Demonstration of increased interaction length in a high gradient dielectric laser acceleraton

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Outline

- Dual-grating DLA structures
- High-gradient ‘short-pulse’ interactions
  - Kerr saturation
  - Compensation of nonlinear saturation via simple ‘pulse-shaping’
- Pulse front tilt interactions
  - Longer interaction (up to 700um) and Larger ΔE (300keV)
  - Longitudinal dynamics (tuning γ_{res} of a stationary bucket)
- Conclusions & Outlook

'Accelerator on a chip'

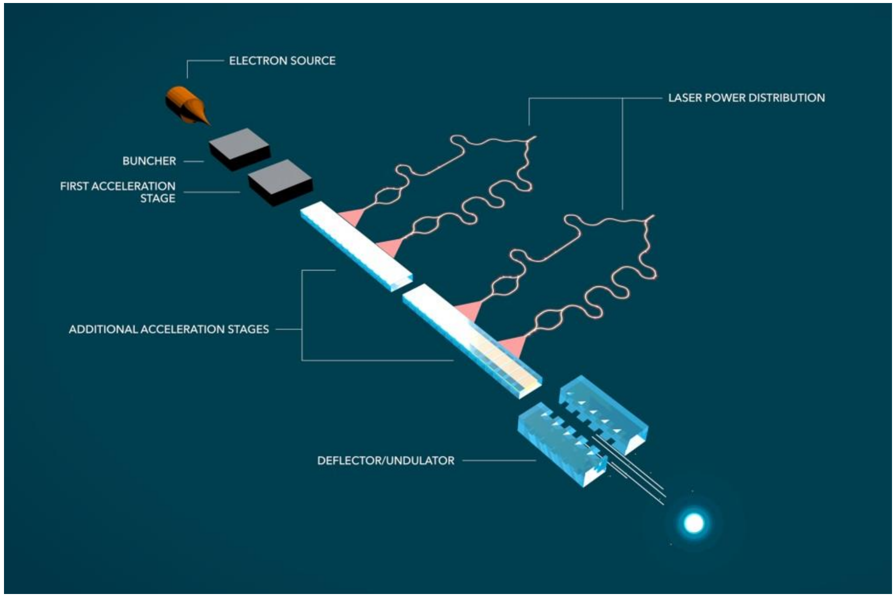
Electron source → injector stage → **acceleration stage(s)** + laser → application

Novel physics at each stage

Acceleration stage goals

- High gradients
- Large energy gain
- Electron-DLA coupling

Mockup of potential DLA components



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

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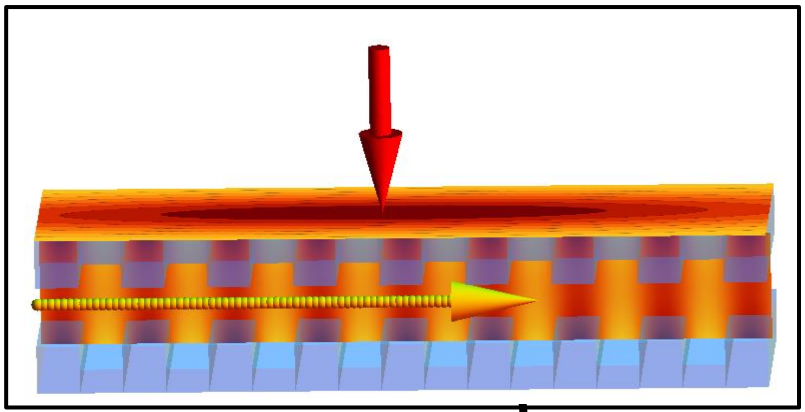
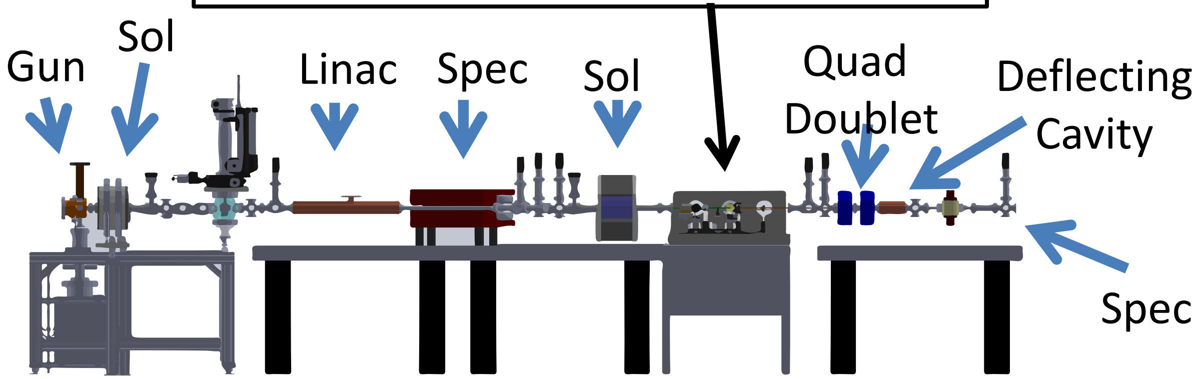
UCLA/SLAC high gradient tests

High gradient tests using the grating structure with a relativistic ($\beta = 0.997$) electron(s).

Dual grating structure. Fabricated and first test by E.Peralta, Nature 2013





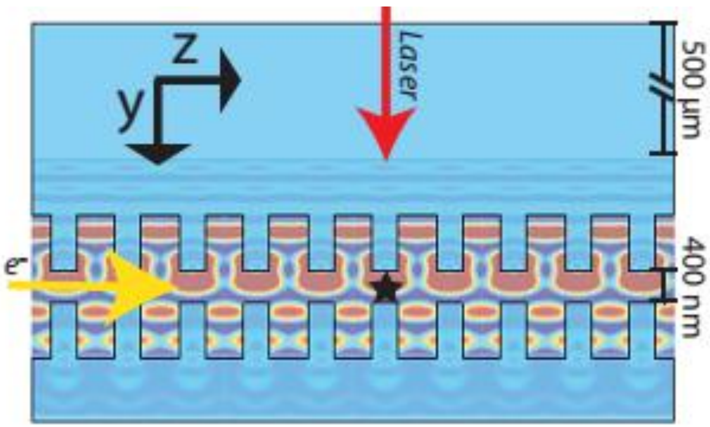
Laser parameters

λ	800 nm
Energy	<300µJ
Fluence	<0.75 J/cm^2
Size (w)	~35µm x 660µm
τ (I fwhm)	45fs

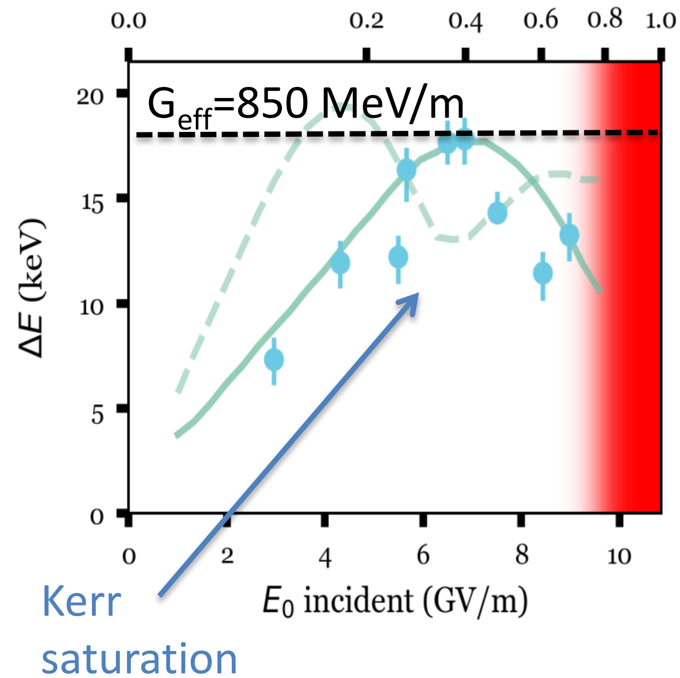
Beam parameters

Energy	6.5 MeV
Charge	300fC→3fC
E spread	< 2 KeV
ϵ_n	40 nm→0.4nm
Bunch length	0.5ps

Measurement of Nonlinear DLA Response



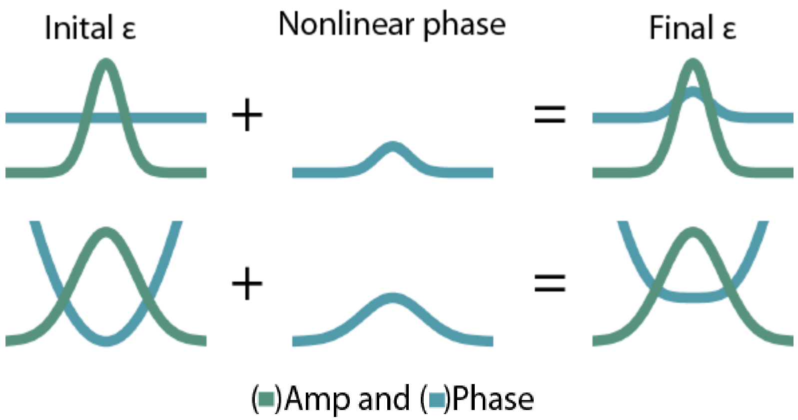
Energy gain vs. incident laser field

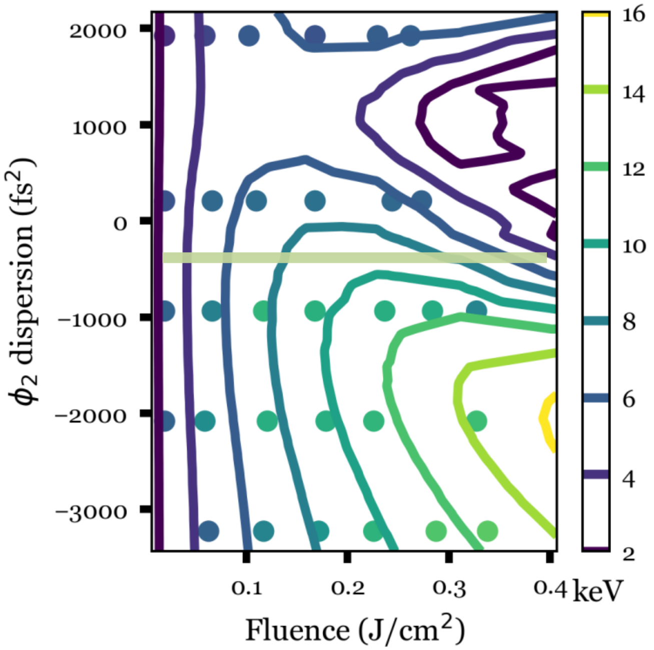


- Peak 'gradient' 850 MeV/m ($E_{z,max}$ 1.8 GV/m)
- First use of ebeam to probe nonlinear dielectric structure response in the near field at optical wavelengths
- Fully reversible saturation explained by simulation (solid green curve) of non- linear Kerr effect
  - Dashed green curve shows theoretical prediction for perfectly aligned beam.

arXiv: "Nonlinear response in high-field dielectric laser accelerators" http://arxiv.org/abs/1707.02364

Compensation of the nonlinearity





Compensation features:

At low intensity introducing dispersion has no effect on energy gain

At high intensity introducing dispersion rapidly increases energy gain

*The green line correspond to the lineouts shown on the previous slide

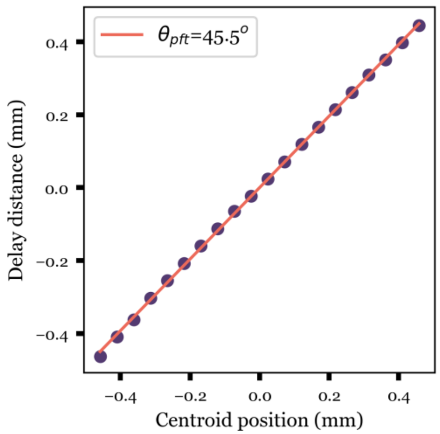
**Data taken with 800nm gap (lower gradient, but stronger signal to noise ratio)

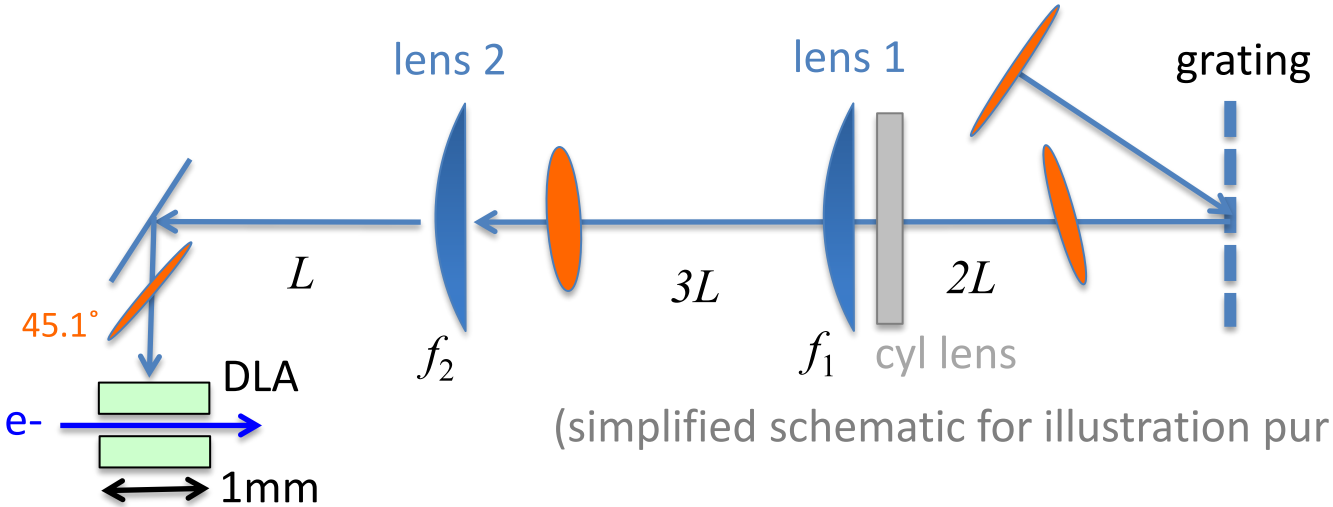
Pulse front tilt: extended high gradient interactions

High gradient interactions benefit from a short pulse

- Pack in power before damage threshold
- Extended interactions via pulse front tilt ("group velocity")

Extended interactions require increasingly careful phase control



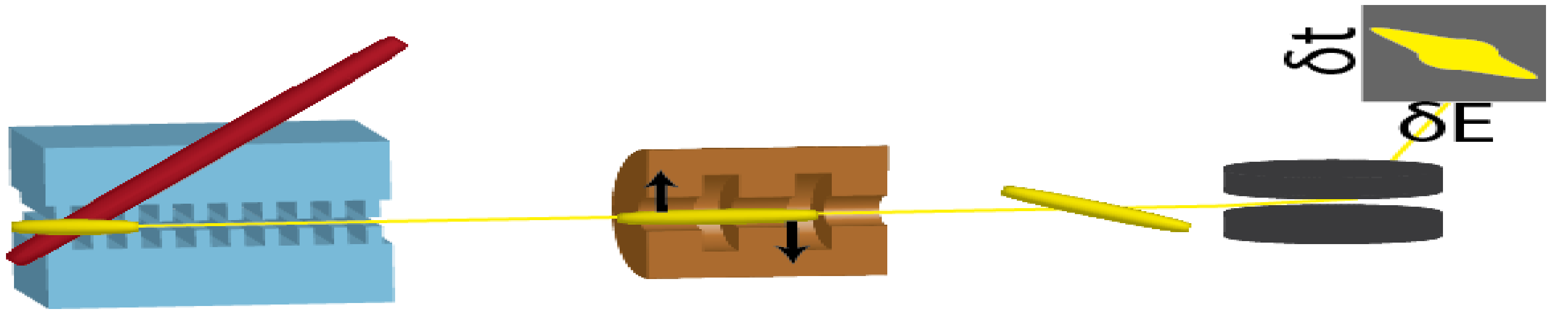


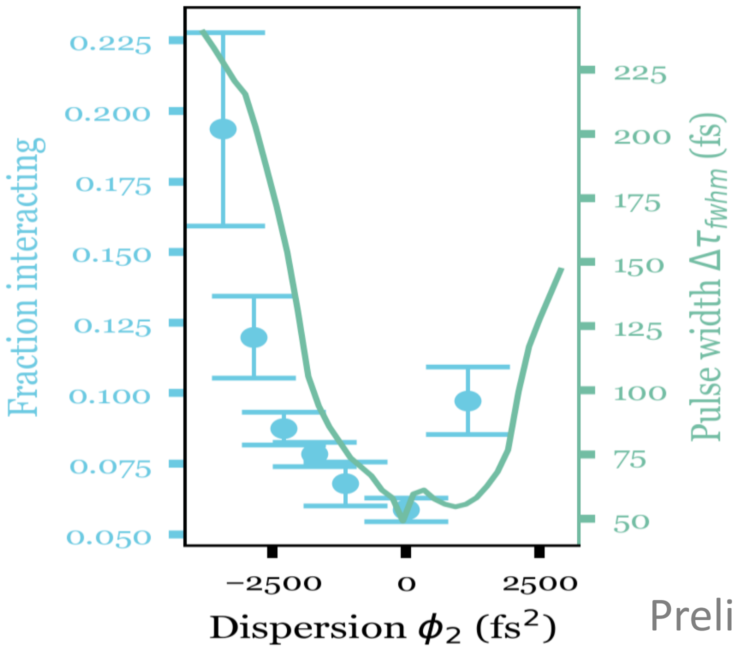
$f_1 = 2L; f_2 = L$

- pt-pt imaging
- angular magnification = 2.25

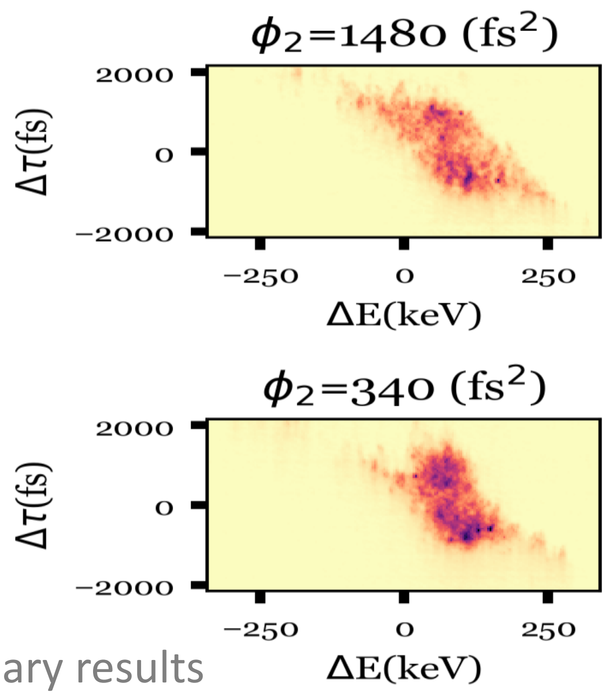
(simplified schematic for illustration purposes)

PFT: Observations in longitudinal phase space



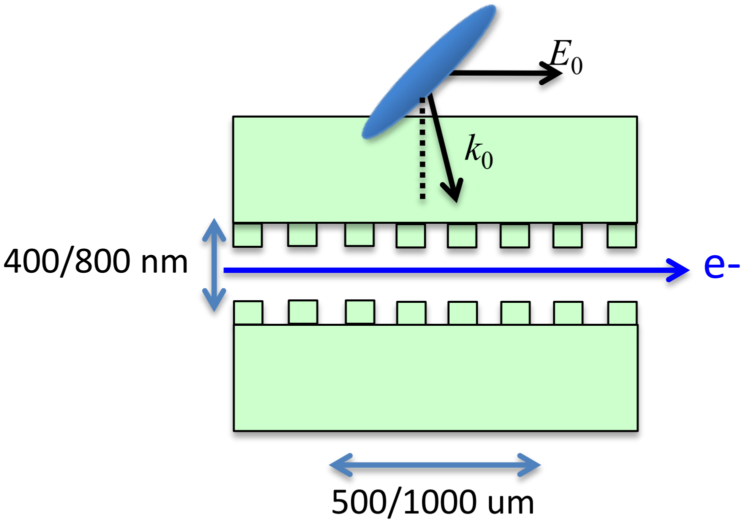


Preliminary results



- Demonstrates that a single (temporal) slice of the transmitted electrons have interacted over a long distance

PFT: Extending the interaction length

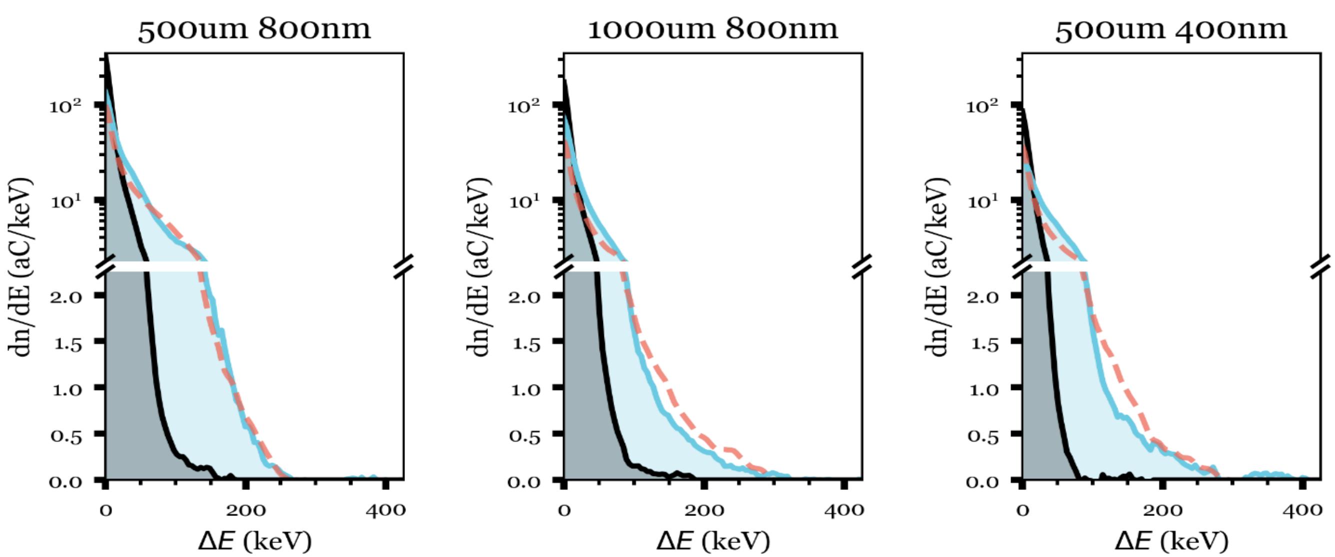


A smaller number of electrons interact for a much longer distance:

- Max energy gain ≈300keV
- 'Interaction length' ≈1000 periods
- Max observed average gradient: ≈500MeV/m over 500 µm (with E0 ≈ 7GV/m + nonlinear saturation)

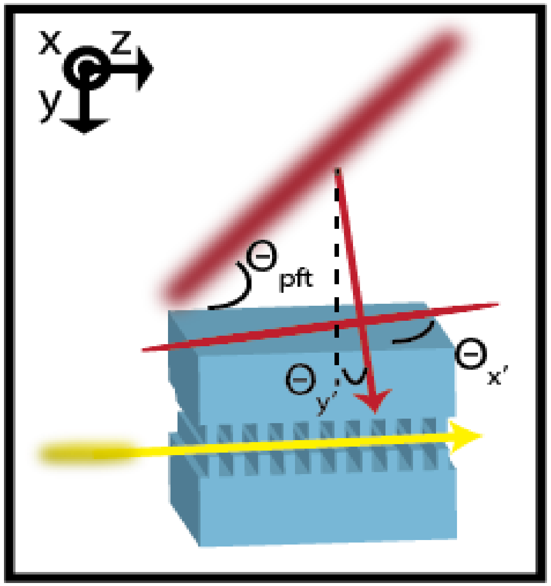
Electron spectra
(DLA length, DLA gap)

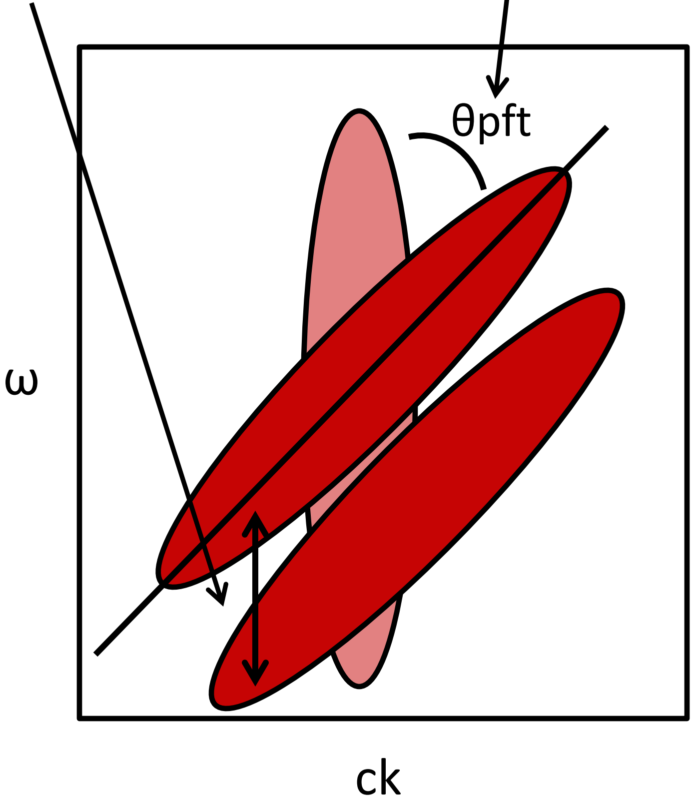
Preliminary results



Tilting the structure

$$\phi_{\text{res}} = \underbrace{k_g\, z + k_0 \sin\left(\theta_{y'}\right) z}_{\text{Offset (match to } \omega 0)} - \omega(k)\, t$$

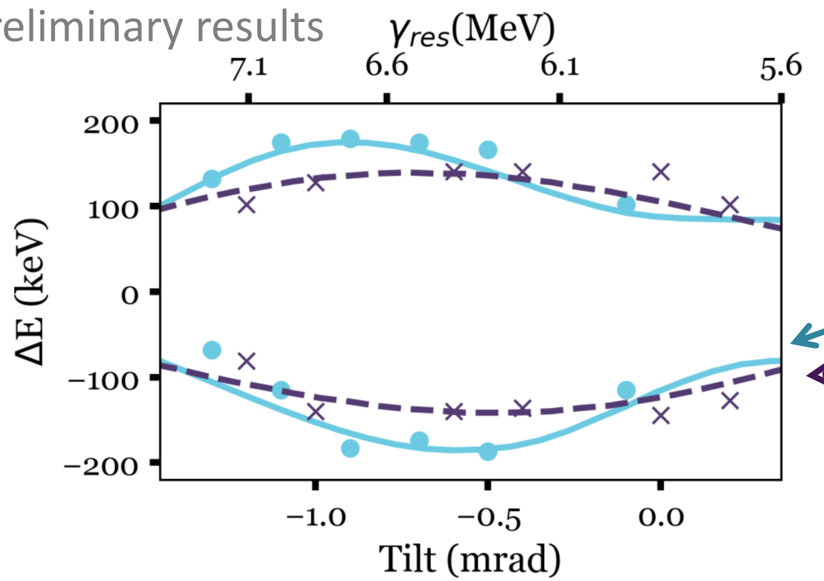


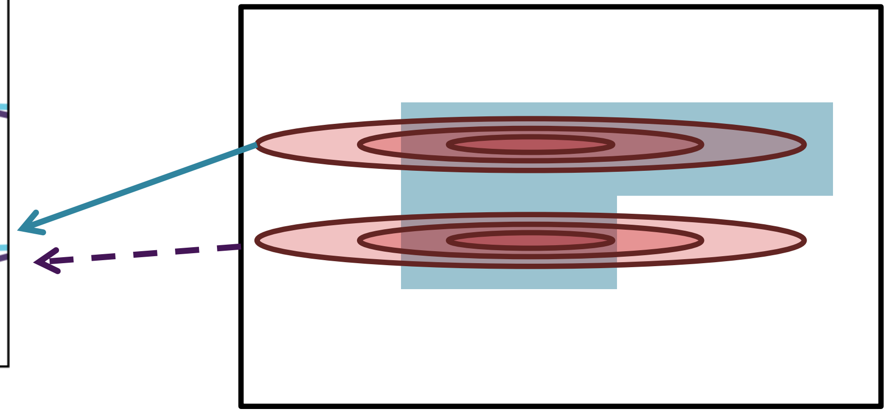


- Θy is equivalent to altering the grating period

Tuning the resonant energy

Preliminary results





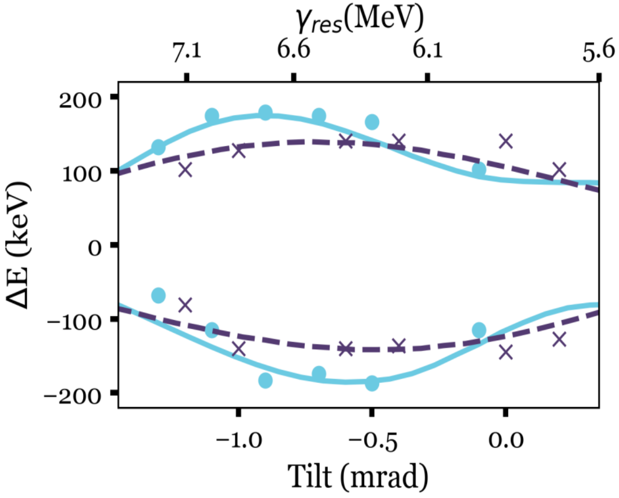
Dephasing (if ΔE≈0): L ≈λ/θ

$$\Delta E = \alpha\, E_0\, sin(\delta k\, l)/\delta k.$$

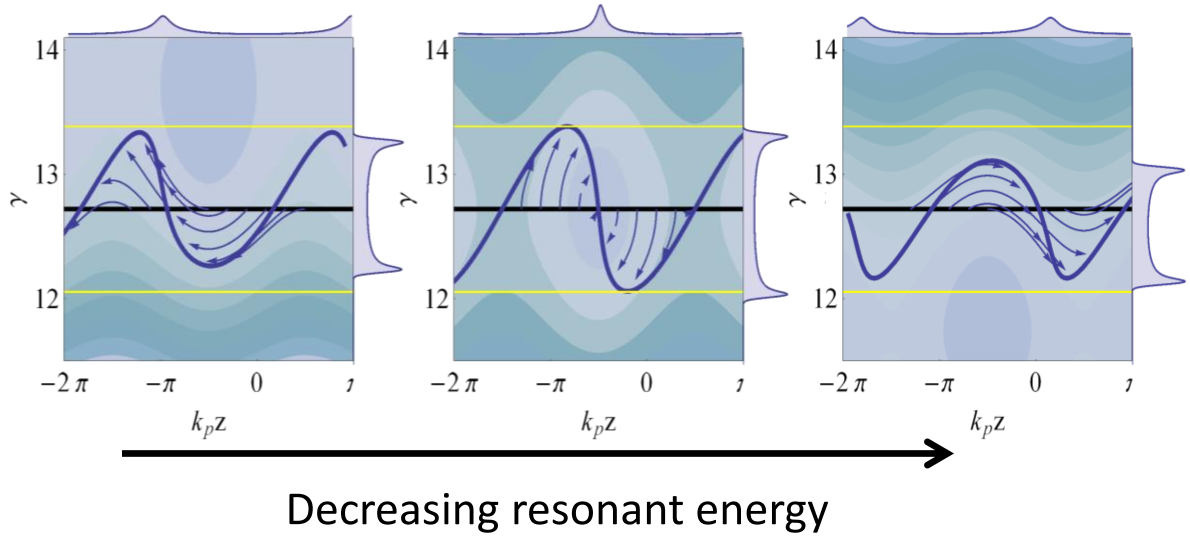
- Laser w=600μm, centered over 500μm channel
- 1mm channel is more sensitive to both linear phase offset and Kerr phase

1D Longitudinal dynamics

Preliminary results



$$H(\gamma,\psi) = \gamma(1-\beta\beta_s) - \alpha\, Sin(\psi)$$



•Extended interactions cause bunching and thereafter asymmetric energy gain/loss

•Optimal detuning for energy transfer:

$$\Delta\gamma_{res} \approx \pm \frac{0.41\,\gamma_{res}^2}{N} \sim 0.4MeV$$

Ponderomotive Focusing in DLAs

Use different spatial harmonics to provide oscillating force.

In [PRL **109** 164803 (2012)], Naranjo and Rosenzweig proposed a method of simultaneous focusing and accelerating in a specially designed photonic bandgap DLA by intentionally exciting two (or more) different harmonics.

Resonant defocusing

Focusing

$$Y'' = Y\left\{\frac{\alpha_0\, k_0^2}{\gamma_0^3\, \beta_0^2}\cos\phi - \frac{\alpha_0^2}{2\,\gamma_0^2\,\beta_0^4}\left[(B+D)+(C+E)\cos(2\,\phi)\right]\right\}$$

Focusing/Defocusing

Resonant defocusing force is substantial: (~ 10^7 m^{-2})

However, by enhancement of the focusing terms, a net focusing force can be achieved.

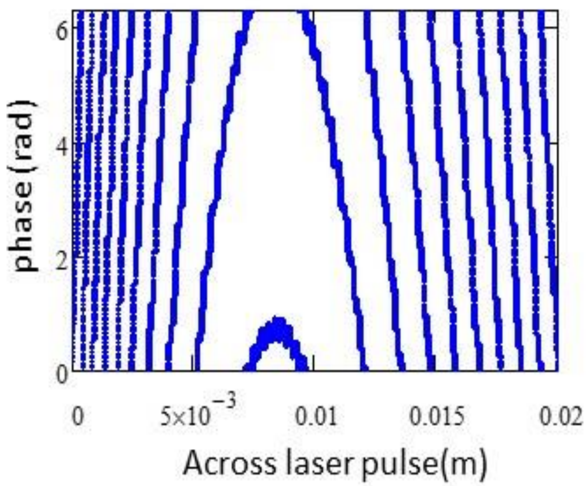
DLA Phase Velocity Taper and Phase Modulation

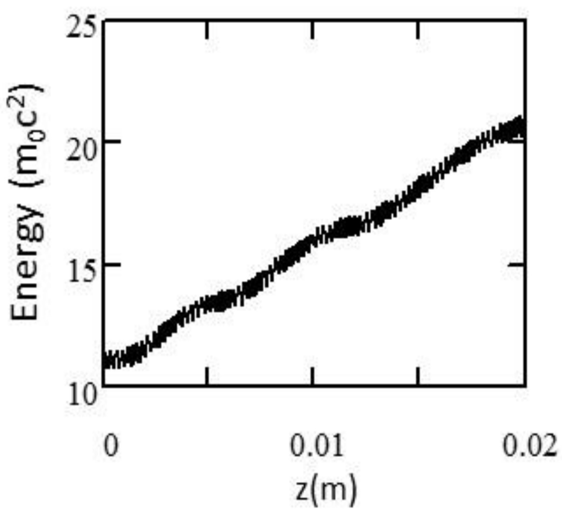
- In pulse front tilt geometry a liquid crystal mask can be used to program arbitrary phase profiles along the beam.

- As an example, we can obtain both a gradient in wave phase velocity (tapering) and the modulation required for ponderomotive focusing using the following phase profile over 2cm interaction distance.

$$\psi_r = 45\,\text{deg}$$
$$E_0 = 2\,\text{GV/m}$$
$$U_0 = \gamma_0 m c^2 = 5\,\text{MeV}$$

Average gradient: 250 MeV/m
Energy gain: 5 MeV





Acknowledgements

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  - UCLA: J.Maxson, Evan Threlkeld, Sean Custodio
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  - Stanford: Si Tan
  - And the entire ACHIP team (https://achip.stanford.edu/)

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  - DOE grant No. DE-AC02-76SP00515

Conclusions

towards free-space demonstration of a stable DLA accelerator

- Resonant mode amplitudes of nearly 2GV/m in fused silica
- Pulse front tilt can group velocity match the laser and electron beam
  - Energy gain of ~300keV with average gradients of up 500MeV/m
- Pulse shaping techniques can be used to maintain particle-wave synchronicity

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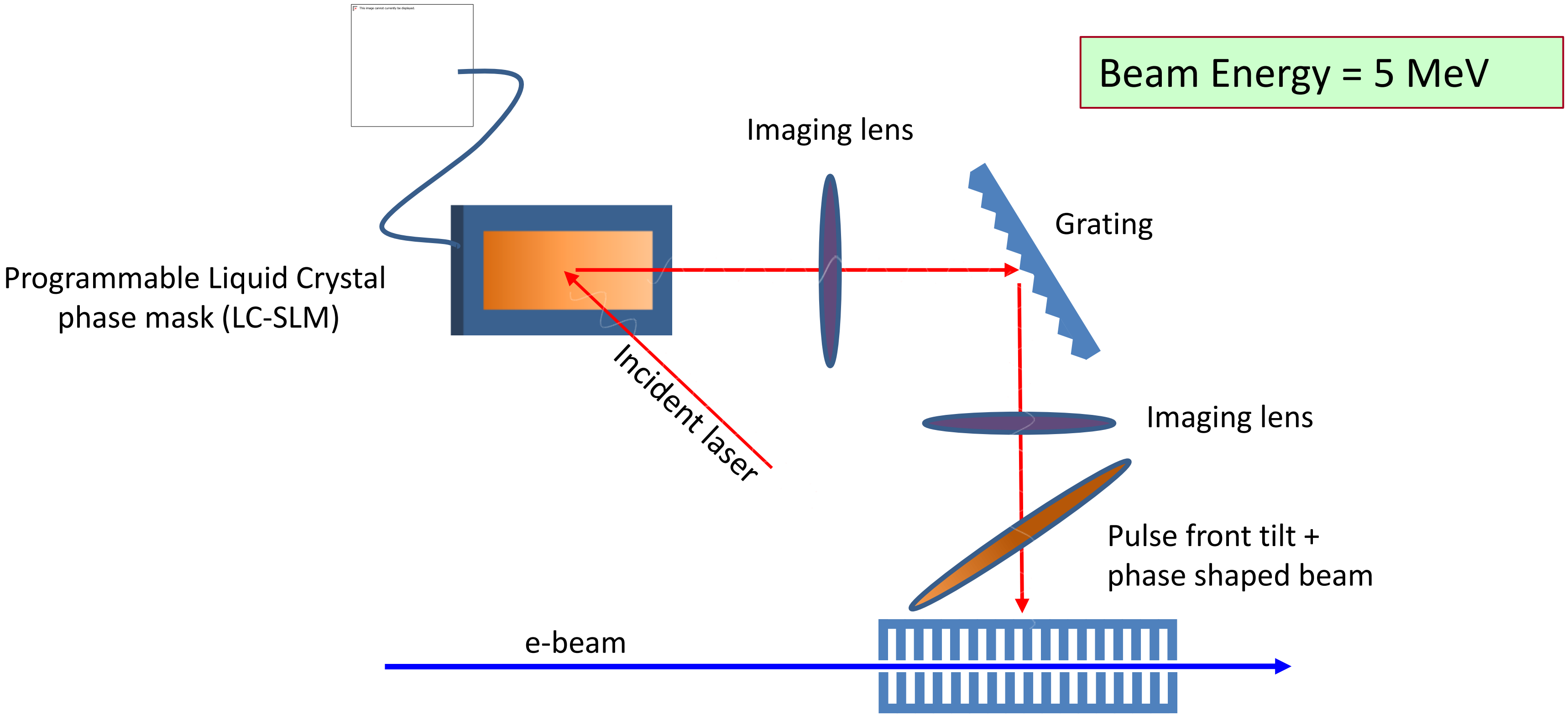
Future Experiments: Chirp + Ponderomotive Focusing

***Focus question**: what are the challenges for maintaining long distance (mm to cm) transport, phase matching, and focusing in a DLA at relativistic energies? What experiment(s) could be devised within the next year to demonstrate these concepts?*



- Microbunching and net acceleration in a DLA.
- Extended interaction over 2 cm with ponderomotive focusing.
- PFT + phase mask provides dynamic control on the phase of the accelerator.

Longitudinal Phase Space Dynamics

Normalized acceleration gradient: $\alpha_0 = \frac{e\,E_0}{m\,c^2\,k_0}$

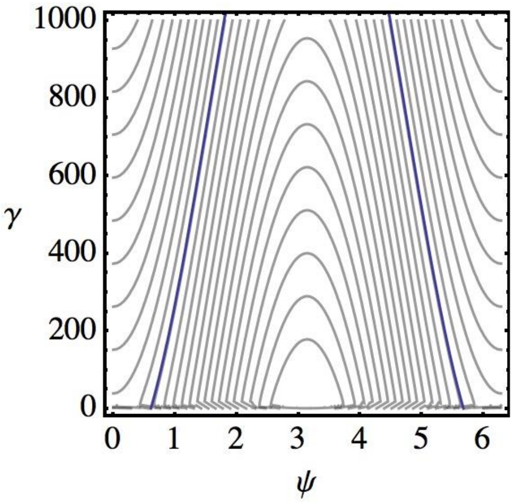
(useful for comparing acceleration schemes)

$$E_0 = 3\,\mathrm{GV/m}$$
$$\lambda = 0.8\,\mu\mathrm{m}$$
$$\alpha_0 = 7.5 \times 10^{-4}$$

Example DLA parameters

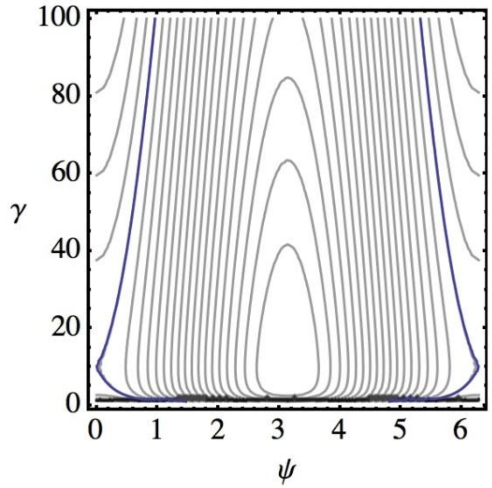
Plasma Accelerator

$\alpha_0 > 5$



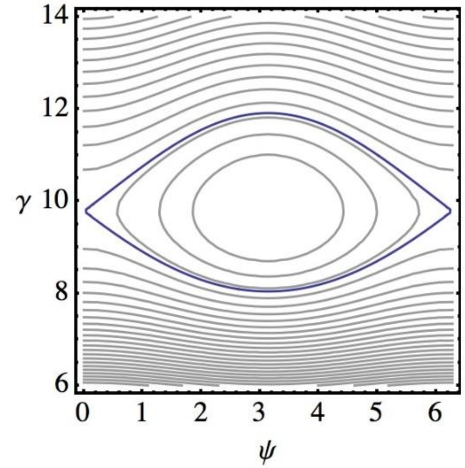
RF Photoinjector

$\alpha_0 \simeq 1$



DLA or Proton Accelerator

$\alpha_0 \approx 0.001$

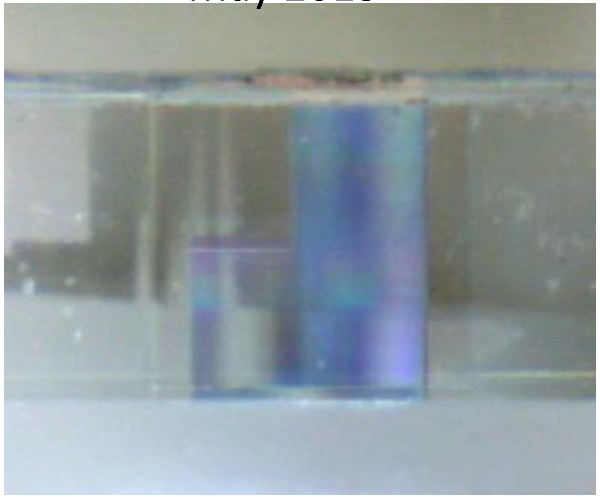


<u>Need to taper the phase velocity of the wave</u> $v_{ph} = \frac{\omega}{k}$:

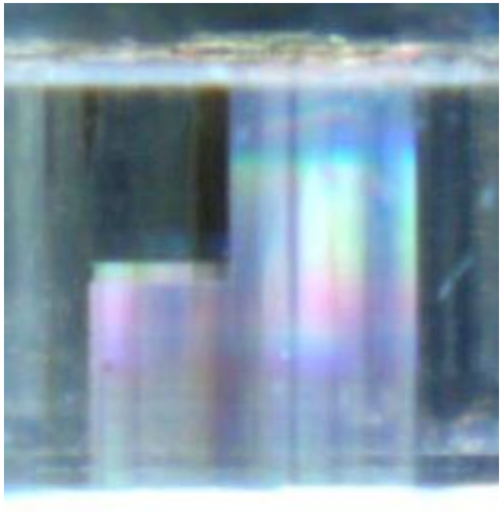
- Change ω
- Change k

DLA photos

Grating in UCLA/SLAC run
pre-acceleration
May 2015



Grating in UCLA/SLAC run
post-acceleration
June 2015



Damage tests:
Adi Hanuka 9/25/2015