SLAC-PUB-16780

Recent demonstration of record high gradients in dielectric laser accelerating structures

1st August 2016

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[2] University of California – Los Angeles
[3] Tech-X Corporation
[4] Technion – Israel Institute of Technology
[5] Stanford University

This material is based upon work supported by the U.S. Department of Energy, Office of Science, Office of Basic Energy Sciences, under Contract No. DE-AC02-76SF0051 and NSF.

Motivating compact electron accelerators

- High gradients enable compact linear accelerators

1947

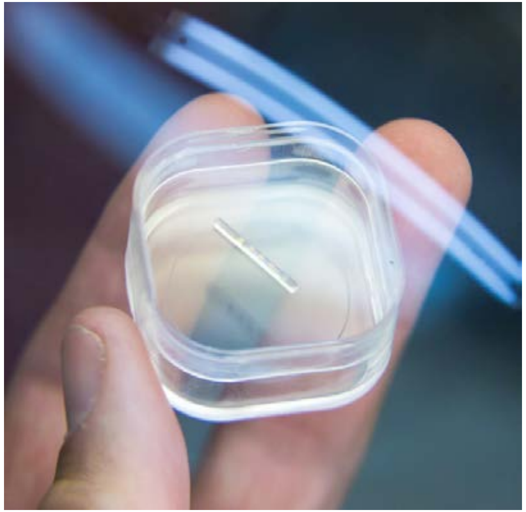
~MeV m^{-1}

SLAC Archives, ARC127

Applications:

- Radiotherapy
- Industrial/security
- Attosecond science

2016



~GeV m^{-1}

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Accelerator on a Chip International Program (ACHIP)

GORDON AND BETTY MOORE FOUNDATION

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

& P. Hommelhoff *(FAU Erlangen)*

$2.7M per annum

5 year programme (2015-2020)

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

In-kind contributions:

- SLAC
- DESY
- PSI

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

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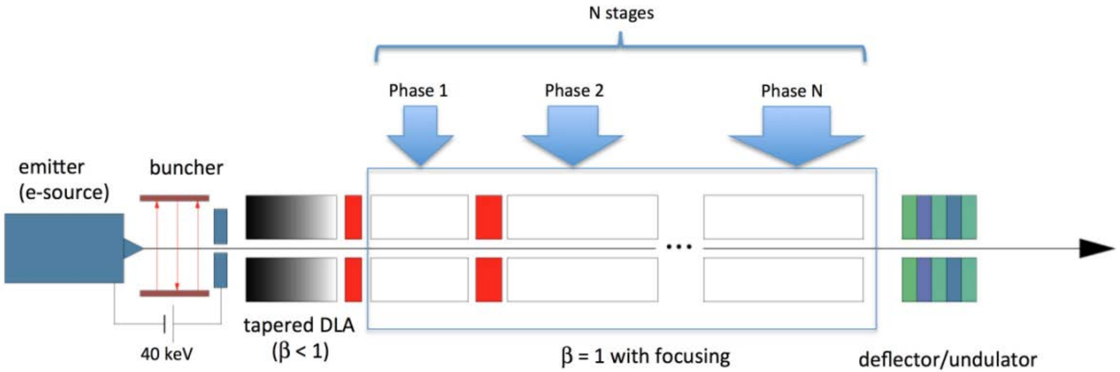
Dielectric Laser Accelerators (DLA)

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

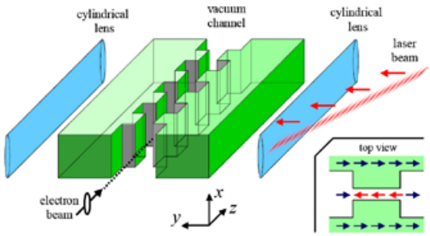
This material is based upon work supported by the U.S. Department of Energy, Office of Science, Office of Basic Energy Sciences under Contract No. DE-AC02-76SF00515 and NSF.

Dielectric laser accelerator structures

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

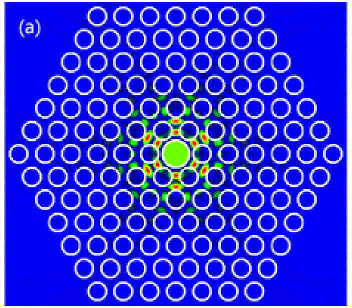
J. McNeur,
Mon WG3 4:20

1-D



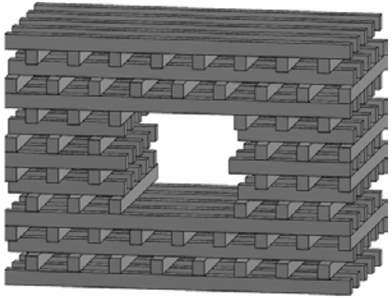
Plettner, et al., *PRSTAB,* 9, 111301 (2006)

2-D

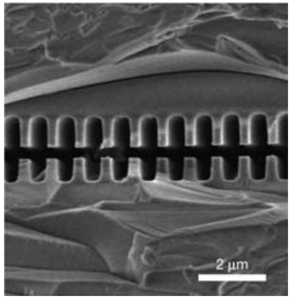


Noble, et al., *PRSTAB,* 14, 121303 (2011)

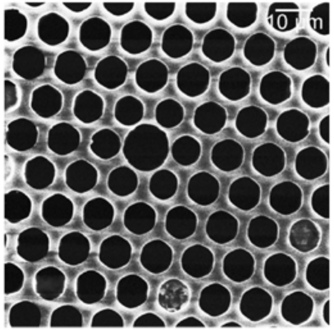
3-D



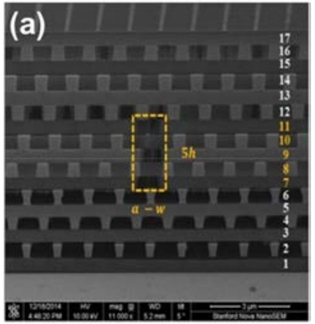
Cowan, *PRSTAB,* 11, 011301 (2008)



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



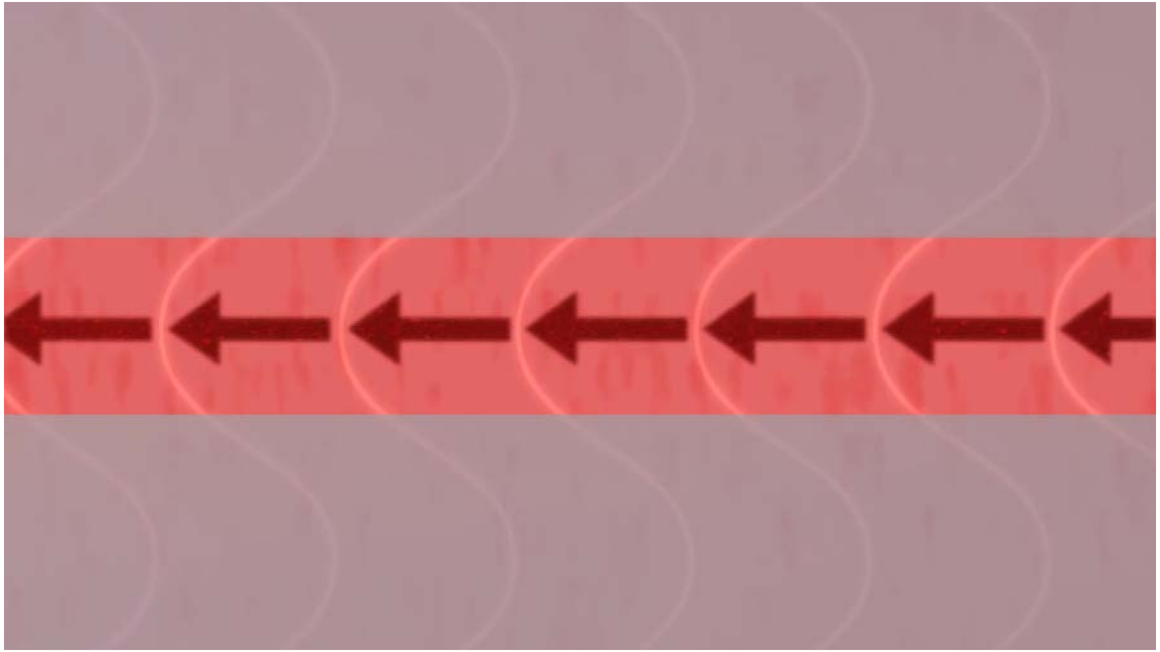
Noble, et al., *PRSTAB,* 14, 121303 (2011)



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

This material is based upon work supported by the U.S. Department of Energy, Office of Science, Office of Basic Energy Sciences under Contract No. DE-AC02-76SF0051 and NSF.

DLA – Dual grating



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

- Lawson-Woodward
- Plane wave
- No acceleration

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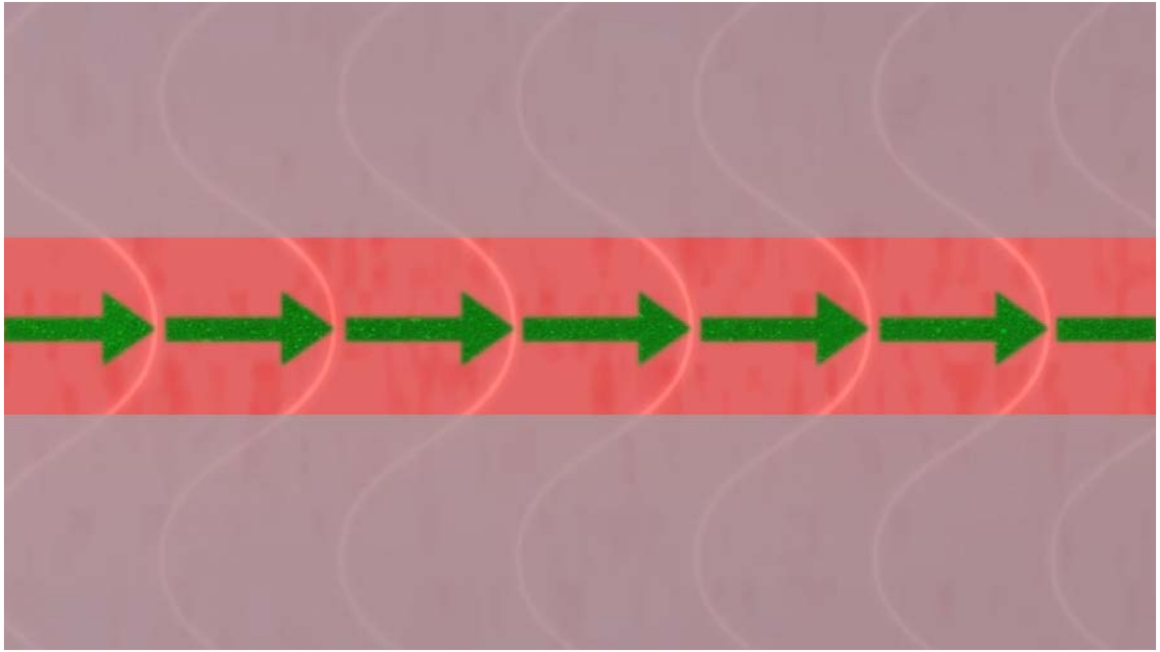

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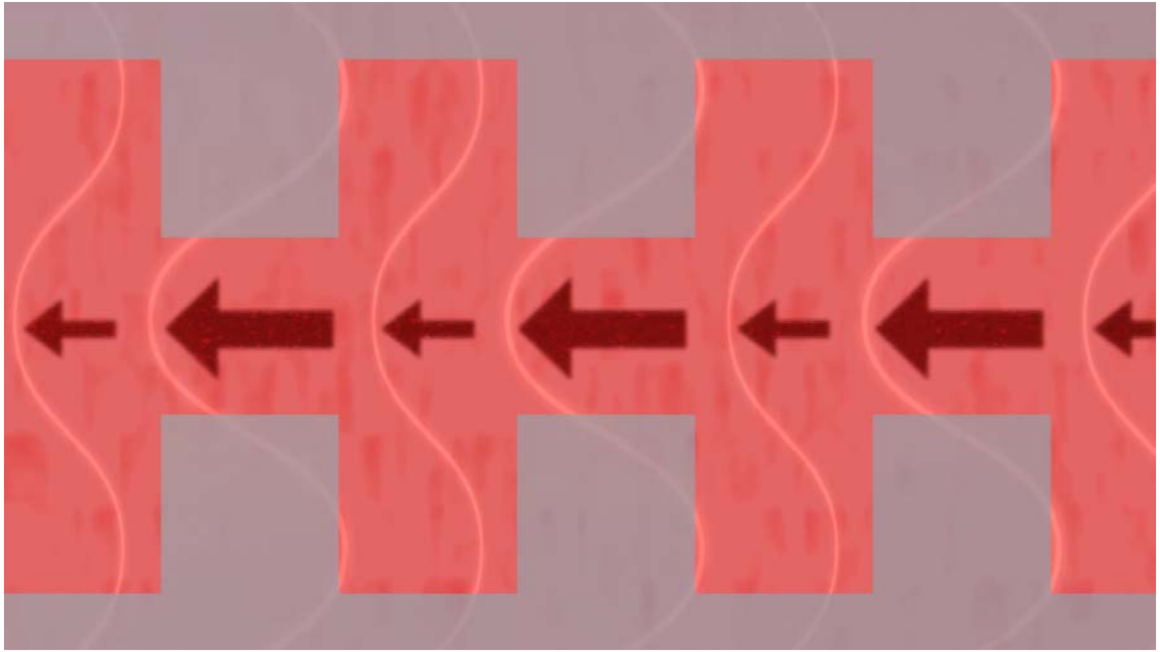

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- Near field structure
- Refractive index modifies phase
- Acceleration

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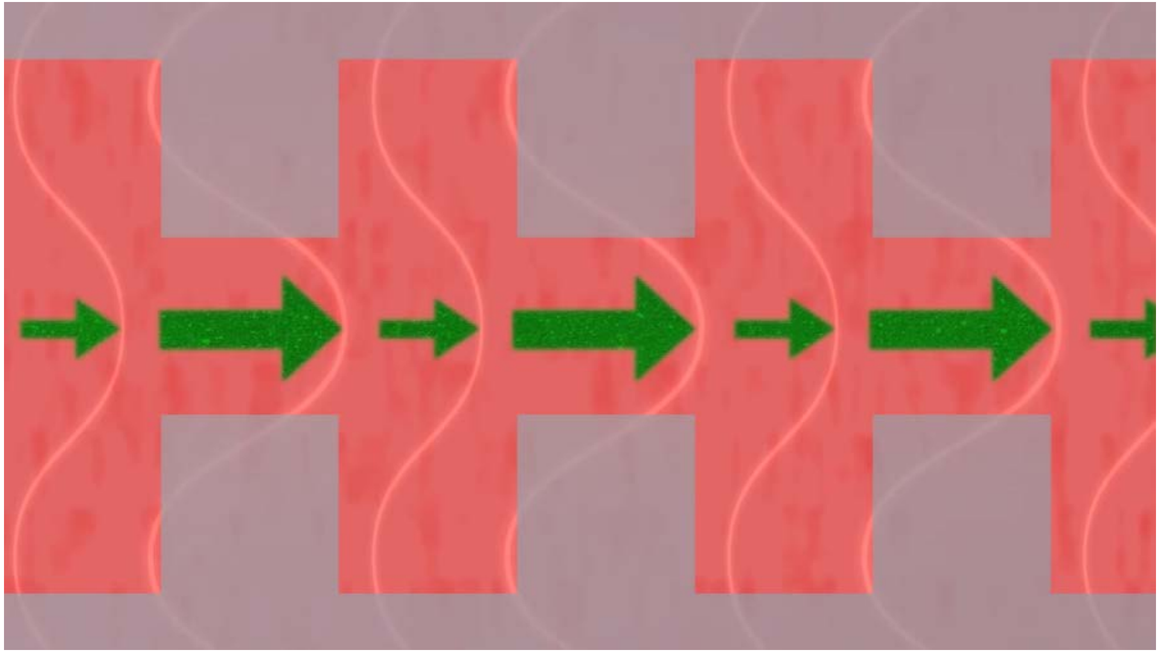
DLA – Dual grating



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

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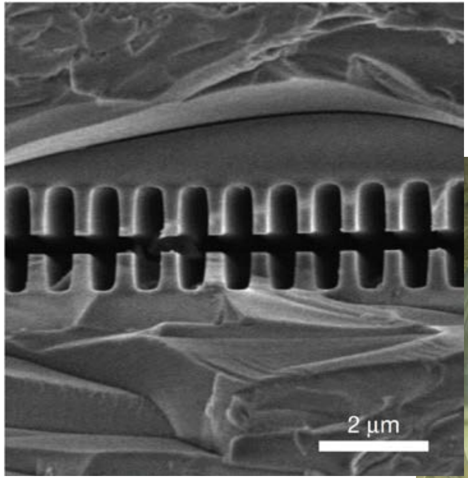
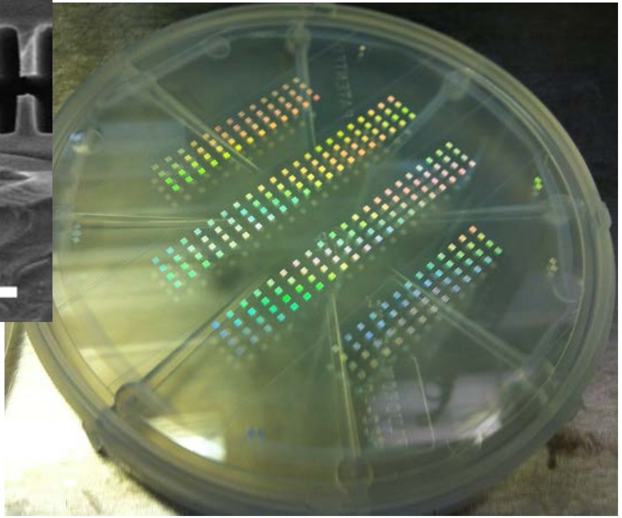
Accelerating structure

- ‘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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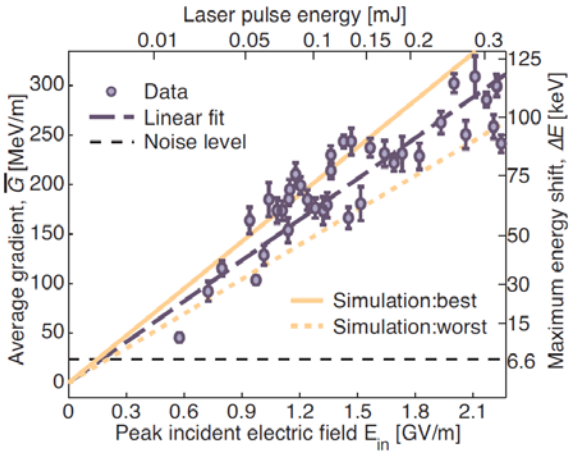
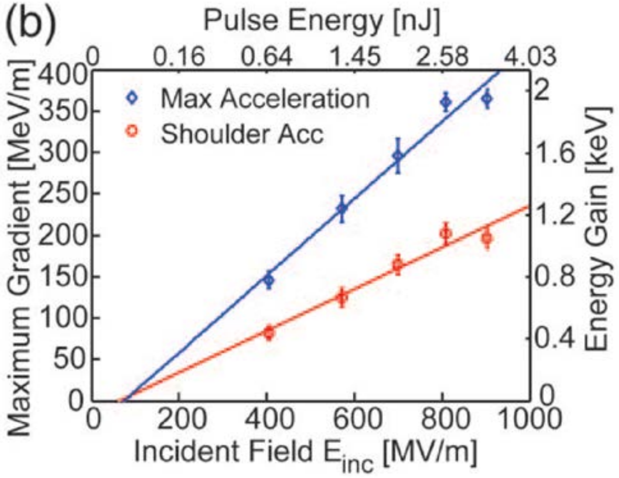
High-gradient DLA – previous experiments

- $\beta \approx 1$, 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)

A. Ceballos, Mon WG3 4:40

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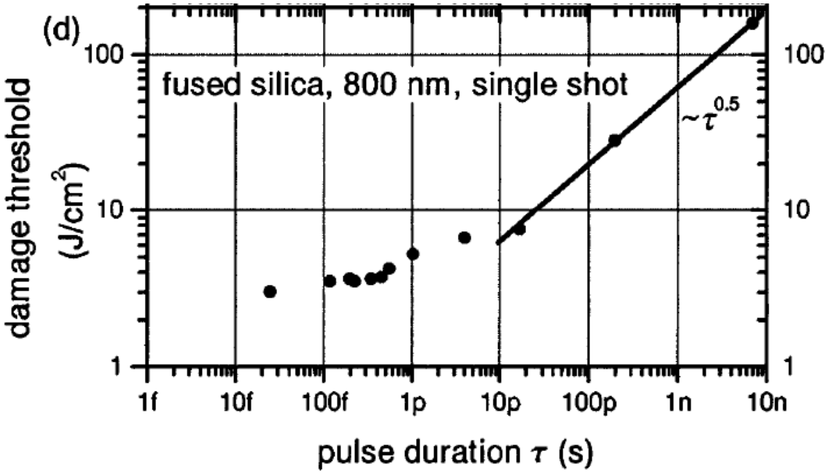
Material damage fluence

- Plateau in single pulse dielectric damage threshold below ~ps pulse duration
- Highest electric (accelerating) field implies shortest pulse duration



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

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Present experiment

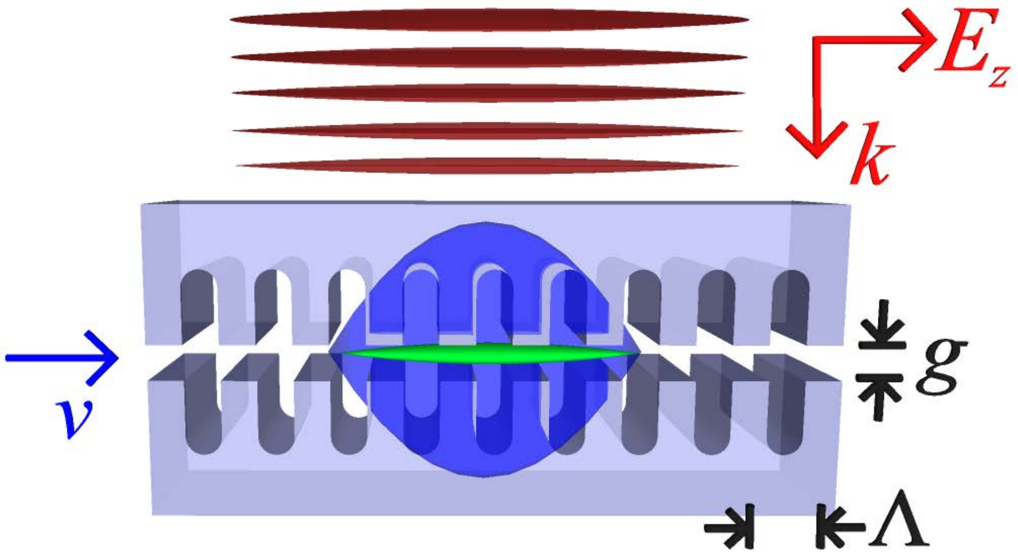
- Single acceleration stage

Goal

- Demonstration that structure supports GV m^{-1} accelerating gradient

Measure

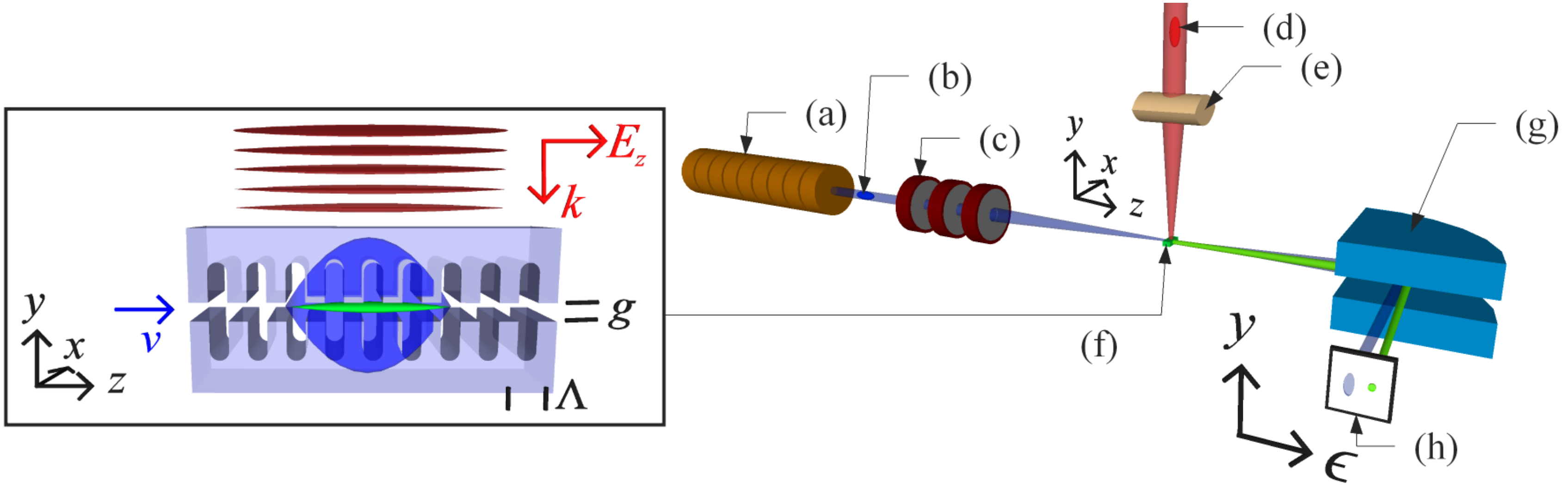
- Electron energy increase
- Incident laser electric field



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

This material is based upon work supported by the U.S. Department of Energy, Office of Science, Office of Basic Energy Sciences under Contract No. DE-AC02-76SF0051 and NSF.

Experimental arrangement at NLCTA (SLAC)



- 60 MeV electrons from linac, 170 fs bunch length (60 cycles)
- Electron beam emittance larger than optimal J. Maxson, Tue WG5 11:30
- 800nm wavelength laser, 90 fs pulse duration
- Bending magnet spectrometer

This material is based upon work supported by the U.S. Department of Energy, Office of Science, Office of Basic Energy Sciences under Contract No. DE-AC02-76SF0051 and NSF.

Determining accelerating gradient

- Previous studies assume Gaussian laser distribution*

$$G = \frac{\Delta\epsilon}{w_{\text{int}}\sqrt{\pi}}, \qquad w_{\text{int}} = \left(\frac{1}{w_l} + \frac{2\ln(2)}{(\beta c \tau_i)^2}\right)^{-1/2}$$

- More generally, laser distribution could deviate from this
- Use measured laser temporal distribution to determine gradient

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

Measured change in energy (keV)

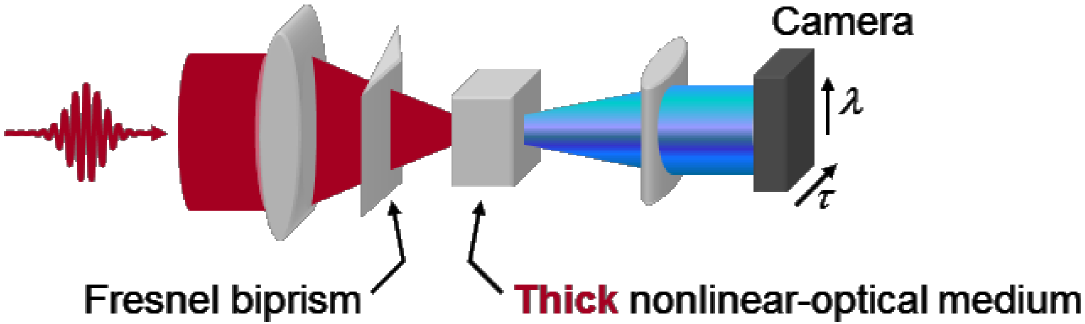
Change in energy arising from interaction with an accelerating gradient of 1 GV m^{-1}

* J. Breuer, et al., Phys. Rev. ST Accel. Beams, 17, 021301 (2014).

This material is based upon work supported by the U.S. Department of Energy, Office of Science, Office of Basic Energy Sciences under Contract No. DE-AC02-76SF0051 and NSF.

Laser pulse measurement

- FROG (GRENOUILLE)
- Measurement of SHG intensity interferogram in time and wavelength
- Reconstruction of fs pulse amplitude and phase using phase retrieval algorithm



http://www.swampoptics.com/

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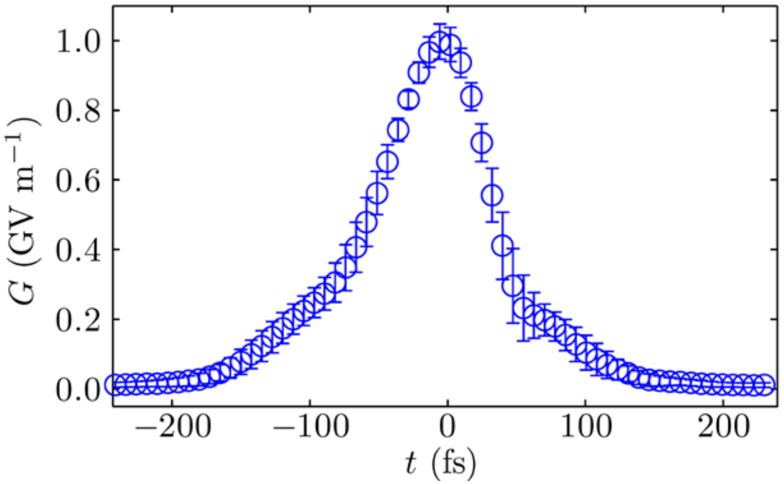
Laser pulse

- Conservatively assume flat phase
- Assume electric field contributes constructively to acceleration
- Integrate measured laser pulse electric field envelope for energy gain



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

K. Wootton, Tues WG3 1:30

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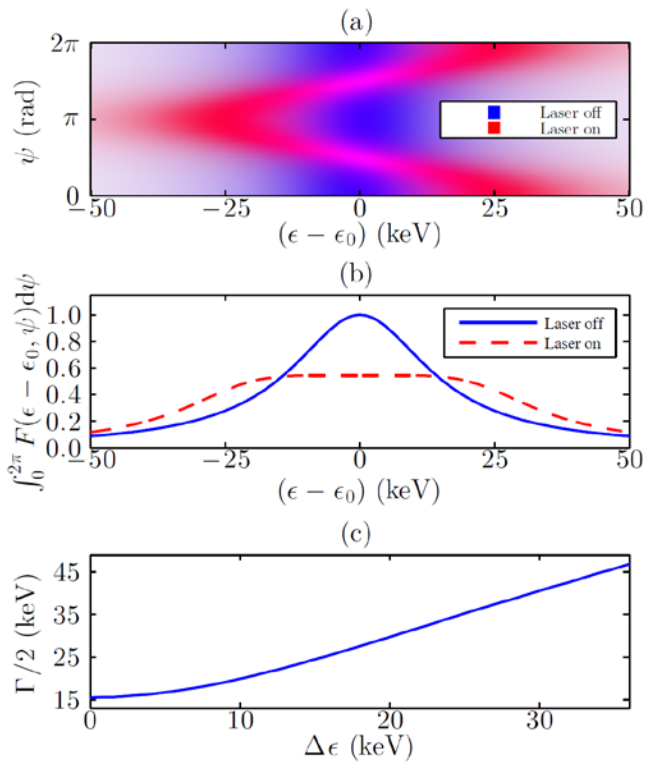
Model – Electron beam response to DLA



- 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

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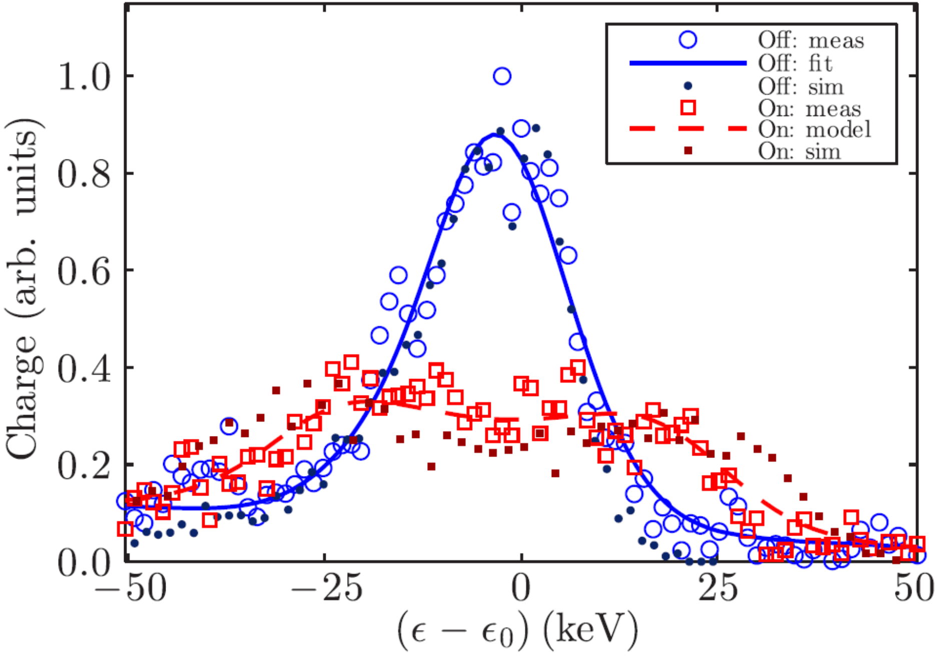
Measured energy spectrum

- Electron beam energy profile, laser on and off
- Measurements, model
- VSim simulations using fitted laser-off spectrum, measured laser parameters

  B. Cowan, Tue WG2 11:10

- Using model,

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



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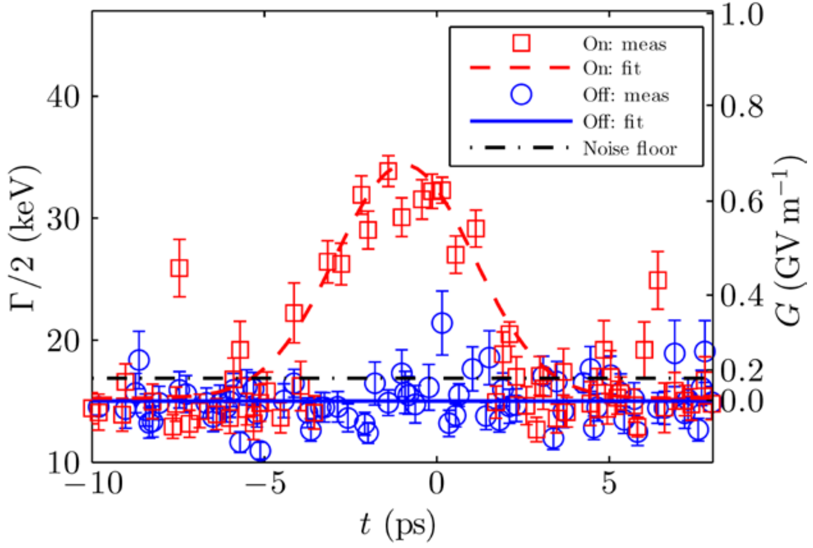
Time of arrival of laser pulse

- 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 (~170 fs)
- Laser spot (330 μm ≈ 1.1 ps)
- Laser–electron jitter (0.48 ps)

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



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In terms of gradients, where to?

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

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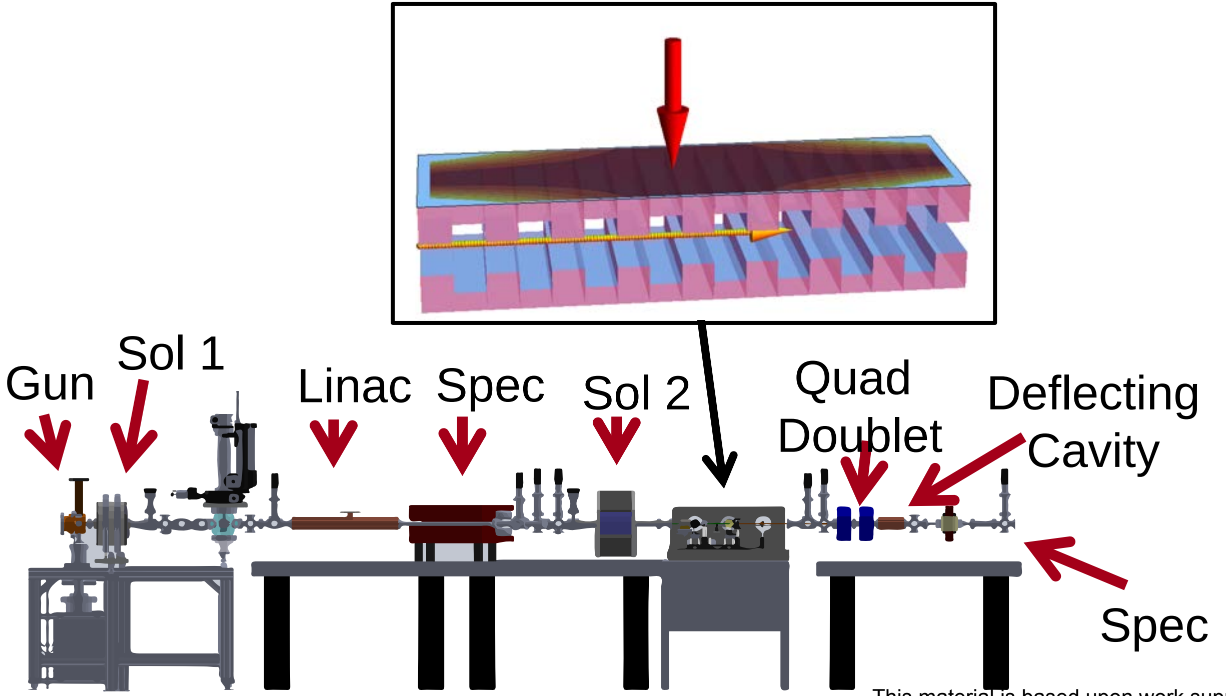
Recent DLA experiments UCLA–SLAC

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

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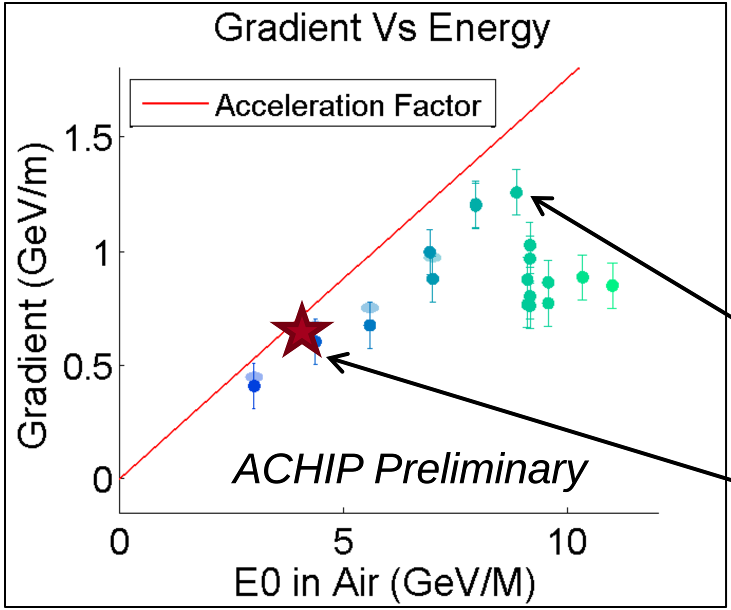
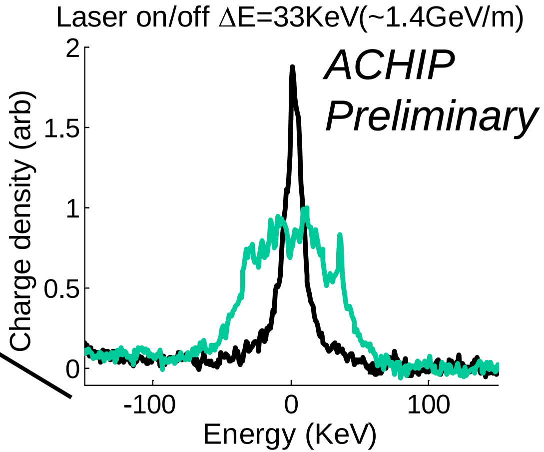
Recent DLA results UCLA–SLAC

D. Cesar,
Tue WG3 1:50

Similar tests at UCLA using a higher intensity laser show greater than 1 GeV/m acceleration





NLCTA

$$G = 690\ \mathrm{MeV\ m^{-1}}$$

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Conclusion

- New record accelerating gradient in a DLA:

$$G = 1.4\ \mathrm{GeV\ m^{-1}}$$

- Higher gradients still possible
- Pulse-front tilt next goal, extending interaction over longer structure length
  - New challenge, only small fraction of transmitted electrons accelerated (by ~1 MeV)
  - 'Partial population modulation'

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Acknowledgements

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Structures were fabricated at the Stanford Nanofabrication Facility, supported by the U.S. National Science Foundation through the NNIN under Grant ECS-9731293.

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Backup

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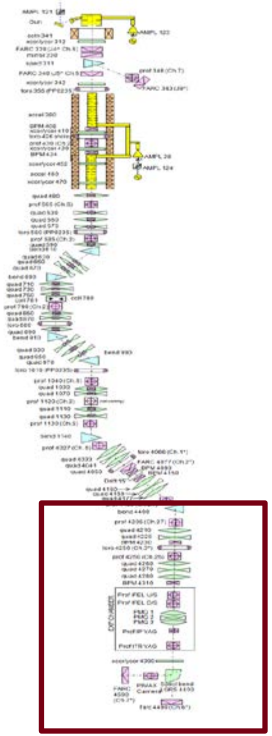
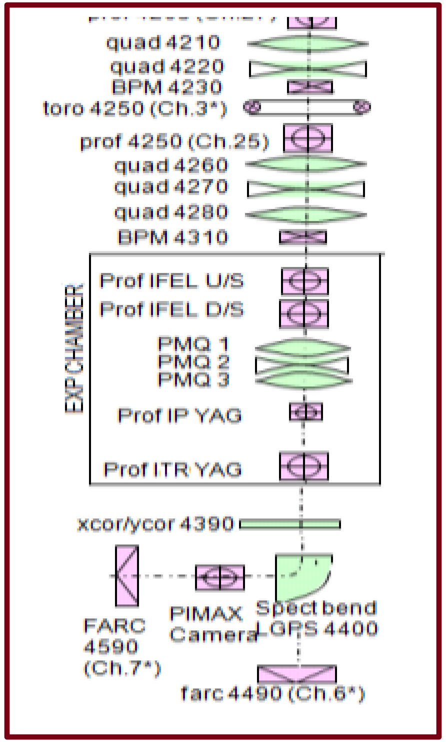
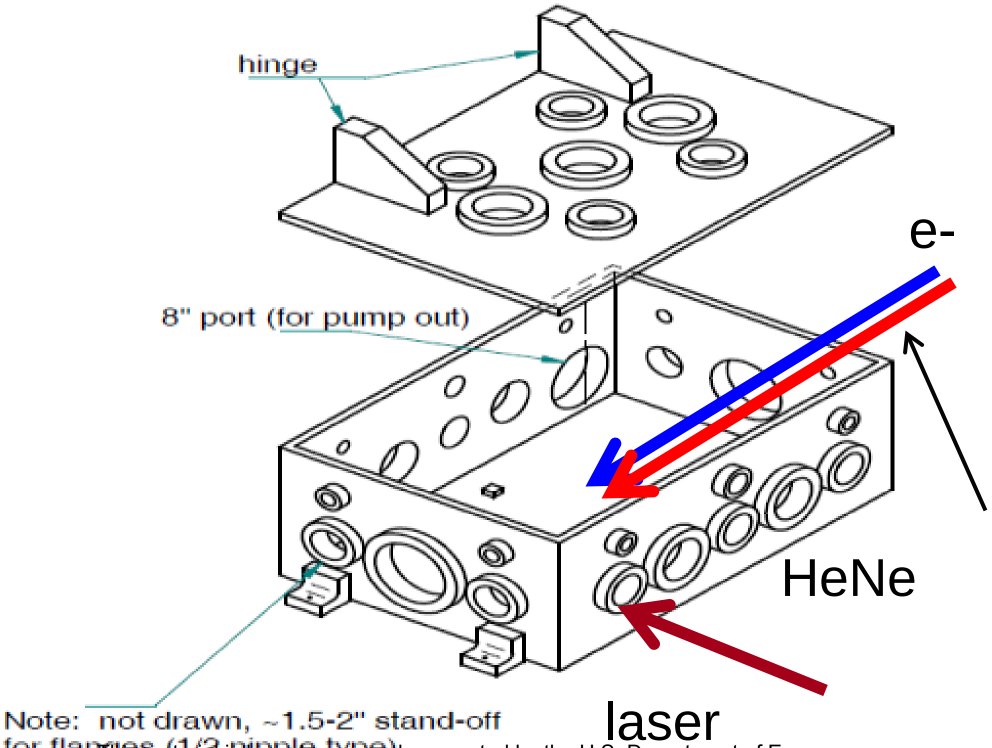
E163 beamline (SLAC)







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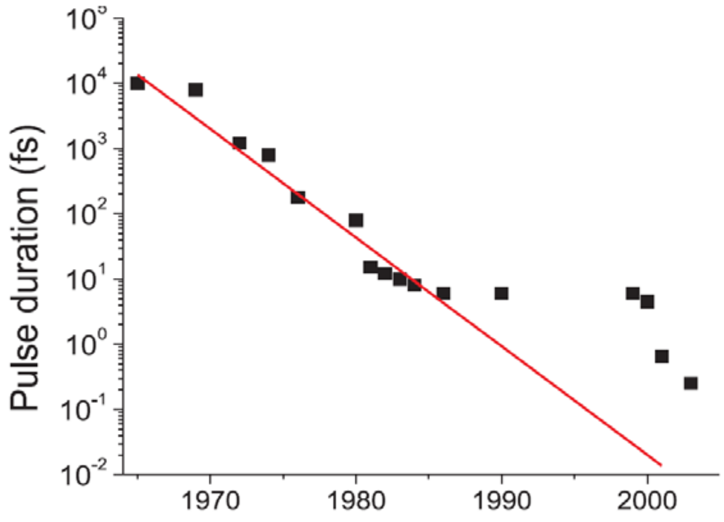
Ultrafast lasers

- fs laser pulse duration (and shorter) commercially available



J. Levesque and P. B. Corkum, *Can. J. Phys.*, 84, p. 1-18 (2006)

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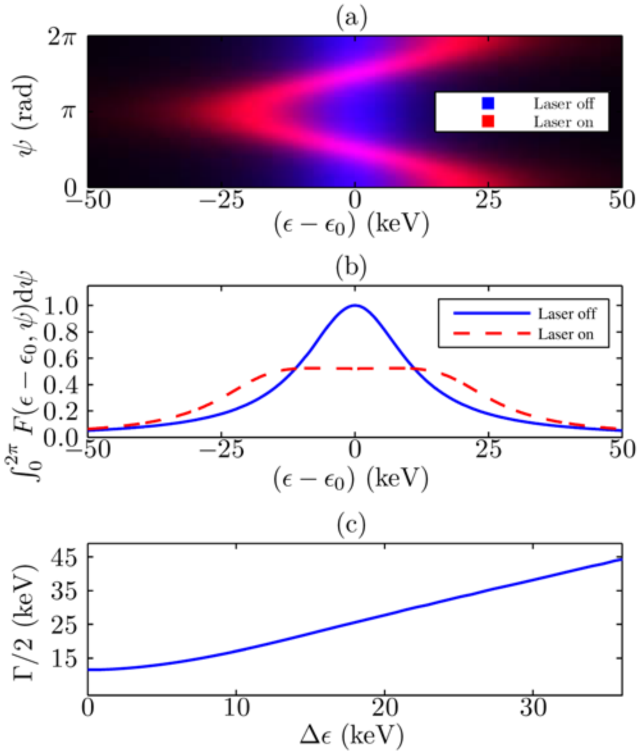
Model



Δε (keV)	HWHM (keV)	Gradient
21.5	29.3	1 GeV m^{-1} (meas phase)
27.0	35.5	1 GeV m^{-1} (flat phase)

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