Numerical optimizations on dielectric laser acceleration(DLA) of electrons in a grating-based microstructure

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Outline

- Background
- Modelling & simulations for DLA
- Summary & Outlook

Dielectric Laser Accelerator(DLA) Concept

Key objective:
- Higher gradient
- Lower cost
- More compact

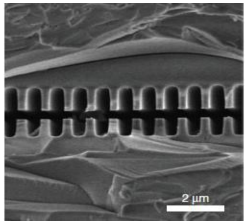
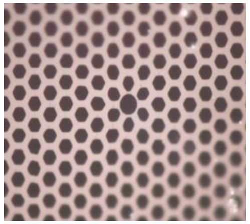
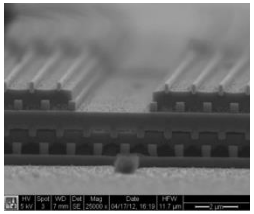
- **Lasers**: high rep rates, strong field gradients, commercial support
- **Dielectrics**: higher damage threshold, higher gradients (1-5 GV/m), leverage industrial fabrication processes

Image courtesy CERN

Conventional RF structure

metal	100 MV/m	λ = 2.5 cm
↓	↓	↓
dielectric	1-2 GV/m	1-10 μm

Dielectric Laser microstructures

What am I talking about?

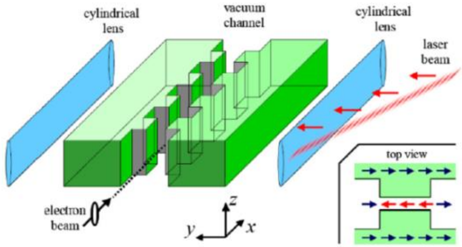
- Various names: "Dielectric Laser Accelerator (DLA)", "Laser Structure Accelerator (LSA)", "Optical Accelerator", "Micro-Accelerator", etc.
- Include: Our DLA concepts operate at optical wavelengths, driven by lasers, and the accelerating fields exist inside of an enclosed structure made of dielectrics, no conducting boundaries.
- Exclude: particle-driven wakefield accelerators, laser plasmas wakefield accelerators, dielectric wakefield accelerator and so on.

Many DLA structures

1-D grating Structure

Silica, λ=800 nm, Ez=700 MV/m

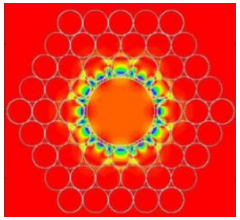
T. Plettner, *et al, PRST-AB,* **9**, 111301 *(2006).*

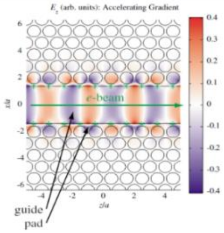


2-D Fiber Structures

Silica, λ=1053 nm, Ez =400 MV/m

B. Cowan, *PRST-AB,* **6**, 101301 (2003).
X. Lin, *PRST-AB,* **4**, 051301 (2001).

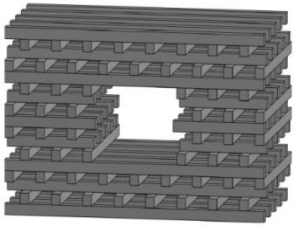


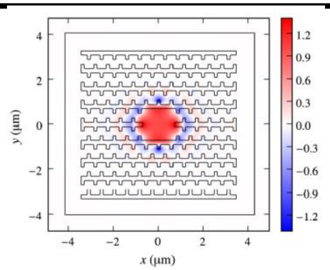


3-D Woodpile Structures

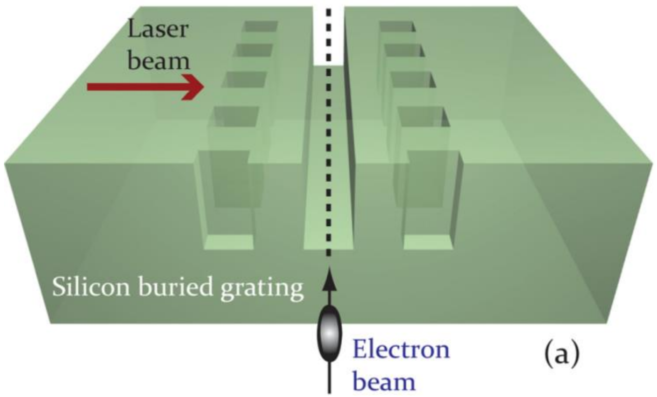
Silicon, λ=1550 nm, Ez=301 MV/m

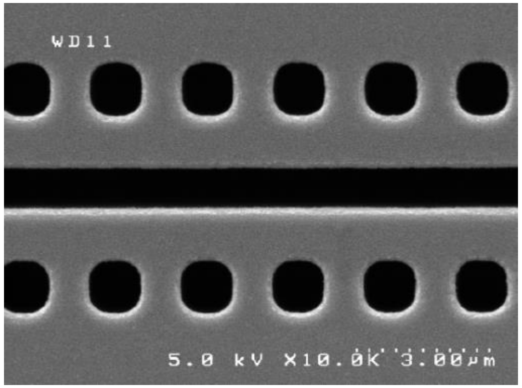
Z Wu, *et al*, *PRST-AB,* **17**, 081301 (2014).
B. Cowan, *et al*, *PRST-AB,* **11**, 011301 (2008).





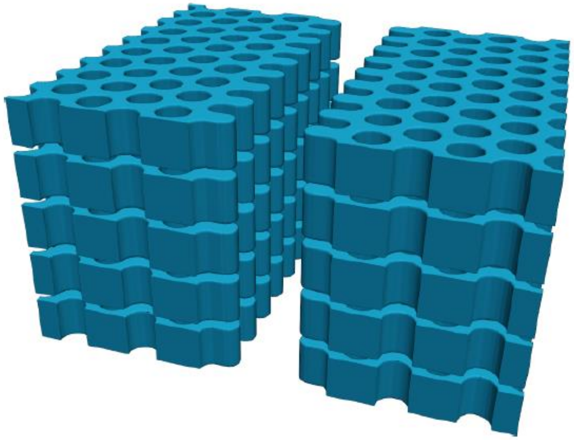
Other DLA structures

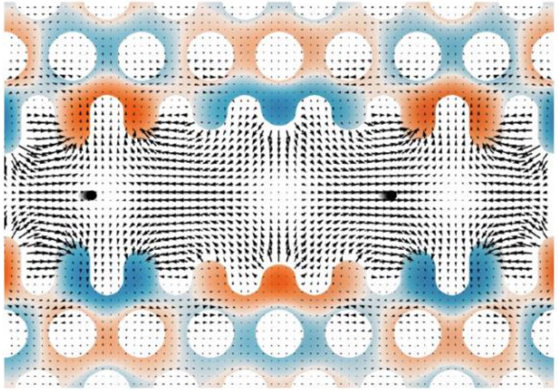




C-M. Chang, O. Solgaard, APPLIED PHYSICS LETTERS **104**, 184102 (2014)

"Buried" phase mask of holes reduces peak fields



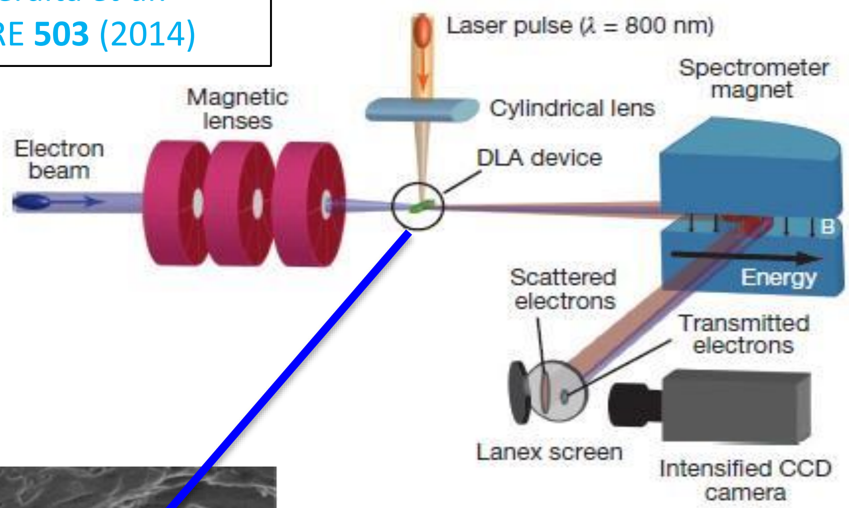


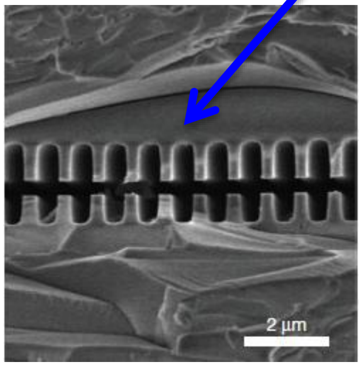
B. Naranjo, A. Valloni, S. Putterman, and J. B. Rosenzweig, PRL **109**, 164803 (2012)

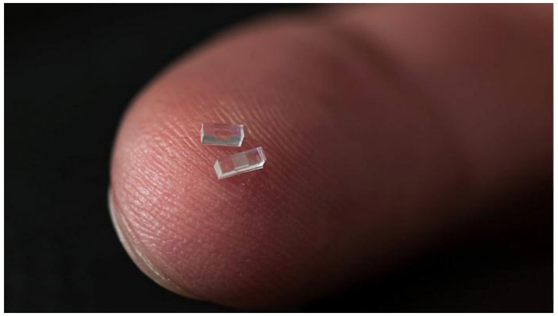
Combination of resonant and non-resonant spatial harmonics provides acceleration and focusing.

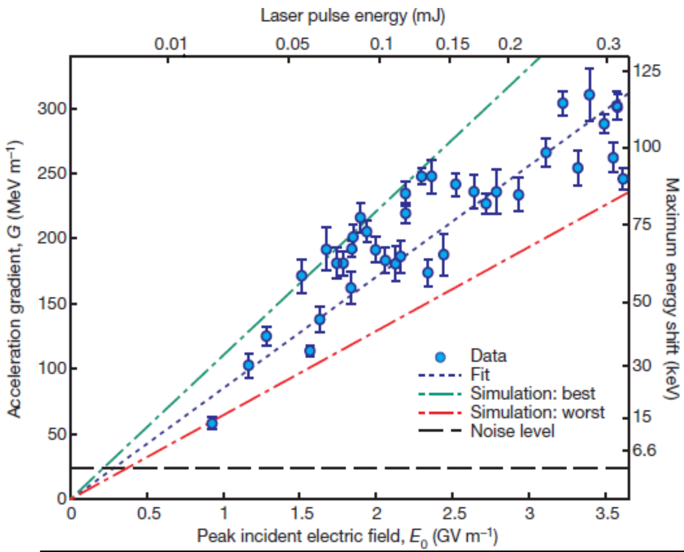
Milestone DLA experiment for high β electrons

E. A. Peralta *et al.*
NATURE **503** (2014)



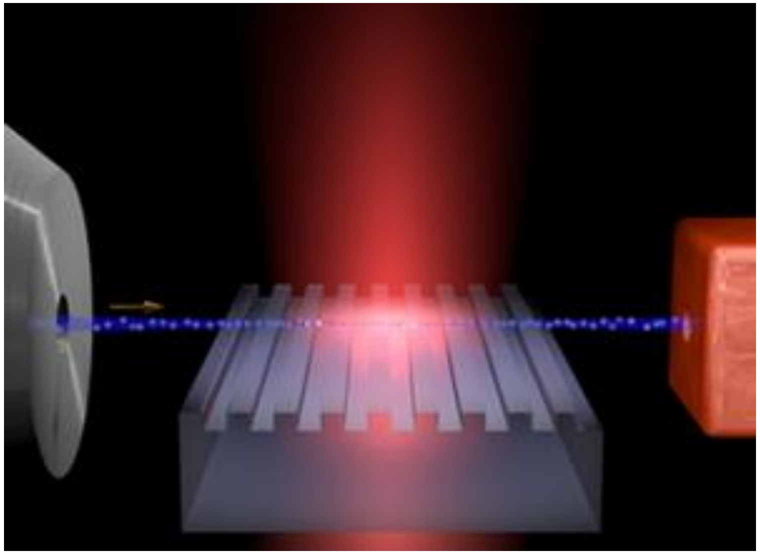






Electron source: 60 MeV;
Acceleration gradient can be higher than 250 MeV/m
Double grating structure

Another DLA experiment for low β electrons

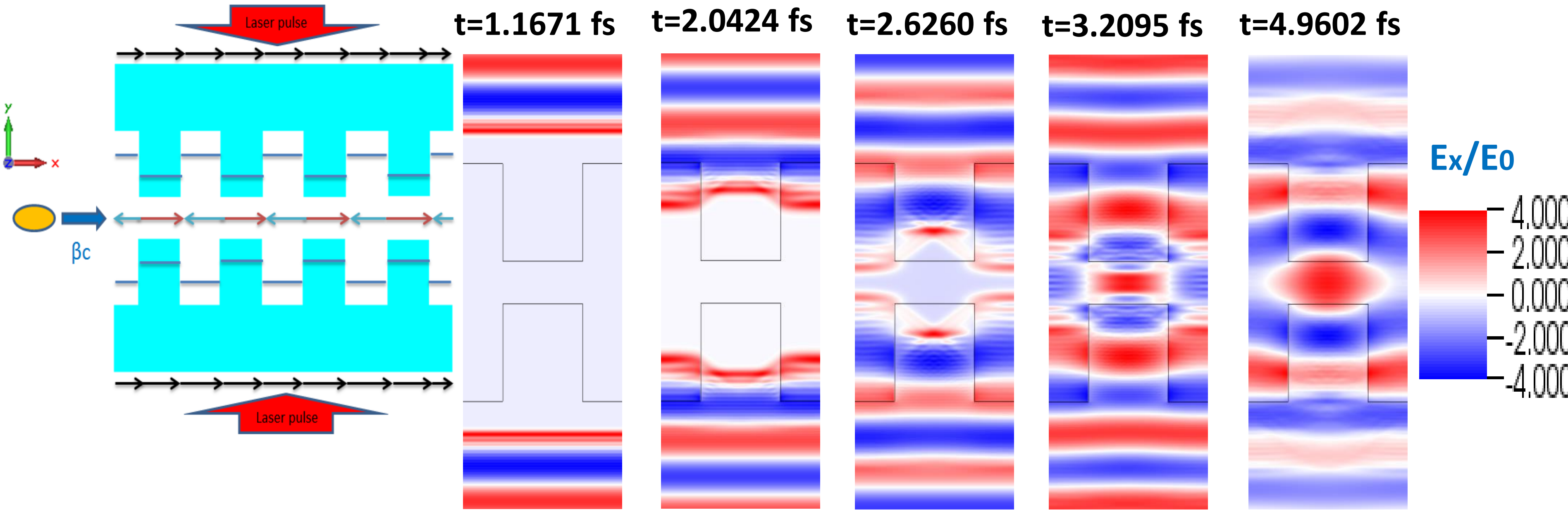


Electron source: 28 keV

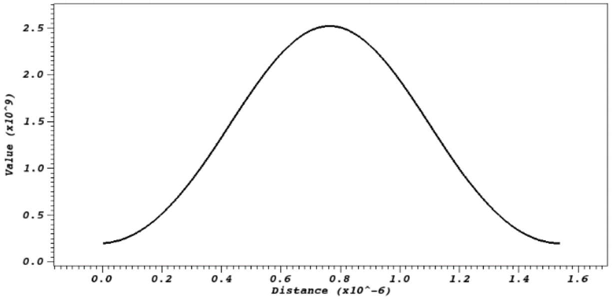
Observed maximum acceleration gradient:
25 MeV/m -- Single grating structure

John Breuer and Peter Hommelhoff, Laser-based acceleration of non-relativistic electrons at a dielectric structure, PRL 111, 134803(2013)

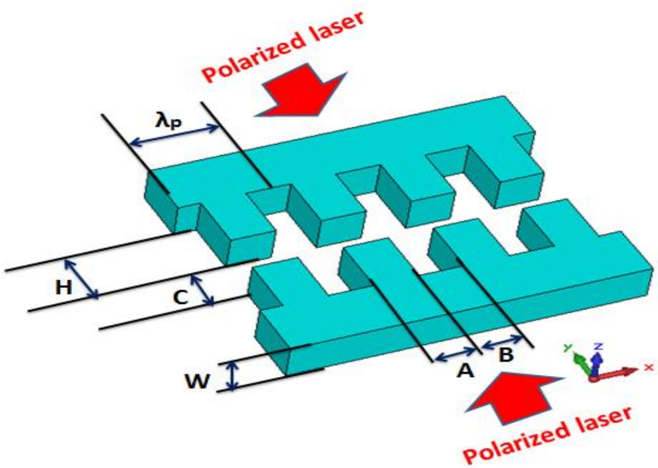
Modelling & Simulation for DLA(1)

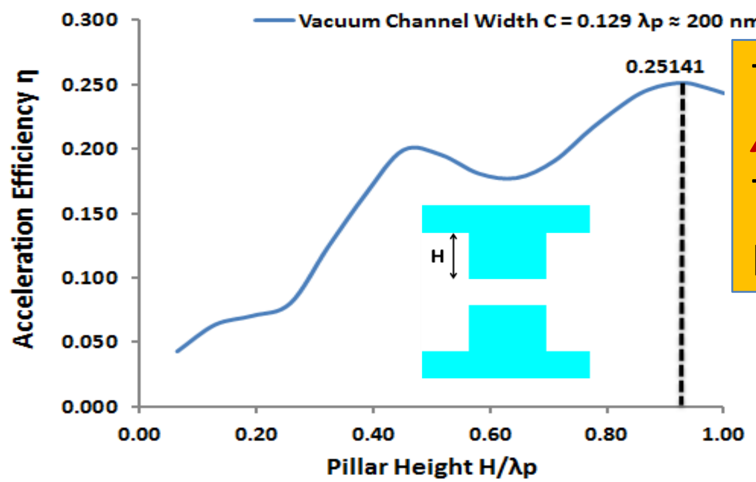


- Illuminated by linearly-polarized laser from both sides;
- Each grating pillar acts as an optical phase-delay to generate π-phase shift with respect to the electric field in the adjacent vacuum space;
- Oscillating electric field in the vacuum channel to interact with electrons;



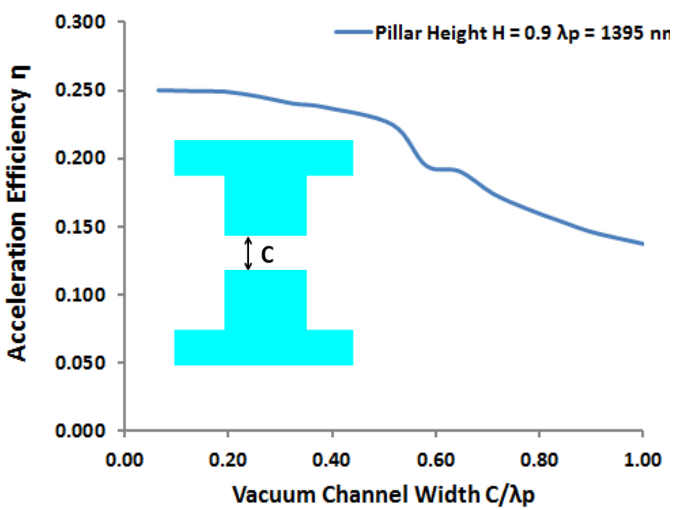
Optimizations for acceleration of high β electrons

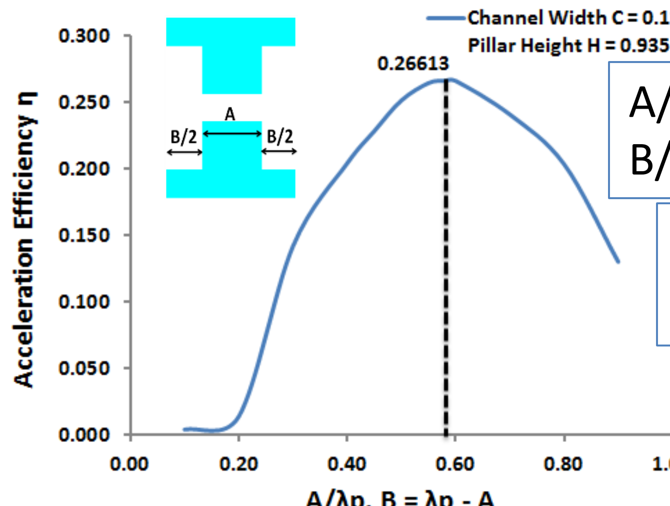




The laser wavelength λ= 1550 nm;
The double grating period λp = 1550 nm

C=200 nm
H=1450 nm





A/ λp = 0.58--**Duty factor**
B/ λp = 0.42

Acceleration efficiency
***η*=G/Ep=0.26613**

G is the average acceleration gradient, Ep is the peak electric field in the grating structure

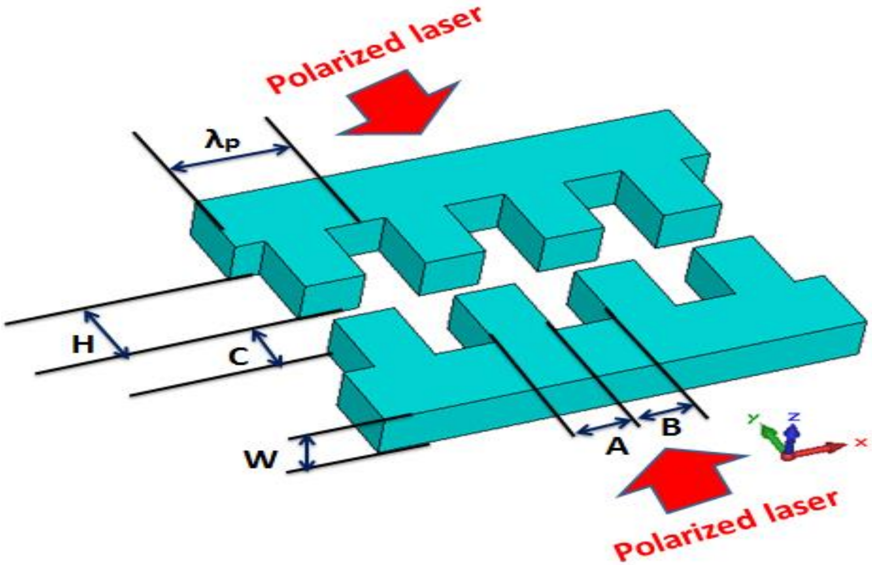
- The dielectric material is chosen as silica(SiO_2);
- The damage threshold is 1 J/cm^2 at 100 fs of laser pulse, which is equivalent to peak field of 8.7 GV/m;

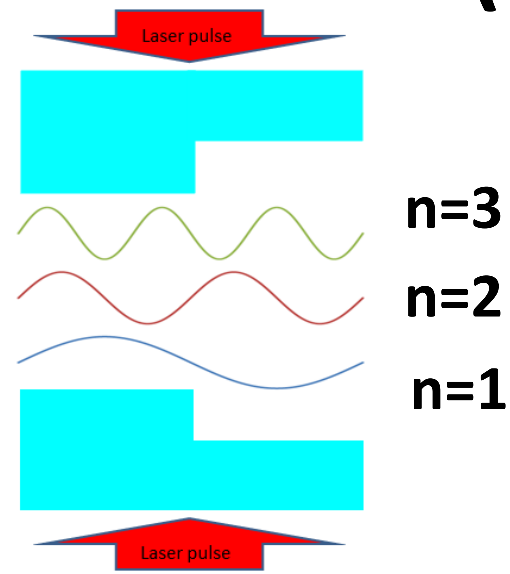
- So the maximum achieved acceleration gradient is about

2.3 GV/m= 0.26613*8.7

Laser parameters	
wavelength	1550 nm(erbium fiber)
Pulse energy	10 μJ
Average power	1 kW
Pulse width	100 fs
Repetition rate	1 MHz

Modelling & Simulation for DLA(2)





- We also need to optimize the C, H and Δ=A-B to maximize the acceleration efficiency $\eta = G/E_p$, for different spatial harmonic, where G is the average acceleration gradient and E_p is the peak electric field in the grating structure

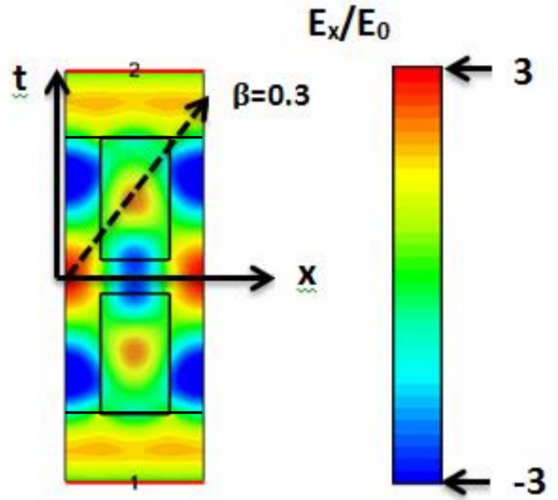
$$\lambda_p = n \beta \lambda$$

n is the numbers of laser cycles per electron passing one grating period, λ_p is the grating period, λ is the incident laser wavelength, *v* is the speed of injection electrons, $\beta = v/c$

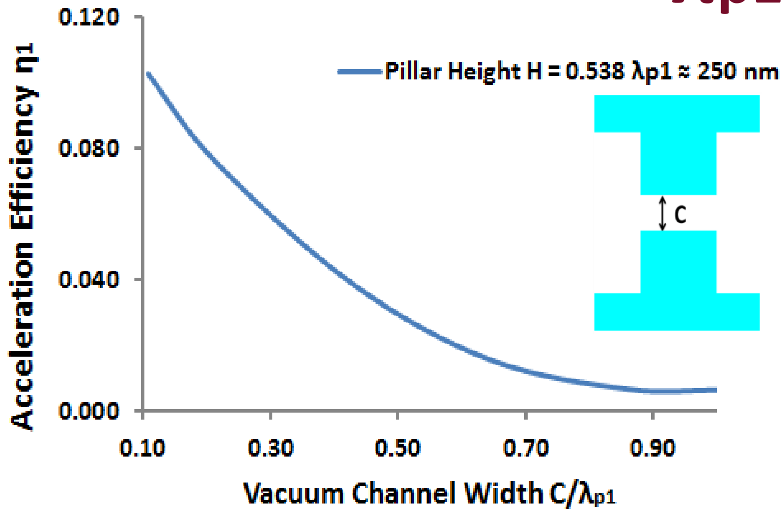
Optimizations for acceleration of low β electrons

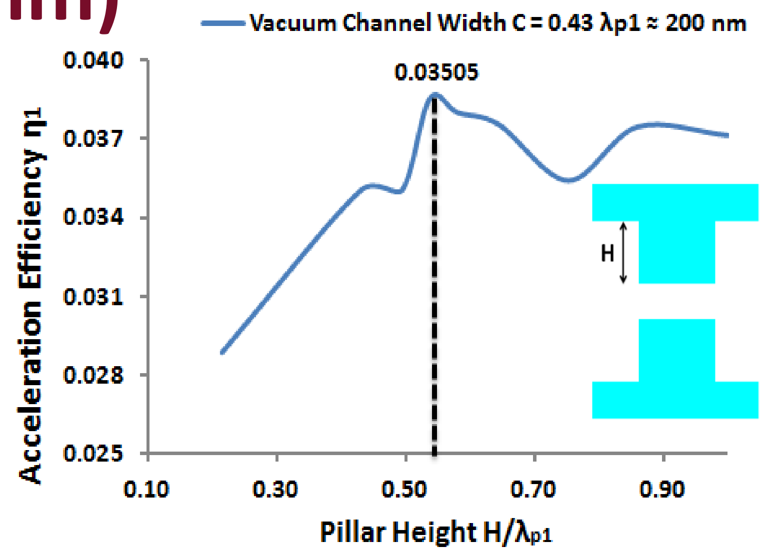
When the injection electron energy is 25 keV (β=0.3), we have three different options to accelerate electrons with this energy:

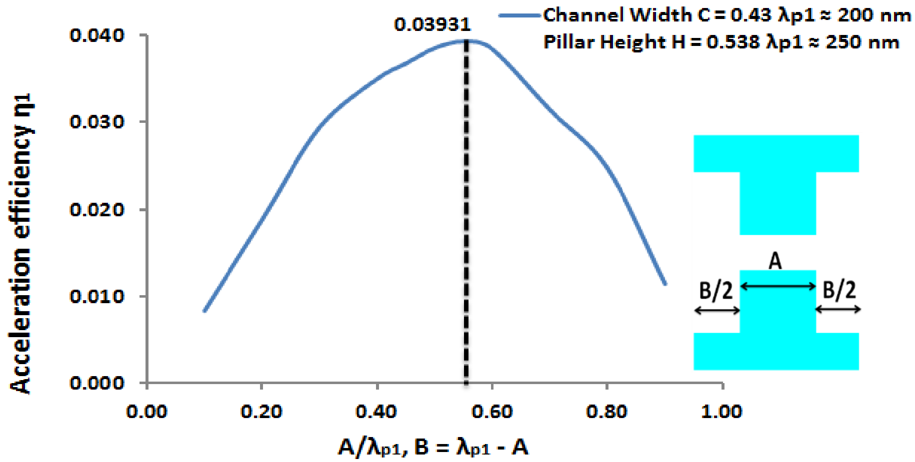
1) Synchronous with first spatial harmonic, n=1
2) Synchronous with second spatial harmonic, n=2
3) Synchronous with third spatial harmonic, n=3



Synchronous with First Spatial Harmonic (β=0.3, λ_{p1}=465 nm)





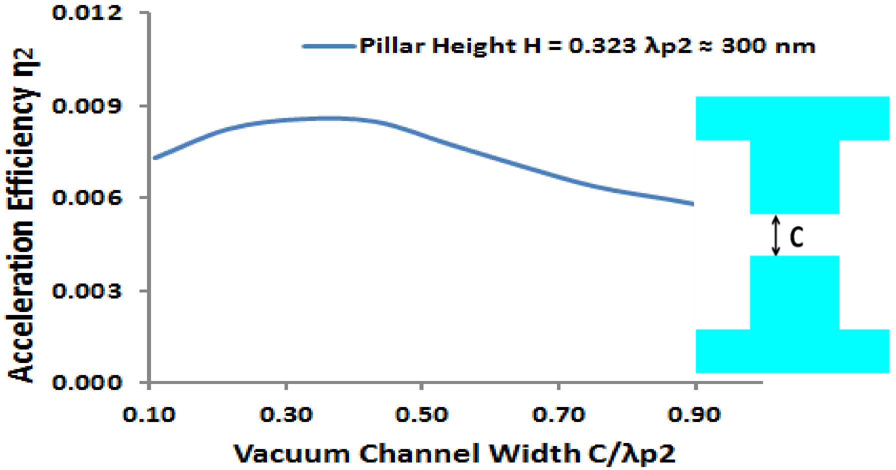


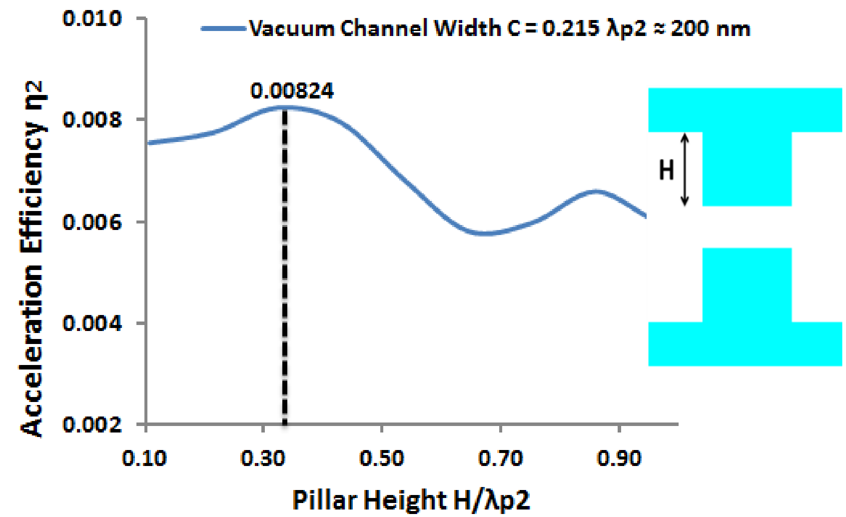
C=200 nm
H=250 nm

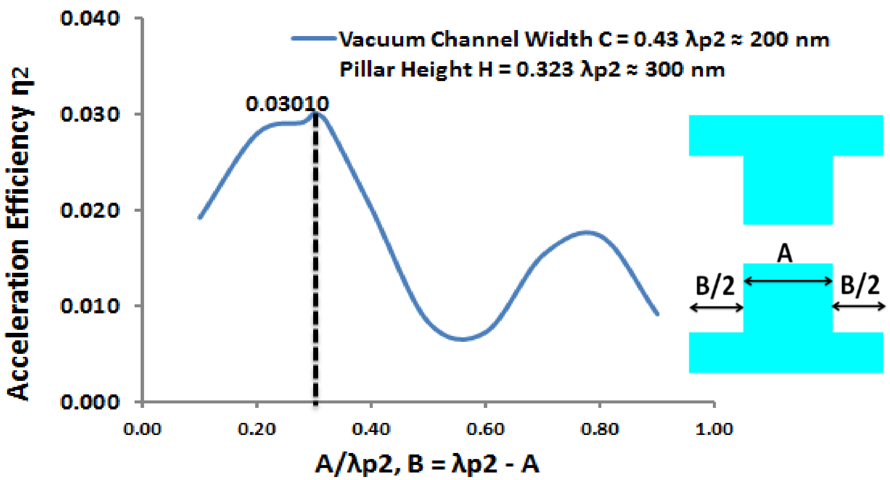
A/λ_{p1} = 0.55
B/λ_{p1} = 0.45

Acceleration efficiency ***η_1*=G/Ep=0.03931**, where G is the average acceleration gradient and Ep is the peak electric field in the grating structure

Synchronous with Second Spatial Harmonic (β=0.3, λ_{p2}=930 nm)





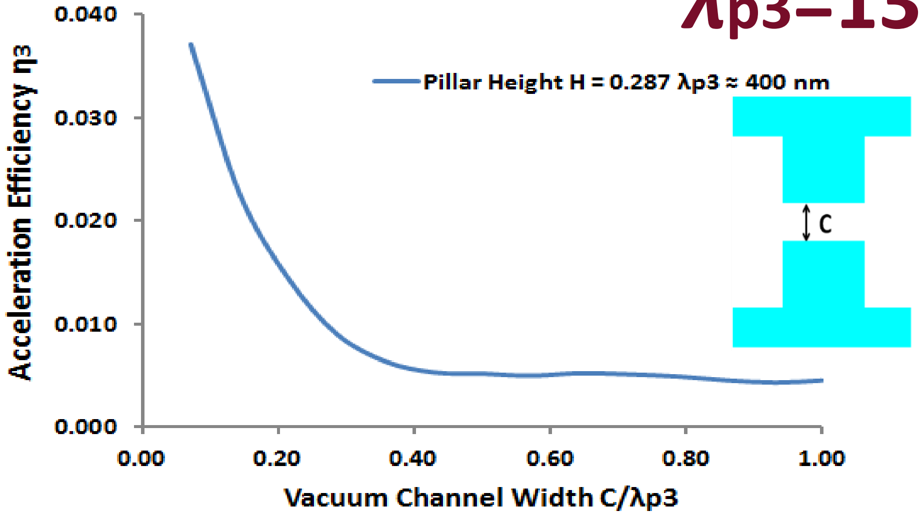


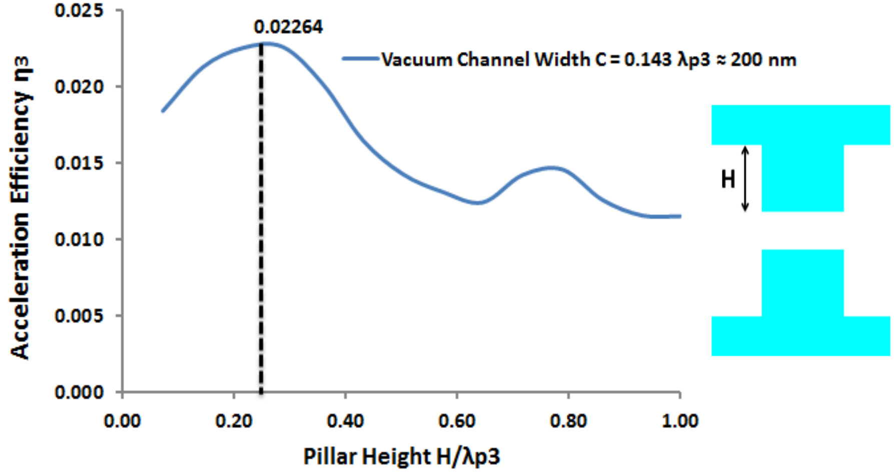
C = 200 nm
H = 300 nm

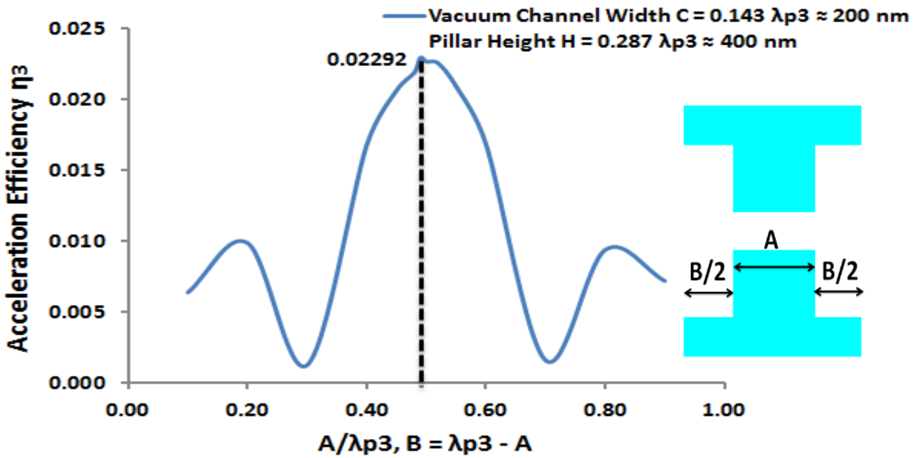
A/ λ_{p2} = 0.30
B/ λ_{p2} = 0.70

Acceleration efficiency
η_2=G/Ep=0.03010, where G is the average acceleration gradient and Ep is the peak electric field in the grating structure

Synchronous with Third Spatial Harmonic (β=0.3, λp3=1395 nm)







C = 200 nm
H = 400 nm

A/ λ_{p3} = 0.49
B/ λ_{p3} = 0.51

Acceleration efficiency
$\eta_3 = G/E_p = 0.02292$, where G is the average acceleration gradient and Ep is the peak electric field in the grating structure

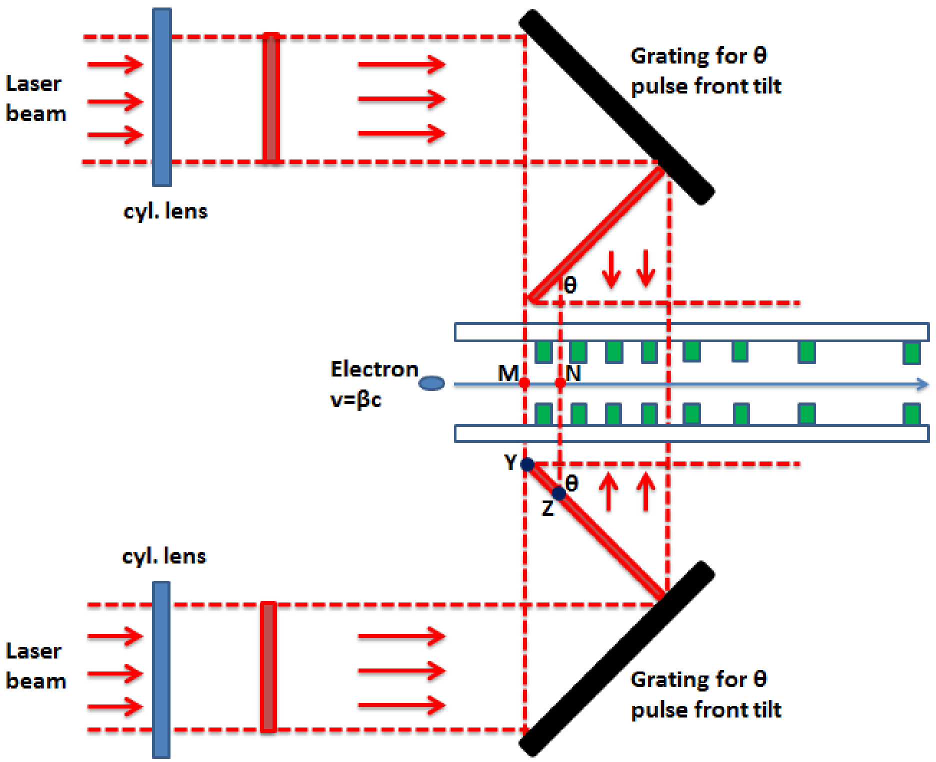
Comparisons

Acceleration Efficiency with a vacuum channel width C=200 nm:

1) **$A=B=\lambda_p/2$, First spatial structure> third > second**
2) **A≠B, First spatial structure> second > third**

Damage threshold for the electric field is E_{th}=8.7 GV/m. When E_p=*8.7 GV/m* was assumed in the simulation, acceleration gradient for **2nd** spatial harmonic can reach up to 260 MV/m when the vacuum channel width C=200 nm and the grating period = 930 nm.

Setup of Multi-stage DLA



- This time delay between Y and Z is:

  $c\,\Delta t = \lambda_p \tan\theta$ (1)

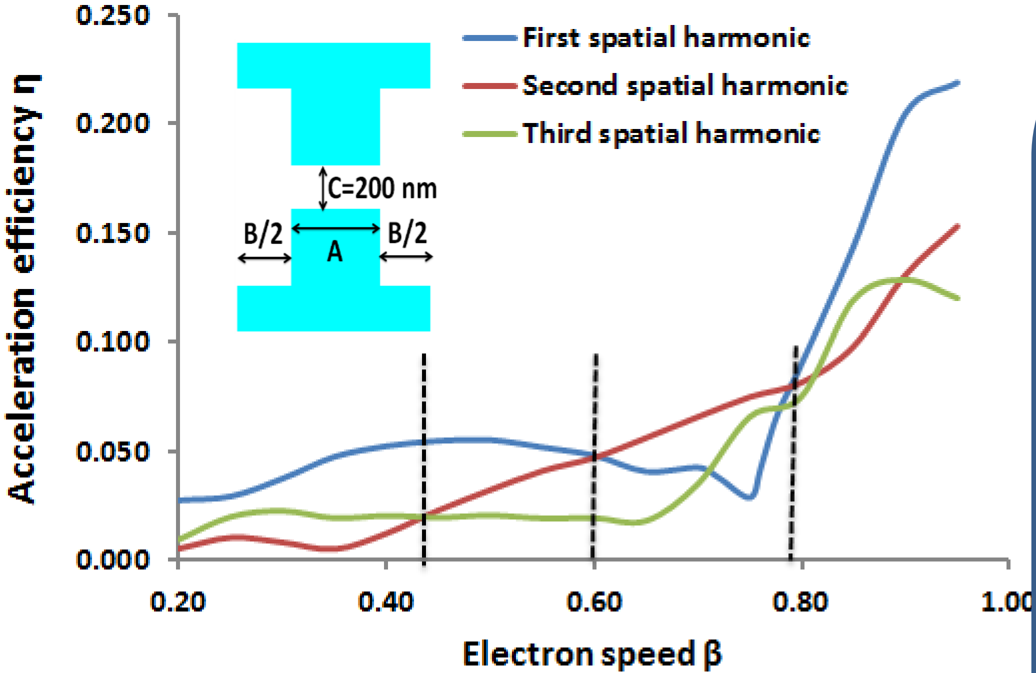
- At this time Δt the electrons just travel from M to N:

  $\lambda_p = v\,\Delta t$ (2)

- Thus we obtain:

  $\beta = v/c = 1/\tan\theta$ (3)

Preliminary Analysis of Multi-stage DLA



- **Analysis**

1) **When electron with speed *β<0.45*, first spatial > third > second;**
2) ***0.45<β<0.60*, first spatial> second > third;**
3) ***0.60<β<0.80*, second spatial structure is most efficient;**
4) ***β>0.80*, first spatial structure is most efficient**

- **$A/\lambda_p = B/\lambda_p = 0.5$, C=200 nm, which are assumed in the simulation;**
- **$\lambda_p = n * \beta * \lambda$**

Summary & Outlook

- Investigation into acceleration of high β electrons in a double grating structure;
- Investigation into acceleration of electrons with β=0.3 in a double grating structure;
- Did some preliminary research on multi-stage dielectric laser acceleration.
- Experimental studies at DL with ASTeC;
- With ULAN/ASTeC: 2D/3D photonic crystal DLA

Thank you!