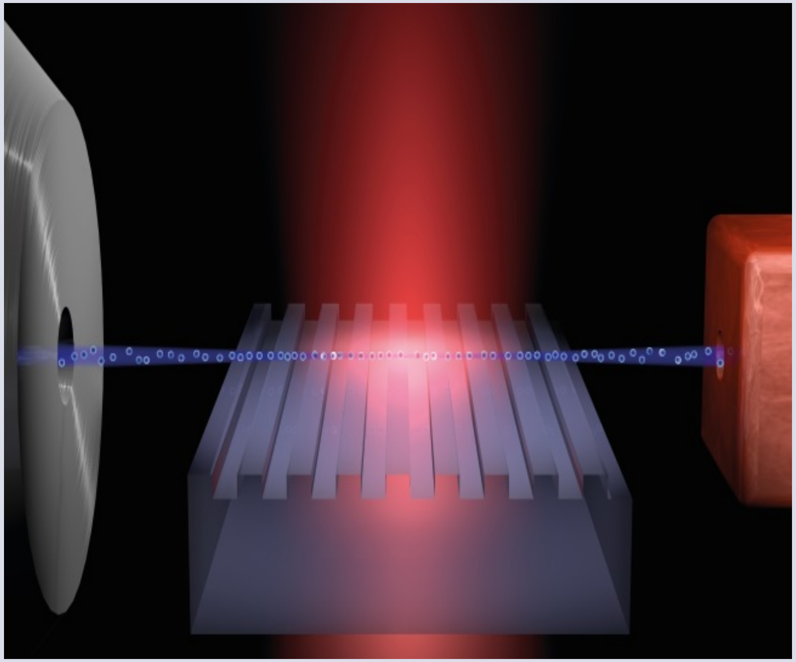
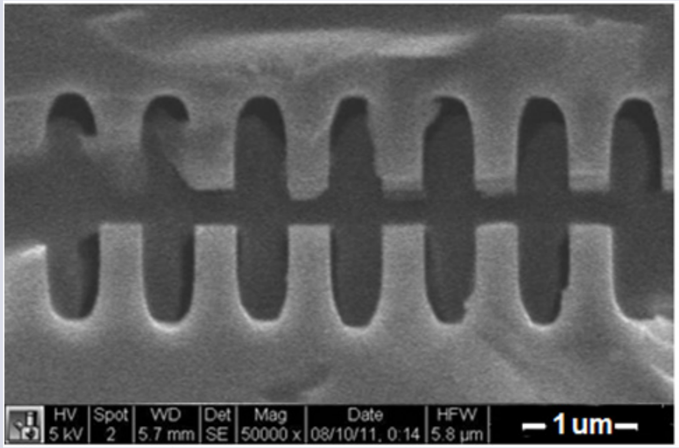
Accelerators on a Chip:
Status and Perspectives for All Optical Accelerators

Peter Hommelhoff
Friedrich Alexander University Erlangen-Nuremberg, Erlangen, Germany
Max Planck Institute for Quantum Optics, Garching / Munich, Germany
Max Planck Institute for the Science of Light, Erlangen, Germany



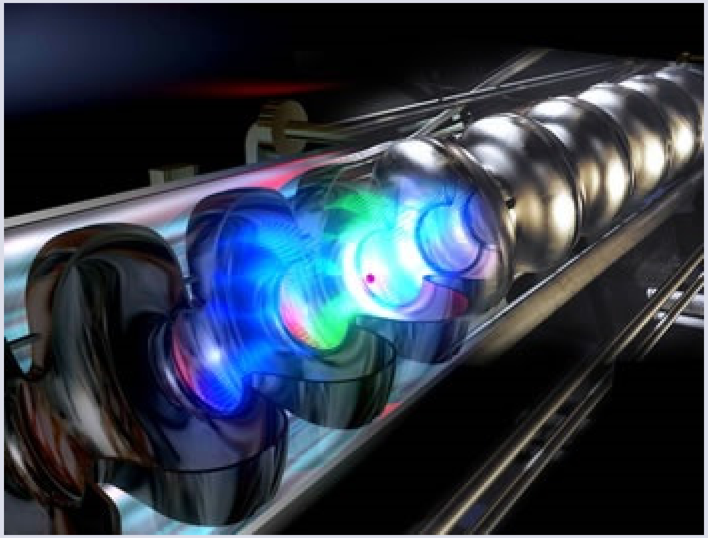
MPQ, now Erlangen



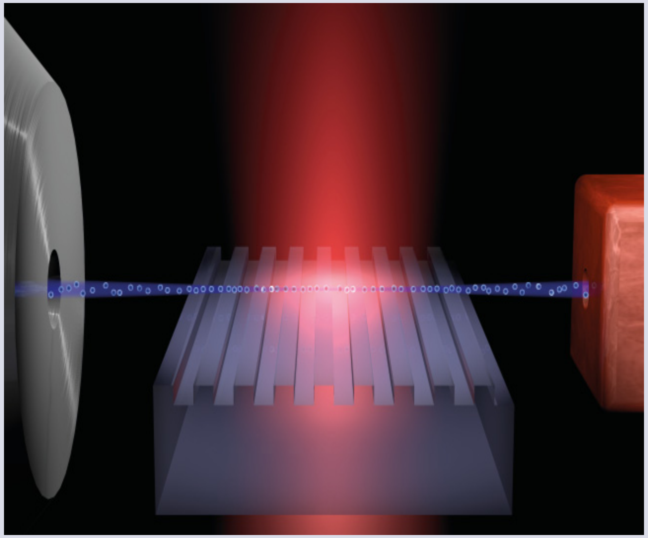
SLAC/Stanford

The Sixth International Particle Accelerator Conference
Richmond, Virginia, 3-8 May, 2015

Particle accelerators: from RF to optical/photonic drive?



RF cavity (TESLA, DESY)



	Conventional linear accelerator (RF)	Laser-based dielectric accelerator (optical)
Based on	(Supercond.) RF cavities	Quartz 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**

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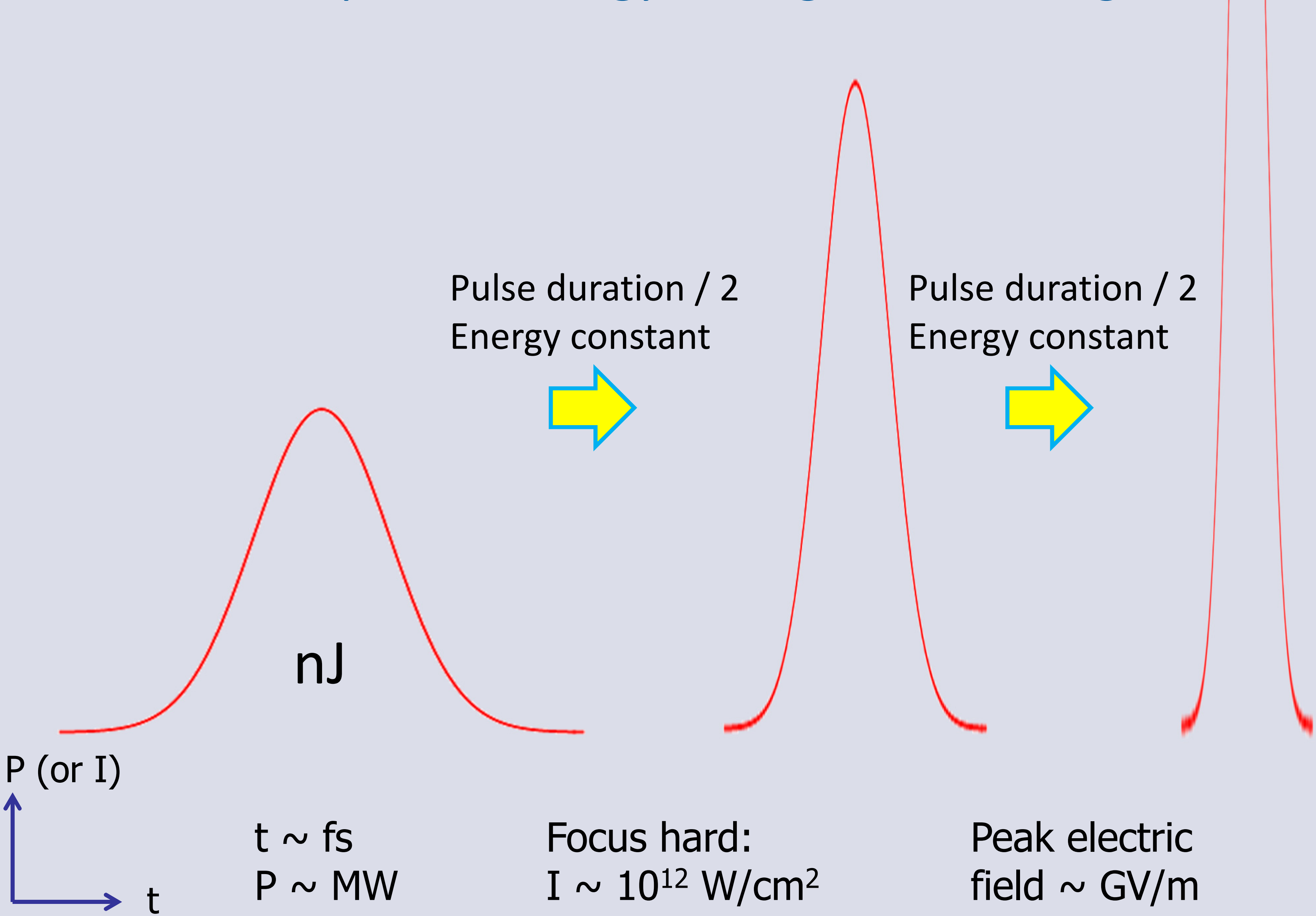
From pulsed energy to large field strengths



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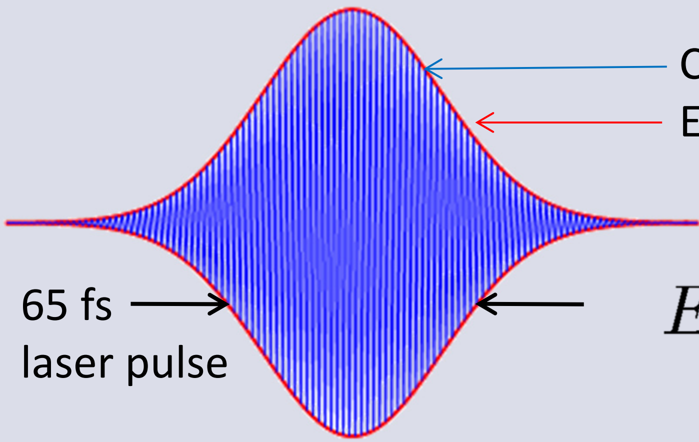
Femtosecond and few-cycle laser pulses

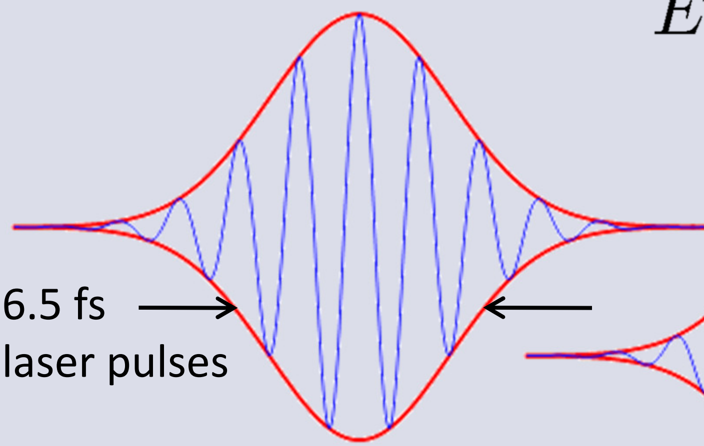
- Energy
- Duration
- Repetition rate
- **Carrier-envelope phase: control over optical electric field**

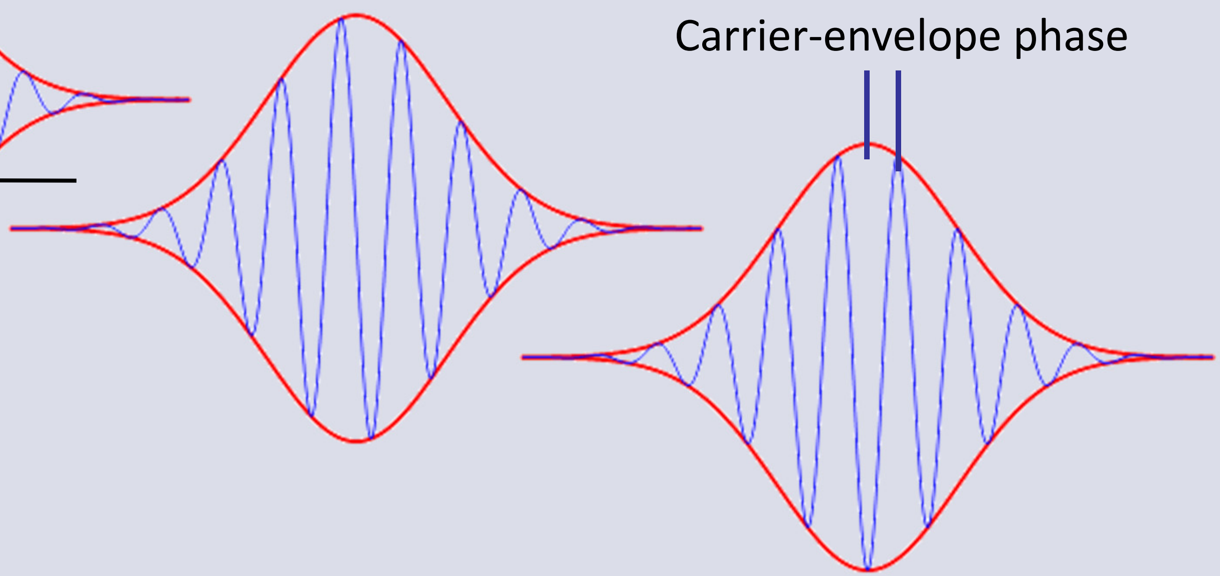


$$E(t) = f(t)\cos(\omega t)$$

$$E(t) = f(t)\cos(\omega t + \Delta\phi)$$

Near infrared light:	
• 800nm • 375 THz	• 2.7 fs • 1.5 eV





Invented in 1998, 2005 Nobel Prize in Physics

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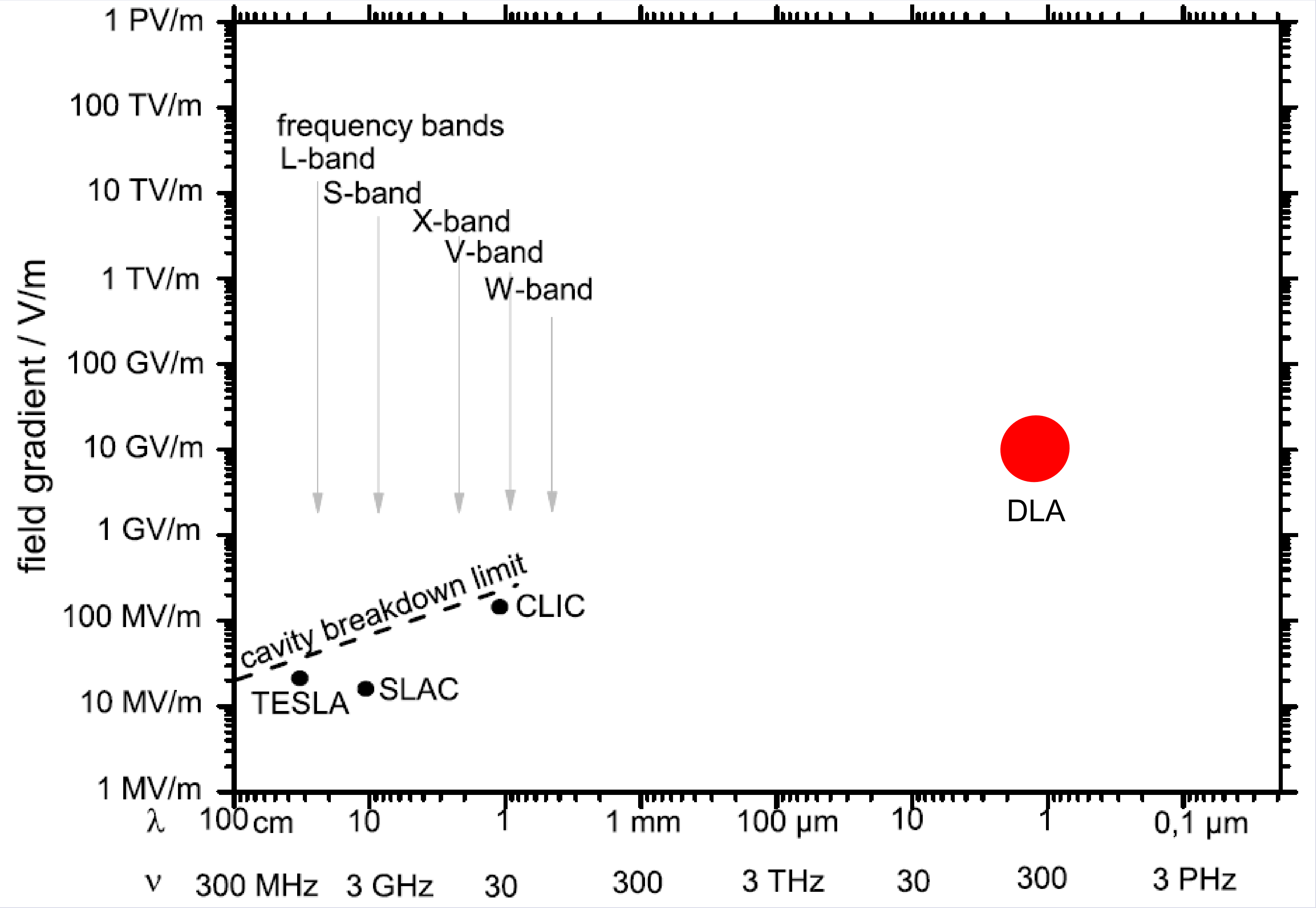
P. Hommelhoff, 6. IPAC, Richmond, VA, USA, May 2015



B. Hidding et al., Phys. Plasmas 16, 043105 (2009)

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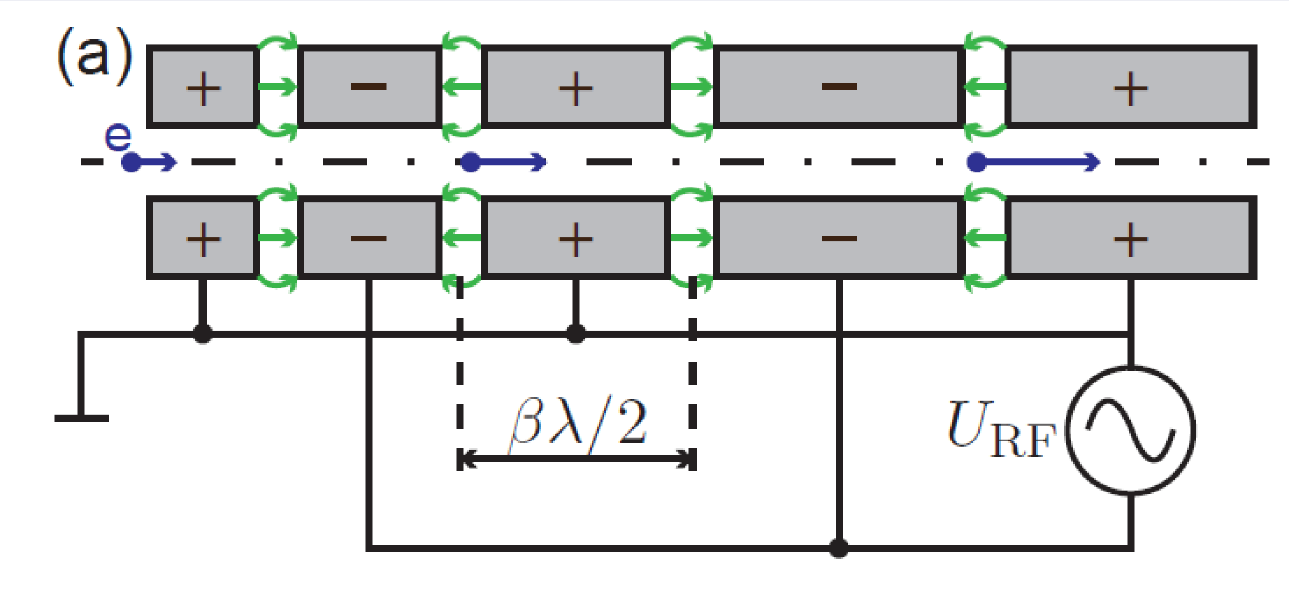
Widerøe linac

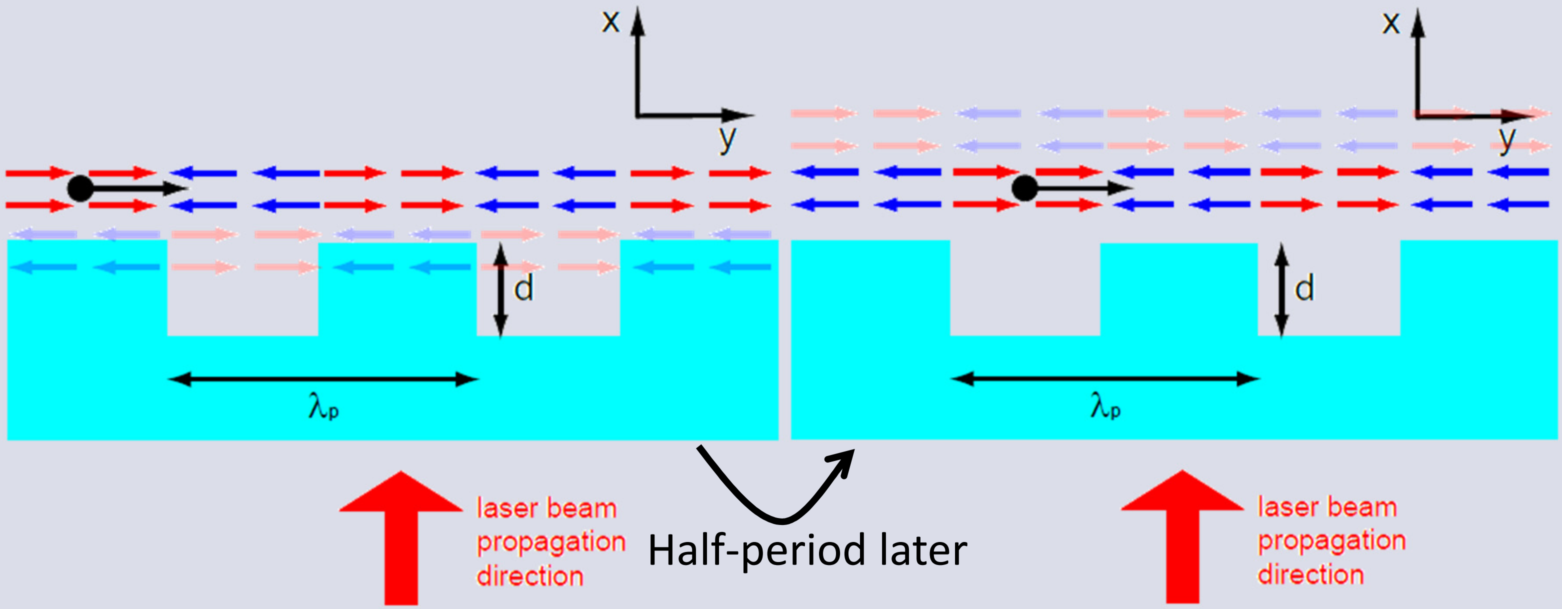


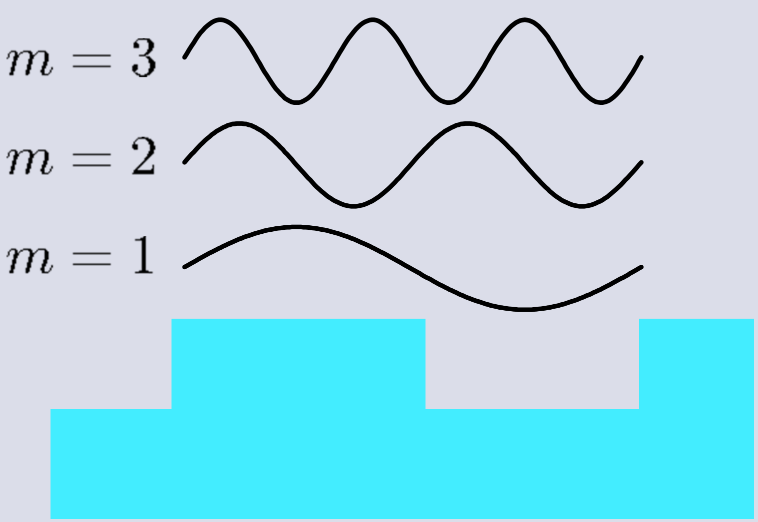
taken from J. Breuer's thesis

Switch fields *synchronous* with the particle's position/velocity

Wideroe, 1928
Ising, 1924

Periodic field reversal and spatial harmonics





Synchronicity condition:

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

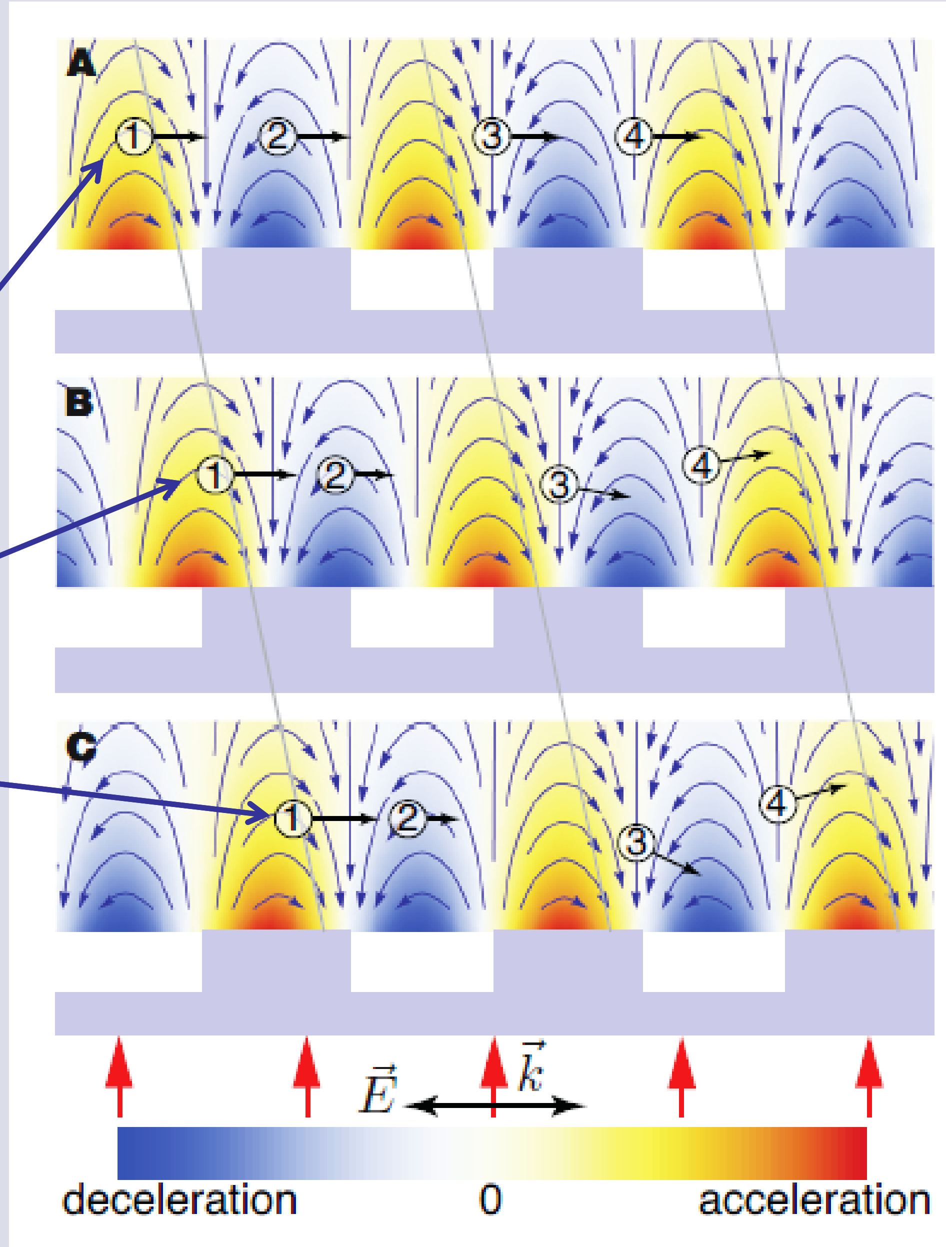
(m: # of laser cycles per electron passing one period, $\beta = v/c$, λ : laser wavelength)

$\lambda = 787\,\mathrm{nm},\ \beta \sim 1/3$ (for 28 keV electrons):

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

We use the third spatial harmonic.

Acceleration by phase-synchronous propagation



1 acceleration
2 deceleration
3 deflection
4 deflection

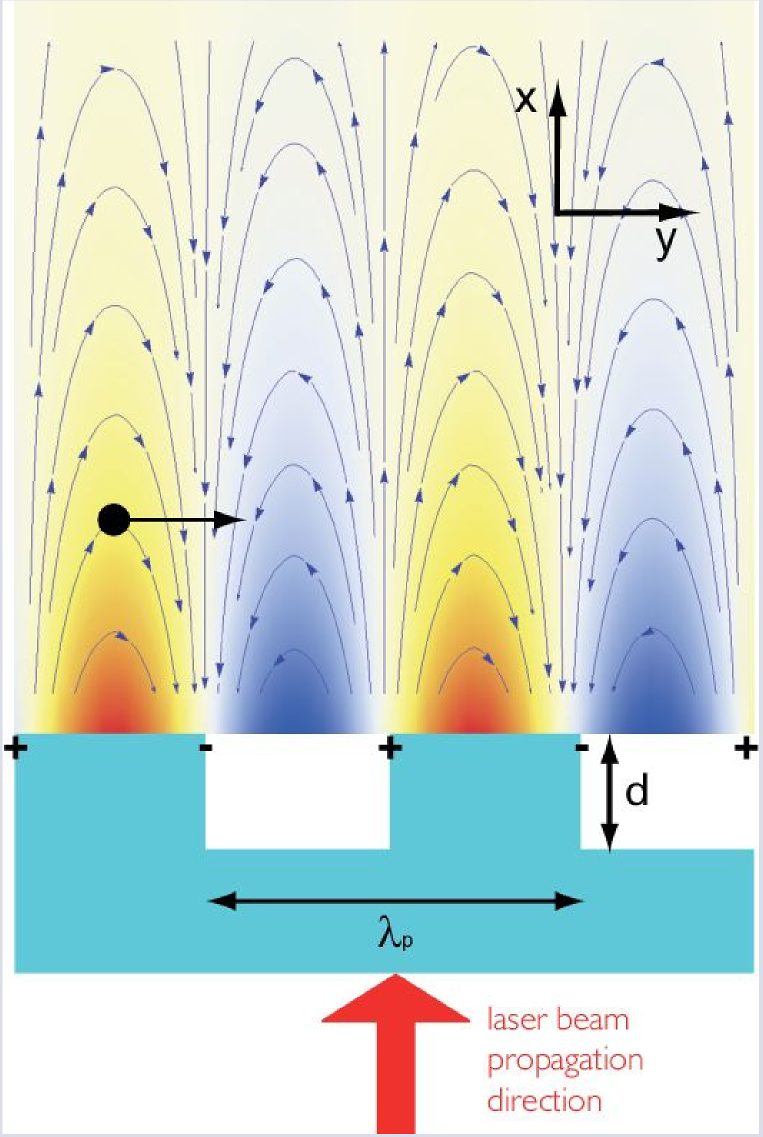
t = 0

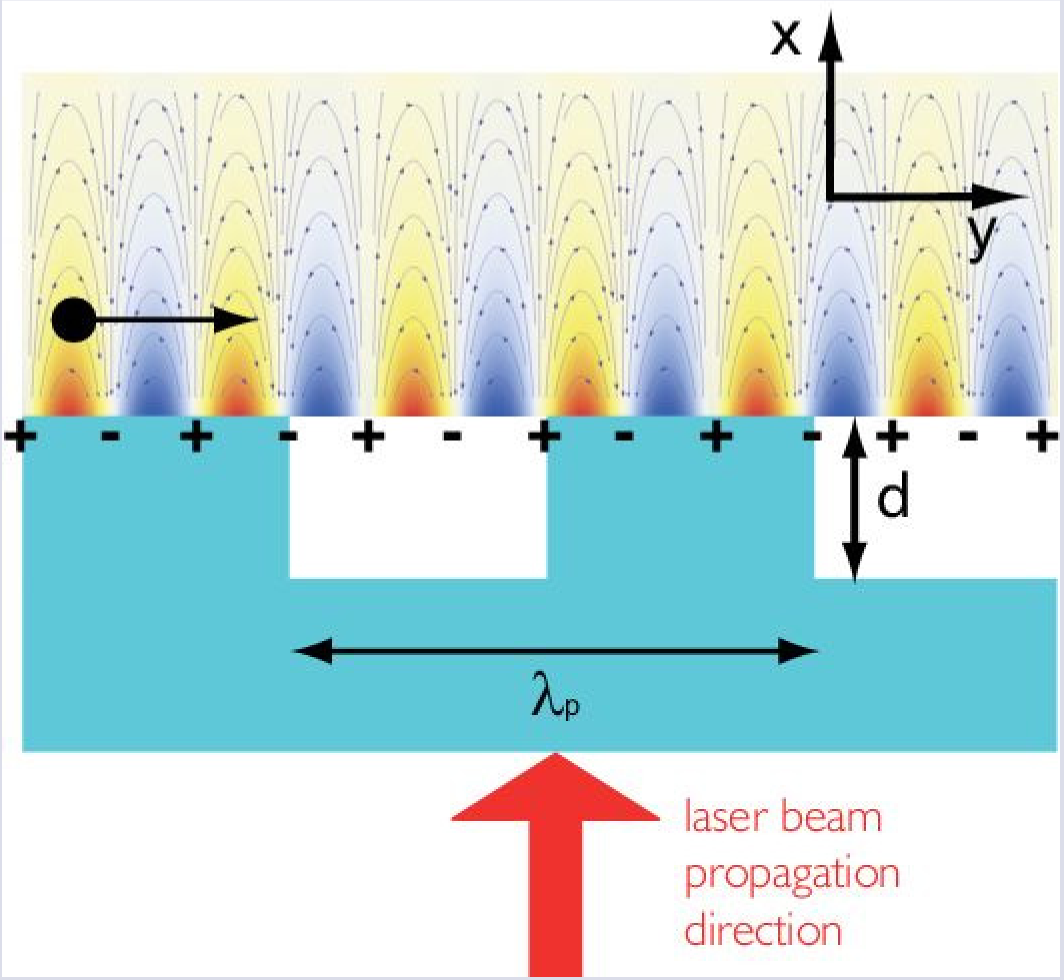
t = π/2

t = π

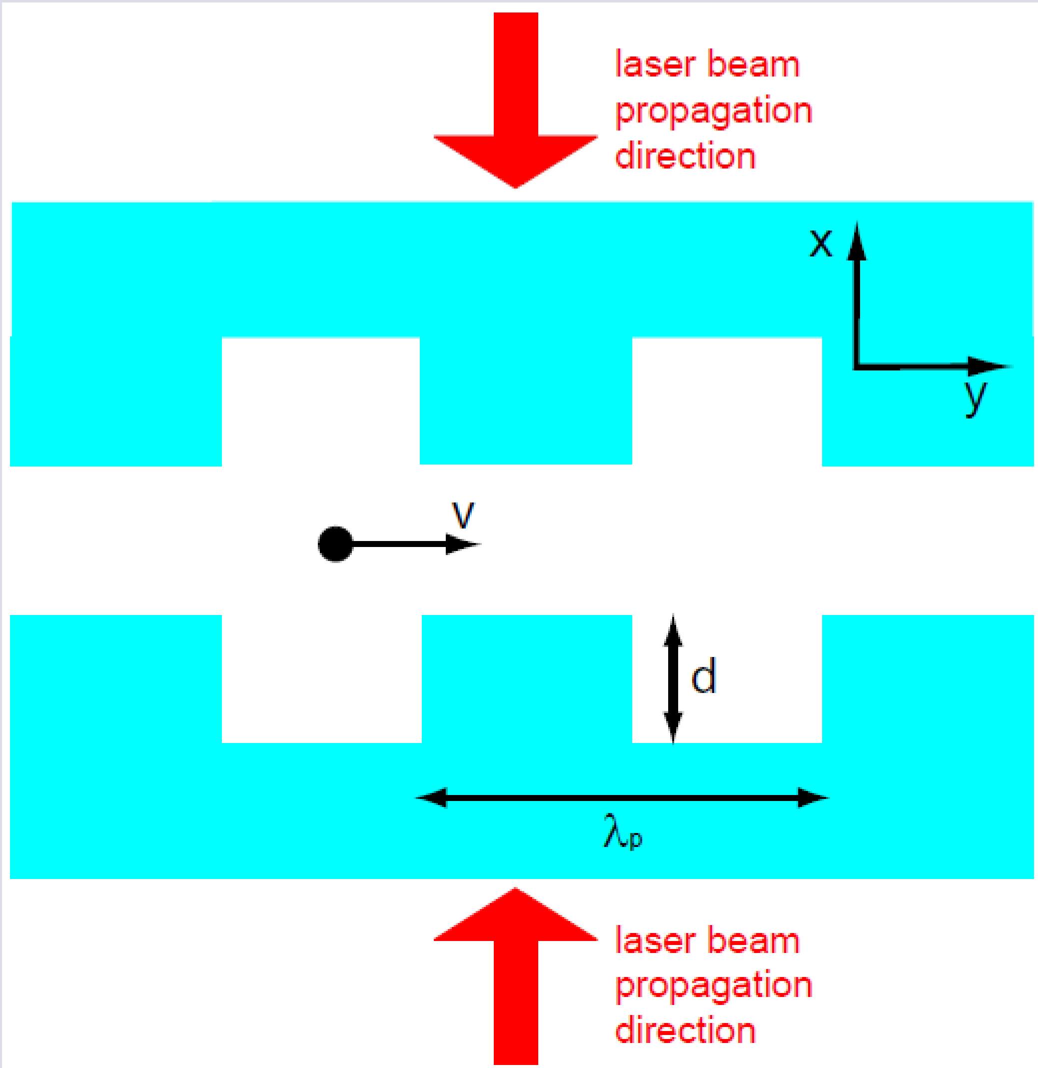
This example:
first spatial harmonic.
Analogous for third spatial harmonic.

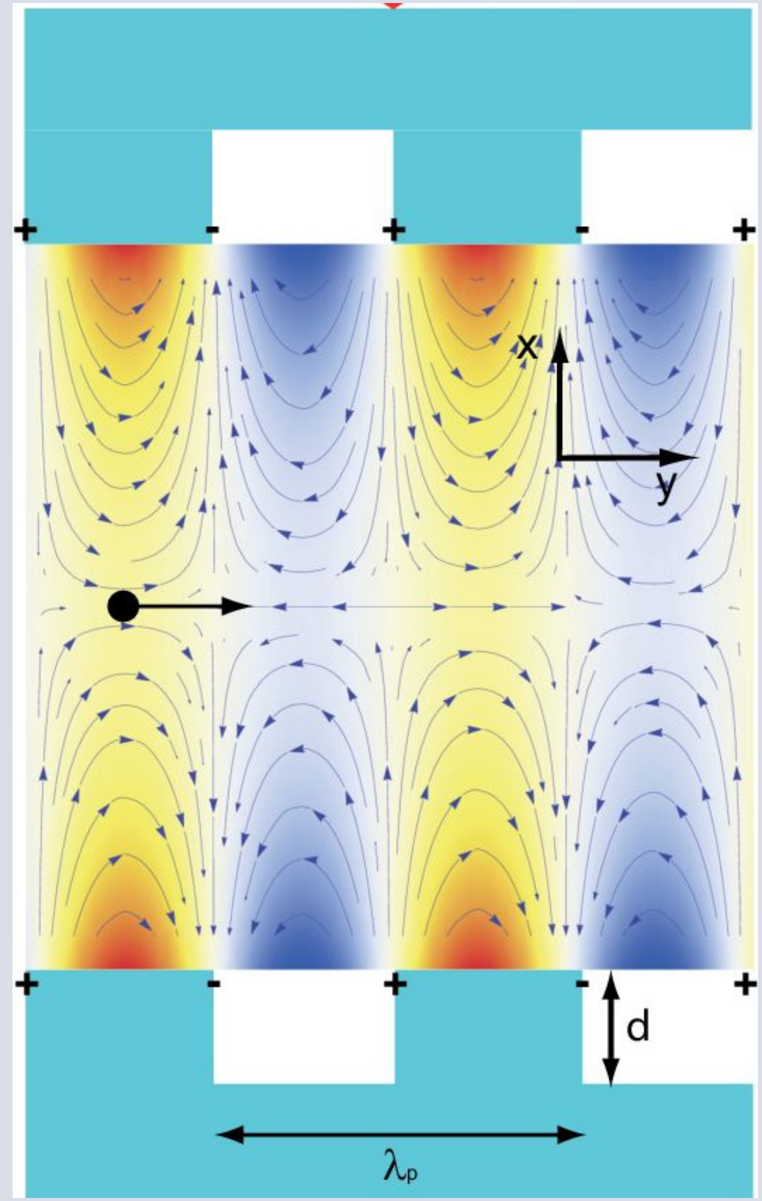
Transverse gradient drops





Two gratings: speed-of-light mode & more stable





More later!

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An old idea

Proposal for an Electron Accelerator Using an Optical Maser

Koichi Shimoda

January 1962 / Vol. 1, No. 1 / APPLIED OPTICS 33

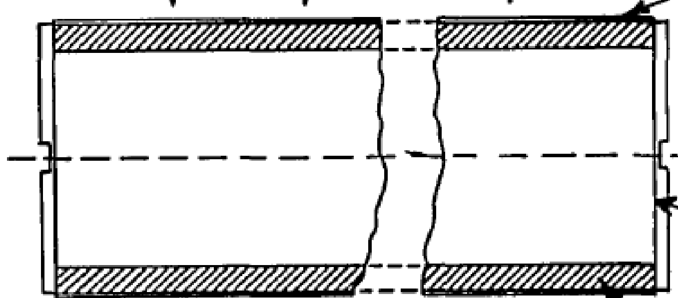


Fig. 1. Schematic diagram of an electron linear accelerator by optical maser.

An old idea

NUCLEAR INSTRUMENTS AND METHODS 62 (1968) 306–310; © NORTH-HOLLAND PUBLISHING CO.

LASER LINAC WITH GRATING

Y. TAKEDA and I. MATSUI

Central Research Laboratory, Hitachi Ltd., Kokubunji, Tokyo, Japan

Received 13 February 1968

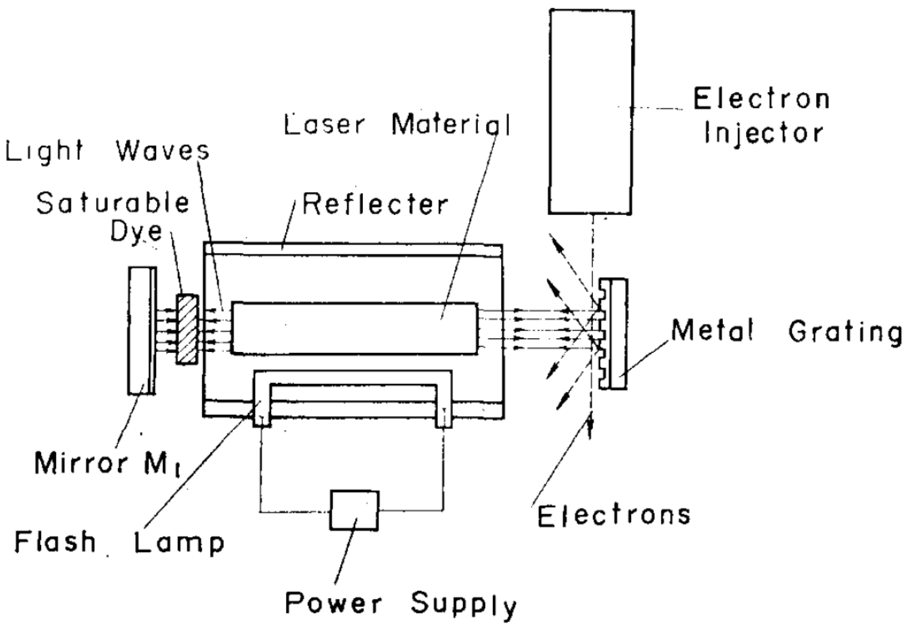


Fig. 1. Schematic diagram of "laser linac with grating".

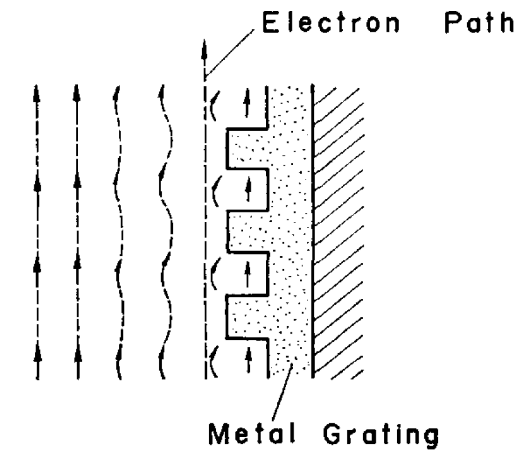


Fig. 2. Configuration of electric-field near grating surface.

In the 90s: dielectrics!

VOLUME 74, NUMBER 13 PHYSICAL REVIEW LETTERS 27 MARCH 1995

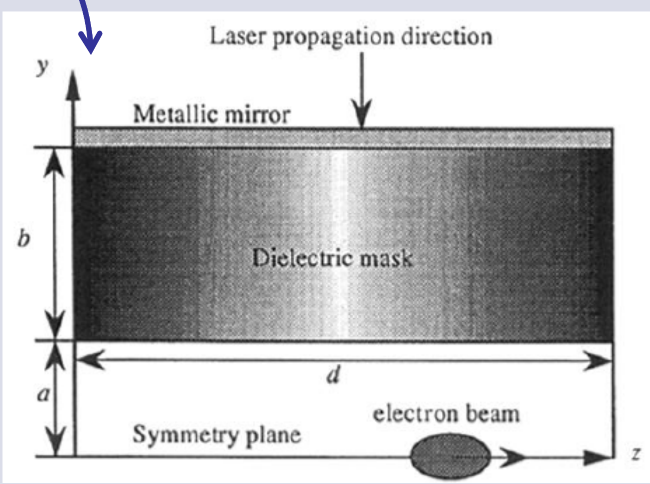
A Proposed Dielectric-Loaded Resonant Laser Accelerator

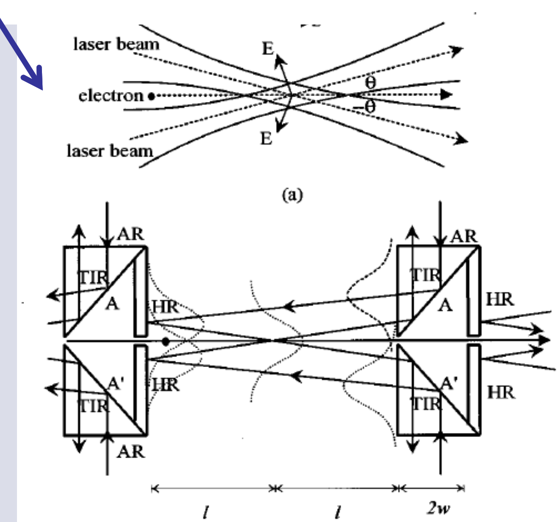
J. Rosenzweig, A. Murokh, and C. Pellegrini
Department of Physics, University of California, Los Angeles, 405 Hilgard Avenue, Los Angeles, California 90024
(Received 2 September 1994)

Proposed structure for a crossed-laser beam, GeV per meter gradient, vacuum electron linear accelerator

Appl. Phys. Lett. 68, 753 (1996)

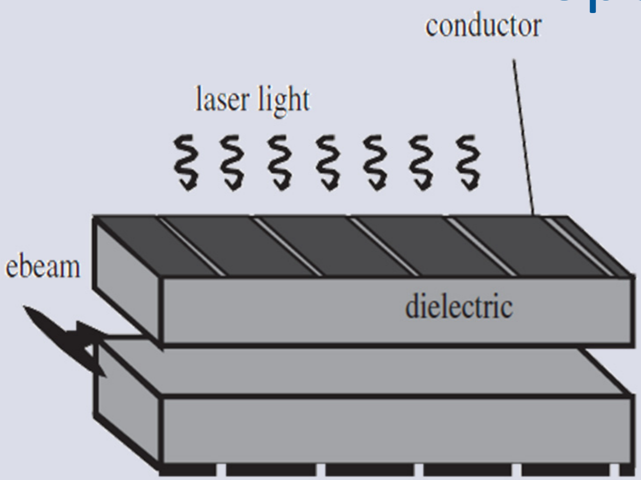
Y. C. Huang, D. Zheng, W. M. Tulloch, and R. L. Byer
Edward Ginzton Laboratory, Stanford University, Stanford, California 94305-4085
(Received 6 October 1995; accepted for publication 4 December 1995)



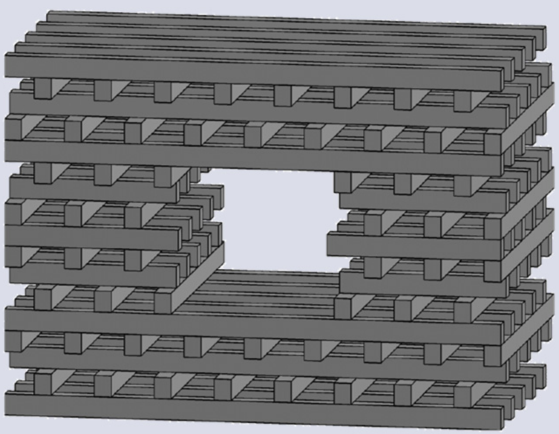


Other longtime players: Sieman group (SLAC), Travish (UCLA), Yoder (Manhattan) …

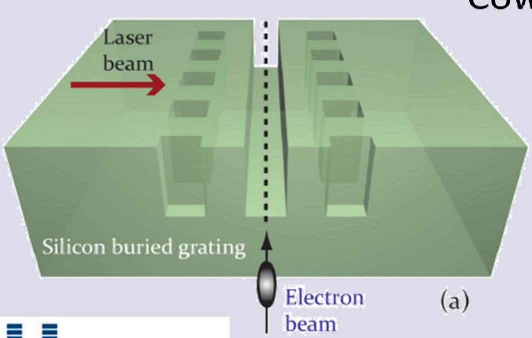
Proposed dielectric structures



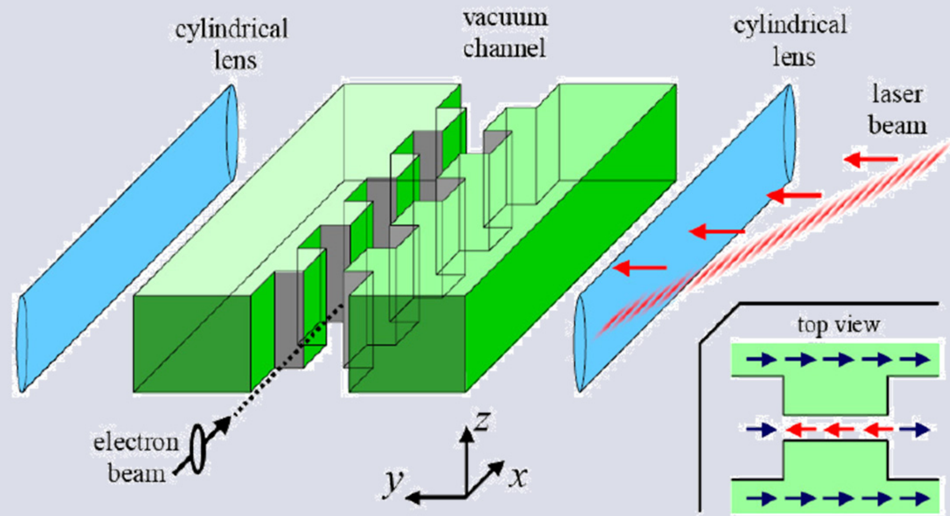
Yoder Rosenzweig, 2005



Cowan, 2008



Chang, Solgaard, 2014



Plettner, Lu, Byer, 2006

… 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

For a review and an extensive list of references, see:
R. J. England et al., “Dielectric laser accelerators”, Rev. Mod. Phys. 86, 1337 (2014)

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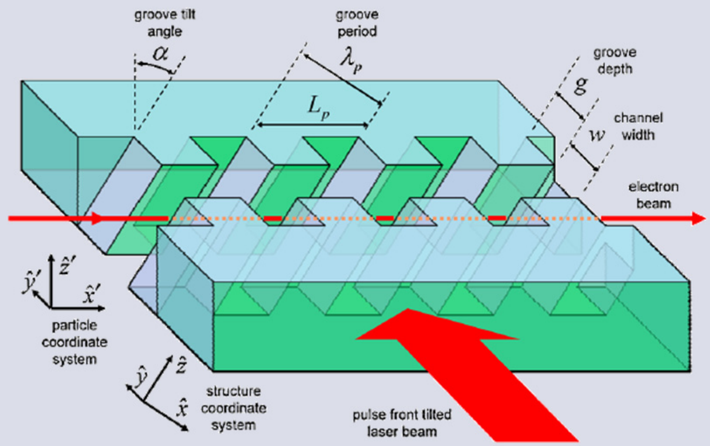
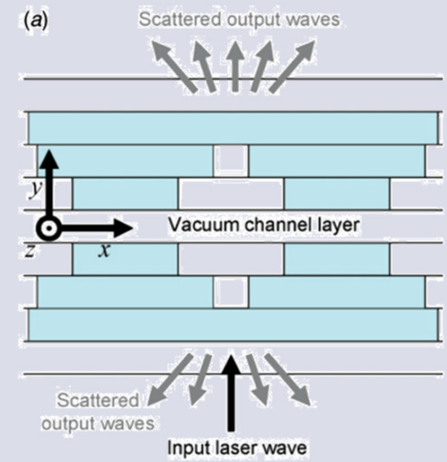
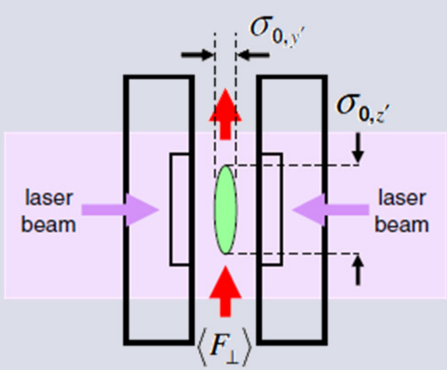
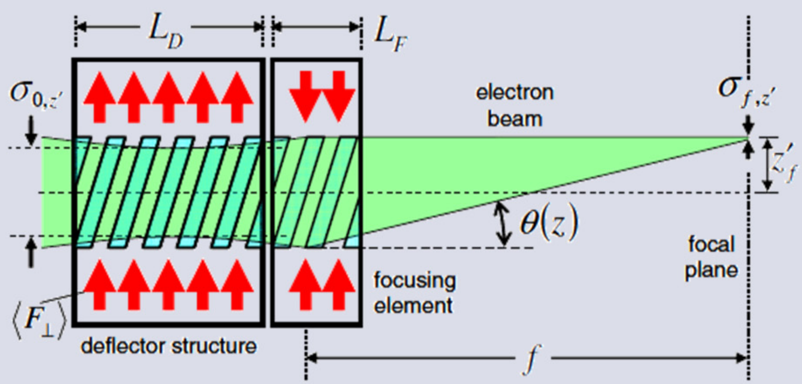
Grating-based DLA structure proposals









- DLA structure: Plettner, Lu, Byer, PRSTAB 2006
- FEL: Plettner, Byer, Nucl. Instr. Meth. A 2008
- Undulator: Plettner, Byer, PRSTAB 2008
- Deflection & focusing: Plettner, Byer, McGuinness, Hommelhoff, PRSTAB 2009
- Layered gratings: Plettner, Byer, Montazeri, J. Mod. Opt. 2011

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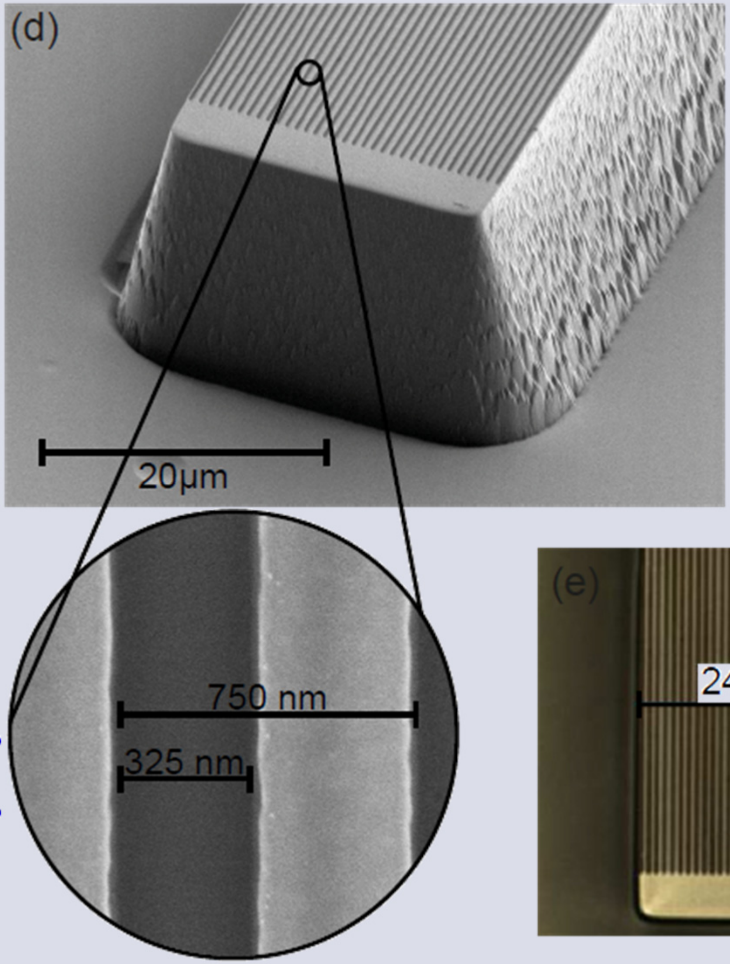
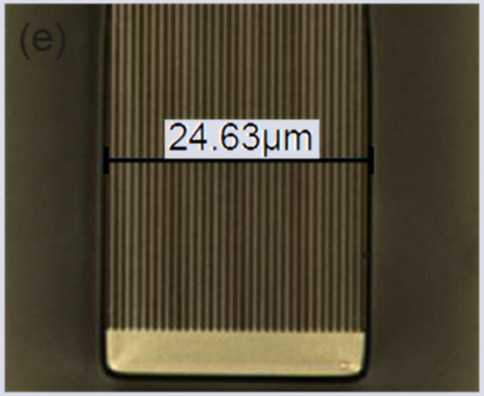
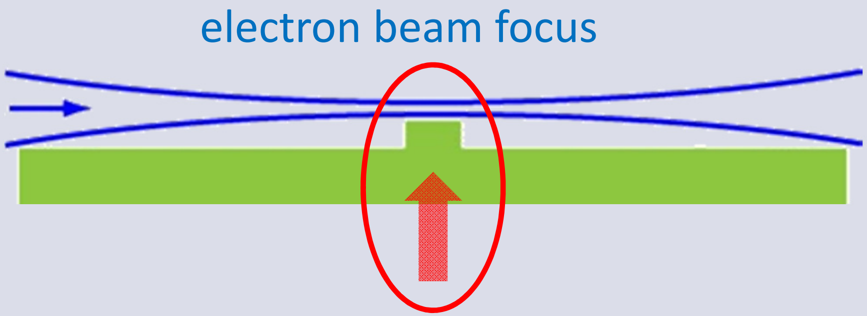
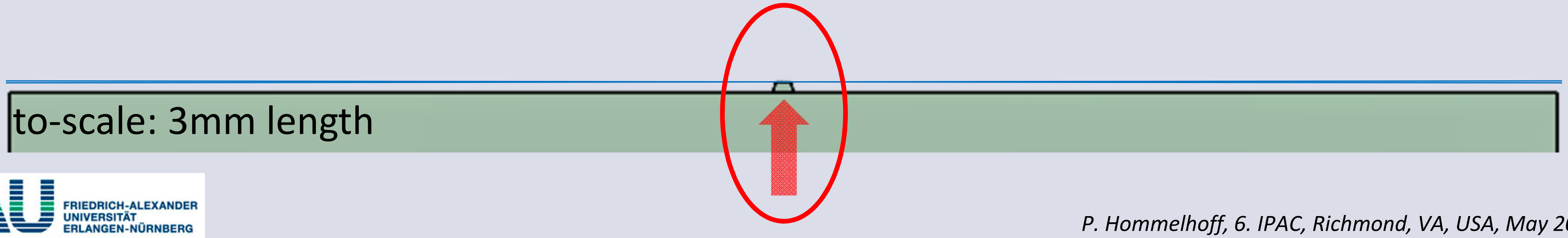
Grating structure

- 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









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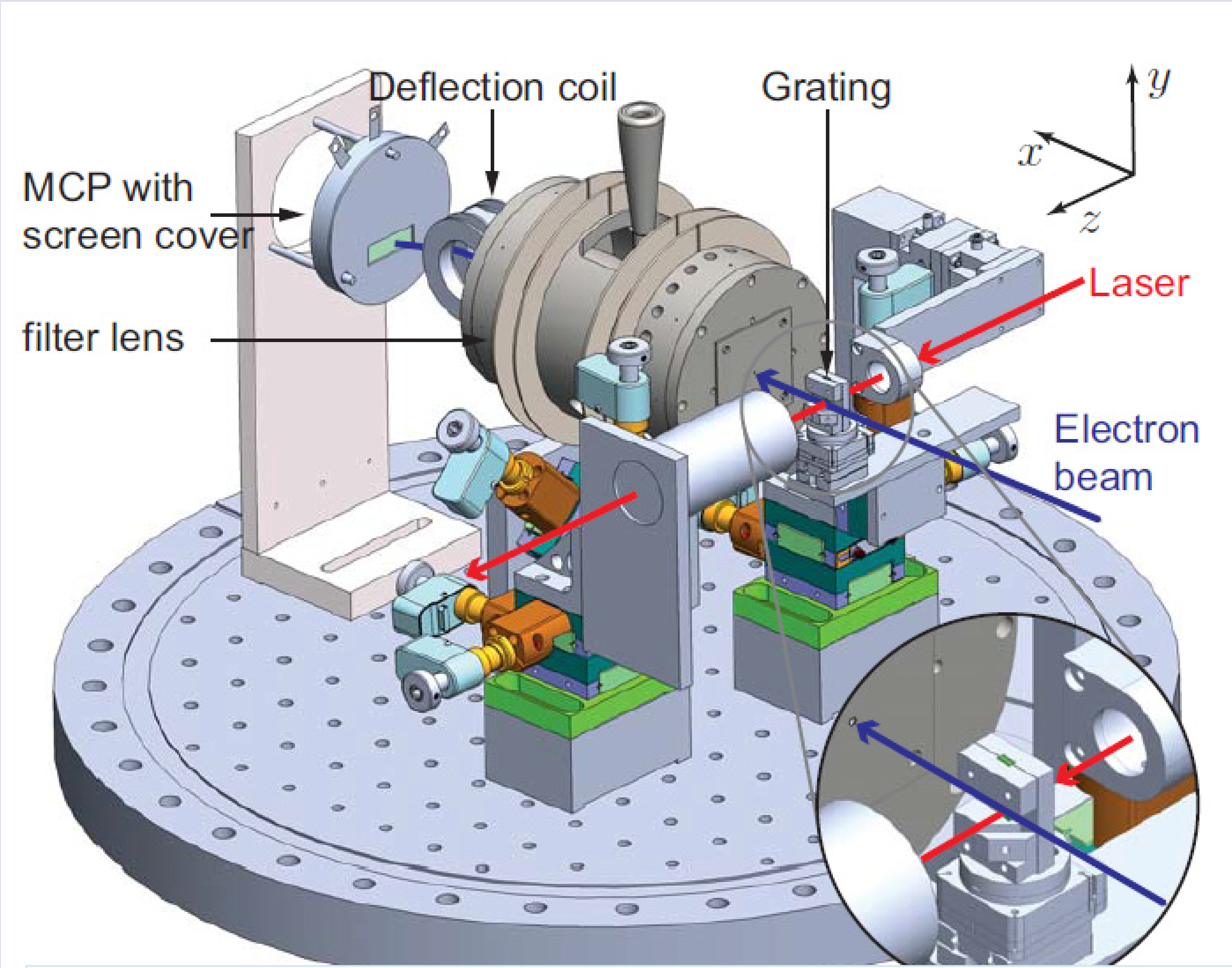
Sketch of setup



Laser parameters:

- 350 mW
- 2.745 MHz
- 110 fs

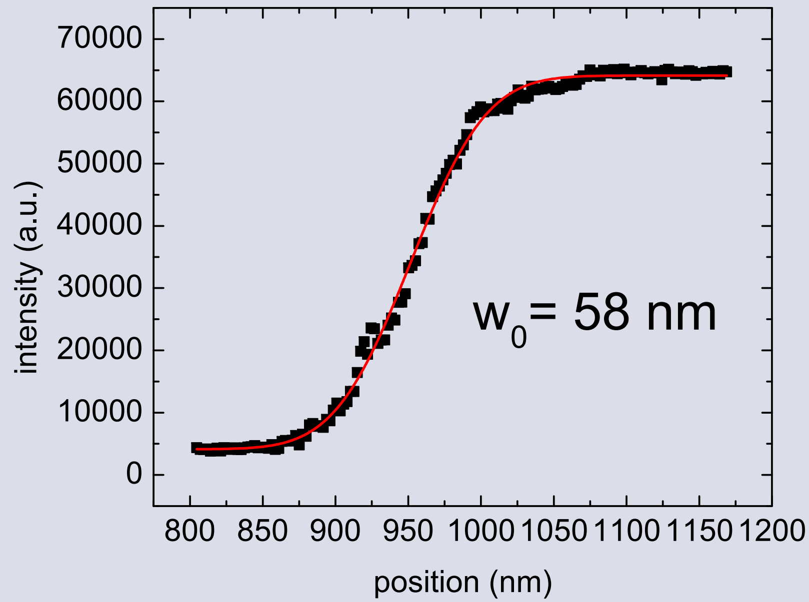
In the focus:

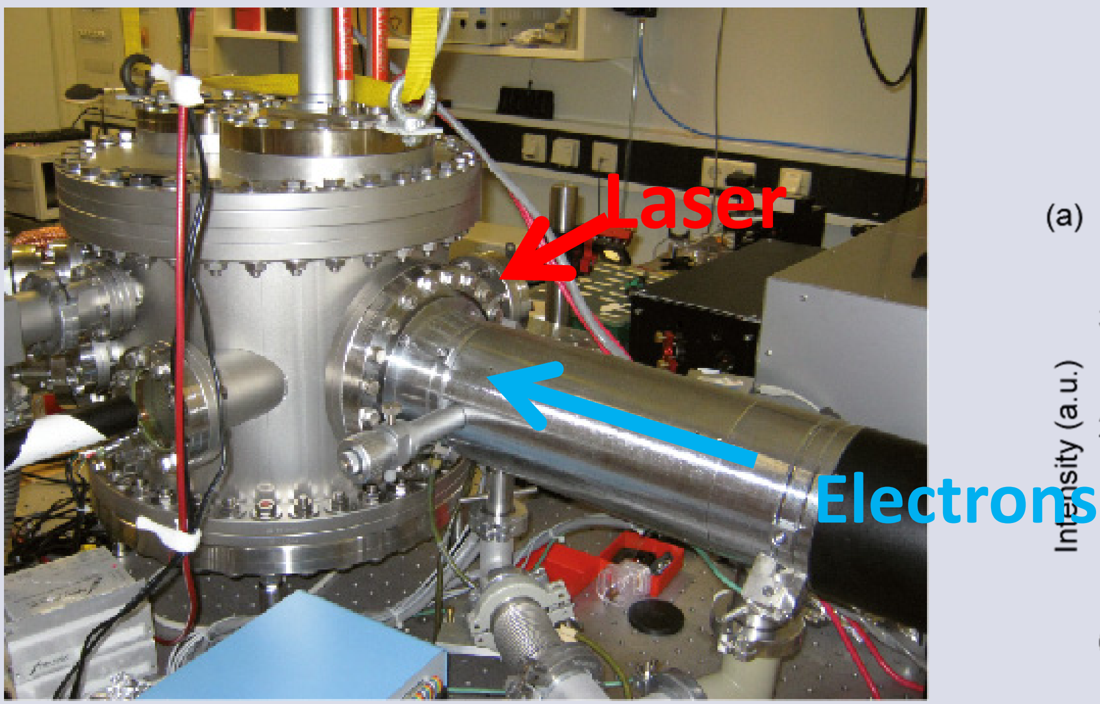
- 8.3 µm beam waist
- 2.76 GV/m
- 2.0 10^{12} W/cm^2

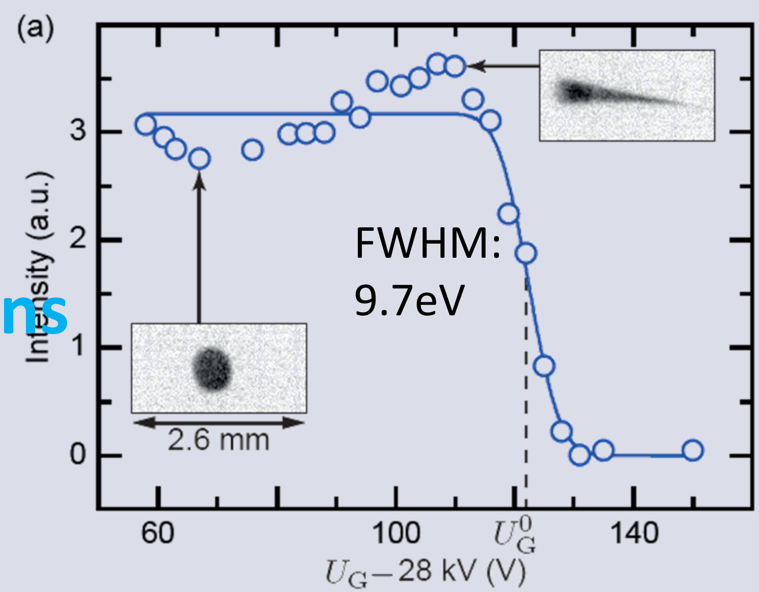
Details on setup: J. Breuer, R. Graf, A. Apolonski, P. Hommelhoff, Phys. Rev. ST-AB 17, 021301 (2014)
on laser: S. Naumov, A. Fernandez, R. Graf, P. Dombi, F. Krausz, and A. Apolonski, NJP 7, 216 (2005).

Experimental Setup

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







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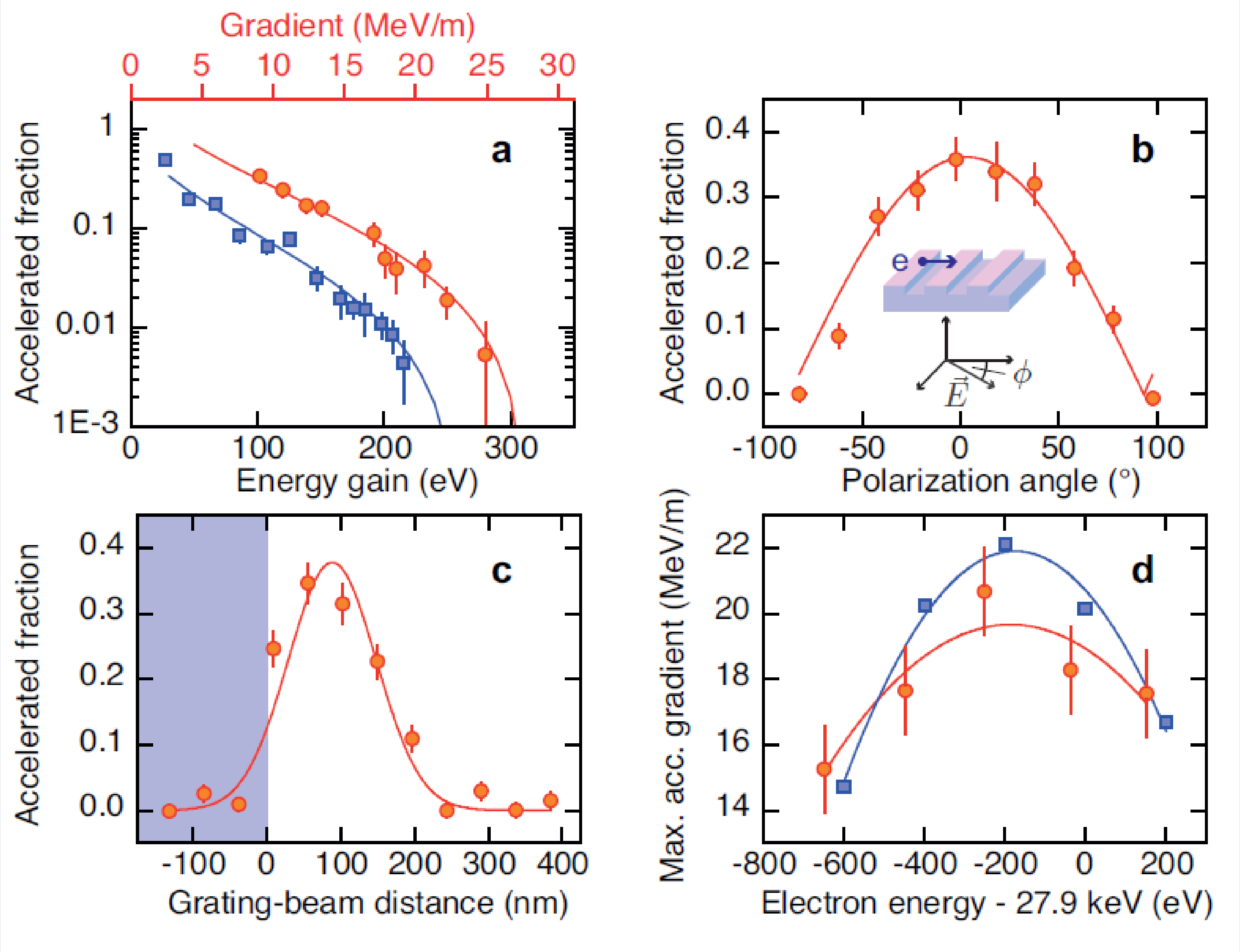
Dielectric laser acceleration results



Max. observed gradient: 25 MeV/m

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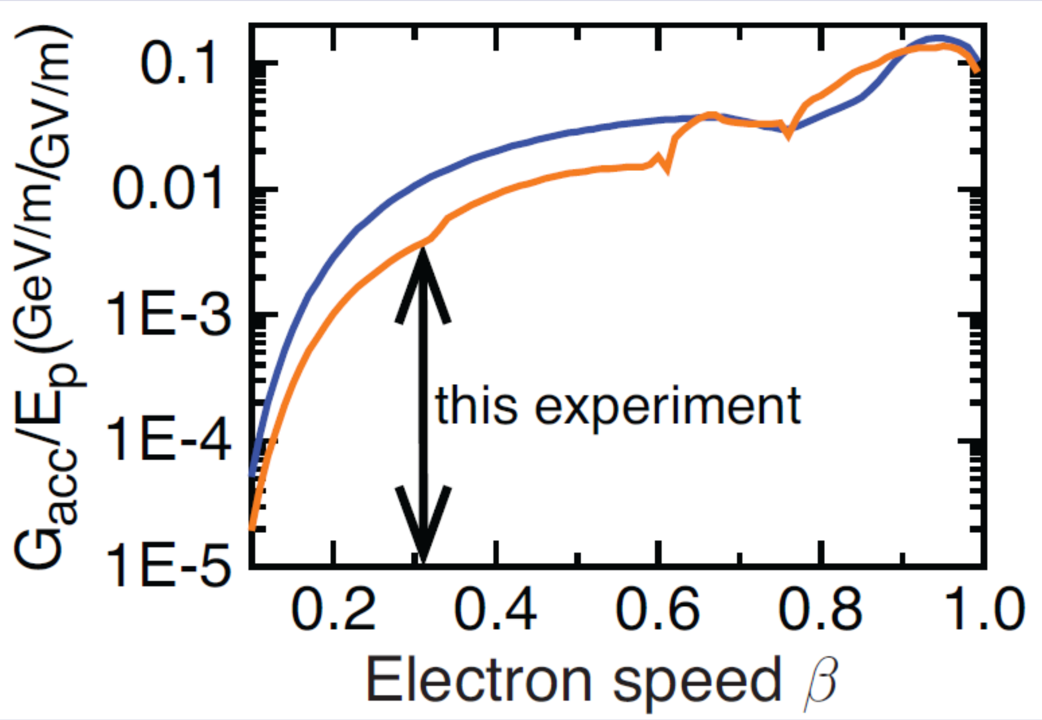
J. Breuer, P. Hommelhoff, Phys. Rev. Lett. 111, 134803 (2013)

Acceleration efficiency: simulation results



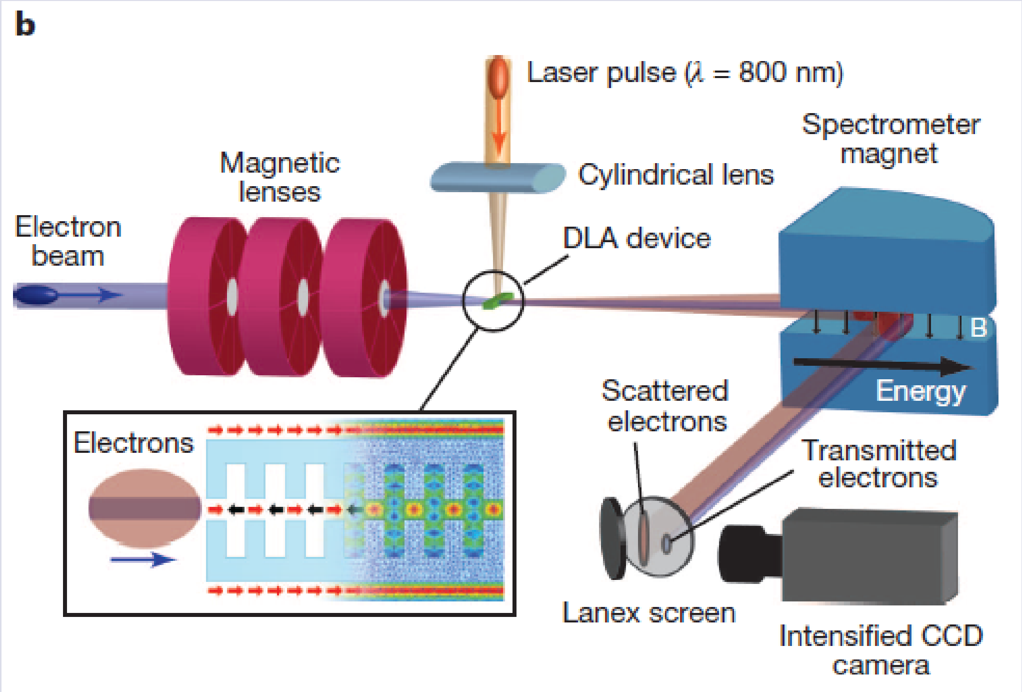
Blue: first spatial harmonic
Orange: third spatial harmonic

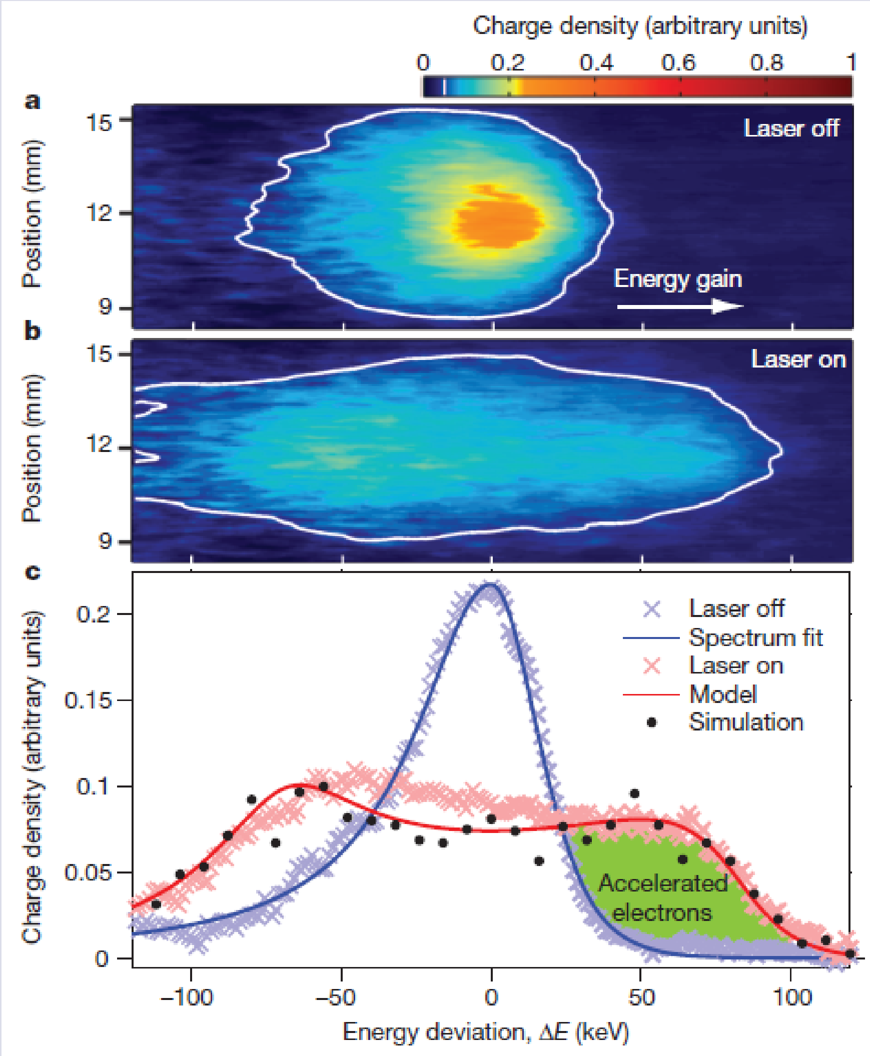
Observed: **25 MeV/m at β = 0.3**: laser power limited (increase by a factor of 3.4 possible to reach damage threshold).
With that, **at β = 0.95: 1.7 GeV/m**

J. Breuer, P. Hommelhoff, Phys. Rev. Lett. 111, 134803 (2013)
J. Breuer, R. Graf, A. Apolonski, P. Hommelhoff, Phys. Rev. ST-AB 17, 021301 (2014)

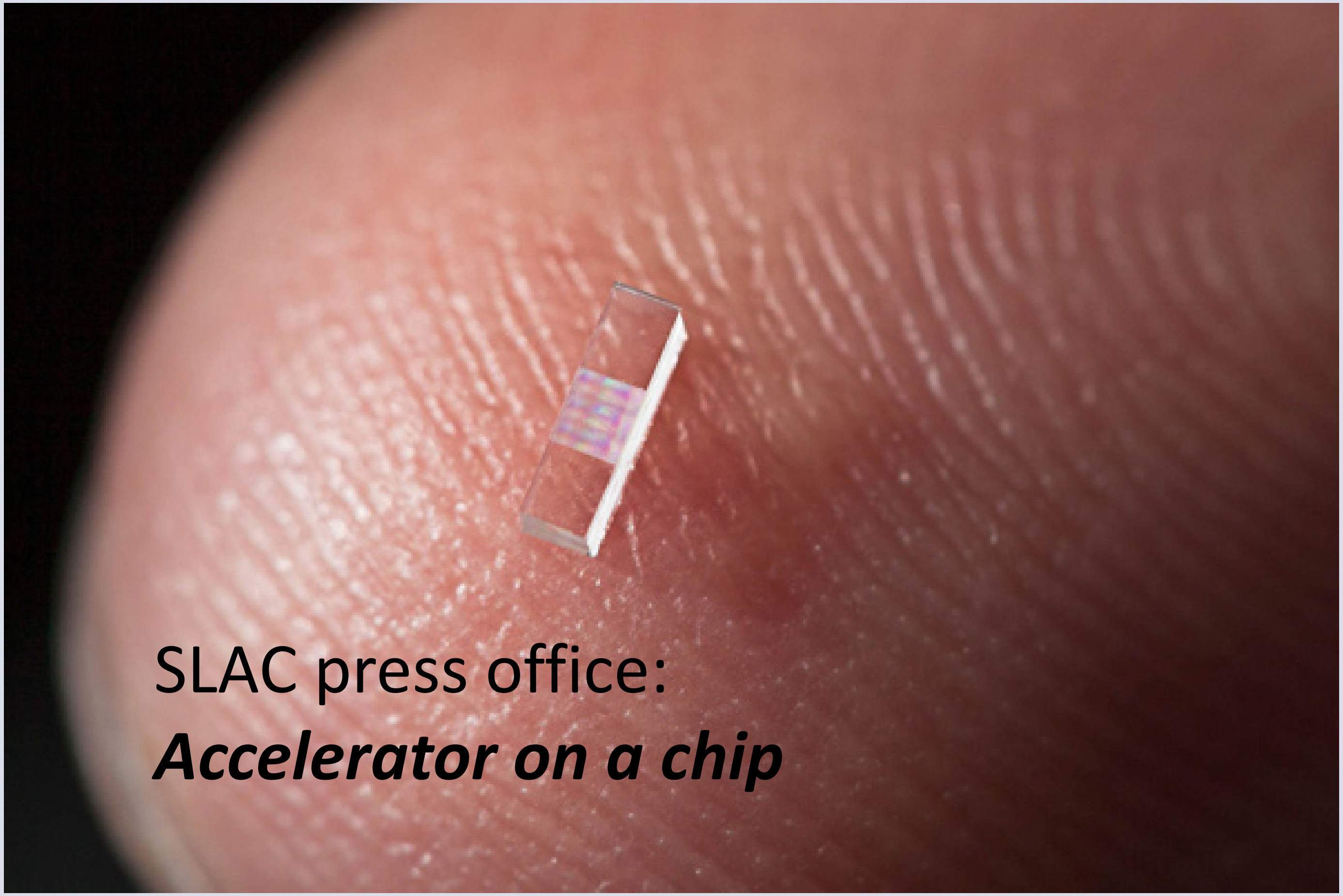
Peralta et al. (Byer group, Stanford), Nature 503, 91 (2013)

Dual-Grating Structure: Dielectric laser acceleration of 60 MeV electrons at SLAC: >250 MeV/m gradient





E. Peralta, Soong, K., England, R. J., Colby, E. R., Wu, Z., Montazeri, B., McGuinness, C., McNeur, J., Leedle, K. J., Walz, D., Sozer, E., Cowan, B., Schwartz, B., Travish, G., Byer R. L., Nature 503, 91 (2013)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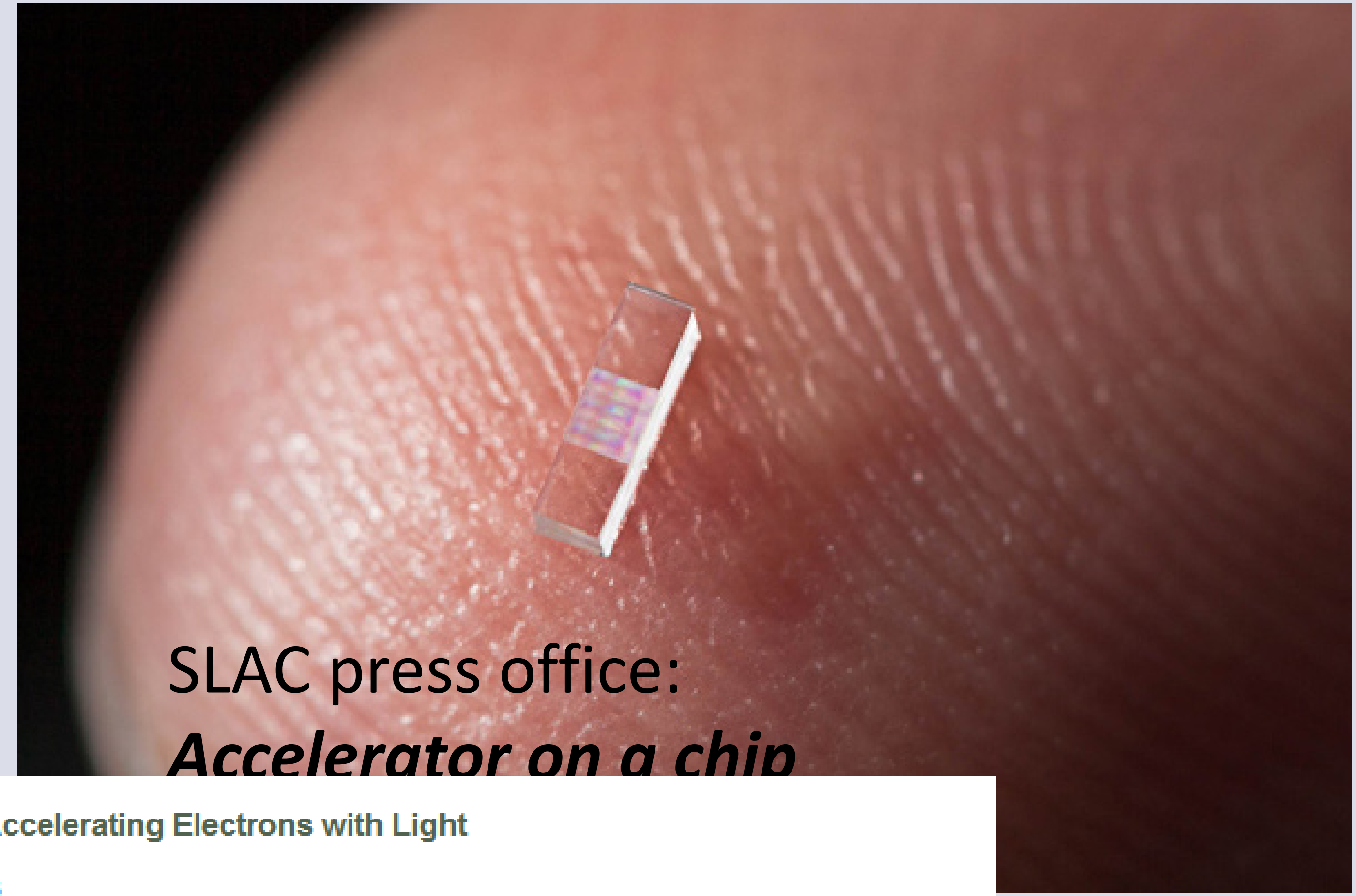
Accelerator on a chip

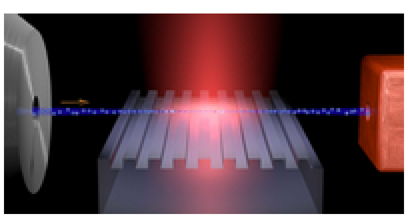


SLAC press office:

Accelerator on a chip

Physics: Accelerating Electrons with Light

September 27, 2013



In a new technique, light pulses accelerate electrons more efficiently than traditional accelerators.
[Focus on Phys. Rev. Lett. **111,** 134803 (2013)]

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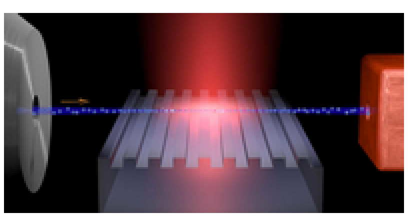

In a new technique, light pulses accelerate electrons more efficiently than traditional accelerators.
[Focus on Phys. Rev. Lett. **111,** 134803 (2013)]

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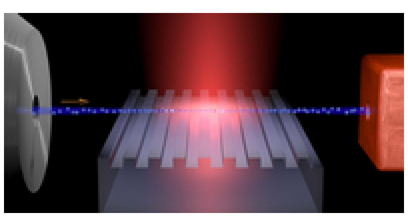

In a new technique, light pulses accelerate electrons more efficiently than traditional accelerators.
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In Duitsland en de VS wordt gewerkt aan de deeltjesversneller van de toekomst. Die past misschien wel op een keukentafel of zelfs op een chip.
Door Martijn van Calmthout Illustratie Raymond van der Molj
Deeltjes versnellen op de keukentafel
SURFENDE ELEKTRONEN OP LASERLICHT
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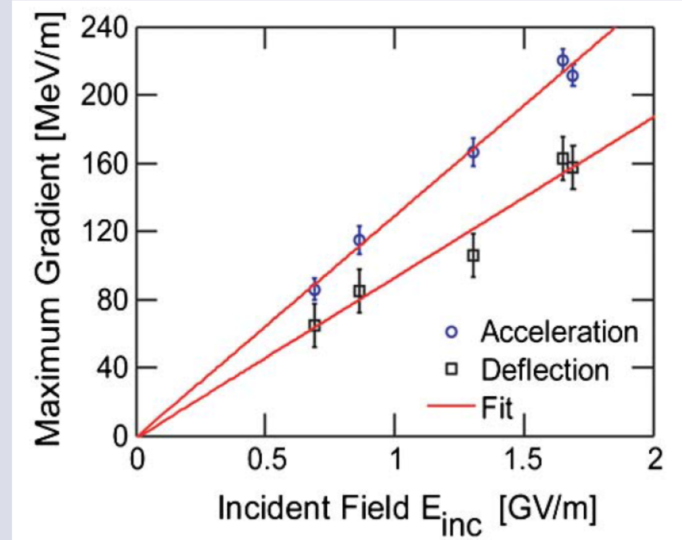
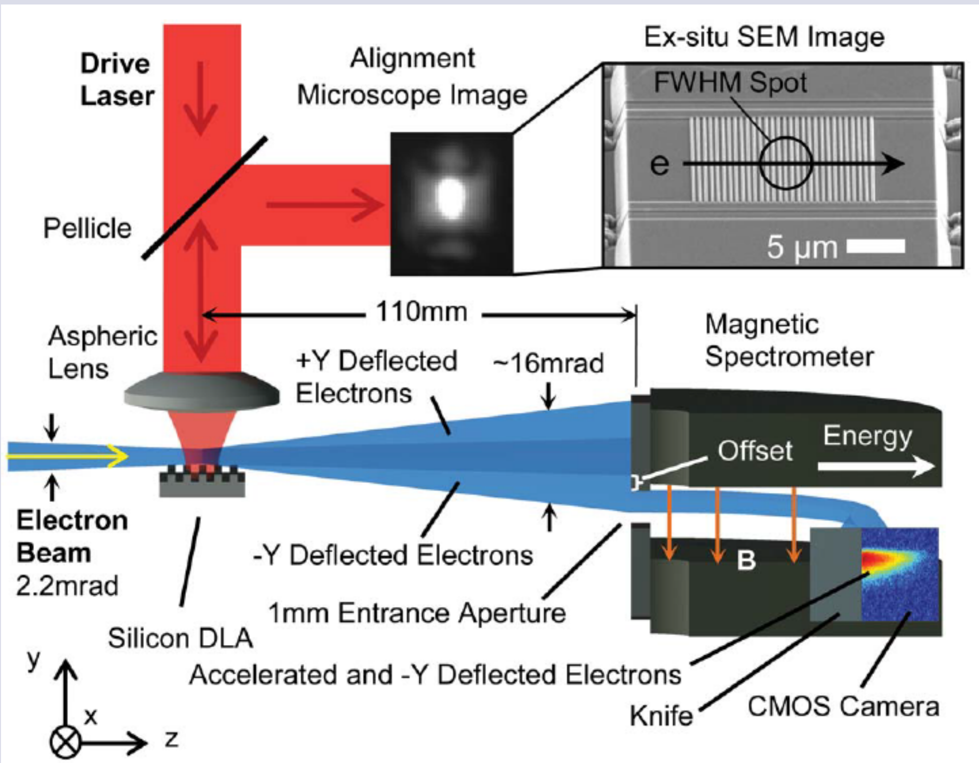
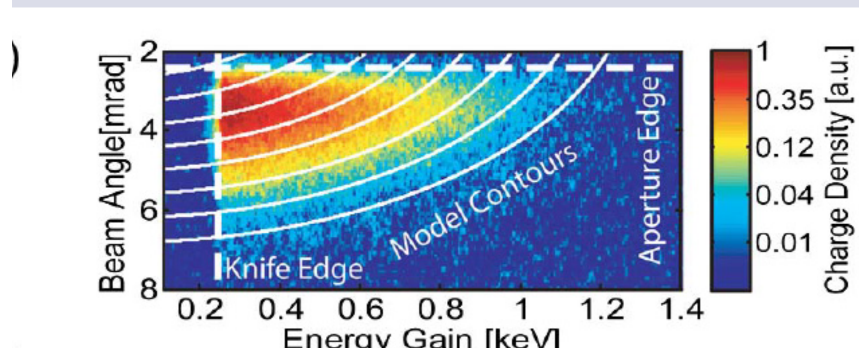
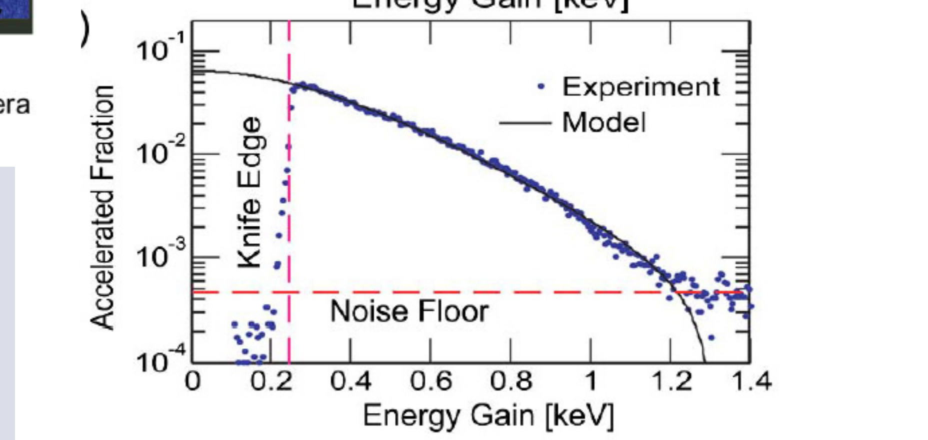
VA, USA, May 2015

Stanford: silicon structure with 100 keV electrons: acceleration *and* deflection









Gradient > 200 MeV/m accel.,
> 150 MeV/m defl.

K. J. Leedle, R. F. Pease, R. L. Byer, J. S. Harris, Optica 2, 158 (2015)

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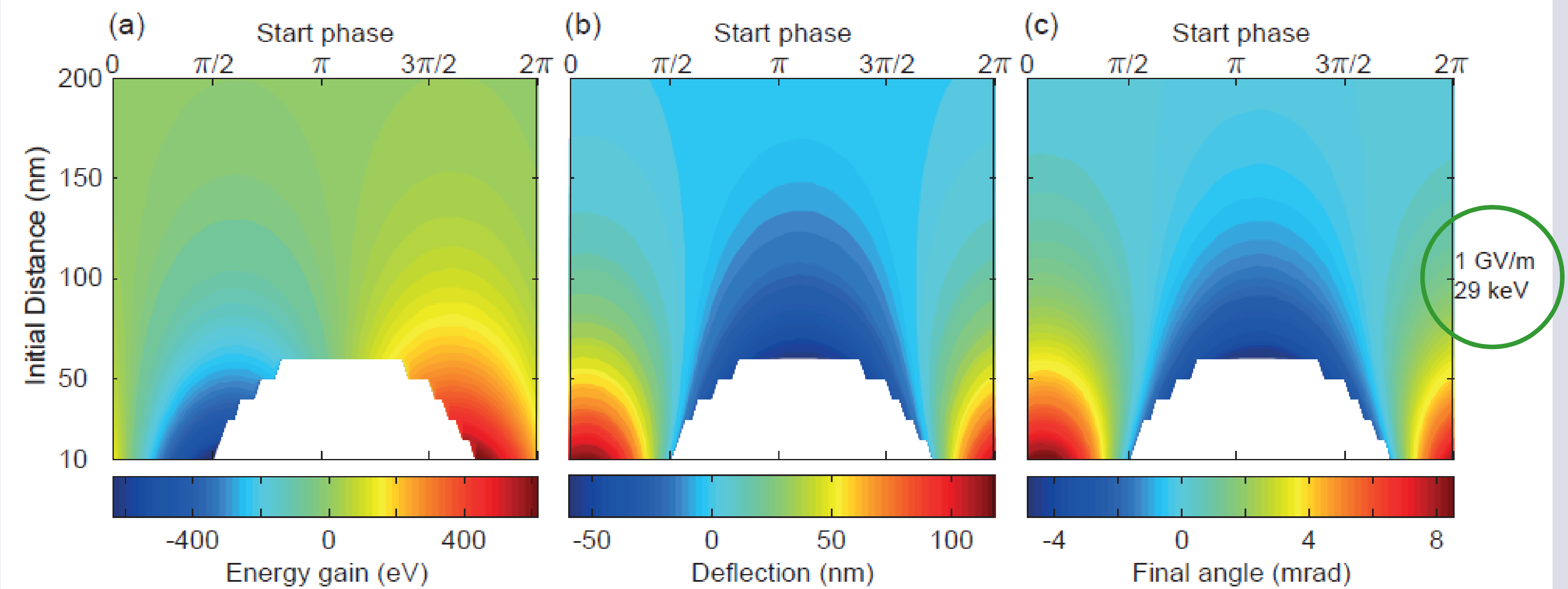
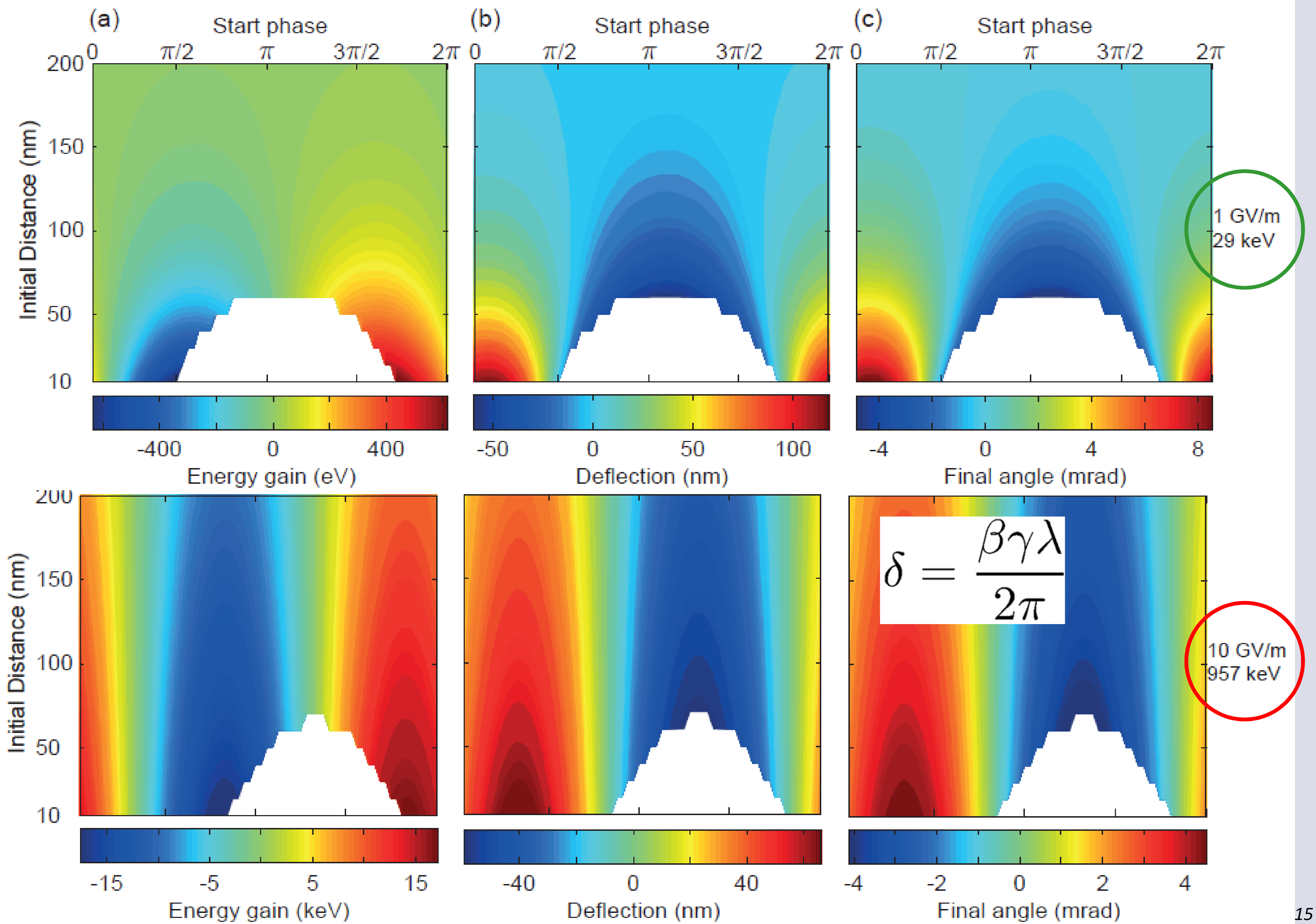
Particle tracing simulation results



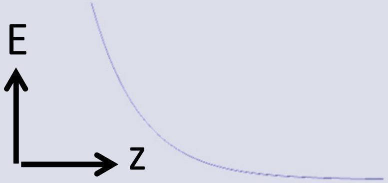
Related to Panofsky-Wenzel theorem (though non-relativistic electrons here):

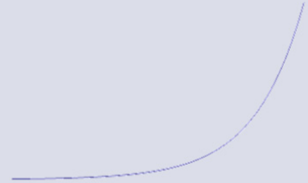
- Shear force for single-sided structure
- Useful for novel streak camera applications etc.?

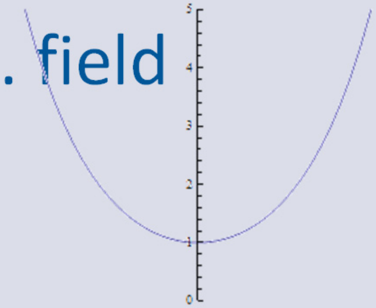
Particle tracing simulation results

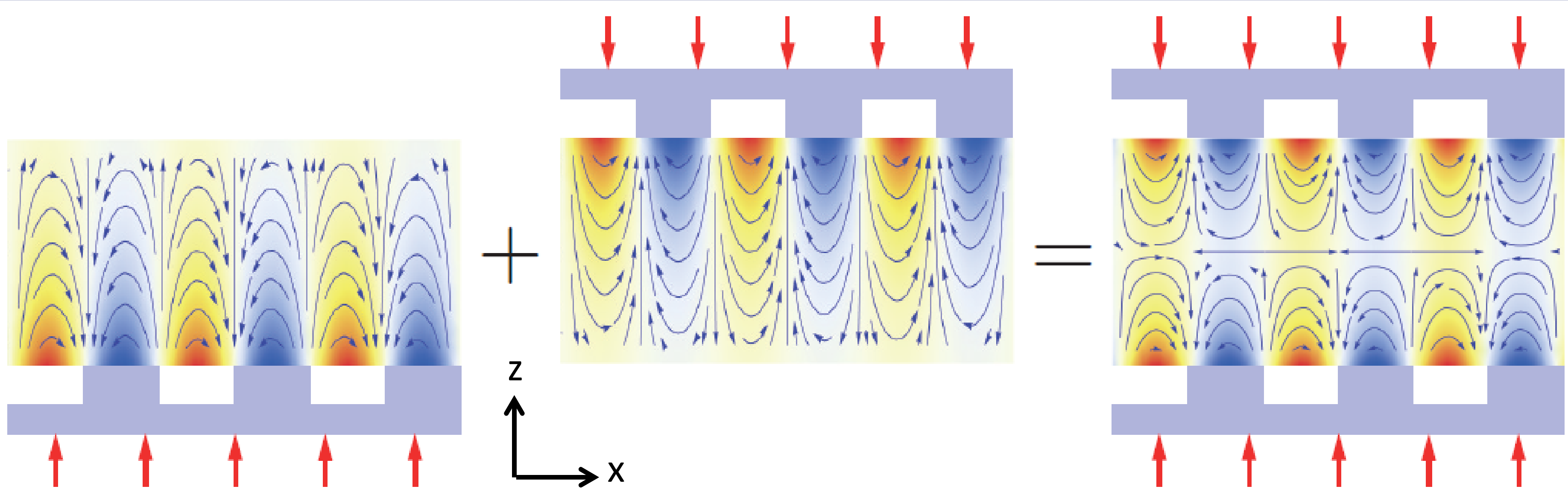


Two-sided structures: uniform accel. field









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

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

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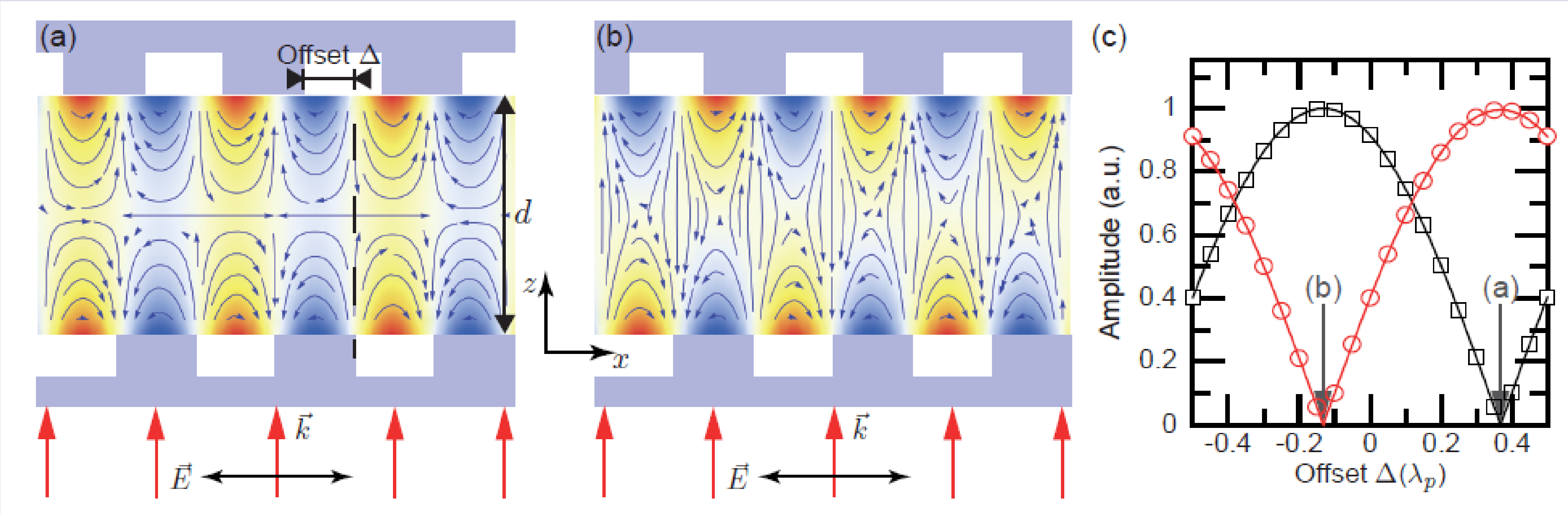
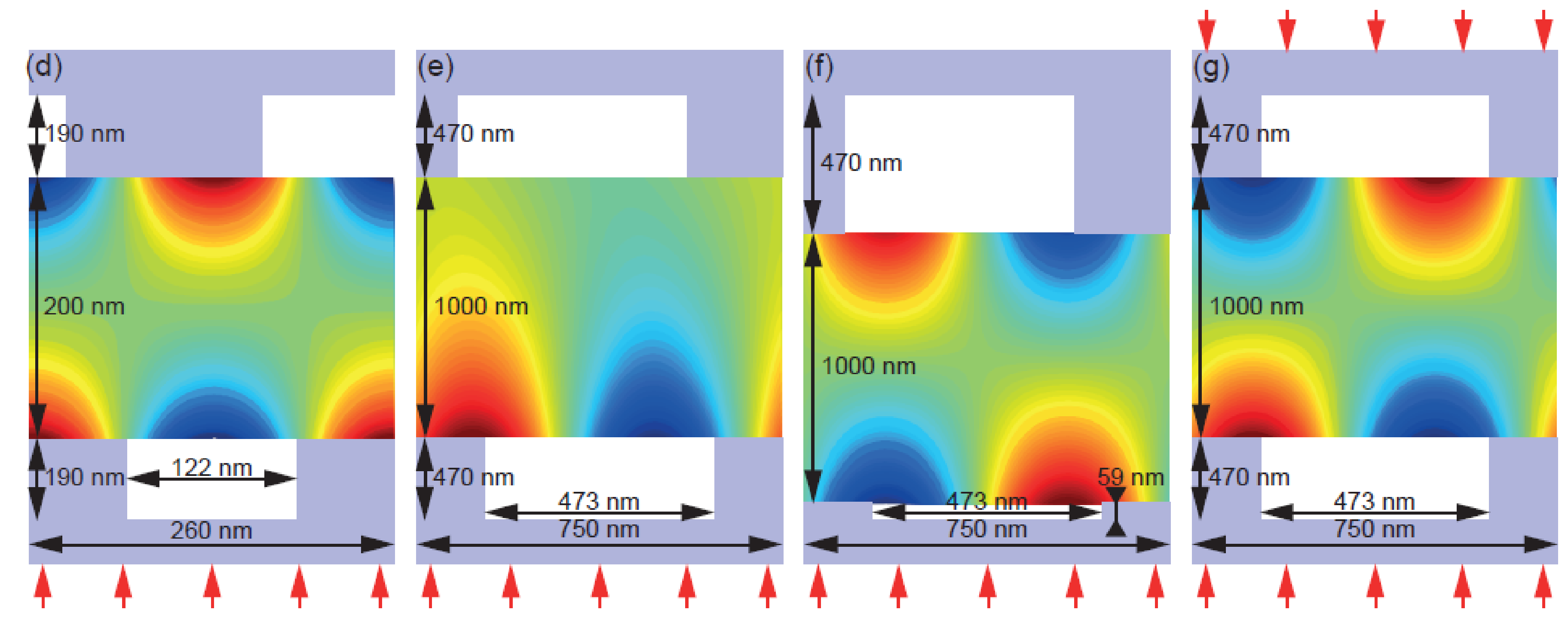
Shift structure: from acceleration to deflection



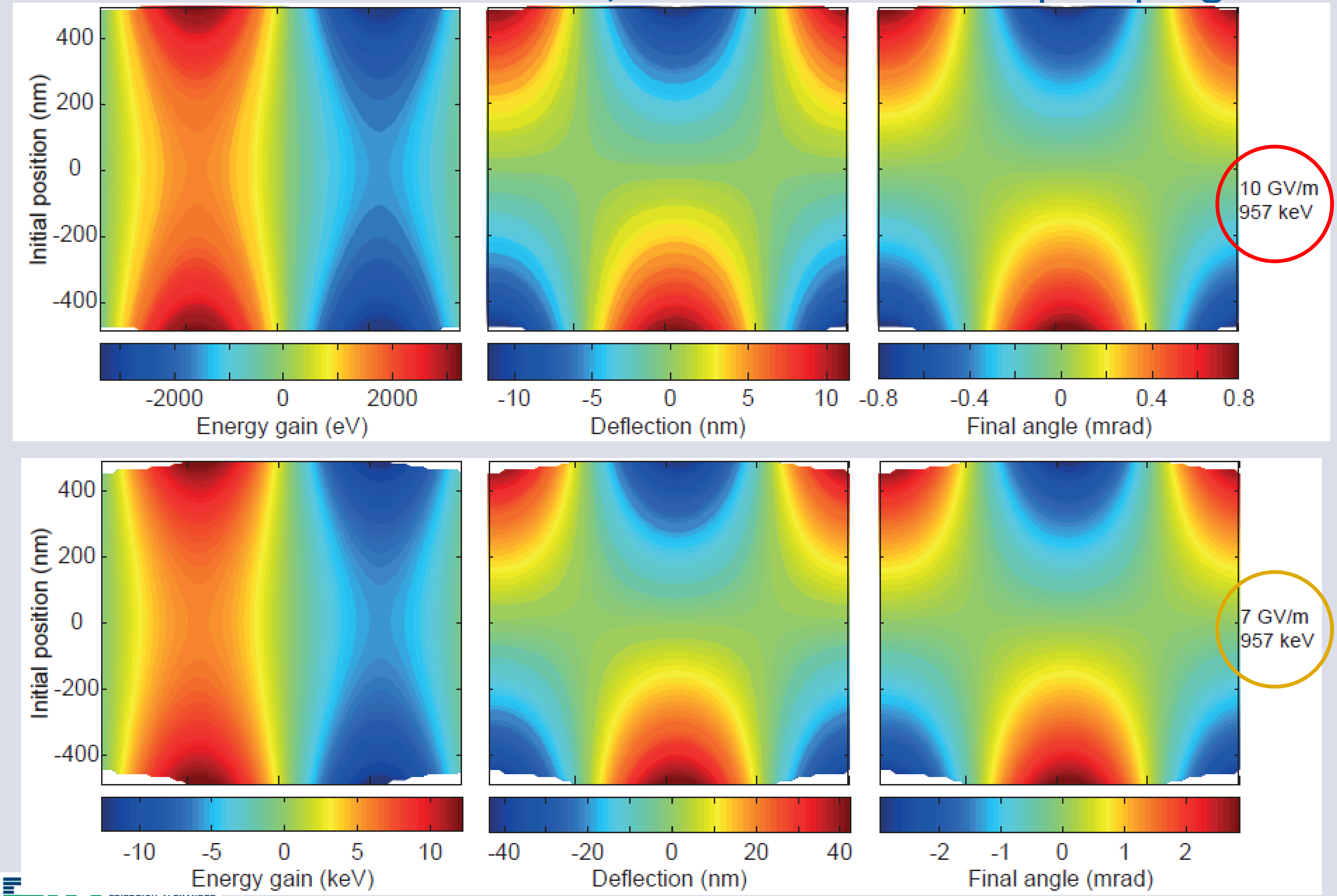
$$\mathbf{F_r} = qc \begin{pmatrix} \frac{1}{\beta\gamma}\left(C_\mathrm{s}\cosh(k_z z) + C_\mathrm{c}\sinh(k_z z)\right)\sin(k_x x - \omega t) \\ 0 \\ -\frac{1}{\beta\gamma^2}\left(C_\mathrm{s}\sinh(k_z z) + C_\mathrm{c}\cosh(k_z z)\right)\cos(k_x x - \omega t) \end{pmatrix}$$

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



Quite a number of structure parameters! Also: form factor not even looked at yet.

Double-sided structure, one- vs. two-sided pumping



Space charge effects: beam envelope equation

Accel. in long. el. field

Focusing in radial el. field

Focusing in axial magn. field

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

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

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Emittance and space charge

Assume emittance limited beam:

$$r_{\mathrm{m}}'' + \frac{\gamma'' r_{\mathrm{m}}}{2\beta^2\gamma} - \frac{\epsilon_{\mathrm{n}}^2}{\beta^2\gamma^2 r_{\mathrm{m}}^3} = 0$$

transverse focusing with laser field:

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

Demanding a stable beam radius yields:

$$\epsilon_{\mathrm{n}}^2 = \frac{2Gr_{\mathrm{m}}^3}{mc^2}$$

With G = 1 GeV/m and r = 100nm:

$$\epsilon_n = 6\,\mathrm{nm}\cdot\mathrm{rad}$$

If perveance term (space charge, treat as perturbation) is 10% of the emittance term: **current limit** of

$$I_{\mathrm{b}} = 0.1 I_0 \frac{G\beta\gamma r_{\mathrm{m}}}{mc^2}$$

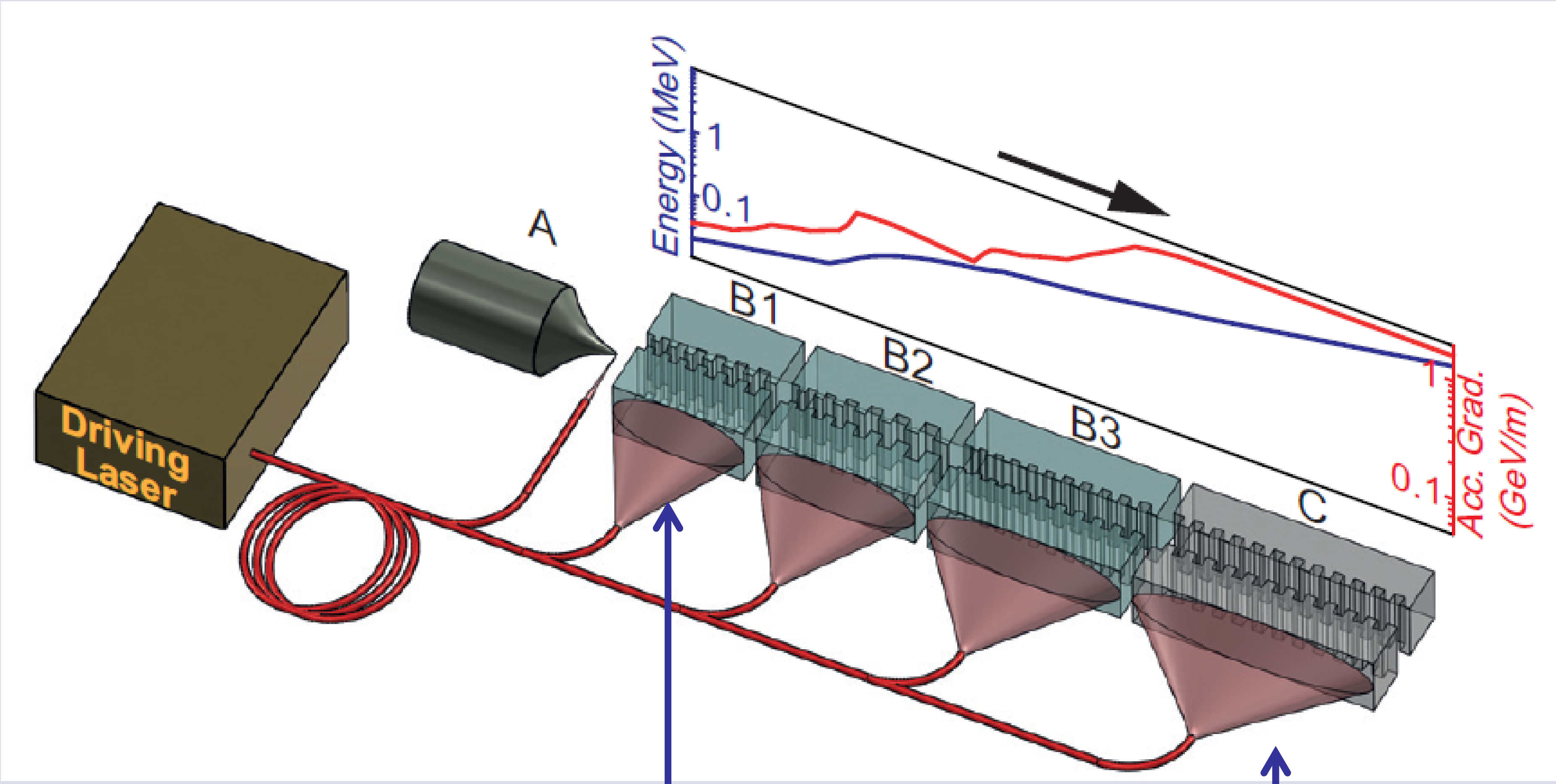
Space-charge limited current

E_p ($\frac{GV}{m}$)	$E_{kin} = 29$ keV, $r_m = 50$ nm			$E_{kin} = 957$ keV, $r_m = 300$ nm		
	λ (μm)			λ (μm)		
	0.8	2	5	0.8	2	5
1	1.8 mA	4.4 mA	11.2 mA	0.28 A	0.68 A	1.72 A
7	12.6 mA	32 mA	80 mA	1.9 A	4.8 A	12 A
10	18 mA	46 mA	114 mA	2.8 A	6.8 A	17.2 A

Total charge (0.1 opt. period long pulse):
3 fC, scales with λ^2
See also loaded acceleration efficiency:
R. H. Sieman, PR-STAB 7, 061303 (2004)

J. Breuer, J. McNeur, P. Hommelhoff,
J. Phys. B. 47, 234004 (2014)

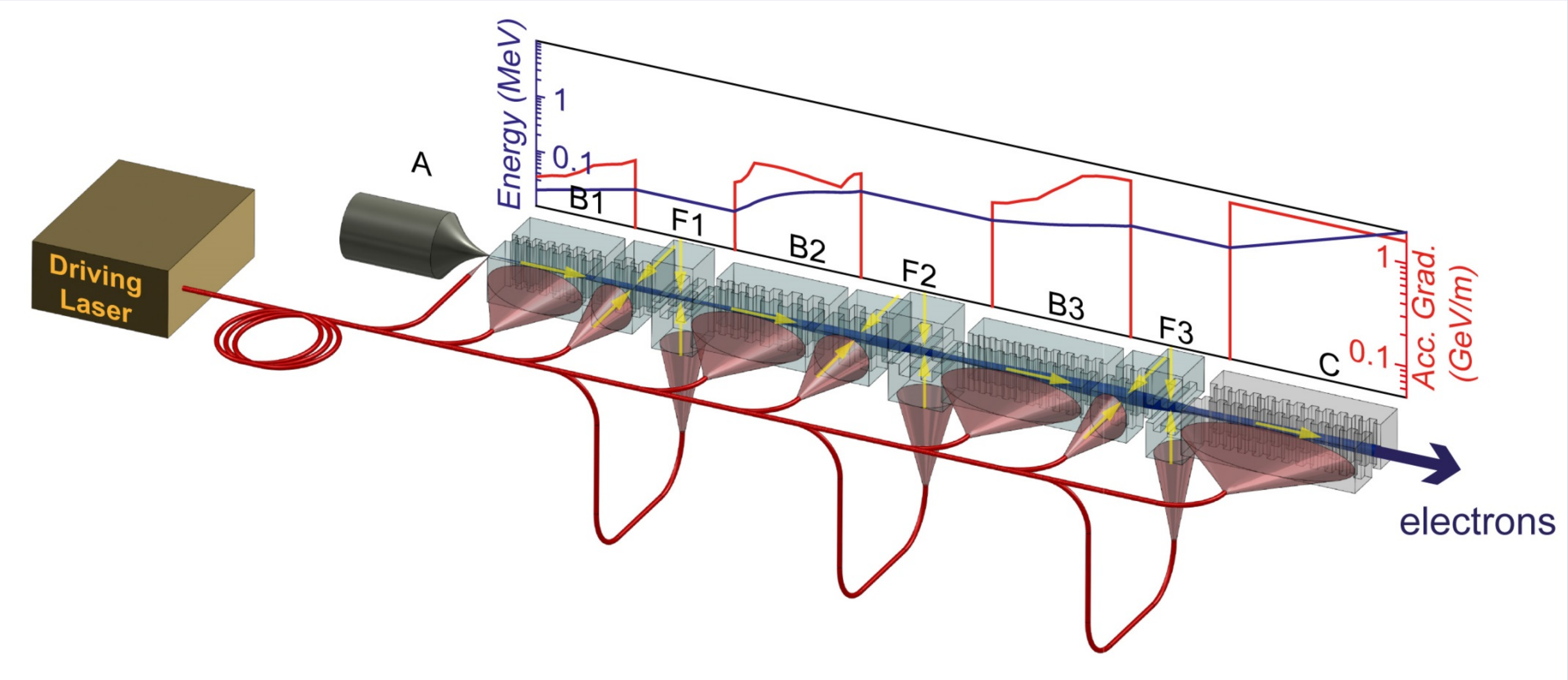
Scalable technology: concatenate structures



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

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Relation to plasma-based schemes

Grating based dielectric scheme:

- extremely low bunch charge
- high rep. rate
- excellent beam needed
- scalability easy
- all-optical beam control
- gradients of 10 GeV/m
- new devices for classical accelerators?

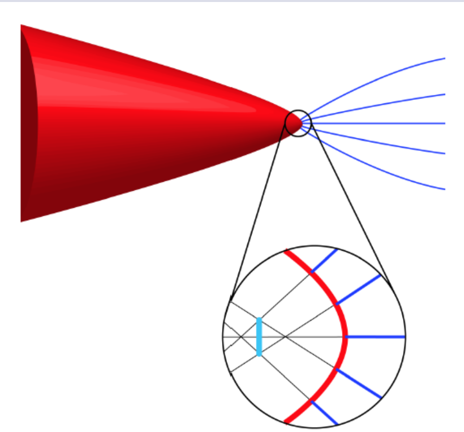
Plasma scheme:

- large bunch charge ok
- low rep. rates
- beam parameters
- scalability?
- classical beam control
- gradients of TeV/m

⇨ Complementary in nature

Extremely low emittance sources: tip (arrays)

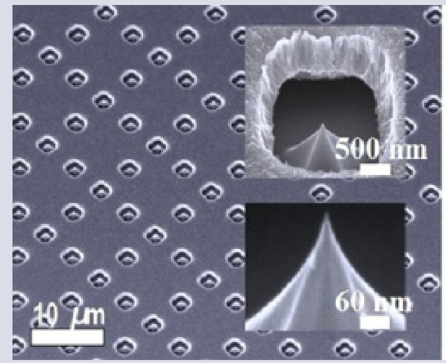
With 20pC, 5A from **regular RF and DC photocathodes**: norm. emitt. = 120nm. Ding et al. PRL 2009



- Virtual source size ~ a few nanometers
- Emittance ~ 0.1nm
- Optimized source design in

Hoffrogge et al., J. App. Phys. 115, 094506 (2014)

- Stanford group (Kasevich, PH)
- Göttingen group (Ropers)
- Nebraska group (Batelaan)
- PSI group (Tsujino)
- MIT /DESY group (Kaertner)
- …



Mustonen, …, Tsujino, APL 2011

Geometrical rms emittance of laser-triggered electrons from tip: 0.08 nm rad (at 44 eV)

Ehberger et al., arXiv:1412.4584 (to appear in PRL)

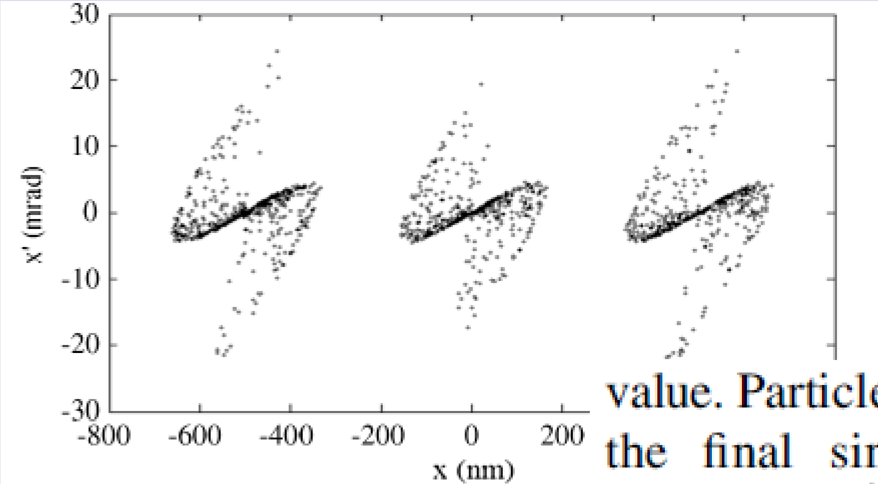
PRL **96,** 077401 (2006) PHYSICAL REVIEW LETTERS week ending 24 FEBRUARY 2006

Field Emission Tip as a Nanometer Source of Free Electron Femtosecond Pulses

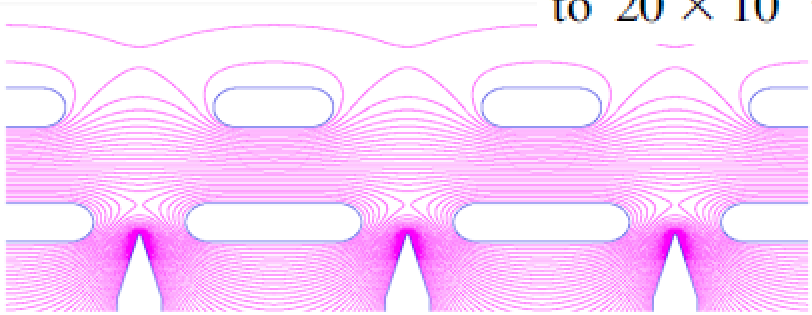
Peter Hommelhoff,* Yvan Sortais, Anoush Aghajani-Talesh, and Mark A. Kasevich
Physics Department, Stanford University, Stanford, California 94305, USA
(Received 25 July 2005; published 21 February 2006)

Emittance exchange from a tip array: generate micro-bunched beam

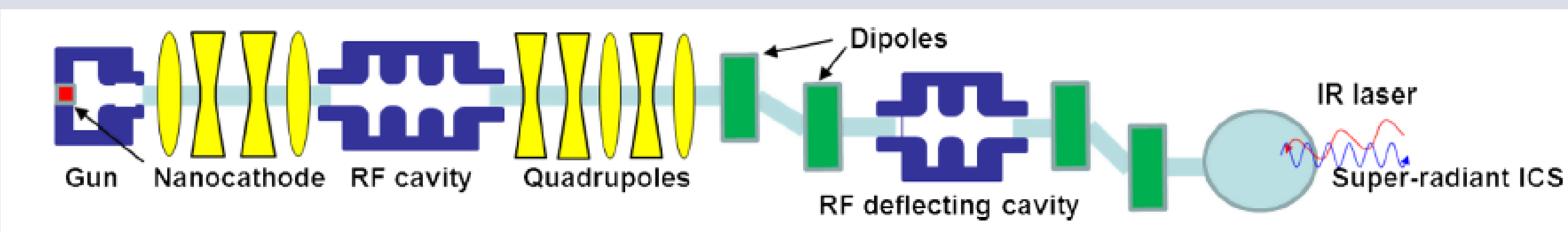
Graves, Kärtner, Moncton, Piot, PRL 2012



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



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



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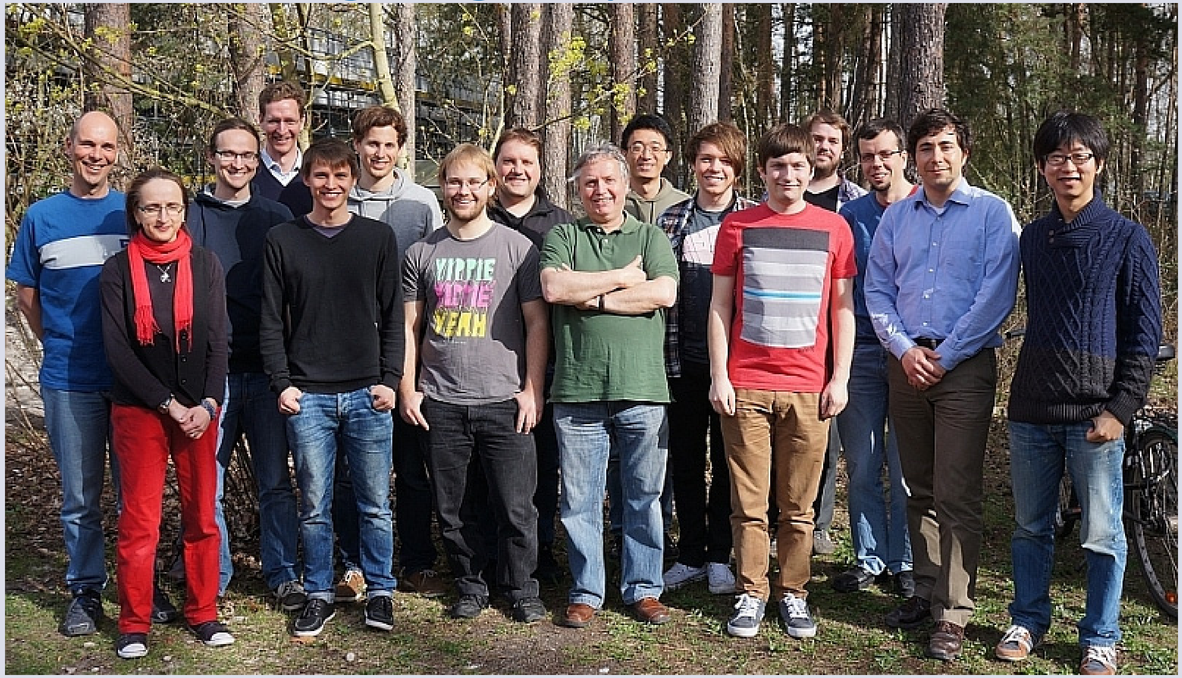
⇨ **Norbert Schönenberger**
Philipp Weber
Peyman Yousefi

⇨ DLA group



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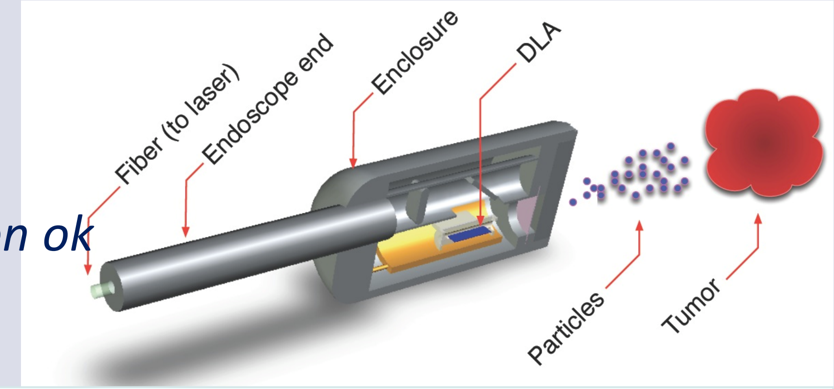
Summary and outlook

Laser acceleration of electrons at a dielectric photonic structure

- Works! Observed max. gradient of
  - > 25 MeV/m (at $\beta = 0.3$) (Breuer, Hommelhoff, PRL 2013)
  - > 250 MeV/m (at $\beta = 0.998$) (Peralta et al., Nature 2013)
  - > 200 MeV/m (at $\beta = 0.52$) (Leedle et al., Optica 2015)
- At relativistic energies: GeV/m expected
- Bunch length in the attosecond regime expected

First applications:
- Ultrafast streak camera
- Ultrafast beam diagnostics on nm – (sub-)fs scales!
- Acceleration / deflection structures

Take advantage of
- *Fast progress in (fiber) laser technology*
- *Extant nano-fabrication technology (silicon ok at wavelengths > 1.5μm!)*



R. J. England et al., "Dielectric laser accelerators", Rev. Mod. Phys. 86, 1337 (2014)

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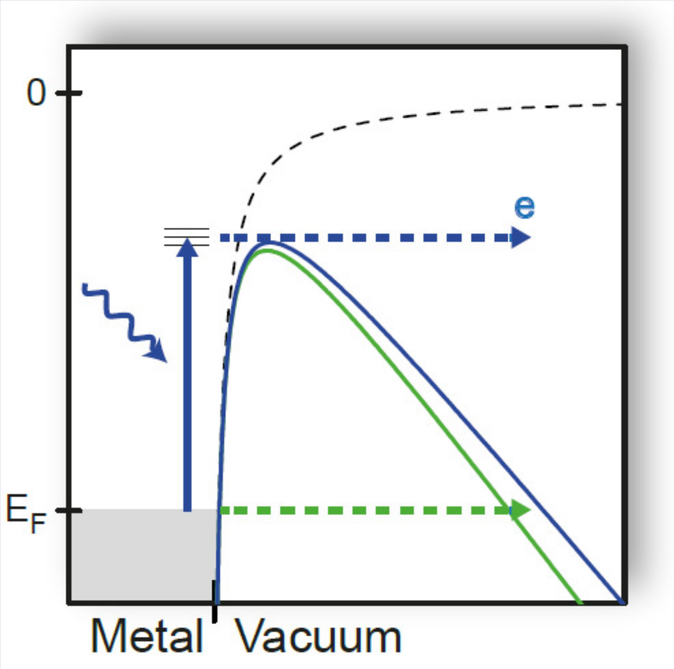
Dephasing length

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

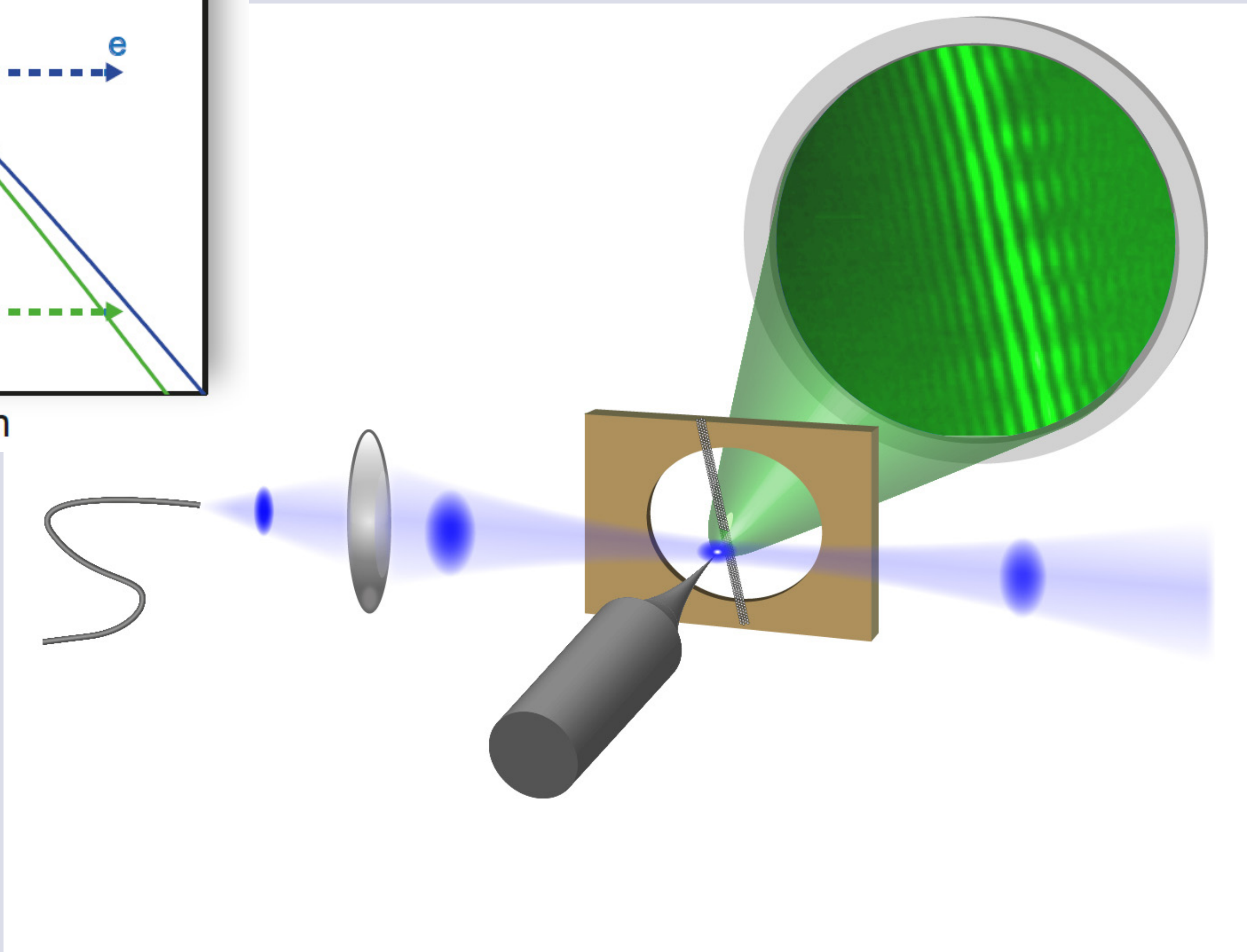
λ (μm)	$E_{\mathrm{kin}} = 29\,\mathrm{keV}$ (Fig. 6(d))		$E_{\mathrm{kin}} = 957\,\mathrm{keV}$ (Fig. 6(g))	
	1 GV/m	10 GV/m	1 GV/m	10 GV/m
0.8	12 μm	4 μm	149 μm	47 μm
2	19 μm	6 μm	236 μm	75 μm
5	31 μm	10 μm	373 μm	118 μm

⇨ Match grating structure: shift or taper grating wavelength after / within given dephasing length

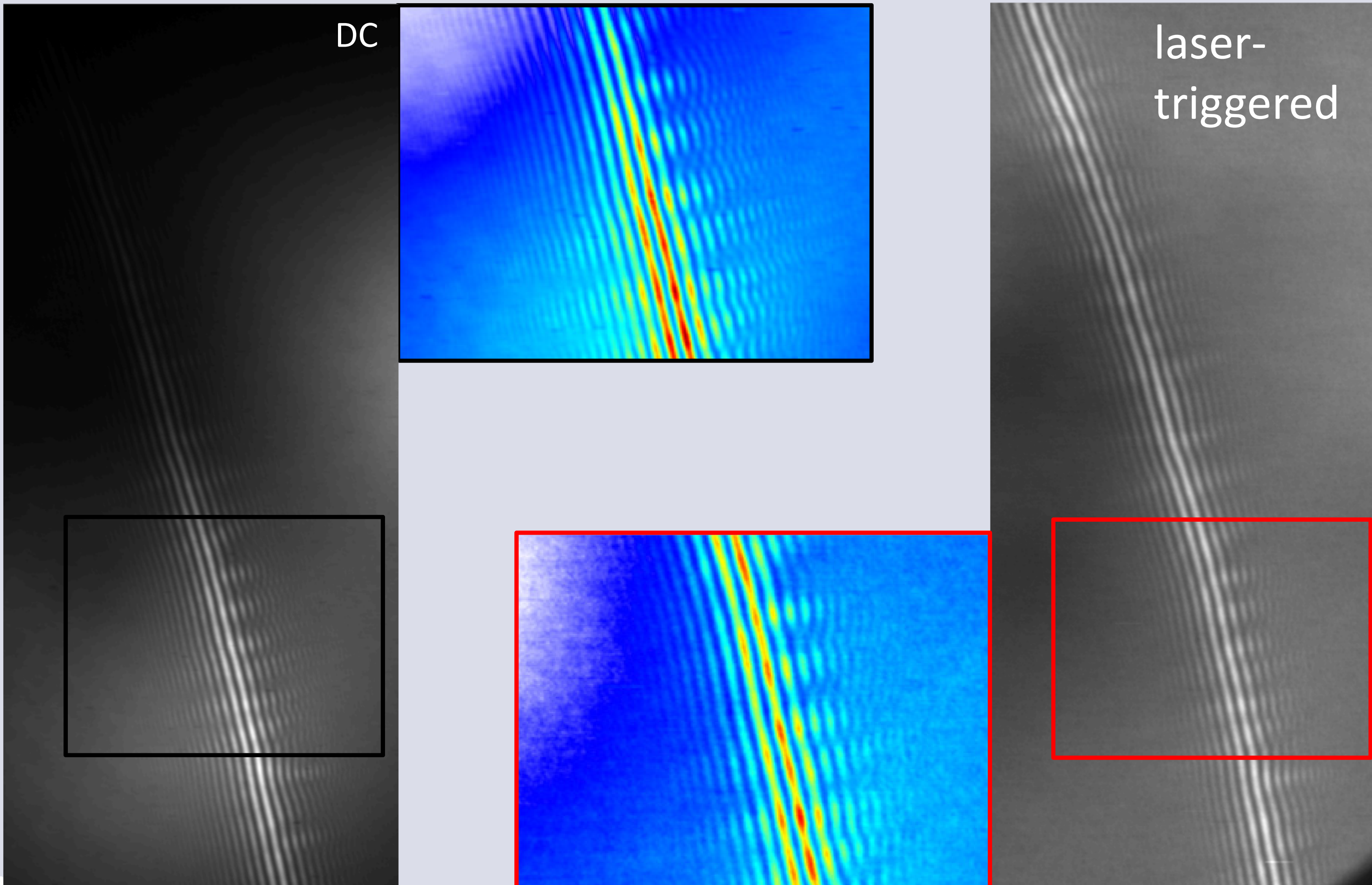
Are laser-triggered electrons coherent?



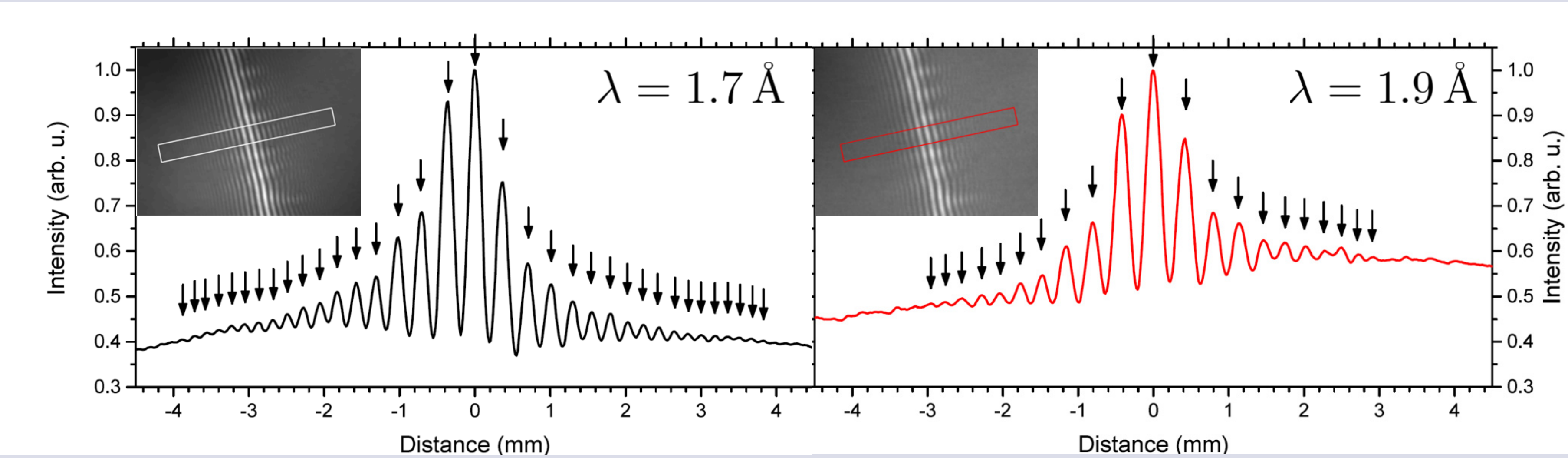
394nm and 405nm (~3.2eV photon energy)



Fringes: DC vs. photo-emitted



Line profiles in DC and laser-triggered emission



$$r_{\text{tip}} = 7 \pm 2\,\text{nm}$$

$$C = 0.43 \qquad C = 0.32$$

$$\xi_\perp \geq 7.7\,\text{mm} \qquad \xi_\perp \geq 5.8\,\text{mm}$$

$$r_{\text{eff}}^{\text{DC}} \leq 0.6\,\text{nm} \qquad r_{\text{eff}}^{\text{lt}} \leq 0.8\,\text{nm}$$

laser-triggered electron emisison with near-UV pulses almost as spatially coherent as DC-field emission

Ehberger, Hammer et al., manuscript submitted