Towards MeV Energy gains in Dielectric Laser Accelerators

Pietro Musumeci
UCLA Department of Physics and Astronomy

European Advanced Accelerator Conference

Elba, September 15-20, 2019

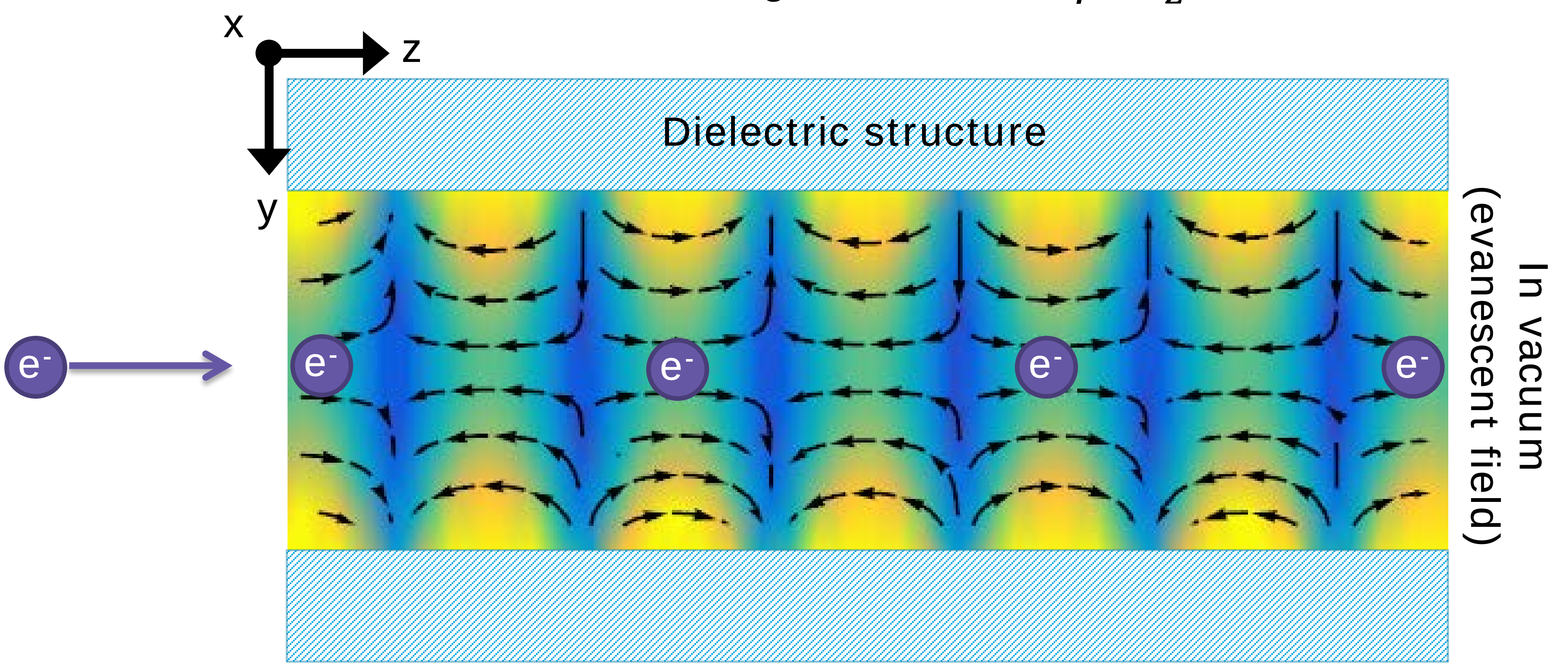
Dielectric laser acceleration

UCLA

What makes a DLA?

Obviously laser driven, but also:

Accelerating mode: $\omega = \beta c k_z$



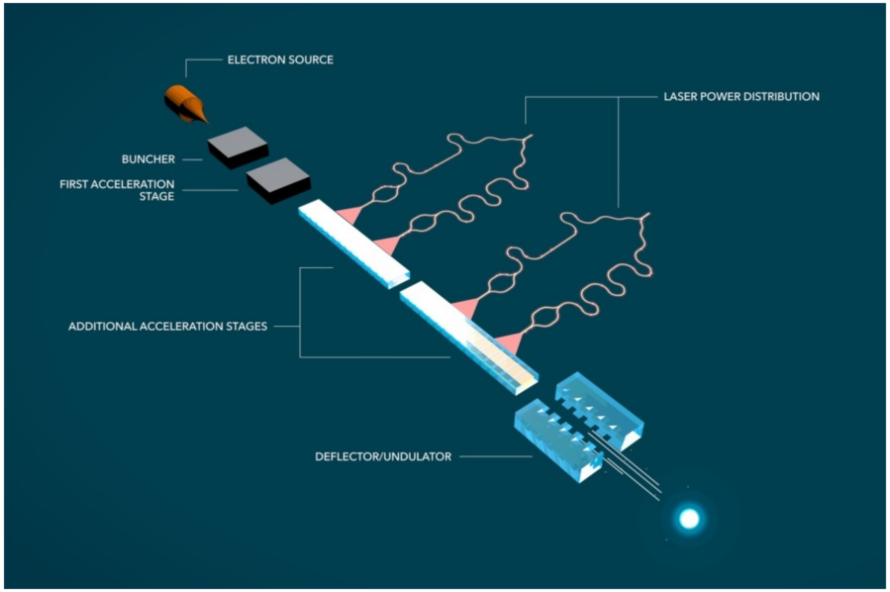
An accelerator on a chip

UCLA

ACHIP design goals:

- Compact, chip-scale accelerator
  - High gradient
  - Modular accelerator components
- Robust fiber-based laser system
  - Modest drive laser energy
  - MHz rep rate

Mockup of potential DLA components



From SLAC newsroom: “$13.5M Moore Grant to Develop Working ‘Accelerator on a Chip’ Prototype” (November 19, 2015)

SLAC NATIONAL ACCELERATOR LABORATORY · STANFORD UNIVERSITY · EPFL ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE · PAUL SCHERRER INSTITUT PSI · PURDUE UNIVERSITY · TECH-X SIMULATIONS EMPOWERING YOUR INNOVATIONS · ACHIP · GORDON AND BETTY MOORE FOUNDATION · FAU FRIEDRICH-ALEXANDER UNIVERSITÄT ERLANGEN-NÜRNBERG · TECHNISCHE UNIVERSITÄT DARMSTADT · UHH Universität Hamburg · DESY · HAMAMATSU PHOTON IS OUR BUSINESS

Relativistic structures experiments

UCLA

Summary of DLA results at UCLA Pegasus (in collaboration with SLAC)

- Observation of non linear dielectric response
- Pulse-front tilt to extend interaction region

- 0.9 GV/m gradient
- 300 keV energy gain

Check for updates

Research Article Vol. 26, No. 22 | 29 Oct 2018 | OPTICS EXPRESS 29216

Optics EXPRESS

Enhanced energy gain in a dielectric laser accelerator using a tilted pulse front laser

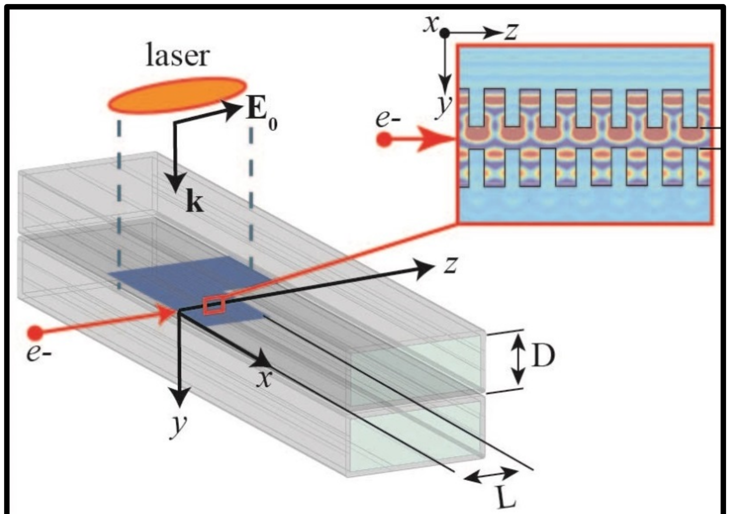
D. CESAR,[1,*] J. MAXSON,[1,4] X. SHEN,[1] K. P. WOOTTON,[2] S. TAN [3] R. J. ENGLAND,[2] AND P. MUSUMECI[1]

[1] *Department of Physics and Astronomy, UCLA, Los Angeles, California 90095, USA*
[2] *SLAC National Accelerator Laboratory, Menlo Park, California 94025, USA*
[3] *Department of Applied Physics, Stanford University, Stanford, California 94305, USA*
[4] *Currently with Department of Physics, Cornell University, Ithaca, NY 14850, USA*
[*] *dcesar@ucla.edu*

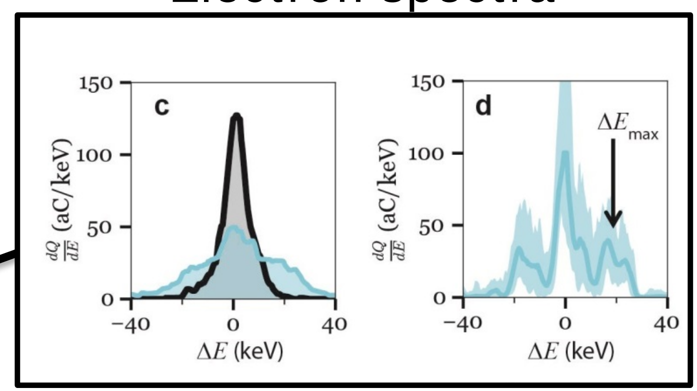
Experimental layout: Pegasus Lab

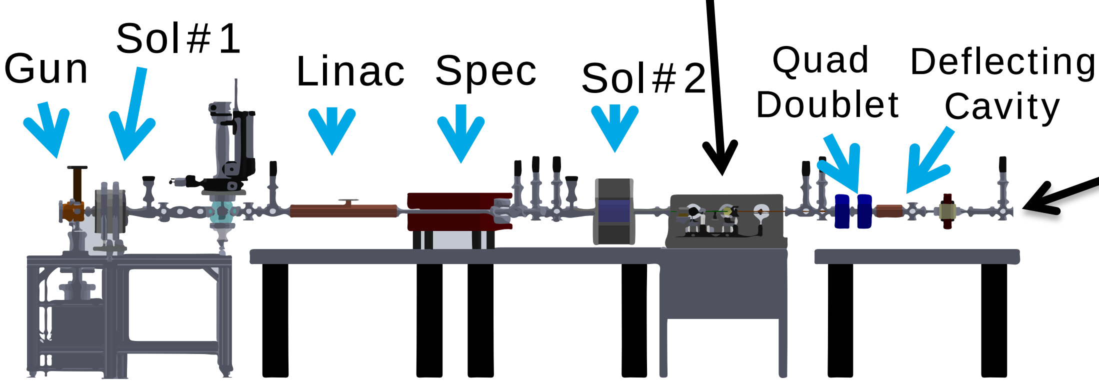
UCLA

- **3-14 MeV student-run university-size accelerator beamline optimized for sub-pC beams**
- Ultralow charge beams with high peak brightness or phase space density:
  - DLA: *few fs acceleration bucket, sub-micron aperture*
  - High resolution ultrafast electron diffraction
  - Single shot imaging / UEM
  - *THz acceleration / amplification*



Electron spectra





Pegasus beamline @ UCLA

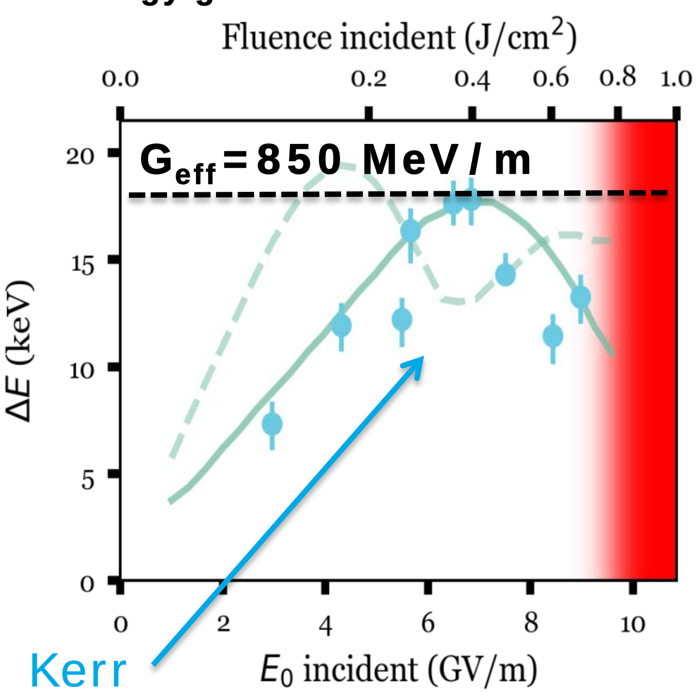
Record gradient & nonlinear effects

UCLA

Relativistic electrons + 45fs laser → 850 MV/m effective gradient

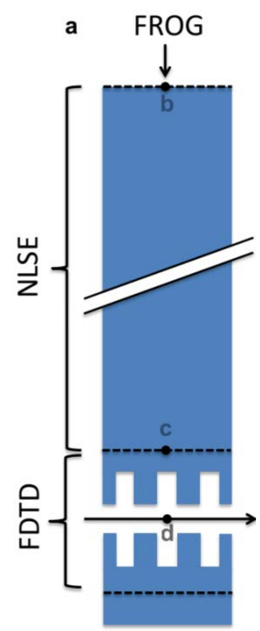
– But limited by dephasing!

Energy gain vs. incident laser field



Kerr saturation

Anatomy of nonlinear dephasing



Intensities of 7TW/cm^2 are incident on the SiO_2 structure

A nonlinear phase grows: $\Psi(z) \propto n_2 I_{laser} k_0 L$

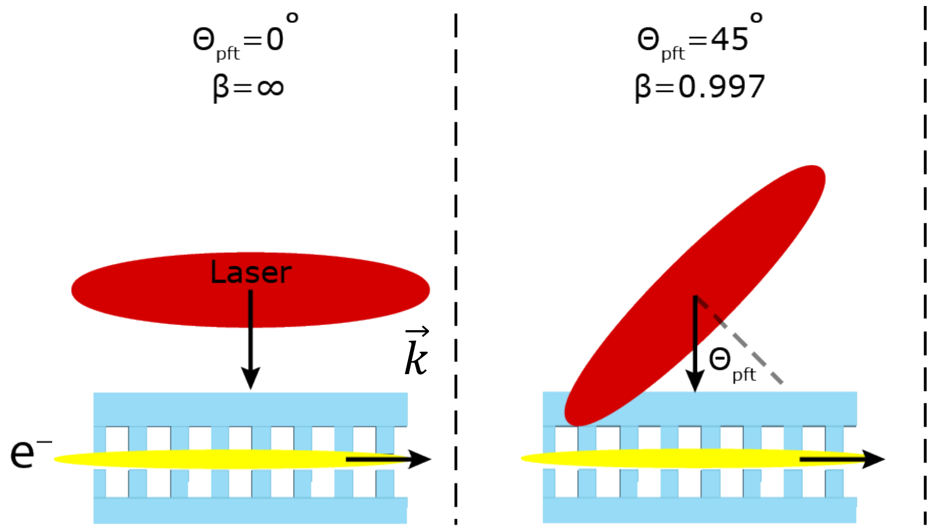
The broadband DLA transmits that phase to the electrons

Peak accelerating field is $\boldsymbol{\kappa E_0 = 1.8\ \mathrm{GV/m}}$

D.Cesar et. al. Comm Phys 2018

Longer interaction: Pulse front tilt

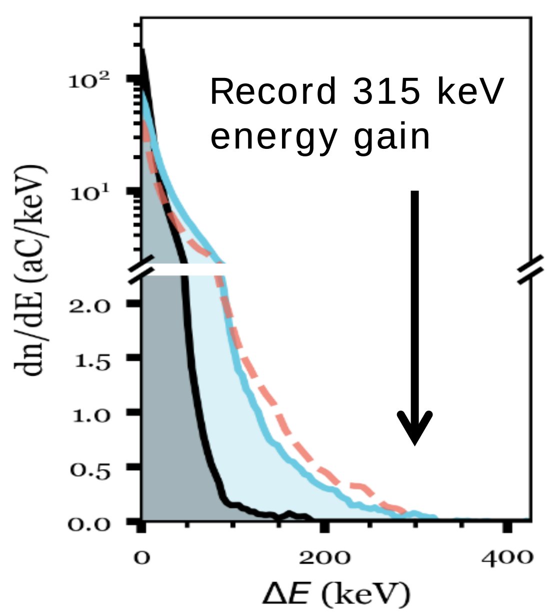
UCLA



Free space technique to study longer interactions

– $\beta = 0.997$: $L = 700\mu m$, $\Delta E = 315$ keV

D.Cesar et. al. Opt.Exp. 2018

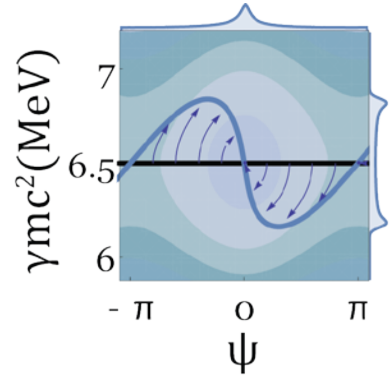


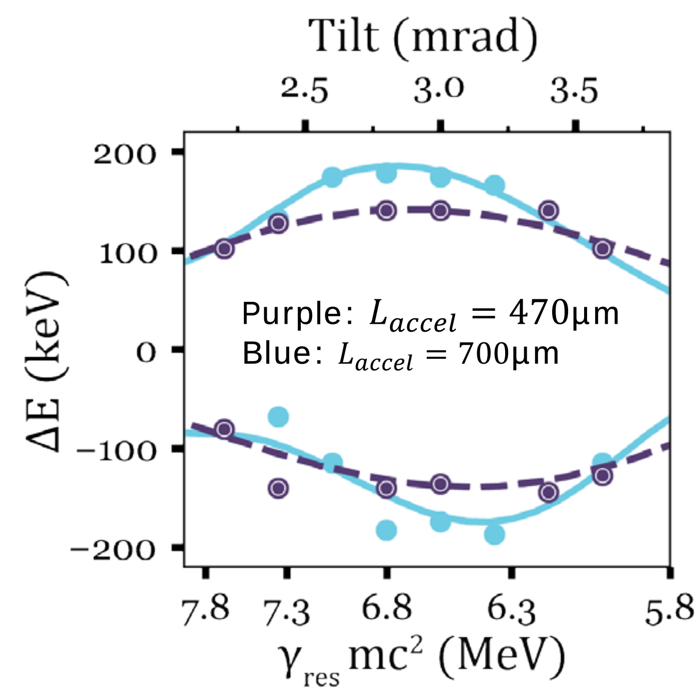
A tilted wavefront changes β:

$$\beta = \omega / \left(k_g + {}^{\omega}/_{c} \sin\phi\right)$$

– Curved wavefront → moving bucket

– Study bucket properties





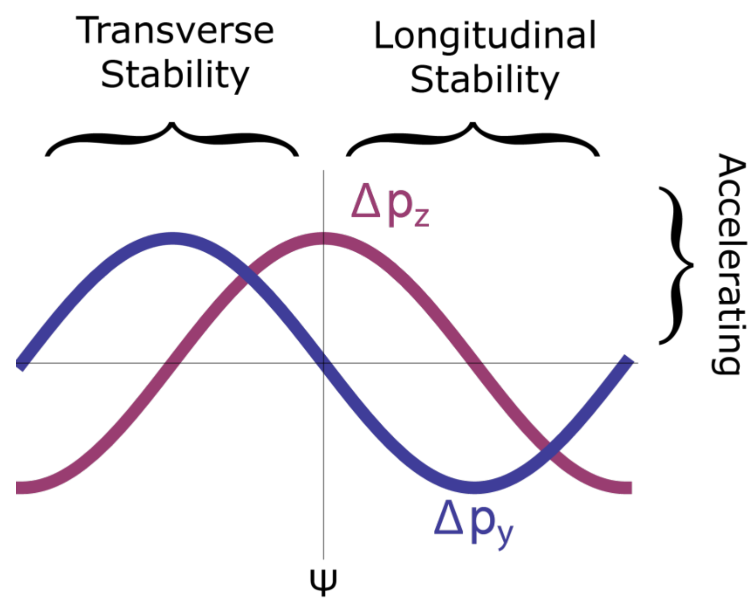
How to do better: overcoming resonant defocusing

UCLA

Control Ψ to switch to focusing phase

- All optical scheme
- Second order, "Ponderomotive"

$$H_\perp = p_y^2 - \frac{\alpha \cos(\Psi)}{\gamma^3\beta^2}(k_z y)^2 \qquad \cos(\phi_{res} + f(z))$$



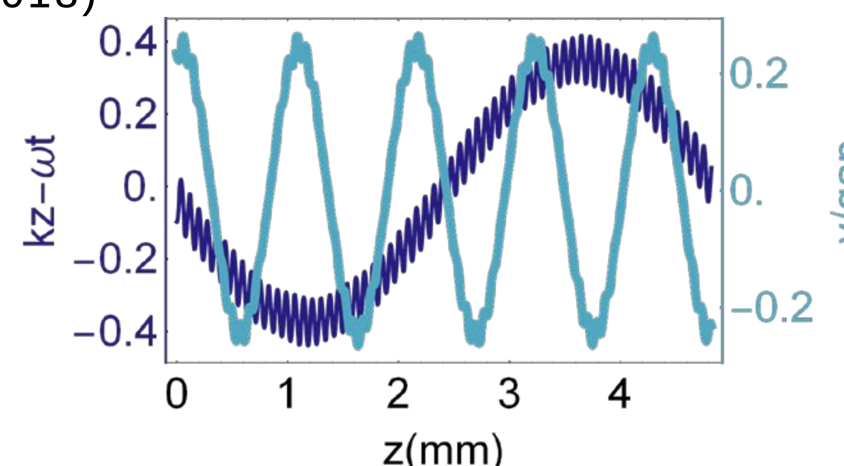
$f(z)$ square wave → FODO lattice, Alternating Phase focusing scheme

see U. Niedermeier PRL 121,214801(2018)

$f(z)$ sinusoidal → ~Mathieu equation

B.Naranjo et. al. PRL 2012

Ponderomotive motion

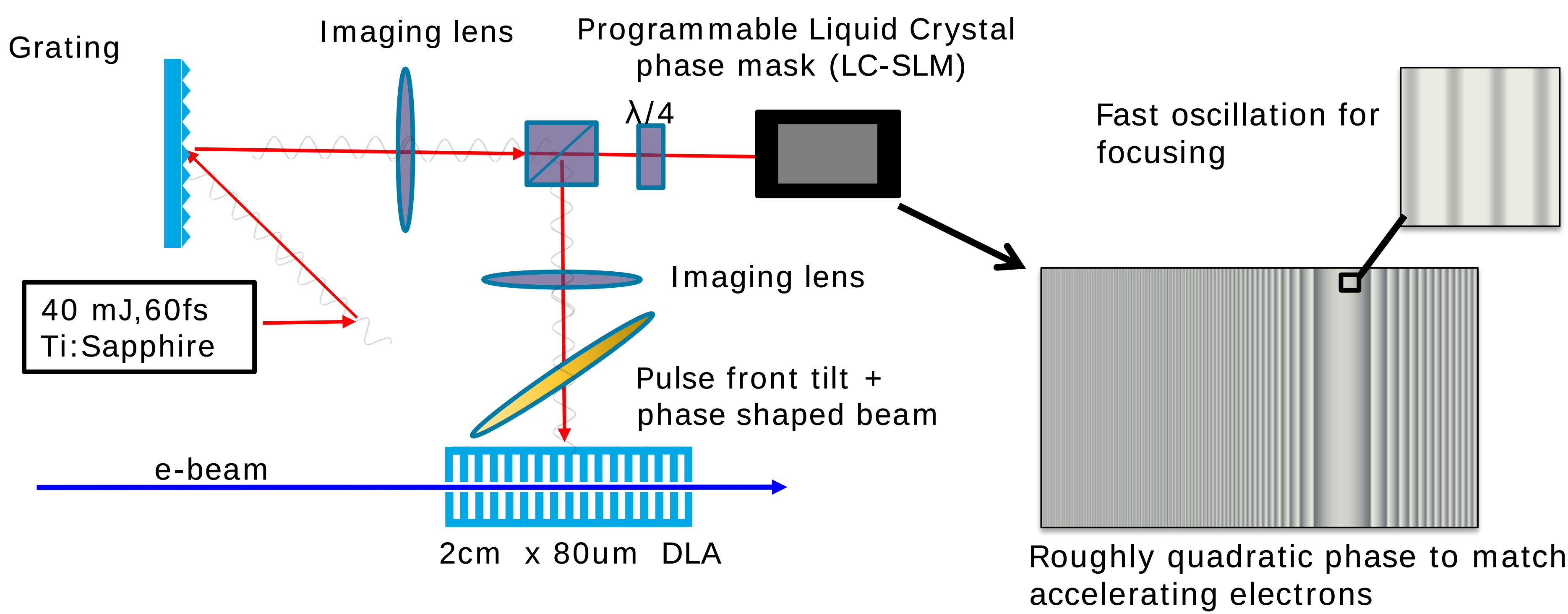


UCLA approach : soft control on DLA focusing and acceleration

UCLA

Use programmable phase mask to design $\Psi(z)$

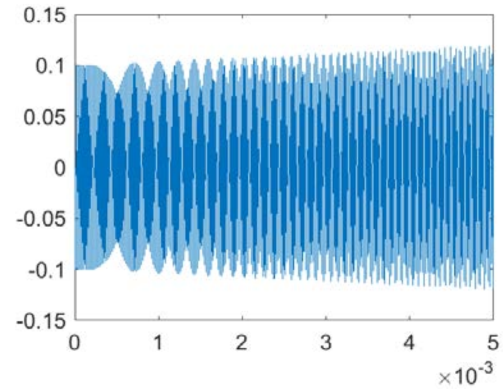
- DLA's are broadband → external phase is preserved
  - Experimental proof by tilting the wavefront & Kerr effect
- Online correction / many knobs for optimization
- Can work for non-relativistic electron as well !



Matlab optimizer

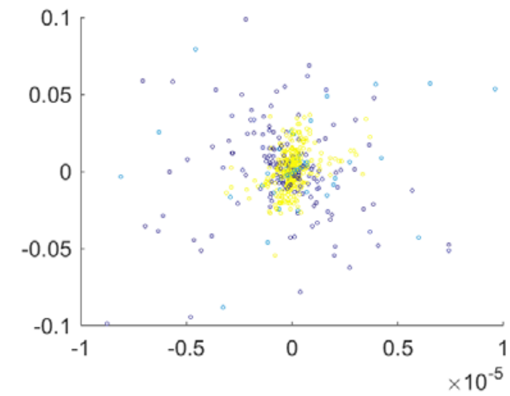
UCLA

- 80 keV
- 2 um laser drive
- 5 mm long structure
- 35 % captured with 500 pm emittance
- Not fully optimized

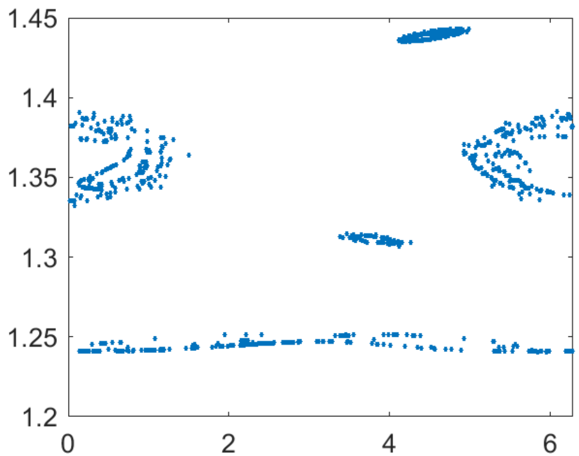


Phase profile

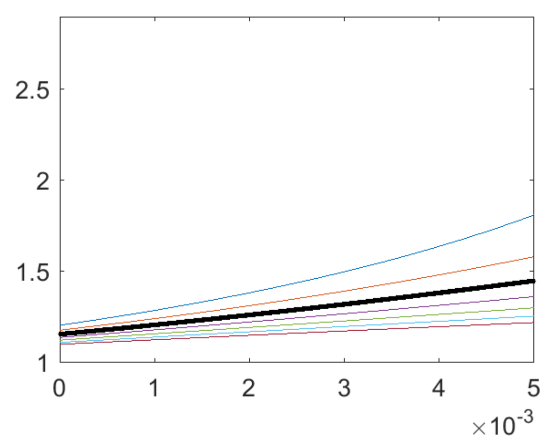
Transverse phase space



Long phase space



Tapering of resonant energy



Towards MeV acceleration

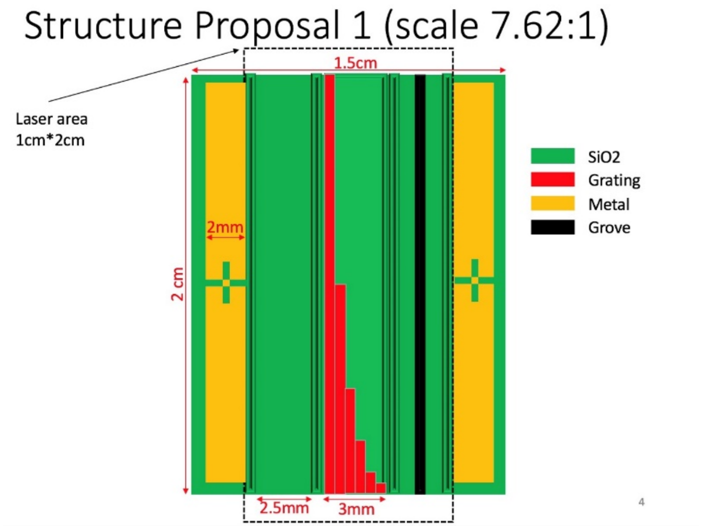
UCLA

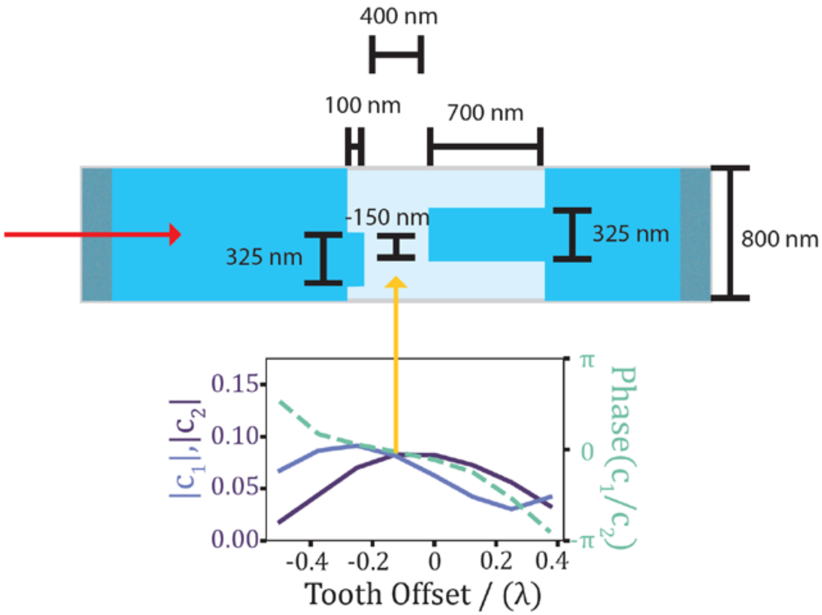
Cm-long structures for MeV energy gain experiment

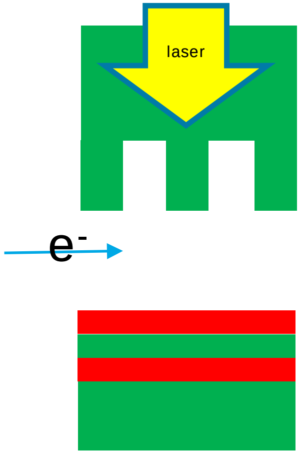
UCLA

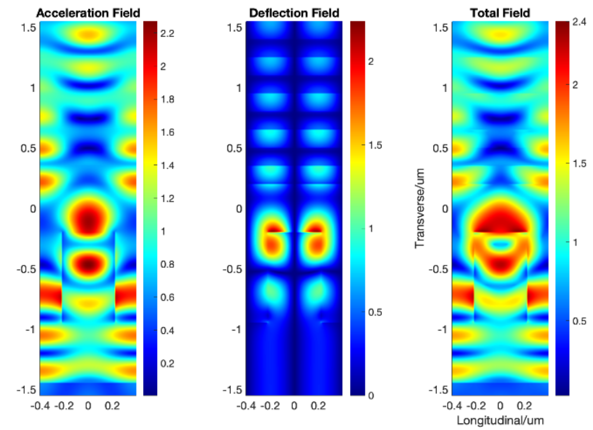
- Single side illumination !
- Two new structures developed:
  - DBR + grating.
  - Bond two different gratings.
- Diffraction measurements using short wavelength lasers to test response
- Damage measurements performed at SLAC

$$F_z \propto qE_0\left(c_1\, e^{-\Gamma y} + c_2\, e^{\Gamma y}\right)\cos(kz - \omega t)$$







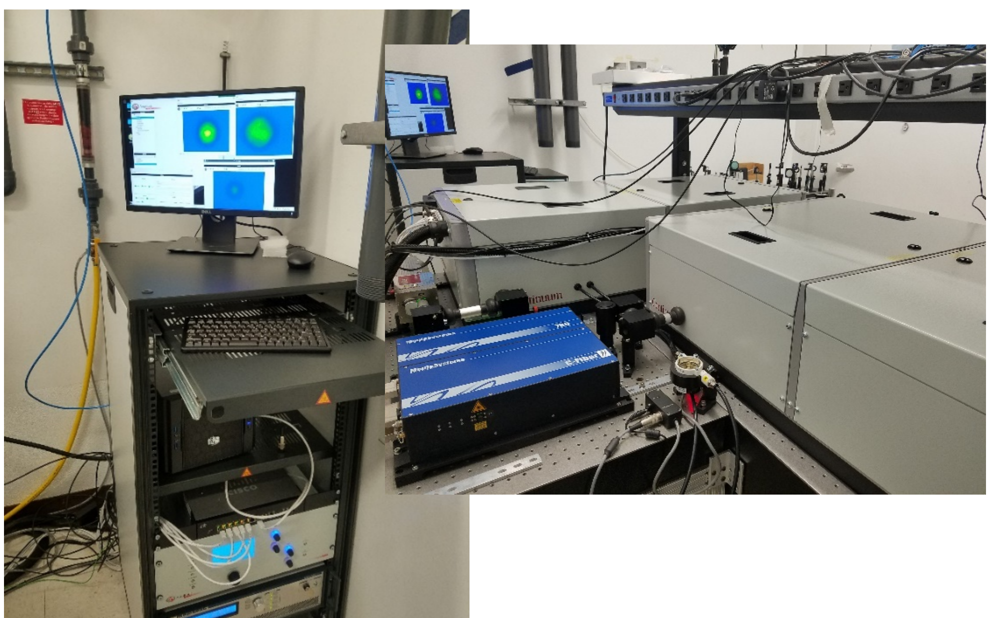


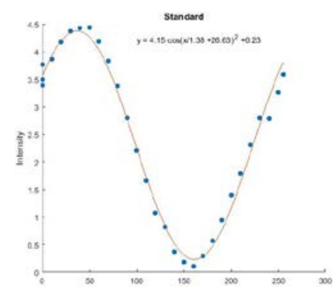
All major hardware in place an commissioned installed and commissioned

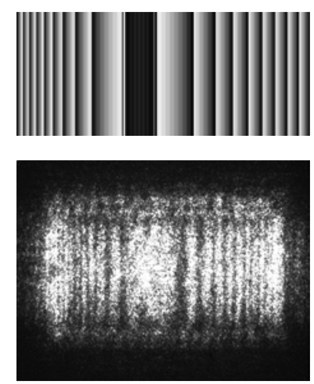
UCLA

- Amplitude Trident laser
- 800 nm , 40 mJ – 80 fs , 10 Hz
- Partially funded by Moore (~ 50 %)
- Chirped pulse to avoid non linearities in the transport (can be compensated by tuning pulse front tilt lenses)
- Synchronization to RF complete

- Exulus liquid crystal phase mask
- Soft-structure computer control
- Parabolic chirp creates linear acceleration
- Modulation for ponderomotive focusing



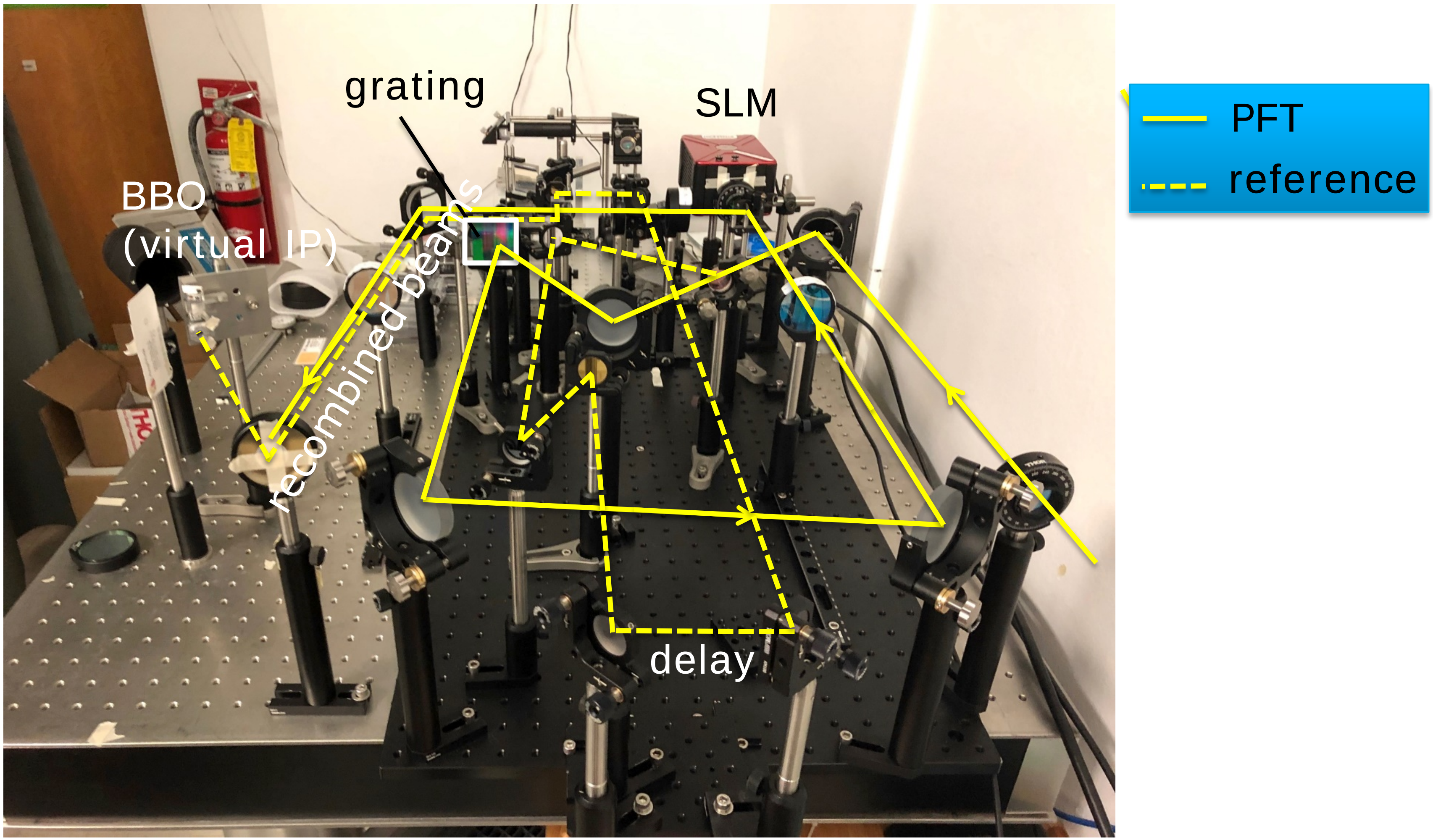




Optical Manipulation Setup

UCLA

- Pre-aligned breadboard to be ported to electron beamline prior to experiment
- Interferometric phase measurement diagnostic
- Timing synchronization and pulse front tilt measurement undergoing

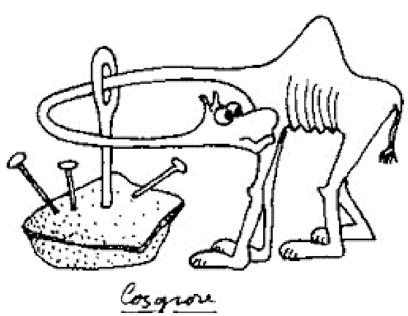


Some general considerations on matching beam brightness for DLA application

UCLA

- 6D brightness (density in phase space) Liouville invariant = phase space volume: $\det(\boldsymbol{\sigma})$
- Common idea of phase space volume as incompressible fluid
- For example, using very strong lenses we can always shape the beam to fit a very small (arbitrarily small) aperture in x-y space, by paying the price of largely increasing the bea mdivergence.
- ...but we can't fit an arbitrary small aperture in x-px space !!!
- Symplectic camels and the non squeezing theorem (Gromov, 1985)

*Gromov, M. L. "Pseudo holomorphic curves in symplectic manifolds". Inventiones Mathematicae. **82**: 307- 347 (1985)*
B. Carlsten, PRSTAB, 14, 050706 (2011): eigen-emittances



The Symplectic Camel: *It is impossible to move a ball of radius ≥ 1 symplectically from one side of the wall to the other.*

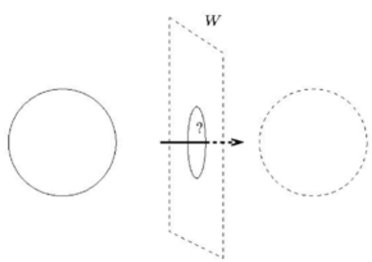
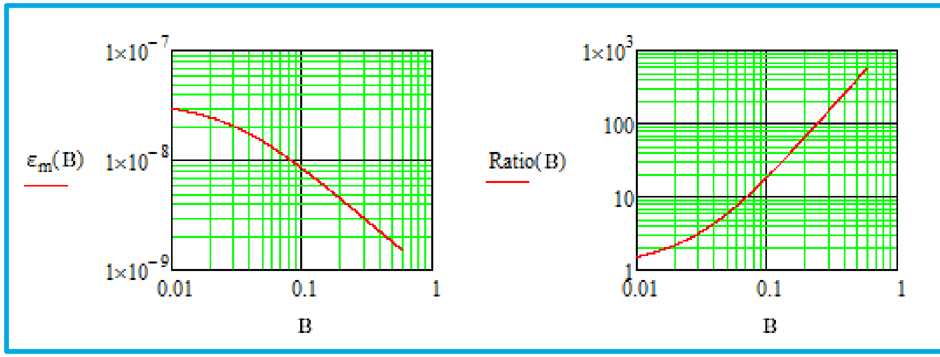


FIGURE 2.3. Can the ball go through the hole?

[6]The name of this problem is a somewhat "in" joke, of the kind appreciated by many mathematicians. The reference is to the saying that it would be easier for a camel to go through the eye of needle than for a rich man to get into heaven. (This saying is probably a mistranslation of a sentence in the bible.)

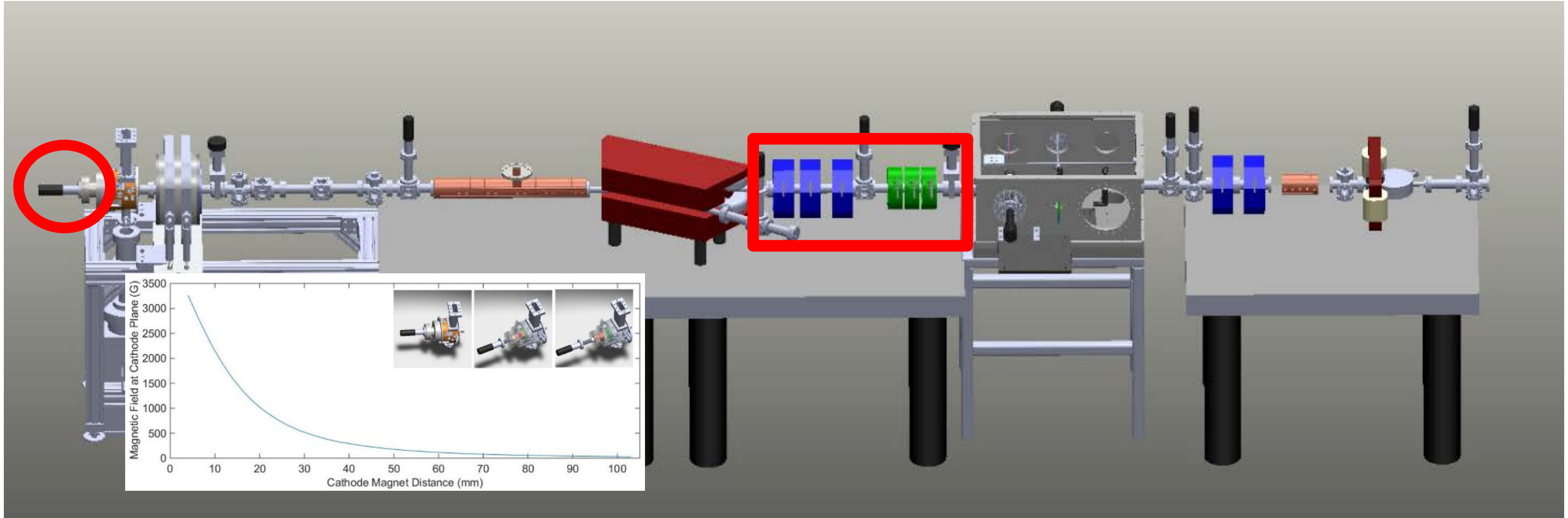
Increase transmission : Flat beam transform beamline

- Magnetized beam + Skew quadrupole beamline implemented at Pegasus
- Machine feedback algorithms to tune the quadrupoles being developed (starting a new collaboration with SLAC)
- Magnetic field dependent QE on cathode?!?
- Simulations predict 2 nm x 200 nm emittances and 1.5 um x 20 um spot sizes at DLA entrance
- Transmitted fraction *should* improve by factor of 10x



$$\epsilon_{\pm} = \epsilon_{eff} \pm L$$

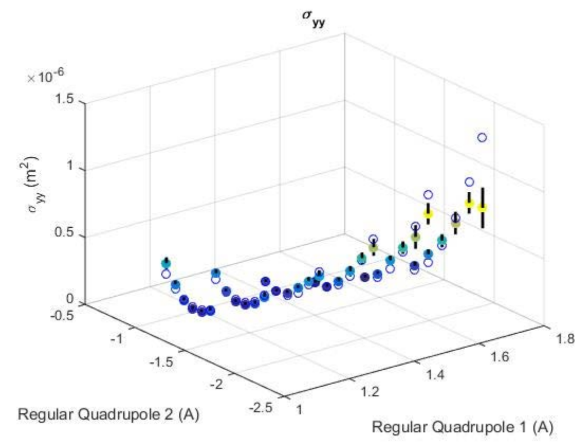
$$\epsilon_{-} \cong \frac{MTE}{e_0 B\, c}$$

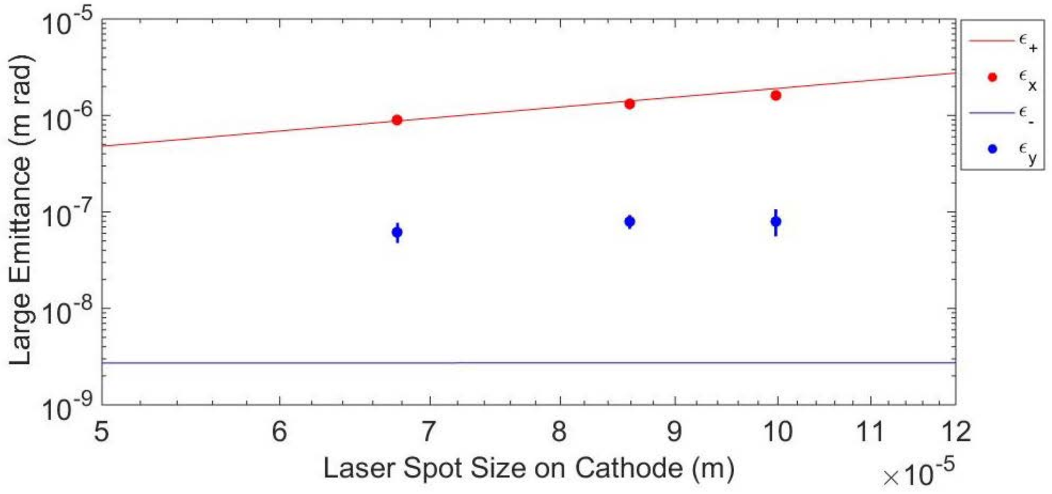


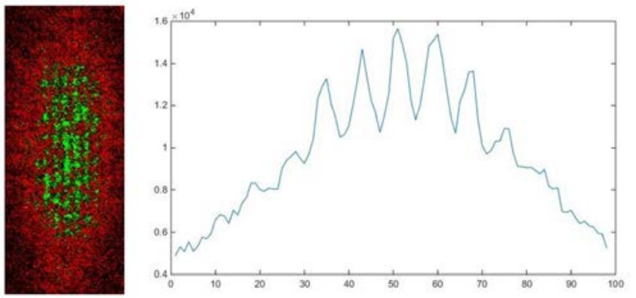
Measuring nm-scale Emittances

UCLA

- Large emittance scales as initial spot size squared
- Small emittance approximately constant, but an order of magnitude larger than expected
  - Smaller than thermal emittance of equivalent round beam (i.e. 80 nm with 100 um rms spot size on cathode)
  - Emittance Ratio >20
- Spurious quadrupole component in gun/solenoid
- Measurement limitation

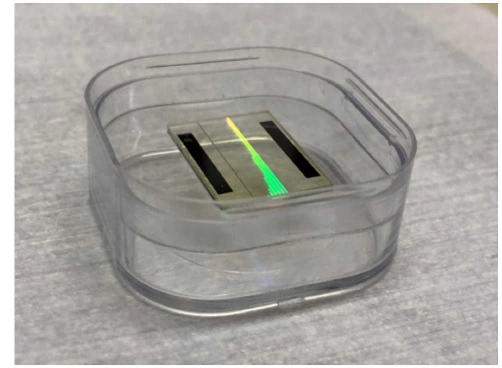




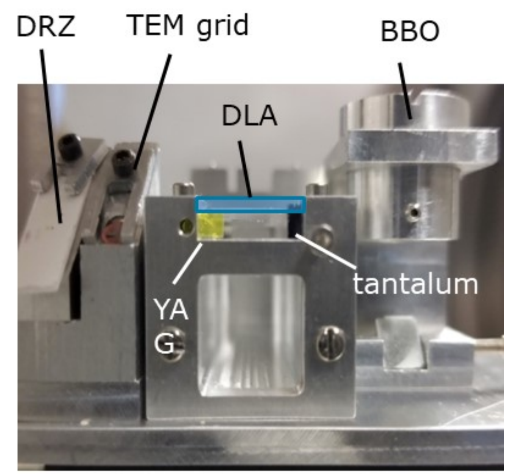


Preliminary Experimental Run (July 2019) UCLA

Purpose of the experiment: verify that we can get some detectable transmission through structure over full 2cm length of the structure.



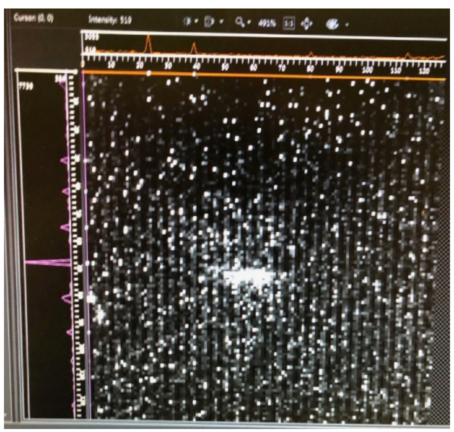
Gratings: 400 nm gap
Spaces between: 1.2 um gap
Alignment channel: 250 um gap



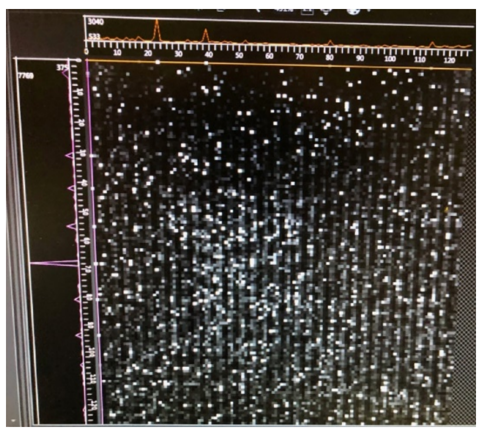
downbeam view

Averaging 10 frames.

beam on



beam off



Observed transmission through the 1.2 micron gap 2 cm long structure !!!

Acknowledgements

UCLA

- UCLA Pegasus Laboratory group

  E. Cropp, P. Denham, S. Crisp, **D. Cesar.** Graduate students.

  N. Burger, R. Hessami, L. Phillips, K. Kabra. Undergraduates.
- All ACHIP group and in particular SLAC group R. J. England, A. Ody, K. Wootton and Y. Miao and D. Black for the new structures
- Collaborators: R. K. Li, J. Maxson, D. Alesini, G. Andonian, F. Carbone, D. Filippetto, J. Luiten, A. Murokh,
- Funding sources
  - GBMF4744 Accelerator on a chip
  - DOE Accelerator Stewardship DE-SC0009914.
  - NSF Accel Science PHY-1734215
  - *U.S. National Science Foundation award PHY-1549132, Center for Bright Beams and award DMR-1548924 STROBE Science and Technology Center.*

Conclusion

UCLA

- DLA MeV energy gain experiment timeline and plan

  Next run planned to start in October at UCLA

  Trident laser transport & coupling to DLA structure

  Synchronization and spatial overlap

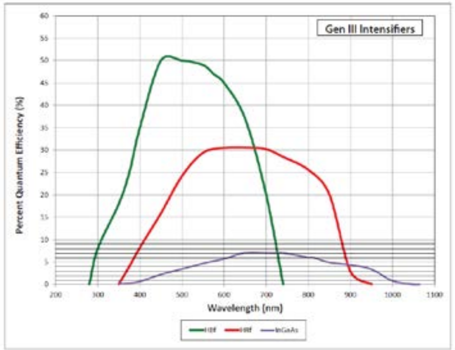
  Improved detection (light collection, new camera)

- DLA Outlook
  - Remarkable progress in DLA acceleration (non relativistic)
    - prebunching and net acceleration
    - attosecond-electron bunches
    - APF transport demonstration
  - All-optical MeV e-source in sight !
  - All integrated on-chip structures
  - Need to accelerate/transport as much charge as possible for any reasonable application
  - High repetition rates and high efficiency
  - Lots of interesting accelerator and beam physics !

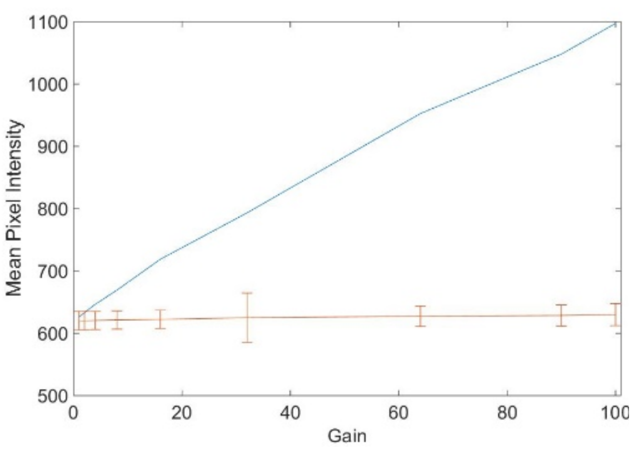
Comparison of PIMAX3 vs. EMICCD PIMAX4

UCLA

- New model PIMAX4 (HR – GEN3 intensifier) – tested at UCLA Aug 21 2019
- Looking at dark current signal (HV: 34 kV, Solenoid Setting:1.1)
- 100 um Yag. Nikon lens f1.2 f = 50 mm - 20 um/pixel
- Signal 40 times larger
- Background increases too, but can be smoothed



Pimax3



Pimax4

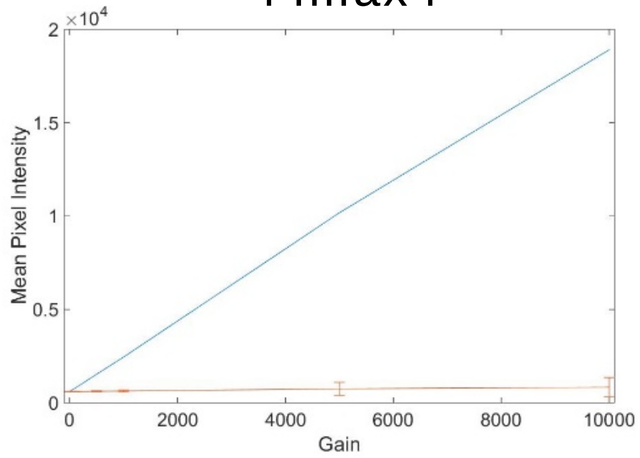
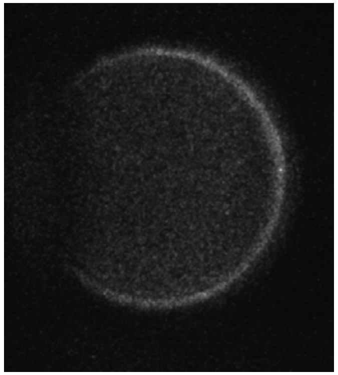
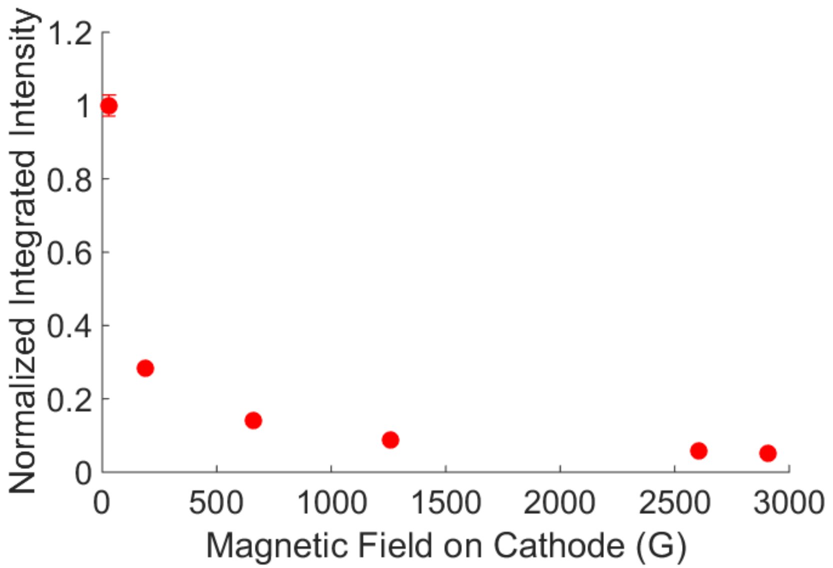


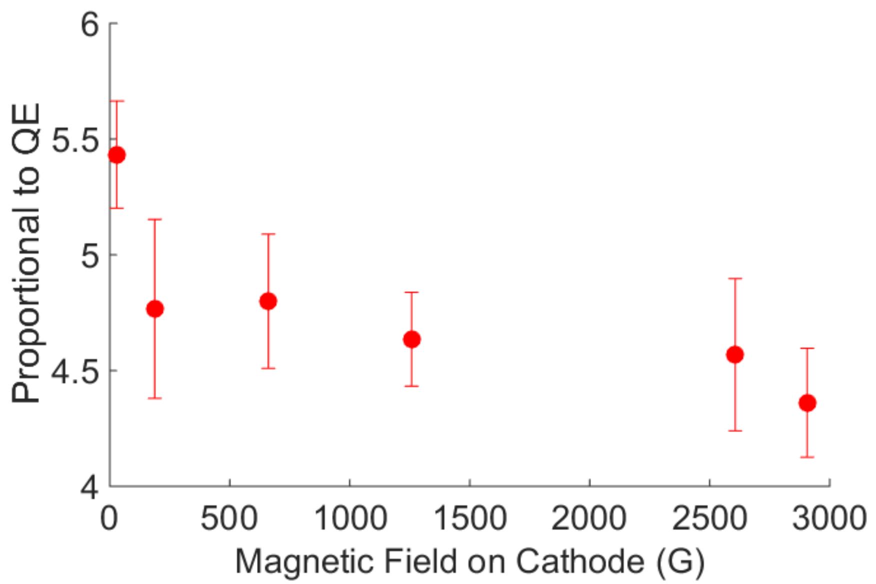
Image example
Background is calculated at the corners outside the Yag screen



Effect of Magnetized Cathode

UCLA





- Dark current decreases rapidly with magnetic field on cathode
- QE also decreases by ~20%
    - Possible explanations related to dark current

Skew Quadrupole Optimization

UCLA

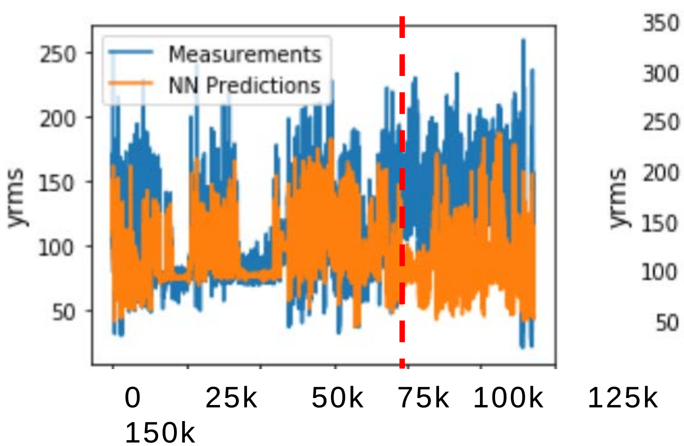
Manual Optimization

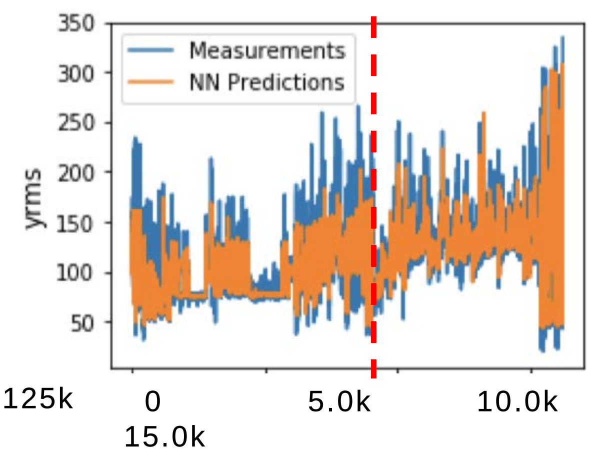
- Maximized up-right aspect ratio on screen downstream
- After focus upstream
- Based on results in particle tracking simulations

Machine Learning

- Machine model able to tune quad gradients with same efficacy as manual tuning
- Model very consistent within a day
- Somewhat consistent day-to-day

Collaboration with SLAC NATIONAL ACCELERATOR LABORATORY





Neural network (NN) predictions of spot size measurements. Data after red line was taken on a new day.

Left: NN was trained only on data from before the red dashed line. Right: NN was trained on data from all days.