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Recent demonstration of record high gradients in dielectric laser accelerating structures

20th September 2016

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Invited talk presented at Stanford Photonics Research Center 2016 Symposium (McMurtry Building, Stanford, 20th Sept 2016).

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U.S. DEPARTMENT OF ENERGY

Office of Science

SLAC NATIONAL ACCELERATOR LABORATORY

ACHIP

Motivating compact electron accelerators

- High gradients enable compact linear accelerators

1947

~MeV m^{-1}

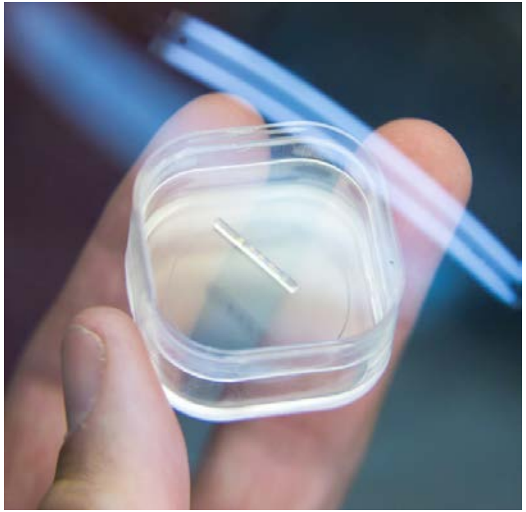
SLAC Archives, ARC127

$$G = \frac{\Delta\epsilon}{\Delta z}\ (\mathrm{eV\ m^{-1}})$$

Applications:

- Radiotherapy
- Industrial/security
- Attosecond science

2016



~GeV m^{-1}

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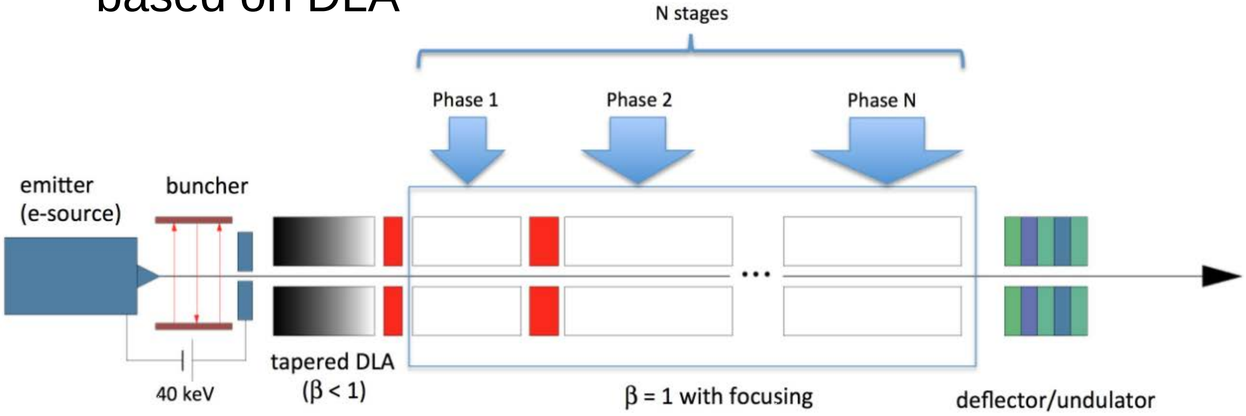
Dielectric Laser Accelerators (DLA)

Demonstrate the key scientific milestones needed for a laser-driven electron source based on DLA



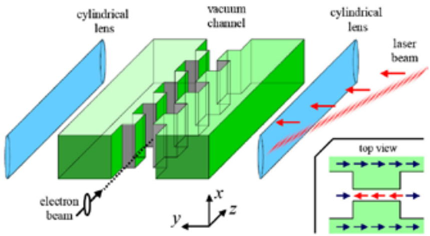
Primary components needed:

1. Low emittance electron emitter
2. Buncher/Injector section (40 keV → 1 MeV)
3. Multi-stage speed-of-light accelerator (1 MeV → ≥20 MeV)
4. Laser-driven dielectric deflector/undulator

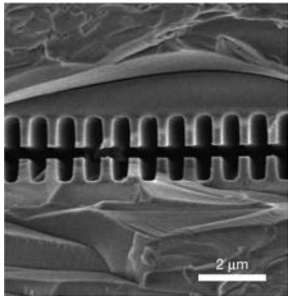
Dielectric laser accelerator structures

- Dielectric-vacuum structures
- Laser provides accelerating field
- Recent subrelativistic structures

1-D

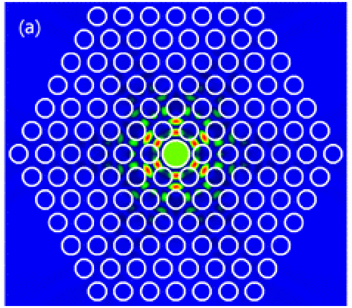


Plettner, et al., *PRSTAB,* 9, 111301 (2006)

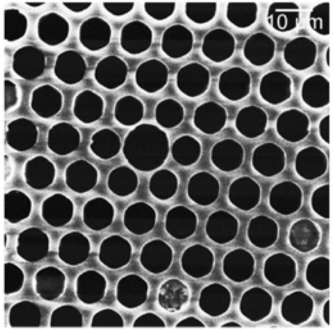


Peralta, et al., *Nature,* 503, p. 91 (2013)

2-D

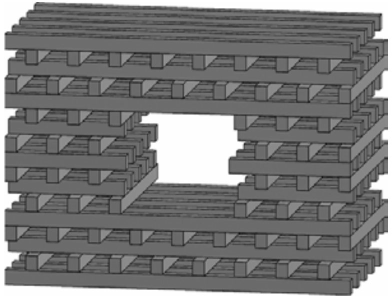


Noble, et al., *PRSTAB,* 14, 121303 (2011)

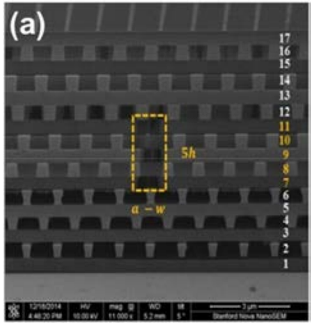


Noble, et al., *PRSTAB,* 14, 121303 (2011)

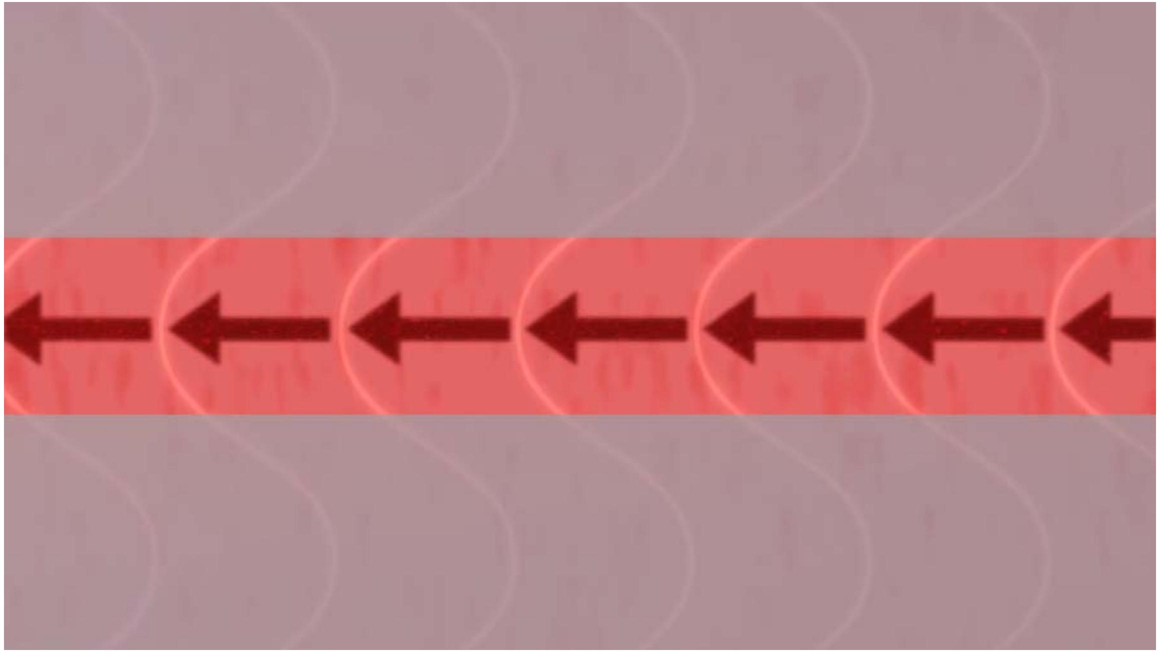
3-D



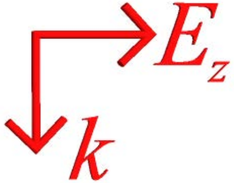
Cowan, *PRSTAB,* 11, 011301 (2008)



Wu, et al., *IEEE JSTQE,* 22, 4400909 (2016)

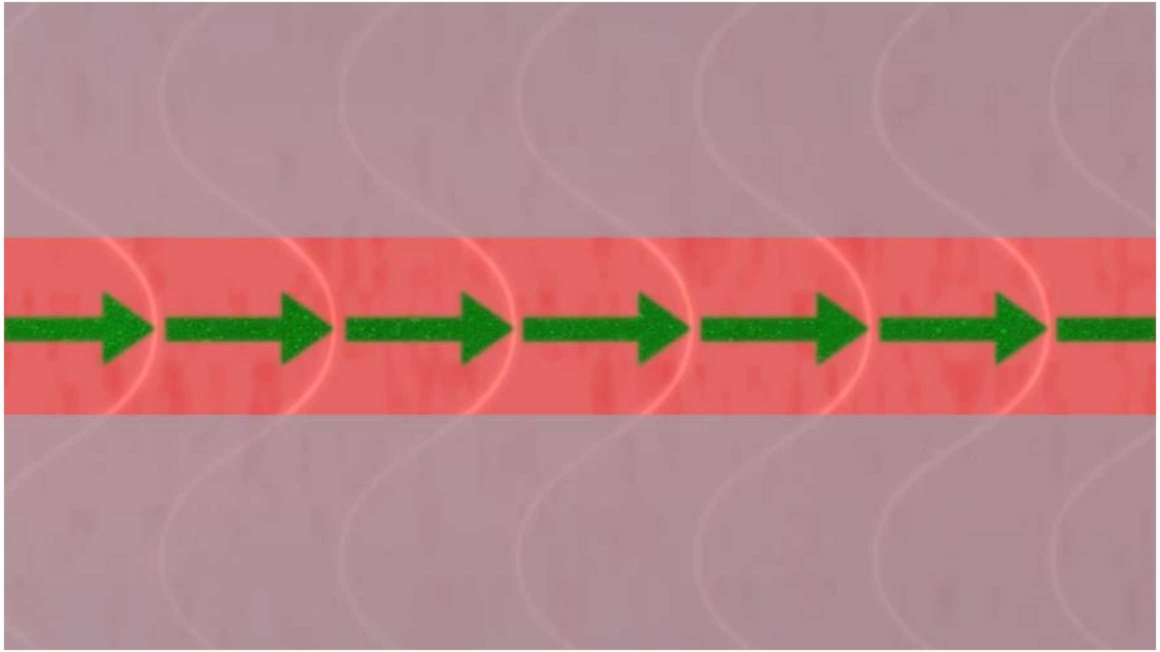


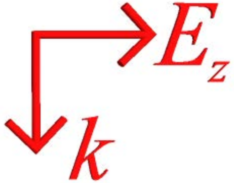
SLAC National Accelerator Laboratory https://youtu.be/V89qvy8whxY



- Plane wave
- No acceleration

DLA – Dual grating





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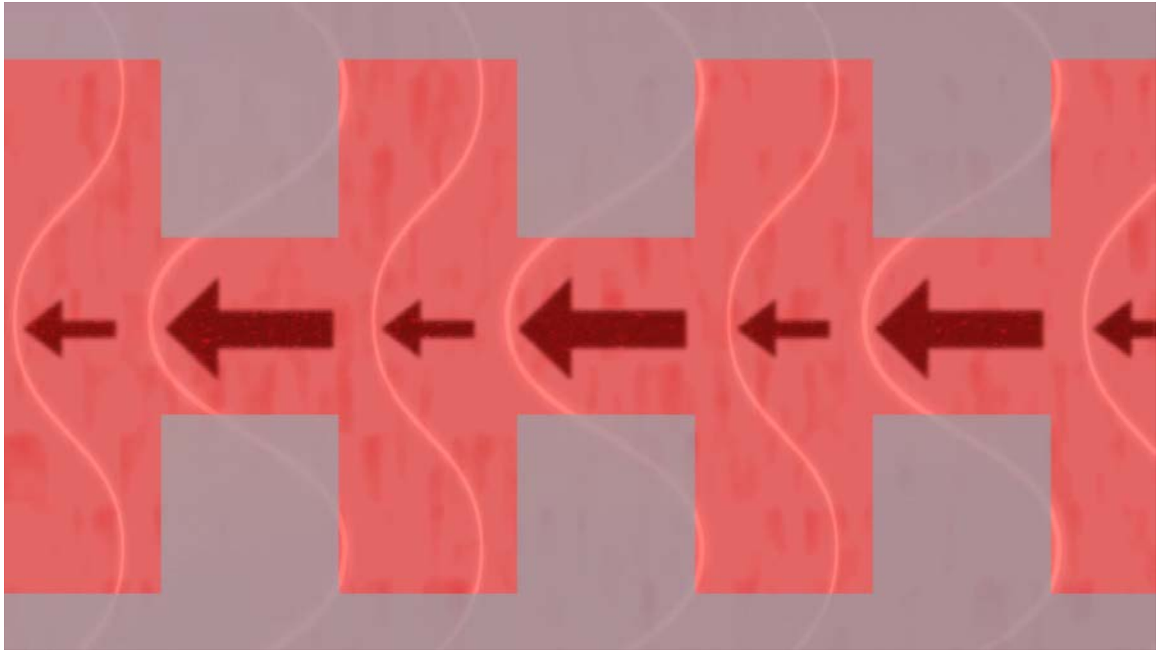
DLA – Dual grating



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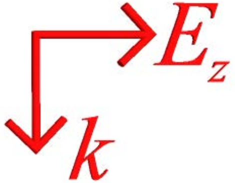
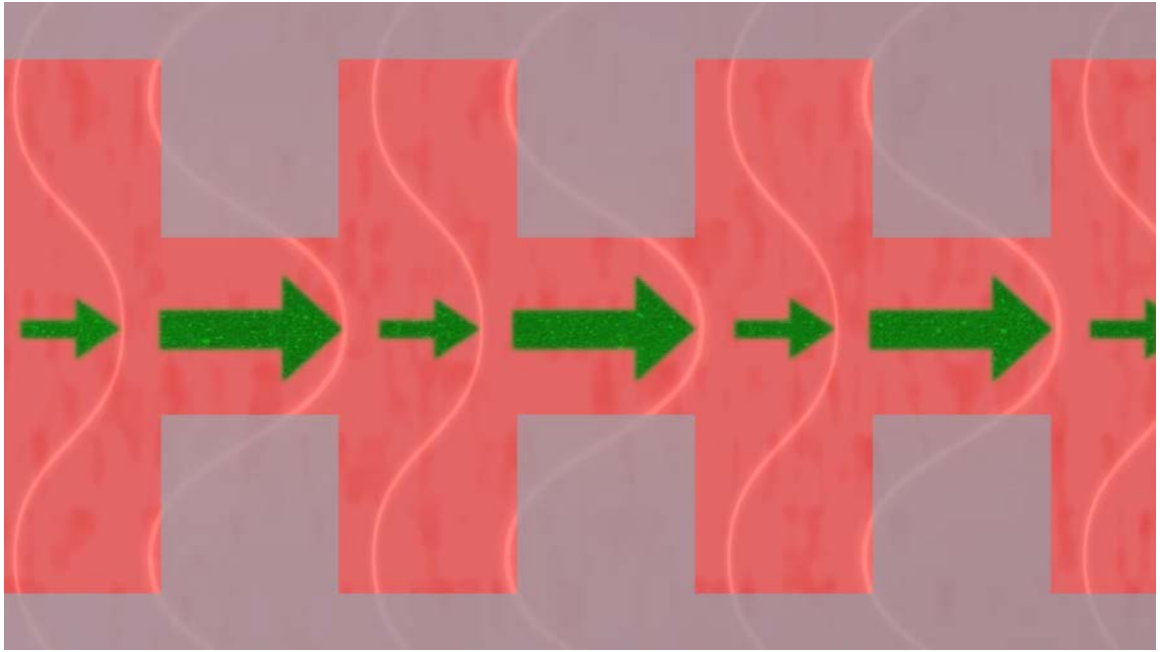
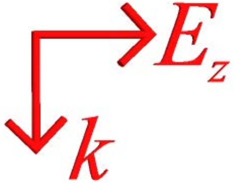


- Plane wave
- No acceleration
- Refractive index modifies phase
- Acceleration

DLA – Dual grating





- Plane wave
- No acceleration
- Refractive index modifies phase
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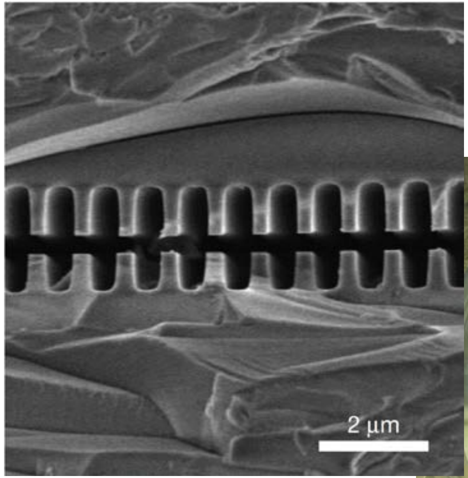
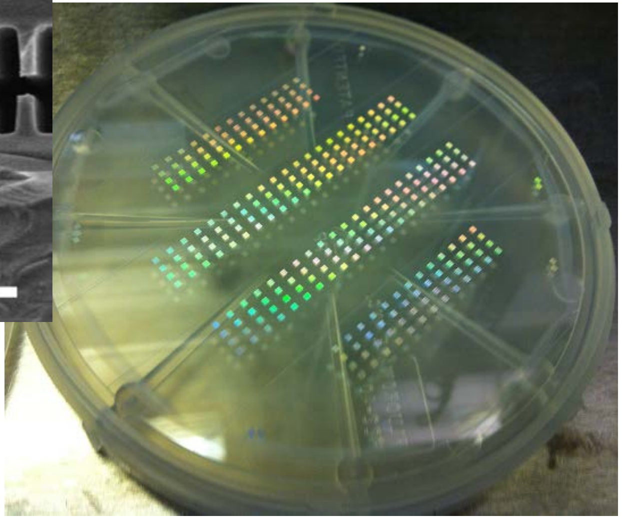
SLAC National Accelerator Laboratory https://youtu.be/V89qvy8whxY

Accelerating structure

- ‘Phase reset’ structure
- Fused silica dual grating
- UV lithography fabrication
- 800 nm period, designed for 800 nm wavelength



Peralta, et al., *Nature*, 503, p. 91 (2013)



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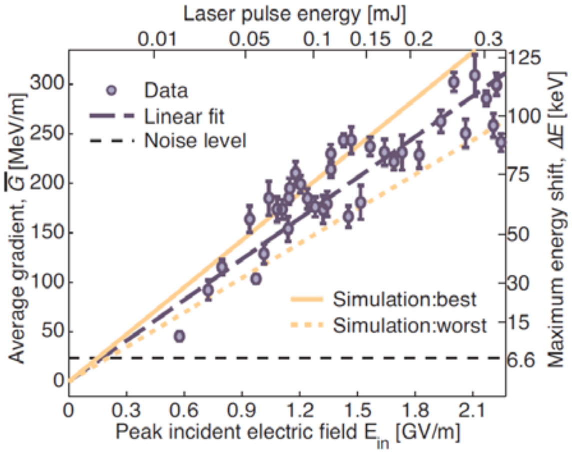
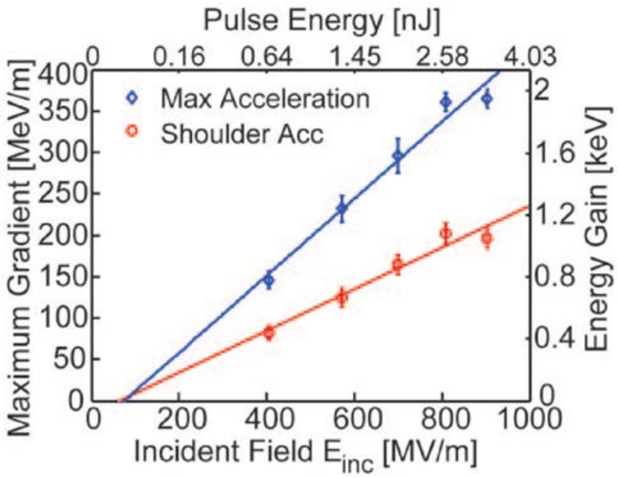
High-gradient DLA – previous experiments

- $\beta \approx 1$, 1.2 ps laser pulse
- $310 \pm 21\ \mathrm{MV\ m^{-1}}$



Peralta, et al., *Nature,* 503, p. 91 (2013)

- $\beta \approx 0.5$, 80 fs laser pulse
- $376 \pm 40\ \mathrm{MV\ m^{-1}}$



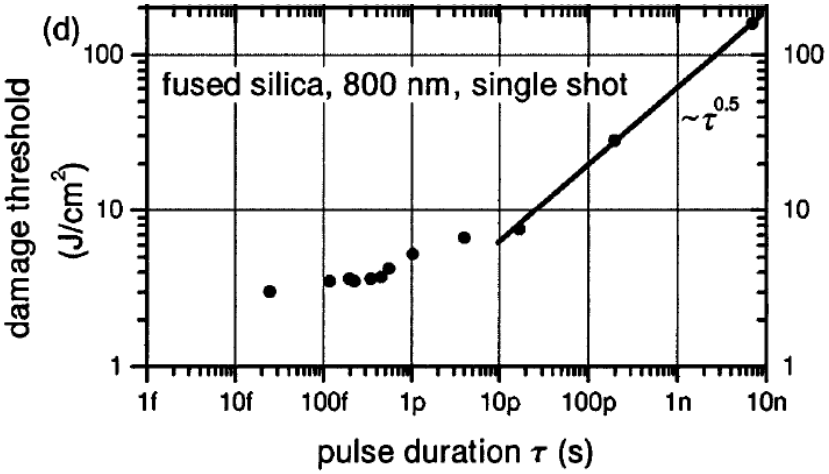
Leedle, et al., *Opt. Lett.,* 40, p. 4344 (2015)

Material damage fluence and accelerating gradient

- Plateau in single pulse dielectric damage threshold below ~ps pulse duration

$$G \propto \sqrt{\frac{F}{\tau}}$$

- Highest electric (accelerating) field implies shortest pulse duration



A.-C. Tien, et al., *Phys. Rev. Lett.*, 82, p. 3883 (1999)

Present experiment

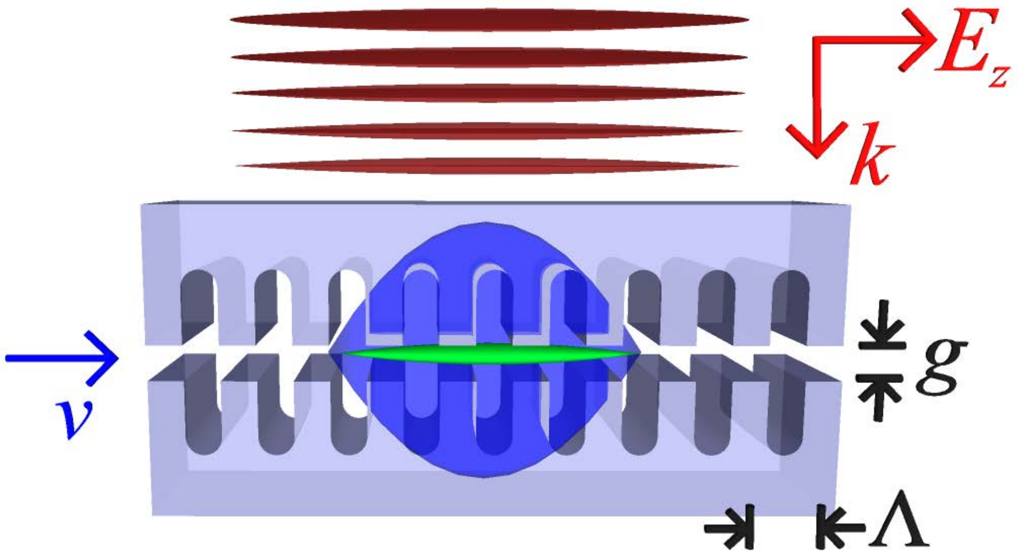
- Single acceleration stage

Goal

- Demonstration that structure supports high accelerating gradient

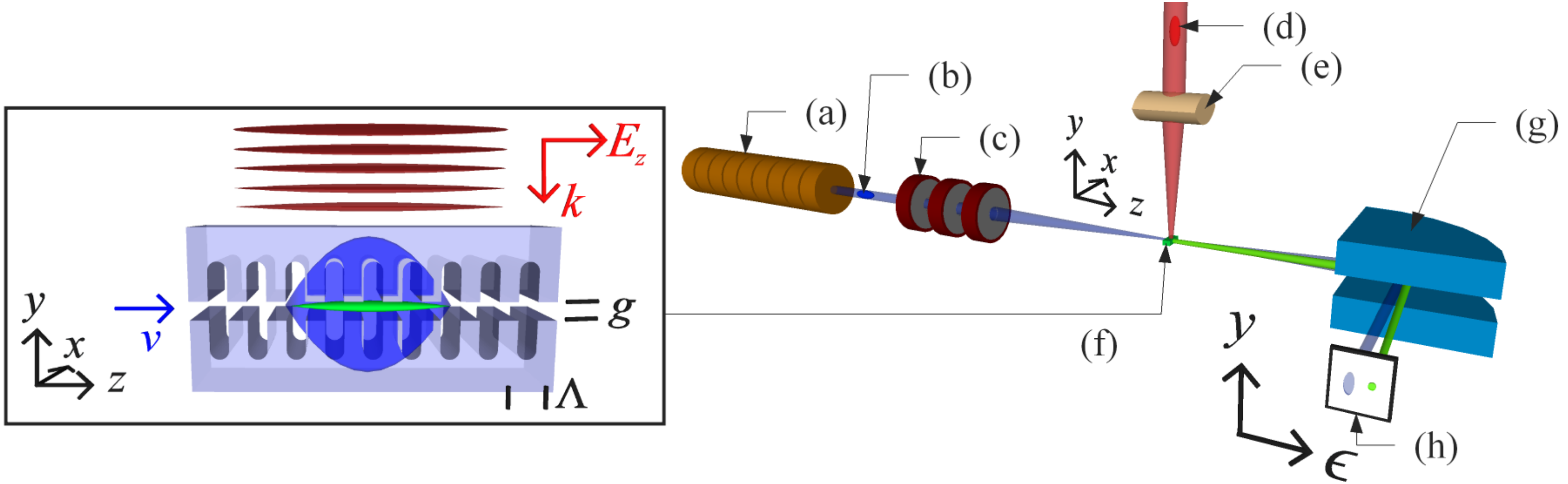
Measure

- Electron energy increase
- Incident laser electric field



K. P. Wootton, et al., Opt. Lett., 41, p. 2696-2699 (2016)

Experimental arrangement at NLCTA (SLAC)



- 60 MeV electrons from linac, 170 fs bunch length (60 cycles)
- 800nm wavelength laser, 90 fs pulse duration
- Bending magnet spectrometer

Determining accelerating gradient

- Use measured laser temporal distribution to determine gradient

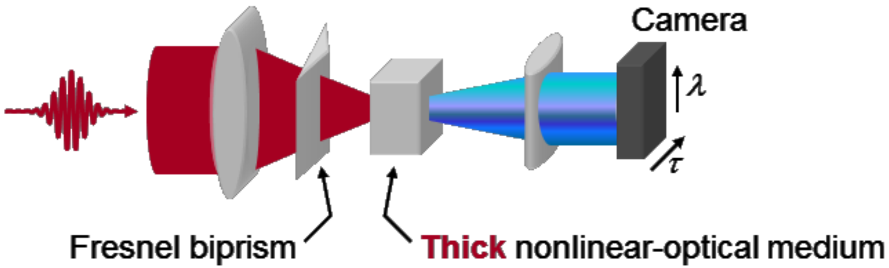
$$G = \frac{\Delta\epsilon}{\Delta\epsilon_1}$$

Measured change in energy (keV)

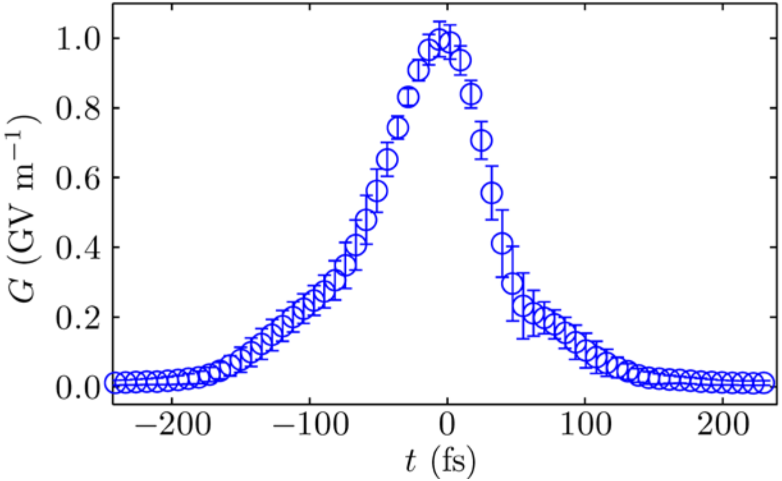
Change in energy arising from interaction with an accelerating gradient of 1 GV m^{-1}

Laser pulse measurement

FROG (GRENOUILLE)

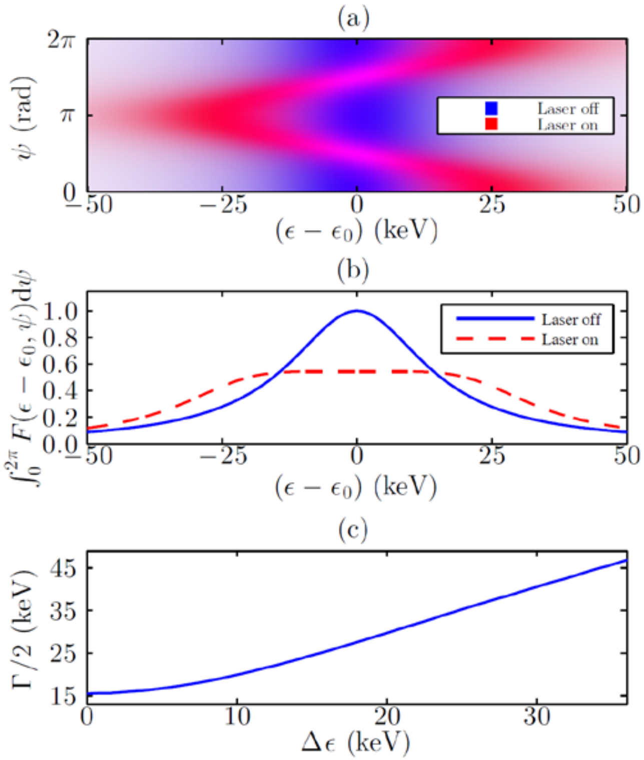


http://www.swampoptics.com/



$$\Delta\epsilon_1 = 35 \pm 5 \text{ keV } (\text{GVm}^{-1})^{-1}$$

Model – Electron beam response to DLA

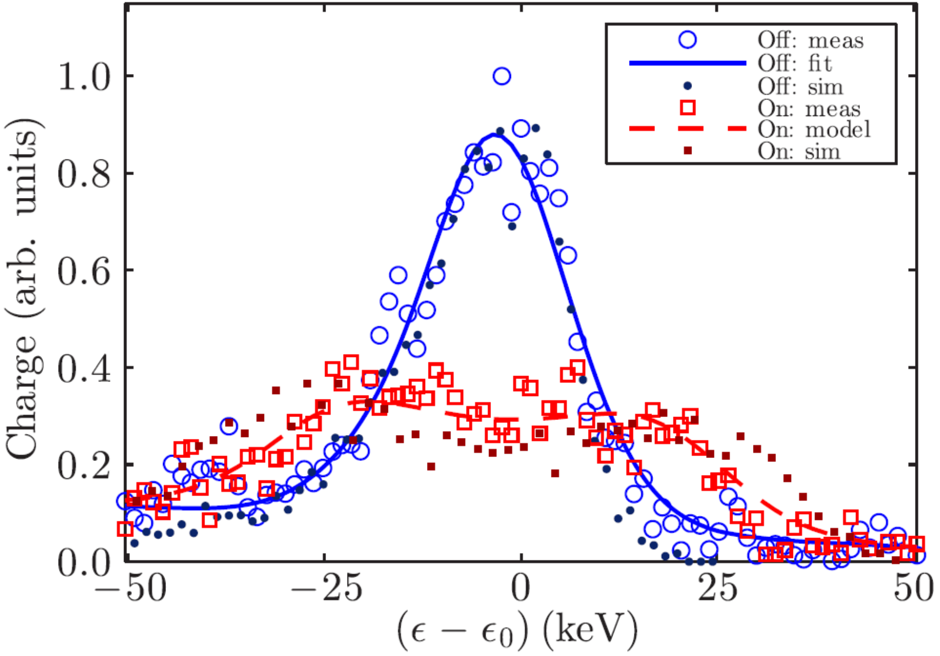


- Electron bunch approximately 60 optical cycles long
- Electrons accelerated or decelerated with respect to laser phase
- Modulation of measured electron beam energy spectrum
- Width corresponds to energy gain

Measured energy spectrum

- Electron beam energy profile, laser on and off
- Measurements, model, particle-in-cell simulations (Ben Cowan, Tech-X)
- Using model,

$$\Delta\epsilon = 24.0 \pm 1.1 \text{ keV}$$

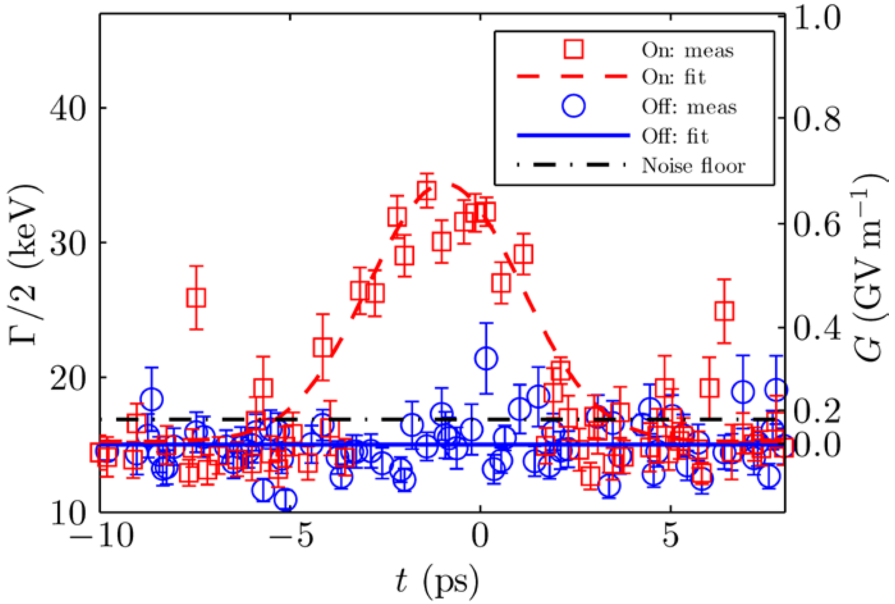


Time of arrival of laser pulse

- Cross-correlation signal, Measured RMS width

  $\sigma_t = 2.0 \pm 0.2$ ps
- Expected $\sigma_t = 1.7 \pm 0.3$ ps
- Laser pulse duration 90 fs
- Electron bunch duration ($\sim$170 fs)
- Laser spot (330 μm ≈ 1.1 ps)
- Laser–electron jitter (0.48 ps)

$$G = 0.69 \pm 0.10 \text{ GeVm}^{-1}$$

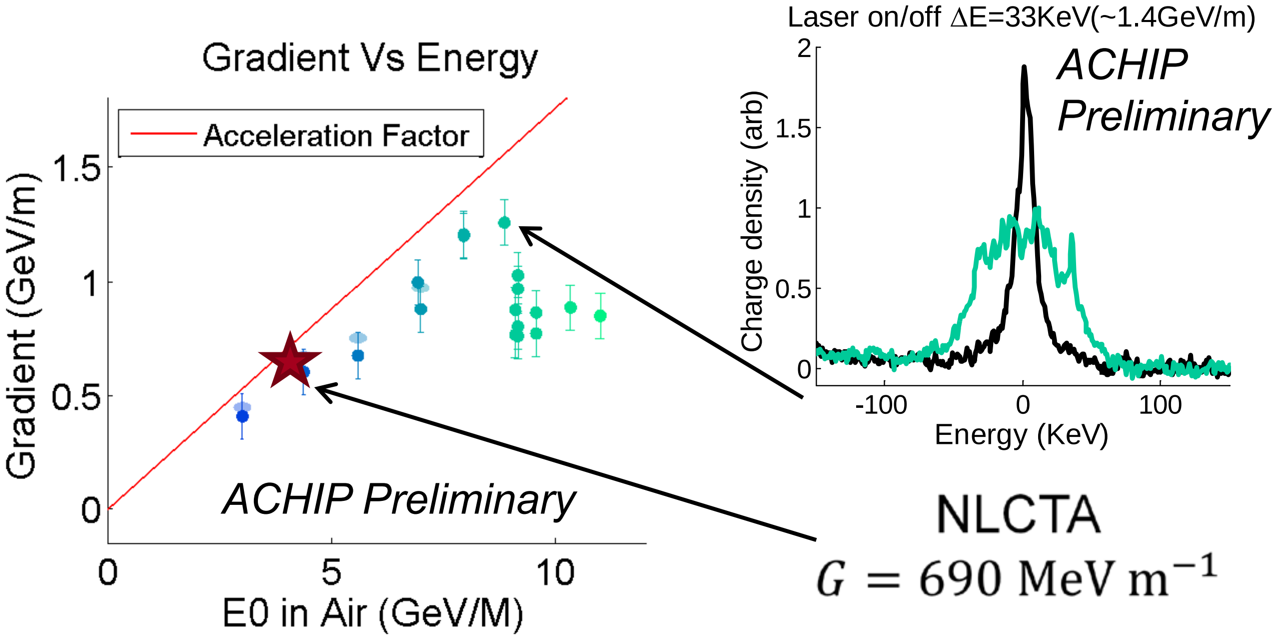


In terms of gradients, where to?

- Fluence $F = 0.17 \pm 0.02 \text{ J cm}^{-2} \rightarrow E_{\text{inc}} = 4.2 \text{ GV m}^{-1}$
- Acceleration ratio $f = \dfrac{nG}{\eta E_{\text{inc}}}$
- Measured $f_{\text{meas}} = 0.11 \pm 0.03$
- Simulation $f_{\text{sim}} = 0.11 \pm 0.02$
- Higher incident electric fields are possible below damage threshold

Recent DLA results UCLA–SLAC

Similar tests at UCLA using a higher intensity laser show greater than $1\ GeV\ m^{-1}$ acceleration



Conclusion

- Demonstrated accelerating gradient in a DLA:

$$G = 0.69 \pm 0.10\ \mathrm{GeVm}^{-1}$$

- Higher gradients still possible, collaboration with UCLA
- Pulse-front tilt next goal, extending interaction over longer structure length $(1\ \mathrm{mm})$

Acknowledgments

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Ziran Wu
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Adi Hanuka

Livermore Natl. Lab
Paul Pax
Mike Messerly

Univ. Colorado
Greg Werner

blue = students

Backup

Accelerator on a Chip International Program (ACHIP)

GORDON AND BETTY MOORE FOUNDATION

PIs: R. L. Byer *(Stanford)*

& P. Hommelhoff *(FAU Erlangen)*

5 year programme (2015-2020)

- Stanford
- FAU Erlangen
- Purdue
- UCLA
- EPFL
- TU Darmstadt
- Hamburg
- Tech-X

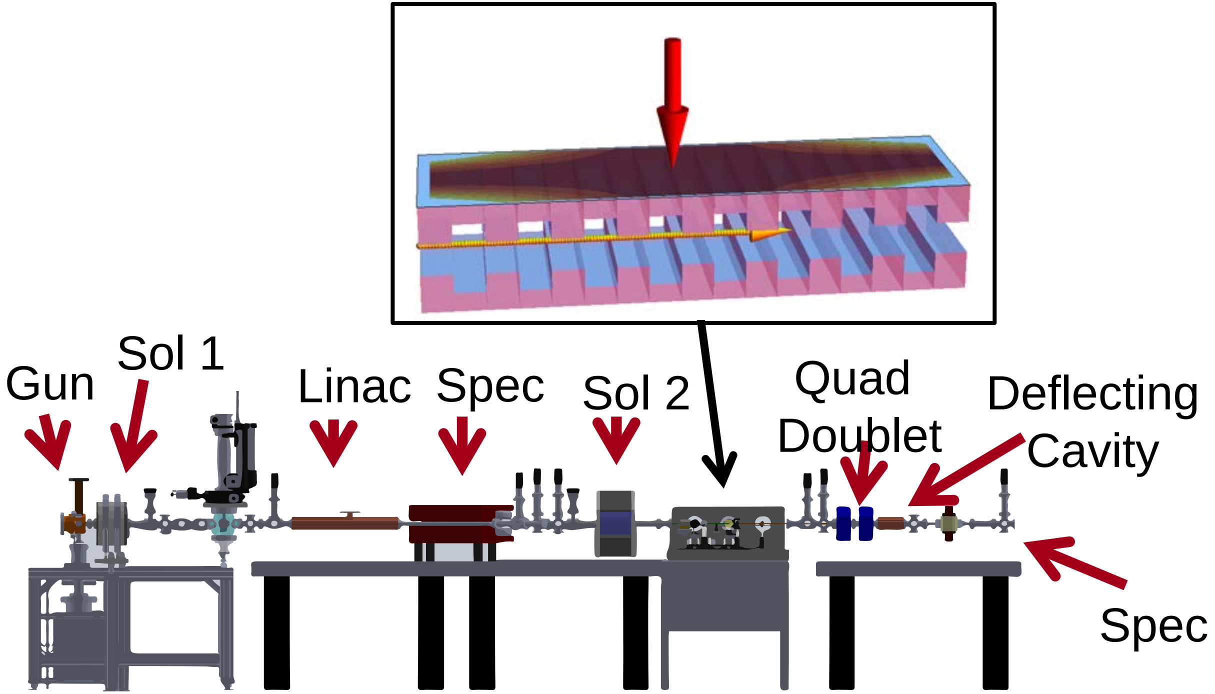
In-kind contributions:

- SLAC
- DESY
- PSI

https://sites.stanford.edu/achip/

Recent DLA experiments UCLA–SLAC

PEGASUS electron accelerator



Laser parameters

λ	800 nm
Energy	<300μJ
Fluence	<0.75 J/cm^2
Size (w)	~50μm x 550μm
τ (I fwhm)	42fs

Electron beam parameters

Energy	8 MeV
Charge	300fC→3fC
E spread	2 KeV
ϵ_n	40 nm→0.4nm
Bunch length	0.5ps