Energy efficiency studies for dual-grating dielectric laser-driven accelerators (DLAs)

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Outline

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- Dual-gratings with a Bragg reflector
- Dual-gratings driven by a pulse-front-tilted(PFT) laser
- Dual-gratings combining a Bragg reflector and a PFT laser
- Summary & outlook

Participants

- The University of Liverpool and Cockcroft Institute, UK
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- Paul Scherrer Institute, Switzerland
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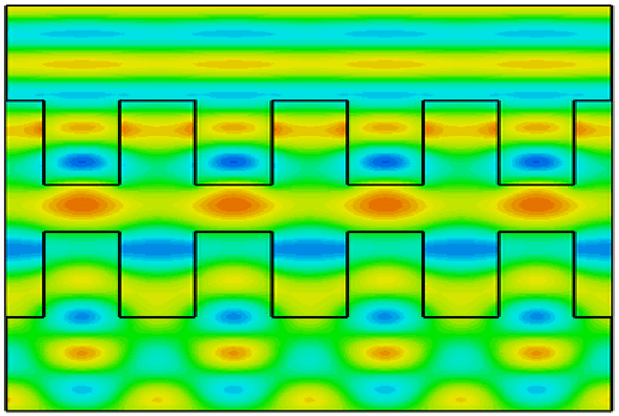
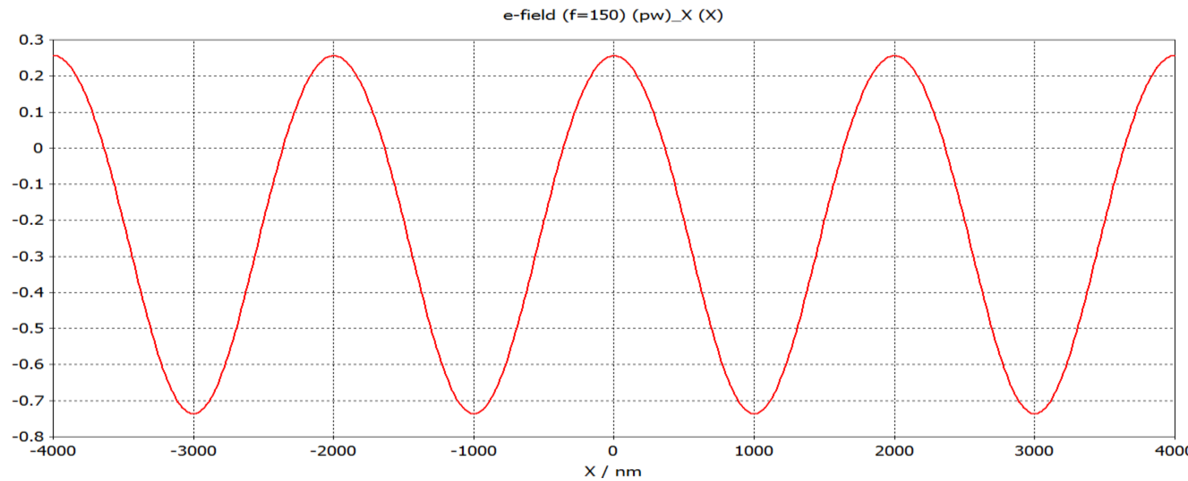
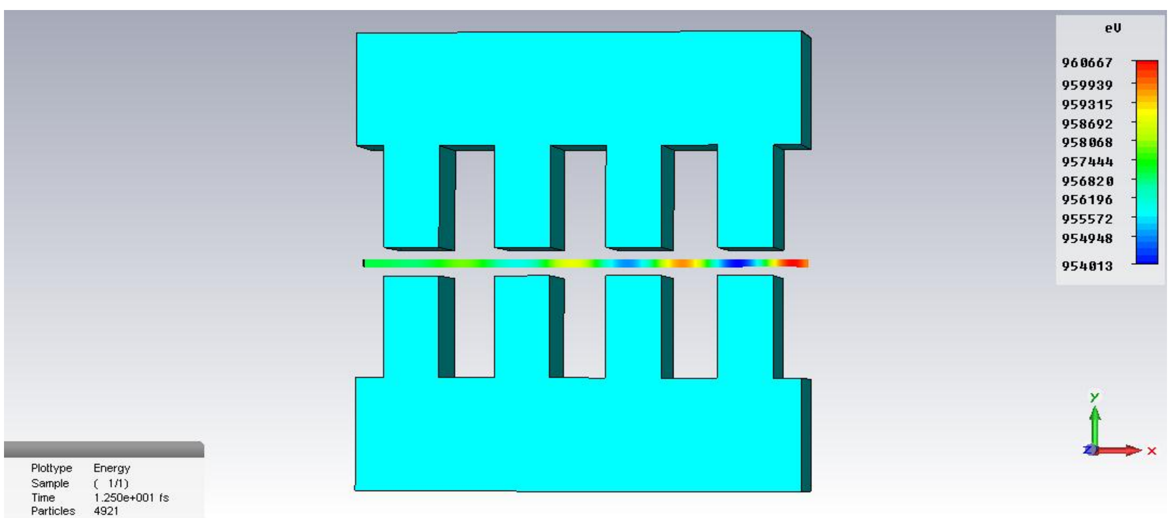
- The Accelerator Science and Technology Centre (ASTeC), UK
  Dr. Steven Jamison
- The University of Manchester and Cockcroft Institute, UK
  Dr. Guoxing Xia
- Tech-X company:
  Jonathan Smith

Working Principle

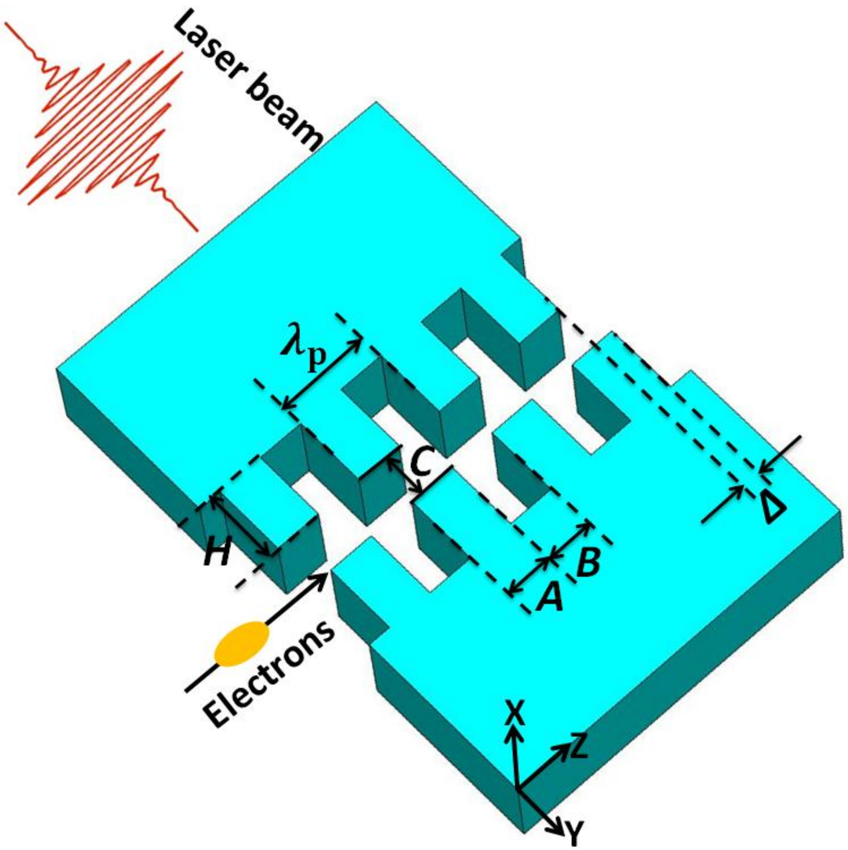






1) **Oscillating electric field in the channel gap center;**
2) **Energy modulation.**

Definitions



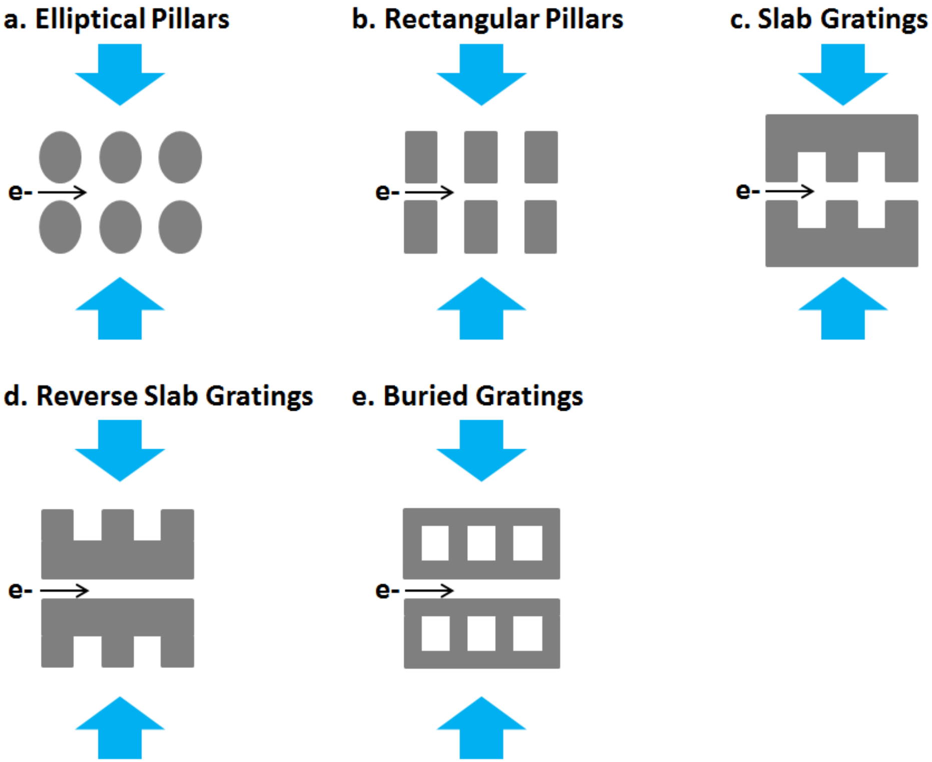
The accelerating gradient

- $G = \frac{1}{\lambda_p}\int_0^{\lambda_p} E_z[z(t), t]dz$,

where λ_p is the grating period, $E_z[z(t), t]$ is the longitudinal electric field along the vacuum channel, $z(t)$ is the position of electrons in the vacuum channel at time t.

1) Energy efficiency / Accelerating efficiency ***AE* = *G*/*E*₀**, where E_0 is the input field.
2) Accelerating factor ***AF* = *G*/*E*ₘ**, where E_0 is the maximum field in the structure for an input field E_0, E_m should not exceed the material damage threshold.

Different dual-grating structures

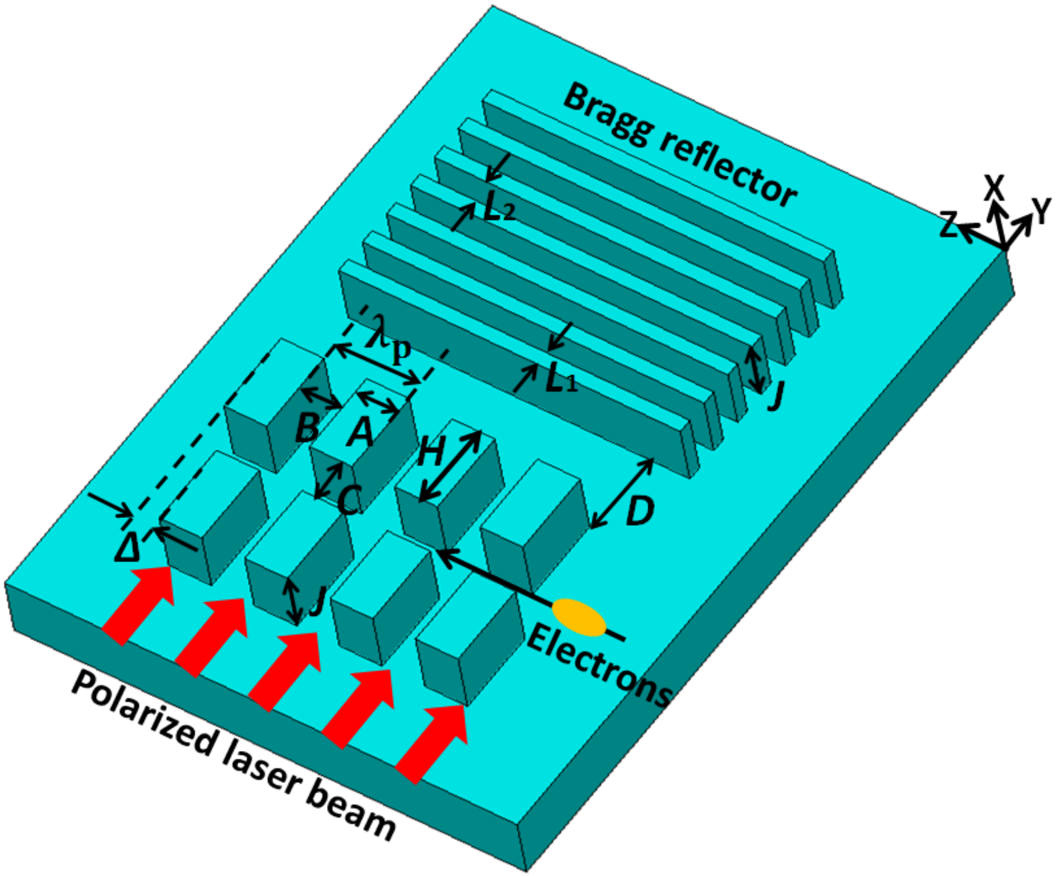


- For reported dual-grating structures, they can be illuminated by a single laser or symmetrical laser;
- They can be made of quartz or silicon, quartz (2 J/cm^2) has a higher damage threshold than silicon (0.2 J/cm^2);
- For single laser illumination, quartz dual-grating structures can generate a maximum accelerating efficiency ***AE = G/E*₀ = 0.50**, and accelerating factor ***AF = G/E*ₘ = 0.25** .

A. Aimidula et al, Phys. Plasmas. 21, 023110 (2014)

A. Aimidula et al, Nucl. Instrum. Methods in Phys. Res., Sect. A 740,108 (2014)

Dual-gratings with a Bragg reflector

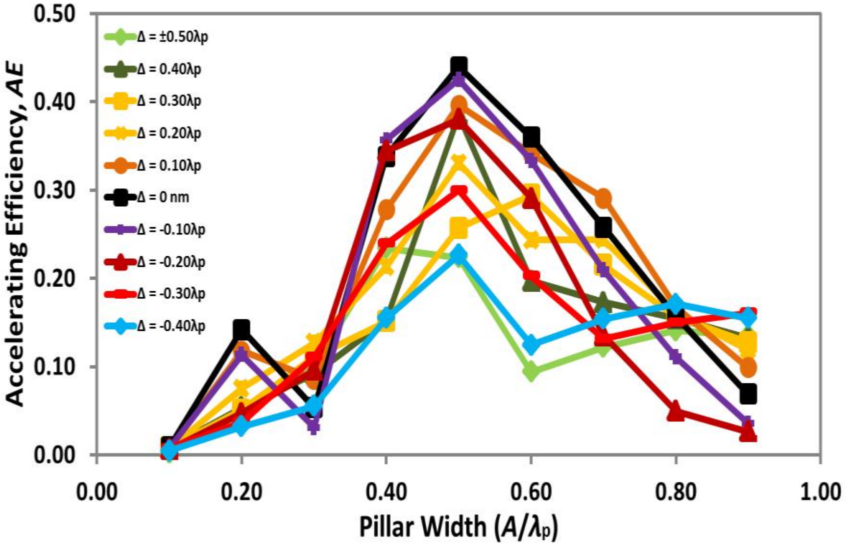


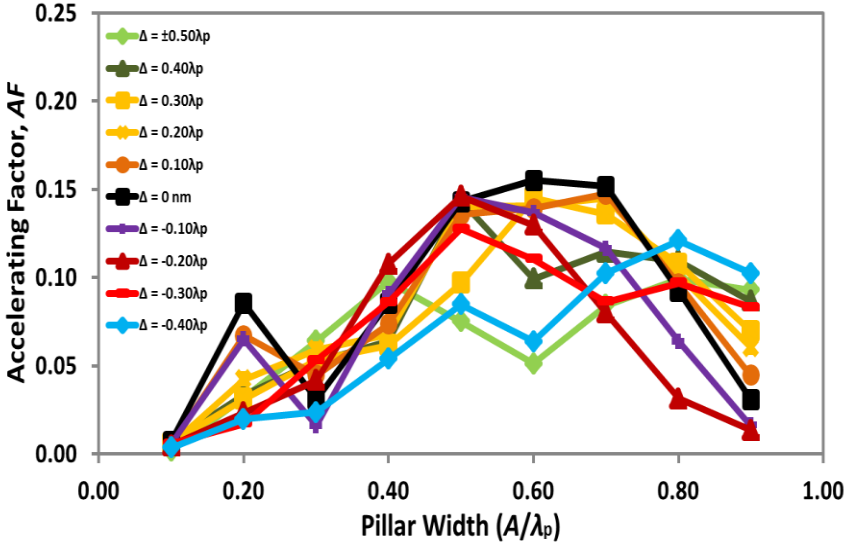
- This design consists of dual-grating structures and a Bragg reflector;
- Advantage 1: a Bragg reflector can boost the accelerating field in the channel centre, thereby resulting in a great a energy gain;
- Advantage 2: a Bragg reflector can be integrated with dual-grating structures in the same wafer using current nanofabrication techniques.

E. Prat, et al, NIMA (2016), in press

Y. Wei, et al, Phys. Plasmas. 24, 073115 (2017)

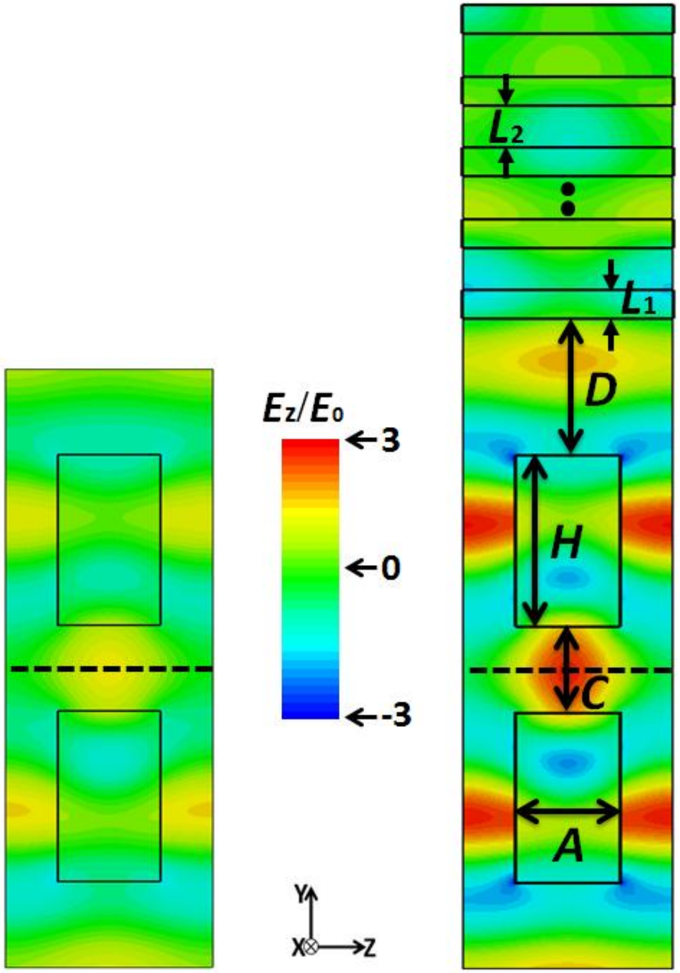
Bare dual-gratings

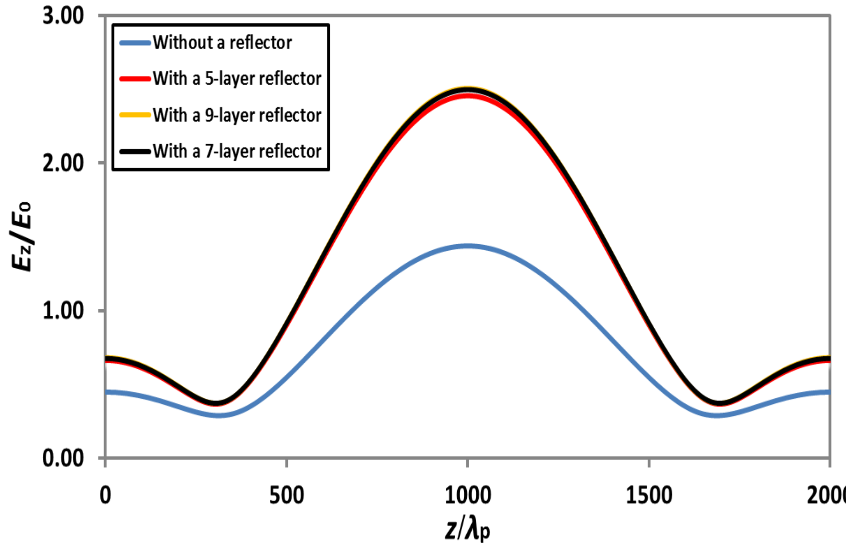




- The maximum *AE* = 0.440 occurs at *C* = $0.50\lambda_p$, H = λ_p, A = $0.50\lambda_p$, Δ = 0 nm while the maximum *AF* = 0.155 can be obtained at C = $0.50\lambda_p$, H = λ_p, A = $0.60\lambda_p$, Δ = 0 nm.

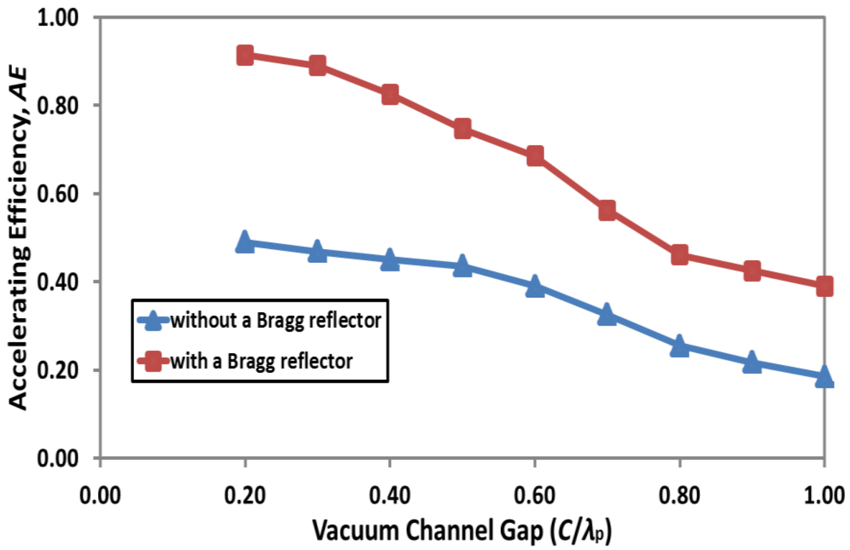
A Bragg reflector is added

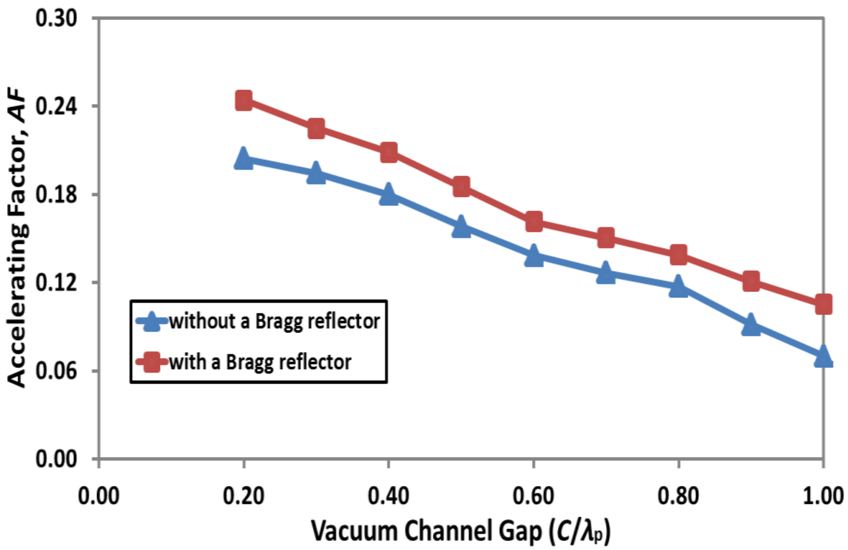




- Power reflectance of 93%, 99% and 99.7% are calculated for a Bragg reflector with N = 5, 7, and 9 respectively;
- A 7-layer Bragg reflector is chosen;
- The maxima *AE* = 0.760 and *AF* = 0.173 are achieved at C = $0.50\lambda_p$, H = λ_p, A = $0.50\lambda_p$, Δ = 0 nm, D = $0.80\lambda_p$.

Vacuum channel gap

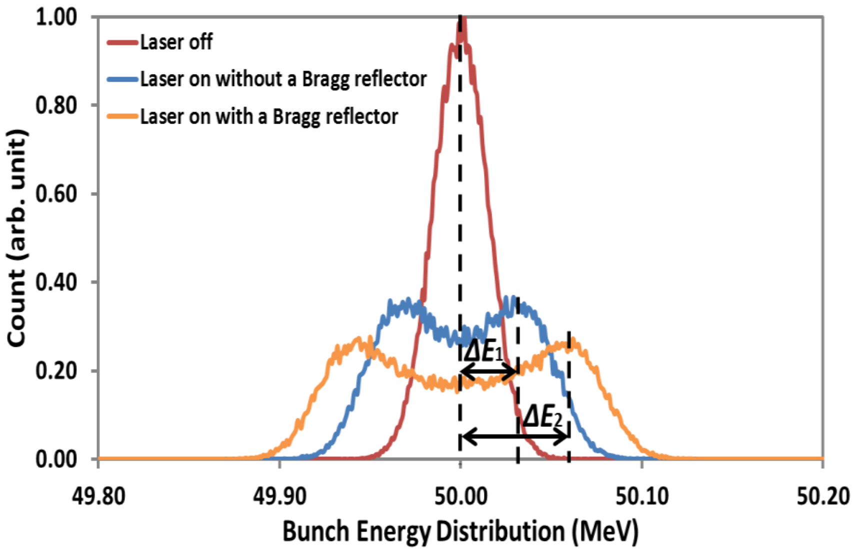




- Each gap is optimized based on the same procedures;
- *AE* is significantly improved by more than 70%, it means that a 65% lower laser power to generate the same accelerating gradient, when a Bragg reflector is added for dual-gratings;
- The minor increments for *AF* are in the range of 0.02 ~ 0.04, which indicates that a Bragg reflector can increase the maximum achievable gradient by 0.18 ~ 0.36 GV/m for 100 fs-pulsed laser illumination.

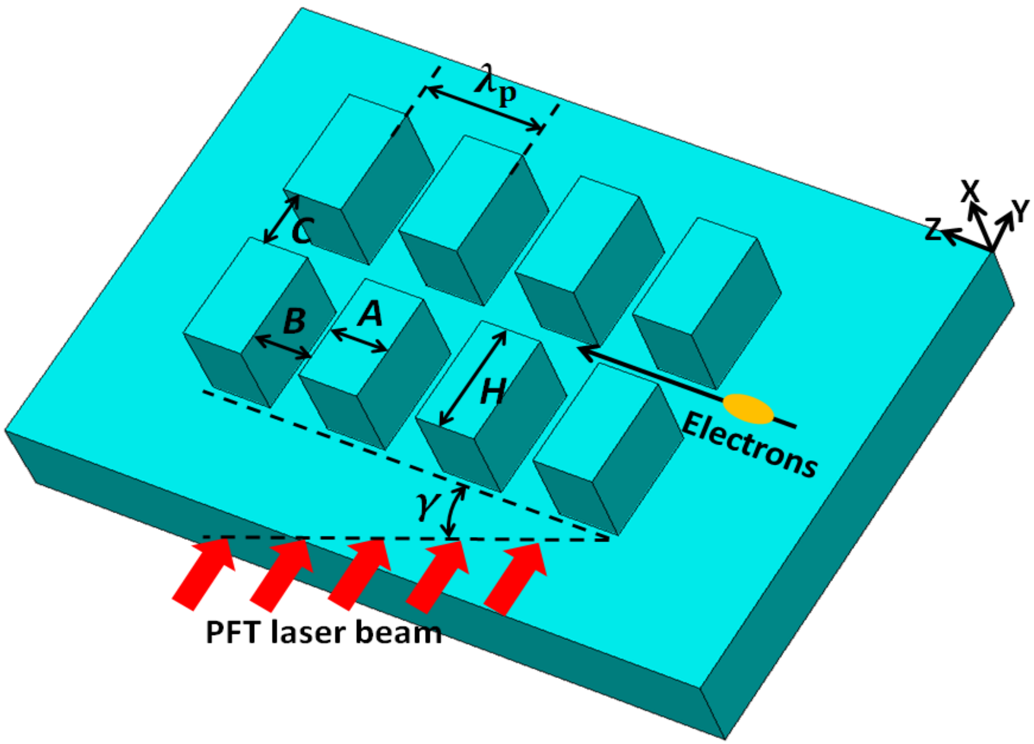
Particle-in-cell simulations

- **Structure parameters**: $C = 0.50\lambda_p$, $H = \lambda_p$, $A = 0.50\lambda_p$, $\Delta = 0$ m, $R = 0.05\lambda_p$, $D = 0.80\lambda_p$, $\lambda_p = 2.0$ μm, $LZ = 200$ μm;
- **Laser parameters**: 2 μm wavelength, 3 μJ pulse energy, 100 fs pulse duration, 50 μm waist radius and peak field E_0 = 2 GV/m
- **Electron bunch parameters**: mean energy of 50 MeV, RMS energy spread of 0.03%



- The maximum energy gain is ΔE_2 = 59 ± 4 keV for optimized dual-gratings with a Bragg reflector, while it is ΔE_1 = 32 ± 4 keV for bare dual-gratings;
- It corresponds to loaded accelerating gradients of 1.48 ± 0.10 GV/m and 0.80 ± 0.10 GV/m, respectively.
- The Energy Efficiency is therefore increased by (85 ± 26)% when a Bragg reflector is added.

Bare dual-gratings driven by a pulse-front-tilted (PFT) laser



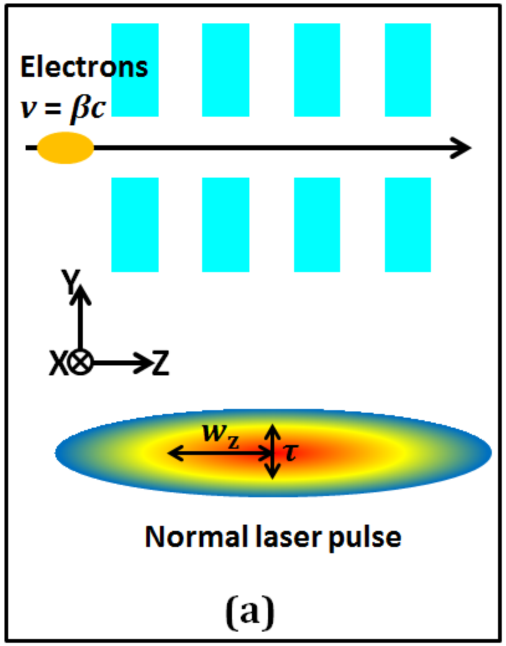
- A PFT laser beam with a tilt angle γ, is used to illuminate the dual-gratings to accelerate electrons with a speed of v;
- Synchronous condition:

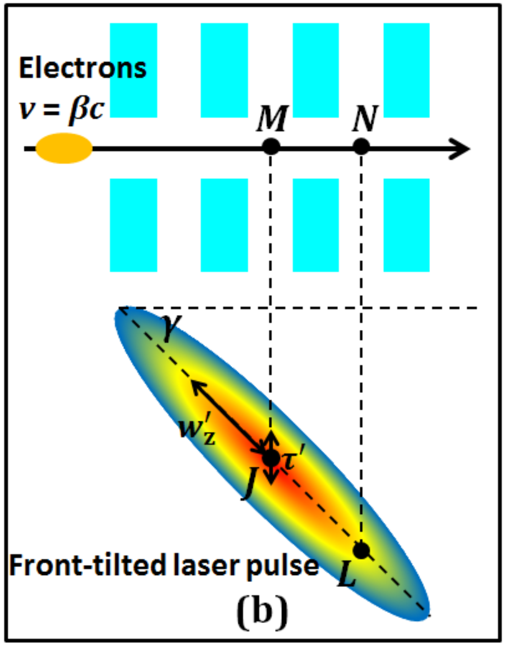
  $$\beta = v/c = 1/\tan\gamma$$

- Advantage : Extend the interaction length and results in a larger energy gain.

Y. Wei, et al, Applied Optics (2017), *accepted*

Comparisons



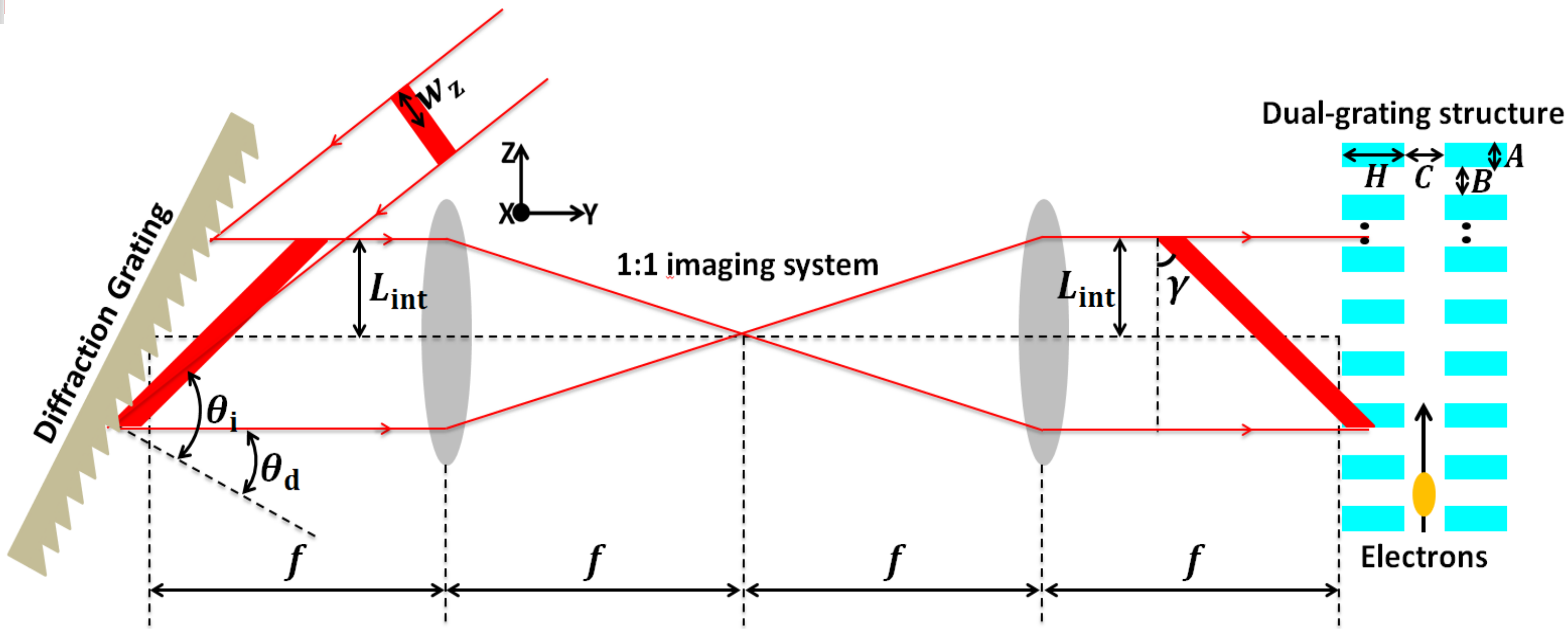


$\tan\gamma = pc$

Where e is the charge of a single electron, G_P is the peak gradient, w_z is the waist radius along z-axis, τ is the FWHM pulse duration, w'_z is the tilted waist radius, τ' is the local pulse duration and $p = \frac{dt}{dz}$ is the PFT factor which is defined by the derivative of the pulse-front arrival time with respect to z, and γ is the PFT angle.

- **Energy gain** $\Delta E = \int_{-0.5LZ}^{0.5LZ} eG_\mathrm{P} e^{-\left(\frac{z}{w_\mathrm{int}}\right)^2} dz$
- **Maximum energy gain** $\Delta E_\mathrm{m} = eG_\mathrm{p}\sqrt{\pi}\, w_\mathrm{int}$, where $w_\mathrm{int} = \left(\frac{1}{w_\mathrm{z}^2} + \frac{2\ln 2}{(\beta c\tau)^2}\right)^{-0.5}$
- **Energy gain** $\Delta E' = \int_{-0.5LZ}^{0.5LZ} eG_\mathrm{P} e^{-\left(\frac{z}{w'_\mathrm{z}\cos\gamma}\right)^2} dz$
- **Maximum energy again** $\Delta E'_\mathrm{m} = eG_\mathrm{p}\sqrt{\pi}\, w'_\mathrm{z}\cos\gamma = eG_\mathrm{p}\sqrt{\pi}\, w'_\mathrm{int}$

Optics setup



- The optical setup consists of a diffraction grating and a 1:1 imaging system with a two-lens telescope;
- When an incident laser pulse travels through the diffraction grating, the upper side of the pulse is diffracted by the grating earlier than the lower side of the pulse. This generates an optical path difference, which contributes to a front-tilted pulse close to the grating. Such a front-tilted pulse has the same pulse duration as the incident laser pulse.

Detailed calculations

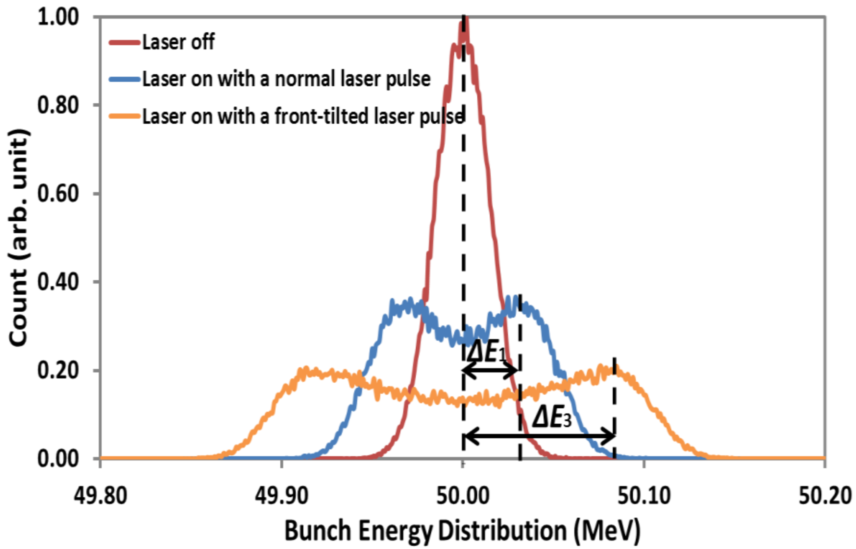
- The grating equation: $\sin\theta_\mathrm{i} + \sin\theta_\mathrm{d} = \frac{\lambda_0}{g}$;
- The tilt angle γ is given by $\tan\gamma = \frac{\lambda_0}{p\cos\theta_\mathrm{d}}$; where θ_i and θ_d are the incidence and diffraction angles respectively, λ_0 is the laser wavelength, g is the grating period.
- So the interaction length is $L_\mathrm{int} = \frac{\sqrt{2}\left(\left(\frac{2w_\mathrm{z}}{\cos\theta_\mathrm{i}}\right)^2 + (2w_\mathrm{z}\tan\theta_\mathrm{i})^2 - 2\frac{2w_\mathrm{z}}{\cos\theta_\mathrm{i}}2w_\mathrm{z}\tan\theta_\mathrm{i}\cos(90^0+\theta_\mathrm{d})\right)^{0.5}}{4}$
- We can get the mathematical expression for the electric field of such a PFT beam:

$$E_\mathrm{z}' = E_0 e^{-\left(\frac{z}{L_\mathrm{int}}\right)^2 - 2\ln 2\left(\frac{t-pz}{\tau_0}\right)^2}\cos(\omega t - k_0 y + \phi_1)$$

- When the incidence angle θ_i is the same as the diffraction angle θ_d, the diffraction efficiency of a grating is usually maximal in Littrow configuration. We can get $\theta_\mathrm{i} = \theta_\mathrm{d} = 26.6^0$. When a laser wavelength of $\lambda_0 = 2.0$ μm is chosen, the grating period is $g = 2.236$ μm, corresponding to a groove density of $n_\mathrm{g} = 447$ lines/mm for the diffraction grating.
- So a groove density of $n_\mathrm{g} = 450$ lines/mm is chosen as an optimum for our optical system. In this case, we can get $\theta_\mathrm{i} = 27.65^0$, $\theta_\mathrm{d} = 25.84^0$.
- By substituting θ_i and θ_d into equation of interaction length, an interaction length of $L_\mathrm{int} = 51$ μm.

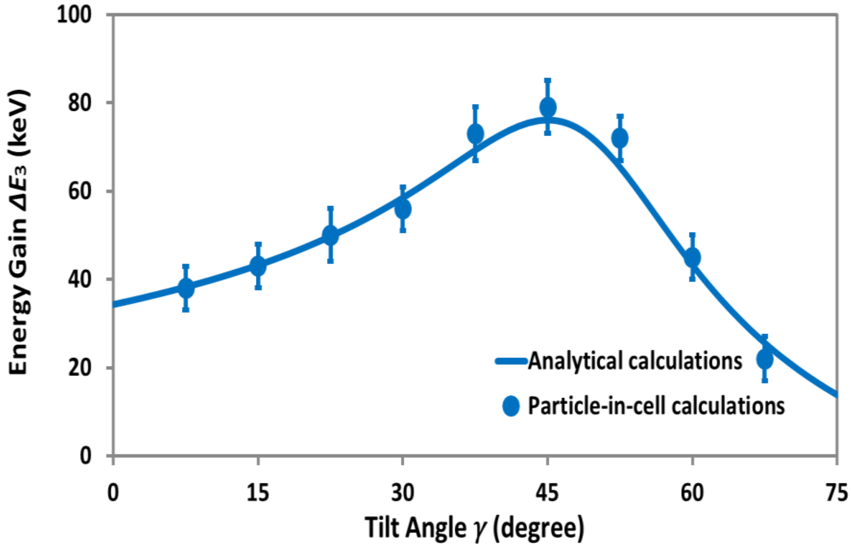
Particle-in-cell simulations

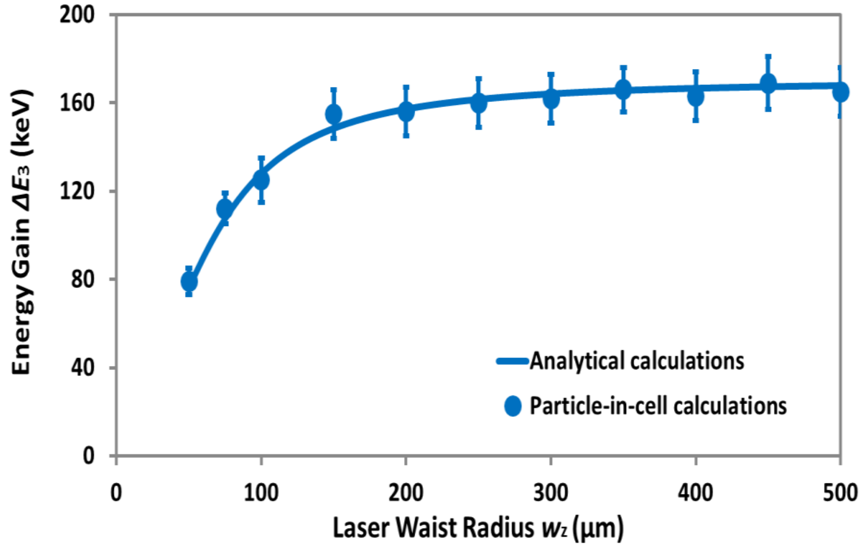
- **Structure parameters**: $C = 0.50\lambda_p$, $H = \lambda_p$, $A = 0.50\lambda_p$, $\Delta = 0$ m, $R = 0.05\lambda_p$, $\lambda_p = 2.0$ μm, $LZ = 200$ μm;
- **Laser parameters**: 2 μm wavelength, 3 μJ pulse energy, 100 fs pulse duration, 50 μm waist radius and peak field $E_0 = 2$ GV/m
- **Electron bunch parameters**: mean energy of 50 MeV, RMS energy spread of 0.03%

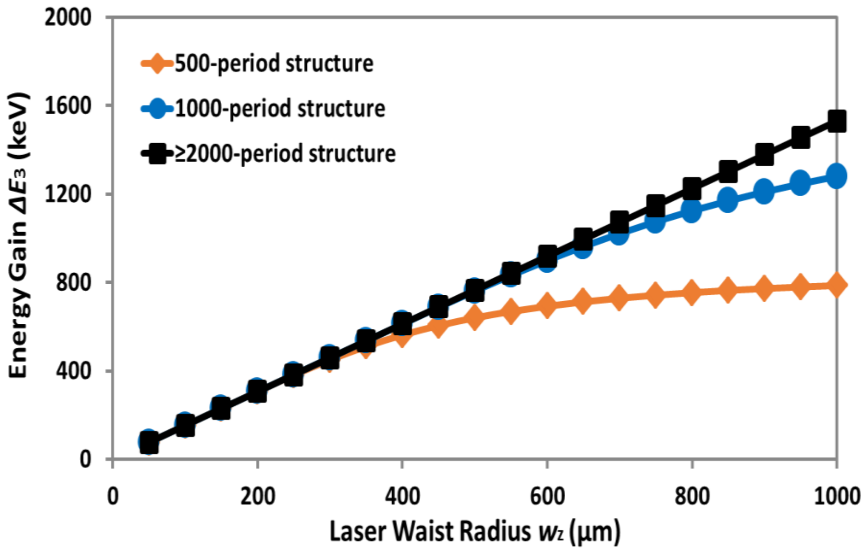


- The maximum energy gain is $\Delta E_1 = 32 \pm 4$ keV for normal laser illumination while it is $\Delta E_3 = 79 \pm 6$ keV for PFT laser illumination;
- This corresponds to a maximum loaded gradients of 0.80 ± 0.10 GV/m and 0.88 ± 0.07 GV/m;
- The Energy Efficiency is increased by (147 ± 36) % compared to normal laser illumination.

Maximum energy gain

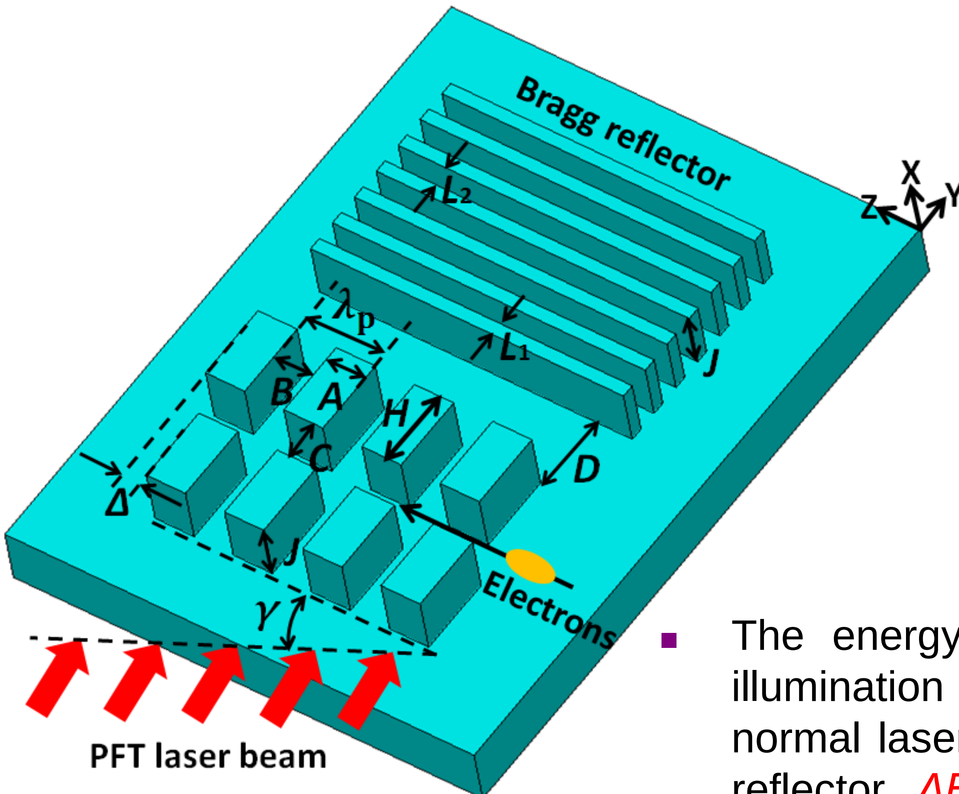


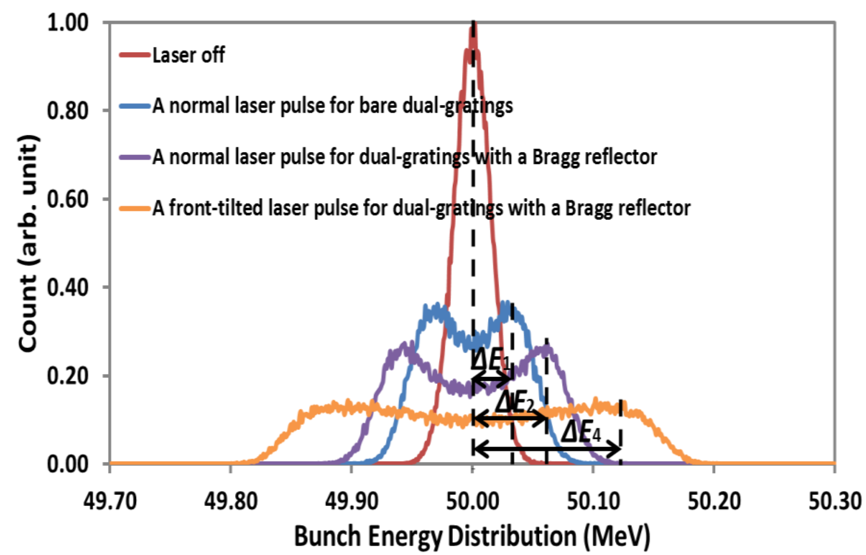




- The maximum energy gain occurs at a tilt angle of $\gamma = 45^0$ for relativistic electrons;
- For a 100-period structure, the energy gain gradually saturates to 170 ± 11 keV;
- For a ≥2000-period structure, the energy gain linearly increases with the laser waist radius, the energy gain reaches about 1.5 MeV when the laser waist radius is 1.0 mm.

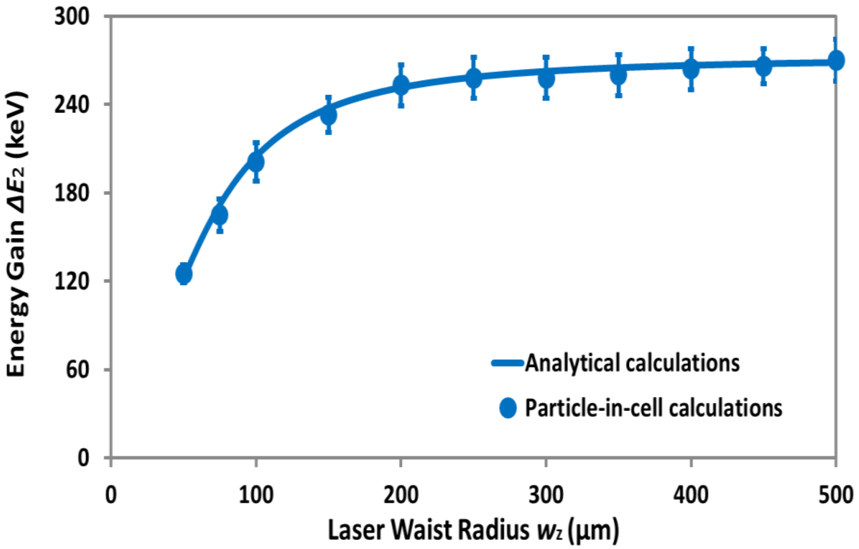
Dual-gratings combining a Bragg reflector and a PFT laser

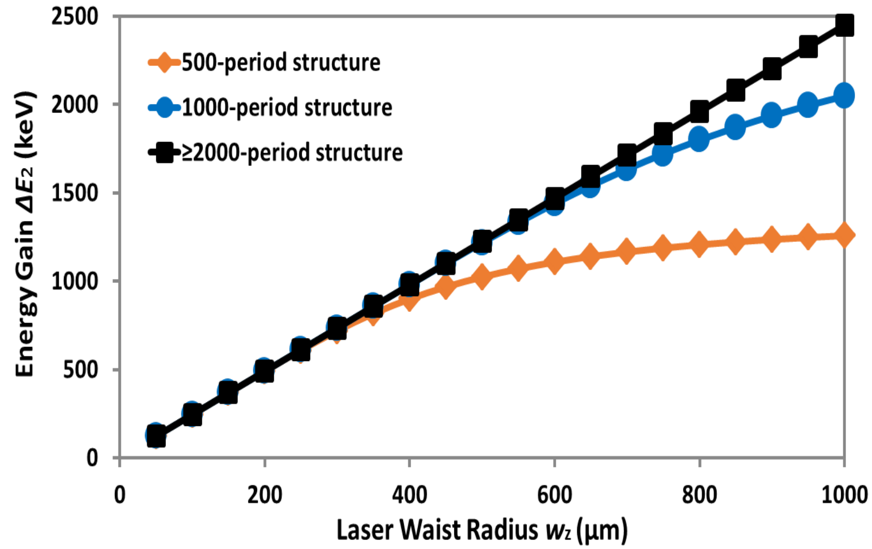




- The energy gain: ΔE_1 = 32 ± 4 keV for normal laser illumination on the bare dual-gratings, ΔE_2 = 59 ± 4 keV for normal laser illumination on the dual-gratings with a Bragg reflector, ΔE_4 = 125 ± 6 keV for PFT laser illumination on the dual-gratings with a Bragg reflector;
- The Energy Efficiency is increased by (291 ± 52) % compared to normal laser illumination on the bare dual-gratings.

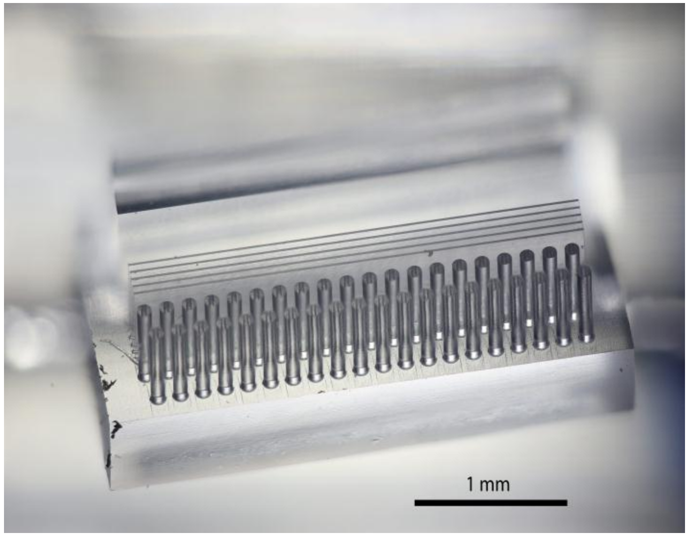
Maximum energy gain

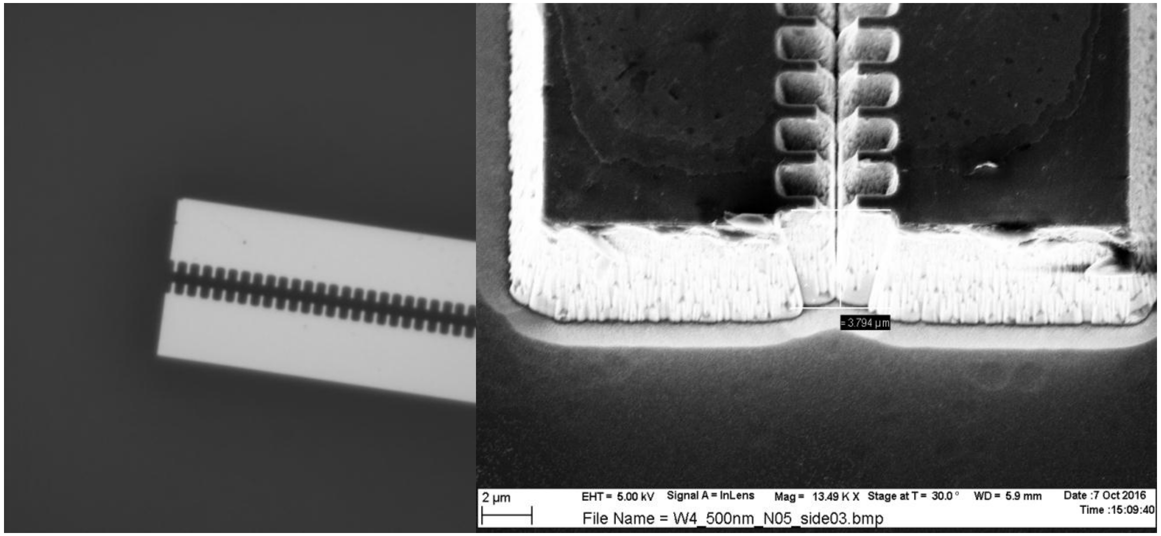




- For a 100-period structure, the maximum energy gain gradually saturates to 270 ± 14 keV;
- For a ≥2000-period structure, the energy gain linearly increases with the laser waist radius, the energy gain reaches about 2.5 MeV when the laser waist radius is 1.0 mm.

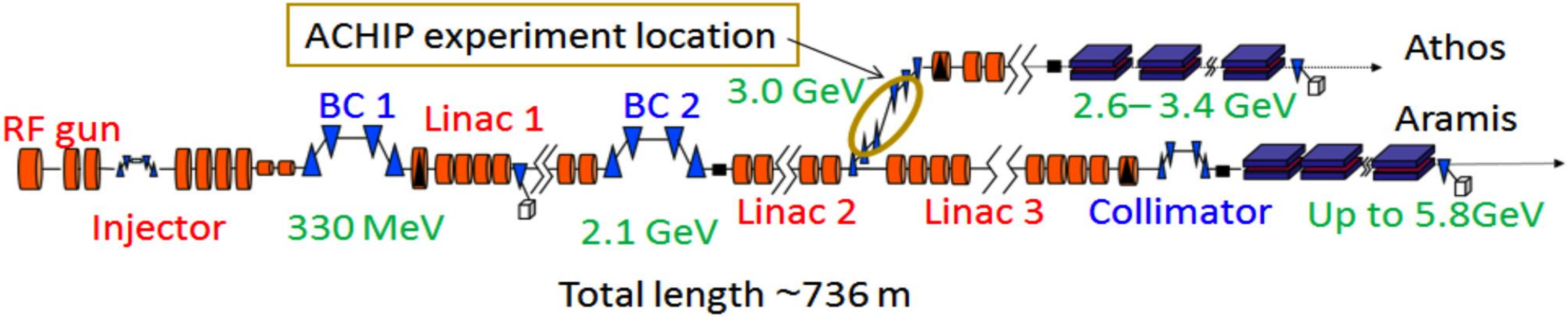
Fabrication and experiment plan





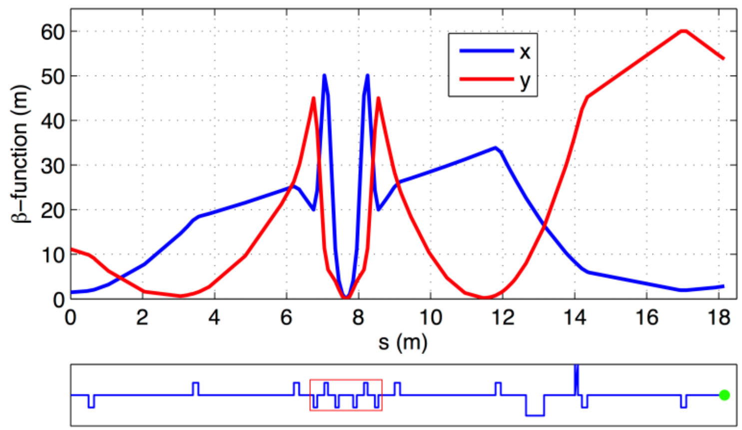
Scaled dual-gratings with a Bragg reflector

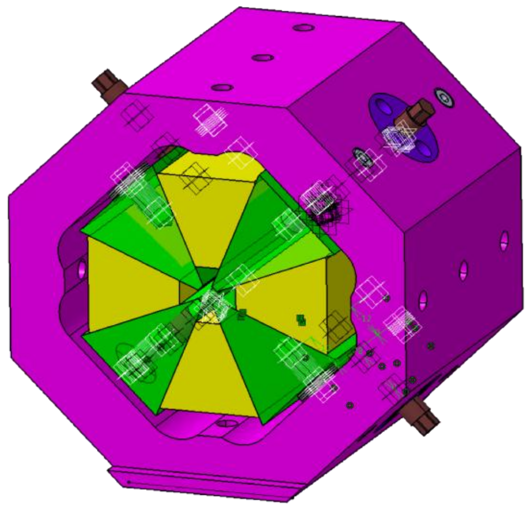
Dual-grating structures with a period of λ_p = 2.0 µm



Slide courtesy of Dr. Eugenio Ferrari from Paul Scherrer Institute

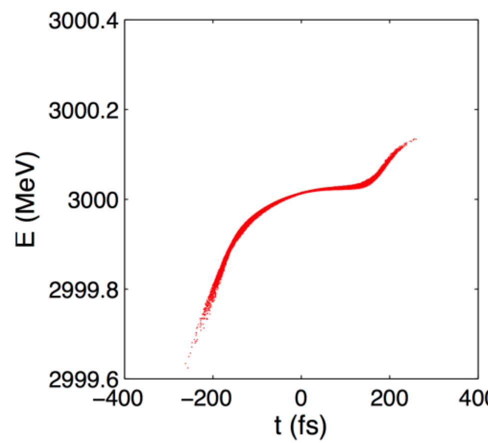
Focusing of the electron beam

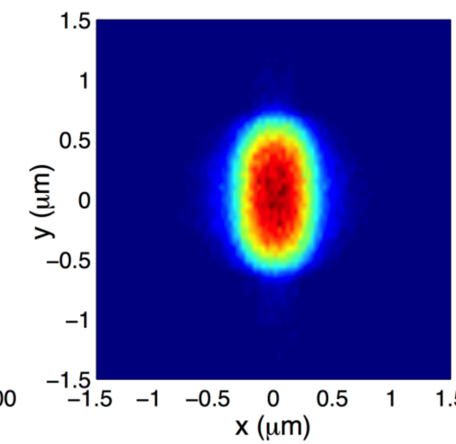




- Adapt beam optics at low charge (1 C):
  - Zero dispersion at interactior
  - Focusing and re-matchinc six permanent magr quadrupoles
  - Measurement of ter the interactior g dipole magne
    (No persion after the dogleg)
- No addition ectromagnetic quadrupoles needed

While being “transparent” to SwissFEL operations





Slide courtesy of Dr. Eugenio Ferrari from Paul Scherrer Institute

Summary and outlook

- A Bragg reflector can be added into a dual-grating structure to improve the energy efficiency by more than 70% from analytically calculations; the loaded gradient is increased by $(85 \pm 26)\%$ for such a structure; ----First scheme
- A PFT laser beam is presented to improve the energy efficiency by more than 100 % for a bare dual-grating structure; ----Second scheme
- A dual-grating structure with a Bragg reflector is illuminated by a PFT laser beam, which improves the energy efficiency by more than 200%; ----Both schemes

- The maximum energy gain is strongly dependent on the incident laser waist radius and the number of structure periods. For a 100-period structure, the maximum energy gain gradually saturates to 270 ± 14 keV; ----Both schemes
- For a ≥2000-period structure, the energy gain linearly increases with the laser waist radius, the energy gain reaches about 2.5 MeV when the laser waist radius is 1.0 mm. ----Both schemes

- Further simulation studies on the wakefield effect;
- Planned experimental studies using SWISS FEL.