67th ICFA Advanced Beam Dynamics Workshop on Future Light Sources (FLS 2023), Lucerne, Switzerland, from 27 August to 1 September 2023

Harmonic Generation from keV-electron-excited Nano-grating

Yen-Chieh Huang, Luo-Hao Peng, Hossein Shirvani, Wen-Chi Chen, Karthickraj Muthuramalingam, Wei-Chih Wang, and Andrzej Szczepkowicz

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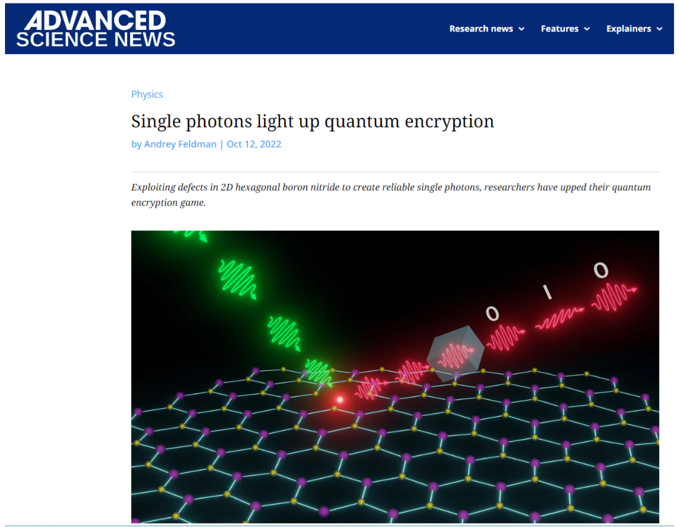
Future light source?

[An imaginary file picture released by Hanwha Corporation]

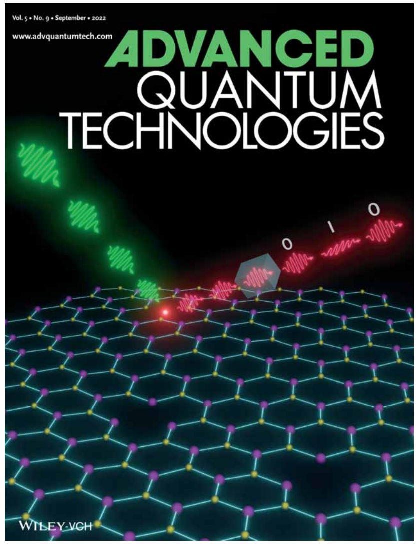


Physics

Single photons light up quantum encryption

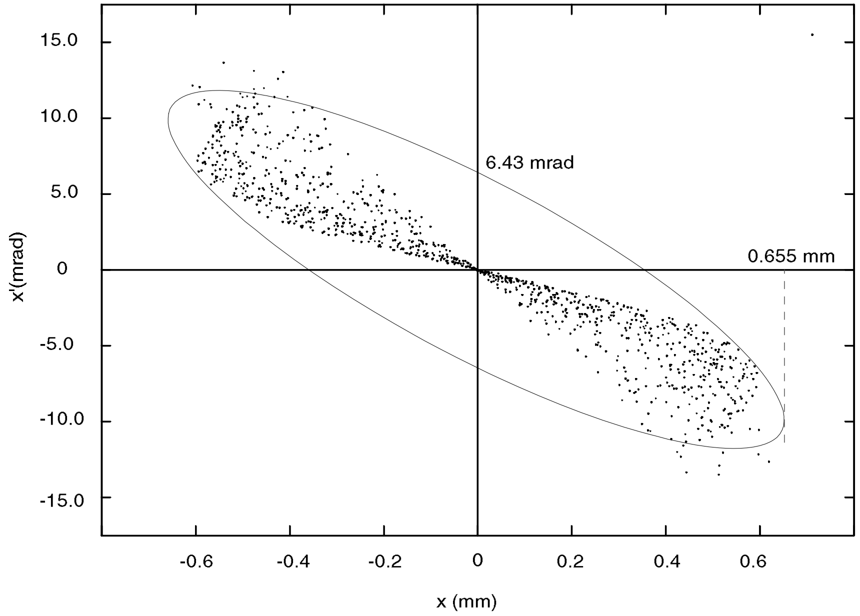
by Andrey Feldman | Oct 12, 2022

Exploiting defects in 2D hexagonal boron nitride to create reliable single photons, researchers have upped their quantum encryption game.

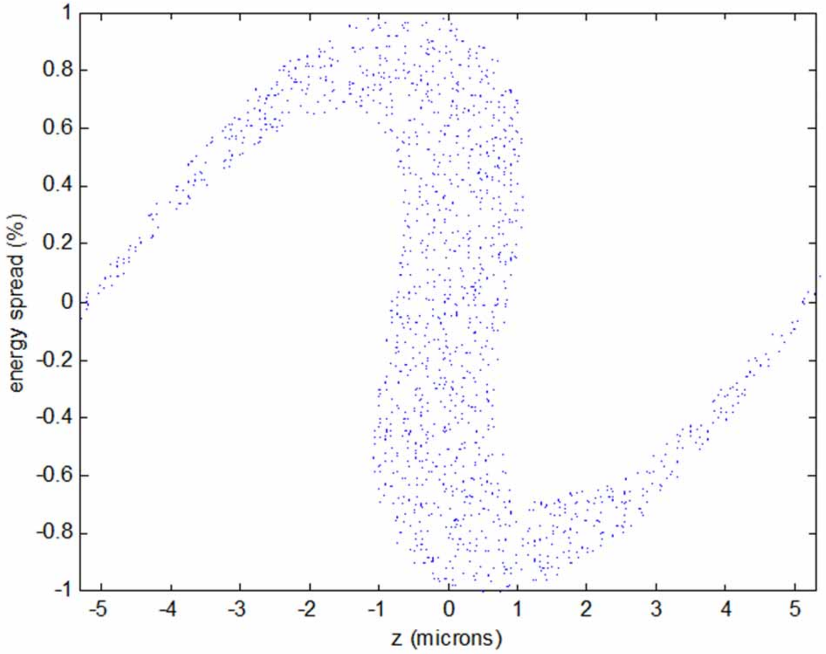


Both the strong and the weak shape up the future….

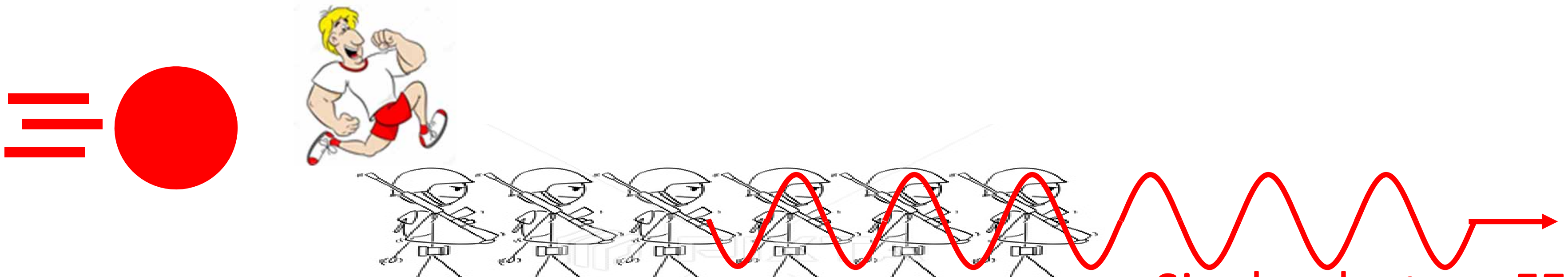
How long have we struggled with emittance, energy spread, space-charge force, and bunching?



Extracted from my PhD thesis (1995)



Let’s pick up just one electron…



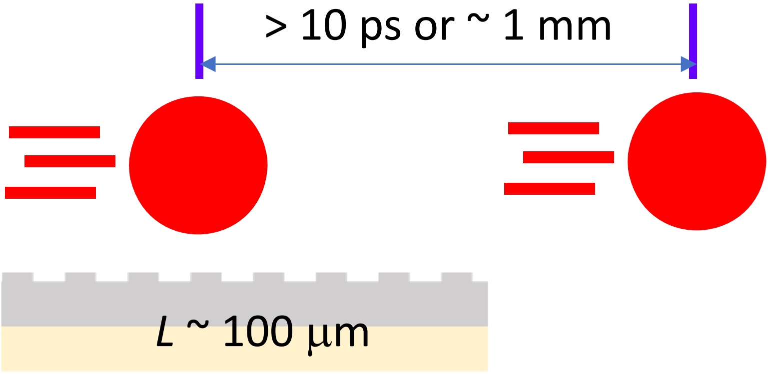
Single-electron FEL?

well-behaved electrons in photonic crystals, meta-materials, plamonic surfaces etc.

https://depositphotos.com/vector/cartoon-running-man-120101504.html https://www.pixtastock.com/illustration/43590645

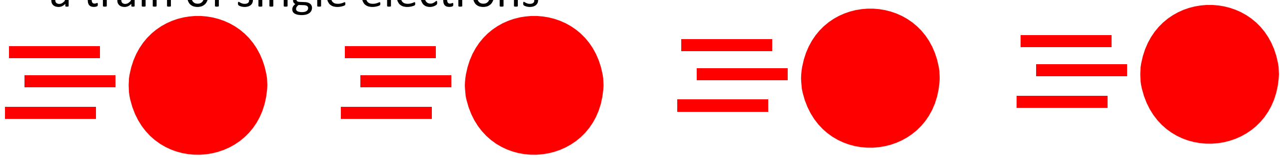
Single-electron sources

(1) CW-current TEM: Nano-Ampere

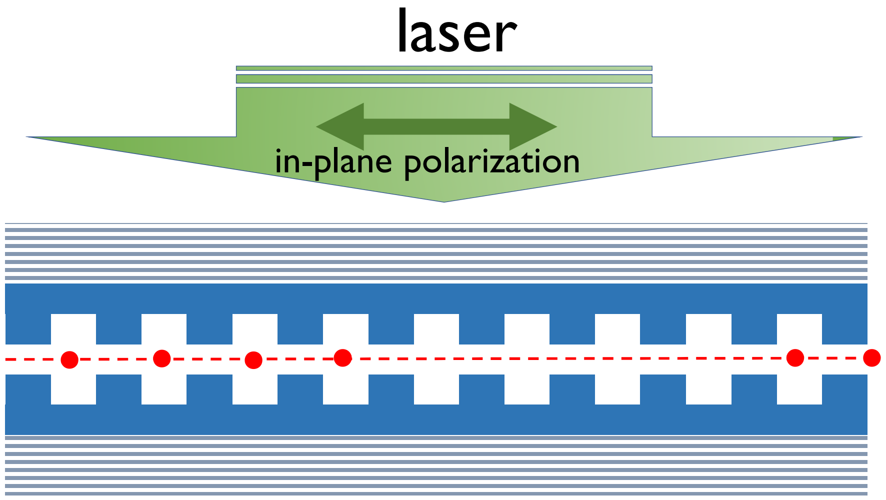


(2) fs-laser-excited TEM: ~1 electron per pulse @ ~100 MHz

a train of single electrons

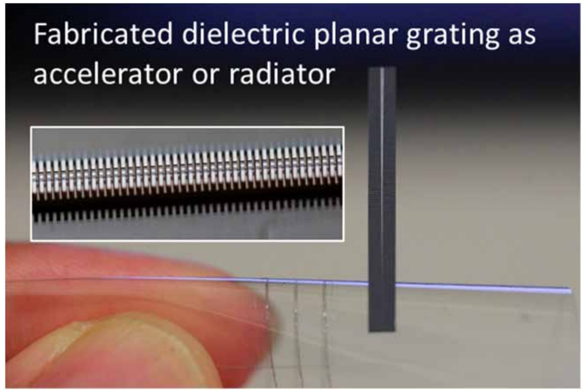


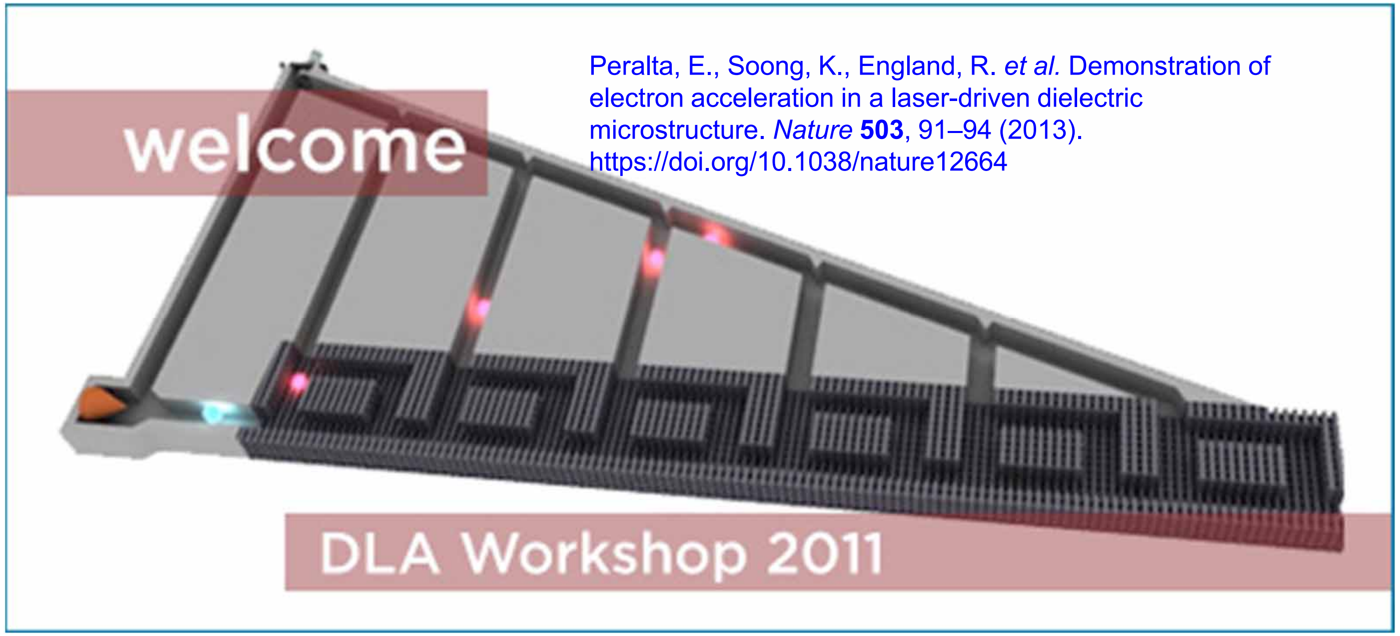
Dielectric Laser Accelerator



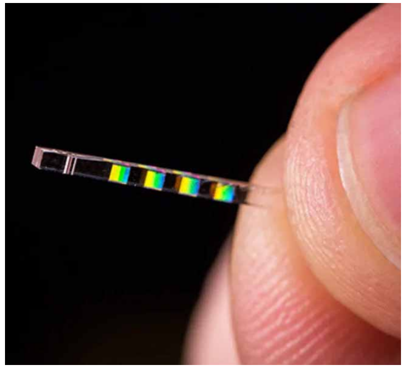
dielectric laser accelerator

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


Fabricated dielectric planar grating as accelerator or radiator

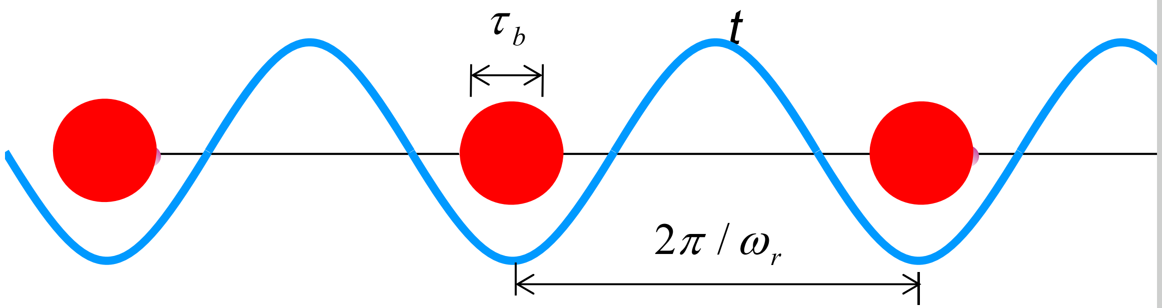


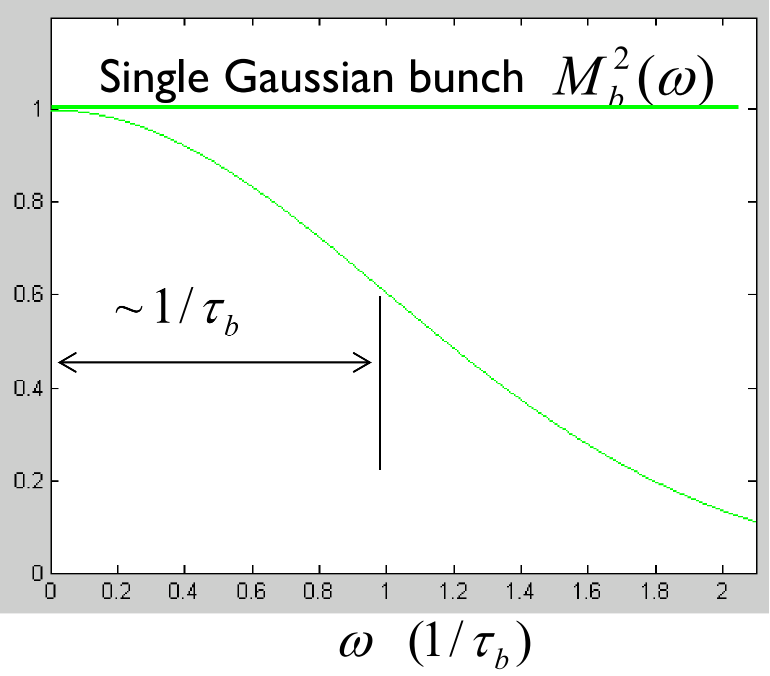
Peralta, E., Soong, K., England, R. *et al.* Demonstration of electron acceleration in a laser-driven dielectric microstructure. *Nature* **503**, 91–94 (2013). https://doi.org/10.1038/nature12664



https://achip.stanford.edu/

Harmonic Content of Periodic Electron Bunches



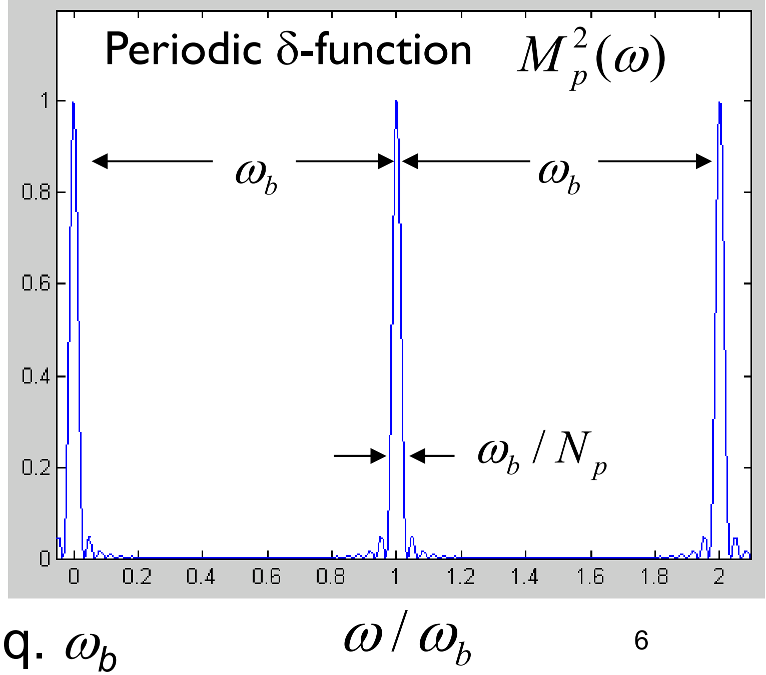


Spectral Energy

$$\left(\frac{dW}{d\omega}\right)_{SR} = \left(\frac{dW}{d\omega}\right)_1 \boxed{\cancelto{1}{N_b^2}} M_b^2(\omega) \boxed{\times N_p^2 M_p^2(\omega)}$$

$M_b(\omega)$:Fourier transform of the bunch shape

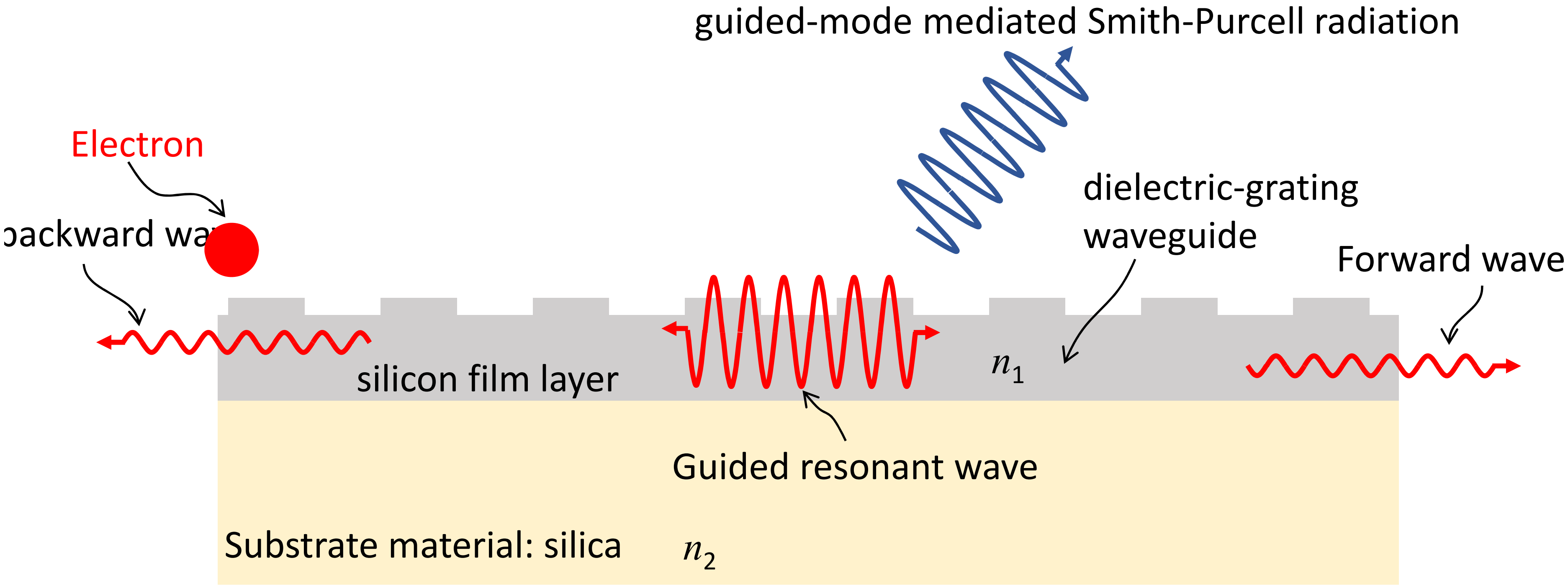
N_b: number of electrons in a bunch



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

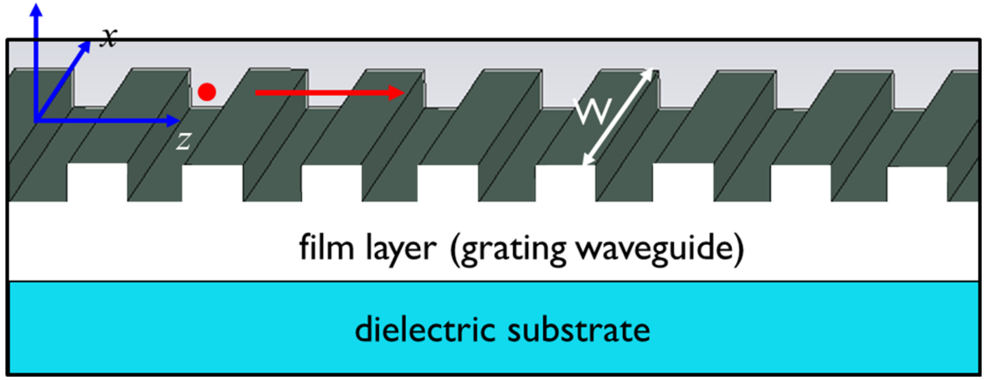
Coherent sum of N_p bunches with bunching freq. ω_b

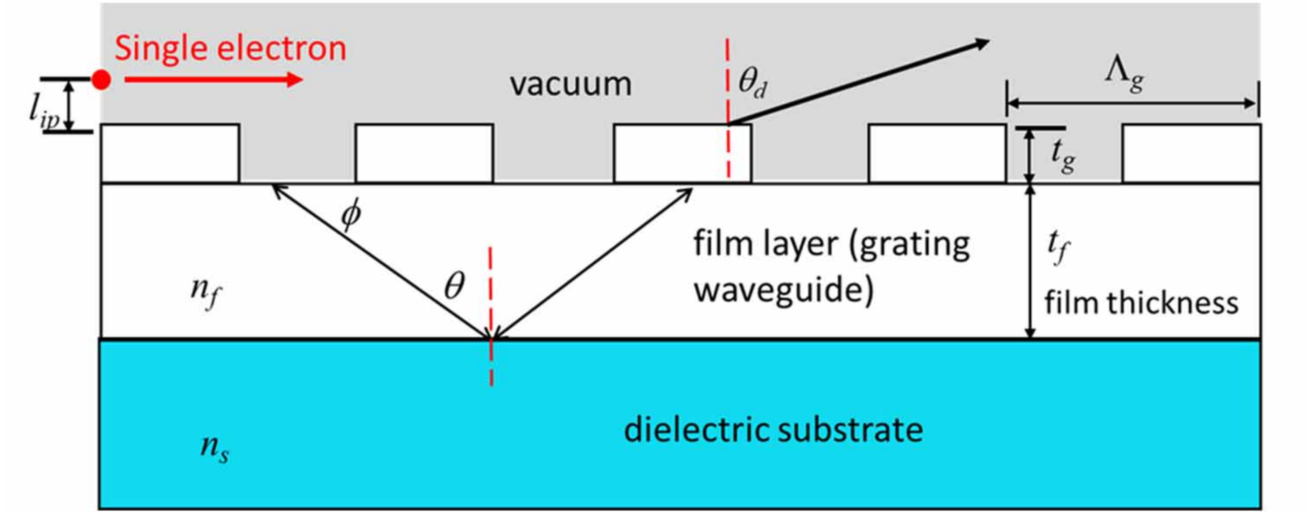
Dielectric-grating-waveguide FEL Chip – 1-D photonic crystal



Design Guidelines

Yen-Chieh Huang, Luo-Hao Peng, Hossein Shirvani, Wen-Chi Chen, Karthickraj Muthuramalingam, Wei-Chih Wang, and Andrzej Szczepkowicz, “Single-electron Nano-chip Free-electron Laser,” APL Photonics **7**, 096101 (2022). (editor featured article and cover story of the journal).





Cherenkov angle $\cos\phi = \dfrac{1}{n_f \beta_e}$,

Guiding condition $\sin\theta > \sin\theta_c = \dfrac{n_s}{n_f}$.

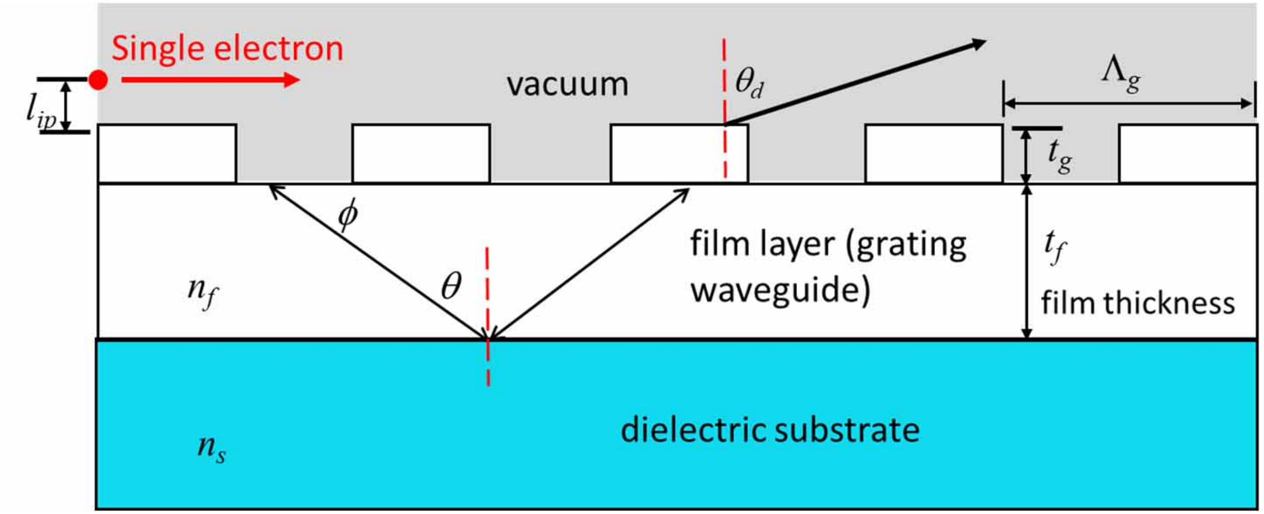
$$\left.\begin{array}{l} \cos\phi = \dfrac{1}{n_f \beta_e}, \\ \sin\theta > \sin\theta_c = \dfrac{n_s}{n_f}. \end{array}\right\} \quad \frac{1}{n_f} < \beta_e < \frac{1}{n_s}.$$

Impact parameter $h = \dfrac{1}{\alpha} = \dfrac{\beta_e \gamma \lambda_0}{2\pi}$

Maximum impedance contrast $$t_g = \frac{\lambda_y}{4} = \frac{\lambda_0}{4 n_f \sin\phi} = \frac{\beta_e \lambda_0}{4\sqrt{\beta_e^2 n_f^2 - 1}},$$

Bragg Resonant Condition $$\Lambda_g = \beta_e \frac{\lambda_0}{2}.$$

Single-mode guiding condition $$t_f < \frac{\lambda_0}{2\sqrt{n_f^2 - n_s^2}}.$$



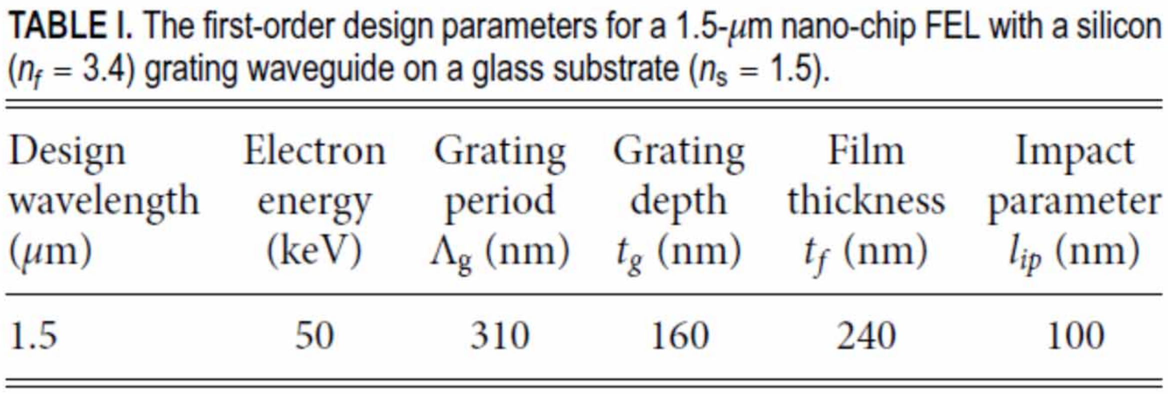
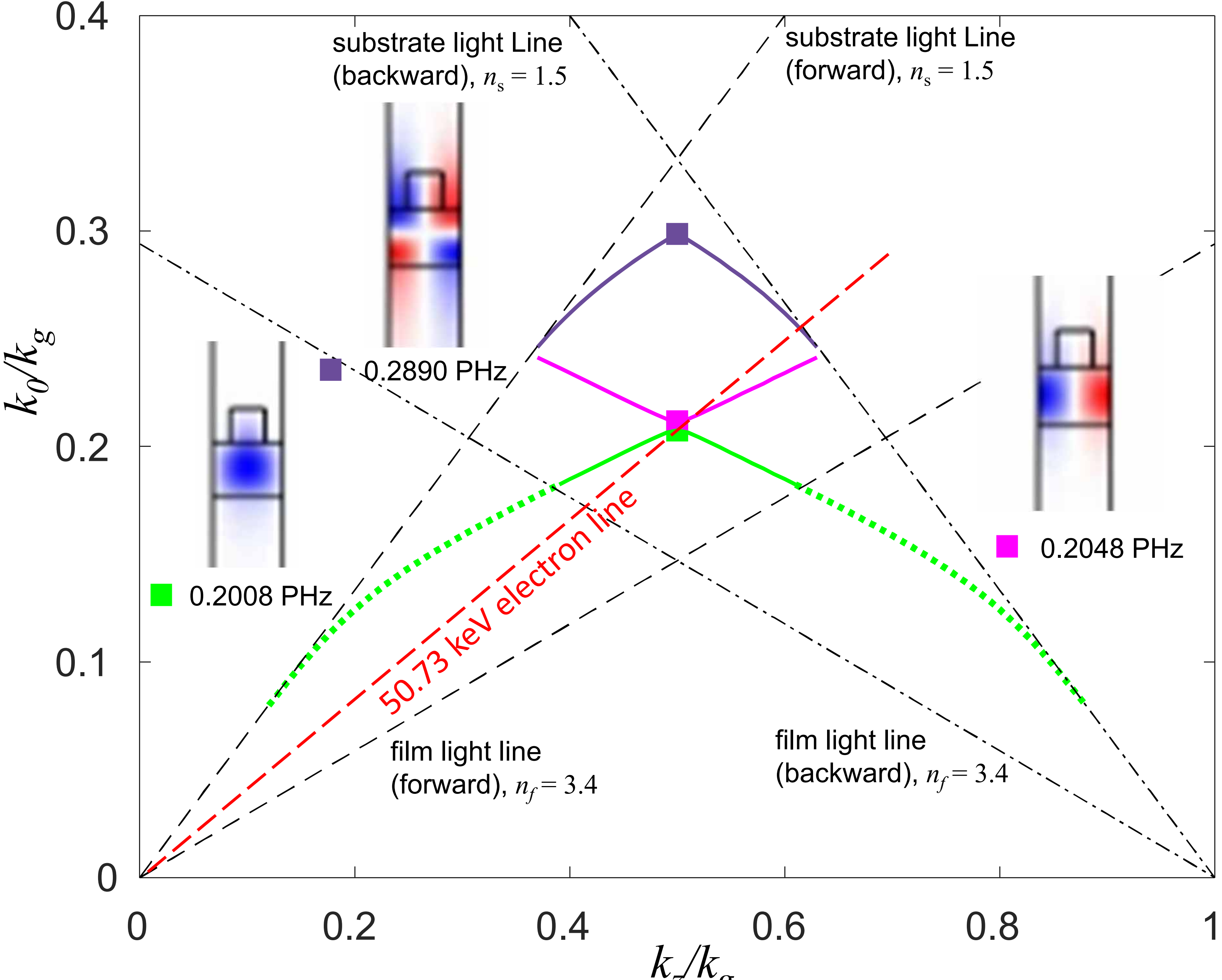


TABLE I. The first-order design parameters for a 1.5-μm nano-chip FEL with a silicon (n_f = 3.4) grating waveguide on a glass substrate (n_s = 1.5).

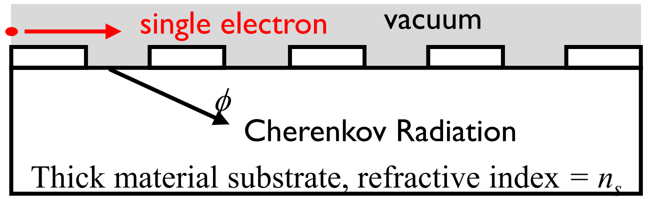
Design wavelength (μm)	Electron energy (keV)	Grating period Λ_g (nm)	Grating depth t_g (nm)	Film thickness t_f (nm)	Impact parameter l_{ip} (nm)
1.5	50	310	160	240	100

for λ_0 = 1.5 μm (0.2 PHz),
50-keV electron
Structure length = 31 μm

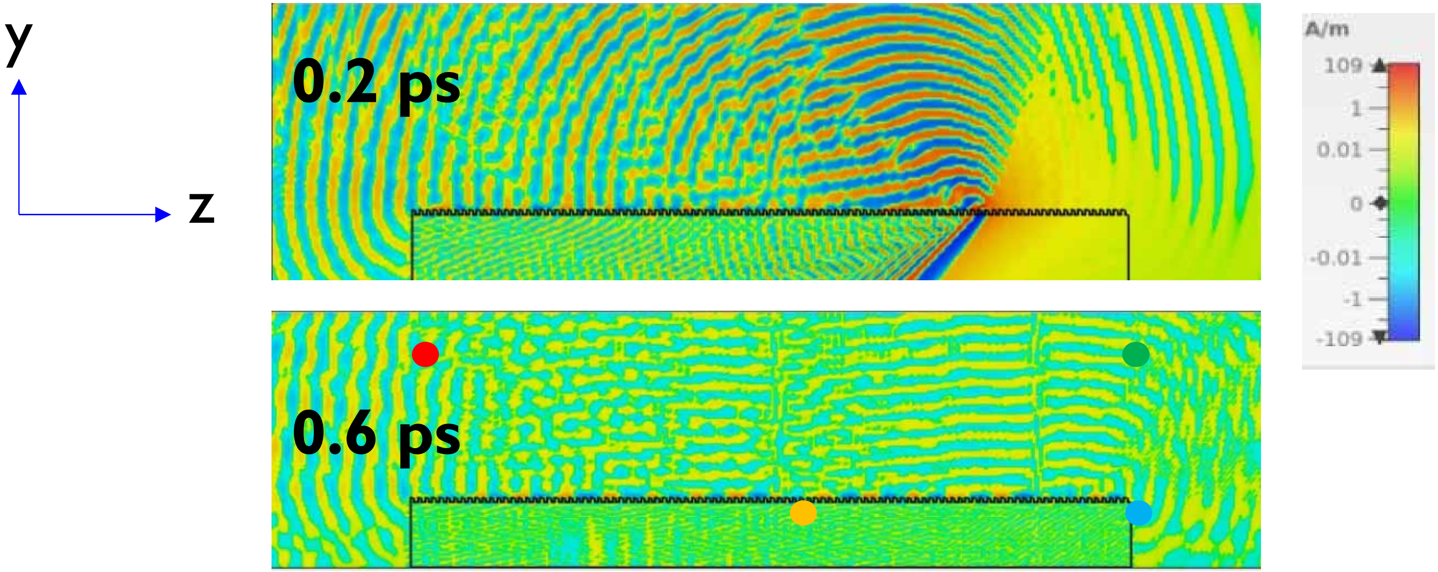
Dispersion Diagram



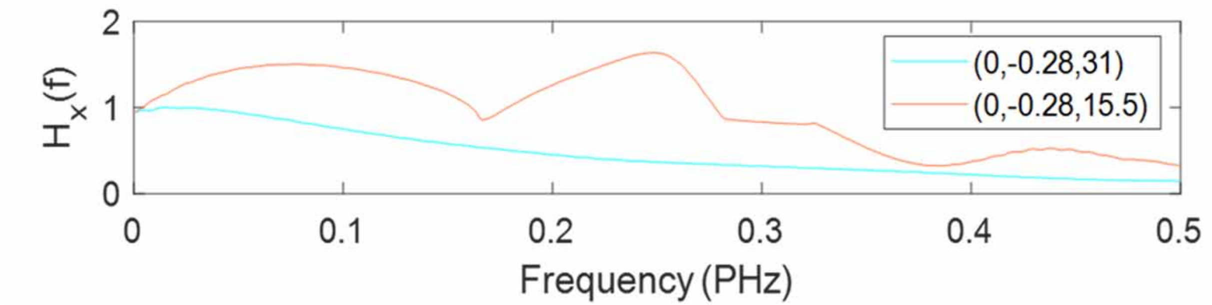
1-electron Radiation w/o Waveguide



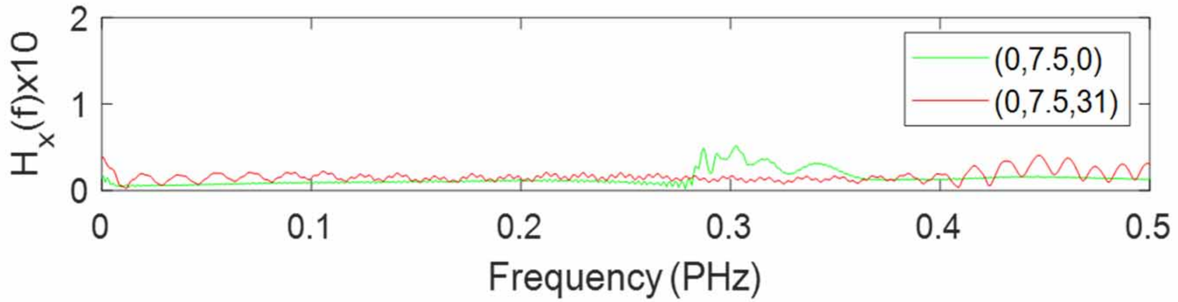
CST simulation



Internal radiation (broadband)

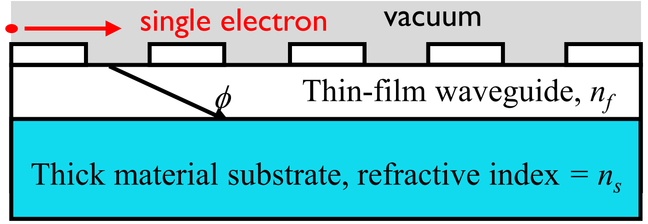


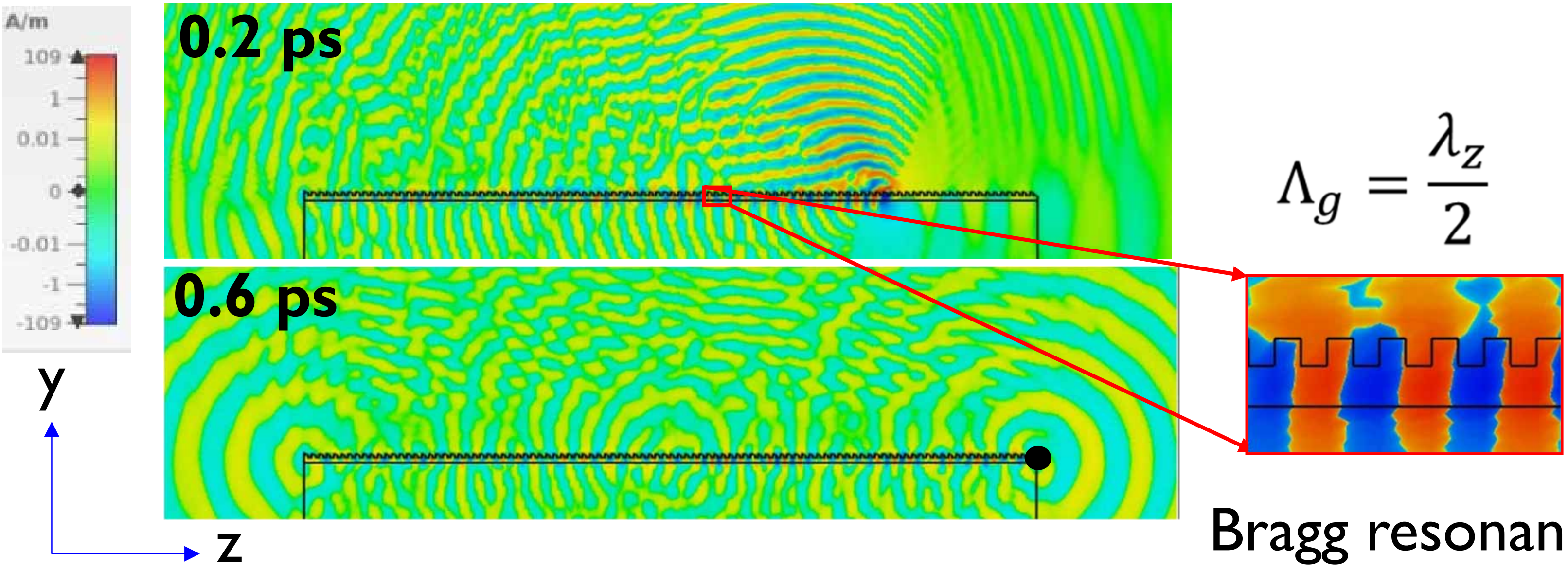
External radiation (weak & broadband)



Grating-waveguide FEL driven by 1 electron

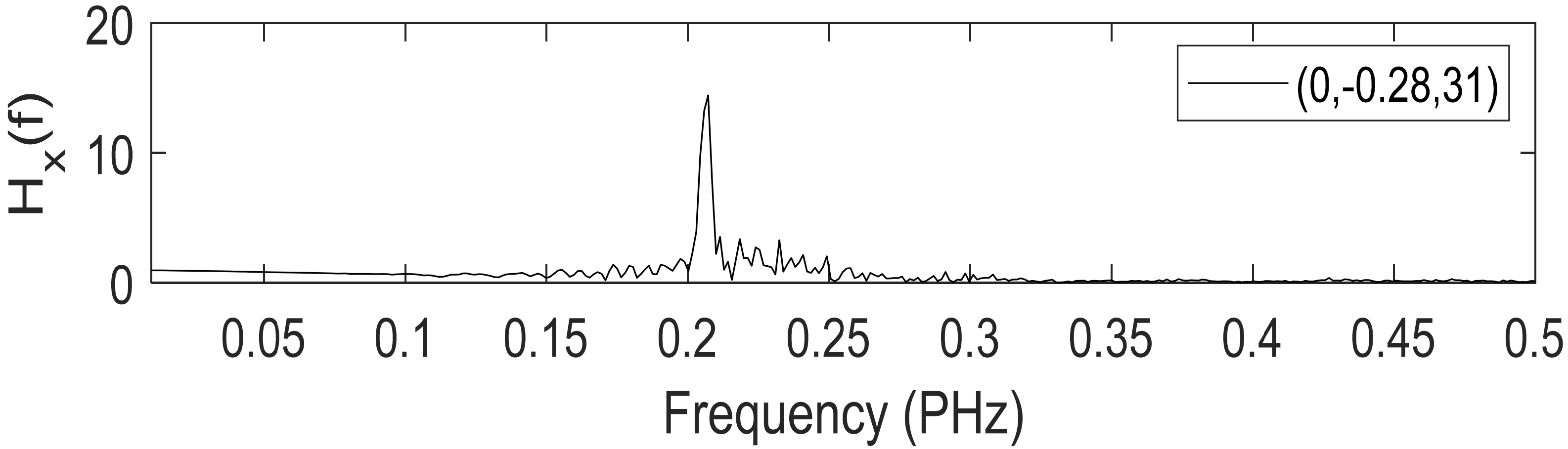
CST simulation



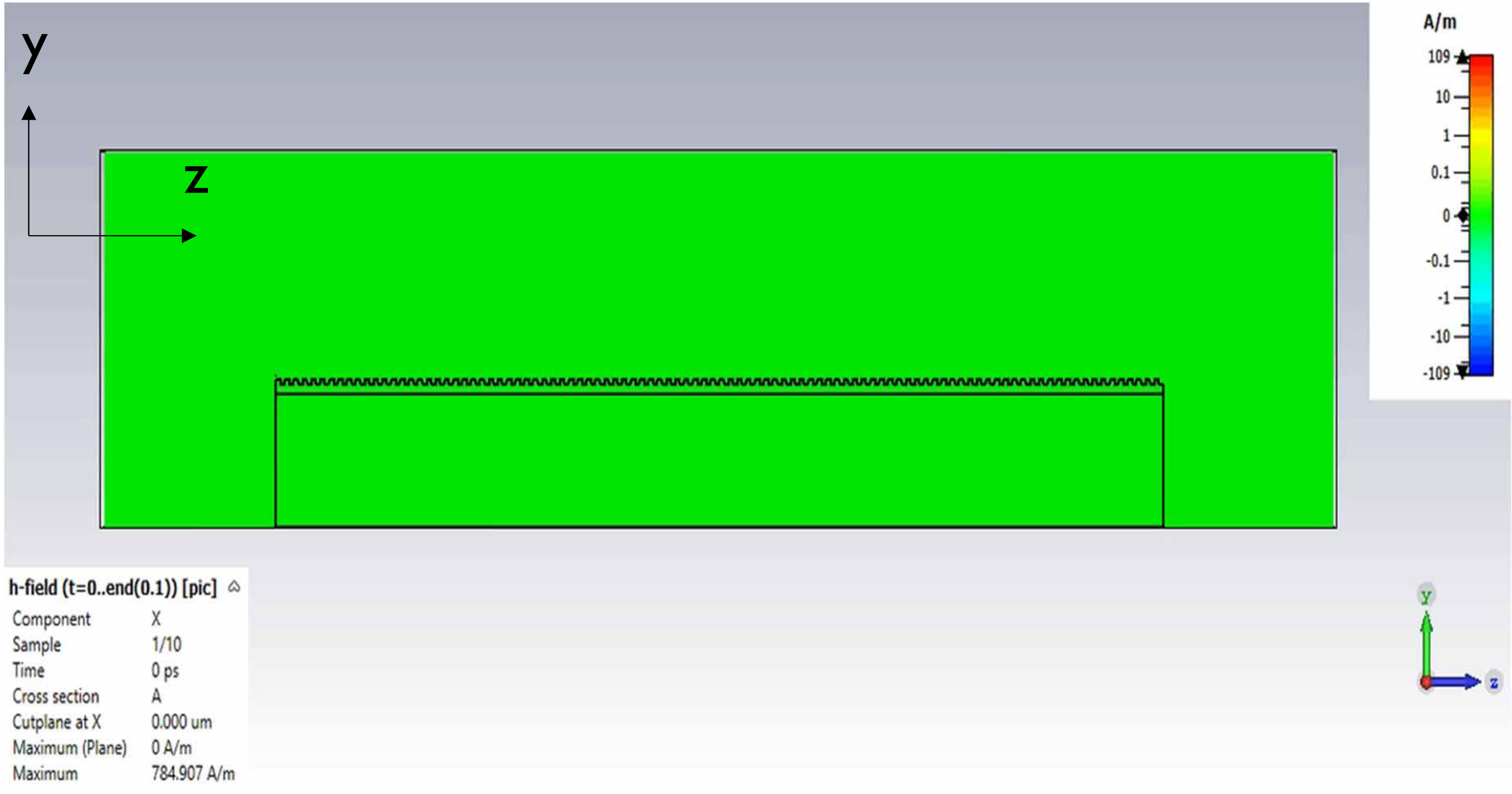


$$\Lambda_g = \frac{\lambda_z}{2}$$

Bragg resonance

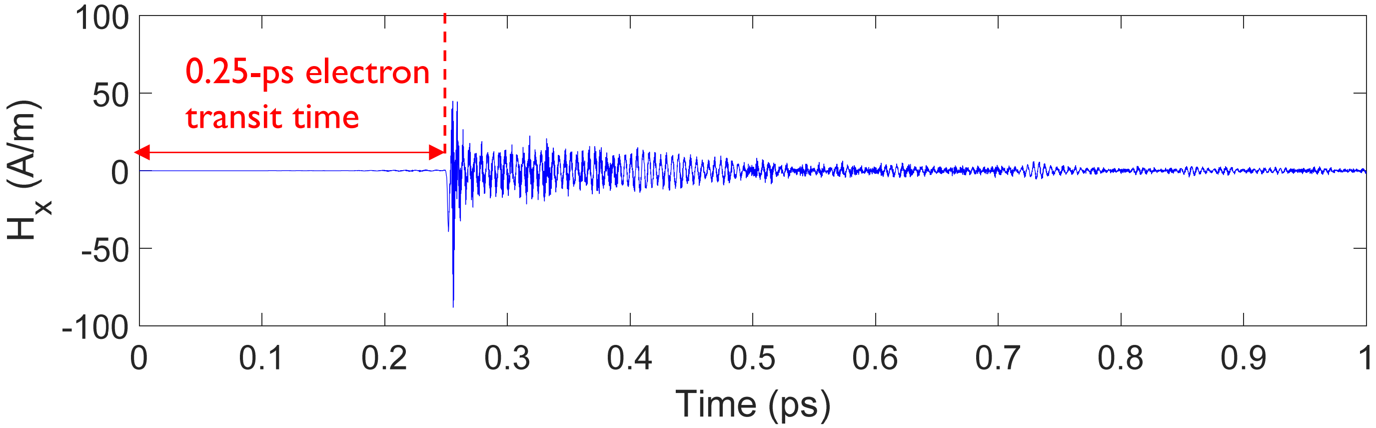


H_x Field Animation



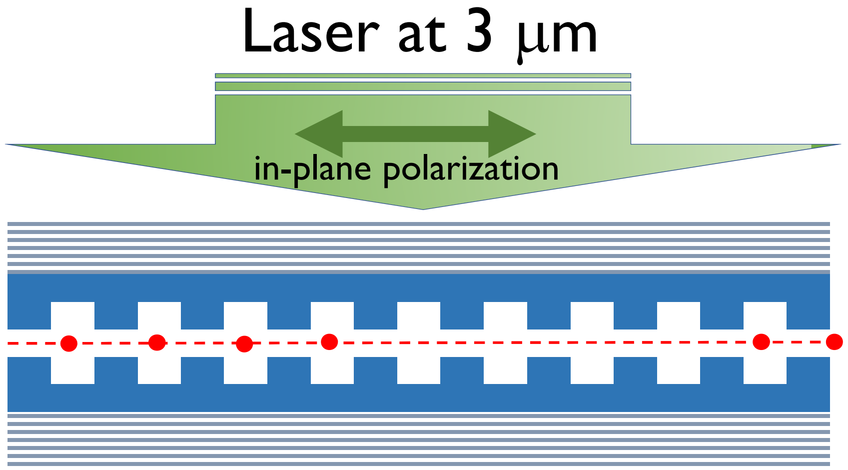
h-field (t=0..end(0.1)) [pic]

Component	X
Sample	1/10
Time	0 ps
Cross section	A
Cutplane at X	0.000 um
Maximum (Plane)	0 A/m
Maximum	784.907 A/m

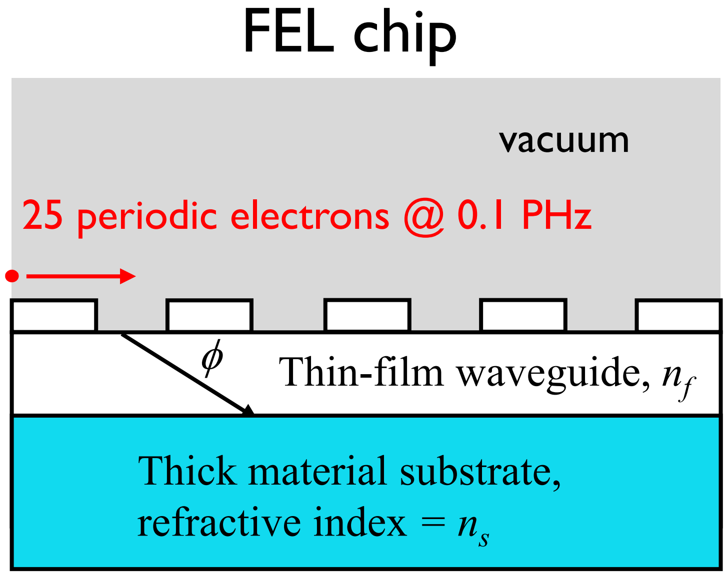


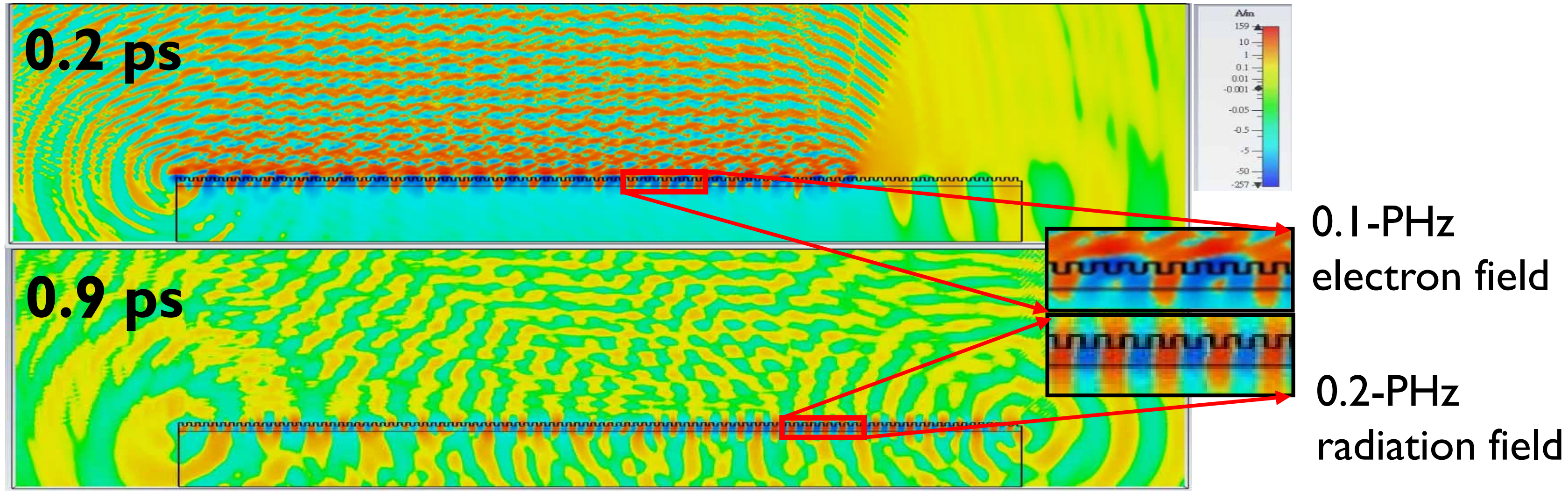
0.25-ps electron transit time

Grating-waveguide FEL driven by Periodic Single Electrons

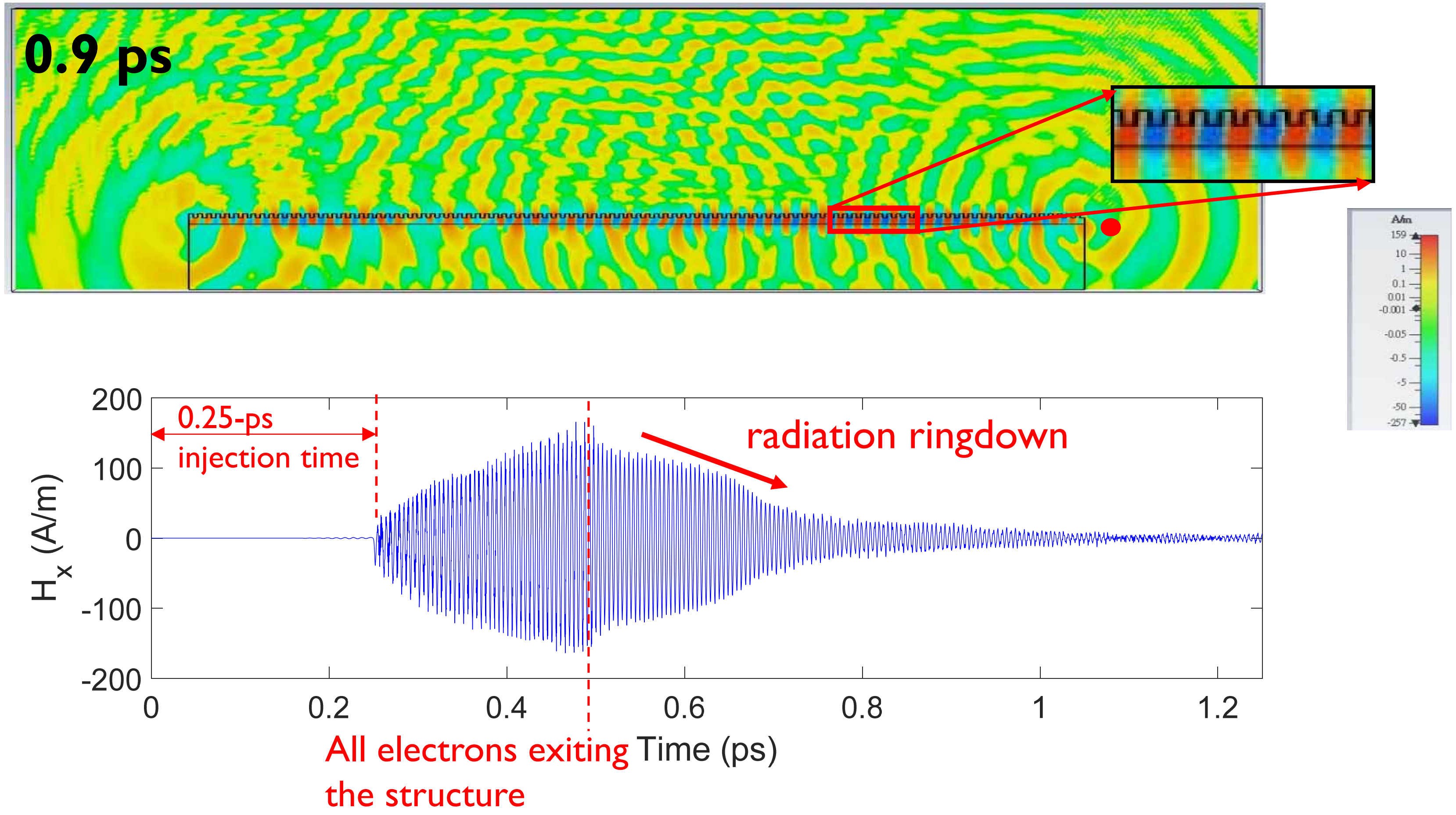


Dielectric laser accelerator
driven by a 3 μm (0.1 PHz) laser

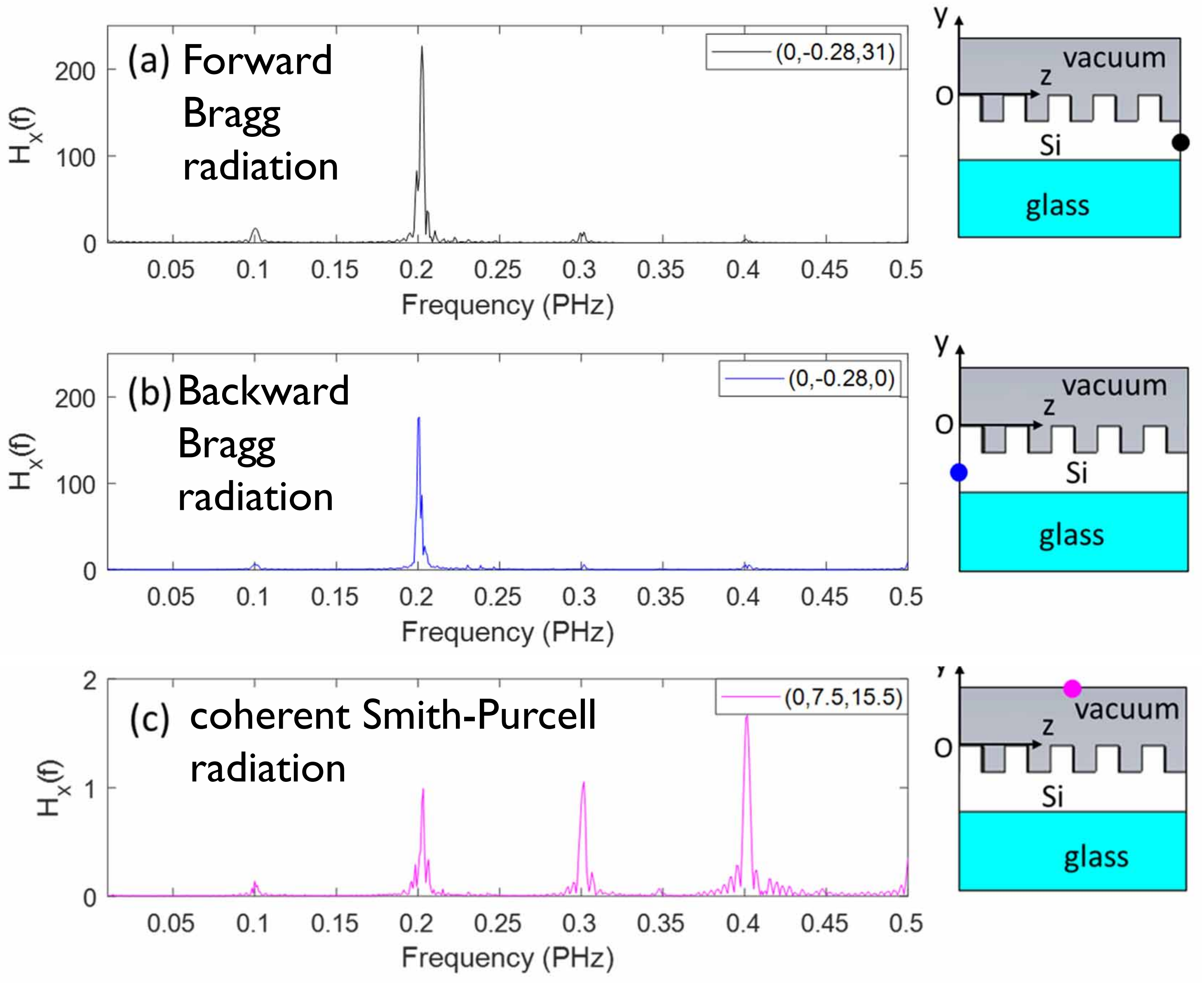




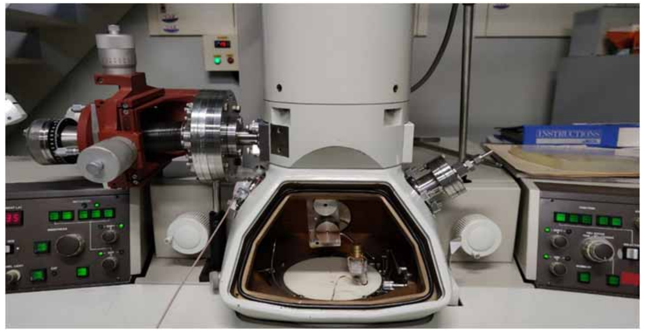
H_x Field Patterns



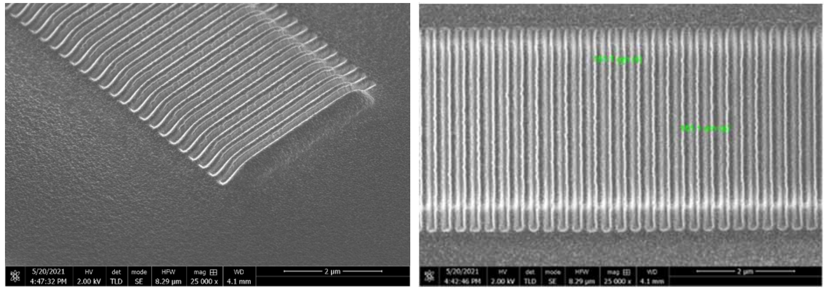
Harmonic Radiation Spectrum



Experiment



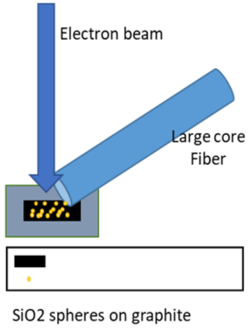
TEM experimental chamber

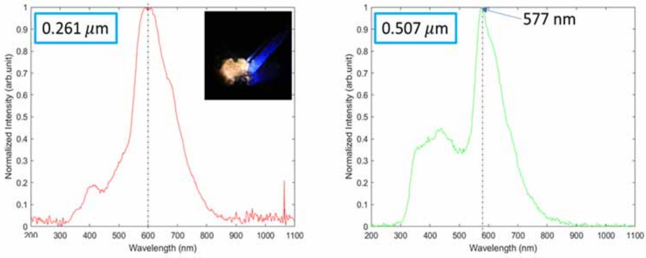


Fabricated structure on Si (courtesy of Prof. Wei-Chih Wang of NTHU)

Radiation from Silica Nanosphere

Xuan-Long Ho

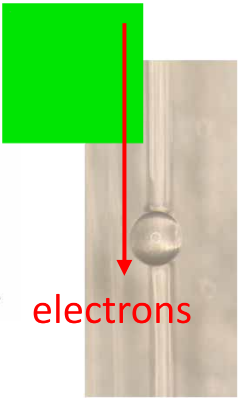


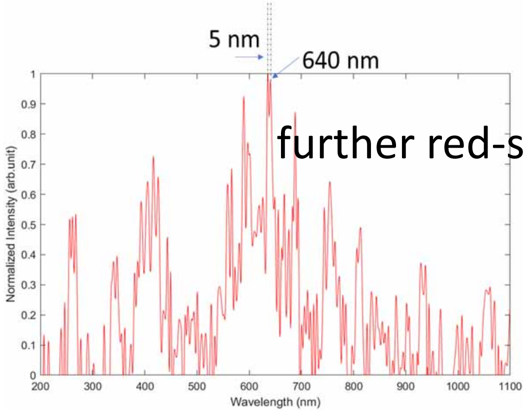


Red shifted with increased size

Radiation from Silica Microsphere

Xuan-Long Ho

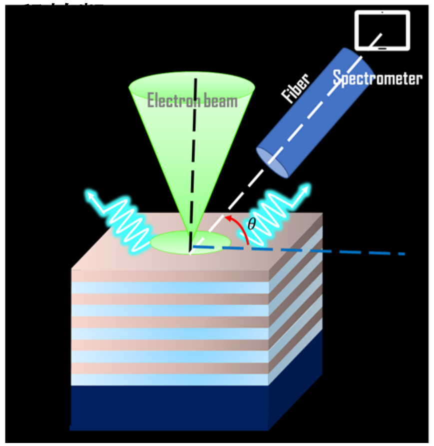


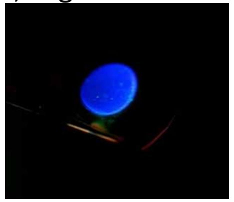


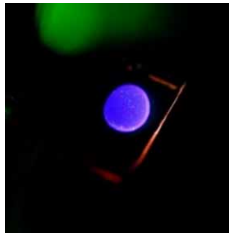
further red-shifted

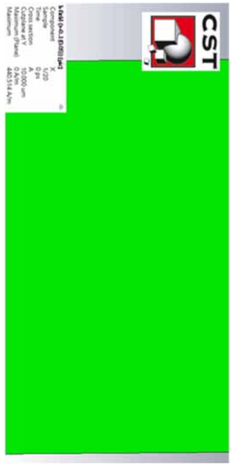
Radiation from optical superlattice

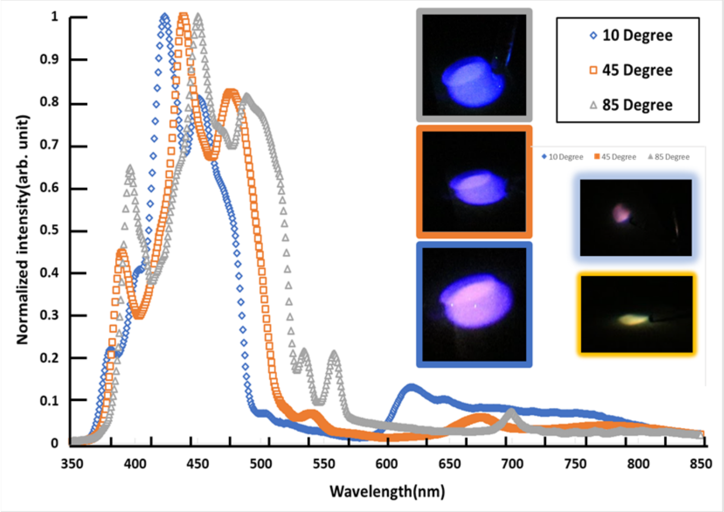
彭珞豪, Xuan-Long Ho, Alexey Kopeykin, Evgenii Kalinovets,







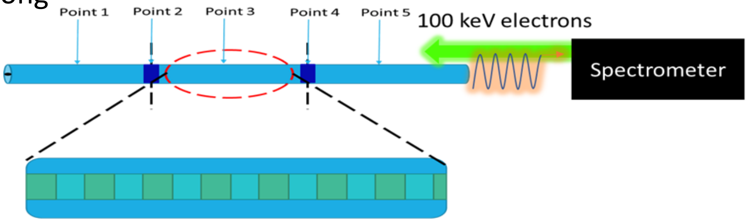




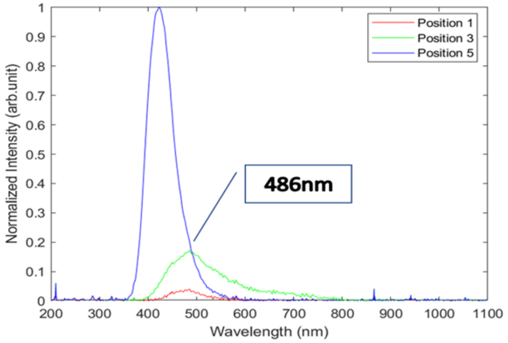
88 quarter-wave dielectric layers with a stopband between 550-675 nm

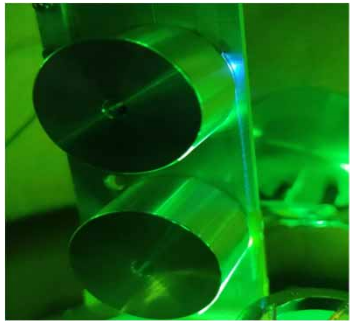
Radiation from fiber grating

彭珞豪, Xuan-Long Ho



Fiber Bragg grating peaked at 1518 nm
(courtesy of Prof.劉文豐 of 逢甲大學)

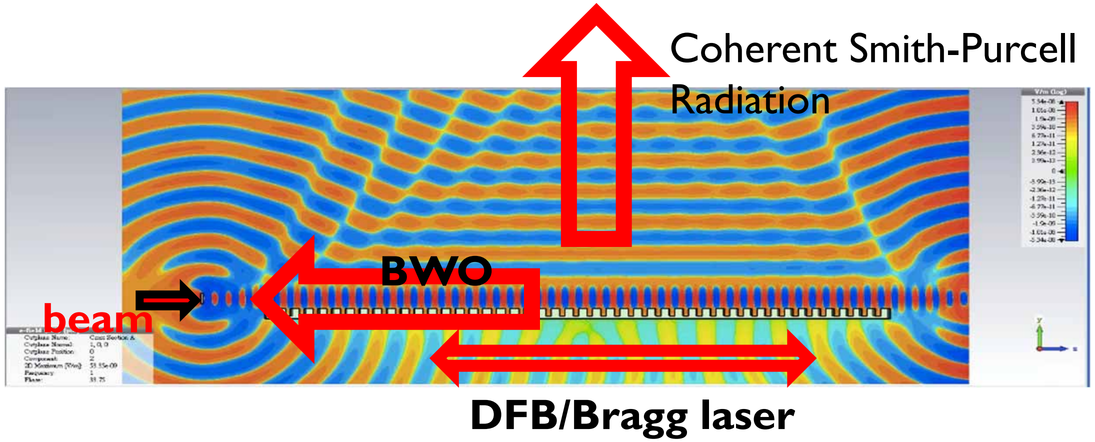




Owing to the grating resonance, the spectrum from the fiber grating is red-shifted with respect to that without the grating. The backward radiation after the grating (point 1) is blocked by the grating at the 3rd order Bragg resonance.

Conclusions

1. A free electron interacting with photonic structures opens up opportunities for ultra-compact coherent radiation sources.



2. Single-electron FEL built upon a dielectric-grating waveguide is numerically demonstrated at 0.2 PHz and its harmonics.

3. Experimental tests are on-going by using a TEM beam.

THANK YOU FOR YOUR ATTENTION