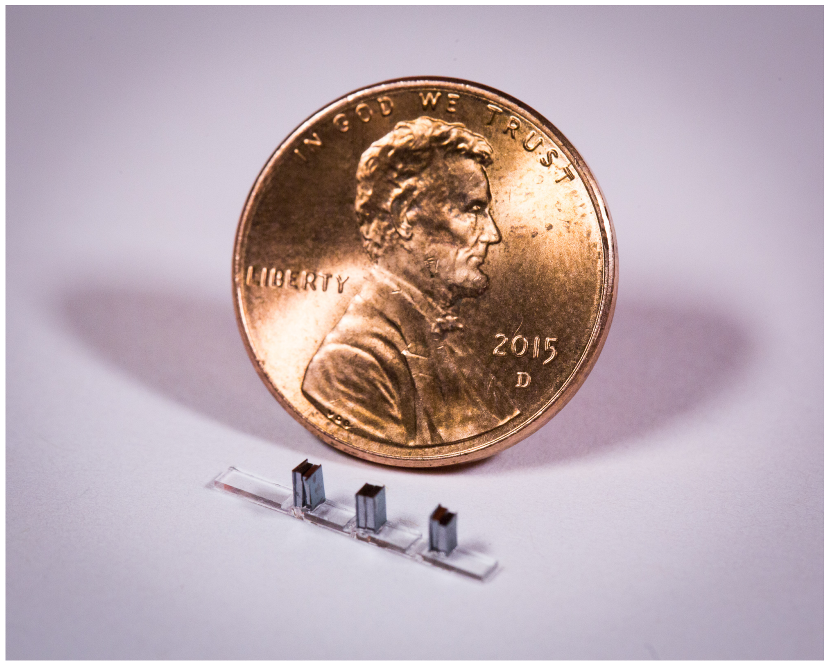
Considerations for Energy Scaling of Dielectric Laser Accelerators

R. Joel England (SLAC)



European Advanced Accelerator Concepts Workshop, Sept 25-29, 2017

New technologies have made micro-accelerators a possibility.

SLAC

High average power,
not high peak power lasers!

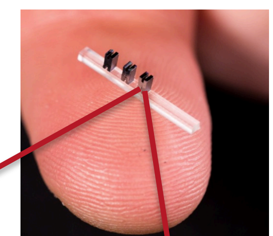
Parameter	DLA Value
Wavelength	**2 μm**
Pulse Duration	**100 fs**
Pulse Energy	**1 μJ**
Laser Power	**100 W**
Rep Rate	**100 MHz**
Laser Efficiency	**30%**
Cost/laser	**$150k**

Solid-state laser

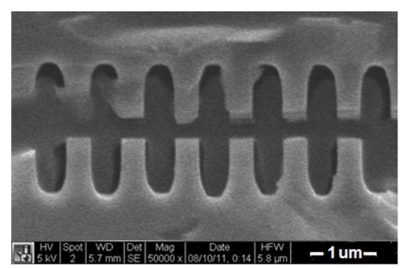
Available now
"off the shelf"

Fabricated using techniques of the integrated circuit industy.

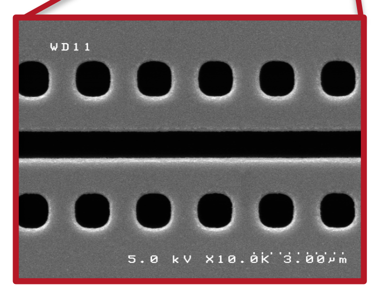
DLA structures are made by students in the Nanofabrication Facilities at partner universities.



SEM images of DLA prototypes tested at NLCTA



fused silica
(UV photolithography)



silicon
(DRIE)

Projected Beam Parameter Comparison with Conventional RF Accelerators

SLAC

Parameter	DLA	RF
Power Source	Commercial IR Laser	Microwave Klystron
Wavelength	1-10 µm	2-10 cm
Bunch Length	10-100 attosec	1-5ps
Bunch Charge	1-10 fC	0.1- 4 nC
Required Norm. Emittance	1-10 nm rad	0.1-1 µm rad
Rep Rate	10-100 MHz	1-1000 Hz
Confinement of Mode	Photonic Crystal (1D, 2D, 3D)	Metal Cavity
Material	Dielectric	Metal
Unloaded Gradient	1-10 GV/m	30-100 MV/m
Power Coupling Method	Free-space/ Silicon WG	Critically-coupled metal WG

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

SLAC

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

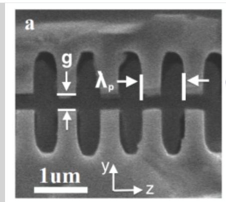
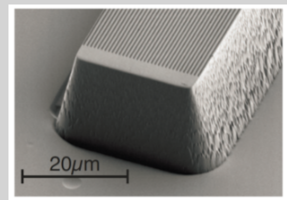
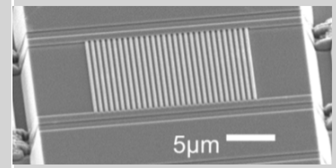
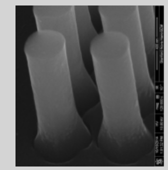
External Collaborators
J. Rosenzweig (UCLA)
E. Simakov (LANL)
Y-C. Huang (Tsing Hua)
Z. Huang (SLAC)

Relativistic DLA experiments
SLAC: England
UCLA: Musumeci
DESY/UnivHH: Assmann,
PSI/EPFL: Ischebeck

Industrial Affiliates
Hamammatsu

See plenary talk by R. Ischebeck, Monday 10:00am

Comparison of Recent DLA Acceleration Experiments

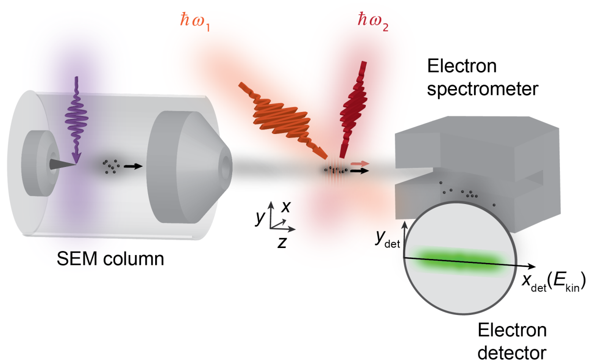
	SLAC & UCLA	Hommelhoff Erlangen	Stanford (Grating)	Stanford (Pillars)
				
Electron Energy	8 MeV	30 keV	96.3 keV	86.5keV
Relativistic β	0.998	0.33	0.54	0.52
Laser Energy	150 uJ	160 nJ	5.2 nJ	3.0 nJ
Pulse Length	40 fs	110 fs	130 fs	130 fs
Interaction Length	~20 um	11 um	5.6 um	5.6 um
Peak Laser Field	10 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

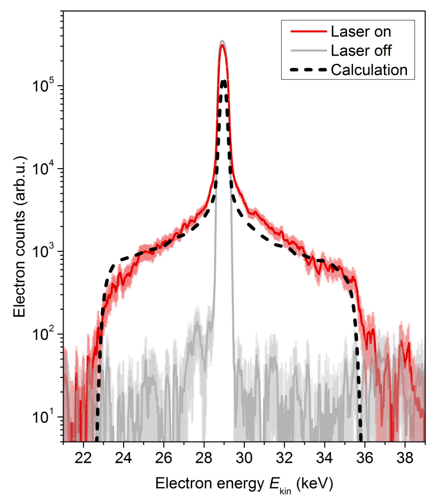
* Preliminary and subject to change

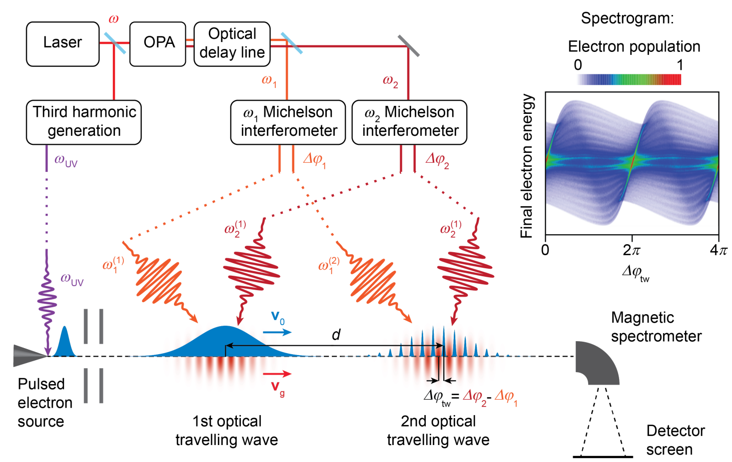
Electron Sources: efficient acceleration and longitudinal phase-space manipulation with electrons

Inelastic electron scattering at a ponderomotive potential of an optical travelling wave in vacuum

Generation and detection of attosecond electron pulse trains







Max. observed gradient: **G=2.2 GeV/m**

Accepted for publication in Nature Physics

In preparation for submission

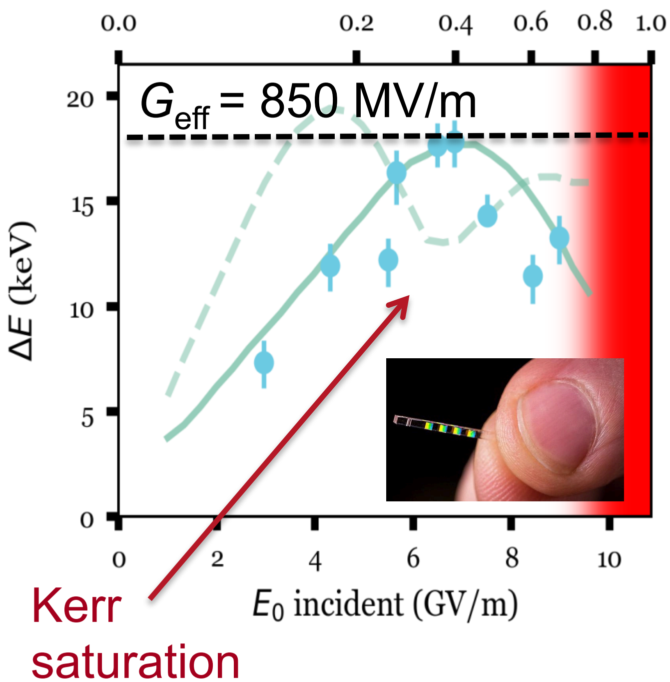
M2.2 Demonstrate gradients >600 MV/m at sub--- relativistic energy and > 1 GV/m at relativistic energy with energy gain ≥ 1 MeV

M1.4 Demonstrate <100 as bunches and successful injection into multi-staged DLA

Further development of the femtosecond laser-triggered SEM for DLA experiments

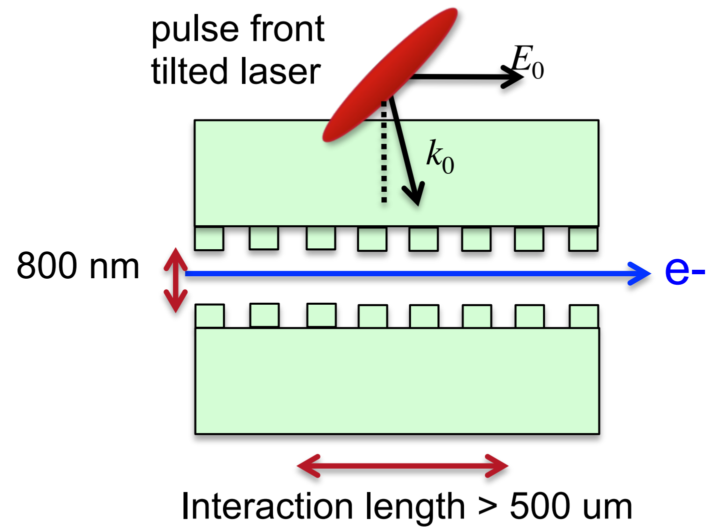
Relativistic Acceleration Highlights

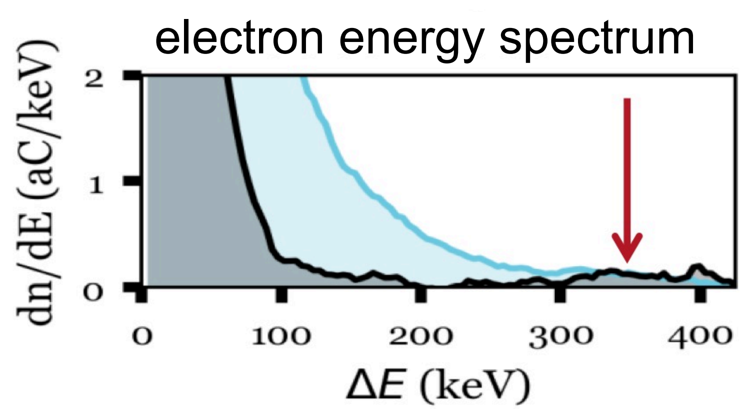
UCLA/SLAC:
Accelerating Field: 1.8 GV/m
Effective Gradient: 0.85 GeV/m*



* submitted (2017) ; ** in preparation (2017)

UCLA/SLAC: 0.3 MeV energy gain**





See talk by D. Cesar, Thursday 4:40pm

Summary of Recent ACHIP Progress Highlights

- → Designs and fabrication prototypes for **compact nano-tip sources** (LaB6, Si, Tungsten) + HV test stations online at Erlangen and Stanford.
- → Sub-relativistic vacuum acceleration with **2.2 GeV/m gradients and attosecond-scale bunching** demonstrated.
- → Design, fabrication, and simulation of new sine-mode buncher+accelerator injector concept; experimental testing to begin soon.
- → Orpheus laser system installed and new Stanford lab space in operation with **dual laser drive** phase-dependent acceleration & deflection demonstrated.
- → Relativistic electron probing of 1.8 GV/m accelerating fields with **0.85 GeV/m** effective gradients and dispersion compensation of nonlinear effects.
- → Pulse front tilt demonstration with record **300 keV energy gains** at Pegasus.
- → First experiments at SwissFEL facility injector: sample irradiation studies.
- → Plans, resource needs, and simulation studies conducted for microbunching, net acceleration, and deflection experiments at DESY SINBAD.
- → On-chip waveguide, coupler, and splitter designs developed based on inverse design and AVM methods, incorporated into **realistic design study of a 1 MeV accelerator**.
- → LIDT at 1.5, 2μm show promising damage thresholds for candidate materials.
- → **Roadmap for start-to-end simulations**; 6D DLA tracking code developed.

DLA is a promising new approach to particle acceleration with a range of potential applications

DLA 2011 ICFA workshop at SLAC: over 50 scientists from relevant fields (lasers, photonics, accelerators).

Conclusions:

No major roadblocks to scale DLA to higher energies using existing laser technology.

Compact footprint and reduced cost would give university labs and smaller facilities greater access.

Sub-optical wavelength **(attosecond) temporal bunch structure** translated into sub-fs radiation pulses could enable ultrafast science (molecular movies, atomic physics).

Compact **portable scanners and radiation sources** for medicine (e.g. direct e-beam oncology), security (Nuclear Fluorescence Imaging), phase contrast imaging, etc.

E. R. Colby and L. K. Len (DoE, Office of Science – HEP)

"As with the other advanced concepts, the primary challenges are to

(1) demonstrate the practical gradient limit (believed to be >1GeV/m),
(2) demonstrate operation at a very high repetition rate and discover the practical bunch charge limits of such devices (required to produce useful beam power for most applications),
(3) demonstrate practical technologies for accelerating structures, beam focusing, bending, and diagnosis,
(4) develop techniques for achieving the submicron-class alignment required to preserve emittance,
(5) develop electron and positron sources matched to the unique phase space requirements, and
(6) develop fully compatible, high-efficiency laser sources.

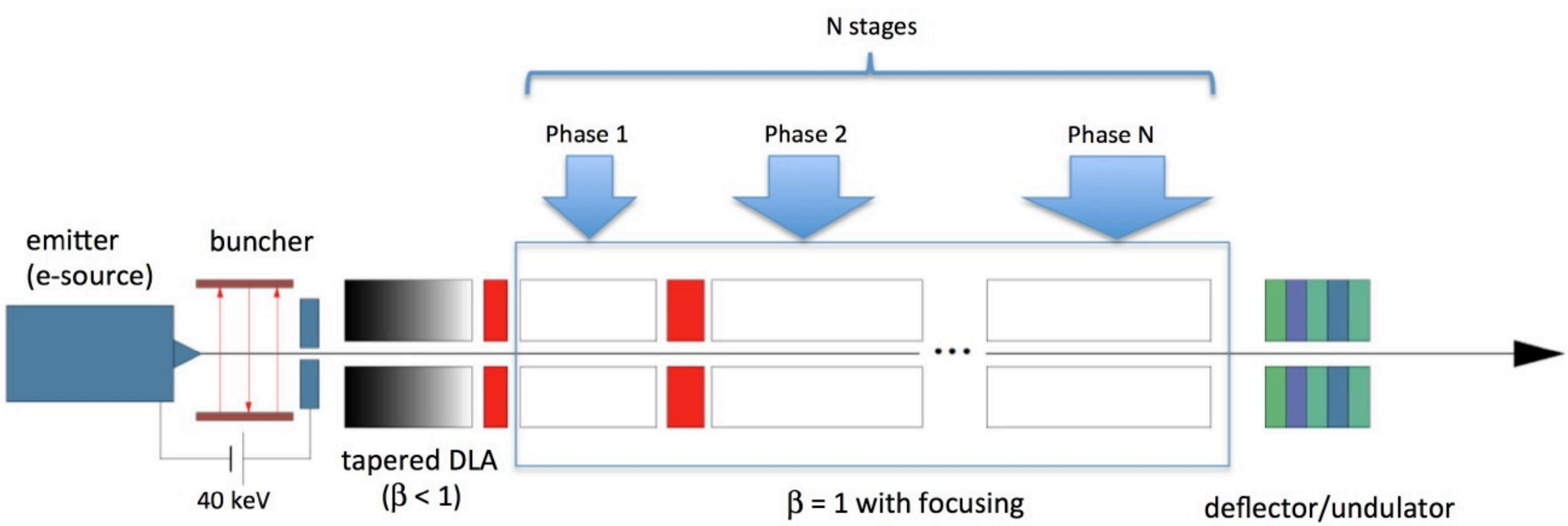
- Of these activities, (1) and (3) have received the most attention to date.
- For this technology to move forward to near-term applications, (2), (5) and (6) must be addressed.
- The intrinsic attosecond- and micronscale operation of the DLA could potentially offer synchronized attosecond sources of electrons and radiation (e.g. THz, visible, X-rays) that provide the tools for directly monitoring and *controlling* chemical reactions."

E. R. Colby & L. K. Len, "Roadmap to the Future," Rev. Accel. Sci. Technol., 09, 1-18 (2016)

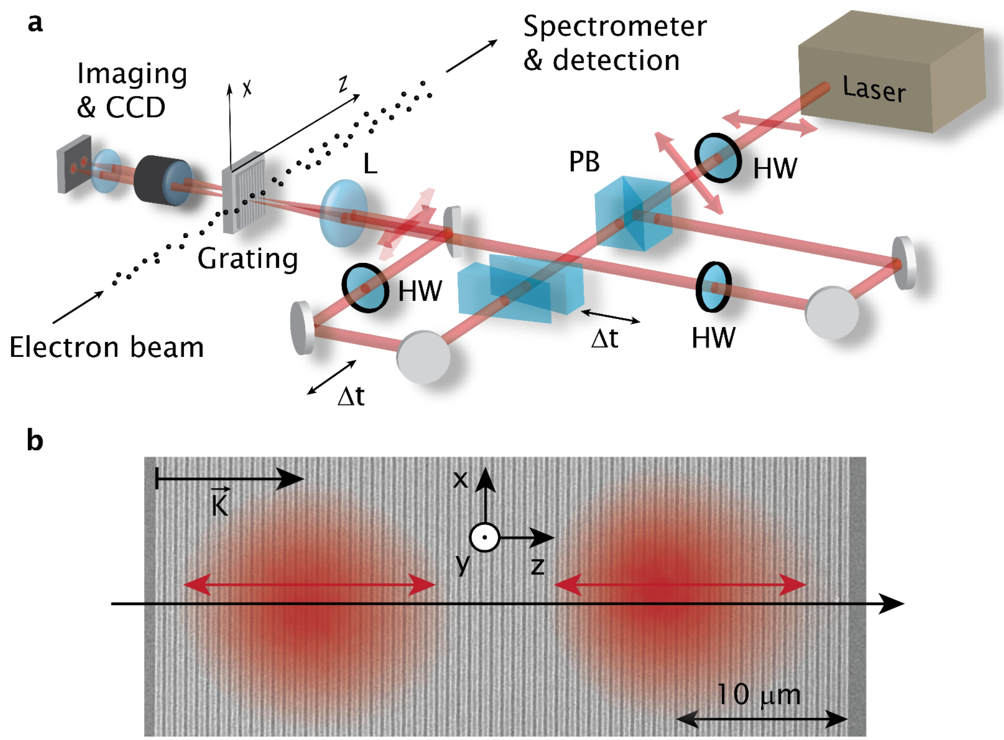
What do we mean by Energy Scaling?

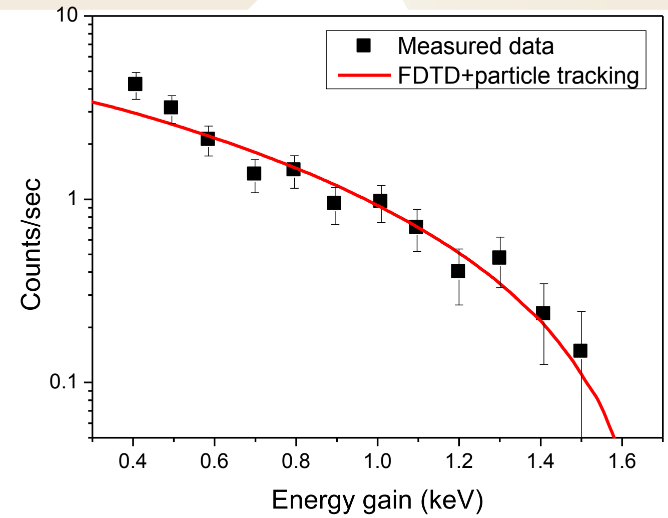
Overall goal: The demonstration of an integrated multi-stage particle "accelerator on a chip" will validate the potential to scale to energy levels of interest for "real-world" applications.

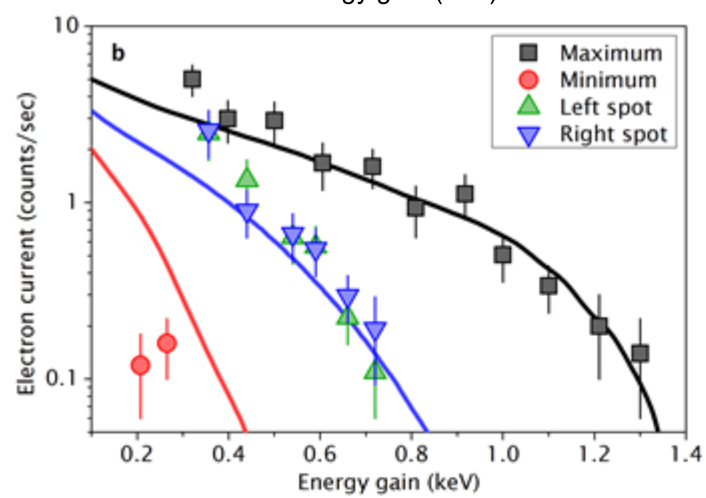
1. On-chip electron source
2. DLA structure development: (a) subrelativistic, (b) relativistic
3. Multi-staged acceleration
4. Coupling of laser to DLA
5. Laser-driven deflectors and undulators



Staging of nonrelativistic beams has been achieved by Hommelhoff group.



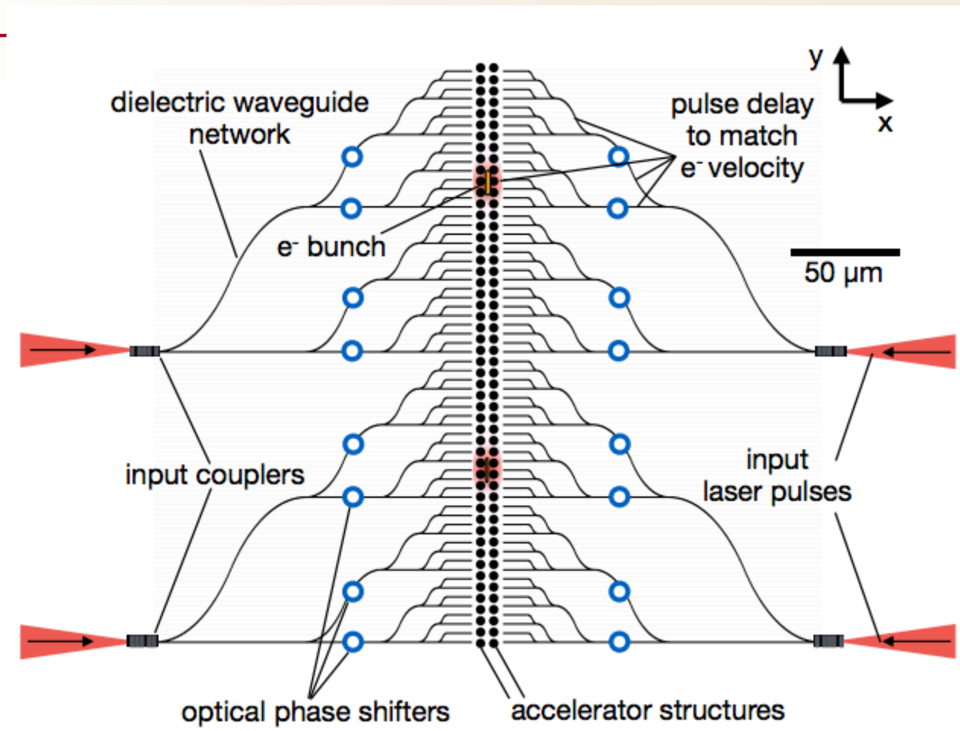


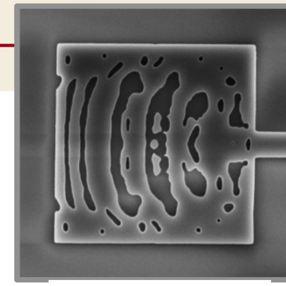


- Si grating instead of SiO_2
- 70 MV/m gradient for $\beta = 0.3$
- Staging with two laser pulses

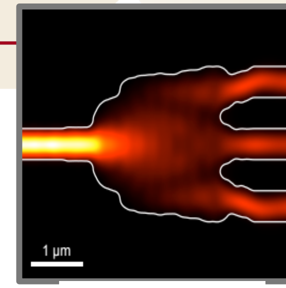
Acceleration scales linearly with number of stages and/or interaction distance.

Laser Coupling Highlights

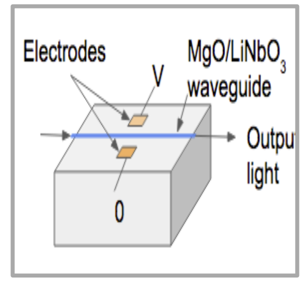




couplers



splitters



phase shifters

1. **Detailed Study of Integrated Multi-Stage DLA Network with Realistic Component Parameters:**
   - Proposed 'tree-branch' fractal waveguide structure to accomplish all practical goals of laser coupling.
   - Structure performs at 100 MV/m gradients, 49 stages to reach 1MeV for interaction length of 192 um.
2. **Adjoint-Based DLA Structure Optimizations**
   - Structures qualitatively very similar to recent Erlangen structure proposals, implies optimal design.
   - Acceleration factor (G/Emax) Generated structures with 50% improvement for improved damage handling.
3. **Tapered Slot Waveguide Accelerator**
   - Longitudinal E-field in slot waveguide to drive acceleration with 0.2 GV/m over 20um length.
   - Non-resonant, favorable sensitivity and tolerance to fabrication defects.

Longitudinal Phase Space Dynamics

SLAC

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

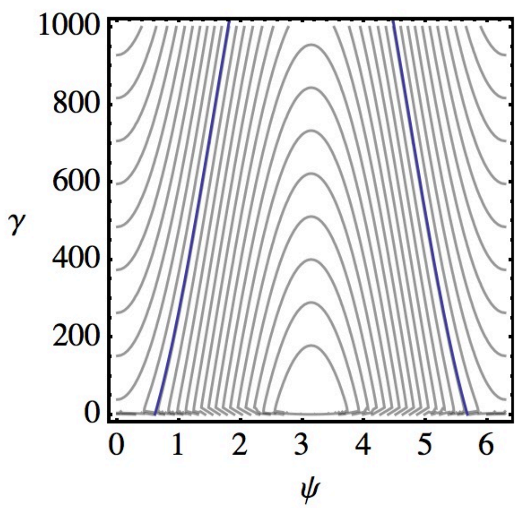
(useful for comparing acceleration schemes)

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

Example DLA parameters

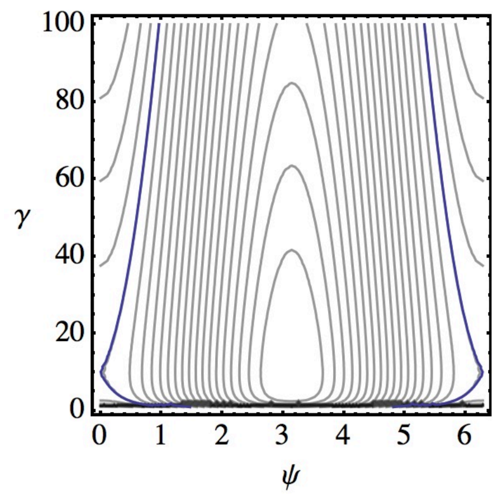
Plasma Accelerator

$\alpha_0 > 5$



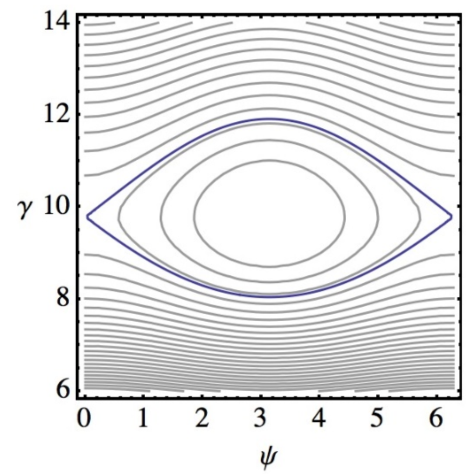
RF Photoinjector

$\alpha_0 \simeq 1$



DLA or Proton Accelerator

$\alpha_0 \approx 0.001$

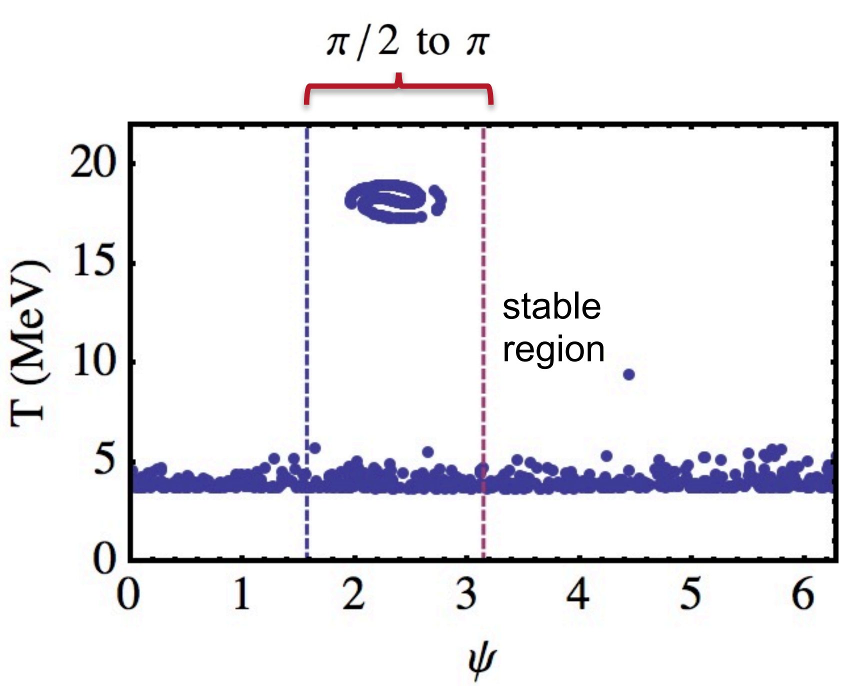


Extended interaction lengths require tapering the phase velocity of the wave.

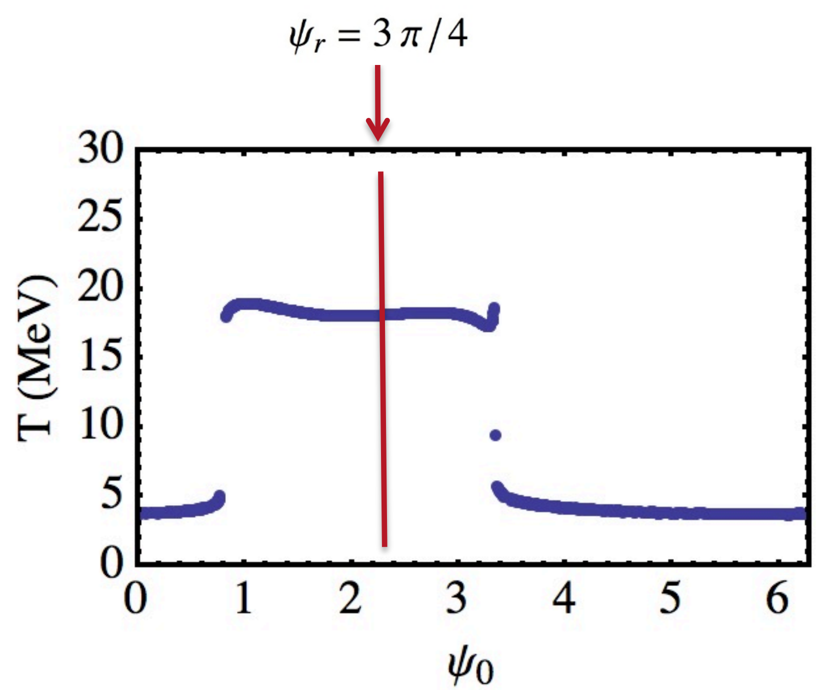
Resonant Mode Acceleration & Capture

SLAC

Integration of longitudinal equations of motion for particles distributed randomly over 2π of injection phase.
Resonant phase is tradeoff b/w gradient and capture efficiency.
Stable bucket region in longitudinal phase space is between π and 3π/2.
Simulation done with E_0 = 1 GV/m; accelerator length L = 2 cm;
Injection energy = 4 MeV
Linear change of resonant energy → quadratic chirp on the phase



Final (capture) phase



Initial (injection) phase

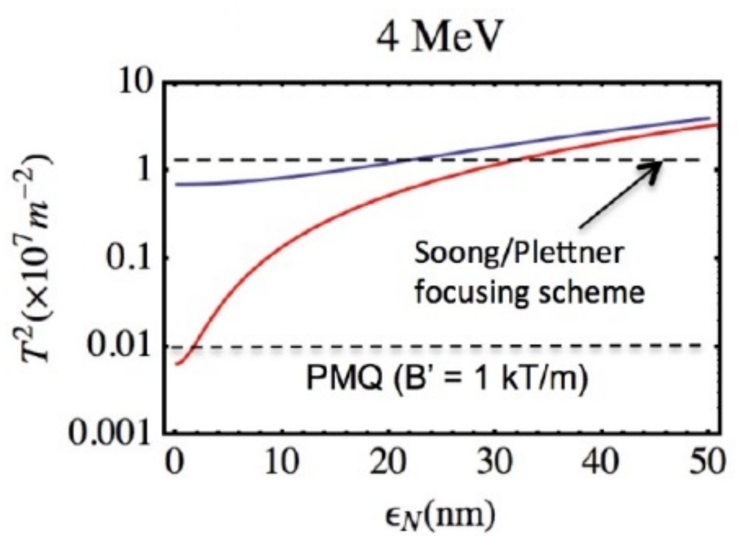
But…….resonant defocusing

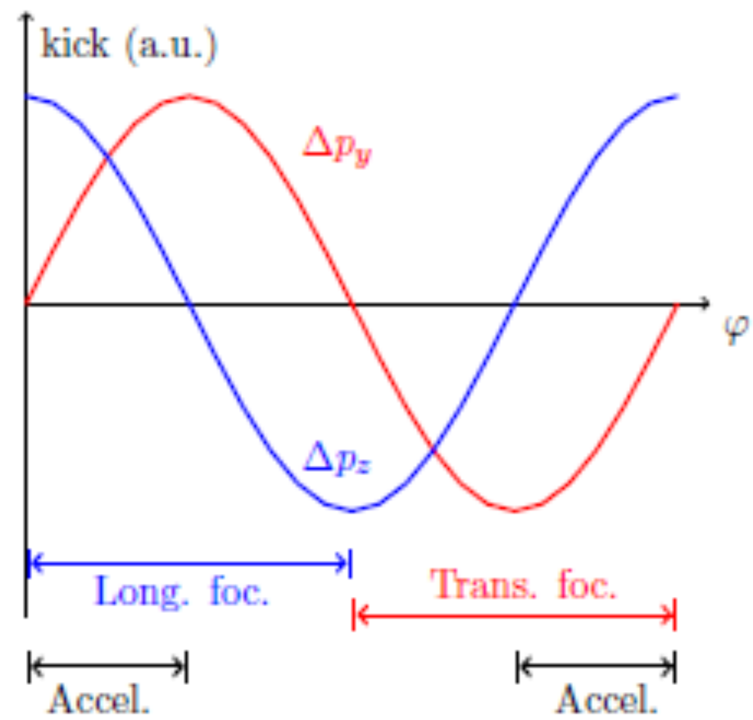
Even if we could generate a beam with emittance small enough to have significant transmission in a 2 cm long channel, it would not work!

Panofsky-Wenzel theorem to estimate transverse kicks

$$T^2[\mathrm{m}^{-2}] = \frac{e\,E_0}{k_r\,m\,c^2}\,\frac{a_r\,k_r{}^2}{\gamma_r{}^3\,\beta_r{}^2}\cos\psi_r$$

For 5 MeV beam and $\psi_r = \pi/4$ this is ~ 10^7 m^{-2}
For comparison see discussion in Ody et al. where this term was not considered!





Ponderomotive Focusing Formulation

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Use different asynchronous spatial harmonics to provide oscillating force.

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

Resonant defocusing

Focusing

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

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.

Custom Phase Velocity Taper

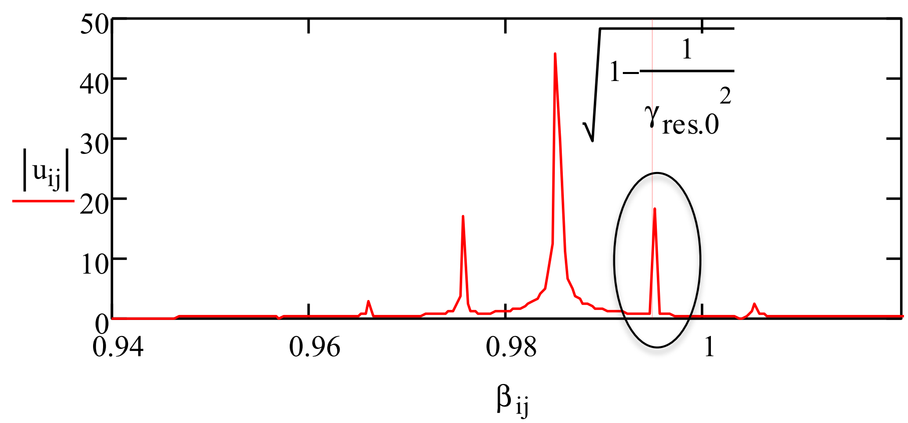
SLAC

- Naranjo, Valloni, Putterman, Rosenzweig PRL **109** 164803 (2012)
- Use non-resonant harmonics to provide focusing force.
- In practice, we can add a sinusoidal phase variation along z using the LC-SLM.
- This is equivalent to a Bessel function spectrum of spatial harmonics.

$$e^{i A_p \cos k_p z} = \sum_n i^n J_n(A_p)\, e^{i n k_p z}$$

This obviously reduces the available gradient, but provides the much-needed resonant field.

Phase velocities of different harmonics



The fundamental is shifted by ‘angle-tuning’

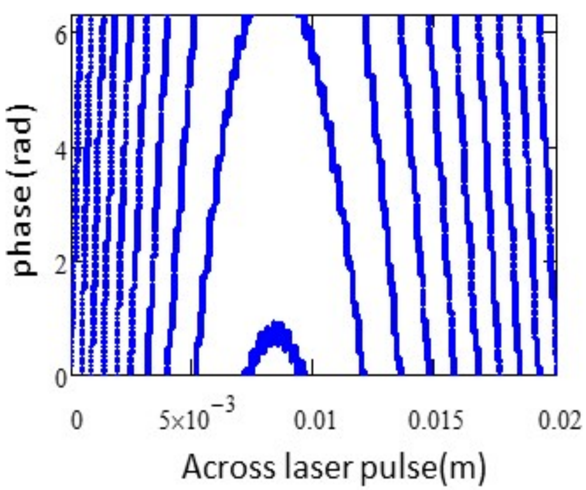
In this case: $\gamma_r = 10$, $\theta = 5\,\text{mrad}$

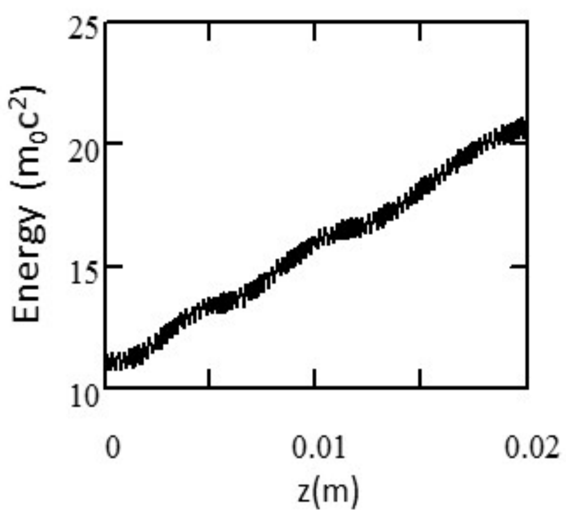
DLA Phase Velocity Taper by Phase Modulation

- In pulse front tilt geometry the liquid crystal mask can be used to program arbitrary phase profiles along the beam.
- Equivalent to varying the angle of incidence along the spot: $\theta(z) = \frac{1}{k(z)} \frac{d\varphi}{dz}$
- As an example, the gradient in wave phase velocity can be obtained 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

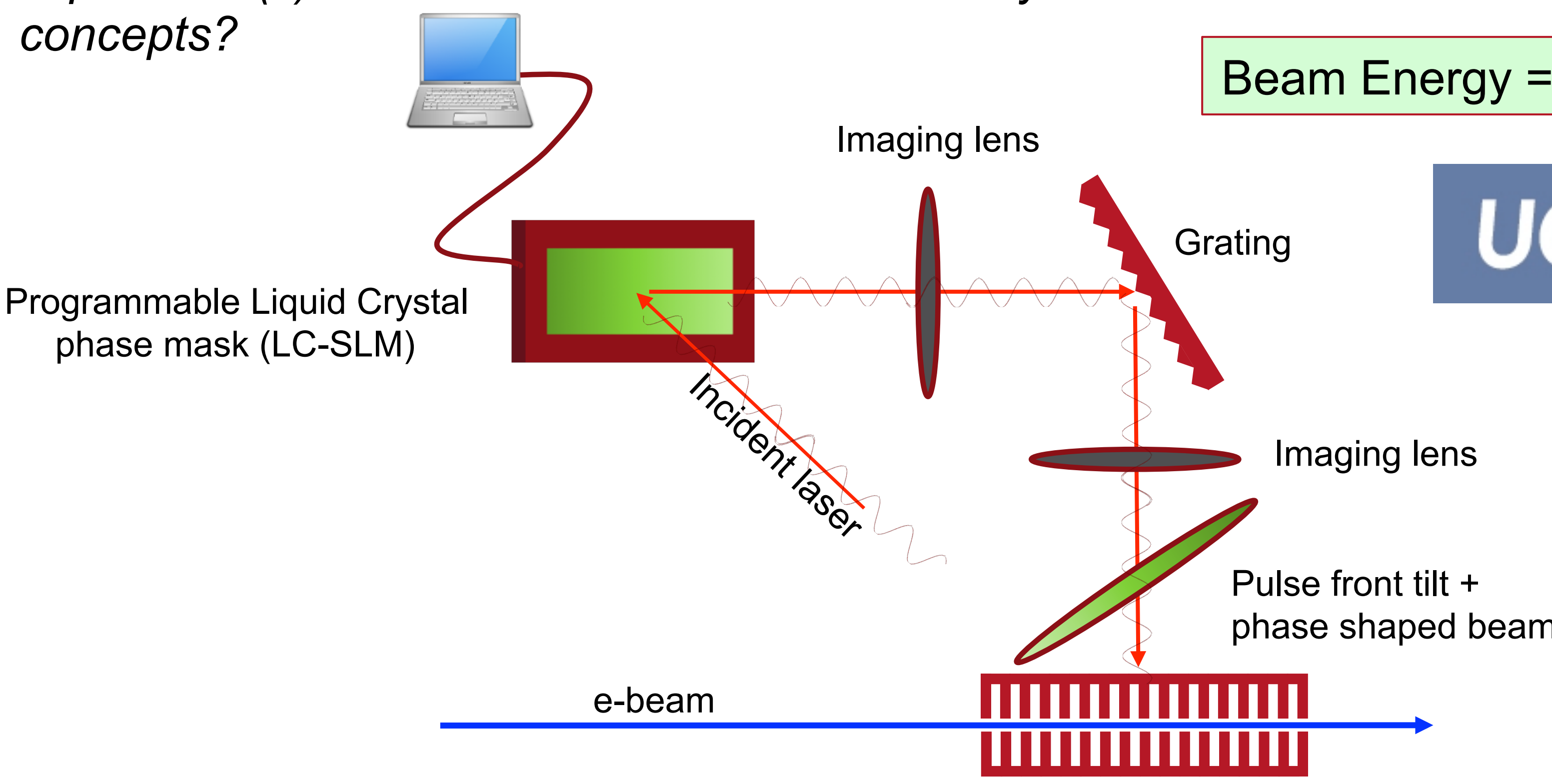




Future Experiments: Chirp + Ponderomotive Focusing

***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?*

Beam Energy = 5 MeV

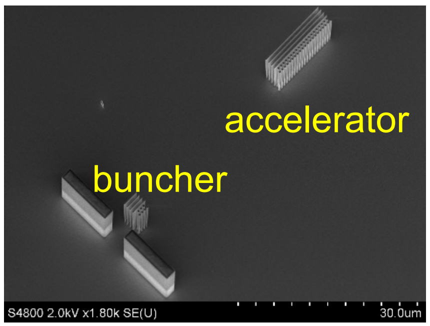


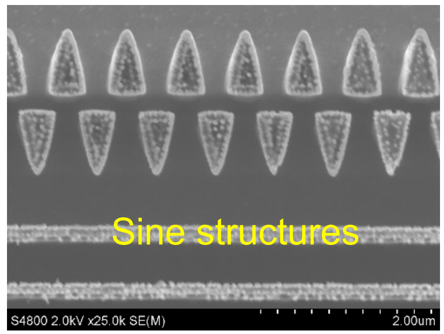
- Possible configuration for microbunching and net acceleration in a DLA.
- Extended interaction over 2 cm with ponderomotive focusing.
- **PFT + phase mask provides dynamic control on the phase of the accelerator.**

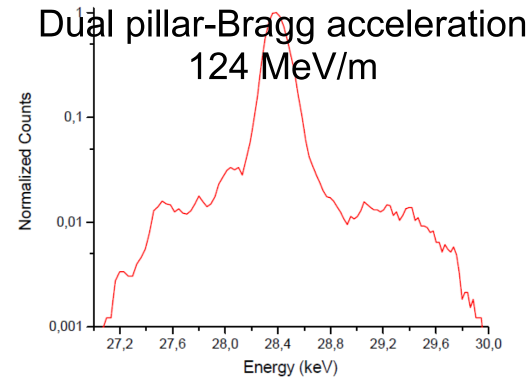
Subrelativistic Acceleration Highlights

See talk by J. McNeur, WG3 Thursday 4:00pm

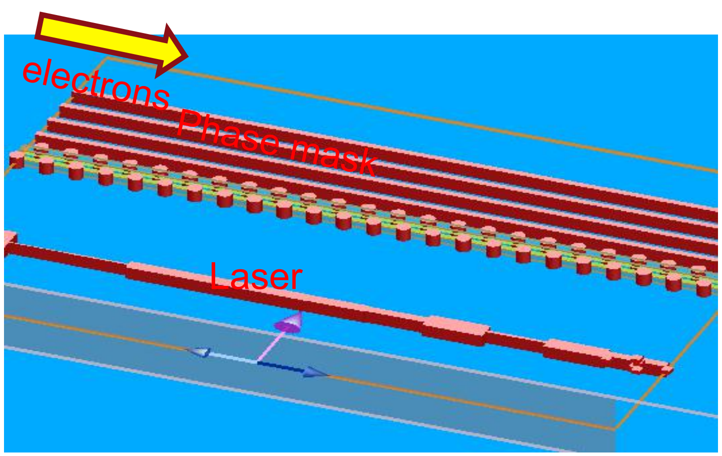
- New designs (dual pillar – bragg, sine structures, bunching structures) fabricated and tested/soon to be tested in Erlangen

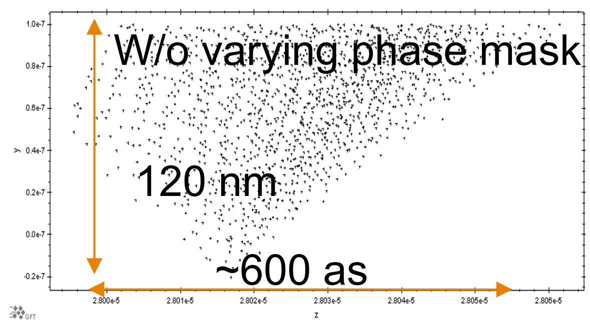






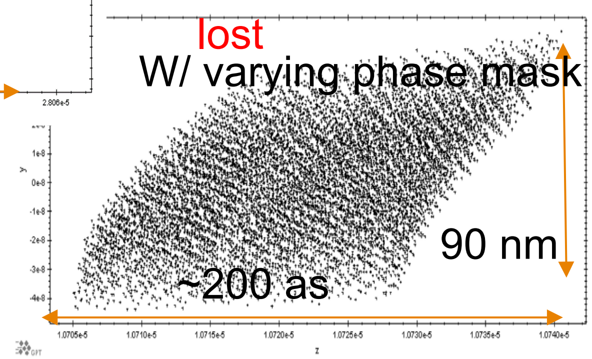
- Design for simultaneous focusing/bunching/accelerating structure yields encouraging simulation results. To be experimentally verified





Most electrons already lost due to wall collisions

No electrons lost



Simulations: Semi-Analytic 6D DLA Tracker

U. Niedermayer et al, submitted to PRAB (arxiv.org/abs/1707.09815)

One kick per grating cell
(numerically lightweight)

Symplectic code

→ No artificial emittance increase
→ Natural emittance increase properly determined

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TECH-X

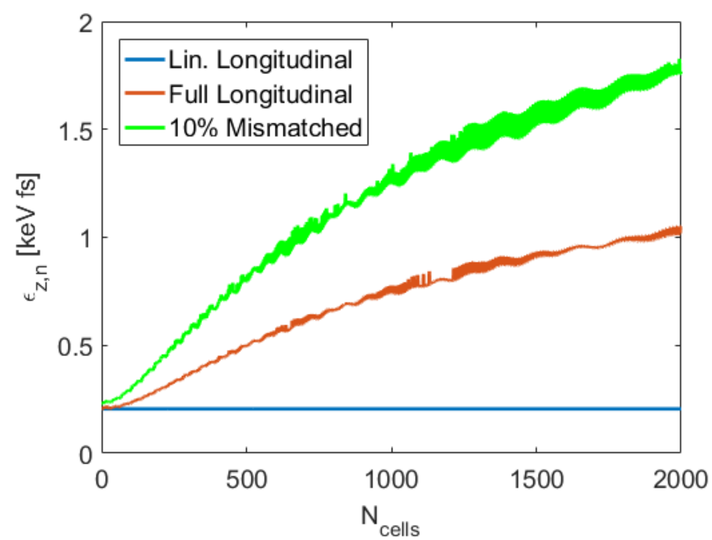
$$\begin{pmatrix} x \\ x' \\ y \\ y' \\ \varphi \\ \delta \end{pmatrix}^{(n+1)} = \begin{pmatrix} x \\ Ax' + \Delta x'(x,y,\varphi) \\ y \\ Ay' + \Delta y'(x,y,\varphi) \\ \varphi \\ \delta + \Delta\delta(x,y,\varphi;\varphi_{\text{sync}}) \end{pmatrix}^{(n)} + \begin{pmatrix} \lambda_{gz} x'(x,y,\varphi) \\ 0 \\ \lambda_{gz} y'(x,y,\varphi) \\ 0 \\ -\frac{2\pi}{\beta^2\gamma^2}\delta(x,y,\varphi) \\ 0 \end{pmatrix}^{(n+1)}$$

Kicks by resonant Fourier coefficient
(one complex number per grating cell)
Transverse kick by Panofsky-Wenzel theorem

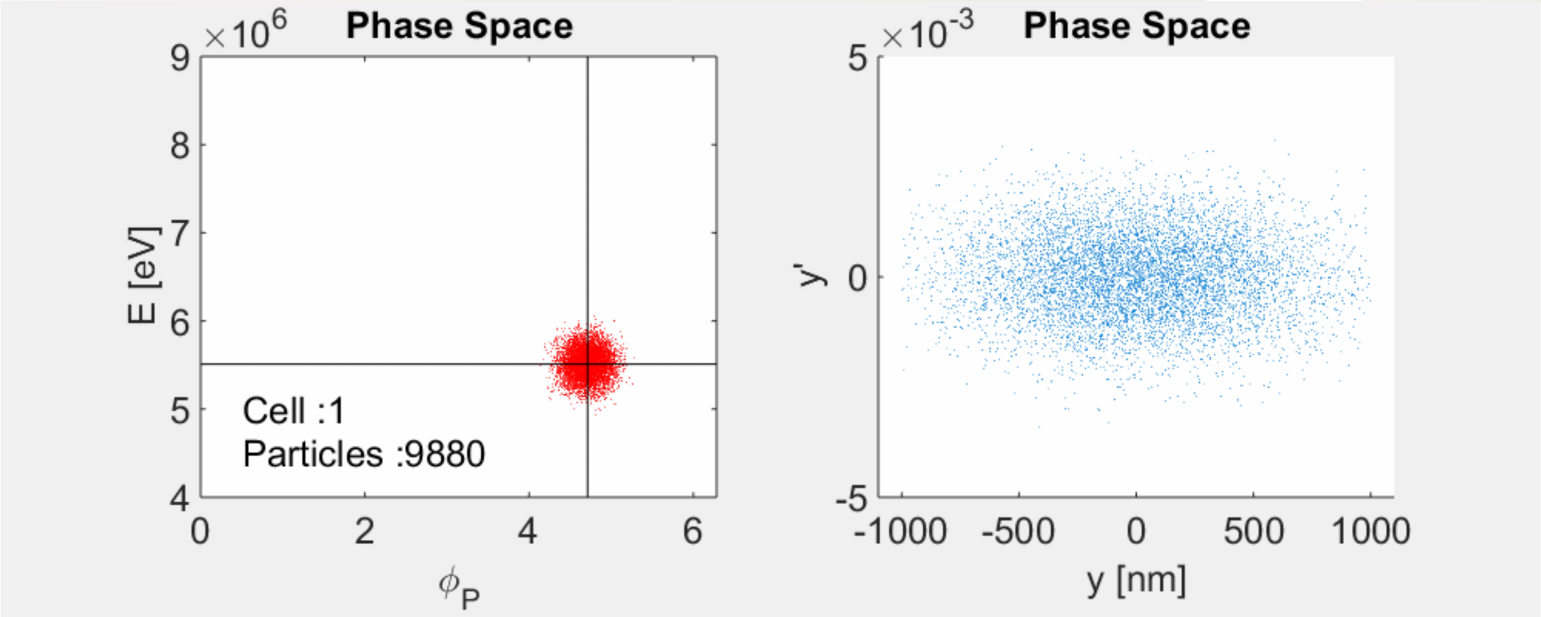
Can be applied to laterally coupled structures

- Subrelativistic structures / Relativistic structures
- Tilted grating structures
- Alternating phase / Spatial Harmonic focusing structures

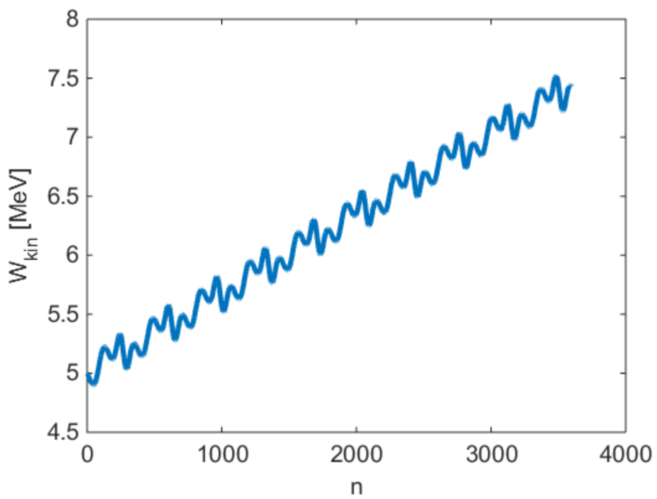
Emittance conservation



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



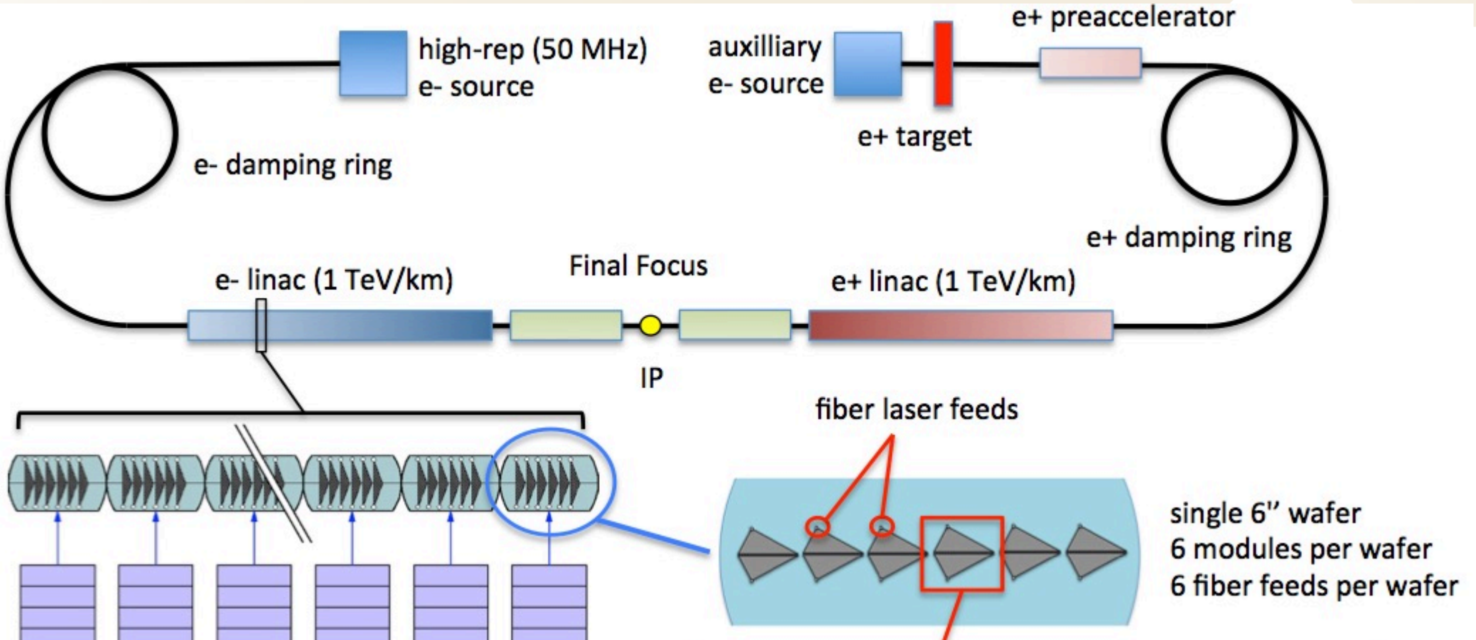
R&D topics for DLA 10-20 Year Roadmap

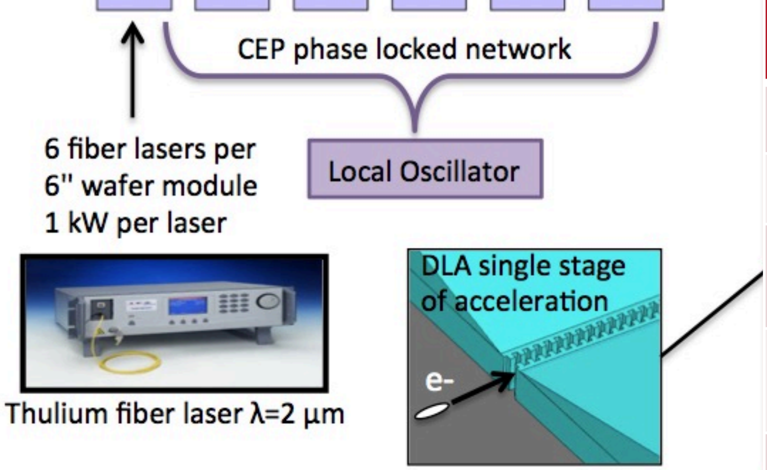
	Topics	Description
1	**Transport**	Study issues related to long-distance particle transport and beam quality
2	**High-Field**	Evaluate nonlinear high-field processes in dielectrics and develop mitigation strategies
3	**Sources**	Evaluate techniques for positron production and for integration of novel electron sources
4	**Final Focus**	Understand the final focus physics and technical requirements
5	**Efficiency**	Determine realistically achievable efficiency, power, and cost estimates for a collider facility

A variety of sub-topics were developed under each category and then discussed and prioritized.

See plenary talk by B. Cros, Monday 12:00pm

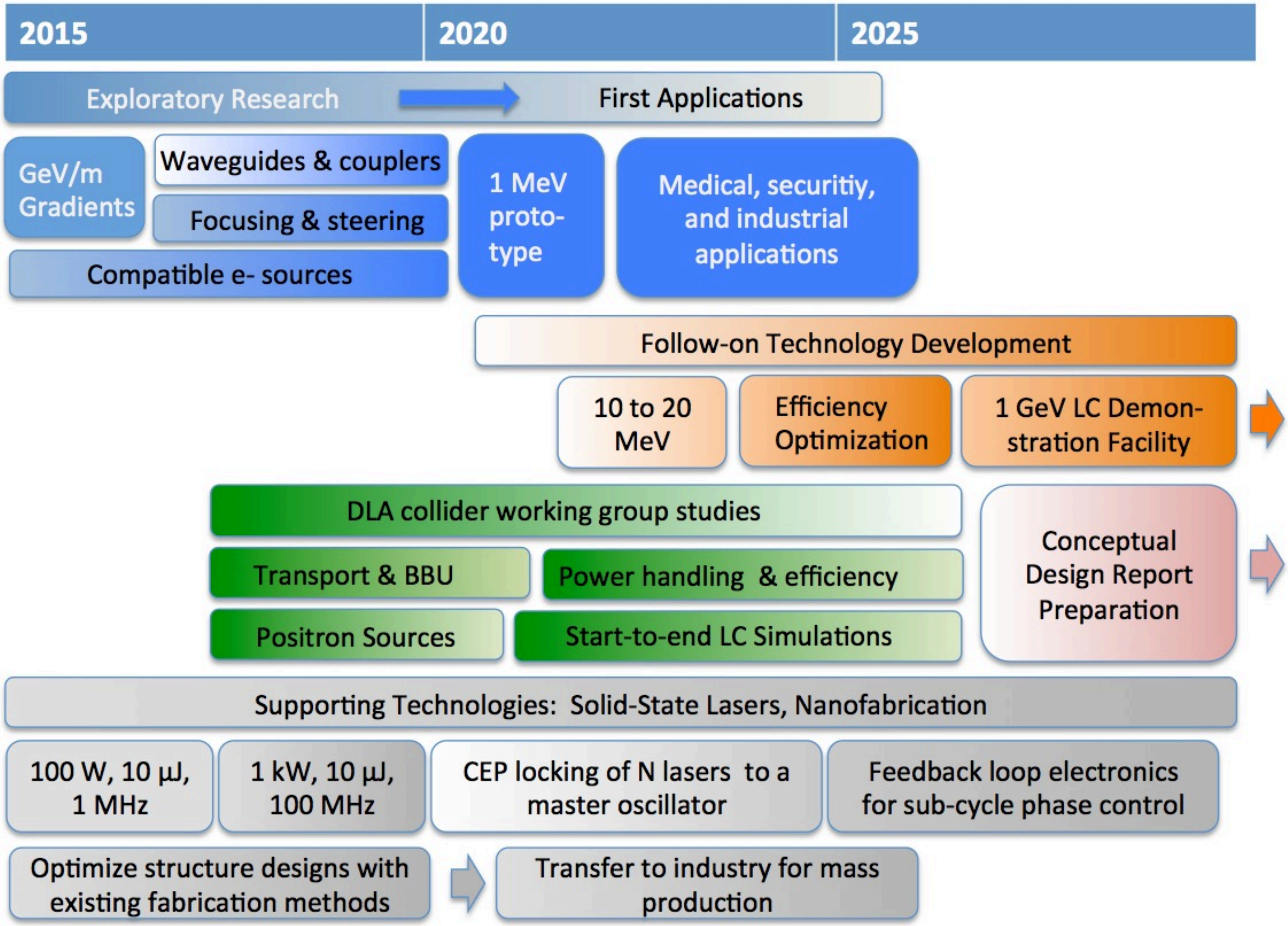
ANAR: Linear Collider Strawman





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

ANAR: DLA 10 Year Roadmap



Summary

SLAC

High profile DLA experimental results within the ACHIP collaboration

- sub-relativistic 2.2 GV/m laser injector concept with 100 attosecond microbunching
- high gradient (0.85 GeV/m) operation and 0.3 MeV energy gain

Key focus areas identified for scaling to multi MeV energy gains (and beyond)

- on-chip waveguiding and phase control with multiple stages
- enhancing interaction length per stage with pulse front tilt or other techniques
- phase velocity tapered structures (i.e. resonant acceleration)
- simultaneous laser focusing to overcome the resonant defocusing effect

Work on multiple fronts planned within next year to tackle these and other issues

- combined microbunching and accelerator injection demonstrations
- ponderomotive focusing and PFT incorporated into DLA structure designs
- formation of new working group for “integration” of a working accelerator
- simulation of transverse and longitudinal wake effects for long-distance transport
- testing of on-chip “treebranch” waveguide splitter arrays and phase shifters

Thank you!

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

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