Towards MeV Energy gains in Dielectric Laser Accelerators

Pietro Musumeci
UCLA Department of Physics and Astronomy
Dielectric laser acceleration

What makes a DLA?

Obviously laser driven, but also:

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

In vacuum (evanescent field)
An accelerator on a chip

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)
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
Experimental layout: Pegasus Lab

- **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
Relativistic electrons + 45fs laser → 850 MV/m effective gradient
– But limited by dephasing!

Peak accelerating field is $\kappa E_0 = 1.8$ GV/m

D.Cesar et. al. Comm Phys 2018
Longer interaction: Pulse front tilt

Free space technique to study longer interactions
- $\beta = 0.997$: $L = 700\,\mu m$, $\Delta E = 315\,\text{keV}$

$\Theta_{\text{pt}} = 0^\circ$, $\beta = \infty$
$\Theta_{\text{pt}} = 45^\circ$, $\beta = 0.997$

A tilted wavefront changes $\beta$:
- $\beta = \omega/\left(k_g + \omega/c \sin \phi\right)$
- Curved wavefront $\rightarrow$ moving bucket
- Study bucket properties

Record 315 keV energy gain

D. Cesar et al. Opt. Exp. 2018

Tilt (mrad)
How to do better: overcoming resonant defocusing

Control $\Psi$ to switch to focusing phase

- All optical scheme
- Second order, "Ponderomotive"

$H_\perp = p_y^2 - \frac{\alpha \cos(\Psi)}{\gamma^3 \beta^2} (k_z y)^2$

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

see U. Niedermeier PRL 121,214801(2018)

$f(z)$ sinusoidal $\rightarrow$ $\sim$Mathieu equation

B.Naranjo et. al. PRL 2012

Transverse Stability

Longitudinal Stability

Accelerating

$\Delta p_y$

$\Delta p_z$

Ponderomotive motion
Use programmable phase mask to design $\Psi(z)$
- DLA’s are broadband $\rightarrow$ 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!

UCLA approach: soft control on DLA focusing and acceleration

- Grating
- Imaging lens
- Programmable Liquid Crystal phase mask (LC-SLM)
- $\lambda/4$
- Fast oscillation for focusing
- Pulse front tilt + phase shaped beam
- 40 mJ, 60fs Ti:Sapphire
- 2cm $\times$ 80um DLA
- Roughly quadratic phase to match accelerating electrons
- 80 keV
- 2 um laser drive
- 5 mm long structure
- 35% captured with 500 pm emittance
- Not fully optimized

Matlab optimizer

Phase profile

Transverse phase space

Long phase space

Tapering of resonant energy
Towards MeV acceleration
Cm-long structures for MeV energy gain experiment

- 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

\[ F_z \propto qE_0(c_1 e^{-\Gamma y} + c_2 e^{\Gamma y})\cos(kz - \omega t) \]
All major hardware in place and commissioned installed and commissioned

- 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

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

![Optical setup diagram](image-url)

- BBO (virtual IP)
- Delay
- Grating
- SLM
- Recombined beams
- PFT
- Reference
Some general considerations on matching beam brightness for DLA application

- 6D brightness (density in phase space) Liouville invariant = phase space volume: $\det(\sigma)$
- 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 beam divergence.
- ...but we can’t fit an arbitrary small aperture in x-px space !!!
- Symplectic camels and the non squeezing theorem (Gromov, 1985)

B. Carlsten, PRSTAB, 14, 050706 (2011): eigen-emittances
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

\[ \epsilon_\pm = \epsilon_{\text{eff}} \pm L \]

\[ \epsilon_- \approx \frac{MTE}{e_0Bc} \]
Measuring nm-scale Emittances

- 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
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

Averaging 10 frames.
beam on
beam off

Observed transmission through the 1.2 micron gap 2 cm long structure !!!
• UCLA Pegasus Laboratory group
  E. Cropp, P. Denham, S. Crisp, D. Cesar. Graduate students.

• 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.
• 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

- 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

Image example
Background is calculated at the corners outside the Yag screen
Effect of Magnetized Cathode

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

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

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.