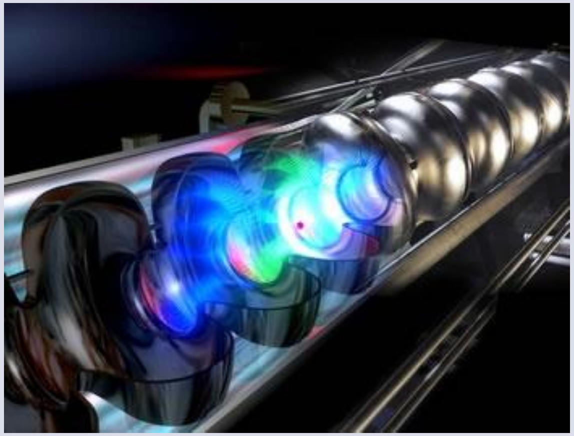
High-gradient novel laser accelerators

Trends in free electron laser physics – Erice, May 2016

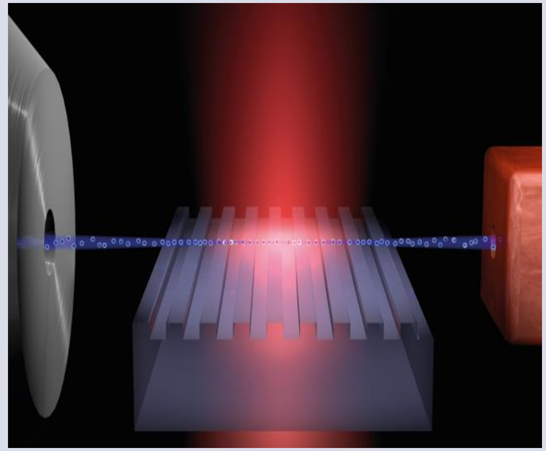
Joshua McNeur

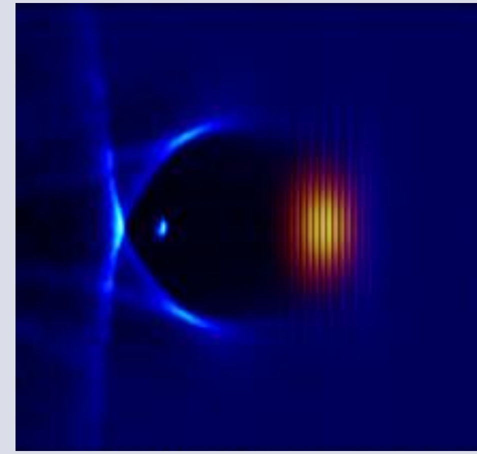
FRIEDRICH-ALEXANDER UNIVERSITÄT ERLANGEN-NÜRNBERG

Particle accelerators: from RF to beyond?



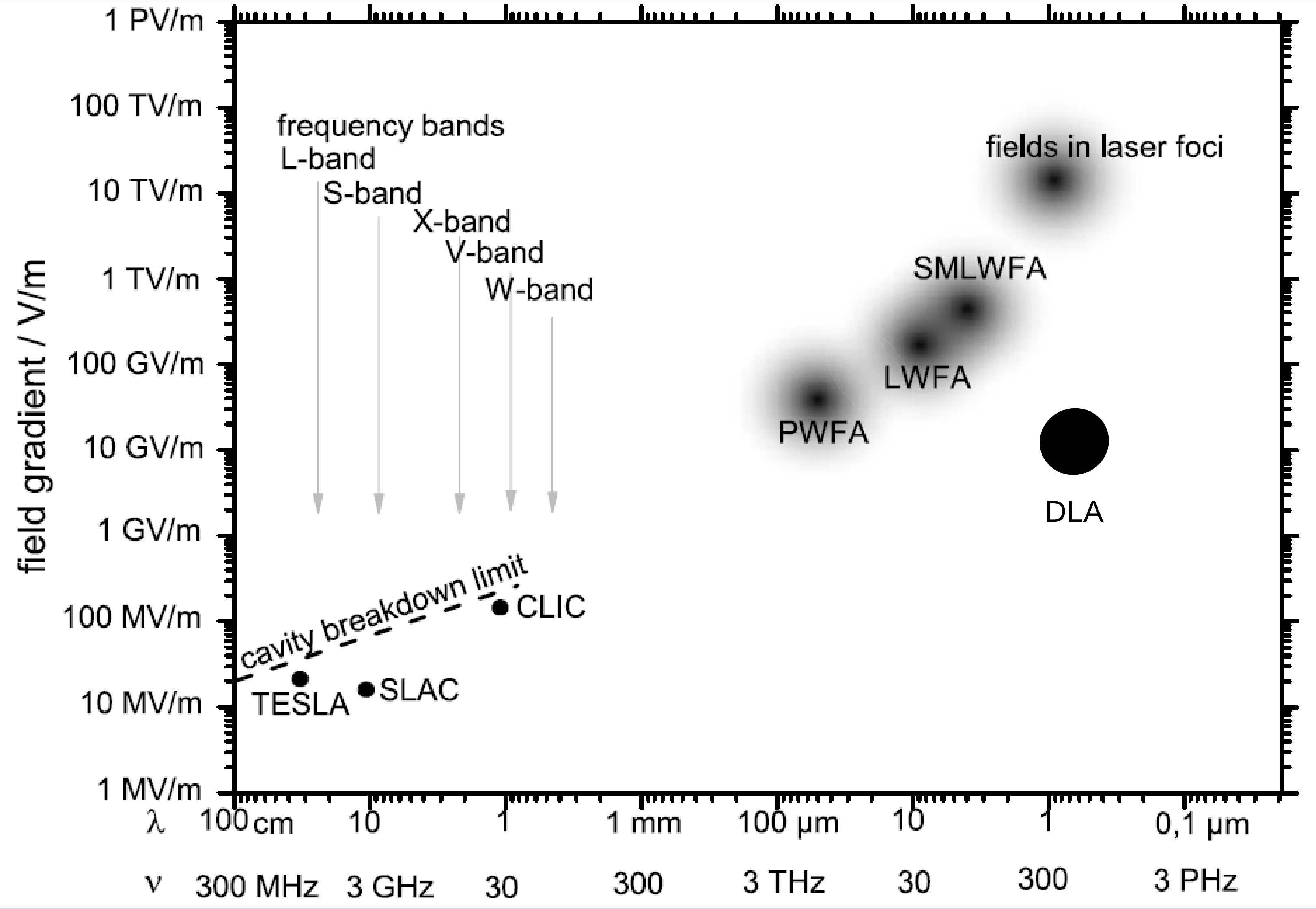
RF cavity (TESLA, DESY)





	RF accelerator	Dielectric laser accelerator	Laser plasma accelerator
Based on	(Supercond.) RF cavities	Dielectric grating structures	Plasmas
Peak fields limited by	**Surface breakdown: ~100 MV/m**	**Damage threshold: up to 30 GV/m**	**Wave breaking fields (100s of GeV/m)**
Max. achievable gradients	50 MeV/m	10 GeV/m	100s of GeV/m

Accelerator Scaling



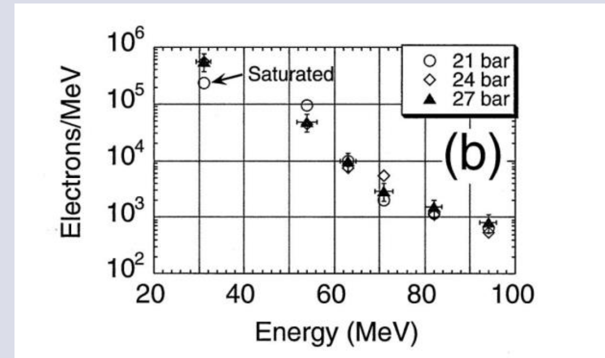
adapted from B. Hidding et al., Phys. Plasmas 16, 043105 (2009)

Motivation for laser plasma accelerators

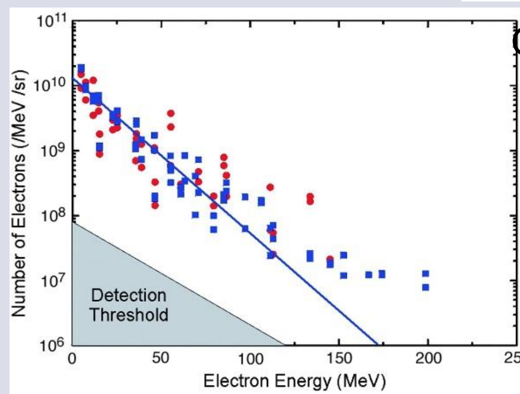
Have ability to sustain accelerating gradients in excess of

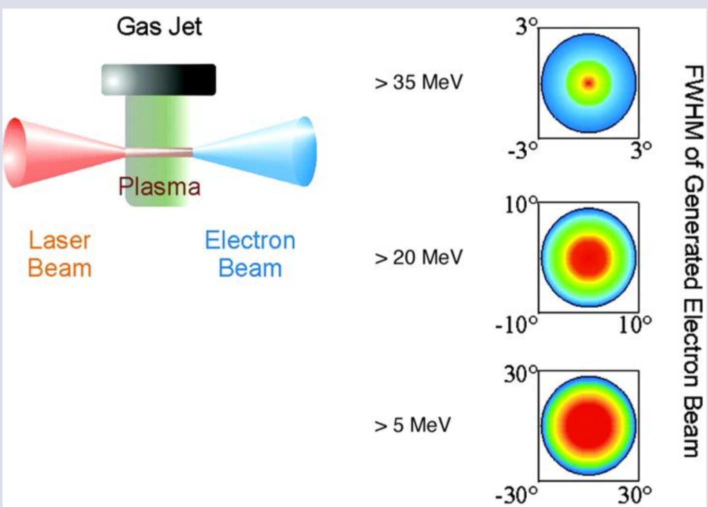
$$E_0 = \frac{c m_e \omega_p}{e} \cong 96\sqrt{n_0(cm^{-3})} \qquad \omega_p = \sqrt{\frac{4\pi n_0 e^2}{m_e}}$$

For $n_0 = 10^{18}$ cm^{-3} , E_0= 96 GV/m



Gordon et al., *PRL* 80 10 (1998)





>200 GeV/m max accel. gradient

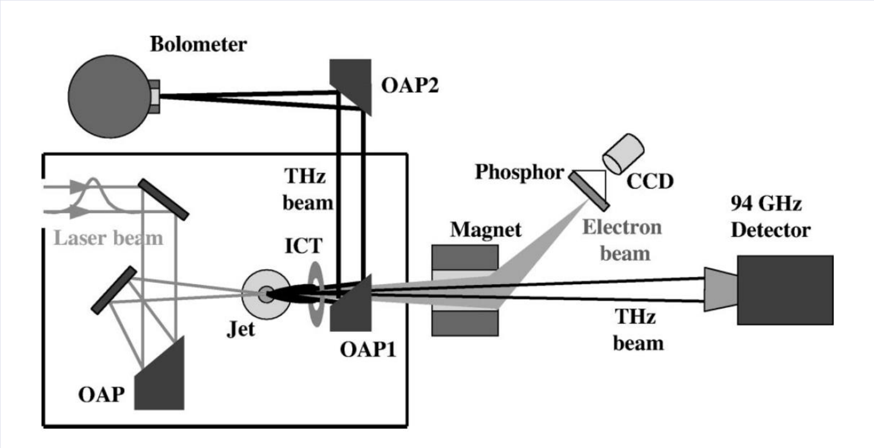
Malka et al., *Science* 22 298 (2002)

Motivation for laser plasma accelerators

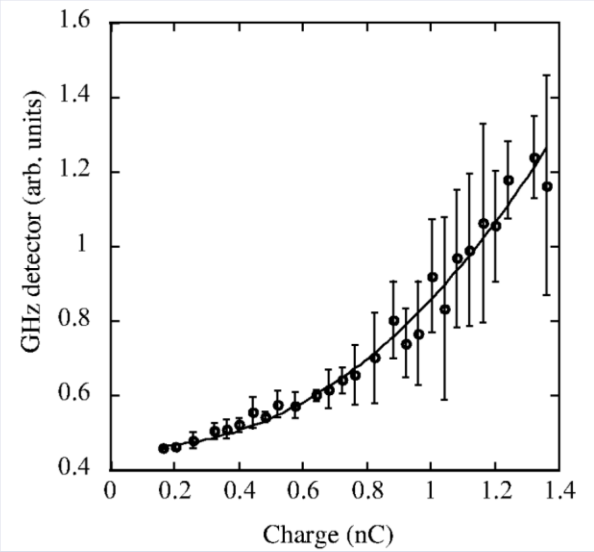
Generated/accelerated electrons have bunch lengths less than

$$\lambda_p(\mu m) = \frac{2\pi c}{\omega_p} \cong 3.3 * 10^{10}/\sqrt{n_0(cm^{-3})}$$

For $n_0 = 10^{18}$ cm^{-3} , λ_p= 33 μm and $\tau_B < \frac{\lambda_p}{c} = 100\ fs$



Leemans et al., *Phys. Plas.* 11 5 (2004)



Coherent transition radiation spectrum consistent with bunch length <50 fs

Characterizing the fields - parameters

Convenient to use normalized potentials $\phi = e\Phi/m_e c^2$ and $\boldsymbol{a} = e\boldsymbol{A}/m_e c^2$

Laser strength parameter a_0 is the peak amplitude of the laser field, related to intensity and power:

$$I_0 = \left(\frac{\pi c}{2}\right)\left(\frac{m_e c^2 a_0}{e\lambda}\right)^2 \;\&\; P = \pi r_0^2 I_0/2$$

$$a_0^2 \approx 7.3 * 10^{-19}[\lambda(\mu m)]^2 I_0\left(\frac{W}{cm^2}\right) \;\&\; P(GW) = 21.5\left(\frac{a_0 r_0}{\lambda}\right)^2$$

Conservation of transverse canonical momenta => $\boldsymbol{a} = \boldsymbol{p}_\perp/m_e c$ is the normalized transverse quiver motion.

When $a_0^2 > 1$, quiver motion is relativistic and the plasma-laser interaction is nonlinear
-for $n_0 = 10^{18}$ cm^3 , laser intensities of $>10^{18}$ W/cm^2 required at wavelength= 1 μm

Fields in the linear regime

a_0^2<<1: Wakefields driven by ponderomotive force

Leading term in electron fluid motion is quiver motion $\boldsymbol{p}_q$, with $\partial \boldsymbol{p}_q / \partial t = e\boldsymbol{E}$

Letting $\boldsymbol{p}=\boldsymbol{p}_q + \delta\boldsymbol{p}$, second order of electron fluid motion is described by the radiative, ponderomotive force

$$d\delta p/dt = -m_e c^2 \nabla(a^2/2)$$

Leading to the generation of wakes as electrons are expelled from the region of highest intensity. In the linear regime, the resulting wakefields can be analyzed through the Poisson equation, continuity equation, and fluid momentum equation, with a solution:

$$\delta n/n_0 = (c^2/\omega_p)\int_0^t dt' \sin[\omega_p(t-t')]\nabla^2 a^2(r,t')/2$$

$$\delta \boldsymbol{E}/E_0 = -c\int_0^t dt' \sin[\omega_p(t-t')]\nabla a^2(r,t')/2$$

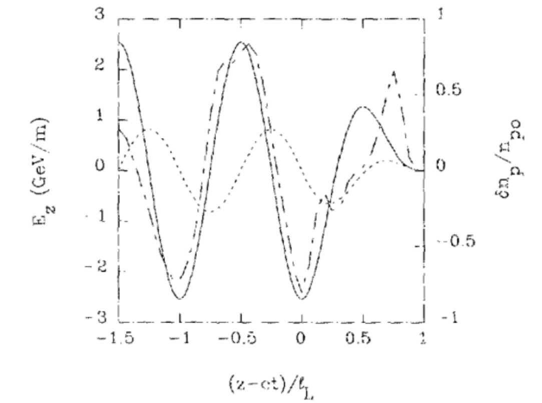


FIG. 2. Theoretical axial wakefield (solid curve), theoretical density wake (dotted curve), and the axial wakefield obtained from the particle code FRIEZR (dashed curve) for $l_L = \lambda_p = 0.03$ cm, $a_{L0}^2 = 0.31$ and $r_L = 0.038$ cm. The laser pulse extends over the region $0 \leq (z-ct)/l_L \leq 1$.

Sprangle et al., *APL* **53**, 2146 (1988)

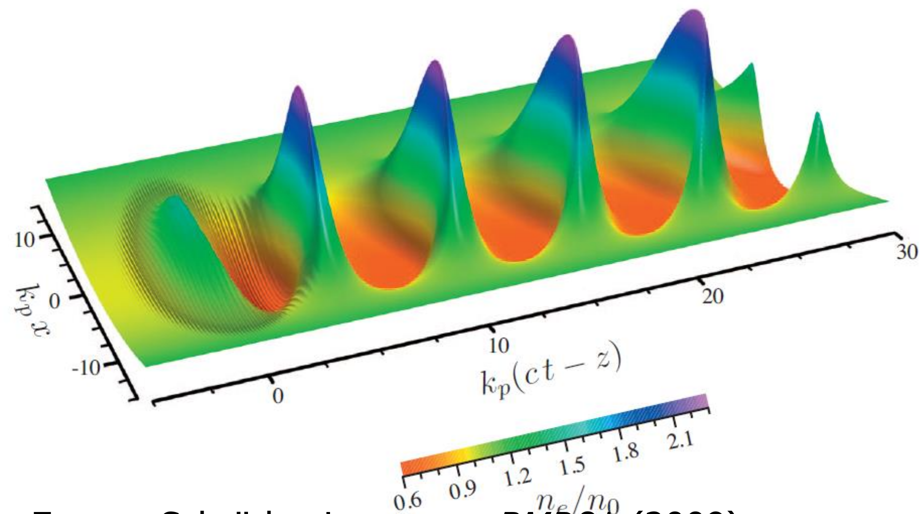
Fields in the nonlinear regime

When $a_0^2 > 1$, the plasma wave becomes highly nonlinear. The Poisson equation (when combined with the quasistatic fluid momentum and continuity equations) becomes

$$k_p^{-2}\frac{\partial^2\phi}{\partial^2\xi} = \gamma_p^2\left\{\beta_p\left[\frac{1+a^2}{\gamma_p^2(1+\phi)^2}\right]^2 - 1\right\}$$

$$\xi = z - ct \quad \beta_p = v_p/c \quad \gamma_p = (1-{\beta_p}^2)^{-1/2}$$

$$E_z = -E_0\frac{\partial\phi}{\partial\xi}$$



Esarey, Schröder, Leemans, *RMP* 81 (2009)

FIG. 2. (Color) Plasma density perturbation excited by Gaussian laser pulse with $a_0=1.5$, $k_0/k_p=20$, $k_pL_{\rm rms}=1$, and $k_pr_0=8$. Laser pulse is traveling to the left.

As *a* increases, plasma wave steepens and wavelength increases

Shorter wavelength away from peak intensity (i.e. off-axis)

Periodic wave solutions exist for amplitudes up to "wave breaking limit"

$$E_{WB} = \sqrt{2}\left(\gamma_p - 1\right)^{1/2}E_0$$

Esarey, E., and M. Pilloff, Phys. Plasmas **2**, 1432 (95)

$$\gamma_g = (\omega/\omega_p)[(\gamma_\perp + 1)/2]^{1/2}$$

$$\gamma_\perp^2 = 1 + u_\perp^2 = 1 + a^2$$

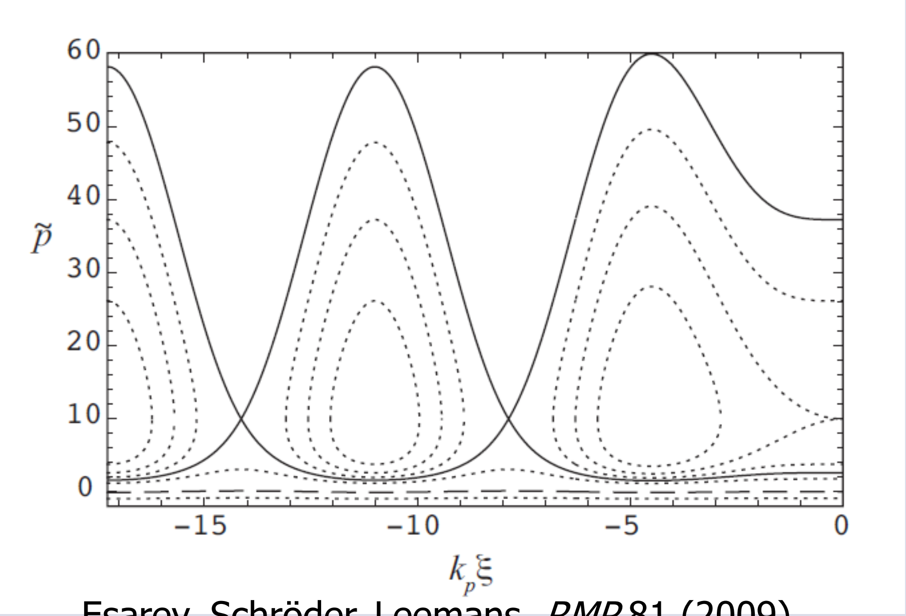
Characterizing the particle dynamics

Dynamics of accelerated electrons (for 1d nonlinear plasma wave) described by Hamiltonian

$$H(\tilde{p},\psi) = \tilde{\gamma} - \beta_p \tilde{p} - \phi(\psi)$$

With $\phi(\psi)$ solved for in the Poisson eqn, orbits are determined by paths of constant H

Depending on initial cond'ns, particles are either trapped or untrapped



Esarey, Schröder, Leemans, *RMP* 81 (2009)

For trapped particles, maximum energy is given by (Esarey, E., and M. Pilloff, Phys. Plasmas **2**, 1432 (95))

$$\tilde{\gamma}_{max} \cong 2\gamma_p^2 \times \begin{cases} 2\hat{E}_{max} & \text{for } 2 \gg \hat{E}_{max}^2 \gg 1/4\gamma_p^2 \\ \hat{E}_{max}^2 & \text{for } \hat{E}_{max}^2 \gg 2 \end{cases}$$

Characterizing the particle dynamics

As electrons approach the speed of light, they soon outrun the plasma wave with velocity $v_p < c$.

For $E<E_0$,, the distance L_d over which electrons slip by one half of a period can be approximated by the total energy gain

$$W_{max} = eE_{max}L_d = m_e c^2 \tilde{\gamma}_{max}$$

For $\gamma_p^2 >>1$,

$$L_d = \frac{m_e c^2 \tilde{\gamma}_{max}}{eE_{max}} = \gamma_p^2 \lambda_{Np} \times \begin{cases} 2/\pi & \hat{E}_{max} \ll 1 \\ 1/2 & \hat{E}_{max} \gg 1 \end{cases}$$

Moreover, for $\gamma_p^2 >>1$ and $\gamma_p (\frac{E_{max}}{E_{WB}})^2 \gg 1$

$$\tilde{\gamma}_{max} = 4\gamma_p^3 (\frac{E_{max}}{E_{WB}})$$

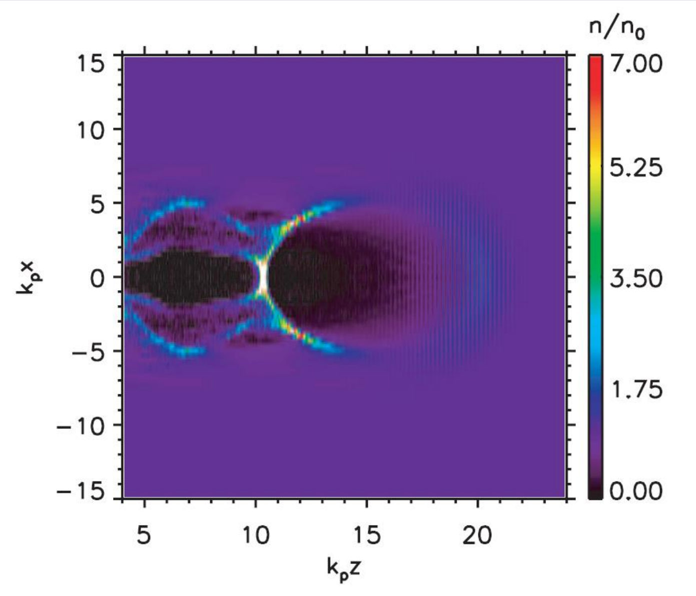
For fixed E_{max}/E_{WB}, the maximum energy gain scales as $n_0^{-3/2}$, so significantly higher single stage energy gains available at lower densities

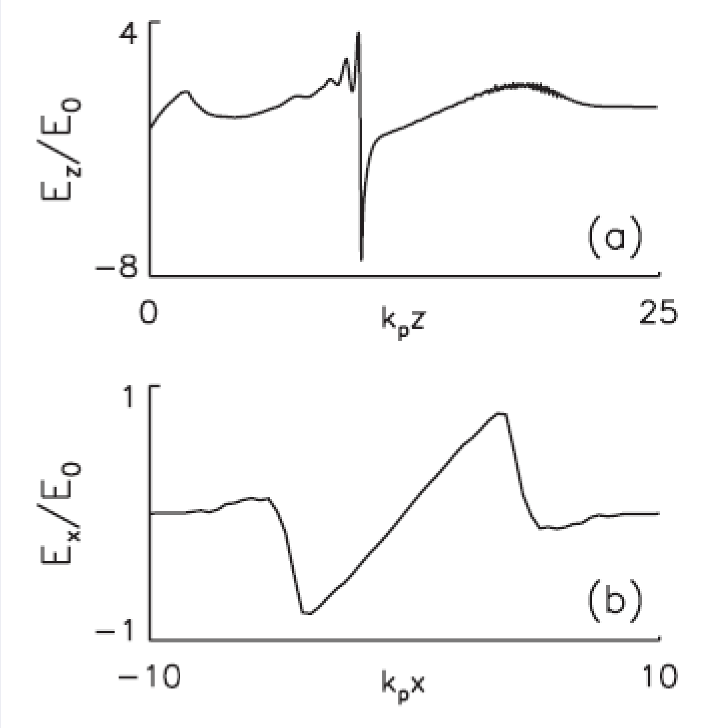
Blowout regime

In blowout regime, electrons are expelled from a "bubble" behind the wavefront

$$a_0^2/(1+a_0^2)^{1/2} \geq k_p^2 r_0^2/4$$

λ_{Np} larger on axis than off (intensity depend.)





Accel. fields linear behind laser pulse

Transverse fields linearly focusing (emittance preserving)

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Blowout regime in PWFAs

Bubble can also be formed due to passage of particle beam and resulting space charge repulsion

$$\frac{n_b}{n_0} > 1, \sigma_b < \lambda_p$$

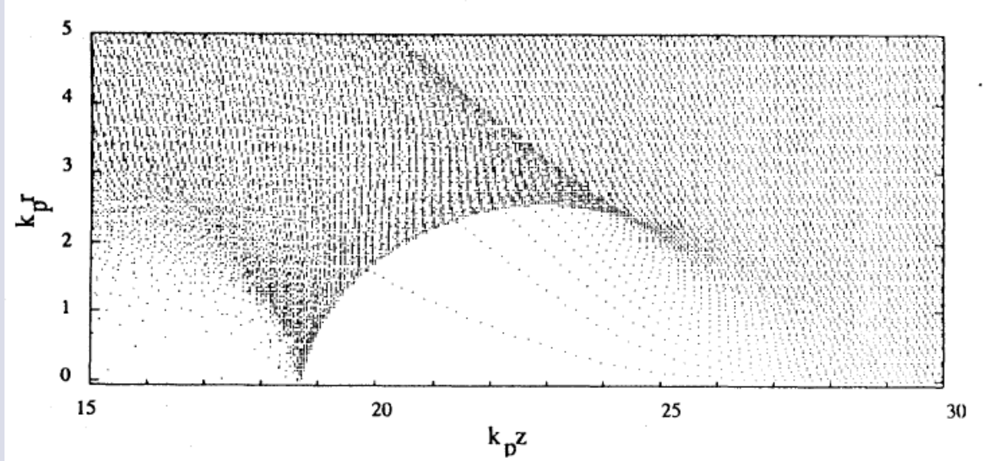
$$E_z \simeq (k_p\zeta/2)E_0,$$

$$E_r \simeq (k_p r/4)E_0,$$

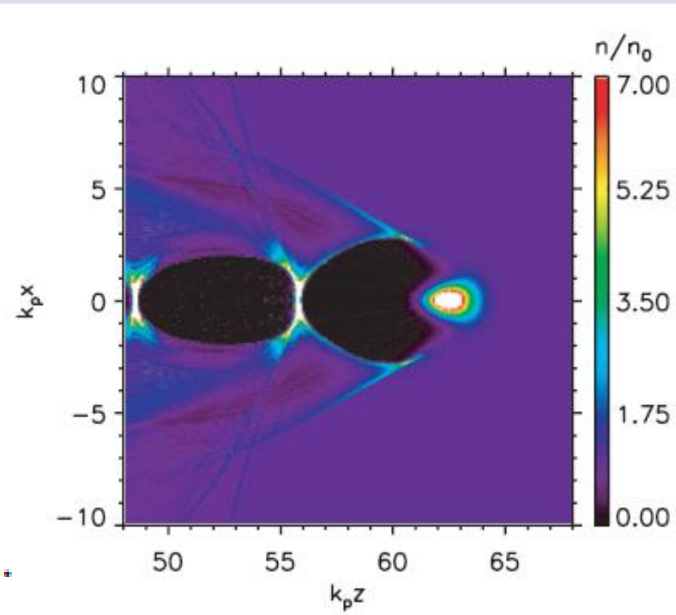
$$B_\theta \simeq -(k_p r/4)E_0.$$

$$F_r = E_r - B_\theta = (k_p r/2)E_0$$

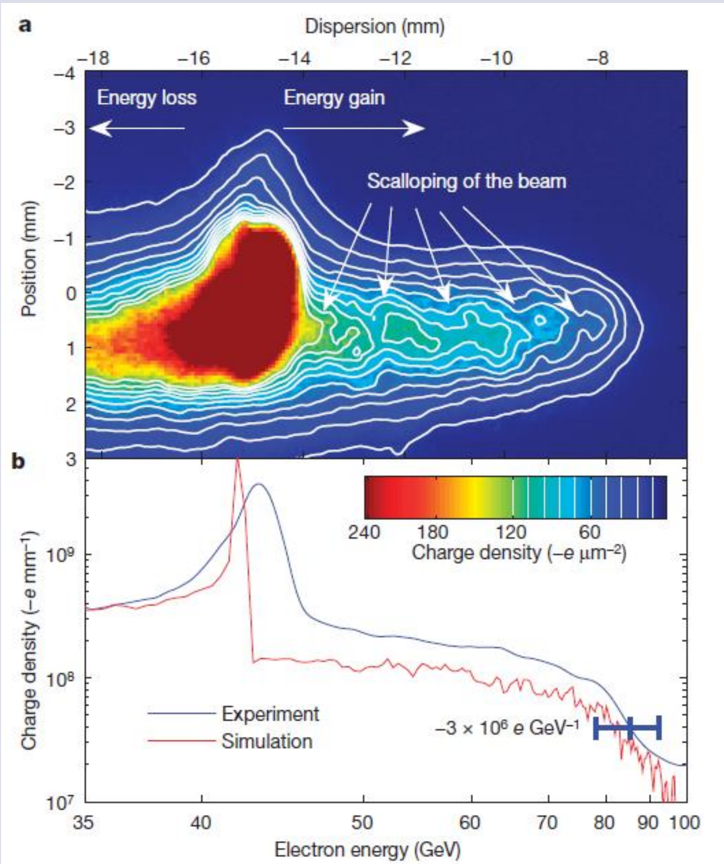
$$E_r(\mathrm{MV/m}) \simeq 9.06 \times 10^{-15} n(\mathrm{cm}^{-3})\sigma_r(\mu\mathrm{m}).$$

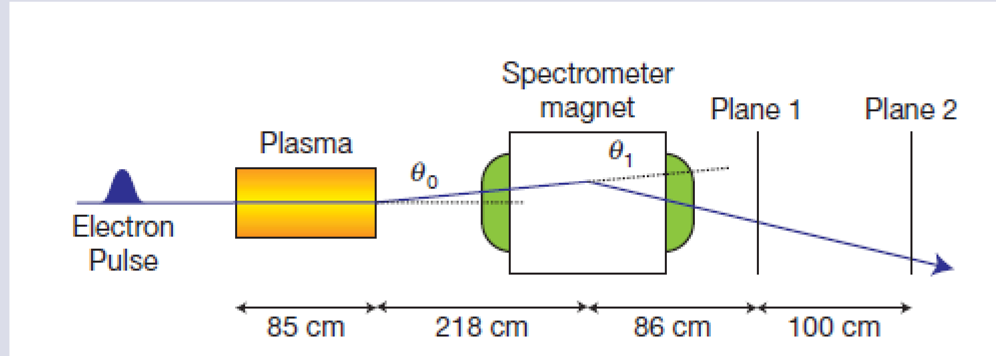


Rosenzweig et al., *Phys. Rev. A*, **44** 10 (1991).



PWFA in the blowout regime





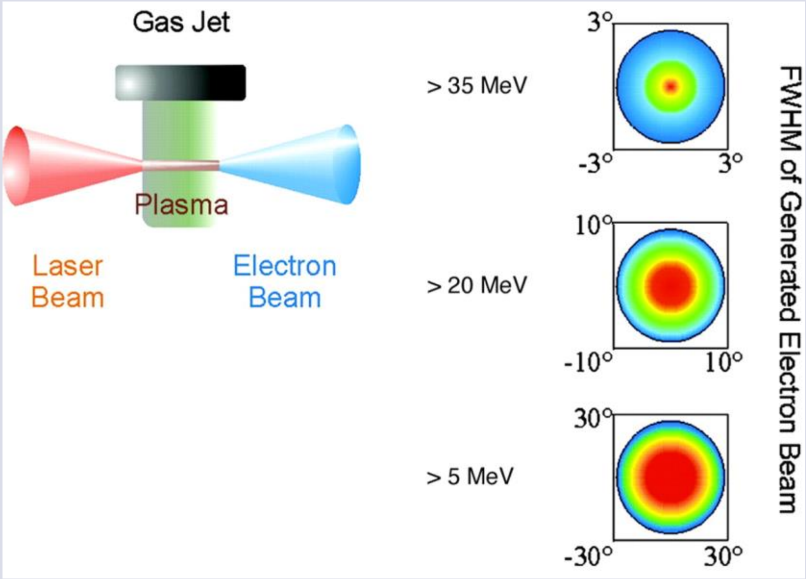
42 GeV, 50 fs bunch injected

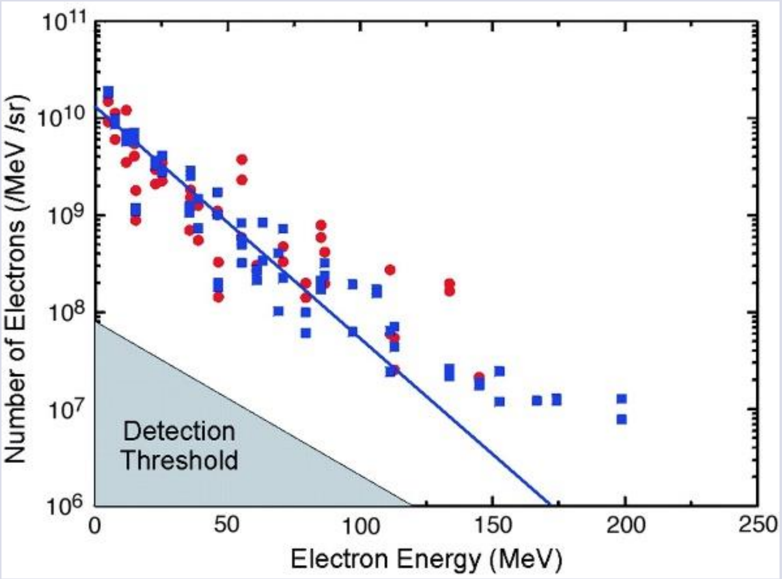
Electrons at front of bunch form wake,
those in tail are accelerated to >80 GeV

Dephasing occurs over longer distance than lasers,
diffraction of laser pulse no longer a problem
Potentially beneficial for long distance incteraction

Blumenfeld et al., *Nature*, **445** (2007).

Acceleration in the blowout regime





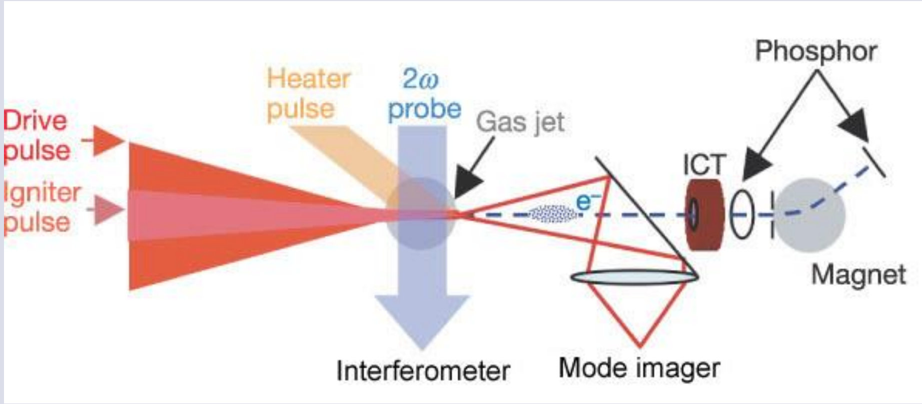
Malka et al., *Science* 22 298 (2002)

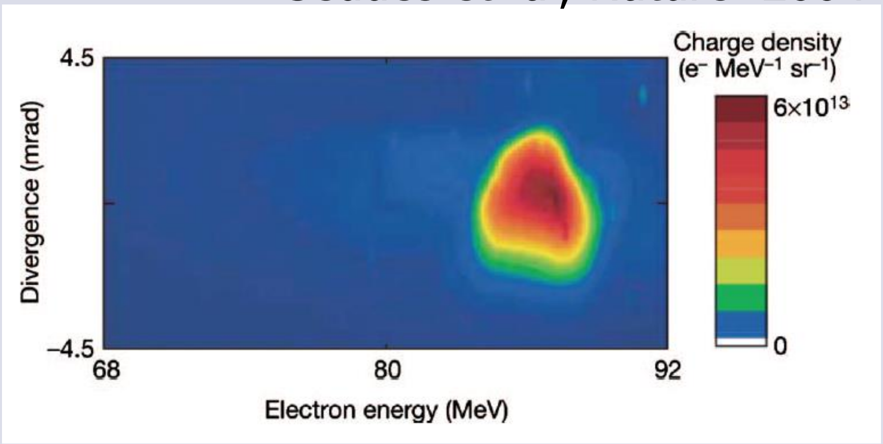
Wake generated in He gas jet (n_0 varied b/w 2*10^{19} and 6*10^{19} cm^{-3}) by 30 fs, 30 TW ($a_0 = 1.2$) laser pulse

Electrons trapped in wake are accelerated to 200 MeV over 900 µm

High quality electron bunches at 100 MeV

Geddes et. al, *Nature* 2004





Wakefields excited in preformed 2 mm long plasma channel, with 9 TW, 55fs, laser spot. Plasma-laser pulse feedback leads to pulse shortening and steepening -> blowout regime

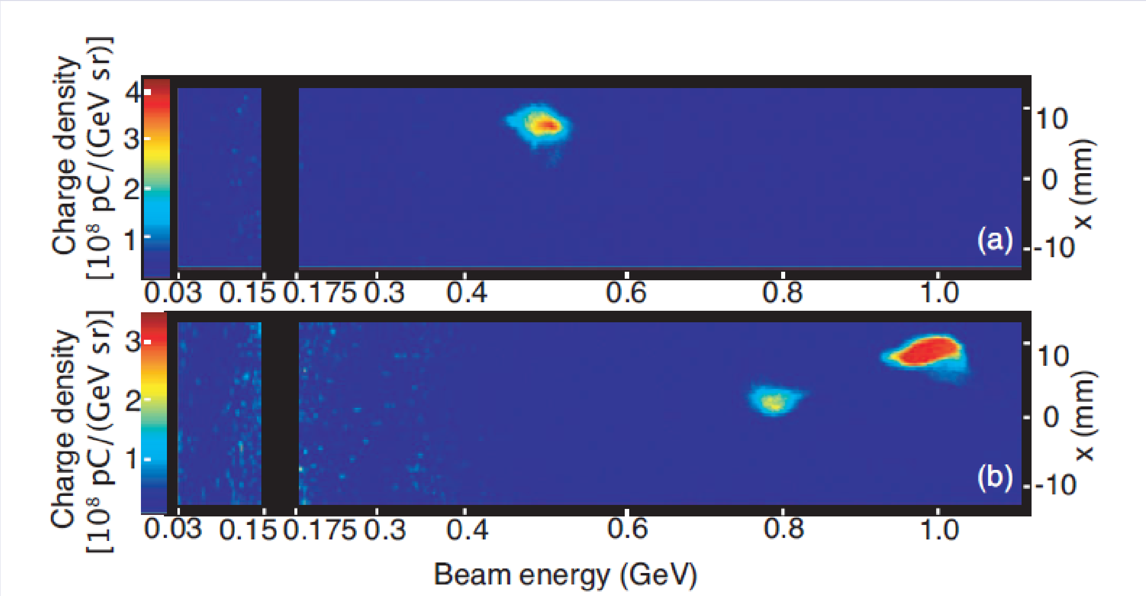
Pre-formed plasma channel keeps laser focused longer than Rayleigh length (on the order of 100 µm due to small focus of 8.5 µm)

Electrons are trapped in the wake (if orbits are within seperatrix) and accelerated

Self-trapping is then terminated due to beam loading (enough electrons – $2*10^9$ to reduce fields below trapping threshold)

Acceleration over long distance reaching the dephasing length (and thus minimal spread)

High quality electron beam at 1 GeV



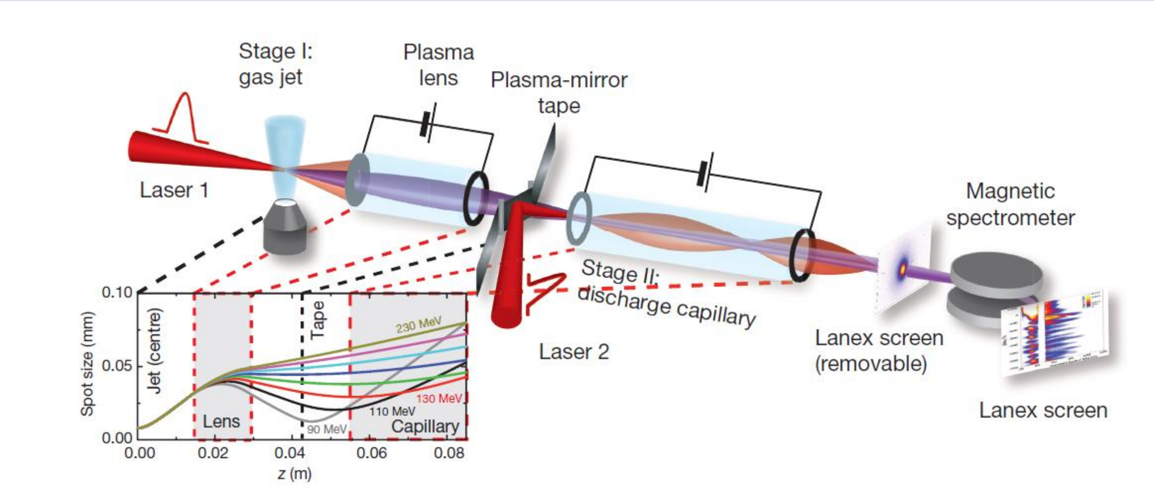
Energy gain extended to 1 GeV by using: 40 TW laser, 3.3cm plasma channel (gas-filled capillary discharge waveguide at lower density ~10^{18})

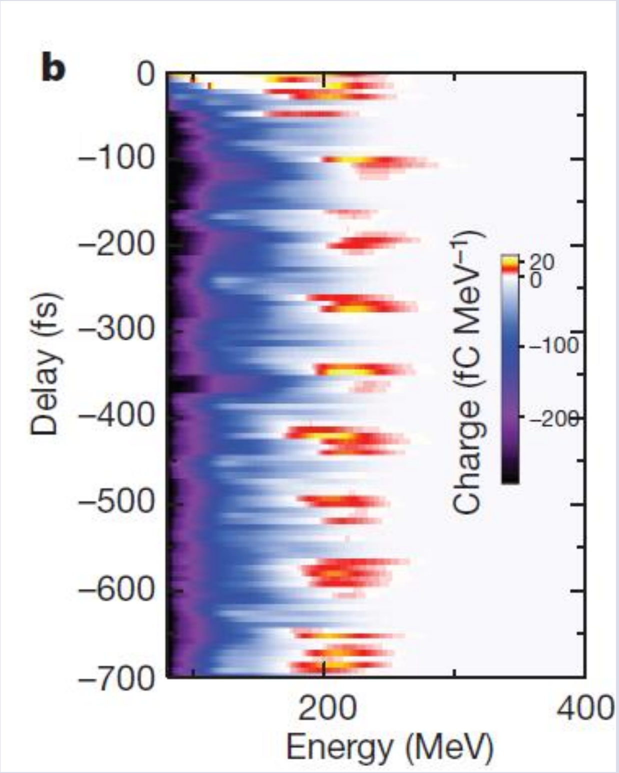
And lower plasma density (so longer dephasing length) -> larger energy gain

50 pC trapped at 0.5 GeV, 30 pC at 1 GeV (gas density varied from 4 to 1 x 10^{18} cm^{-3})

Leemans, Nagler, *et al.*, 2006; Nakamura *et al.*, 2007

Staging in a LPA





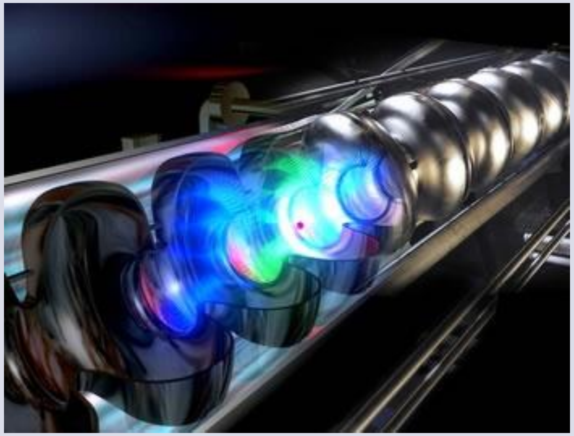
Steinke et al., *Nature* **530** (2016)

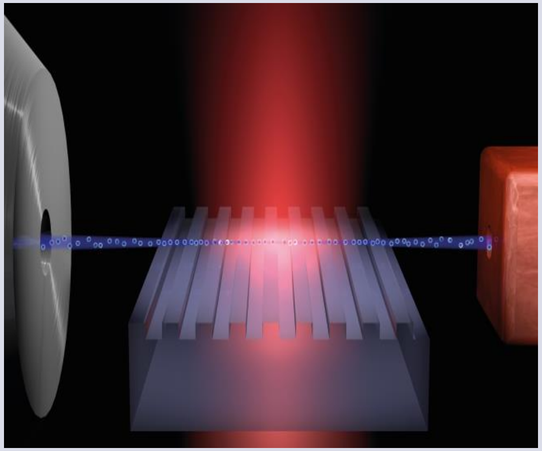
To get to even higher energies (e.g. for HEP), staging is necessary

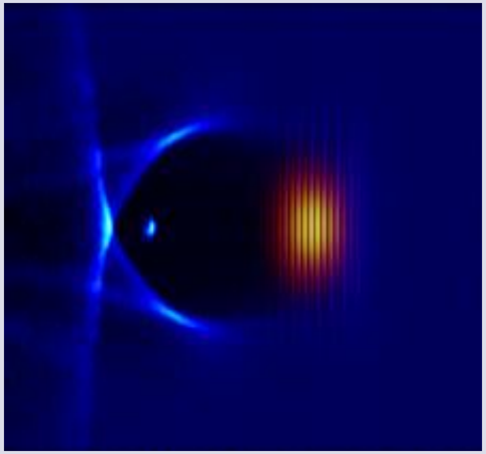
Two stage LPA demonstrated

Energy gain, accelerated charge both oscillate with relative phase of laser pulses in each stage

Particle accelerators: from RF to beyond?







RF cavity (TESLA, DESY)

	RF accelerator	**Dielectric laser accelerator**	**Laser plasma accelerator**
Based on	(Supercond.) RF cavities	Dielectric grating structures	Plasmas
Peak fields limited by	**Surface breakdown: 200 MV/m**	**Damage threshold: up to 30 GV/m**	Wave breaking fields (100s of GeV/m)
Max. achievable gradients	50 MeV/m	10 GeV/m	100s of GeV/m

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

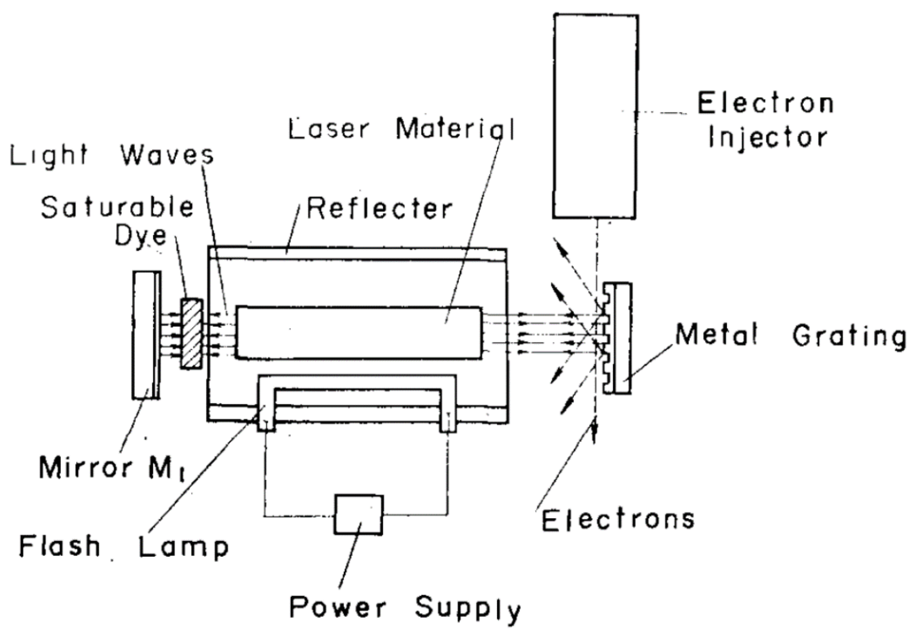


Fig. 1. Schematic diagram of "laser linac with grating".

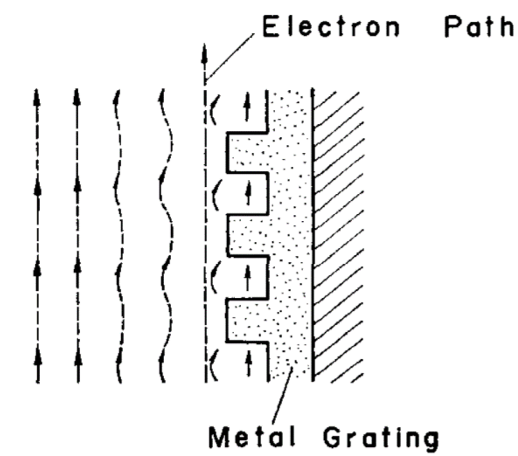


Fig. 2. Configuration of electric-field near grating surface.

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)

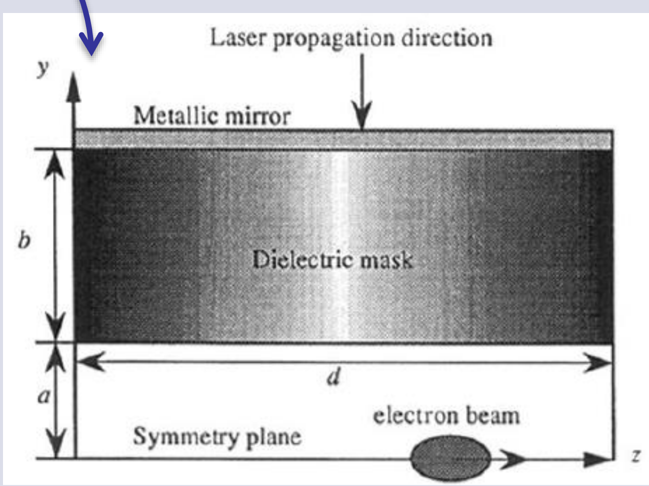
Proposed structure for a crossed-laser beam, GeV per meter gradient, vacuum electron linear accelerator

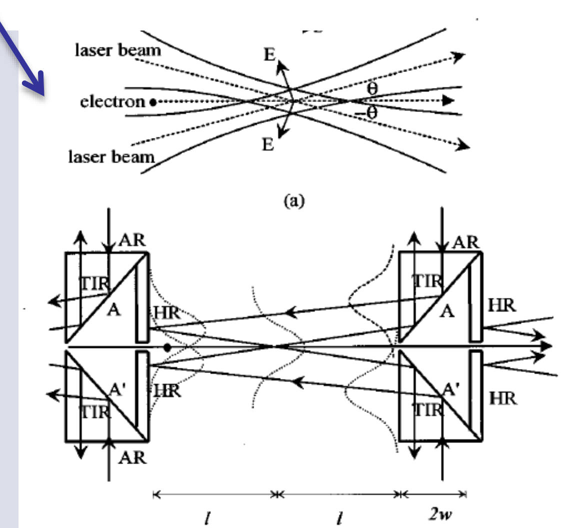
Appl. Phys. Lett. 68, 753 (1996)

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

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

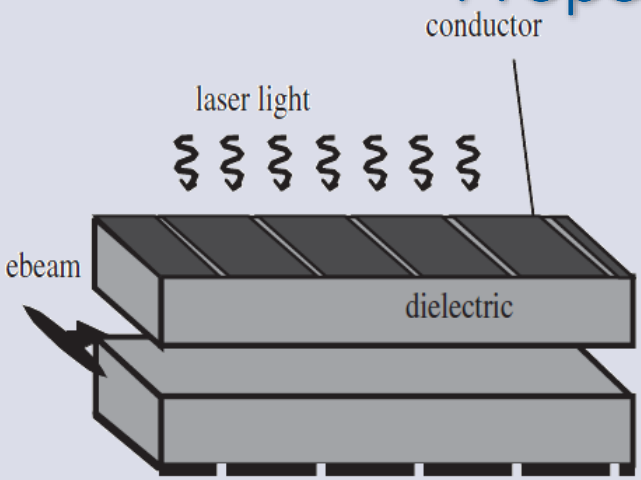
(Received 6 October 1995; accepted for publication 4 December 1995)



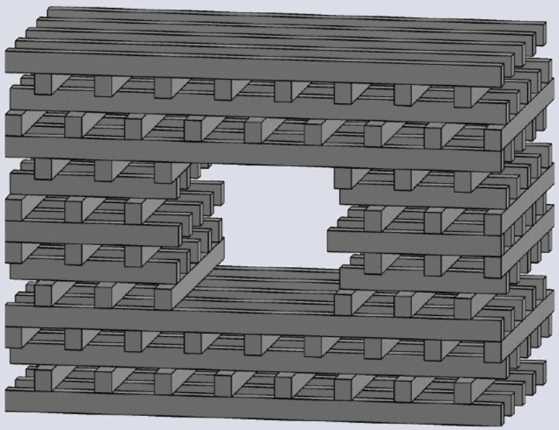


Other longtime players: Sieman group (SLAC), Travish (UCLA), Yoder (Manhattan) …

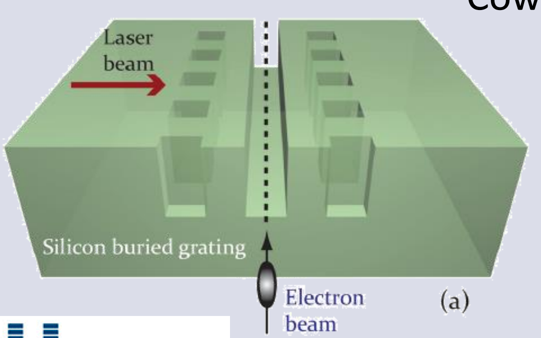
Proposed dielectric structures



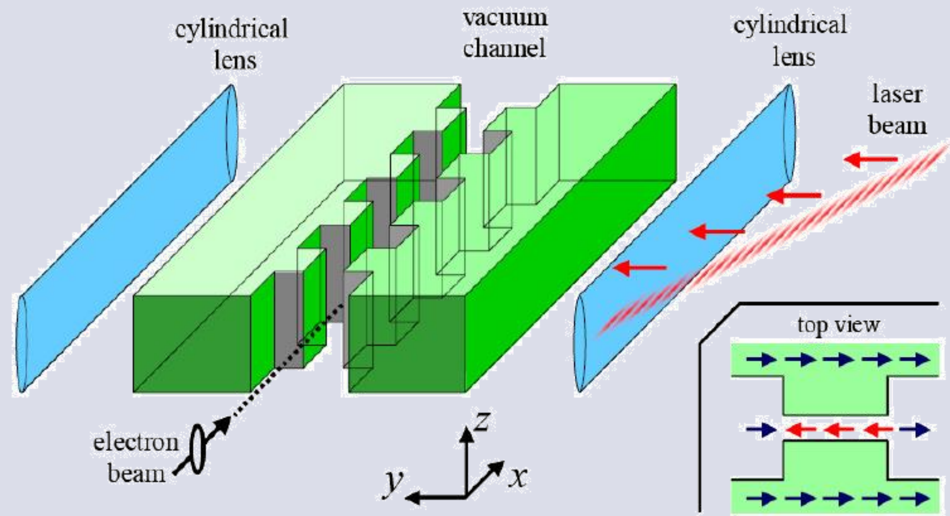
Yoder
Rosenzweig,
2005



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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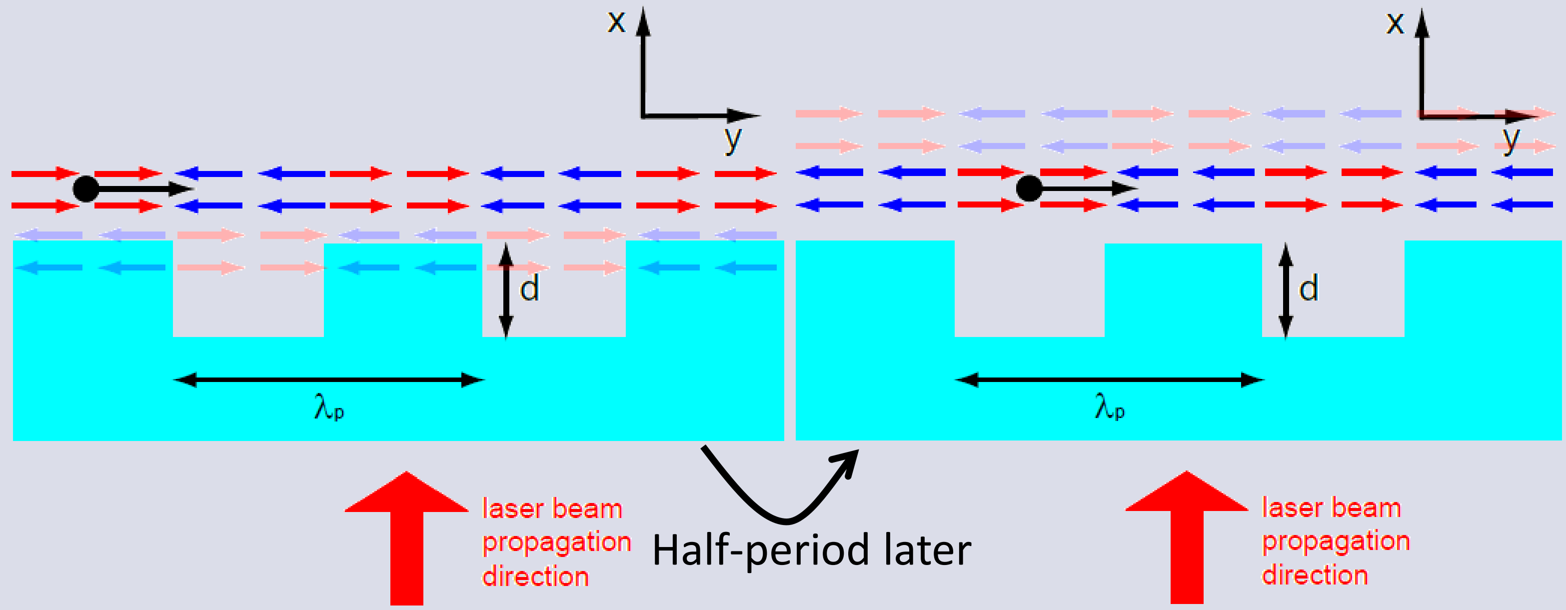
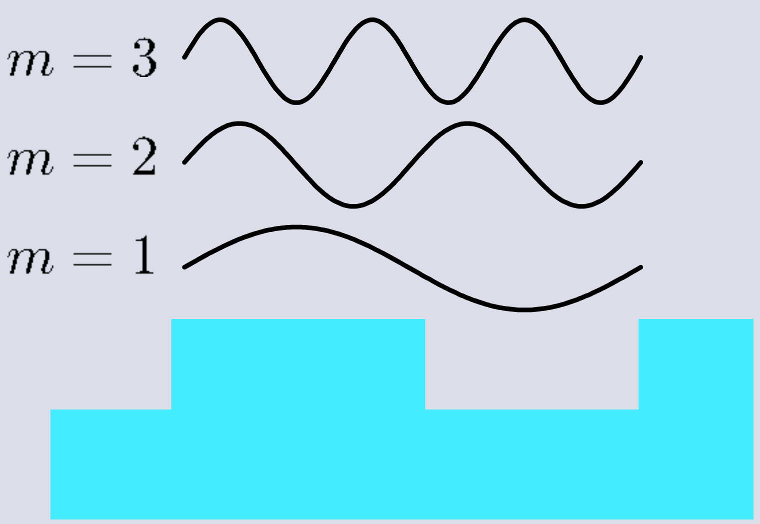
Periodic field reversal and spatial harmonics





Synchronicity condition:

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

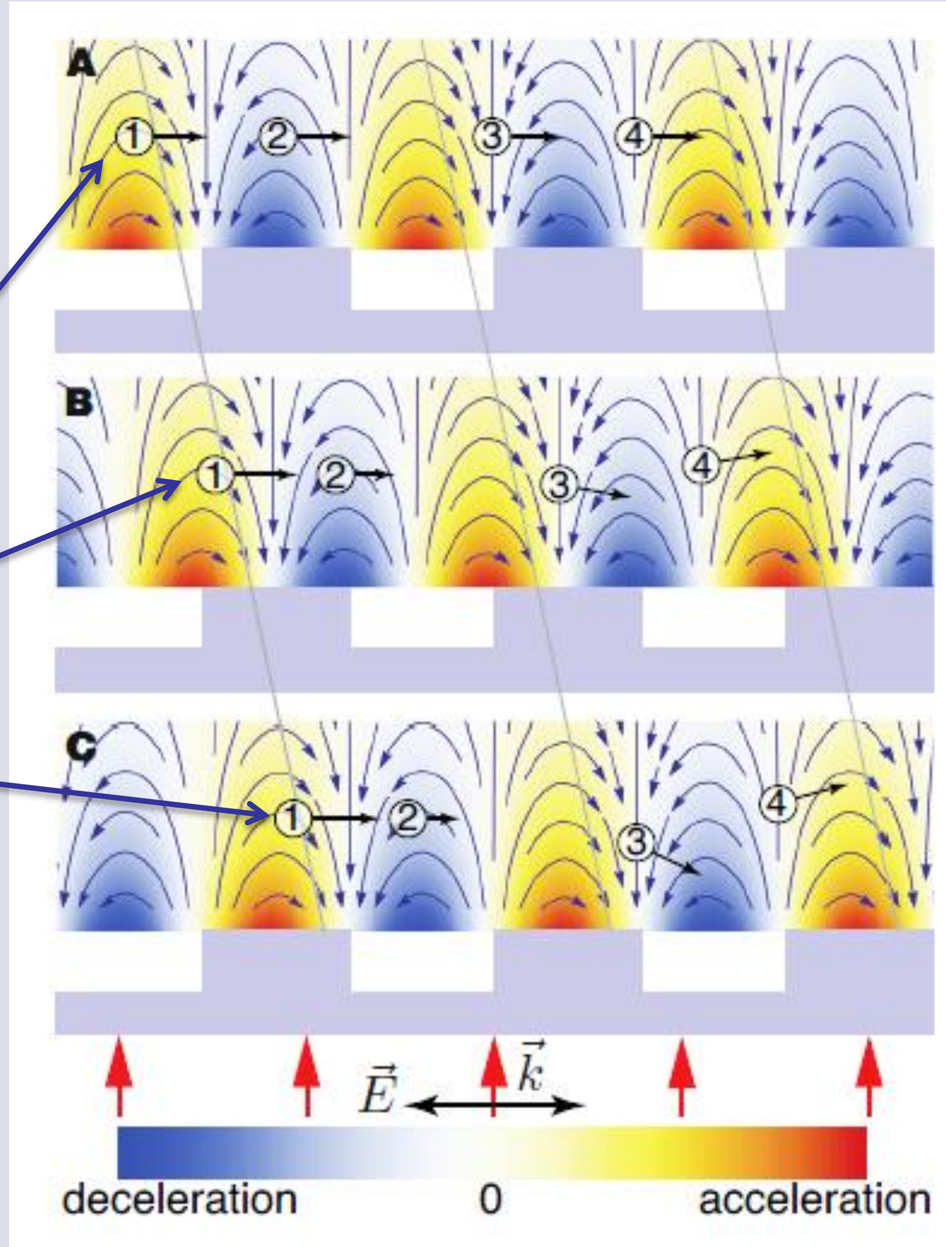
(*m*: # of laser cycles per electron passing one period, $\beta = v/c,\ \lambda$: laser wavelength)

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



t = 0

t = π/2

t = π

1 acceleration

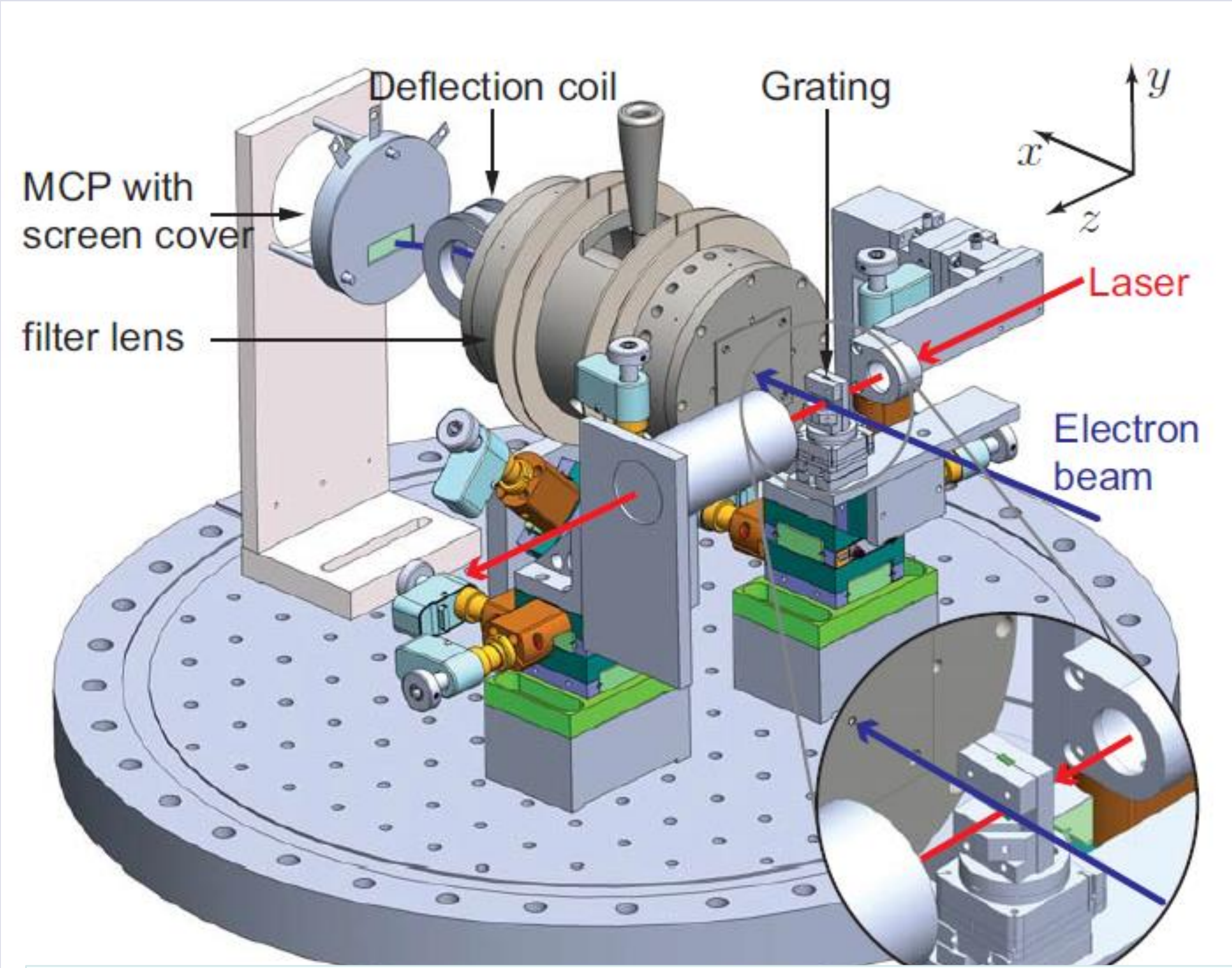
2 deceleration

3 deflection

4 deflection

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

Sketch of setup



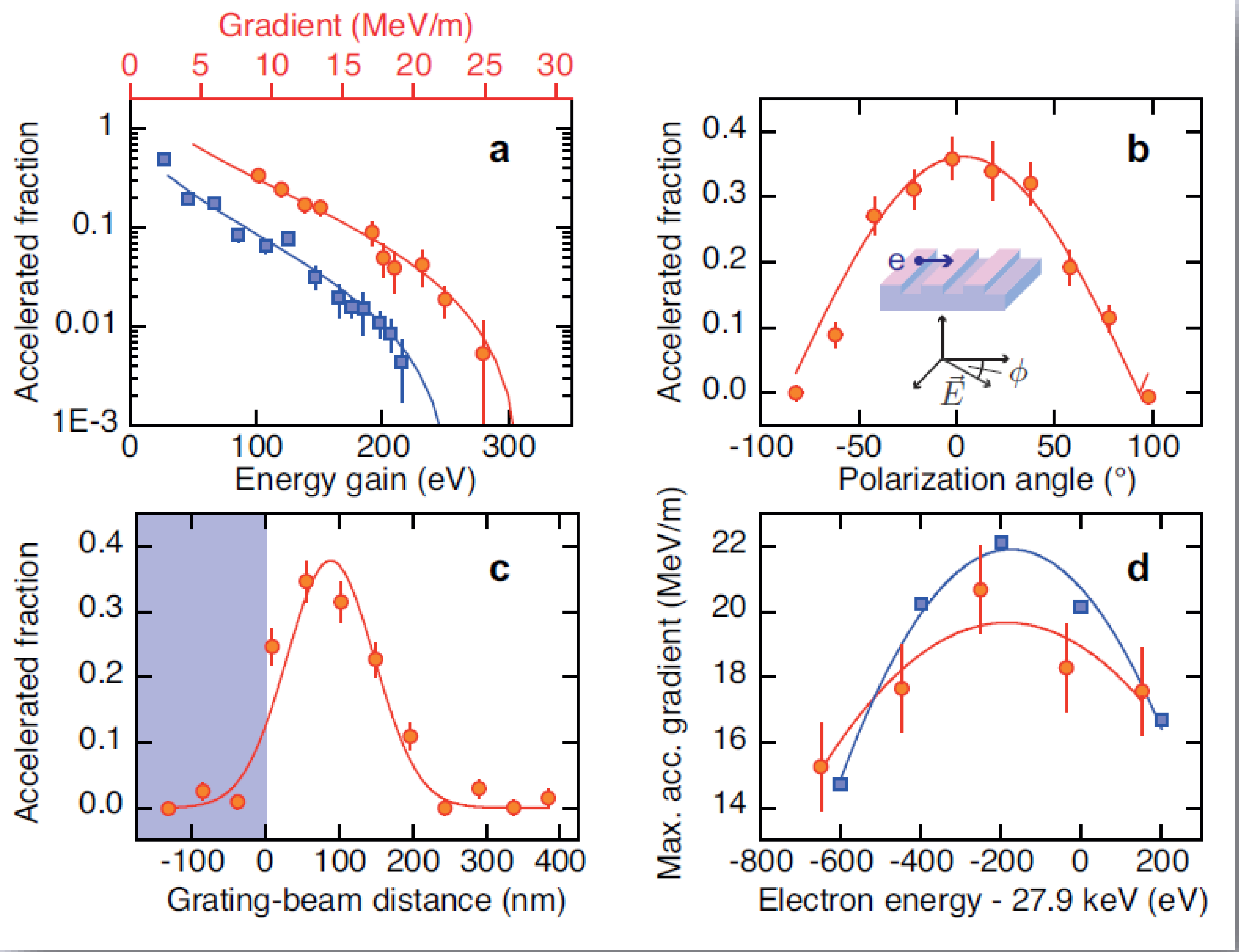
Ti:Sapph
laser parameters:
- 350 mW
- 2.745 MHz
- 110 fs

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

e-beam:
- 3 pA DC
- 3-30 keV energy
- 70 nm focal waist

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).

Single grating DLA results



Max. observed gradient: 25 MeV/m

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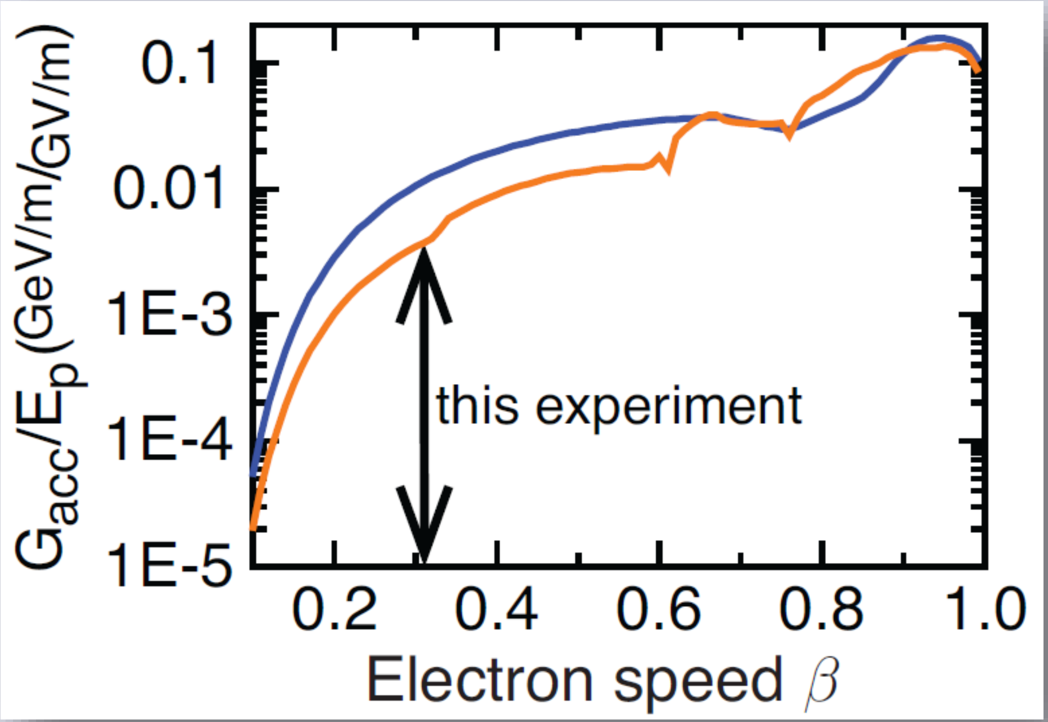
J. Breuer, P. Hommelhoff, Phys. Rev. Lett. 111, 134803 (2013)

Acceleration efficiency: simulation results



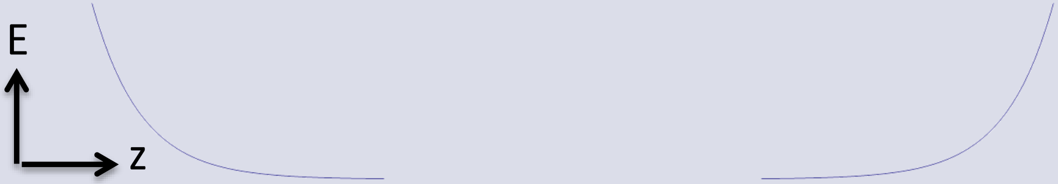
Blue: first spatial harmonic
Orange: third spatial harmonic

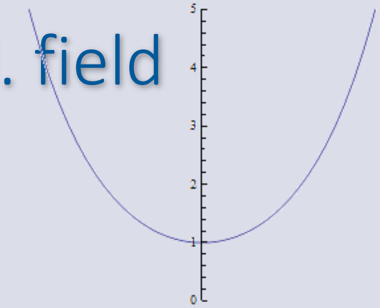
Observed: **25 MeV/m at β = 0.3**: laser power limited (increase by a factor of 3.4 possible to reach damage threshold).
With that, **at β = 0.95: 1.7 GeV/m**

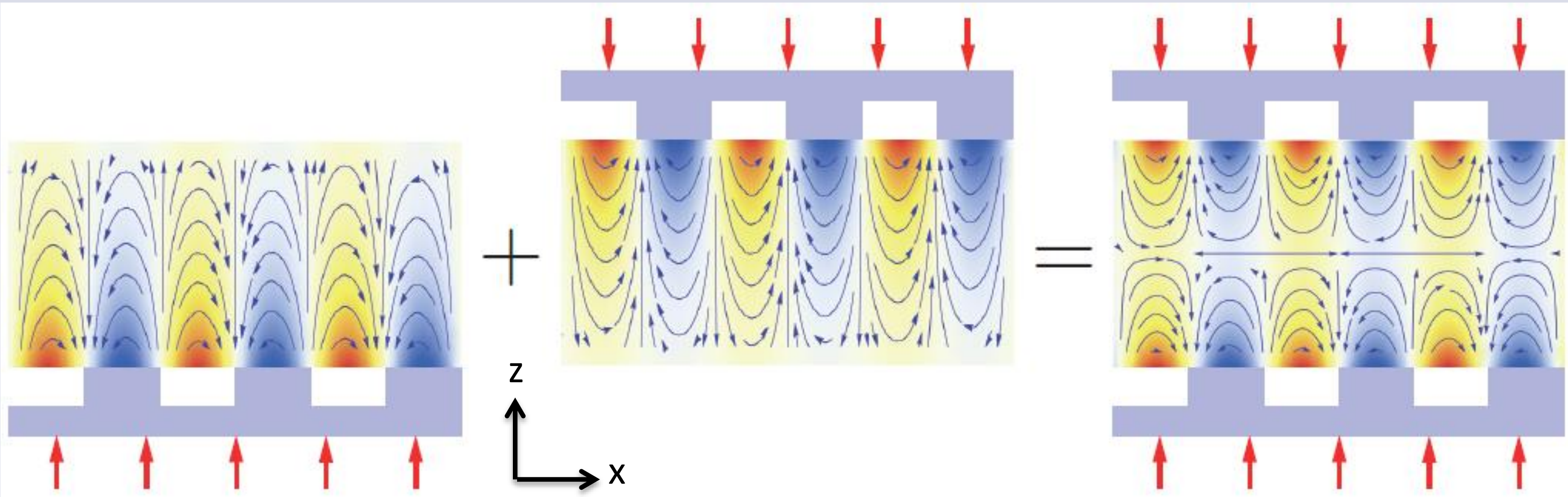
J. Breuer, P. Hommelhoff, Phys. Rev. Lett. 111, 134803 (2013)
J. Breuer, R. Graf, A. Apolonski, P. Hommelhoff, Phys. Rev. ST-AB 17, 021301 (2014)

Peralta et al. (Byer group, Stanford), Nature 503, 91 (2013)
K. Leedle, R. F. Pease, R. L. Byer, J. S. Harris, Optica 2, 158 (2015)

Two-sided structures: uniform accel. field



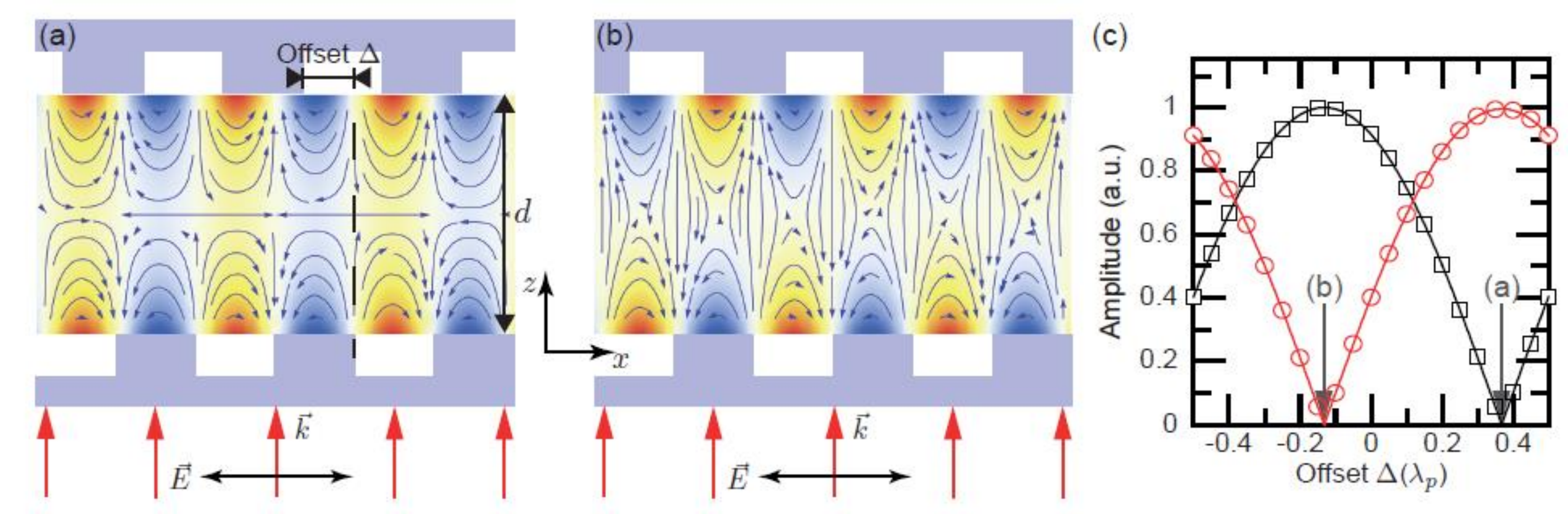




$$\mathbf{F_r} = qc \begin{pmatrix} \frac{1}{\beta\gamma} \left(C_\mathrm{s} \cosh(k_z z) + C_\mathrm{c} \sinh(k_z z) \right) \sin(k_x x - \omega t) \\ 0 \\ -\frac{1}{\beta\gamma^2} \left(C_\mathrm{s} \sinh(k_z z) + C_\mathrm{c} \cosh(k_z z) \right) \cos(k_x x - \omega t) \end{pmatrix}$$

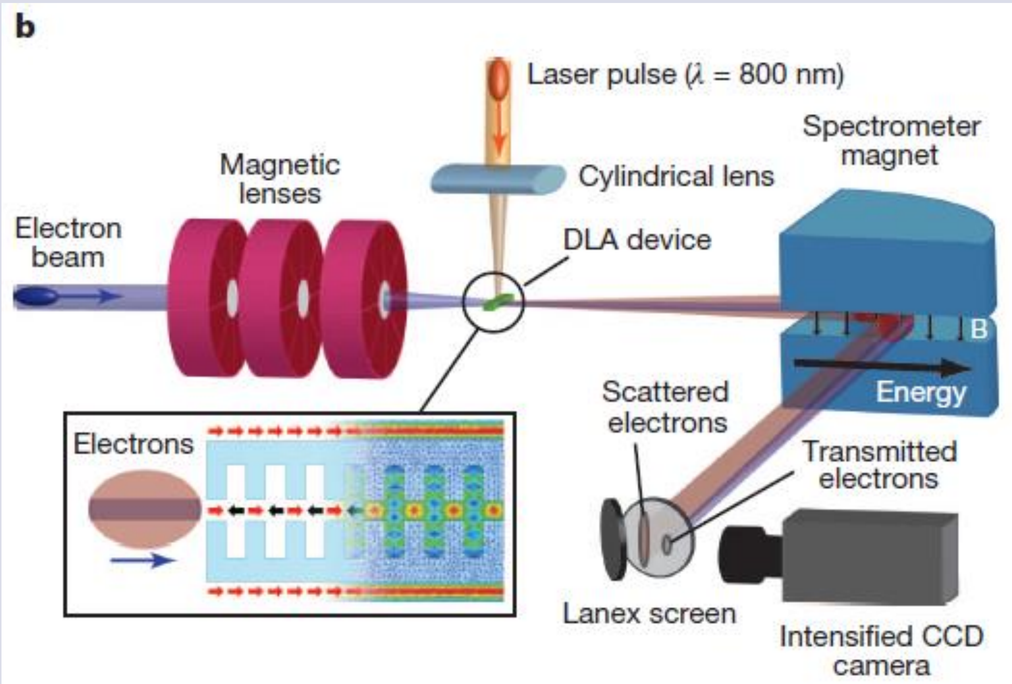
Uniform acceleration gradient: $dF_x/dz \propto d\cosh(k_z z)/dz|_{z=0} = 0$

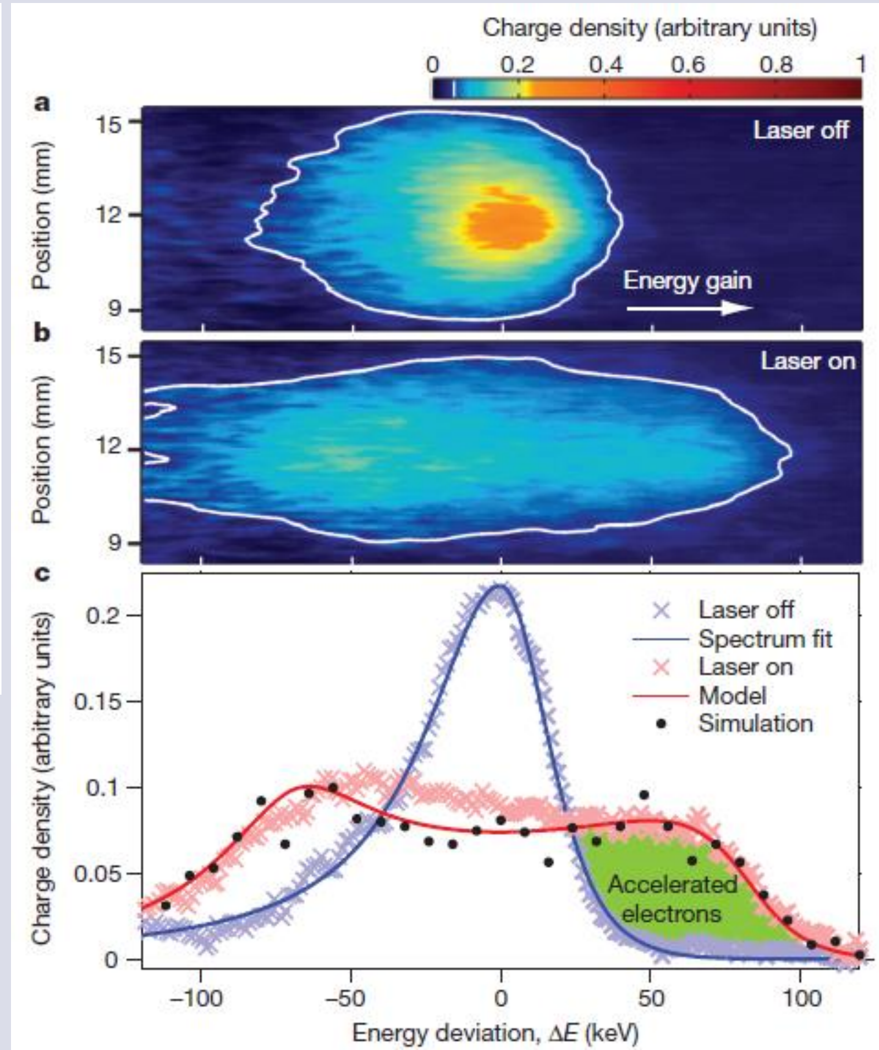
Shift structure: from acceleration to deflection



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

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

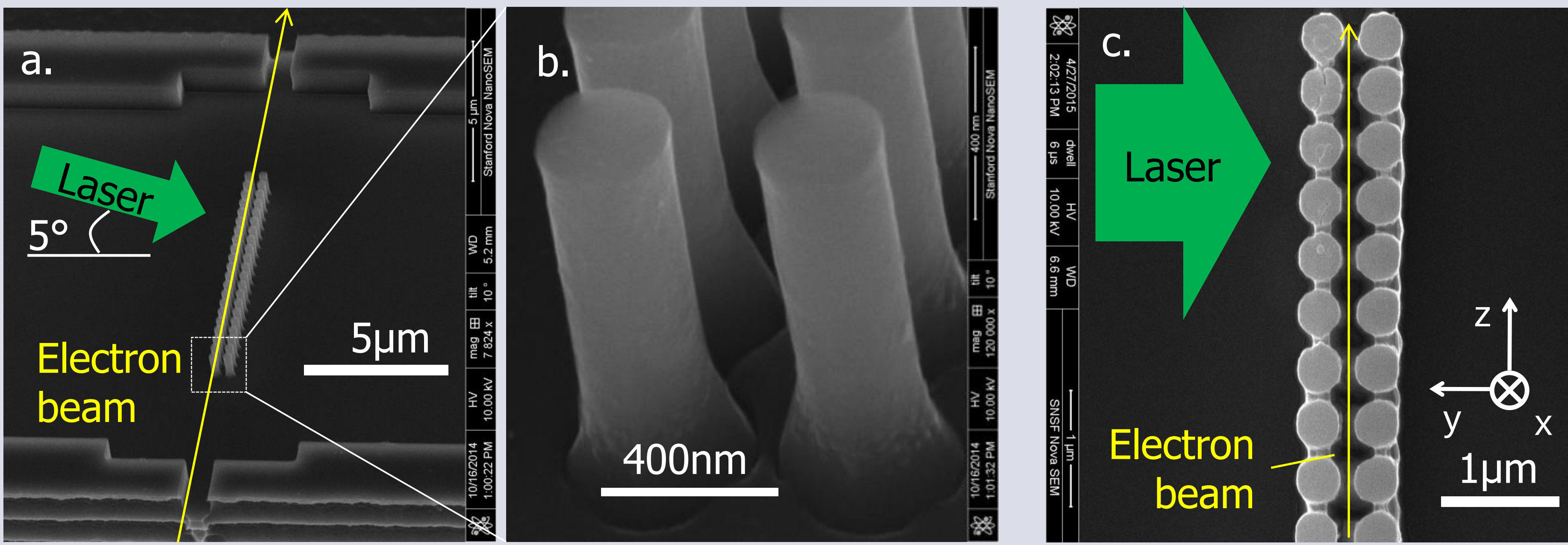




E. Peralta, Soong, K., England, R. J., Colby, E. R., Wu, Z., Montazeri, B., McGuinness, C., McNeur, J., Leedle, K. J., Walz, D., Sozer, E., Cowan, B., Schwartz, B., Travish, G., Byer R. L., Nature 503, 91 (2013)

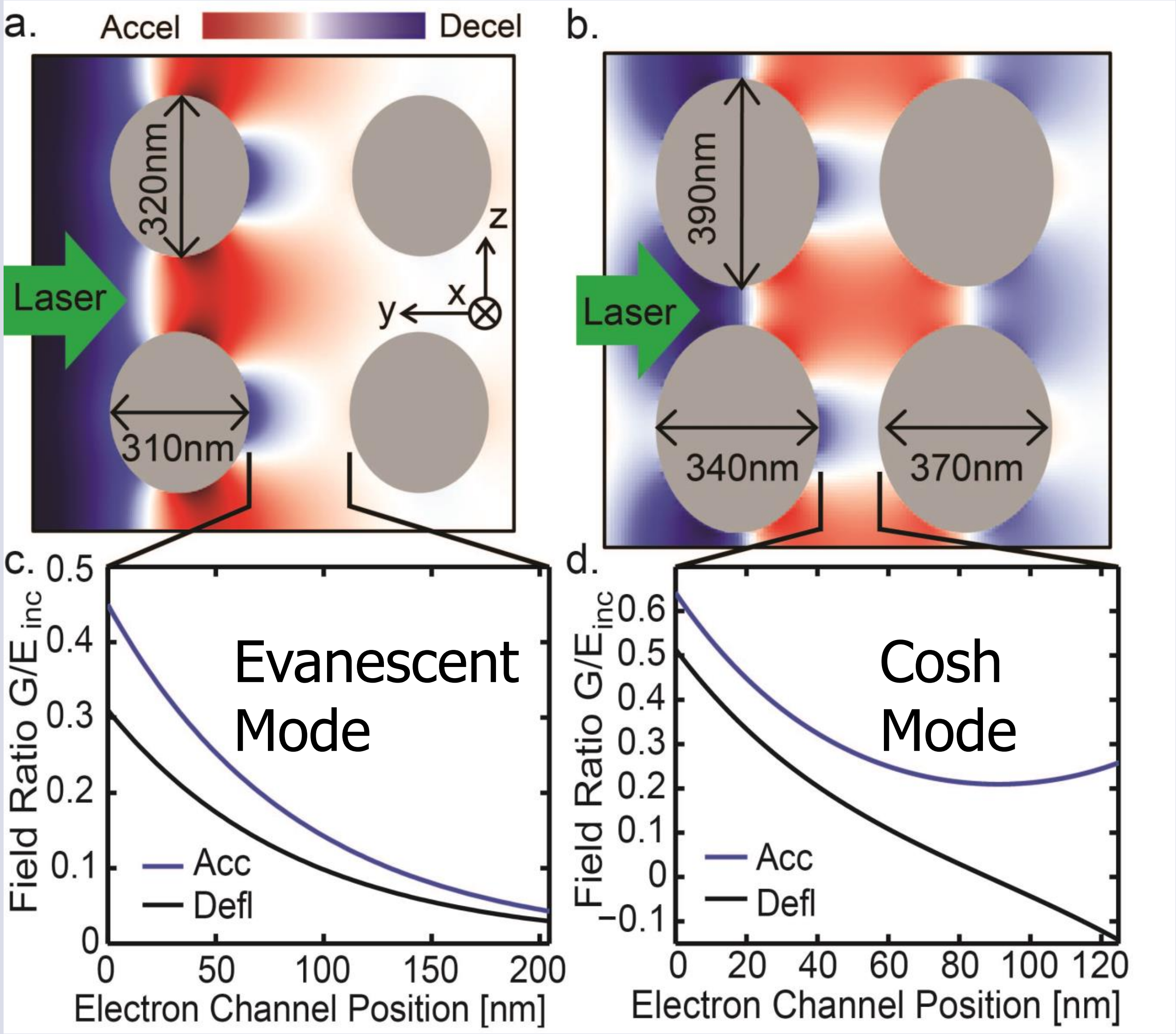
Silicon Dual Pillar Accelerators

- Good cosh-mode field ratios: $G_0 > 0.4\ E_{inc}$ possible
- 1.2µm thermal conduction distance to unheated substrate
- Driven at glancing angle: ~5º
- Electron beam centered 250nm from pillar tops



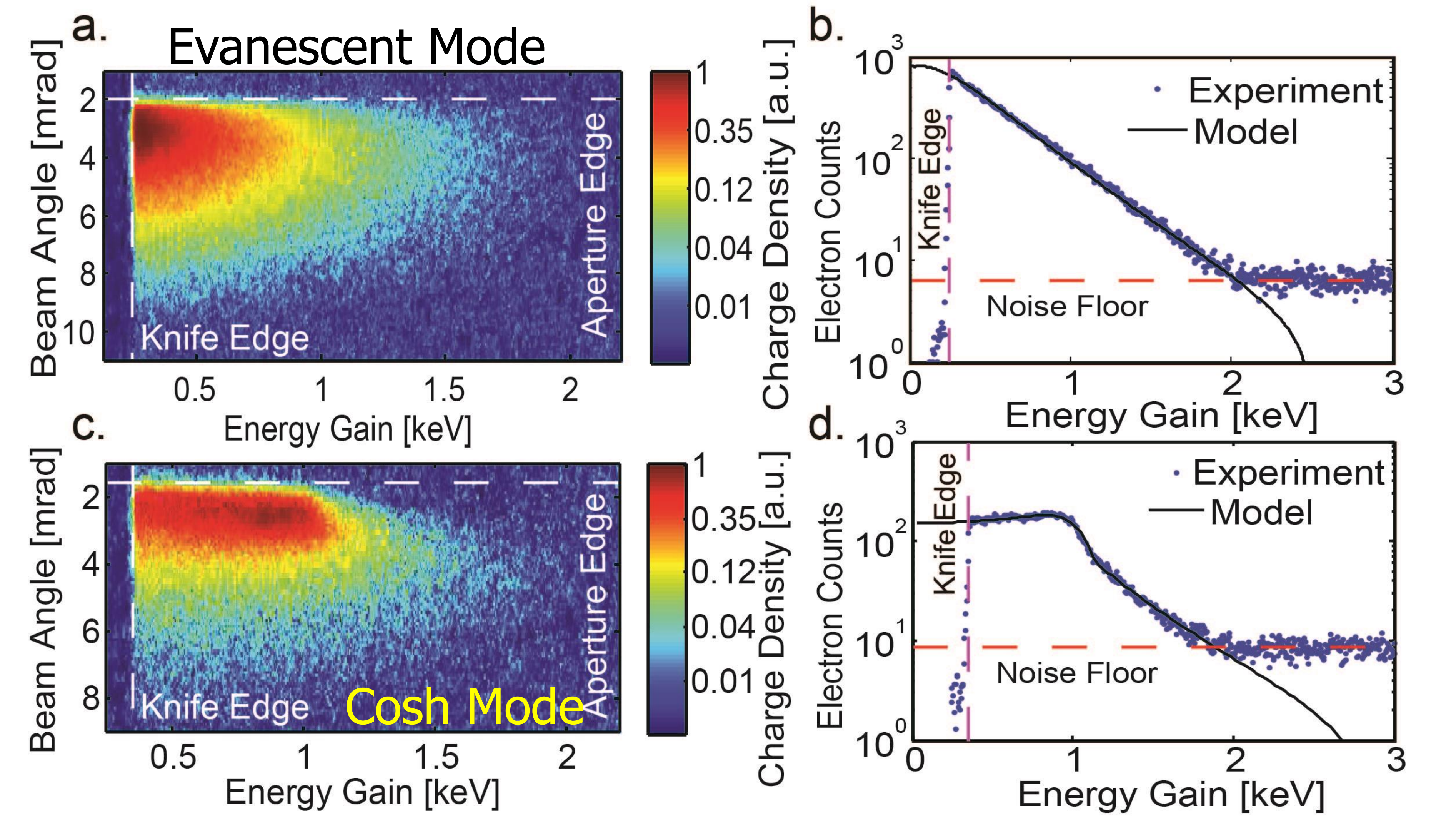
K. J. Leedle, A. Ceballos, H. Deng, O. Solgaard, R. F. Pease, R. L. Byer, and J. S. Harris, Optics Letters 40 (18), 4344-4347 (2015)

Demonstrated Acceleration Field Profiles



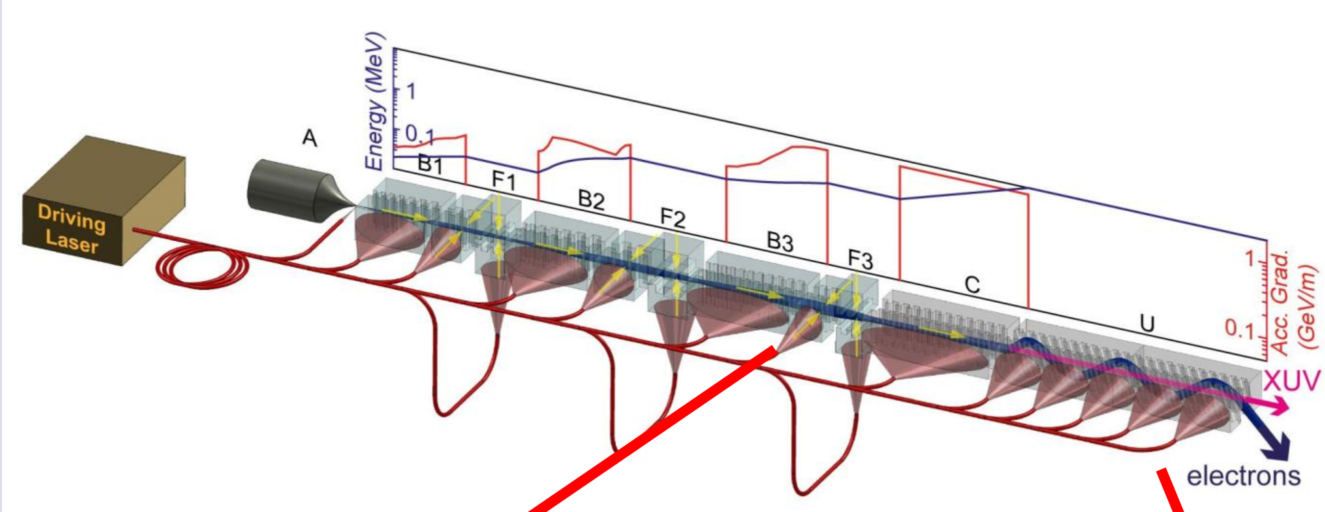
K. J. Leedle, A. Ceballos, H. Deng, O. Solgaard, R. F. Pease, R. L. Byer, and J. S. Harris, Optics Letters 40 (18), 4344-4347 (2015)

Dual Pillar Accelerator Raw Data



K. J. Leedle, A. Ceballos, H. Deng, O. Solgaard, R. F. Pease, R. L. Byer, and J. S. Harris, Optics Letters 40 (18), 4344-4347 (2015)

Future Directions



Compact MeV electron source

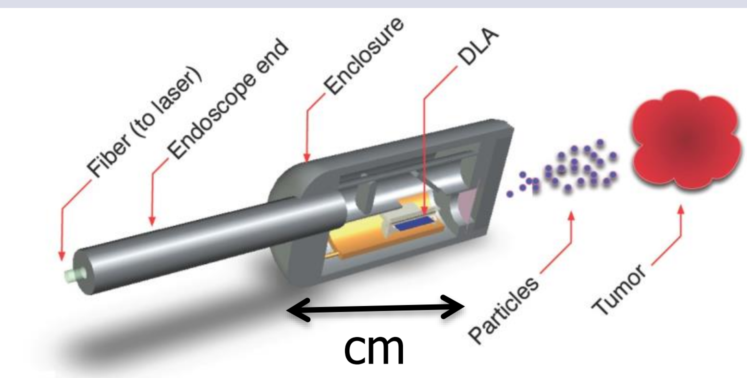
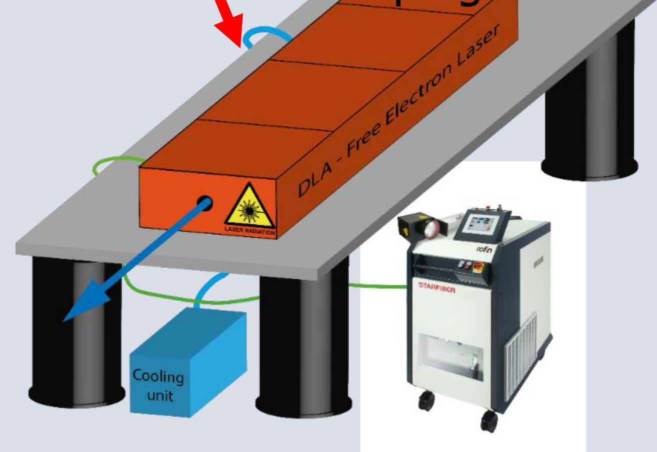
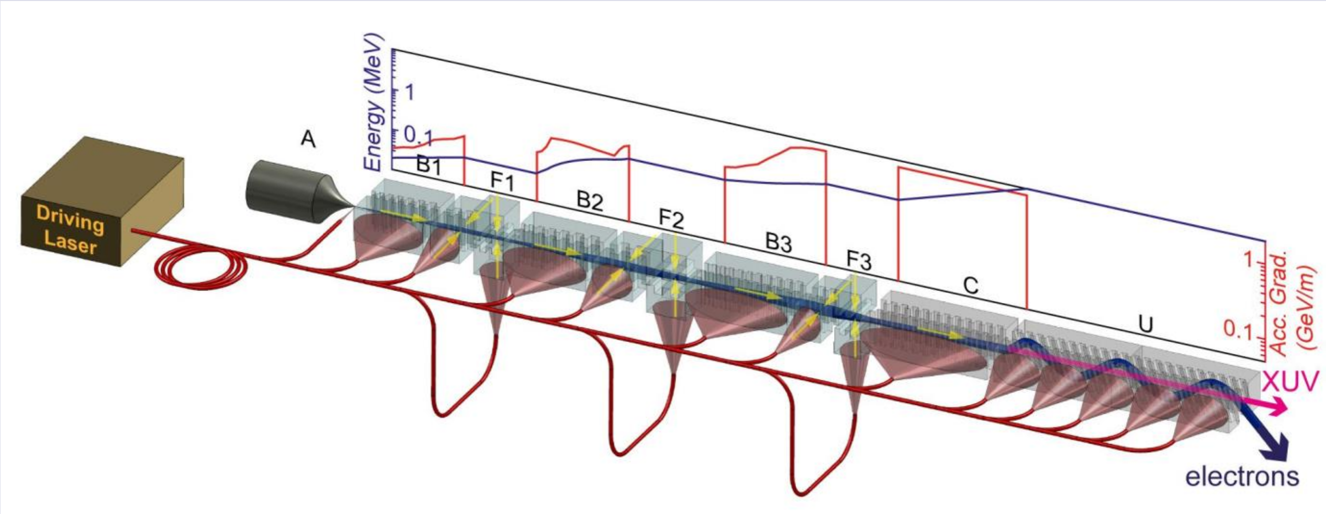


Table-top light source



Future Directions



How do we get here?

1) Improve acceleration efficiency – new structures, laser coupling, electron source
2) Extend interaction region over which electrons are accelerated
3)Demonstrate multi-stage phase-controlled acceleration
4) Demonstrate deflection/focusing

Summary of achievable parameters of extant SEM/TEM electron sources potentially useful in DLA

Emitter Type	Thermionic	Thermionic	Schottky Field Emission	Cold Field Emission
Cathode material	W	LaB_6	ZrO/W (100)	W(310)
Operating temperature [K]	2,800	1,900	1,800	300
Cathode radius [nm]	60,000	10,000	< 1,000	< 100
Effective source radius [nm]	15,000	5,000	**15**	**2.5**
Emission current density [A/cm^2]	3	30	**5,300**	**17,000**
Total emission current [μA]	200	80	200	5
Reduced brightness B_r [A/cm^2.sr.kV]	**1.10^4**	**1.10^5**	**1.10^7**	**2.10^7**
Maximum probe current [nA]	1000	1000	10	0.2
Energy spread @ cathode [eV]	0.59	0.40	**0.31**	**0.26**
Energy spread @ gun exit [eV]	1.5 - 2.5	1.3 - 2.5	0.35 - 0.7	0.3 - 0.7
Beam noise [%]	1	1	1	**5 - 10**
Emission current drift [%/h]	0.1	0.2	< 0.5	**5**
Operating vacuum hPa/mbar	$< 1.10^{-5}$	$< 1.10^{-6}$	$< 1.10^{-8}$	$< 1.10^{-10}$
Typical Cathode life [h]	100	> 1000	> 5000	> 2000
Cathode regeneration	not required	not required	not required	**every 6 to 8 hours**

From www.tedpella.com (manufacturer of SEM/TEM tips)