Dielectric Accelerators and Non-Plasma Accelerator Based Compact Light Sources

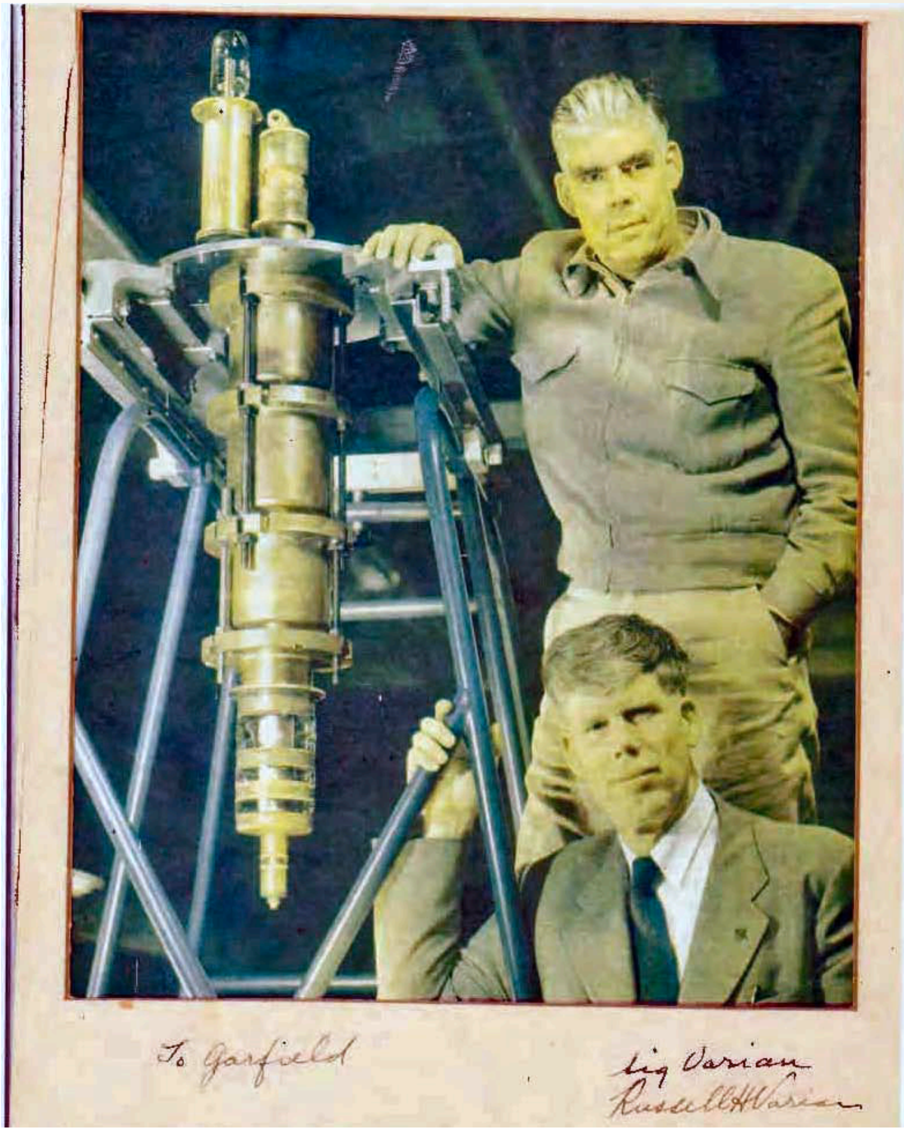
R. J. England (SLAC)

60th ICFA Advanced Beam Dynamics Workshop on Future Light Sources (FLS 2018)
Shanghai, China, March 5-9, 2018

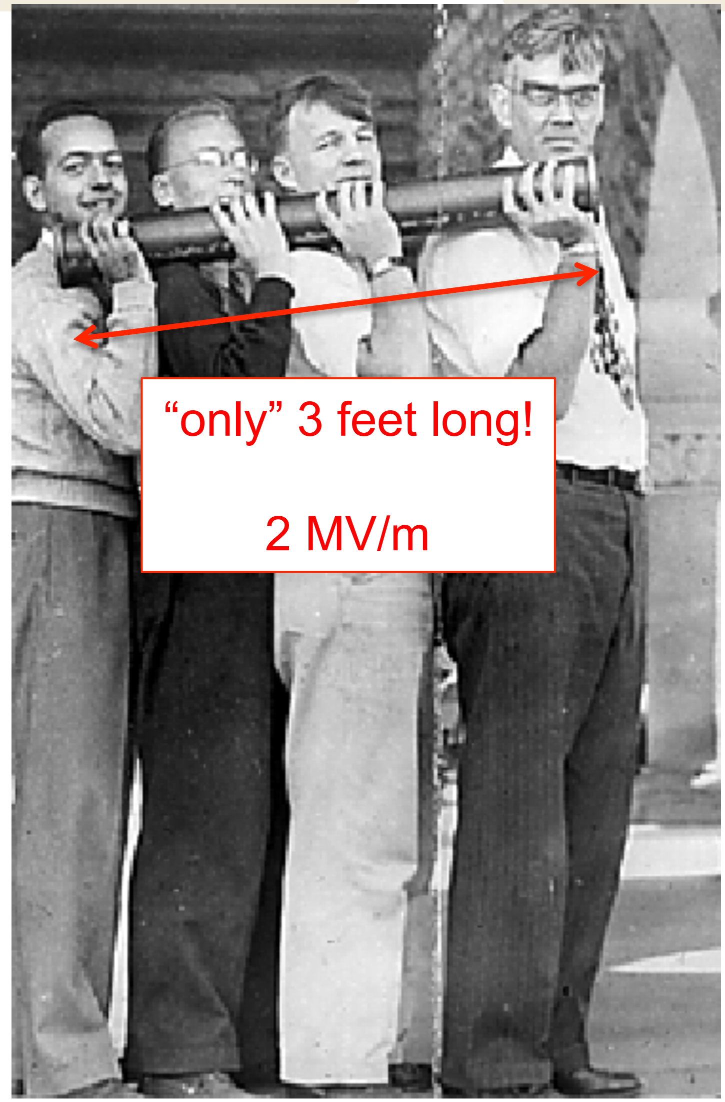
U.S. DEPARTMENT OF ENERGY
Office of Science

SLAC NATIONAL ACCELERATOR LABORATORY

When the SLAC linac and microwave klystron were invented they were revolutionary developments

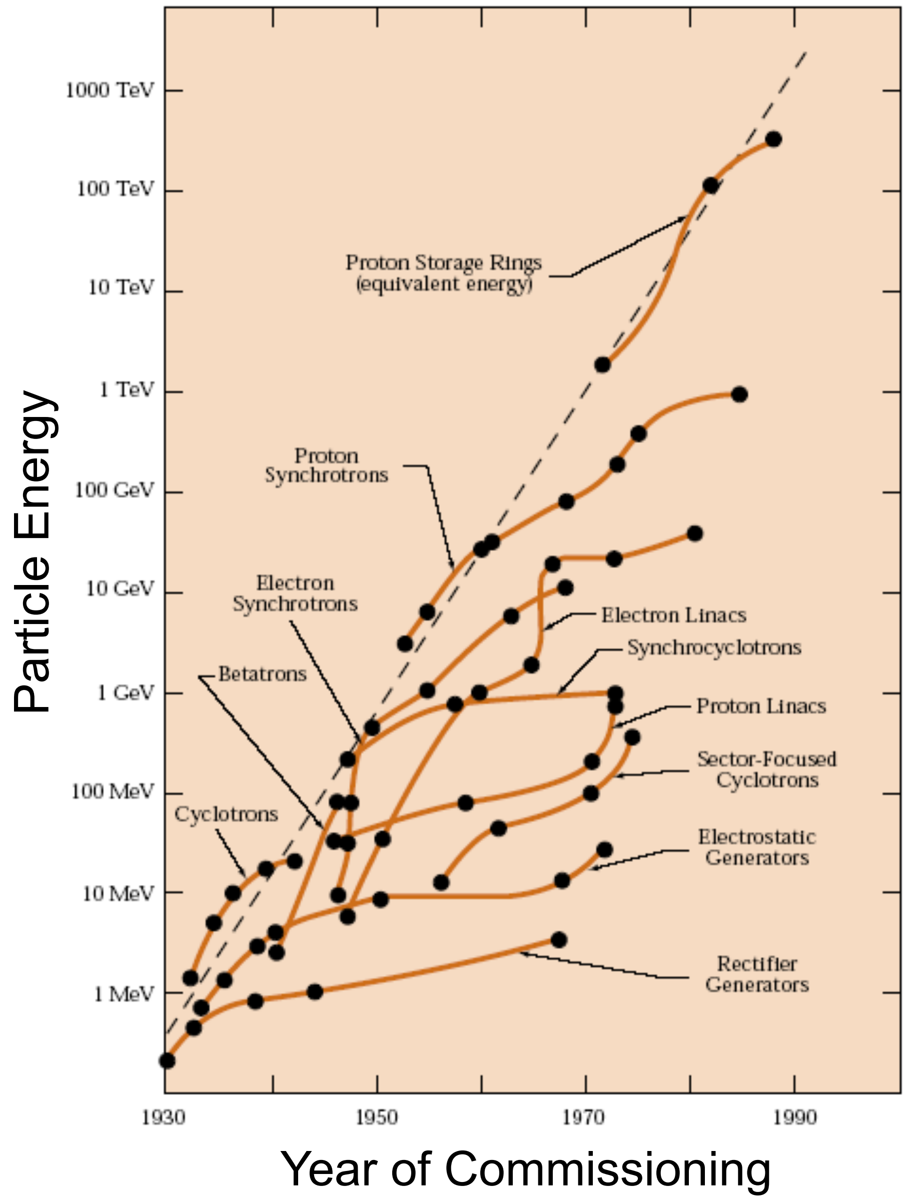


Klystron invented 1937



Microwave linac invented 1948

Innovation leads to exponential progress

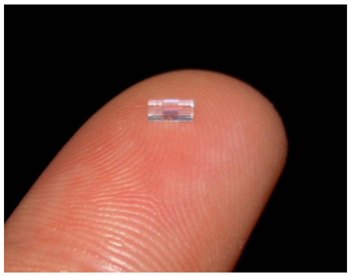


In 1954 Livingston noted that progress in high energy accelerators was exponential with time.

Progress is marked by the saturation of the current technology followed by the adoption of **innovative new approaches** to particle acceleration led by scientists with a **vision** for the future and the **passion** to make it happen.

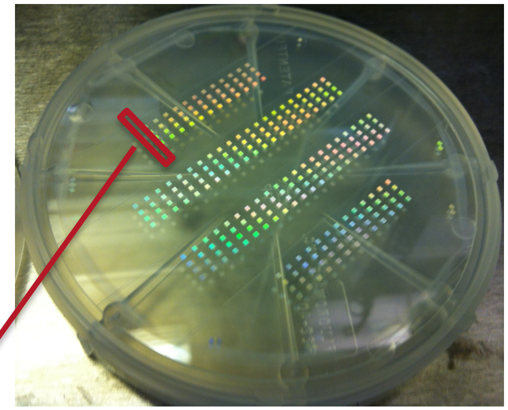
It is clear that there is a need for innovation in the next generation of advanced accelerators.

Dielectric Laser Acceleration (DLA) Concept



laser-driven microstructures
- **lasers:** high rep rates, strong field gradients, commercial support
- **dielectrics**: higher breakdown threshold → higher gradients (1-10 GV/m), leverage industrial fabrication processes

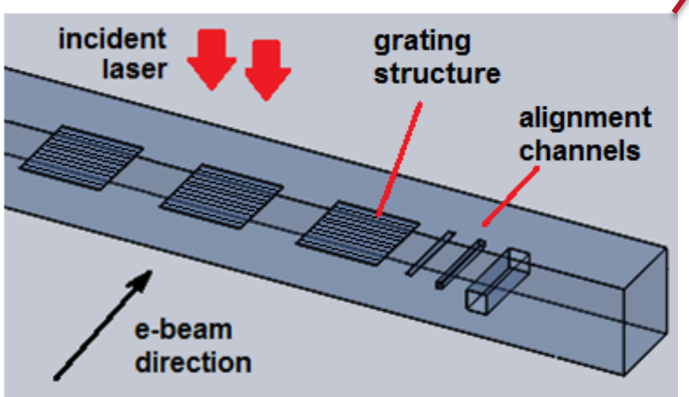
"Accelerator-on-a-chip"

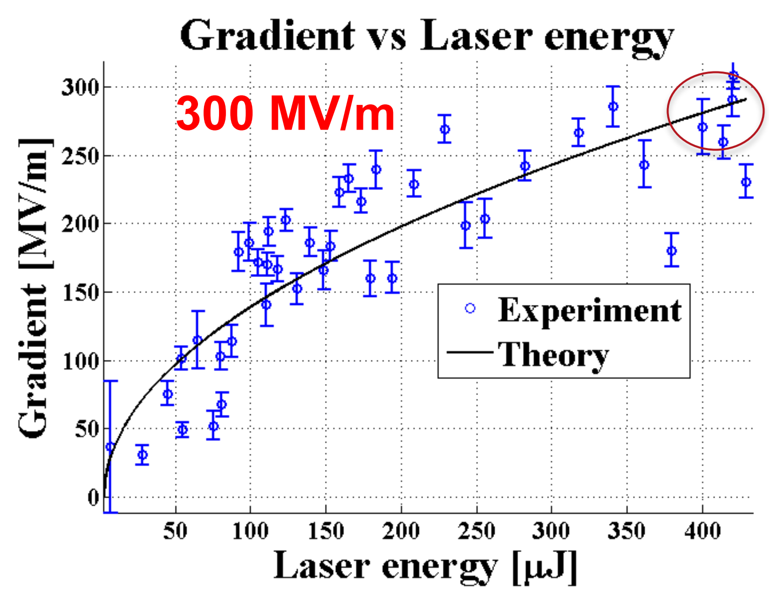


bonded silica phase reset accelerator prototypes fabricated at SLAC/ Stanford

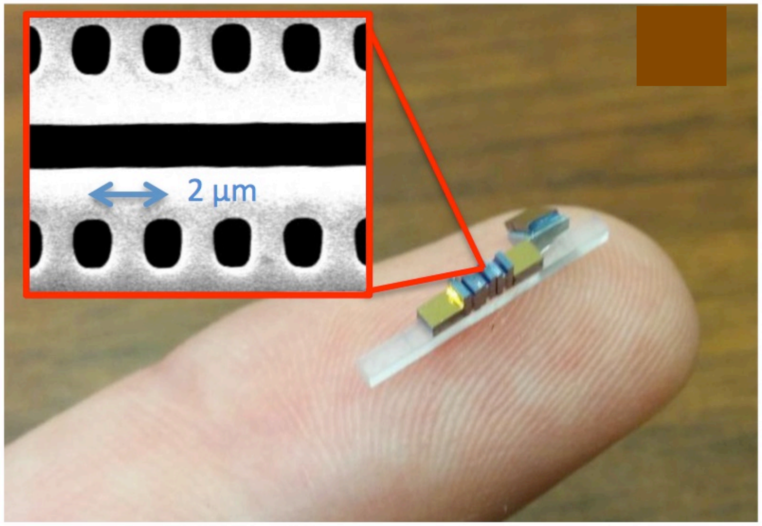
Goal: lower cost, more compact, energy efficient, higher gradient

Wafer is diced into individual samples for e-beam tests.



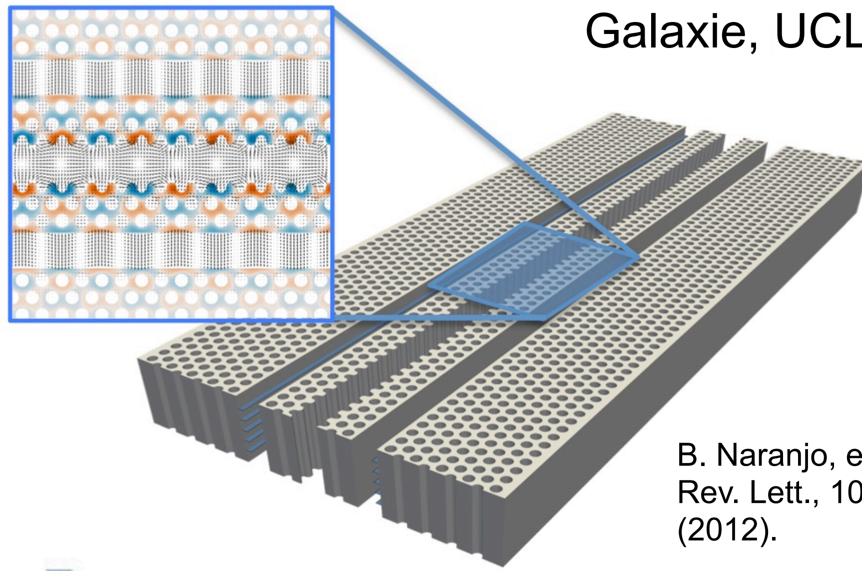


Various DLA Concepts Proposed



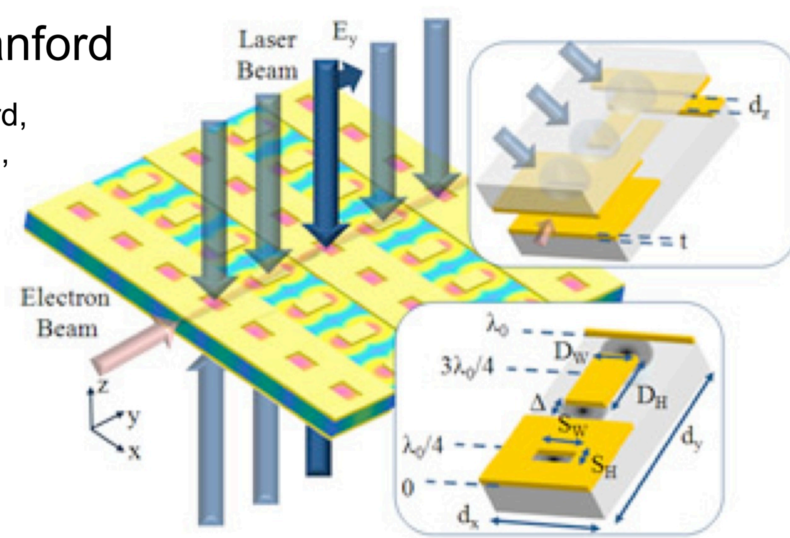
Buried Grating, Stanford

C. M. Chang and O. Solgaard, Applied Physics Letters, 104, 184102 (2014).



Galaxie, UCLA

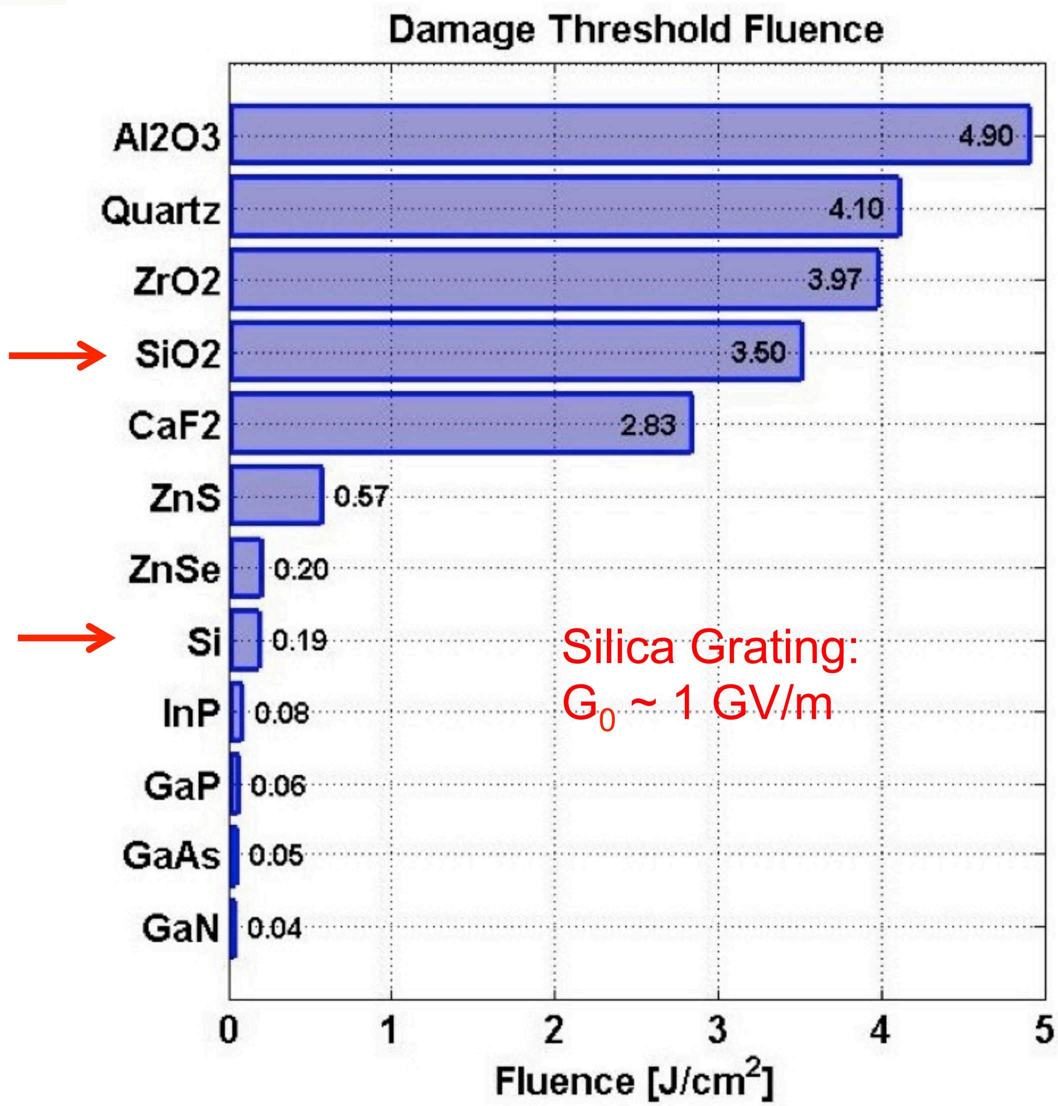
B. Naranjo, et al., Phys. Rev. Lett., 109, 164803 (2012).



MLA, Tel-Aviv

D. Bar-Lev and J. Scheuer, Phys. Rev. ST Accel. Beams, 17, 121302 (2014)

To obtain these high gradients we need materials that can withstand intense laser fields.

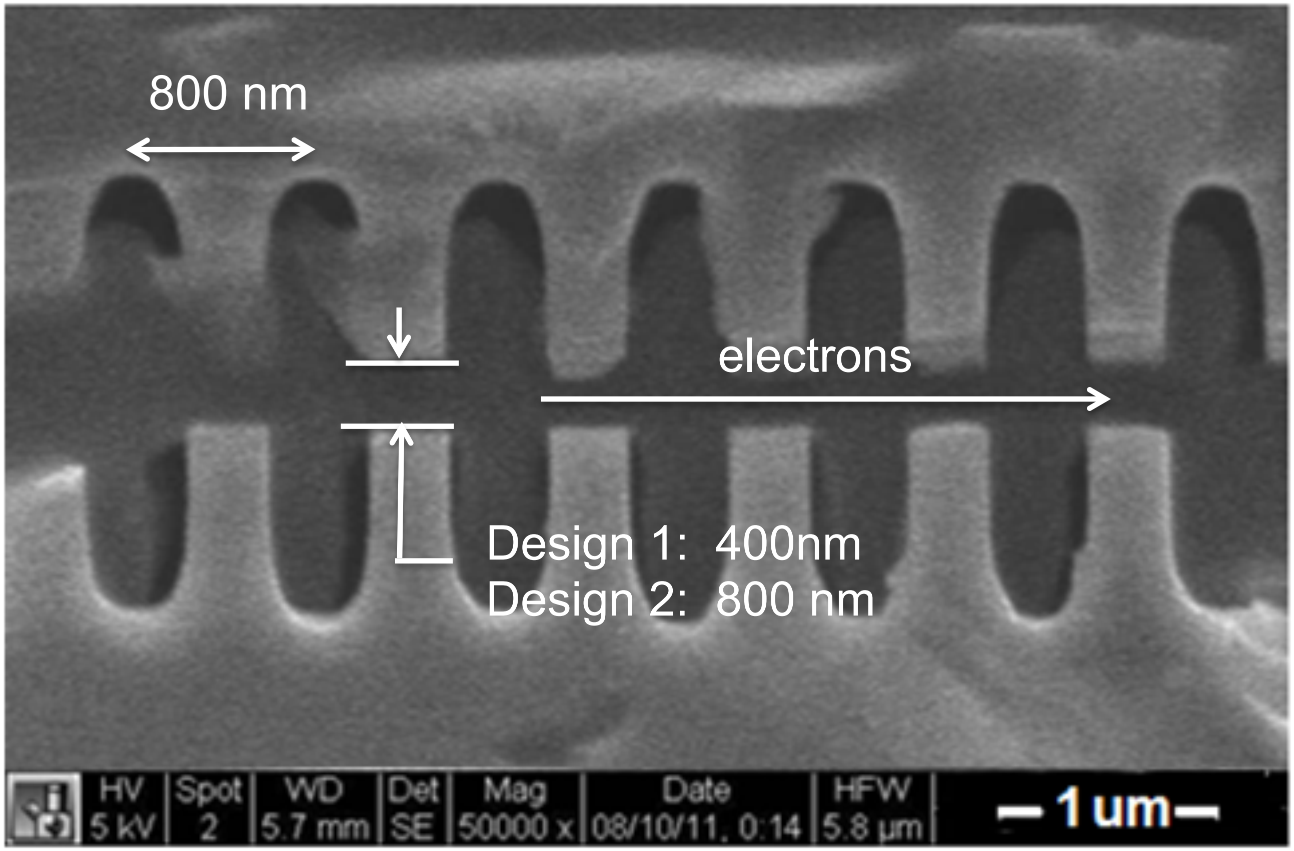


Measurement data from K. Soong

Ti:Sapph Laser wavelength: 800nm; Pulse length: 1ps; <u>Extensive data did not previously exist in this regime</u>.

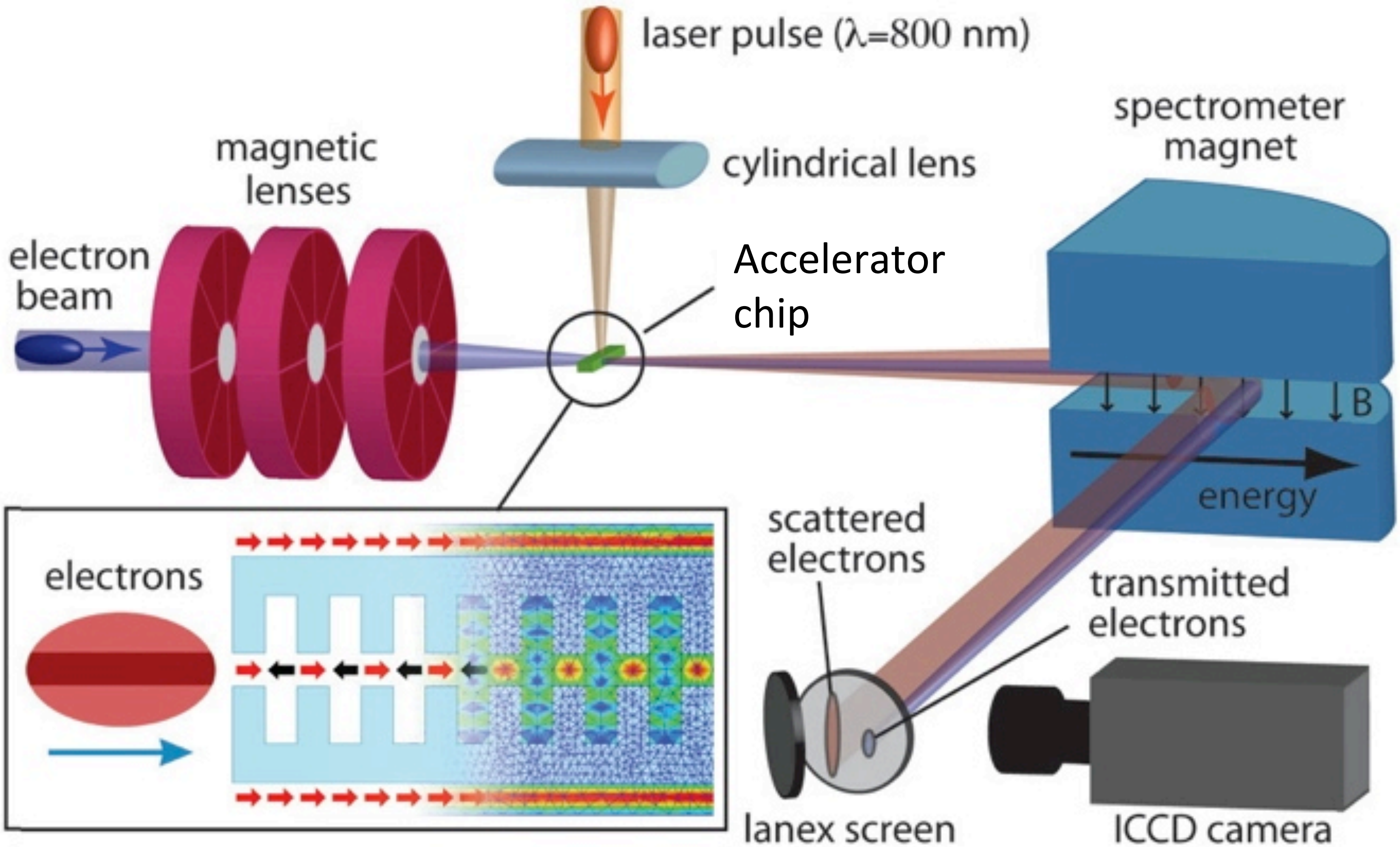
Ken Soong

The first successful prototypes were made of fused silica at Stanford Nanofabrication Facility



Electron microscope image of the bonded structure.
Rough edges are due to damage from sawing the structure in half in order to image the interior.

To demonstrate these devices, we used a pre-accelerated test beam at SLAC.



Gradients in the first experiment were 10 times higher than the main SLAC linac.

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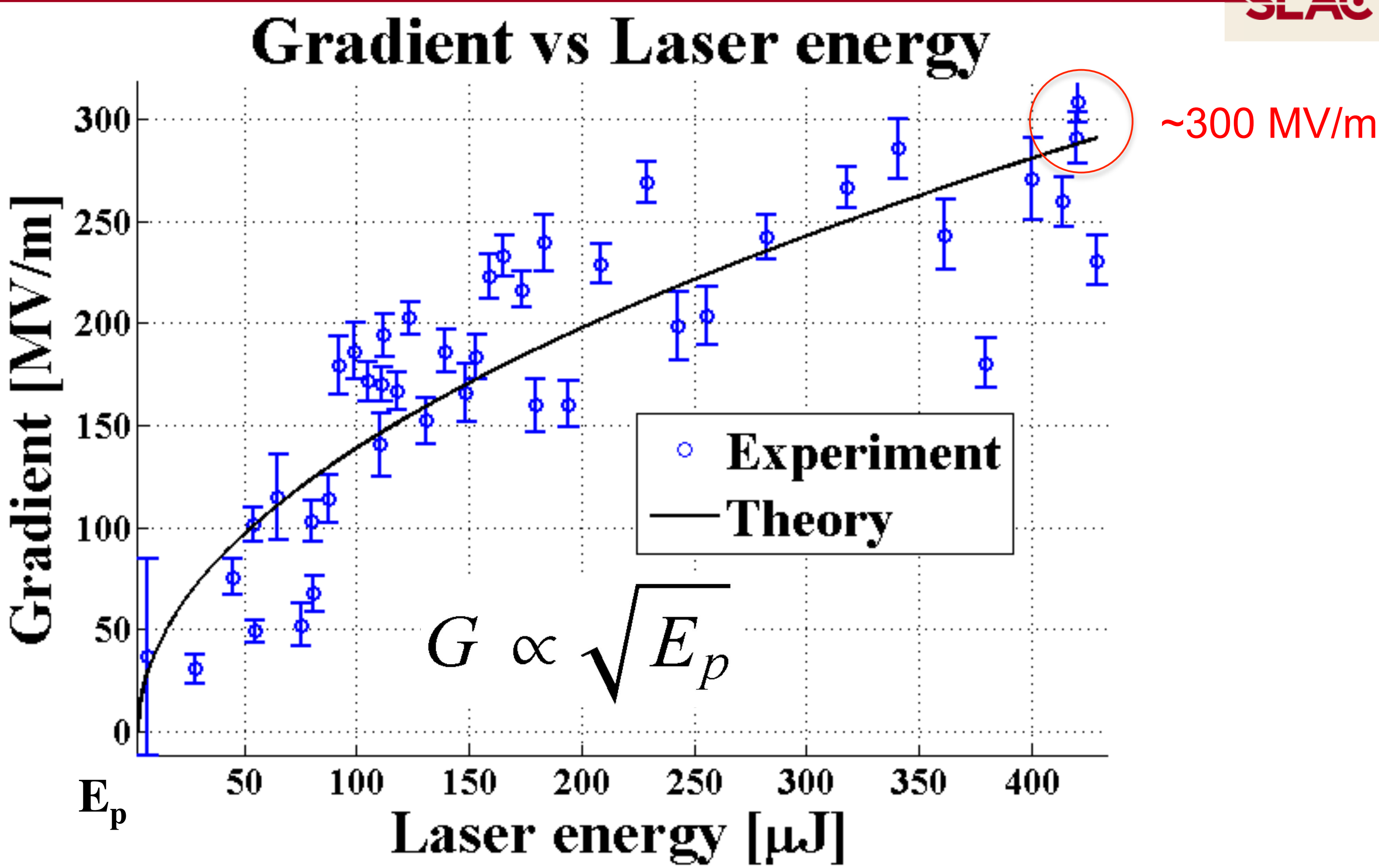

With further optimization of the structure designs, GV/m level gradients should be achievable

Nature, 503, 91-94 (2014)

SLAC

LETTER

038/nature12664

1 Demonstratio
laser-driven c

E. A. Peralta[1], K. Soong[1], R. J. Engla ... lz[2],
E. B. Sozer[4], B. Cowan[5], B. Schwart

Science and technology

The Economist

IOP Physics World - the member magazine of the Institute of Physics

physicsworld.com

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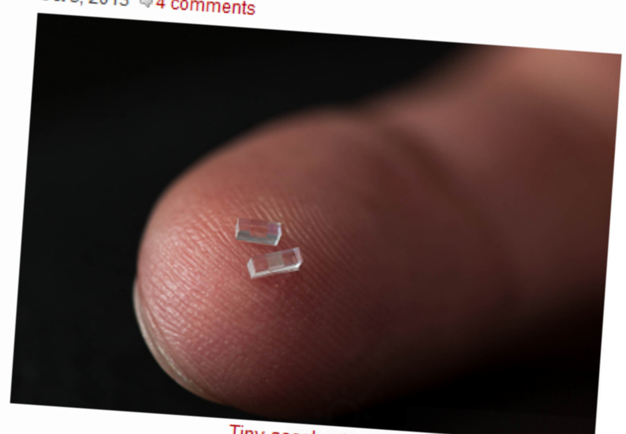
Etched glass could create table-top particle accelerators

Oct 3, 2013 4 comments

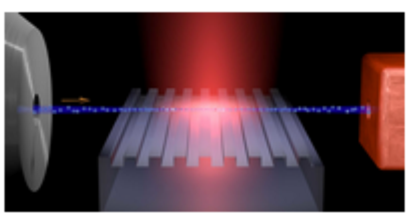


Tiny accelerators

Two independent teams of physicists have used small pieces of glass etched with ...

***Physics:* Accelerating Electrons with Light**

September 27, 2013



In a new technique, light pulses a ... traditional accelerators.
[Focus on Phys. Rev. Lett. **111**, 1 ...

Read Article | More Focus

A 5-Year initiative in DLA has been approved by the Gordon and Betty Moore Foundation (2016 – 2021)

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ACHIP: Accelerator on a Chip International Program

ACHIP

$13.5M / 5 years

GORDON AND BETTY MOORE FOUNDATION

Sub-Relativistic DLA experiments
Stanford: Harris, Solgaard
Erlangen: Hommelhoff

Structure Design & Fabrication
Stanford: Byer, Harris, Solgaard
Erlangen: Hommelhoff

Systems Integration (Core DLA Groups)
Stanford: Byer, Harris, Solgaard
Erlangen: Hommelhoff

Electron source
UCLA: Musumeci
Erlangen: Hommelhoff
Stanford: Harris, Solgaard

Simulations
Tech-X: Cowan
U Darmstadt: Boine-Frankenheim

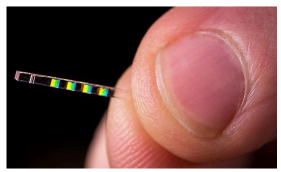
Light Coupling
Stanford: Fan, Vuckovic
Purdue: Qi

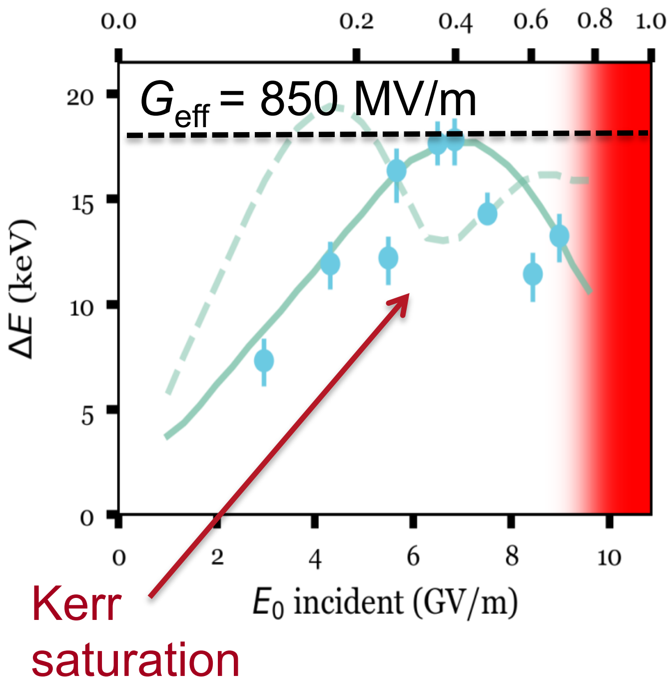
Scientific Advisors
SLAC: Burt Richter
Stanford: Persis Drell

Relativistic DLA experiments
SLAC: England, Tantawi
DESY/UnivHH: Assmann, Kaertner, Hartl
PSI/EPFL: Ischebeck, Frei

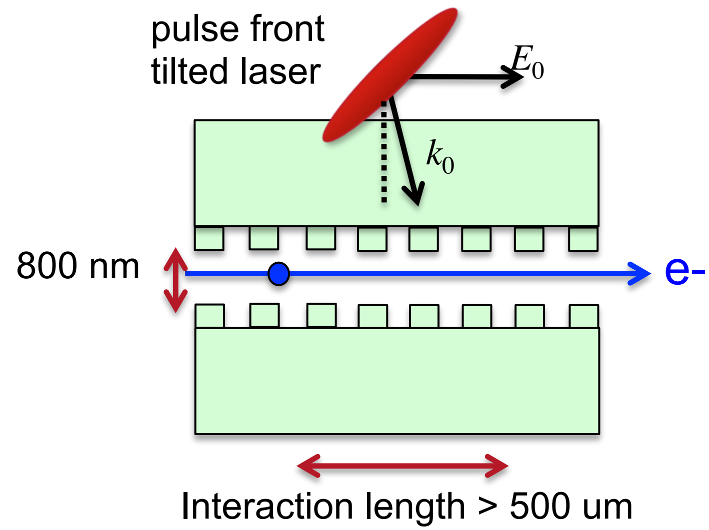
Subsequent joint experiments with UCLA have demonstrated record gradients and energy gain.

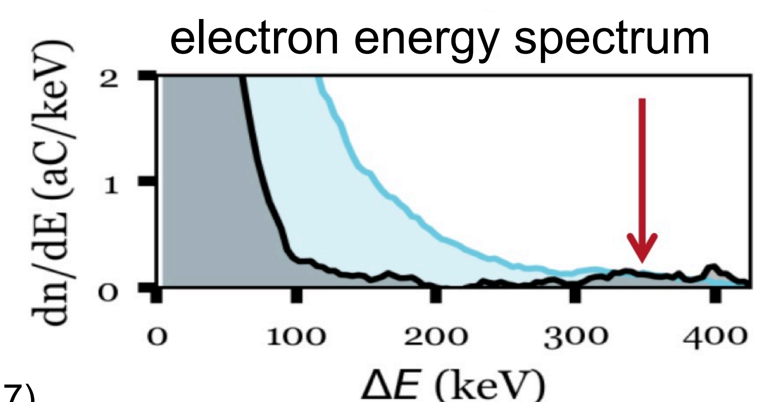
SLAC/UCLA: 0.85 GV/m*





SLAC/UCLA: 0.3 MeV energy gain**





* submitted to Nature Communications Physics (2017)

** in preparation (2017)

A test stand for lower energy (< 100 keV) structures has been implemented at Stanford.

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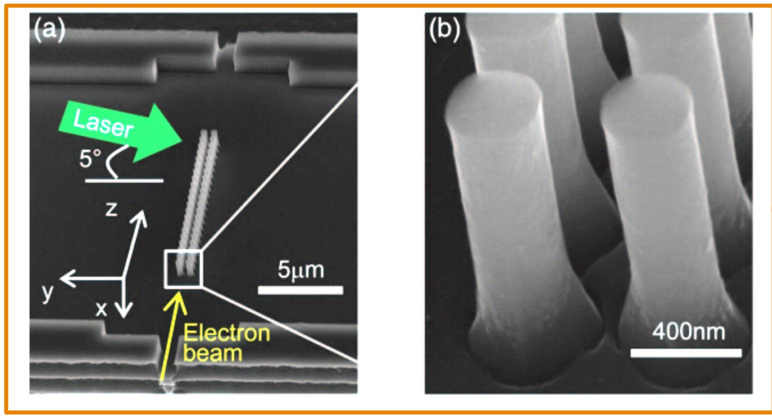
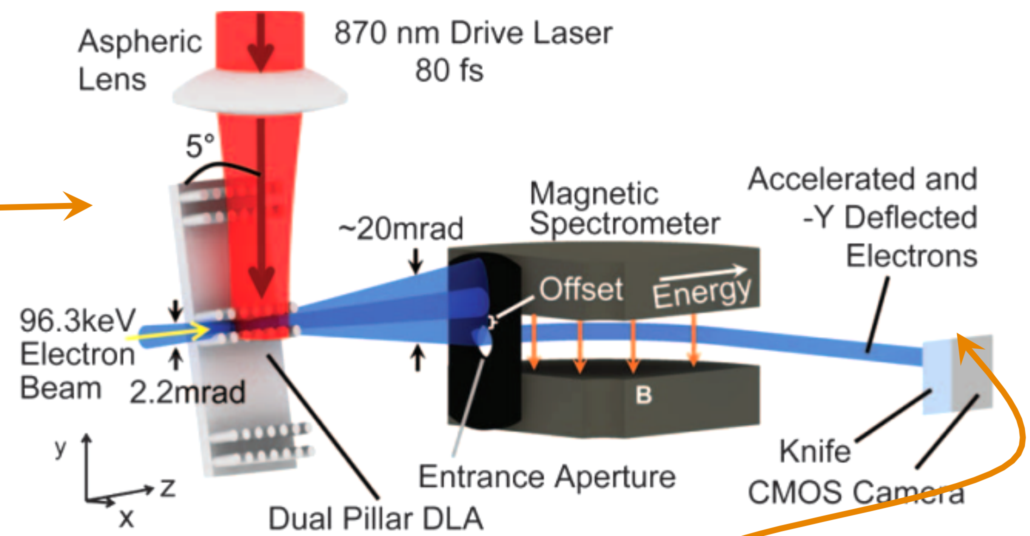
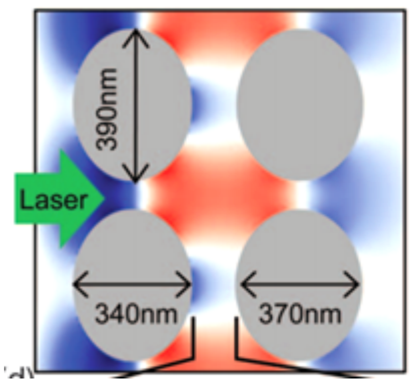
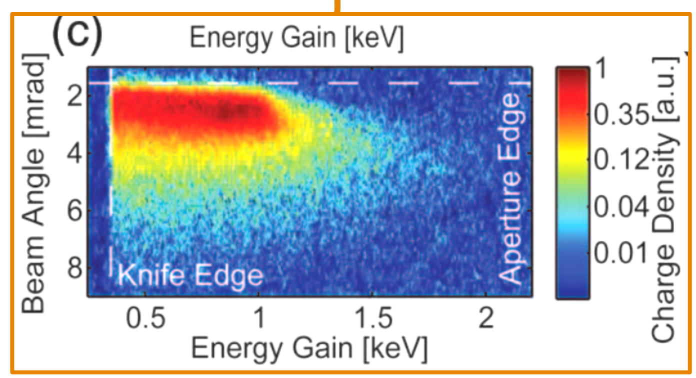




- 2D dual pillar DLA structures with improved accelerating field profiles.
- >370 MV/m for <100 keV (β~0.5).
- **highest gradient DLA for subrelativistic beams**.



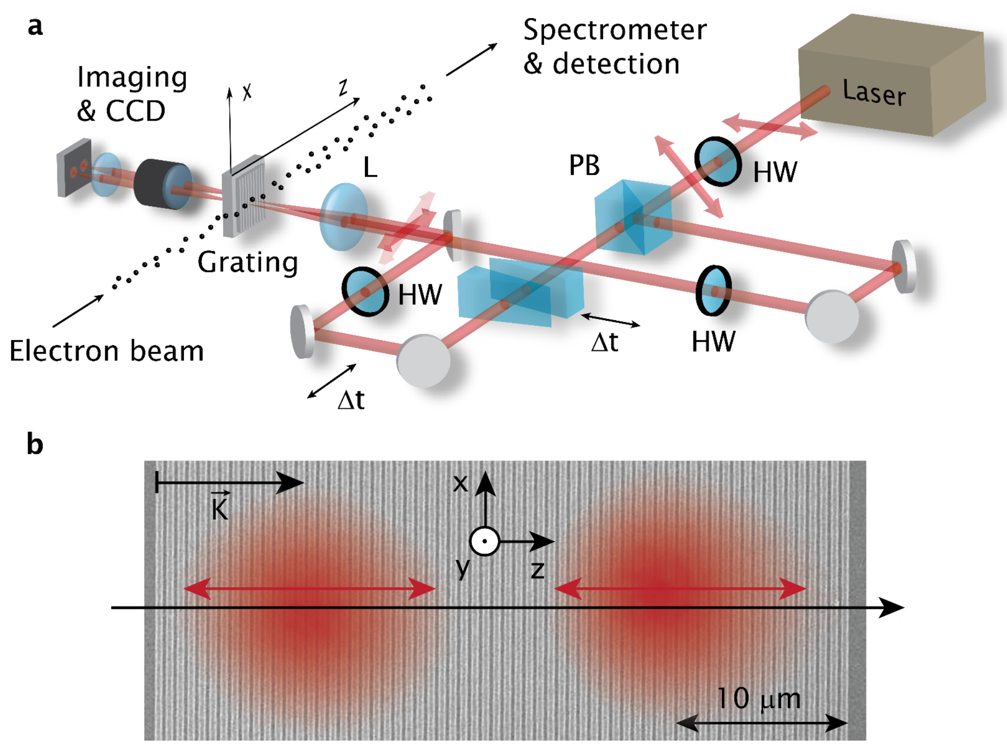


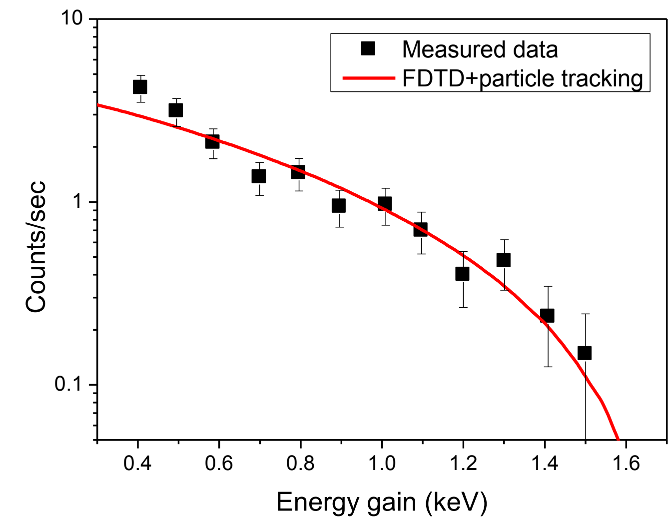
ACHIP

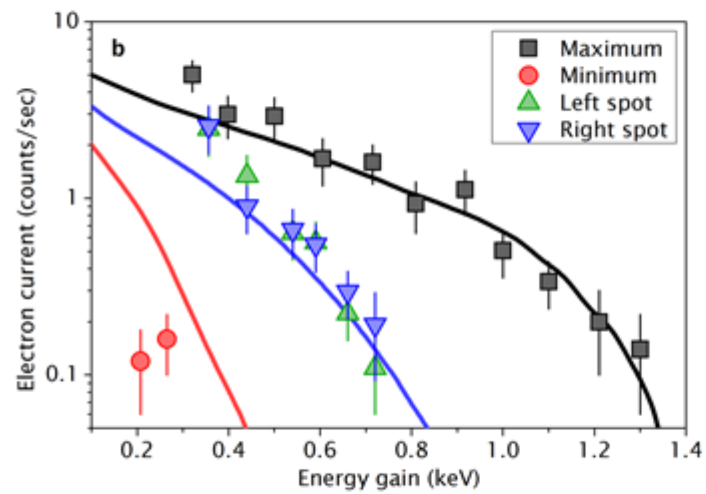
Stanford | ENGINEERING
Electrical Engineering

Leedle, Ceballos, et al., *Opt. Lett.* 40.18 (2015)

Staging of nonrelativistic beams has been achieved by colleagues in Germany.

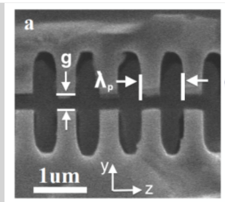
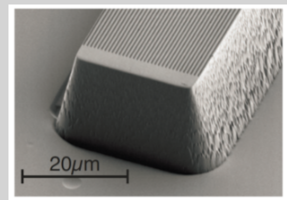
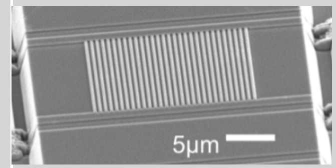
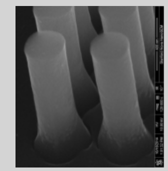






- Si grating instead of SiO_2
- 70 MV/m gradient for β = 0.3
- Staging with two laser pulses on a grating

Comparison of Recent DLA Acceleration Experiments

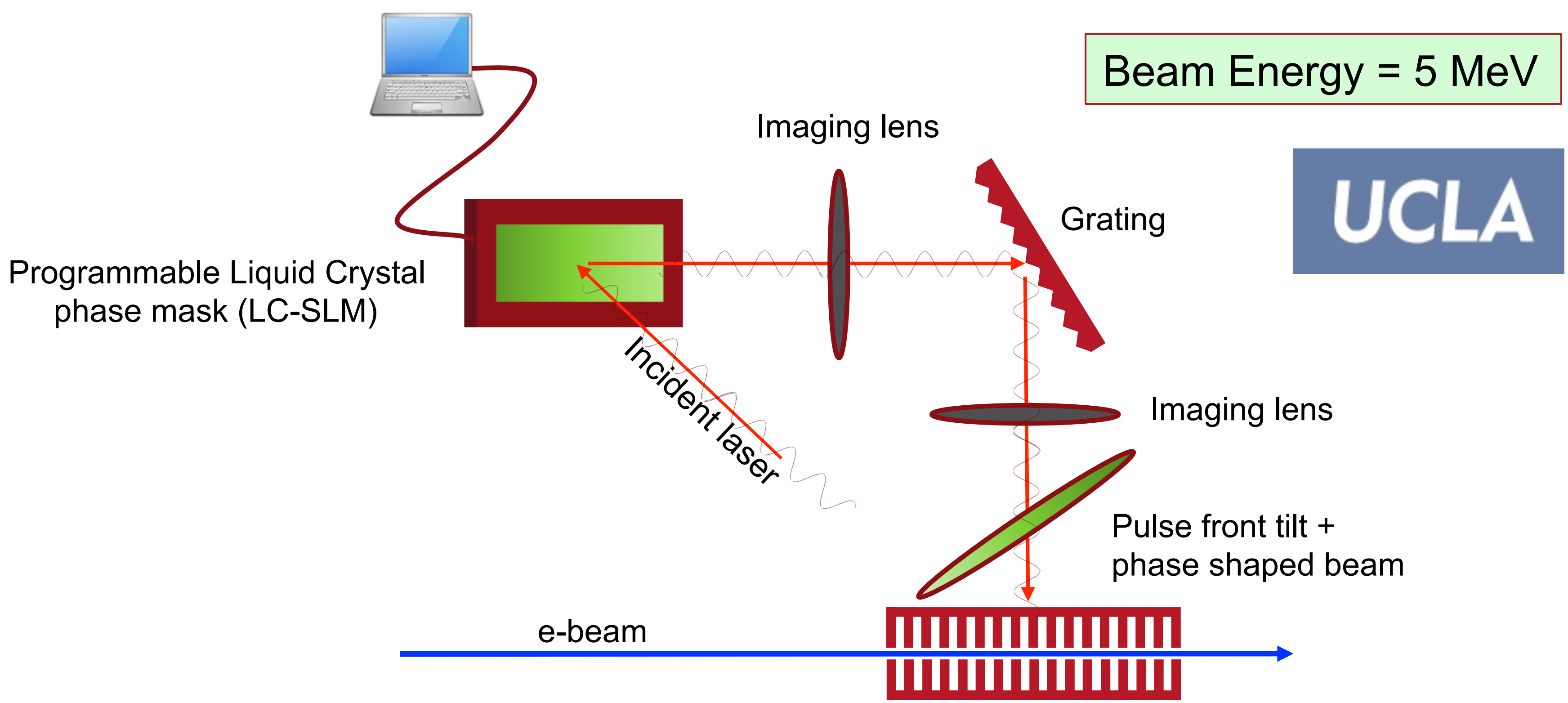
	SLAC & UCLA	Hommelhoff Erlangen	Stanford (Grating)	Stanford (Pillars)
				
Electron Energy	8 MeV	30 keV	96.3 keV	86.5keV
Relativistic β	0.998	0.33	0.54	0.52
Laser Energy	150 uJ	160 nJ	5.2 nJ	3.0 nJ
Pulse Length	40 fs	110 fs	130 fs	130 fs
Interaction Length	~20 um	11 um	5.6 um	5.6 um
Peak Laser Field	3.5 GV/m	2.85 GV/m	1.65 GV/m	~1.1 GV/m
Max Energy Gain	20 keV	0.275 keV	1.22 keV	2.05 keV
Max Acc Gradient	**0.85 GV/m***	25 MeV/m	220 MeV/m	**370 MeV/m**
G_{max}/E_p	~0.18	~0.01	~0.13	~0.4

* Preliminary and subject to change

So single micro-accelerator chips have been demonstrated at various particle energies. What's next?

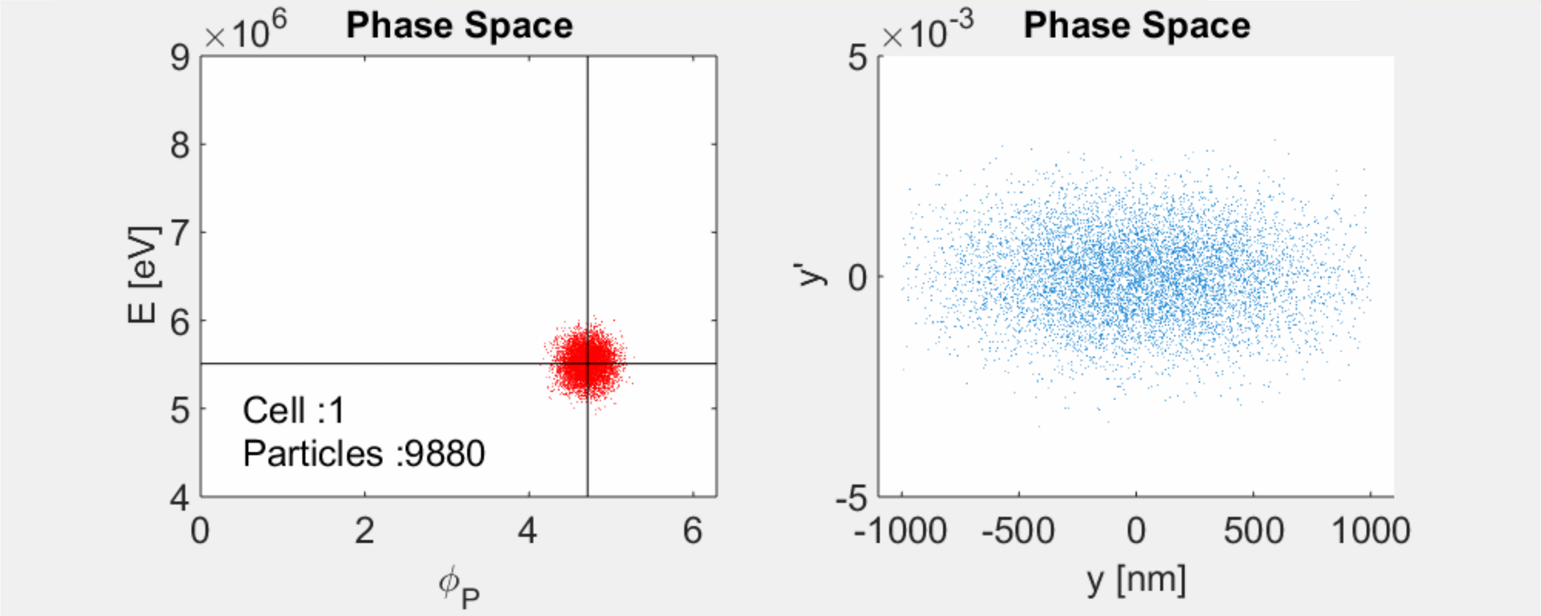
Proposed Experiment to Achieve Multi-MeV Energy Gain by Tapering the Phase Velocity of the Accelerator

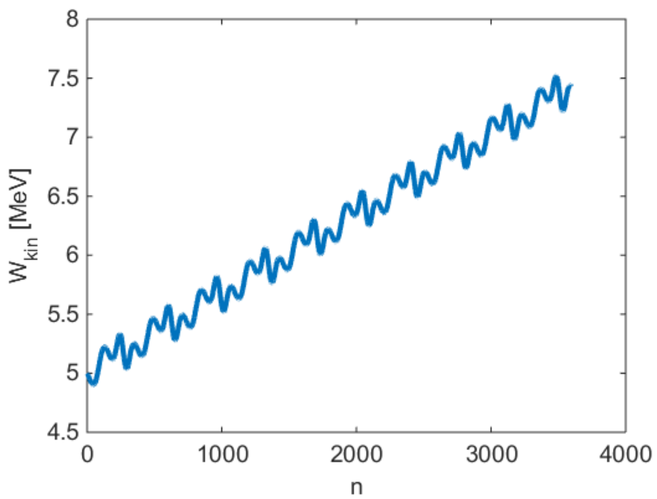
SLAC/UCLA Experiment to Demonstrate Acceleration in a 1cm Structure



- Proposed configuration for 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.**

DLATracker6D of Proposed UCLA Pegasus Programmable Phase Modulation Experiment





Initial electron energy: 5 MeV
Total Energy Gain: 2.5 MeV
Laser wavelength: 2 μm
Interaction length: 0.7cm

Simulation by U. Niedermayer

Developing systems with longer structures and multiple laser feeds…

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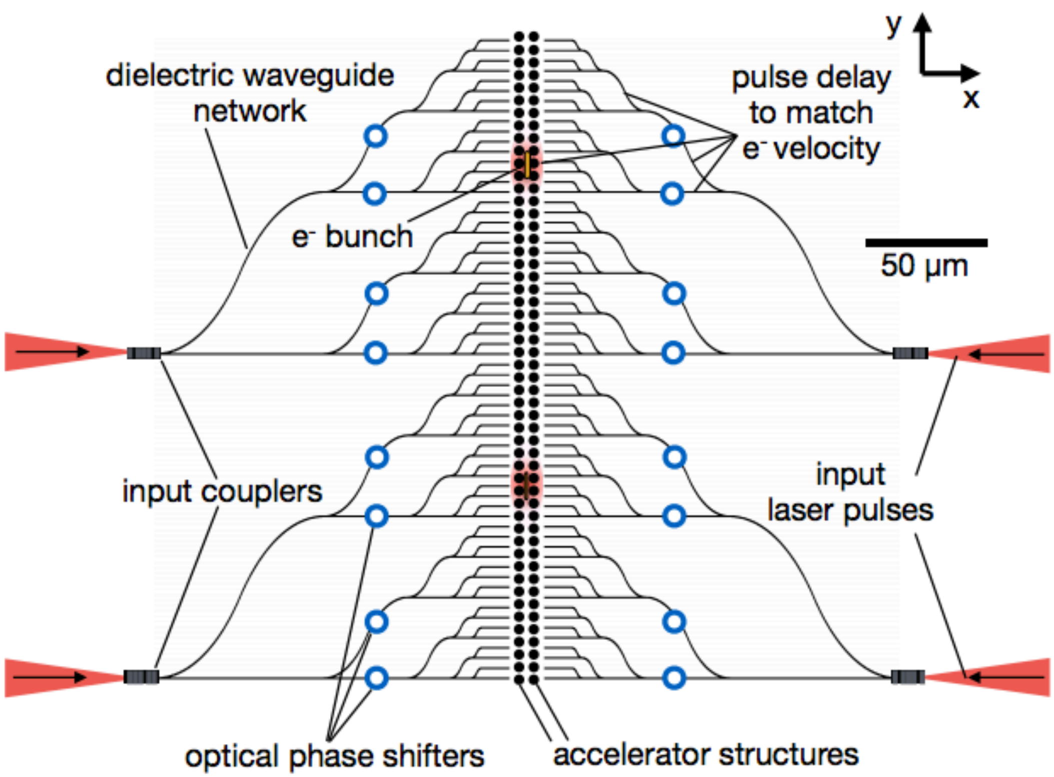
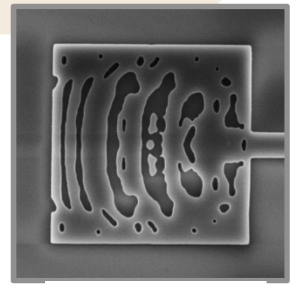
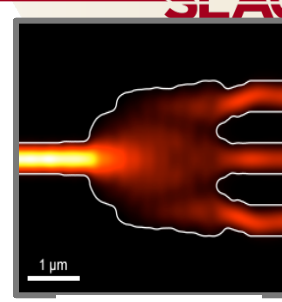
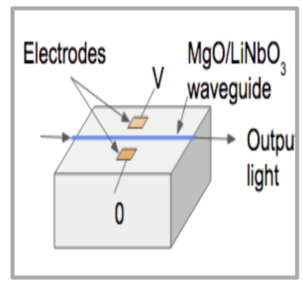




couplers



splitters



phase shifters

Purdue University

Stanford University

T. Hughes, et al. "On-Chip Laser Power Delivery System for Dielectric Laser Accelerators," submitted (2018)

- **Design Study of Integrated Multi-Stage DLA Network**
- **Realistic Component Parameters**
- **Adjoint Variable ("Inverse Design") Based Structure Optimizations**

combined with ultra-small electron sources that are well matched to the structures…

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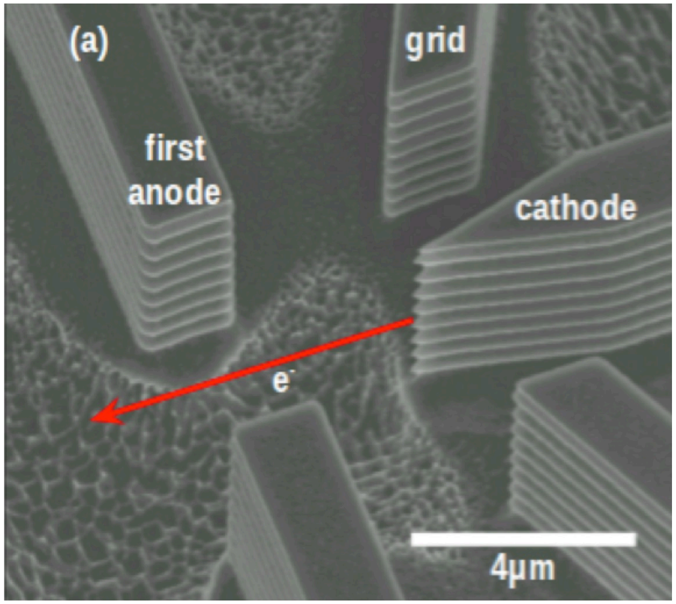
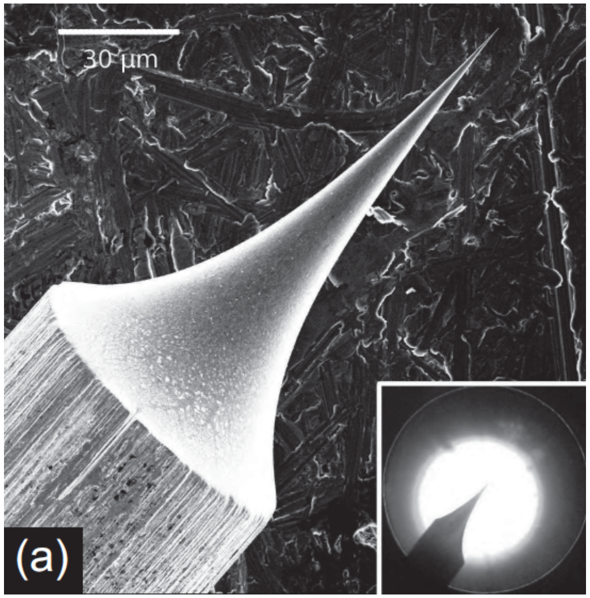


A. Ceballos, Solgaard group, Stanford EE Dept., Ginzton Lab

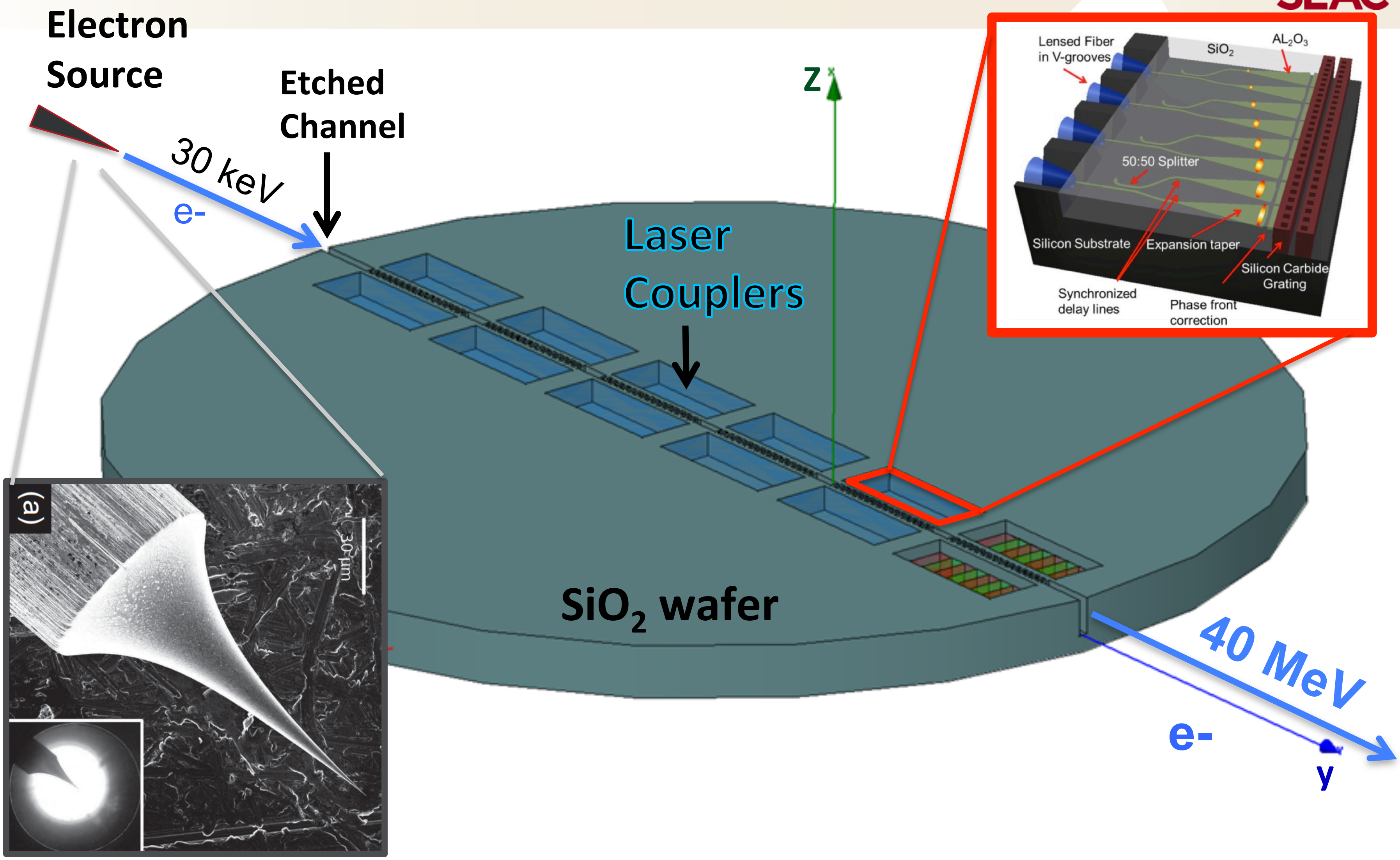


J. Hoffrogge et. al, “A tip-based source of femtosecond electron pulses at 30keV”. arXiv:1303.2383 (2013).

Integrated Si photocathode fabrication with lithographically defined vertical tip array + several additional electrodes in a tetrode configuration (grounded anode not shown).

30 keV electron pulses triggered by a 10 femtosecond 800nm Ti:Sapphire laser with up to 2000 electrons per pulse.

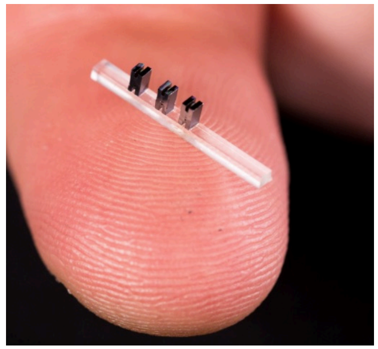
would pave the way for a multi-MeV device on a wafer in a 5 to 10 year timescale.



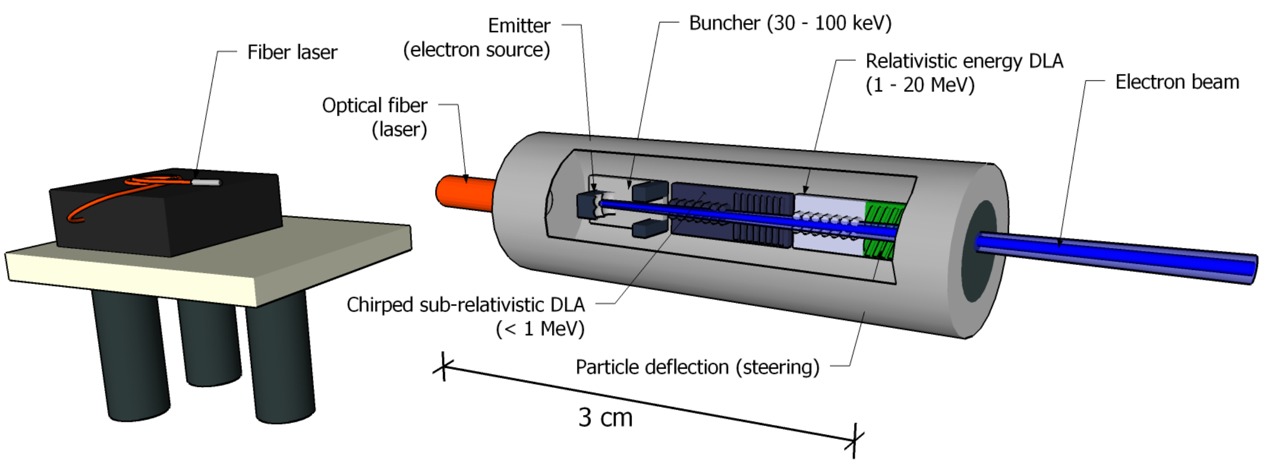
Such a system would have significant near-term applications, such as radiative cancer therapy.

conventional

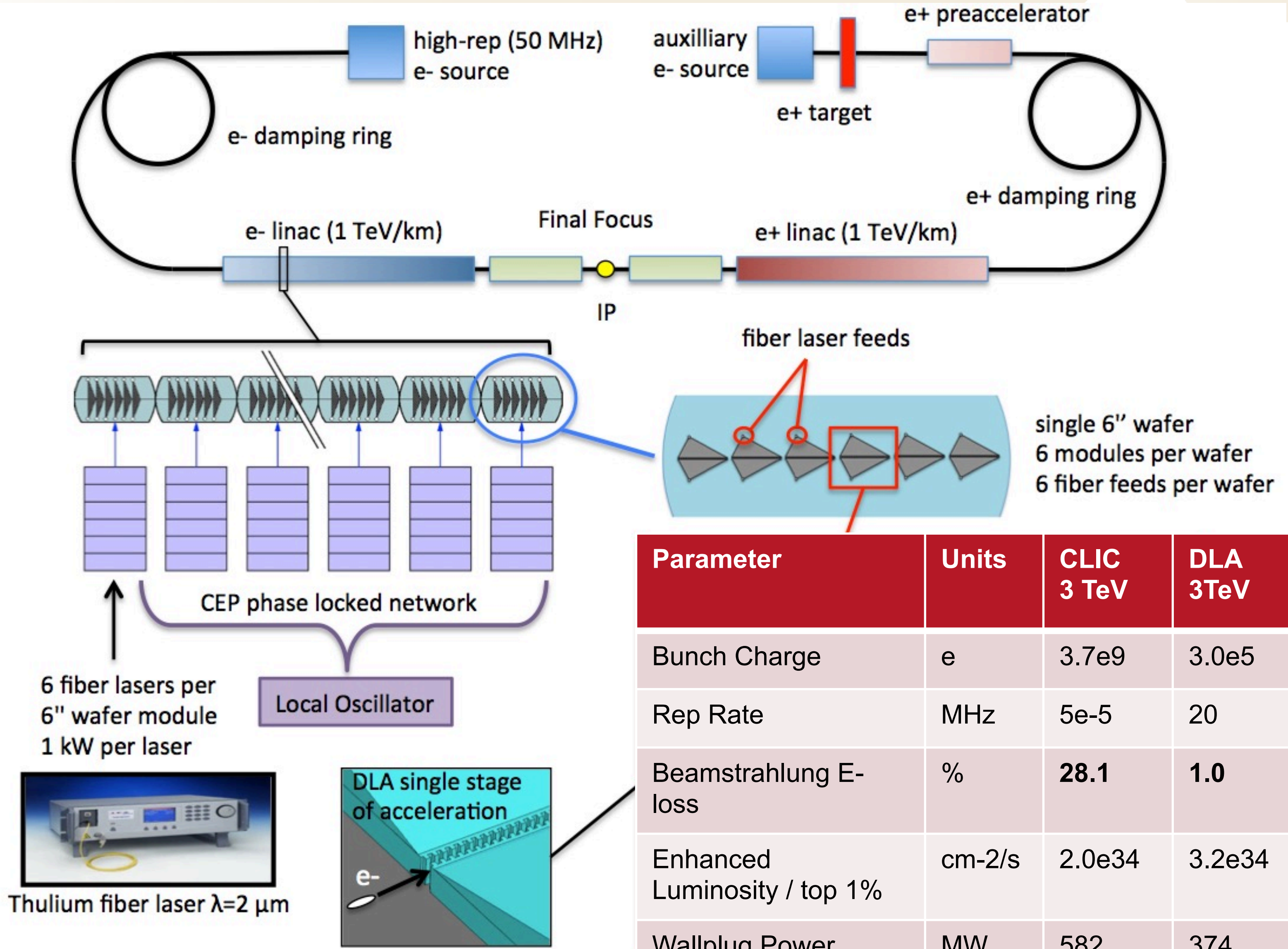
chip-based



- Chip-sized footprint could enable direct ebeam treatment (lower dose, quicker recovery time).
- Required electron current, energy, and power well suited to a single-wafer, single-laser design.



Future high energy physics facilities could be smaller and more affordable.



Parameter	Units	CLIC 3 TeV	DLA 3TeV	DLA 250 GeV
Bunch Charge	e	3.7e9	3.0e5	3.8e5
Rep Rate	MHz	5e-5	20	60
Beamstrahlung E-loss	%	**28.1**	**1.0**	**0.6**
Enhanced Luminosity / top 1%	cm-2/s	2.0e34	3.2e34	1.3e34
Wallplug Power	MW	582	374	152

A miniaturized attosecond light source could enable revolutionary new science capabilities.

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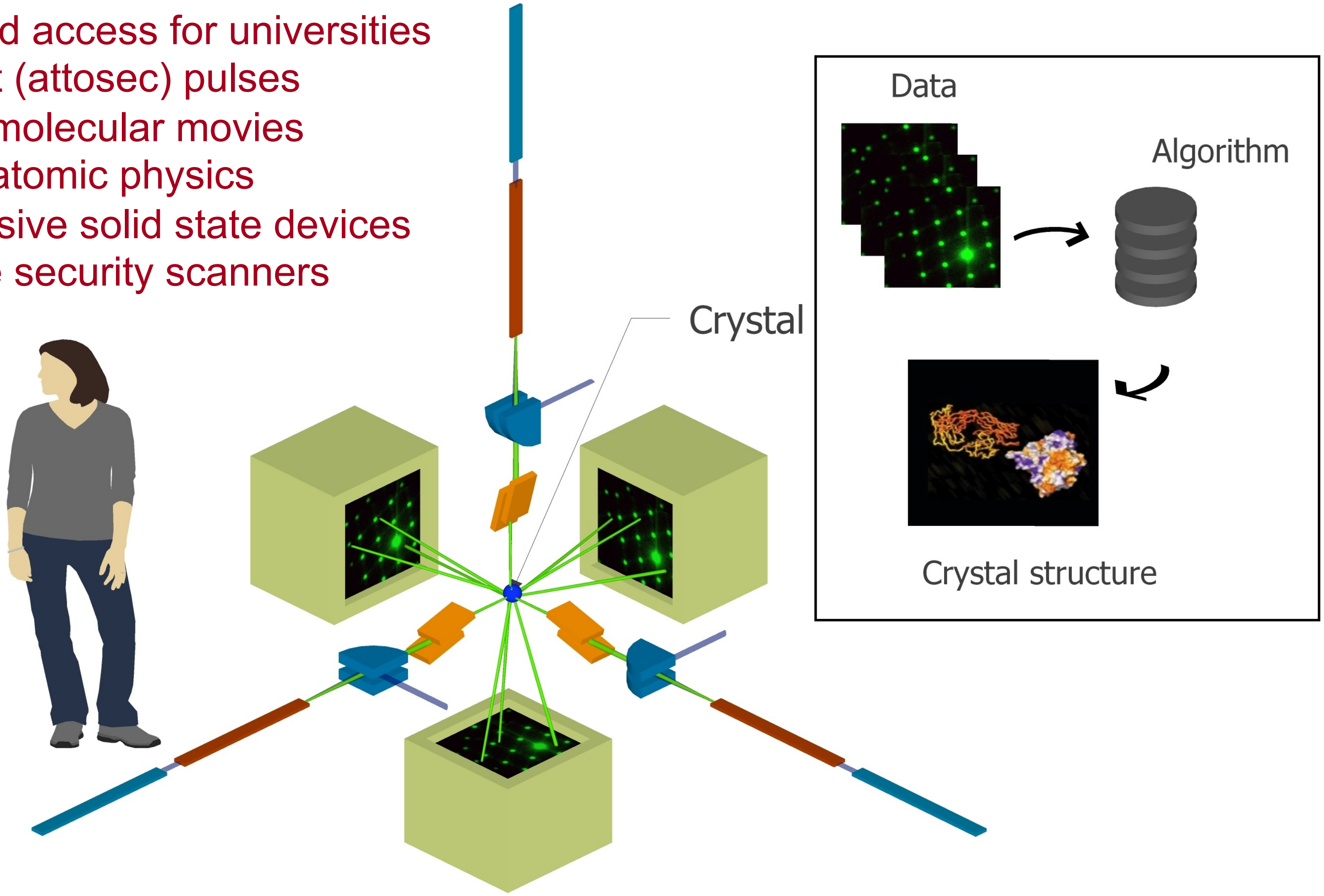
- Improved access for universities
- Ultrafast (attosec) pulses
  - molecular movies
  - atomic physics
- Inexpensive solid state devices
- Portable security scanners

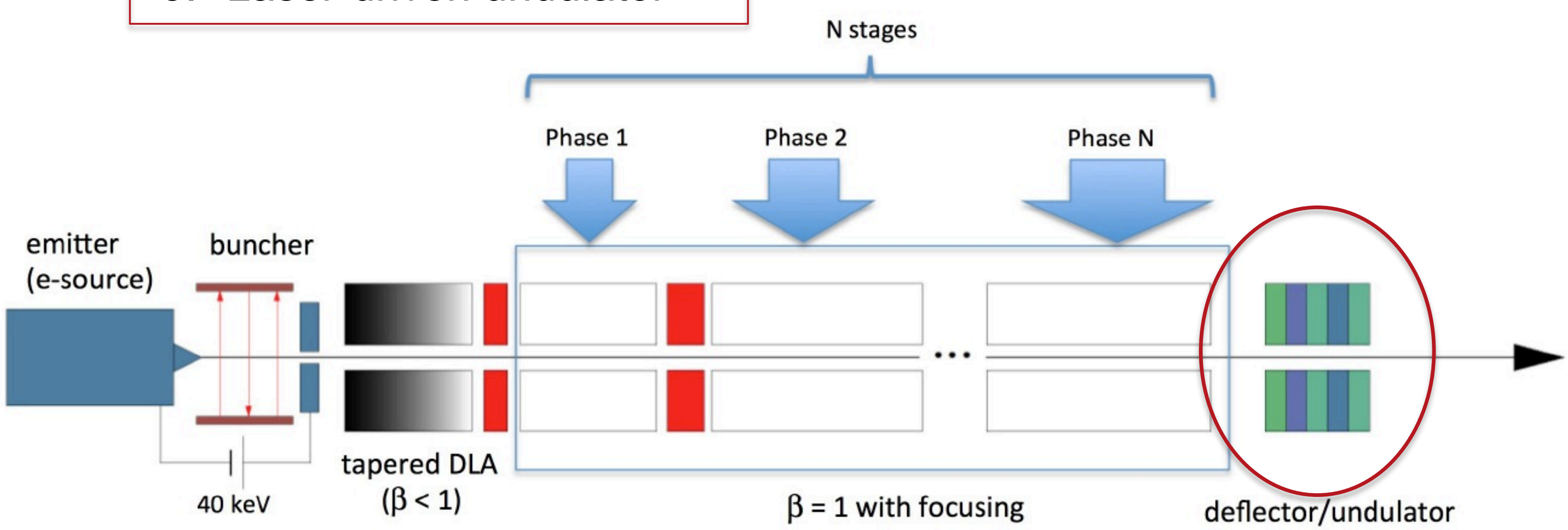


Concept for multi-axis ultrafast tomography with DLA based XFELs (K. Wootton)

Components of a DLA Light Source

Overall goal: The demonstration of an integrated multi-stage particle "accelerator on a chip" will validate the potential to scale to energy levels of interest for "real-world" applications.

1. On-chip electron source
2. DLA structure development: (a) subrelativistic, (b) relativistic
3. Multi-staged acceleration
4. Coupling of laser to DLA
5. Laser-driven undulator



What would be interesting about a DLA based light source?

Large facilities are often oversubscribed (e.g. LCLS has ~ 5 times more proposals than it can accommodate)

Compact footprint and reduced cost would give university labs and smaller facilities greater access (e.g. an FEL in every university)

Sub-optical wavelength **(attosecond) temporal bunch structure** if translated into sub-fs radiation pulses would be useful for ultrafast science (molecular movies, atomic physics).

Compact, **portable scanners** for security (Nuclear Fluorescence), phase contrast imaging, oncology, etc.

Could you make a deflector with a standard dual grating geometry?

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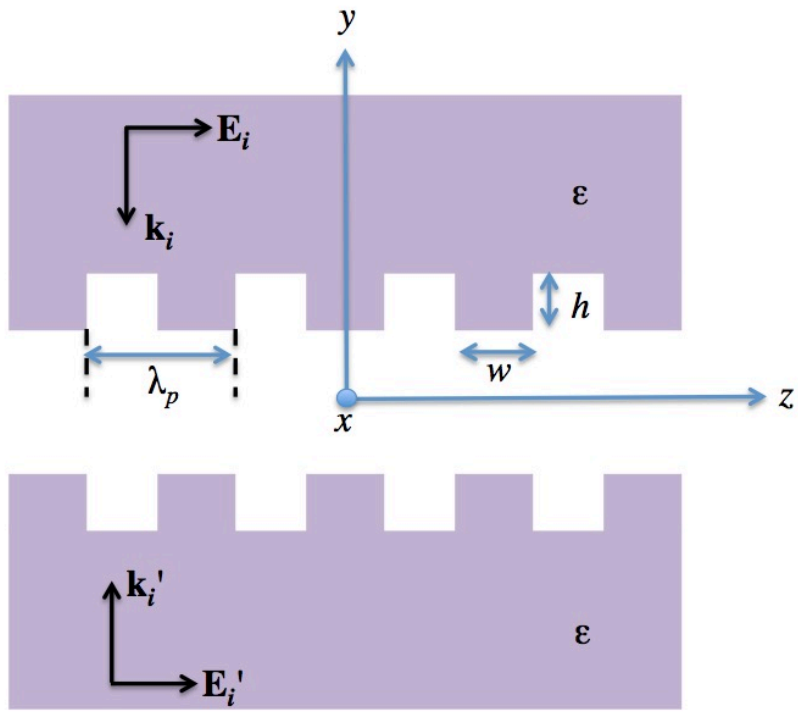

Fields excited by top laser $\mathbf{E_i}$:

$$\mathcal{E}_z = \frac{E_0}{2}\left\{c_1\, e^{\Gamma y} + c_2\, e^{-\Gamma y}\right\} e^{ikz}$$

Fields excited by bottom laser $\mathbf{E_i}$':

$$\mathcal{E}_z{}' = \frac{E_0}{2}\left\{c_1{}'\, e^{\Gamma y} + c_2{}'\, e^{-\Gamma y}\right\} e^{ikz}$$

symmetric excitations: $c_1 = c_2{}' \quad ; \quad c_2 = c_1{}'$

cosh mode: $E_z = \mathcal{E}_z + \mathcal{E}_z{}' = E_0(c_1 + c_2)\cosh(\Gamma y)\, e^{ikz}$

sinh mode: $E_z = \mathcal{E}_z - \mathcal{E}_z{}' = E_0(c_1 + c_2)\sinh(\Gamma y)\, e^{ikz}$

Transverse Forces: Single-Sided Illumination

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$$\frac{d\mathbf{p}}{dt} = \mathbf{F} = q\,(\mathbf{E} + \boldsymbol{\beta}\times\mathbf{B}) \qquad \boldsymbol{\beta}\times\mathbf{B} = \beta\,\hat{\mathbf{z}}\times\mathbf{B} = \beta\begin{cases} -B_y\,\hat{\mathbf{x}} & ;\ S-\text{polarization} \\ B_x\,\hat{\mathbf{y}} & ;\ P-\text{polarization} \end{cases}$$

$$\mathbf{F}_\perp = q\begin{cases} [E_x - \beta\,B_y]\,\hat{\mathbf{x}} & ;\ S-\text{polarization} \\ [E_y + \beta\,B_x]\,\hat{\mathbf{y}} & ;\ P-\text{polarization} \end{cases}$$

S (TE): $$\mathbf{F}_\perp = q\,E_0\,\hat{\mathbf{x}}\sum_n\left(1-\frac{\beta}{\beta_n}\right)\left[a_n\,e^{\Gamma_n y} + b_n\,e^{-\Gamma_n y}\right]e^{i\,k_n z}$$

P (TM): $$\mathbf{F}_\perp = -i\,q\,E_0\,\hat{\mathbf{y}}\sum_n\frac{k_n}{\Gamma_n}\,(1-\beta_n\,\beta)\left[a_n\,e^{\Gamma_n y} - b_n\,e^{-\Gamma_n y}\right]e^{i\,k_n z}$$

Including only resonant mode *n* = *r*, expanded to first order in y, where upper (lower) line is for S/TE (P/TM):

vanishes for synchronous particle

$$\mathbf{F}_\perp = q\,E_0\begin{Bmatrix} (1-\beta/\beta_r) \\ -i\,\frac{k_r}{\Gamma}\,(1-\beta_r\,\beta) \end{Bmatrix}\begin{Bmatrix} \hat{\mathbf{x}} \\ \hat{\mathbf{y}} \end{Bmatrix}[(a\pm b) + (a\mp b)\,\Gamma\,y]\,e^{i\phi}$$

Transverse Forces: Two-Sided Illumination

upper line = both lasers in-phase; lower line = lasers π out of phase

S (TE): $$\mathbf{F}_\perp = q\,E_0\,\hat{\mathbf{x}} \sum_n \left(1 - \frac{\beta}{\beta_n}\right)(a_n \pm b_n) \begin{Bmatrix} \cosh(\Gamma_n\, y) \\ \sinh(\Gamma_n\, y) \end{Bmatrix} e^{i\,k_n\,z}$$

P (TM): $$\mathbf{F}_\perp = -i\,q\,E_0\,\hat{\mathbf{y}} \sum_n \frac{k_n}{\Gamma_n}\,(1 - \beta\,\beta_n)\,(a_n \pm b_n) \begin{Bmatrix} \sinh(\Gamma_n\, y) \\ \cosh(\Gamma_n\, y) \end{Bmatrix} e^{i\,k_n\,z}$$

Including only resonant mode $n = r$, expanded to first order in y

$$\mathbf{F}_\perp = q\,E_0 \begin{Bmatrix} (1 - \beta/\beta_r) \\ -i\,\frac{k_r}{\Gamma}\,(1 - \beta_r\,\beta) \end{Bmatrix} \begin{Bmatrix} \hat{\mathbf{x}} \\ \hat{\mathbf{y}} \end{Bmatrix} [(a \pm b)]\, e^{i\,(k_r\,z - \omega\,t)} \quad ; \quad \Gamma g \ll 1,\ \beta \to 1$$

upper line: S-polarization; TE; lasers in-phase
lower line: P-polarization; TM; lasers π out of phase

Note: x-deflection from TE mode vanishes for resonant particle;
y-deflection for antisymmetric TM mode is also accelelerating

Non-symmetric excitation will produce a deflecting force on the beam; detrimental for longer structures

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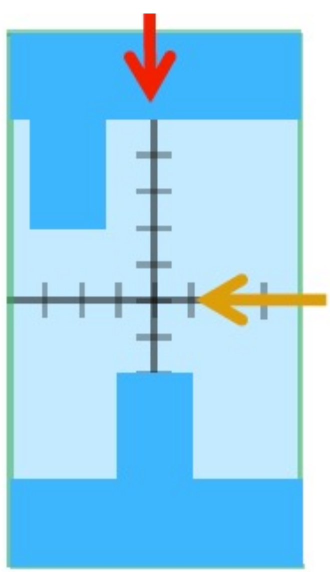
The more general form applies if the excitations are unequal in amplitude/ phase or the top-bottom teeth are misaligned:

$$E_z = \frac{E_0}{2}\left\{c_1\, e^{\Gamma y} + c_2\, e^{-\Gamma y}\right\} e^{ikz}$$

Expanding in a Taylor Series about the vertical dimension:



$$E_z \simeq \frac{E_0}{2}\{(c_1 + c_2) + (c_1 - c_2)\,\Gamma\, y\}\, e^{ikz}$$

acceleration

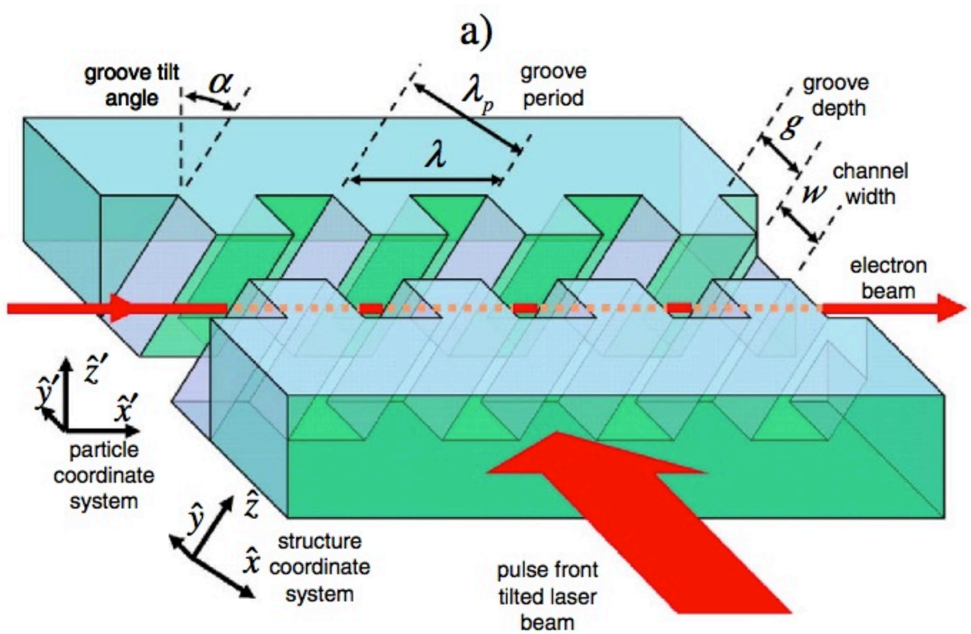
deflection

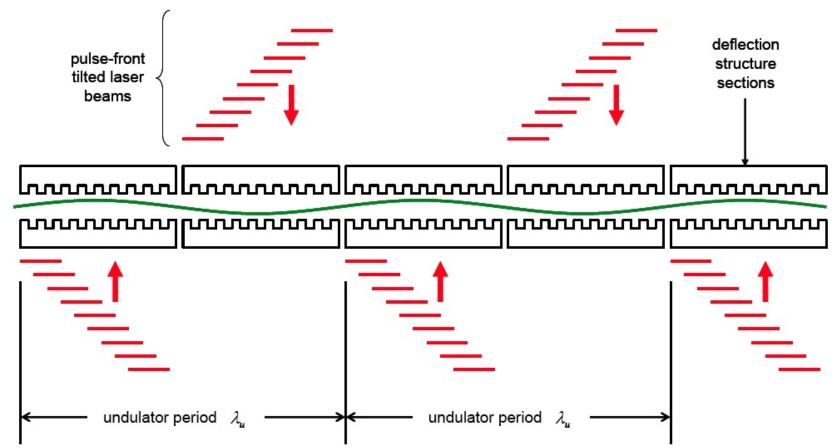
Panofsky Wenzel Theorem

$$\Delta \boldsymbol{p}_\perp \simeq -i\,\frac{e\,c}{\omega\, v}\int_0^{\ell} \boldsymbol{\nabla}_\perp E_z\, dz$$

Simulation studies with Lumerical and GPT tracking underway to see how this affects particle transmission

Tilted grating geometry allows for synchronous deflection





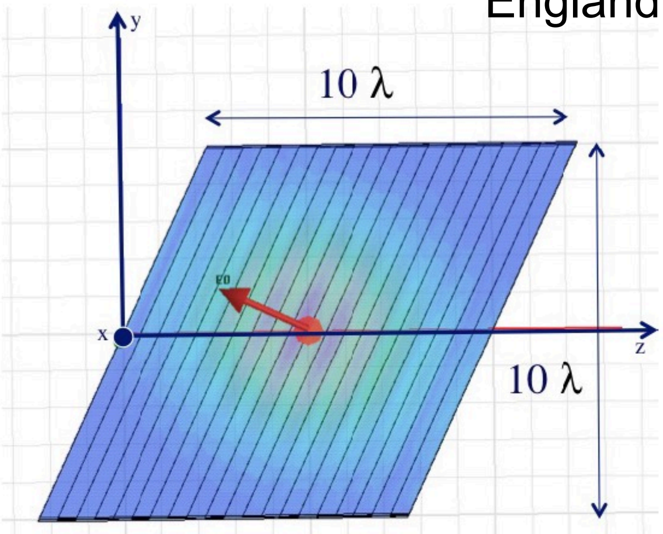
T. Plettner, R. Byer, PRSTB 11, 30704 (2008)

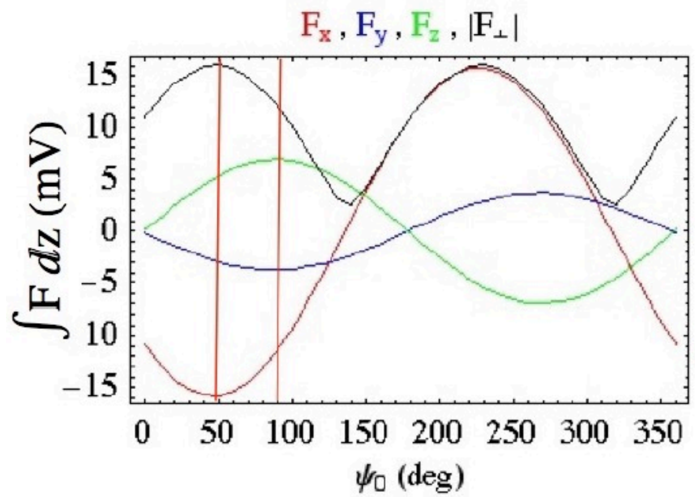
- Excitation via side illumination with pulsed laser
- Phase synchronous deflection of e-beam
- Undulator period can be many optical wavelengths λ
- Channel width w ~ λ/2 (limits max beam size)

Plettner, Byer, PRSTAB **11**, 030704 (2008).

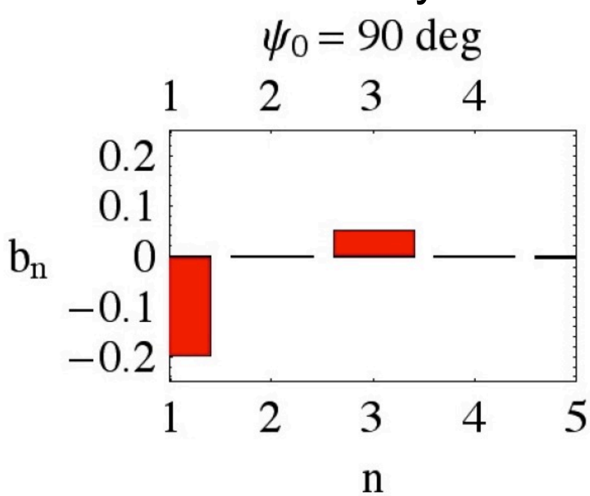
FEM Simulation of tilted grating deflector

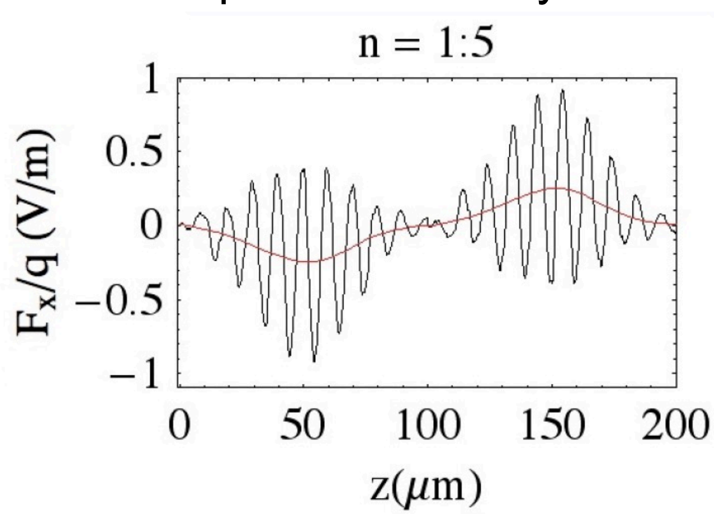
England, PAC 2013 – MOPAC28



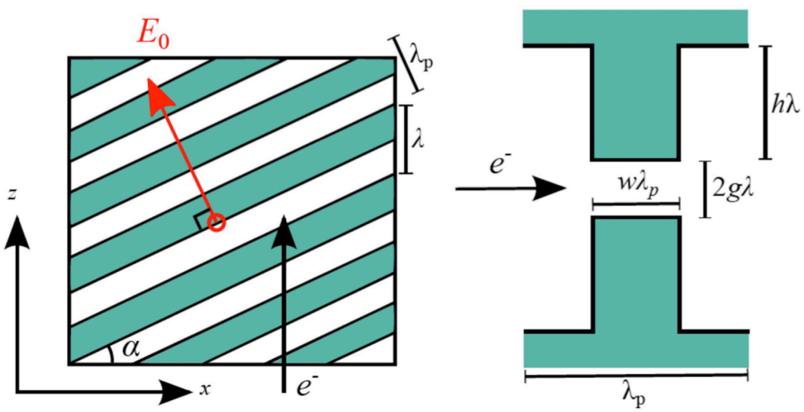


Harmonic analysis of one undulator period driven by two lasers:

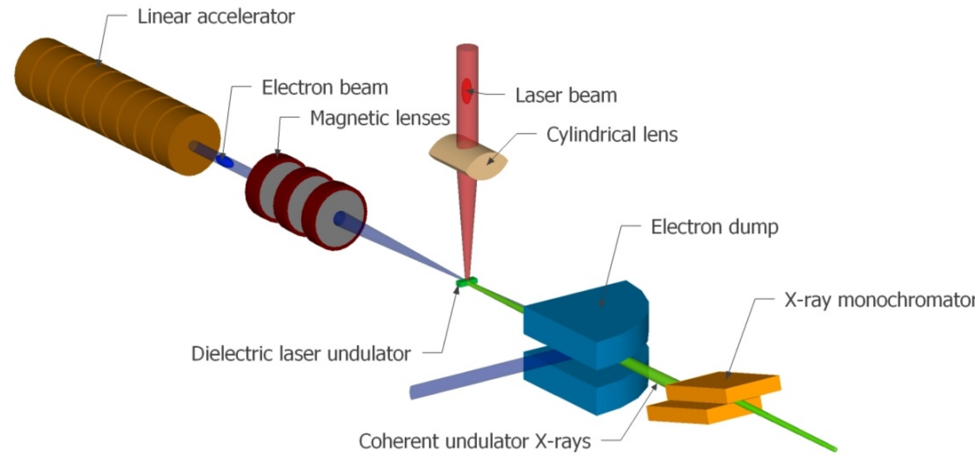




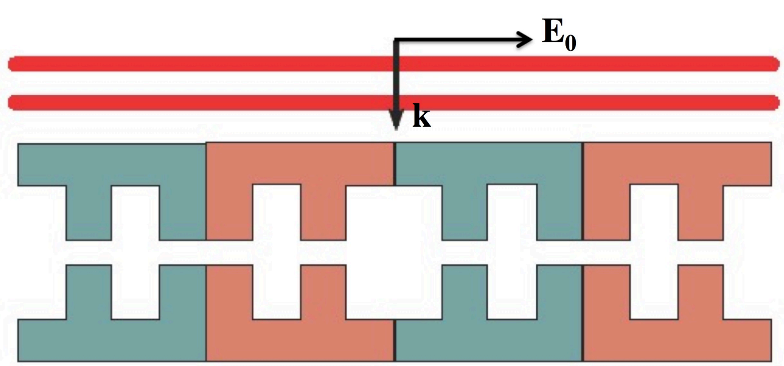
Introducing a periodic π phase shift could allow a single drive laser over many undulator periods.



Single undulator “half-period” deflector



Schematic of proposed experimental setup



Multi-period undulator concept

Parameter	Value	Units
e- energy	60	MeV
Undulator period	100	µm
N periods	10	
Undulator Effective B	4	T
X-ray wavelength	3.6	nm
Photon Flux	1340	photons/sec

K. Wootton, et al., IPAC 2015

DLA's attosecond bunch structure raises the possibility of making attosecond X-ray pulses

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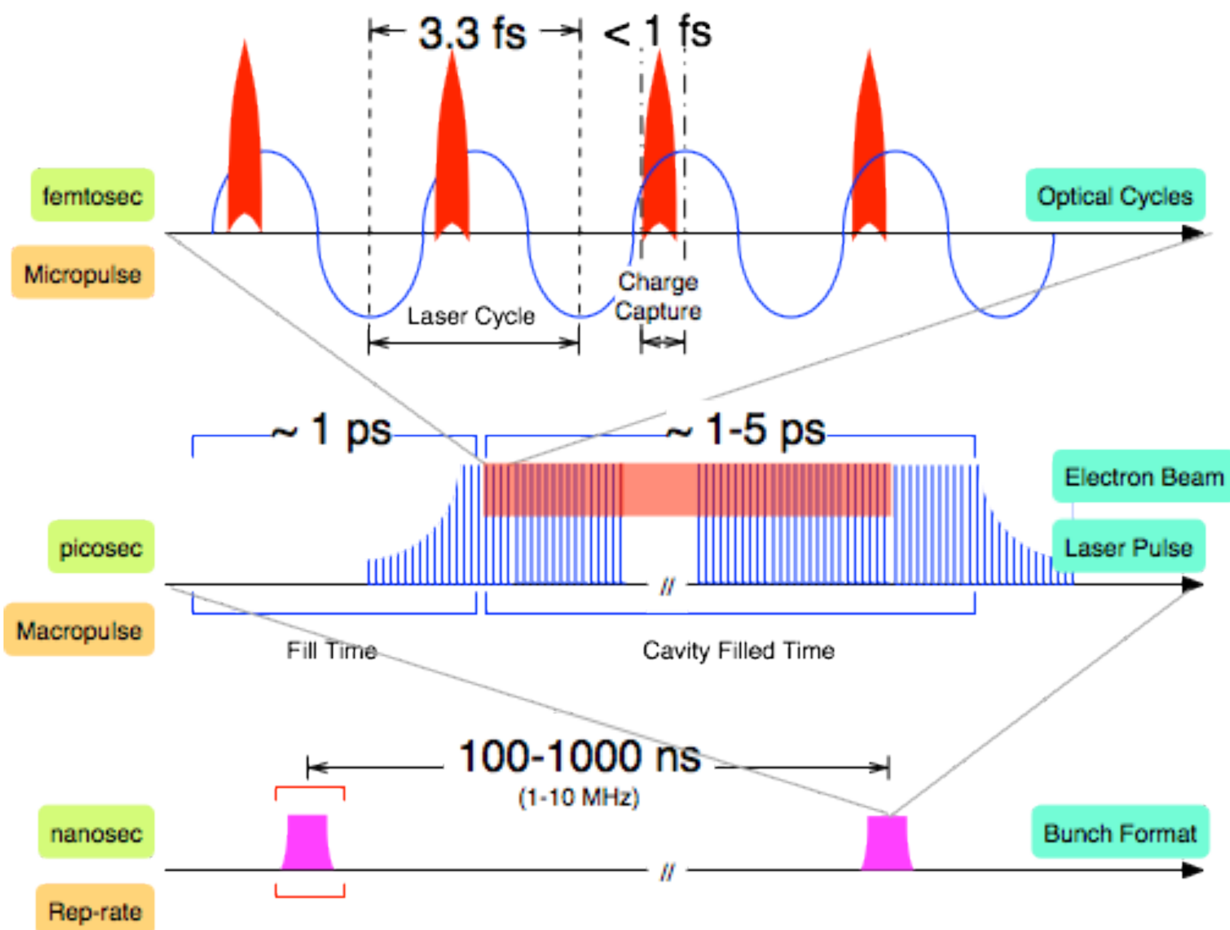
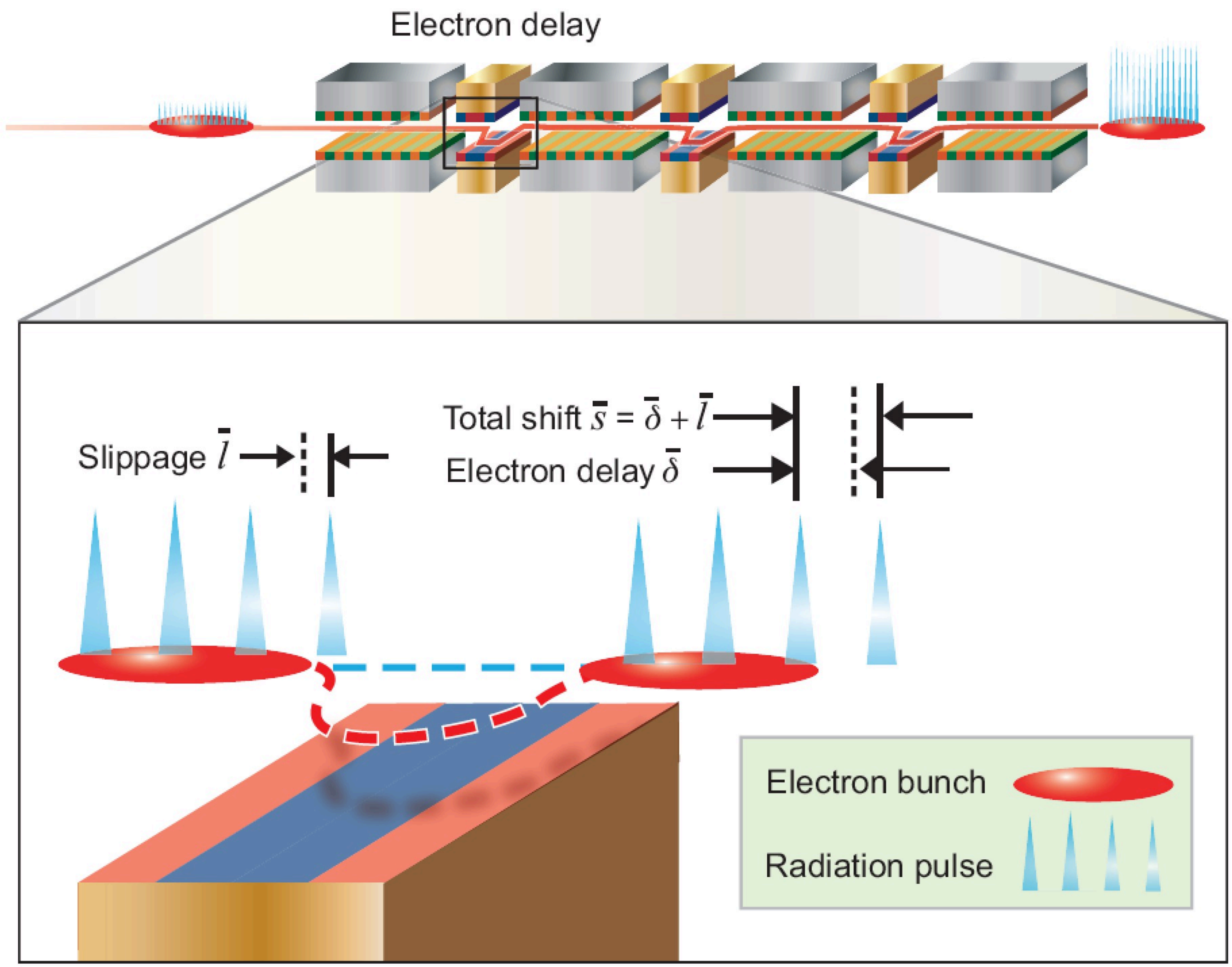
Optical structures naturally have sub-fs time scales and favor high repetition rate operation



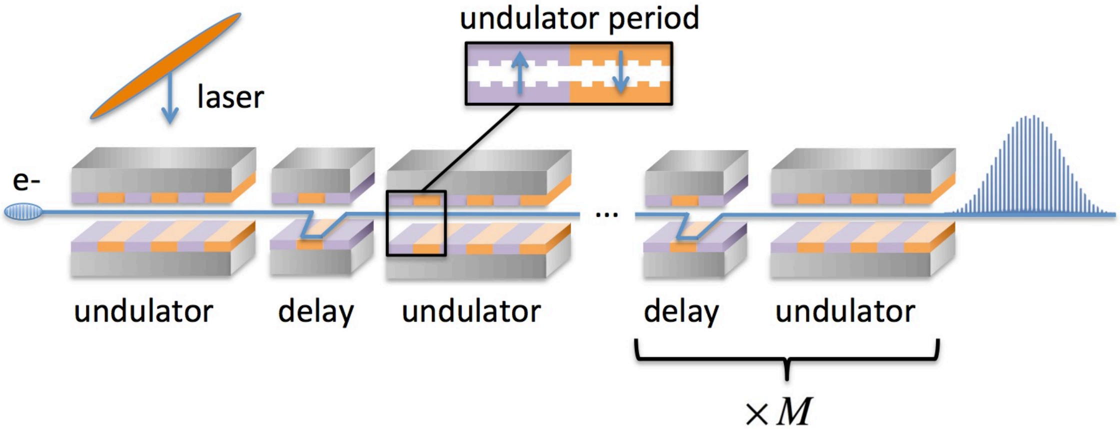
Method to preserve attosecond pulse structure in radiation from density modulated ebeam.

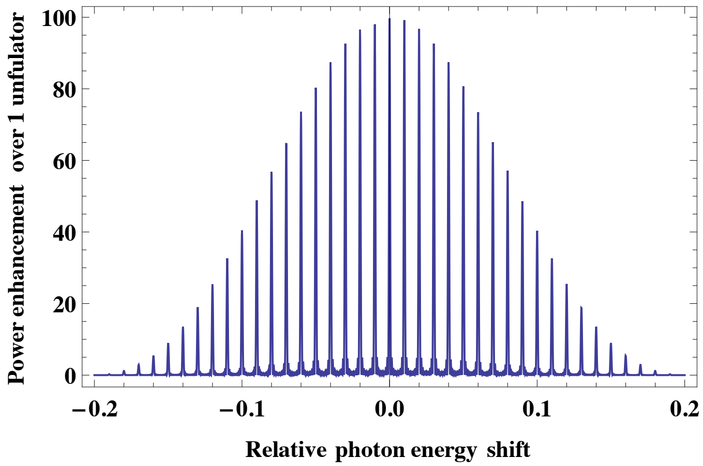


E. Kur, et al., New J. Phys **13** 063012 (2011).

EUV Attosecond Frequency Comb

Modelocking scheme proposed could enable attosecond radiation pulses (R. J. England, Z. Huang, these proceedings)





Parameter	Unit	Value
Beam Energy	MeV	40
Microbunch Charge	fC	10
Undulator Period	μm	250
Number of periods / Delay Modules	#	10 / 100
EUV Photon Energy	eV	50
Radiated Pulse Energy	nJ	100

DLA XFEL Strawman Parameter Table

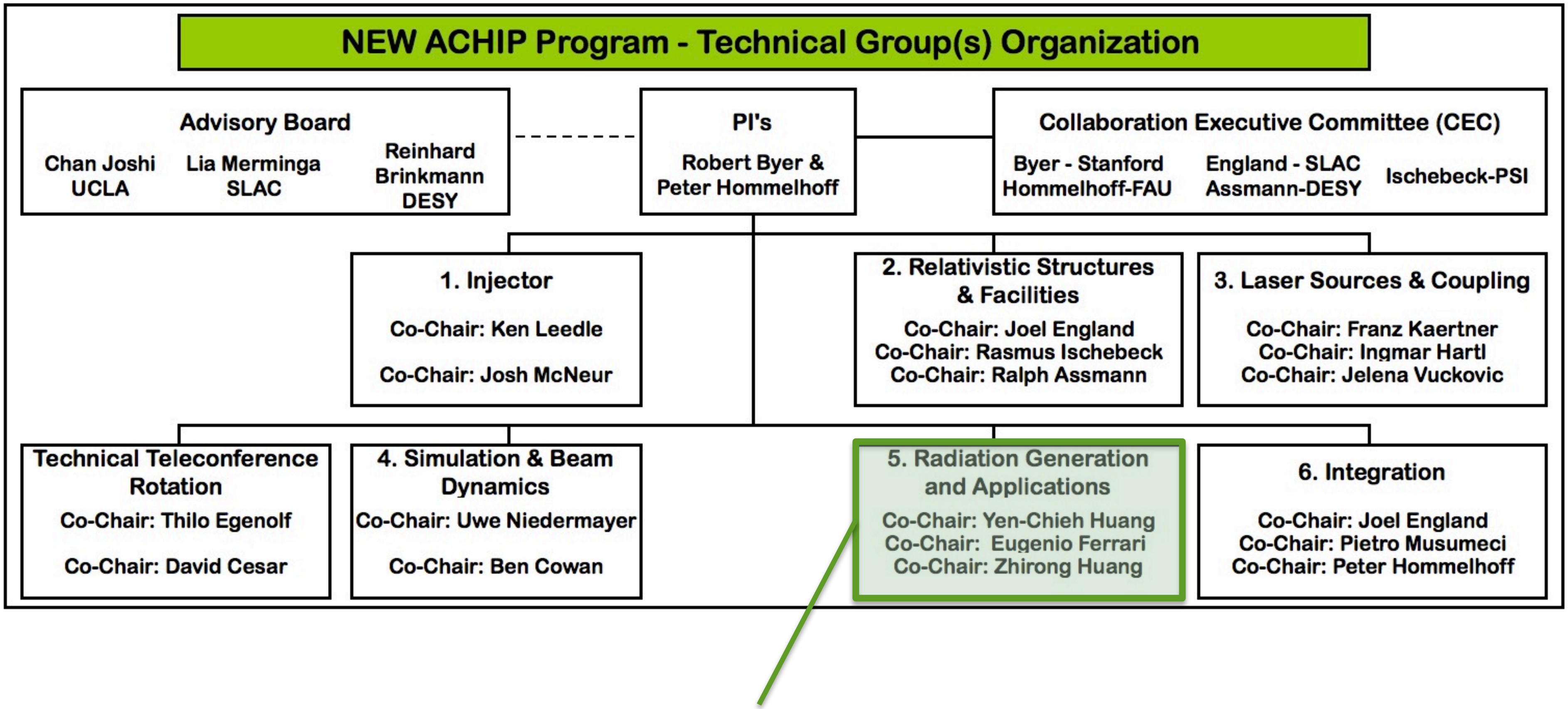
Parameter	Units	Value
Ebeam Energy	GeV	1.056
Microbunch Charge	fC	0.5
Bunches per Train		150
Rep Rate	MHz	100
Normalized Emittance	nm	0.87
Laser Wavelength	µm	2
Laser Pulse Duration	ps	1
Undulator Period	mm	0.9
Equivalent Undulator B	T	1.6
Undulator K		0.14
Pierce Parameter		2.29E-04
Undulator Length	m	0.9
Photon Energy	keV	11.5
Gain Length	m	0.18
Photons per Bunch		6.6E+04
Photon Flux	photons/sec	9.9E+14
Brightness	SBU*	1.05E+21

* 1 "SBU" = ph/s/mm^2/mrad^2/0.1%BW

A DLA X-ray source would be in or near the Quantum FEL regime:

$$\frac{\hbar\omega}{\gamma m c^2} = 10^{-5}$$

ACHIP Org Chart Year 3 – New Group Structure



Newly Added Radiation and Applications Group

DLA Applications Workshop, March 13

SLAC

Applications of Dielectric Laser Accelerators

13 March 2018

We are pleased to announce a one-day by-invitation-only meeting to be hosted on March 13, 2018 at Paul Scherrer Institut in Villigen, Switzerland. The goal of this meeting is to explore applications for a future compact dielectric micro-structure based accelerator powered by ultrafast solid state lasers. This approach to particle acceleration, colloquially referred to as an "accelerator on a chip", has garnered increasing interest in recent years.

Meeting Organizers:
Prof. Zhirong Huang (SLAC National Accelerator Laboratory)
Prof. Yenchieh Huang (National Tsing Hua University, Taiwan)
Dr. Eugenio Ferrari (Paul Scherrer Institute)

Host of Meeting at PSI: Dr. Rasmus Ischebeck

Starts 13 Mar 2018 08:00
Ends 13 Mar 2018 20:30
Europe/Zurich

Paul Scherrer Institute
OVGA/412
5232 Villigen, Switzerland

Conclusions

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Significant progress in DLA over the last few years:

Demonstrations of several structure types at different facilities
Gradients ~ 1 GV/m, energy gain > 0.3 MeV recently demonstrated
Staging with co-phased laser pulses on a single DLA

ACHIP: 5-Year Moore Foundation program in this area

6 University partners + 3 national labs (SLAC, DESY, PSI)
1 Industry partner (Tech-X)

Prospects for DLA-based Radiation Sources

Concepts for compatible laser-driven undulators exist.
Plans underway to fabricate and experimentally demonstrate them.
Preservation of attosecond pulses appears conceptually feasible.
Need to understand theory/simulation for DLA Quantum FEL regime.
New working group formed under ACHIP to tackle these challenges.

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Thank you!

Group photo, ACHIP collaboration meeting in Villigen, Switzerland, March 1-3, 2017.

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http://achip.stanford.edu
http://slac.stanford.edu/dla

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