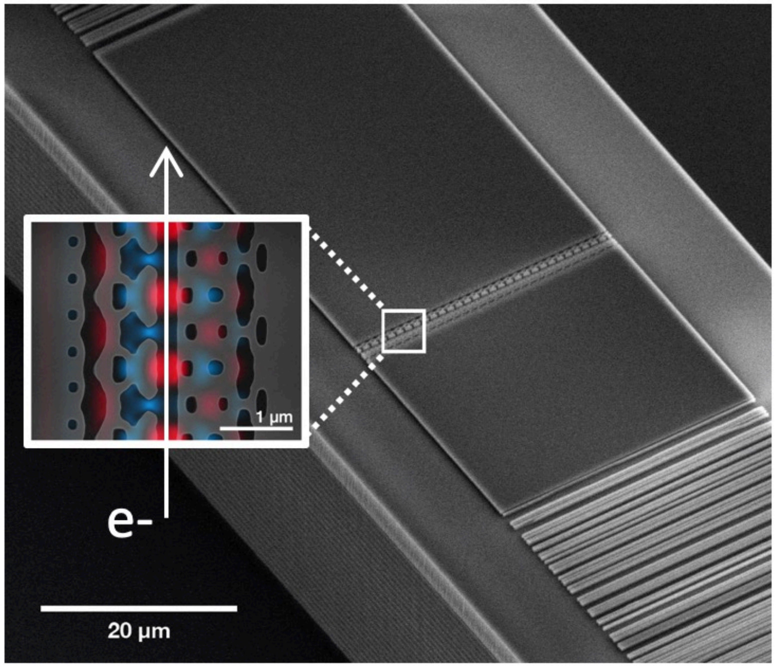
Dielectric Laser Accelerators

Snowmass AF6 Meeting Sept 23, 2020

R. J. England

Co-authors: B. Cowan, L. Schachter, Y-C. Huang, U. Niedermayer, W. D. Kimura, E. I. Simakov, M. Ferrario, G. Andonian, S. Chattopadhyay, P. Musumeci, R. Assmann, F. Burkart, R. Ichebeck, P. Hommelhoff, and R. L. Byer



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

Global DLA Effort & Funding

CURRENT ACTIVE PROGAMS: ACHIP (multiple PIs), Euclid Tech Labs, U. Tokyo (Uesaka), LANL (Simakov), U. Liverpool (Welsch)

Accelerator on a Chip International Program (ACHIP) 2015 to 2022

- Major international effort (8 universities, 2 US + 2 EU labs, 2 companies)
- Countries involved: US, Germany, Taiwan, Japan, Switzerland, Israel
- Funded by Moore Foundation plus in-kind DOE support
- Most DLA effort worldwide falls under this program; additional work in UK, China

Existing programs provide guidance on future R&D Costs

ACHIP - $19.5M / 7 years = $2.7M/year (Moore Foundation, low overhead ~ 12%)
LANL (2018-2020) - $3M over 3 years = $1M/year
SLAC, DESY, PSI: International Lab (DOE & internal) in-kind support (~$1.8M/year)

Future program(s) should be at similar effort levels to maintain critical mass

May be subdivided into parallel programs under multiple funding sources.
Assumes funding from government funding agencies (50 to 60% overhead).
Due to low overhead of Moore Foundation gift grant, continuation under other funding sources would need ~ 2x current funding for equivalent effort level.

Current State of the Art

DLA included under ANAR and ALEGRO 2017-2019 workshops. HEP roadmaps developed on 30 year time scale with core working group established.

Supporting Technologies are Well-Established:

- Laser Requirements: 1-10 μJ, <1 ps, 10-50 MHz rep rate (low cost, form factor, off-the-shelf)
- Integrated Photonics: facilitated by microchip industry; low-cost, nanometric precision

Gradient and Energy Scalability:

- High-gradient operation with **850 MeV/m** average electron gradient and **0.3 MeV** energy gain and **phase/dispersion control**. Higher gradients possible -- 1.8 GV/m axial fields experimentally demonstrated in fused silica DLA. (UCLA, D. Cesar 2018)
- POCs have demonstrated key concepts needed for energy scaling: transverse and longitudinal **focusing**, optical **pre-bunching** and injection, **net acceleration**, integrated waveguide **coupling,** extended transport**, staging** of laser pulses**.**
- **ACHIP aims to develop a cm-scale 1 MeV tabletop accelerator by FY21**

Particle Source Technology:

- DLA approach works equally well with electrons and positrons.
- HEP luminosity (2e34 for ILC) in DLA scenario is feasible with 2e6 particles per bunch train (100-500 fC, divided into 100-200 microbunches) at 20-40 MHz train rep rate of modern lasers.
- Proposed source for HEP is low-charge high-rep SRF gun + positron target & damping rings
- Nanotip sources (fA - pA average current) used in recent POCs are attractive for intermediate applications (e.g. UED, medical); but **not** indicative of ultimate beam current limits

Intermediate Applications

- Technical group established under ACHIP to evaluate a range of applications.
- Three DLA Applications workshops with external experts (most recent June 23, 2020).
- R&D developments needed for intermediate applications (e.g. beam transport, staging, higher beam current) are also relevant for HEP.

Promising near-term (< 5 year) applications include medical, radiobiology, attosecond pump-probe and UED/UEM: leverages nanotip source technology, with moderate energies (1 to 10 MeV) and beam currents (< 1 nA).

DLA Applications Matrix (ACHIP)

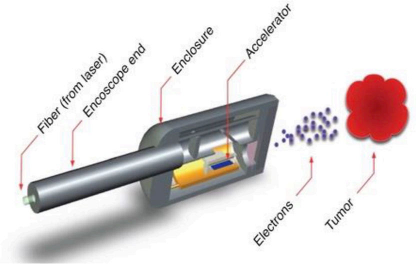
Application	Field	Time-Scale	Kinetic Energy	Species	Beam Power
Radiobiology	**Science**	**5 yrs**	**100 keV to 5 MeV**	**e-**	**5 mW**
UED/UEM Source	**Science**	**5 yrs**	**1-5 MeV**	**e-**	**10 to 50 μW**
Catheterized Electron Source	**Medical**	**5 yrs**	**1 to 10 MeV**	**e-**	**1-3 mW**
Compton X-ray Source	Medical	5-10 yrs	10 to 60 MeV	e-	20 to 60 mW
Low-power EUV	Industry	5-10 yrs	10 to 100 MeV	e-	0.5 W
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

U.S. DEPARTMENT OF ENERGY | Office of Science

Basic Research Needs Workshop on
Compact Accelerators for Security and Medicine

Tools for the 21st Century

May 6-8, 2019



New "on a chip devices" are coming forward presently and may offer significant improvement in delivery of radiation, from collimation to brachytherapy compatibility, to array use, and finally to cost.

Current and Future Test Facilities

Current Test Facilities:

UCLA Pegasus: 1-8 MeV photoinjector+linac; Ti:Sapphire laser; low-charge, norm. emittance ~ 30nm-rad

High gradient and high energy gain demonstration experiments

Stanford: 30 to 100 keV nanotip emission sources for low-energy structure evaluation

FAU Erlangen: 30 kV SEM and supertip field emission source test stands; 2μm laser testing

Future Planned (Funded) Test Facilities (1 to 5 year timeline):

PSI SwissFEL 3 GeV beam line - dedicated DLA diagnostic and vacuum chamber

Laser driven undulator, wakefield studies, radiation damage testing

DESY SINBAD 100 MeV beamline -- short bunches (few fs); optically microbunched beams anticipated

Net acceleration experiments; particle deflection/streaking

FAU and Stanford: 1 MeV university test bench: demonstrate basic staging and integrated component capabilities; proposed outcome of ACHIP

Other Potential Test Facilities (1 to 5 year timeline):

NLCTA (SLAC) – currently in minimal operation mode; used in earlier (2013-2015) experiments

ATF (BNL) – high power CO_2 laser; capabilities for hosting advanced accelerator experiments

Summary

Key Advantages of Dielectric Laser Accelerators (DLA) for e+e- linear collider (LC):

Linear acceleration mechanism in a static structure with vacuum channel.

Critical technologies (laser development, nanofab) already near LC requirements.

Unique bunch format (fC charge at 10 to 50 MHz rep rate) with beamstrahlung loss ~ 1%

High fiber laser efficiencies (30 to 50% wallplug) facilitate modest power consumption.

Primary Challenges for a DLA Collider:

Small beam apertures → challenge with regard to wakes, halo, and long-distance transport.

Need high-rep (10 – 50 MHz) low charge (fC) normalized emittance (< 1 nm) e- and e+ sources.

Funding for this area of research is not directly focused on HEP applications.

Takeaway Points:

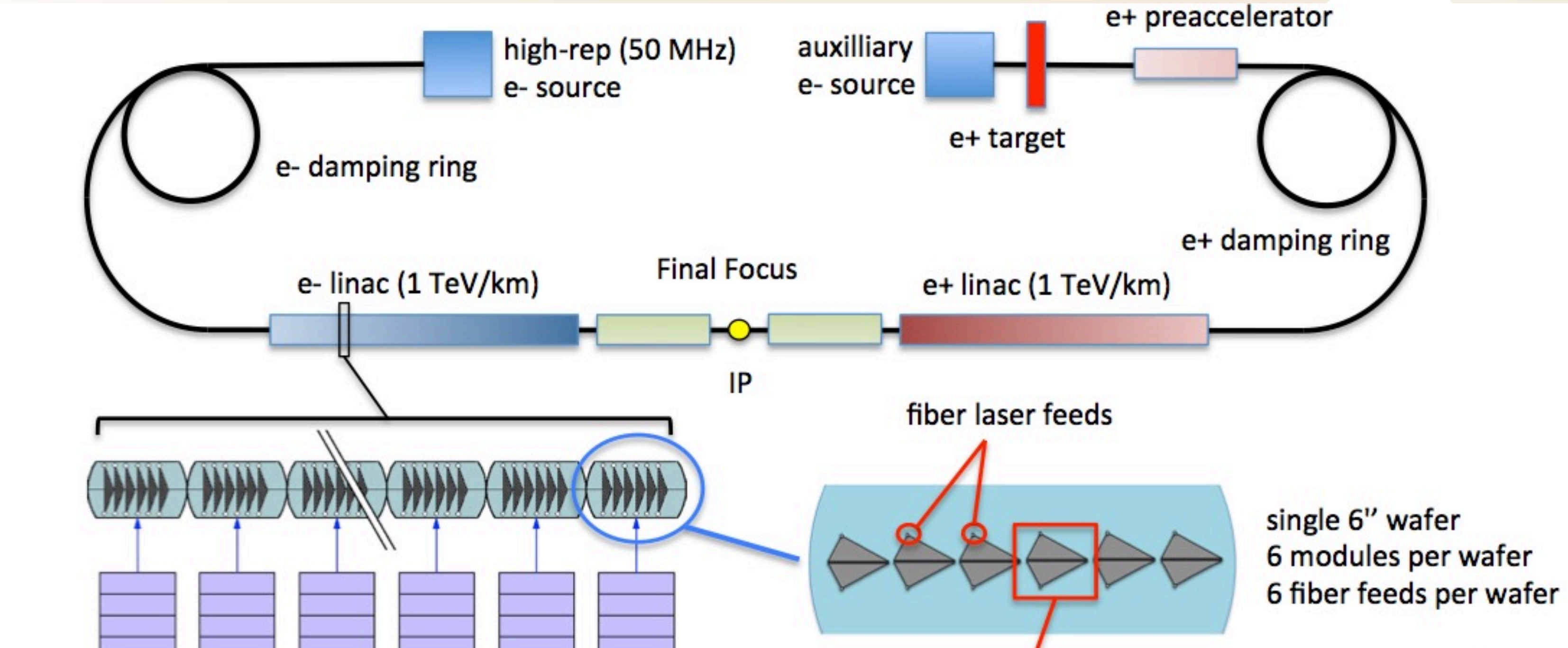
DLA has compelling advantages that position it as a competitive LC technology

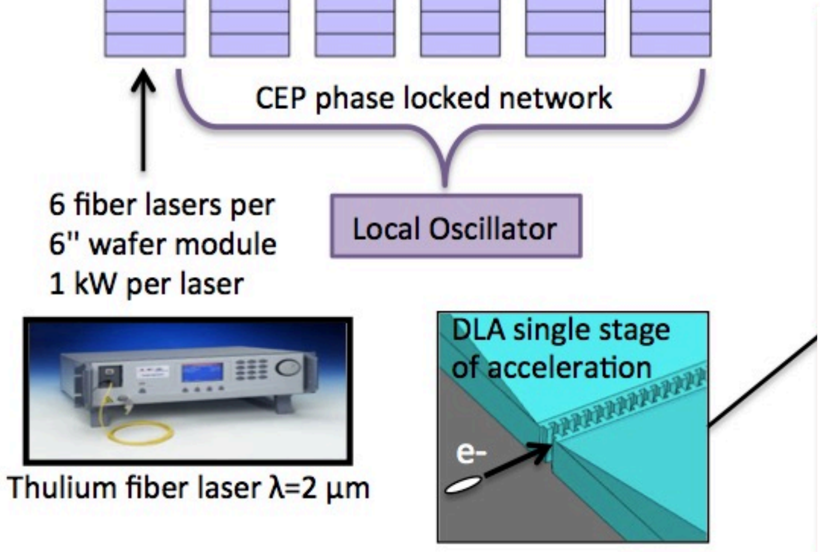
Requirements of a LC impose major technical challenges for all advanced concepts

DLA's challenges are distinct from other concepts but not necessarily less surmountable

Backup Slides

Strawman Collider Parameters

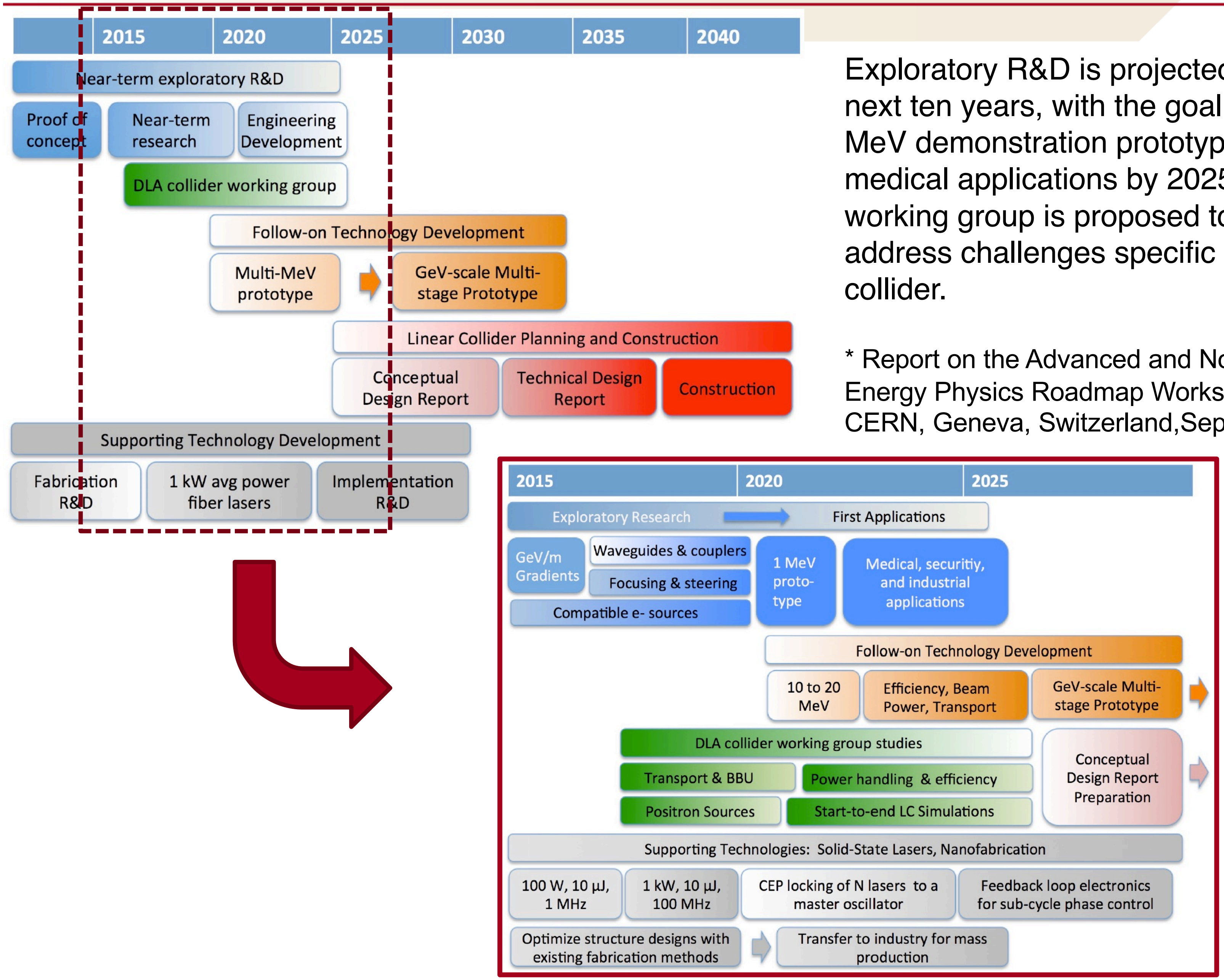




Parameter	Units	CLIC 3 TeV	DLA 3TeV	DLA 250 GeV
Bunch Charge	e	3.7e9	3.0e5	3.8e5
Rep Rate	MHz	5e-5	20	60
Beamstrahlung E-loss	%	**28.1**	**1.0**	**0.6**
Enhanced Luminosity / top 1%	cm-2/s	2.0e34	3.2e34	1.3e34
Wallplug Power	MW	582	374	152

DLA Roadmap (10 to 30 Year)

SLAC



2015 2020 2025 2030 2035 2040

Near-term exploratory R&D

Proof of concept

Near-term research

Engineering Development

DLA collider working group

Follow-on Technology Development

Multi-MeV prototype

GeV-scale Multi-stage Prototype

Linear Collider Planning and Construction

Conceptual Design Report

Technical Design Report

Construction

Supporting Technology Development

Fabrication R&D

1 kW avg power fiber lasers

Implementation R&D

2015 2020 2025

Exploratory Research

First Applications

GeV/m Gradients

Waveguides & couplers

Focusing & steering

Compatible e- sources

1 MeV proto-type

Medical, securitiy, and industrial applications

Follow-on Technology Development

10 to 20 MeV

Efficiency, Beam Power, Transport

GeV-scale Multi-stage Prototype

DLA collider working group studies

Transport & BBU

Power handling & efficiency

Positron Sources

Start-to-end LC Simulations

Conceptual Design Report Preparation

Supporting Technologies: Solid-State Lasers, Nanofabrication

100 W, 10 μJ, 1 MHz

1 kW, 10 μJ, 100 MHz

CEP locking of N lasers to a master oscillator

Feedback loop electronics for sub-cycle phase control

Optimize structure designs with existing fabrication methods

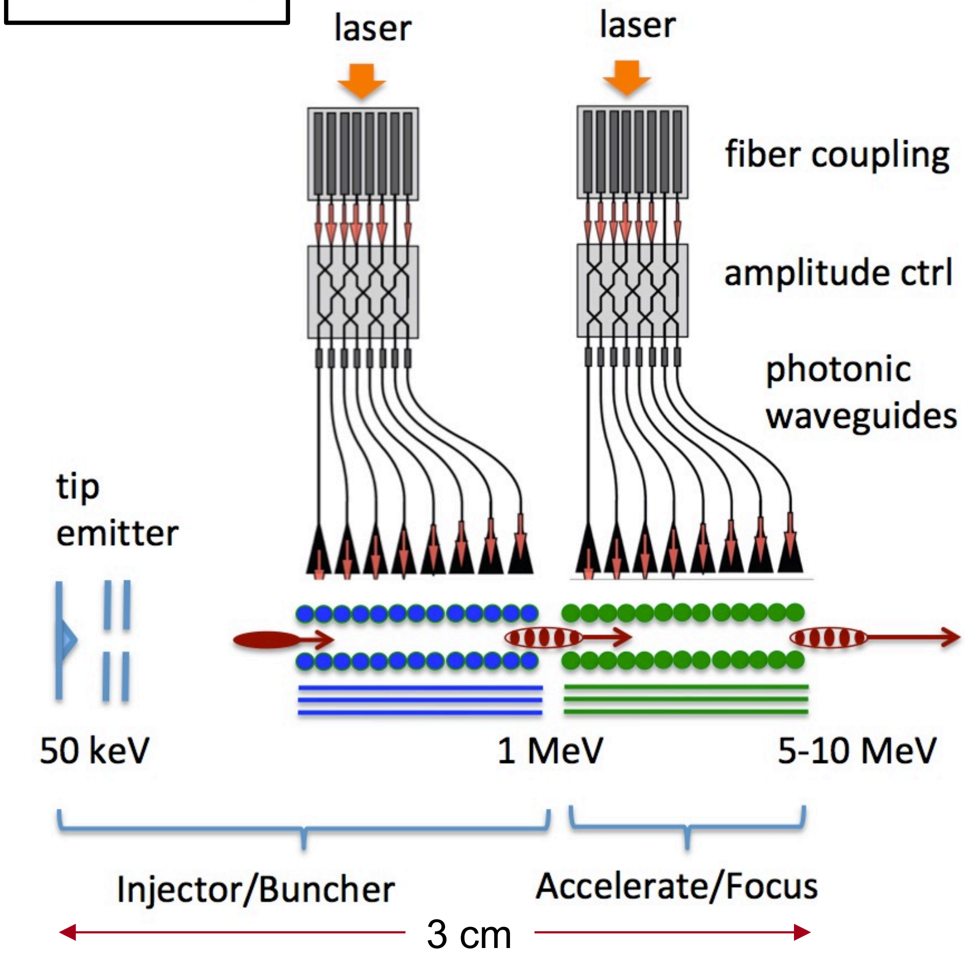
Transfer to industry for mass production

Exploratory R&D is projected to continue over the next ten years, with the goal of developing few-MeV demonstration prototypes for industrial or medical applications by 2025. A dedicated working group is proposed to proceed in parallel to address challenges specific to a linear collider.

* Report on the Advanced and Novel Accel-erators for High Energy Physics Roadmap Workshop (ANAR 2017). CERN, Geneva, Switzerland,September 2017

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

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

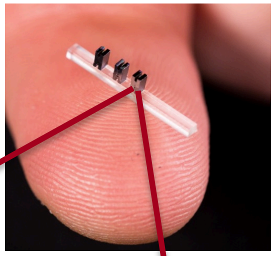


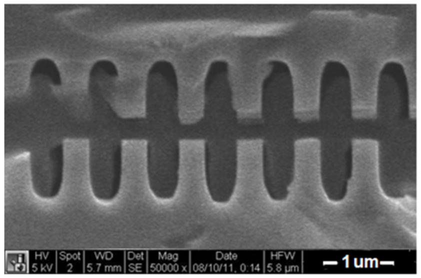
Required lasers are MHz rep rate, low pulse energy, wallplug efficiency ~ 30%

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

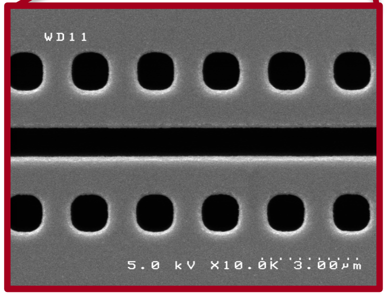
Can be mass produced using techniques of the integrated circuit industy.

SEM images of DLA prototypes tested at SLAC





fused silica

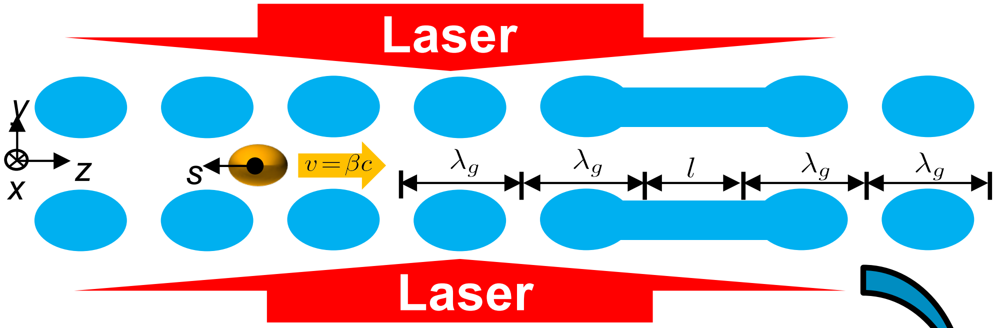


silicon

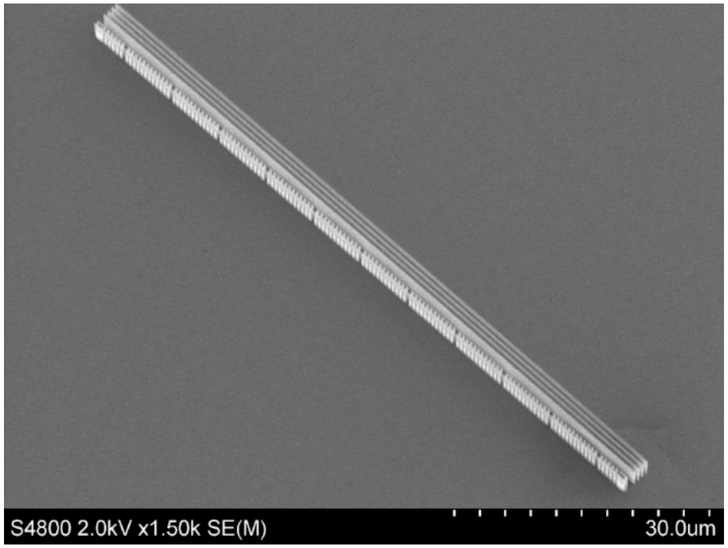
DLA research aims to produce ultracompact nanofabricated devices for particle acceleration, powered by efficient solid-state lasers.

Highlighted Recent Results: Proof of Concept Experiments

laser-driven focusing

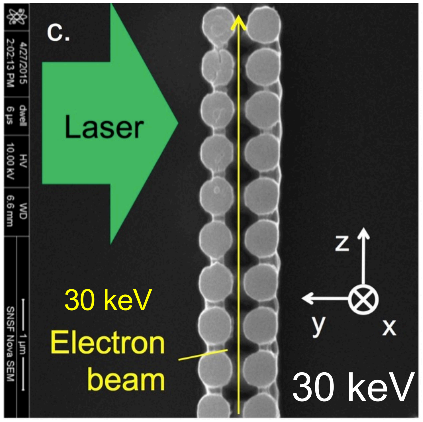


Niedermayer, et al., PRL **121**, 214801 (2018)

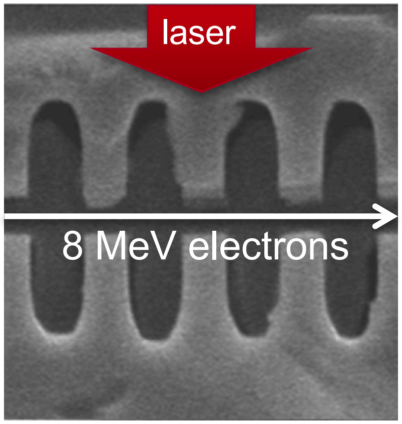


Hommelhoff Group, FAU Erlangen, Germany

high gradient (0.3 → 0.85 GV/m)

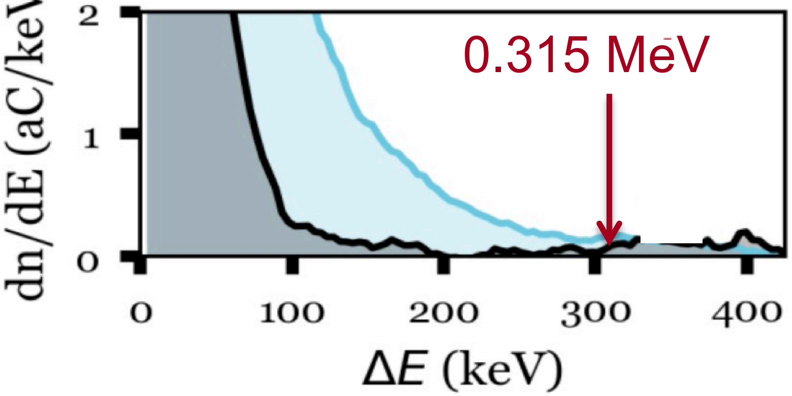


Leedle, et al. Opt. Lett. 40, 4344 (2015)



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

increased energy gains

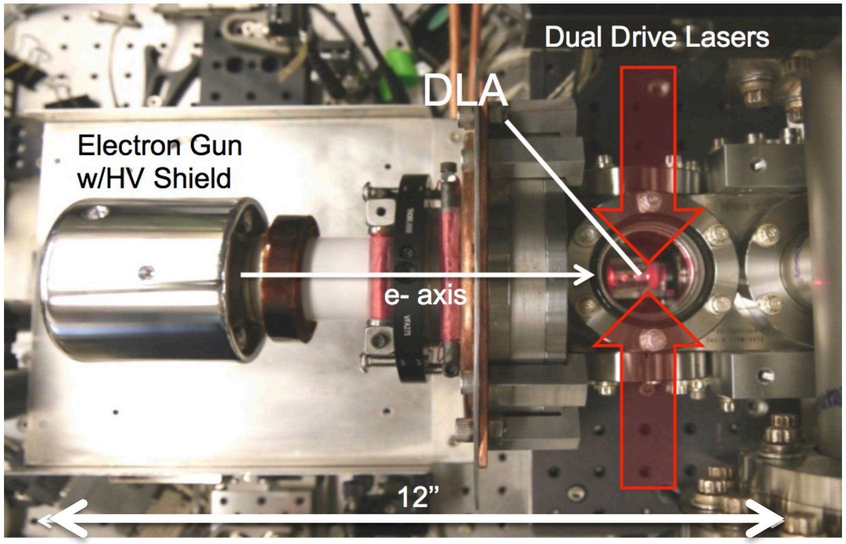


D. Cesar, et al., Optics Express **26** (22), 29216 (2018)

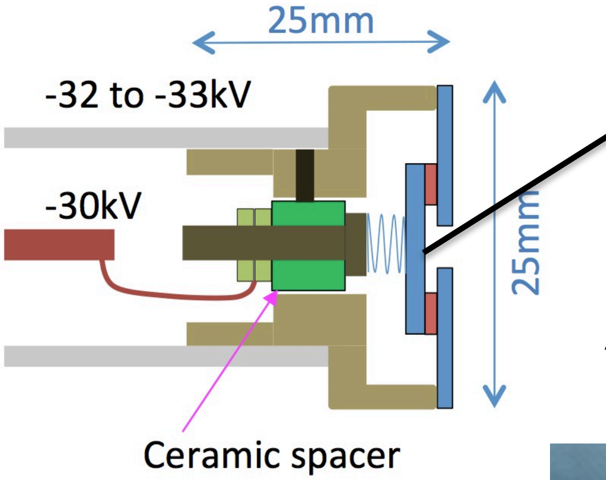
POC experiments use non-ideal test beams. With microbunching, focusing, and nanotip sources, net acceleration to MeV scale is possible.

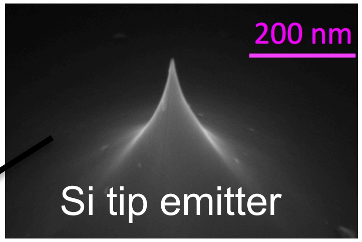
Highlighted Recent Results:
Towards an MeV-Scale Tabletop Device

Stanford “shoebox” test system



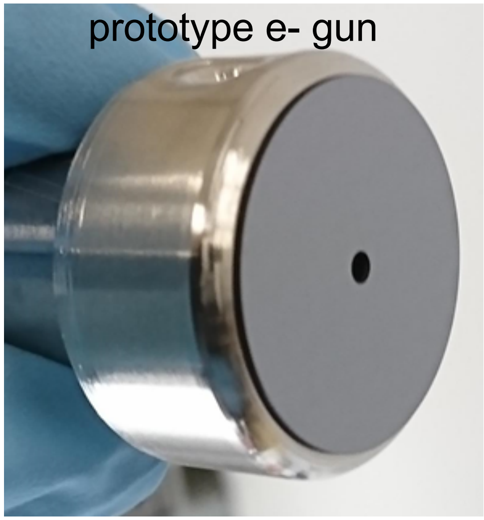
compact electron gun w/electrostatic lens





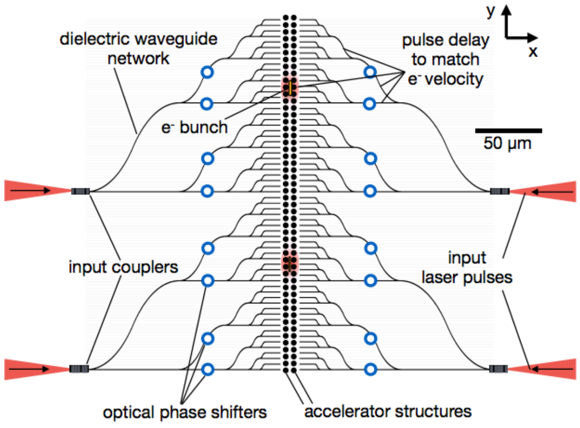
3000 e-/pulse,100 kHz rep
0.2 nm emittance
A. Ceballos, Stanford

prototype e- gun



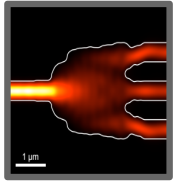
courtesy T. Hirano
(Hamamatsu, visiting scientist
at Stanford University)

optimized DLA components via inverse design

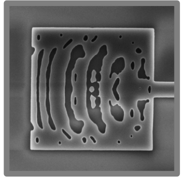


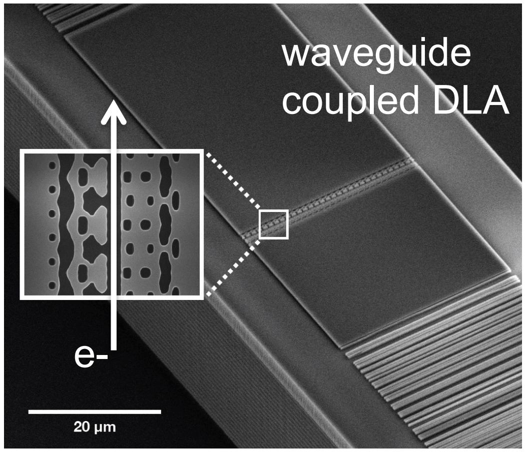
T. Hughes, et al, Phys. Rev. Appl. 9, 054017 (2018)

splitters



couplers





N. Sapra, et al., submitted
Nature Photonics (2019)

Projected ACHIP Parameters (1 vs. 5 Year Time Scale)

Parameter	Units	Near Term 1 Year*	Longer Term 2-3 Years	R&D Improvement Path
Final Electron Kinetic Energy	MeV	1	5	Multi-stage high-gradient relativistic linac
Peak Unloaded Gradient	MeV/m	73	357	AVM optimization of structure field enhancement
Trapped MacroBunch Charge	e	9	1511	Improved coupling of emitter to DLA
Bunch repetition rate	MHz	0.1	10	Upgrade to high-rep rate fiber laser systems
Laser Pulse Duration	fsec	250	250	
Microbunch Charge	e	0.05	8.3	
Microbunch duration	attosec	260	260	
Microbunches per Train	#	181	181	
Design wavelength	micron	2	2	
Invariant Emittance	nm	0.05	0.10	
RMS Beam Size X	micron	0.05	0.05	
RMS Beam Size Y	micron	1.00	1.00	Confinement in orthogonal (invariant) direction
Electron Capture Efficiency	#	0.21	0.56	Improved pre-bunching and injection
Electron Channel Width	nm	420	420	
Beam Power	**µW**	**0.2**	**3657**	Improved efficiency, e.g. laser recirculation
Delivered Dose	**Gy/s**	**5e-4**	**1.6**	(Assumes 1 cm delivery area with dE/dz of Water)
Total Laser Power	W	0.4	478	Upgrade to phase locked fiber lasers
Laser Pulse Energy	µJ	3.9	7.5	
Geographical Gradient	MeV/m	73	203	
Total Linac Length	**mm**	**13**	**24**	

Values represent conservative near-term estimates and not ultimate limitation on the technology.

*Includes several month setup of new test chambers (“glass” box and Erlangen shoebox).