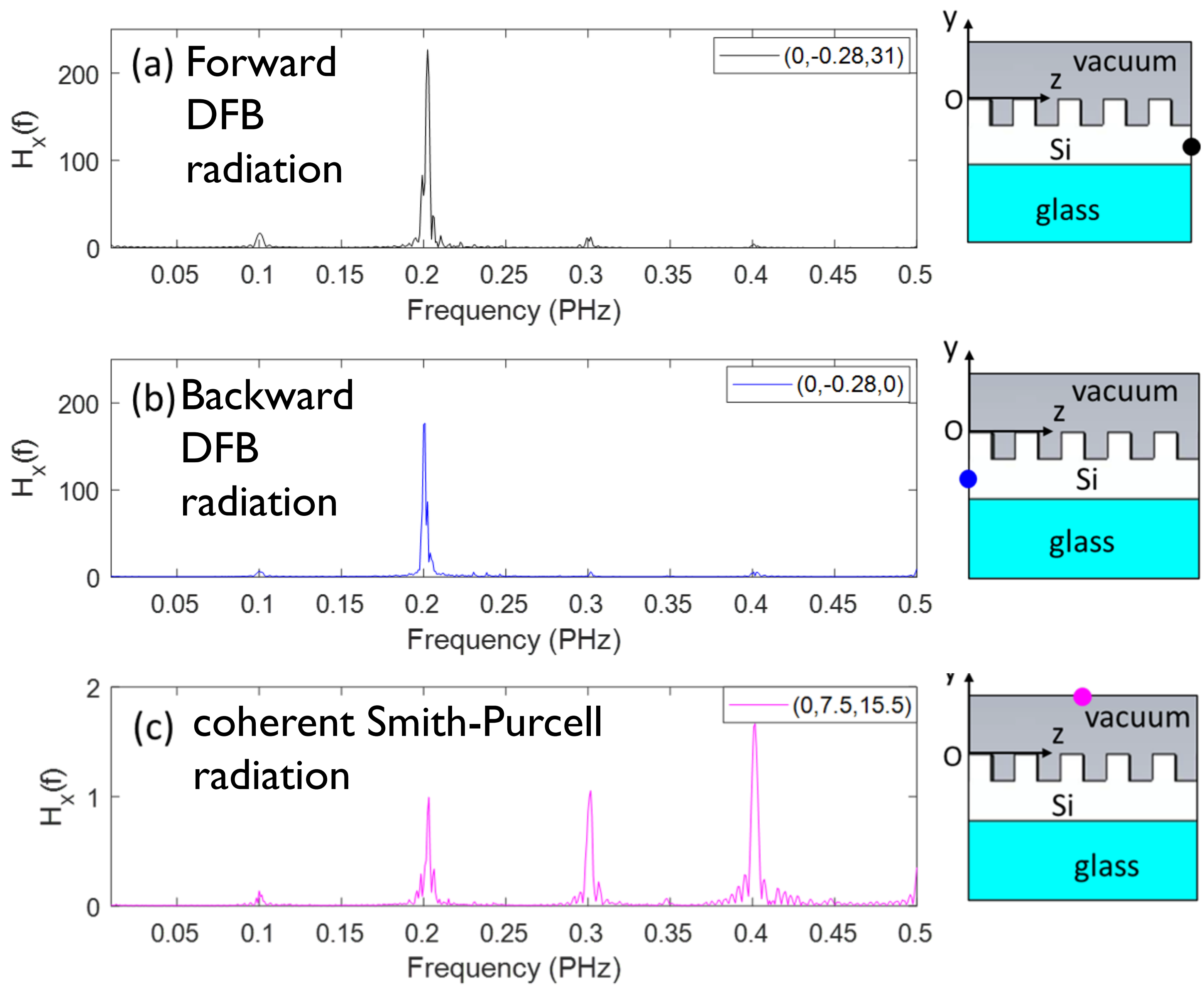
0.2-PHz
radiation field

H_x Field Patterns





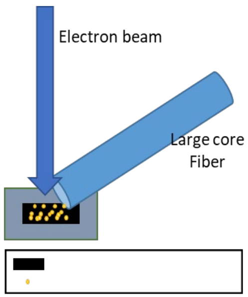
Harmonic Radiation Spectrum



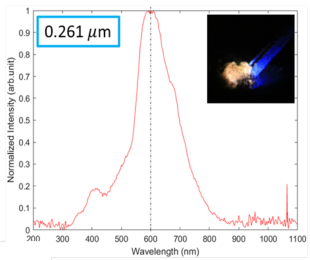
Experiments Using a TEM Beam

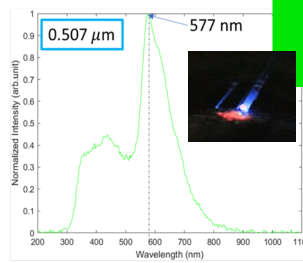
Radiation from Silica Nanosphere

Xuan-Long Ho



SiO2 spheres on graphite

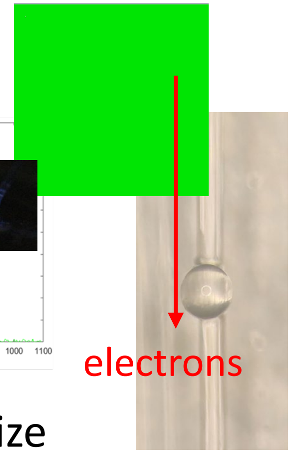


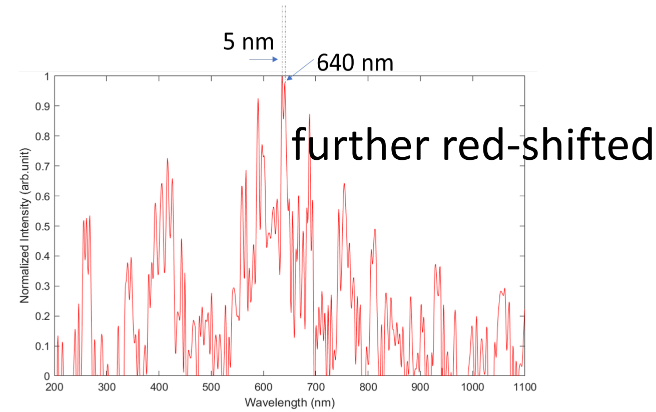


Red shifted with increased size

Radiation from Silica Microsphere

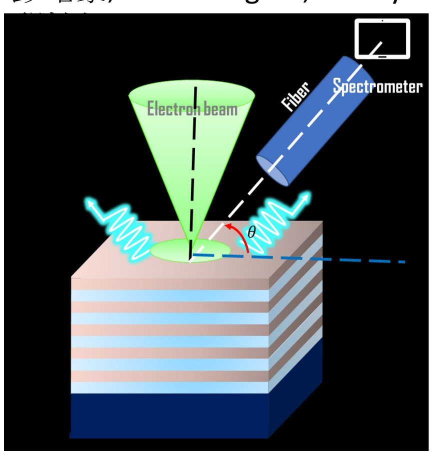
Xuan-Long Ho

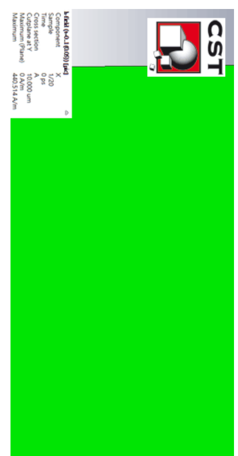


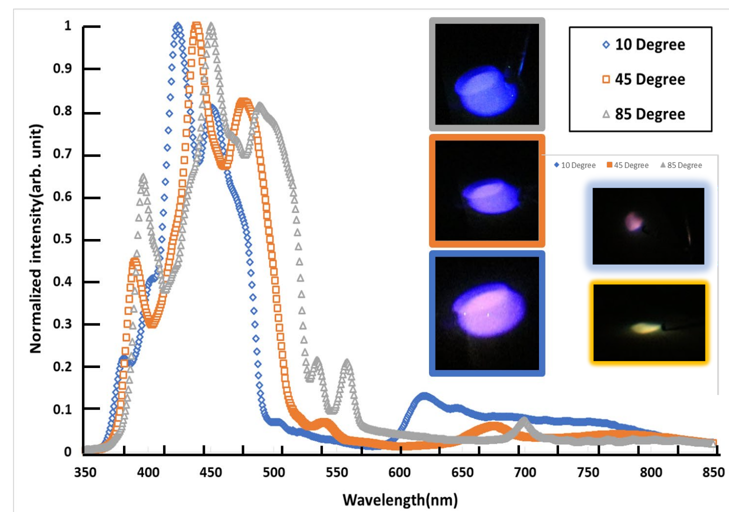


Radiation from optical superlattice

彭珞豪, Xuan-Long Ho, Alexey Kopeykin, Evgenii Kalinovets,

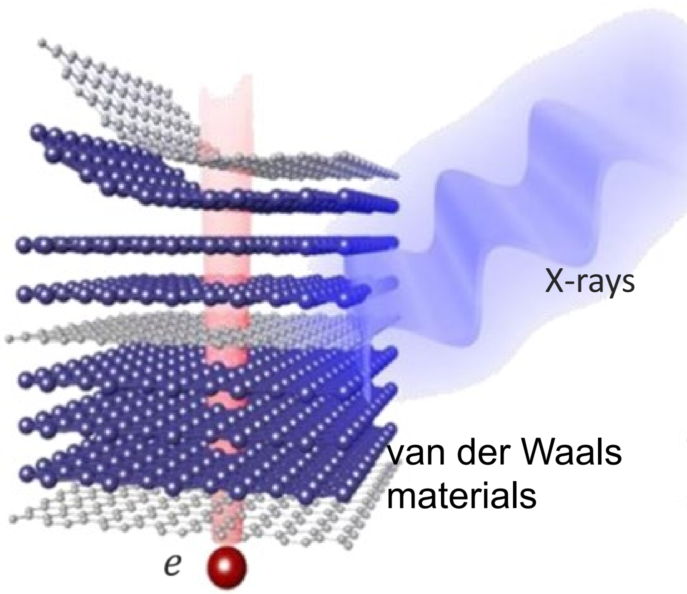




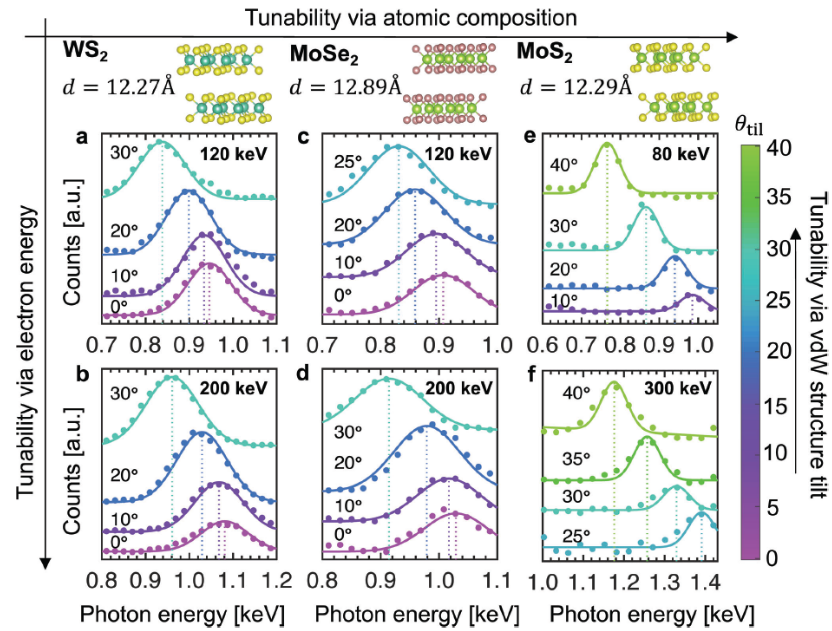


88 quarter-wave dielectric layers with a stopband between 550-675 nm

Atomic-scale Smith-Purcell x-ray Radiator driven by ~100keV beam

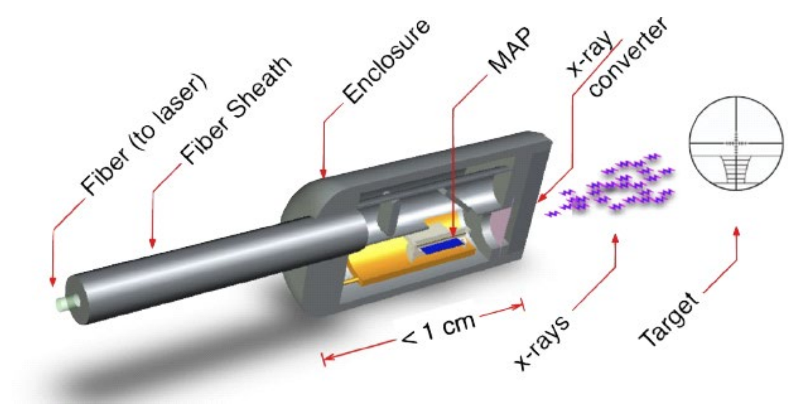


Shentcis, Michael, *et al., Nature Photonics* 14.11 (2020): 686-692.



Huang et. al., *Adv. Sci.,* 2105401 (2022)

Artist's rendering of a hand-held XFEL driven by DLA!!



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

What if fC, GeV electrons are produced from DLA?

FREE ELECTRON LASERS 1996
G. Dattoli, A. Renieri (eds.)
1997 Elsevier Science B.V.

Ultra-compact, High-gain, High-power Free-electron Lasers Pumped by Future Laser-driven Accelerators

Y.C. Huang[1], R.L. Byer

Edward L. Ginzton Laboratory, Stanford University, CA 94305-4085, USA

Abstract

The electron bunch length and emittance from a ~ GeV/m laser-driven accelerator are significantly smaller than those from a conventional RF accelerator. We show that in the future a λ = 1.5 Å single-pass free-electron laser with peak and average power comparable to the Linac Coherent Light Source could be constructed within a 25 meter distance, including a 20-meter, 15-GeV accelerator and a ~ 5-meter wiggler.

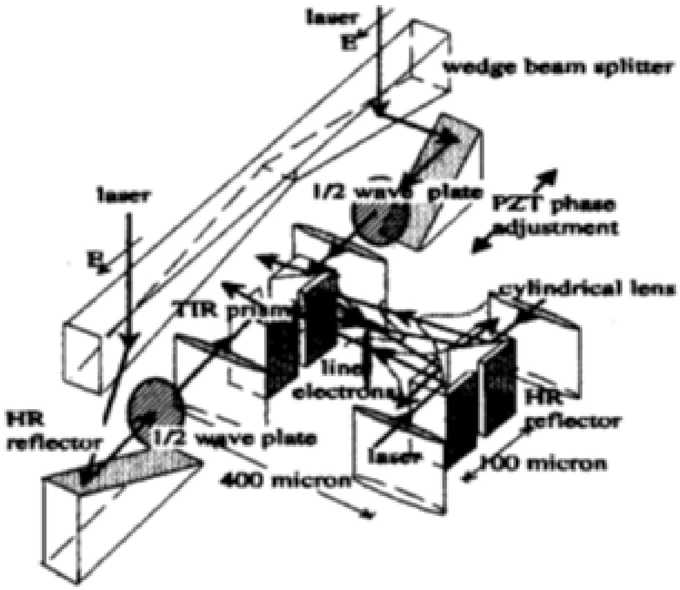


Fig. 1. The Stanford laser-driven accelerator

Table 1. Parameters used for the LCLS and the LA-FEL.

parameters	LCLS	LA-FEL
wavelength (Å)	1.5	1.5
normalized emittance (m)	10^{-6}	10^{-9}
peak current (A)	5000	5000
energy spread (%)	0.02	0.02
rms pulse length l_b	50 μm	0.5 Å
macro repetition rate	120 Hz	50 kHz
wiggler period λ_w	3	3
wiggler parameter a_w	2.6	2.6
beta function β (m)	10	10
gain length	3.1 m	0.2 m
saturation length (m)	58	1 ~ 5 m
peak photon power	40 GW	300 GW
average photon power	0.6 W	0.8 W

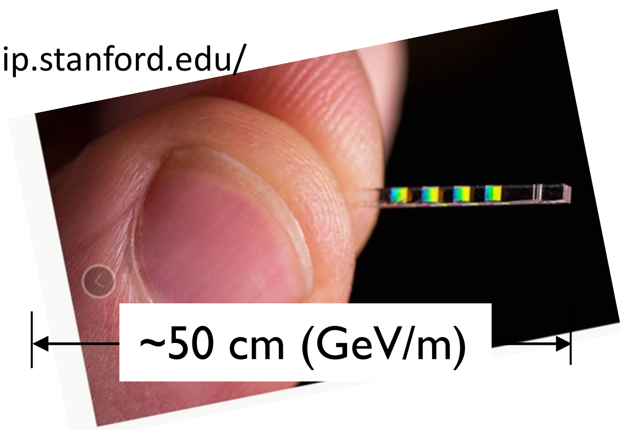
@ Ginzton Lab, Stanford

We had a **big** dream…

Envisaged DLA-driven Coherent Undulator Radiation (CUR)

Dielectric laser accelerator (DLA)

https://achip.stanford.edu/



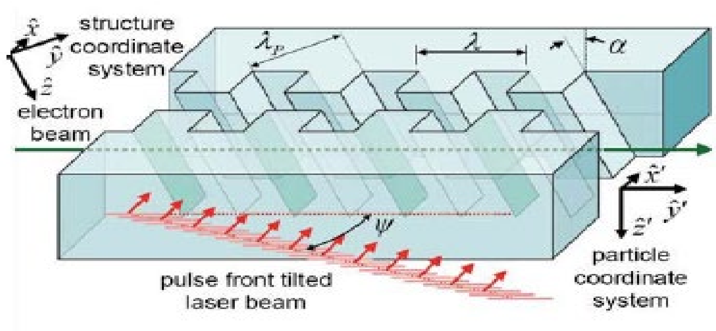
Driving wavelength λ ~ 1 μm

electron bunch length ~ 1 nm

Bunch Charge = 1~ 10 fC

Energy = ~500 MeV

Dielectric laser undulator (DLU)



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

100 cm

λ_u = 1 mm (N_u = 1000, 0.1% bandwidth)

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

a_u = ~0.22 (undulator parameter)

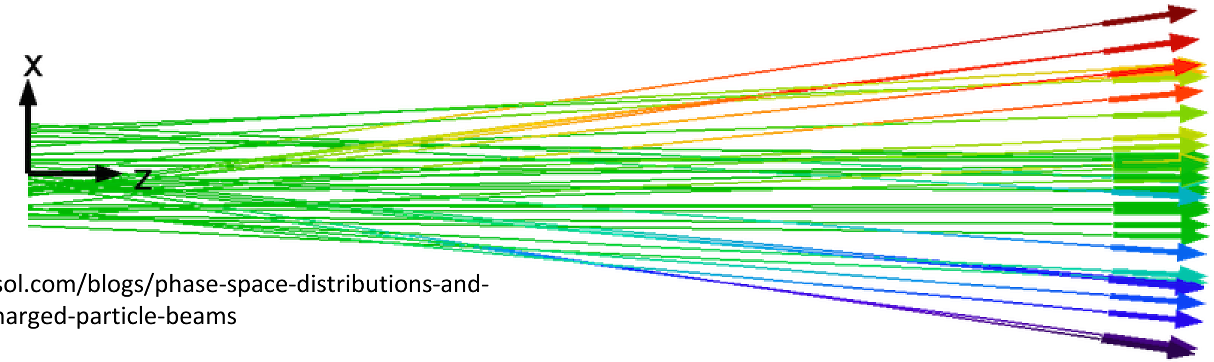
Parameters for calculating peak and average brilliances of coherent undulator radiation (CUR) driven by DLA (0.5~5 kW beam power)

System parameters			Remark
item	unit	quantity	
Driving laser wavelength, λ	µm	1	100,000th of the 10-cm S-band RF wavelength
FWHM bunch length, τ_b	Attosecond /nm	2.35/0.7	scaled for the 1-µm optical wavelength based on demonstrated 100~200-fs RF bunch
Bunch Charge*	**fC**	**1, 10**	**6,250 and 62,500 electrons/bunch**
Bunch rate, f_b	GHz	1	100 optical cycles in a ~300-fs pulse repeating at 10 MHz
Beam energy	GeV	< 0.5	Used as a variable to tune the radiation wavelength
Undulator period	mm	1	Eg. a fixed value to radiate at λ > 0.5 nm for beam energy < 0.5 GeV
Undulator parameter, a_u	NA	0.22	3.3-T peak undulator field under laser damage to dielectric undulator
Number of undulator periods, N_u	NA	1000	radiation bandwidth ~0.1%

***R. H. Siemann, "Energy efficiency of laser driven, structure based accelerators," *Phy. Rev. ST-AB* 7, 061303 (2004).**

Brilliance of DLA-driven Undulator Radiation (diffraction-limited)

photons/s/mm^2/mrad^2/0.1%BW



https://www.comsol.com/blogs/phase-space-distributions-and-emittance-in-2d-charged-particle-beams

Average Brilliance

Short-bunch superradiance

$$B_a(\omega) = f_b \tau_s B_p(\omega) = 4.6\times 10^{-5} \times [N_{DLA}(N_{DLA}-1)e^{-(\omega\tau_b)^2} + N_{DLA}]\frac{N_u f_b[s^{-1}]}{\lambda^2[\mu m^2]}[JJ]$$

Bunch frequency

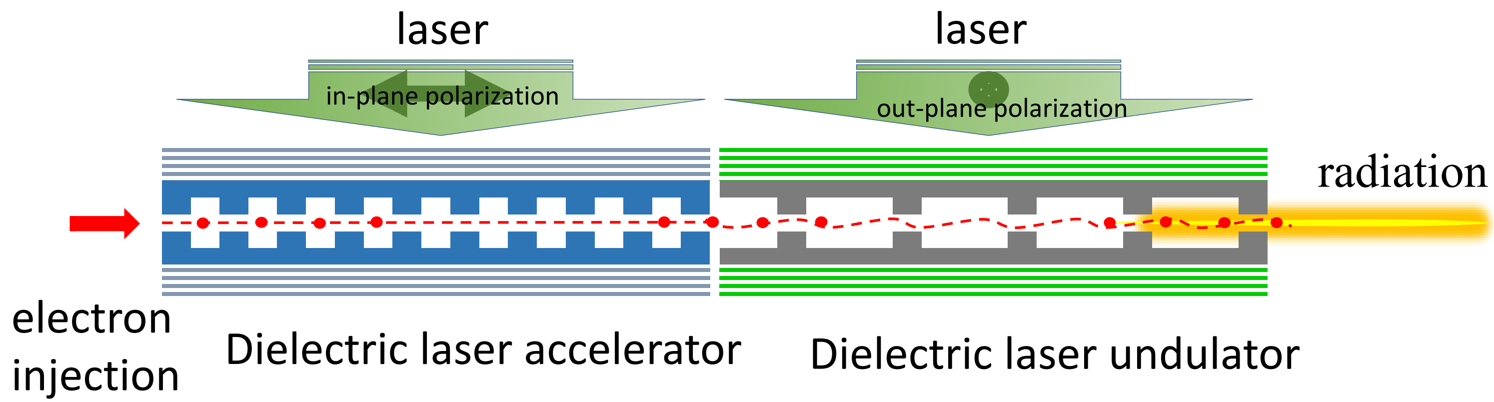
Radiation pulse length = slippage length $\tau_s = 2\pi N_u / \omega$

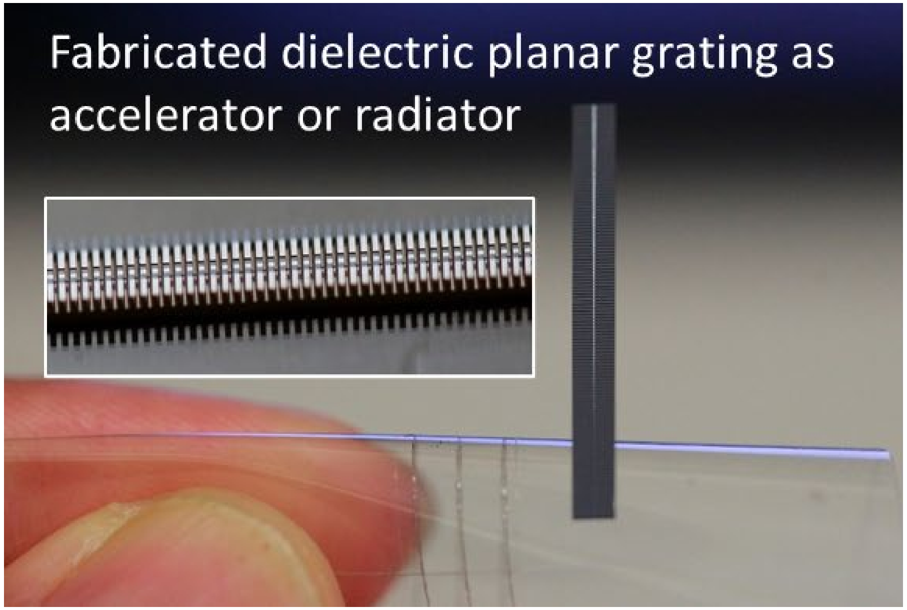
Competing terms

Diffraction-limited beam

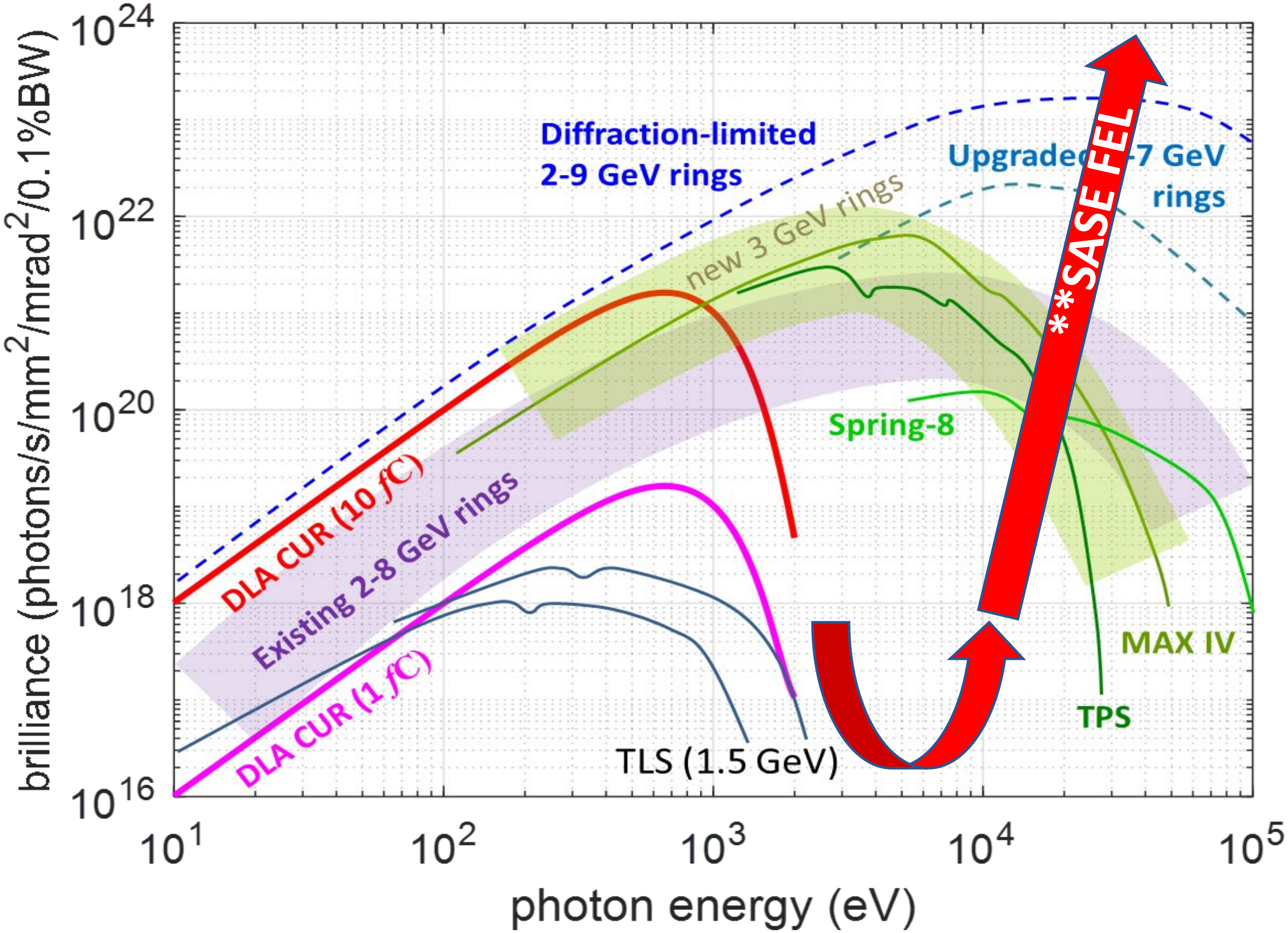
https://doi.org/10.48550/arXiv.2208.04099

A bold comparison between DLA CUR and a synchrotron





DLA-CUR's average brilliance comparable to 3rd-generation light sources in the EUV/soft-x-ray spectrum (due to high bunch rate + superradiance)



*Curves other than DLA CUR are adapted from Zirong Huang, SLAC-PUB-15449.

T. Plettner and R. L. Byer, Proposed dielectric-based microstructure laser-driven undulator. *Phys. Rev. ST Accel. Beams* **11, 030704 (2008).

R. Joel England et al., Dielectric laser accelerators. *Rev. Mod. Phys.* 86, 1337 (2014).

~GW circulating power

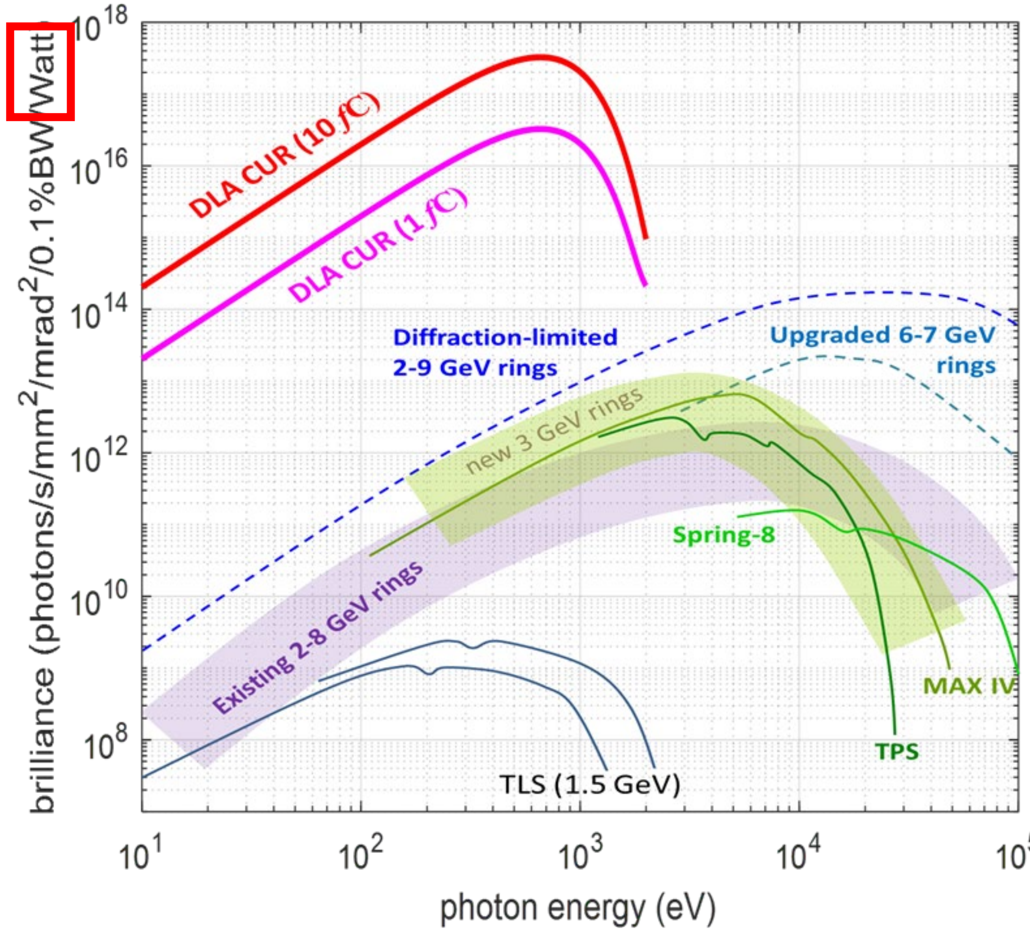
(Taiwan photon source)

0.5 kW ~ 5 kW beam power

(adapted from https://achip.stanford.edu/)

DLA average beam power is comparable to that of a kitchen oven!

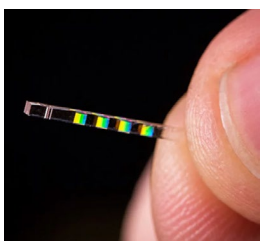
DLA CUR stands high when normalized to beam power



Yen-Chieh Huang and Robert L. Byer, "Ultra-bright Coherent Undulator Radiation Driven by Dielectric Laser Accelerator," arXiv:2208.04099

CONCLUSIONS

~GW circulating power (Taiwan photon source)



0.5 kW ~ 5 W power

(adapted from https://achip.stanford.edu/)

1. Sub-MeV energy gain is just demonstrated from a chip-size dielectric laser accelerator.

2. keV periodic single-electrons from DLA permit chip-size FEL across the visible and x-ray spectrum.

3. GeV nano-bunches with fC electrons from future DLA permit high-brightness superradiance in the VUV/EUV/soft x-ray spectrum.

3. Future DLA-driven CUR could have average brilliance comparable to a synchrotron.

4. In units of brilliance/beam-power, future DLA-driven coherent undulator radiation (CUR) is 6 orders of magnitude brighter than a synchrotron.

THANK YOU FOR YOUR ATTENTION