Dielectric Laser Accelerators

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R. J. England

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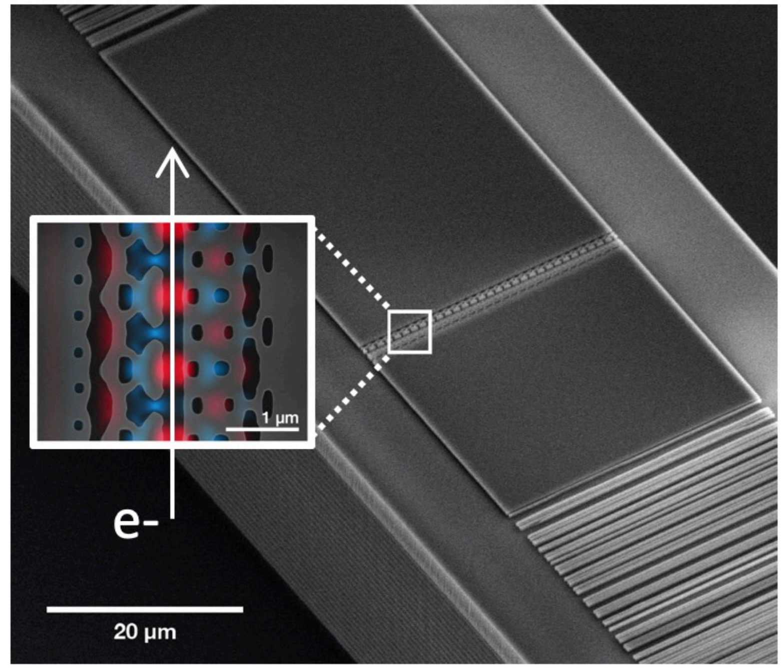
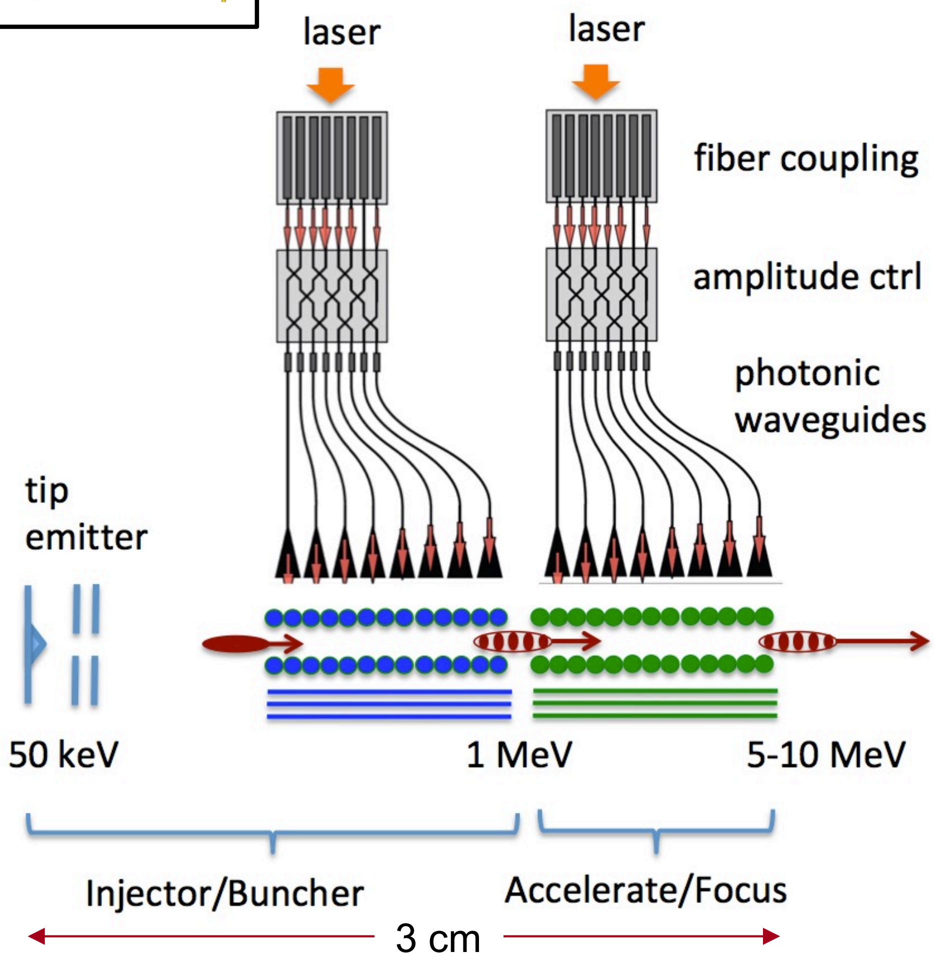


N. Sapra, et al., Science **367**, 6473 (2020)

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

SLAC

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

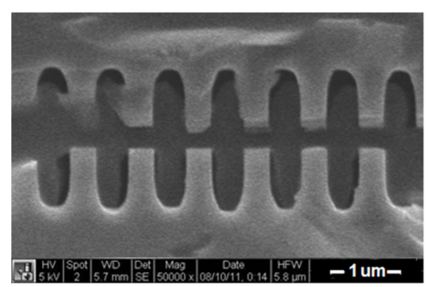


Required lasers are MHz rep rate, low pulse energy, wallplug efficiency ~ 30%

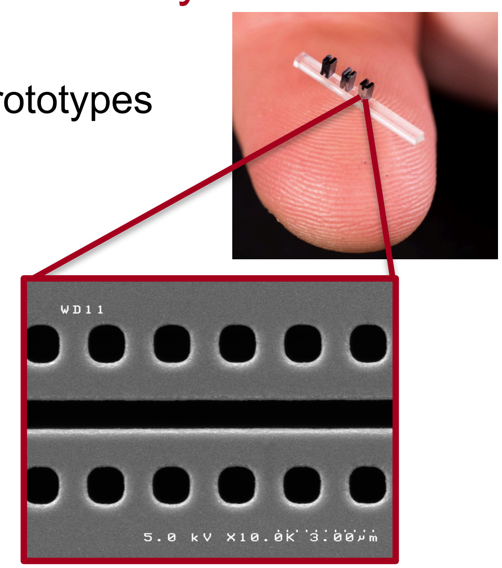
Dielectric materials can withstand GV/m fields and kilowatts of average power

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

SEM images of DLA prototypes tested at SLAC



fused silica



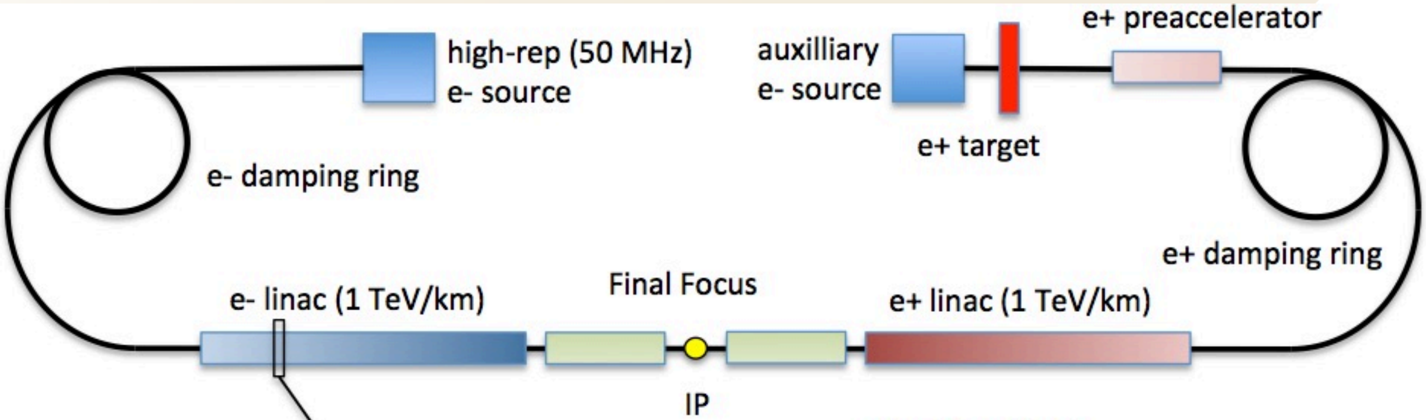
silicon

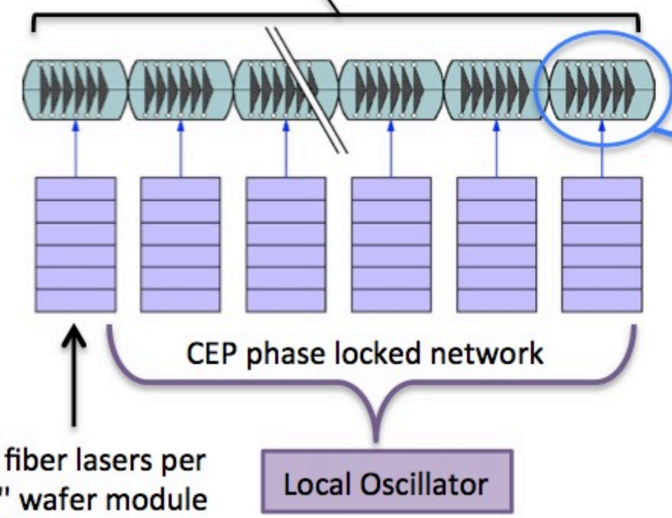
DLA research aims to produce ultracompact nanofabricated devices for particle acceleration, powered by efficient solid-state lasers.

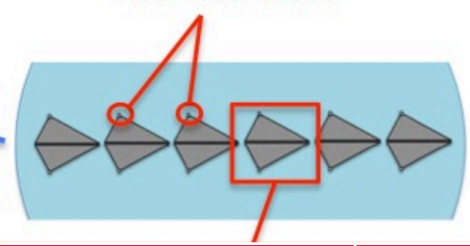
DLA Comparison with Conventional RF Accelerators

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	30-100 MV/m
Power Coupling Method	Free-space/Silicon WG	Critically-coupled metal WG

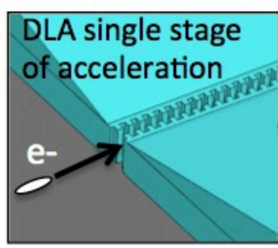
Strawman Collider Parameters – ALEGRO/ANAR





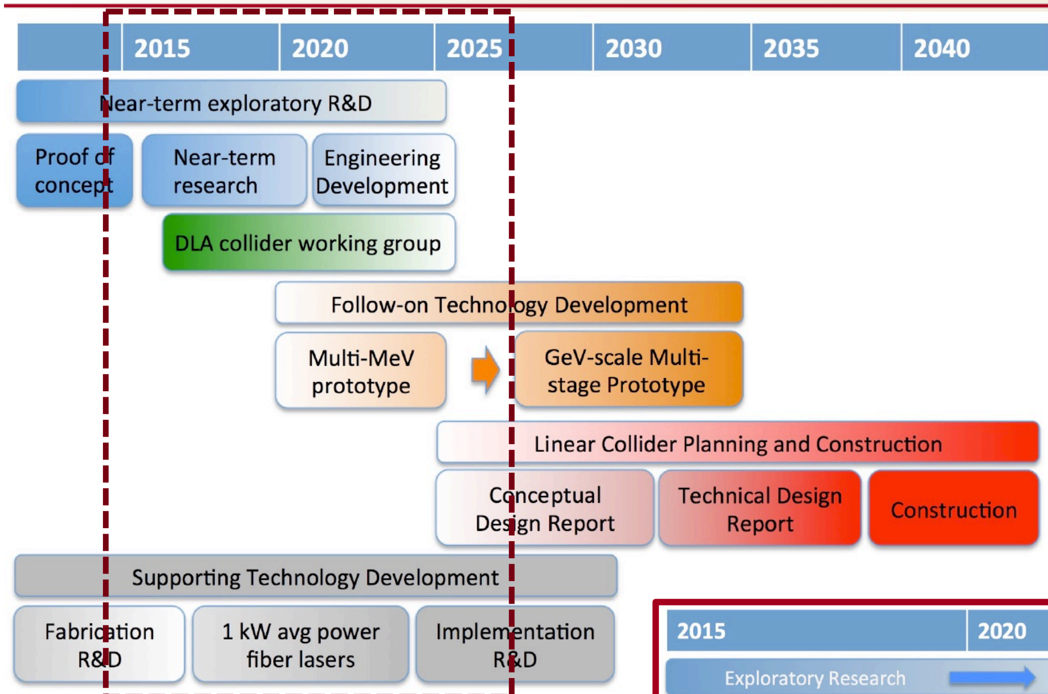


Thulium fiber laser λ=2 μm



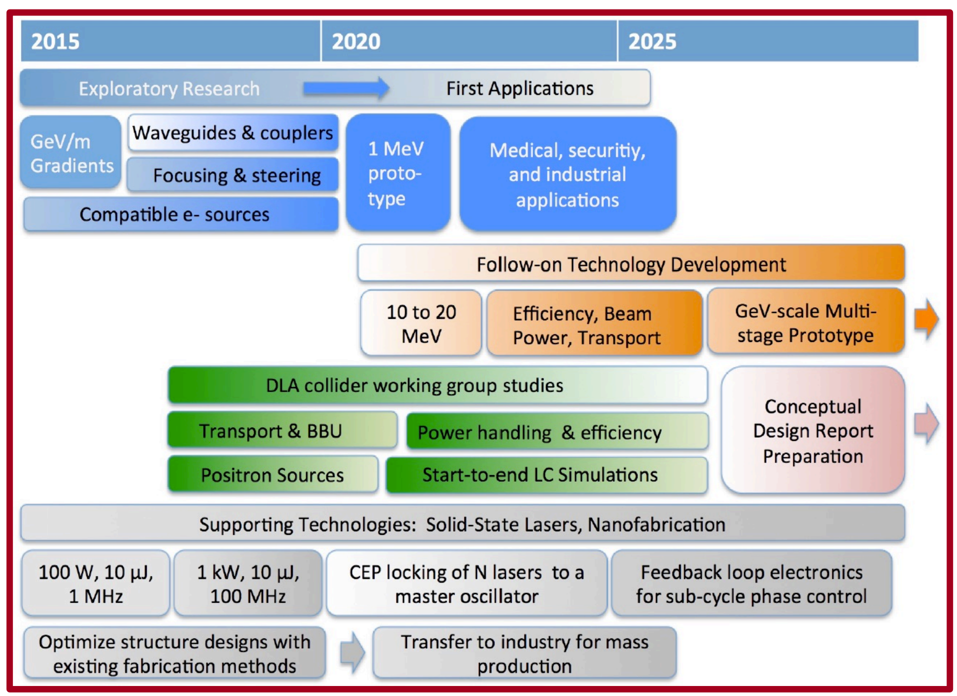
Parameter	Units	CLIC 3 TeV	DLA 3TeV	DLA 250 GeV
Bunch Charge	e	3.7e9	3.0e5	3.8e5
Rep Rate	MHz	5e-5	20	60
Beamstrahlung E-loss	%	**28.1**	**1.0**	**0.6**
Enhanced Luminosity / top 1%	cm-2/s	2.0e34	3.2e34	1.3e34
Wallplug Power	MW	582	374	152

DLA Roadmap (10 to 30 Year)



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

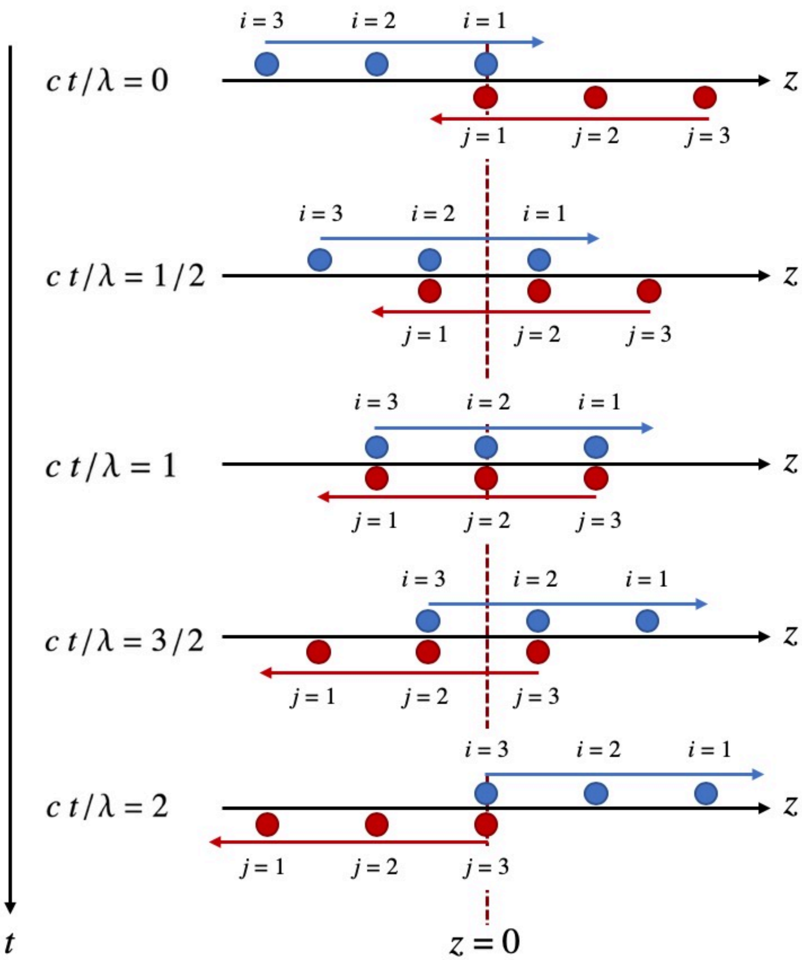


Objectives and Challenges: ALEGRO/ANAR

R&D Thrusts		Sub-Topics	Priority
1	Transport	Periodic focusing requirements for long-distance transport	High
		Radiation hardness and charging effects	High
		Wakefields - longitudinal and transverse - mitigation strategies	High
		BBU	High
		Start-to-end modeling	Med
		Halo and Beam Collimation	High
		Intrabeam Scattering of the bunch particles	Med
		Combining of multiple parallel beams	Med
		Sub-micron coalignment over km distances	Med
2	High-Field	Choice of Laser Wavelength	Med-Low
		Laser technical requirements	Low
		High-field damage mechanisms in dielectrics	Low
		SPM, Dispersion, and Raman Scattering	Med
		Stark band-splitting	Low
		Heat dissipation at high laser rep rate	Med
3	Sources	Electron sources	Med
		Positron sources	High
		Gamma-Gamma	Low
4	Final Focus	Requirements for final focus system	Low
		Luminosity, disruption, beamstrahlung	Low
		Requirements for dispersive microbunch smear-out	Low
5	Efficiency	Achievable laser wall-plug efficiency	Low
		Laser to dielectric coupling efficiency	Med
		Field to electron efficiency	Med
		Cost drivers and trends/projections	Med
		Linear collider power requirements; achievable beam power	Med

Multibunch Luminosity Enhancement

Example bunch format for M = 3



Luminosity for (i,j) crossing:

$$\mathcal{L}_{ij} = \frac{n^2}{4\pi} \frac{2}{(\sigma_i^2 + \sigma_j^2)}$$

Total Luminosity and Enhancement

$$\mathcal{L} = \sum_{i,j=1}^{M} \mathcal{L}_{ij} \;\; ; \;\; \mathcal{H}_D = \frac{\mathcal{L}}{\mathcal{L}_0} = \frac{1}{M^2} \sum_{i,j=1}^{M} \frac{2\sigma_0^2}{(\sigma_i^2 + \sigma_j^2)}$$

Number density of bunch train

$$\rho(\mathbf{r}, t) = \frac{1}{M} \sum_{j=1}^{M} F_j(\mathbf{r}_\perp) G_j(z, t)$$

$$F_j(\mathbf{r}_\perp) \equiv g(x, \sigma_j) g(y, \sigma_j),$$
$$G_j(z, t) \equiv g(z + \beta c t - (j-1)\lambda, \sigma_z)$$

Efficiency Optimization

Following the multi-bunch efficiency argument of Hanuka, the laser field (red, below) in the accelerator should have a trailing “bump” which counters the resulting wake field (green, below) in the structure.

A. Hanuka and L. Schachter, PRAB 21, 064402 (2018)

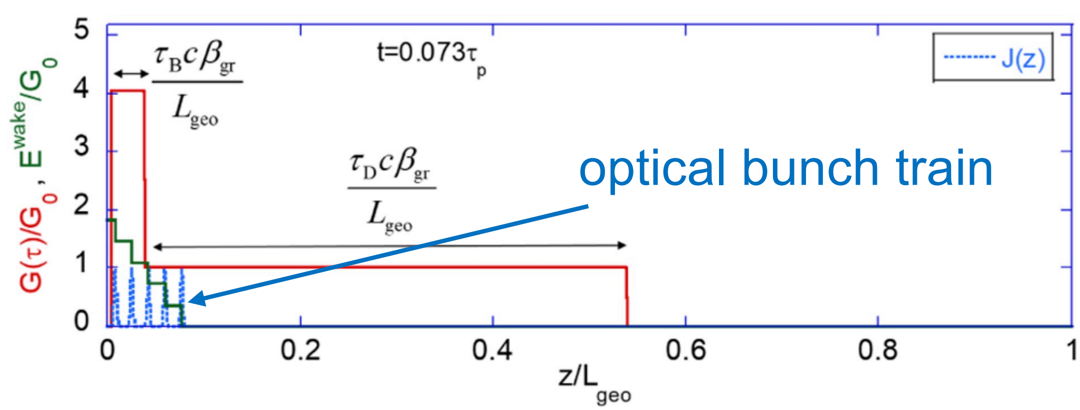
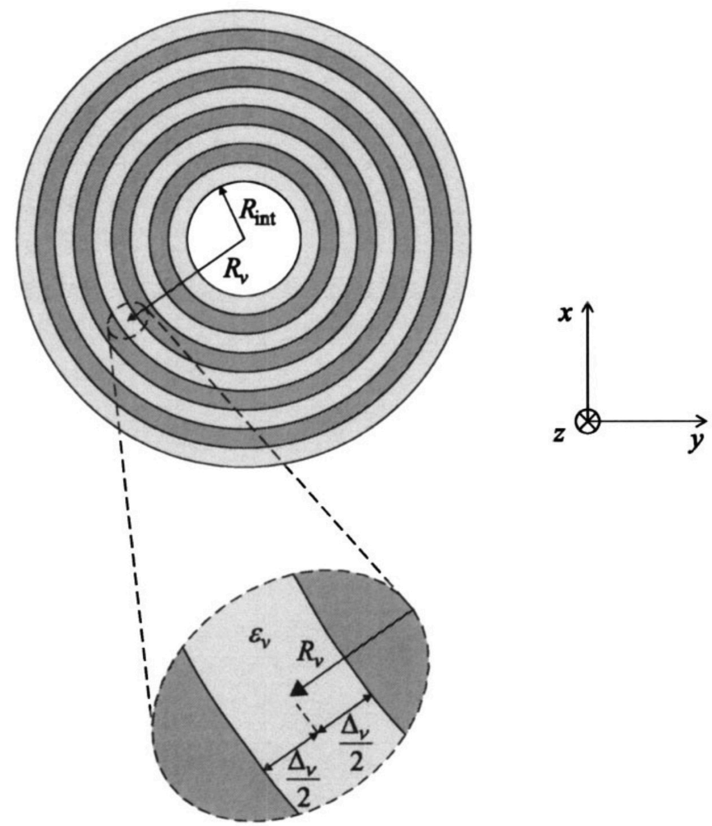


TABLE II. Structure parameters corresponding to a cylindrical Bragg geometry [ref Mizrahi and Schachter].

Parameter	Symbol	Value
Normalized Group Velocity	β_g	0.5
Laser Wavelength (μm)	λ	2
Single-Stage Length (mm)	L	0.2
Channel Radius (μm)	a	1.0
Characteristic Impedance (Ω)	Z_C	115
Cherenkov Impedance (Ω)	Z_H	240
Fundamental Loss Factor ($\times 10^{20}$ V/m)	k	21.5
Cherenkov Loss Factor ($\times 10^{20}$ V/m)	h	180
Damage Factor	f_D	2

Cylindrical Bragg accelerator

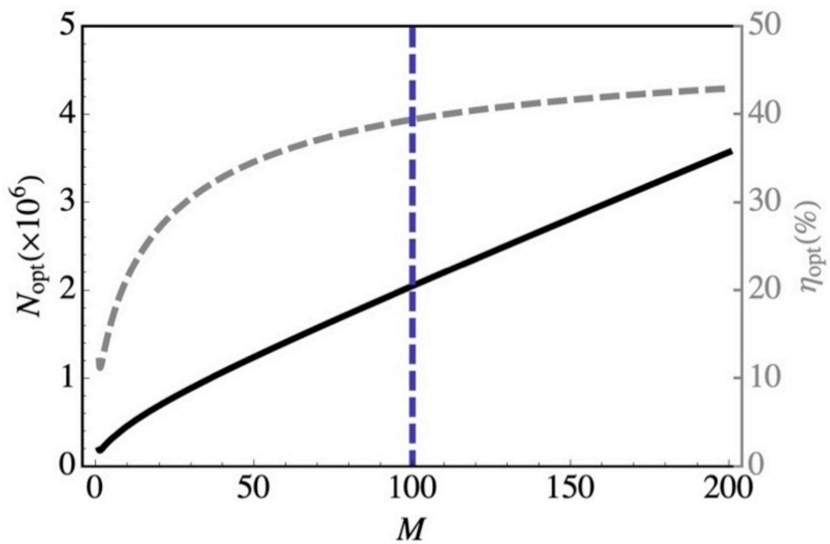
Mizrahi, Schachter PRE 70, 016505 (2004)

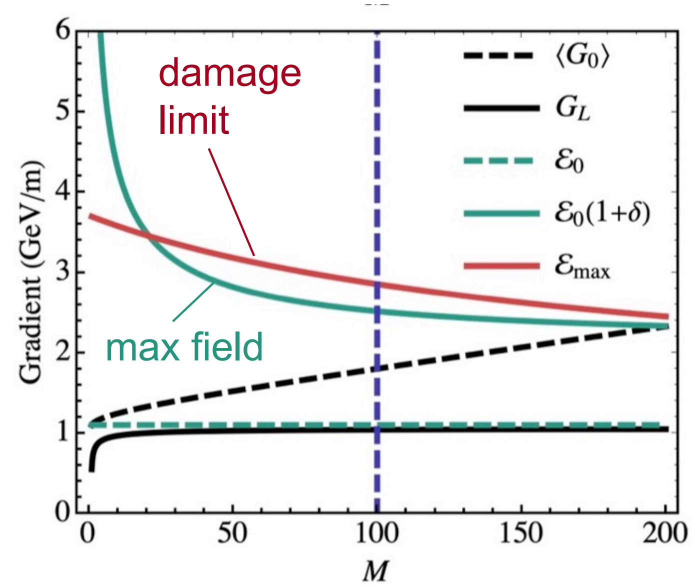


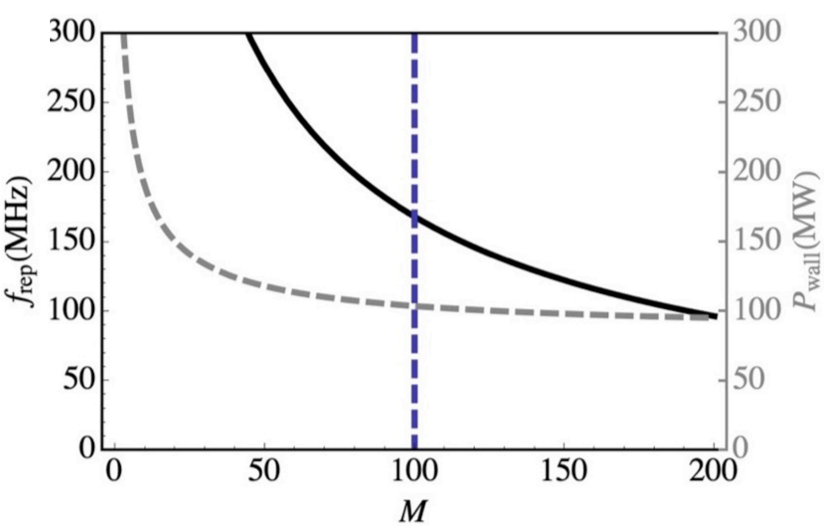
Parameter Optimization

Collider parameters matched to the luminosity of ILC (2e34 $cm^{-2}s^{-1}$) at 1 TeV

M = # microbunches per bunch train







Wallplug power assumes:
10% optical loss
75% laser efficiency

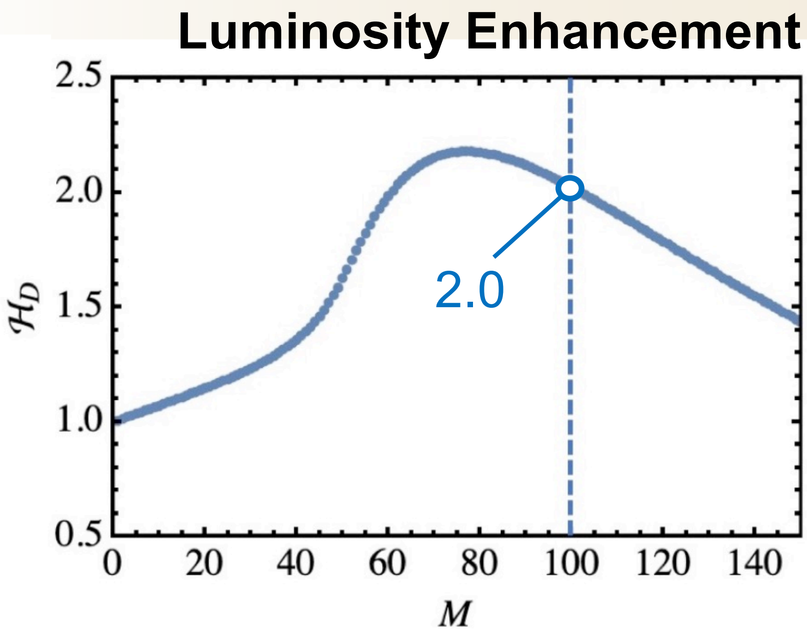
Optimized Parameters

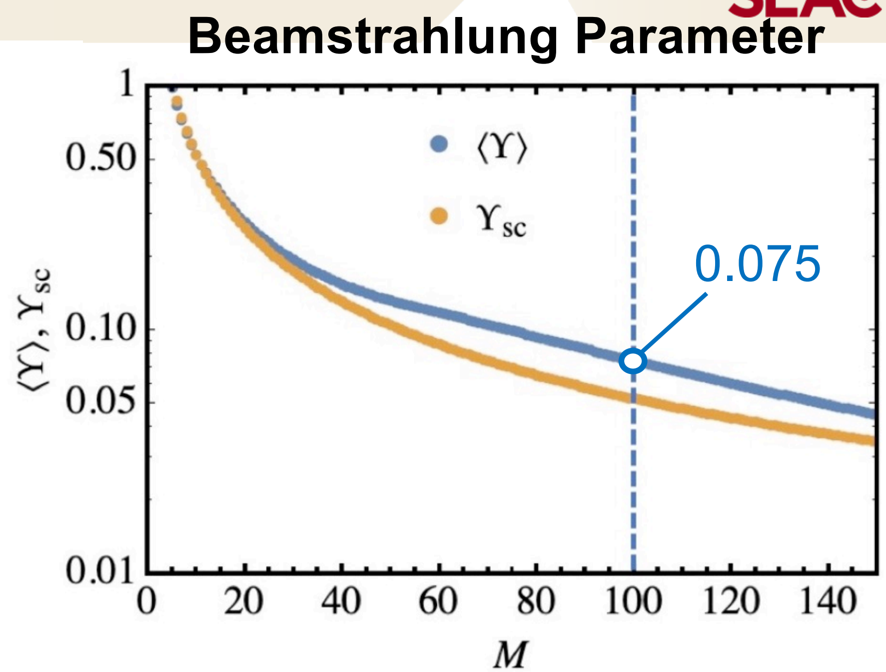
These are not a global optimum but they appear reasonable.

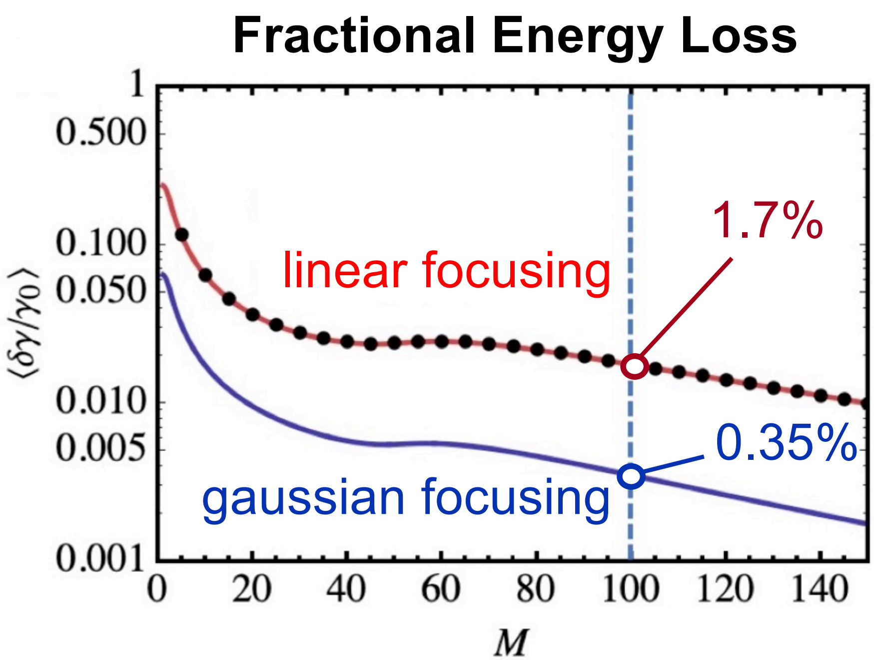
TABLE III. Parameters and bunch number M_{opt} for matching to the reference luminosity $\bar{\mathcal{L}}_{\mathrm{ref}}$ in Eq. (9).

Parameter	Symbol	Value
Beam Energy (GeV)	γmc^2	500
Field Intensity (GV/m)	$\mathcal{E}_0$	1.1
Train Repetition Rate (MHz)	f_{rep}	168
IP Normalized Emittance (nm)	ϵ_n	4.65
IP Spot Size (nm)	σ_0	0.76
Laser Pulse Duration (ps)	τ_P	1.3
Laser Wallplug Efficiency	η_L	0.75
Optical Copuling Efficiency	η_c	0.90
Wake Correction (GV/m)	$\mathcal{E}_0(1+\delta)$	2.51
Field Threshold (GV/m)	$\mathcal{E}_{\mathrm{max}}$	2.85
Unloaded Gradient (GeV/m)	$\langle G_0 \rangle$	1.80
Loaded Gradient (GeV/m)	G_L	1.04
Optimal Number of Bunches	M_{opt}	100
Microbunch Population ($\times 10^4$)	q_{opt}/e	2.05
Bunch Train Population ($\times 10^6$)	N_{opt}	2.05
IP Beta Function (μm)	β^*	121
Normalized Plasma Frequency	Ω^2	0.042
Normalized Emittance	Θ^2	0.00027
Coupling Efficiency	η_{opt}	39%
Wallplug Power (MW)	P_{wall}	103

Luminosity Enhancement and Beamstrahlung







Calculations based on classical formulation of equations of motion for Gaussian bunches with radiation reaction force included.

England and Schachter, “Beam-Beam Interaction in a DLA Based Collider,” in preparation for PRAB (2021)

Intermediate Applications

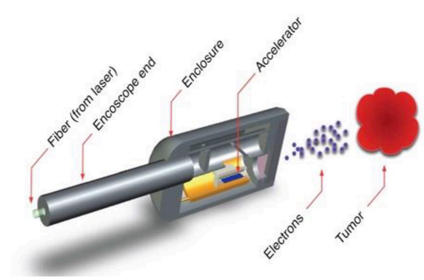
SLAC

- 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



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.

ACHIP Highlighted Recent Results: Proof of Concept Experiments

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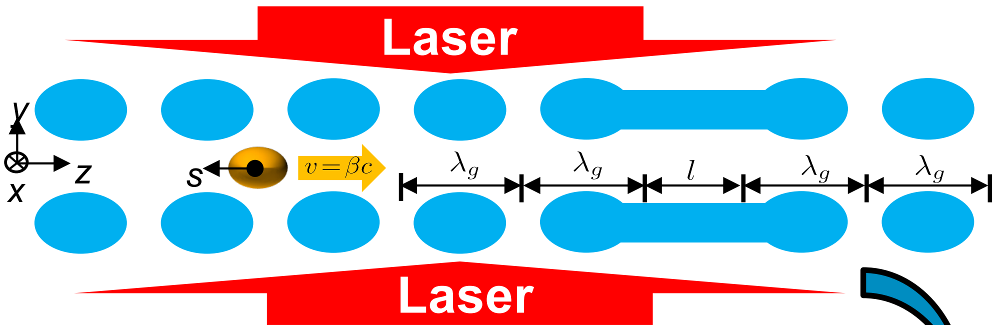
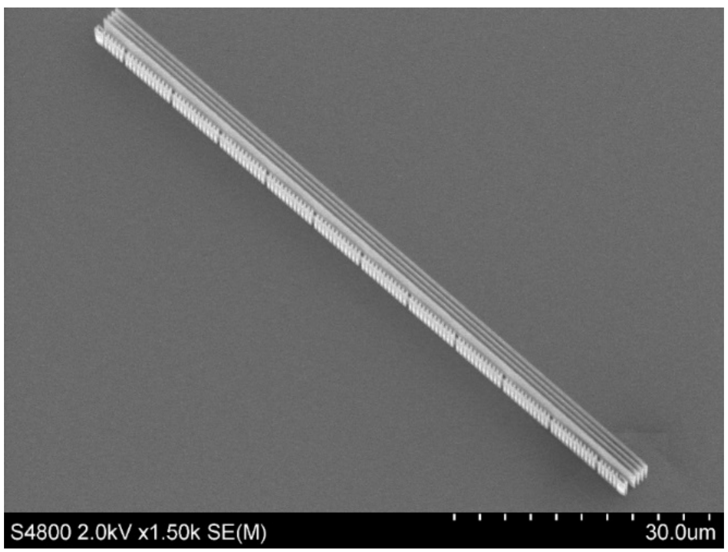
laser-driven focusing

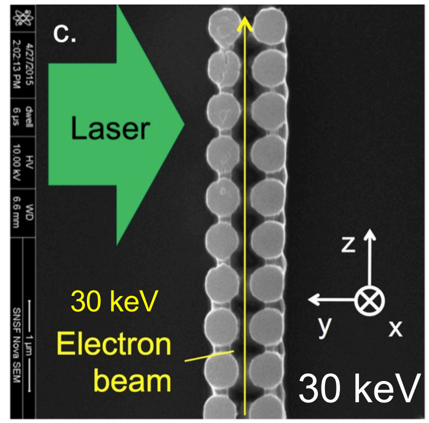


Niedermayer, et al., PRL **121**, 214801 (2018)

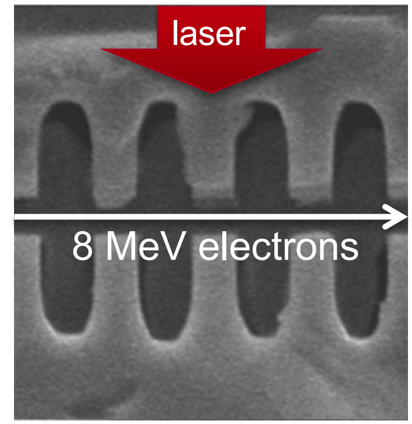


Hommelhoff Group, FAU Erlangen, Germany

high gradient (0.3 → 0.85 GV/m)

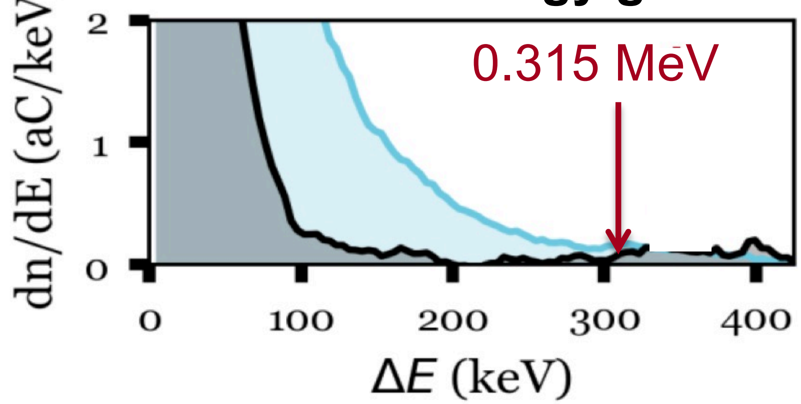


Leedle, et al. Opt. Lett. 40, 4344 (2015)



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

increased energy gains

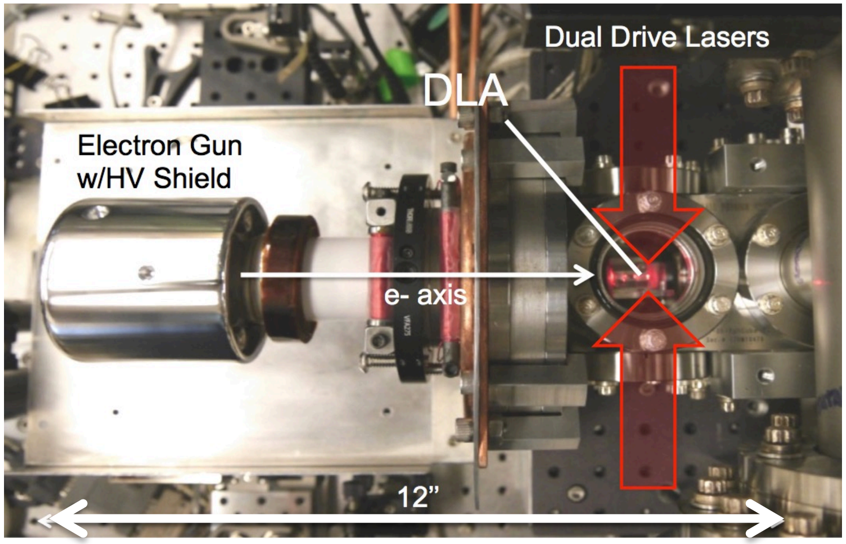


D. Cesar, et al., Optics Express **26** (22), 29216 (2018)

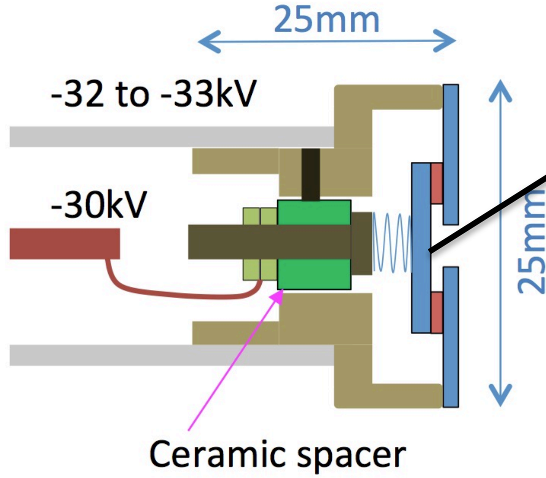
POC experiments use non-ideal test beams. With microbunching, focusing, and nanotip sources, net acceleration to MeV scale is possible.

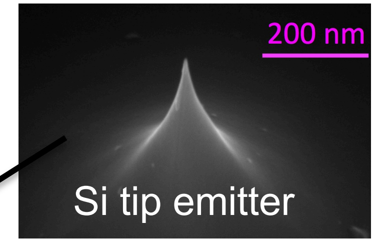
ACHIP Highlighted Recent Results: Towards an MeV-Scale Tabletop Device

Stanford "shoebox" test system

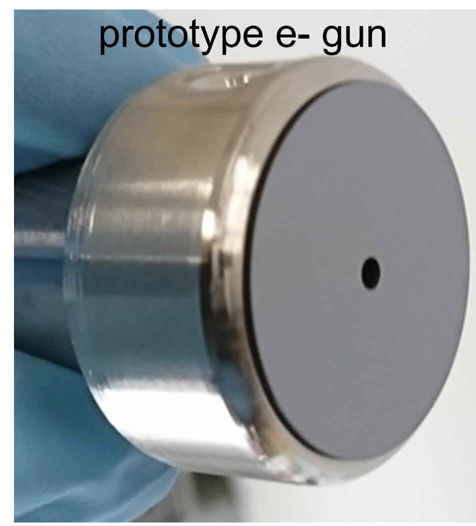


compact electron gun w/electrostatic lens



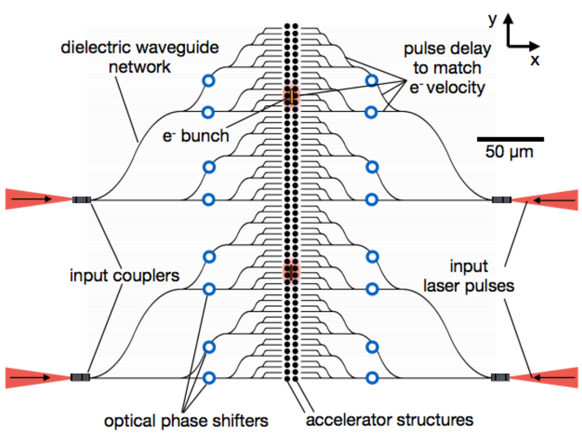


3000 e-/pulse,100 kHz rep
0.2 nm emittance
A. Ceballos, Stanford



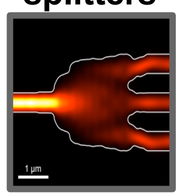
courtesy T. Hirano
(Hamamatsu, visiting scientist at Stanford University)

optimized DLA components via inverse design

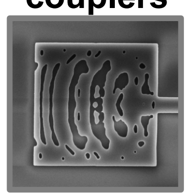


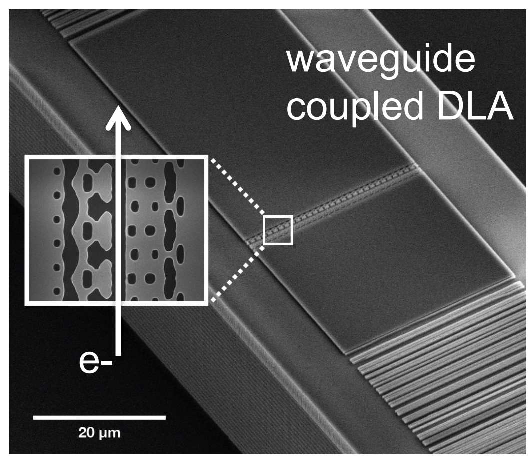
T. Hughes, et al, Phys. Rev. Appl. 9, 054017 (2018)

splitters



couplers





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

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

SLAC

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

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

Planned (Funded) Test Facilities (now coming online):

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.

Current 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