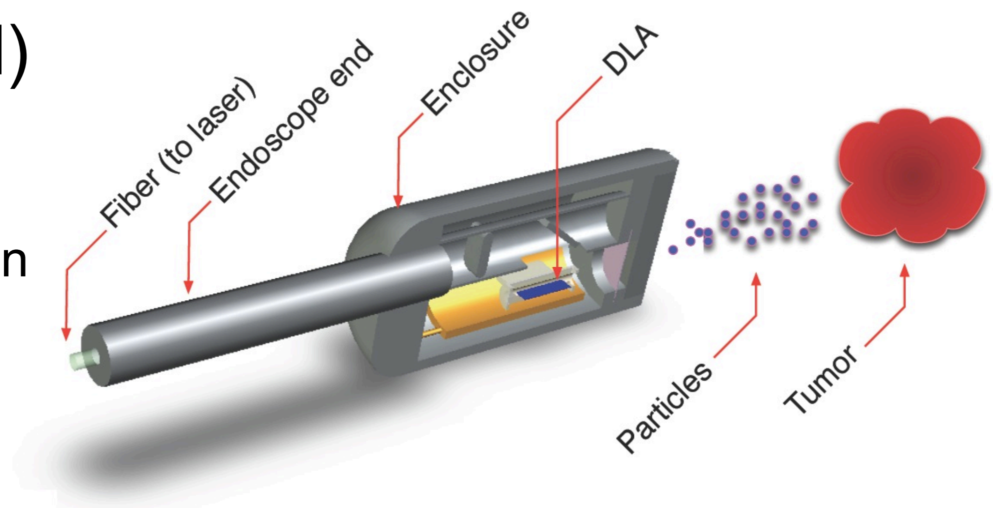
Applications for a Laser-Driven Accelerator on a Chip

R. J. England (SLAC, Stanford)

SPIE Optics and Optoelectronics,
Workshop on Applications of Laser-Driven Particle Accelerators (ALPA)
April 2-3, Prague, Czech Republic



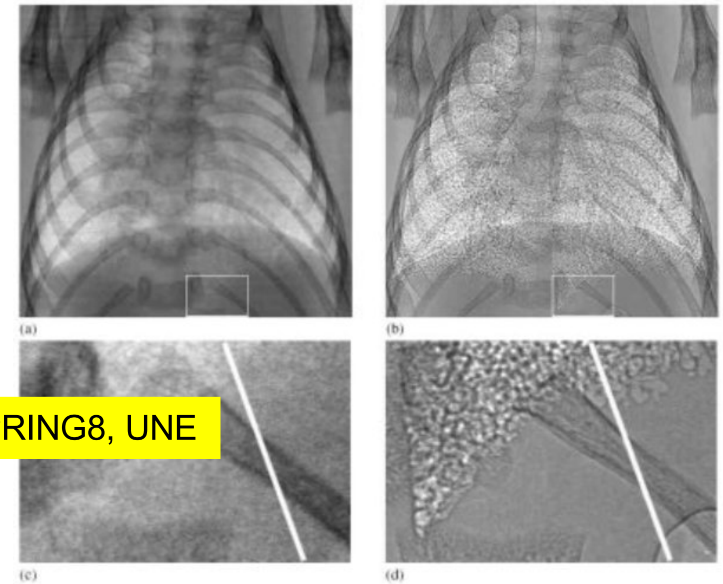
U.S. DEPARTMENT OF ENERGY
Office of Science

SLAC NATIONAL ACCELERATOR LABORATORY

In what ways could smaller more affordable particle accelerators benefit us?

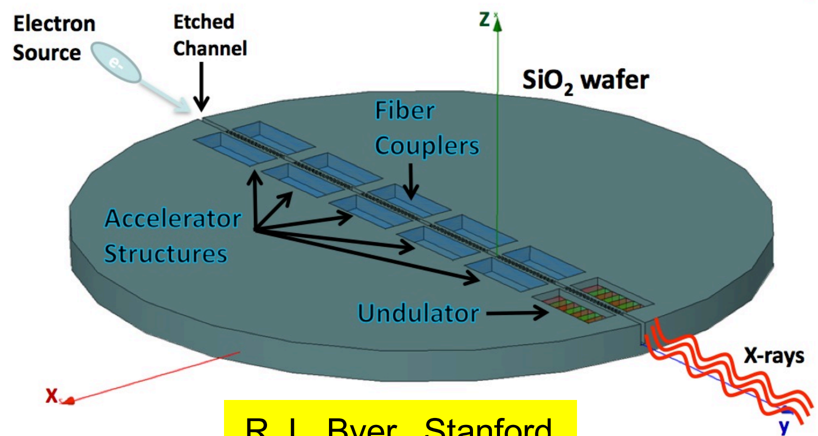
SLAC

phase contrast imaging



SPRING8, UNE

university-scale x-ray laser



R. L. Byer, Stanford

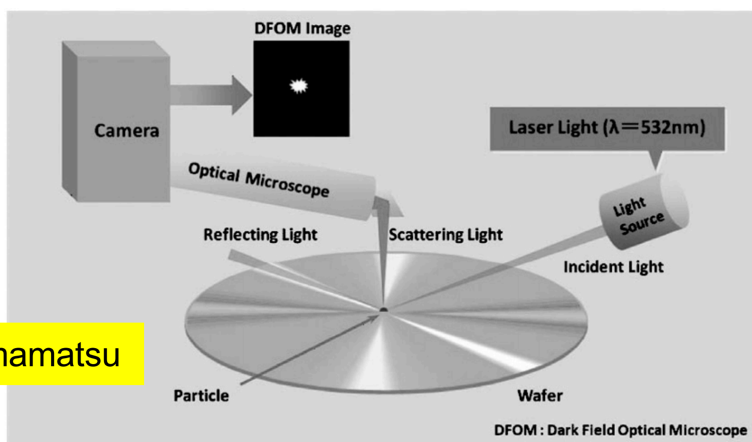
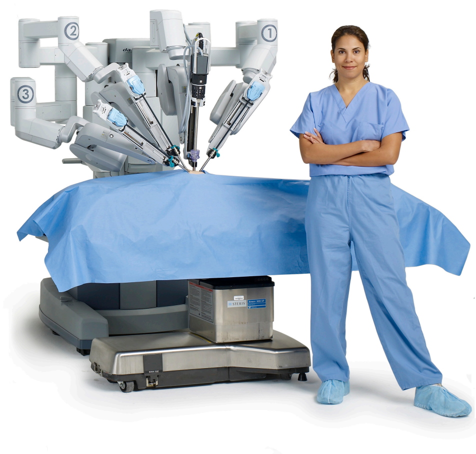
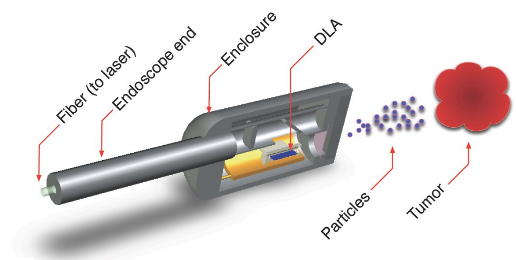


Fig. 3 Dark field optical microscope on review SEM.

Hamamatsu

industrial wafer inspection

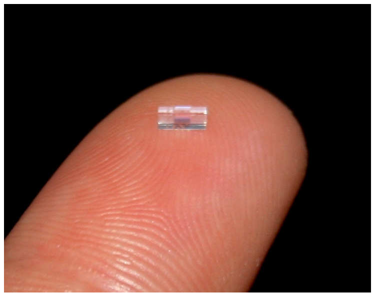




Gil Travish, UCLA

portable cancer treatment

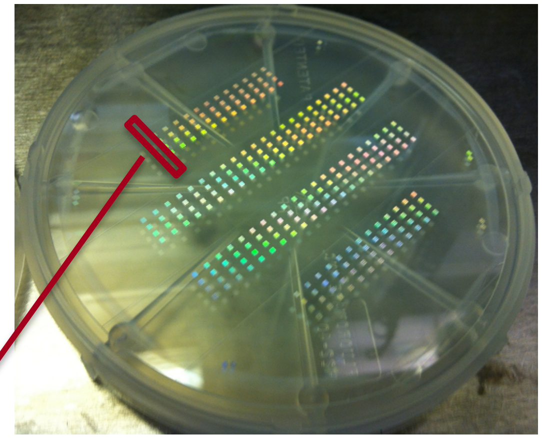
Dielectric Laser Acceleration (DLA) Concept



laser-driven microstructures

- **lasers:** high rep rates, strong field gradients, commercial support
- **dielectrics**: higher breakdown threshold → higher gradients (1-10 GV/m), leverage industrial fabrication processes

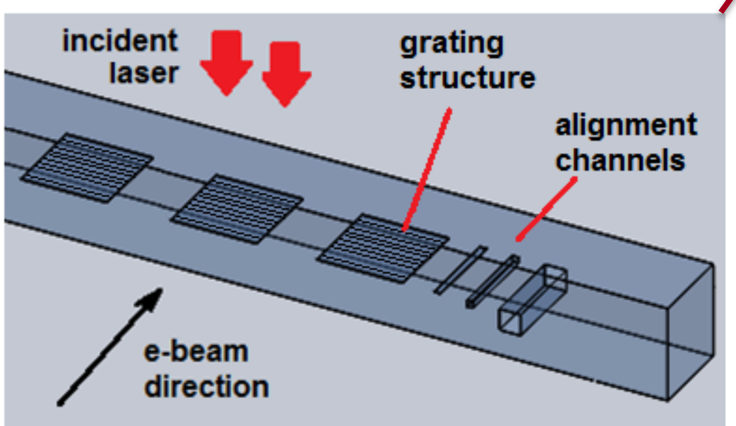
"Accelerator-on-a-chip"

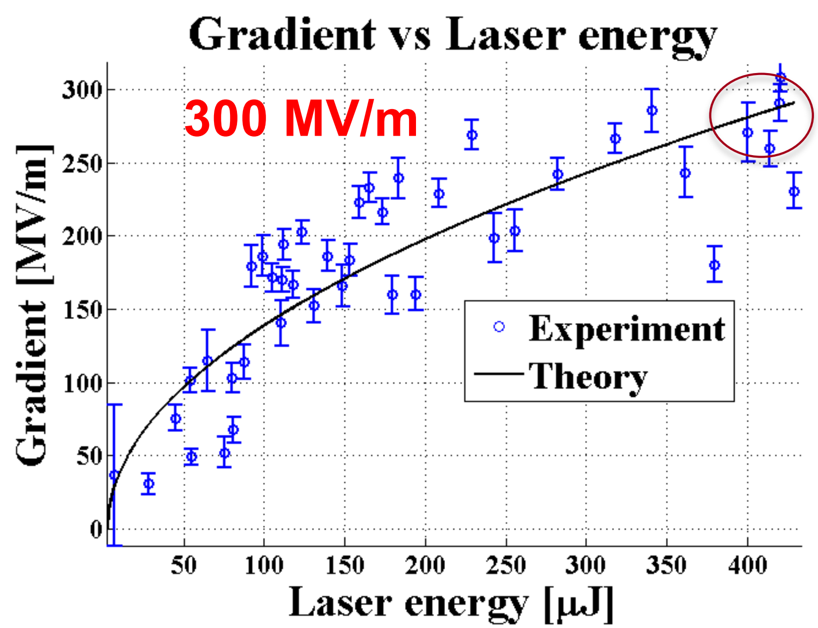


bonded silica phase reset accelerator prototypes fabricated at SLAC/Stanford

Goal: lower cost, more compact, energy efficient, higher gradient

Wafer is diced into individual samples for e-beam tests.





DLA leverages advances in two major industries: solid state lasers + semiconductor fabrication

Not high peak power lasers!

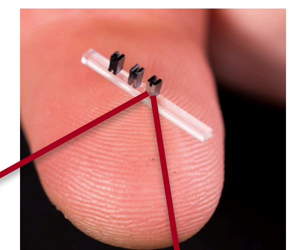
Parameter	DLA Value
Wavelength	2 µm
Pulse Duration	100 fs
Pulse Energy	1 µJ
Laser Power	100 W
Rep Rate	100 MHz
Laser Efficiency	30%
Cost/laser	$150k

Solid-state laser

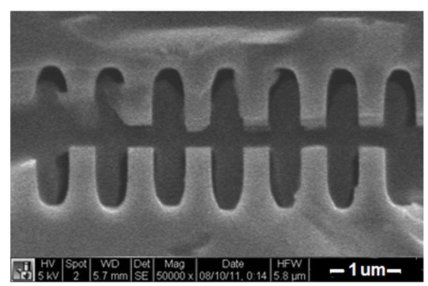
Available now "off the shelf"

Fabricated using techniques of the integrated circuit industy.

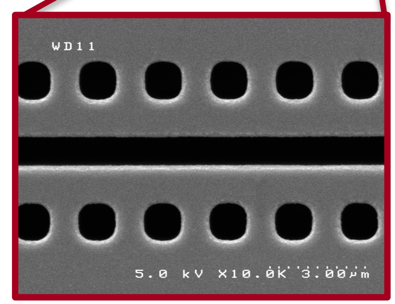
DLA structures are made by students in the Nanofabrication Facilities at partner universities.



SEM images of DLA prototypes tested at NLCTA



fused silica



silicon

A 5-Year initiative in DLA has been funded by the Gordon and Betty Moore Foundation (2015 – 2020)

Executive Committee:

R. L. Byer (Stanford), P. Hommelhoff (FAU), R. J. England (SLAC), R. Assmann (DESY), R. Ischebeck (PSI)

Sub-Relativistic DLA experiments
Stanford: Harris, Solgaard
Erlangen: Hommelhoff

Structures
Stanford: Harris, Solgaard, Byer
Erlangen: Hommelhoff

System integration (Core DLA groups)
Stanford: Byer, Harris, Solgaard
Erlangen: Hommelhoff

Electron source
UCLA: Musumeci
Erlangen: Hommelhoff
Stanford: Harris, Solgaard

Simulations
Tech-X: Cowan
U Darmstadt: Boine-Frankenheim

Light Coupling
Stanford: Fan, Vučković

Relativistic DLA experiments
SLAC: England
DESY/UnivHH: Assmann, Kaertner, Hartl
PSI/EPFL: Ischebeck, Rivkin

Associated Scientific Collaborators
Yenchieh Huang (Tsinghua)
Evgenya Simakov (Los Alamos)
Zhirong Huang (SLAC)
Kazu Koyama (Tokyo U)

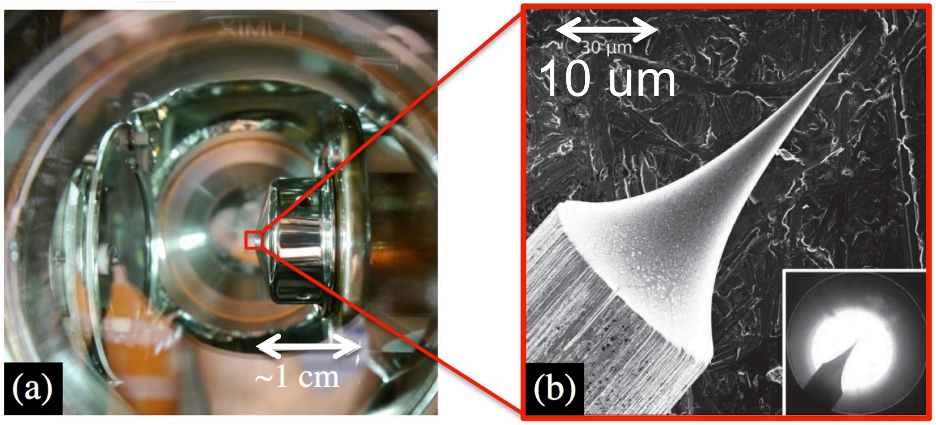
Industrial affiliate
Hamamatsu Corp. Japan
(joined June 2017)

Program start: Dec. 2015

ACHIP Scientific Advisory Board:
Chan Joshi (UCLA), Tor Raubenheimer (SLAC) , Reinhard Brinkmann (DESY)

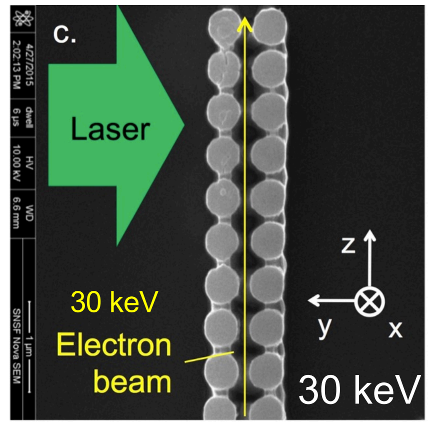
What has been done to date?

compact field emission e- sources

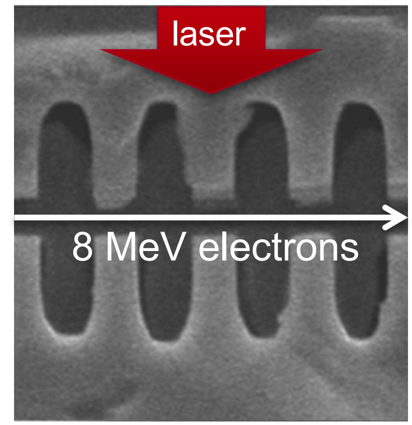


Hoffrogge, et al. J. Appl. Phys. 115, 094506 (2014)

high gradient (0.3 → 0.85 GV/m)

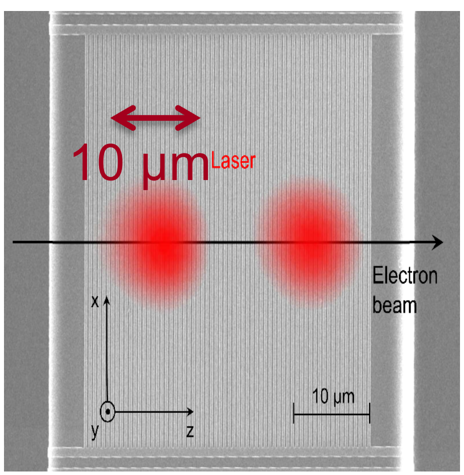


Leedle, et al. Opt. Lett. 40, 4344 (2015)

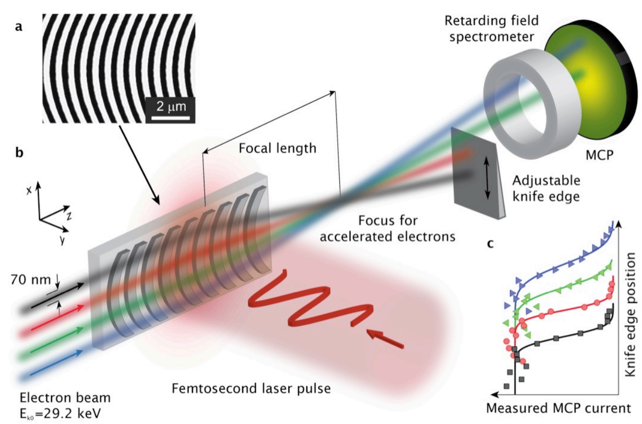


Cesar et al., Nat. Comm. Phys. (2018)

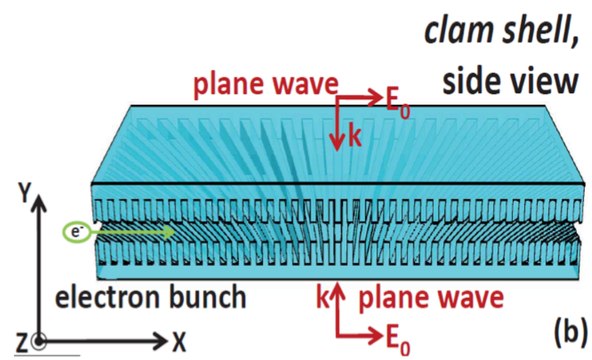
"staging" with 2 lasers



sub-relativistic focusing



beam position monitor



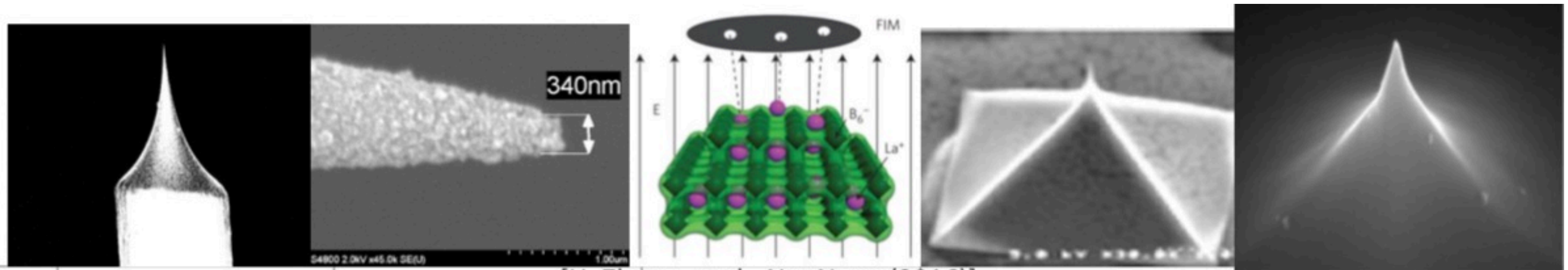
Opt. Lett., **37** (5) 975-977 (2012)

Opt. Lett., **39** (16) 4747 (2014)

J. McNeur, "Elements of a Dielectric Laser Accelerator," Optica 5 (6), 687 (2018)

High Brightness Photocathodes Tested Under the ACHIP Program...

SLAC

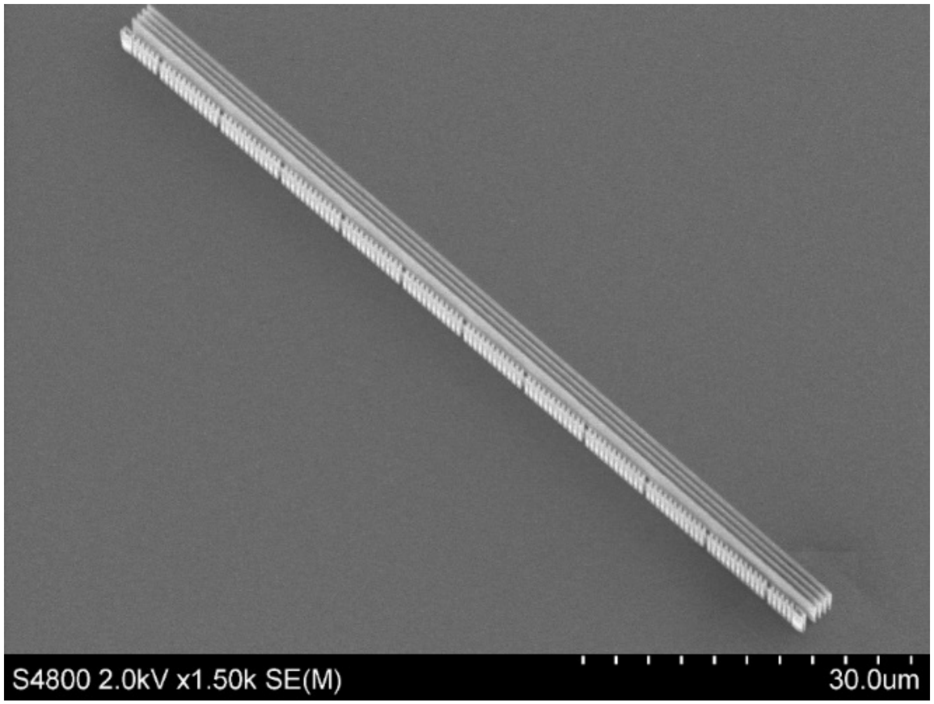


[H. Zhang, et al., Nat Nano (2016)]

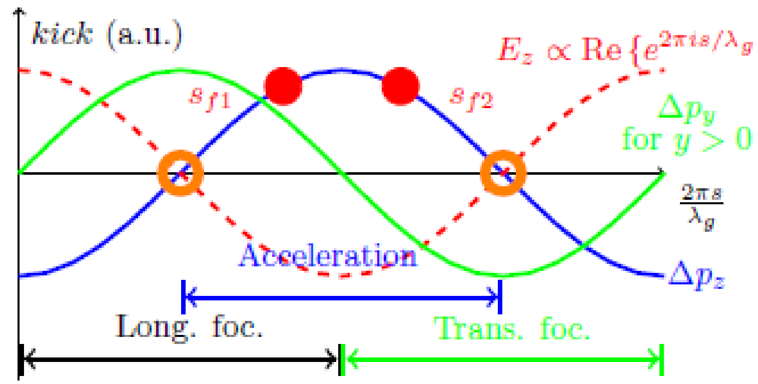
	W tip (Erlangen)	W tip w/ diamond (Erlangen)	LaB_6 nanowire (Erlangen)	diamond pyramid (Los Alamos)	Si nanotip
R (nm)	(<1.0)	170	(1.5)	<10	**15**
max e^-/pulse	625	1000	20	12000	**1000**
ϵ_n (nm)	0.1	0.35	0.1	?	**0.25**
$B_{5D,n}$ (A/cm^2)	6.7e12	1e10	1.1e12	?	**1e12**
stability	30 min	>1 hour	?	>1 hour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

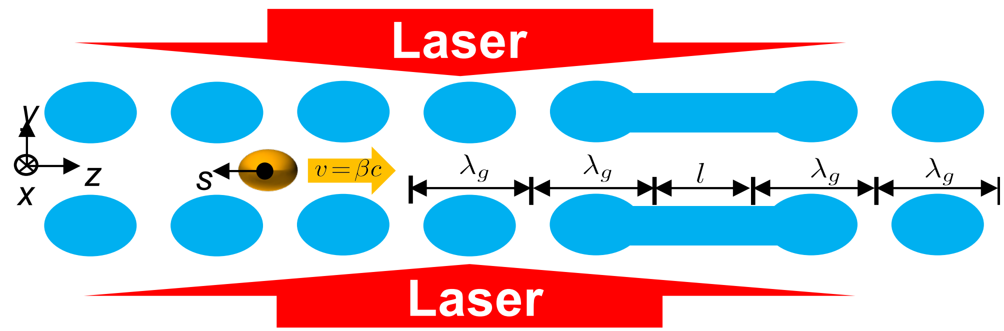
A. Ceballos, DLA Applications Workshop, March 26 (2019)

Structures Incorporating Laser-Driven Focusing Have Been Recently Fabricated for Experimental Tests



Hommelhoff Group, FAU Erlangen, Germany



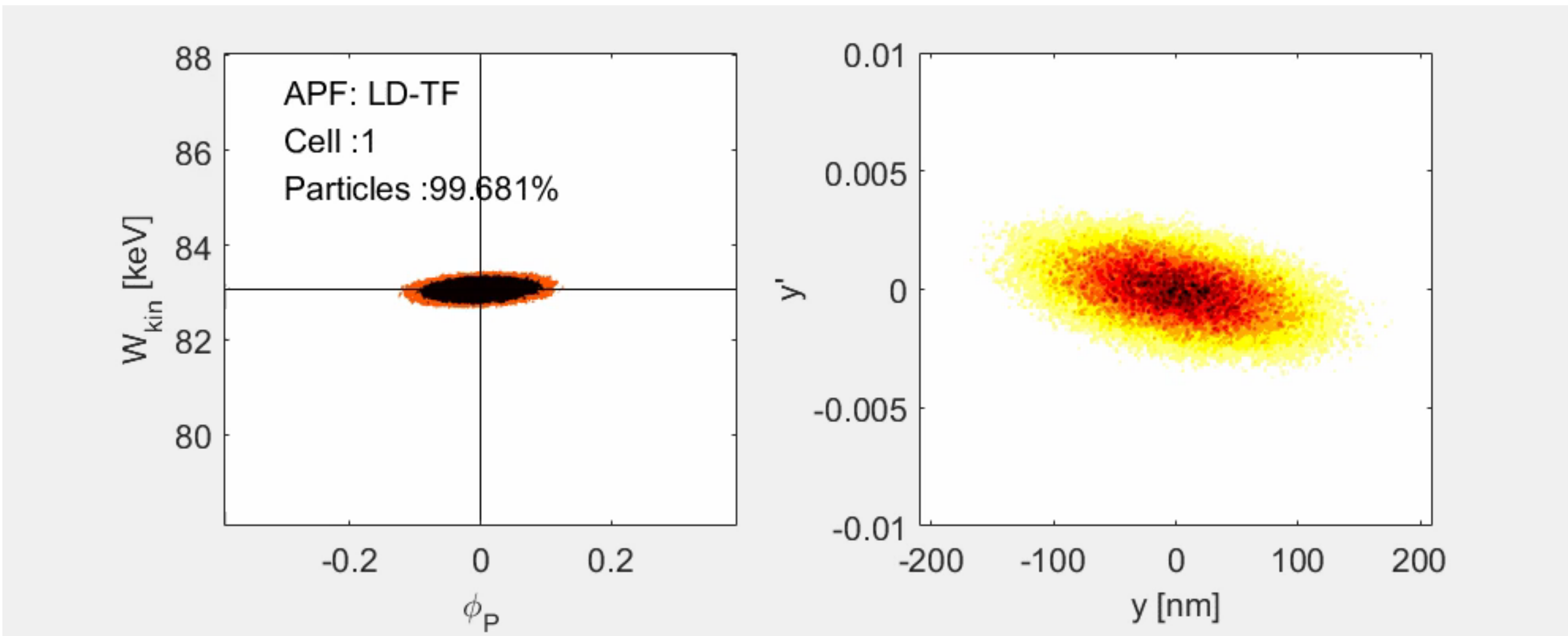


Niedermayer, et al., PRL **121**, 214801 (2018)

- First APF structure optimized for 2000 nm laser wave length and 26.478 keV electron beam Structure length required pulse front tilted (PFT) laser pulses
- Structure is only for guiding as a proof-of-principle
- Goal is to see a maximum laser ON/OFF contrast of 2.5:1
- Additionally the contrast should scale with incident laser power

Phase manipulation provides a means of transverse focusing using the laser field itself

*Alternate between transverse focusing-longitudinal defocusing and transverse defocusing-longitudinal focusing → **net focusing***

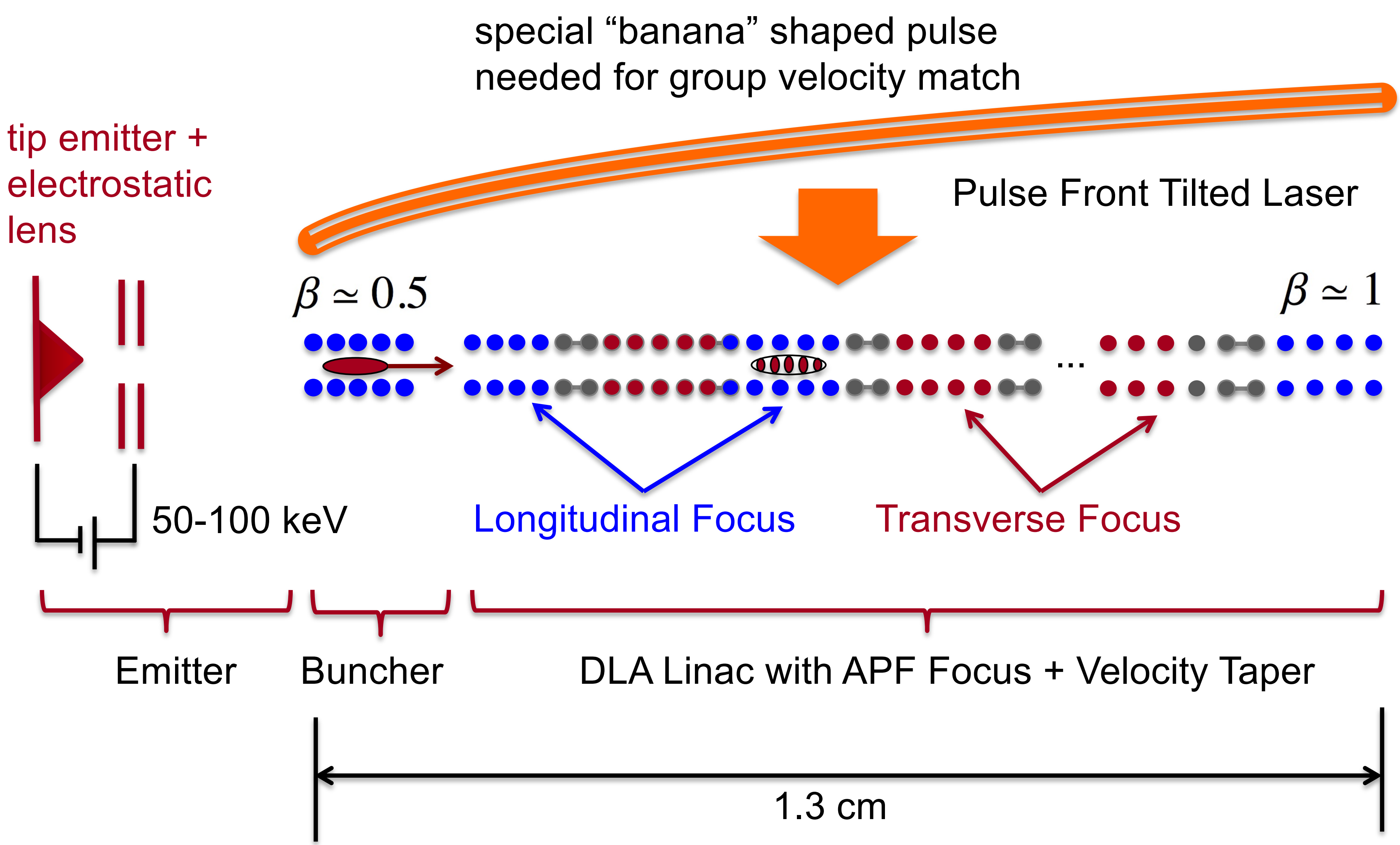


83 keV → >1 MeV:
56% transmission for 100pm emittance,
93% for 25pm emittance

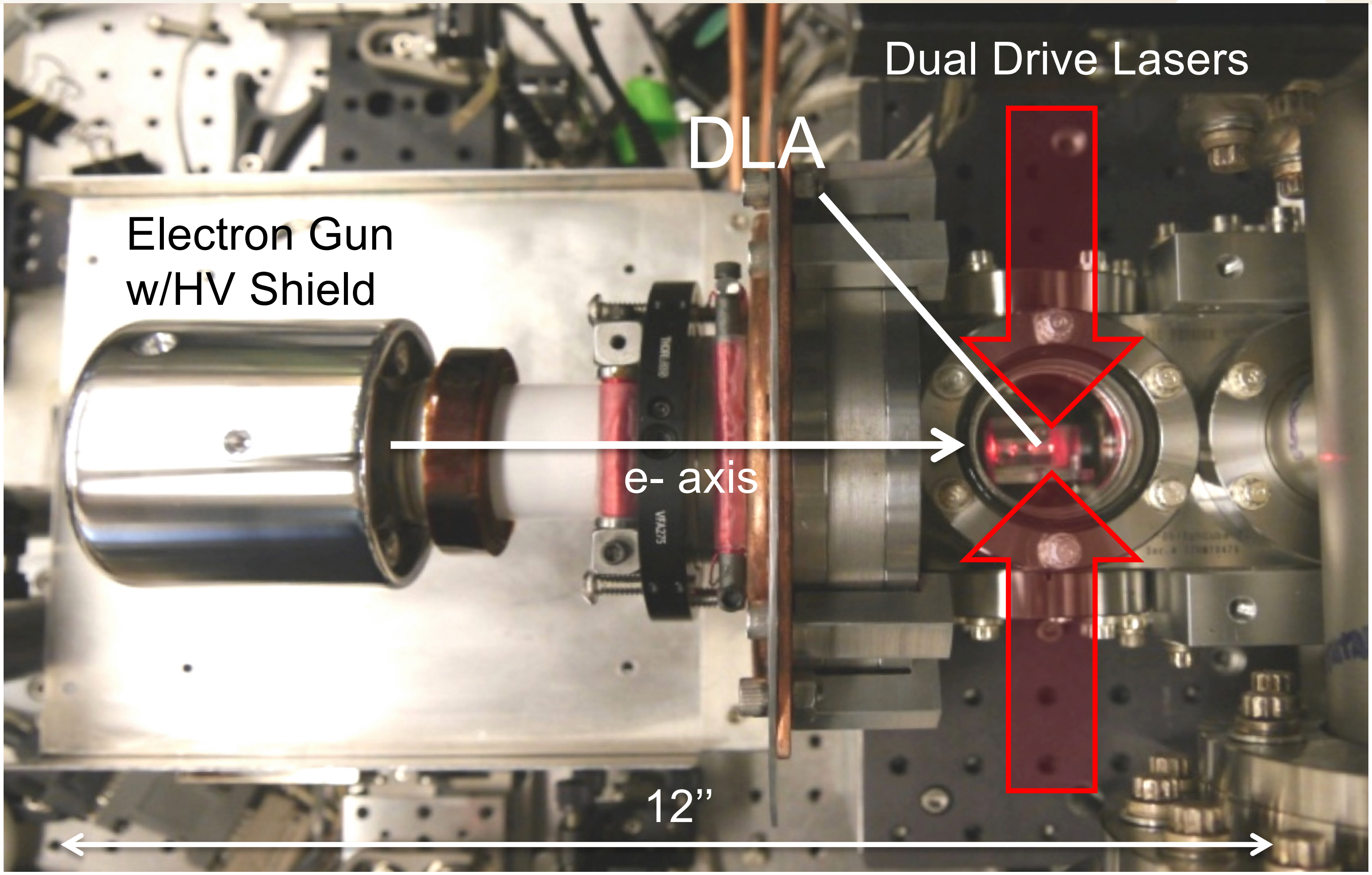
U. Niedermayer, T. Egenolf, O. Boine-Frankenheim, P. Hommelhoff, Phys. Rev. Lett. 121, 214801 (2018)

Concept for 1 MeV "Shoebox" Accelerator (1 Year)

A single bunching/acceleration/focusing stage driven by a tilted laser pulse.



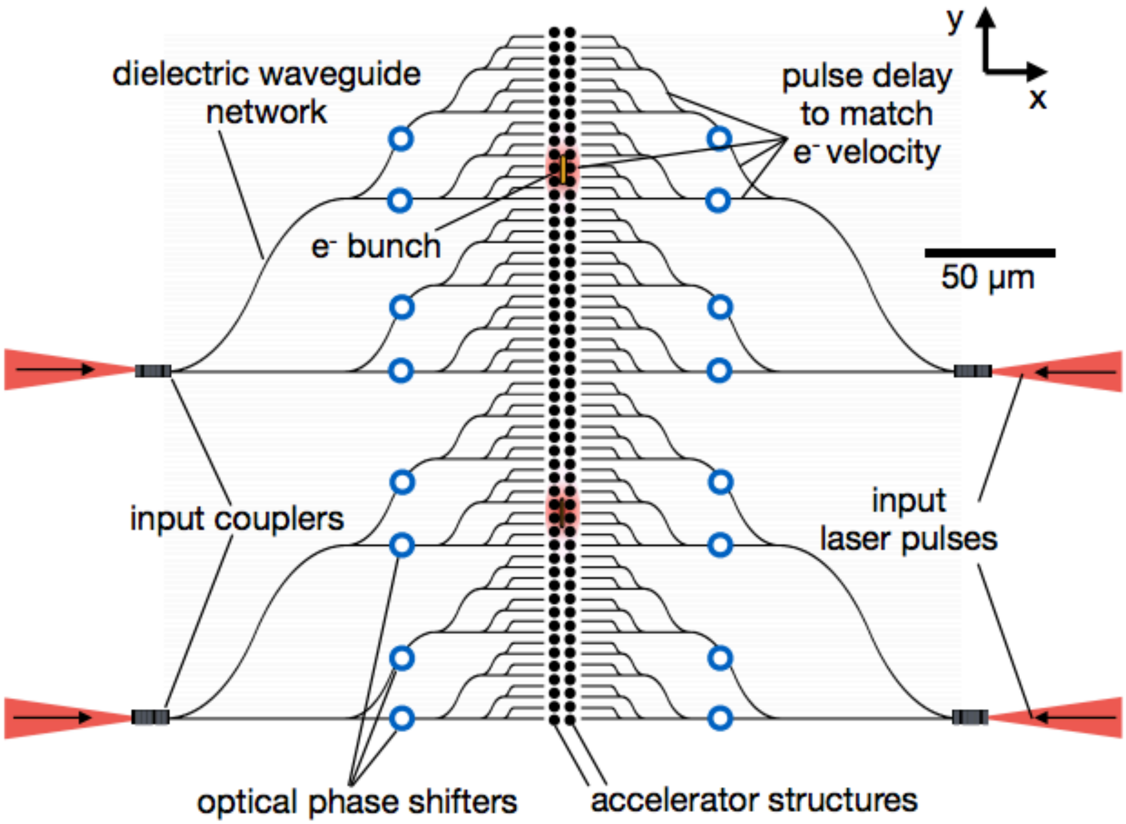
A compact prototype "shoebox" test system is now operating at Stanford University – goal of 1 MeV energy

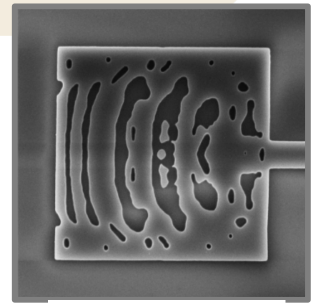


55 keV e- gun; nA beam current
Silicon tip emission source; Hexapod positioning stage

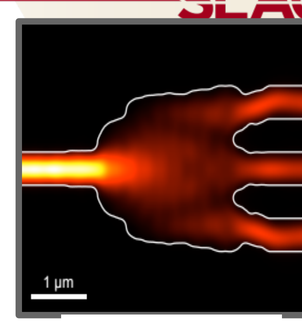
image courtesy K. Leedle, J. Harris lab (Stanford University)

Multistage Waveguide Network Design for a Dielectric Laser accelerator

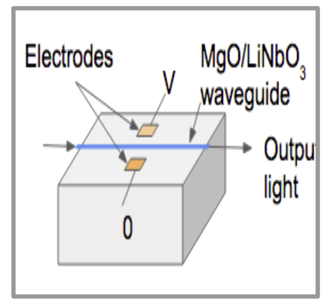




couplers



splitters



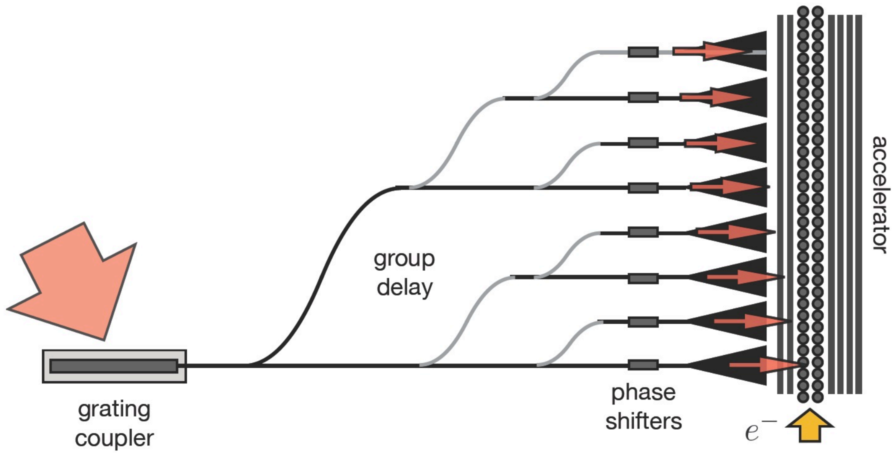
phase shifters

T. Hughes, et al. "On-Chip Laser Power Delivery System for Dielectric Laser Accelerators,"
Phys. Rev. Appl. 9, 054017 (2018)

- **Design Study of Integrated Multi-Stage DLA Network**
- **Realistic Component Parameters**
- **Adjoint Variable ("Inverse Design") Based Structure Optimizations**

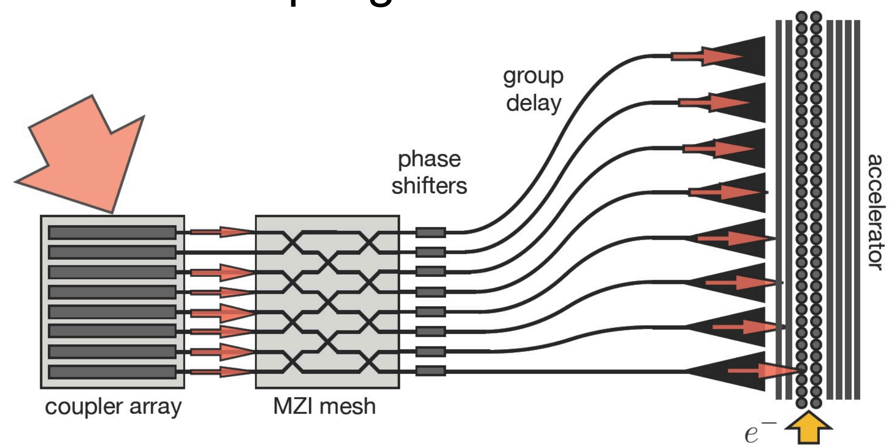
Direct Coupling to a Waveguide Network with MZI Control Removes Bottlneck at the Input Facet

splitting structure

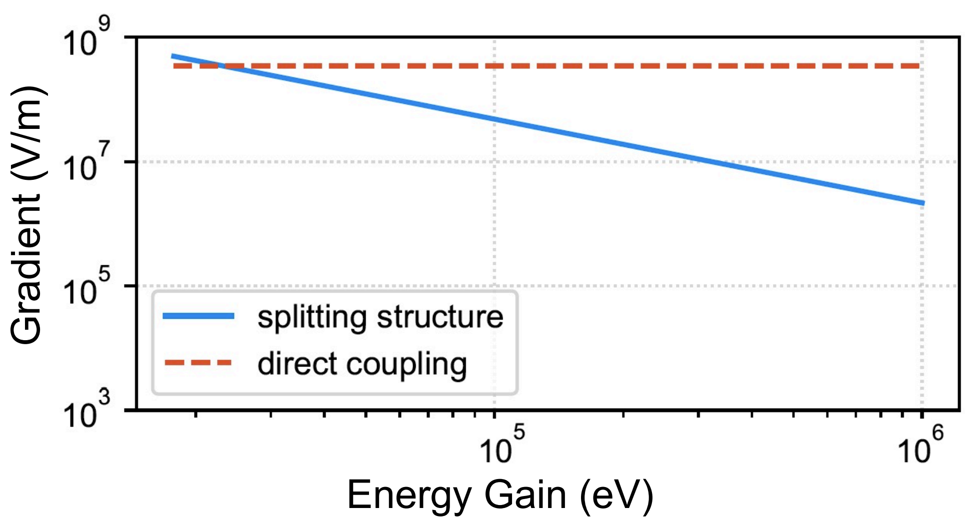


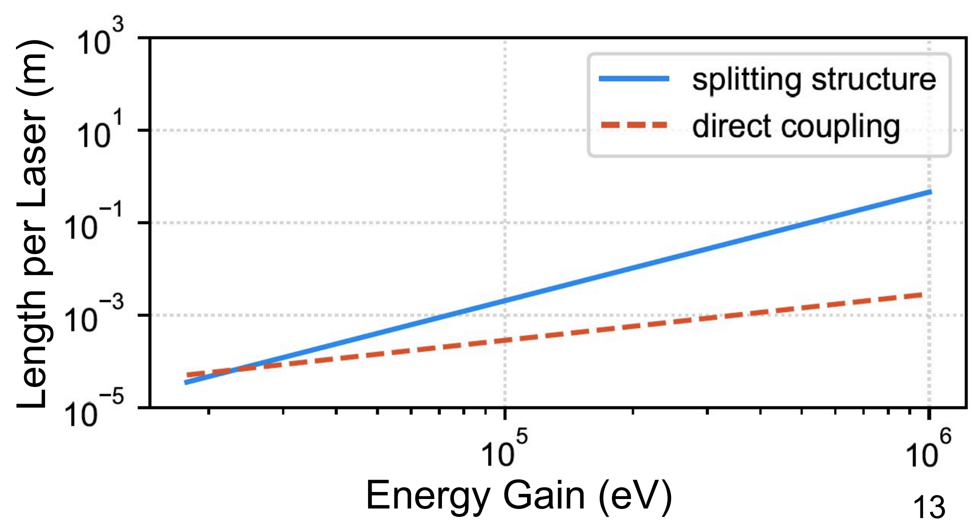
Hughes, et al. PRA **9**, 054017 (2018)

direct coupling with MZI mesh

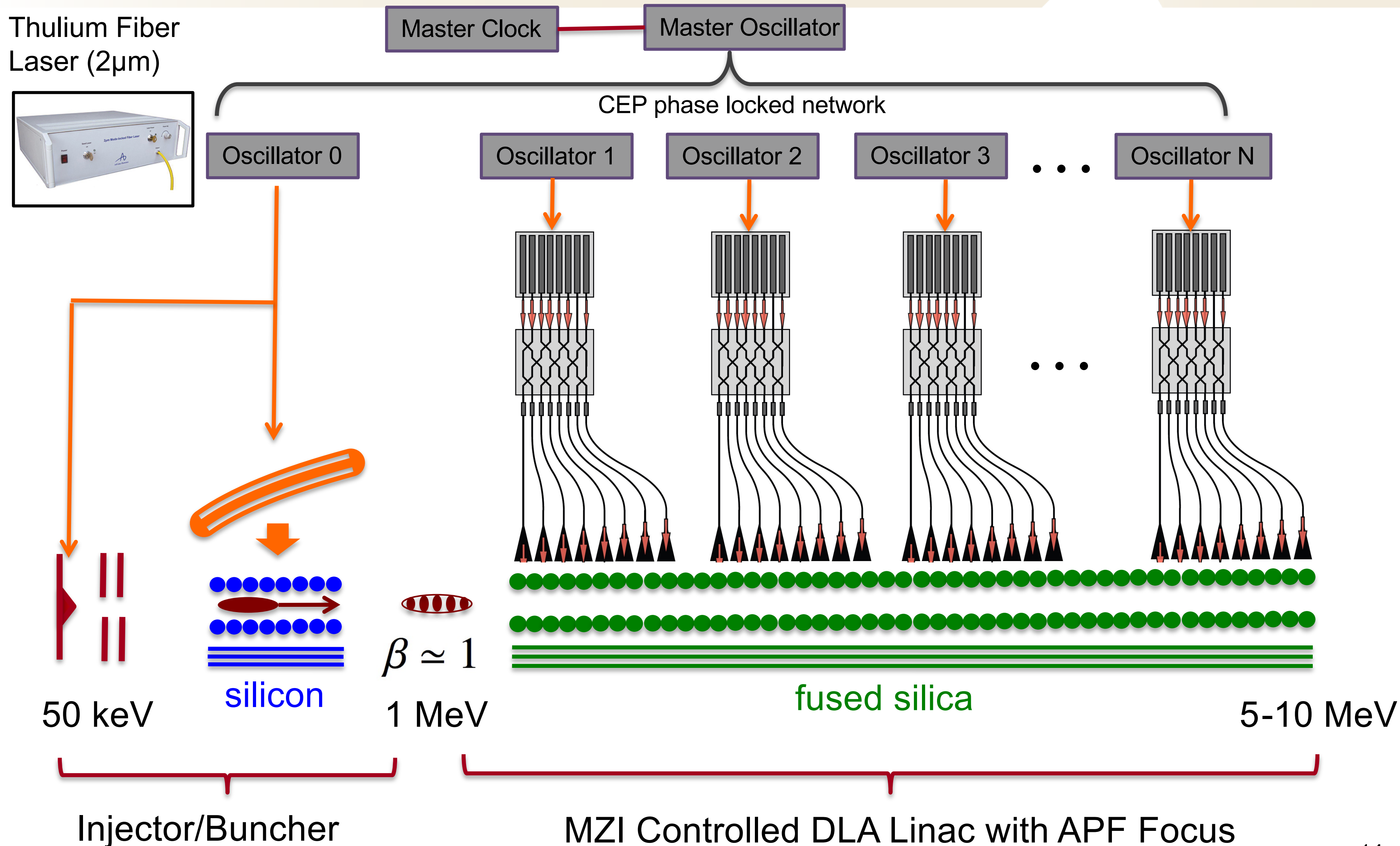


Hughes, England, Fan, submitted, PRA (2019)





Concept for Injector + Multistage Accelerator (2-5 Year)



A 1-Day workshop was held last week at Stanford University to explore potential Applications

SLAC

2nd workshop on Applications of Dielectric Laser Accelerators

26 March 2019
Stanford University
US/Pacific timezone

- Overview
- Timetable
- Contribution List
- Registration
  - Modify my Registration
- Participant List
- Workshop Dinner
- Workshop Location

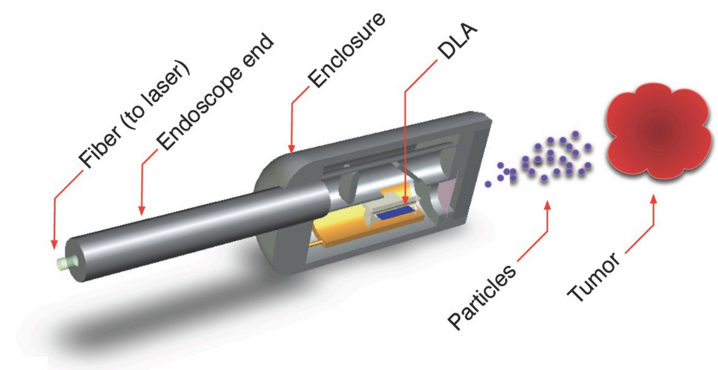
We are pleased to announce a one-day by-invitation-only meeting to be hosted on March 26, 2019 at Stanford University. The goal of this meeting is to explore applications for a future compact dielectric micro-structure based accelerator powered by ultrafast solid state lasers. This approach to particle acceleration, colloquially referred to as an "accelerator on a chip", has garnered increasing interest in recent years.

The Accelerator on a Chip International Program (ACHIP), a multi-institutional research program led by Stanford University and Friedrich-Alexander-University Erlangen-Nuremberg (FAU), and funded by the Gordon and Betty Moore Foundation, has been formed to address the many scientific and engineering challenges of advancing this technology toward useful applications. As part of this program, we have established a working group to explore Radiation Generation and Applications for dielectric laser-driven accelerators.

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

potential areas of industry interest

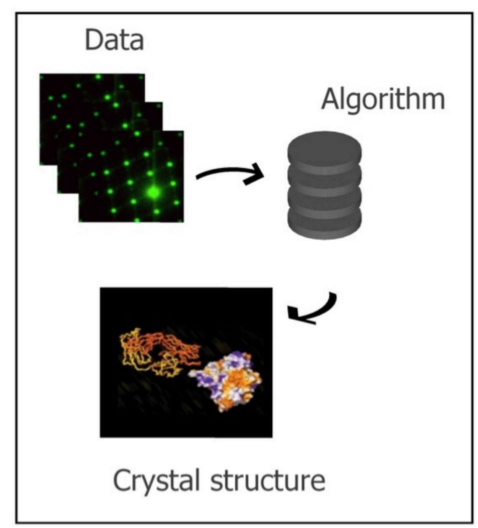
- Biomedicine industry
  -- Radiation therapy



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

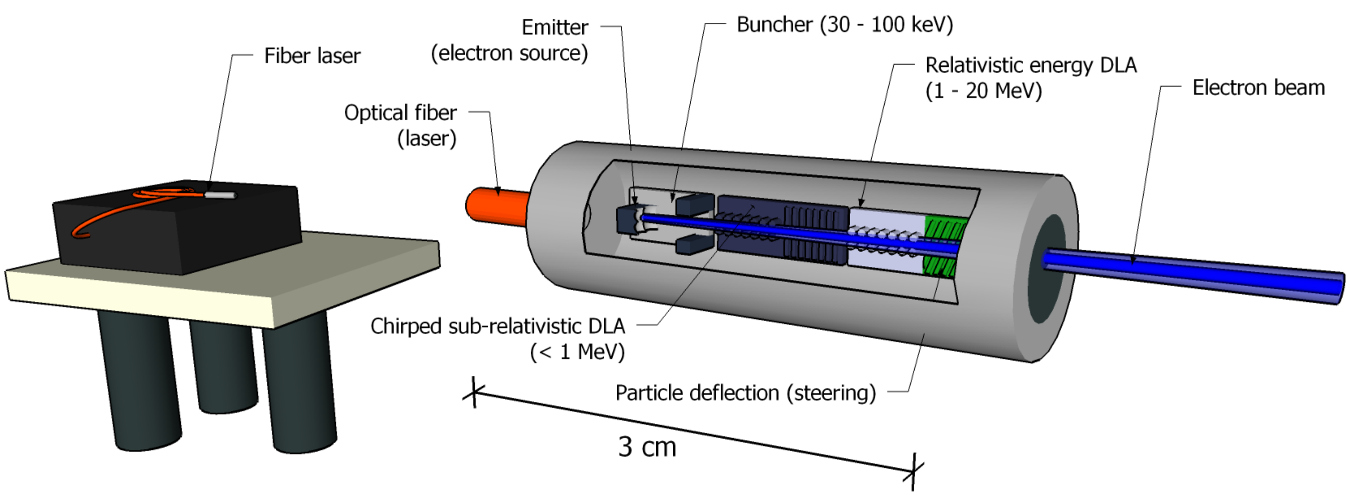
potential areas of scientific interest

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

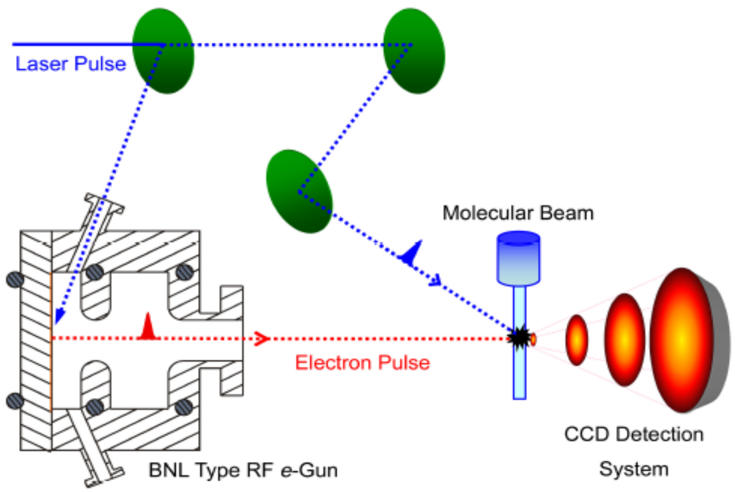


A Small Footprint Medical Accelerator Directly Maps to DLA's Unique Features

Parameter	Desired Capability	Unique DLA Features
Electron energy	10-20 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



High-Brightness DLA Beams for Ultrafast Electron Diffraction – Renkai Li (SLAC, Tsing Hua U., Beijing)



Typical UED beam parameters

Parameters	Values
rep. rate	SS - 180 Hz
beam energy	2 - 4 MeV
bunch charge	10^4-10^6
emittance	2 - 20 nm
bunch length	<50 fs rms

- *e*- probes can tackle broad range of scientific puzzles
- Imaging and energy loss spectroscopy more challenging, which require energy spread and stability
- DLAs based UED will be compact, all optical control
- Lower emittance, potentially reduced time-of-arrival jitter
- Promising sources for UED with improved probe size, q-resolution, and temporal resolution

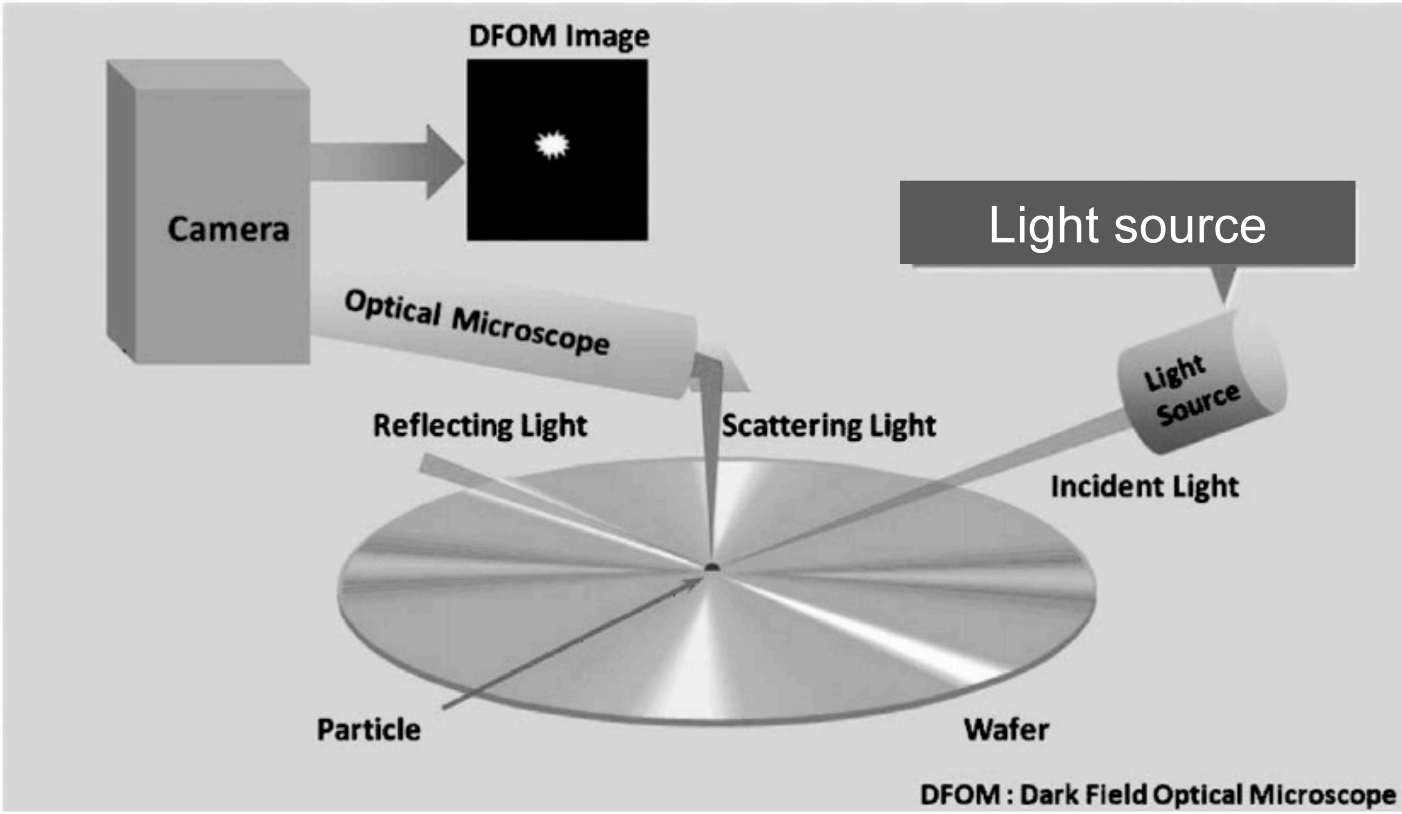
Characteristics of Interest for Industrial Applications

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

EUV Source for Wafer Inspection



J. Vac. Soc. Japan **10**, 578 (2010)

Rayleigh scattering intensity, $I = k\, I_0\, d^6 / \lambda^4$
k = constant, I_0 = incident light intensity
d = particle diameter, λ = wavelength

Higher power and shorter wavelength are better

What about the possibility of a DLA based light source?

Large facilities are often oversubscribed (e.g. the Linac Coherent Light Source at SLAC has ~ 5 times more proposals than it can accommodate)

Compact footprint and reduced cost would give university labs and smaller facilities greater access (e.g. an FEL in every university)

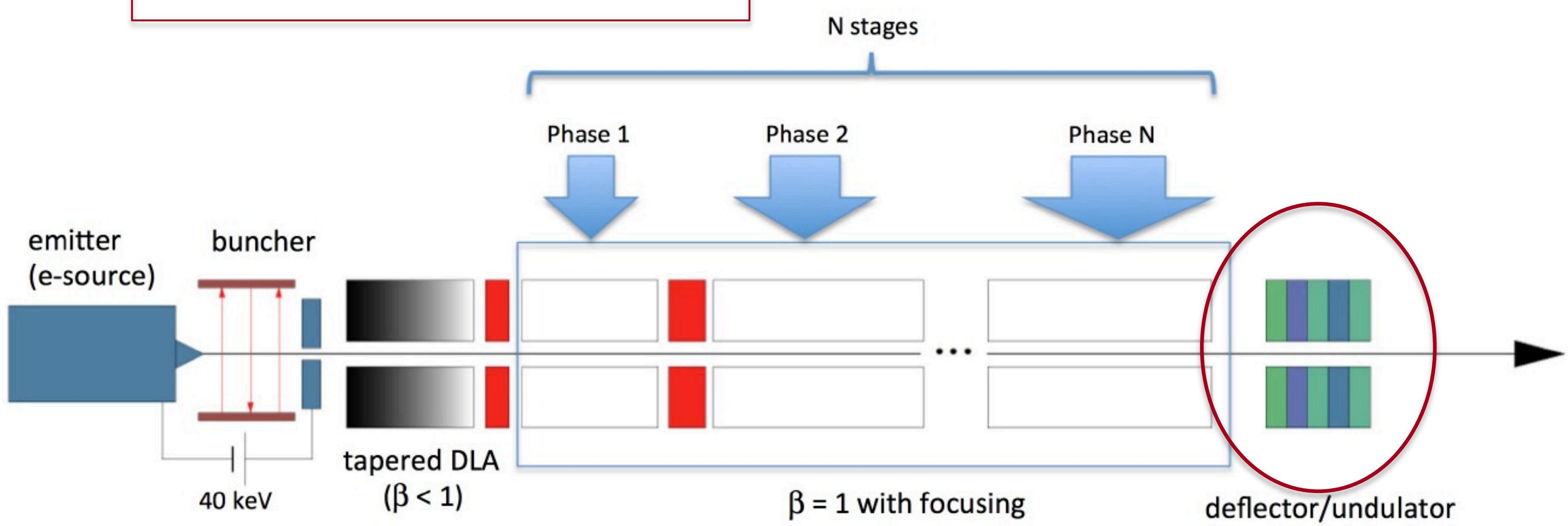
Sub-optical wavelength **(attosecond) temporal bunch structure** if translated into sub-fs radiation pulses would be useful for ultrafast science (molecular movies, atomic physics).

Compact, **portable scanners** for security (Nuclear Fluorescence), phase contrast imaging and medicine.

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.

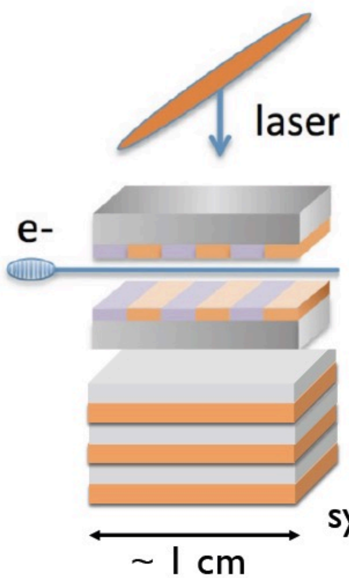
1. On-chip electron source
2. DLA structure development: (a) subrelativistic, (b) relativistic
3. Multi-staged acceleration
4. Coupling of laser to DLA
5. Laser-driven undulator



Concept for a compact laser-driven undulator for EUV production

SLAC

Light Source



One potential use for a dielectric deflecting structure is as a miniature (~1cm total undulator length) EUV light source

Bragg Reflector, one possible method to symmetrize fields without the need for a second driving laser

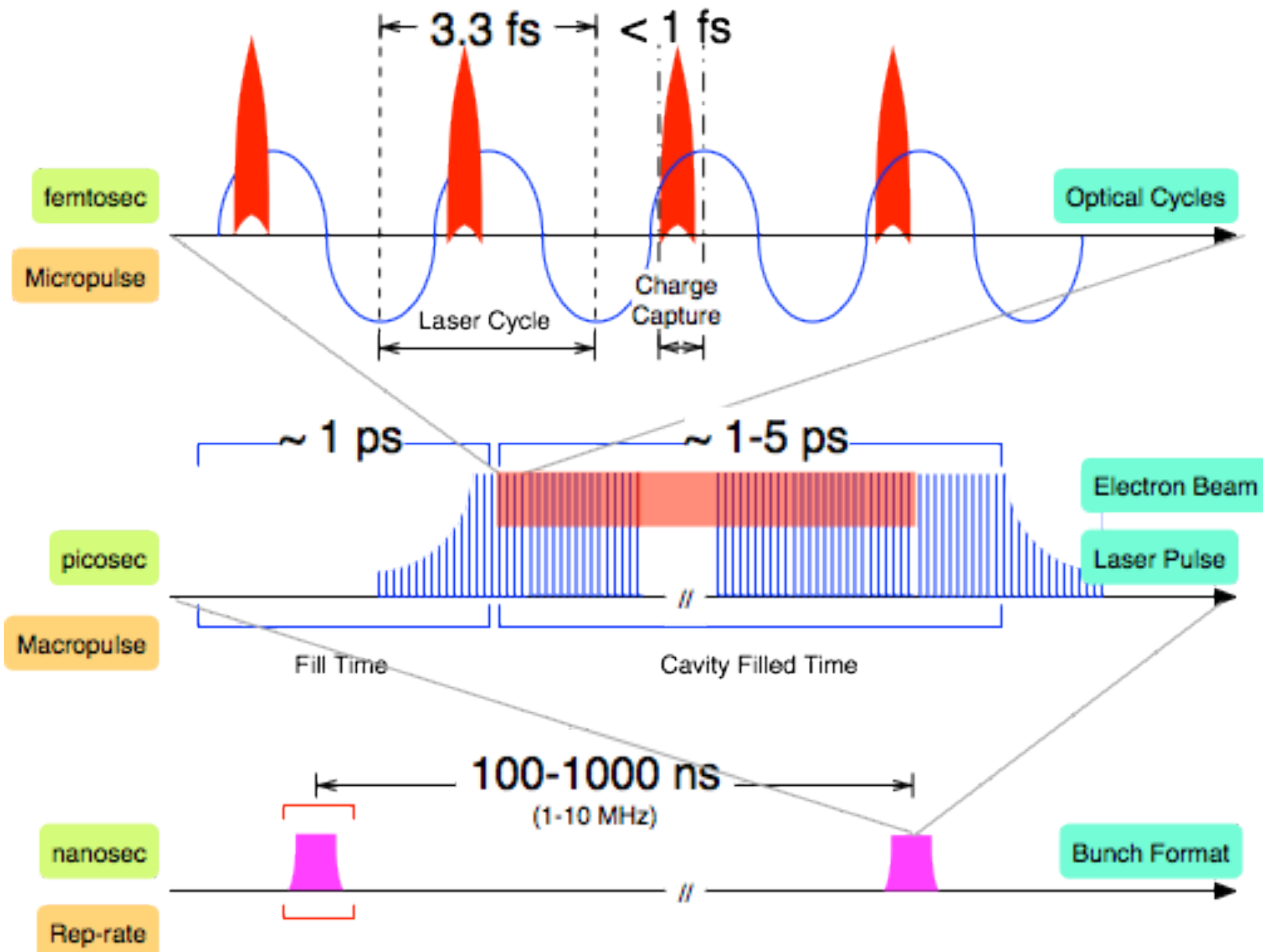
Spontaneous EUV Radiation Parameters	
Beam Energy	100 MeV
Bunch Charge	0.5 fC
Bunch Rep Rate	100 MHz
Average Current	5 nA
Electron Bunch Length	10 as / 3nm
Undulator Field	2.1 T
Undulator Period	1 mm
Number of Periods	10 (~1cm total length)
Undulator Parameter	~0.20
Radiated Wavelength	~13 nm
Photon Flux	~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, Advanced Accelerator Concepts Workshop 2018

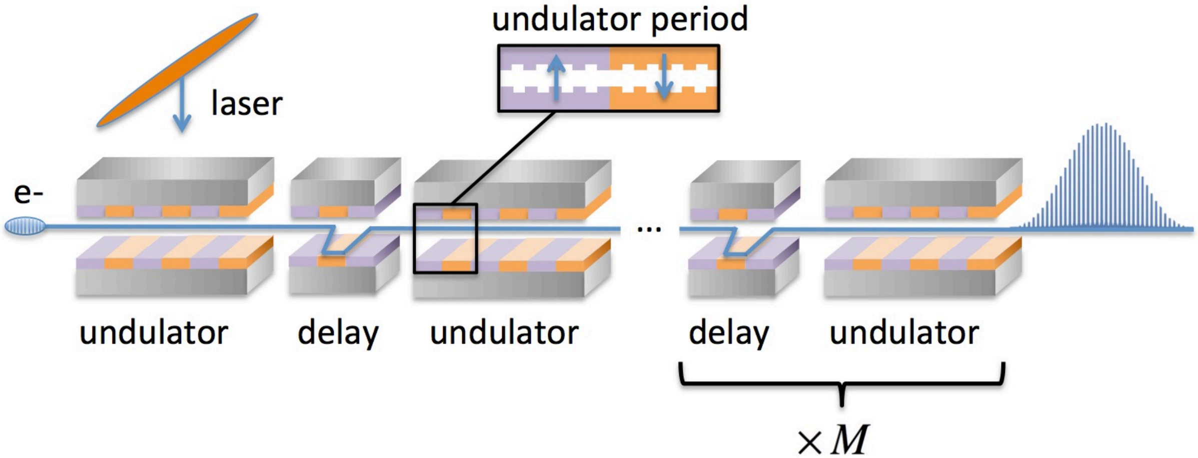
DLA's attosecond bunch structure raises the possibility of making attosecond radiation pulses

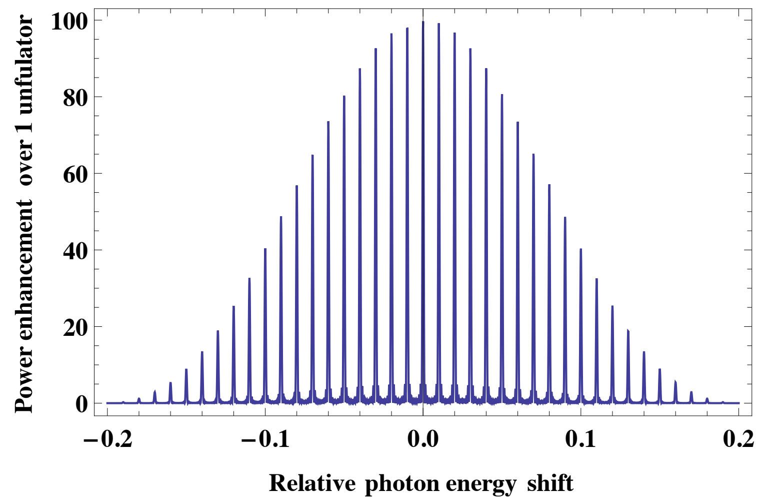
Optical structures naturally have sub-fs time scales and favor high repetition rate operation



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

DLA X-ray FEL Strawman Parameter Table

SLAC

Parameter	Units	Value
Ebeam Energy	GeV	1.056
Microbunch Charge	fC	0.5
Bunches per Train		150
Rep Rate	MHz	100
Normalized Emittance	nm	0.87
Laser Wavelength	µm	2
Laser Pulse Duration	ps	1
Undulator Period	mm	0.9
Equivalent Undulator B	T	1.6
Undulator K		0.14
Pierce Parameter		2.29E-04
Undulator Length	m	0.9
Photon Energy	keV	11.5
Gain Length	m	0.18
Photons per Bunch		6.6E+04
Photon Flux	photons/sec	9.9E+14
Brightness	SBU*	1.05E+21

A DLA X-ray source would be in or near the Quantum FEL regime:

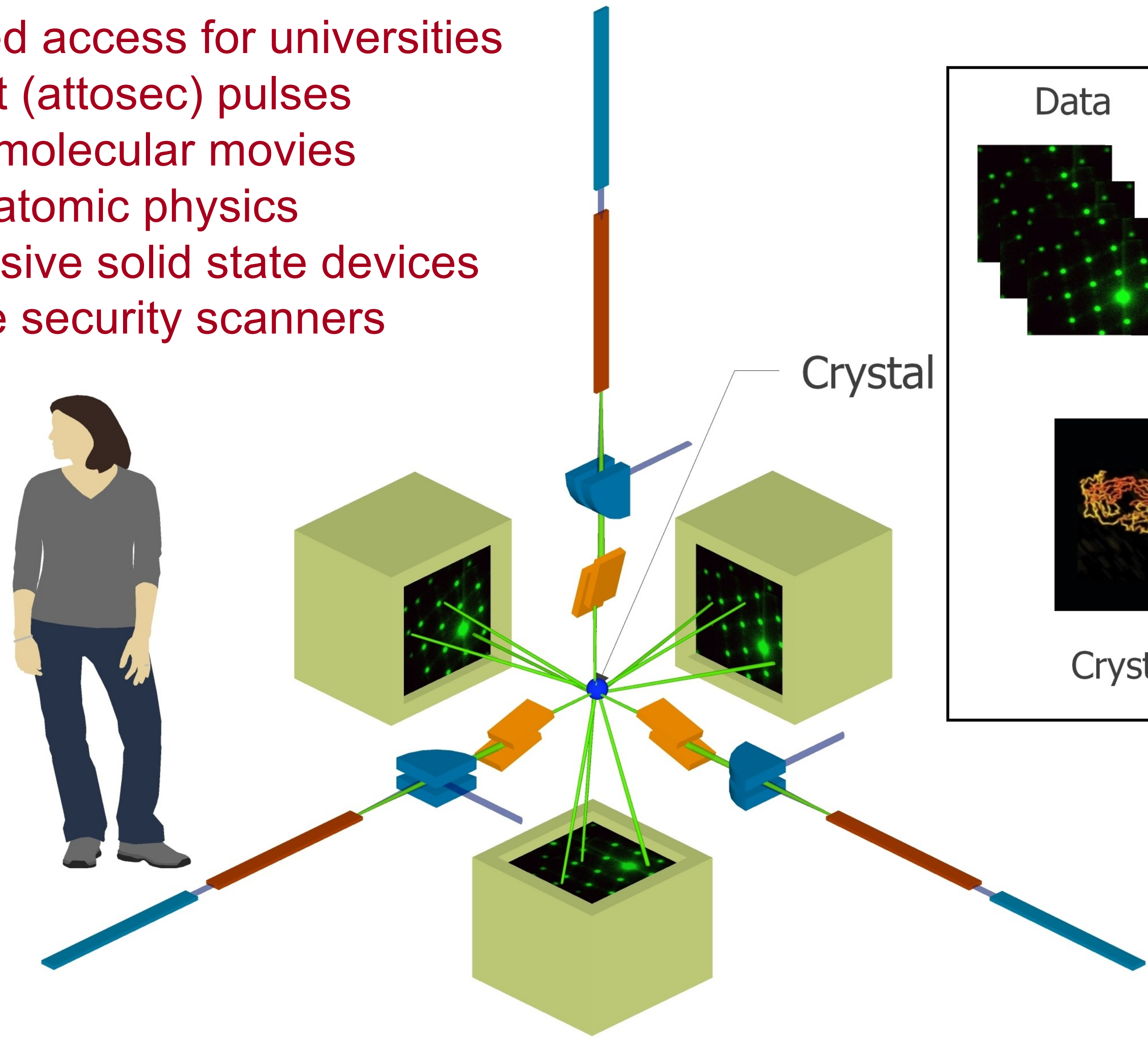
$$\frac{\hbar\omega}{\gamma\, m\, c^2} = 10^{-5}$$

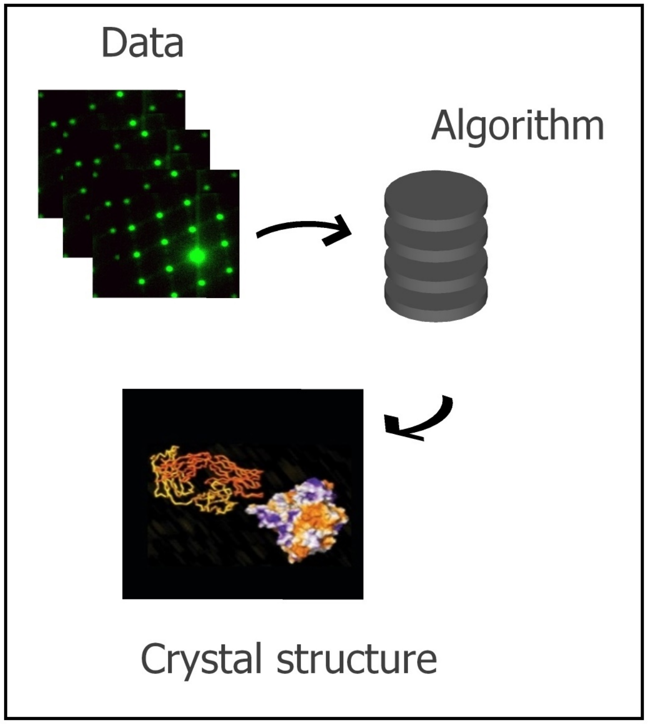
* 1 "SBU" = ph/s/mm^2/mrad^2/0.1%BW

A miniaturized attosecond XFEL could enable revolutionary new science capabilities.

SLAC

- Improved access for universities
- Ultrafast (attosec) pulses
  molecular movies
  atomic physics
- Inexpensive solid state devices
- Portable security scanners





Concept for multi-axis ultrafast tomography with DLA based XFELs (K. Wootton)

What about protons or ions?

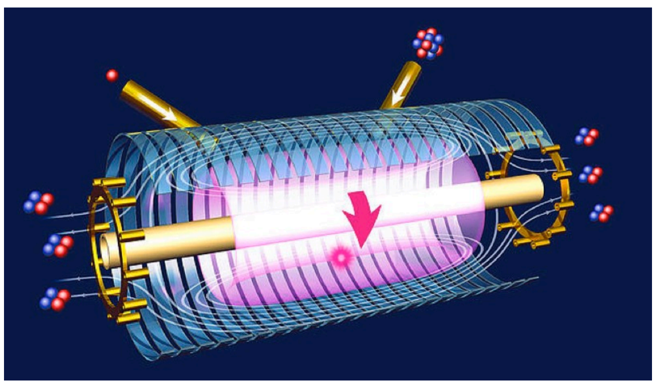
SLAC

Motivation

Reduce size/cost for **colliding beam fusion reactor (CBFR)**.
Possible uses for plasma diagnostic measurements of ion temperature, plasma density with lower beam powers.

Desired Delivery Parameters (c/o: Dr. M. Thompson, Tri-Alpha)

Parameter	Value
Proton Energy	15 keV to 1 MeV
Beam power	1 MW
Beam Brightness	low / unimportant



Preliminary Estimated Source Requirements

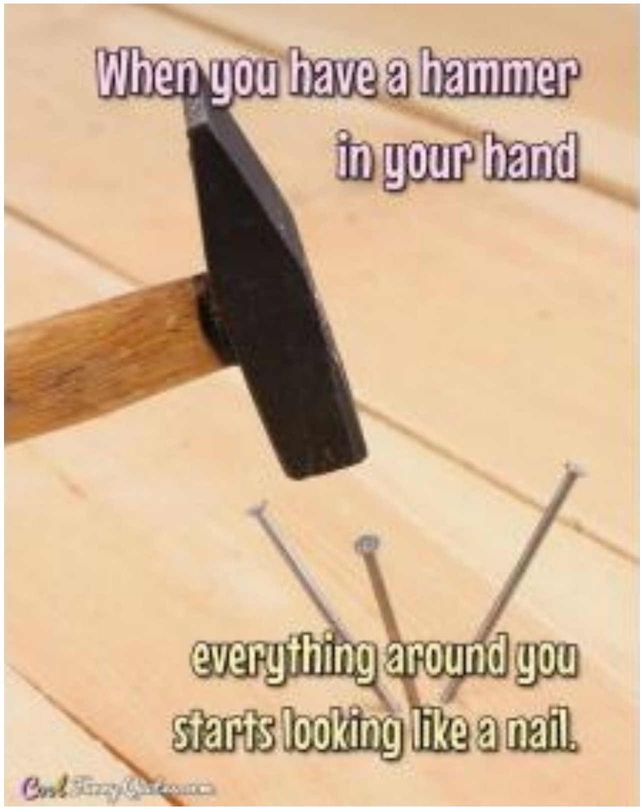
Parameter	Value
Proton Energy	> 10 MeV desired
Size	Compact (< 1 meter)
Emittance	<< 1 µm
Beam format	Pulsed, laser synced, high rep rate (MHz)

- In principle DLA can accelerate any charged particle.
- Existing tabletop p+ sources not suitable for a final device, but may be useful for demonstration tests; feasibility studies needed.
- Demonstration experiments would be interesting with suitable test facilities.

What are DLA's Unique Capabilities?

SLAC

"Create a matrixed list or table of all DLA related applications that have been proposed or discussed so far, both near and long-term, including industrial, scientific, and medical. Please evaluate each application in terms of area of interest (light source, HEP, industry, medicine, security, etc.), feasibility (is DLA a good match?), time scale (near-term vs. long-term), and ***degree to which it leverages DLA's unique capabilities****."*



Features of a DLA Accelerator:

- **C**ompactness: x10^{-2} longitudinal, x10^{-4} transverse
- **E**fficiency: solid state lasers (> 30% wall-plug)
- **B**unch Format: fC charge at MHz rep rates
- **A**ttosecond Time Scale: intrinsic optical bunching
- **U**niquely enabled by DLA?

DLA Applications Matrix

Application	Field	Time-Scale	Compactness	Efficiency	Brightness	Attosecond	Unique to DLA?
Compton X-ray Source	Medical	Mid	√				
Catheterized Electron Source	Medical	Mid	√				√
Proton/Hadron Therapy	Medical	Long	√				
Linear Collider	HEP	Long	√	√	√		
Low-power EUV for inspection	Industry	Mid	√				
Colliding Beam Fusion	Industry	Long	√	√			
Micro-beams for radiobiology	Science	Near	√				
UED/UEM Source	Science	Near	√		√	√	
Compact XFEL	Science	Long	√	√	√	√	
Multi-Axis Tomography	Science	Long	√	√	√	√	√

Conclusions

Significant progress in DLA over the last few years:

Ongoing 5-year international collaboration funded by Moore Foundation
Gradients ~ 1 GV/m, energy gain > 0.3 MeV recently demonstrated
Components for an integrated on-chip system in development
Prototype "shoebox" demonstration system ready for testing

Key Strengths of DLA

short-bunch superradiance, diffraction-limited radiation (high brightness)
nm spatial and temporal resolution
energy efficient for applications (precise beam pointing)
reduced size and cost

Prospects for DLA-based Applications

medical radiation oncology (direct ebeam treatment)
industrial EUV sources for low-power wafer inspection
attosecond science, electron diffraction, microscopy

New ideas are welcome!

Acknowledgments

SLAC

Stanford University
Prof. Bob Byer
Prof. James Harris
Prof. Olav Solgaard
Prof. Shanhui Fan
Prof. Jelena Vuckovik
K. Leedle
Andrew Ceballos*
Neil Sapra*
Huiyang Deng
Alex Ody

Tech-X Corporation
Ben Cowan

DESY
Ralph Assmann
Frank Mayet
Willi Kuropka
Ingmar Hartl
Franz Kaertner

SLAC National Accelerator Laboratory
Joel England
Zhirong Huang
Tor Raubenheimer

Purdue Univ.
Minghao Qi
Yunjo Lee

Erlangen Univ., Germany
Peter Hommelhoff
Josh McNeur
Martin Kozak

Paul Scherrer Inst.
Rasmus Ischebeck

TU Darmstadt
Oliver Boine-Frankenheim
Uwe Niedermayer

UCLA
Pietro Musumeci
Jamie Rosenzweig
David Cesar

Tel-Aviv Univ.
Jacob Scheuer
Doron Bar-Lev
Avi Gover

Technion
Levi Schachter
Adi Hanuka

Livermore Natl. Lab
Paul Pax
Mike Messerly

blue = students; * = current Bob Siemann fellows

Thank you!

SLAC

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

contact: england@slac.stanford.edu

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

Special thanks to K. Leedle, Z. Huang, Y-C. Huang, T. Hirano, U. Niedermayer for contributions of slides.