Working Group C: Compact Light Sources

Conveners: Massimo Ferrario/ LNF
Masaki Kando/ QST
Yenchieh Huang/ NTHU, Philippe Piot (on-site)

# of papers: 22

MO4/Orion-DC3, 16:30 ~ 18:00
TU1/Coronado, 8:30 ~ 10:30, TU4P, poster session
WE2/Orion-DC3, 11:00 ~ 12:00
TH2/Coronado, 11:00 ~ 12:30
FR1/Coronado. 08:30 ~ 10:30, **summary talk**

Please send your 1-page summary slide to Prof. Philippe Piot ppiot@niu.edu
AND copy the email to Prof. Yenchieh Huang ychuang@ee.nthu.edu.tw
by 5 pm, Wednesday, Aug. 30th

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

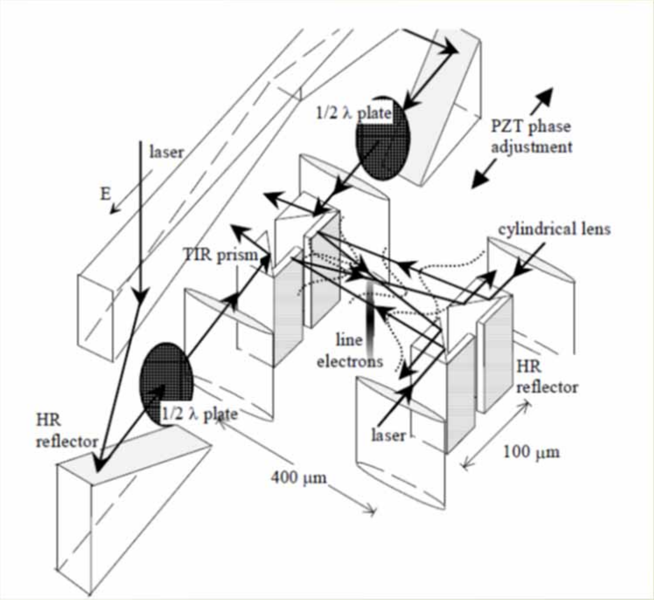
Ultra-bright Coherent Undulator Radiation Driven by Dielectric Laser Accelerator

Yen-Chieh Huang and Robert L. Byer***

*HOPE Laboratory, Institute of Photonics Technologies, National Tsing Hua University, Hsinchu 20013, Taiwan

**Department of Applied Physics, Stanford University, Stanford 94309, USA

DLA in 1996



•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).

OUTLINE

1. Dielectric laser accelerator (DLA)

2. Short-bunch radiation

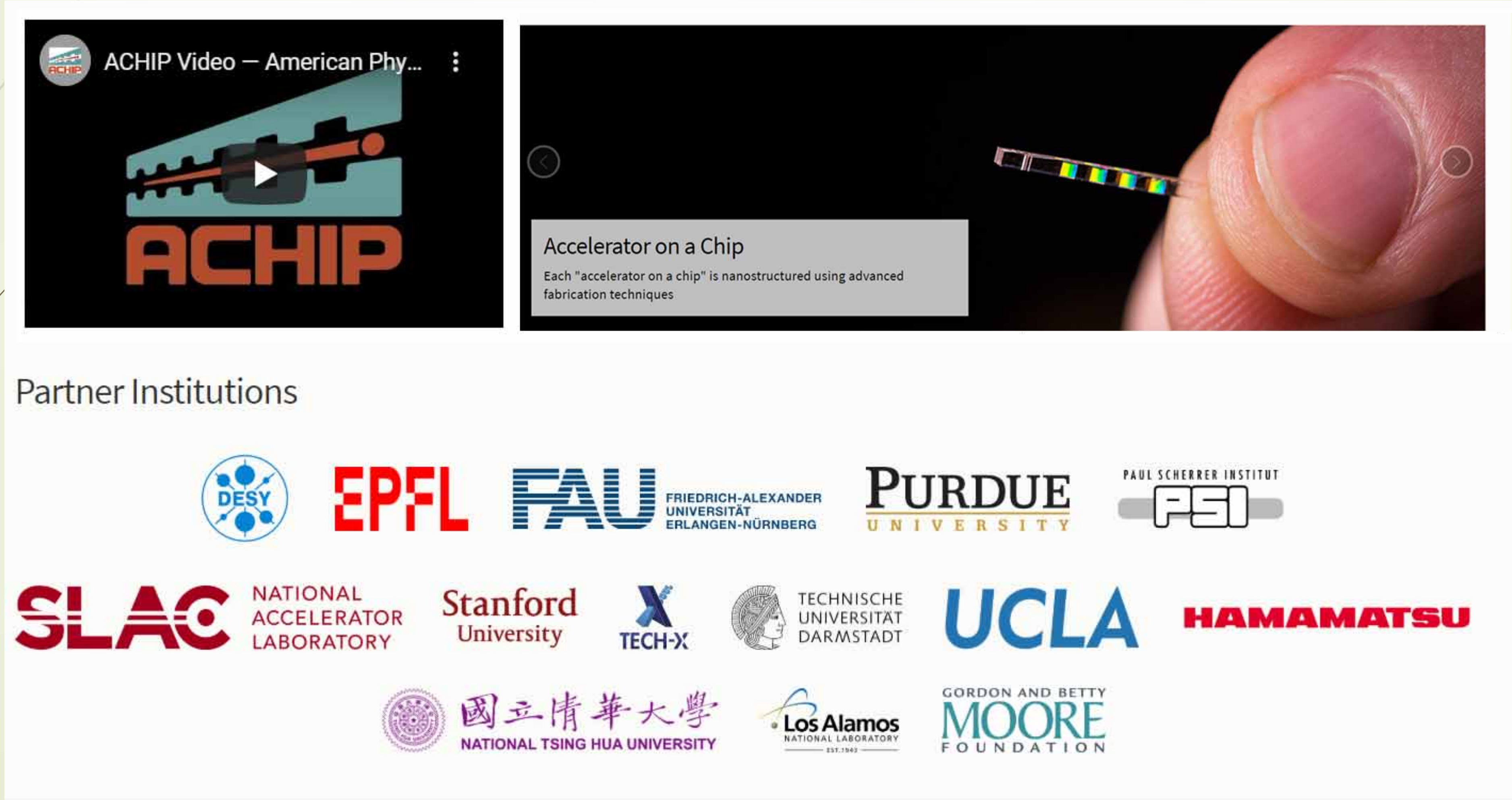
3. Brilliance of DLA-driven coherent undulator radiation (CUR)

4. Conclusions

Accelerator on a Chip (ACHIP)

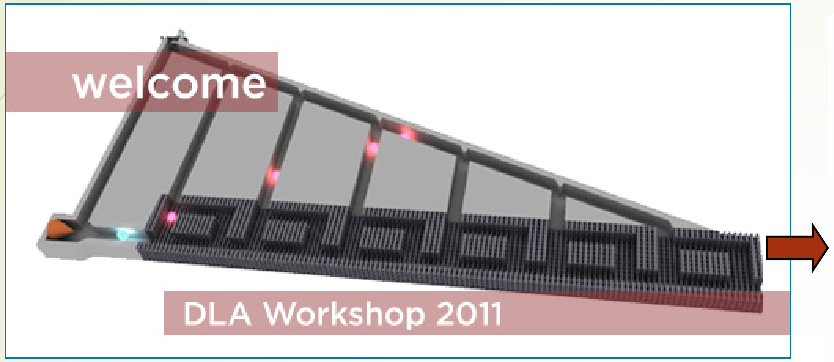
https://achip.stanford.edu/

- Direct-field acceleration
- High laser damage resistance on dielectric – high acceleration gradient



Envisaged DLA-driven Coherent Undulator Radiation

Dielectric laser accelerator (DLA)



~50 cm (GeV/m)

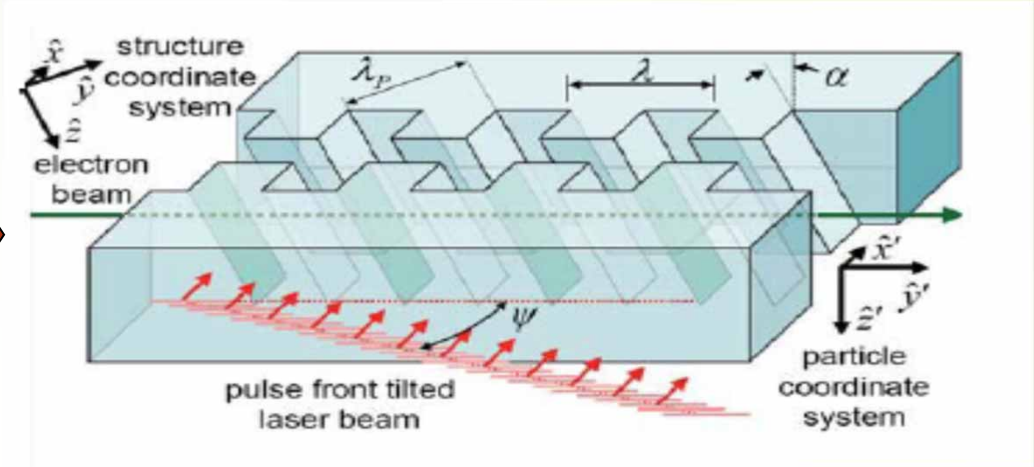
Driving wavelength λ ~ 1μm

electron bunch length ~ 1 nm

Bunch Charge = 1~ 10 fC

Gamma = ~500 MeV

Dielectric laser undulator (DLU)



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

100 cm

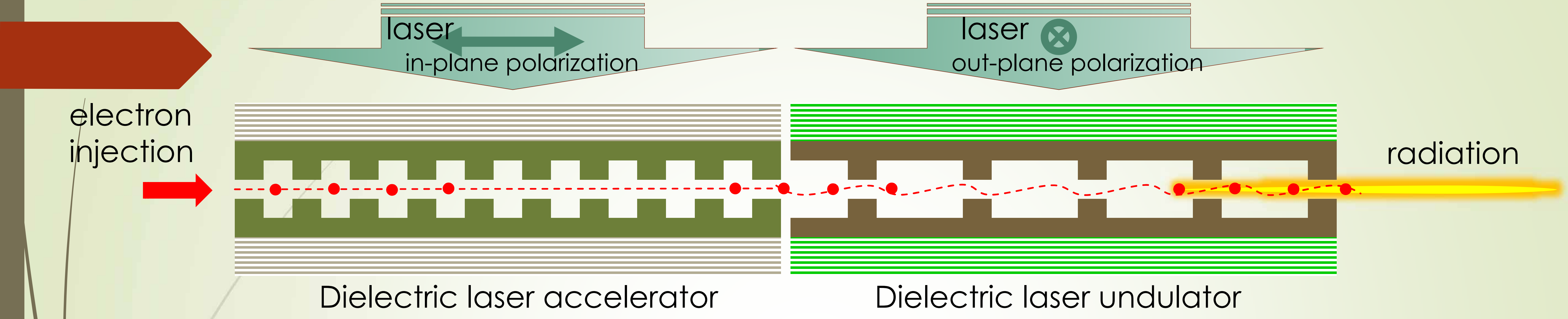
λ_u = 1 mm (N_u = 1000, 0.1% bandwidth)

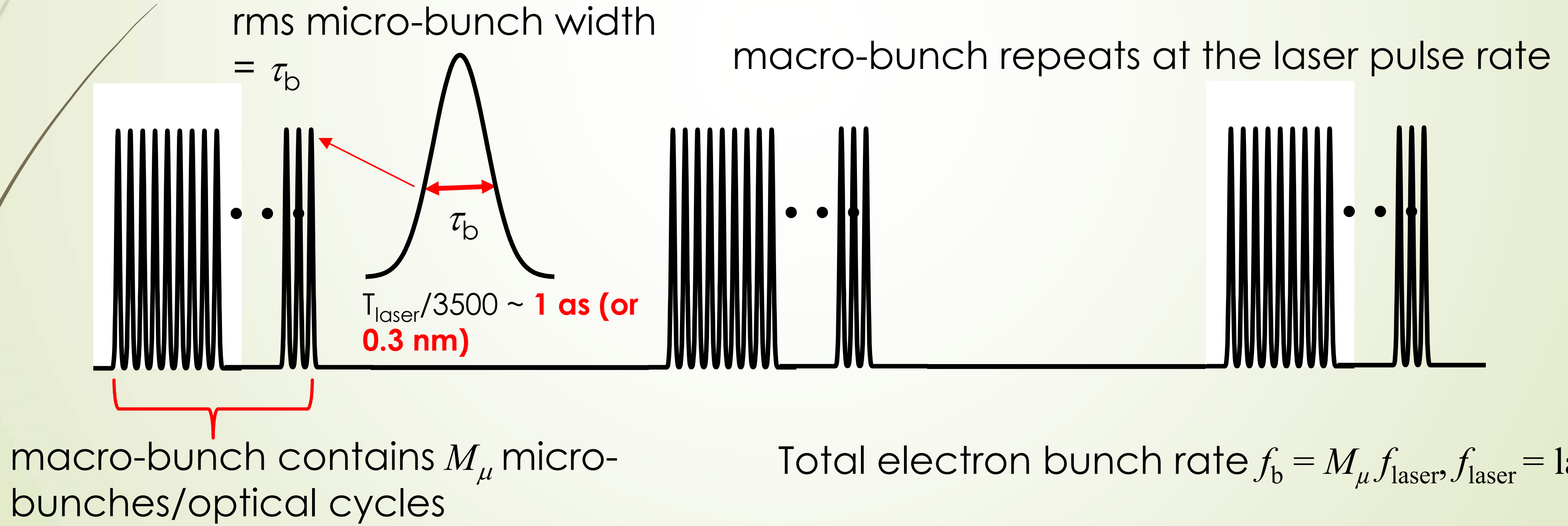
B_{peak} = 3 T (subject to laser damage)

a_u = ~0.22 (undulator parameter)

*good scheme to keep a_u for small λ_u

Bunch Structure of a DLA





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

*The scaling factor of 3500 is extrapolated from RF accelerator (RFA)

Short-bunch enhanced radiation - superradiance

Total radiation spectral power is $P_N(\omega) = f_b W_1(\omega)[N(N-1)|b(\omega)|^2 + N]$

$W_1(\omega)$: radiation spectral energy of 1 electron

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

N: # of electrons in a micro-bunch

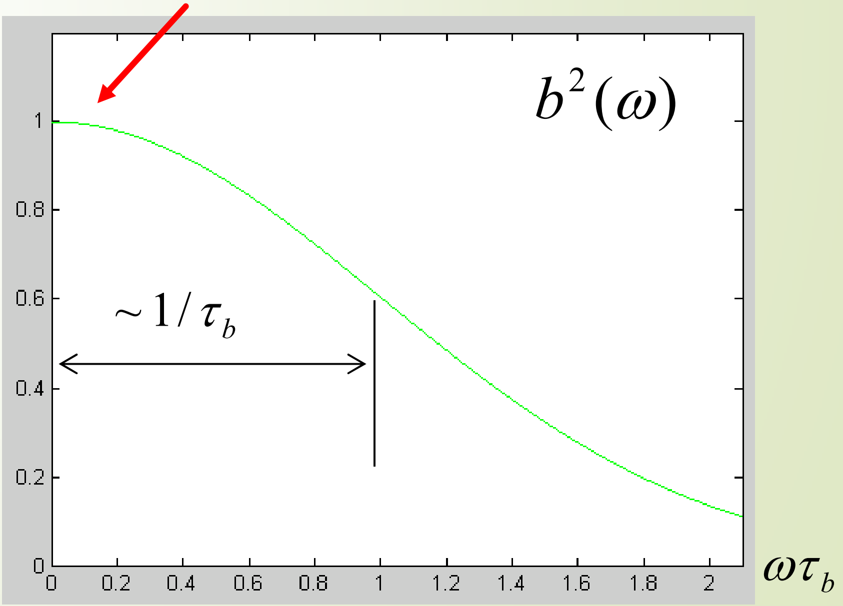
f_b: electron bunch rate

For Gaussian bunch with an rms bunch width τ_b

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

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

Bunch length << λ, $P_N(\omega) \propto N^2$



Much Reduced Beam Power for High-brightness Radiation

At, say, $\lambda = 10$ nm, where $|b_{RFA}(\omega)|^2 \sim 0$ and $|b_{DLA}(\omega)|^2 \sim 1$,

Ratio of radiation spectral power
$$\frac{P_{N_{DLA}}(\omega)}{P_{N_{RFA}}} \cong \frac{N_{DLA}^2 \left|b_{DLA}(\omega)\right|^2}{N_{RFA}}$$

for an equal bunch rate f_b and $N >> 1$ for both the DLA and RFA beams.

For $P_{N_{DLA}}(\omega) = P_{N_{RFA}}(\omega)$, ➡ $N_{DLA} = \dfrac{\sqrt{N_{RFA}}}{\left|b_{DLA}(\omega)\right|} \sim \sqrt{N_{RFA}}$, given $|b_{DLA}(\omega)|^2 \sim 1$.

Eg. $N_{DLA} = 8\times10^4$ (13 fC) for $N_{RFA} = 6.25\times10^9$ (1 nC). A much lower beam current and beam power for DLA to achieve same radiation power.

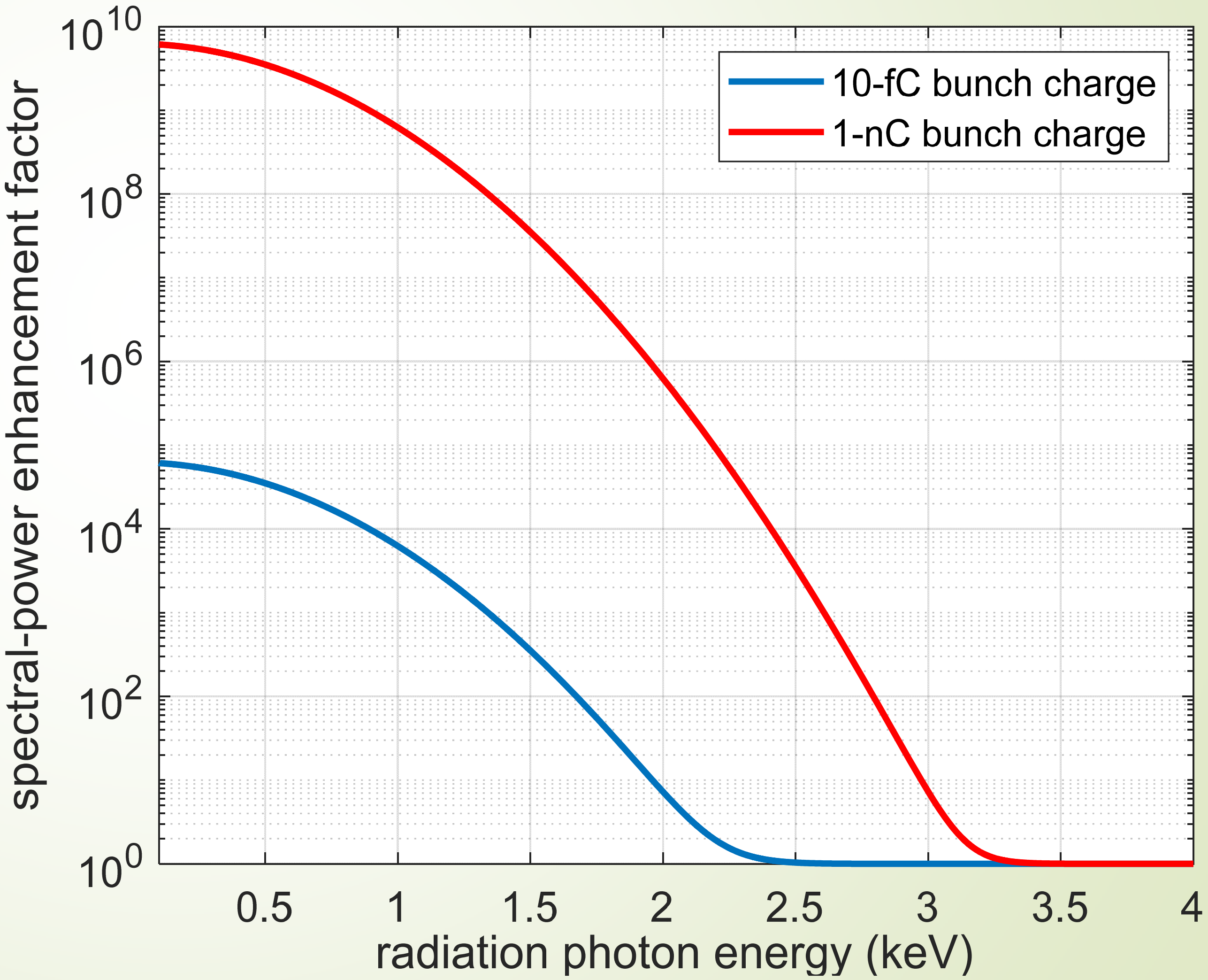
Spectral power enhancement factor subject to same beam power

$$f_{\mathbf{b,DLA}} N_{\mathbf{DLA}} = f_{\mathbf{b,RFA}} N_{\mathbf{RFA}}$$

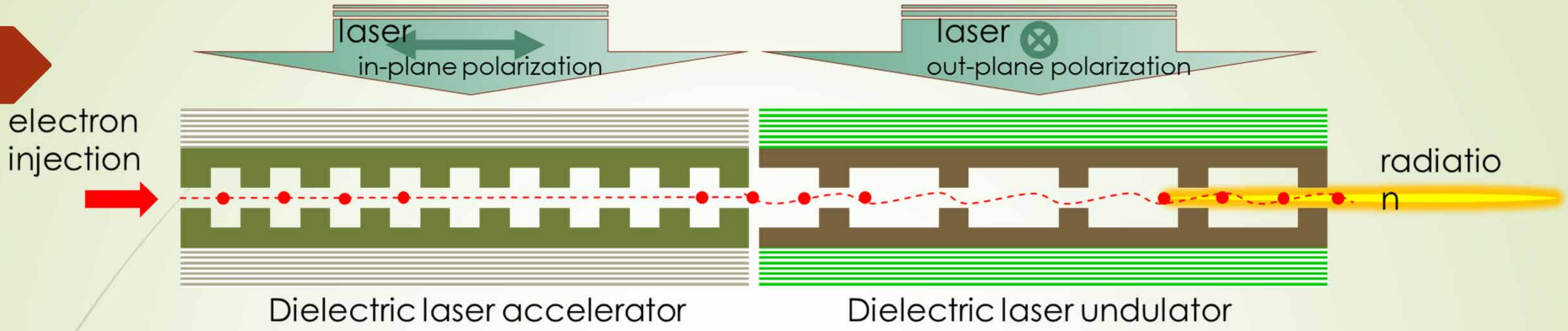
with $\tau_{b,\,DLA} = 1$ attosecond (2.35-attosecond FWHM))

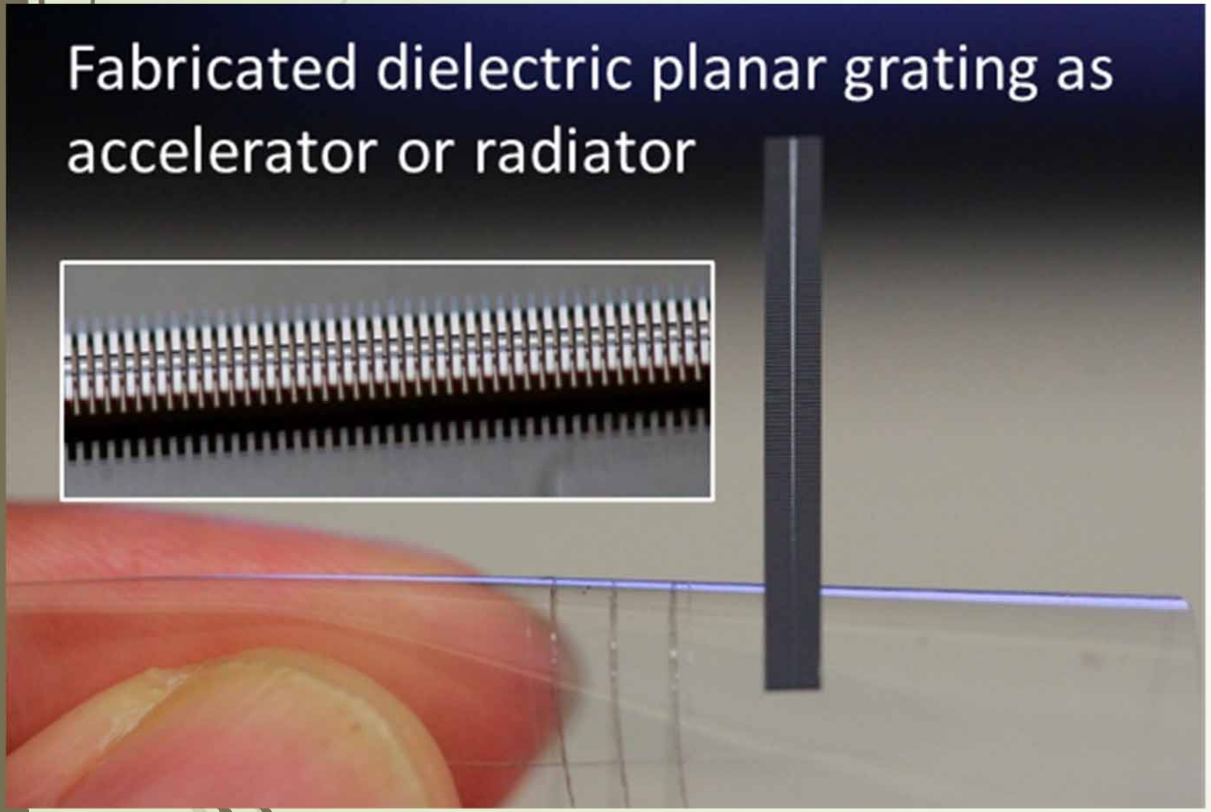
(planar, multi-beam DLA?)

$$\frac{P_{N,DLA}(\omega)}{P_{N,RFA}(\omega)} = [(N_{DLA} - 1)|b_{DLA}(\omega)|^2 + 1]$$



A bold comparison between DLA CUR and a synchrotron





Brilliance of Coherent Undulator Radiation

photons/s/mm²/mrad²/0.1%BW

$$B(\omega) \propto \boxed{[(N_{DLA}-1)|b(\omega)|^2+1])\times N_{DLA}}[JJ]\Delta\omega_{0.1\%}$$

Short-bunch enhancement

where $[JJ] \equiv 4M \times [J_0(M) - J_1(M)]^2 \sim 1$ with $M \equiv a_u^2 / 2(1+a_u^2)$

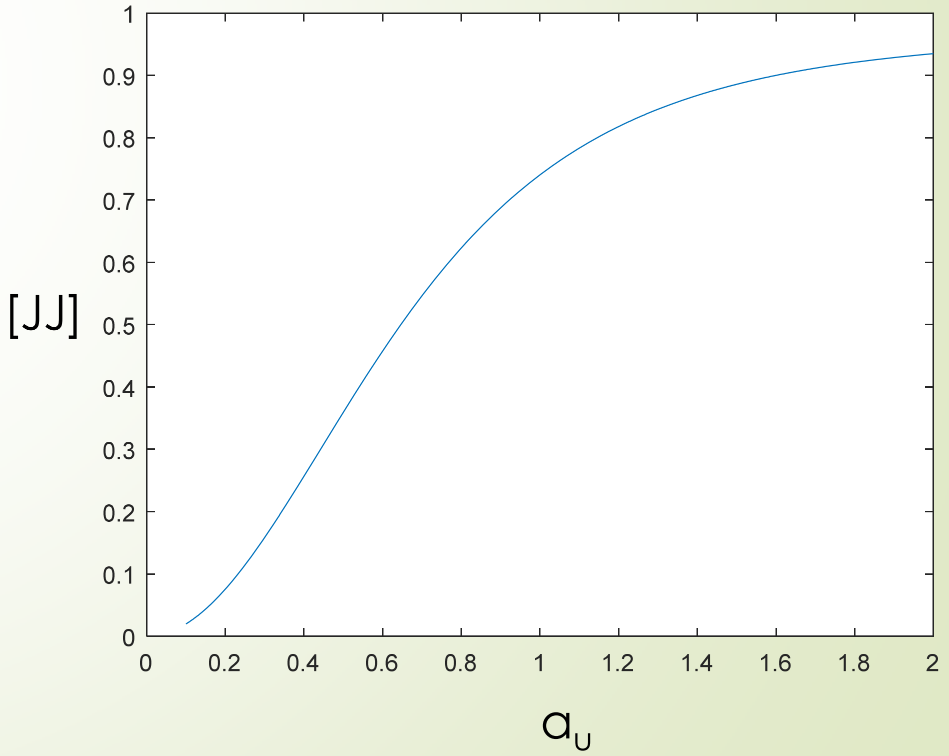
for a planar undulator.

N_{DLA} : # of μ-bunch electrons

Given a design wavelength,

(1) it is desirable to have a large N_{DLA}

(2) A high bunch rate increases the average brilliance.



Brilliance of DLA Undulator Radiation (diffraction limited)

photons/s/mm²/mrad²/0.1%BW

Peak Brilliance

$$B_p(\omega) = 7.3\times10^{-6}\times[N_{DLA}(N_{DLA}-1)e^{-(\omega\tau_b)^2}+N_{DLA}])\frac{\omega[s^{-1}]}{\lambda^2[\mu m^2]}[JJ]$$

Competing terms

Average Brilliance

$$B_a(\omega) = f_b\tau_s B_p(\omega) = 4.6\times10^{-5}\times[N_{DLA}(N_{DLA}-1)e^{-(\omega\tau_b)^2}+N_{DLA}]\frac{N_u f_b[s^{-1}]}{\lambda^2[\mu m^2]}[JJ]$$

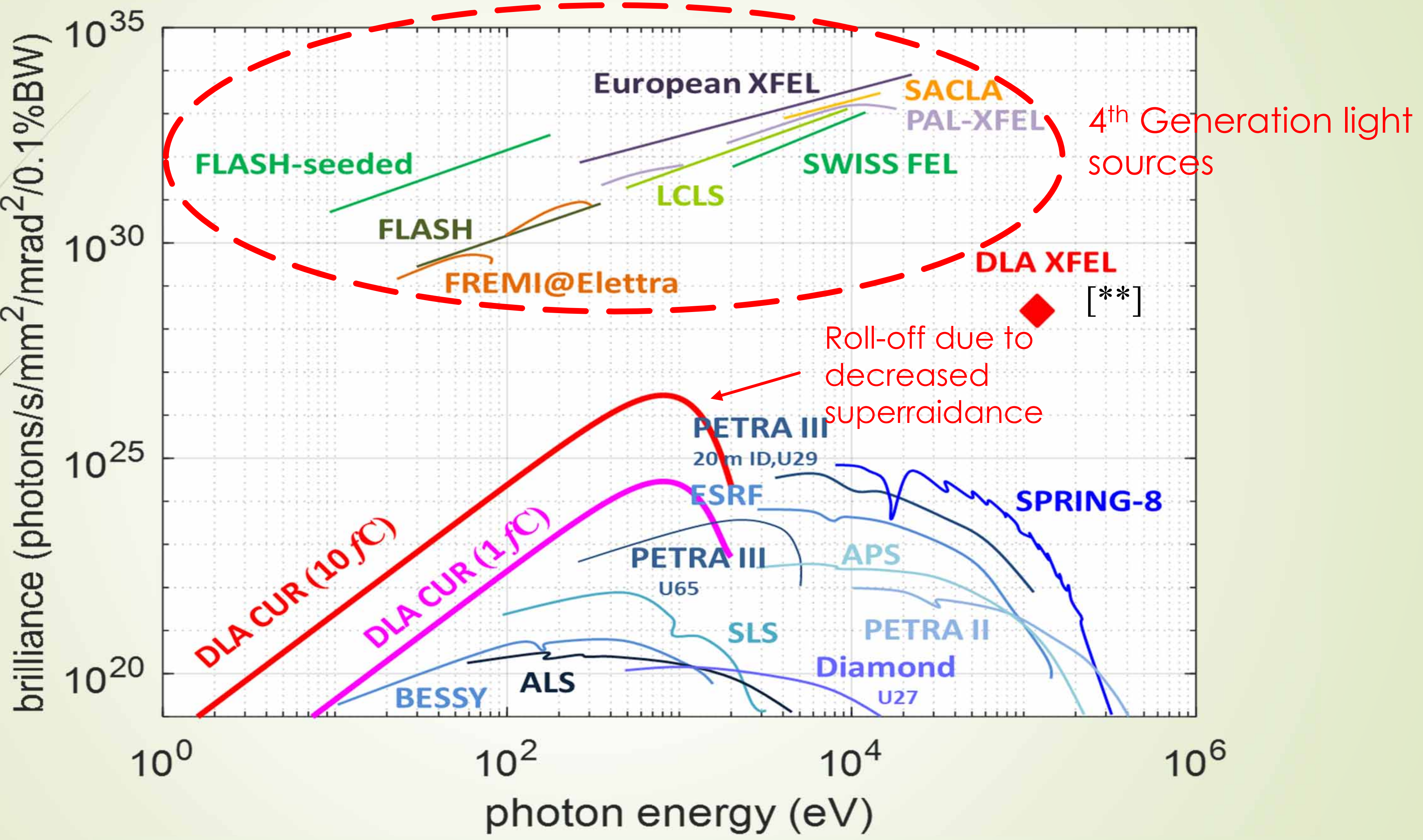
Radiation pulse length
= slippage length $\tau_s = 2\pi N_u/\omega$

Competing terms

System 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	2.35	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%

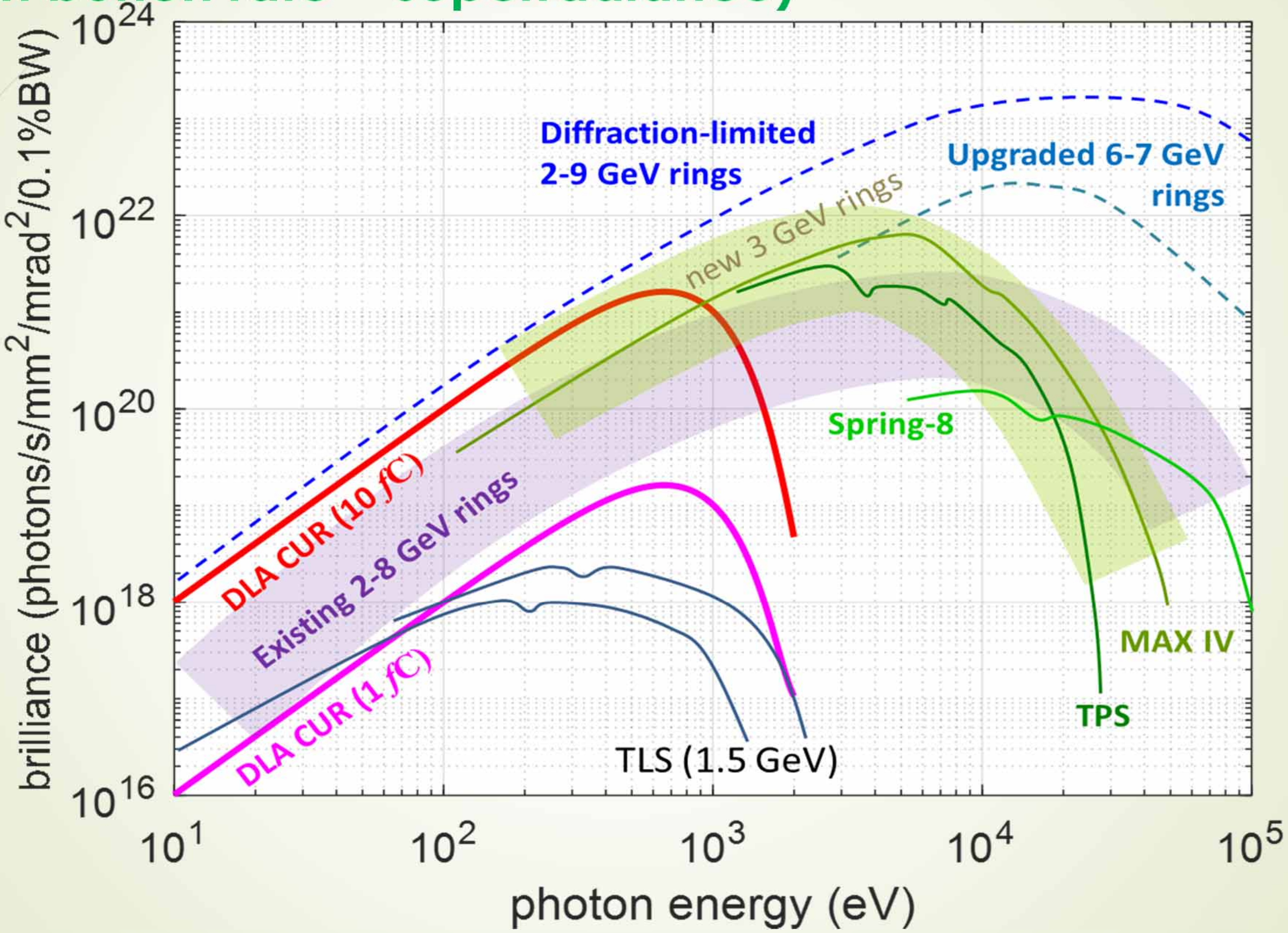
Peak brilliance higher than or comparable to 3rd-generation light source (due to superradiance)



*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).

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



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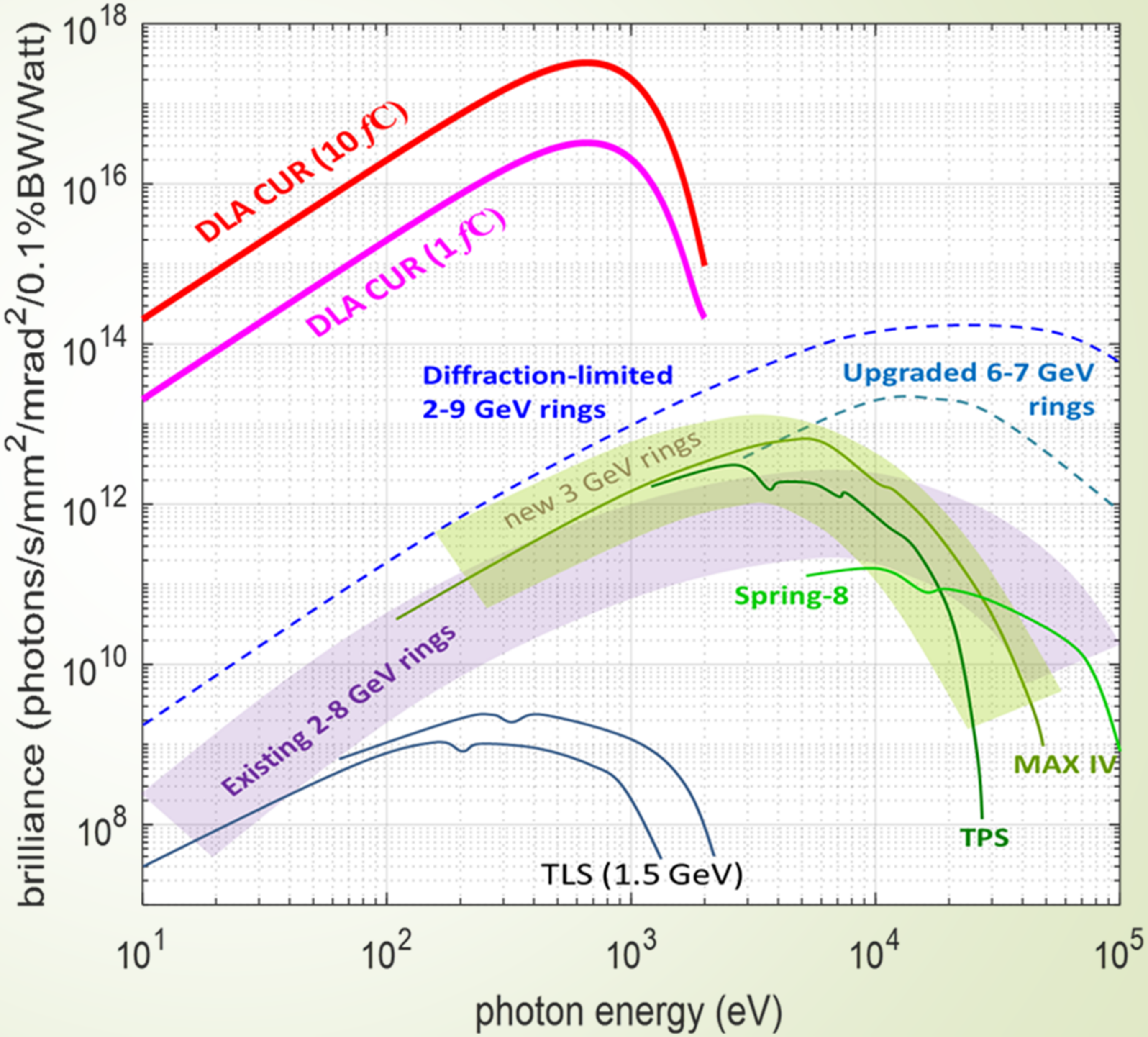
~GW circulating power
(Taiwan photon source)

0.5 kW ~ 5 kW beam power

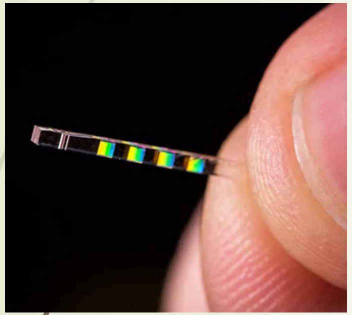
DLA average beam power is much smaller!

DLA stands high when normalized to beam power



CONCLUSIONS

~GW circulating power (Taiwan photon source)



0.5 kW ~ 5 W power (adapted from https://achip.stanford.edu/)

1. Dielectric laser accelerator (DLA) is potentially compact, stable, high-gradient, and high-efficiency for radiation generation.

2. Nano-bunches from DLA permit high-brightness superradiance in the VUV/EUV/soft x-ray spectrum. DLA-driven CUR is predicted to have peak/average brilliance comparable to a synchrotron.

3. In particular, DLA-driven coherent undulator radiation has a much higher brilliance/beam-power than a synchrotron.

THANK YOU FOR YOUR ATTENTION

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