

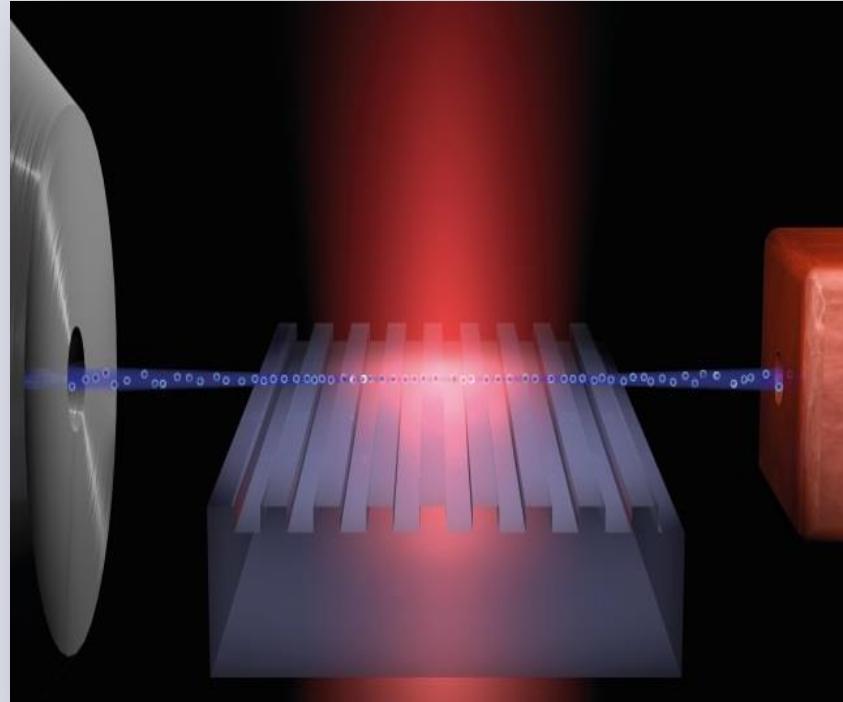
# Dielectric laser acceleration

*Peter Hommelhoff*

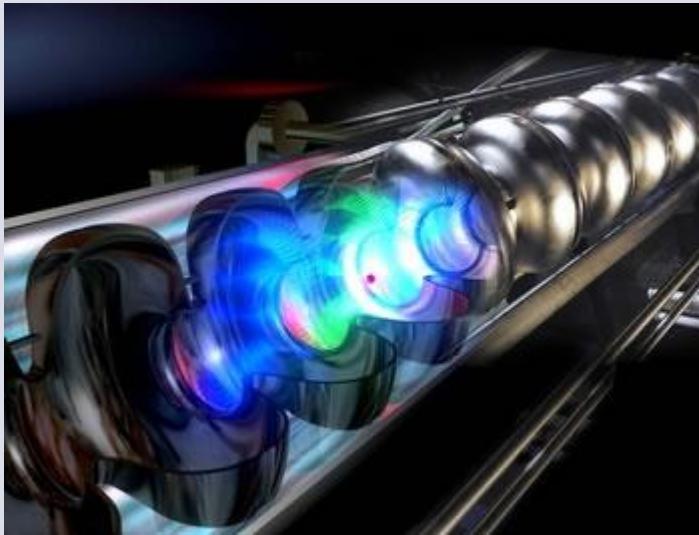
**Friedrich-Alexander-Universität Erlangen-Nürnberg, Erlangen**

*Max Planck Institute for Quantum Optics, Garching / Munich, Germany*

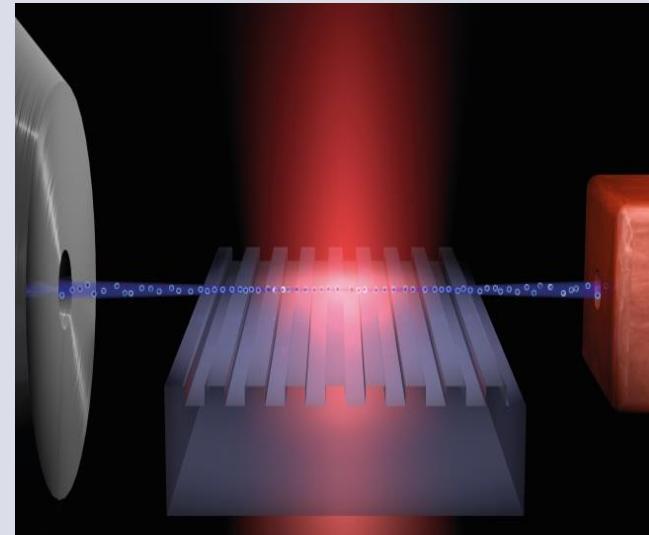
*Max Planck Institute for the Science of Light, Erlangen, Germany*



# Particle accelerators: from RF to optical/photonic drive?

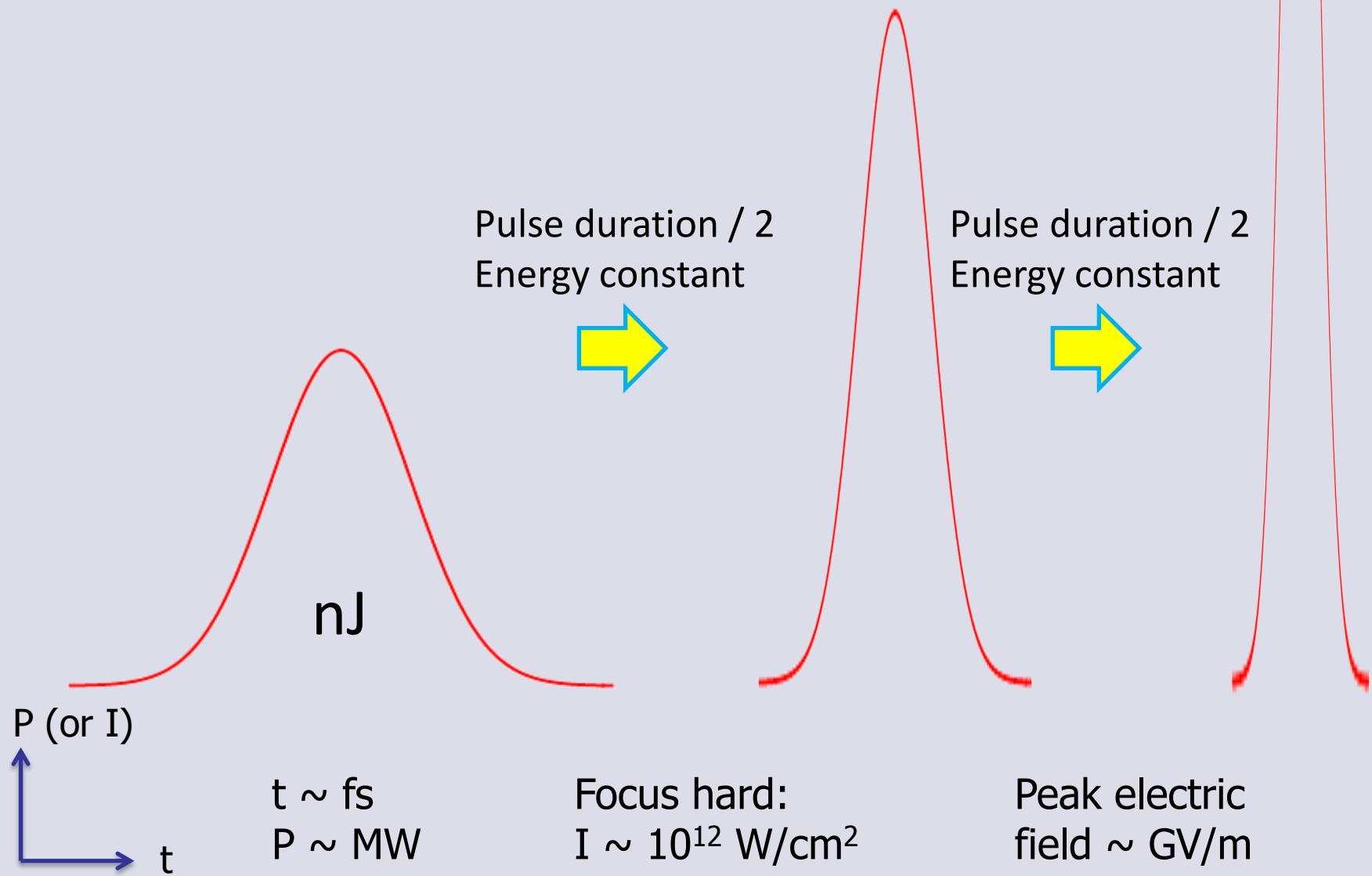


RF cavity (TESLA, DESY)

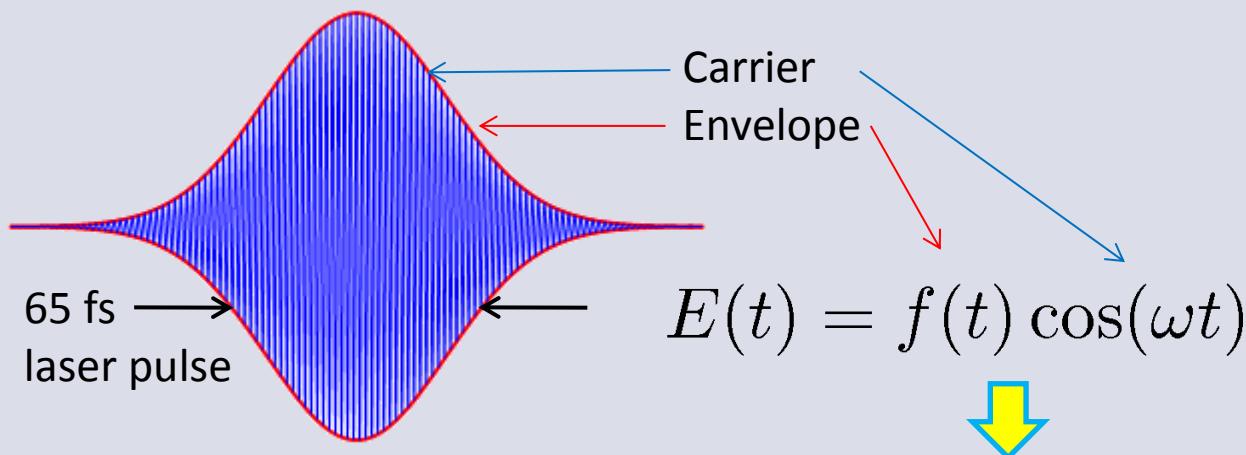


	Conventional linear accelerator (RF)	Laser-based dielectric accelerator (optical)
Based on	(Supercond.) RF cavities	Quartz grating structures
Peak field limited by	<b>Surface breakdown: 200 MV/m</b>	<b>Damage threshold: 30,000 MV/m</b>
Max. achievable gradients	<b>50 MeV/m</b>	<b>10,000 MeV/m</b>

# From pulsed energy to large field strengths



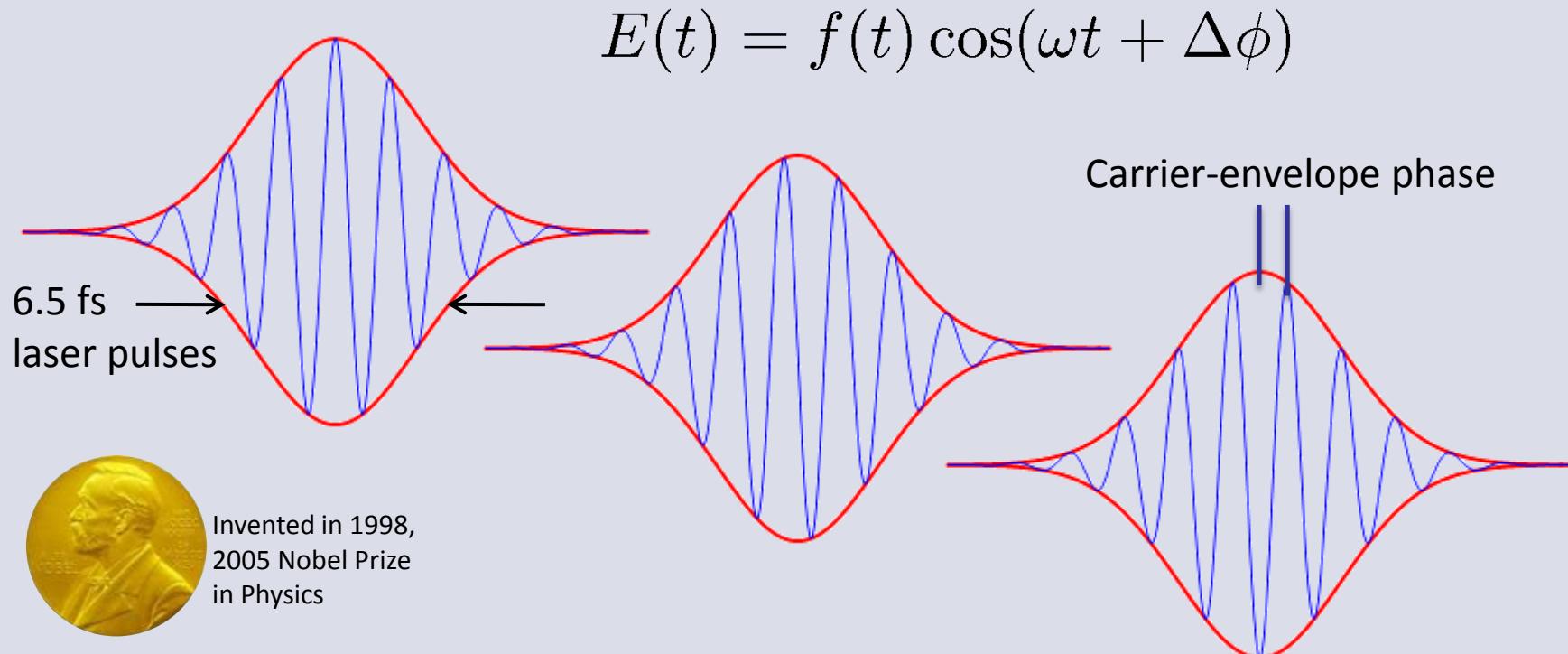
# Femtosecond and few-cycle laser pulses

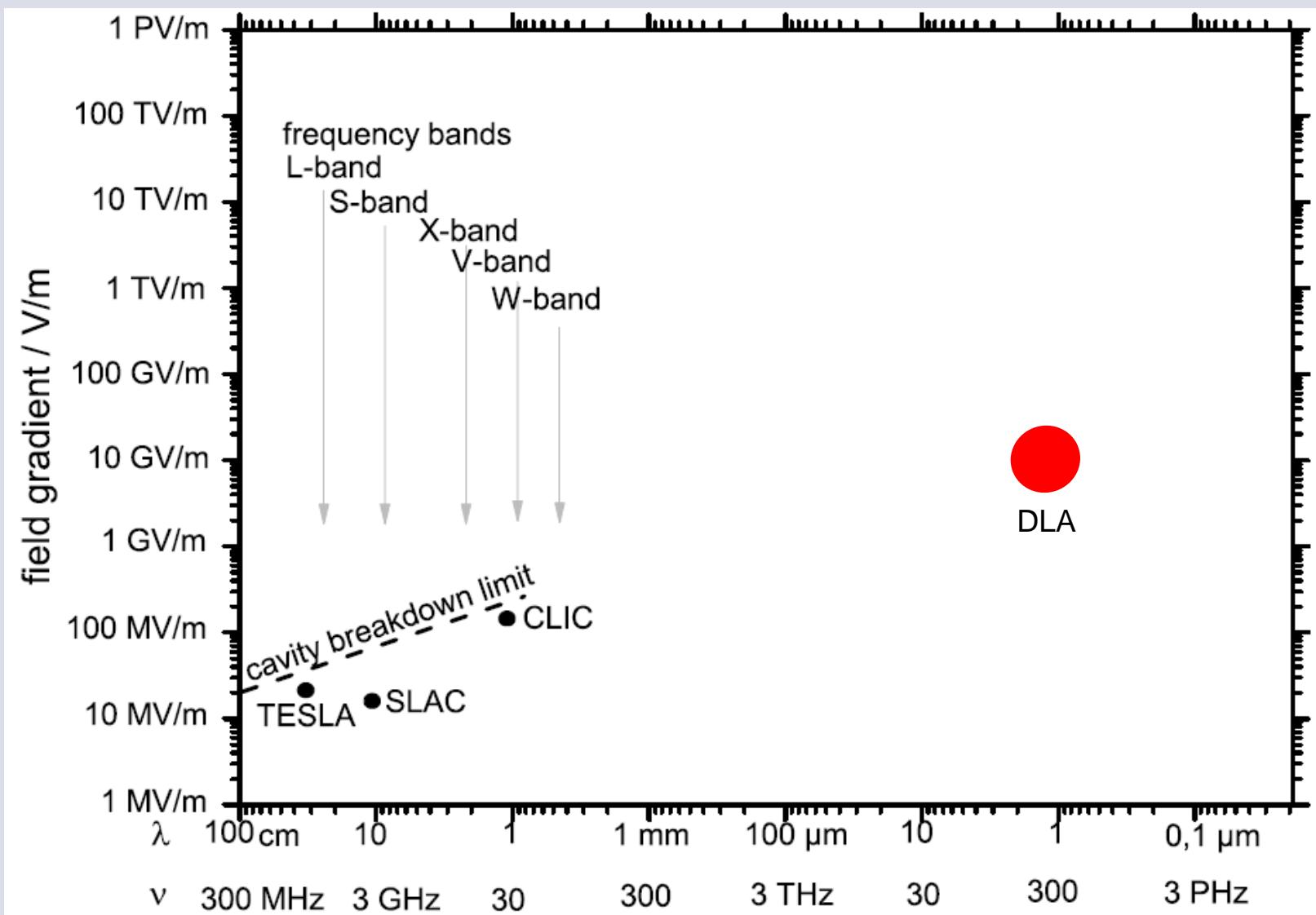


- Energy
- Duration
- Repetition rate
- Carrier-envelope phase: control over optical electric field

Near infrared light:

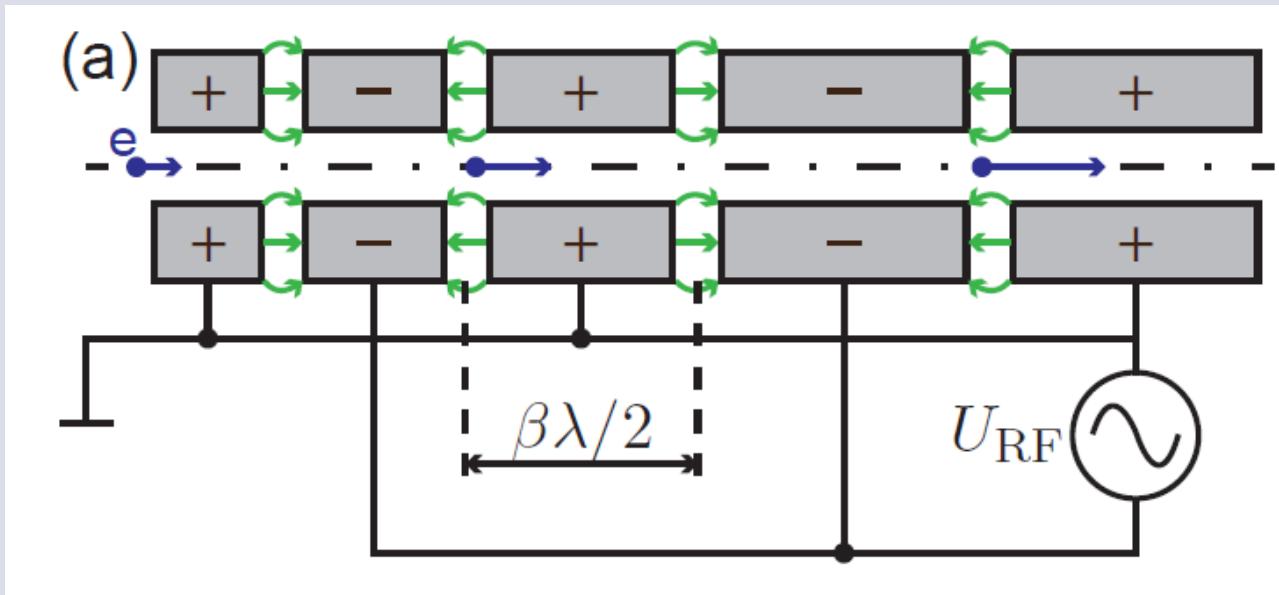
- |           |          |
|-----------|----------|
| • 800nm   | • 2.7 fs |
| • 375 THz | • 1.5 eV |





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

# Widerøe linac

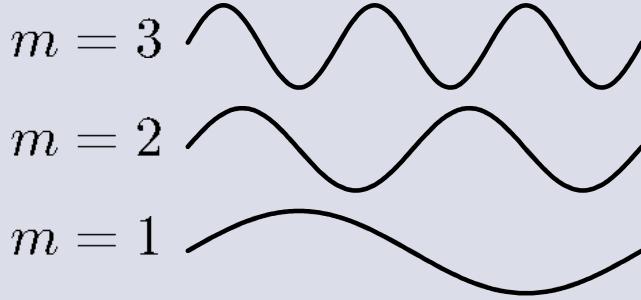
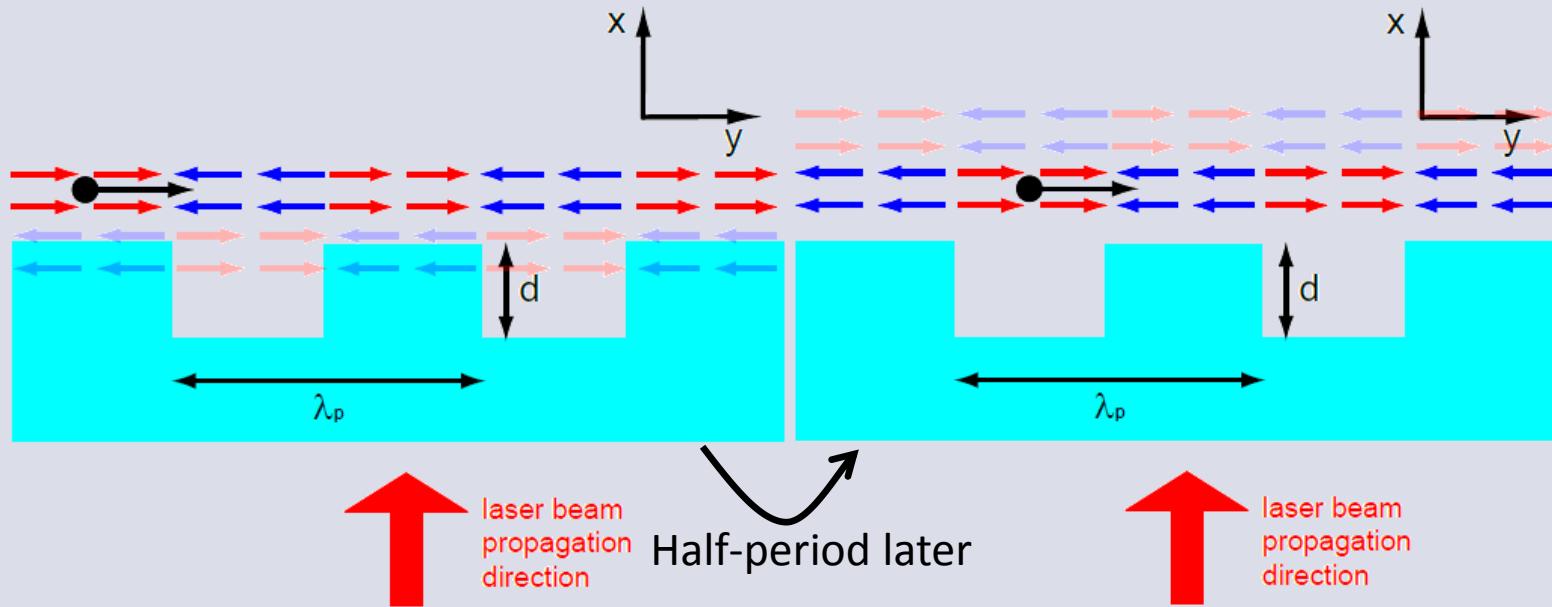


taken from J. Breuer's thesis

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

Wideroe, 1928  
Ising, 1924

# Periodic field reversal and spatial harmonics



**Synchronicity condition:**

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

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

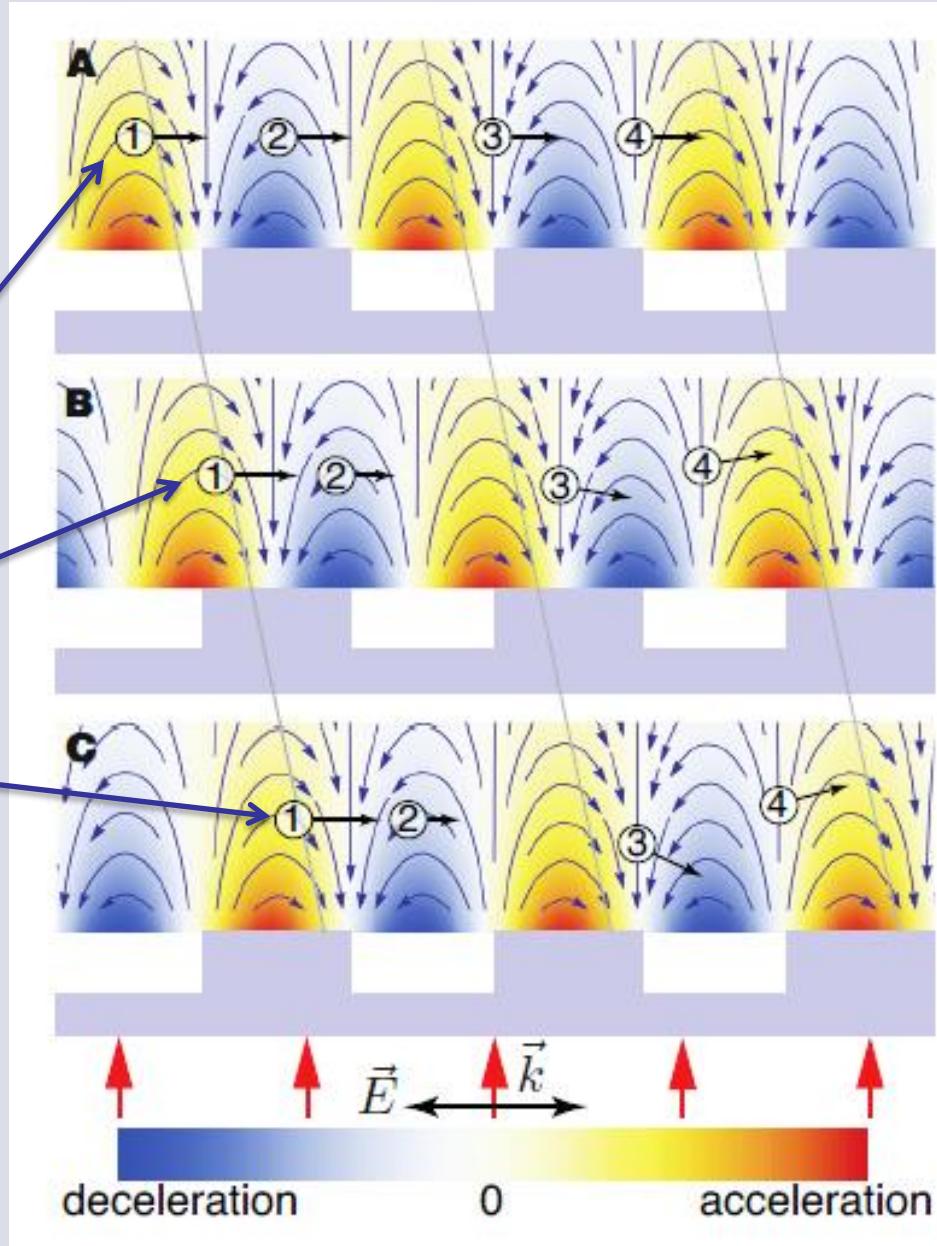
$$\lambda = 787 \text{ nm}, \beta \sim 1/3 \quad (\text{for } 28 \text{ keV electrons}):$$

$$\lambda_p = 250 \text{ nm}, 500 \text{ nm}, 750 \text{ nm}, 1000 \text{ nm}, \dots$$

We use the third spatial harmonic.

# Acceleration by phase-synchronous propagation

- 1 acceleration
- 2 deceleration
- 3 deflection
- 4 deflection



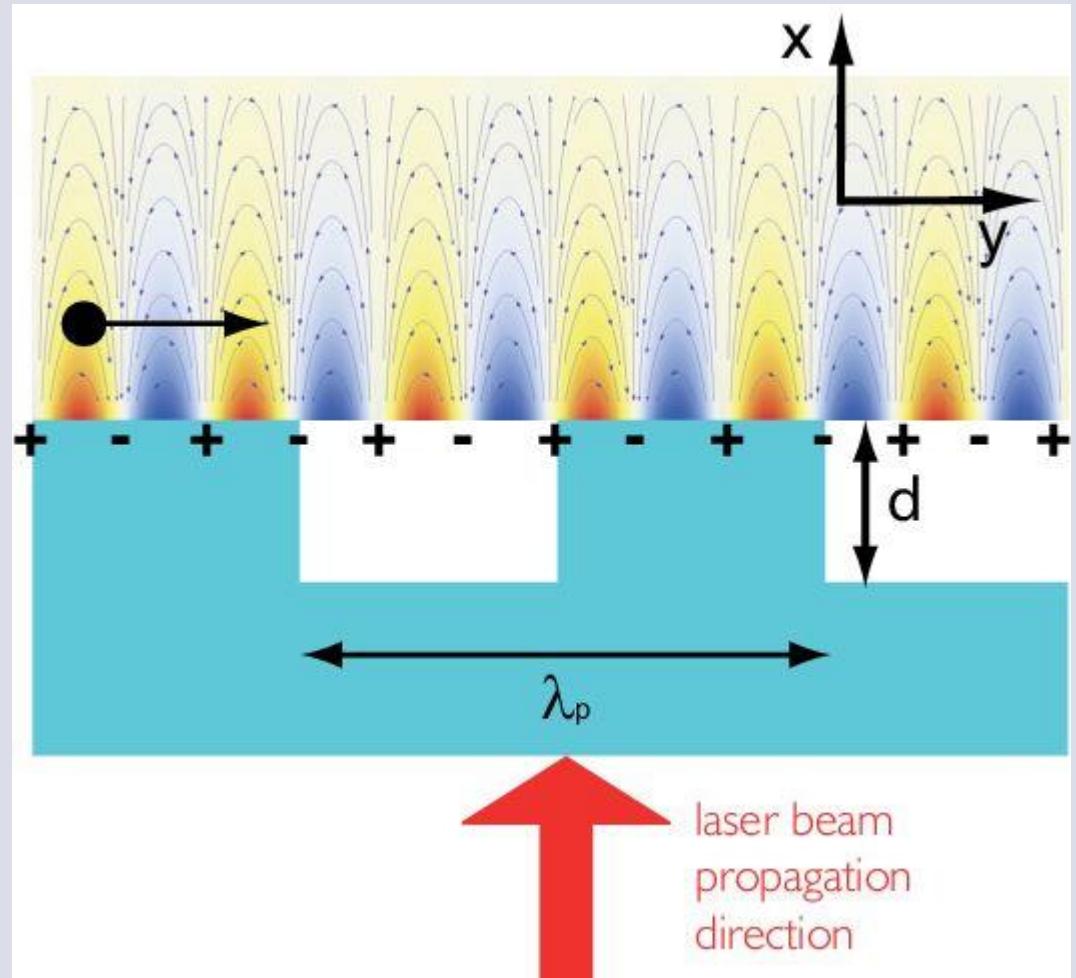
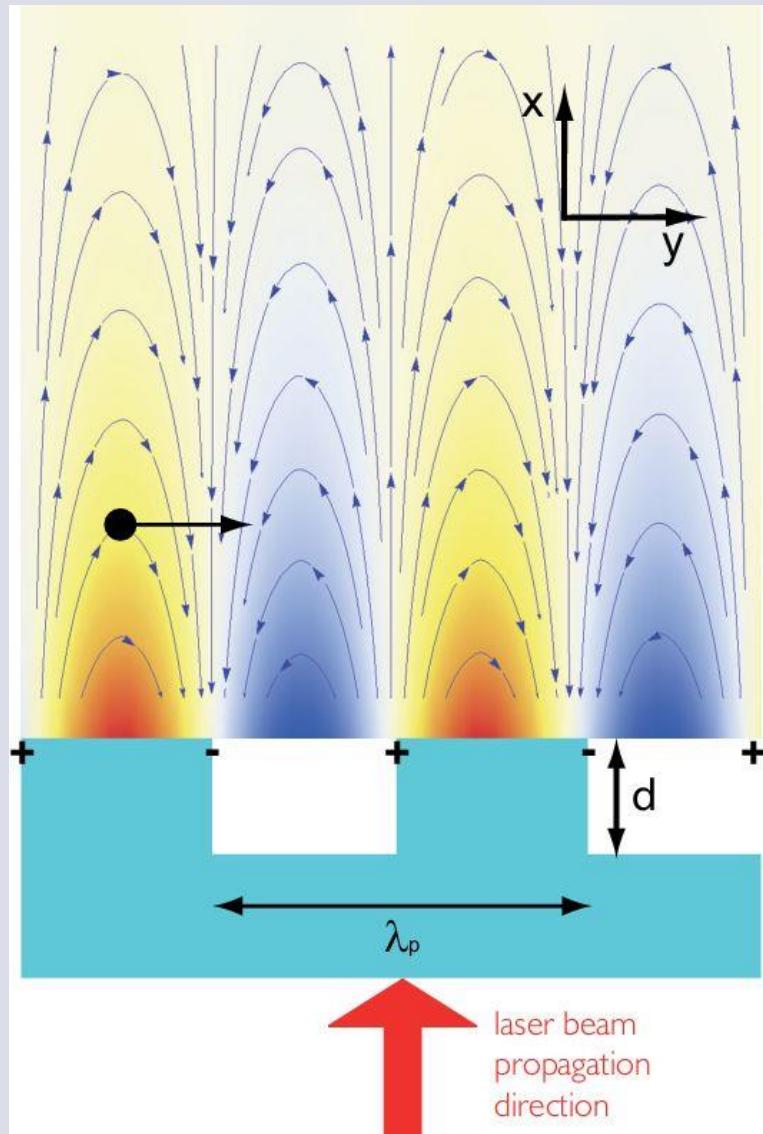
$t = 0$

$t = \pi/2$

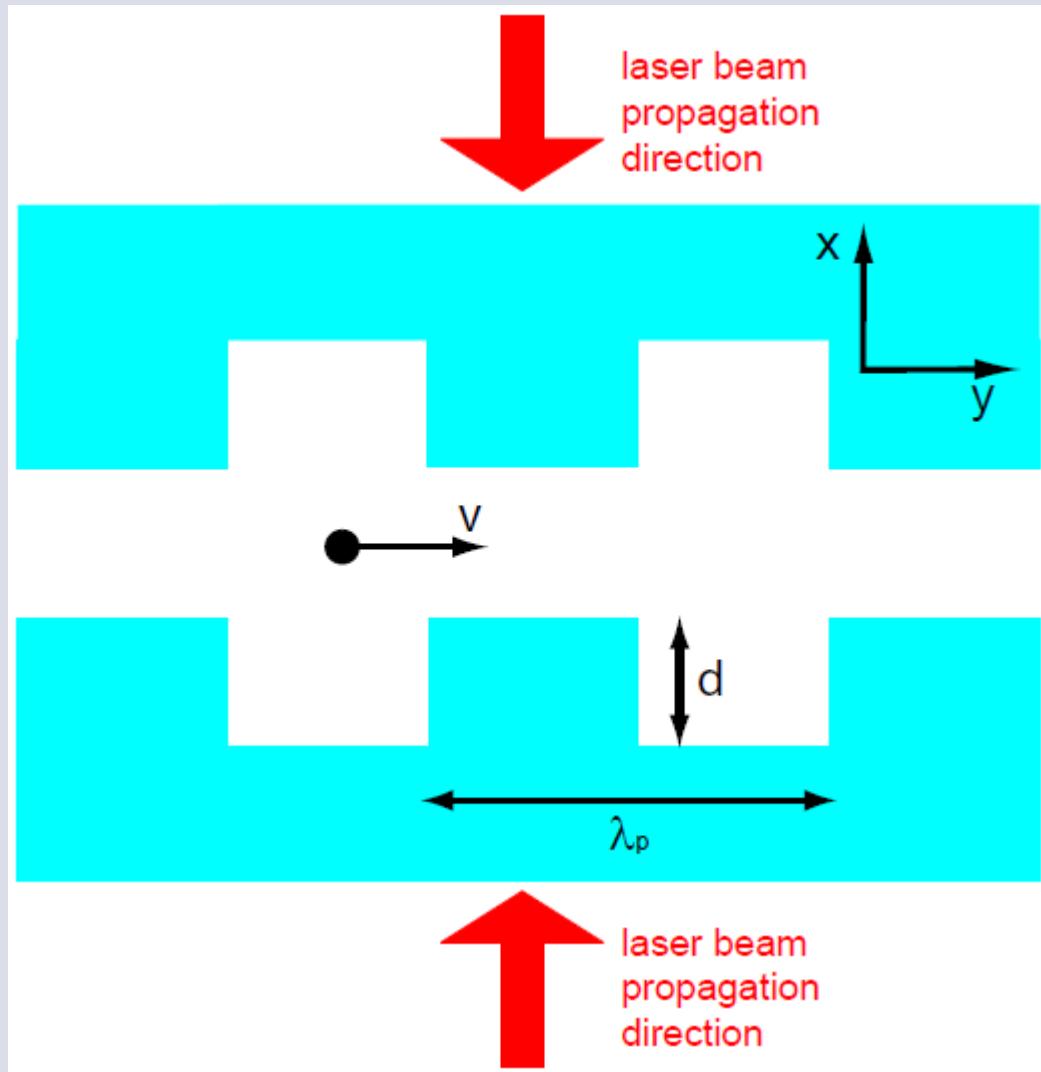
$t = \pi$

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

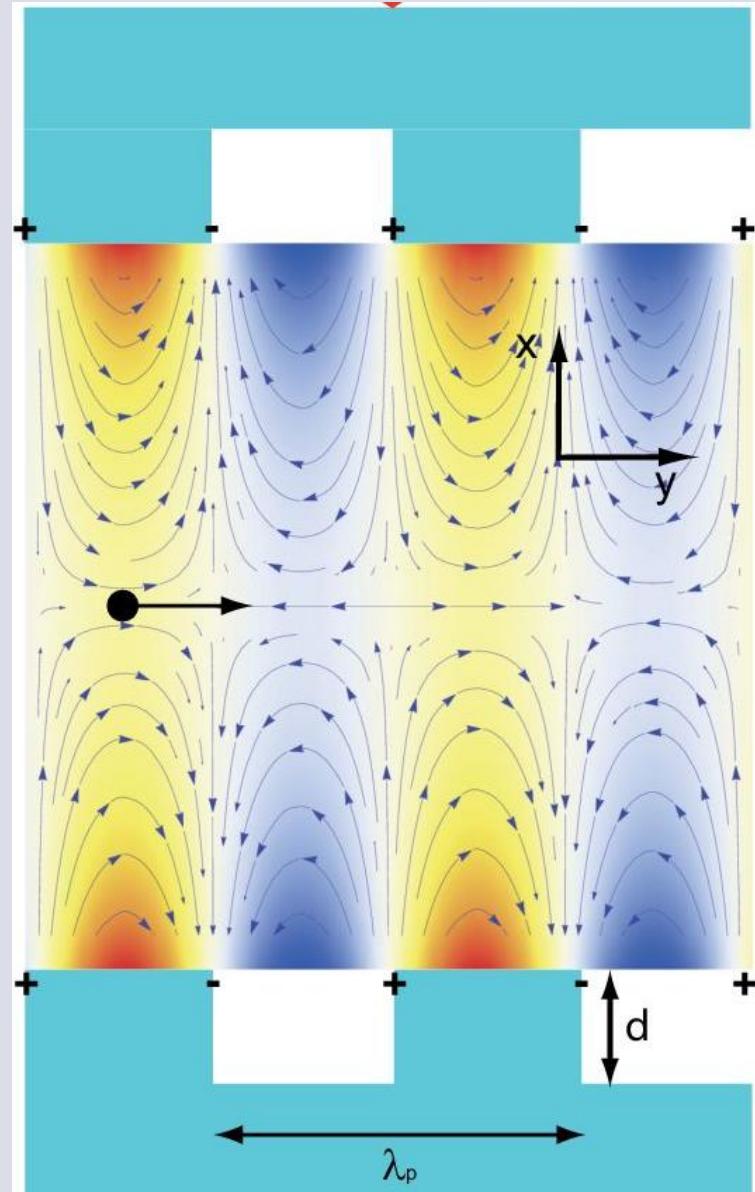
# Transverse gradient drop



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



More later!



# An old idea

## Proposal for an Electron Accelerator Using an Optical Maser

Koichi Shimoda

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

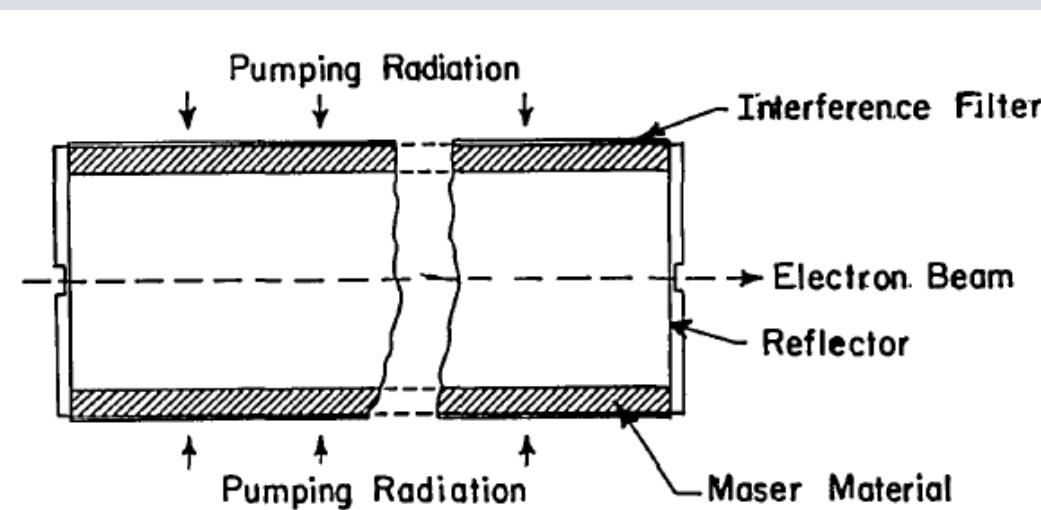


Fig. 1. Schematic diagram of an electron linear accelerator by optical maser.

# 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

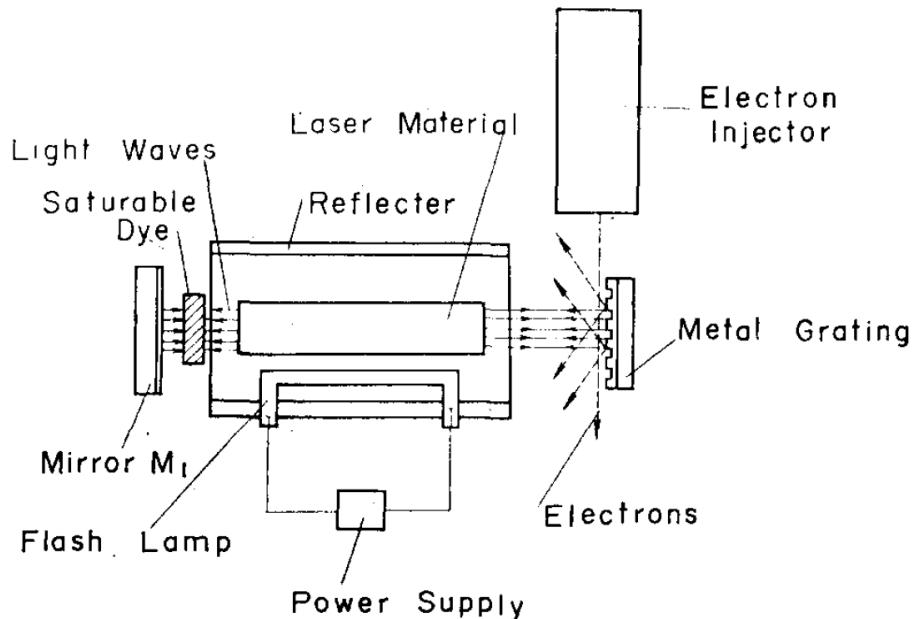


Fig. 1. Schematic diagram of "laser linac with grating".

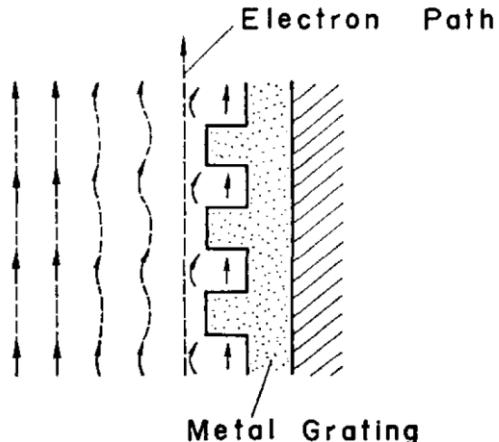


Fig. 2. Configuration of electric-field near grating surface.

# 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)

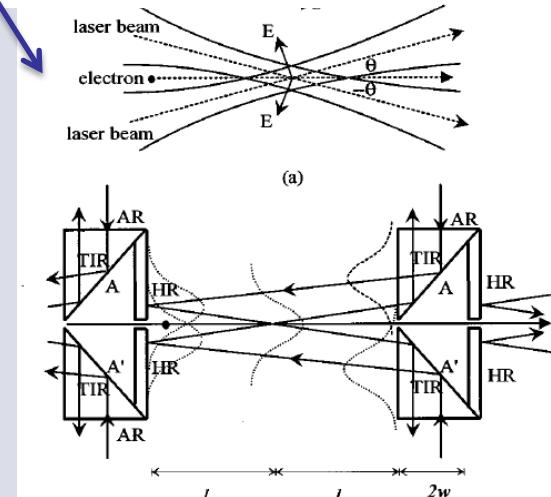
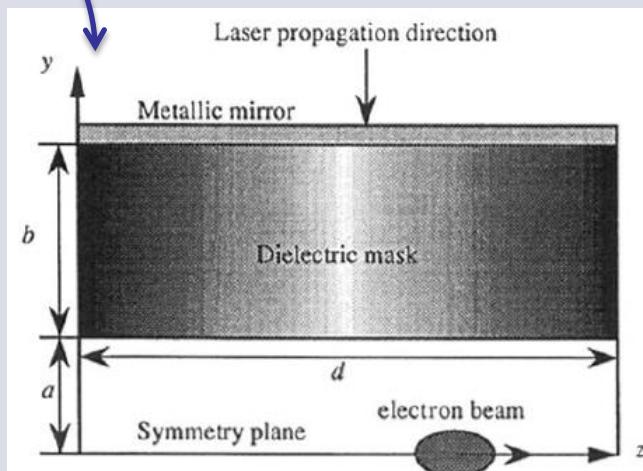
## Proposed structure for a crossed-laser beam, GeV per meter gradient, vacuum electron linear accelerator

Y. C. Huang, D. Zheng, W. M. Tulloch, and R. L. Byer

Edward Ginzton Laboratory, Stanford University, Stanford, California 94305-4085

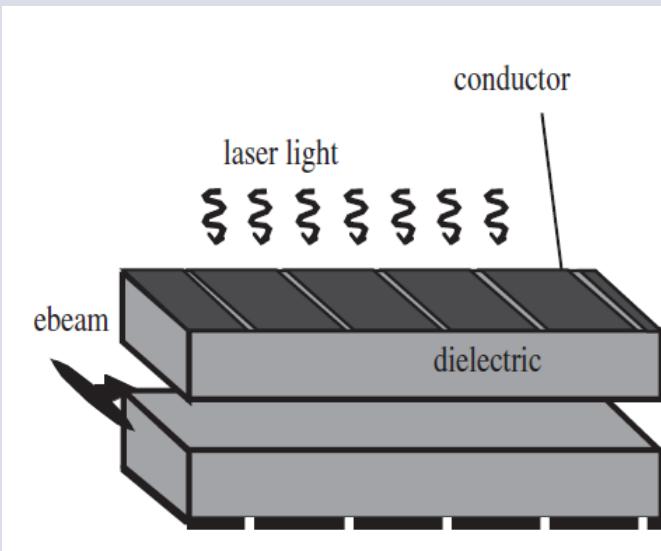
(Received 6 October 1995; accepted for publication 4 December 1995)

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

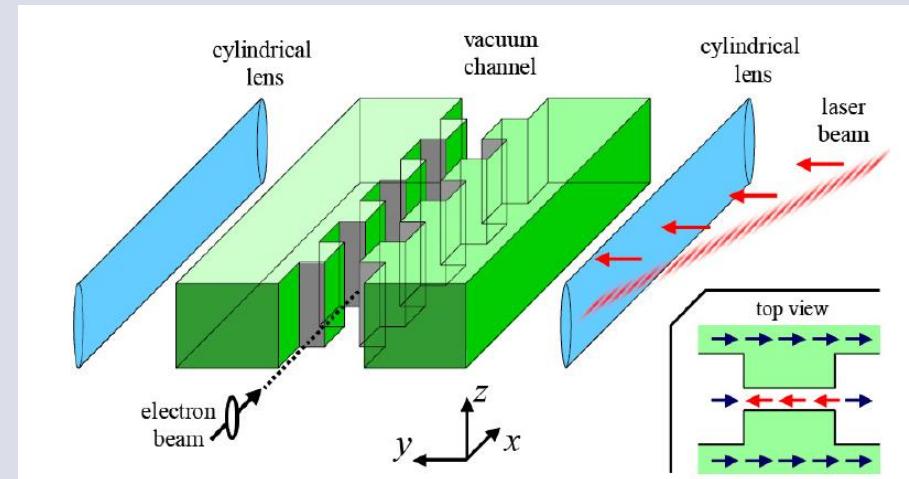


Other longtime players: Sieman group (SLAC), Travish (UCLA), Yoder (Manhattan) ...

# Proposed dielectric structures

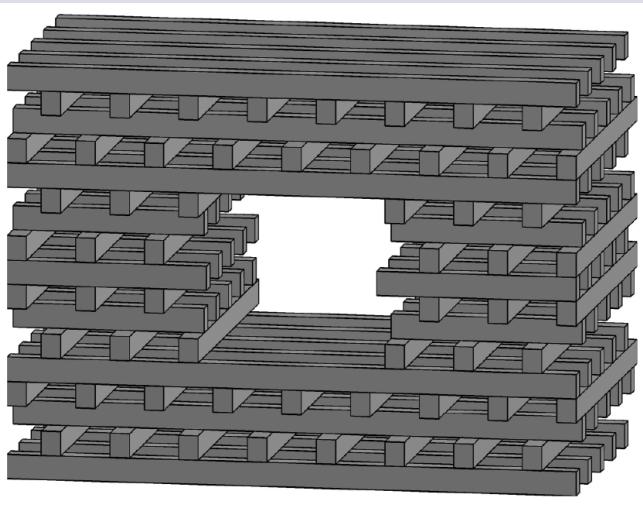


Yoder, Rosenzweig, 2005



Plettner, Lu, Byer, 2006

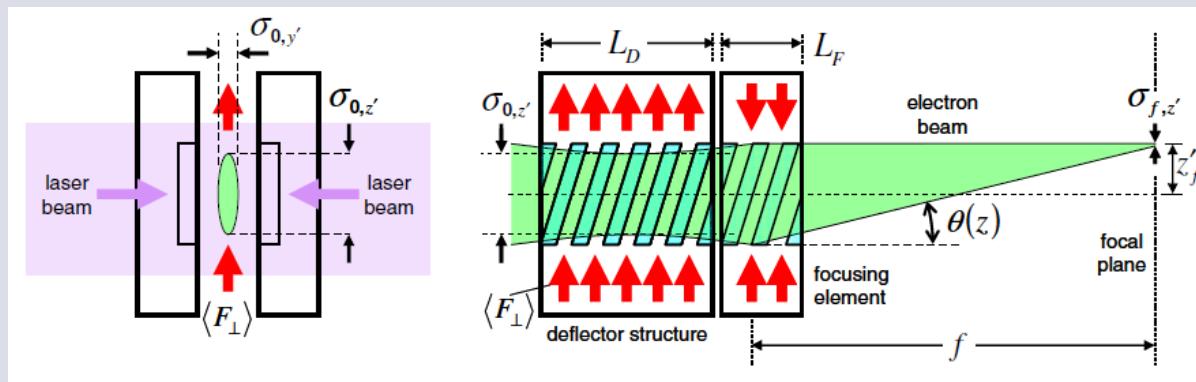
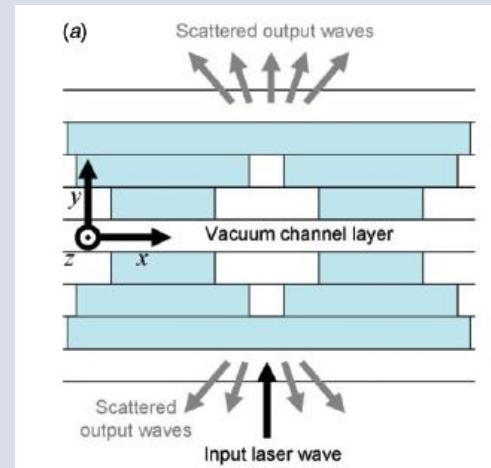
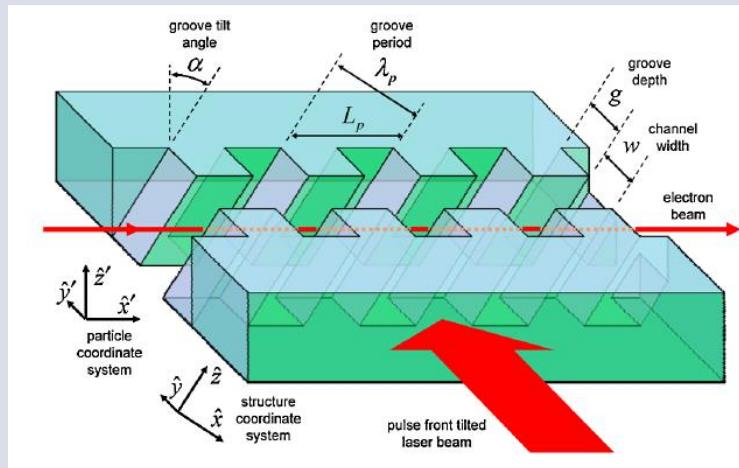
... and variants



Cowan, 2008

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

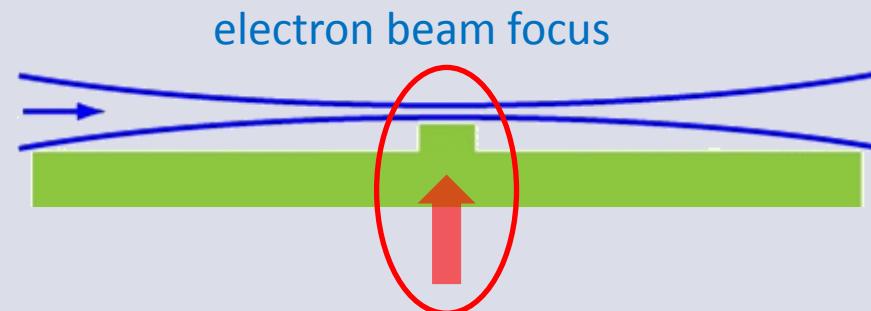
# Grating-based DLA structure proposals: Plettner & Byer



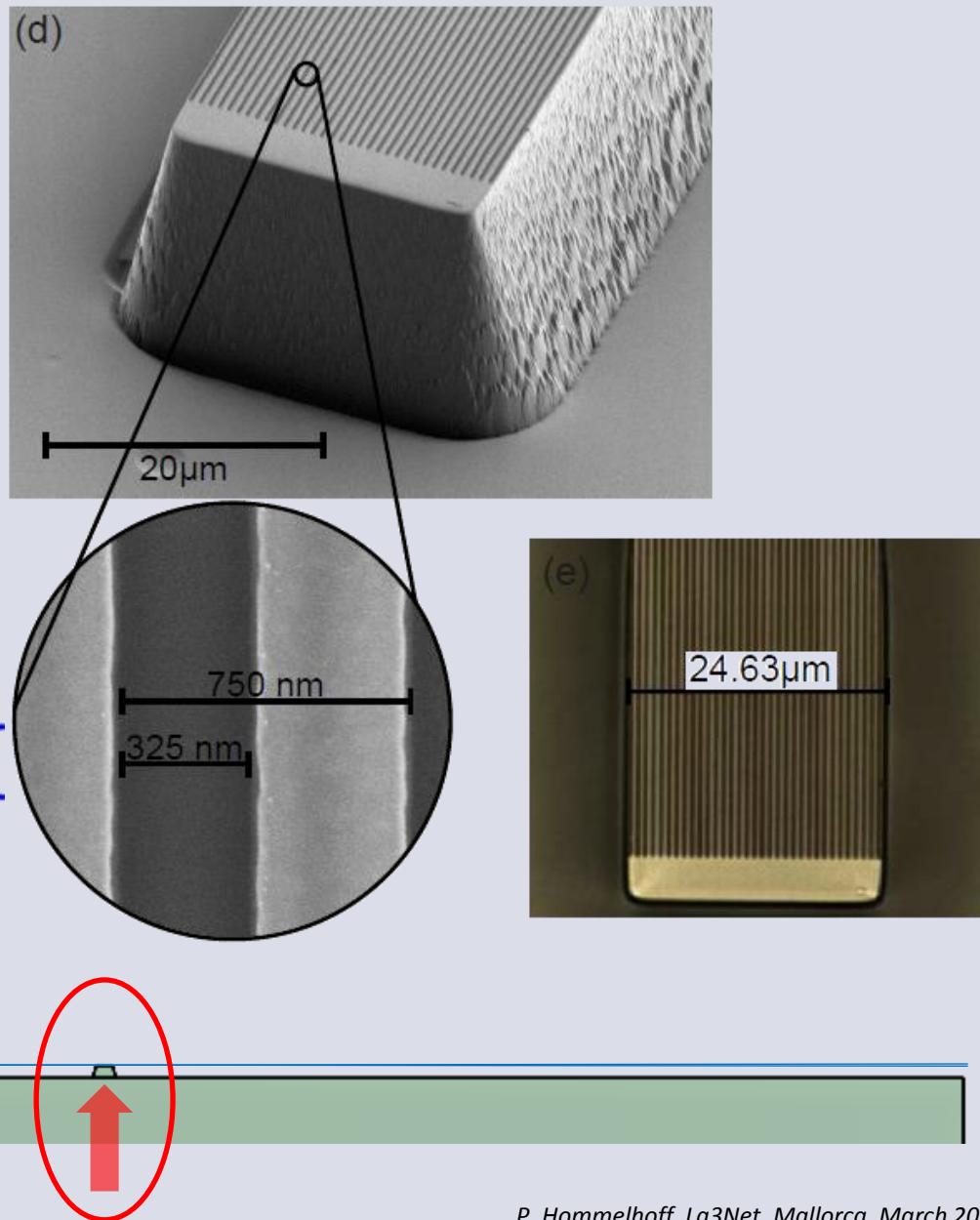
- DLA structure: Plettner, Lu, Byer, PRSTAB 2006
- FEL: Plettner, Byer, Nucl. Instr. Meth. A 2008
- Undulator: Plettner, Byer, PRSTAB 2008
- Deflection & focusing: Plettner, Byer, McGuinness, Hommelhoff, PRSTAB 2009
- Layered gratings: Plettner, Byer, Montazeri, J. Mod. Opt. 2011

# Grating structure

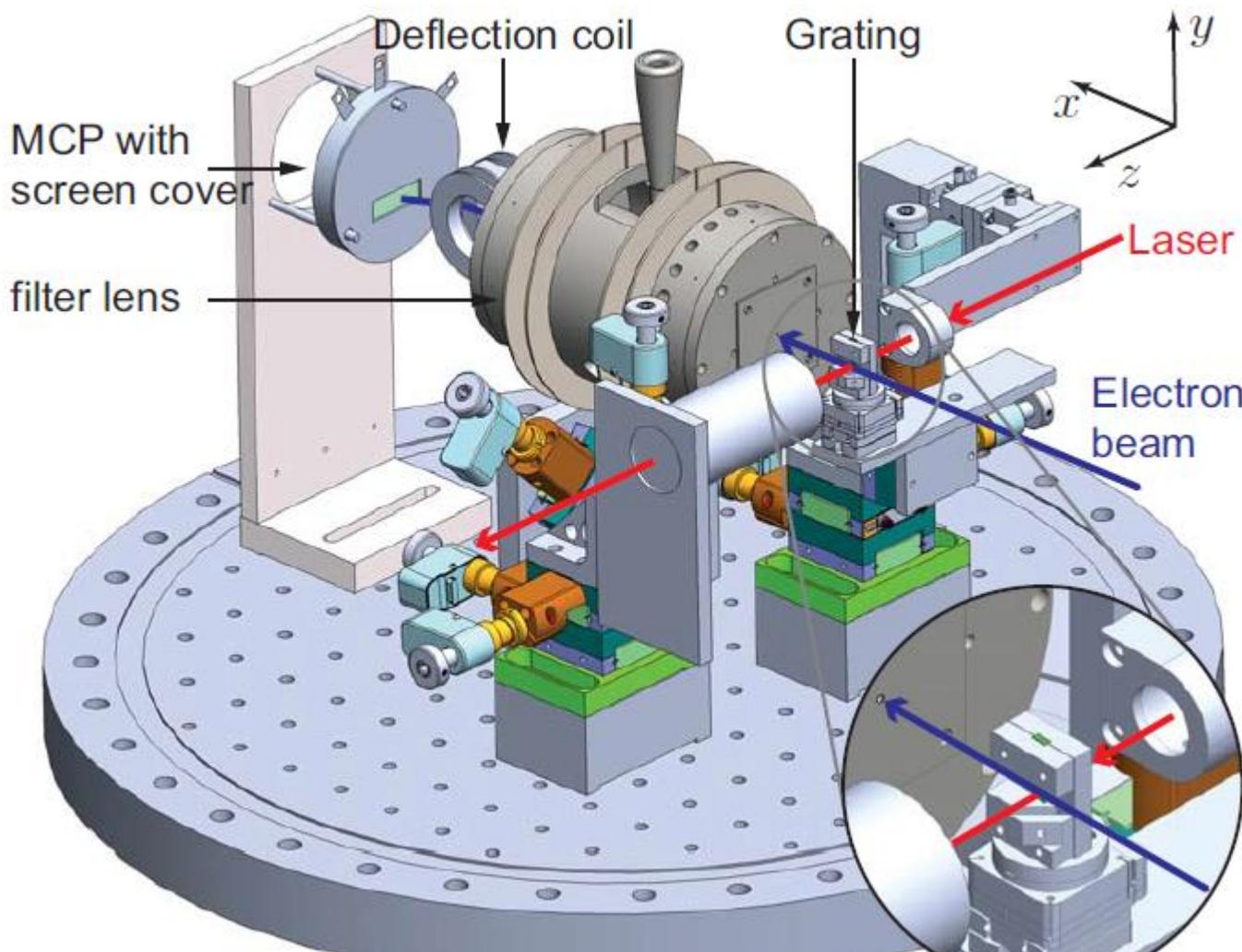
- Grating period: 750nm
- Grating depth: 282nm
- **Challenge:** get close enough (<200nm) to the grating surface without clipping the beam  
→ put grating on 20 $\mu$ m high mesa structure



to-scale: 3mm length



# Sketch of setup



Laser parameters:

- 350 mW
- 2.745 MHz
- 110 fs

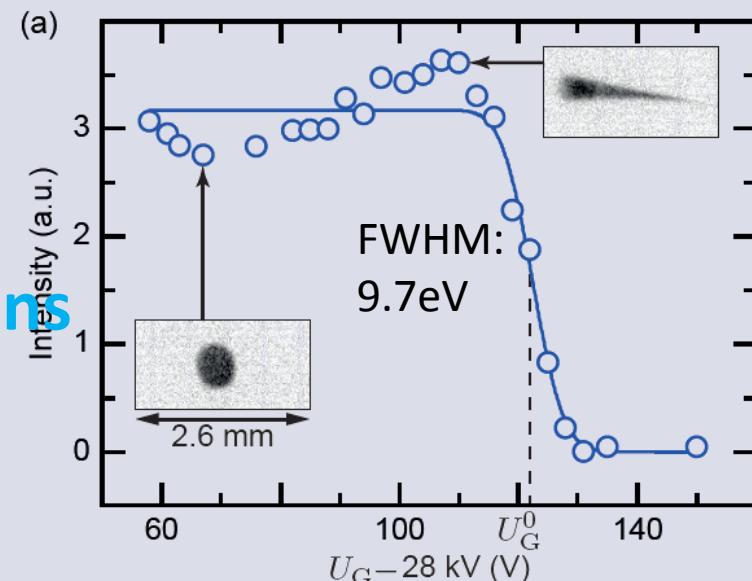
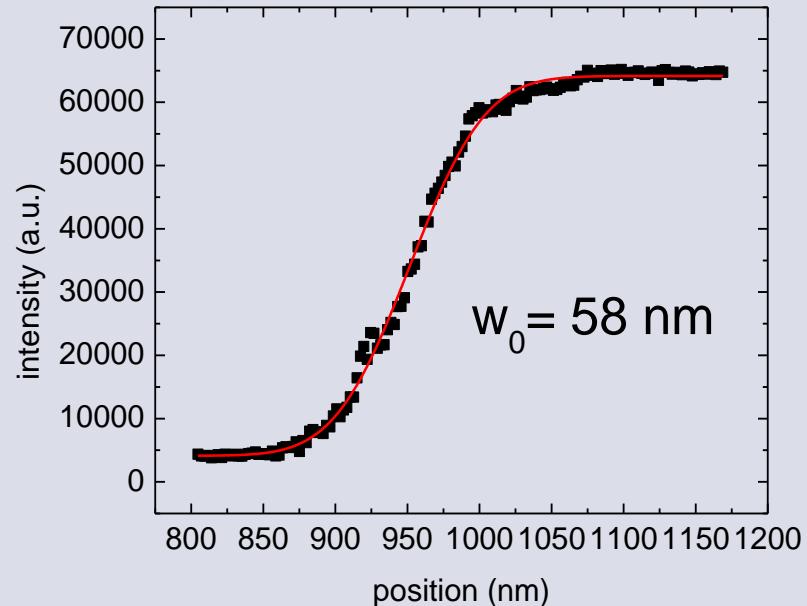
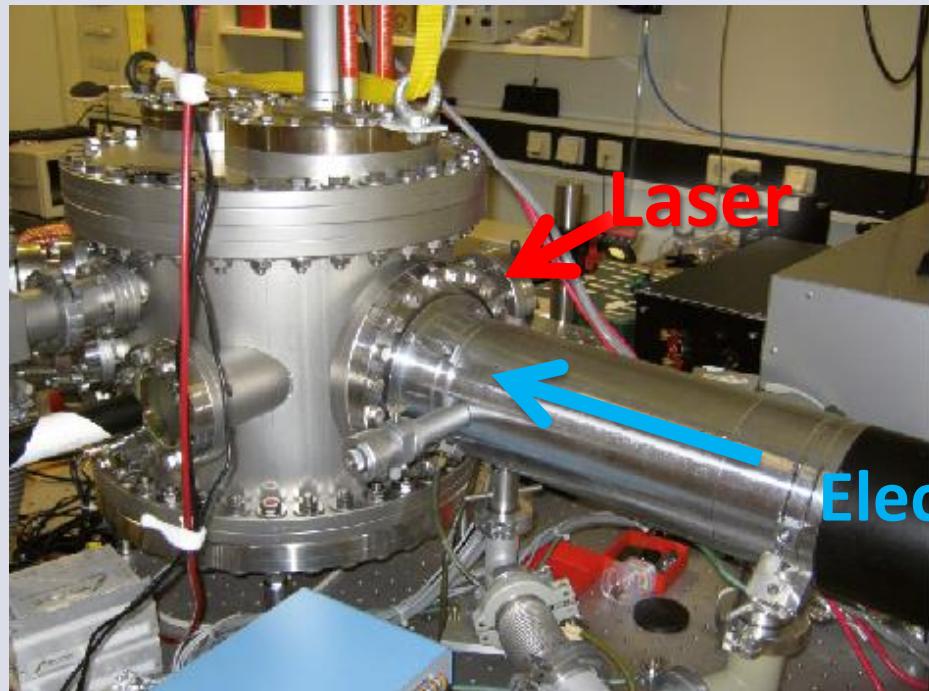
In the focus:

- $8.3 \mu\text{m}$  beam waist
- $2.76 \text{ GV/m}$
- $2.0 \cdot 10^{12} \text{ W/cm}^2$

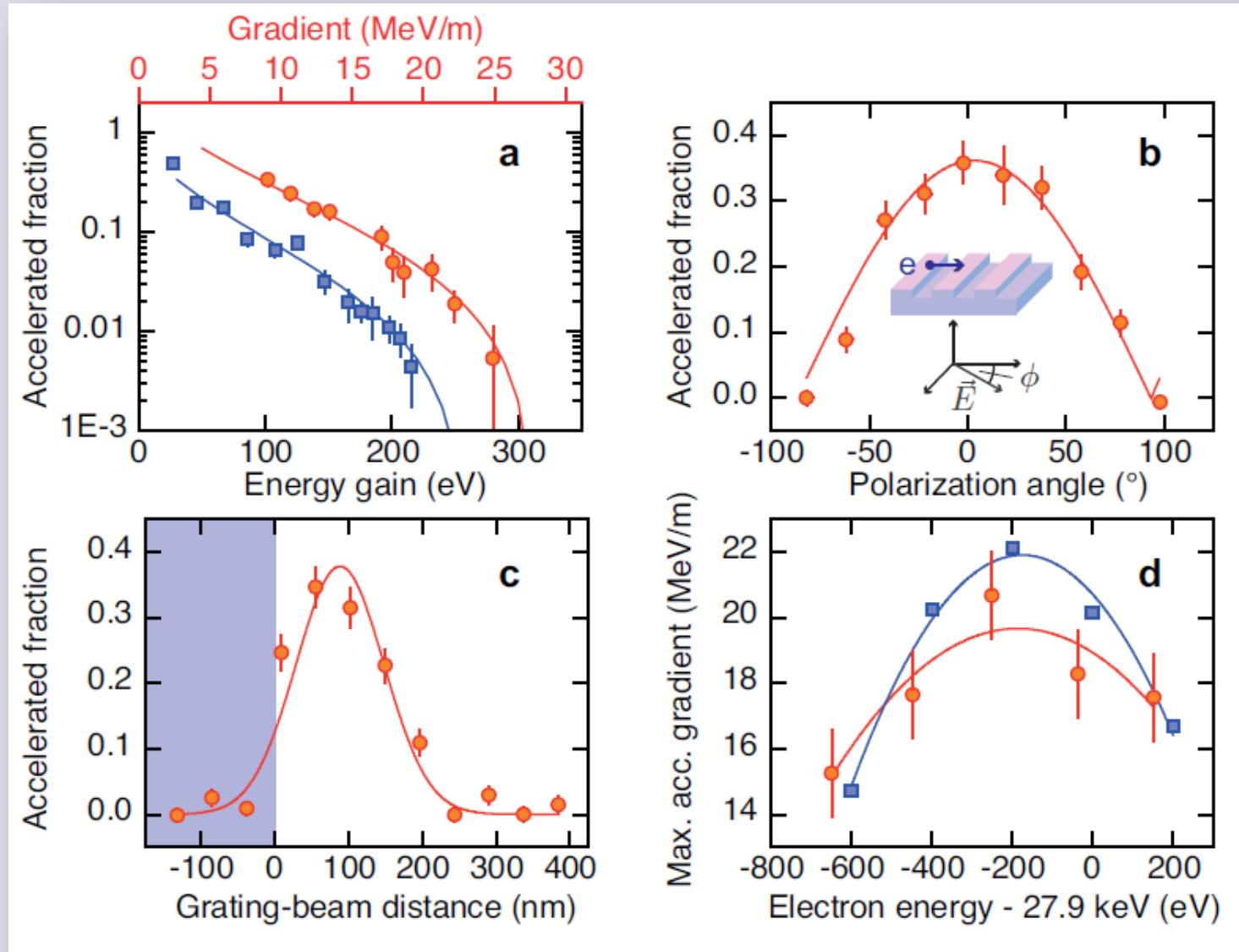
Details on setup: J. Breuer, R. Graf, A. Apolonski, P. Hommelhoff, Phys. Rev. ST-AB 17, 021301 (2014)  
on laser: S. Naumov, A. Fernandez, R. Graf, P. Dombi, F. Krausz, and A. Apolonski, NJP 7, 216 (2005).

# Experimental Setup

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



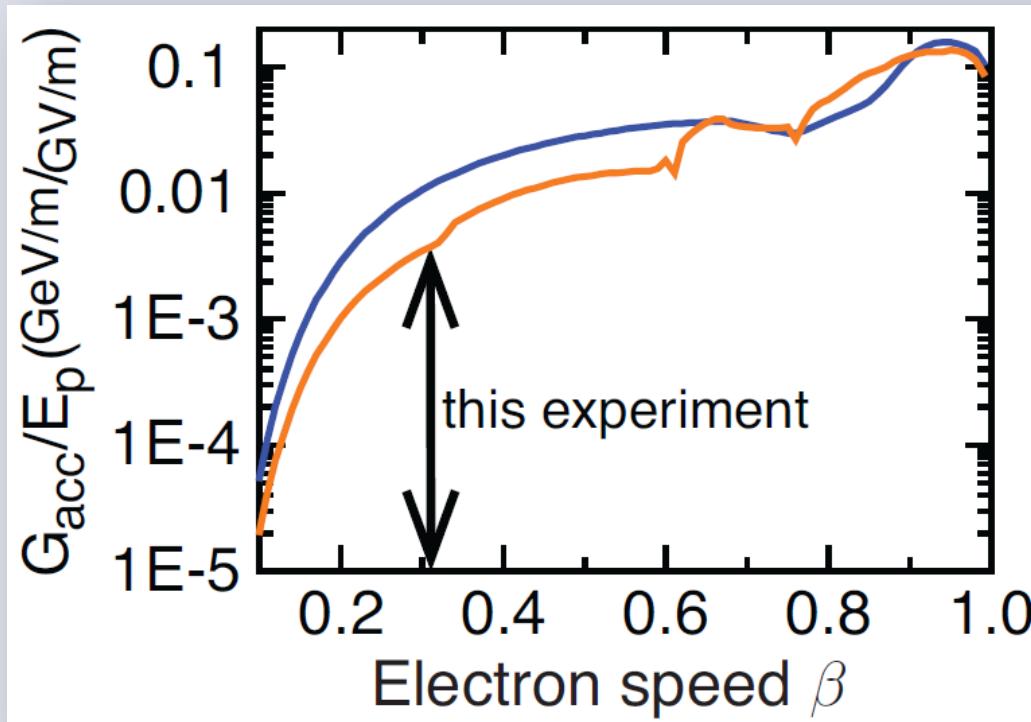
# Dielectric laser acceleration results



**Max. observed gradient: 25 MeV/m**

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

# Acceleration efficiency: simulation results



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

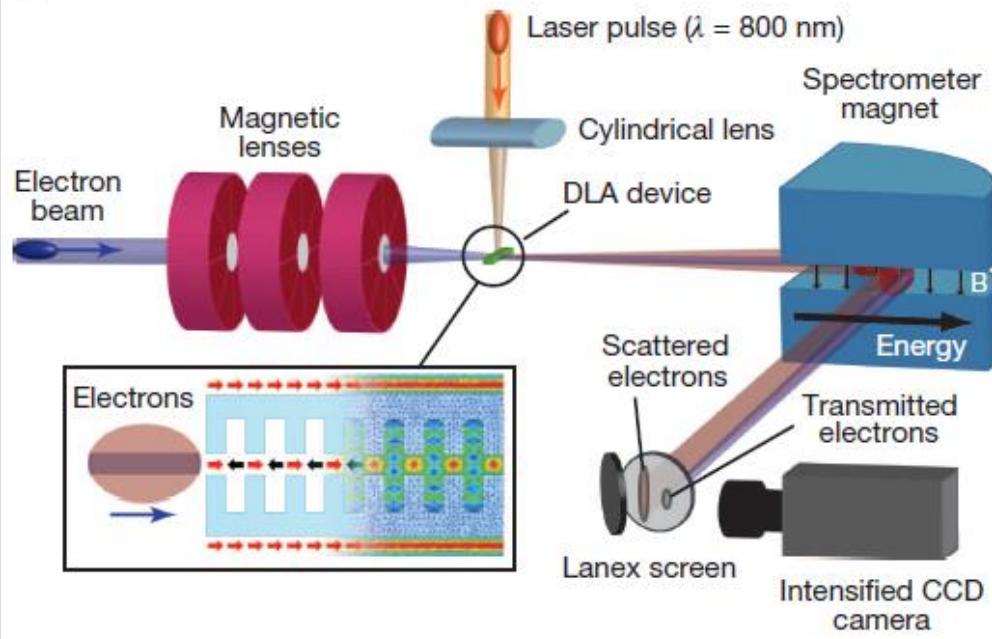
J. Breuer, P. Hommelhoff, Phys. Rev. Lett. 111, 134803 (2013)

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

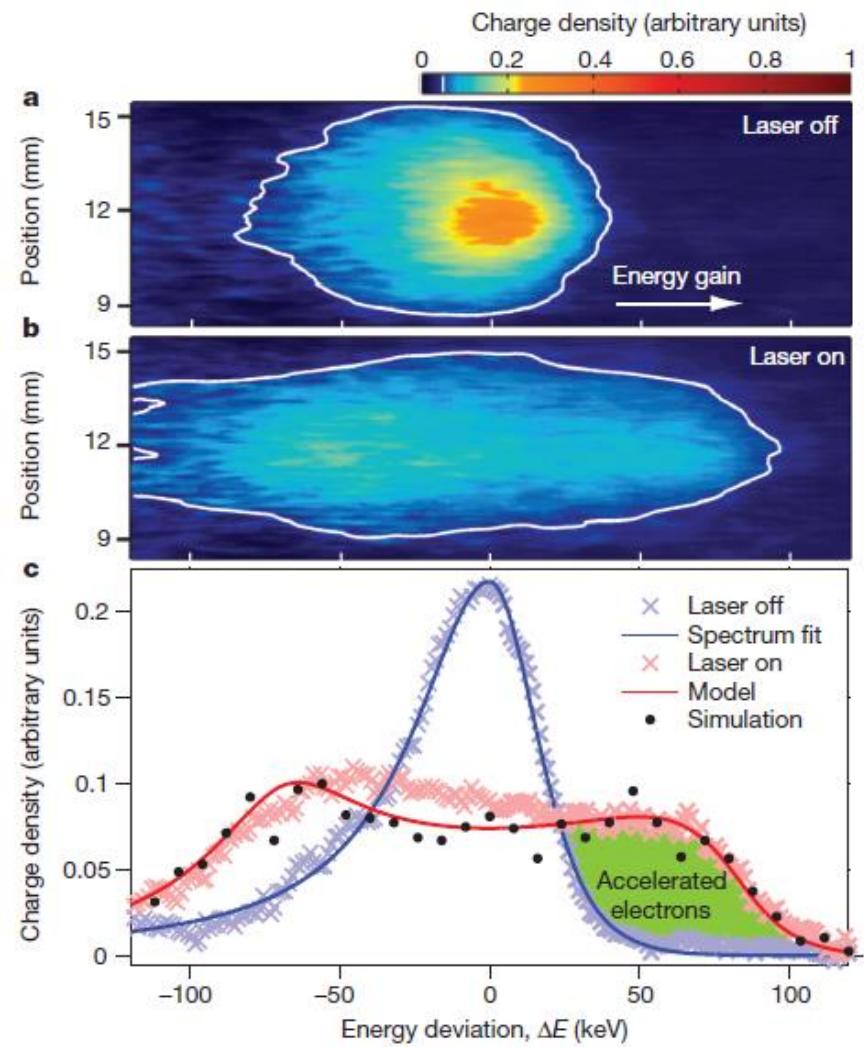
Peralta et al. (Byer group, Stanford), Nature 503, 91 (2013)

# Dual-Grating Structure: Dielectric laser acceleration of 60 MeV electrons at Stanford/SLAC

b



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)



**Science and technology**

# The Econom

## Versneller

DE VOLKSKRANT BV JACOB BONTUSSPLAATS 9, POSTBUS 1000, 1000 EA, AMSTERDAM

# de Volkskrant

DONDERDAG 28  
EUROPEAN NEWS

THE 0900-562 9222 KLANTEN

shavera ★ 5 / 5 (3)

yeah the bulk of scientific research is carried on PhD student backs. What this may do, though, is allow for cheaper smaller accelerators to be present in more locations, reducing cost of doing science.

Lorentz Descartes ★ 1 / 5 (4)

cool research. has anyone read the article and knows what the efficiency of this is? how much of the light's energy is transferred to the electrons?

LordHellFire666 ★ 1.8 / 5 (5)

Three words that any Military will love: Particle Beam Weapons

mhenriday ★ 3 / 5 (2)

"Another possible application is small, portable X-ray sources to improve medical care for people injured in combat, ..." I applaud the science - but is it not about time that we started thinking more about eliminating "combat", i.e., war, even if not declared by the US Congress, as required by Article I, Section 8 of the US Constitution, than about improving medical for (some of) the injured resulting from the same ?...

**Phys**

September 2013

**Friedrich-Alexander Universität Erlangen-Nürnberg**

**FAU**

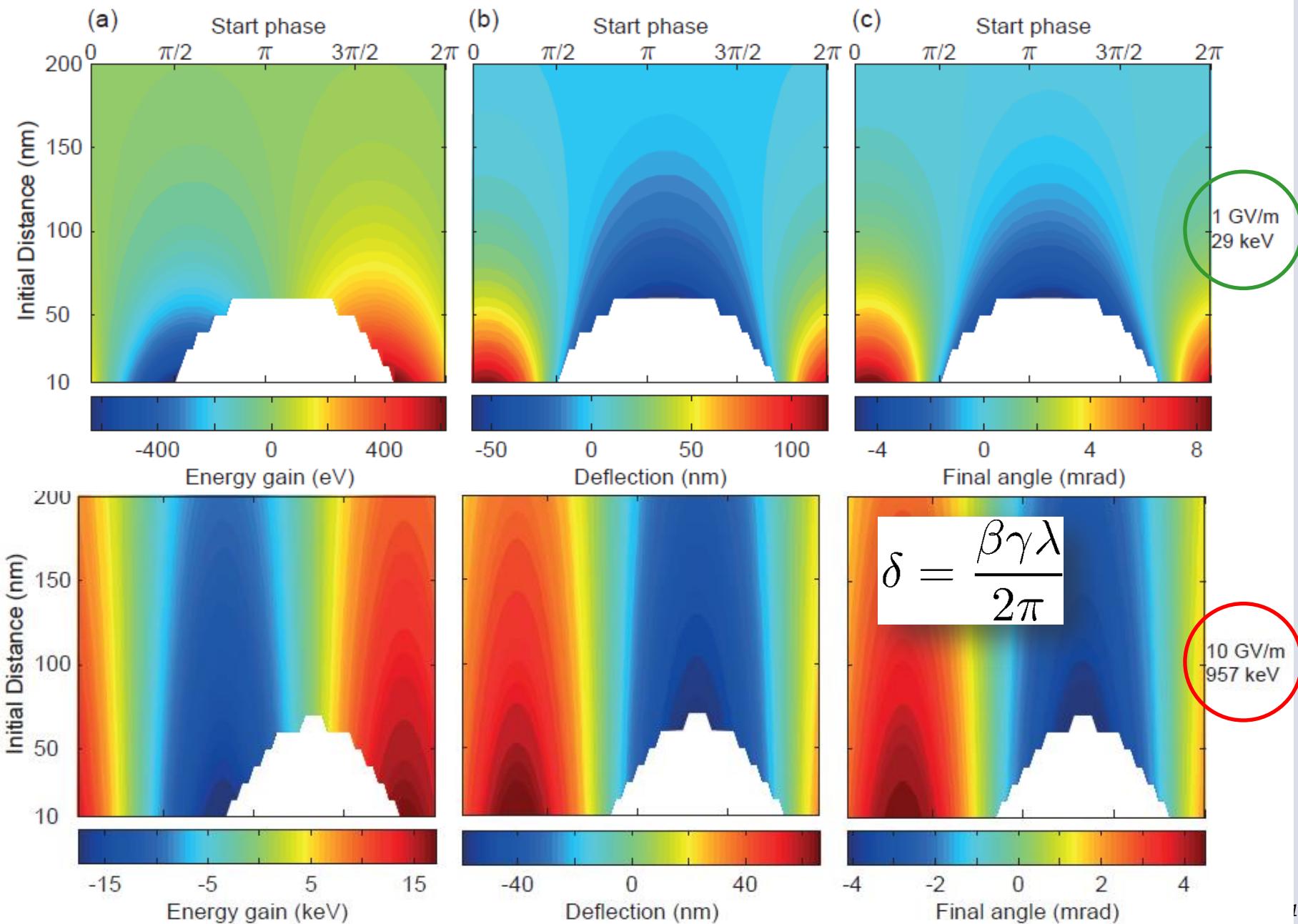
FOCUS ON PHYSICS

Read Article | More | ...

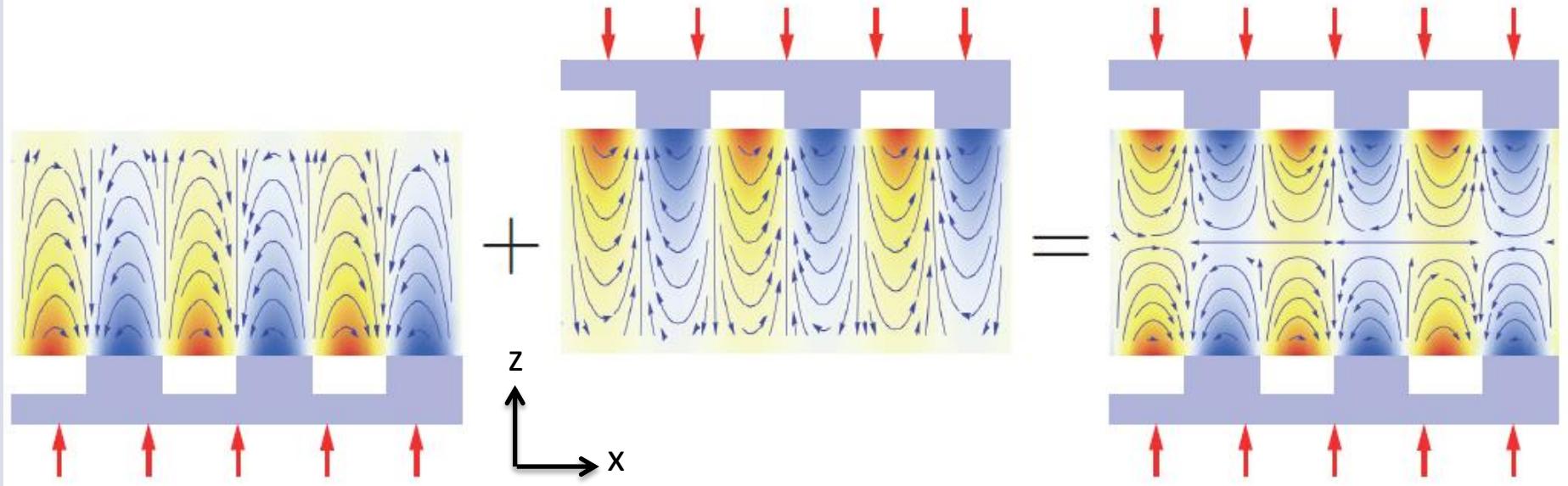
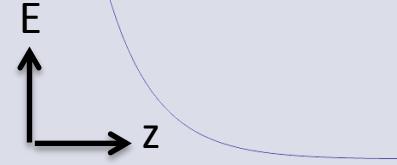
2005

Ilorca, March 2015

# Particle tracing simulation results



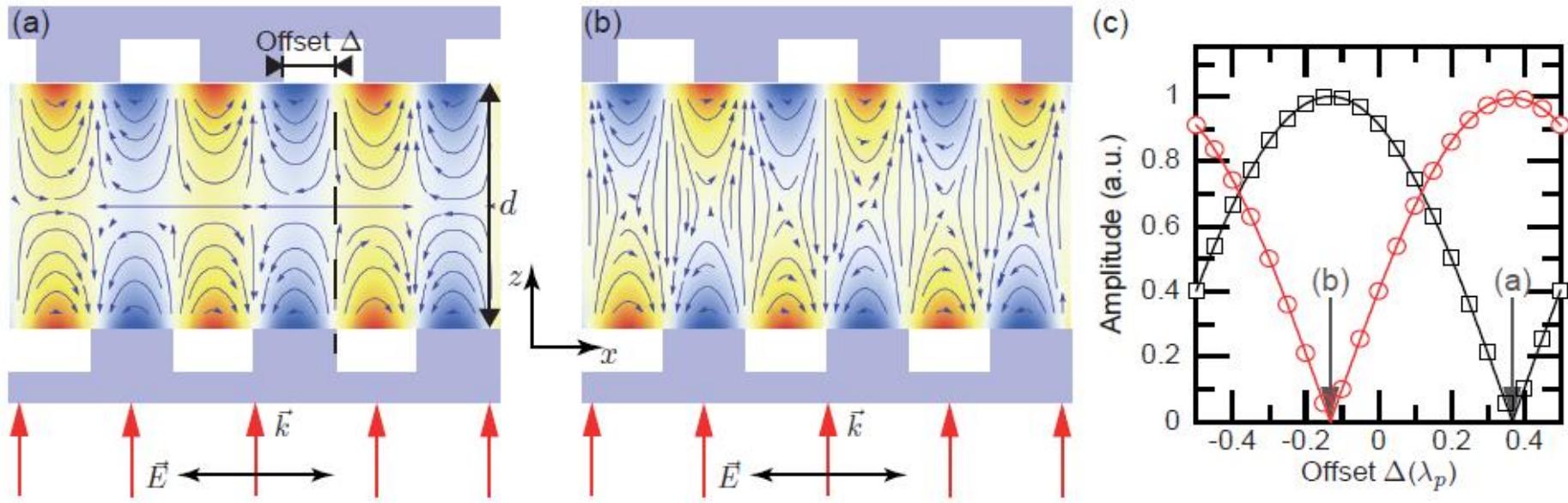
# Two-sided structures: uniform accel. field



$$\mathbf{F}_r = qc \begin{pmatrix} \frac{1}{\beta\gamma} (C_s \cosh(k_z z) + C_c \sinh(k_z z)) \sin(k_x x - \omega t) \\ 0 \\ -\frac{1}{\beta\gamma^2} (C_s \sinh(k_z z) + C_c \cosh(k_z z)) \cos(k_x x - \omega t) \end{pmatrix}$$

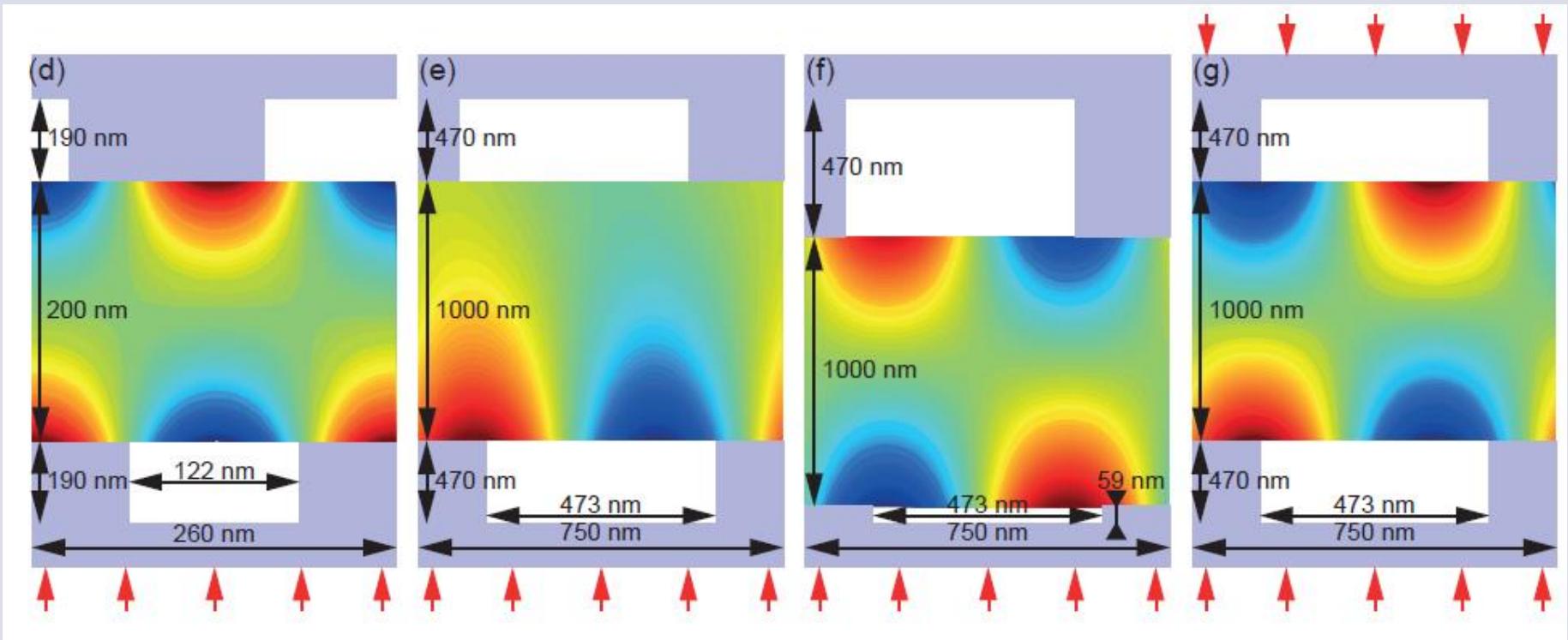
Uniform acceleration gradient:  $dF_x/dz \propto d \cosh(k_z z)/dz|_{z=0} = 0$

# Shift structure: from acceleration to deflection



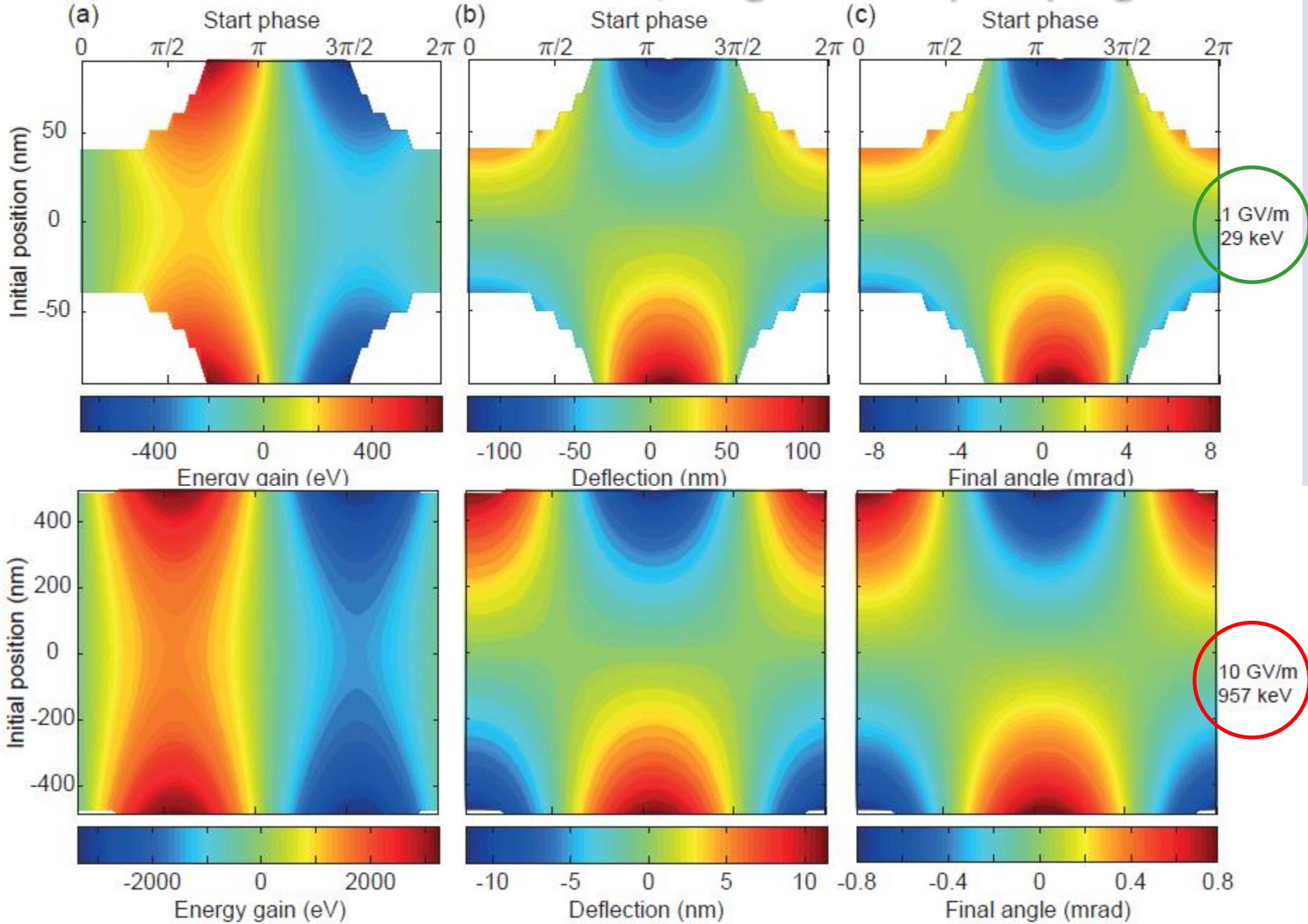
$$\mathbf{F}_r = qc \begin{pmatrix} \frac{1}{\beta\gamma} (C_s \cosh(k_z z) + C_c \sinh(k_z z)) \sin(k_x x - \omega t) \\ 0 \\ -\frac{1}{\beta\gamma^2} (C_s \sinh(k_z z) + C_c \cosh(k_z z)) \cos(k_x x - \omega t) \end{pmatrix}$$

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

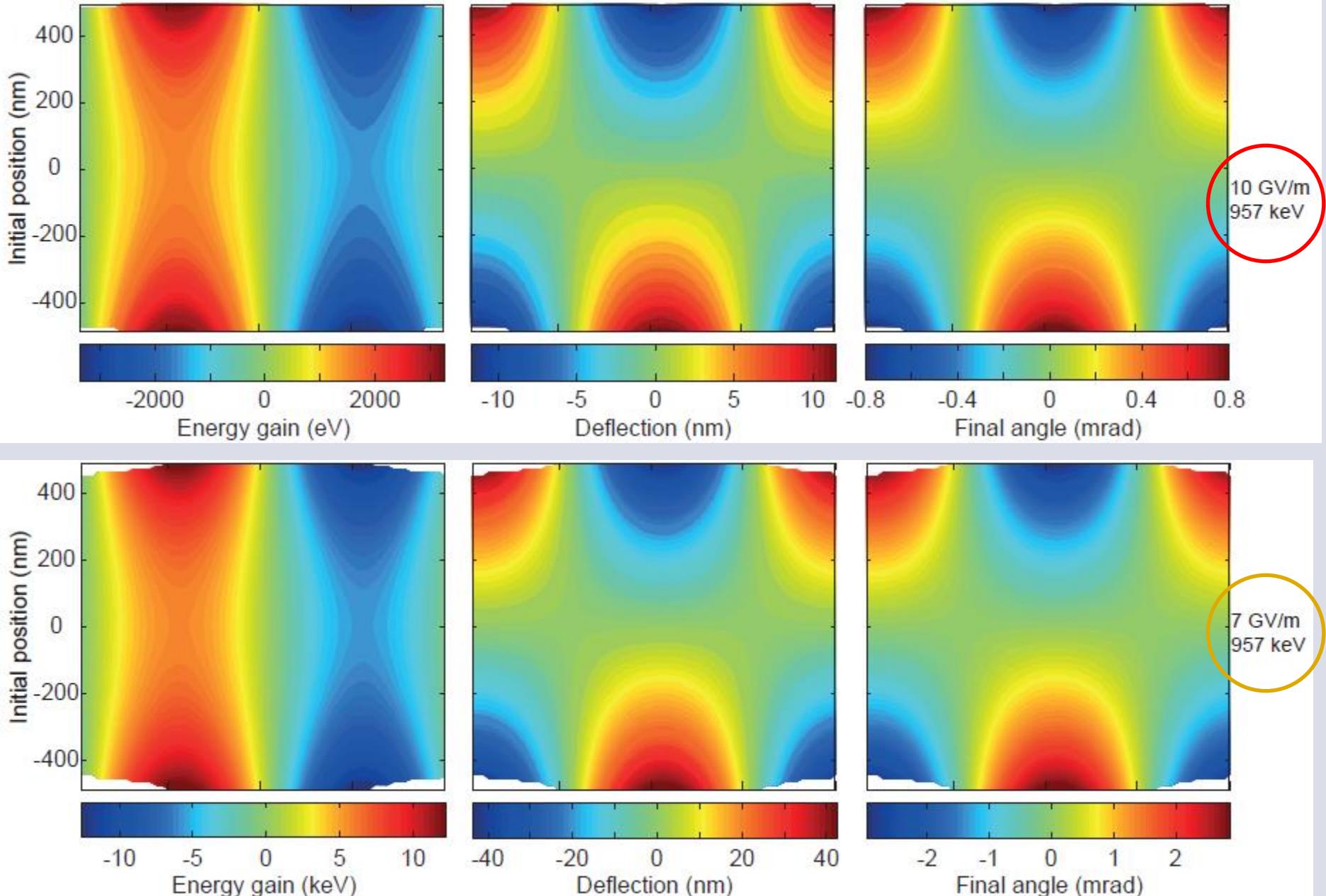


Quite a number of structure parameters!

# Double-sided structure, single-sided pumping



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



# Space charge effects: beam envelope equation

$$r_m'' + \frac{\gamma' r_m'}{\beta^2 \gamma} + \frac{\gamma'' r_m}{2\beta^2 \gamma} + \left( \frac{qB}{2mc\beta\gamma} \right)^2 r_m$$
$$- \left( \frac{p_\theta}{mc\beta\gamma} \right)^2 \frac{1}{r_m^3} - \frac{\epsilon_n^2}{\beta^2 \gamma^2 r_m^3} - \frac{K}{r_m} = 0$$

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

Accel. in long. el. field

Focusing in radial el. field

Focusing in axial magn. field

# Emittance and space charge

Assume emittance limited beam:

$$r_m'' + \frac{\gamma'' r_m}{2\beta^2\gamma} - \frac{\epsilon_n^2}{\beta^2\gamma^2 r_m^3} = 0$$

transverse focusing with laser field:

$$\gamma'' = \frac{2qE_\perp}{mc^2 r_m} = \frac{2G}{mc^2 r_m \gamma}$$

Demanding a stable beam radius yields:

$$\epsilon_n^2 = \frac{2Gr_m^3}{mc^2}$$

With  $G = 1 \text{ GeV/m}$  and  $r = 100 \text{ nm}$ :

$$\epsilon_n = 6 \text{ nm} \cdot \text{rad}$$

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

$$I_b = 0.1 I_0 \frac{G\beta\gamma r_m}{mc^2}$$

# Space-charge limited current

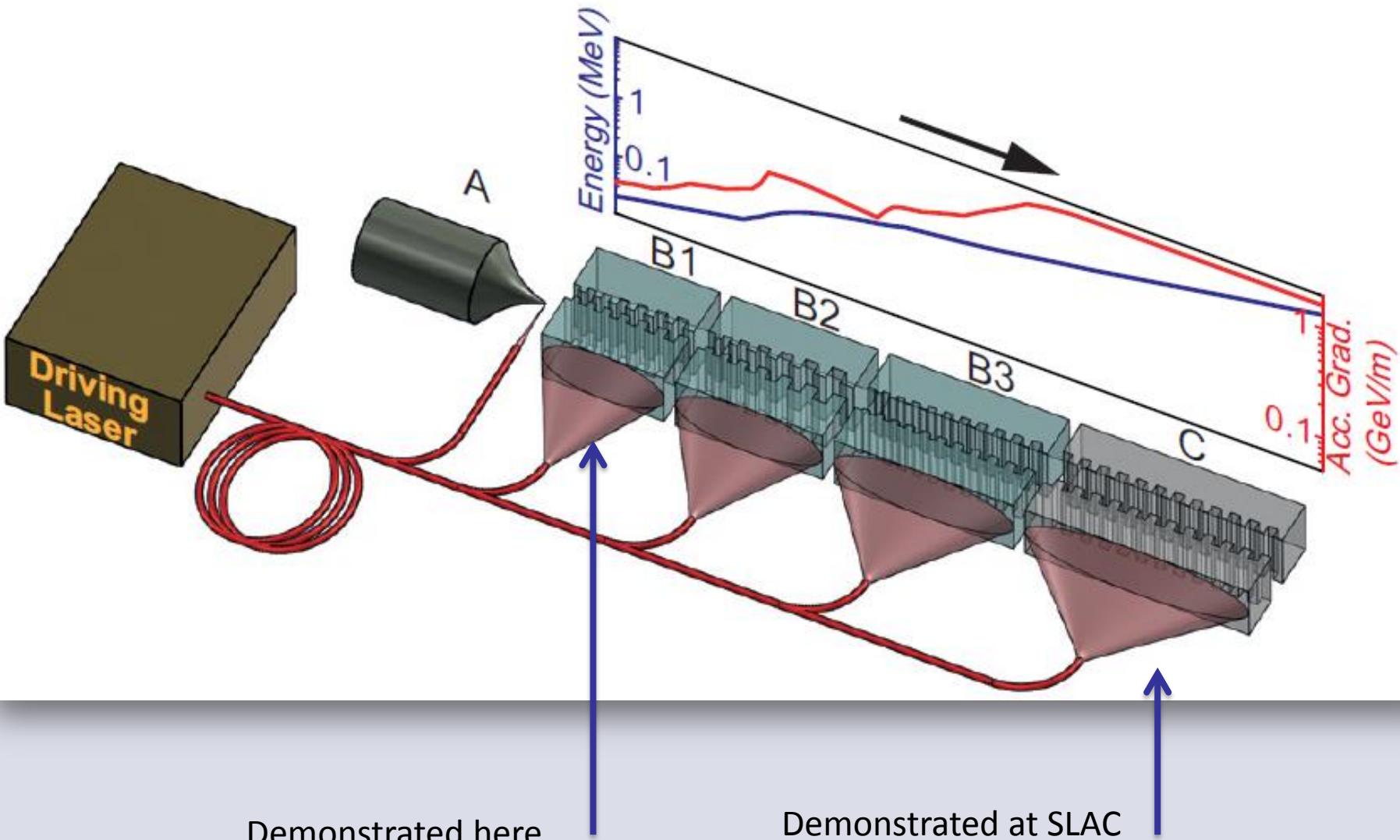
$E_p$ ( $\frac{\text{GV}}{\text{m}}$ )	$E_{\text{kin}} = 29 \text{ keV}$ , $r_m = 50 \text{ nm}$			$E_{\text{kin}} = 957 \text{ keV}$ , $r_m = 300 \text{ nm}$		
	$\lambda (\mu\text{m})$			$\lambda (\mu\text{m})$		
	0.8	2	5	0.8	2	5
1	1.8 mA	4.4 mA	11.2 mA	0.28 A	0.68 A	1.72 A
7	12.6 mA	32 mA	80 mA	1.9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



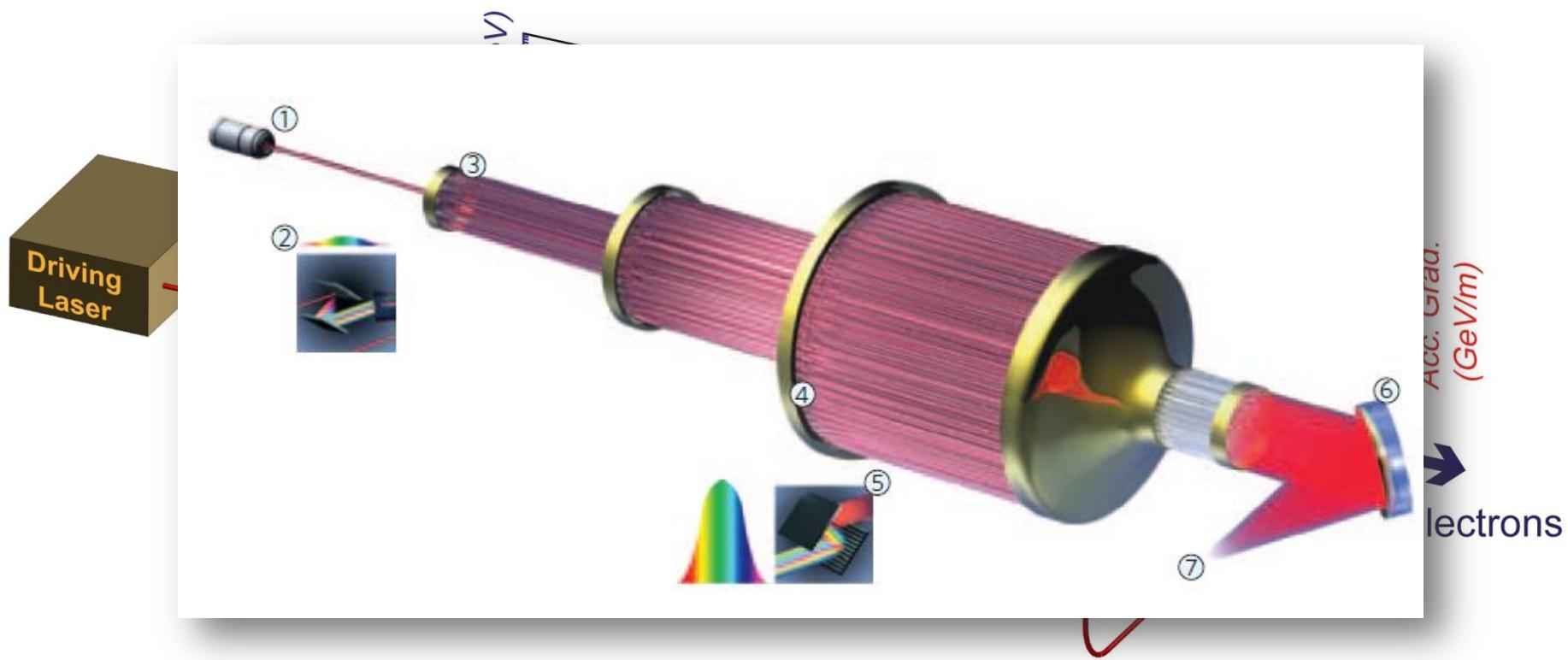
Total charge (0.1 opt. period long pulse):  
3 fC, scales with  $\lambda^2$

J. Breuer, J. McNeur, P. Hommelhoff, to appear in  
J. Phys. B. arXiv:1407.6688

# Scalable technology: concatenate structures



# 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

# 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



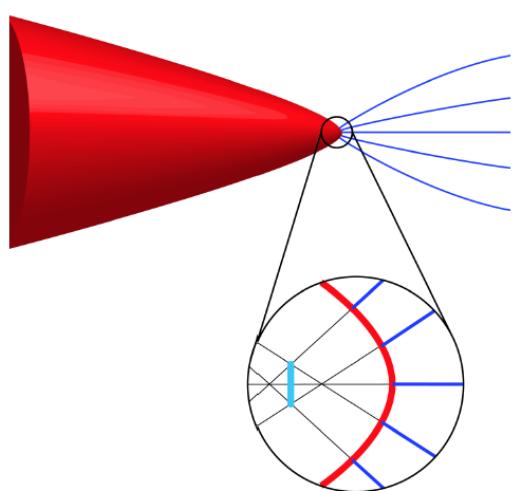
Complementary in nature

# Extremely low emittance sources: tip (arrays)

With 20pC, 5A from **regular RF and DC**

**photocathodes**: norm. emitt. = 120nm.

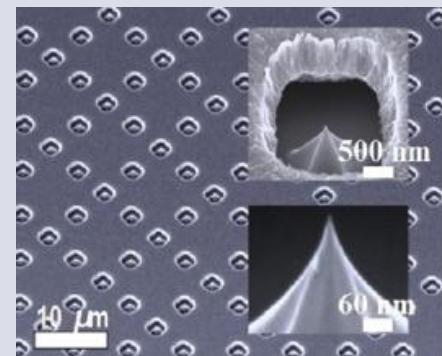
Ding et al. PRL 2009



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

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

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



Mustonen, ..., Tsujino, APL 2011

PRL 96, 077401 (2006)

PHYSICAL REVIEW LETTERS

week ending  
24 FEBRUARY 2006

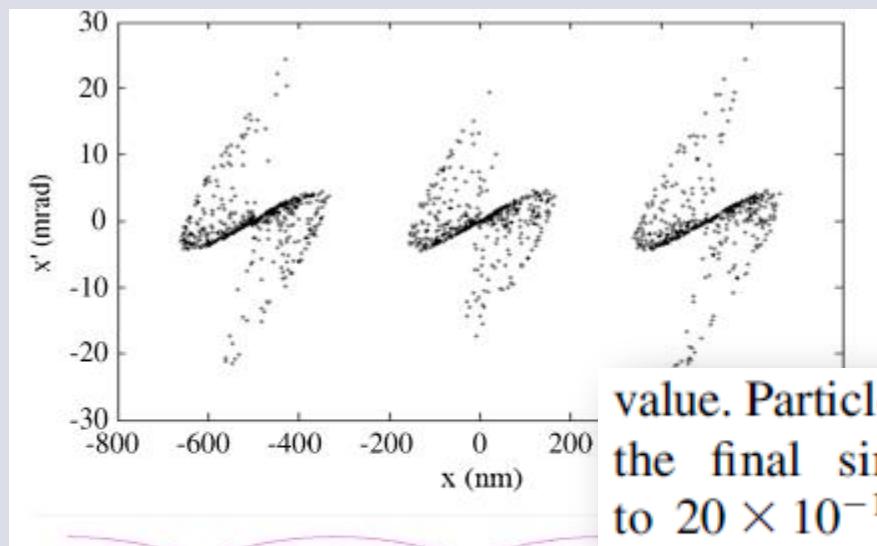
## Field Emission Tip as a Nanometer Source of Free Electron Femtosecond Pulses

Peter Hommelhoff,\* Yvan Sortais, Anoush Aghajani-Talesh, and Mark A. Kasevich

Physics Department, Stanford University, Stanford, California 94305, USA

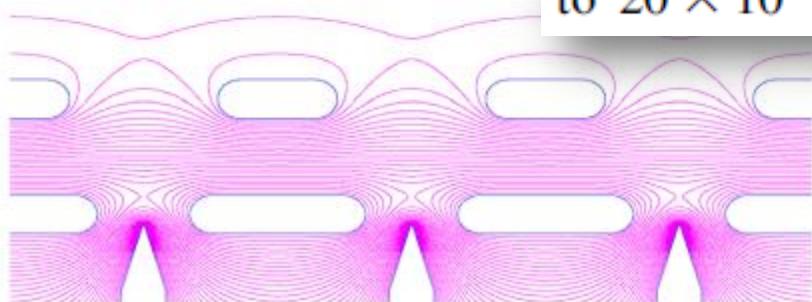
(Received 25 July 2005; published 21 February 2006)

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

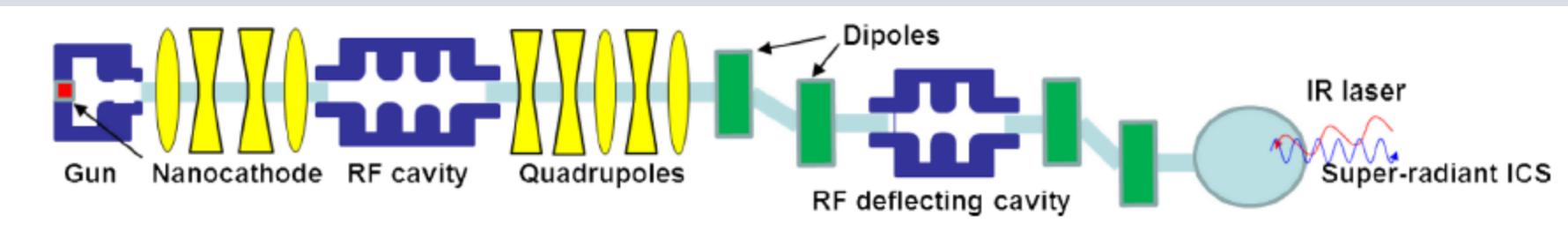


Graves, Kärtner,  
Moncton, Piot, PRL 2012

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

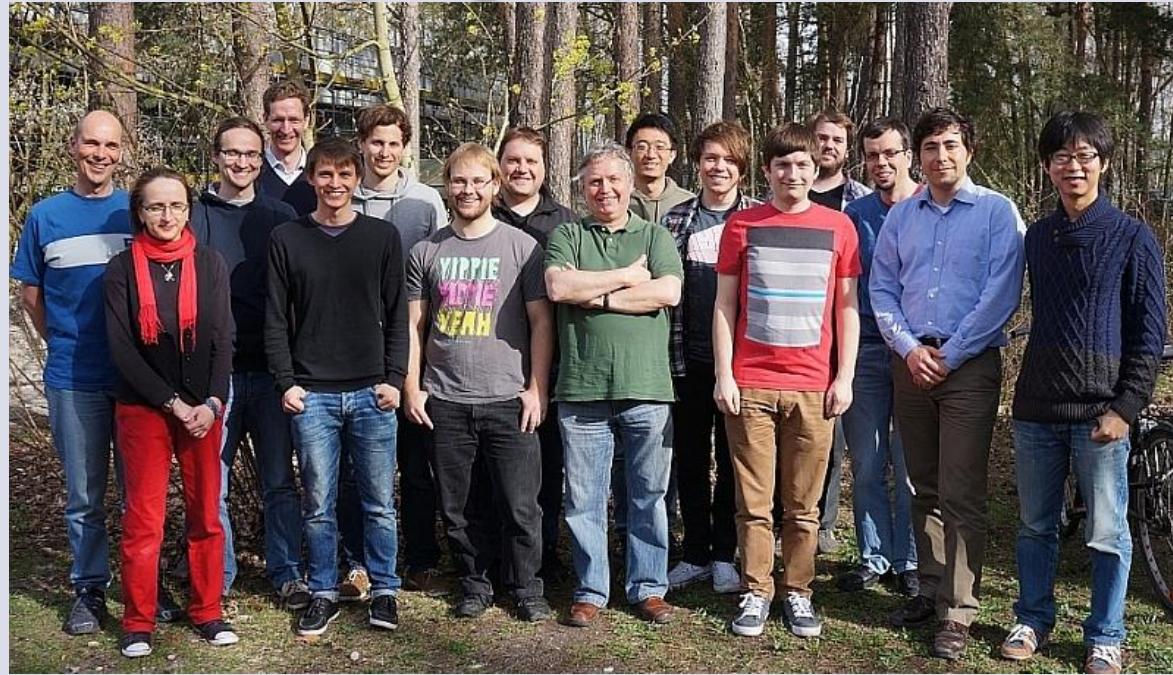


Transverse-to-longitudinal emittance exchange: beam bunched at the wavelength of the desired radiation



# Erlangen group

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Kerstin Gondosch  
Jakob Hammer  
Christian Heide  
Takuya Higuchi  
Martin Hundhausen  
Martin Kozak  
Ang Li  
Joshua McNeur  
Timo Paschen  
Jürgen Ristein  
Ella Schmidt  
Alexander Tafel  
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R. Holzwarth, MenloSystems



IMPRS-APS

P. Hommelhoff, La3Net, Mallorca, March 2015

# Summary and outlook

## Laser acceleration of electrons at a dielectric photonic structure

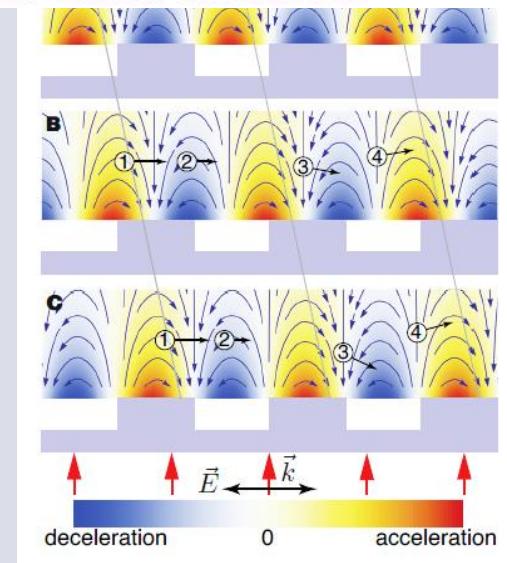
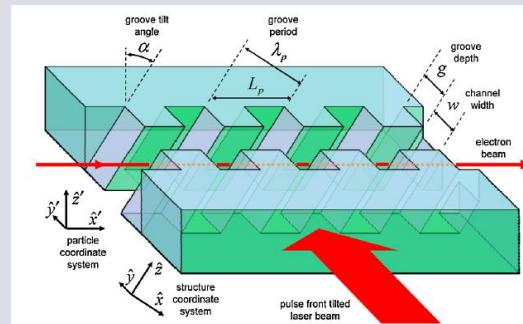


## Laser acceleration and deflection of 96.3 keV electrons with a silicon dielectric structure

KENNETH J. LEEDLE,<sup>1,\*</sup> R. FABIAN PEASE,<sup>1</sup> ROBERT L. BYER,<sup>2</sup> AND JAMES S. HARRIS<sup>1,2</sup>

Take advantage of

- Fast progress in (fiber) laser technology
- Existing nano-fabrication technology (silicon ok at wavelengths  $> 1.5\mu\text{m}$ !)





# Damage threshold measurements

Fused silica grating, coated with 10nm gold, at  $10^{-6}$  hPa

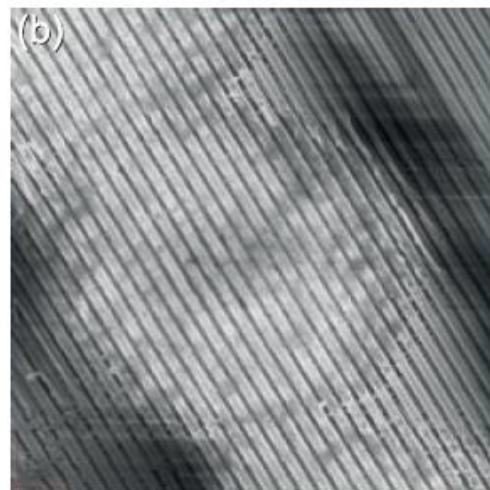
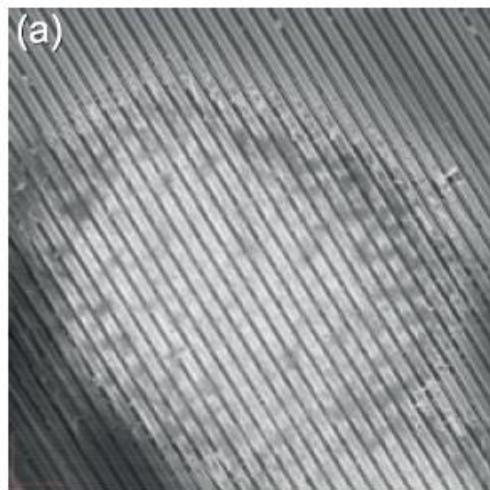
5um spot radius, 70fs pulses, 2.7 MHz

$$P = 400\text{mW}$$

$$E_p = 6.1 \text{ GV/m}$$

$$I_p = 1.0 \cdot 10^{13} \text{ W/cm}^2$$

$$F_p = 0.37 \text{ J/cm}^2$$

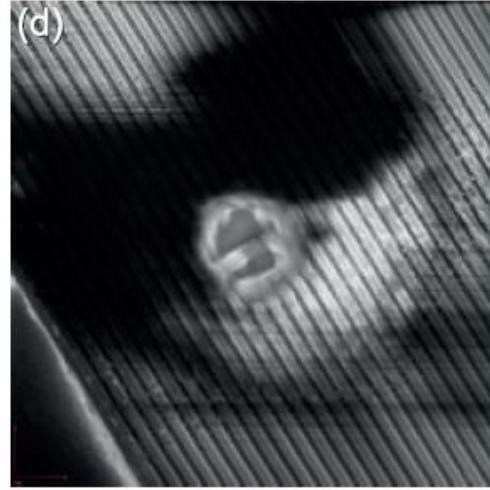
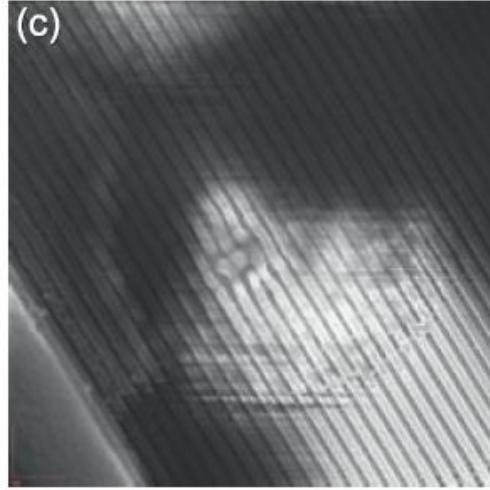


$$P = 500\text{mW}$$

$$E_p = 6.9 \text{ GV/m}$$

$$I_p = 1.3 \cdot 10^{13} \text{ W/cm}^2$$

$$F_p = 0.47 \text{ J/cm}^2$$



$$P = 500\text{mW}$$

$$E_p = 6.9 \text{ GV/m}$$

$$I_p = 1.3 \cdot 10^{13} \text{ W/cm}^2$$

$$F_p = 0.47 \text{ J/cm}^2$$

$$P = 620\text{mW}$$

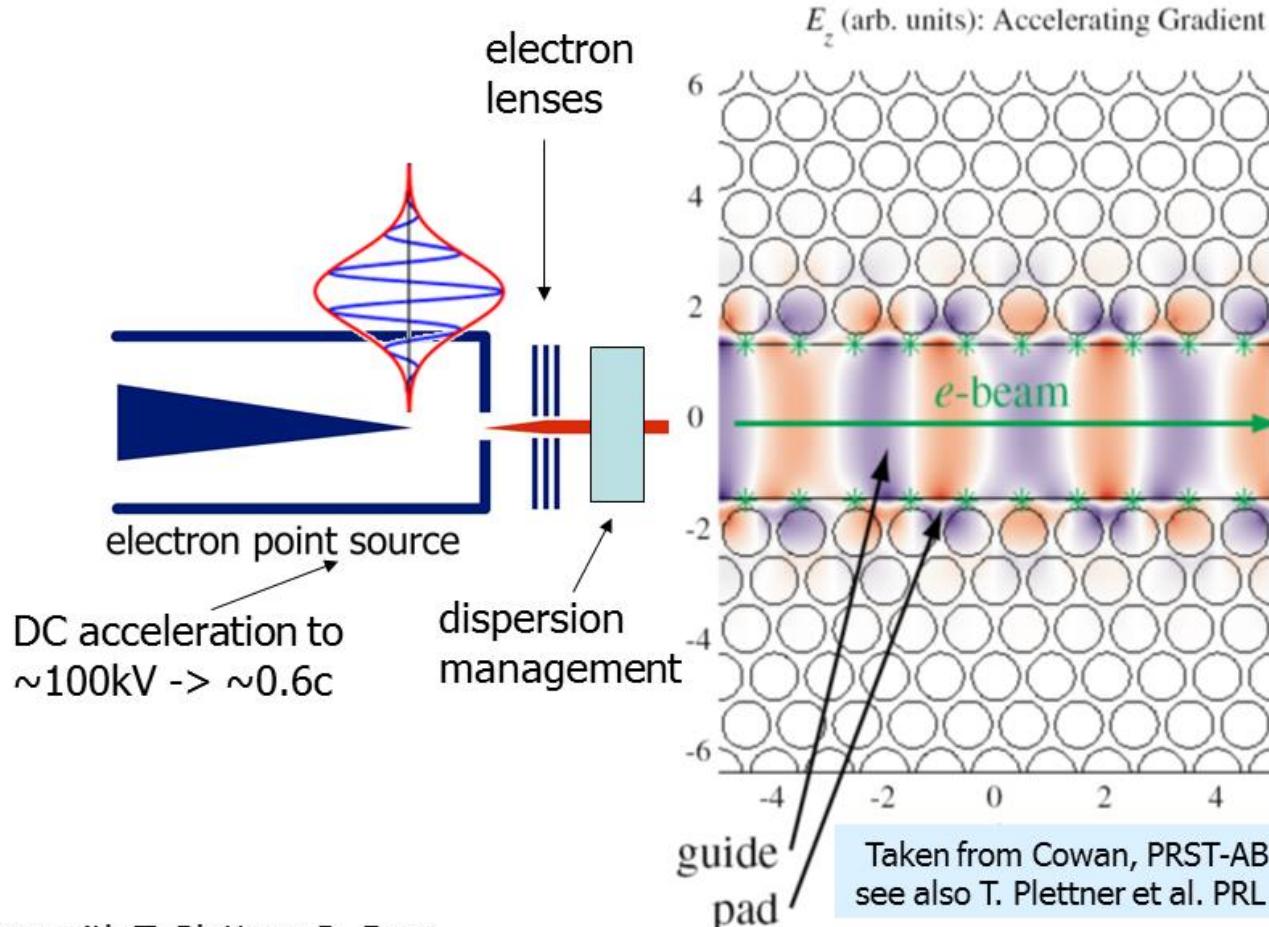
$$E_p = 7.6 \text{ GV/m}$$

$$I_p = 1.5 \cdot 10^{13} \text{ W/cm}^2$$

$$F_p = 0.57 \text{ J/cm}^2$$

# 2006 SPRC Symposium

## Far future (?): laser electron accelerator

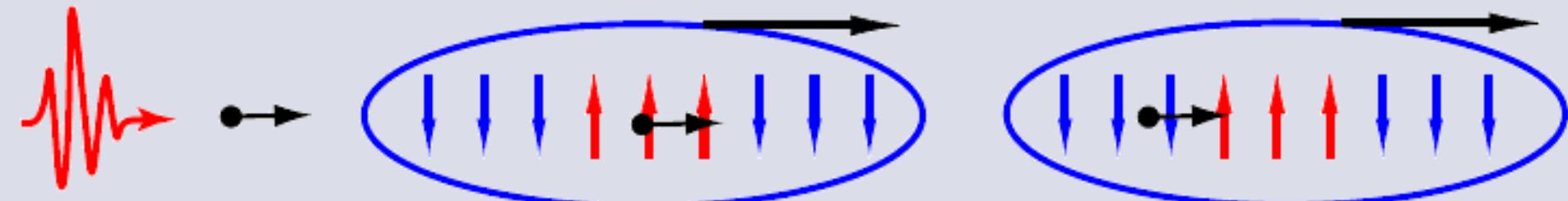


Together with T. Plettner, R. Byer  
(Stanford Applied Physics & SLAC)

STANFORD UNIVERSITY



# No acceleration in free space (over more than $\lambda$ )



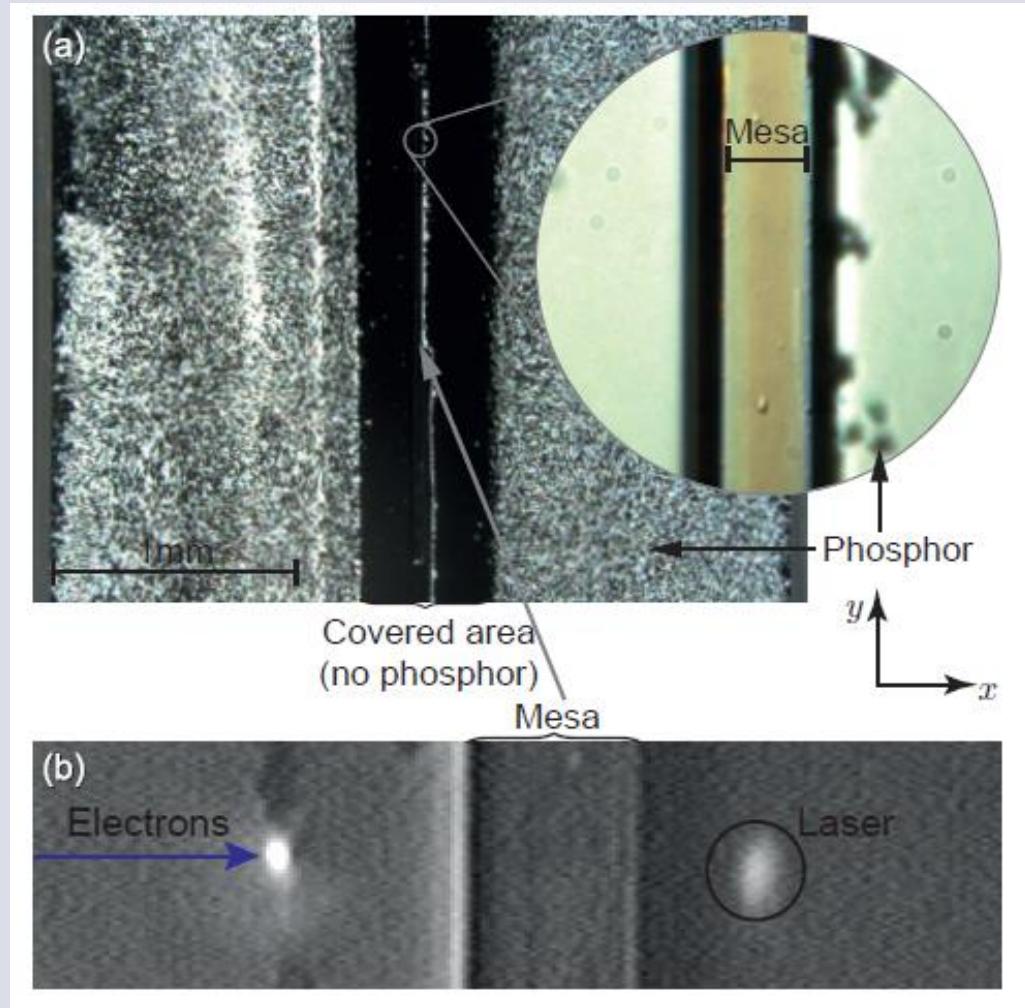
Electromagnetic waves are transversely polarized  
and faster than any particle!



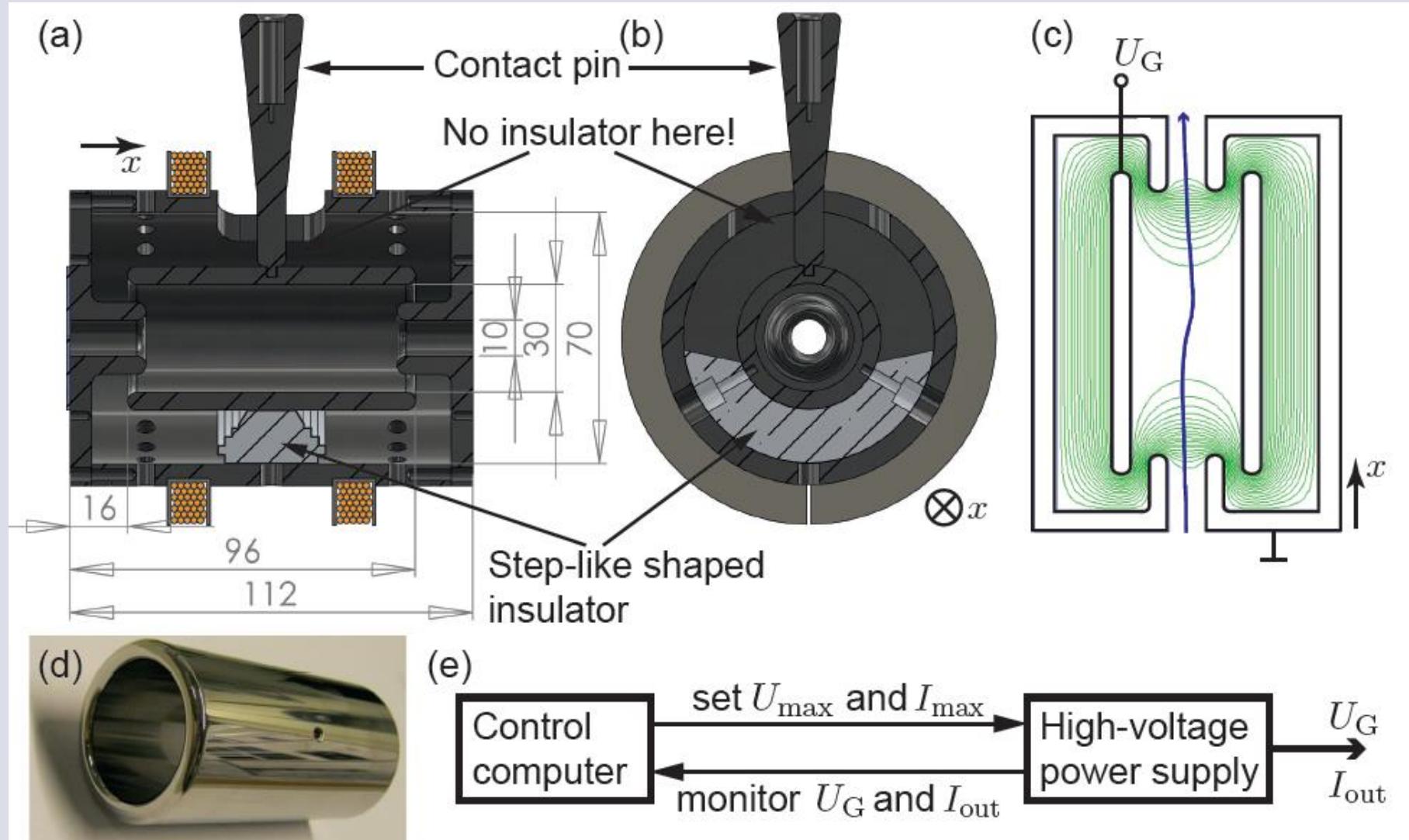
Net particle acceleration/deflection with e.m. waves in vacuum  
does also not work (“Lawson-Woodward-theorem”: energy-  
momentum conservation)

# Grating structure – phosphor and metal coating

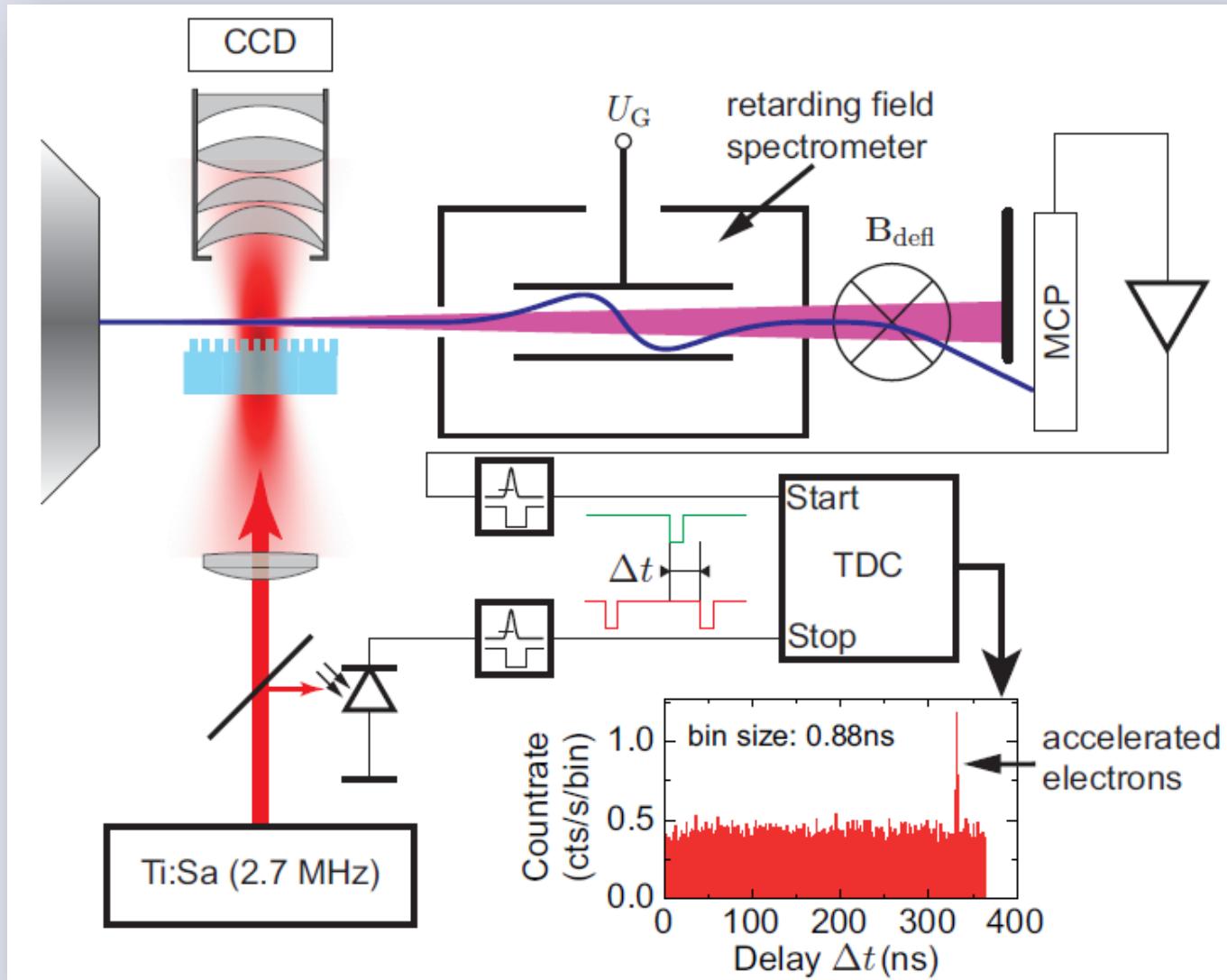
- charging of dielectric surface leads to beam deflection  
→ thin transparent (10nm) gold coating
- overlap electron beam with laser  
→ thin phosphor layer next to mesa, monitoring of beam/laser position via in-chamber microscope objective



# Retarding field spectrometer: high pass filter



# Coincidence measurement

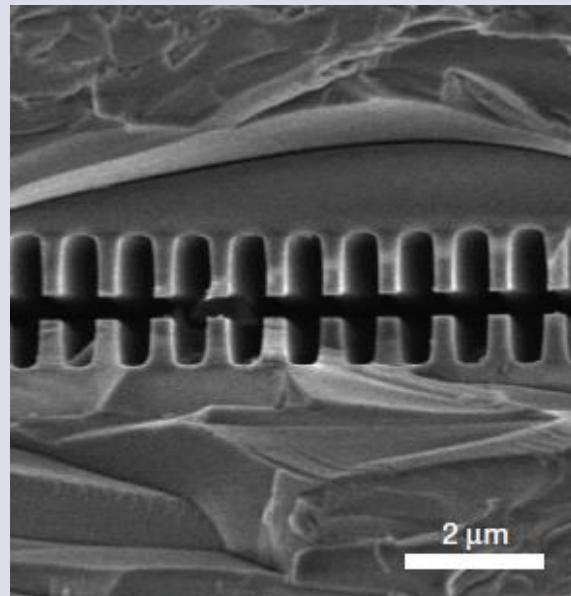


# Dual-Grating Structure: Dielectric laser acceleration of 60 MeV electrons at Stanford/SLAC

Byer group



NLCTA Beamlne

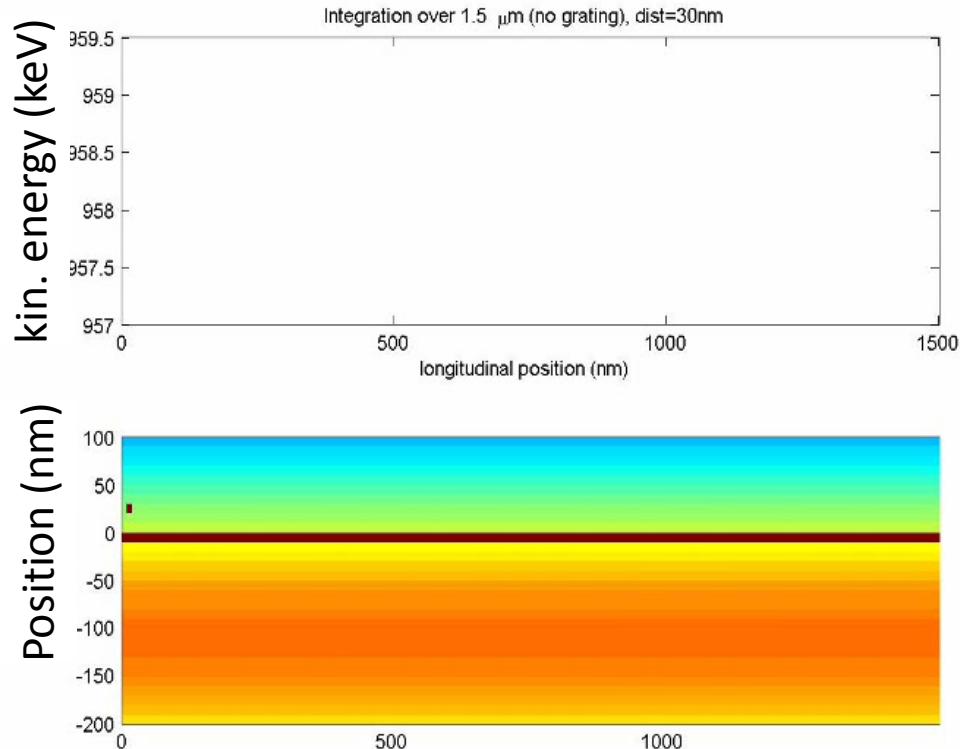


SEM image of sample cross-section

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)

# Animation of accelerating effect

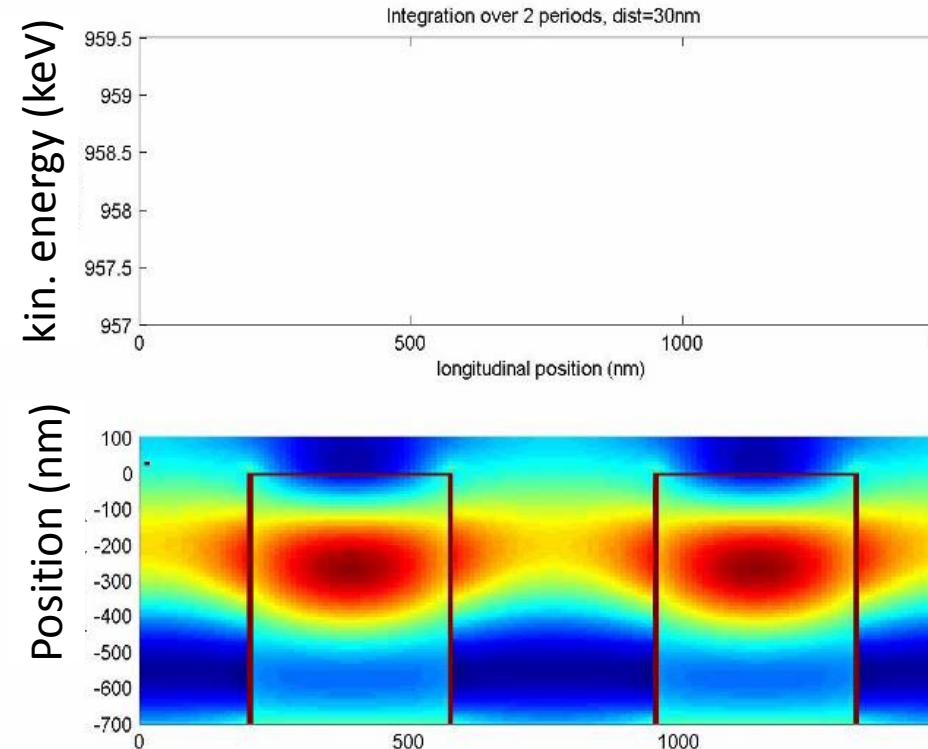
no grating



Longitudinal position (nm)

No net acceleration!

grating



Longitudinal position (nm)

Net acceleration: 1.1 GeV/m

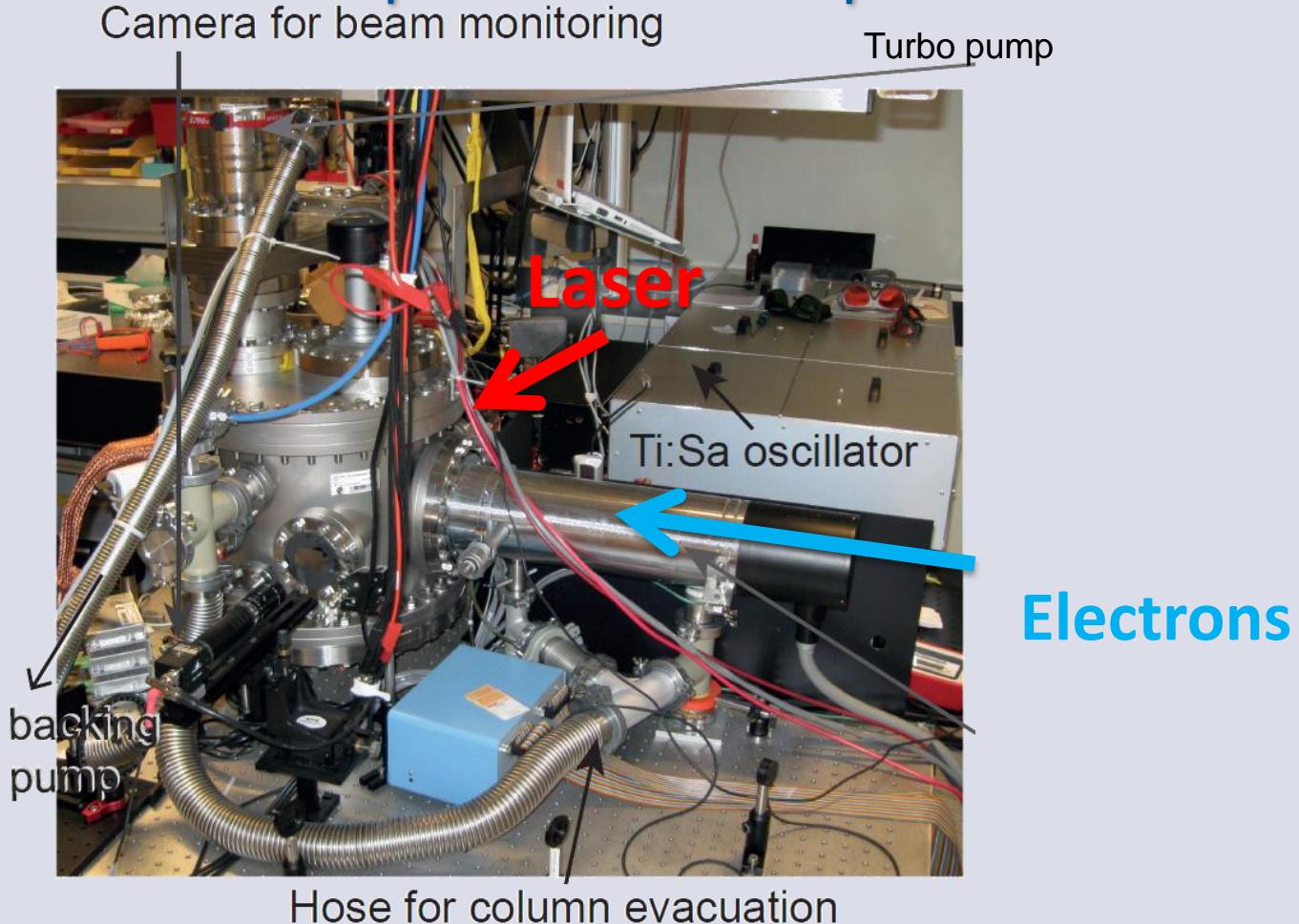
# Dephasing length

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

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

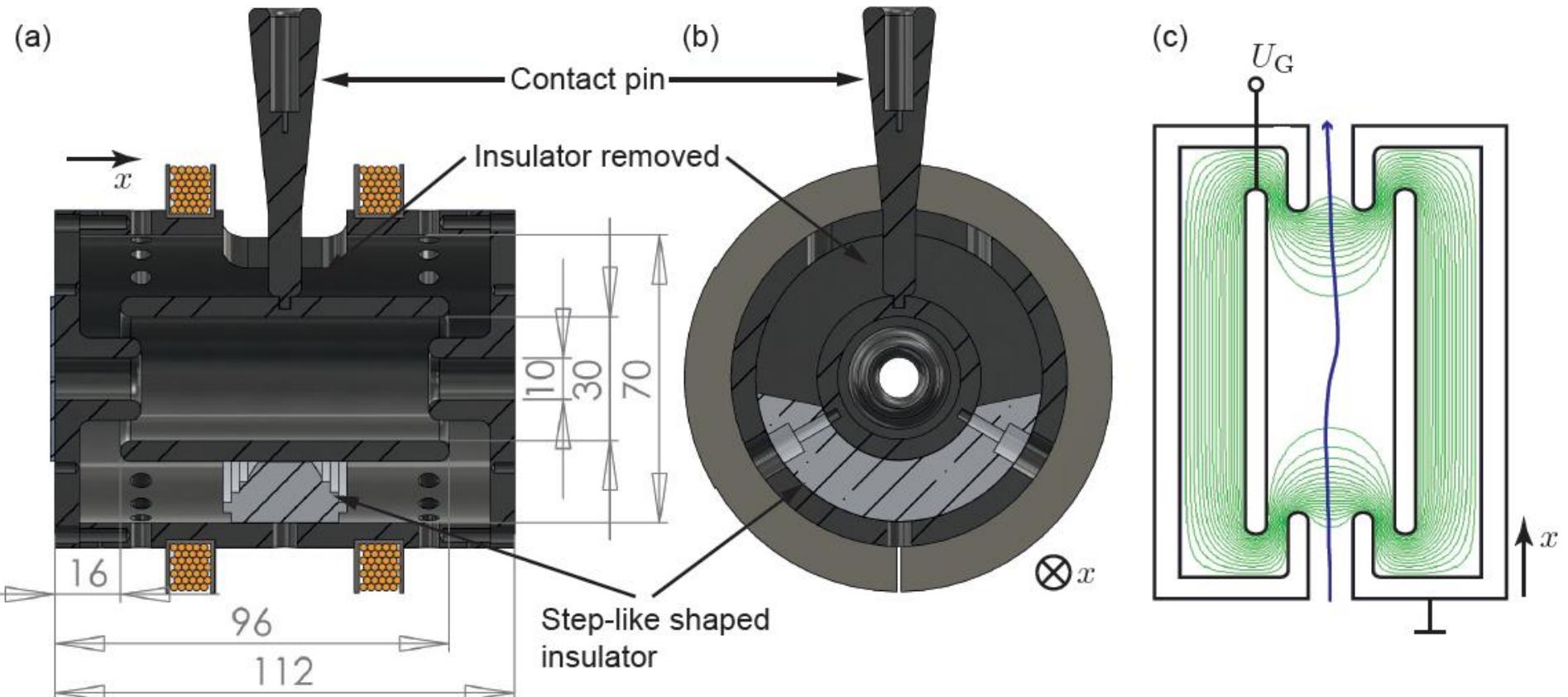
→ Match grating structure: shift or taper grating wavelength after / within given dephasing length

# Experimental setup

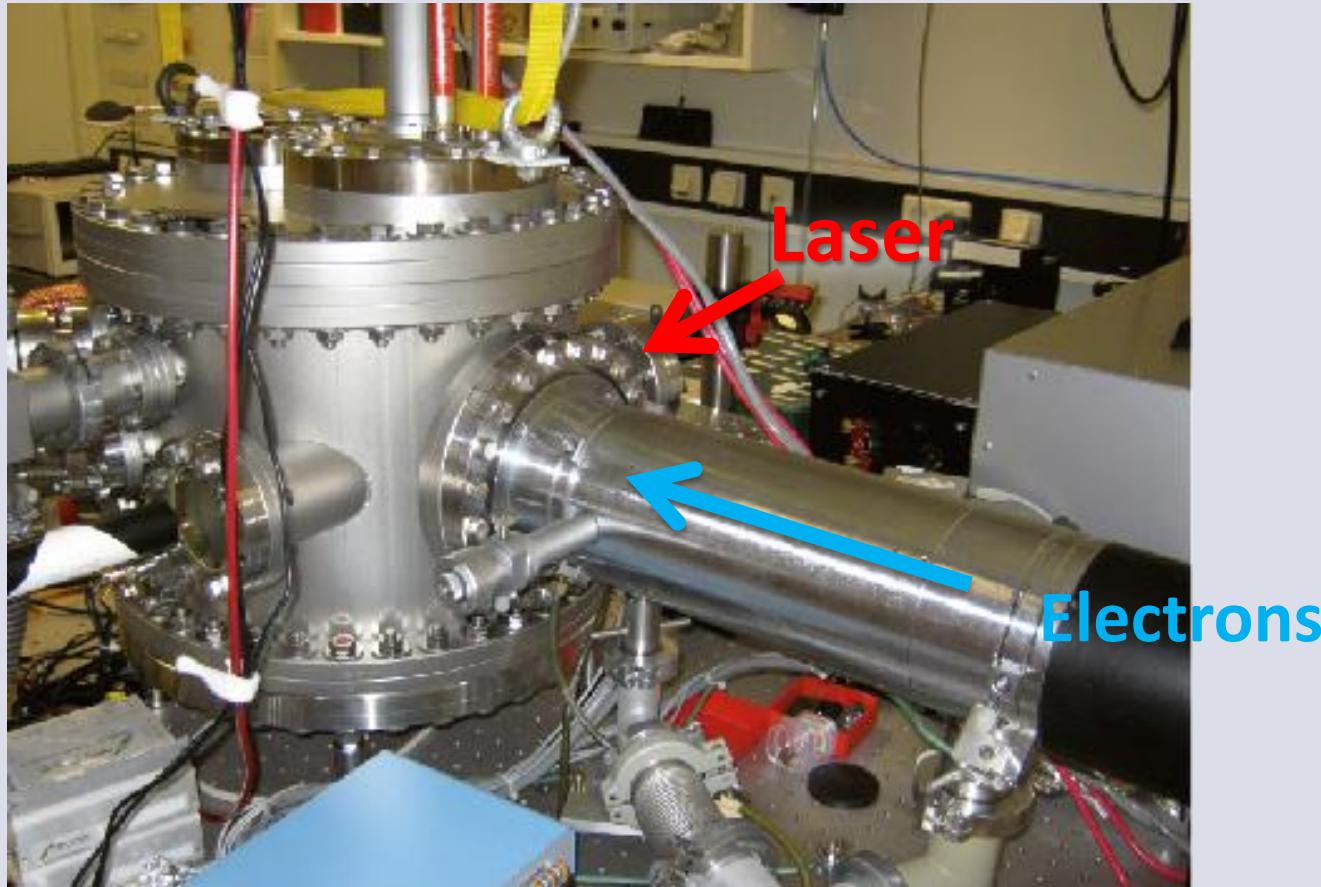


- continuous beam out of electron column from scanning electron microscope
- excellent control over beam focus and position
- narrow energy spectrum
- DC beam current:  $3.2 \pm 0.2 \text{ pA}$  (!)

# Electron spectrometer



# Experimental setup



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

# Beam envelope equation, contributing terms only

$$r_m'' + \frac{\gamma'' r_m}{2\beta^2 \gamma} - \frac{K}{r_m} = 0$$

Old!!

with transverse focusing with laser field:

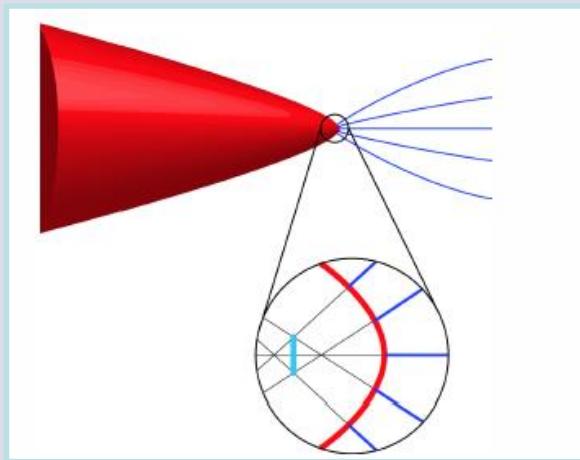
$$\gamma'' = \frac{2qE_\perp}{mc^2 r_m} = \frac{2G}{mc^2 r_m \gamma}$$

yields a **maximum beam current** for a stable beam ( $\gamma''=0$ ):

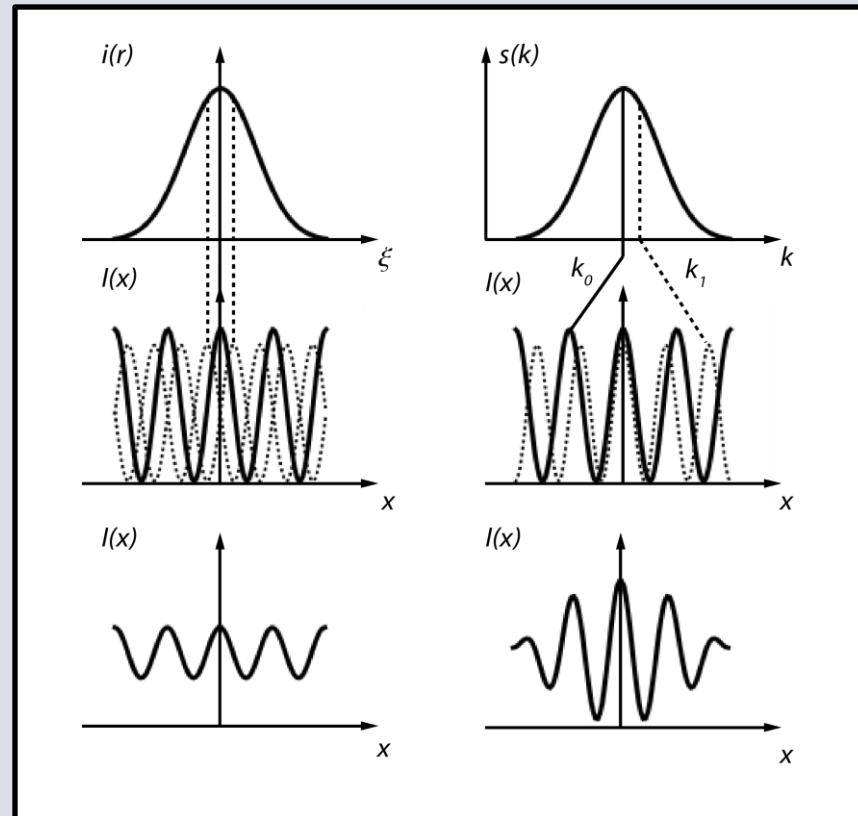
$$I_b = I_0 \frac{G \beta \gamma r_m}{2mc^2}$$

$I_0 = 17,000\text{A}$ :  
Budker or Alfen  
current

# Spatial coherence and virtual source size



- Figure of merit for degree of spatial coherence
- Smallest values measured for W field emitters: 0.4...0.7 nm [1,2]
- Connected to **transverse coherence length**  $\xi_{\perp}$  via van Cittert-Zernicke theorem:



tip-detector distance

deBroglie wavelength

$$\xi_{\perp} = \frac{b\lambda}{\pi r_{\text{eff}}}$$

effective source radius

- [1] Spence et al., *J. Vac. Sci. Technol. A*, **12**, 2 (1994).  
[2] B. Cho et al., *Phys. Rev. Lett.*, **92**, 246103(2004).

# Nano-biprism for evaluation of spatial coherence properties

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PHYSICAL REVIEW LETTERS

week ending  
18 JUNE 2004

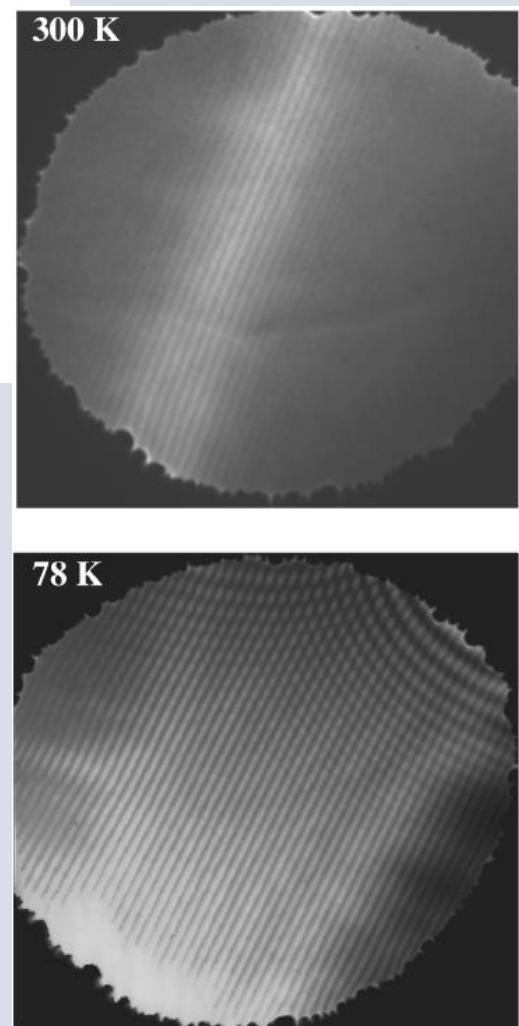
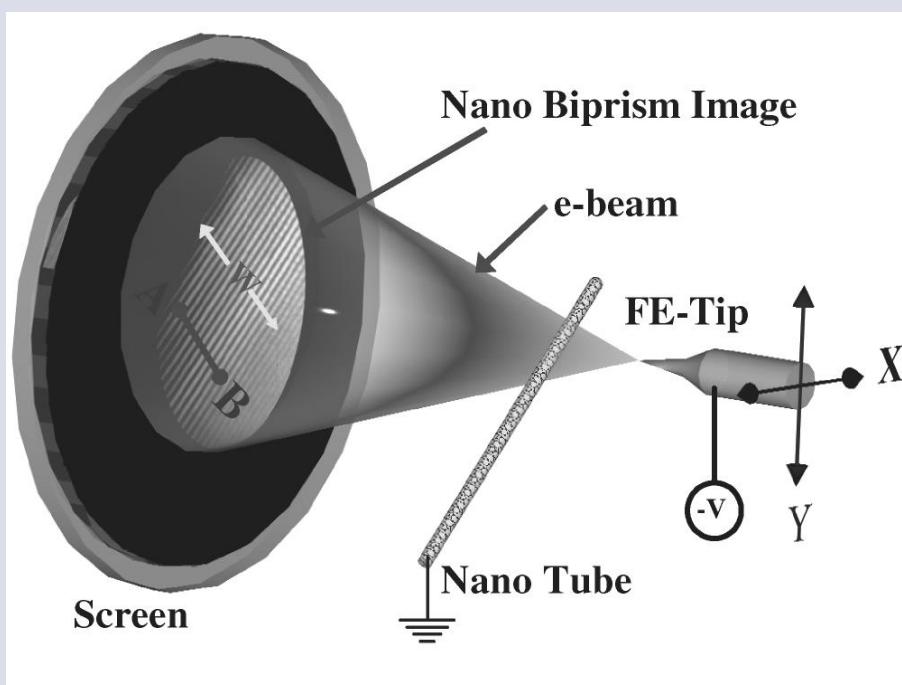
## Quantitative Evaluation of Spatial Coherence of the Electron Beam from Low Temperature Field Emitters

B. Cho,<sup>1,\*</sup> T. Ichimura,<sup>2</sup> R. Shimizu,<sup>3</sup> and C. Oshima<sup>1,2</sup>

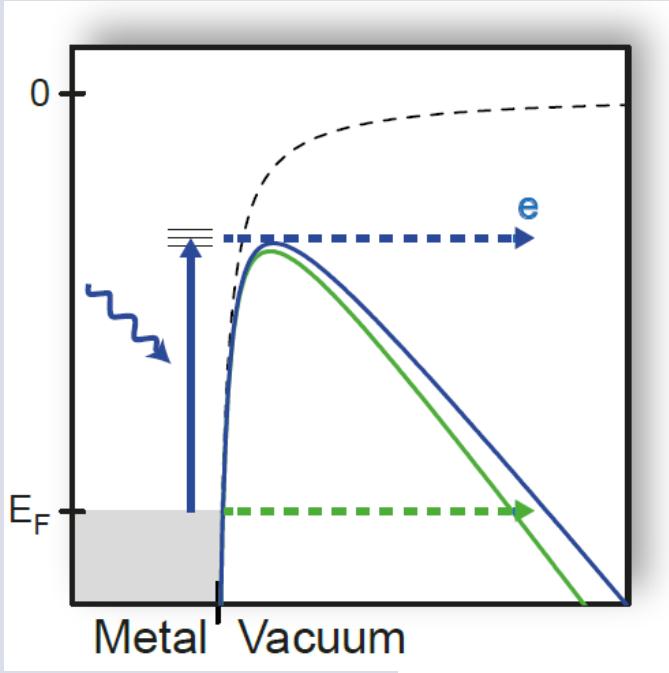
<sup>1</sup>*Kagami Memorial Laboratory for Material Science and Technology, Waseda University,  
2-8-26 Nish-waseda, Shinjuku-ku, Tokyo 169-0051, Japan*

<sup>2</sup>*Department of Applied Physics, Waseda University, 3-4-1 Okubo, Shinjuku, Tokyo 169-8555, Japan*

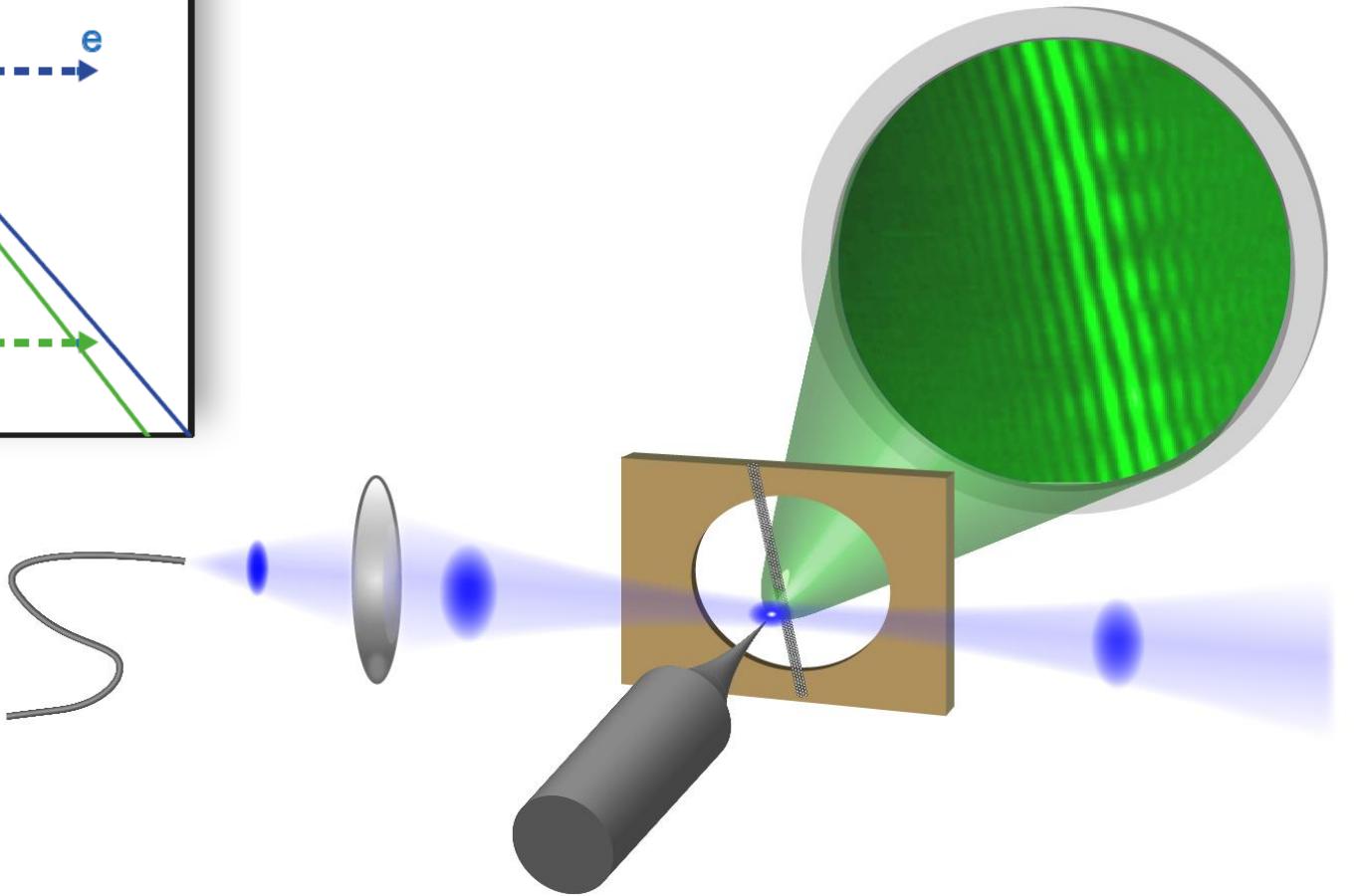
<sup>3</sup>*Department of Information Science, Osaka Institute of Technology, 1-79-1, Kitayama, Munakata-shi, Osaka, 173-0196, Japan*  
(Received 28 August 2003; published 16 June 2004)



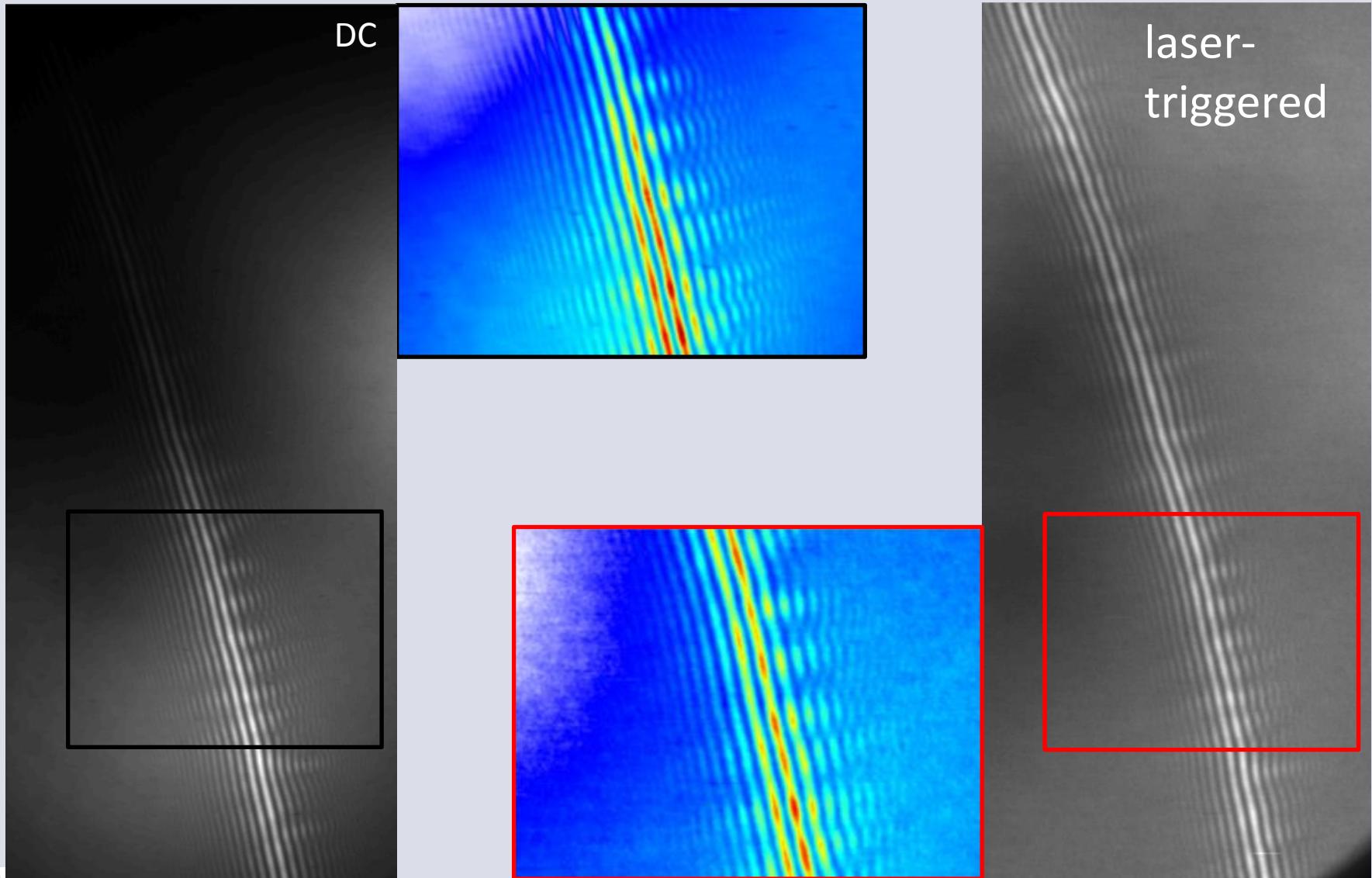
# Are laser-triggered electrons coherent?



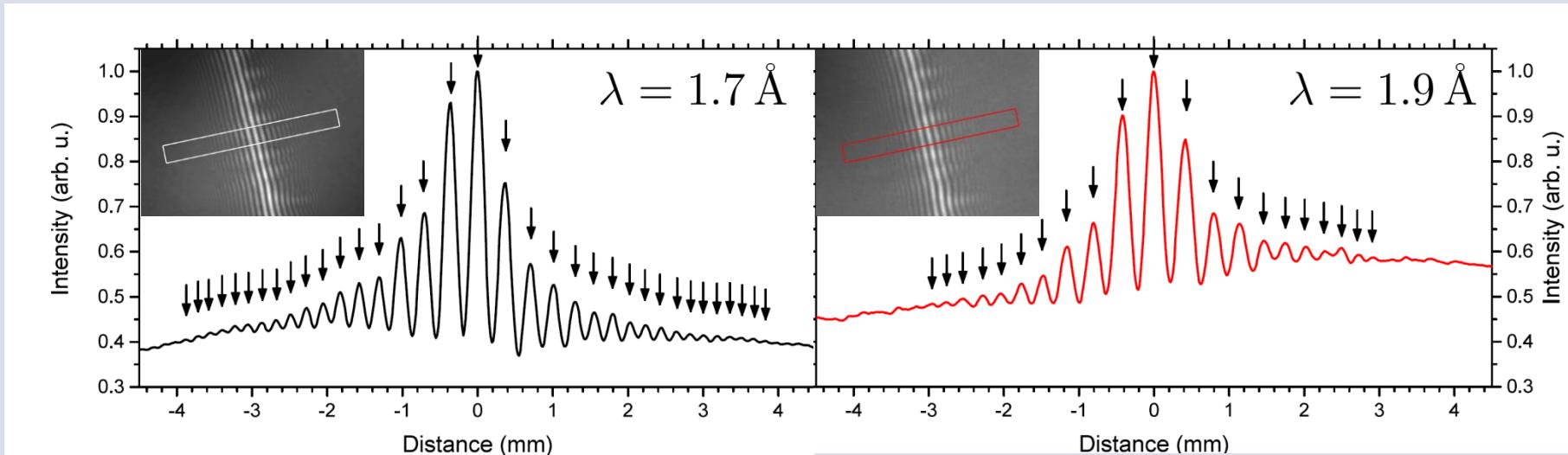
394nm and  
405nm  
(~3.2eV  
photon energy)



# Fringes: DC vs. photo-emitted



# Line profiles in DC and laser-triggered emission



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

$$C = 0.43$$

$$\xi_{\perp} \geq 7.7 \text{ mm}$$

$$r_{\text{eff}}^{\text{DC}} \leq 0.6 \text{ nm}$$

$$C = 0.32$$

$$\xi_{\perp} \geq 5.8 \text{ mm}$$

$$r_{\text{eff}}^{\text{lt}} \leq 0.8 \text{ nm}$$



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