Progress in Multi-MeV Energy Gain in a Relativistic Dielectric Laser Accelerator

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GORDON AND BETTY MOORE FOUNDATION

ACHIP

UCLA

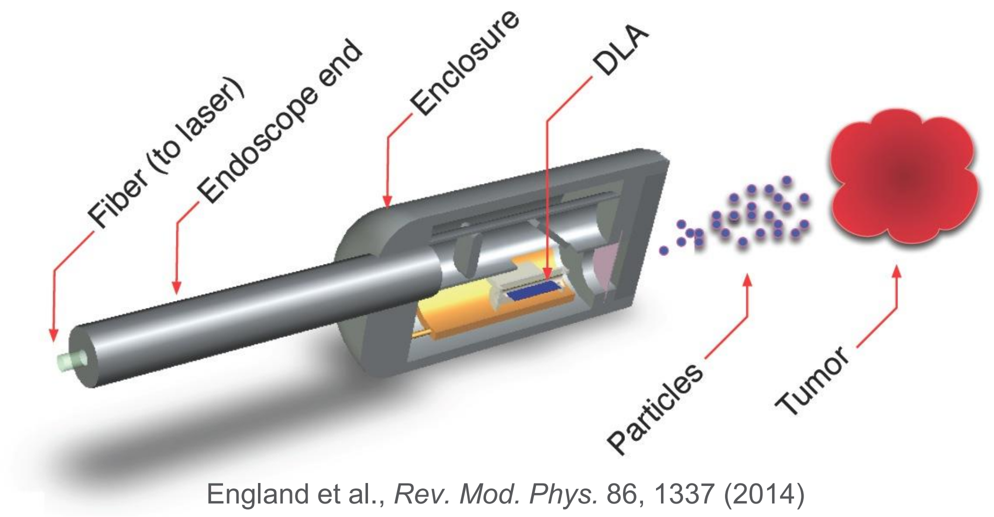
The Need for Smaller Accelerators

Many applications for a compact, ultrafast source:

- Catheterized high energy electron source
- UED/UEM Source
- Compact incoherent x-ray source

Why DLA?

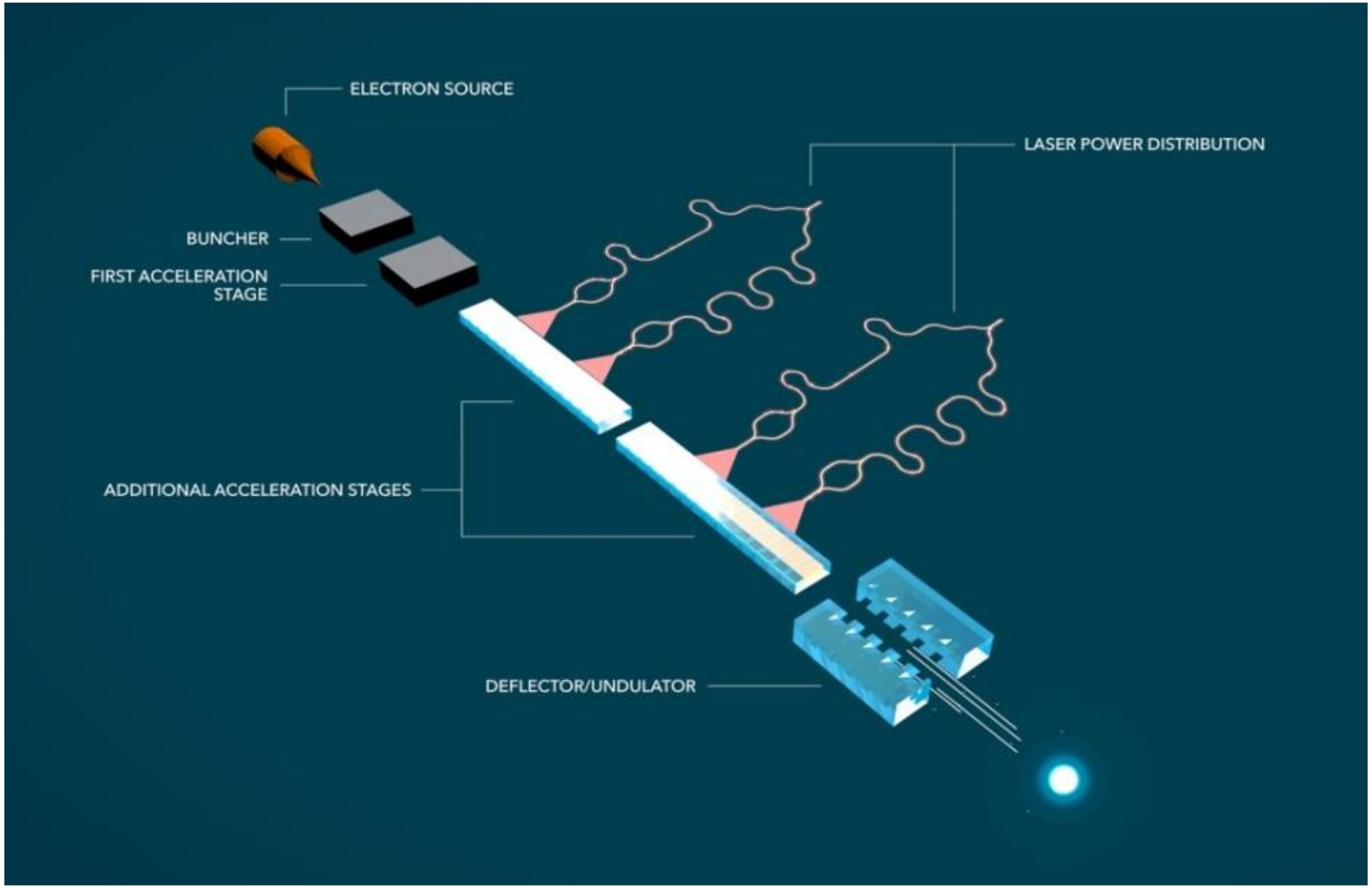
- Silicon manufacture is ubiquitous
  - High damage threshold leads to GeV/m gradients
- Laser technology readily available



England et al., *Rev. Mod. Phys.* 86, 1337 (2014)

England et al., “Dielectric Laser Accelerators”, *Snowmass AF6 Meeting* (2020)

Overview of a Dielectric Laser Accelerator

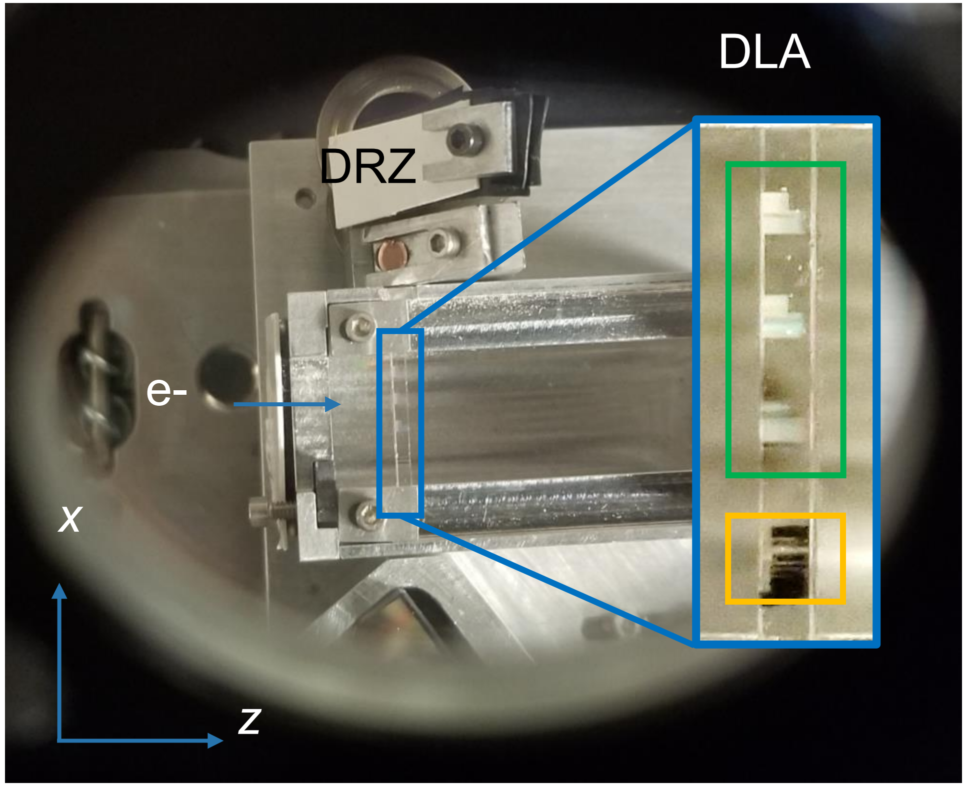


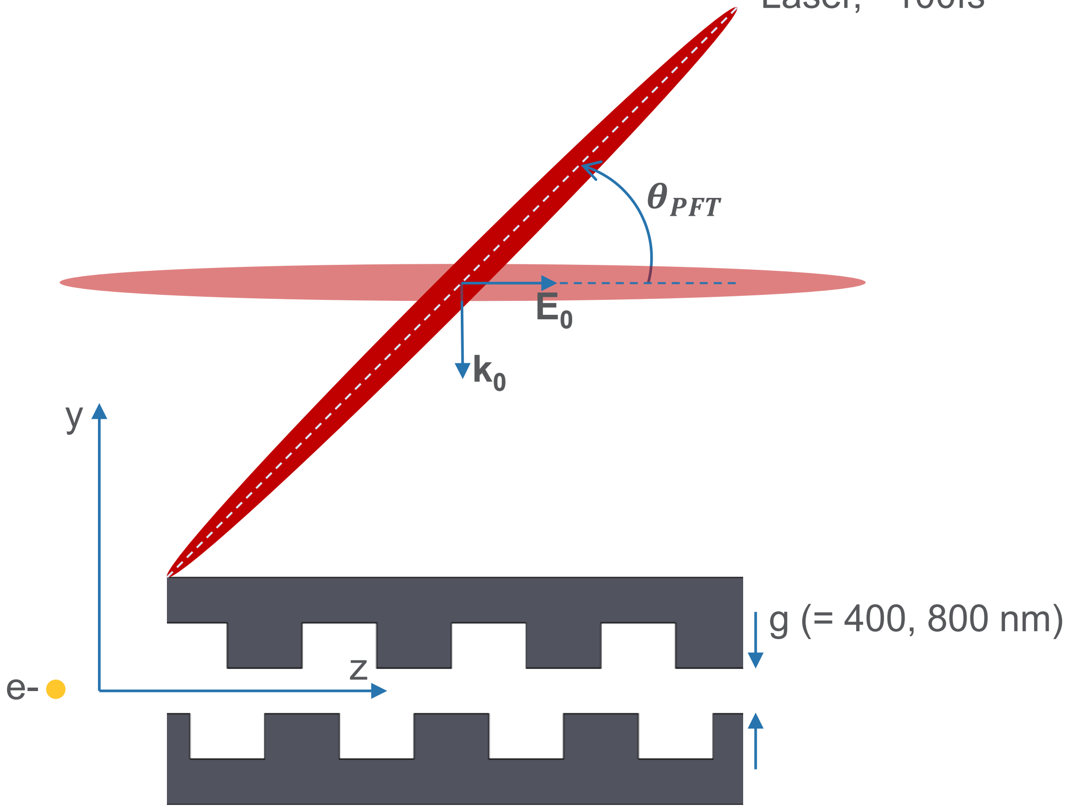
- Hirano et al., "A compact electron source for the dielectric laser accelerator", Appl. Phys. Lett. (2020)
- Schonenberger et al., "Generation and Characterization of Attosecond Microbunched Electron Pulse Trains via Dielectric Laser Acceleration", Phys. Rev. Lett. 123, 264803 (2019)
- Black et al., "Net Acceleration and Direct Measurement of Attosecond Electron Pulses in a Silicon Dielectric Laser Accelerator", Phys. Rev. Lett. (2019)
- Niedermayer et al., "Three Dimensional Alternating-Phase Focusing for Dielectric-Laser Electron Accelerators", Phys. Rev. Lett., 125, 164801 (2020)
- Sapra et al., "On-chip integrated laser-driven particle accelerator", Science, 367, 6473 (2020)

From SLAC newsroom: "$13.5M Moore Grant to Develop Working 'Accelerator on a Chip' Prototype" (November 19, 2015)

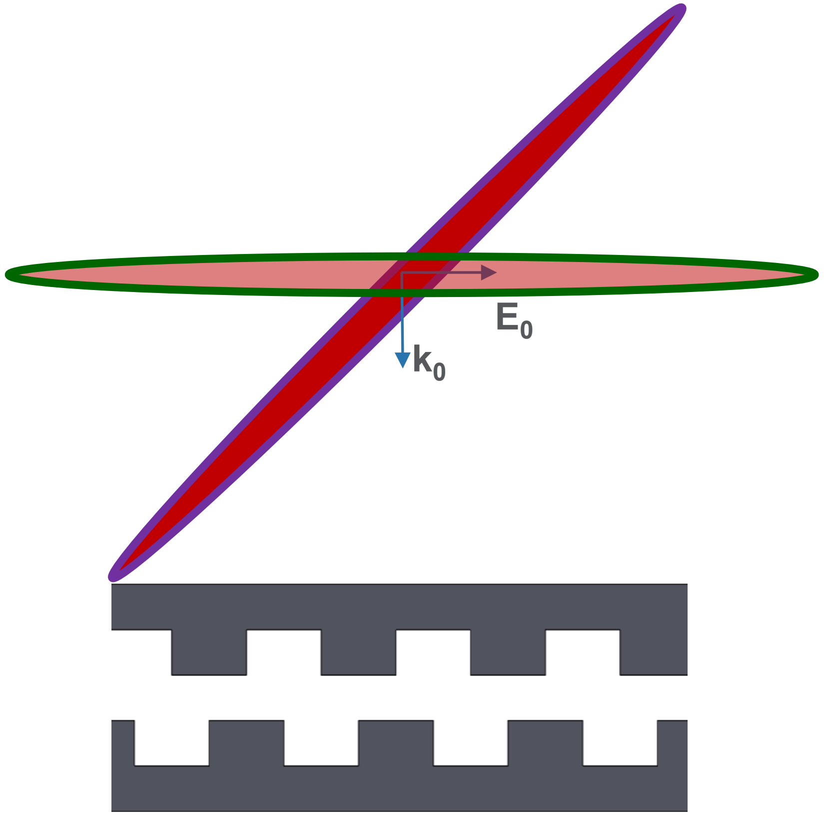
Single Side Illuminated Long Interaction DLA Geometry

Overhead

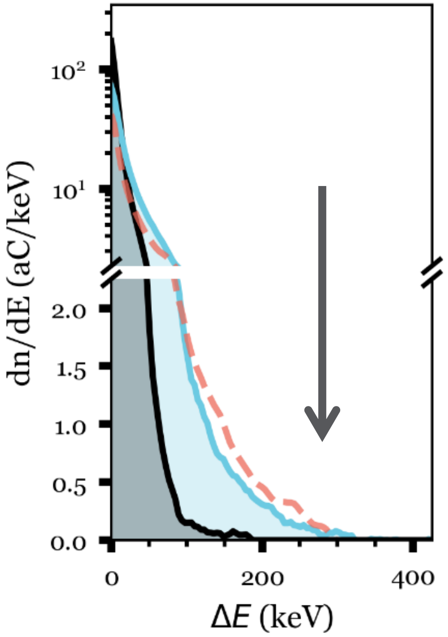




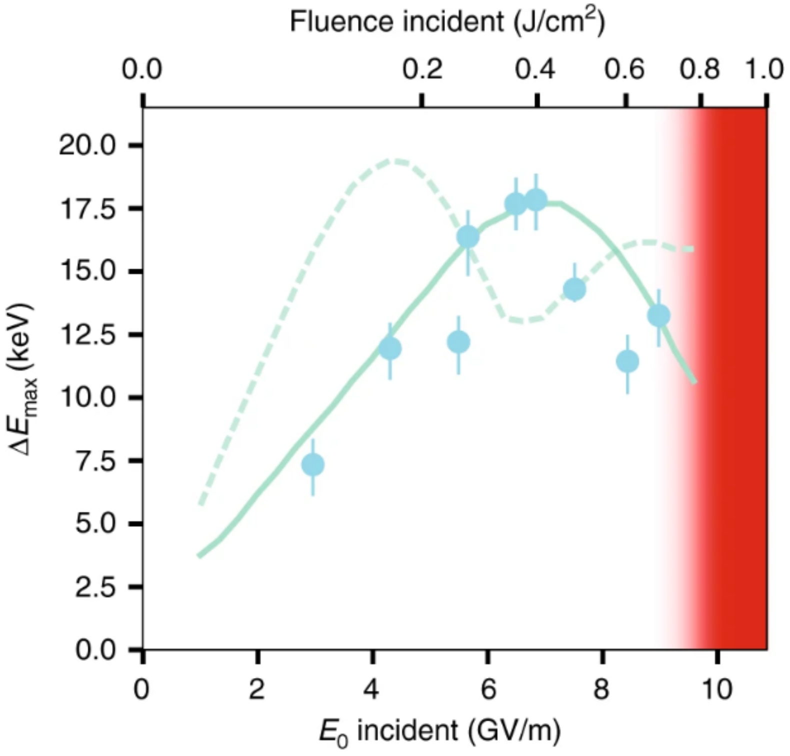
Previously, Record Energy Gain, Gradient Reached at UCLA



315 keV energy gain
700 um Interaction Length



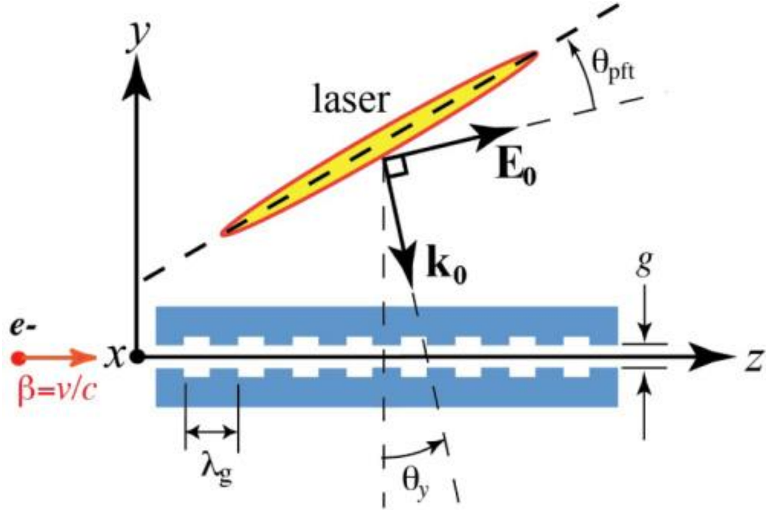
1.8 GeV/m Peak Gradient

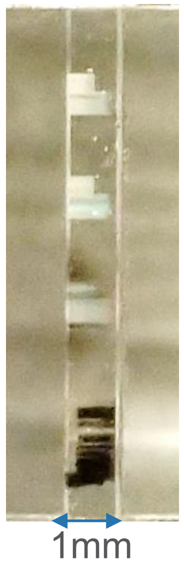


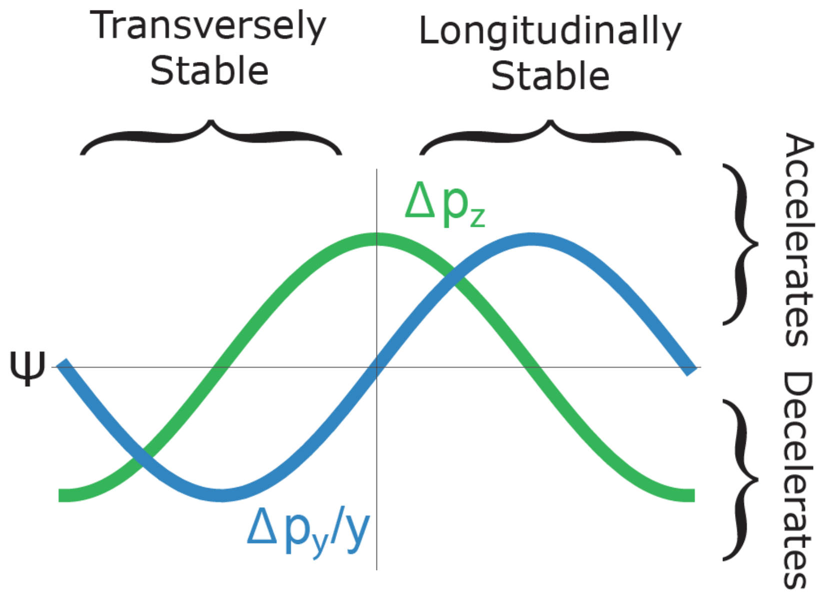
D. Cesar et al. Opt. Exp., 2018
D. Cesar et al. Communications Physics, 2018

Limiting Factors for MeV Energy Gain

- Laser-electron interaction time
- Total structure length
- Dynamic effects – over longer lengths, e- will defocus

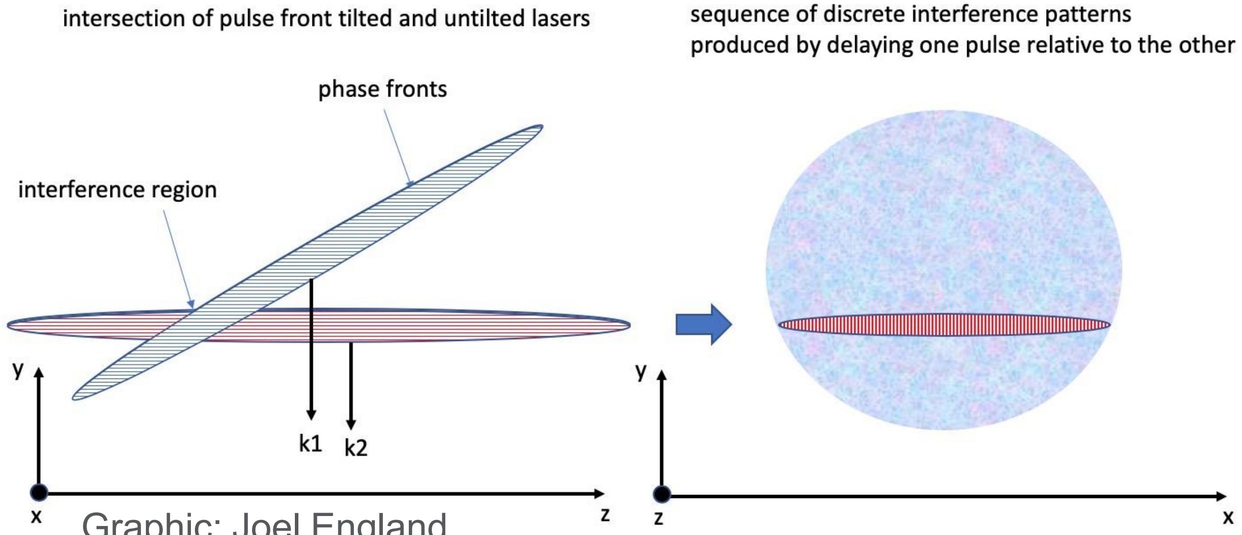




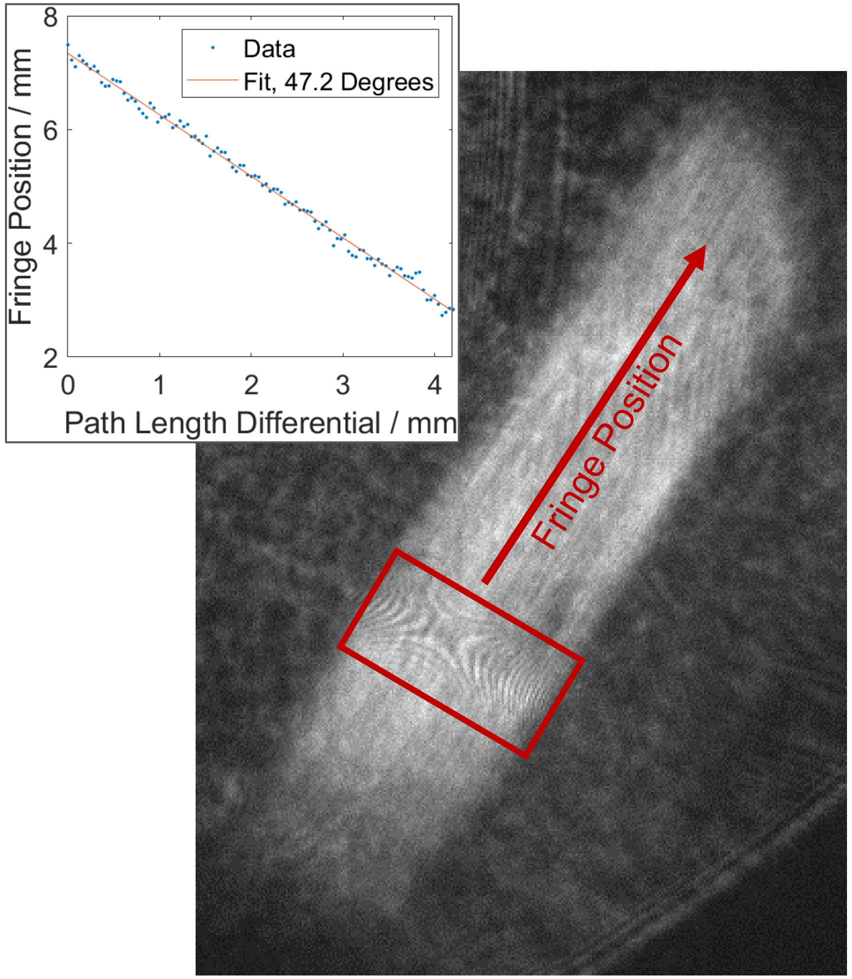


Pulse Front Tilt Measurement Over 4.2mm

- Pulse front tilt (PFT) created by grating imaged onto DLA plane
    - Angle determined by system magnification -> lens positions controlled by desired overall magnification and damage concerns



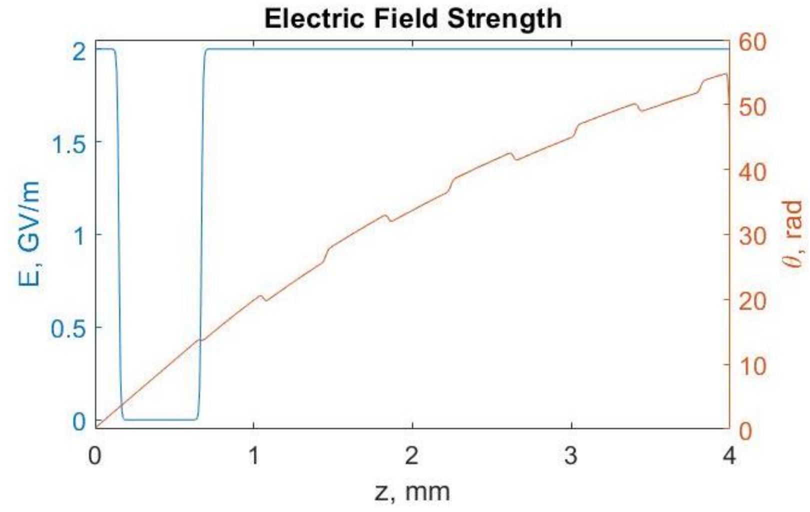
Graphic: Joel England

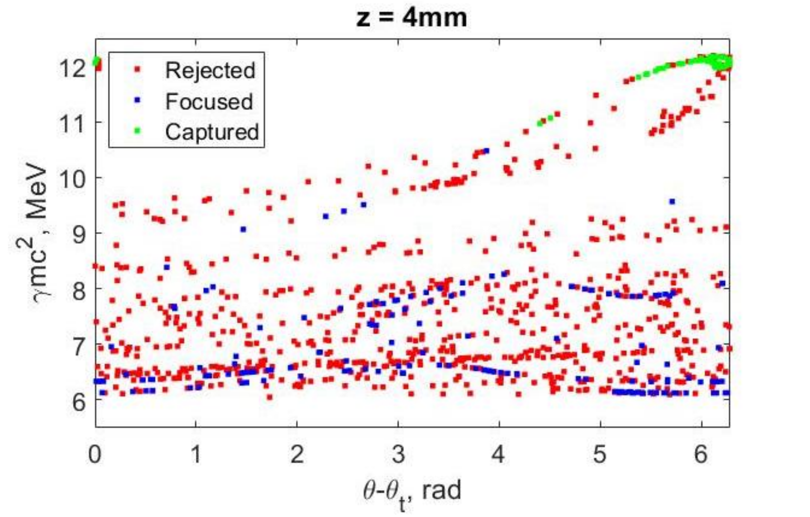


Alternate phase focusing allows acceleration over mm-scale interactions

- Spatial Harmonic based simulation code to test possible phase and amplitude modulation
  - Based on Ody, A et al., *NIMA*, *1013, 165635 (2021)* and Niedermayer et al., Phys. Rev. Lett., 121, 214801 (2018)

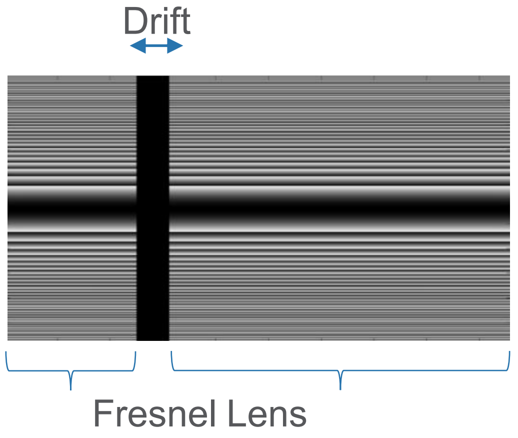
Parameter	Value
Initial Energy	6.5 MeV
Emittance	0.5 nm
Laser Wavelength	780 nm
Peak Field	2 GV/m
Buncher Length	0.15 mm
Resonant Phase	$-\pi/4$
Energy Gain	4.8 MeV
Percent Capture	<7%

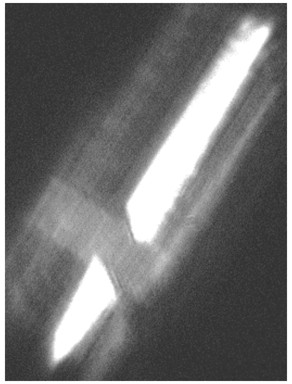


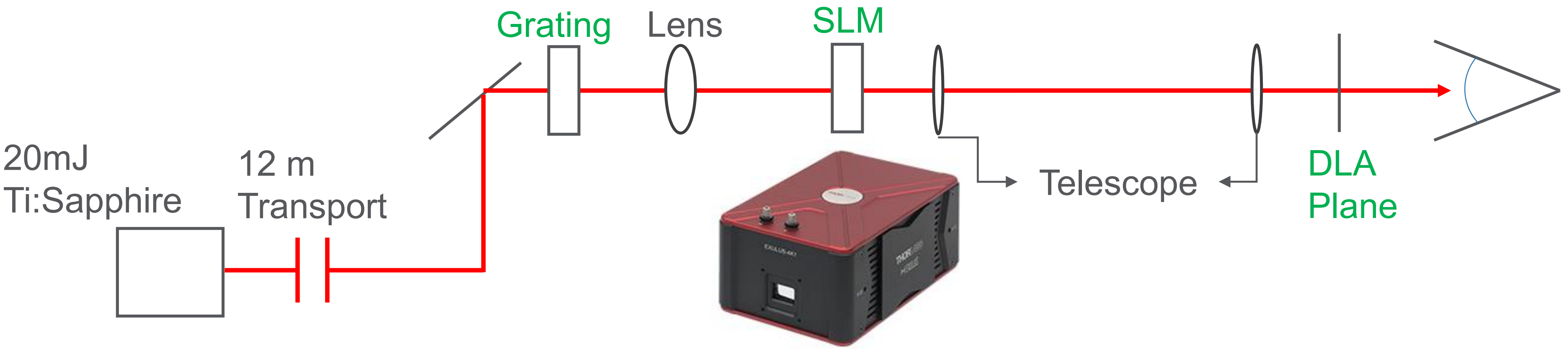


Soft Tuning of Phase and Amplitude

- Grating profile is imaged onto spatial light modulation (SLM), and then sample plane, for requisite pulse front tilt
- Liquid crystal mask is imaged in the electron travel direction, so any profile can be transported to the electrons
    - By not imaging in the transverse dimension, we can introduce amplitude modulation







Ingredients for a Multi-MeV DLA Experiment

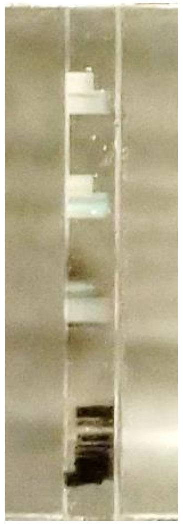
Alternating phase focusing (APF) scheme to compensate for defocusing effects

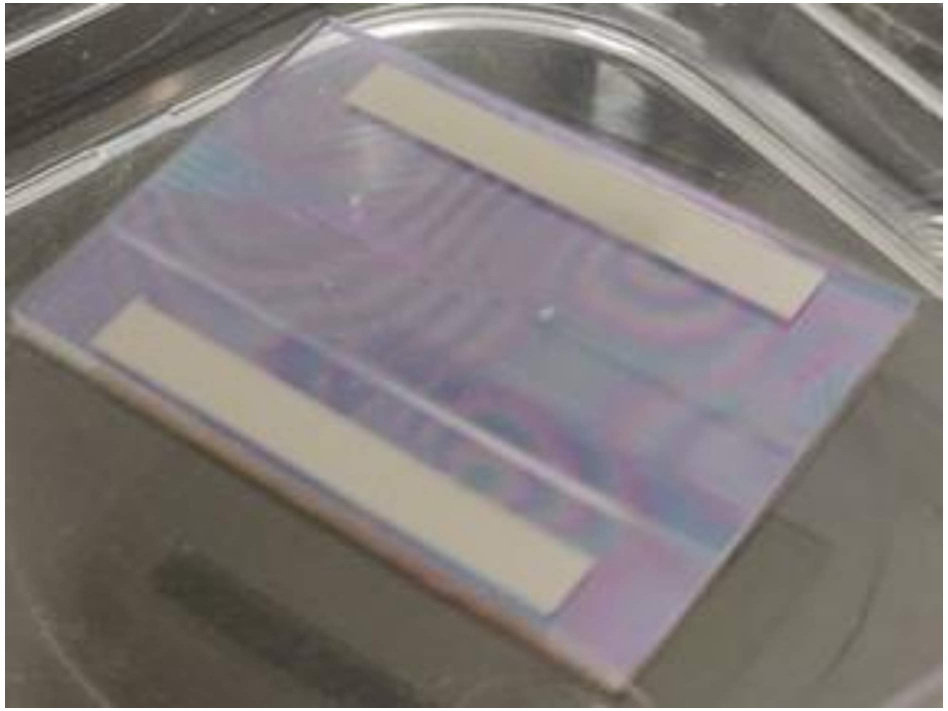
Pulse front tilt demonstrated over 4.2mm

Spatial light modulator to allow soft tuning of phase and amplitude profile

Extending Structure Length Proved Non-Trivial

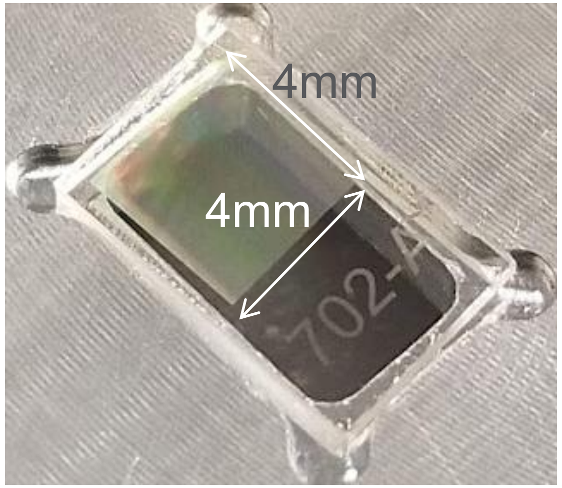
- Thin film interference shows bonding was non-uniform, introducing many microns of separation





4mm Grating Structures Have Been Assembled

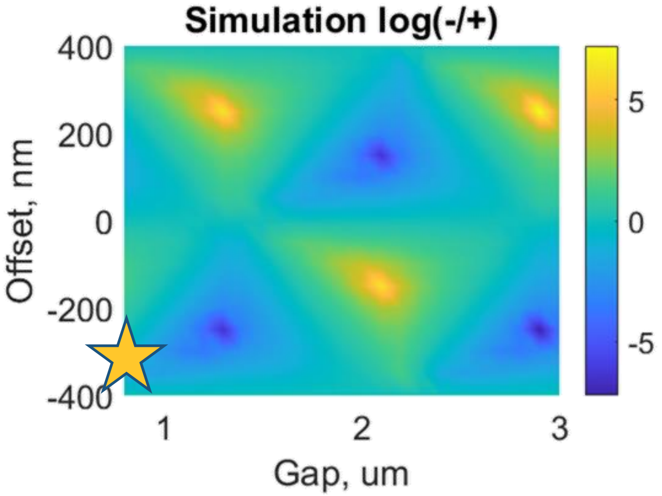
- Commercial gratings are mounted entirely independently
- Lower grating is mounted on a 3-piezo stage with 12um total travel, to nm precision alignment
- Grating periodicity: 800nm

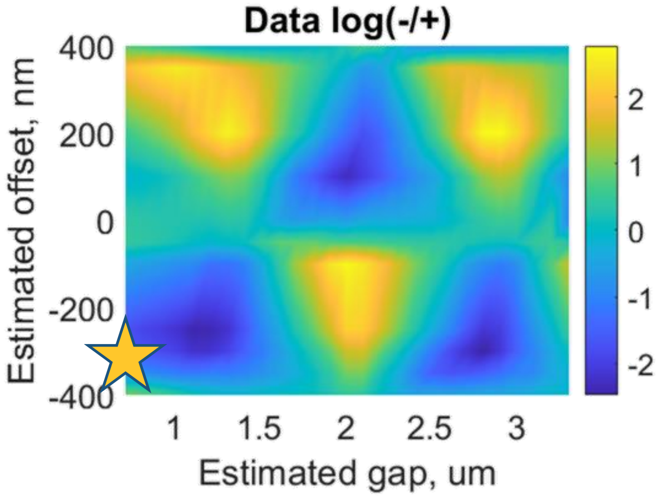


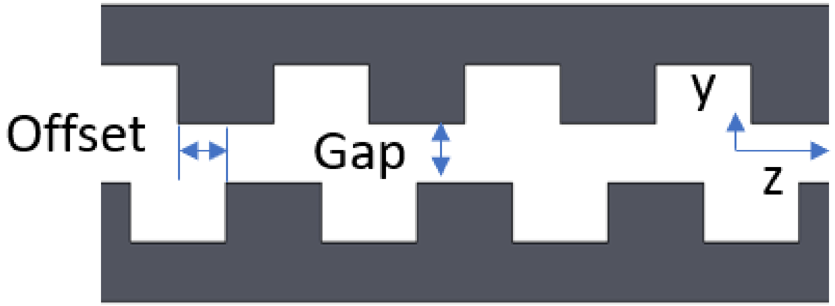
Course x',y',z'
Course xy,z
Fine x,y,z, x',y',z' (12um range)
Relative Rotation

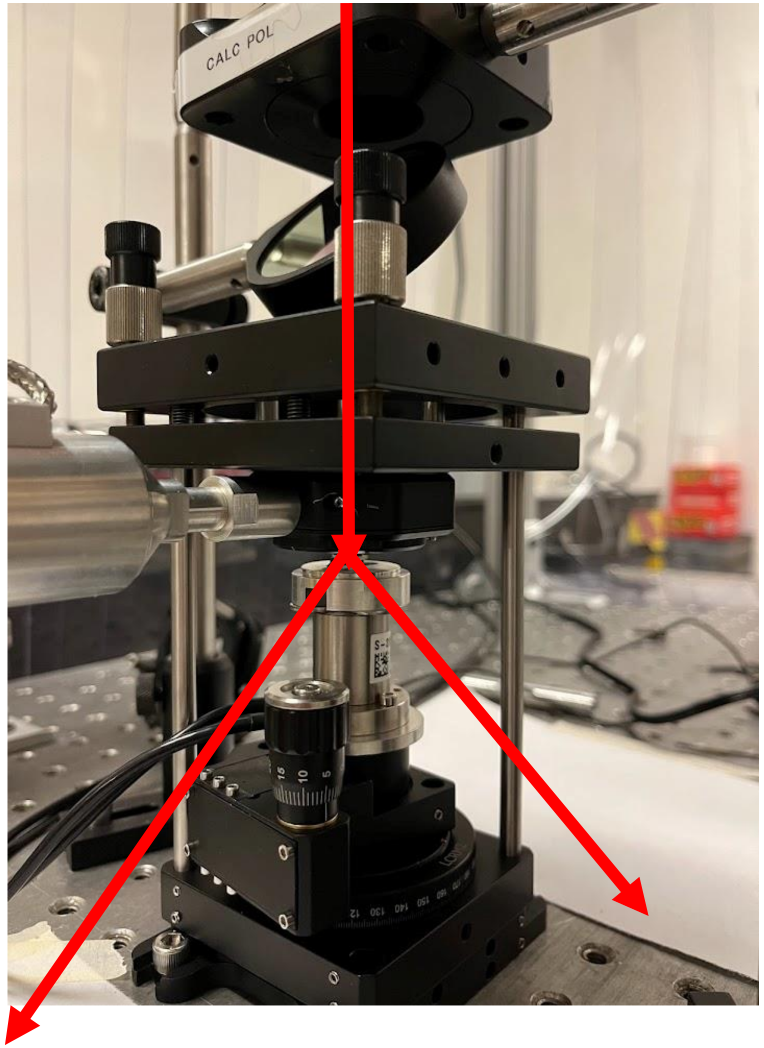
Structures are Characterized Optically

- Diffraction based diagnostic using the ratio of m = $\pm$ 1 diffraction orders



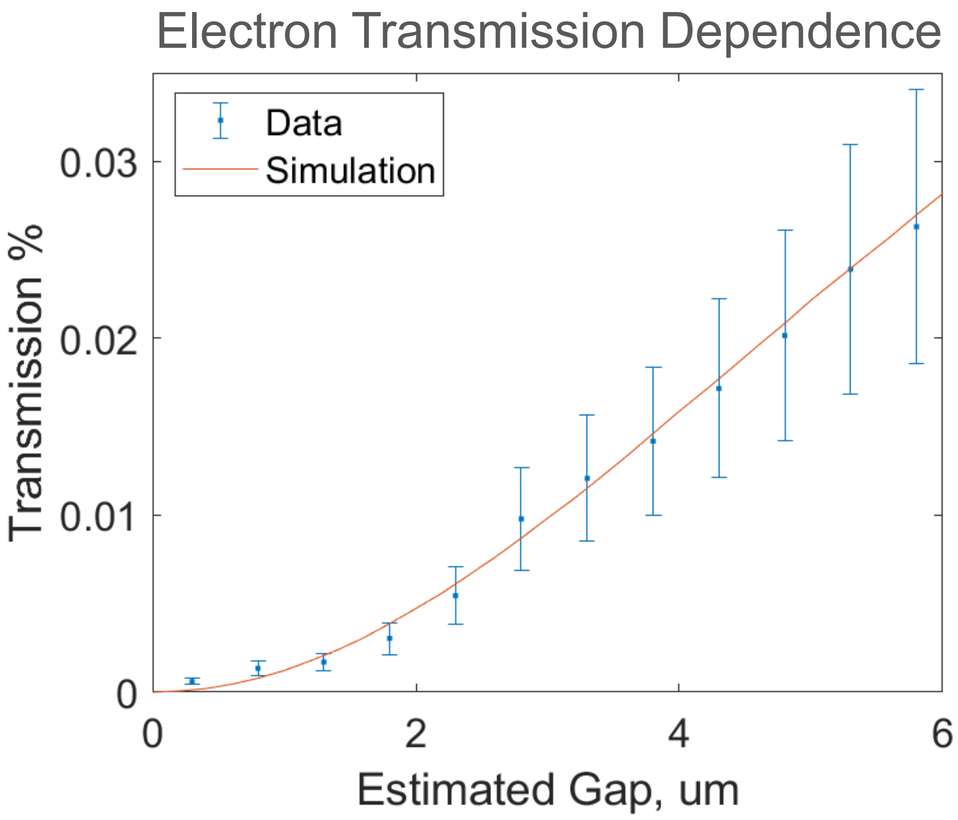




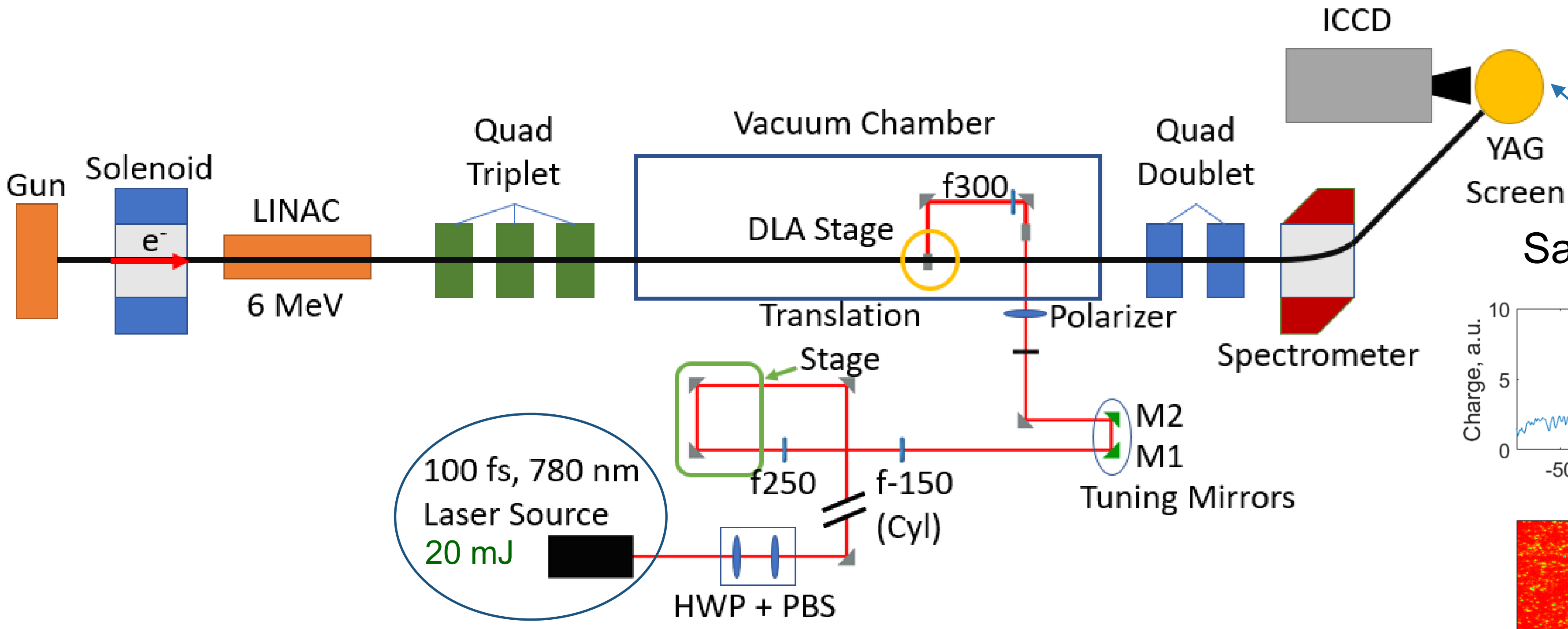


Structures are Characterized Optically and via Electron Transmission

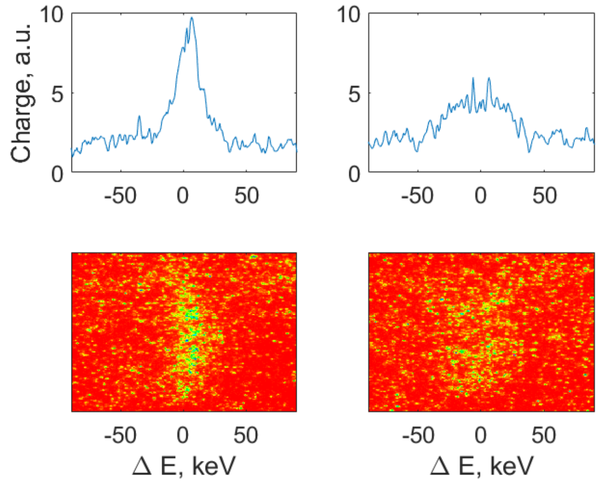
Structures are in the beamline!



Experiments Take Place at the Pegasus Beamline



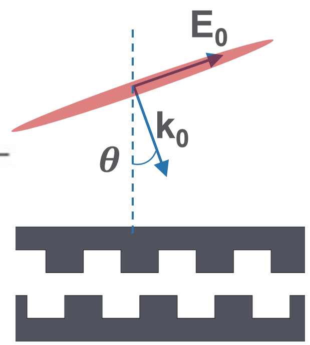
Sample electron spectra:

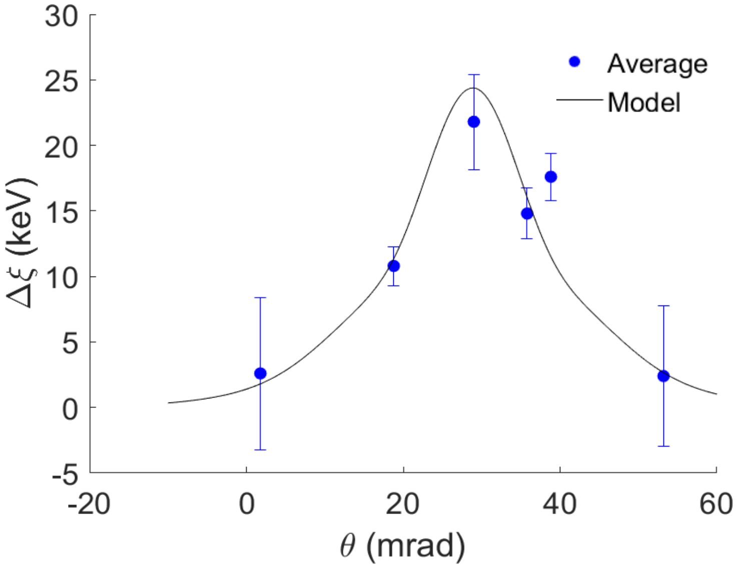


Modulation Recovered using Peralta Dual Grating Structures

- Mismatched: 780nm laser wavelength, 800nm grating wavelength

Parameter	Value
Beam Energy	6 MeV
Beam Energy Spread (FWHM)	23.5 keV
Beam Charge	1-2 pc
Beam RMS size at DLA	50 μm
Beam Length	.25 ps
Laser pulse length (FWHM)	100 fs
Laser spot size at DLA (FWHM)	1.5mm x 345 μm
Laser Energy	1 mJ
DLA length	500 μm
DLA vacuum gap	800 nm





Resonant phase matching by oblique illumination of a dielectric laser accelerator

S. Crisp, A. Ody, P. Musumeci, and R. J. England
Phys. Rev. Accel. Beams **24**, 121305 – Published 21 December 2021

- Phase matching condition

$$k_g - \frac{\omega_l}{c\beta} + \frac{\omega_l}{c}\sin\theta = 0$$

satisfied here by $\theta = 29$mrad

- 600MeV/m gradient established, with a structure factor of 0.18

Conclusion

- Commissioned a new optical system combining pulse front tilt with Spatial Light Modulator
- Built and characterized new commercially based structures
  - Installed in the beamline and ready to be laser-driven
- Looking toward MeV energy gains
  - Soft tuning utilizing Alternating Phase Focusing

Lots of exciting work on the way!

Acknowledgements

Thank you to:

- Pietro Musumeci (UCLA)
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- Joel England (SLAC)
- Kenneth Leedle (Stanford)
- Eric Cropp (UCLA)
- David Cesar (SLAC)

Structure Parameters

Parameter	Value
Grating Periodicity	800nm
Tooth Height	855 nm
Tooth Width	536 nm
Gap Size	800nm->6um

Component	Dimension	Control	Range	Resolution
a: Kinematic Mount	x’, z’	3 100 TPI Screws	x’, z’: ±50 mrad	
b: 2-D Translation Mount	x, z	x: 100 TPI Screw z: Stepper motor	x: 2 mm z: 2 mm	z: 0.25 μm
c: Piezo Mount	y, x’, z’	3 Piezo Motors	y: 12 μm x’, z’: ±1.2 mrad	y: 0.4 nm x’, z’: 0.1 μrad
d: Translation Mount	y	Micrometer	2 mm	1 μm
e: Rotation Mount	y’	Micrometer	±120 mrad	1 mrad

Structures are Simulated to Find Ideal Configuration

- Single side illumination on a symmetric structure lead to asymmetric fields
  - → Introduce an offset between the gratings
- Structure factor: ratio between incident field and induced gradient