Compact Radiation Sources Using Dielectric Laser Accelerators

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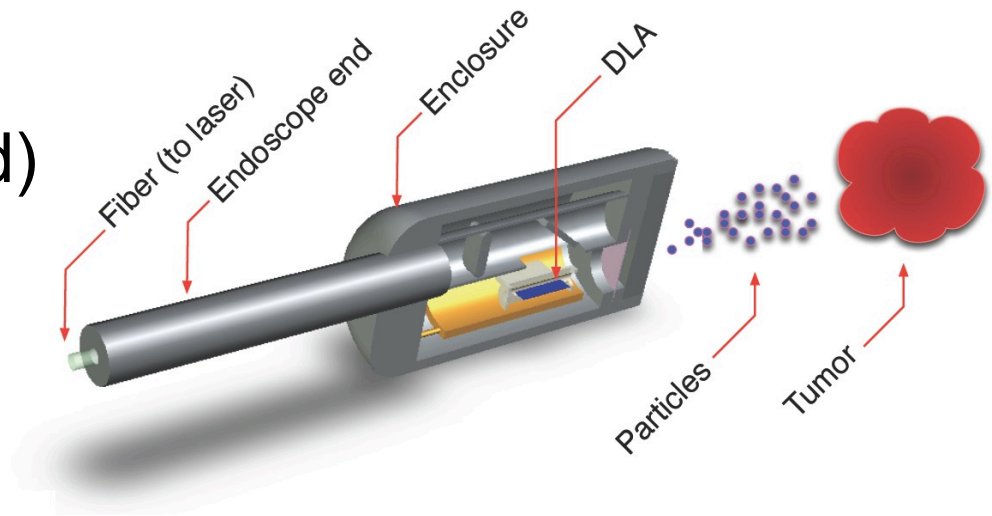


4th European Advanced Accelerator Concepts Workshop, Elba, Italy
Sept 16-20, 2019

GORDON AND BETTY MOORE FOUNDATION

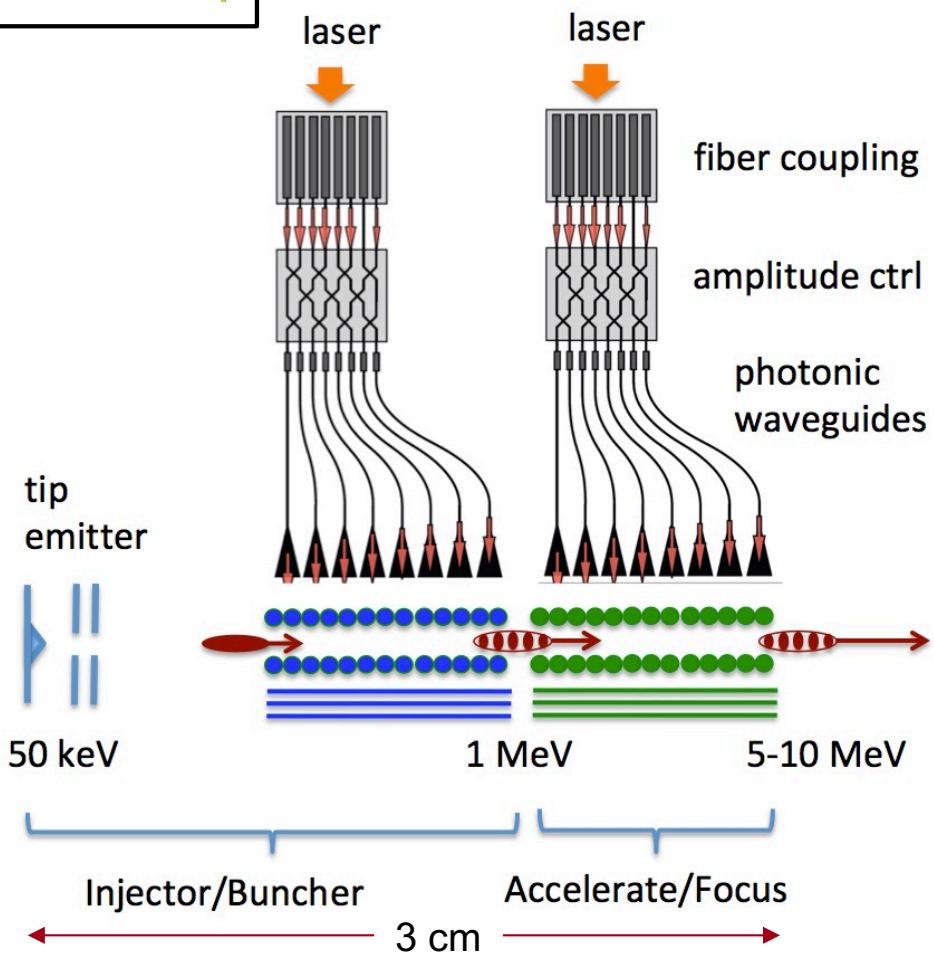
U.S. DEPARTMENT OF ENERGY Office of Science

ACHIP

SLAC NATIONAL ACCELERATOR LABORATORY

Dielectric Laser Accelerator (DLA) Concept: Towards an "Accelerator on a Chip"

Modelocked Thulium Fiber Laser (λ = 2μm, 10μJ, $300k)

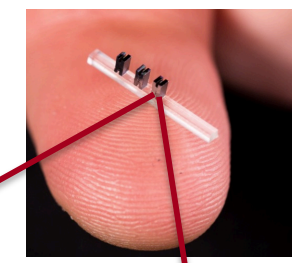


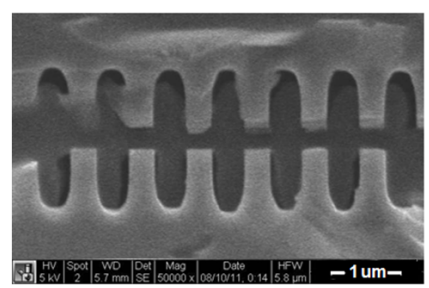
Required lasers are MHz rep rate, low pulse energy, wallplug efficiency ~ 30%

Dielectric materials can withstand GV/m fields and kilowatts of average power

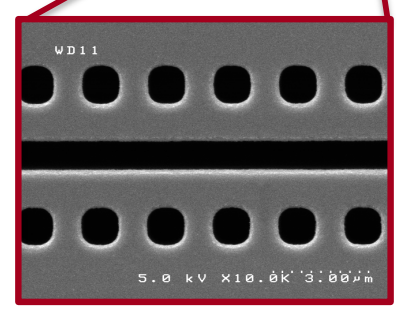
Can be mass produced using techniques of the integrated circuit industy.

SEM images of DLA prototypes tested at SLAC





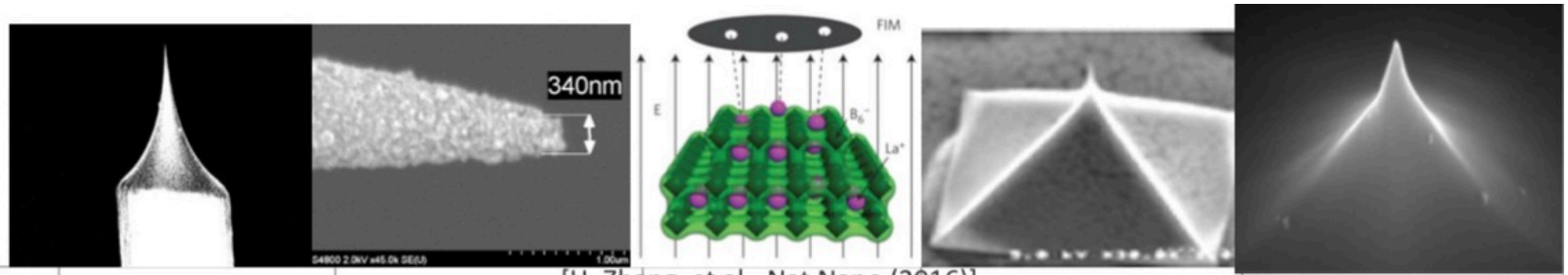
fused silica



silicon

DLA research aims to produce ultracompact nanofabricated devices for particle acceleration, powered by efficient solid-state lasers.

High Brightness Photocathodes



[H. Zhang, et al., Nat Nano (2016)]

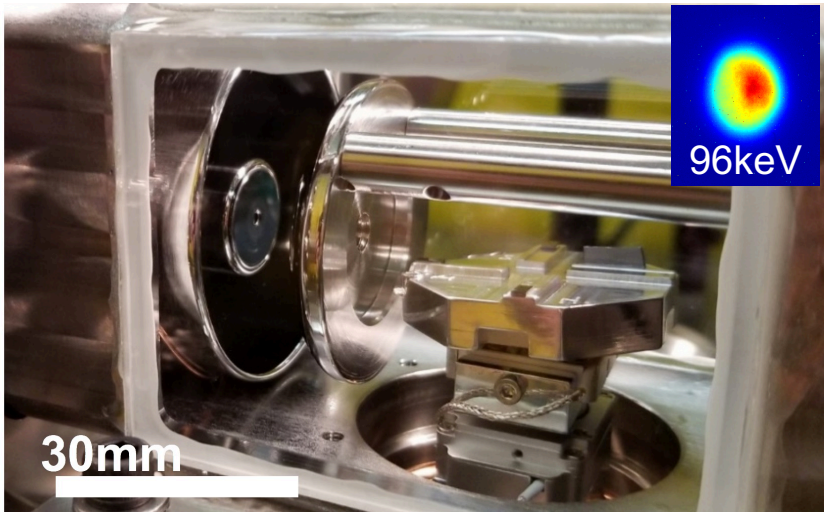
	W tip (Erlangen)	W tip w/ diamond (Erlangen)	LaB_6 nanowire (Erlangen)	diamond pyramid (Los Alamos)	Si nanotip
R (nm)	(<1.0)	170	(1.5)	<10	**15**
max e^-/pulse	625	1000	20	12000	**1000**
ϵ_n (nm)	0.1	0.35	0.1	?	**0.25**
$B_{5D,n}$ (A/cm^2)	6.7e12	1e10	1.1e12	?	**1e12**
stability	30 min	>1 hour	?	>1 hour	**>1 hour**
integrated	N	N	N	Y	**Y**

A. Ceballos, DLA Applications Workshop, March 26 (2019)

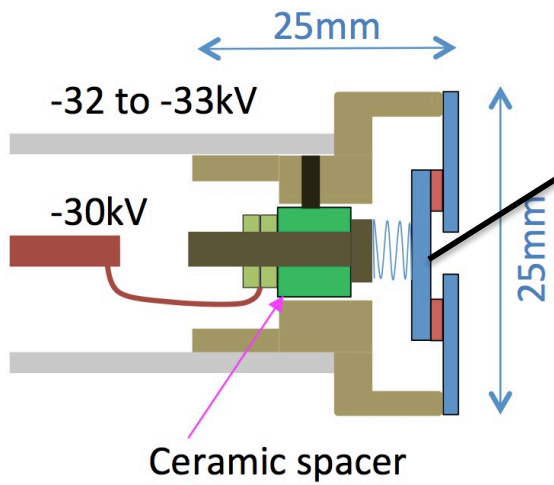
Integrating the components for a 1 MeV accelerator

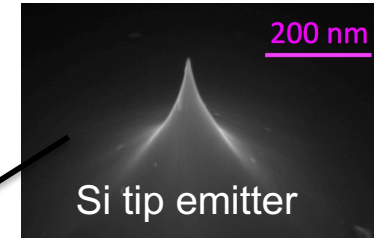
see talk by P. Hommelhoff (Wed Plenary)

Stanford "glassbox" test system



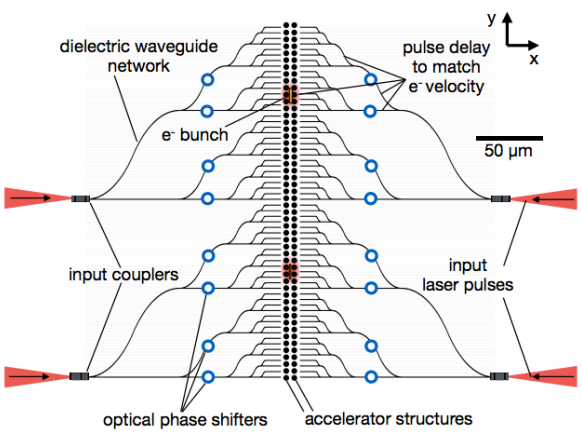
compact electron gun w/electrostatic lens





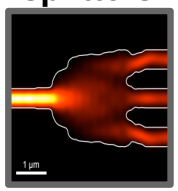
3000 e-/pulse,100 kHz rep
0.2 nm emittance
A. Ceballos, Stanford

optimized DLA components via inverse design

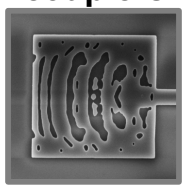


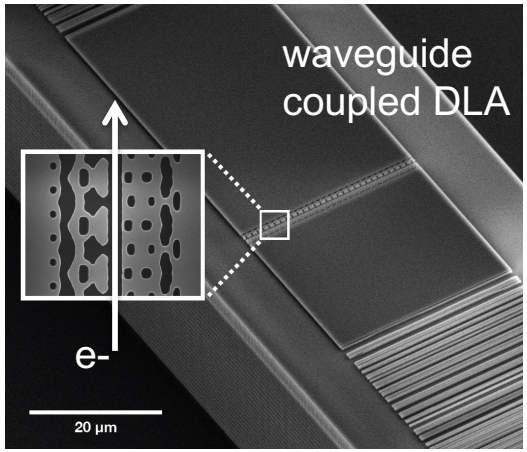
T. Hughes, et al, Phys. Rev. Appl. 9, 054017 (2018)

splitters



couplers





N. Sapra, et al., in review Science (2019)

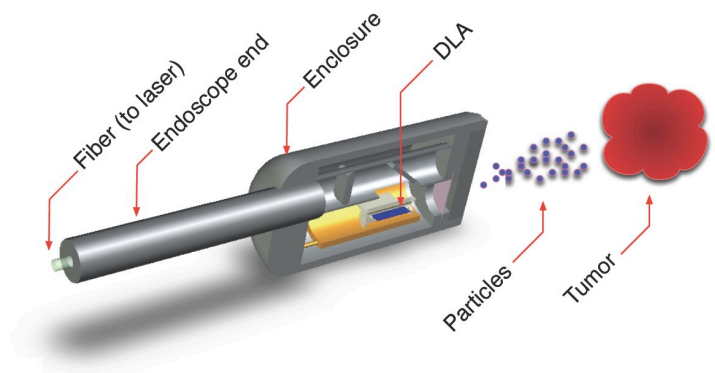
courtesy T. Hirano (Hamamatsu, visiting scientist at Stanford University)

Applications Identified by the March 2019 DLA Applications 1-Day Workshop

SLAC

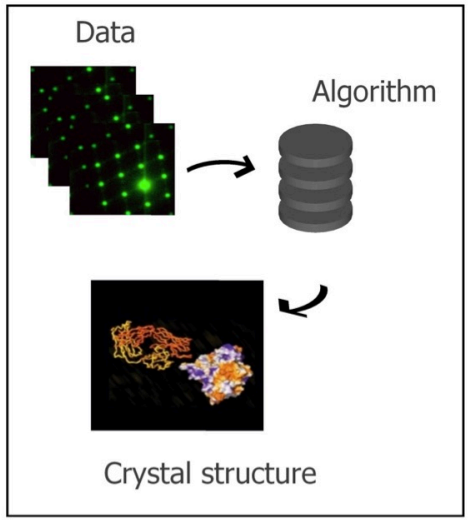
potential areas of industry interest

- Biomedicine industry
  -- Radiation therapy
- Semiconductor industry
  -- low-power EUV for mask/wafer inspection/calibration



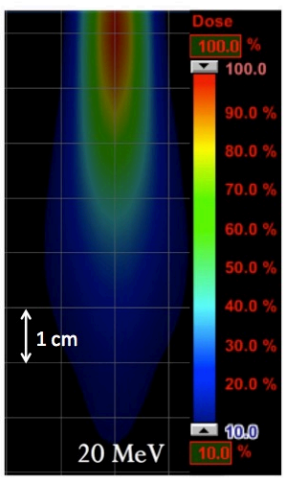
potential areas of scientific interest

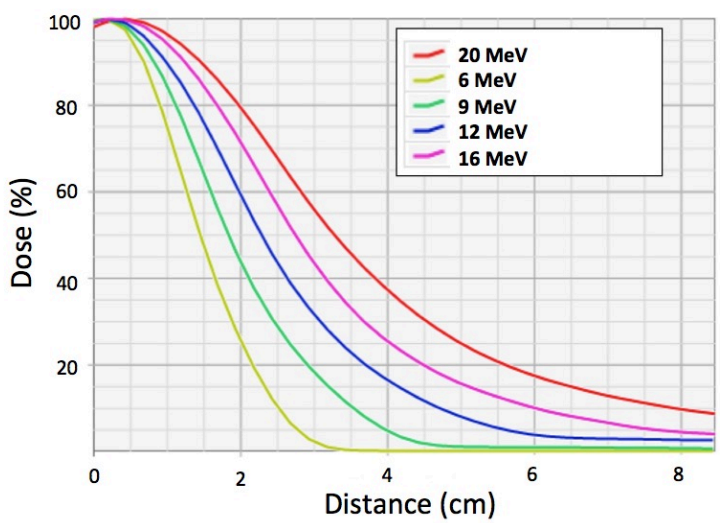
- Nano- or micro-beam for radiobiology and radiation chemistry
- Ultrafast electron diffraction, X-ray pulses at sub-fs time scales



Strawman Parameters for a DLA Based Medical Linac

Parameter	Desired Capability	Unique DLA Features
Electron energy	1-20 MeV	Single-wafer design with 1 GV/m gradient
Useful dose	1 Gray/sec	2000 e- per bunch; 2 MHz rep rate
Treatment Volume	5-10 cm^3	Directed (vs omnidirectional) beam and on-chip deflection to scan tumor area
Small footprint	~ 1 cm x 10 cm	2um wavelength optical scale device with 2 cm active linac length
Wall Plug Power	< 100 Watt	Modest 2.9% wall-plug to electron efficiency





- Electron penetration depth set by adjusting beam energy.
- Customized dose distribution by "rastering" with steering elements.

Simulations by B. Fahimian, B. Loo (Stanford) Proceedings of Advanced Accelerator Concepts Workshop (2014)

A small-footprint medical accelerator directly maps to DLA's unique features.

Radiation Parameters of Interest for Industrial Applications

Parameter	Desired specifications
Wavelength	UV to X-ray, broad or narrow band
Brilliance	> 10^{10} photon/(sec mm2 mrad2 0.1%BW)
Brightness	> 10^{8}-10^{12} photons/(sec sr)
Pulse width	< Sub femto second for High speed image < 1ns for inspection
Repetition rate	> 1-100 MHz
Unit cost	Depends on application

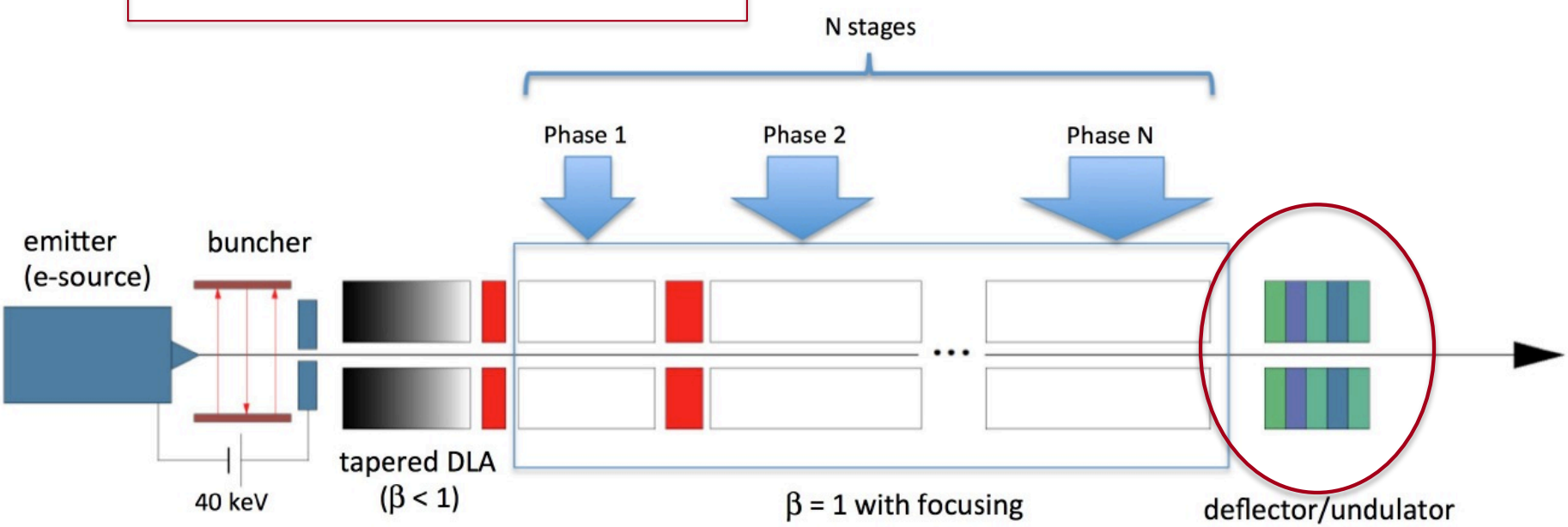
- Inspection for semiconductor wafer, mask
- Spectroscopy
- Imaging

slide courtesy T. Hirano, Hamamatsu

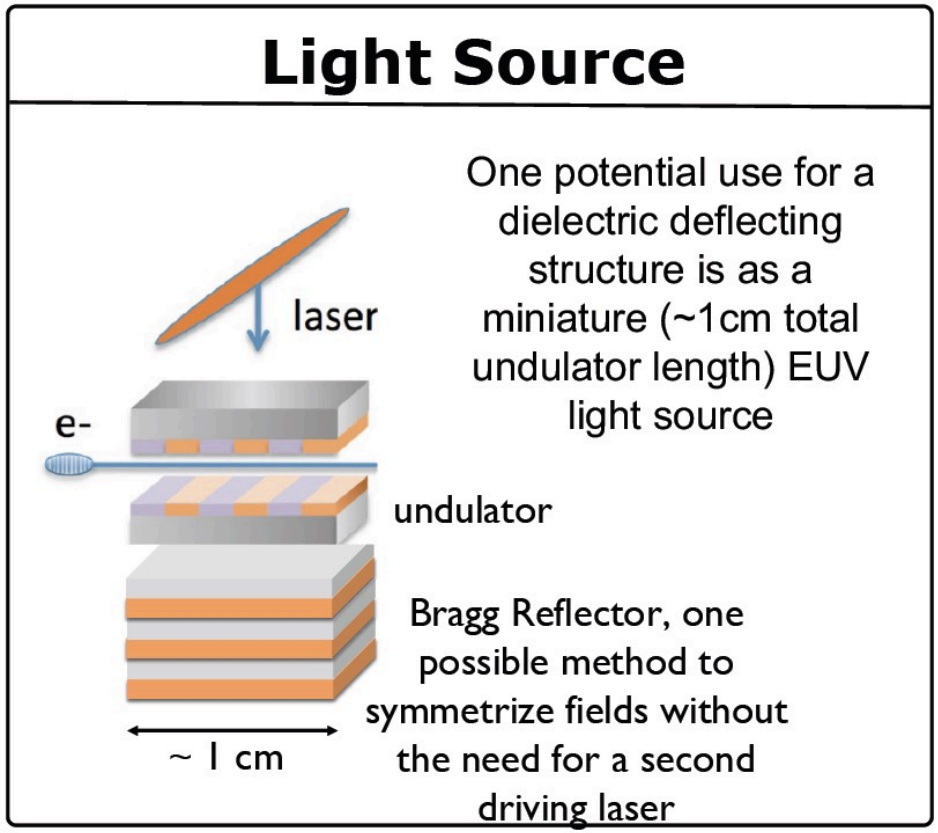
Components of a DLA Light Source

Overall goal: The demonstration of an integrated multi-stage particle "accelerator on a chip" will validate the potential to scale to energy levels of interest for "real-world" applications.

1. On-chip electron source
2. DLA structure development: (a) subrelativistic, (b) relativistic
3. Multi-staged acceleration
4. Coupling of laser to DLA
5. Laser-driven undulator



Concept for a compact laser-driven undulator for EUV production



Spontaneous EUV Radiation Parameters	
Beam Energy	100 MeV
Bunch Charge	0.5 fC
Bunch Rep Rate	100 MHz
Average Current	5 nA
Electron Bunch Length	10 as / 3nm
Undulator Field	2.1 T
Undulator Period	1 mm
Number of Periods	10 (~1cm total length)
Undulator Parameter	~0.20
Radiated Wavelength	~13 nm
Photon Flux	$\sim 10^{10}\ s^{-1}$

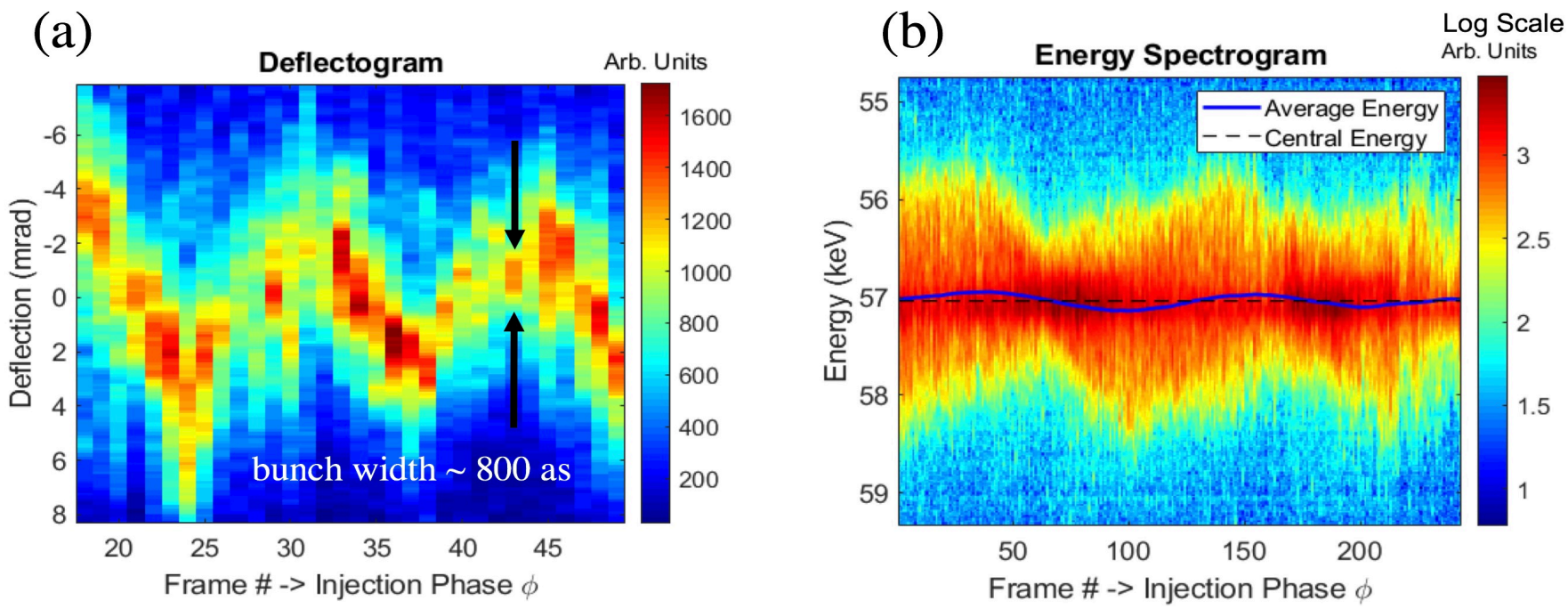
An equal superposition of the TE and TM fundamental modes produces a pure deflection mode (i.e. no E_z component)!

A. Ody, R. J. England, Z. Huang, AAC 2018 and SLAC-PUB
T. Plettner and R. L. Byer, Phys. Rev. ST-AB **11**, 030704 (2008)

DLA's attosecond bunch structure raises the possibility of making attosecond radiation pulses

Optical structures naturally have sub-fs time scales and favor high repetition rate operation

Pre-proposal for NSF Science and Technology Center (June, 2019)

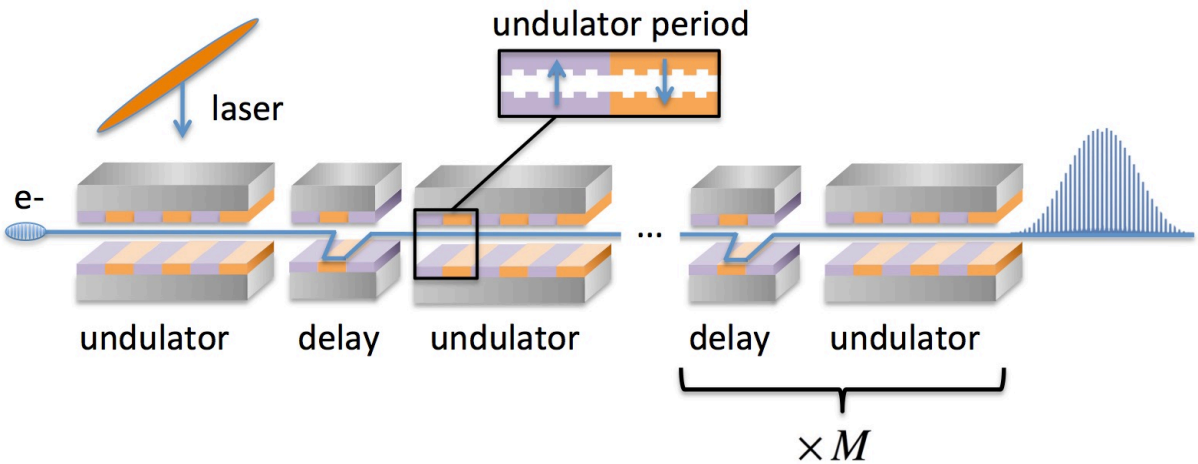


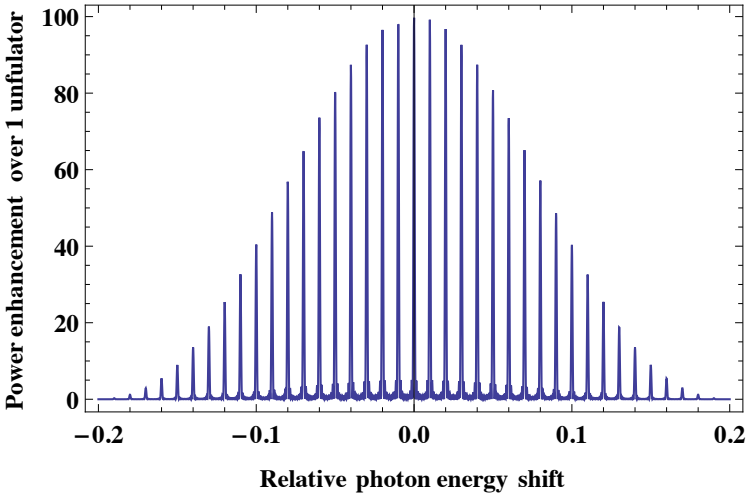
Recent experiments have demonstrated (a) laser-driven particle deflection in nanophotonic devices to generate and measure trains of sub-fs electron bunches and (b) laser-driven net acceleration and energy gain of these bunches as a function of relative laser phase.

See also talks by P. Hommelhoff (Wed Plenary), N. Shönenberger (Mon WG3)

EUV Attosecond Frequency Comb

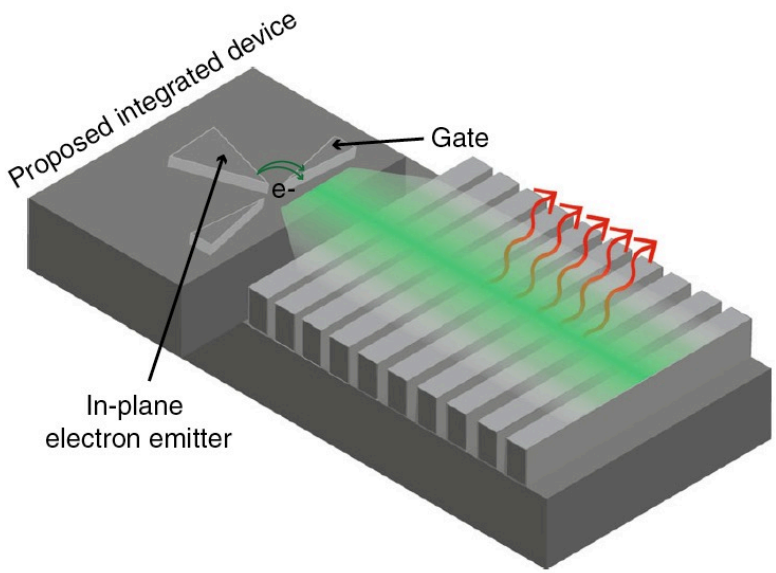
Modelocking scheme proposed could enable attosecond radiation pulses (R. J. England, Z. Huang, FLS 2018)





Parameter	Unit	Value
Beam Energy	MeV	40
Microbunch Charge	fC	10
Undulator Period	μm	250
Number of periods / Delay Modules	#	10 / 100
EUV Photon Energy	eV	50
Radiated Pulse Energy	nJ	100

Possibility of On-Chip Coherent Radiation Sources (EUV to Mid-IR)



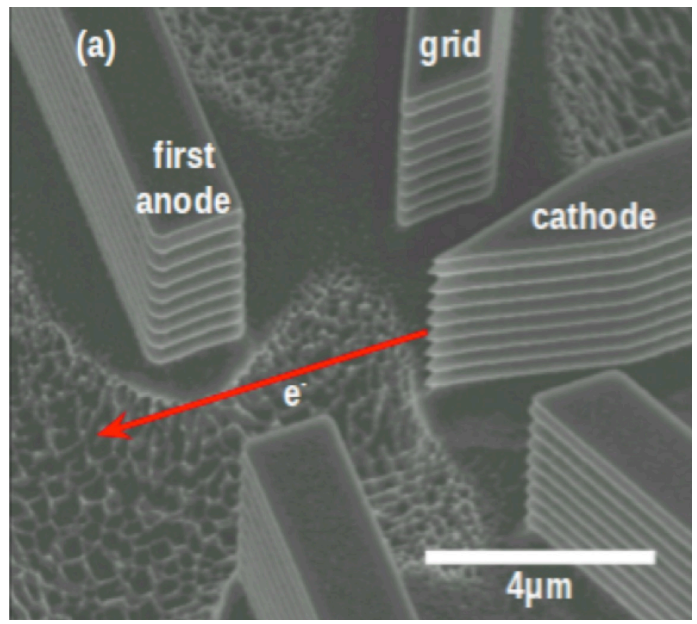
Conceptual illustration borrowed from C. Roques-Carmes, et al., Nature Communications (2019)

An integrated nanoemitter combined with Smith-Purcell radiator is of interest as a tunable on-chip source of EUV to mid-IR for telecom, LIDAR, and photon science.

ACHIP goals

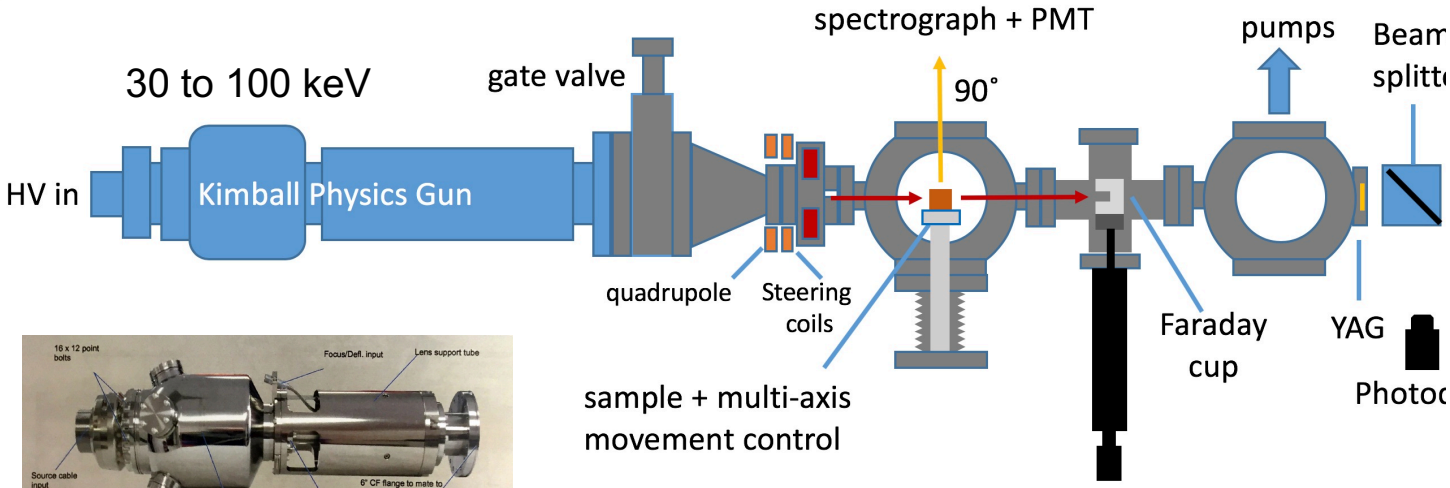
Develop an efficient tuneable radiator using inverse design with Silicon (or other materials) Target 50-200 nm EUV and IR to mid-IR.

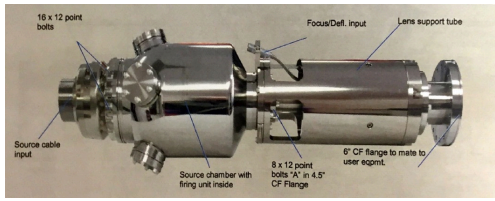
Initial experiments could be conducted using a commercial DC electron gun.

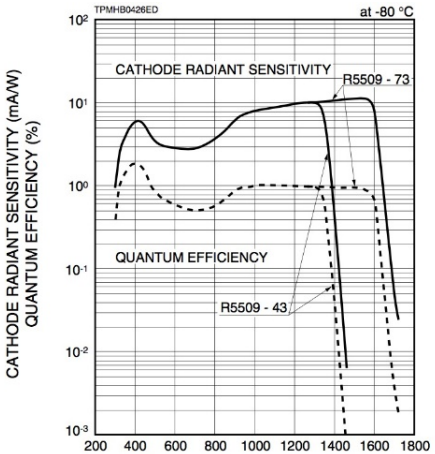


Fabrication prototype for silicon-based on-chip field emission source (Solgaard Group, Stanford)

DC Electron Test Stand for DLA Radiation Studies

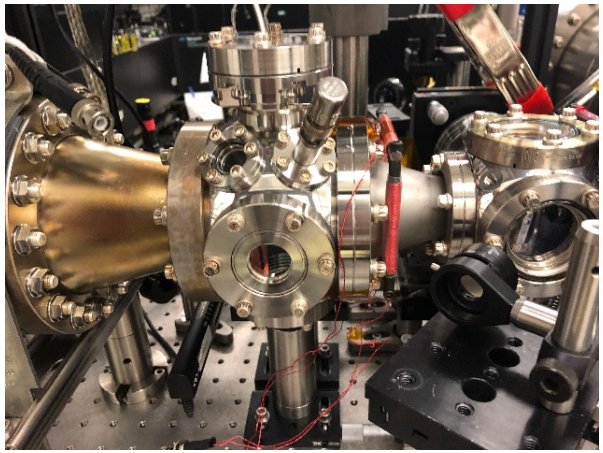






Newport MS260i imaging spectrograph

Hamamatsu R5509-73 PMT



Experimental Plan:

1. Beam characterization study (complete – emittance ~ 20 nm-rad)
2. Incoherent IR radiation from Silicon grating (in progress now)
3. Coherent SP and Cherenkov studies using optimized structures (next 6-9 months) for EUV to mid-IR

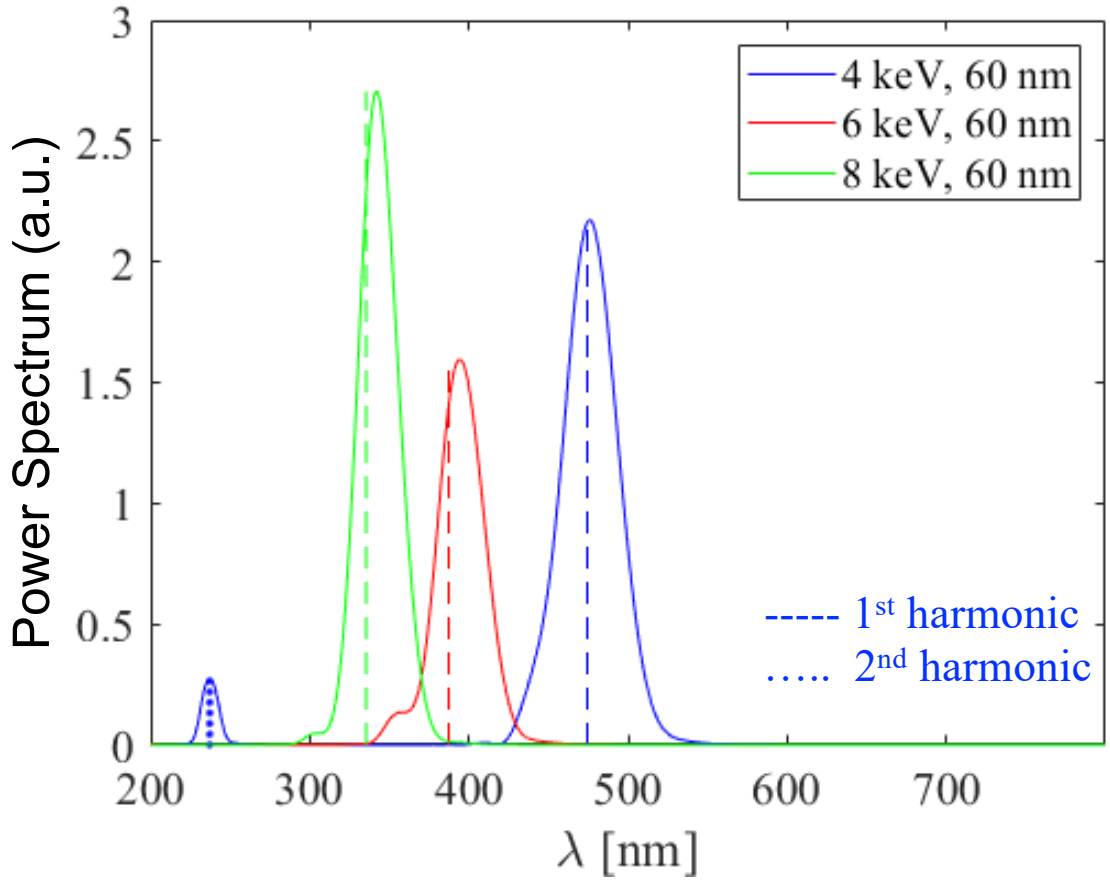
Wavelength Tunability – FDTD Simulation

Note: example parameters chosen to benchmark numerical method and do not necessarily correspond to a planned experiment.

Parameters:

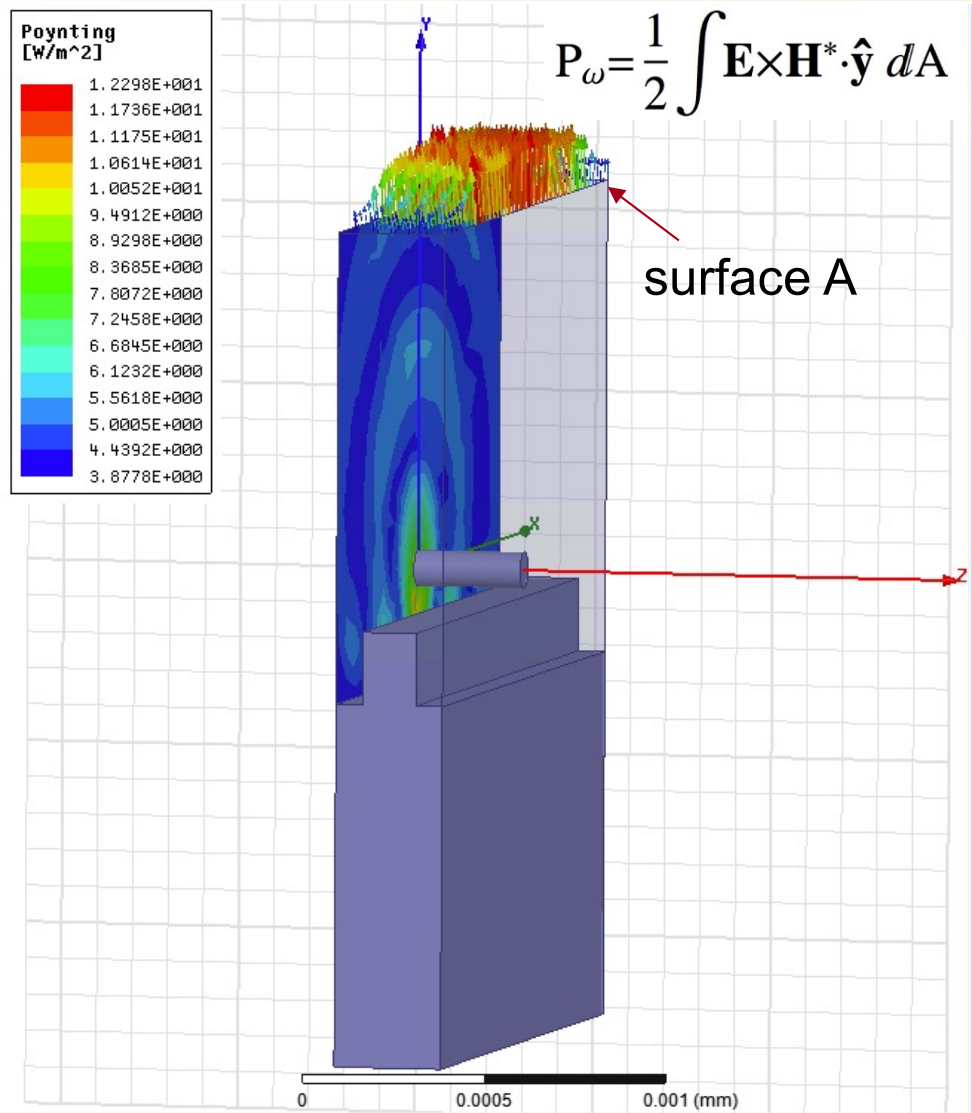
Grating period : 50 nm
Number of gratings : 20-55 units.
Electron energy : 4-8 keV
Material : Si, Au coating
observation at 90˚ to e-beam axis

$$\lambda_{sp} = \frac{\lambda_p}{n}\left(\frac{1}{\beta} - \cos\theta\right)$$



simulation by N. Cohen (Technion) under ACHIP Radiation group;
see Massuda, et al, ACS Photonics 2018, 5, 3513−3518 for description of methodology

Power Estimation for 200 μm Grating with 666 periods and 1 μA beam current



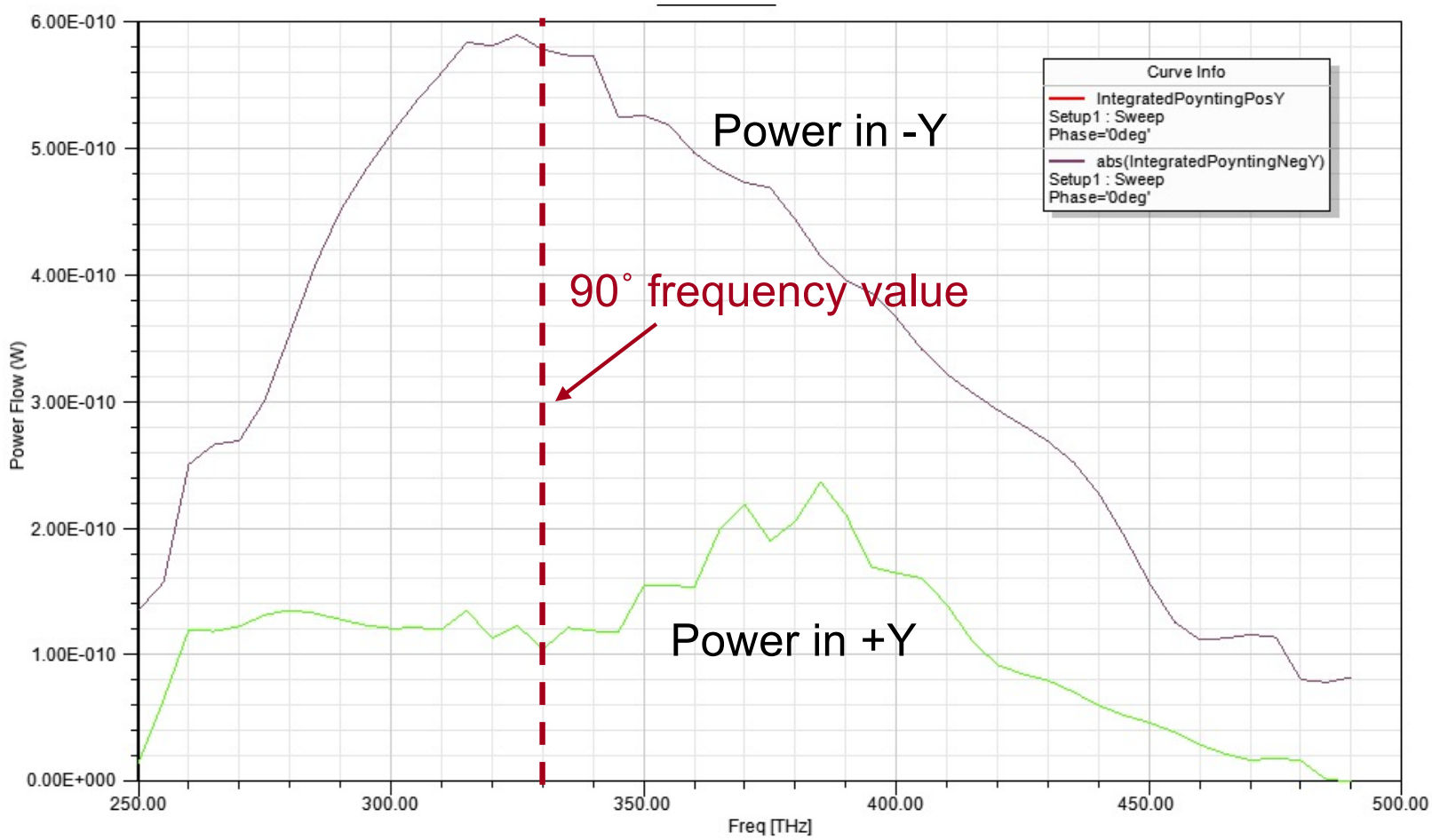
$$\Delta\omega = 2\pi\,\Delta f \;;\;\; \Delta f = 5\ \mathrm{THz}$$

$$U_e = \frac{P_\omega}{\Delta\omega} = \mathrm{Energy}\,/\,e\,/\,\mathrm{period}$$

$$P_{\mathrm{rad}} = U_e\,\frac{I_{\mathrm{beam}}}{q}\,N_{\mathrm{periods}}$$

Parameter	Symbol	Value
Grating period	λ_p	300 nm
Energy	T_0	30 keV
Velocity	β	0.328
Angle	θ	90 deg
Central radiation wavelength	λ_{rad}	913 nm
Power in +y direction	P_ω	1.04e-10 W
Energy/e/period	U_e	3.3e-24 J
No. of periods	N_{periods}	666
Beam current	I_{beam}	1 μA
Photon flux		3.5e11 s^{-1}
Total power	P_{rad}	**13.7 nW**

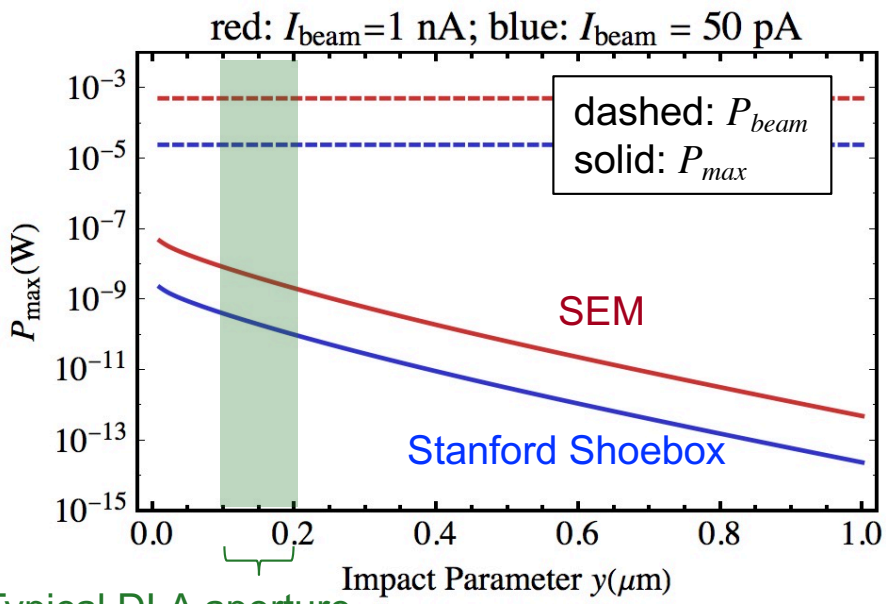
Incoherent Smith Purcell Spectrum



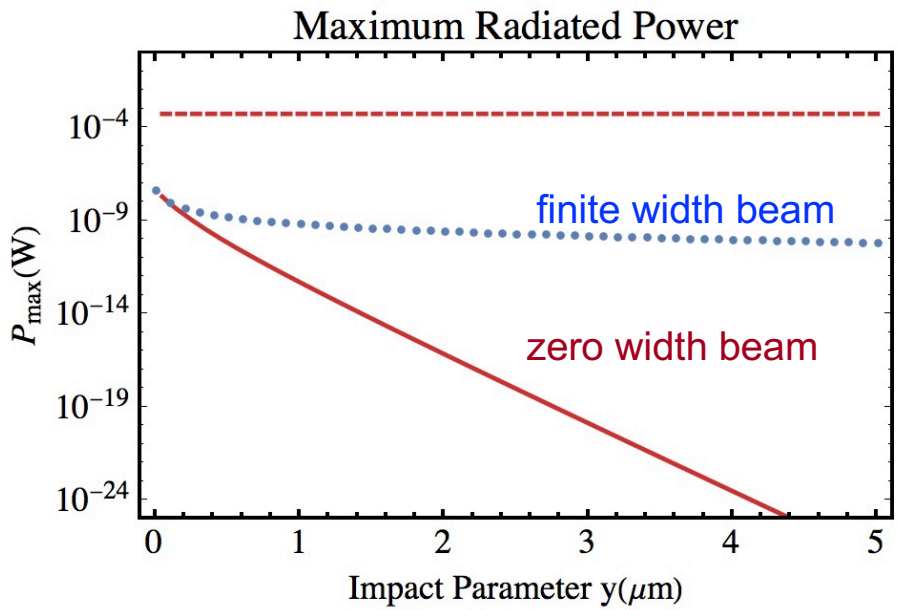
Interestingly, the simulation predicts more power flow into the silicon than into the vacuum region above the grating. However, the absorptive loss of silicon (not included here) may reduce this discrepancy.

Maximum Power Emission

Silicon n = 3.43, Electron Energy = 50 keV, Structure period = 1 μm; Structure length = 200 μm; linear material and neglect wavelength dependence of index n



Typical DLA aperture

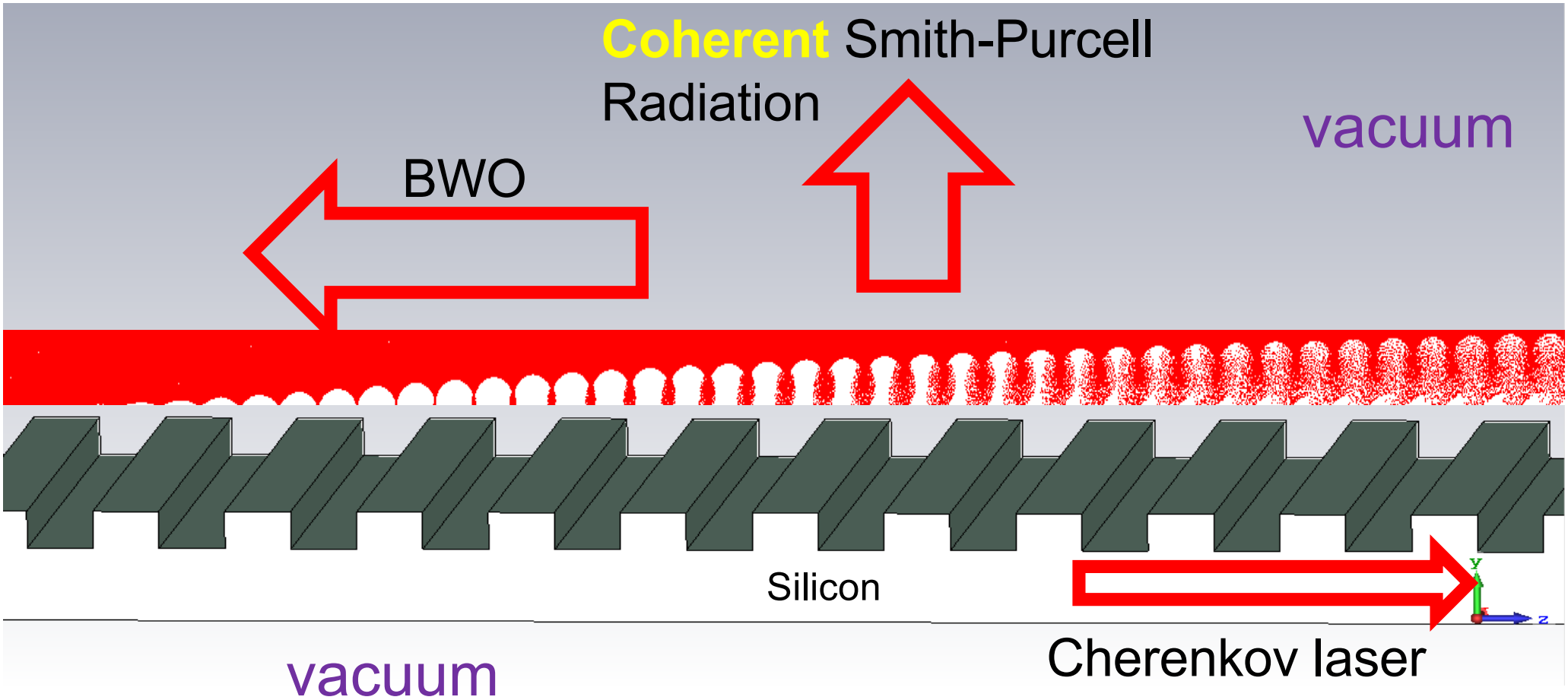


Suggests that for typical DLA impact parameters (r ~ 0.1 to 0.2 μm) radiation power can theoretically be in the nW range for nA beam current.

May require specialized structures (e.g. inverse design).
Potential for coherent enhancement via microbunched beams.

see methodology of Yang, et al., Nature Physics 14, 894-899 (2018)

Possible coherent radiations from a periodic Si structure



Simulations by Y-Ch. Huang, Tzuchih Liu (National Tsing Hua Univ)

CST Simulation for Si grating (@ 20 ps): Coherent TM Radiation at 1.1 μm detected at 90th period

(Y-C. Huang, Tzuchih Liu)

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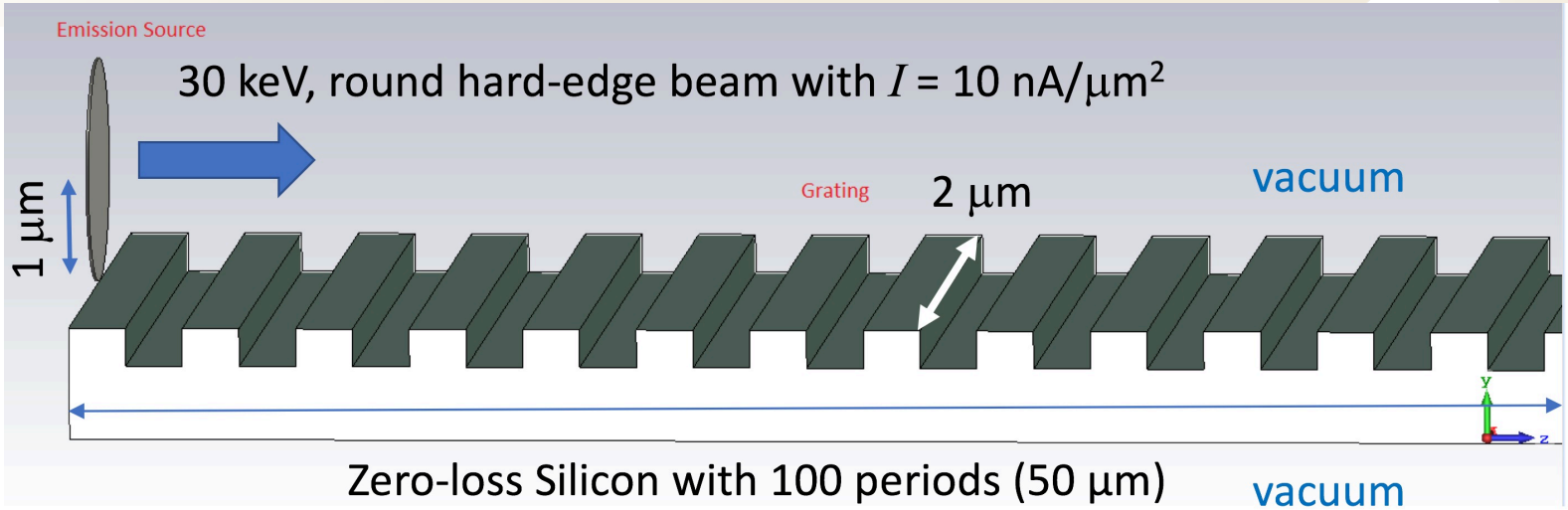
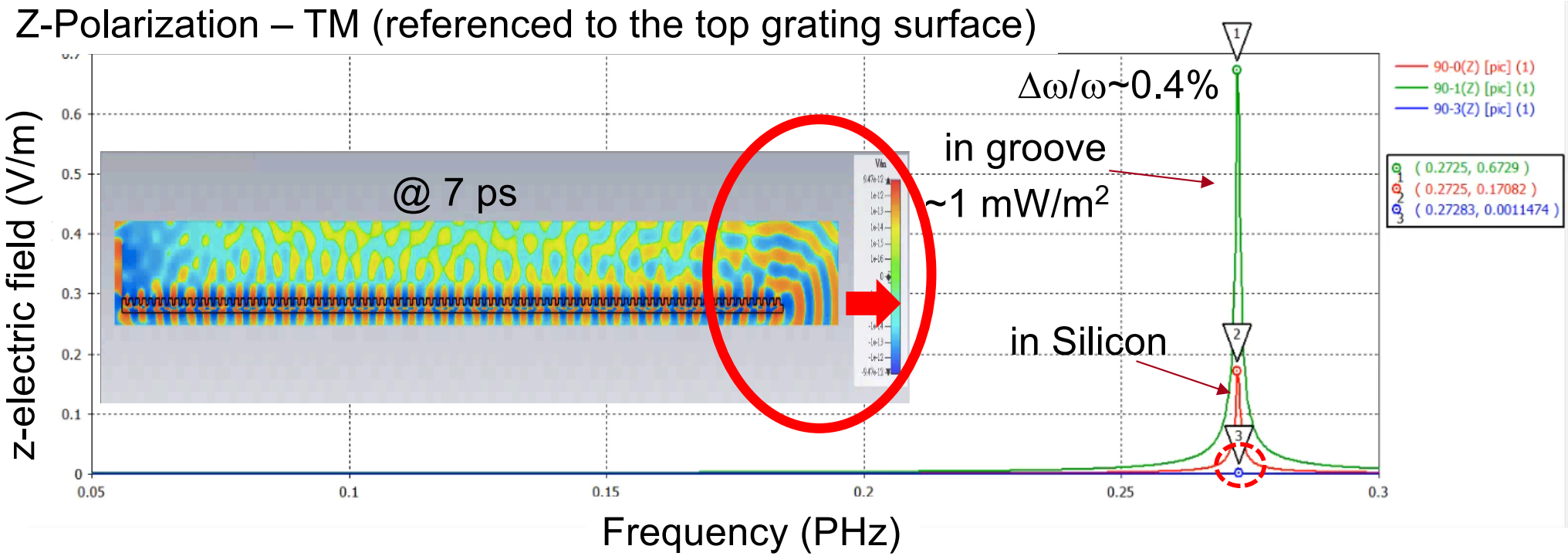


Z-Polarization – TM (referenced to the top grating surface)



Conclusions

SLAC

- → A sub-group of ACHIP has been established to explore radiation generation and applications for DLA technology
- → Workshop conducted in March outlined future directions for attosecond science, microscopy, radiobiology, and medical applications
- → A laser driven undulator combined with a DLA provides a potential future compact source of coherent attosecond undulator radiation for EUV or X-ray production
- → Near-term experiments planned to study coherent radiation generation in silicon and other DLA-like structures (inverse radiative processes of the acceleration mechanism)
- → DC Electron gun test stand now in operation to facilitate these investigations. Partnerships with Technion, NTHU for experiment and simulation.

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Doron Bar-Lev
Avi Gover

Technion
Levi Schachter
Naama Cohen

Univ. of Wroclaw
Andrzej Szczepkowicz

blue = students; * = current Bob Siemann fellows

Thank you!

Group photo, ACHIP collaboration meeting at DESY, Hamburg, Germany, Sept 19-21, 2018.

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http://achip.stanford.edu
http://slac.stanford.edu/dla

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