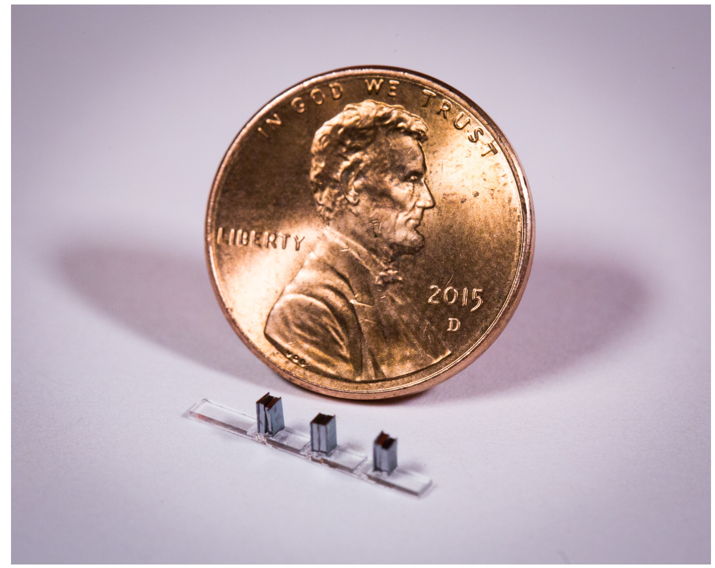
Dielectric Laser Acceleration

R. J. England (SLAC, Stanford)



ATF Science Planning Workshop
Brookhaven National Laboratory
October 15-17, 2019

ACHIP

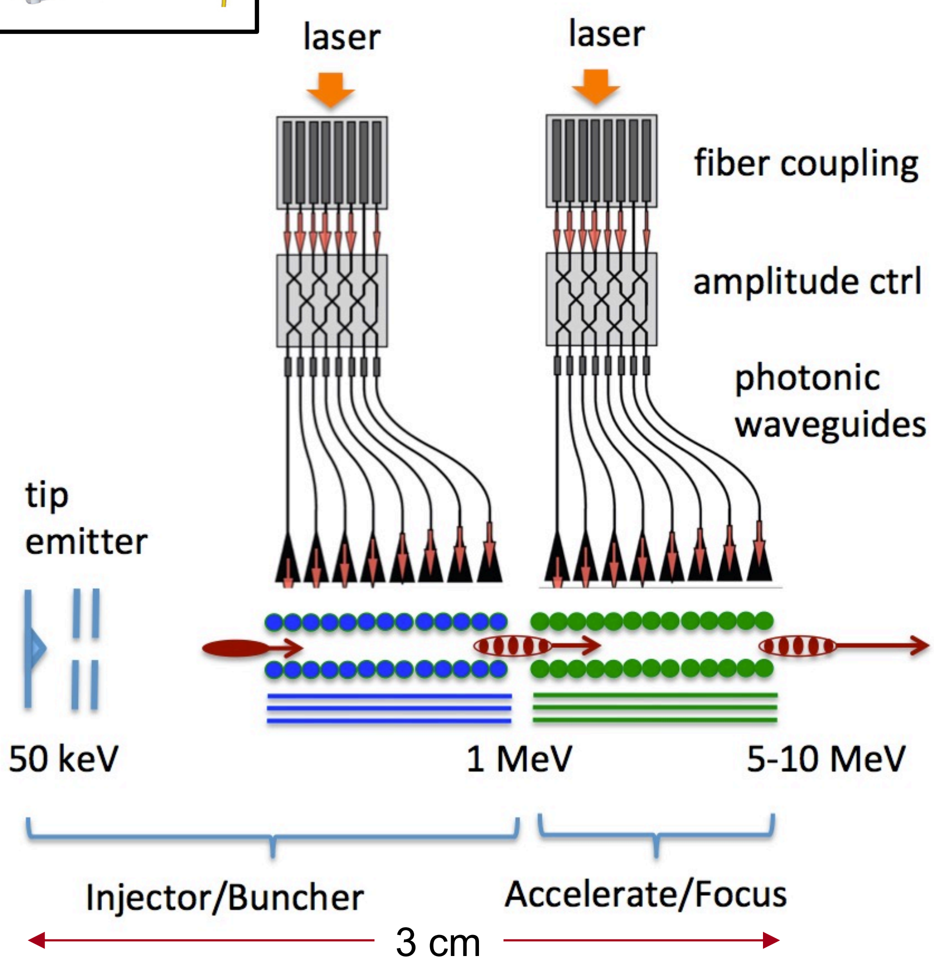
GORDON AND BETTY MOORE FOUNDATION

U.S. DEPARTMENT OF ENERGY Office of Science

SLAC NATIONAL ACCELERATOR LABORATORY

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

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

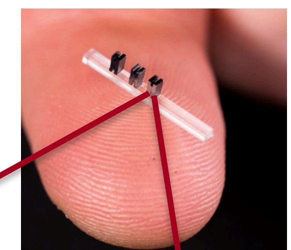


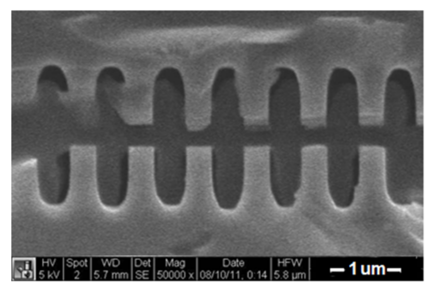
Required lasers are MHz rep rate, low pulse energy, wallplug efficiency ~ 30%

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

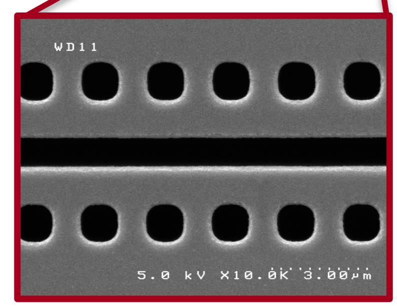
Can be mass produced using techniques of the integrated circuit industy.

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.

Fiber lasers suitable for driving future integrated DLA systems are compact and low-peak power

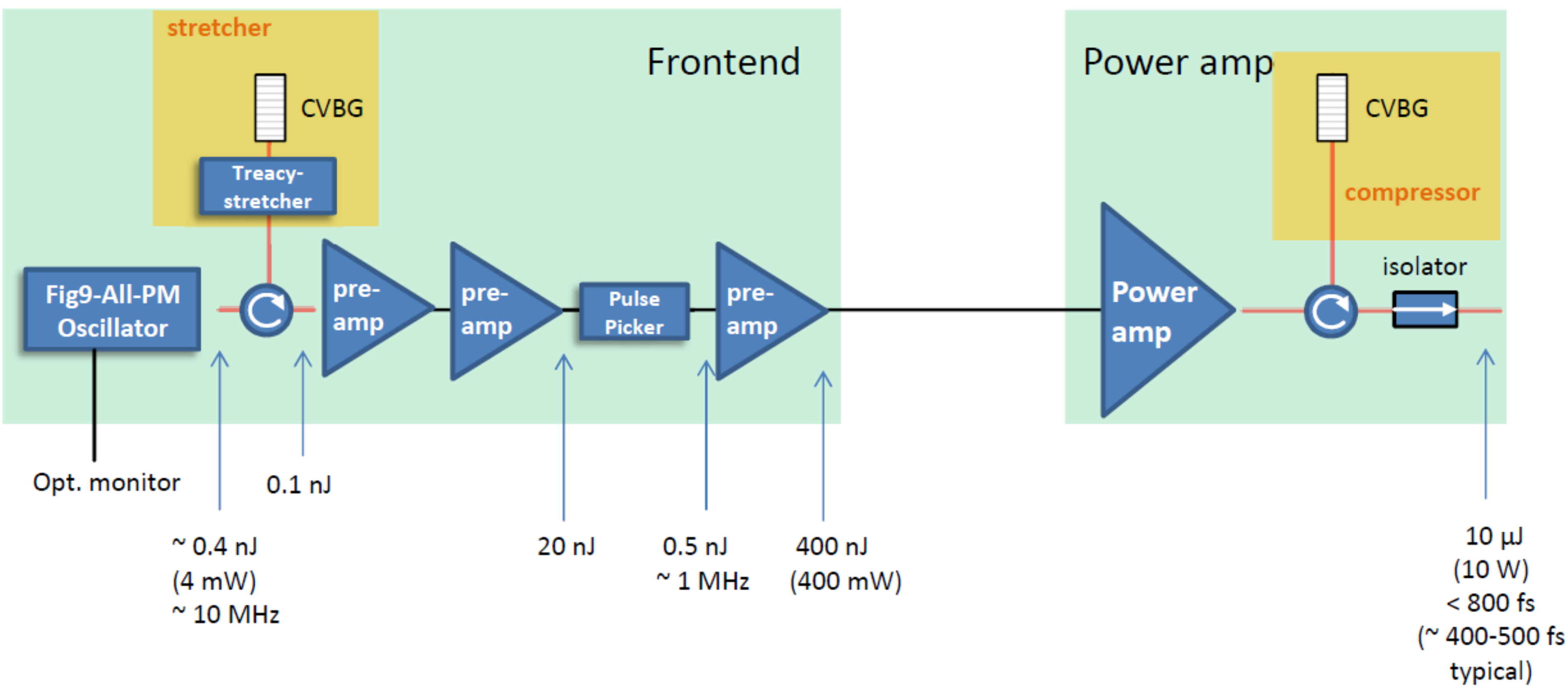
Menlo Systems 2um Fiber Laser

All polarization maintaining TmHo fiber with free space stretcher/compressor

2050nm, 1 MHz, 10 uJ, 10W average, 400-500fs, $300k

Demonstrated Fiber MOPA

Large Mode Area Fiber Amp



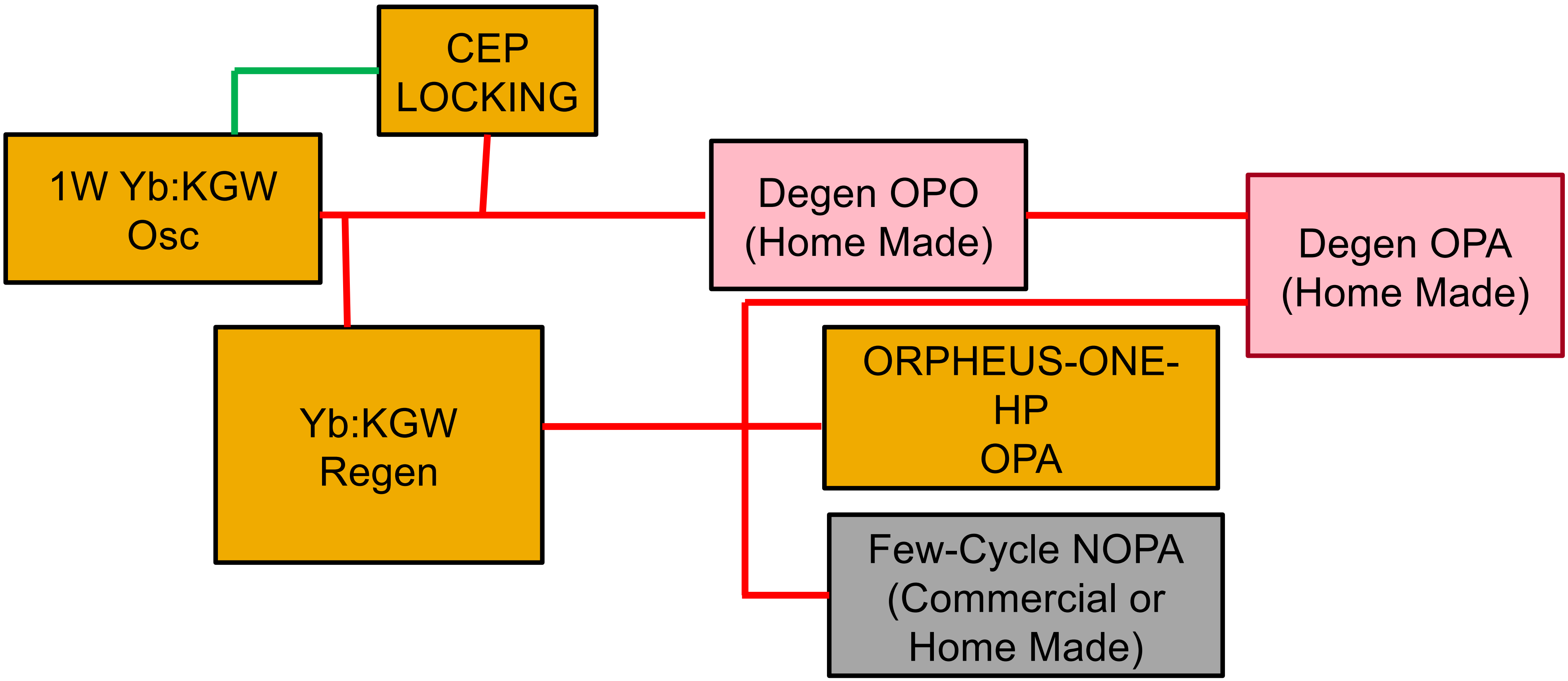
Research lasers employed in university settings provide greater versatility for initial demonstrations

Stanford ACHIP Laser: Light Conversion Yb:KGW Regen + OPA

1W, 1030 nm, 76MHz, 80fs CEP locked oscillator

20W, 50-200kHz, 100-400uJ, 290fs Regen

2.3W, 100kHz, 23uJ, 250fs 2um Signal from OPA



Global DLA Effort & Funding

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Accelerator on a Chip International Program (ACHIP) 2015 to 2020

- 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 - $13.5M / 5 years = $2.7M/year (Moore Foundation, low overhead ~ 12%)
LANL - $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.

Large international effort in this area largely funded by Moore Foundation. Since that program will end in 2020, other funding sources are being explored.

Highlighted Recent Results: Proof of Concept Experiments

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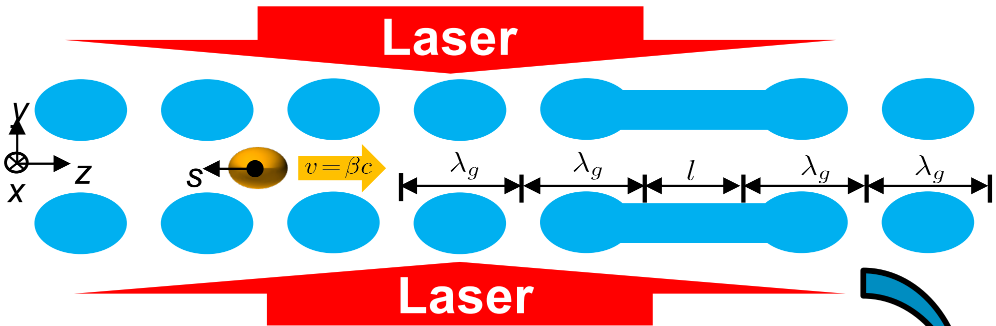
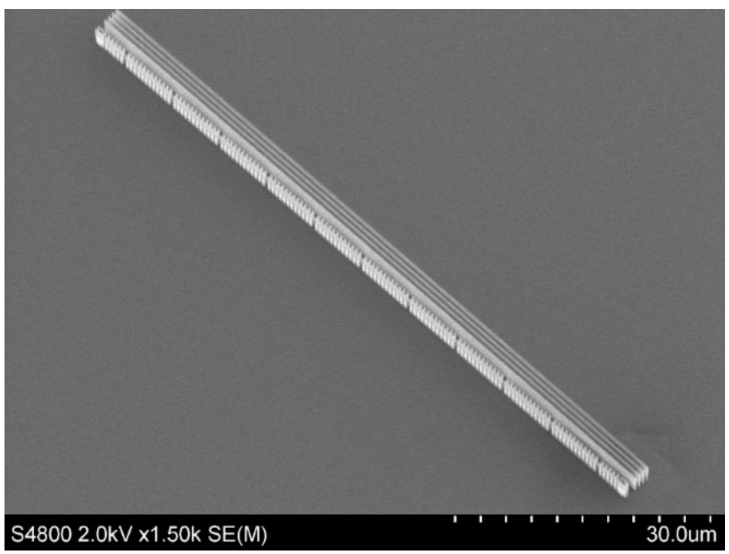
laser-driven focusing

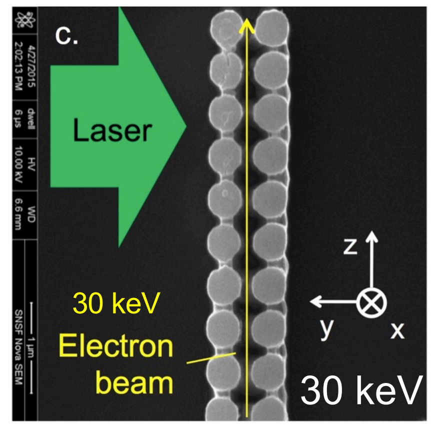


Niedermayer, et al., PRL **121**, 214801 (2018)

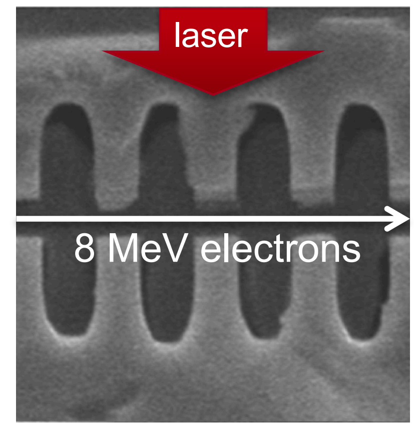


Hommelhoff Group, FAU Erlangen, Germany

high gradient (0.3 → 0.85 GV/m)

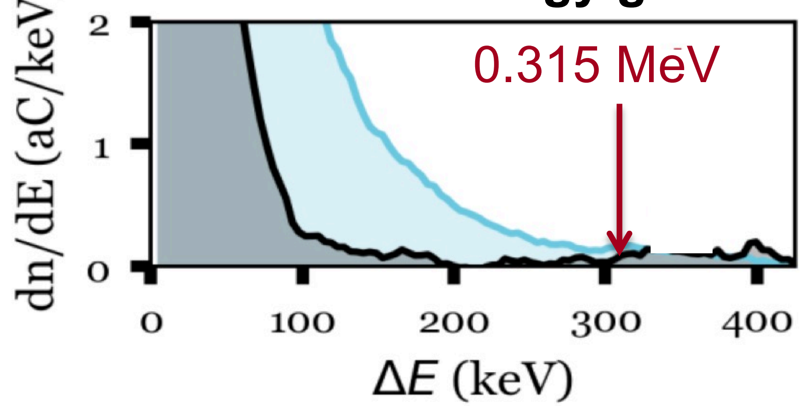


Leedle, et al. Opt. Lett. 40, 4344 (2015)



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

increased energy gains

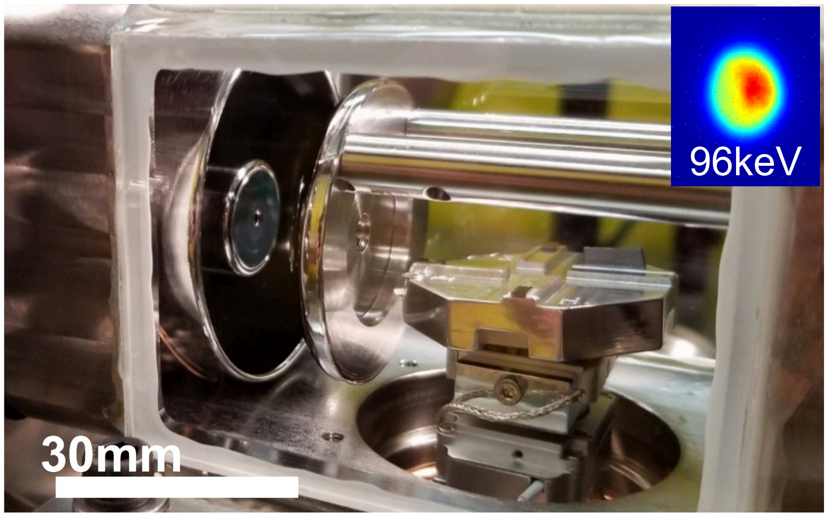


D. Cesar, et al., Optics Express **26** (22), 29216 (2018)

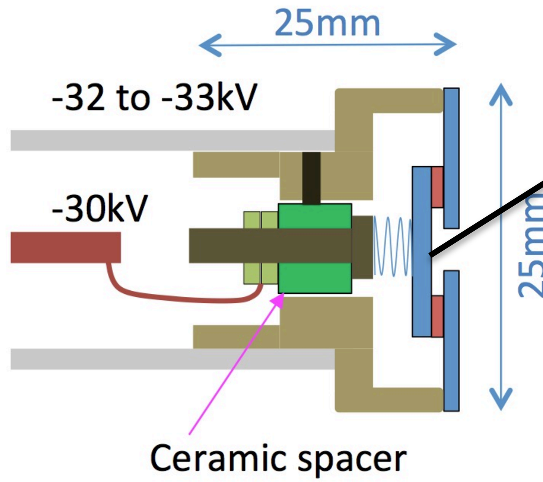
POC experiments use non-ideal test beams from conventional sources. With microbunching, focusing, and nanotip sources, MeV net acceleration is possible.

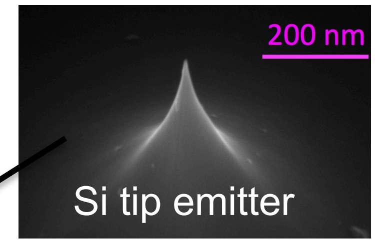
The components for an integrated 1 MeV shoebox sized accelerator are coming together

Stanford “glassbox” test system



compact electron gun w/electrostatic lens

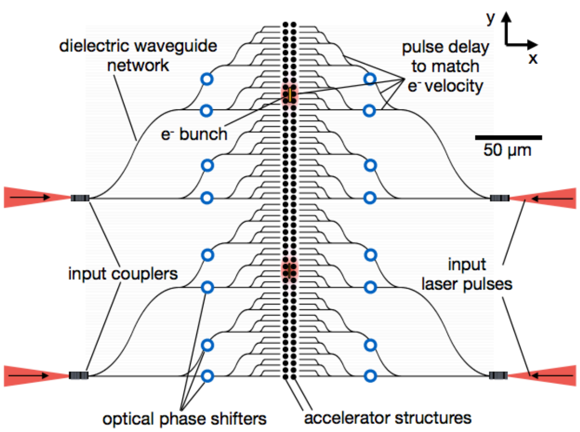




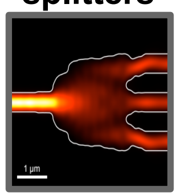
3000 e-/pulse,100 kHz rep
0.2 nm emittance
A. Ceballos, Stanford

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

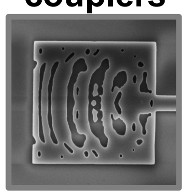
optimized DLA components via inverse design

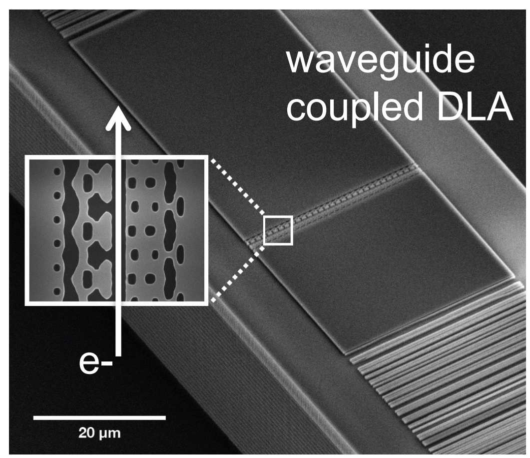


splitters



couplers

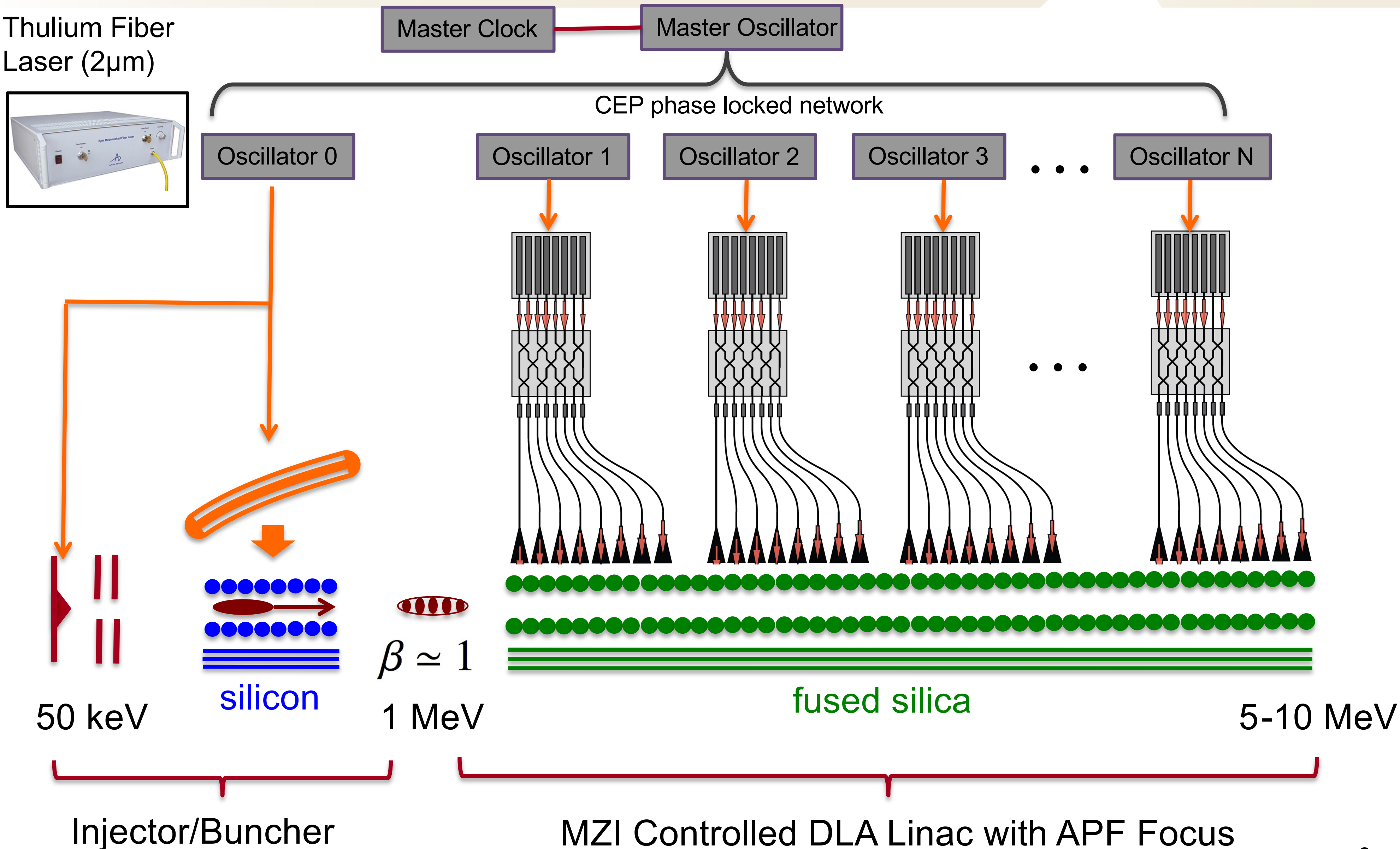




T. Hughes, et al, Phys. Rev. Appl. 9, 054017 (2018)

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

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



Relativistic vs. Subrelativistic Experiments

Future integrated DLA systems are envisioned to combine sub-relativistic nanotip injector with a relativistic (≥ 1 MeV) energy linac. Conventional DC and RF electron sources provide interrim solutions for parallel studies in both regimes.

Subrelativistic Energy Experiments (e.g. Stanford, Erlangen):

- Compatible with university optics labs, DC electron sources (30-100 keV)
- Integration with compatible nanotip field emission sources (Si, Diamond, LaB6)
- Low-charge, low-emittance bunches (1 to 1000 e/pulse, < 1 nm emittance)
- Targeting low-current applications e.g. electron diffraction, compact medical

Relativistic Energy Experiments (e.g. SLAC, UCLA, DESY, PSI):

- Utilize available high-brightness RF photoinjector electron beams (pC, 1-10 Hz)
- POC demonstrations of fundamental beam dynamics in DLA structures
- Compatibility with SiO_2 and other high damage threshold materials
- Highest gradients and energy gains demonstrated in this energy regime

Relativistic test facilities enable crucial advances in gradient, energy gain, and understanding of beam dynamics with fC bunches.

A 5-Year initiative in DLA has been approved by the Gordon and Betty Moore Foundation (2016 – 2021)

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ACHIP: Accelerator on a Chip International Program

ACHIP

$13.5M / 5 years

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

Structure Design & Fabrication
Stanford: Byer, Harris, Solgaard
Erlangen: Hommelhoff

Systems 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

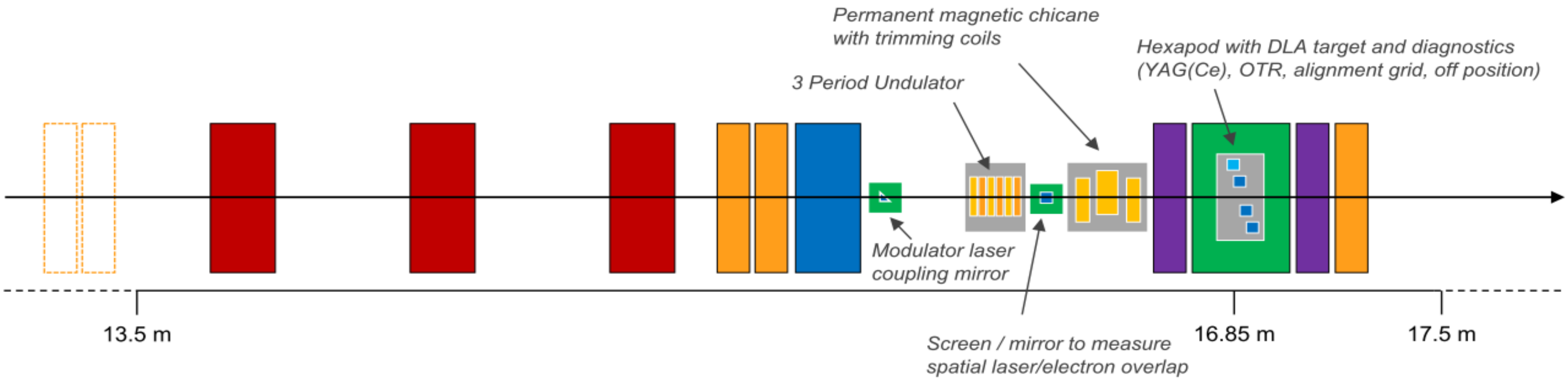
Light Coupling
Stanford: Fan, Vuckovic
Purdue: Qi

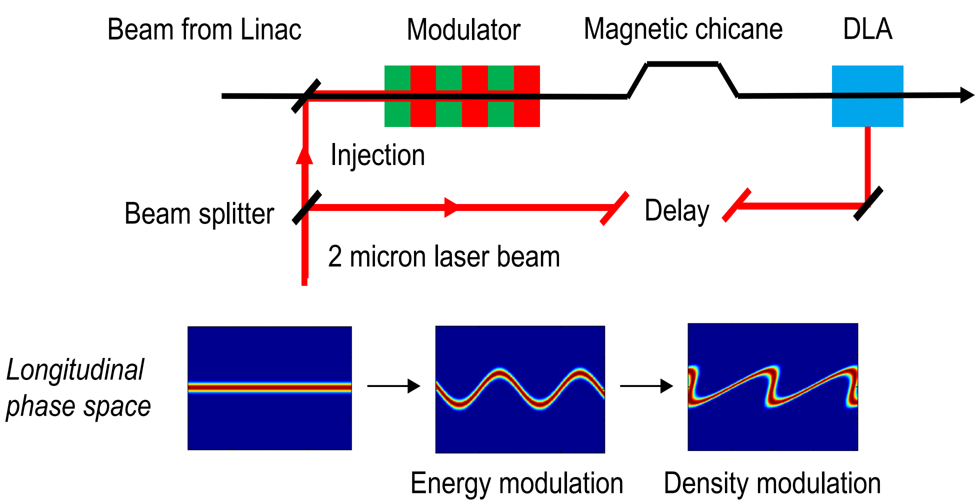
Scientific Advisors
SLAC: Burt Richter
Stanford: Persis Drell

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

Planned Relativistic DLA Experiments: DESY/Hamburg

Main goal at SINBAD: Demonstration of net-energy gain in grating DLAs





Stage 1: Short-bunch beam demonstration

First experiment with ultra-short bunches leveraging the compression techniques available @ ARES

Stage 2: Microbunching + net acceleration

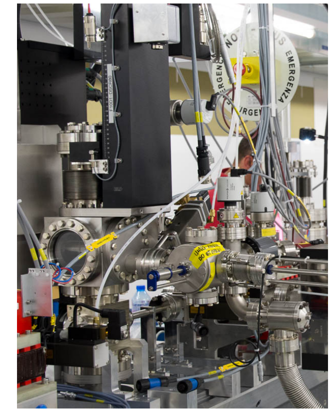
Drive both the energy **modulation** of a long bunch **and the DLA interaction** with the **same laser** to achieve sub-fs microbunches and phase-lock

- Detailed experimental plan developed with simulational support
- Commissioning of DLA test area proceeding with first experiments starting now
- New DLA drive laser for 2um operation being installed with Hartl and Kaertner groups

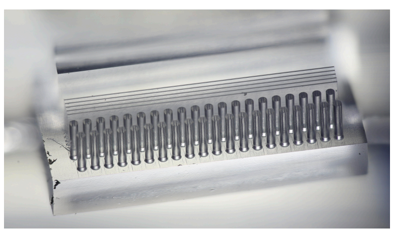
Planned Relativistic DLA Experiments : PSI/EPFL

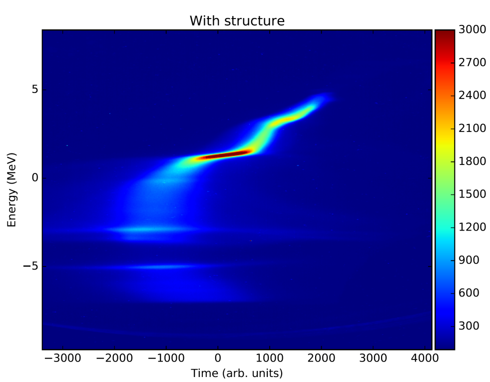
Infrastructure for ACHIP experiments at SwissFEL:

- DLA test facility for 3 GeV beam injection
- Electron optics, instrumentation & alignment system
- Laser system to be donated from FAU Erlangen
- Wake effects, FEL seeding, radiation studies

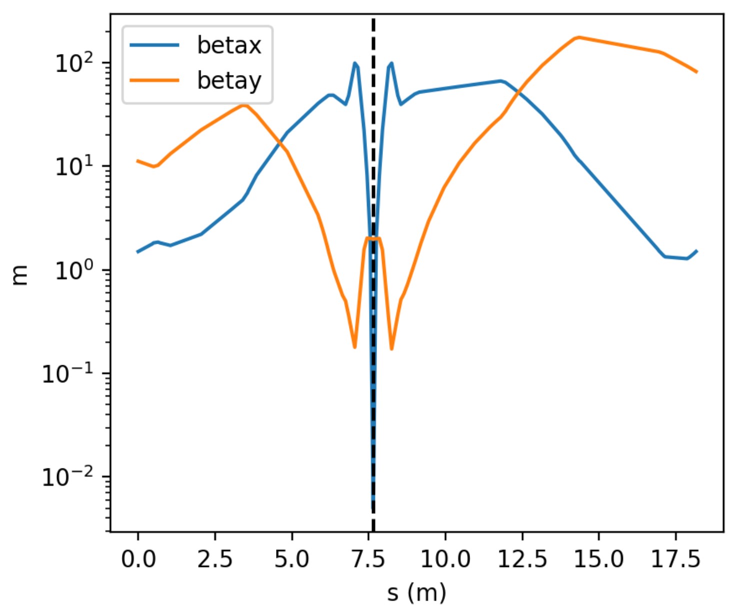


Wake effects

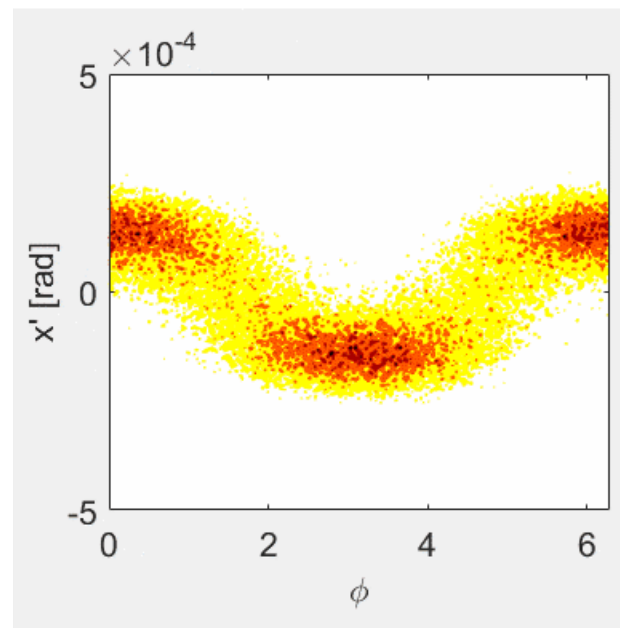




Simulation of e-beam modulation experiment



Asymmetric beta function

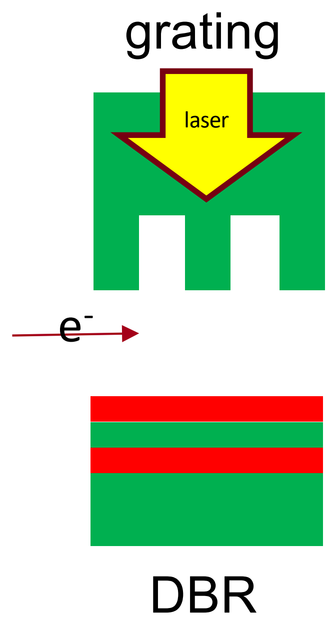


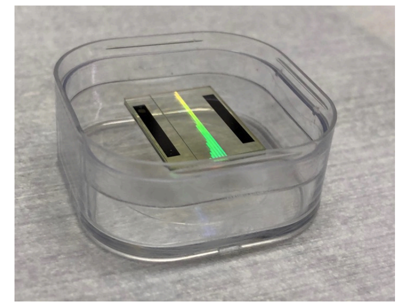
Modulation after 1 mm

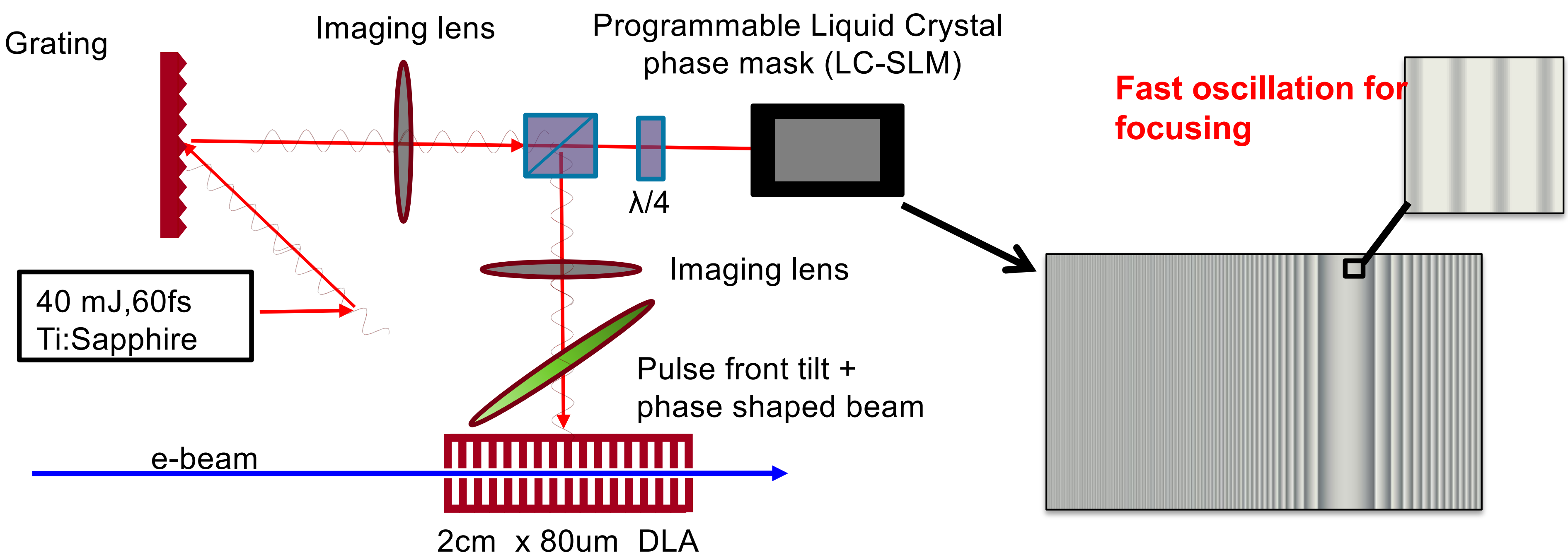
Planned Relativistic DLA Experiments : UCLA

Experiments at UCLA Pegasus Facility

- High gradient & energy gain (0.85 GV/m, 300 keV) results from FY17 published
- Experiment with 2cm DLA acceleration and > 1 MeV energy gain anticipated to begin Fall FY20
- New laser purchased/installed with ACHIP support
- Flat beam transform optics implemented
- Electron transmission test completed in July 2019







Recent UCLA laser upgrade informs the requirements for future relativistic energy DLA experiments

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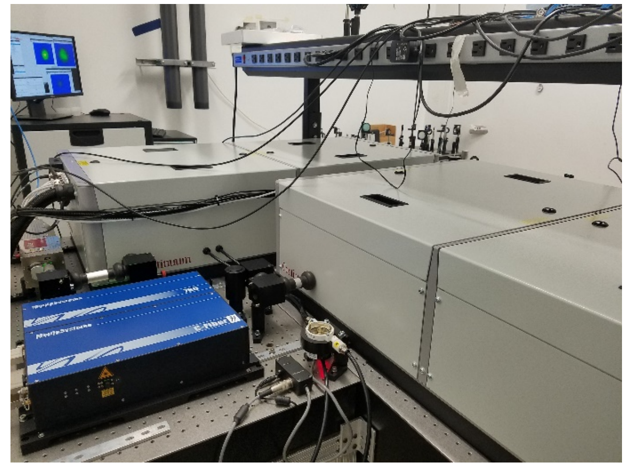
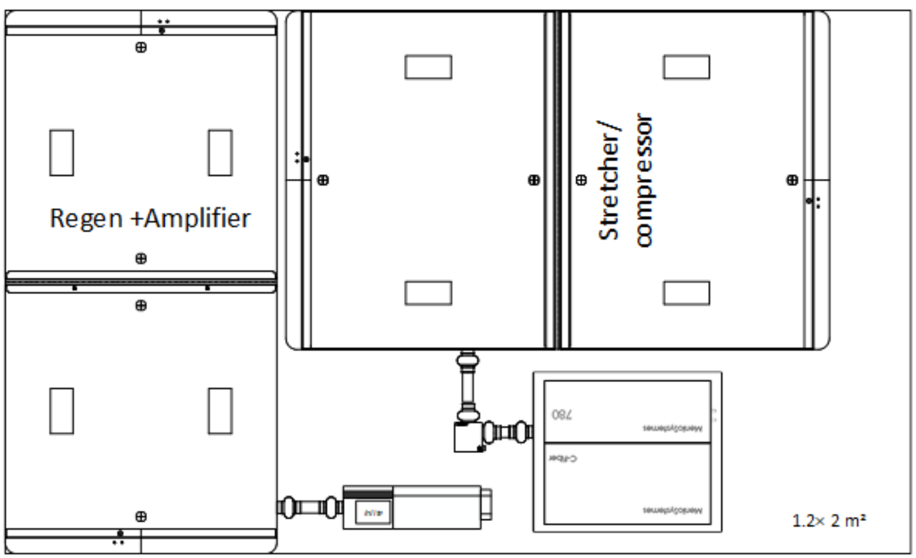
UCLA Pegasus: Continuum Trident X-40-100

- New transport line to bunker installed
- Partially funded by Moore (~ 50 %)
- Specs: 800 nm , 40 mJ – 80 fs , 10 Hz
- Transport in Pegasus bunker in August
- Chirped pulse to avoid non linearities
- Synchronization to RF



Laser layout schematic



Factory Tests

Parameter	Measured
Pulse Energy	45 mJ
Pulse Duration	61 fs
Central Wavelength	783 nm
Angle Jitter	1.65 μrad
M_x^2	1.34
M_y^2	1.38

Relativistic Energy DLA Science Thrusts

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Electron beam only:

- Electron irradiation tests (radiation hardness, charging of dielectrics)
- Transmission testing and "drifting current" wakefield measurements

Laser only:

→ • Materials characterization (laser induced damage threshold, LIDT)

Electron + Laser:

→ • Net acceleration of compressed and/or optically microbunched beams
→ • High energy gain using a single pulse front tilted laser pulse
→ • Ponderomotive Focusing and Energy-Gain via phase control of the laser
• Higher current studies (wakefields, beam loading efficiency, transport, halo)
• Demonstration of a DLA-based (laser-driven dielectric) undulator

ATF experiments could contribute in multiple areas. Although some efforts (green arrows) are planned at other facilities, ATF's capabilities would enable unique studies with higher beam currents and relaxed tolerances.

Desired Beam and Laser Parameters for DLA Experiments at Relativistic Injection Energies

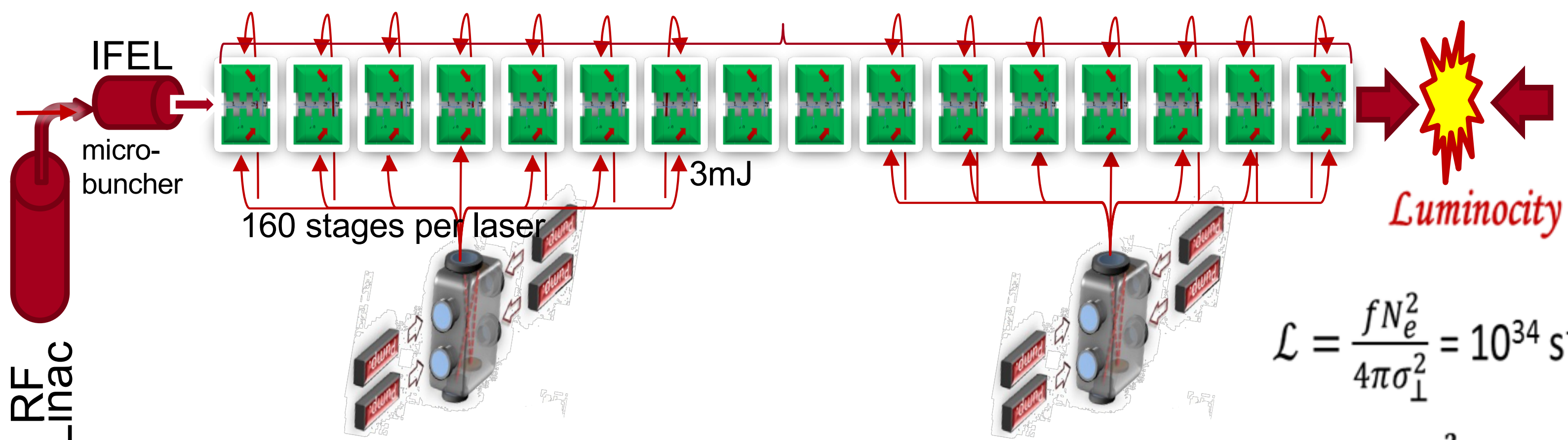
Parameter	Demonstration	Ideal
Bunch Charge	≤ 1 pC	1-5 fC
Beam Energy	1 to 100 MeV	-
Normalized Emittance	≤ 1 μm	1-5 nm
RMS Spot Size	1 to 10 μm	10 to 100 nm
Laser Wavelength	1 to 10 μm	1 to 2 μm
Laser Pulse Length	0.25 to 3 ps	0.1 to 1 ps
Laser Pulse Energy	0.2 to 30 mJ	1 to 10 μJ
Rep Rate	1-10 Hz	10-100 MHz
Energy Spread	2.6e-4	2.6e-4

ATF appears equipped to meet most requirements for demonstration experiments at 10 micron wavelength.

CO_2-Laser-Driven Dielectric Laser Accelerator

W. D. Kimura, I. V. Pogorelsky, and L. Schächter

- 10 μm wavelength has many advantages for driving DLAs
  - 10X larger grating dimensions → higher charge, easing of *e*-beam requirements, reduced fabrication tolerances, easier staging, less wakefield losses
- Can use same CO_2 laser to drive IFEL prebuncher to send microbunches into DLA → increases amount of accelerated charge
- Over 10 MeV energy gain in 1-cm DLA possible using ATF 9-GW CO_2 laser
- Fe:ZnSe-laser-pumped CO_2 laser being developed by ATF
  - Enables considering strawman collider design (10,000 x 1 cm DLA stages)
  - 63 CO_2 laser amplifiers operating at 20 kHz delivering 100 pulses resulting in 2 MHz pumping of DLAs



$$\mathcal{L} = \frac{f N_e^2}{4\pi\sigma_\perp^2} = 10^{34}\ s^{-1}cm^{-2}$$

provided $\sigma_\perp^2$=2.5 nm^2

W. Kimura (STI Optronics)– AAC 2018 presentation

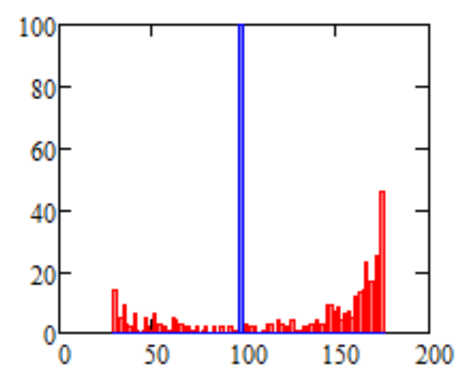
Benefits of 10 um DLA Experiments at ATF

- 10x aperture and 10x angular acceptance → 100x more charge
- More effective ponderomotive focusing / smaller resonant defocusing
- 10 times easier to fabricate structure (but which material?)
- Optically pumped CO_2 laser for compactness and efficiency
- Unique experimental opportunity at ATF. Only facility in the world with high power CO_2 laser and relativistic electron beam.
- Reliable bunching schemes in place. (Cascaded buncher, N. Sudar PRL 2018)

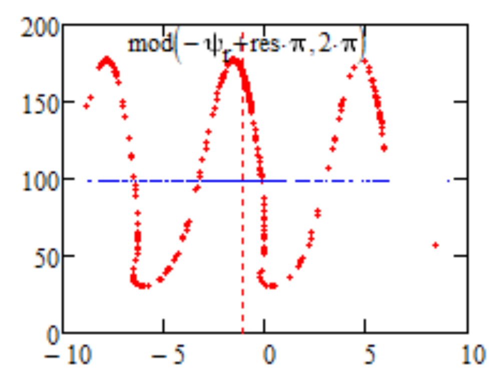
Input energy	50 MeV
Max output energy	90 MeV
Charge accelerated	1 pC
Effective Gradient	1.7 GV/m
Laser energy	20 mJ
Laser pulse length	2 ps
DLA Length	2 cm
Spot size	5 um
Emittance	20 nm

Simulation for 5cm structure (75 MeV gain)

Energy distribution



Long. Phase space

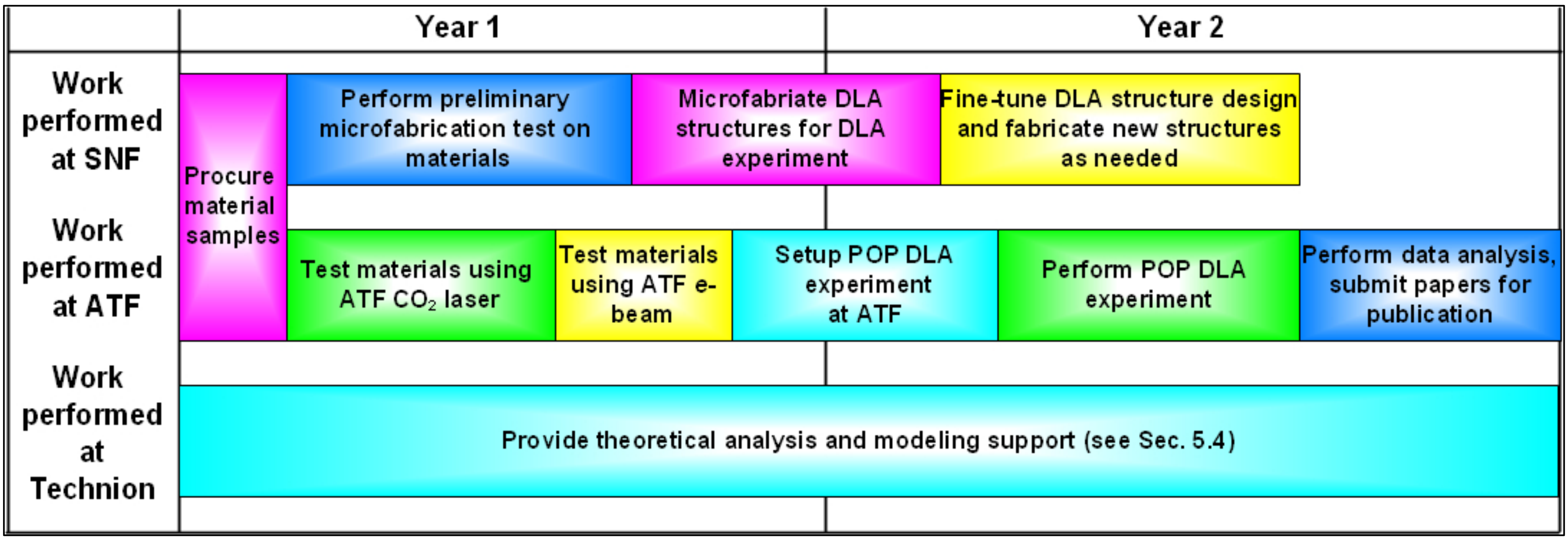


W. Kimura and P. Musumeci

Experiment Timetable for 10 Micron Structure Development and Testing at ATF

Primary Tasks:

1. Exploration of MIR-compatible materials (Si, Ge, BaF_3, CaF_2, GaAs, GaN, etc)
2. Structure fabrication and damage testing (laser only) at ATF
3. POC experiment with a pulse front tilted CO_2 laser on a 2cm DLA



From joint NSF-BSF proposal submitted Nov. 2018, O. Solgaard, W. Kimura, L. Schachter, I. Pogorelski, R. L. Byer, J. Harris, R. J. England

Conclusions

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Significant progress in DLA over the last 4 years:

Ongoing 5-year international collaboration funded by Moore Foundation
Gradients ~ 1 GV/m, energy gain > 0.3 MeV demonstrated
Prototype “shoebox” demonstration system online at Stanford
Dedicated ACHIP working group for relativistic energy experiments

Parameters for DLA experiments using RF injectors

low-charge low-emittance operation (≤ 1 pC, e_N ~ 3 to 100 nm)
moderate peak-power (20-40 milliJoule)
laser pulse front tilt and optically microbunched electrons desired

Desirable Features for Experiments at ATF

10 μm operation allows relaxed tolerances on structure size, aligment
high pulse energies would enable extended (10-MeV scale) interactions
studies of high (pC) charge throughput, beam loading, wake effects
requires material studies, new structures designed for 10 μm*

*Primary cost hurdle is structure development. Other funding avenues being explored.