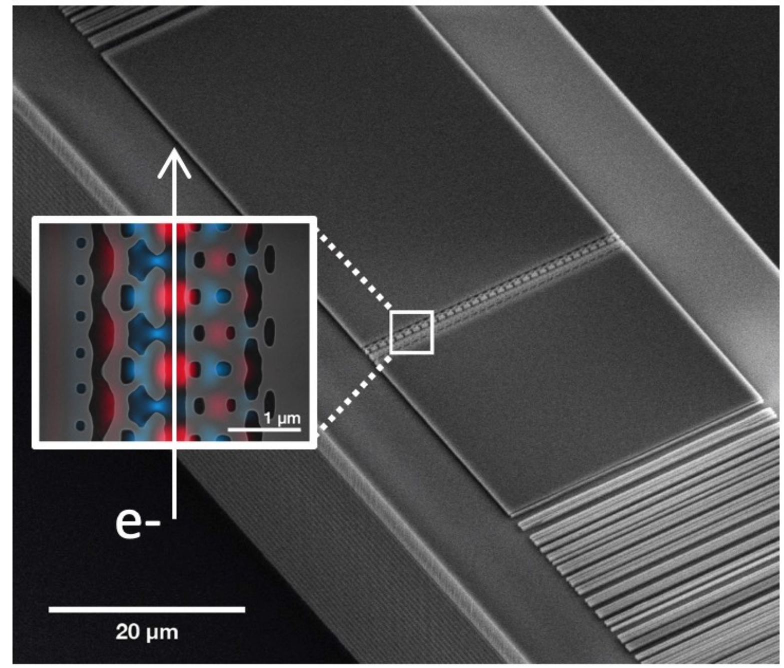
Progress in Developing an Accelerator on a Chip

R. Joel England (SLAC, Stanford)
R. L. Byer (Stanford)
P. Hommelhoff (FAU – Erlangen)

13th International Particle Accelerator Conference (IPAC '22)
Bangkok, Thailand June 13-17, 2022



N. Sapra, et al., Science **367**, 6473 (2020)

ACHIP

GORDON AND BETTY MOORE FOUNDATION

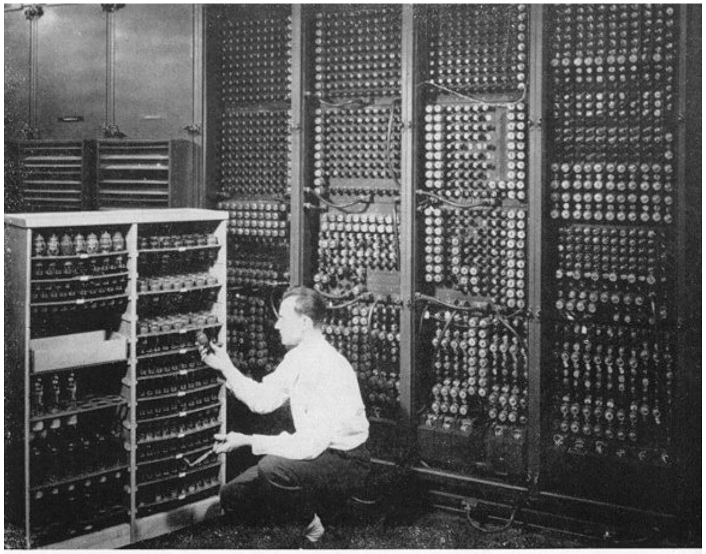
FAU Stanford University

SLAC NATIONAL ACCELERATOR LABORATORY

Can we do for particle accelerators what the microchip industry did for computers?

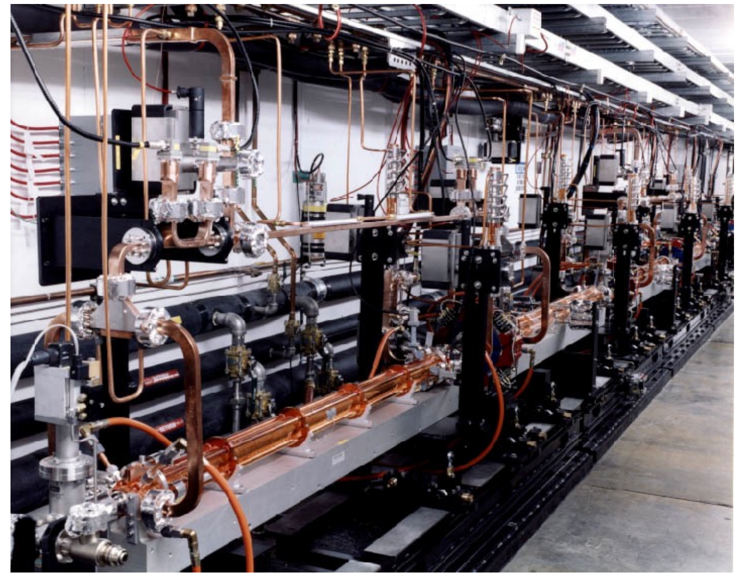
SLAC

ENIAC, early computer



Replacing a bad tube meant checking among ENIAC's 19,000 possibilities.

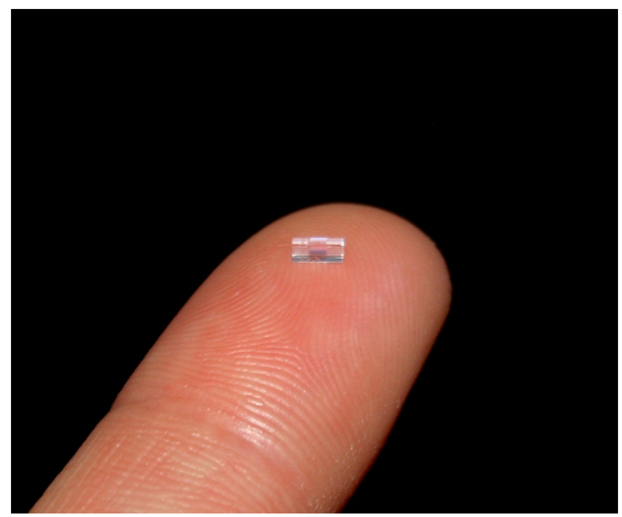
NLCTA accelerator at SLAC



smaller, affordable, faster, better

integrated circuit CPU

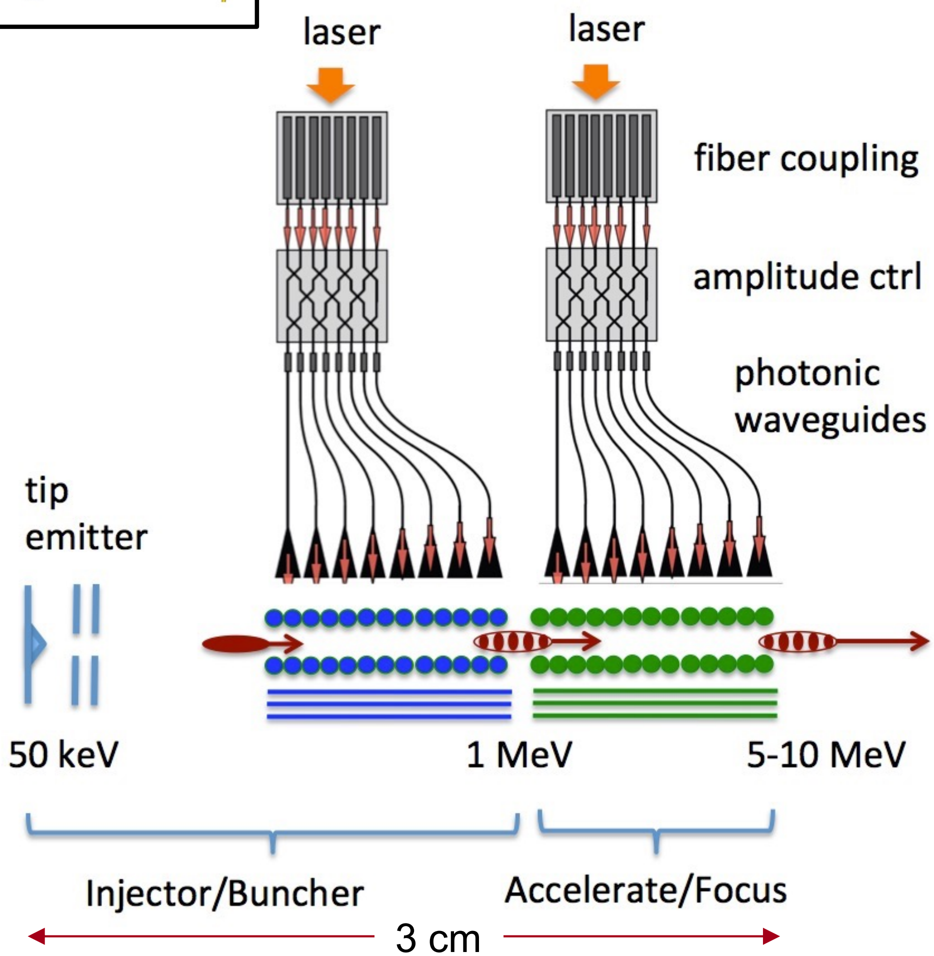
Micro-accelerator fabricated at Stanford



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

SLAC

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

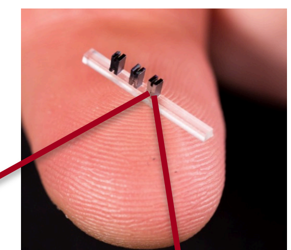


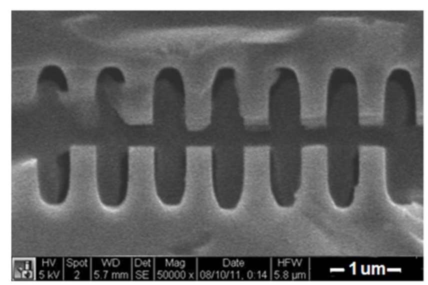
Required lasers are MHz rep rate, low pulse energy, wallplug efficiency ~ 30%

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

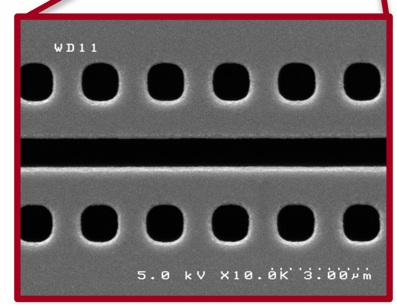
Can be mass produced using techniques of the integrated circuit industy.

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.

New technologies have made micro-accelerators a possibilty.

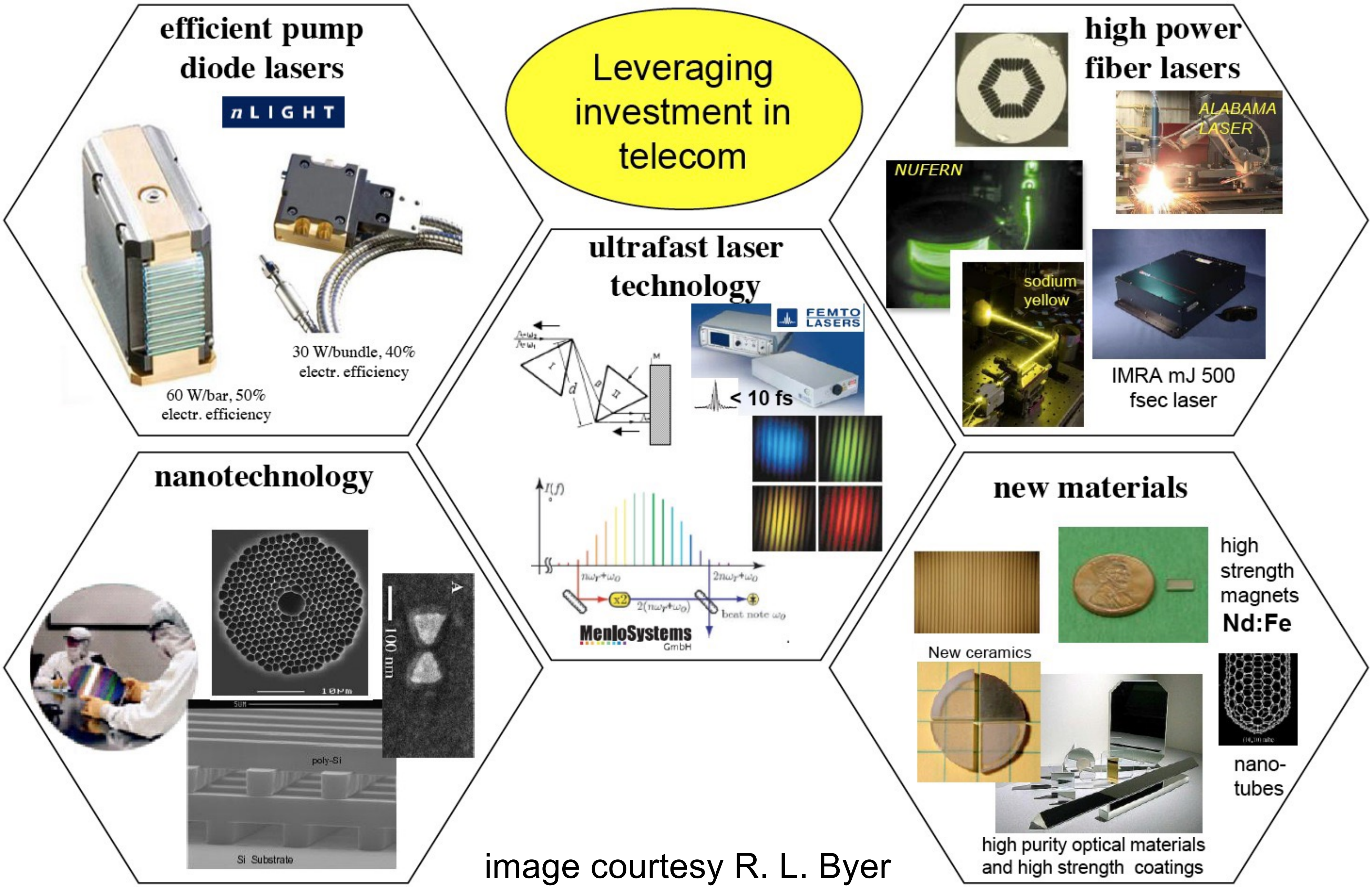
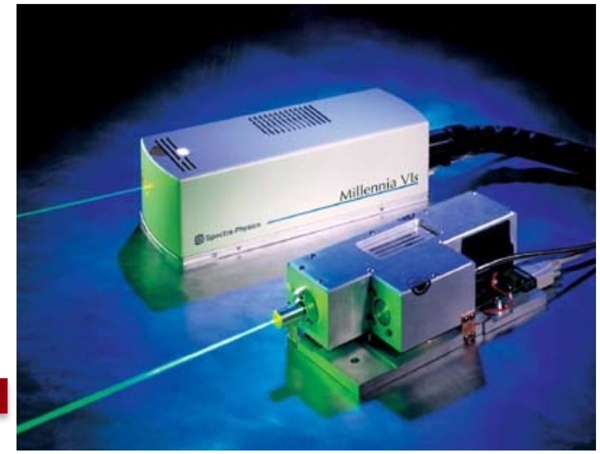


image courtesy R. L. Byer

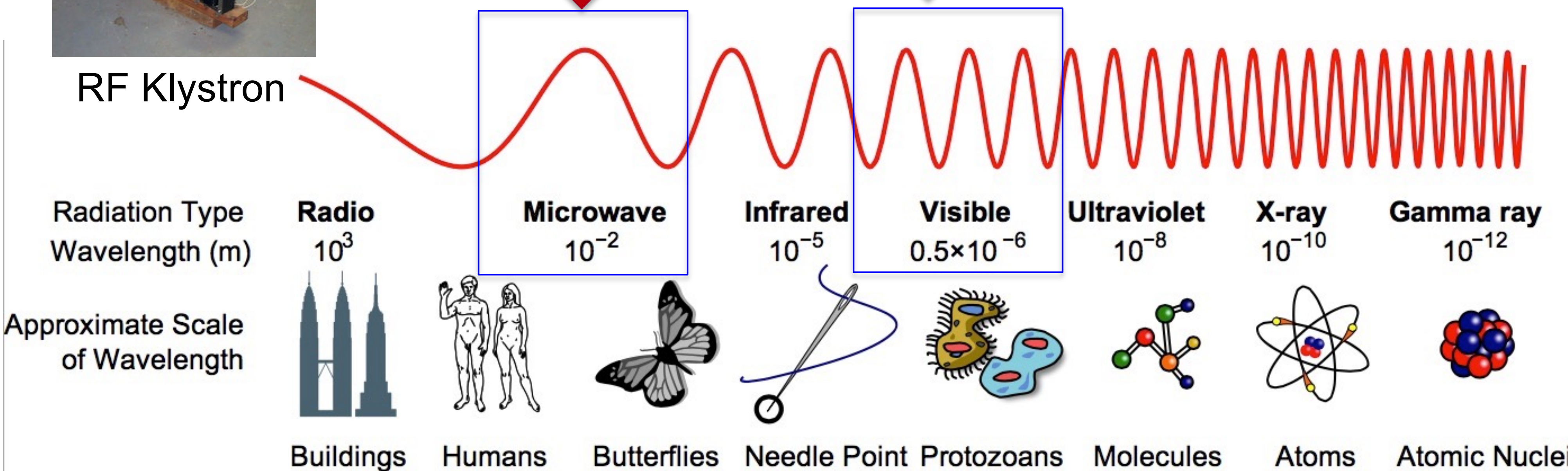
Lasers are a natural choice to power these accelerators.

RF Klystron

1. Smaller/less expensive than RF.
2. Energy efficient (near 50%).
3. High repetition rate (1 to 100 MHz).
4. Large electric fields (GV/m).



Solid-state laser



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

Not high peak power lasers!

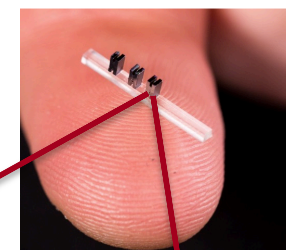
Parameter	DLA Value
Wavelength	2 µm
Pulse Duration	100 fs
Pulse Energy	1 µJ
Laser Power	100 W
Rep Rate	100 MHz
Laser Efficiency	30%
Cost/laser	$150k

Solid-state laser

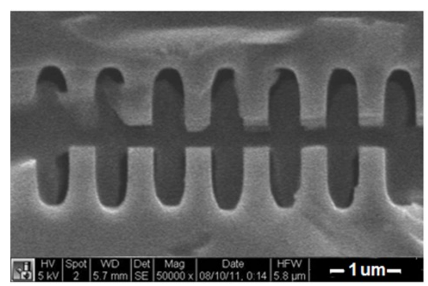
Available now "off the shelf"

Fabricated using techniques of the integrated circuit industy.

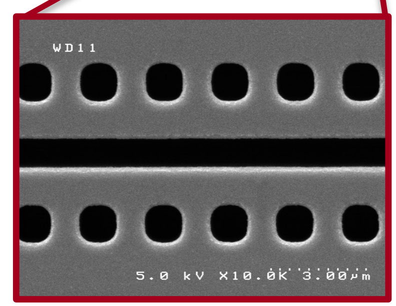
DLA structures are made by students in the Nanofabrication Facilities at partner universities.



SEM images of DLA prototypes tested at NLCTA



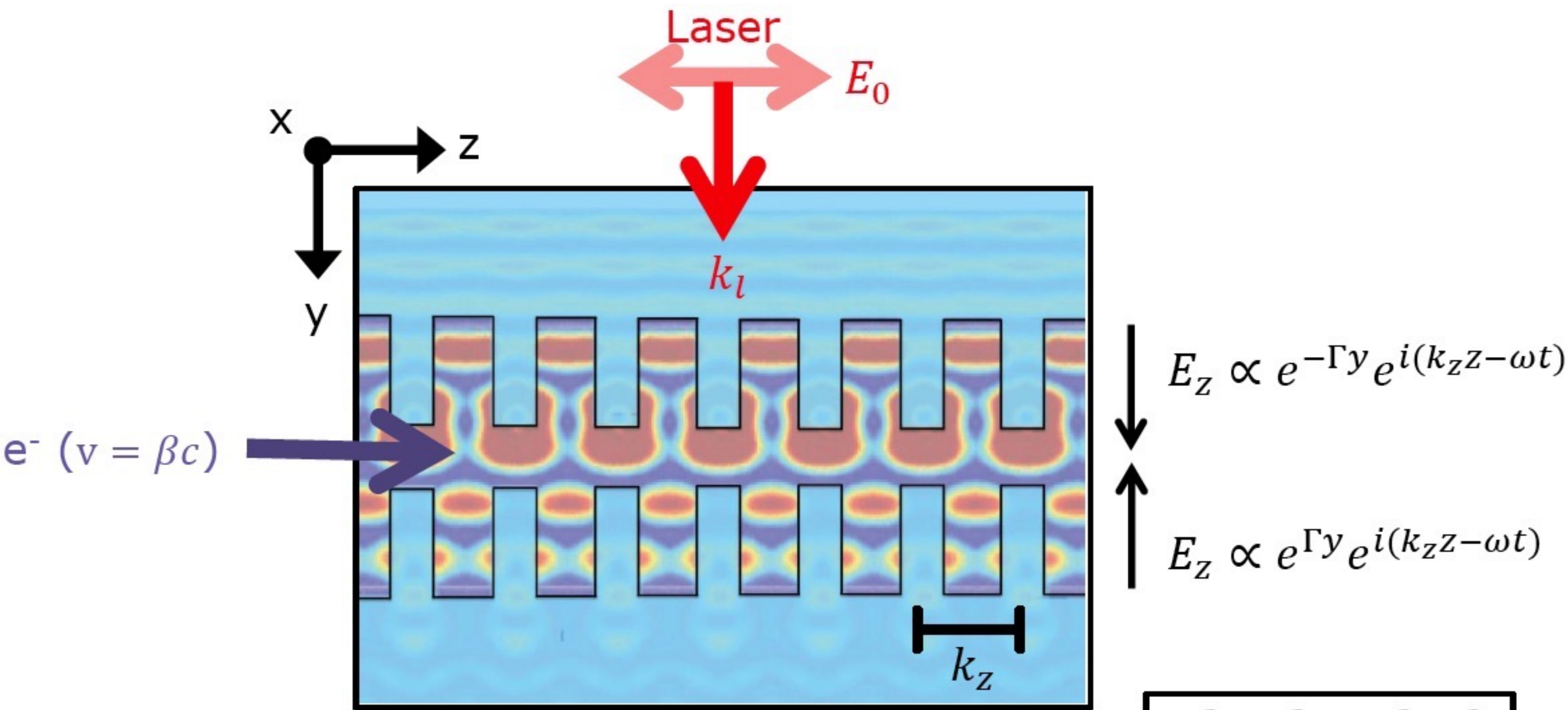
fused silica



silicon

Operating Principle: Planar Grating Structure

SLAC



Accelerating mode: $\omega = \beta c k_z$

$$\Gamma^2 - k_z^2 = \omega^2 / c^2$$
$$\Rightarrow \Gamma = k_z / \gamma$$

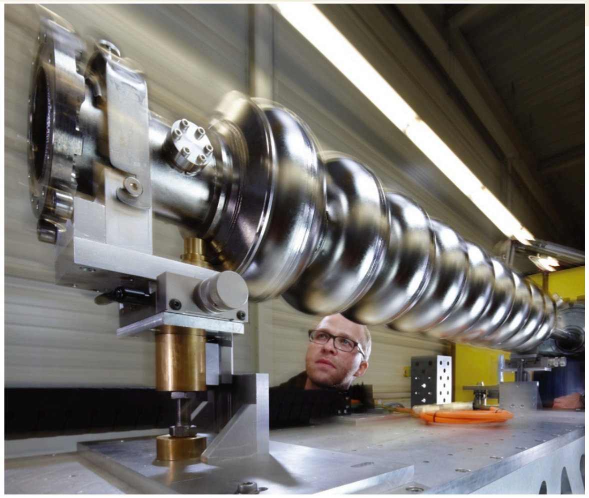
image courtesy D. Cesar (UCLA)

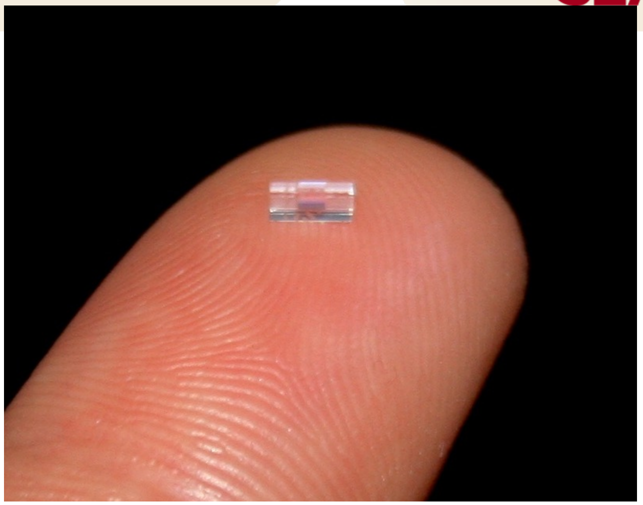
DLA Comparison with Conventional RF Accelerators

SLAC

Parameter	DLA	RF
Power Source	Commercial IR Laser	Microwave Klystron
Wavelength	1-10 μm	2-10 cm
Bunch Length	10-100 attosec	1-5ps
Bunch Charge	1-10 fC	0.1- 4 nC
Required Norm. Emittance	1-10 nm rad	0.1-1 μm rad
Rep Rate	10-200 MHz	1-1000 Hz
Confinement of Mode	Photonic Crystal (1D, 2D, 3D)	Metal Cavity
Material	Dielectric	Metal
Unloaded Gradient	1-10 GV/m	10-50 MV/m
Power Coupling Method	Free-space/Silicon WG	Critically-coupled metal WG

An important figure of merit for a particle accelerator is accelerating gradient (energy gain per unit length)



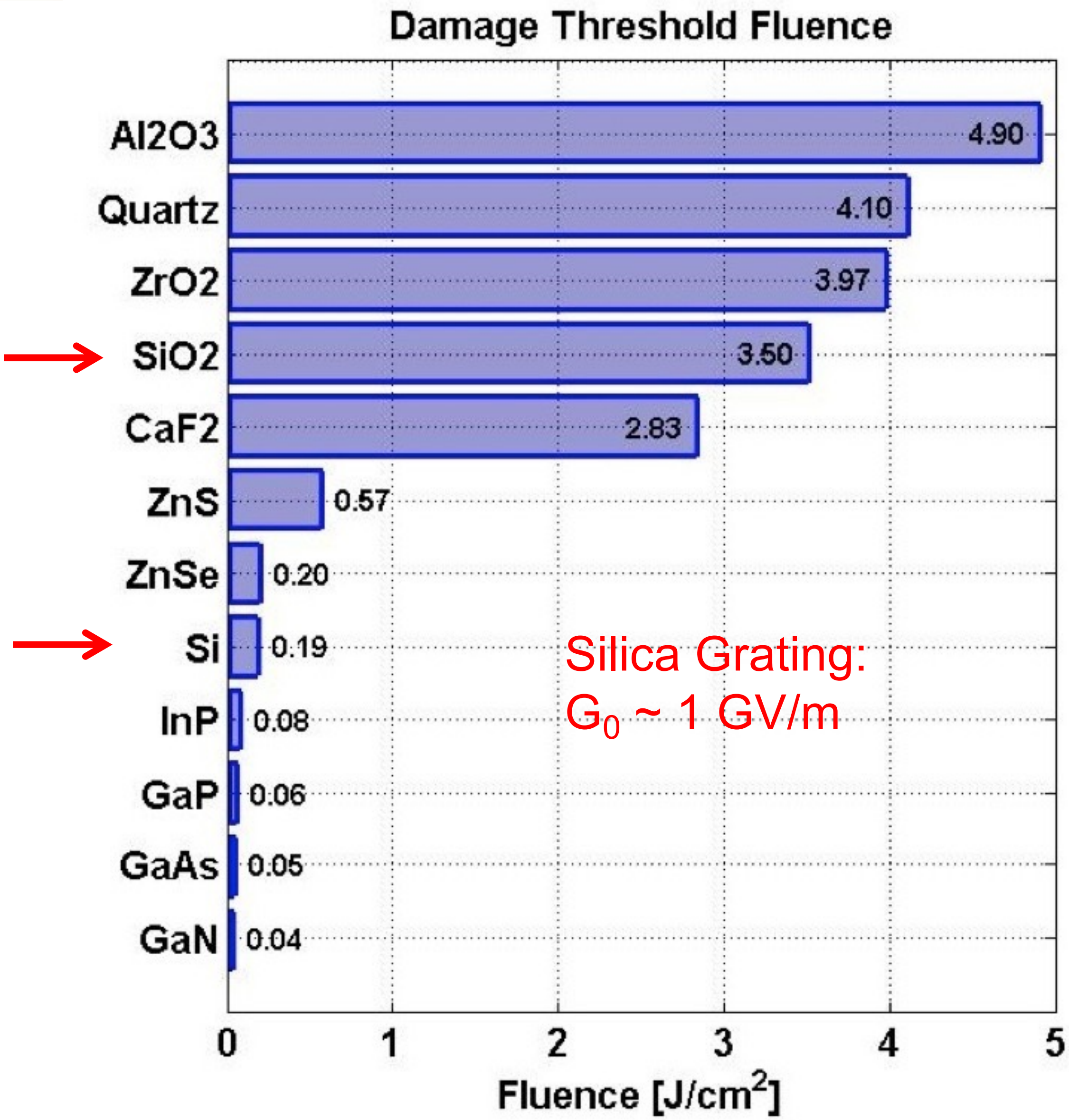


Conventional linear accelerator (RF)

Laser-based dielectric accelerator (optical)

	Conventional linear accelerator (RF)	Laser-based dielectric accelerator (optical)
Based on	(Supercond.) RF cavities	Quartz grating structures
Limited by	**Surface breakdown: 200 MV/m**	**Damage threshold: 30,000 MV/m**
Max. achievable gradients	**10-50 MeV/m**	**1000-10,000 MeV/m**

To obtain high accelerating gradients we need materials that can withstand intense laser fields.

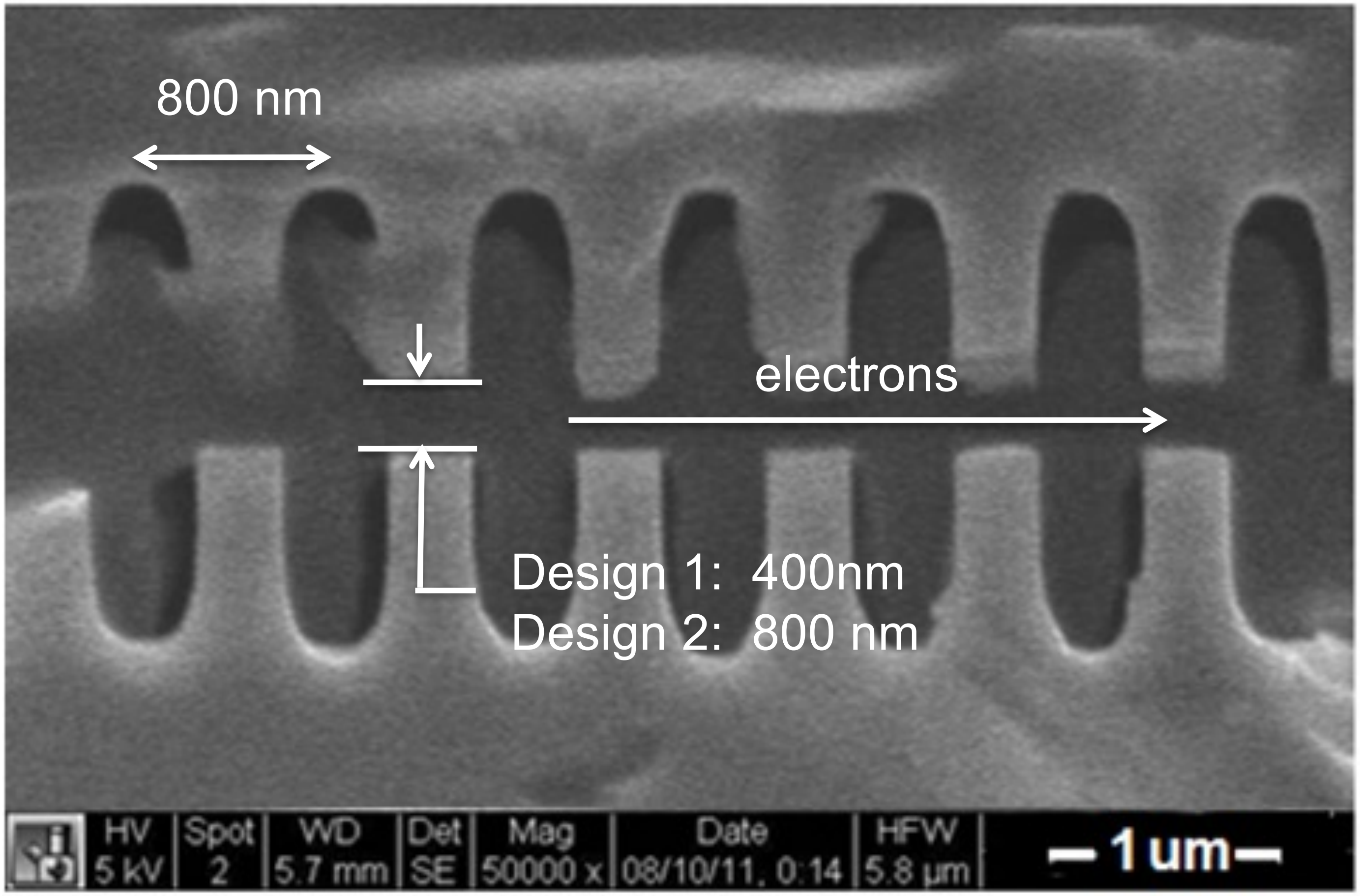


Measurement data from K. Soong

Ti:Sapph Laser wavelength: 800nm; Pulse length: 1ps; <u>Extensive data did not previously exist in this regime</u>.

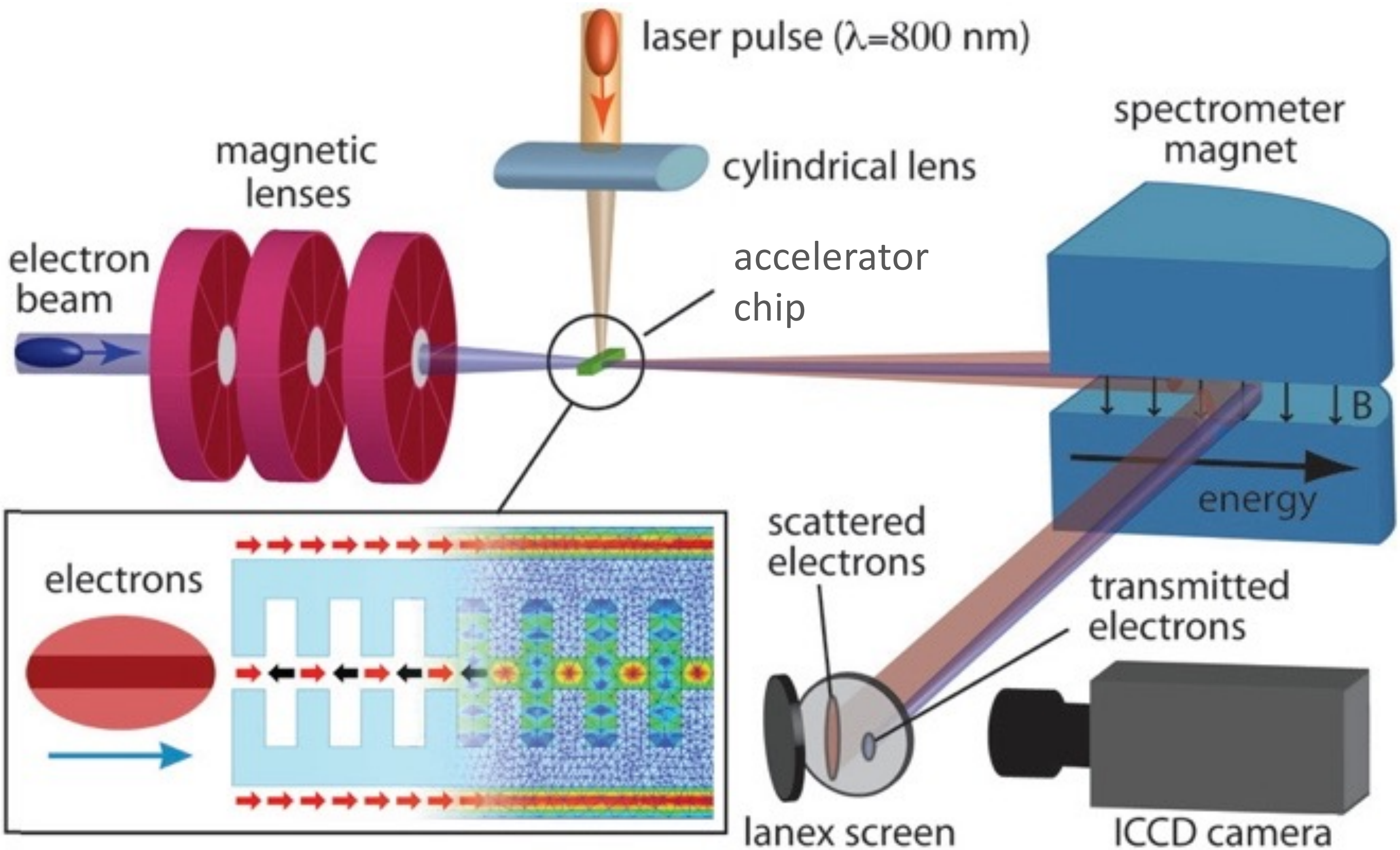
Ken Soong

The first successful prototypes were made of fused silica at Stanford Nanofabrication Facility



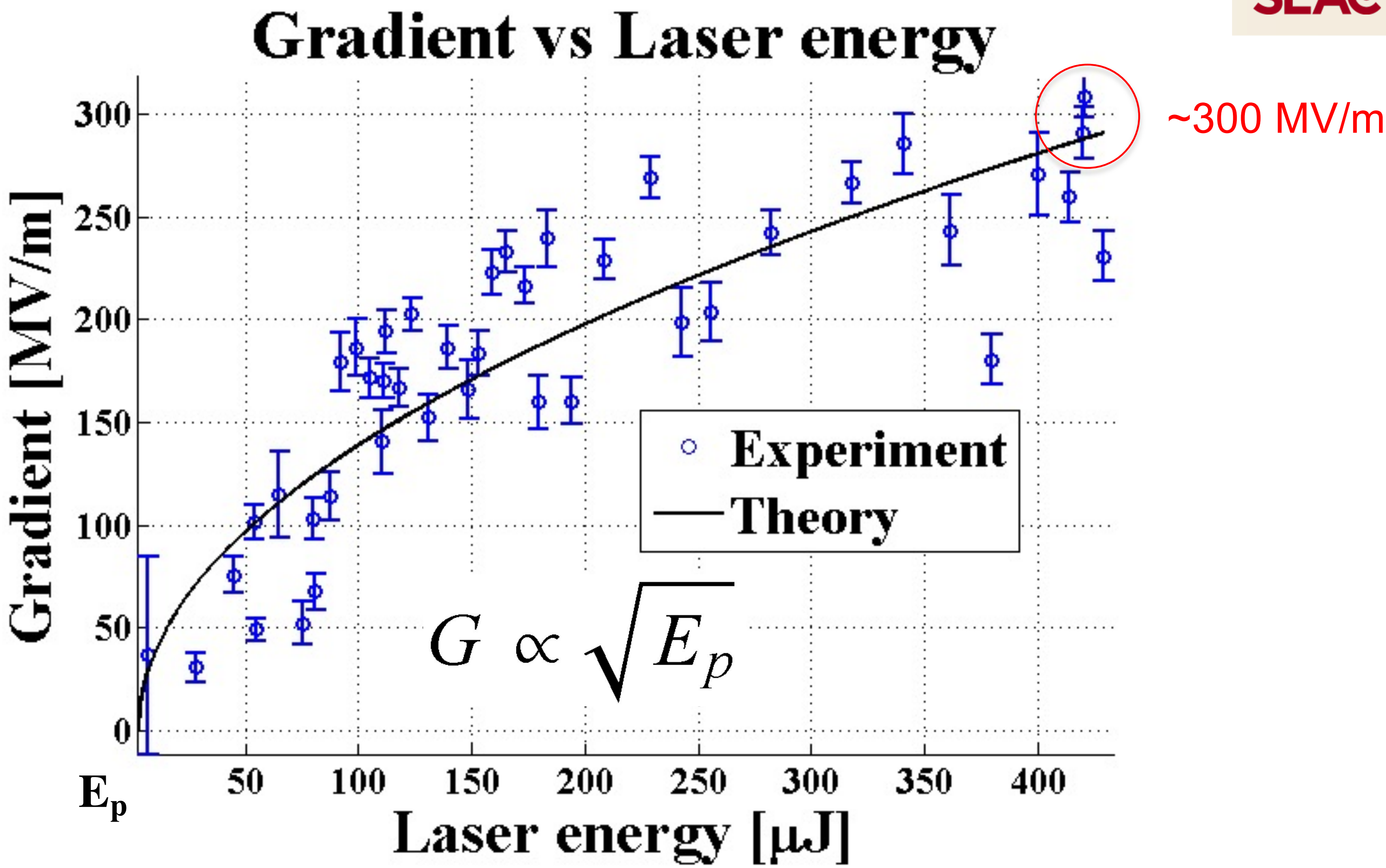
Electron microscope image of the bonded structure.
Rough edges are due to damage from sawing the structure in half in order to image the interior.

To demonstrate these devices, we used a pre-accelerated test beam at SLAC.



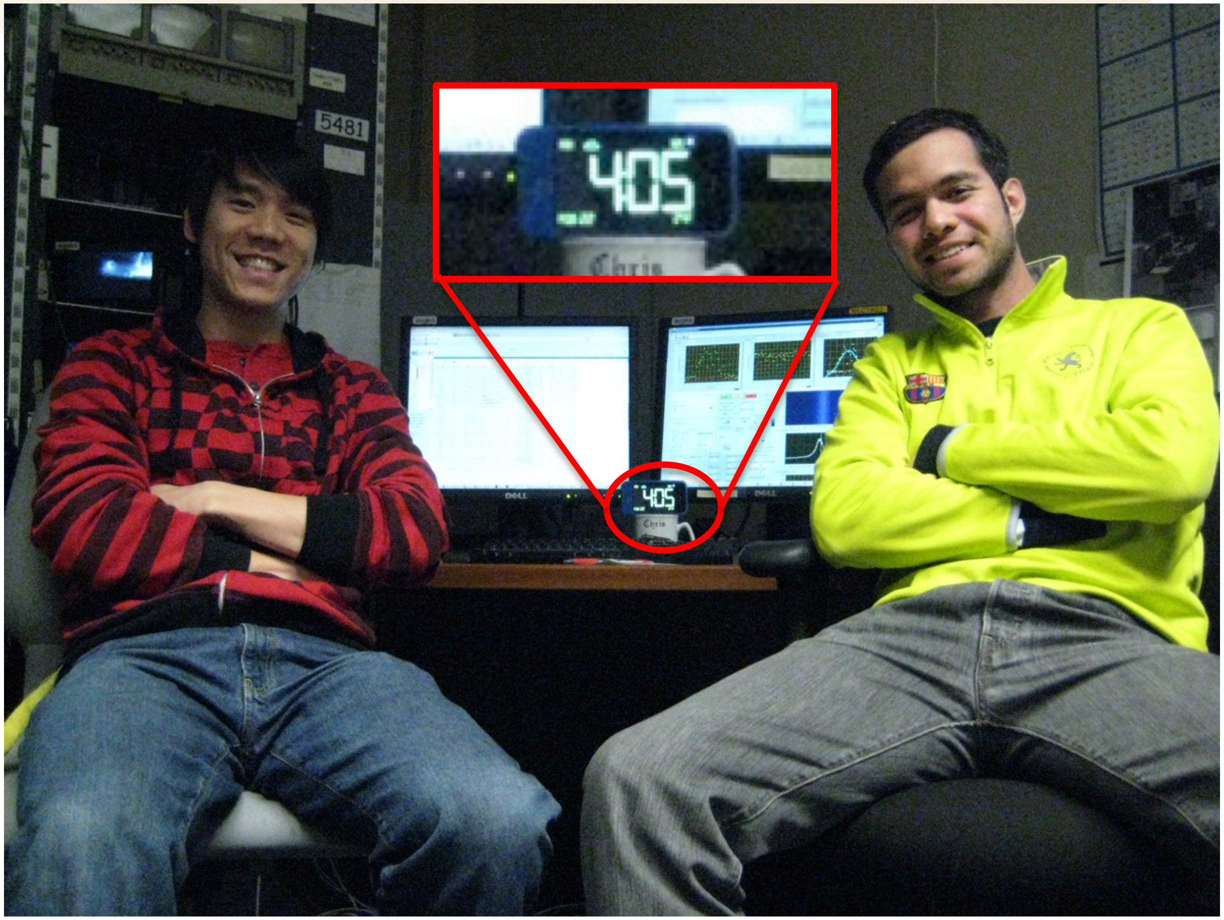
E. Peralta, et al., Nature 503, 91-94 (2013)

Gradients in the first experiment were 10 times higher than the main SLAC linac.



With further optimization of structure and laser parameters, GV/m level gradients have been demonstrated

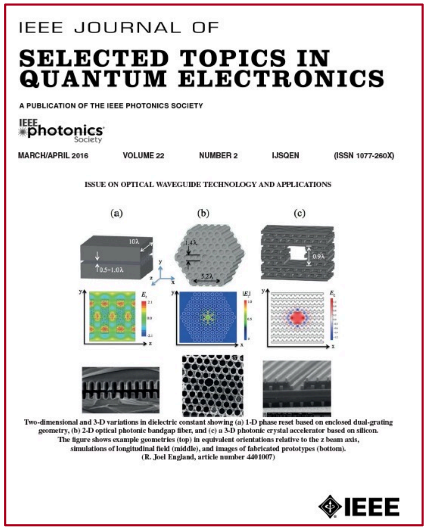
As any experimentalist knows, the best results are often obtained in the middle of the night.

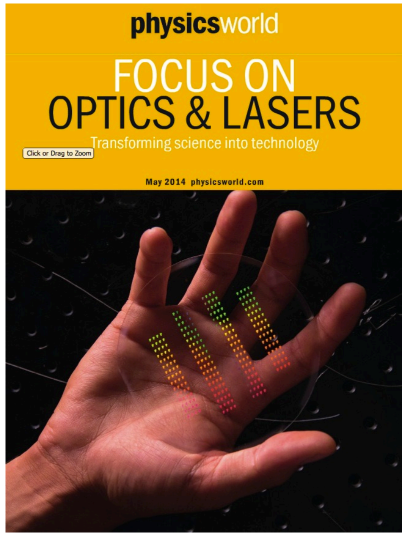


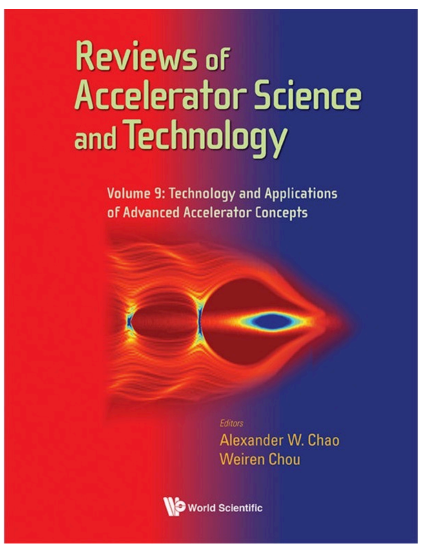
Students Ken Soong and Edgar Peralta at 4am. Why are they smiling? They just demonstrated the first laser-powered dielectric accelerator!

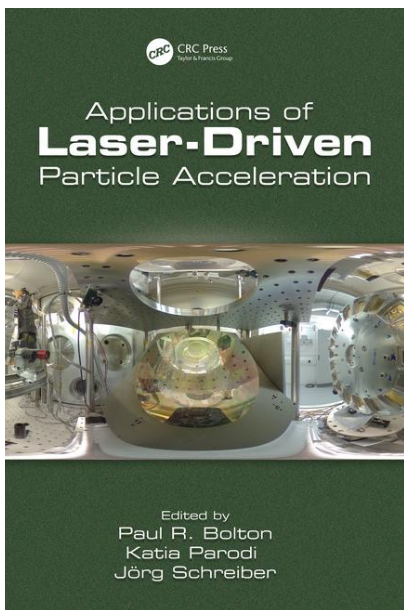
Highlighted DLA Publications

SLAC









LETTER **nature** doi:10.1038/nature12664

Demonstration of electron acceleration in a laser-driven dielectric microstructure

E. A. Peralta[1], K. Soong[1], R. J. England[2], E. R. Colby[2], Z. Wu[2], B. Montazeri[3], C. McGuinness[1], J. McNeur[4], K. J. Leedle[3], D. Walz[2], E. B. Sozer[4], B. Cowan[5], B. Schwartz[5], G. Travish[4] & R. L. Byer[1]

REVIEWS OF MODERN PHYSICS

Dielectric laser accelerators

R. Joel England *et al.*
Rev. Mod. Phys. **86**, 1337 – Published 23 December 2014

COMMUNICATIONS PHYSICS

a natureresearch journal

High-field nonlinear optical response and phase control in a dielectric laser accelerator

D. Cesar, et al., Comm. Phys. 1, 46 (2018)

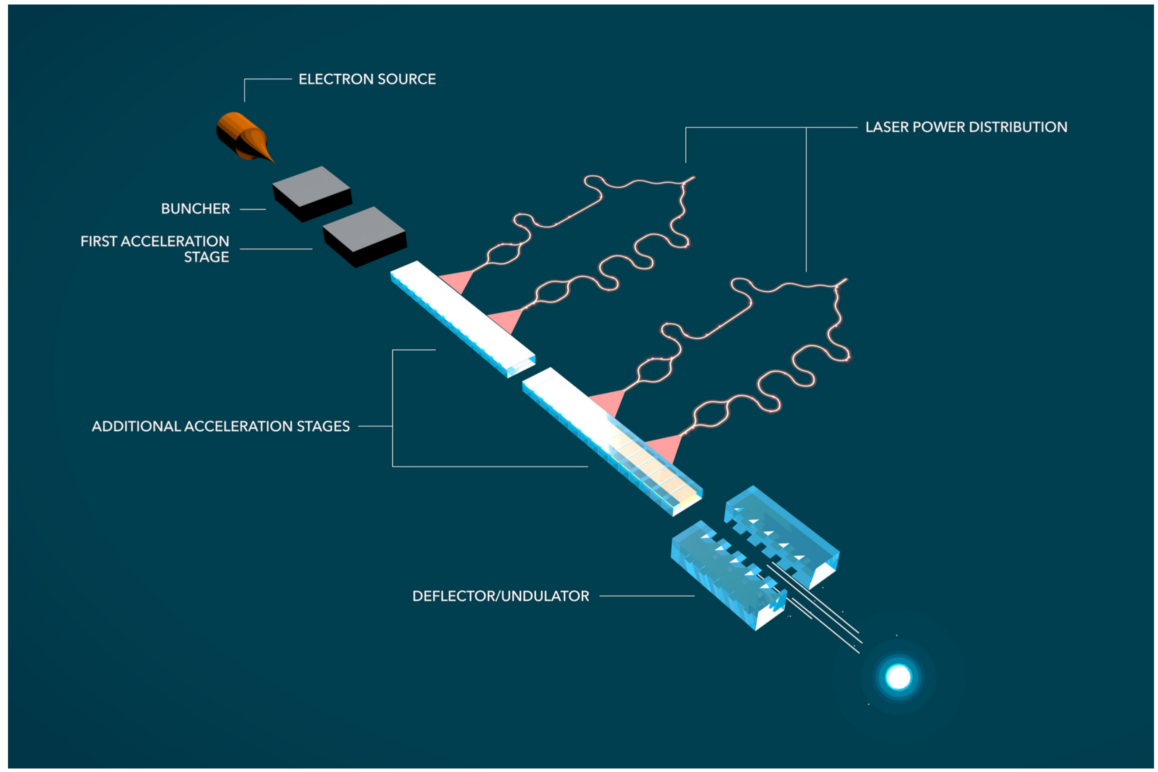
A 7-Year initiative in DLA was funded by the Gordon and Betty Moore Foundation (2015 – 2022)

SLAC

Moore Foundation "Accelerator on a Chip" Program (started Dec 2015)

$19.5M / 7 years
6 universities, 3 partner labs
2 industry partners

(DOE Web Feature 2015)



Goals of ACHIP:

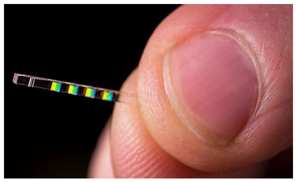
(1) An MeV class benchtop DLA accelerator.
(2) Transverse dynamics (focusing, deflection, undulators, diagnostics)

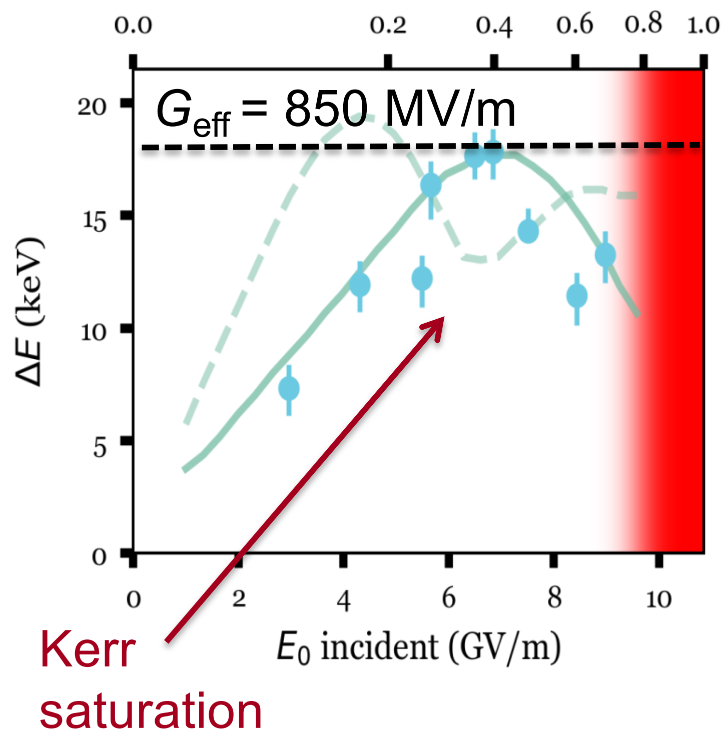
Encouraged by recent rapid progress in DLA, Moore Foundation funded an international program in this area as part of its mission to advance basic science.

Experiments with relavistic (7 MeV) beams have demonstrated record gradients and energy gain.

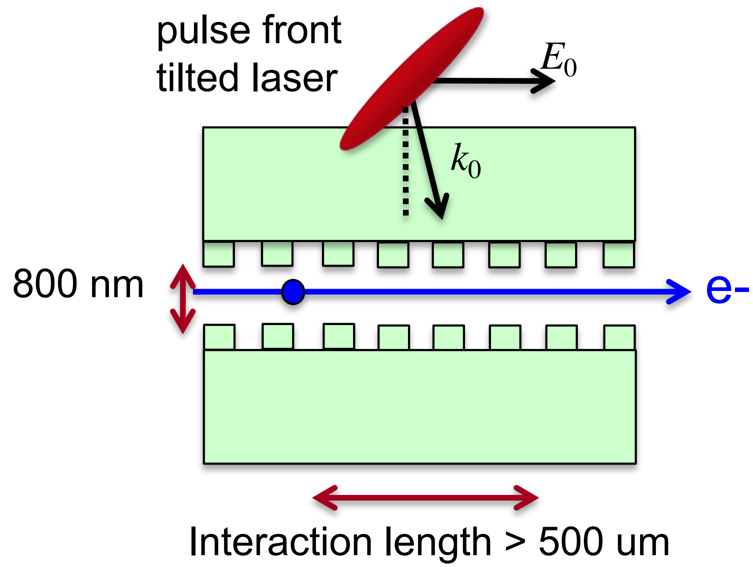
SLAC

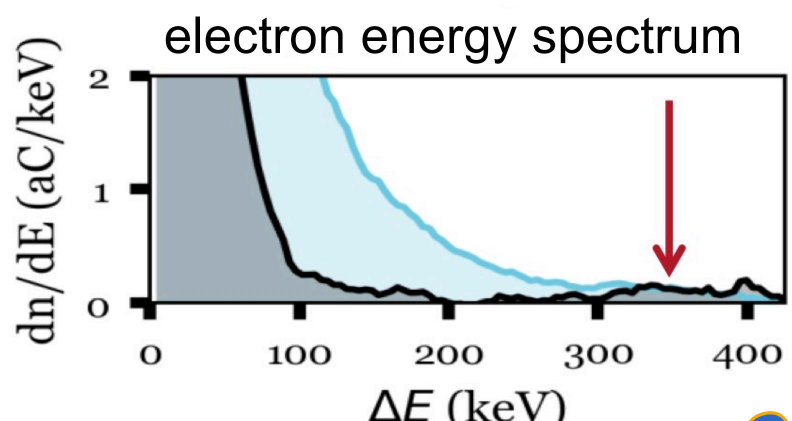
SLAC/UCLA: 0.85 GeV/m*





SLAC/UCLA: 0.3 MeV energy gain**

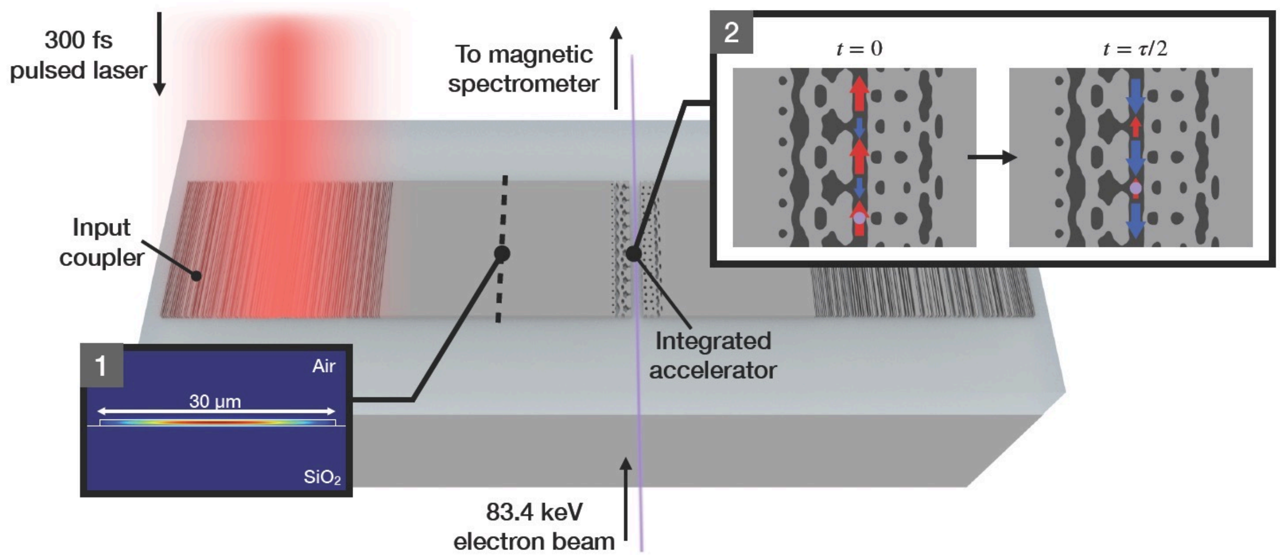


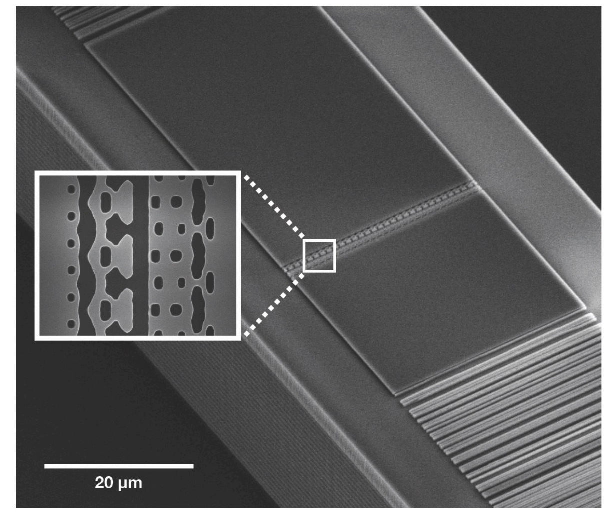


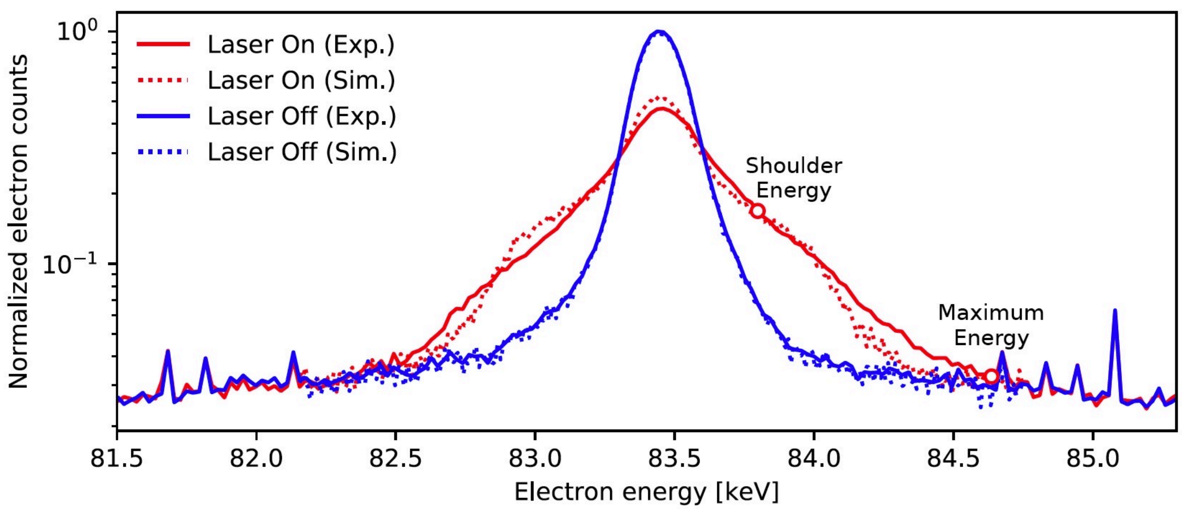
* D. Cesar et al, Communications Physics 1(4), 1-7 (2018)
** D. Cesar et al, Optics Express 26 (22), 29216 (2018)

Ucla

First demonstration of a waveguide-coupled DLA produced using inverse design optimization





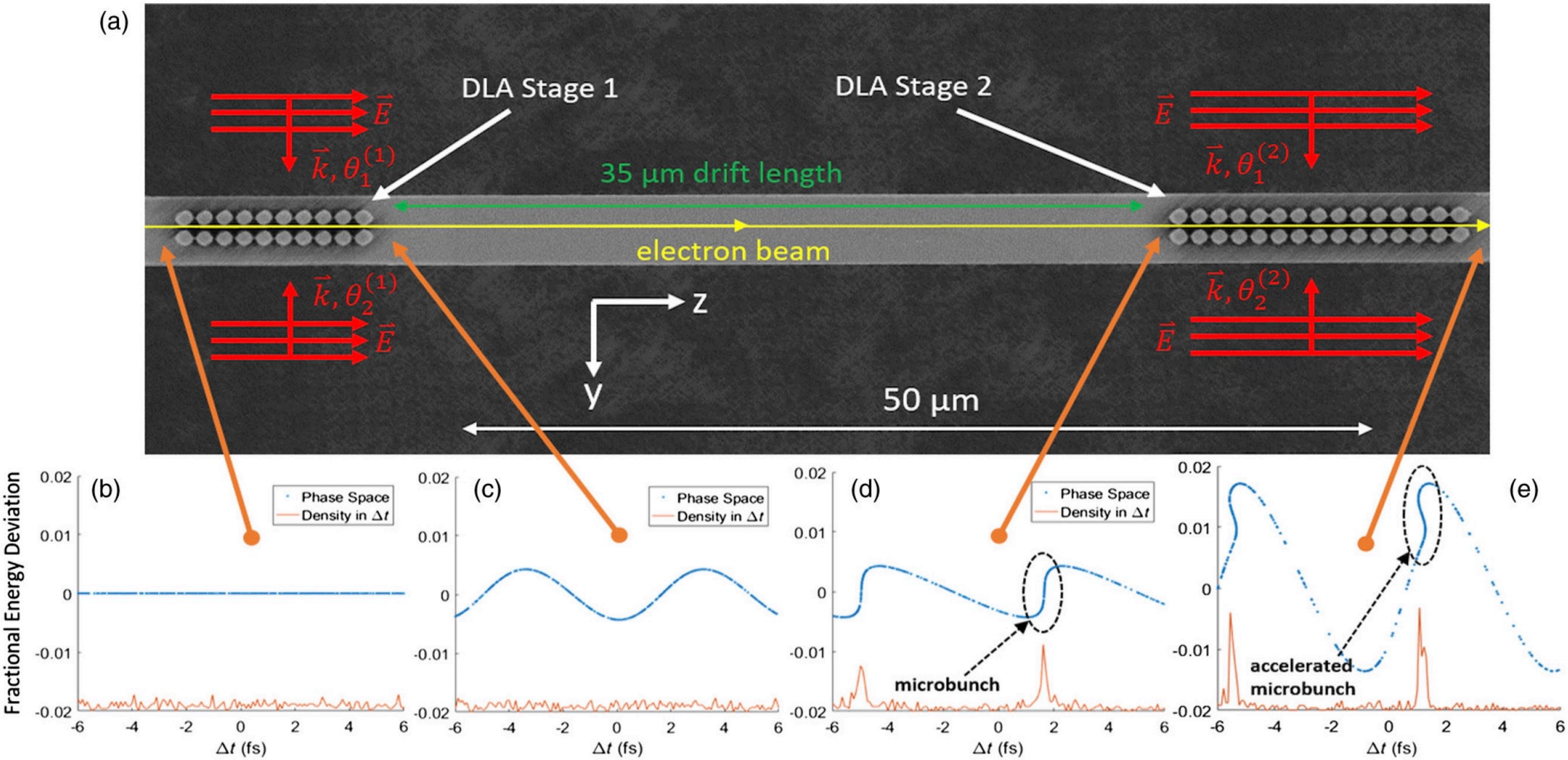


- First demonstration of acceleration in a waveguide-coupled DLA
- Acceleration of 1.2 keV over 30 μm (gradient of 40.3 MeV/m)
- Illustrates utility of inverse design methods to optimize over unique parameter constraints

$$\underset{p, E^1, E^2, \ldots, E^m}{\text{maximize}} \quad \sum_{i=1}^{m} |G_z(E^i)| - |G_y(E^i)|$$

N. Sapra, et al., "On-chip laser driven particle acceleration through inverse design," Science **367** (6473), 79 (2020)

Experimental demonstration of staging, bunching, and net acceleration in a DLA accelerator



D. Black, U. Niedermayer, Y. Miao, O. Soolgard, R. L. Byer, K. Leedle, PRL 123, 264802 (2019)
N. Schönenberger, A. Mittelbach, P. Yousefi, J. McNeur, U. Niedermayer, P. Hommelhoff, PRL 123, 264803 (2019)

FAU FRIEDRICH-ALEXANDER UNIVERSITÄT ERLANGEN-NÜRNBERG

TECHNISCHE UNIVERSITÄT DARMSTADT

Stanford University

Demonstration of 2D (Transverse + Longitudinal) Laser-Driven Focusing in a DLA

nature

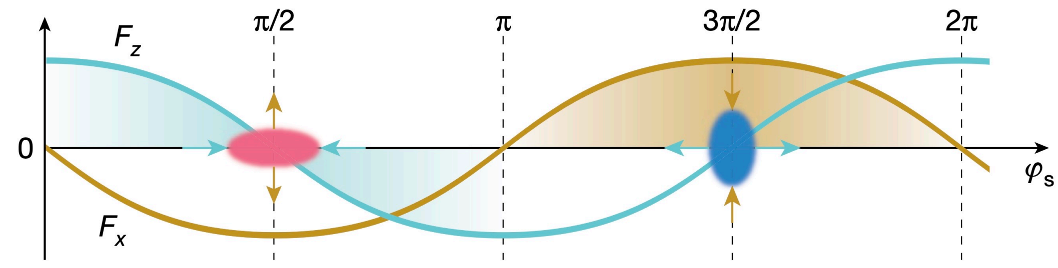
Article | Published: 22 September 2021

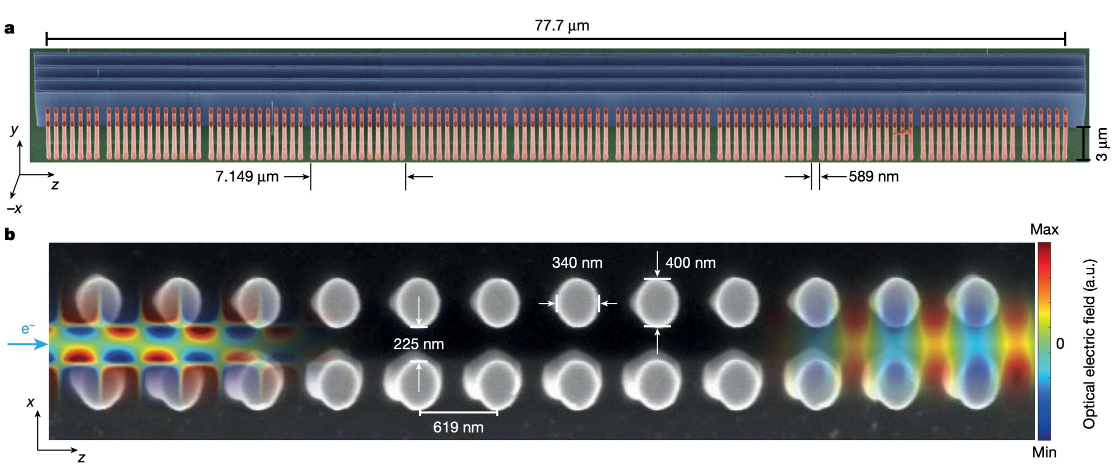
Electron phase-space control in photonic chip-based particle acceleration

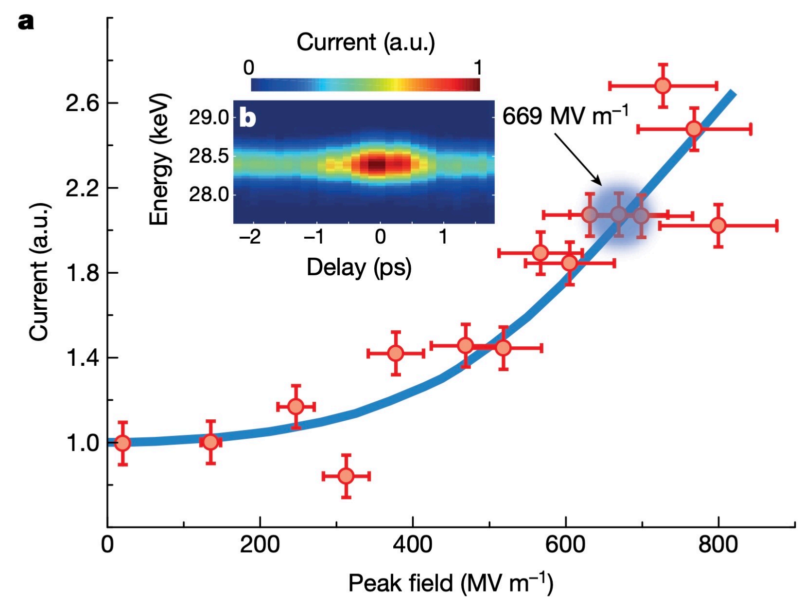
R. Shiloh, J. Illmer, T. Chlouba, P. Yousefi, N. Schönenberger, U. Niedermayer, A. Mittelbach & P. Hommelhoff

Nature **597**, 498–502 (2021) | Cite this article

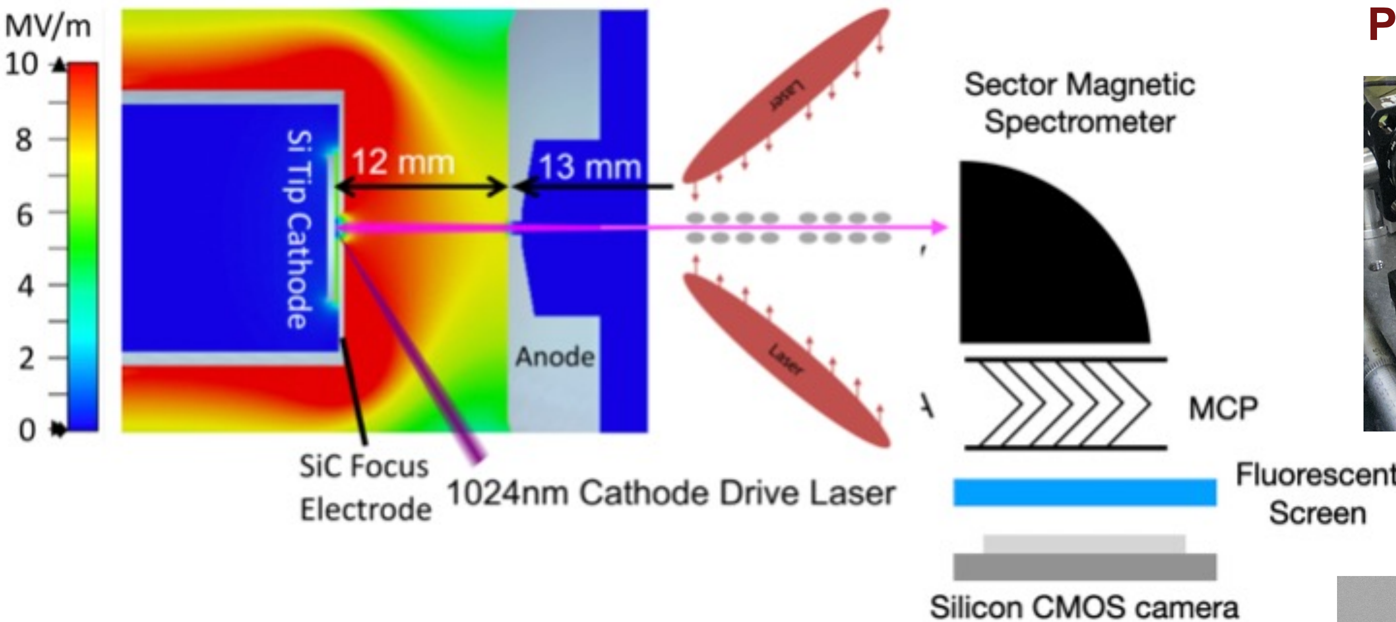
Alternating Phase Focusing (APF)





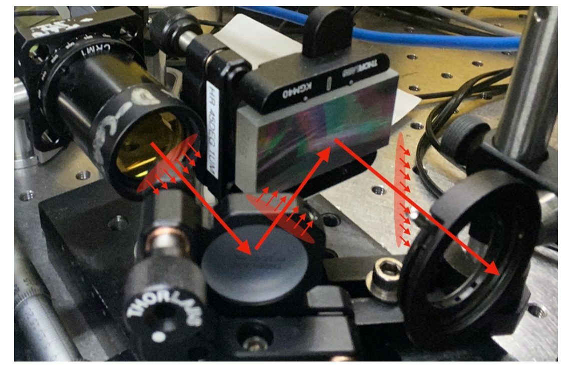


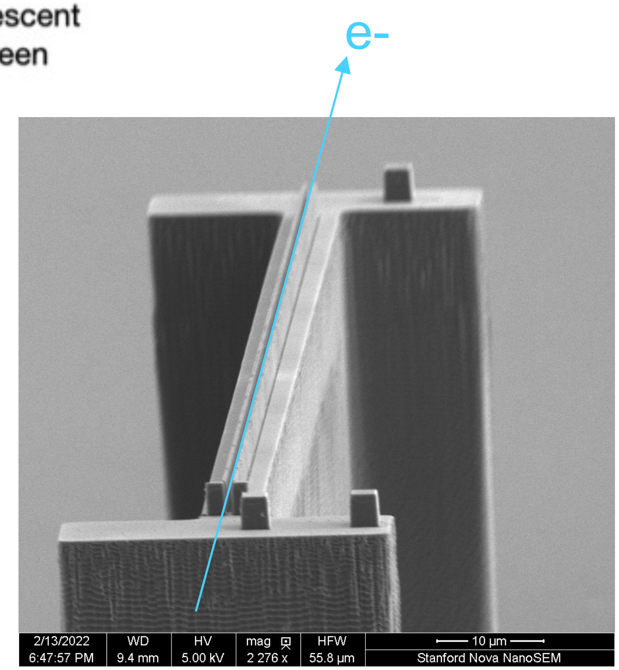
Bunch Capture and Acceleration with 2D Laser Focusing: Setup



Parameter	Value
Laser wavelength	1995 nm
Incident E-field	266 MV/m
Starting Electron Energy	96 keV
Interaction Length (2 designs)	476, 480 µm

Blazed Grating used for Pulse Front Tilt (60.5˚)

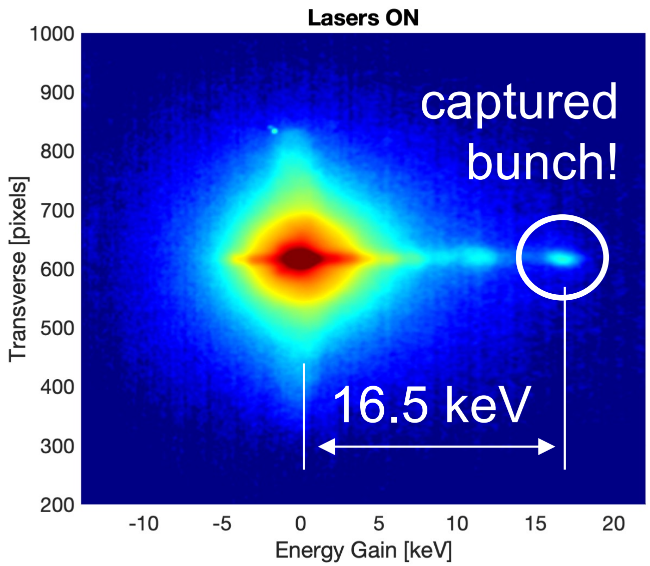




Bunch Capture and Acceleration with 2D Laser Focusing: Initial Results

Stanford University

Uwe70: 480um Interaction Length

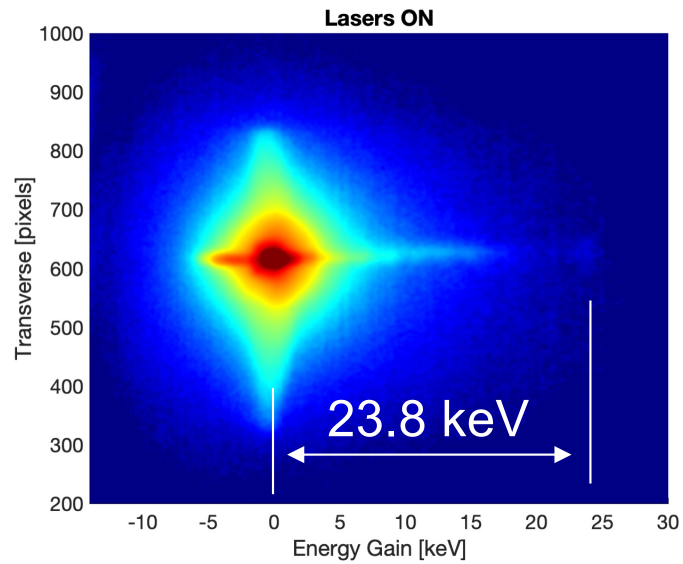


Expected Energy Gain:	16.5 keV
Measured Energy Gain:	16.5 keV

14 unit cells

17.5% Energy Gain

Dylan100: 476um Interaction Length



Expected Energy Gain:	22.86keV
Measured Energy Gain:	23.8keV

23.5 unit cells

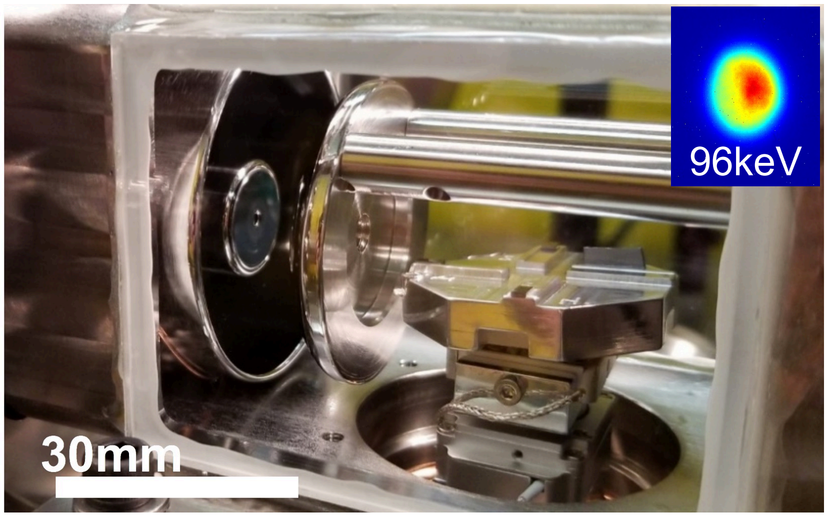
25% Energy Gain

Structures have been designed for longer interaction lengths up to 1.4 mm. Intermediate goal for sub-relativistic structures is to reach 100% energy gain in a single acceleration stage (energy-doubler) by end of FY22.

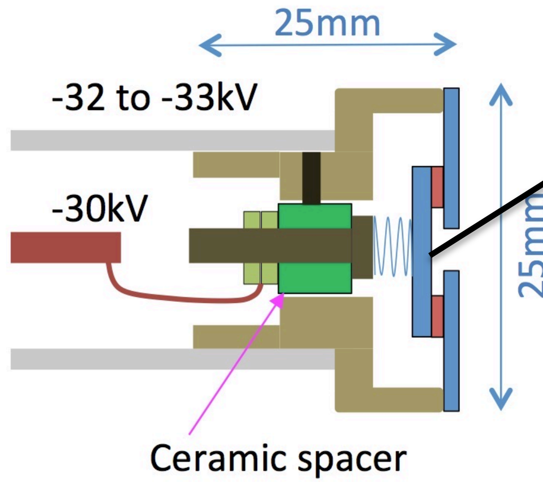
The components for an integrated tabletop accelerator are coming together

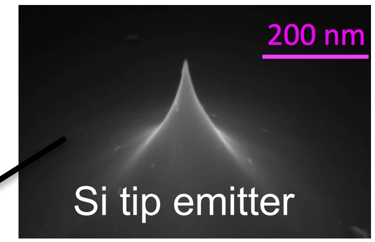
Stanford University

Stanford "glassbox" test system



compact electron gun w/electrostatic lens

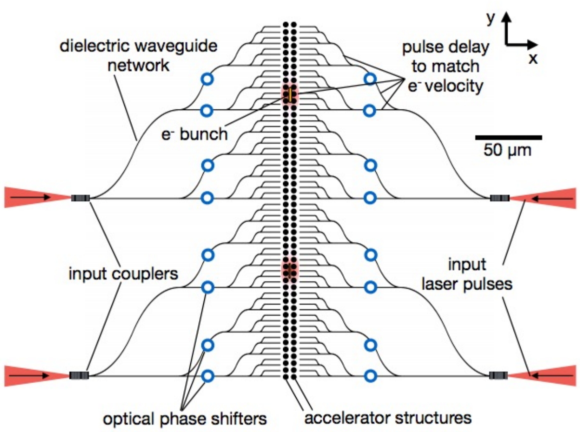


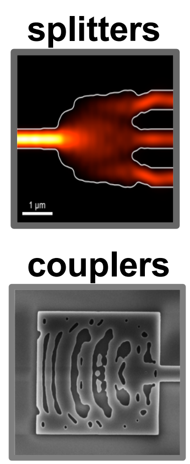


3000 e-/pulse,100 kHz rep
0.2 nm emittance
A. Ceballos, Stanford

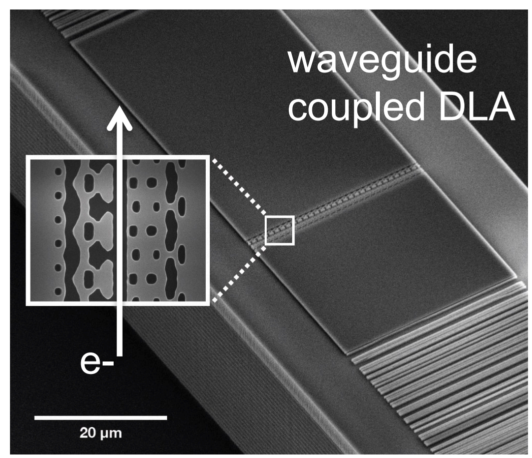
T. Hirano, et al., Appl. Phys. Lett. 116, 161106 (2020)

optimized DLA components via inverse design



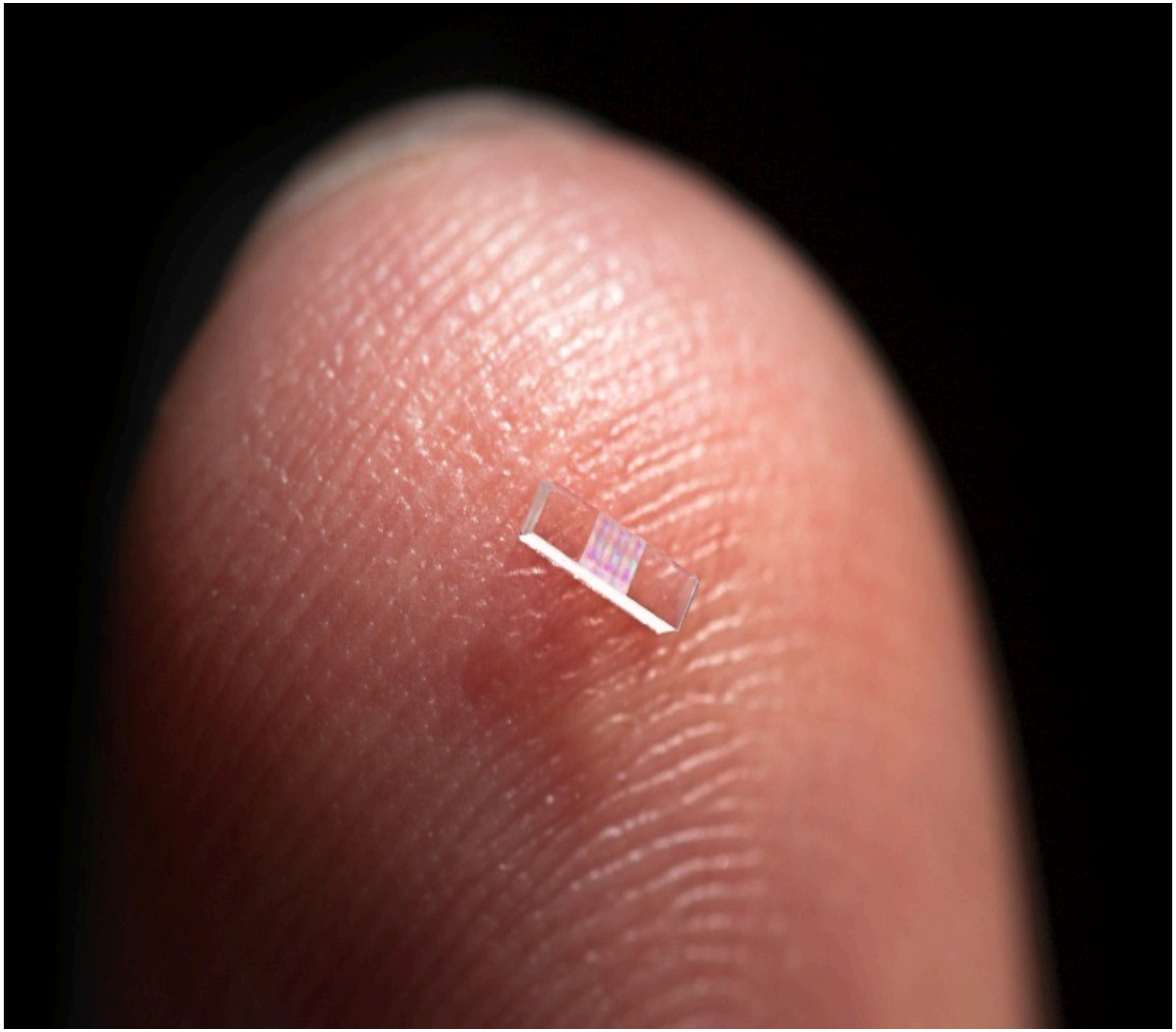


T. Hughes, et al, Phys. Rev. Appl. 9, 054017 (2018)



N. Sapra, et al., Science 367, 79-83 (2020)

So single micro-accelerator chips have been demonstrated at various energies. What's next?



Both near and long term applications are now being explored

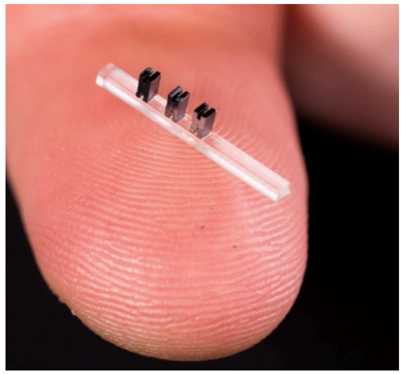
Application	Field	Time-Scale	Kinetic Energy	Species	Beam Power
Radiobiology, Endoscopic RT	**Medical**	**5 yrs**	**100 keV to 10 MeV**	**e-**	**1-5 mW**
UED/UEM and Attosecond Science	**Science**	**5 yrs**	**1-5 MeV**	**e-**	**10 to 50 μW**
Radiation Sources (EUV, IR, THz)	**Industry**	**5-10 yrs**	**10 to 100 MeV**	**e-**	**0.5 W**
Compton X-ray Source	Medical	5-10 yrs	10 to 60 MeV	e-	20 to 60 mW
Proton/Hadron Therapy	Medical	10-20 yrs	70 to 250 MeV	p+	3-400 mW
Compact XFEL	Science	10-20 yrs	1 GeV	e-	1.5 kW
Multi-Axis Tomography	Science	10-20 yrs	1 GeV	e-	1.5 kW
Colliding Beam Fusion	Industry	20+ yrs	15 keV to 1 MeV	p+	1 MW
Linear Collider	HEP	20+ yrs	1 to 10 TeV	e-/e+	10 to 200 MW

Near term applications in attosecond and quantum information science are well matched to DLA performance (ultrafast, low charge, high rep).

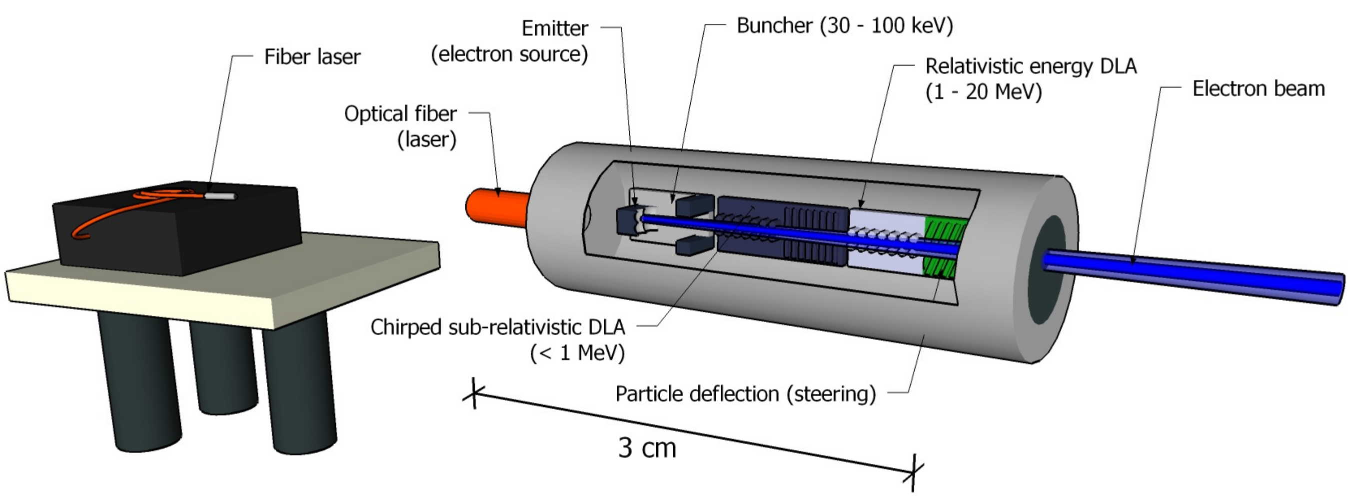
One potential near-term application could be a catheterized device for radiative cancer therapy.

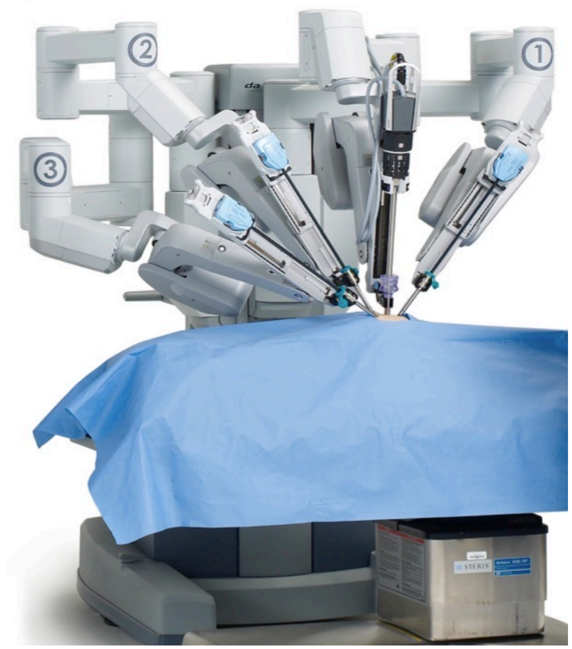
conventional

chip-based



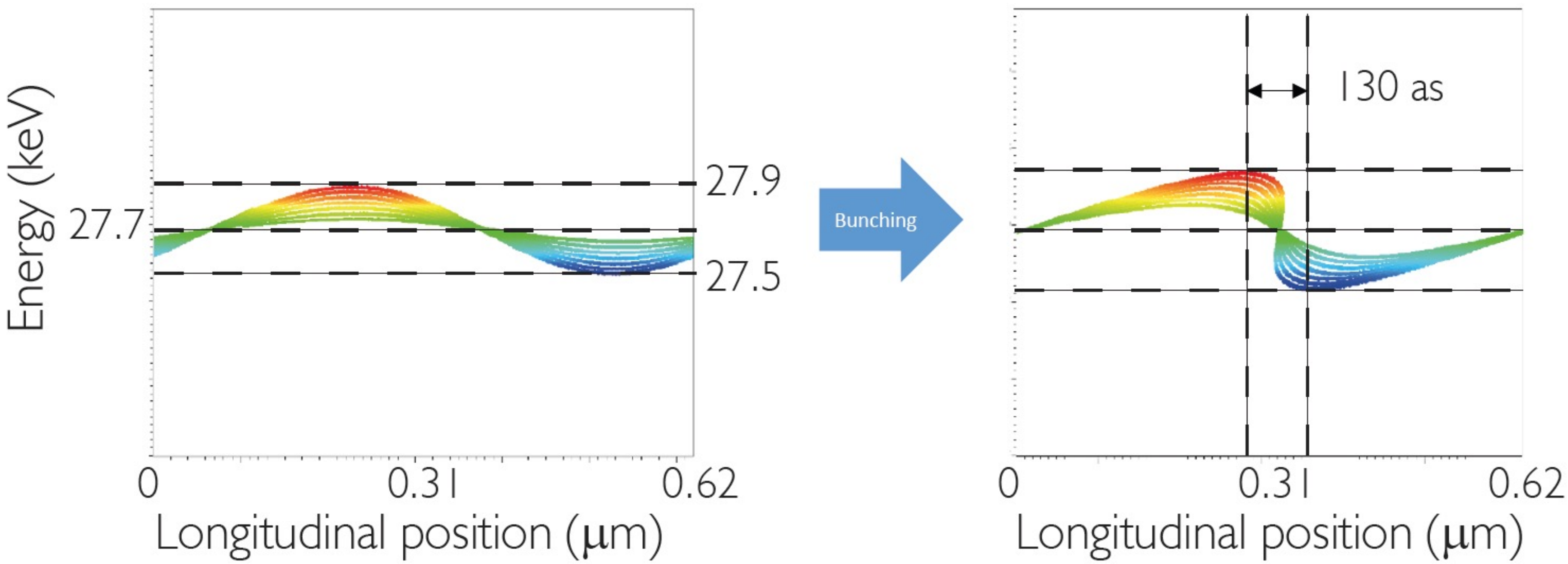
- Chip-sized footprint could enable direct ebeam treatment (lower dose, quicker recovery time).
- Required electron current, energy, and power well suited to a single-wafer, single-laser design.

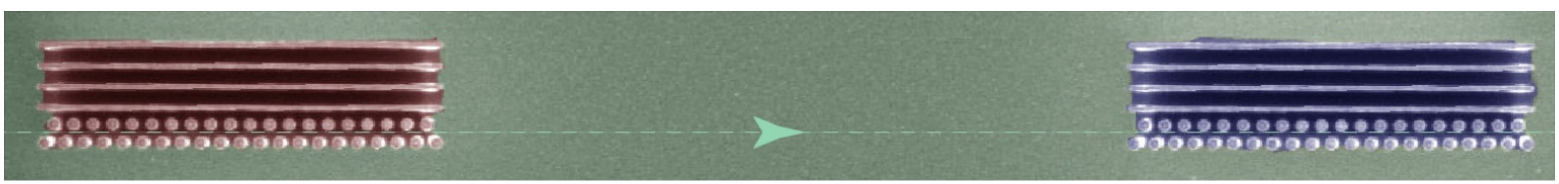




DLA could enable ultracompact devices for direct electron radiation therapy, employed via robotic control.

DLA intrisically enables “on-chip” attosecond temporal bunching of electron beams...





Buncher *30 μm apart* *Analyzer*

Shortest micropulse: (270 ± 80) attoseconds *(world record)*

D. Black, U. Niedermayer, Y. Miao, O. Soolgard, R. L. Byer, K. Leedle, PRL 123, 264802 (2019)
N. Schönenberger, A. Mittelbach, P. Yousefi, J. McNeur, U. Niedermayer, P. Hommelhoff, PRL 123, 264803 (2019)

FAU FRIEDRICH-ALEXANDER UNIVERSITÄT ERLANGEN-NÜRNBERG TECHNISCHE UNIVERSITÄT DARMSTADT Stanford University

... inspiring new theoretical predictions with applications to quantum systems.

SLAC

New **techniques for optically modulating electron beams** have inspired theoretical investigations* which provide several **new (experimentally untested) predictions**:

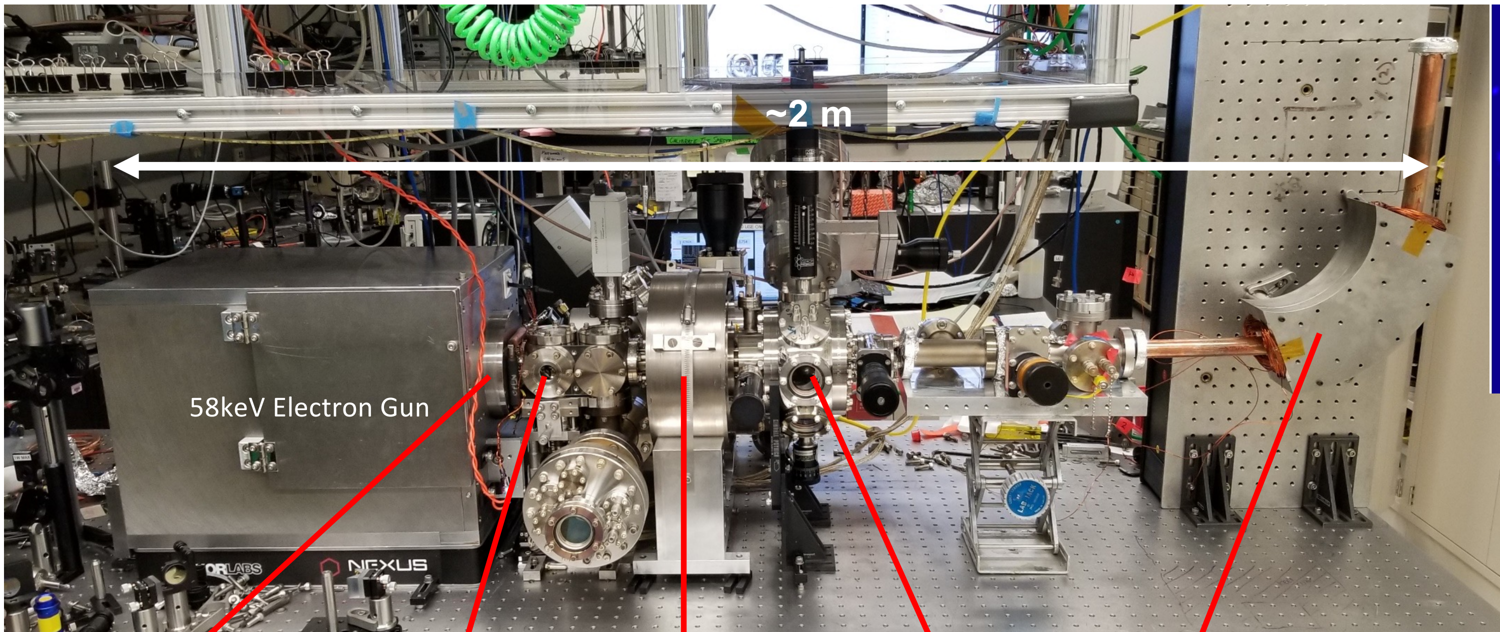
1. Modulated electron beams can stimulate emission from excited two-level systems.
2. Cathodoluminescence (CL) generated by a modulated electron beam is coherent with the modulating light source.
3. The quantum state of the entangled electron beam and/or color center can be uniquely determined using spectroscopy (frequency domain) and streaking (time domain) information.

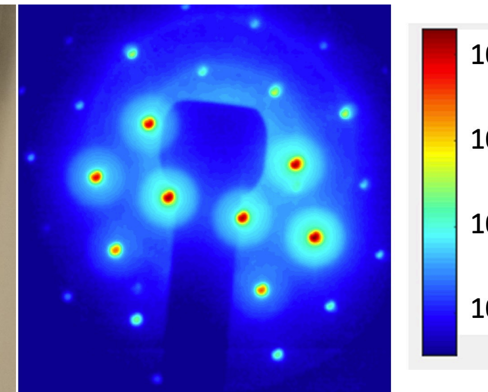
Experimental demonstrations of these predictions would lend new insight into modulated-electron/solid-state interactions, including:

- modulated cathodoluminescence (CL) of color centers in bulk materials
- individual preparation and probing of coupled quantum systems
- fundamental quantum properties of coupled photons and electrons.

* Kfir, et al., arxiv:2010.14948v2 (2020), Reinhardt and Kaminer, ACS Photonics 7, 2859 (2020), Gover and Yariv, PRL 124, 064801 (2020), Pan and Gover, Phys. Rev. A 99, 052107 (2019)

A DLA "beam line" for electron diffraction has been built in the Stanford ACHIP lab (Ginzton Labs)



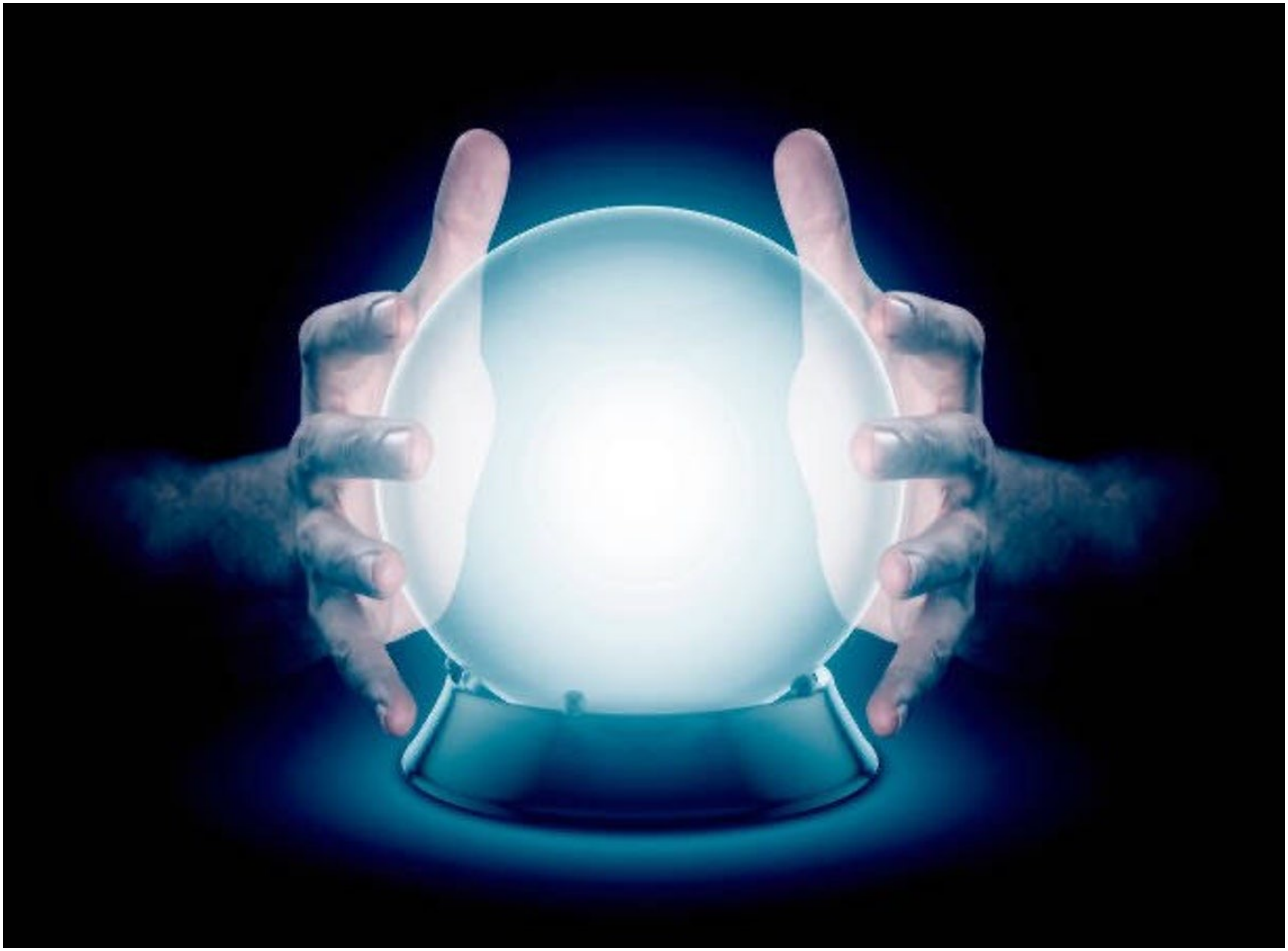


UED time-resolved (20 ps) measurement of h-BN lattice heating using ACHIP beam line

- 200 keV (by end of FY22) after DLA acceleration
- <0.3 nm·rad normalized emittance
- 200 to 400 nm spot size at DLA exit
- 10 to 1000 electrons/pulse @1 MHz

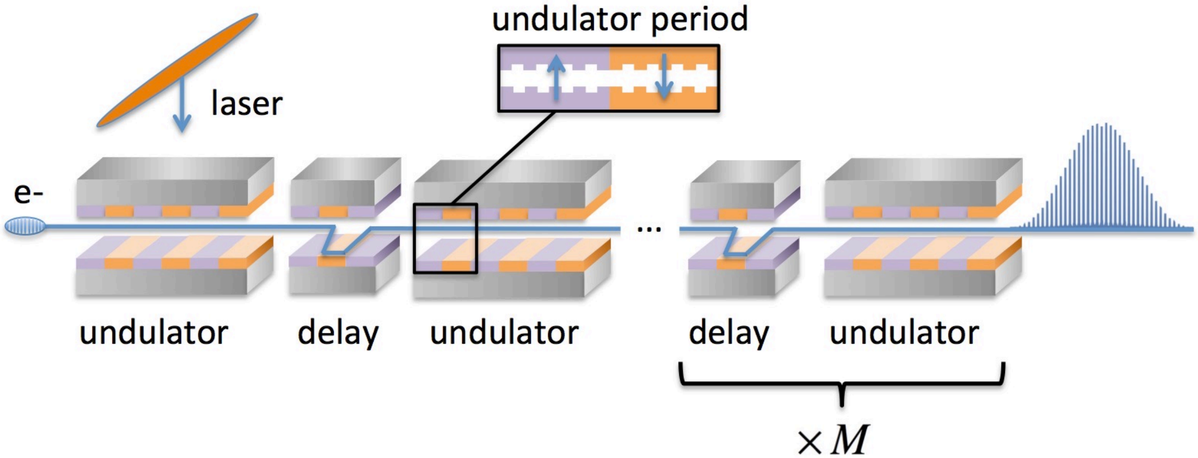
Anticipated ACHIP performance parameters appear well suited as a source for tabletop **ultrafast electron diffraction (UED)**.

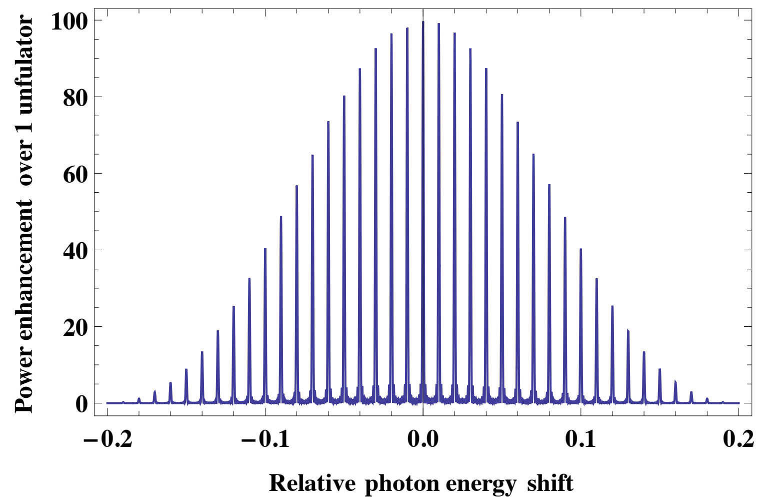
What could the future hold for microchip accelerators?



EUV Attosecond Frequency Comb

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

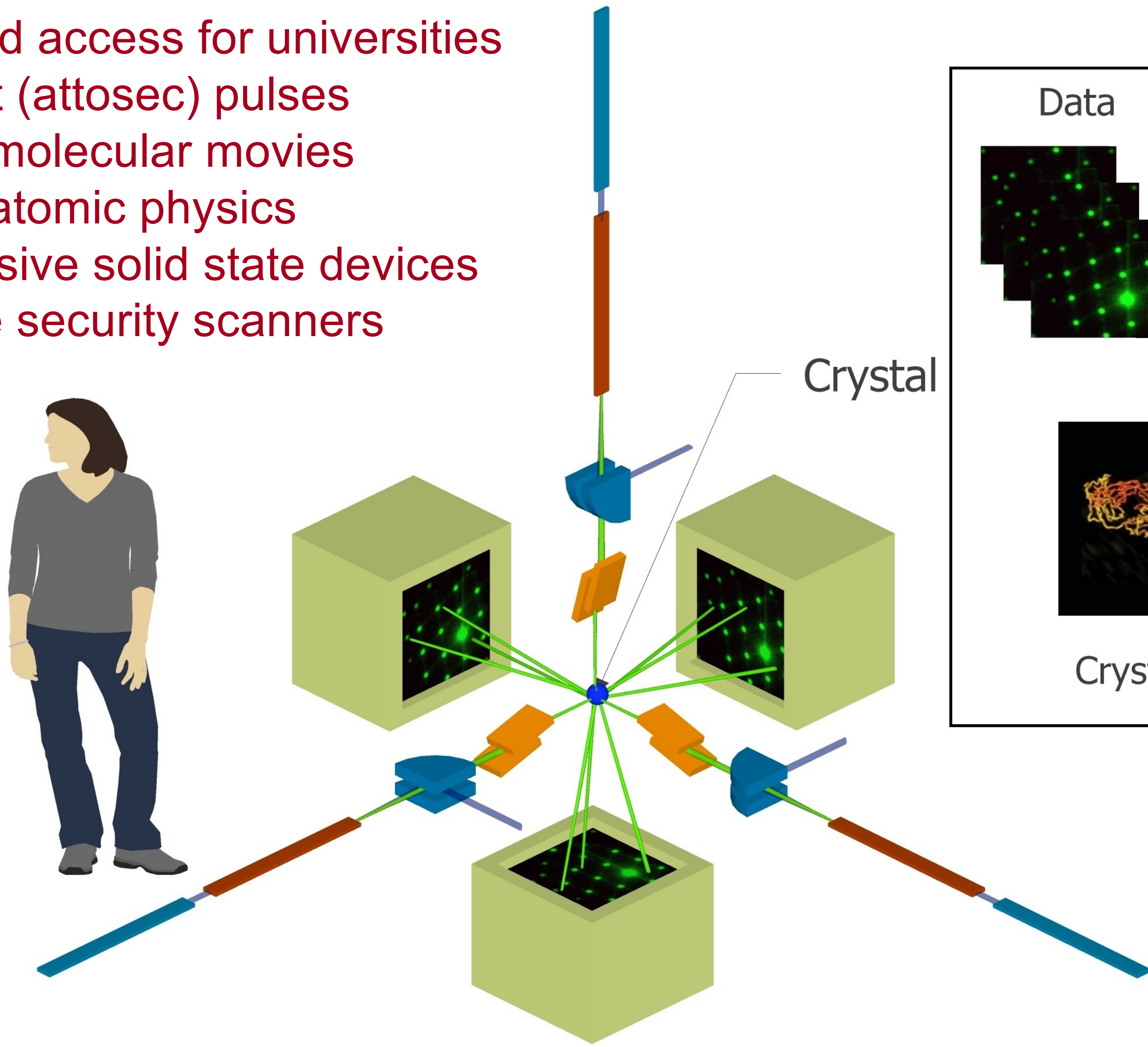


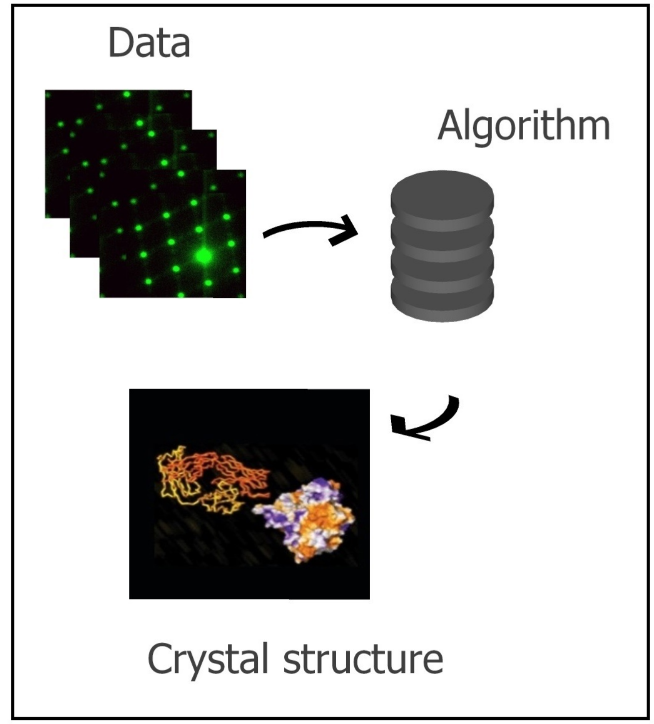


Parameter	Unit	Value
Beam Energy	MeV	40
Microbunch Charge	fC	10
Undulator Period	μm	250
Number of periods / Delay Modules	#	10 / 100
EUV Photon Energy	eV	50
Radiated Pulse Energy	nJ	100

A miniaturized attosecond XFEL could enable revolutionary new science capabilities.

- 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)

High Energy Physics Related Papers/Workshops

Beam dynamics in dielectric laser acceleration

U. Niedermayer[1], K. Leedle[2], P. Musumeci[3] and S.A. Schmid[1]

Published 6 May 2022 • © 2022 The Author(s)

Journal of Instrumentation, Volume 17, May 2022

PAPER • FREE ARTICLE

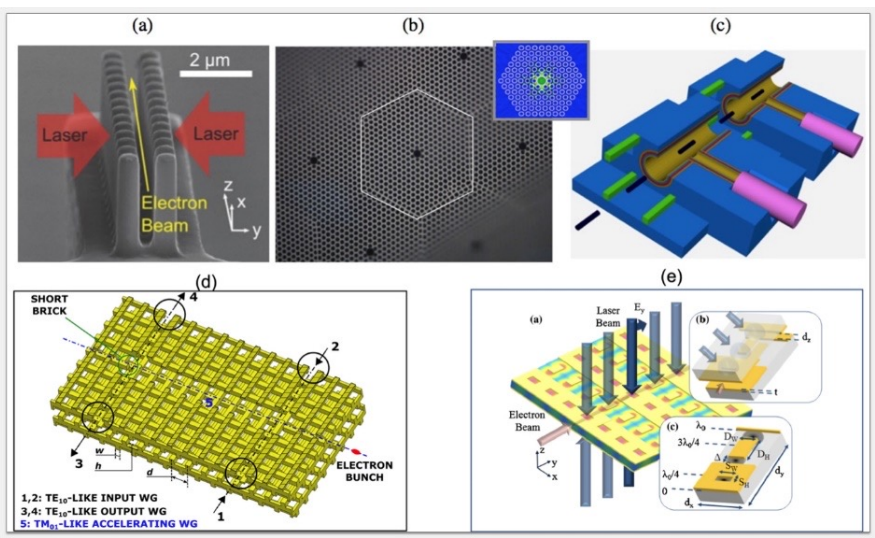
Considerations for a TeV collider based on dielectric laser accelerators

R.J. England[1], U. Niedermayer[2], L. Schächter[3], T. Hughes[4], P. Musumeci[5], R.K. Li[6] and W.D. Kimura[7]

Published 6 May 2022 • © 2022 IOP Publishing Ltd and Sissa Medialab

Journal of Instrumentation, Volume 17, May 2022

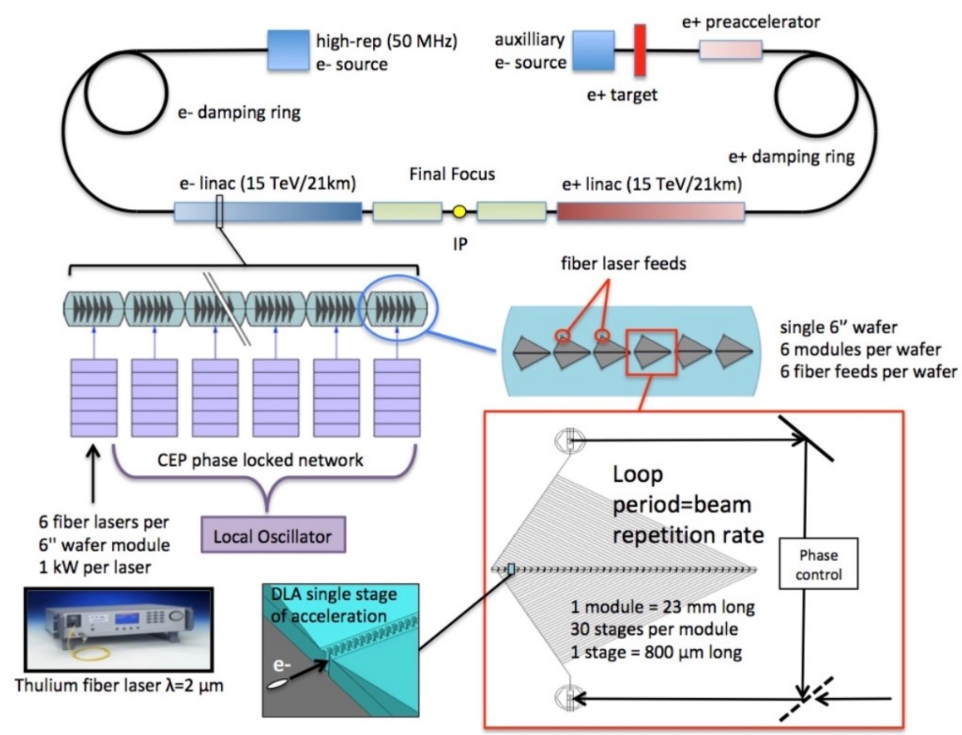
Accepted in JINST, 2022



Laser-Driven Structure-Based Accelerators: White Paper for Snowmass 2021 Topical Group AF06 - Advanced Acceleration Concepts

R. J. England, D. Filippetto, G. Torrisi, A. Bacci, G. Della Valle, D. Mascali, G. S. Mauro, G. Sorbello, P. Musumeci, J. Scheuer, B. Cowan, L. Schächter, Y-C. Huang, U. Niedermayer, W. D. Kimura, R. Li, R. Ischebeck, E. Simakov, P. Hommelhoff, R. L. Byer

Snowmass Contribution, March 15, 2022

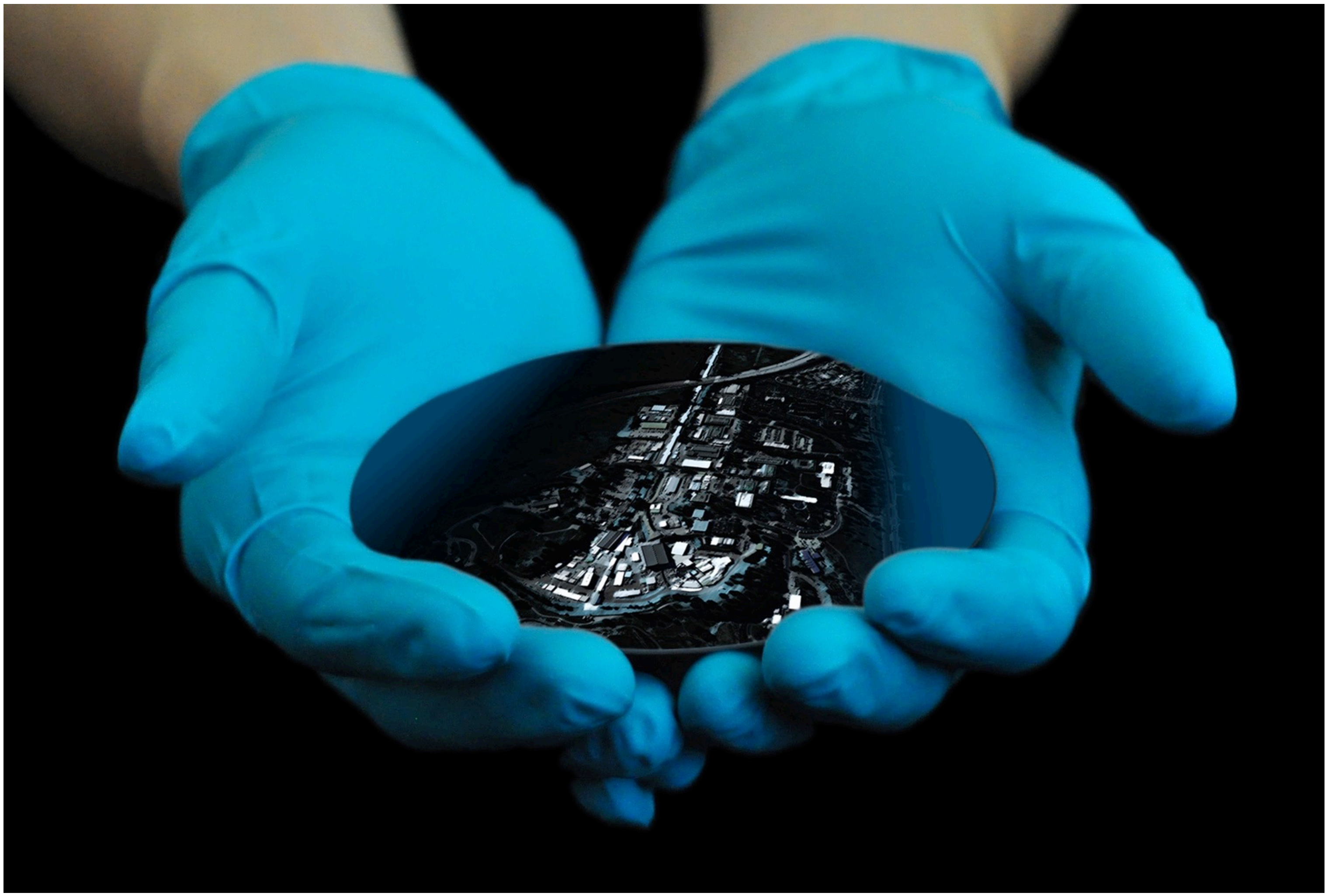


Although decades away for TeV scale HEP, DLA has unique advantages, including efficiency, cost, and low beamstrahlung energy loss.

And maybe some day...

Laser?

SLAC: Stanford ~~Linear~~ Accelerator Center



photoshop rendering of SLAC on a wafer by K. Soong

Thank you!

Group photo, ACHIP collaboration meeting in Hamburg, Germany, September 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 and to the U.S. Dept. Energy, European Research Council, and Gordon and Betty Moore Foundation for support.

Acknowledgments

Stanford University
Prof. Bob Byer
Prof. James Harris
Prof. Olav Solgaard
Prof. Shanhui Fan
Prof. Jelena Vuckovik
K. Leedle
Dylan Black*
Neil Sapra*
Yu Miao
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 = current & former students;
* = Bob Siemann fellows