Recent Experimental Results and Future Directions of Dielectric Laser Accelerators

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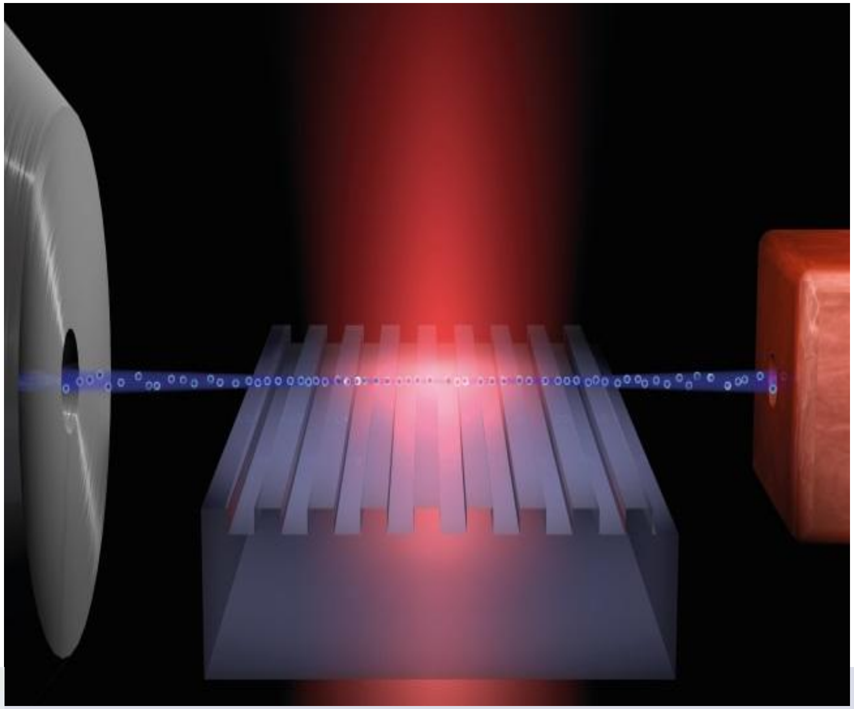

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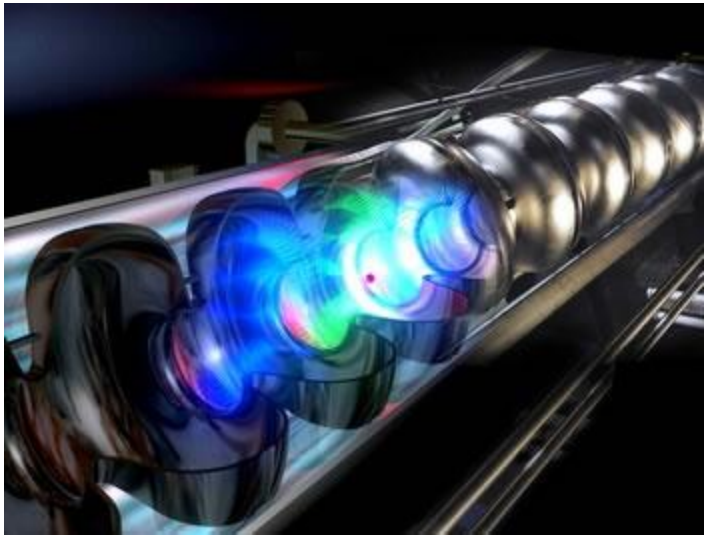
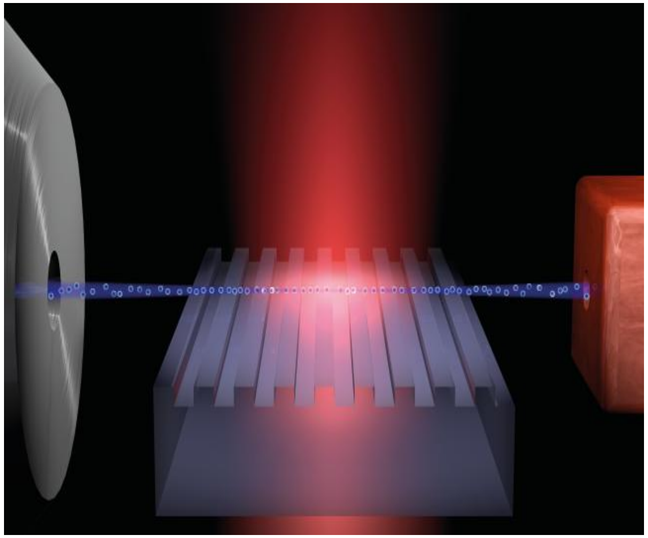
SLAC

Particle accelerators: from RF to Optical

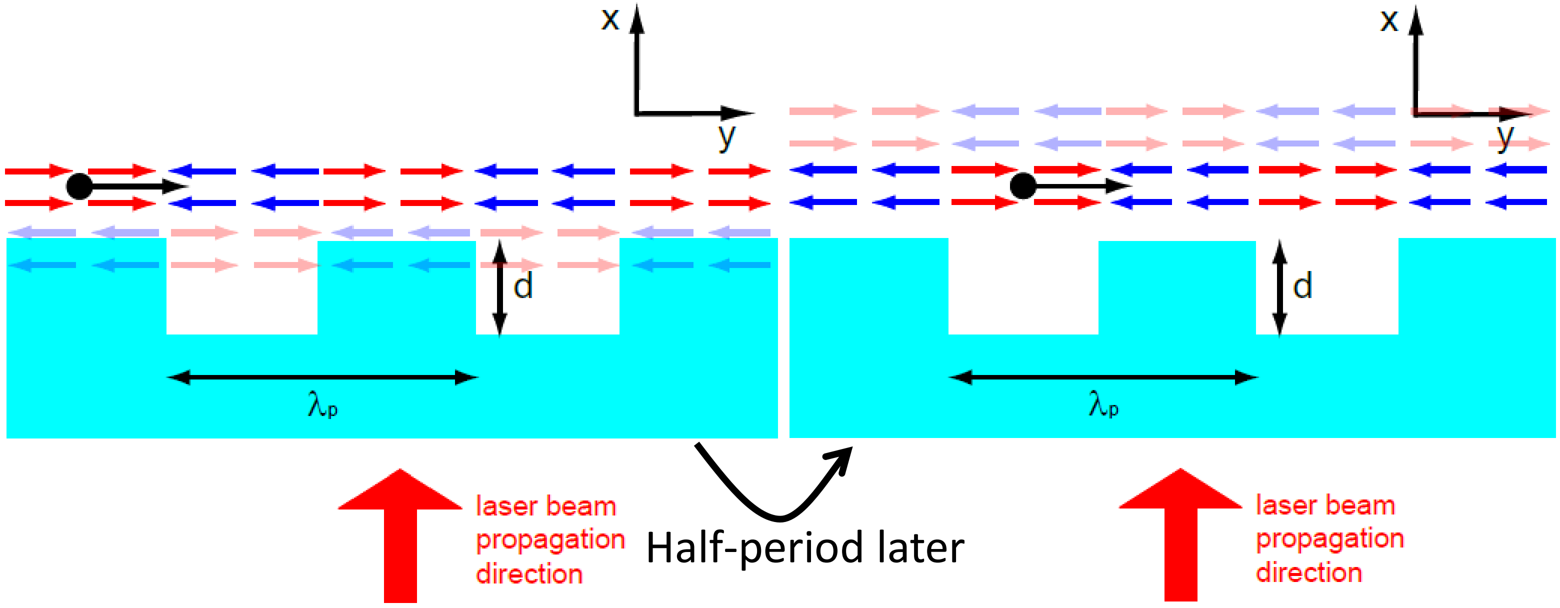


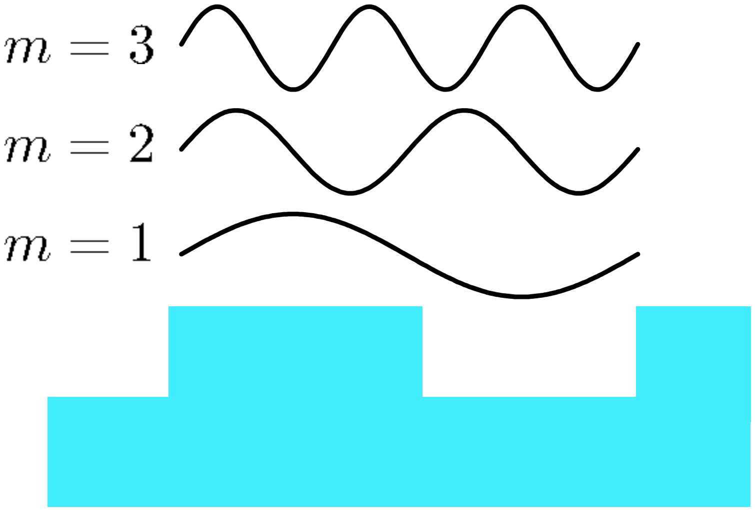
RF cavity (TESLA, DESY)



	Conventional linear accelerator (RF)	**Laser-based dielectric accelerator (optical)**
Based on	(Supercond.) RF cavities	Fused silica grating structures
Peak field limited by	**Surface breakdown: 200 MV/m**	**Damage threshold: 30 GV/m**
Max. achievable gradients	**50 MeV/m**	**10 GeV/m**

The Single Grating Structure





Synchronicity condition:

$$\lambda_p = m\beta\lambda \quad (m = 1, 2, 3, \ldots)$$

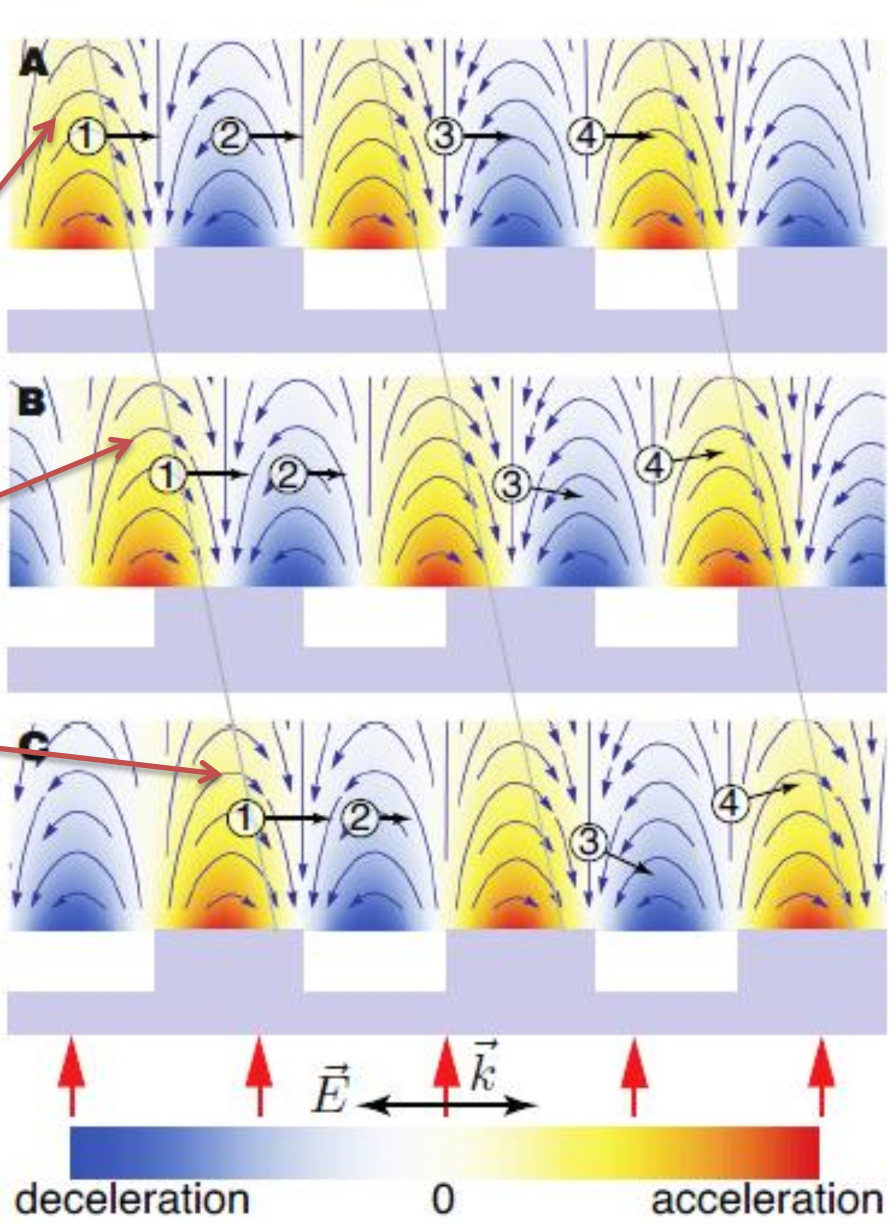
(*m*: # of laser cycles per electron passing one period, $\beta = v/c$, λ : laser wavelength)

$\lambda = 787\,\mathrm{nm}, \;\; \beta \sim 1/3$

$\lambda_p = 250\,\mathrm{nm}, 500\,\mathrm{nm}, \mathbf{750}\,\mathrm{nm}, 1000\,\mathrm{nm}, \ldots$

We use the third spatial harmonic.

Acceleration Depends on Injection Phase



① acceleration

② deceleration

③ deflection

④ deflection

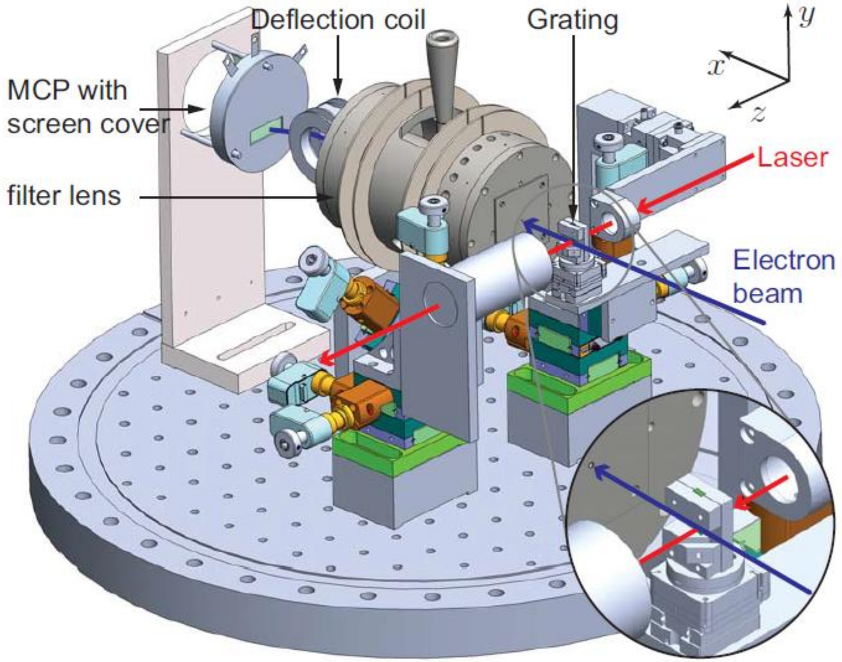
t = 0

t = π/2

t = π

This example:
first spatial harmonic.
Analogous for third
spatial harmonic.

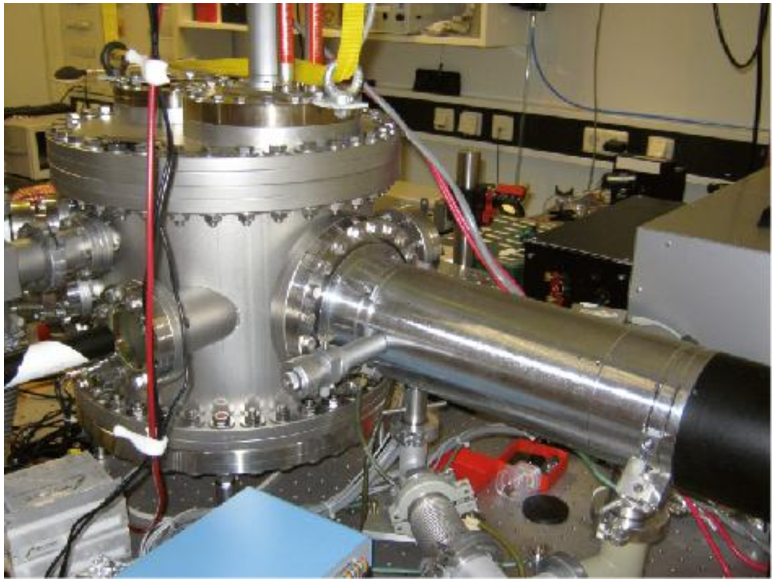
Experimental setup



Laser parameters:
- 400 mW
- 2.745 MHz
- 110 fs

In the focus:
- 8.3 µm beam waist
- 2.76 GV/m
- 2.0 10^{12} W/cm^2

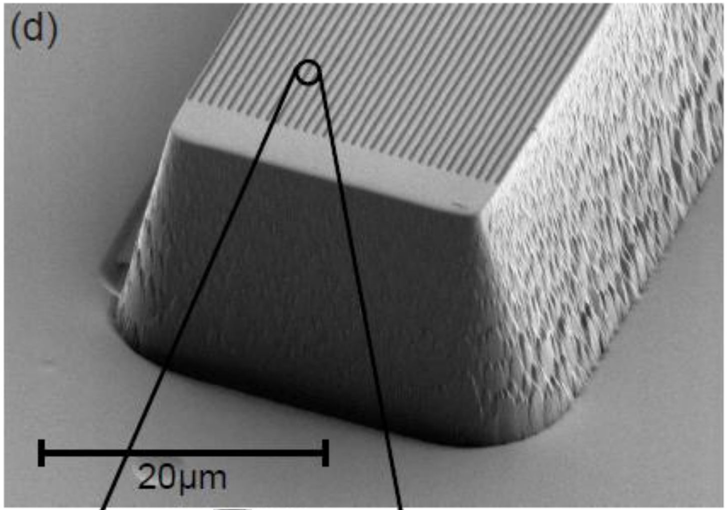
Electron beam parameters:
- continuous beam out of electron column from scanning electron microscope
- excellent control over beam focus and position
- narrow energy spectrum
- beam current: 3.2 ± 0.2 pA

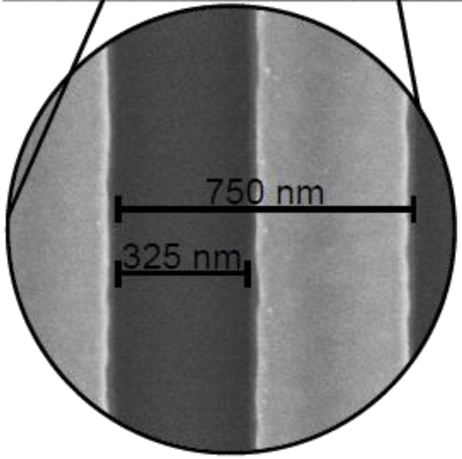


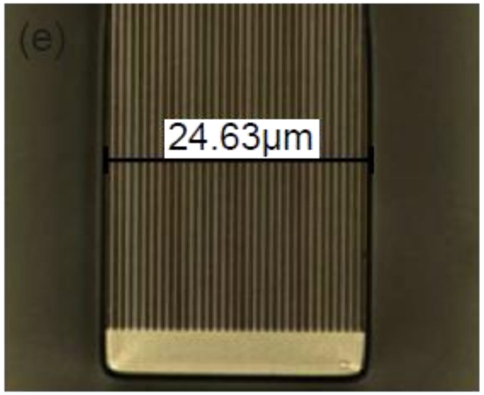
Details on laser: S. Naumov, A. Fernandez, R. Graf, P. Dombi, F. Krausz, and A. Apolonski, N. J. Phys. 7, 216 (2005).

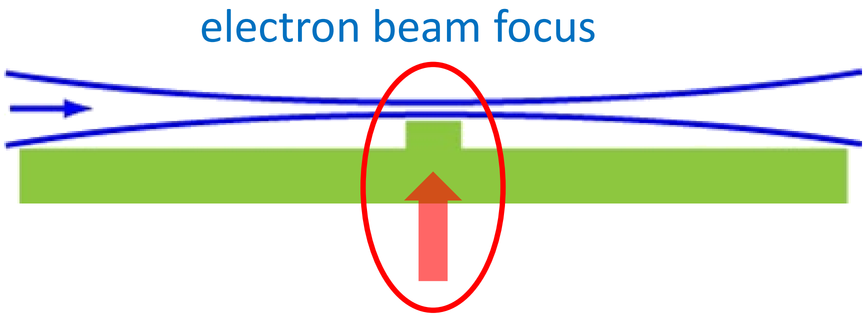
Grating structure

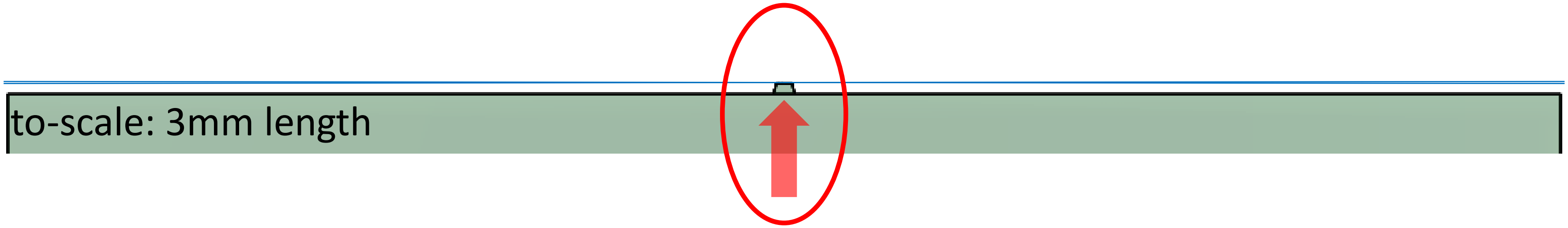
- Grating period: 750nm
- Grating depth: 282nm
- **Challenge:** get close enough (<200nm) to the grating surface without clipping the beam
  → put grating on 20µm high mesa structure



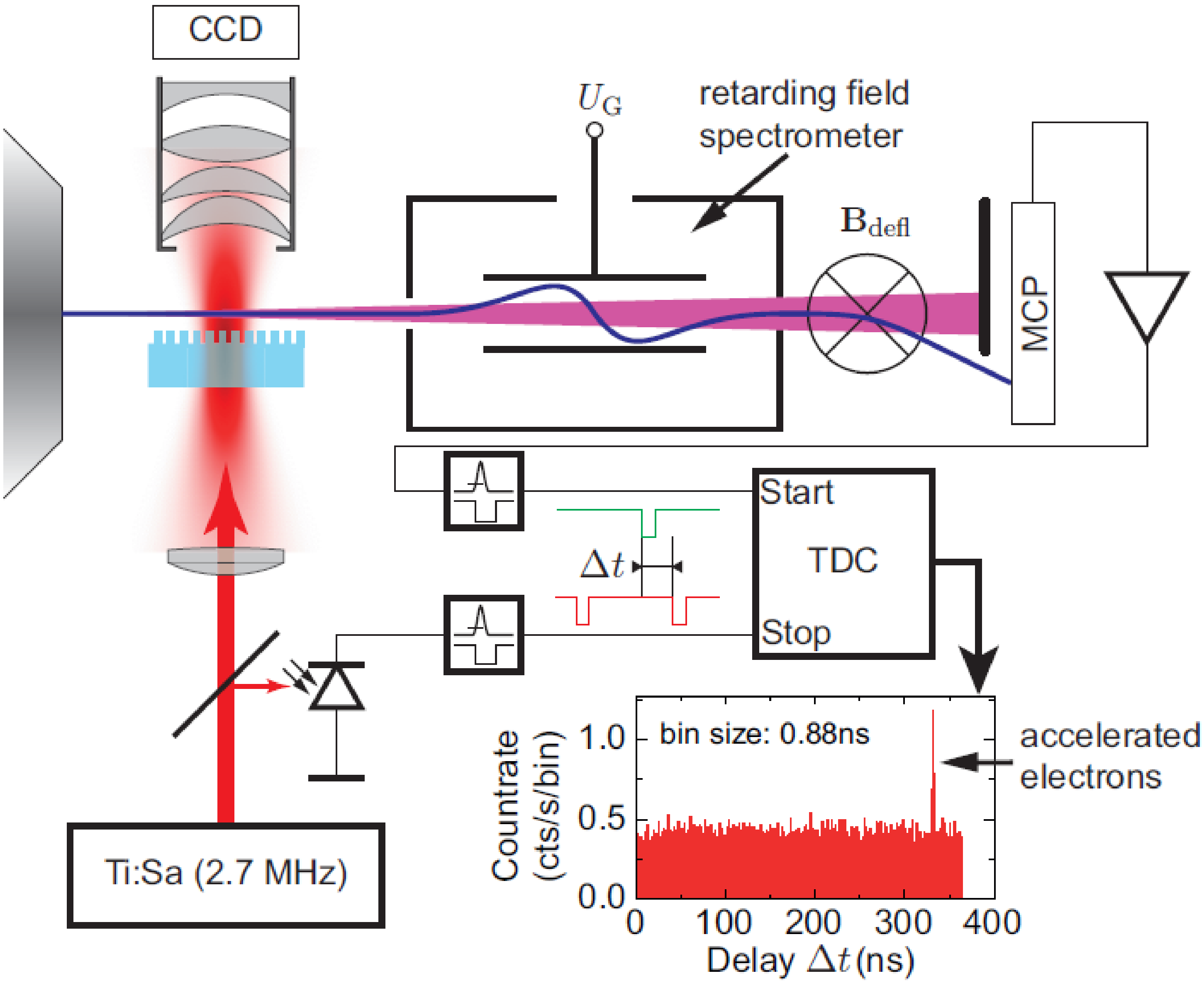




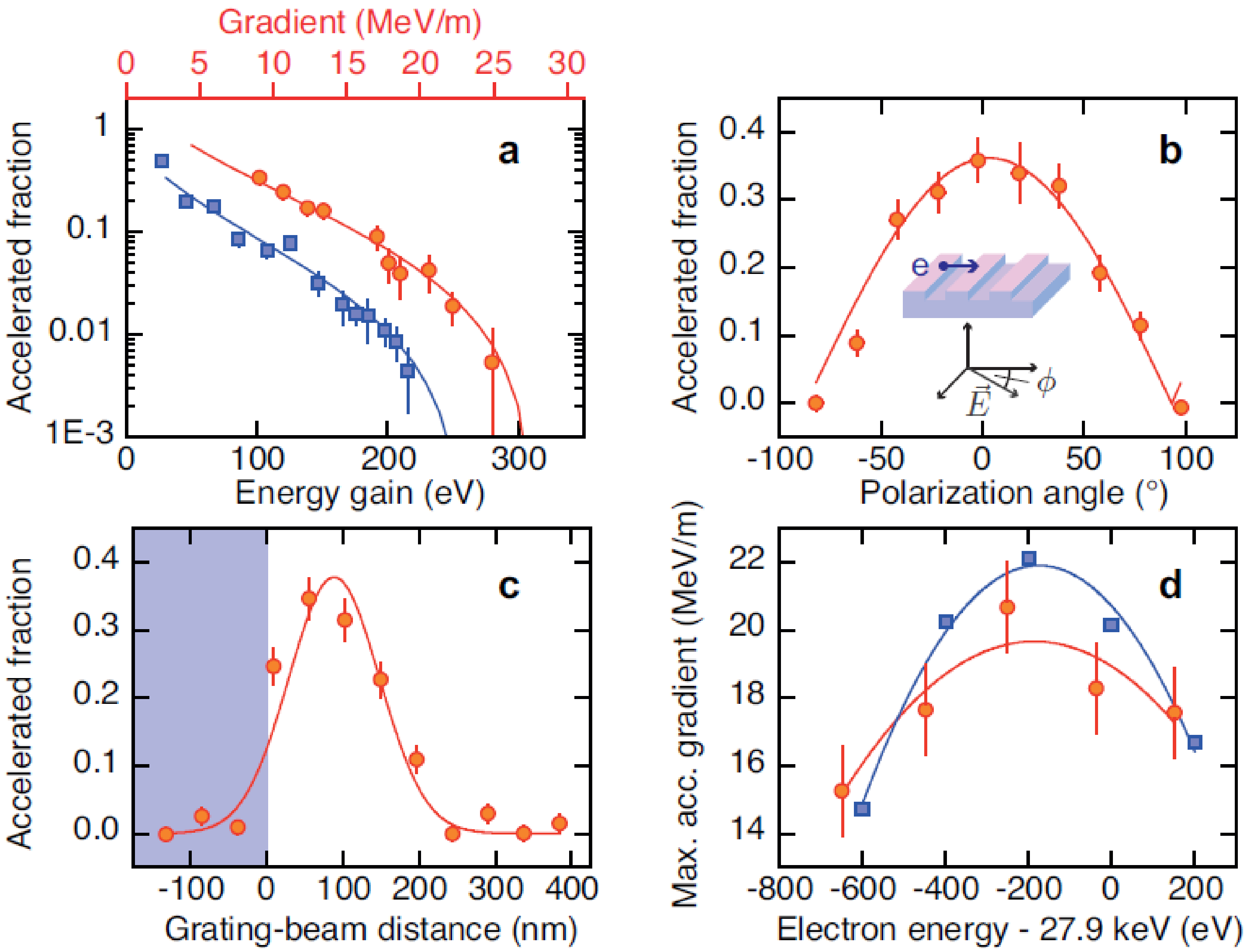




Dielectric laser acceleration detection



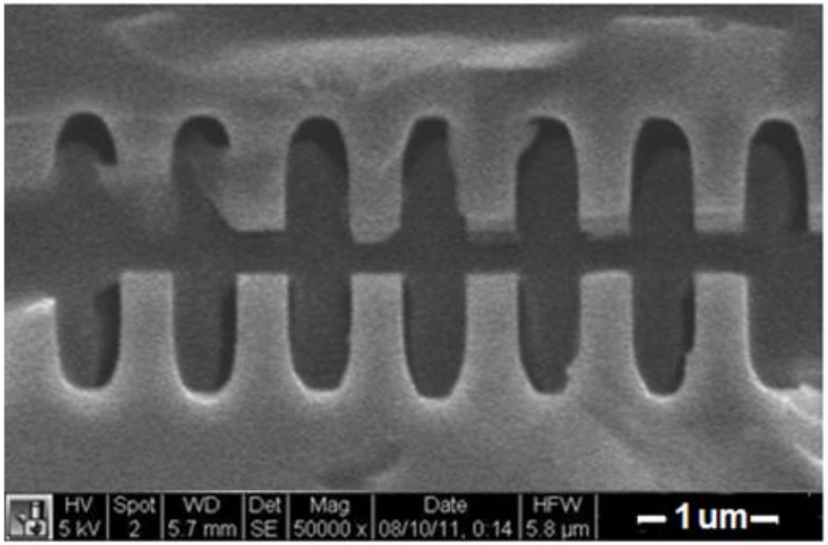
Dielectric laser acceleration results



Max. observed gradient: 25 MeV/m

J. Breuer, P. Hommelhoff, Phys. Rev. Lett. 111, 134803 (2013)

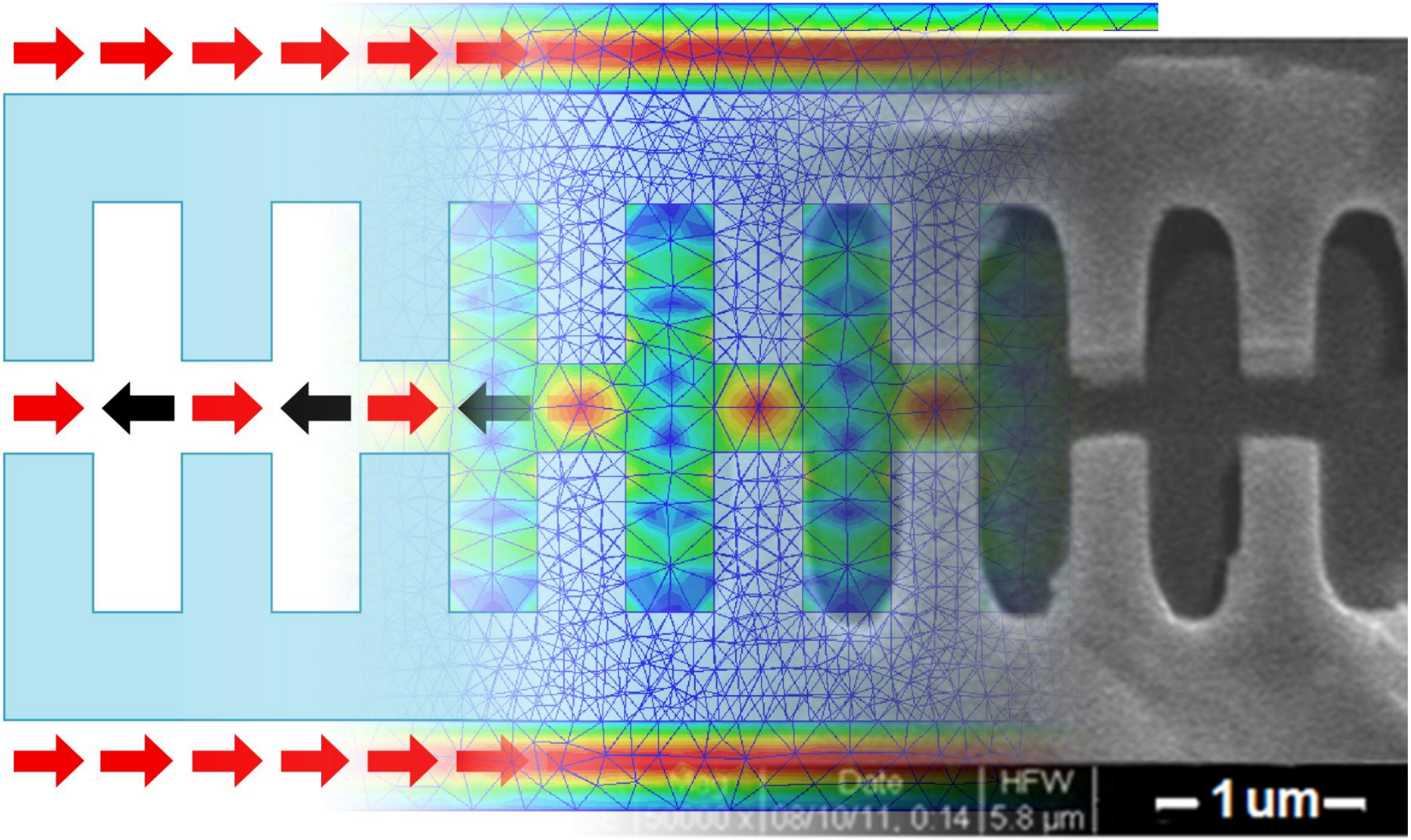
Duel-Grating Acceleration at SLAC



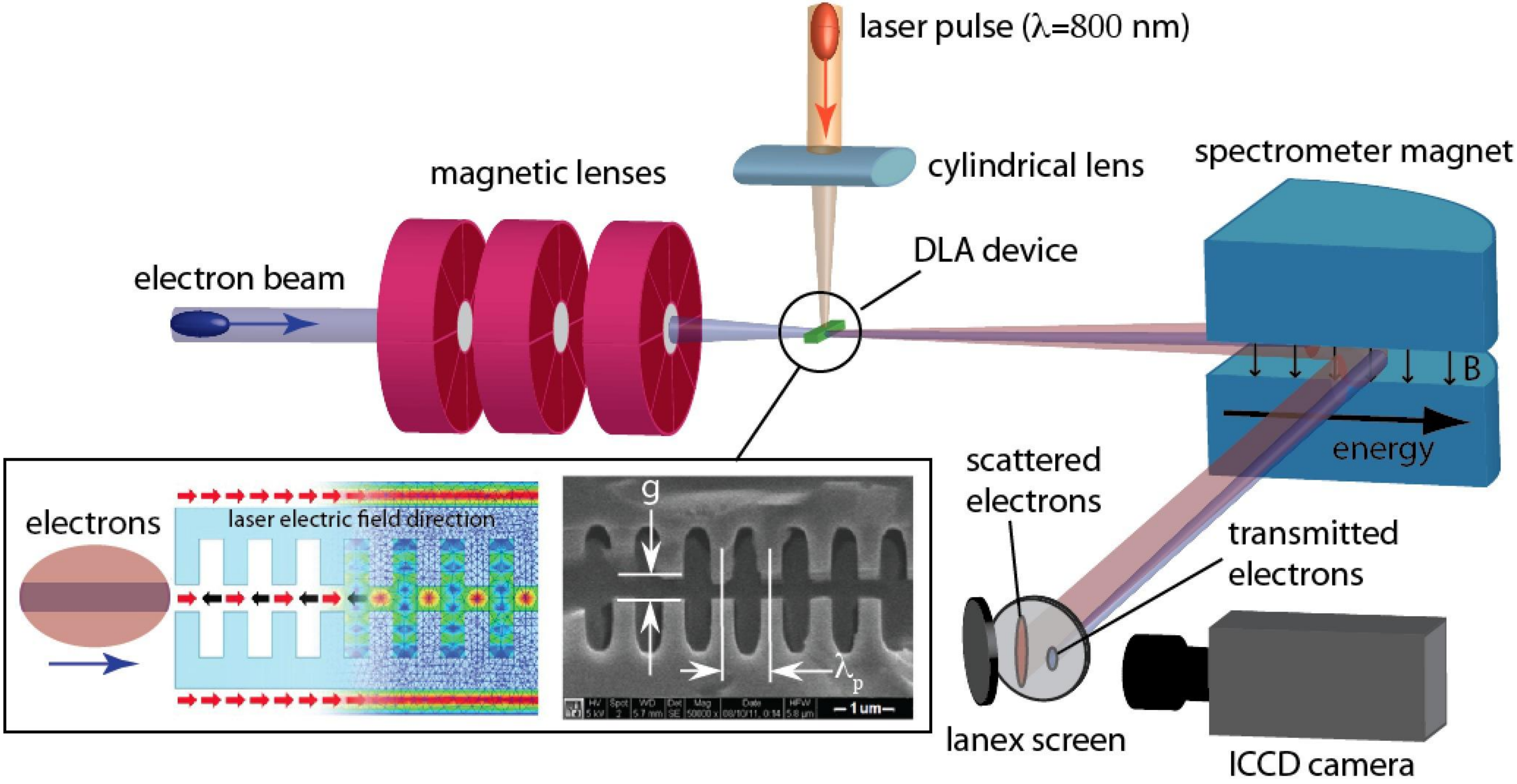
SEM image of sample cross-section

Peralta, McNeur et al., Nature 503, 91 (2013)

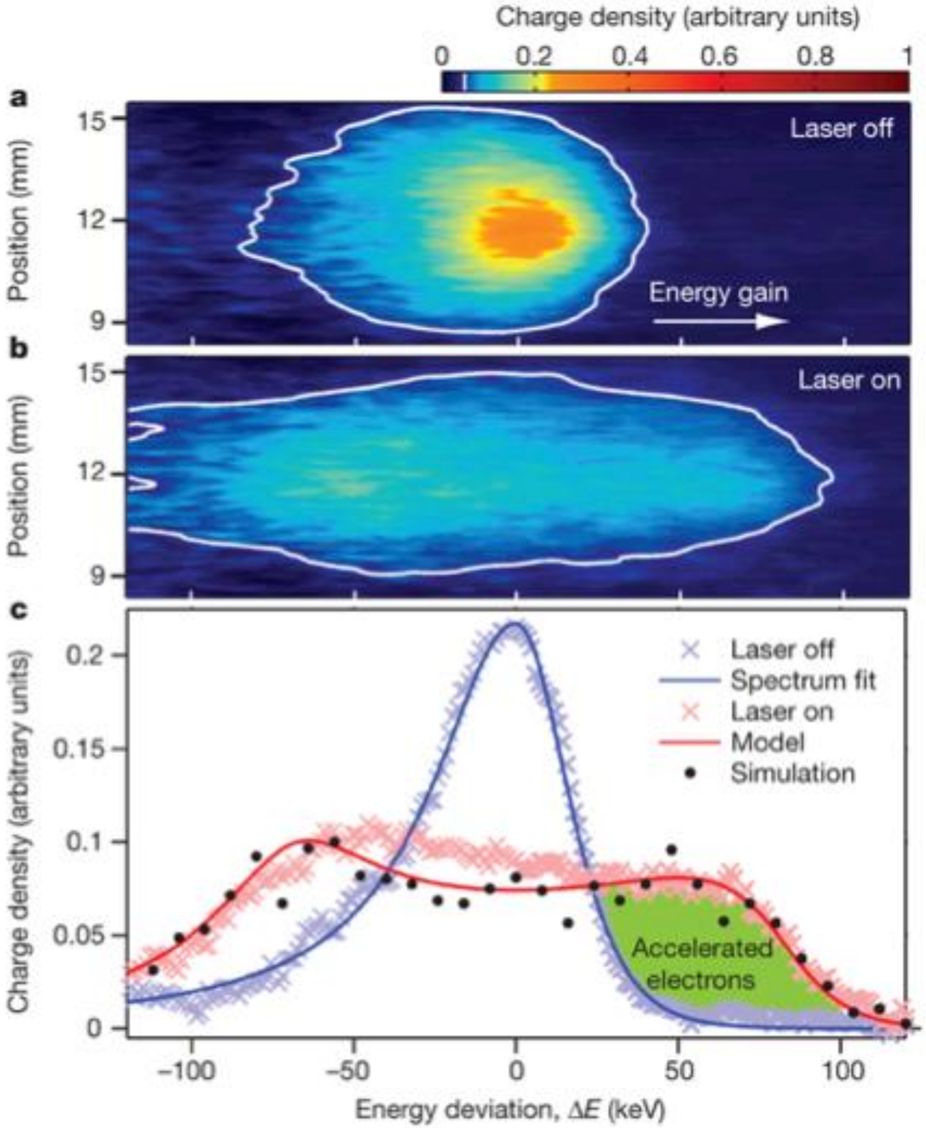
Two gratings: speed-of-light mode supported



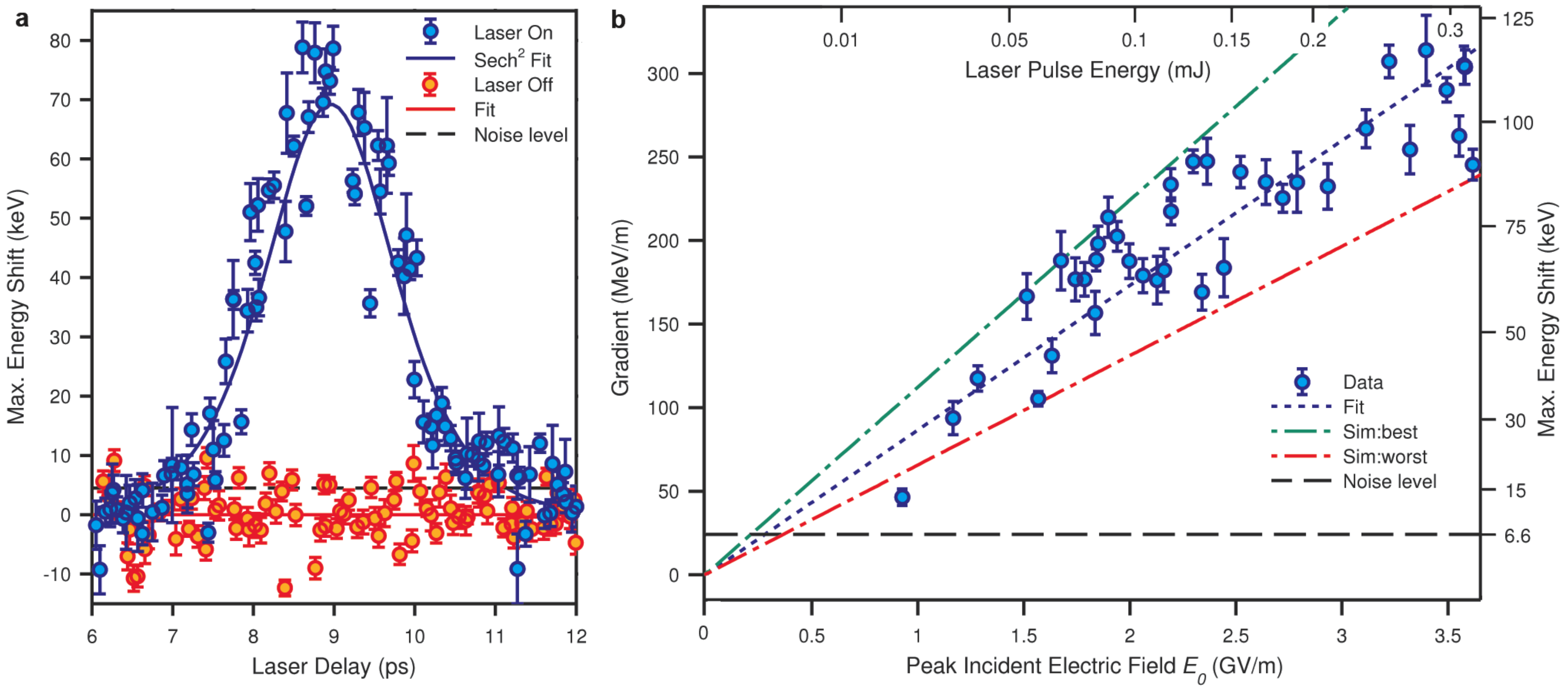
Experimental Setup



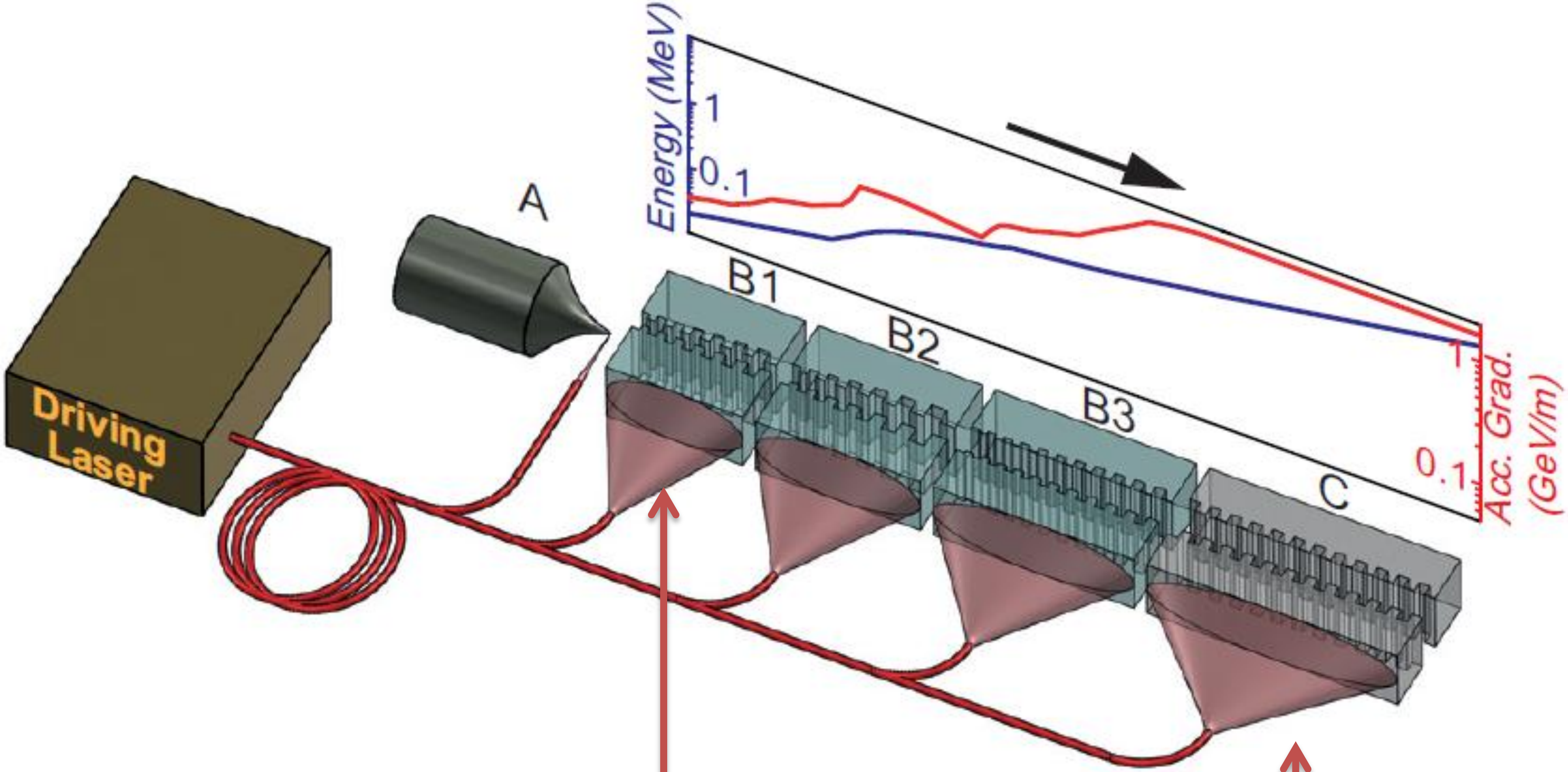
Dielectric laser acceleration results



Dielectric laser acceleration results



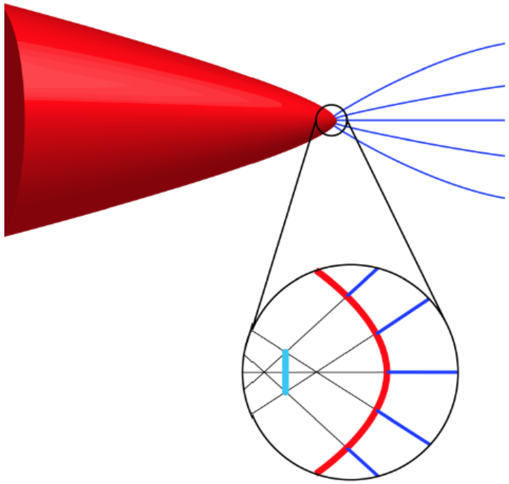
FUTURE DIRECTIONS



Demonstrated here

Demonstrated at SLAC
Peralta et al. (Byer group, Stanford)

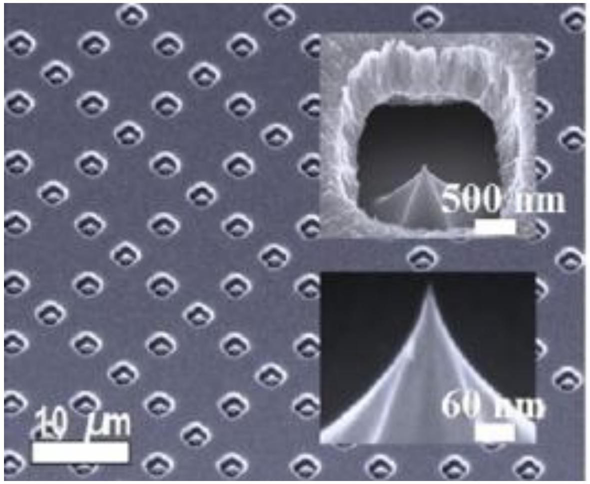
Extremely low emittance sources: tips



- Virtual source size a few nanometers
- Emittance ~ 0.1nm

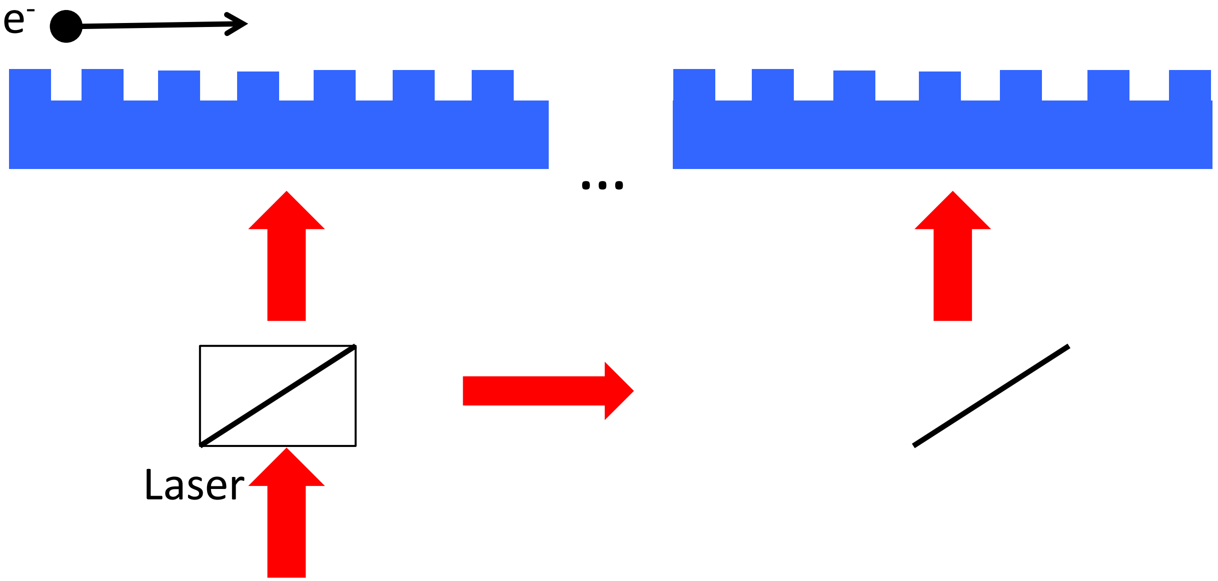
- Stanford group (PH, Kasevich)
- Göttingen group (Ropers)
- Nebraska group (Batelaan)
- ***PSI group(s) (Tsujino)***
- MIT group (Kaertner)
- Toulouse group (Chatel)
- …

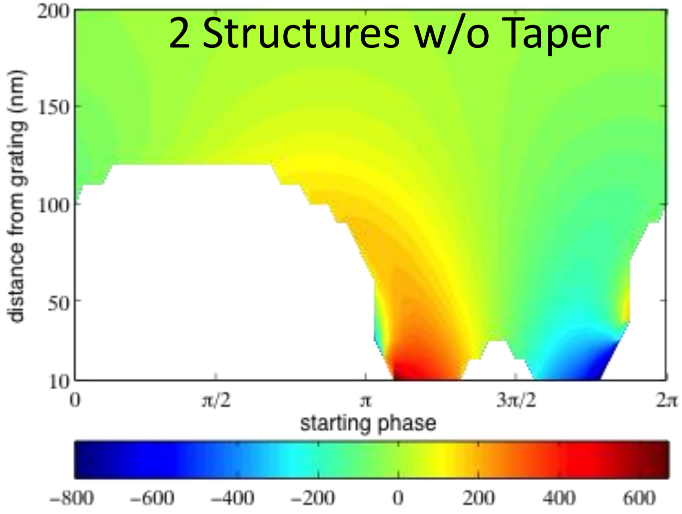
- With **ZrC tip** (r ~ microns): 150pC, 2.4 A peak current. Ganther et al. (PSI group) PRL 2008
- With 20pC, 5A from **regular RF and DC photocathodes**: norm. emitt. = 120nm. Ding et al. PRL 2009

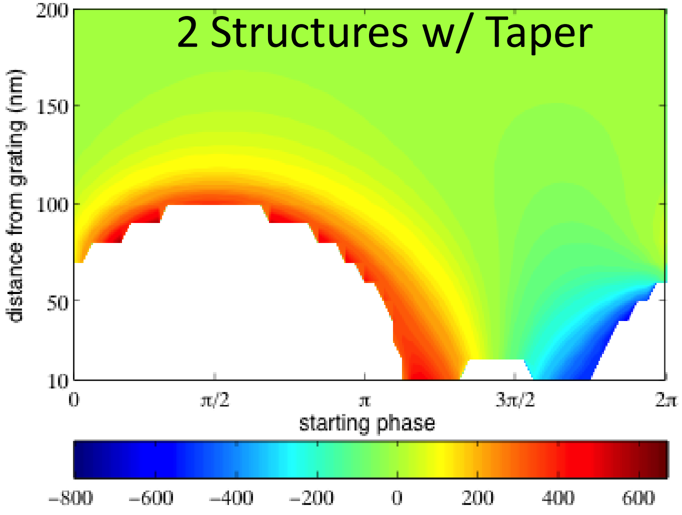


Mustonen, …, Tsujino, APL 2011

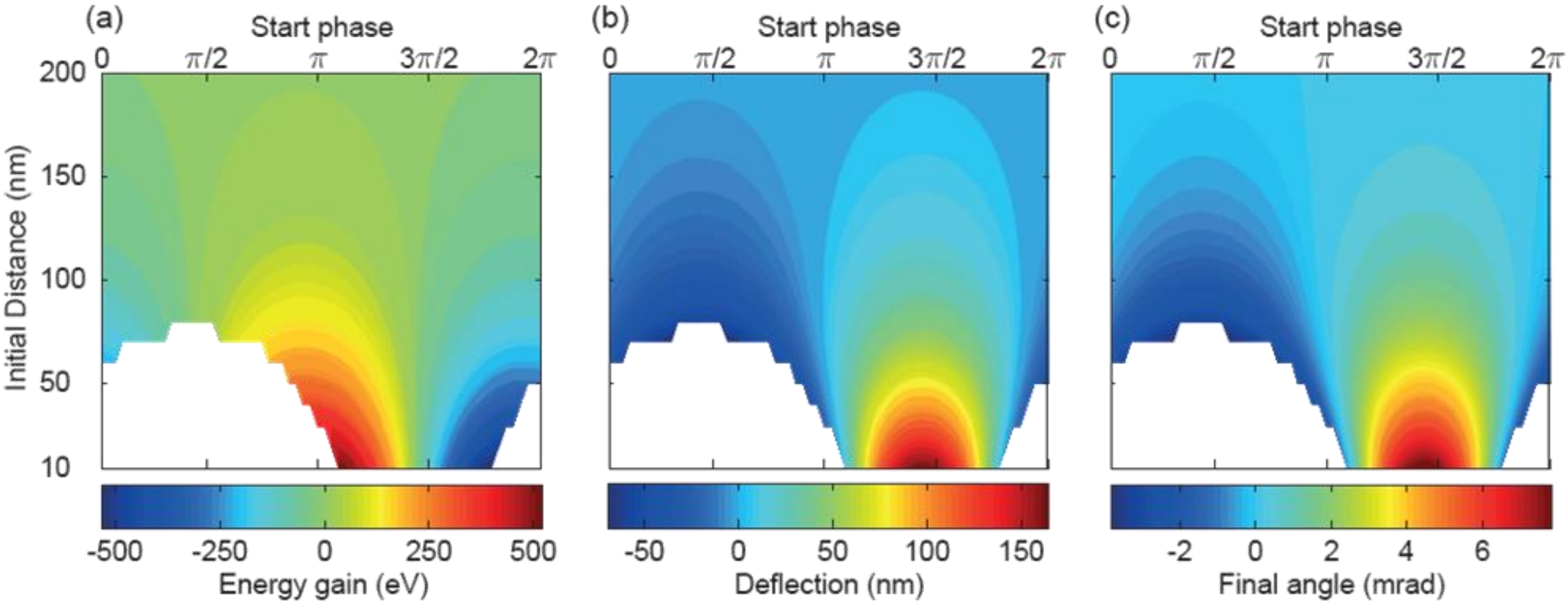
Concatenated Structures




2 Structures w/o Taper


2 Structures w/ Taper

Simulation results: Deflection

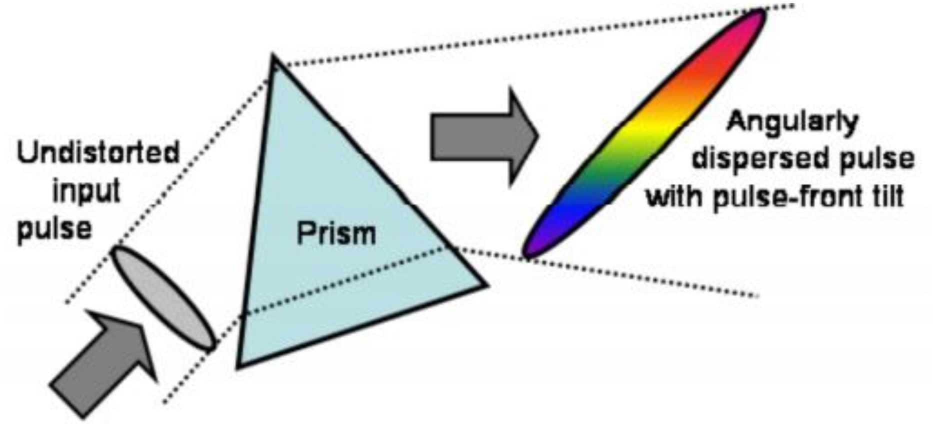


Related to Panofsky-Wenzel theorem (though non-relativistic electrons here):

- Shear force for single-sided structure
- Still useful for novel streak camera or so? (Thanks to Klaus Flöttmann!)
- Analogous forces in double grating can lead to focusing DLA structure

Increasing Acceleration Efficiency

- Increase interaction between laser and electrons
  - Elliptical laser spot
  - Pulse front tilting



PI: Peter Hommelhoff
Postdoc: Joshua McNeur
Masters Students: Alex Tafel, Ang Li
Bachelors Student: Jonas Hammer

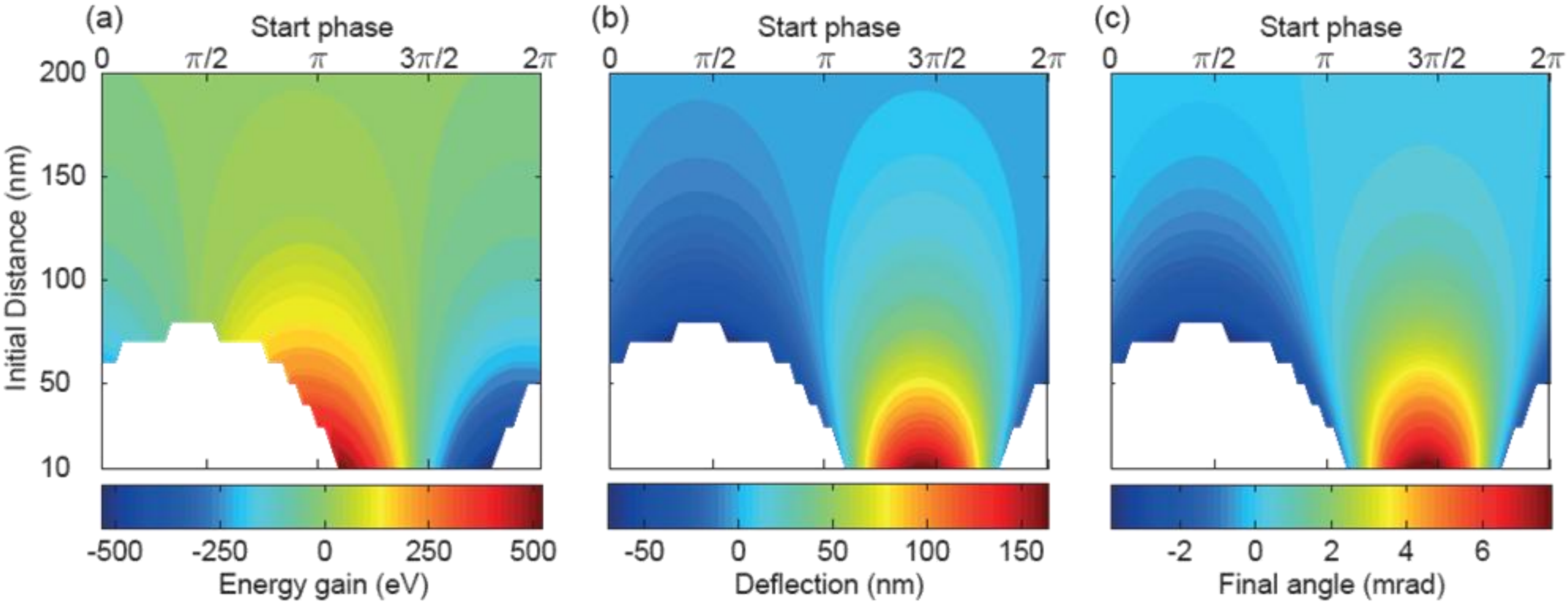
Looking for more graduate students!

Contact: Joshua.McNeur@fau.de
Peter.Hommelhoff@physik.un-erlangen.de

Thank you for your time and attention

Additional Slides

Simulation results



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- Shear force for single-sided structure
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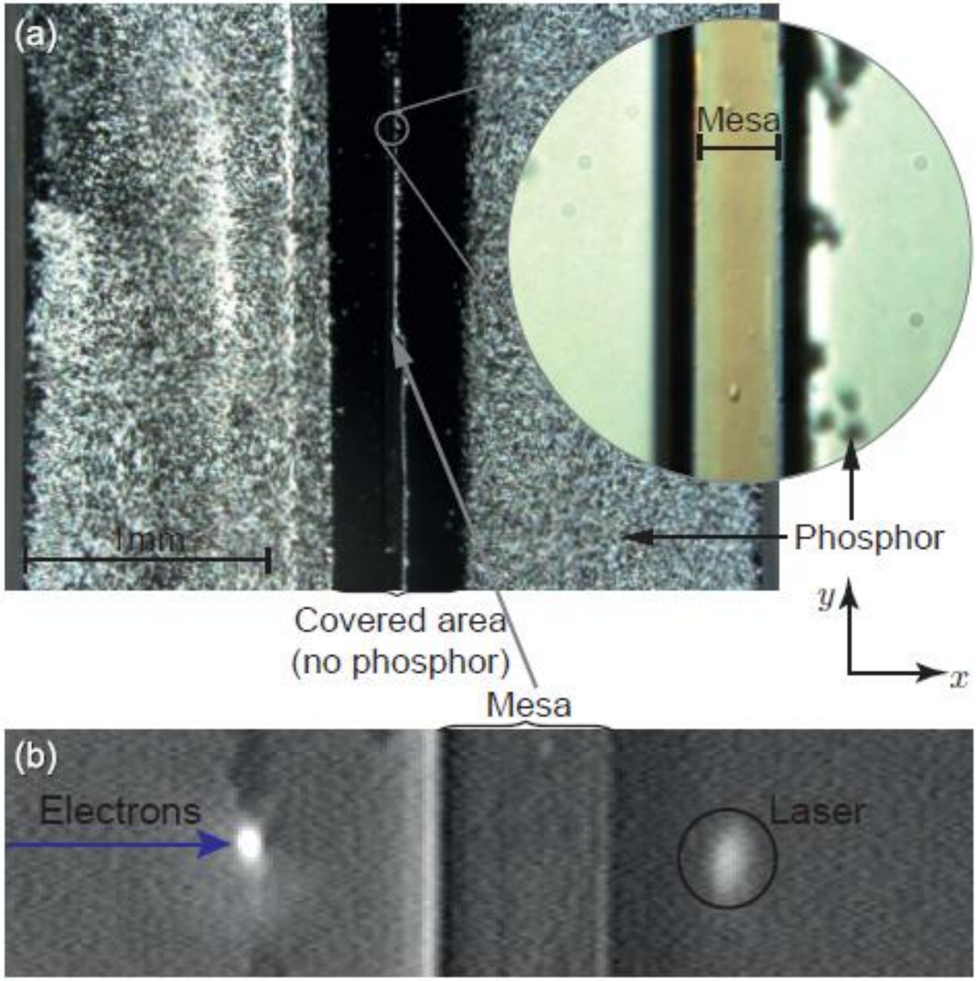
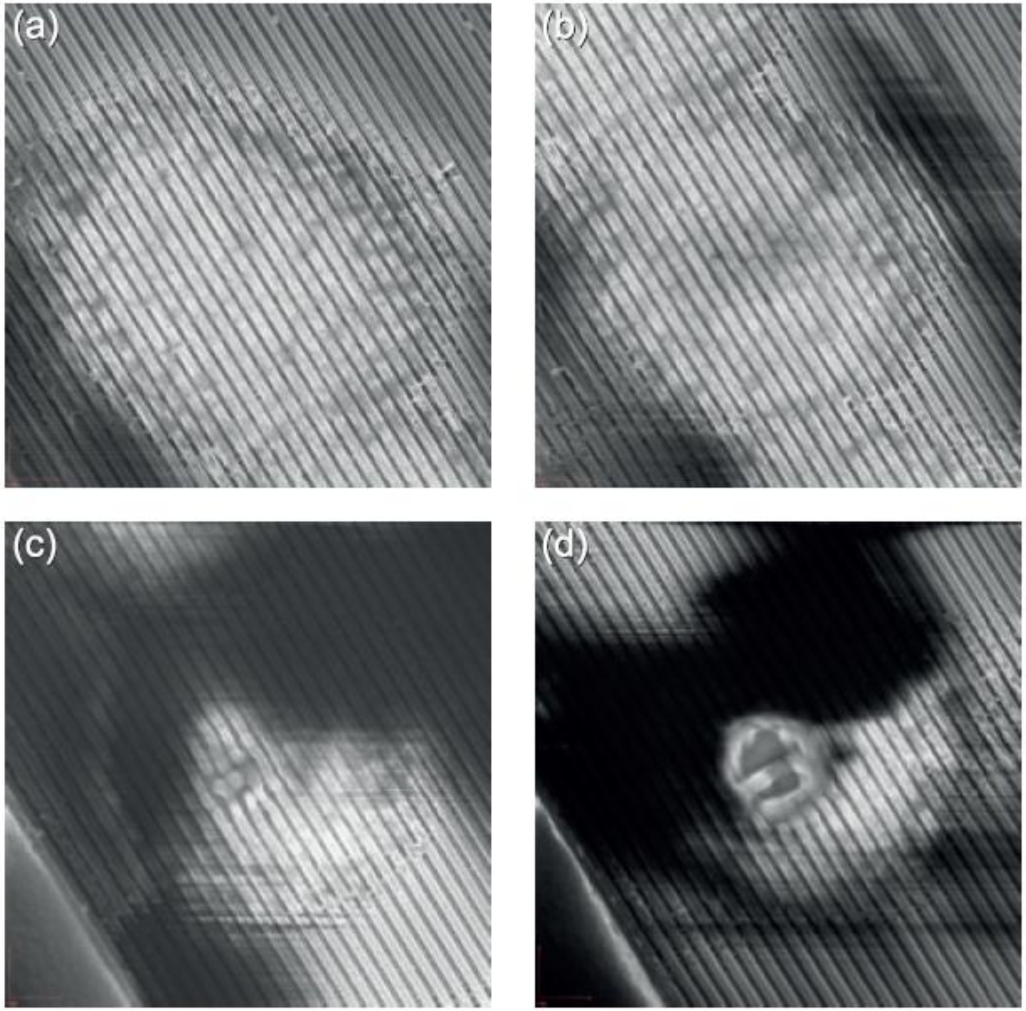
Grating structure – phosphor and metal coating

- charging of dielectric surface leads to beam deflection
  → thin transparent (10nm) gold coating
- overlap electron beam with laser
  → thin phosphor layer next to mesa, monitoring of beam/laser position via in-chamber microscope objective



Damage threshold measurements

Fused silica grating, coated with 10nm gold, at 10^{-6} hPa
5um spot radius, 70fs pulses, 2.7 MHz



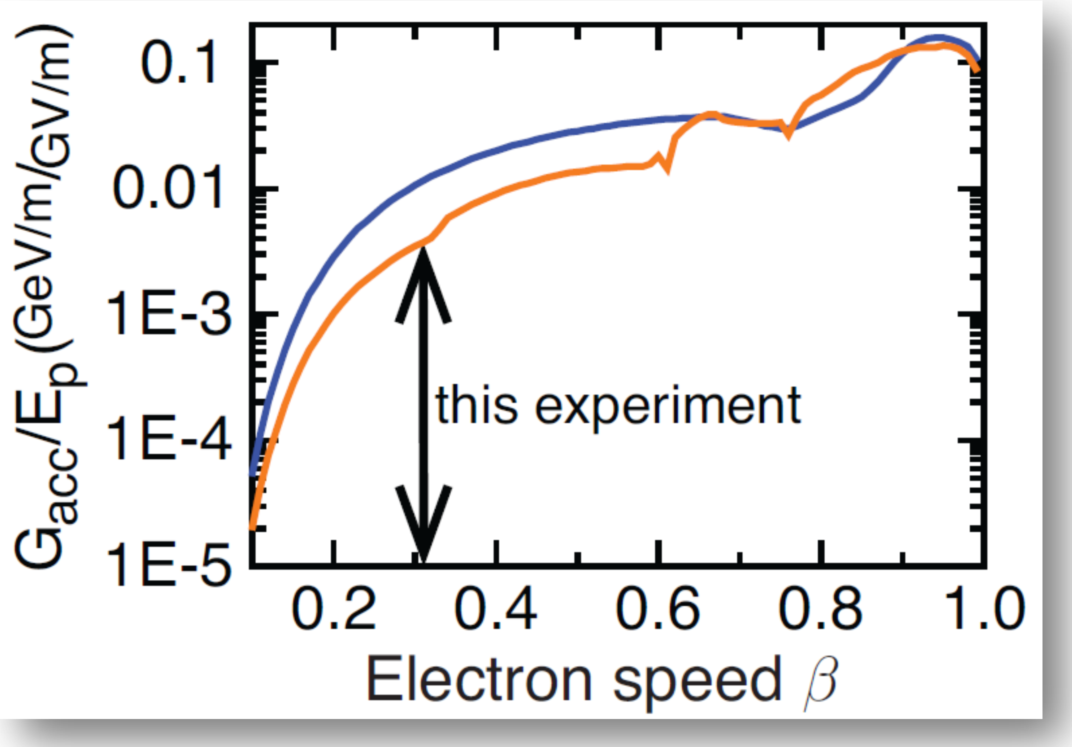
P = 400mW
E_p = 6.1 GV/m
I_p = 1.0 10^{13} W/cm^2
F_p = 0.37 J/cm^2

P = 500mW
E_p = 6.9 GV/m
I_p = 1.3 10^{13} W/cm^2
F_p = 0.47 J/cm^2

P = 550mW
E_p = 7.2 GV/m
I_p = 1.4 10^{13} W/cm^2
F_p = 0.51 J/cm^2

P = 620mW
E_p = 7.6 GV/m
I_p = 1.5 10^{13} W/cm^2
F_p = 0.57 J/cm^2

Acceleration efficiency: simulation

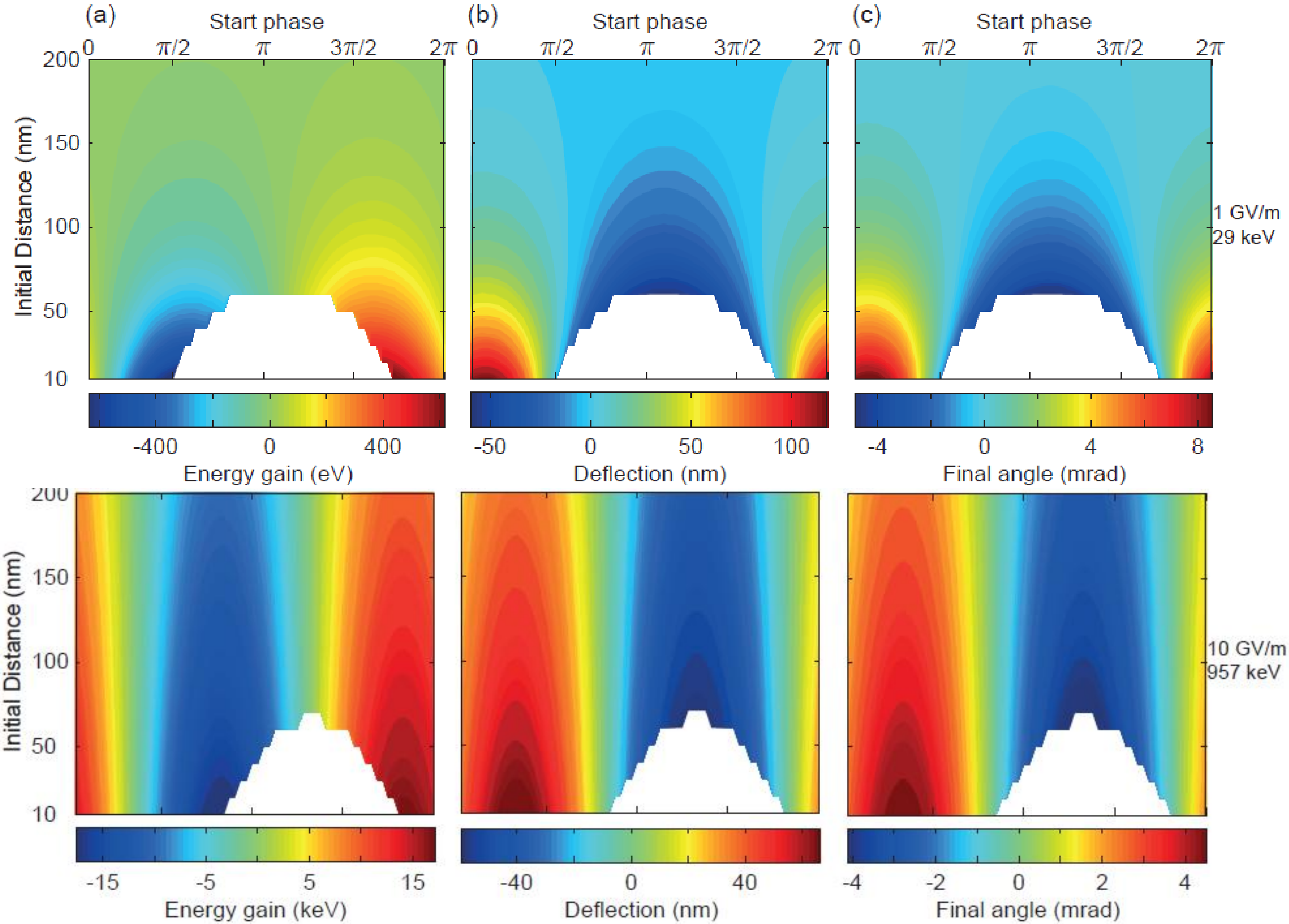


Observed: **25 MeV/m at β = 0.3**: laser power limited
(increase by a factor of 3.4 possible to reach damage threshold).
With that, **at β = 0.95: 1.7 GeV/m**

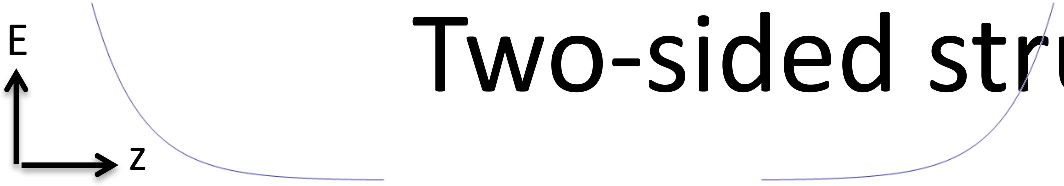
J. Breuer, P. Hommelhoff, Phys. Rev. Lett. 111, 134803 (2013)

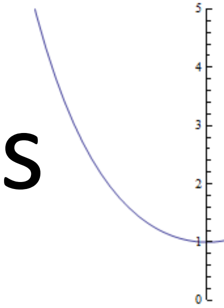
Peralta, McNeur et al. (Byer group, Stanford), Nature 503, 91 (2013)

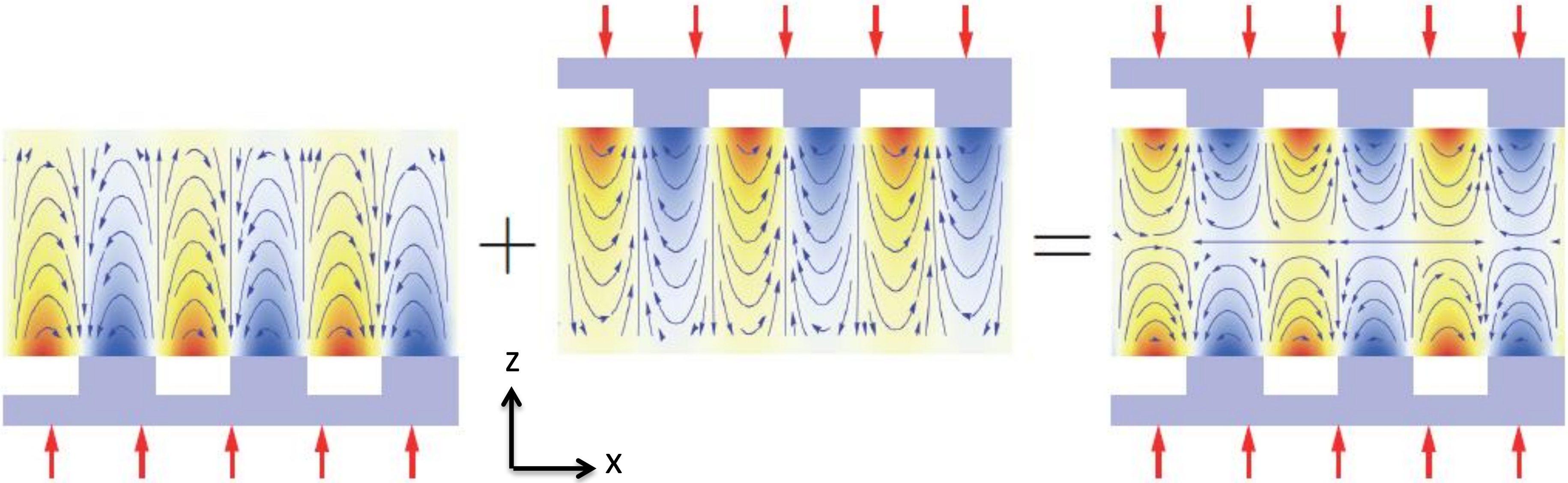
Blue: first spatial harmonic
Orange: third spatial harmonic


(a)
(b)
(c)
Start phase
0
π/2
π
3π/2
2π
Initial Distance (nm)
200
150
100
50
10
-400
0
400
Energy gain (eV)
-50
0
50
100
Deflection (nm)
-4
0
4
8
Final angle (mrad)
1 GV/m
29 keV
-15
-5
5
15
Energy gain (keV)
-40
0
40
Deflection (nm)
-4
-2
0
2
4
Final angle (mrad)
10 GV/m
957 keV

Two-sided structures

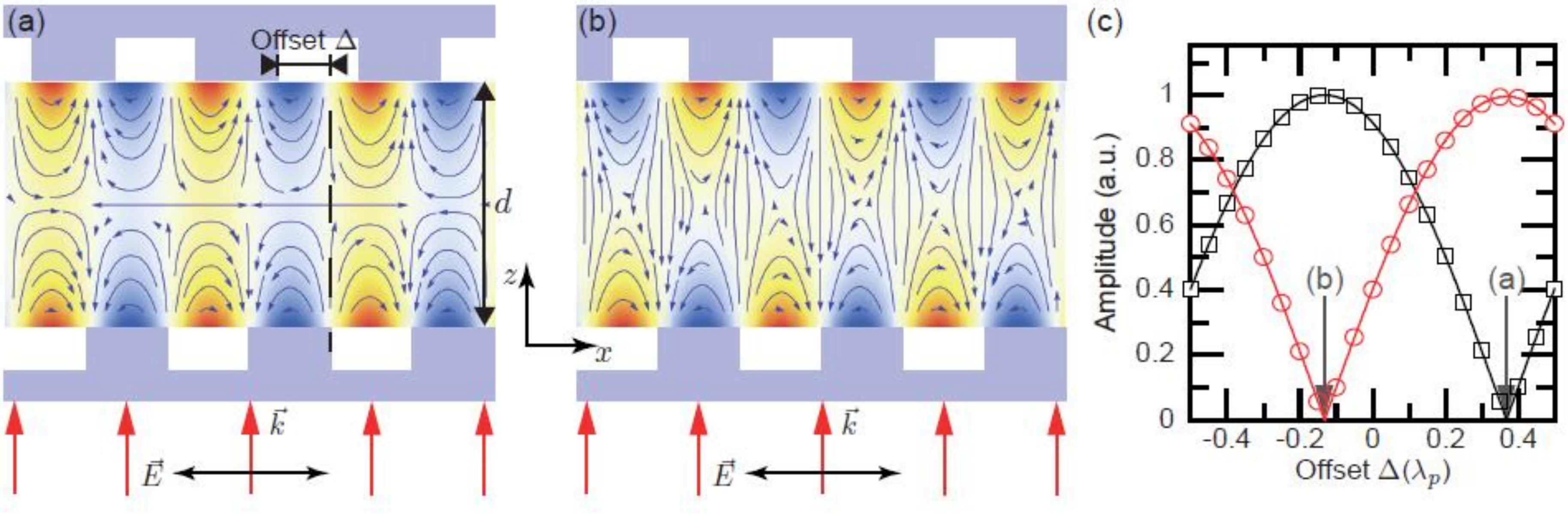






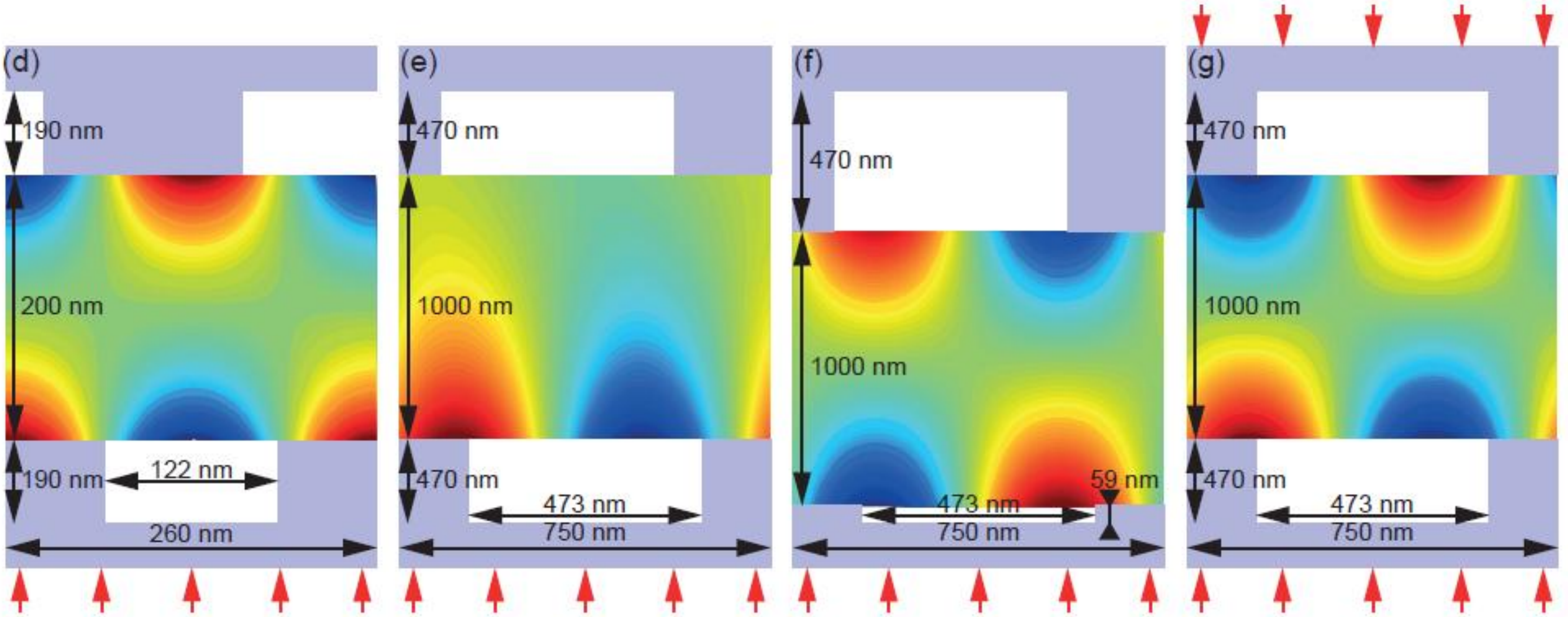
$$\mathbf{F_r} = qc \begin{pmatrix} \frac{1}{\beta\gamma}\left(C_\mathrm{s}\cosh(k_z z) + C_\mathrm{c}\sinh(k_z z)\right)\sin(k_x x - \omega t) \\ 0 \\ -\frac{1}{\beta\gamma^2}\left(C_\mathrm{s}\sinh(k_z z) + C_\mathrm{c}\cosh(k_z z)\right)\cos(k_x x - \omega t) \end{pmatrix}$$

Uniform acceleration gradient: $dF_x/dz \propto d\cosh(k_z z)/dz|_{z=0} = 0$



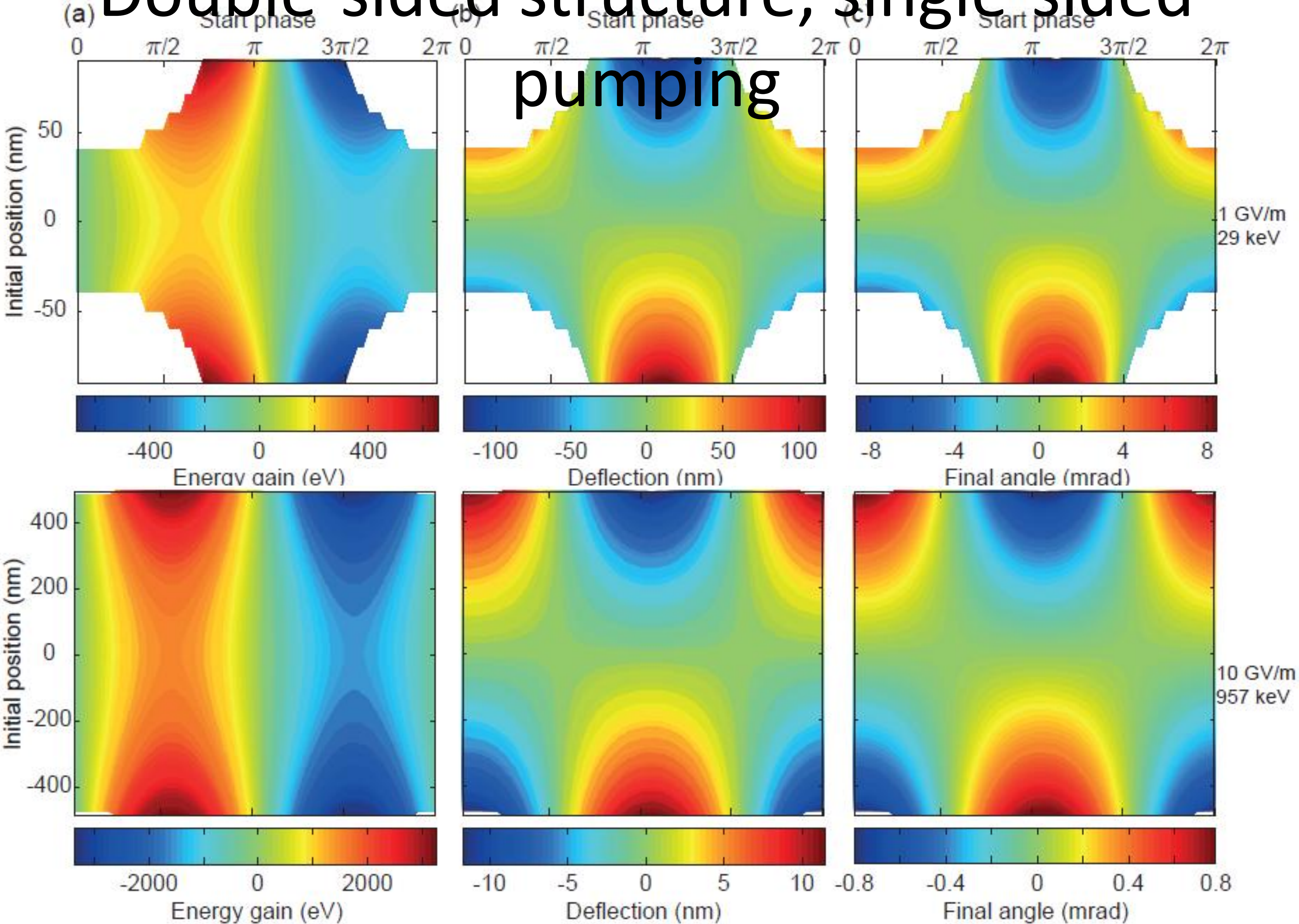
$$\mathbf{F}_{\mathbf{r}} = qc \begin{pmatrix} \frac{1}{\beta\gamma}\left(C_{\mathrm{s}}\cosh(k_z z) + C_{\mathrm{c}}\sinh(k_z z)\right)\sin(k_x x - \omega t) \\ 0 \\ -\frac{1}{\beta\gamma^2}\left(C_{\mathrm{s}}\sinh(k_z z) + C_{\mathrm{c}}\cosh(k_z z)\right)\cos(k_x x - \omega t) \end{pmatrix}$$

Double-sided gratings, one- or two-sided illumination

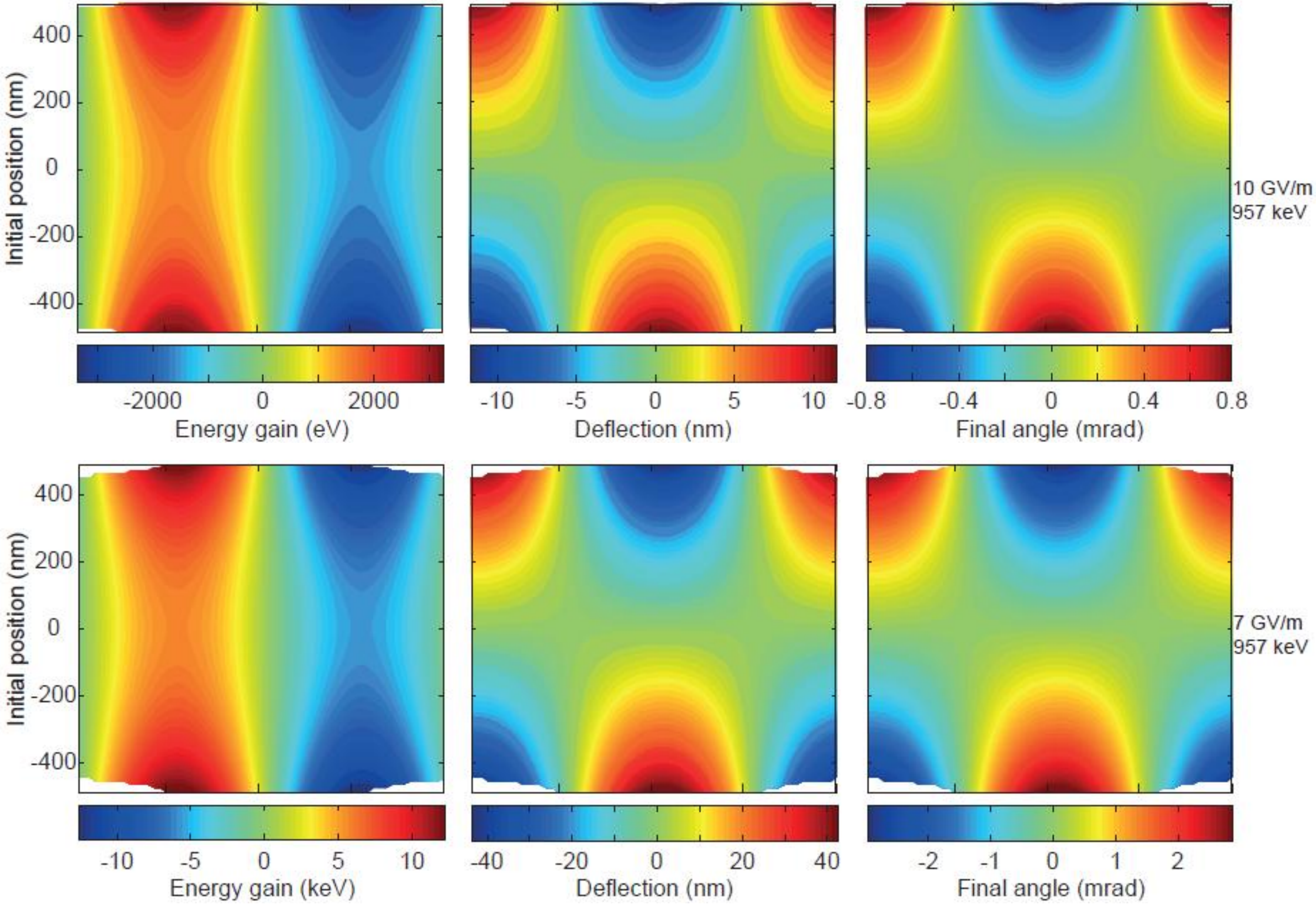


B-field component plotted. Quite a number of parameters!

Double-sided structure, single-sided pumping



Double-sided structure, one- vs. two-



Dephasing length

$$x_{\mathrm{deph}} = \left(\frac{\beta_0 \lambda_0 E_{\mathrm{kin}} \left(\frac{E_{\mathrm{kin}}}{m_0 c^2} + 1 \right) \left(\frac{E_{\mathrm{kin}}}{m_0 c^2} + 2 \right)}{4 G_{\mathrm{max}}} \right)^{1/2}$$

λ (μm)	$E_{\mathrm{kin}} = 29$ keV (Fig. 6(d))		$E_{\mathrm{kin}} = 957$ keV (Fig. 6(g))	
	1 GV/m	10 GV/m	1 GV/m	10 GV/m
0.8	12 μm	4 μm	149 μm	47 μm
2	19 μm	6 μm	236 μm	75 μm
5	31 μm	10 μm	373 μm	118 μm

Space charge effects: beam envelope equation

Accel. in long. el. field

Focusing in radial el. field

Focusing in axial magn. field

$$r''_{\mathrm{m}} + \frac{\gamma' r'_{\mathrm{m}}}{\beta^2\gamma} + \frac{\gamma'' r_{\mathrm{m}}}{2\beta^2\gamma} + \left(\frac{qB}{2mc\beta\gamma}\right)^2 r_{\mathrm{m}} - \left(\frac{p_\theta}{mc\beta\gamma}\right)^2 \frac{1}{r_{\mathrm{m}}^3} - \frac{\epsilon_{\mathrm{n}}}{\beta^2\gamma^2 r_{\mathrm{m}}^3} - \frac{K}{r_{\mathrm{m}}} = 0.$$

Defocusing due to ang. mom.

Defocusing due to norm. emittance

Defocusing due to space charge

$$K = 2I/(I_0\beta^3\gamma^3)$$

Generalized perveance: measure for space charge effects

… reduces for space-charge limited

$$r_{\mathrm{m}}'' + \frac{\gamma'' r_{\mathrm{m}}}{2\beta^2\gamma} - \frac{K}{r_{\mathrm{m}}} = 0$$

with transverse focusing with laser field:

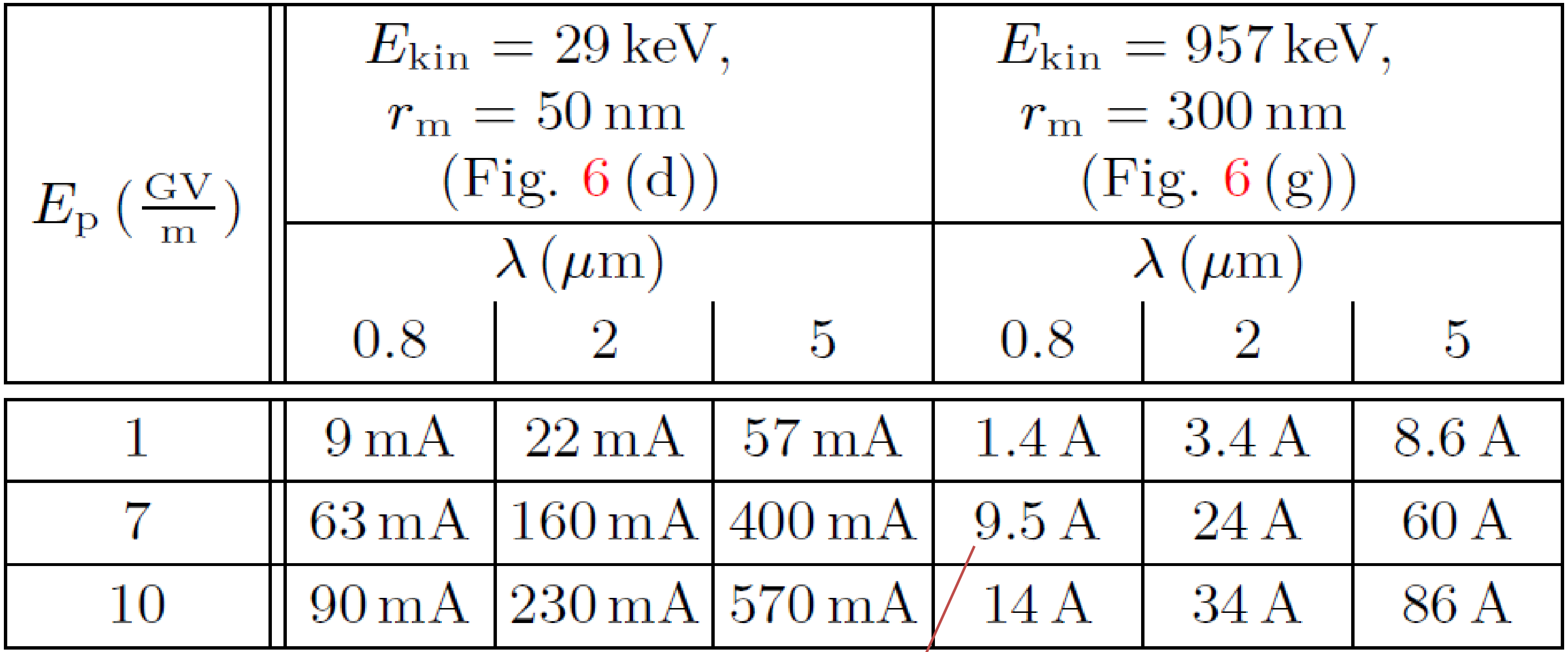
$$\gamma'' = \frac{2qE_{\perp}}{mc^2 r_{\mathrm{m}}} = \frac{2G}{mc^2 r_{\mathrm{m}}\gamma}$$

yields a **maximum beam current** for a stable beam (γ''=0):

$$I_{\mathrm{b}} = I_0 \frac{G\beta\gamma r_{\mathrm{m}}}{2mc^2}$$

I_0 = 17,000A: Budker or Alfen current

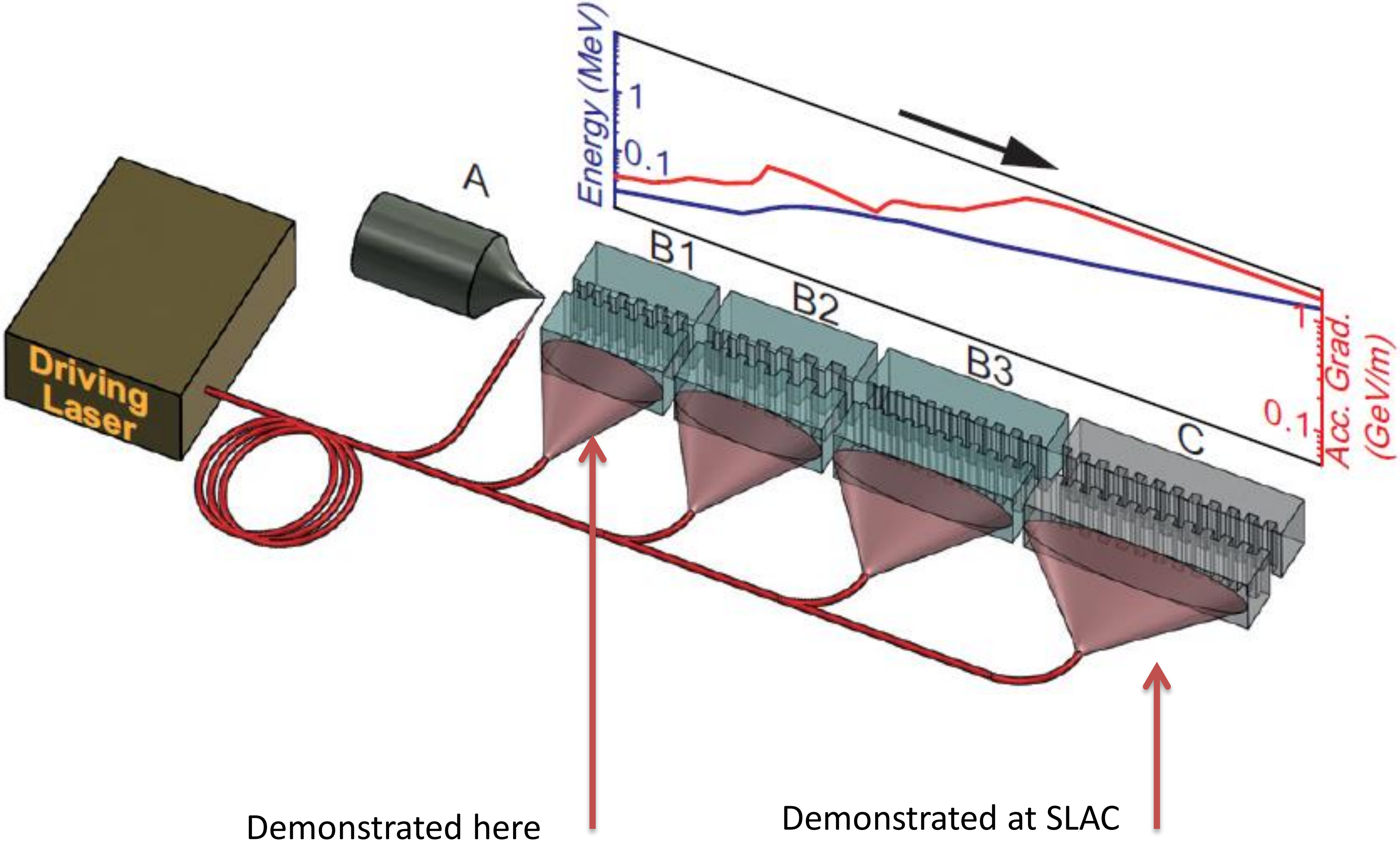
Space-charge limited current



$E_\mathrm{p}\,(\frac{\mathrm{GV}}{\mathrm{m}})$	$E_\mathrm{kin} = 29\,\mathrm{keV}$, $r_\mathrm{m} = 50\,\mathrm{nm}$ (Fig. 6 (d))			$E_\mathrm{kin} = 957\,\mathrm{keV}$, $r_\mathrm{m} = 300\,\mathrm{nm}$ (Fig. 6 (g))		
	$\lambda\,(\mu\mathrm{m})$			$\lambda\,(\mu\mathrm{m})$		
	0.8	2	5	0.8	2	5
1	9 mA	22 mA	57 mA	1.4 A	3.4 A	8.6 A
7	63 mA	160 mA	400 mA	9.5 A	24 A	60 A
10	90 mA	230 mA	570 mA	14 A	34 A	86 A

Total charge (0.1 opt. period long pulse):
2.7fC, scales with λ^2

Scalable technology: concatenate



Demonstrated here

Demonstrated at SLAC
Peralta et al. (Byer group, Stanford)

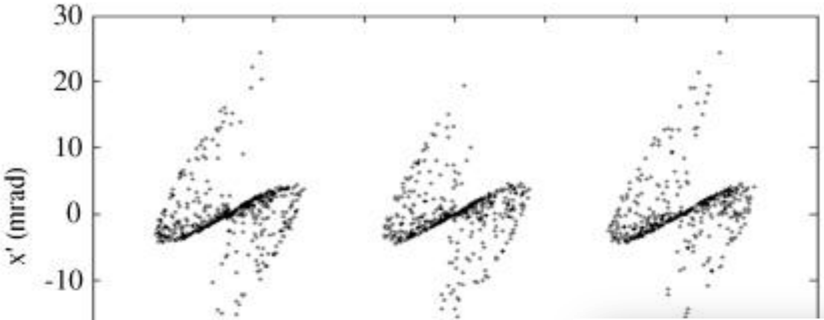
Stable operation: all elements (focusing etc.) can be made

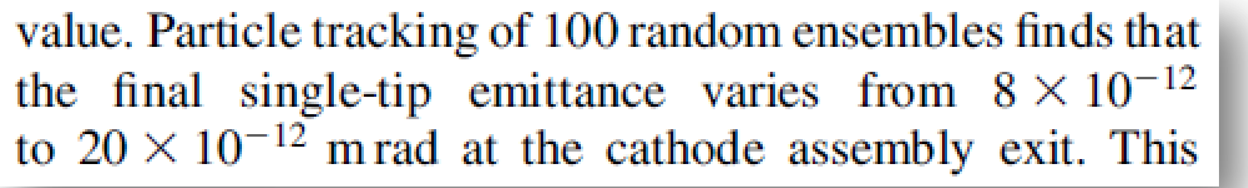
Proposals for

- accelerator structure: Plettner, Lu, Byer, Phys. Rev. STAB 2006
- optical focusing elements: Plettner , Byer, McGuinness, P.H., Phys. Rev. STAB 2009
- optical-structure-driven FEL: Plettner, Byer, Nucl. Instrum. Methods A 2008

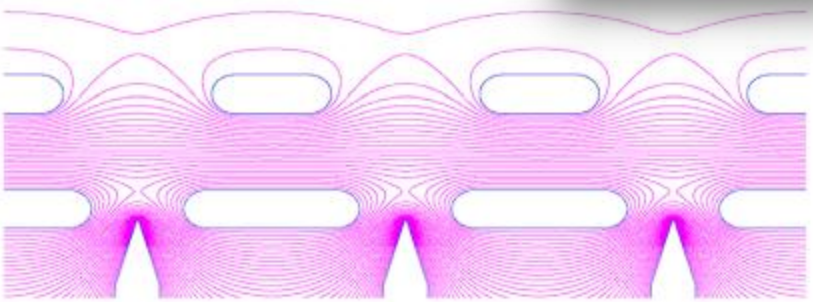
Required: phase coherent amplification & timed distribution ---- that's doable!
→ see Int. Coherent Amplification Network (ICAN), Mourou et al. Nat. Phot. 2013

Emittance exchange from a tip array: micro-bunched beam

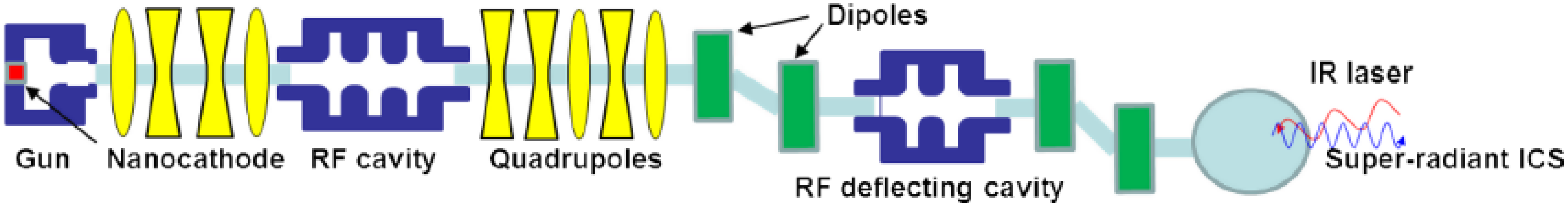



value. Particle tracking of 100 random ensembles finds that the final single-tip emittance varies from 8×10^{-12} to 20×10^{-12} m rad at the cathode assembly exit. This

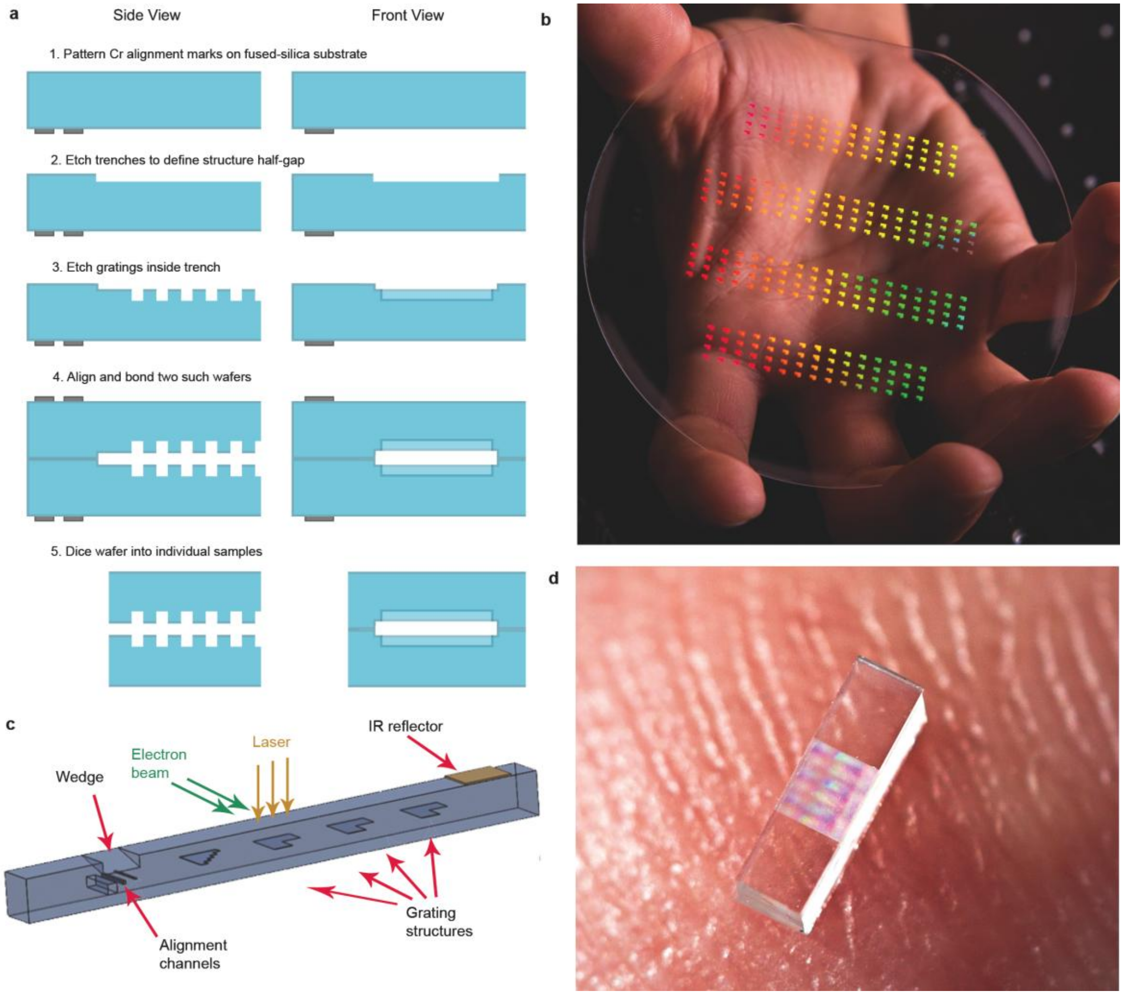
Graves, Kärtner,
Moncton, Piot, PRL 2012



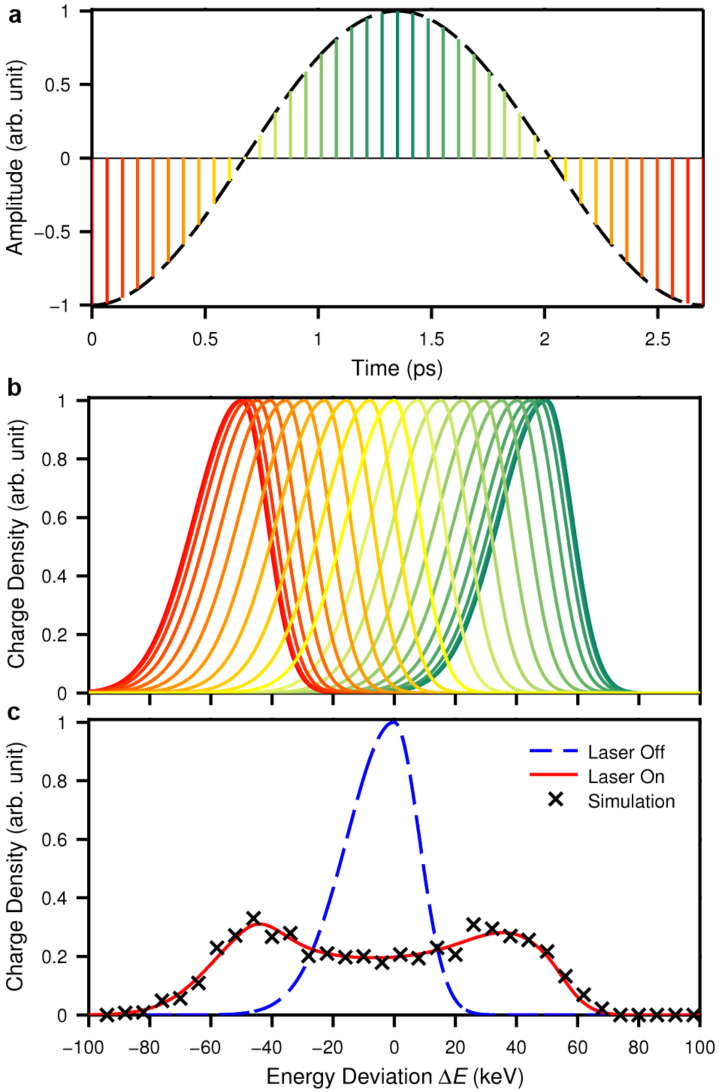
Transverse-to-longitudinal emittance exchange: beam bunched at the wavelength of the desired radiation



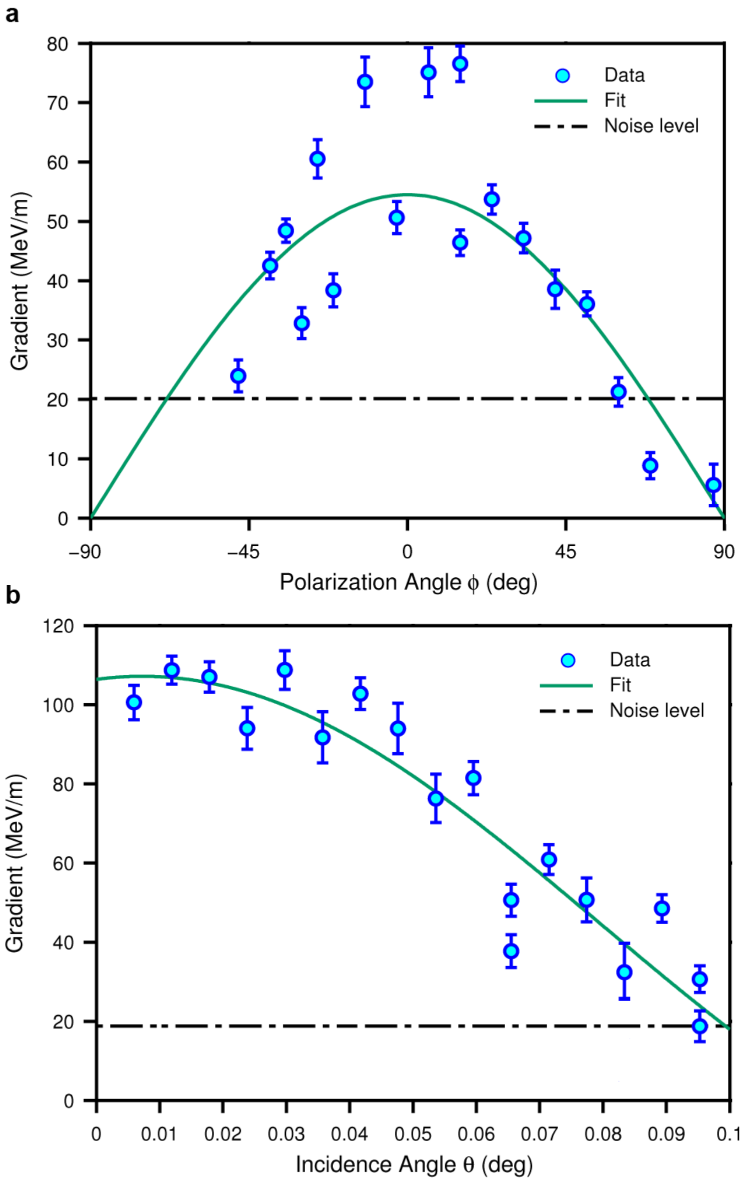
Double Grating Fabrication



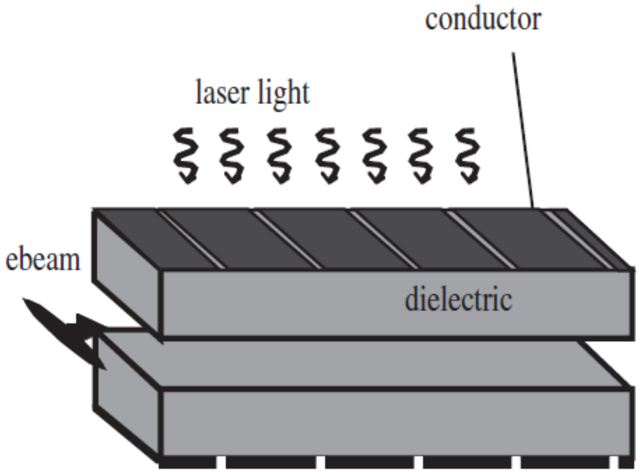
Acceleration Signal: Agreement Between Simulation, Analysis and Experiment



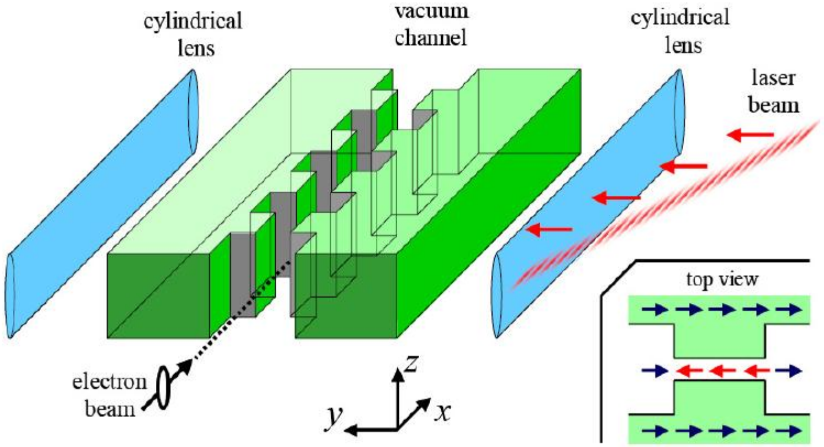
Acceleration vs. Experimental Parameters



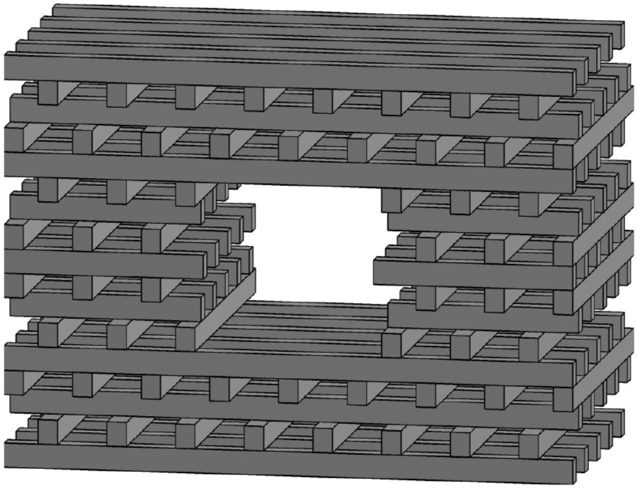
Proposed dielectric structures



Yoder, Rosenzweig, 2005



Plettner, Lu, Byer, 2006



Cowan, 2008

… and variants

- Goal: generate a mode that allows momentum transfer from laser field to electrons
- Use first order effect (efficient!)
- Second order effects (ponderomotive) too inefficient