FEL Frontiers 07, Elba, Italia

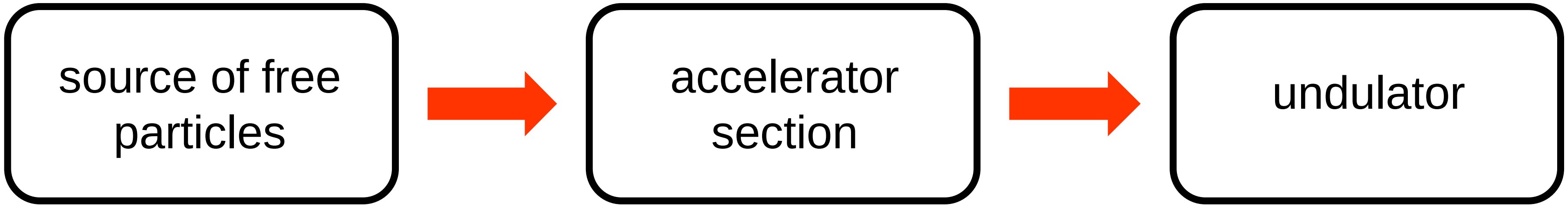
September 12, 2007

Proposed microstructure dielectric laser-driven undulator

T. Plettner, R.L. Byer

Stanford University

The broad picture…



dielectric structure based laser-driven particle accelerators

Dielectric structure

Relativistic electron laser-acceleration group

Chris McGuinness | Bob Siemann | Bob Byer | Eric Colby | Chris Sears

Rasmus Ischebeck | Chris Barnes | Ben Cowan | Tomas plettner | Jim Spencer

Bob Noble
Dieter Walz

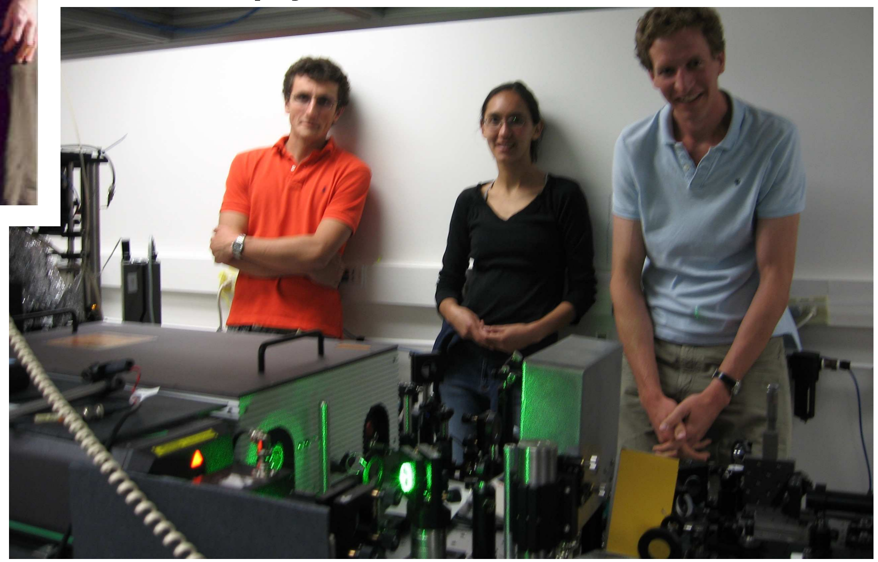
past collaborators

Y.C. Huang
T.I. Smith
H. Wiedemann

Low-energy electron laser acceleration group

Mark Kasevich
Patrick Lu,
K-Xun Sun

Anthony Serpry | Catherine Kealhofer | Peter Hommelhoff



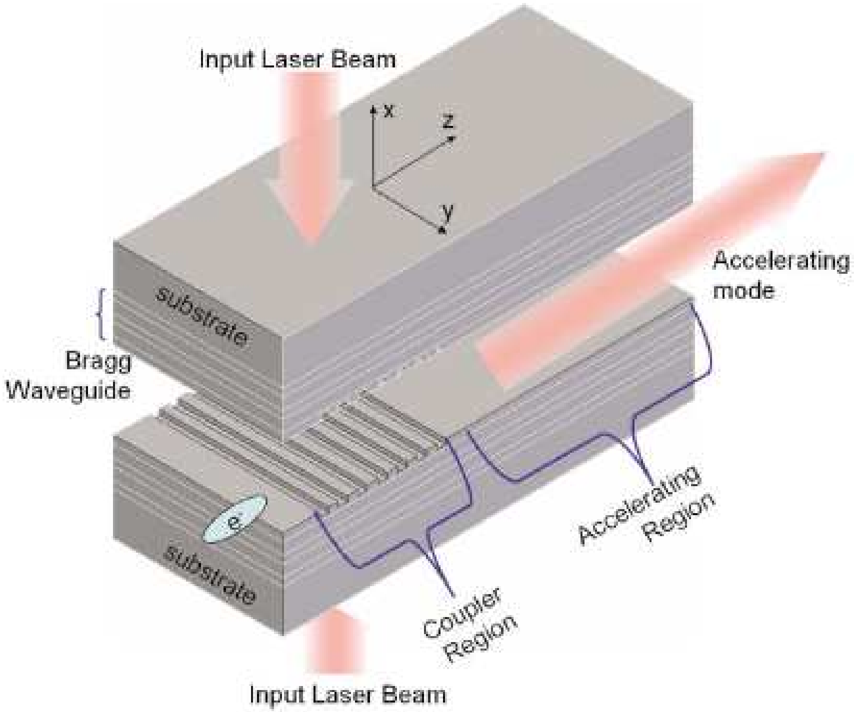
Talk outline

1. **Structure-based laser-driven particle accelerators**
   - their principle of operation
   - motivation of possible FEL application

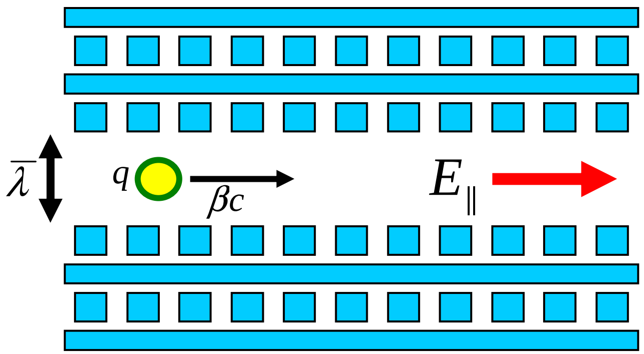
2. **The proposed X-ray system**
   - the electron injector
   - the accelerator
   - the undulator
   - predicted FEL performance

3. **Experiments and future work**
   - near-term experiments
   - longer-term goals
   - summary

Properties of structure-based laser accelerators



Z. Zhang, S. G. Tantawi, R. D. Ruth, Phys. Rev. ST AB 8, 071302 (2005)



~ 1 GeV/m gradient

1 J/cm² laser damage fluence

Optical bunching

$$\tau_{bunch} \sim \tau_{laser} / 10^3$$

Low energy spread

$$\Delta\gamma / \gamma < 1\%$$

Low emittance [1]

$$\varepsilon_N \sim 10^{-9}\ \mathrm{m}$$

Low bunch charge [2]

$$Q_b \sim 1 - 10\ \mathrm{fC}$$

$$K_L \sim 100\ \mathrm{GeV/m/pC}$$

1. B. Cowan, PhD thesis AARD482 (2007)
2. R.H. Siemann, Phys. Rev. ST AB 7, 061303 (2004)

Motivation for an FEL application

~ 1 GeV/m gradient	GeV electron beam in 1-2 m
Few-attosec pulse structure	Short undulator → preserve the few-attosec pulse structure on the photons
Possibility for high rep. rate	Modelocked lasers and low-power amplifiers

Requirements:
- **Suitable electron injector**
- **Matching short undulator**

E-163

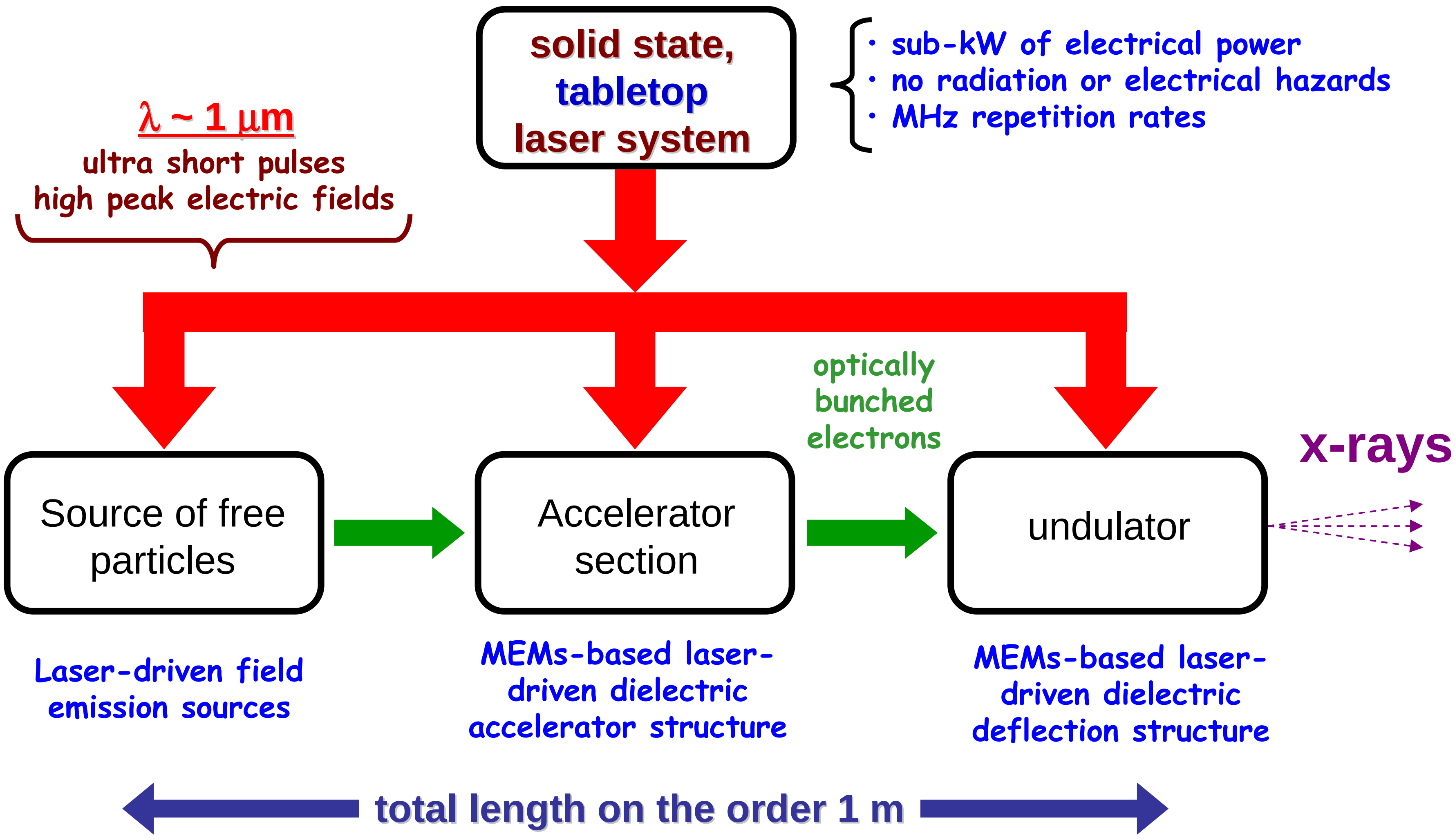
High-energy physics
“the TeV collider”

LCLS

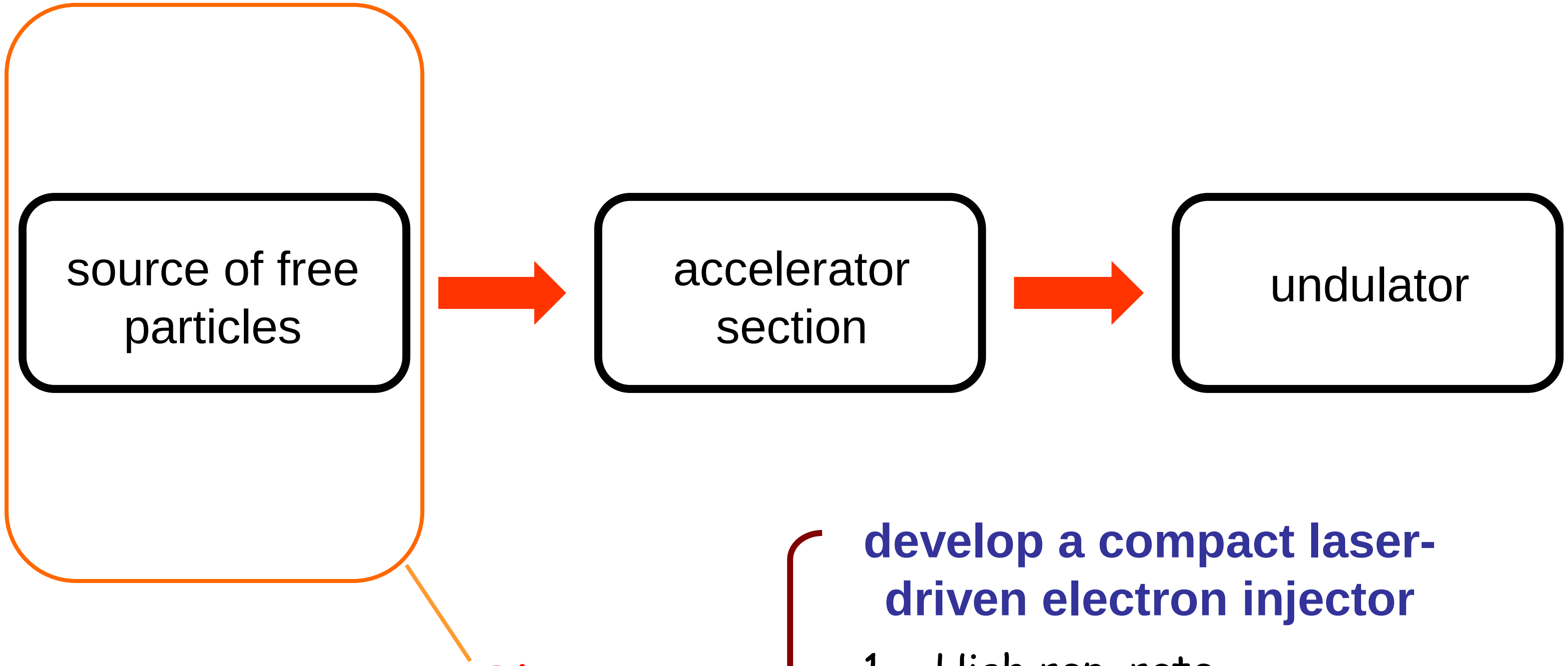
… could we generate coherent X-ray photons with our accelerators?

Y. C. Huang and R. L. Byer, "Ultra-Compact, High-Gain, High-Power Free-Electron Lasers Pumped by Future Laser-Driven Accelerators," in Free Electron Lasers 1996, G. Dattoli and A. Renieri, eds. (Elsevier Science B.V., 1997), pp. II-37-II-38.

Architecture of a laser-driven free-electron X-ray source



Development of the three key laser-driven components



Objective:

develop a compact laser-driven electron injector

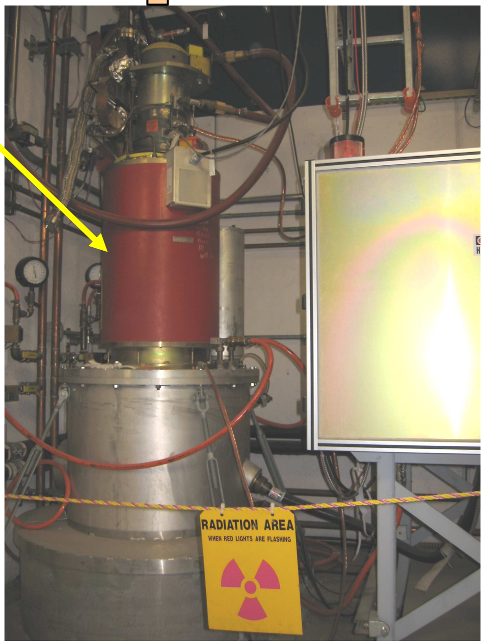
1. High rep. rate
2. Low power consumption
3. Ultra low emittance (~10^{-9} m-rad)
4. ~10 MeV in a few-cm structure

A conventional electron injector

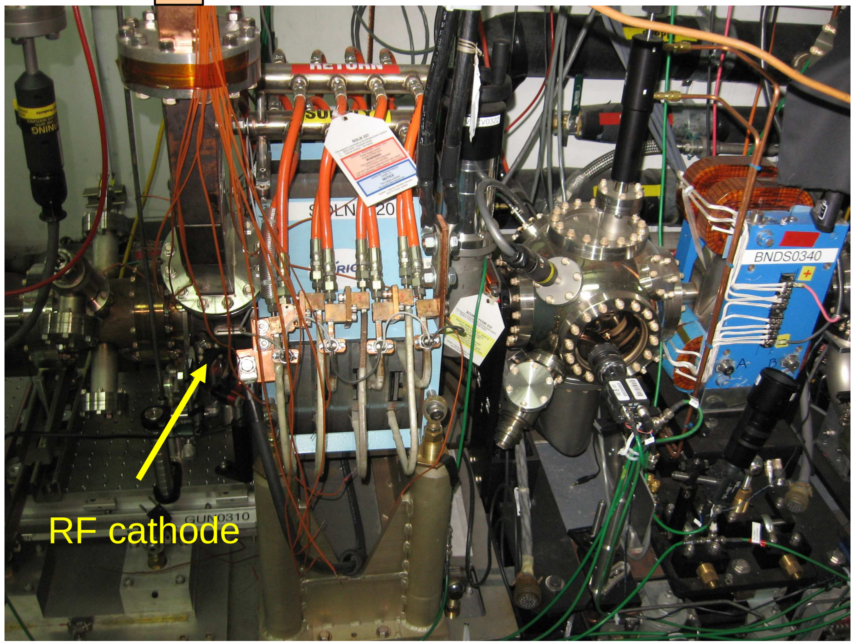
a room full of lethal and bulky equipment…

The klystron

- ~2 m tall
- **1/3 MV !**
- high power
- water cooling
- X-ray radiation
- **10 Hz** rep. rate



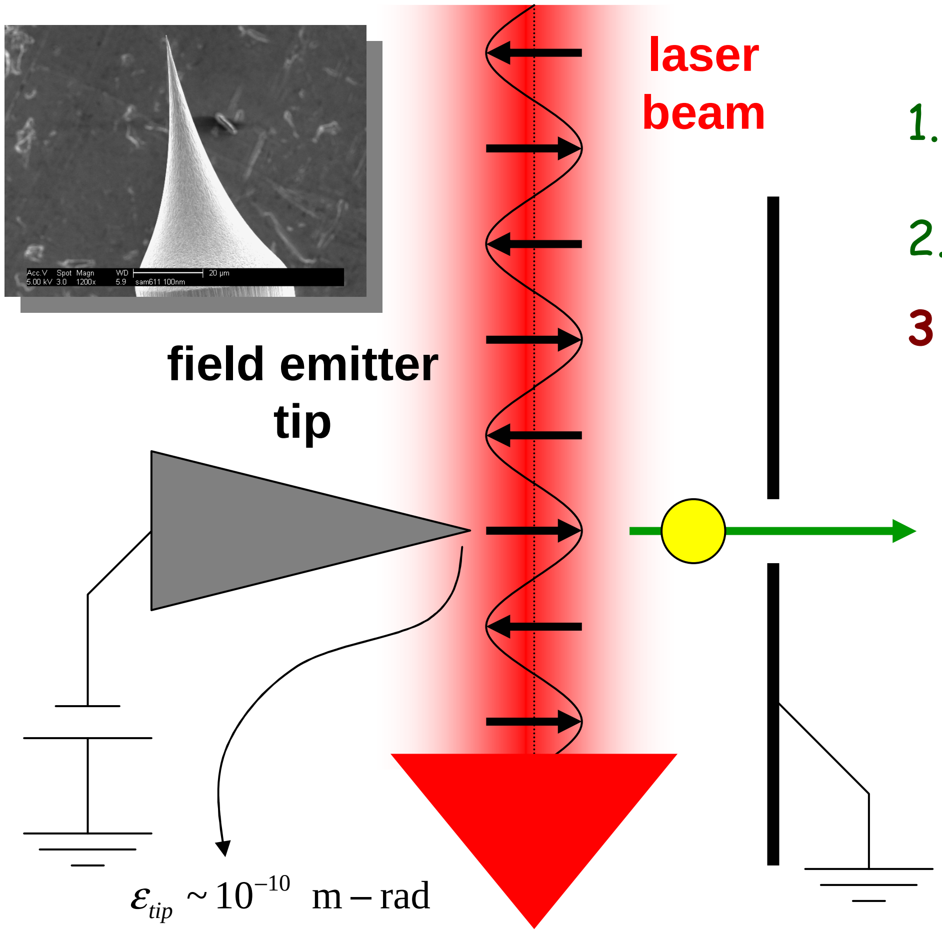
The NLCTA accelerator front end



temporary solution for present
laser-acceleration experiments

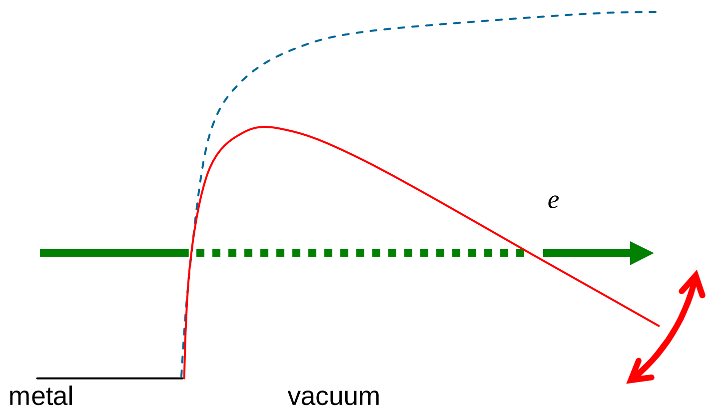
A laser-driven field-emission free-electron source

P. Hommelhoff et al, Kasevich group



Field emission tip properties

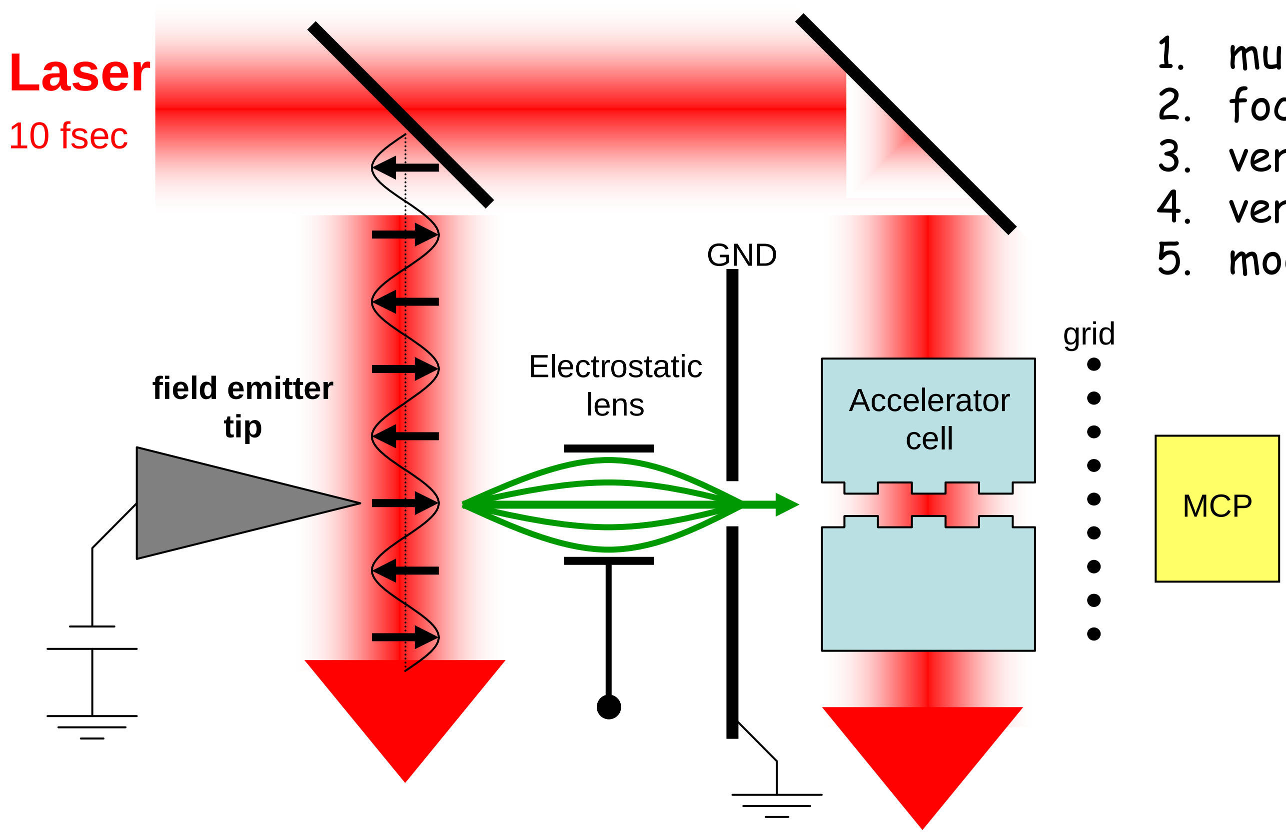
1. laser-assisted tunneling of electrons from the atom to free space
2. Highly nonlinear
3. **Potential for timed sub-optical cycle electron emission**



P. Hommelhoff, Y. Sortais, A. Aghajani-Talesh, M. A. Kasevich, “Field Emission Tip as a Nanometer Source of Free Electron Femtosecond Pulses”, PRL 96, 077401 (2006)

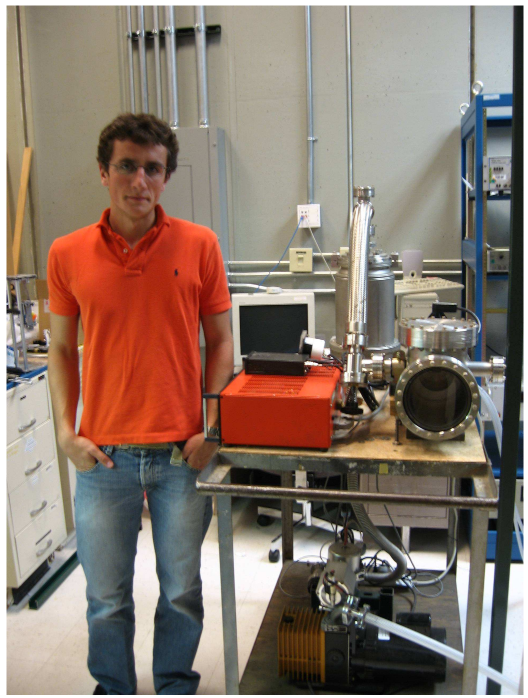
Addition of a low-energy laser-accelerator cell

Collaboration work with the Kasevich group



objectives

1. multiple-electron emission
2. focusing with electrostatic lens
3. verify ultra-low emittance
4. verify ~700 attosec bunch
5. modulate energy

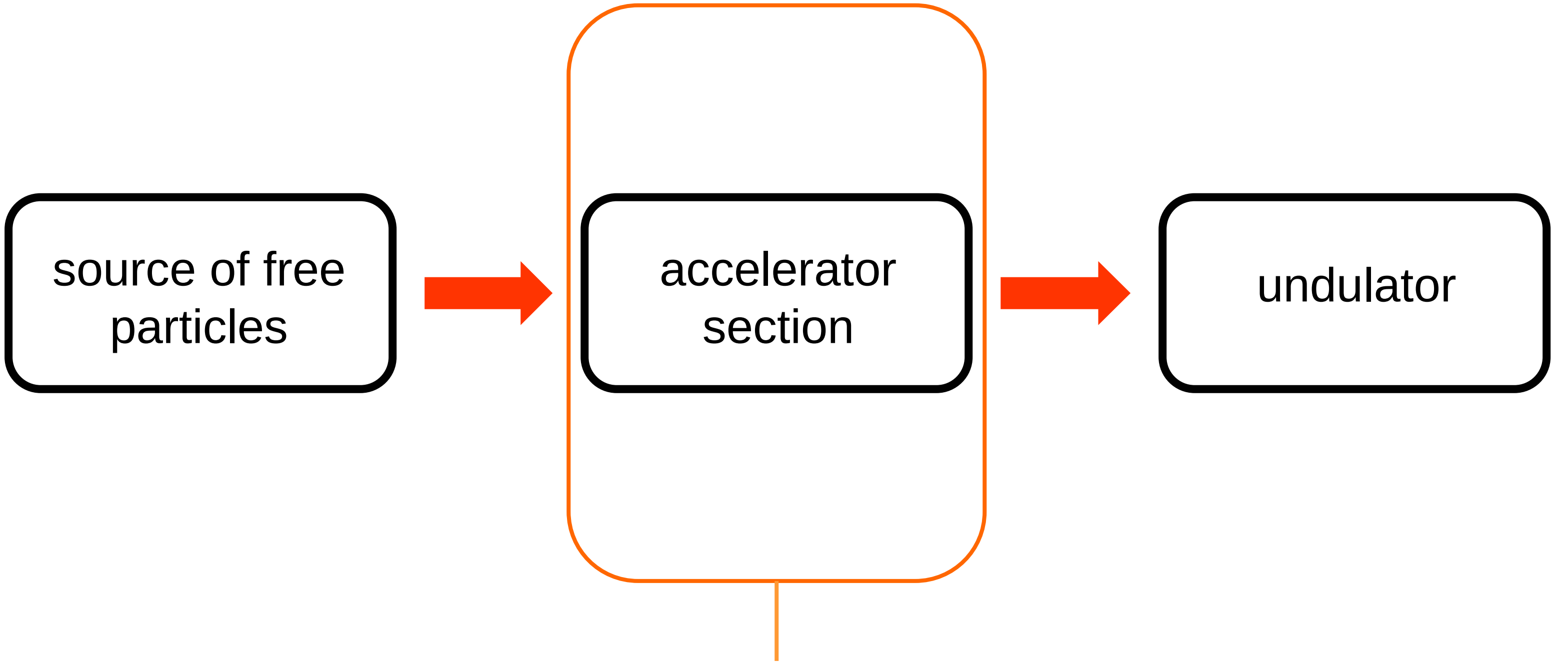


graduate student
A. Serpry

Concept of field-emission arrays:

J.W. Lewellen, J. Noonan, "Field-emission cathode gating for rf electron guns", Phys. Rev. ST AB 8 033502 (2005)

Development of the three key laser-driven components



Objective:

develop MEMs based laser-driven accelerator structures

1. Dielectric optical MEMs structures
2. High acceleration gradients (~ 1 GeV/m)
3. Mono-energetic, maintenance of low emittance

Structure-based laser-driven particle acceleration

E-163 (formerly "LEAP")

Initial motivation

high energy physics → high gradient structures

Semi-open structures

1978

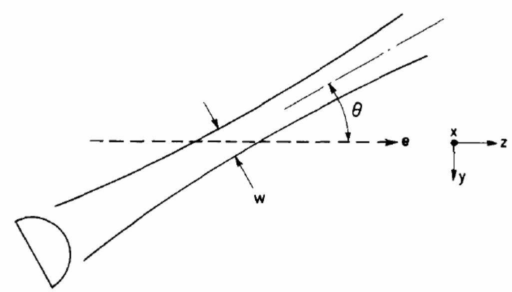
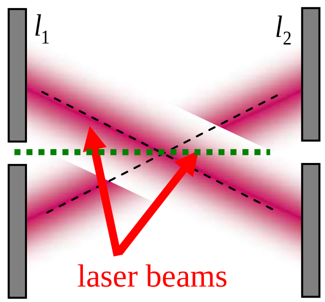
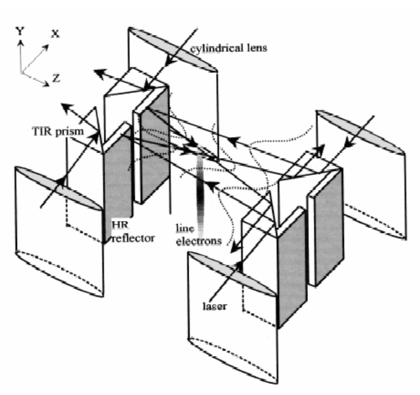


FIG. 1. The electrons move in the z direction and the wave is propagating at an angle θ to this direction. It is assumed that the field can be represented by a plane wave in the interaction region, with the field vector polarized in the yz plane. A cylindrical lens is used so that there is little variation in field intensity in the x direction.

R.H. Pantell, M.A. Piestrup, Appl. Phys. Lett. 32, 781 (1978).

1995

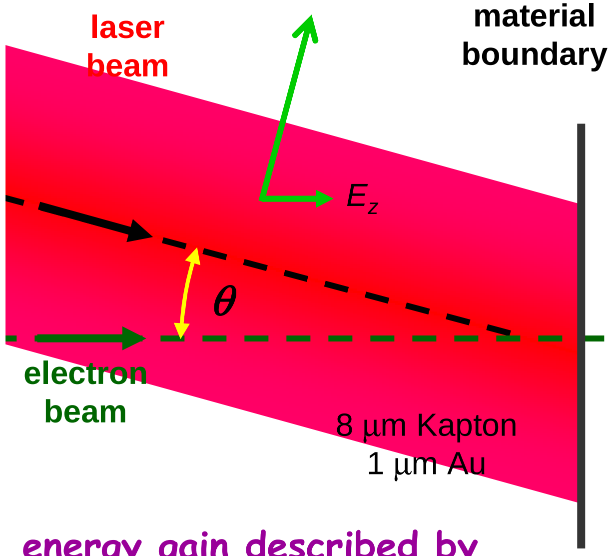




Y.C. Huang, et al, Appl. Phys. Lett. 68 (6) (1996) 753.

The single laser beam, disposable boundary setup

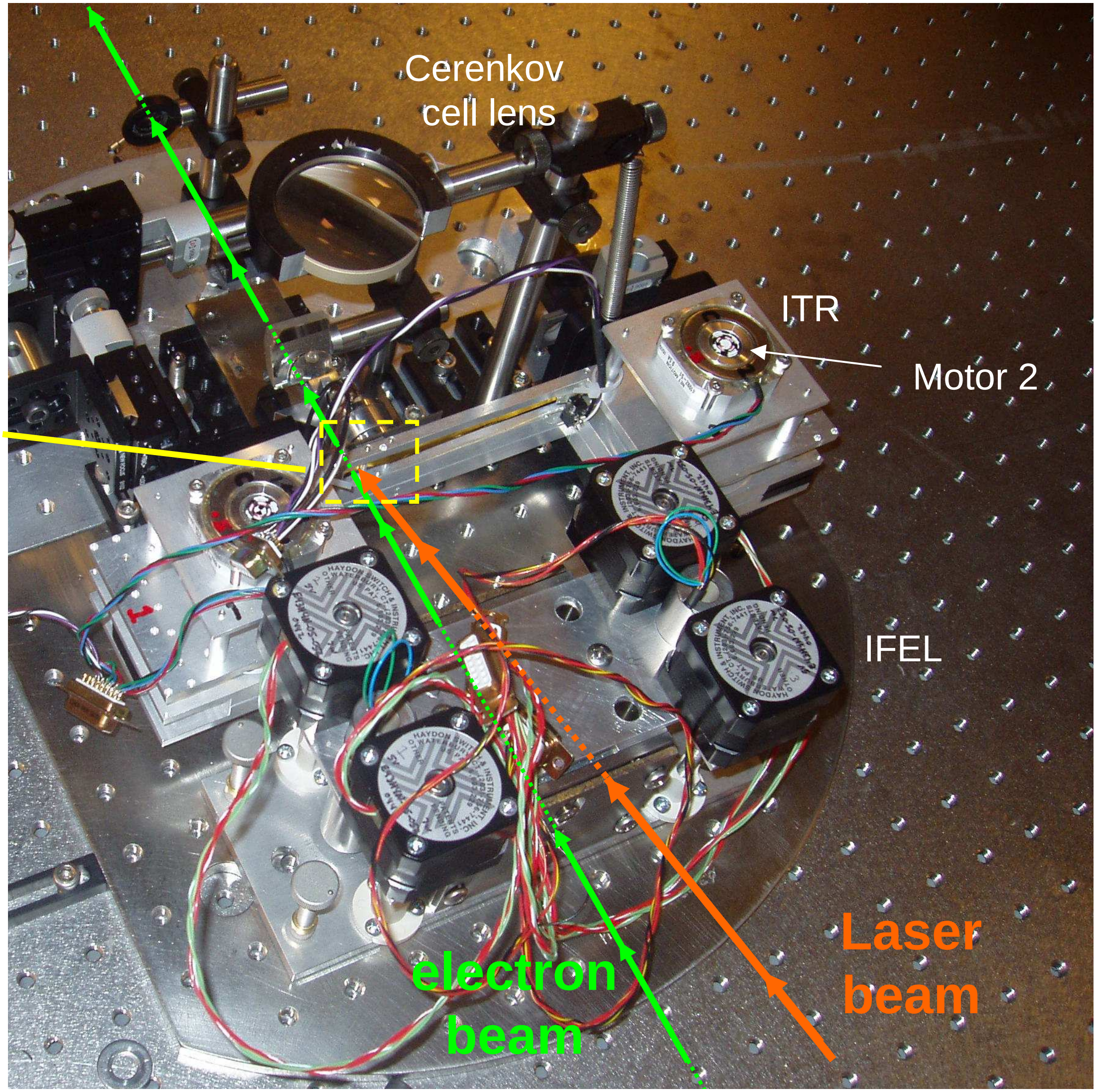
Schematic of the interaction region



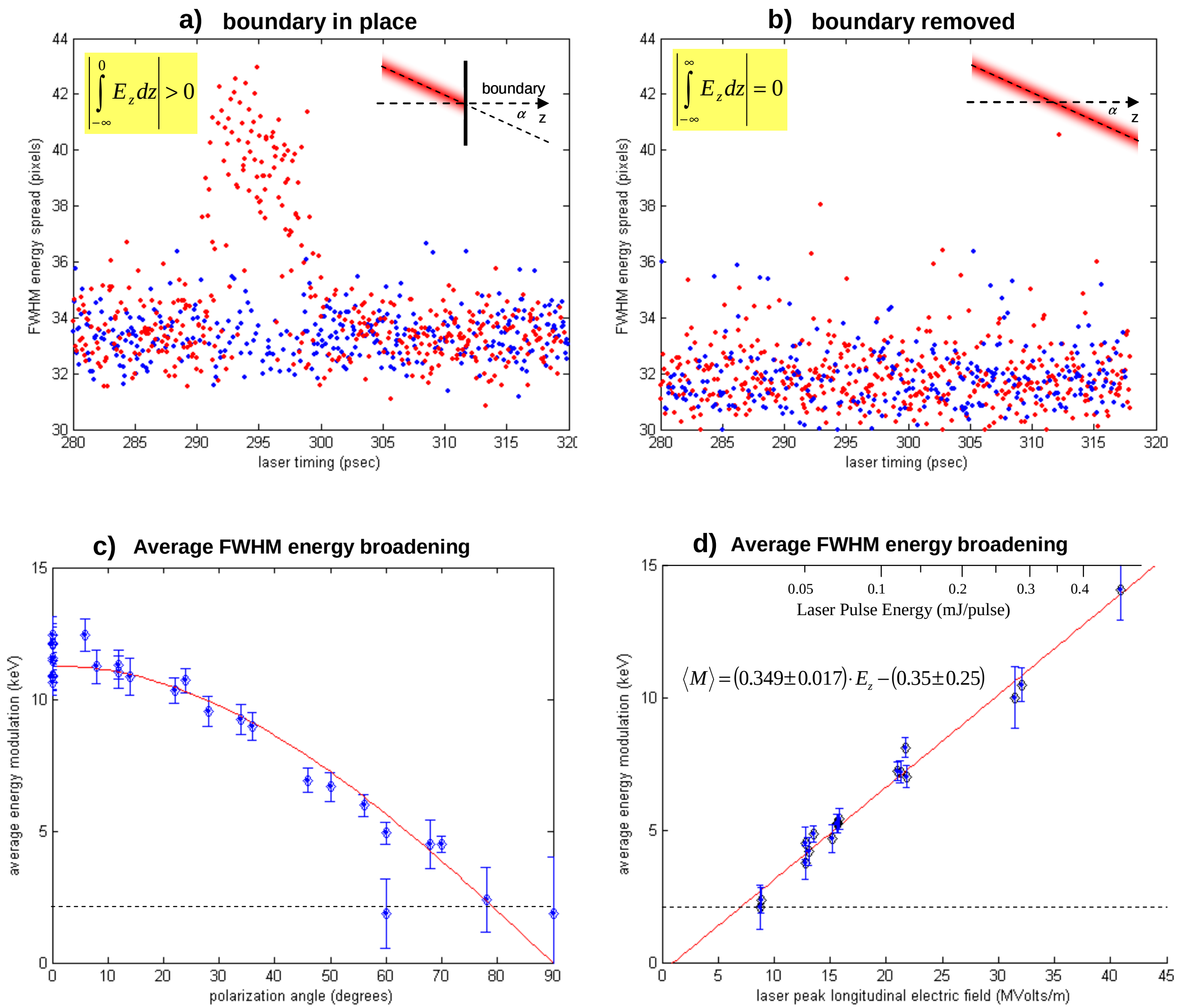
energy gain described by

$$\Delta U = \int_{-\infty}^{0} E_z dz$$

Not a microstructure accelerator structure but <u>sufficient for the observation of the key physics</u>

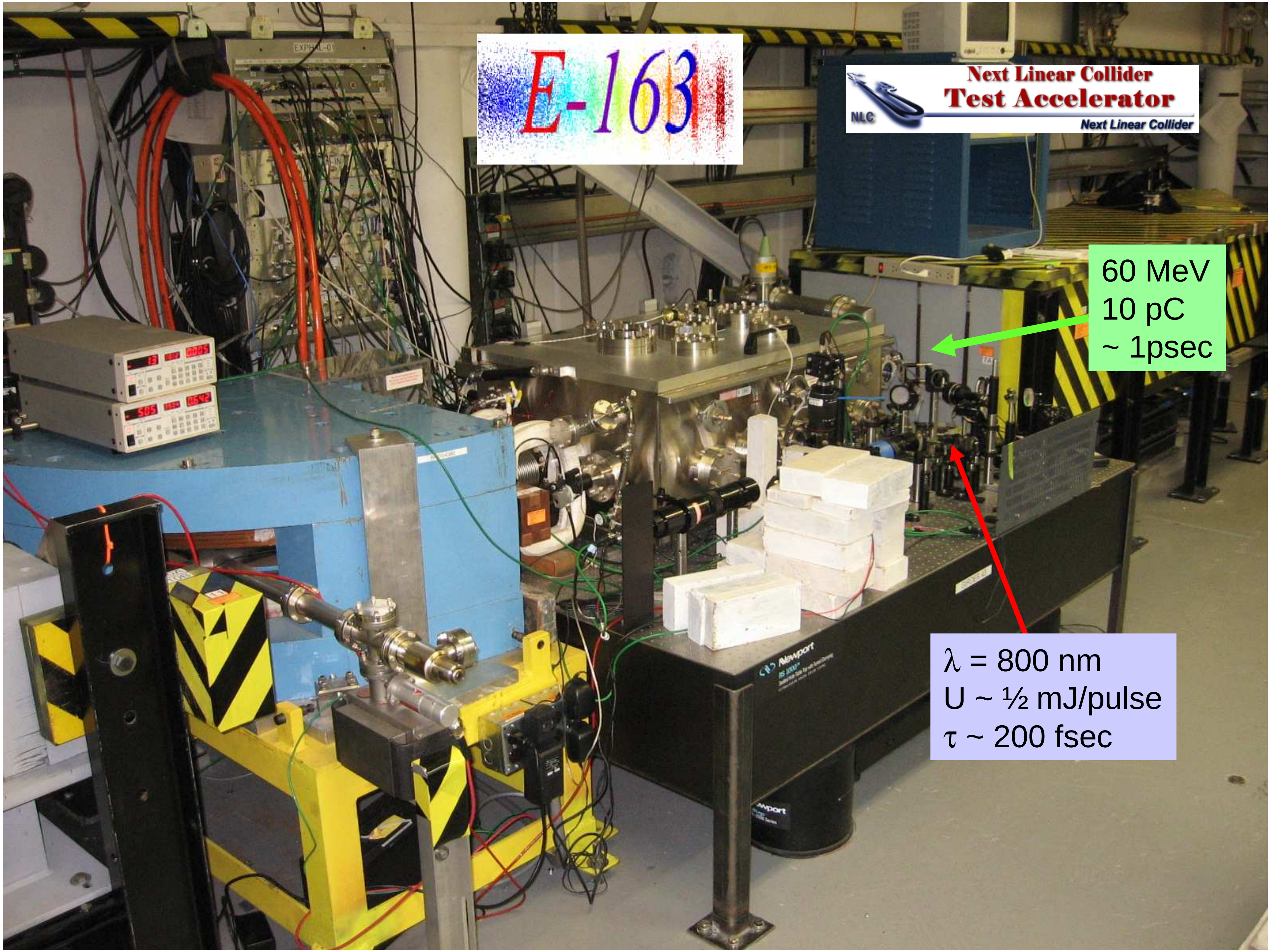


Confirmation of the Lawson-Woodward theorem



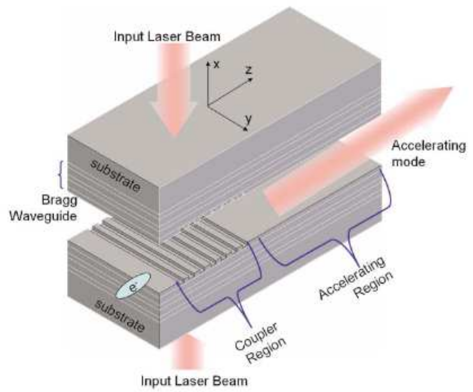
T. Plettner, R.L. Byer, E. Colby, B. Cowan, C.M.S. Sears, J. E. Spencer, R.H. Siemann, “Visible-laser acceleration of relativistic electrons in a semi-infinite vacuum”, **Phys. Rev. Lett. 95, 134801 (2005)**

T. Plettner, R.L. Byer, E. Colby, B. Cowan, C.M.S. Sears, J. E. Spencer, R.H. Siemann, “Proof-of-principle experiment for laser-driven acceleration of relativistic electrons in a semi-infinite vacuum”, **Phys. Rev. ST Accel. Beams 8, 121301 (2005)**


E-163
Next Linear Collider
Test Accelerator
NLC
Next Linear Collider
60 MeV
10 pC
~ 1psec
λ = 800 nm
U ~ ½ mJ/pulse
τ ~ 200 fsec

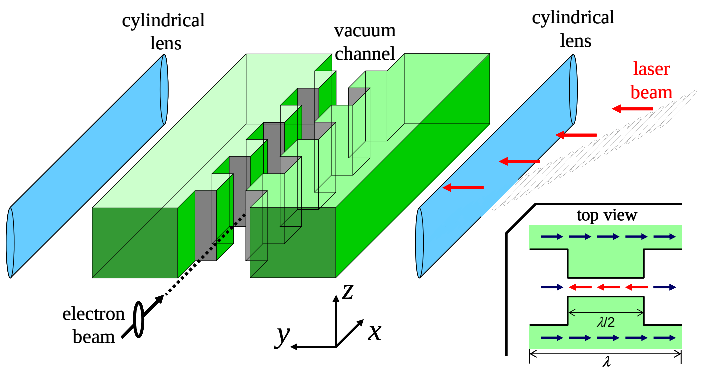
Many possible dielectric microstructure architectures

Planar waveguide structures



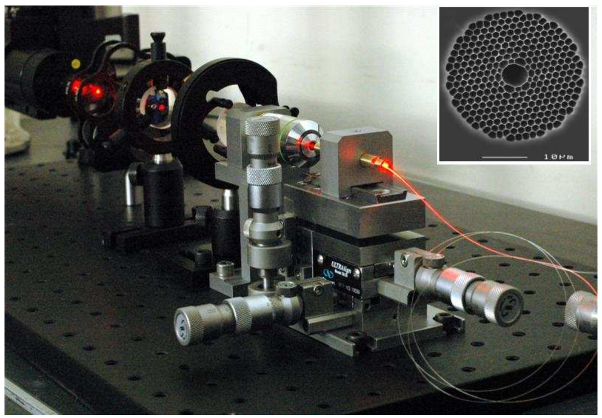
Z. Zhang et al. Phys. Rev. ST AB 8, 071302 (2005)

Periodic phase modulation structures



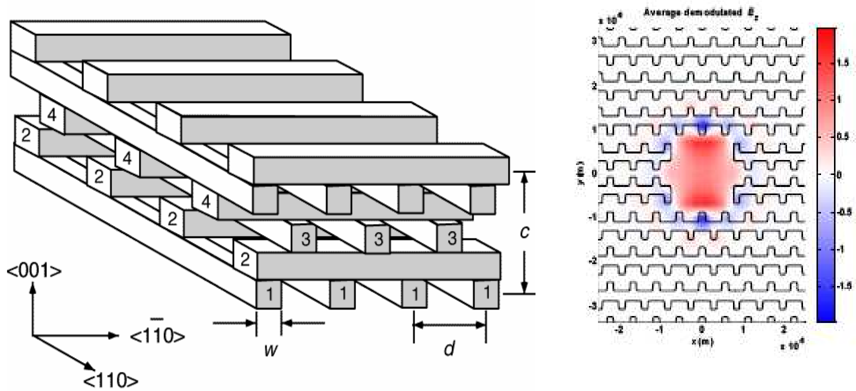
T. Plettner et al, Phys. Rev. ST Accel. Beams 4, 051301 (2006)

Hollow core PBG fibers



X.E. Lin, Phys. Rev. ST Accel. Beams 4, 051301 (2001)

3-D photonic bandgap structures

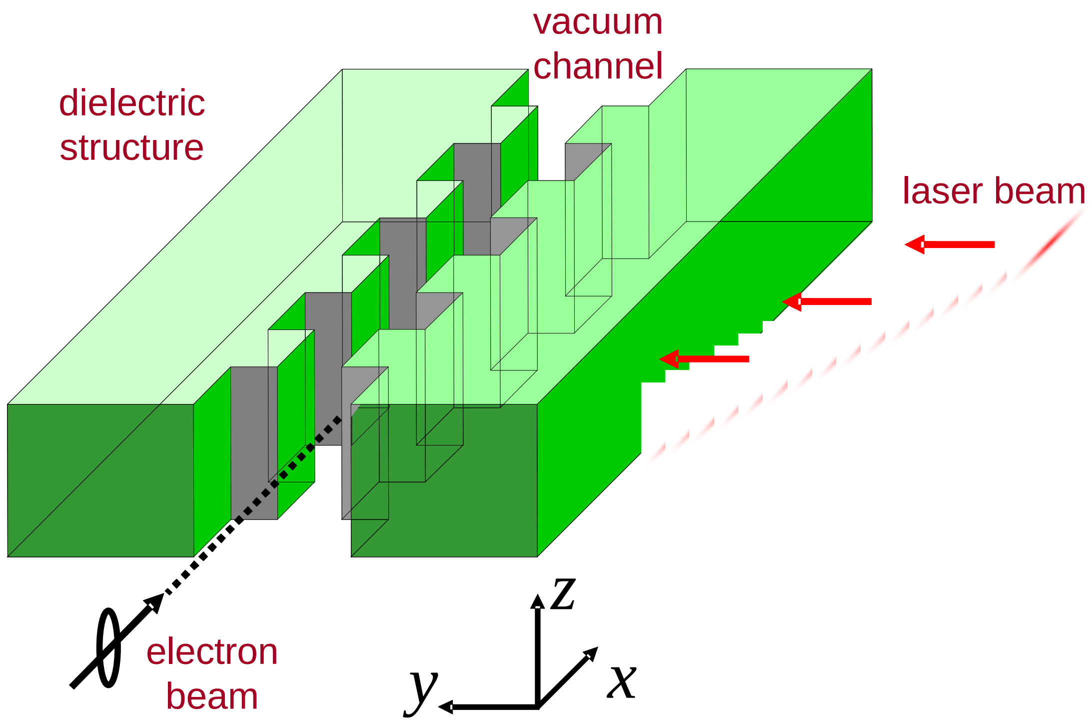


B. M. Cowan, Phys. Rev. ST Accel. Beams , 6, 101301 (2003).

Transverse pumped phase-reset structure

Main concept: quasi phase-matching of the EM field

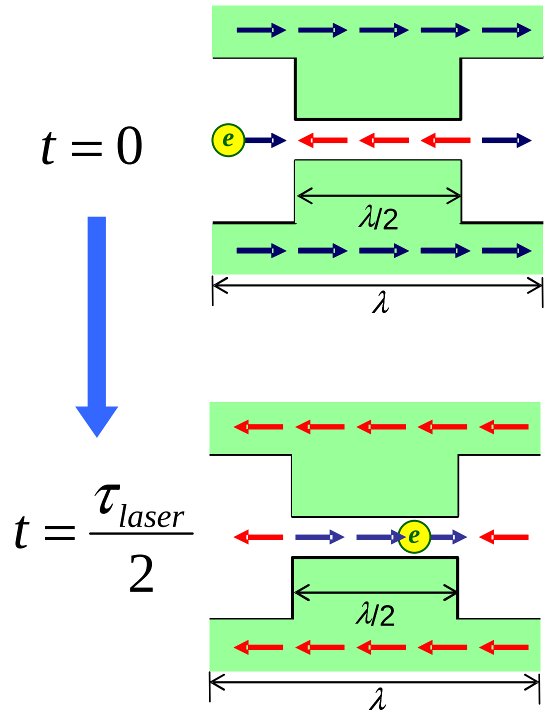
perspective view



T. Plettner et al, Phys. Rev. ST Accel. Beams 4, 051301 (2006)

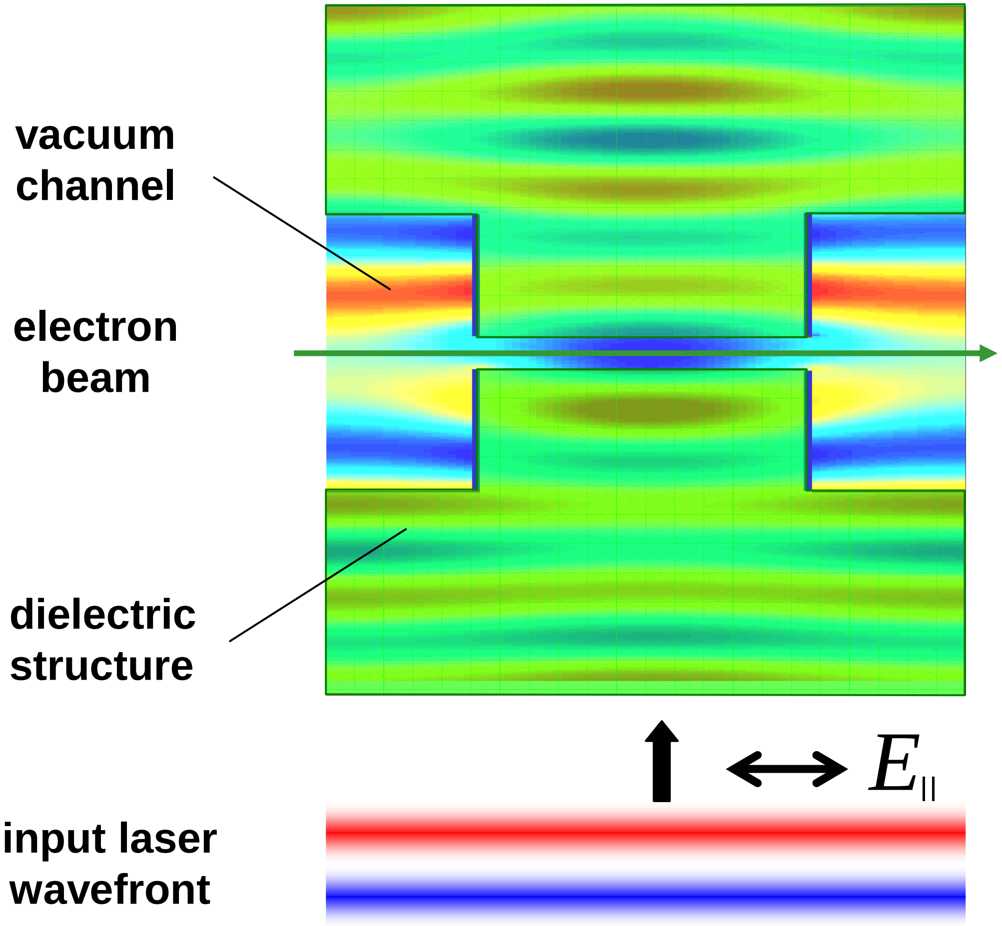
top view

traveling electron experiences accelerating force at all times



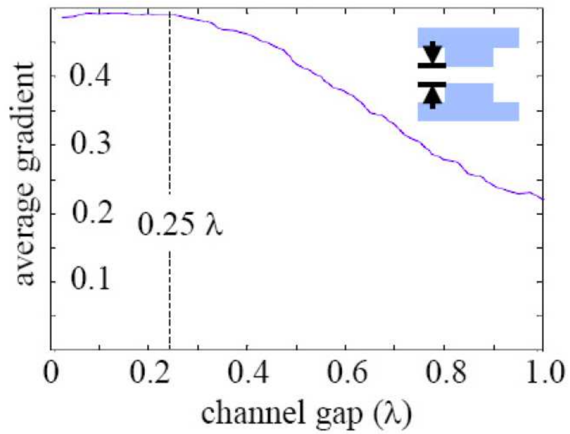
Transverse pumped phase-reset structure

EM field map in one unit



$$\langle \vec{F}_{\perp} \rangle = 0$$

vacuum channel width < λ

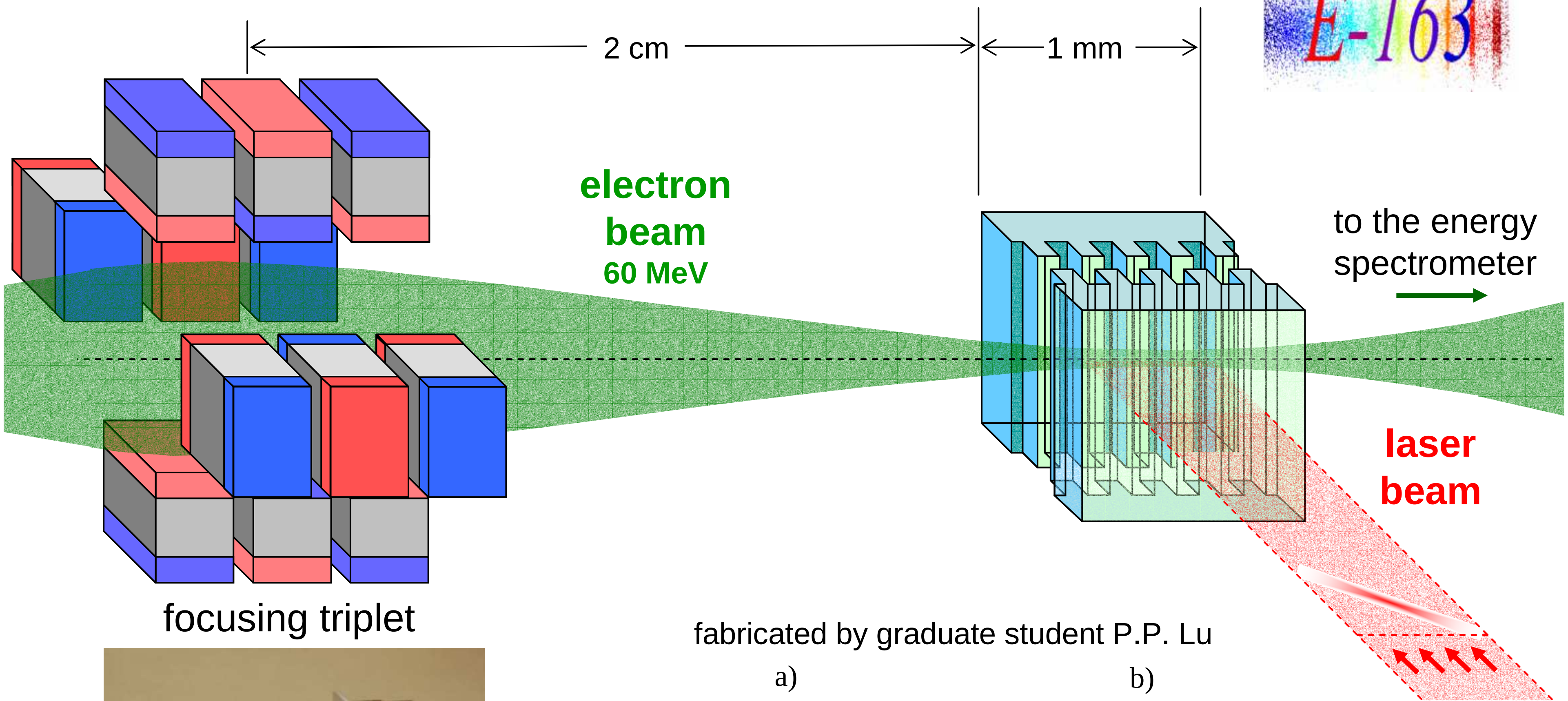


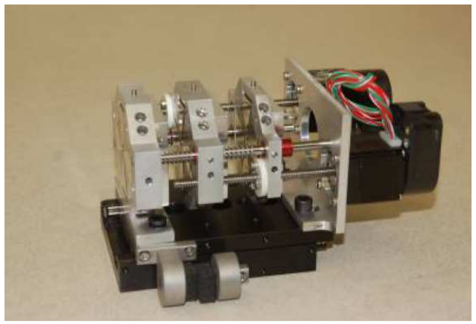
$$\langle \vec{E}_{||} \rangle \sim \tfrac{1}{2} E_{laser}$$

1 J/cm² fluence
~10 fsec pulses

$$\langle G_{acceleration} \rangle > 2\,\mathrm{GeV/m}$$

Transverse pumped phase-reset structure

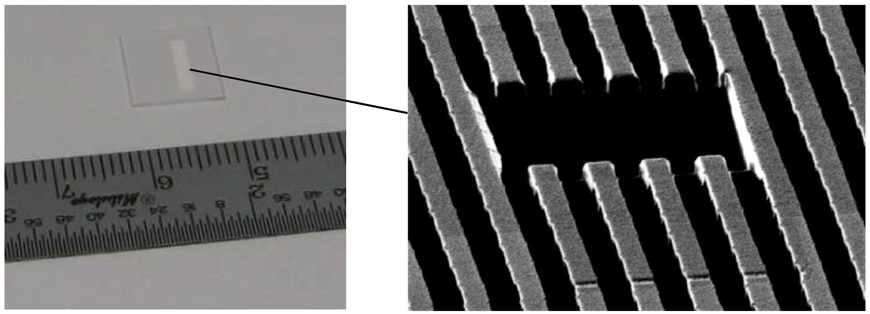




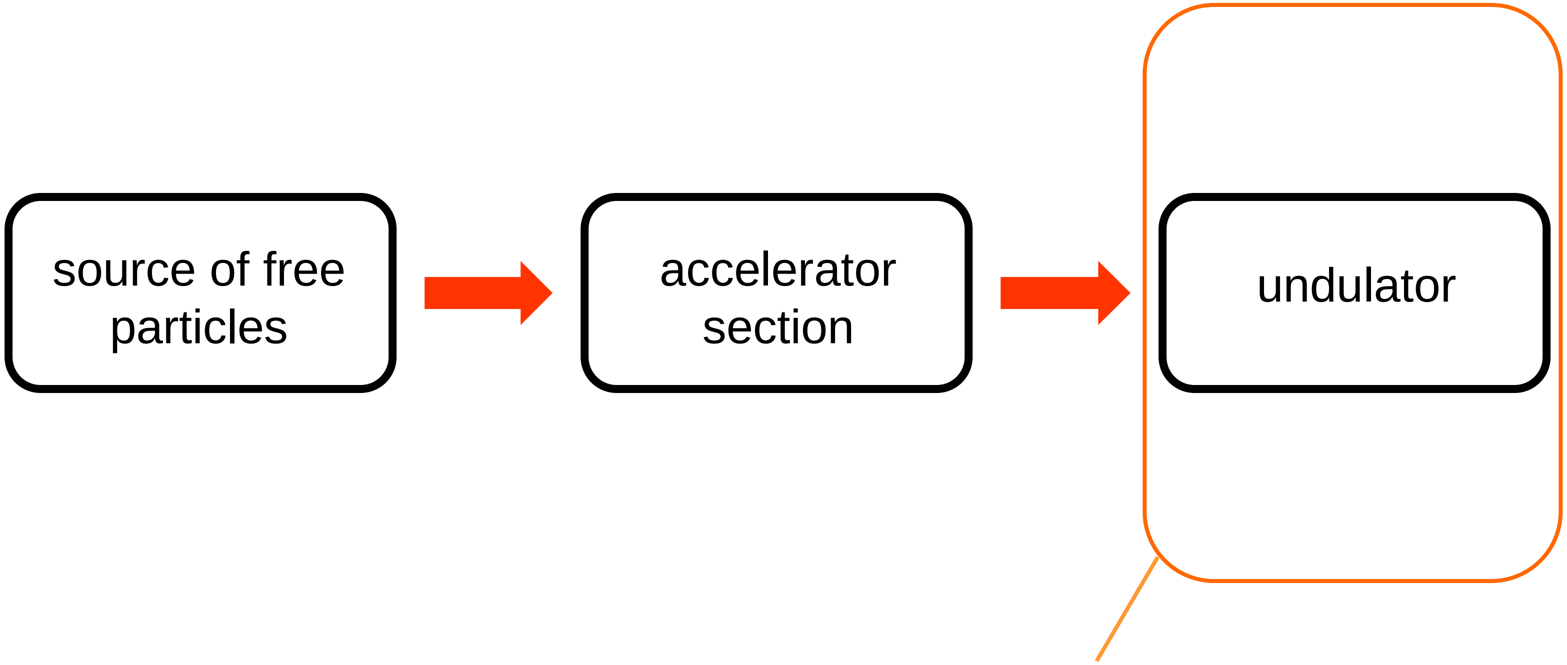
fabricated by graduate student C.M. Sears

fabricated by graduate student P.P. Lu

a) b)



Development of the three key laser-driven components



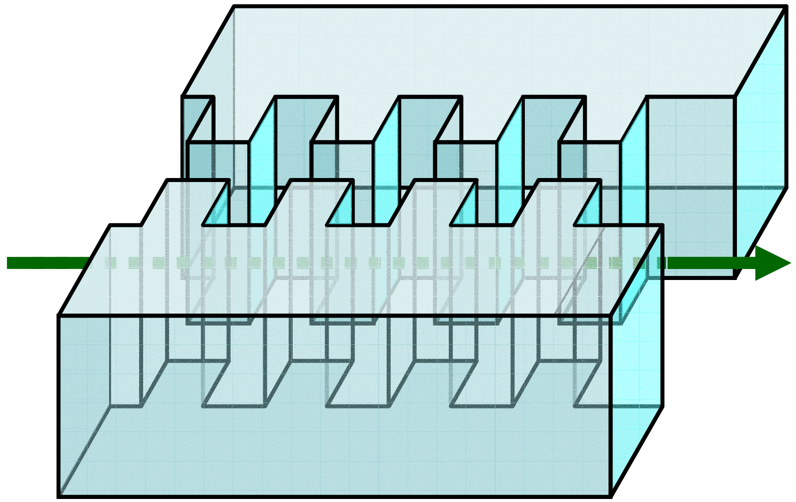
develop MEMs based laser-driven deflection structures

Objective:

1. Dielectric optical MEMs structures
2. High gradients (~ 1 GeV/m)
3. Possibility for compact undulators

The structure geometry determines the force component

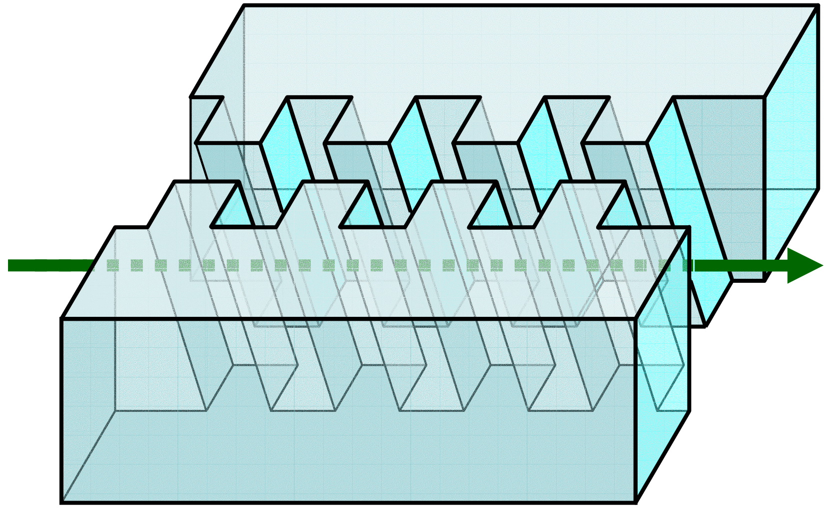
accelerator structure



$$\left\langle \vec{E}_\perp + \left(\vec{v}\times\vec{B}\right)_\perp \right\rangle = 0$$

$$\left\langle \vec{E}_\parallel \right\rangle \sim \tfrac{1}{2} E_{laser} \rightarrow \sim 4\,\mathrm{GeV/m}$$

deflection structure



$$\left\langle \vec{E}_\perp + \left(\vec{v}\times\vec{B}\right)_\perp \right\rangle \neq 0$$

$$\left\langle \vec{F}_\perp / q \right\rangle \sim \tfrac{1}{5} E_{laser} \rightarrow \sim 2\,\mathrm{GeV/m}$$

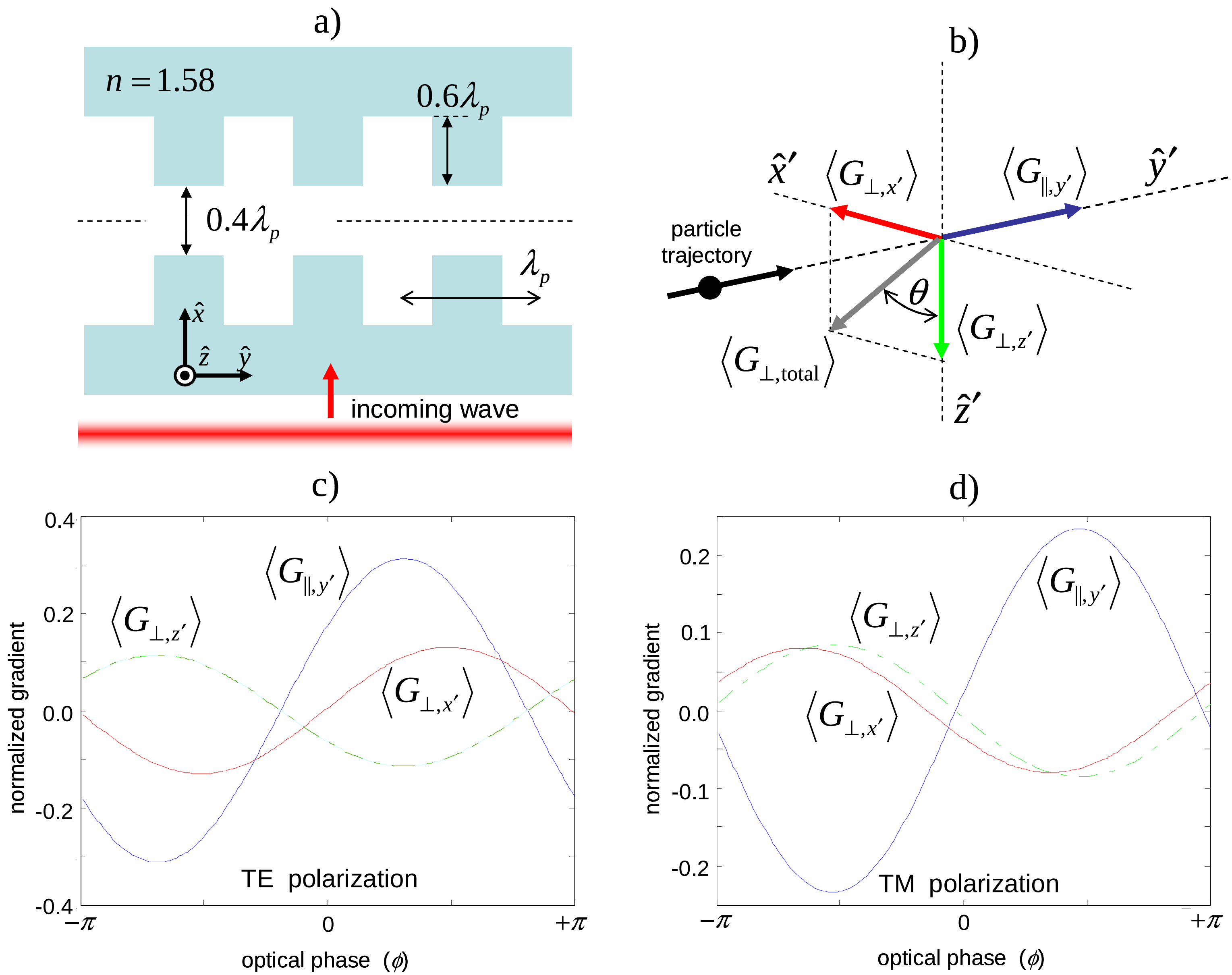
key idea

extended phase-synchronicity between the EM field and the particle

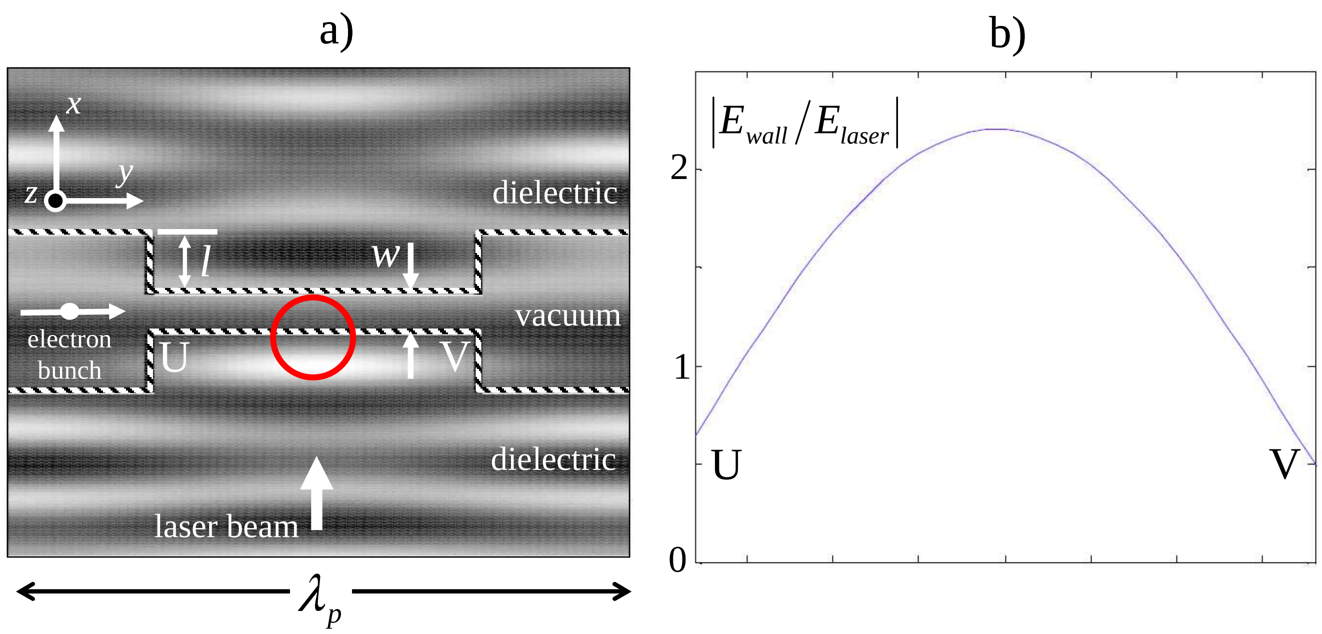
---

T. Plettner, *"Phase-synchronicity conditions from pulse-front tilted laser beams on one-dimensional periodic structures and proposed laser-driven deflection",* submitted to Phys. Rev. ST AB

The expected phase-synchronous force components



The expected maximum gradients



$$\langle \vec{G}_{\perp,TE} \rangle \sim 0.15 |E_{laser}|$$

$$\langle \vec{G}_{\parallel,TE} \rangle \sim 0.3 |E_{laser}|$$

$\div 2$

$$\langle \vec{G}_{\perp,TE} \rangle \sim 0.07 |E_{\max}|$$

$$\langle \vec{G}_{\parallel,TE} \rangle \sim 0.15 |E_{\max}|$$

10 fsec laser pulse

1 J/cm² → $|E_{\max}| \sim 25\,\mathrm{GV/m}$ →

$$\langle G_{\parallel,TE} \rangle \sim 4\,\mathrm{GV/m}$$

$$\langle G_{\perp,TE} \rangle \sim 2\,\mathrm{GV/m}$$

Y. Min Oh et al, International Journal of Heat and Mass Transfer 49 (2006) 1493–1500
B. C. Stuart et al, Physical Review Letters 74, 2248 (1995)
M. Lenzner et al, “Femtosecond Optical Breakdown in Dielectrics”, Phys. Rev. Lett. 80, 4076 (1998)

The most simplistic wakefield picture

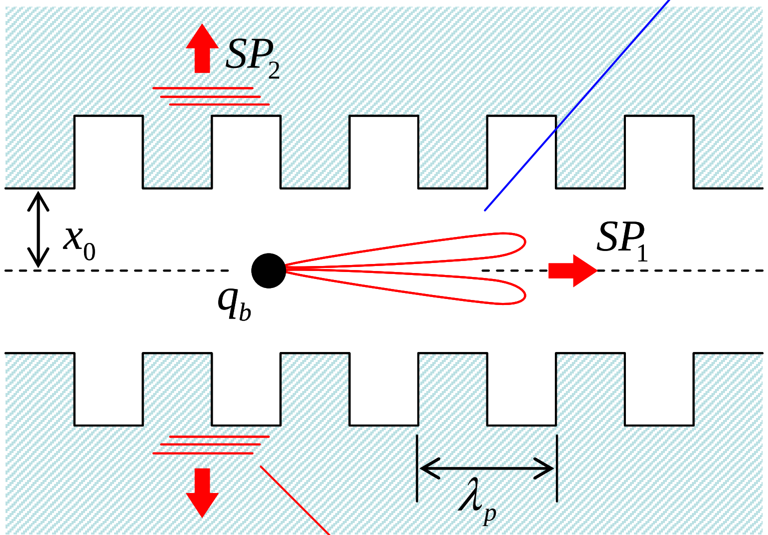
Assume a "perfect" dielectric (real index of refraction)

→ The loss factor mechanisms come from diffraction

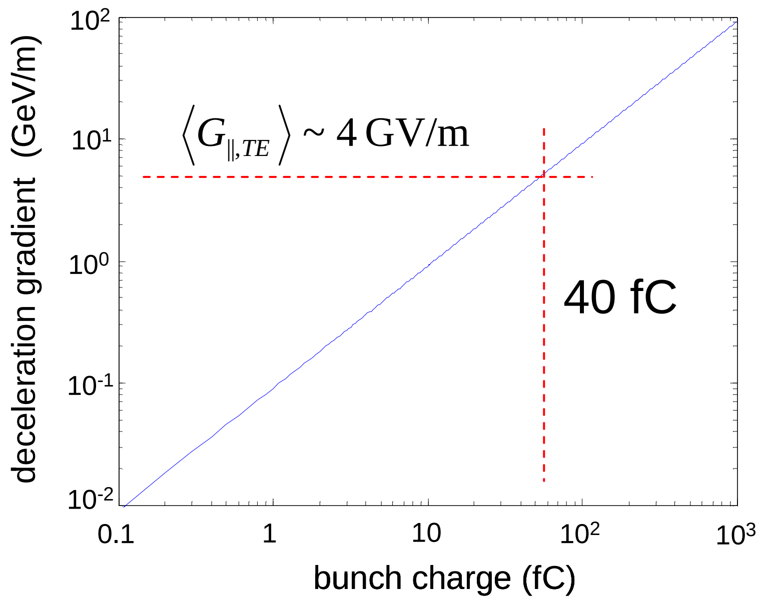
fwd. Smith-Purcell [1]

$4\pi x_0 / \lambda_p \sim 1/\gamma$

a)



$K_C \sim 100\,\mathrm{GeV/m/pC}$



beam loading [2,3,4]

$$qV = \frac{DL}{2Z_0}\left(E_L^2 - (E_L + E_W)^2\right)\tau_L$$

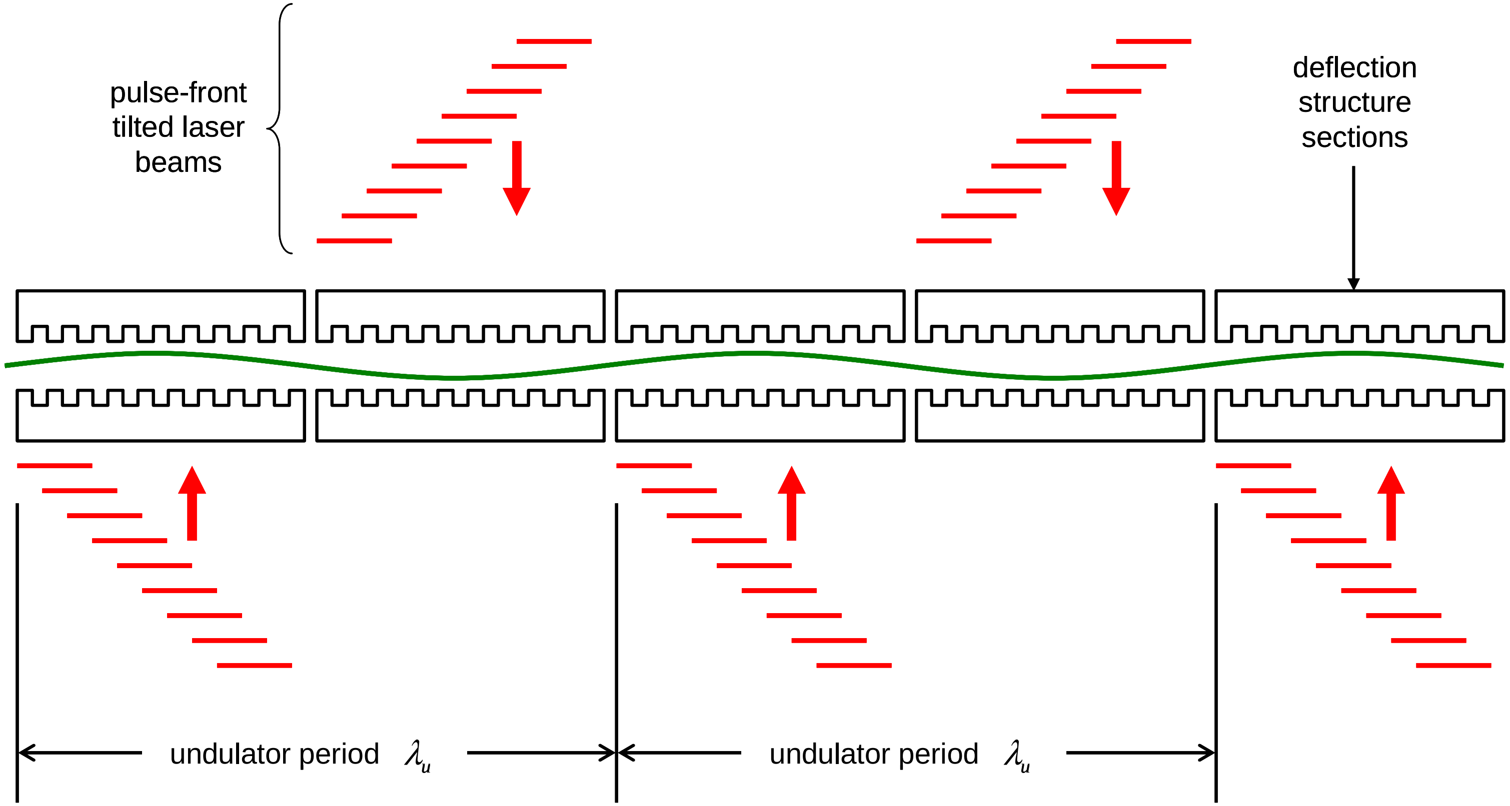
but I have neglected the broadband Cherenkov wake…

$K_C \sim 100\,\mathrm{GeV/m/pC}$

→ $Q_b \sim 20\ \mathrm{fC}$

[1] Phys. Rev. Lett. 74, 3808 (1995)
[2] Phys. Rev. STAB 6 02441 (2003)
[3] Phys. Rev. STAB 9, 111301 (2006)
[4] Phys. Rev. STAB 7, 061303 (2004)

A dielectric structure undulator



- **same loss factor** as the laser accelerator: ~100 GV/m/pC
- **similar structure geometry** → fabrication compatibility

Design considerations: the 1-D FEL model

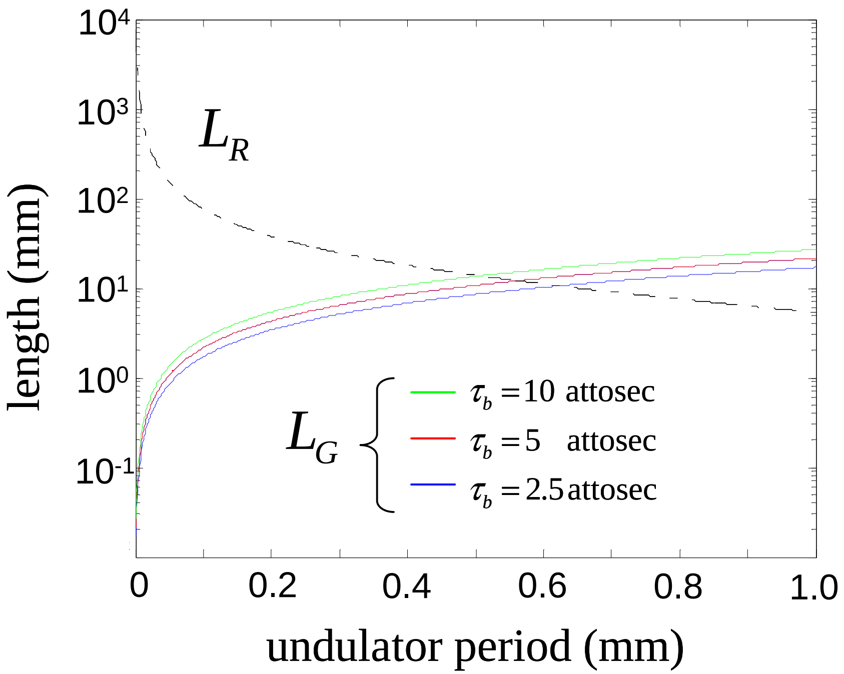
$U_b = 2\ \mathrm{GeV}$
$\varepsilon_N = 10^{-9}\ \mathrm{m\text{-}rad}$
$Q_b = 20\ \mathrm{fC}$
$\sigma_r = 200\ \mathrm{nm}$
$\beta^* = 4\ \mathrm{cm}$

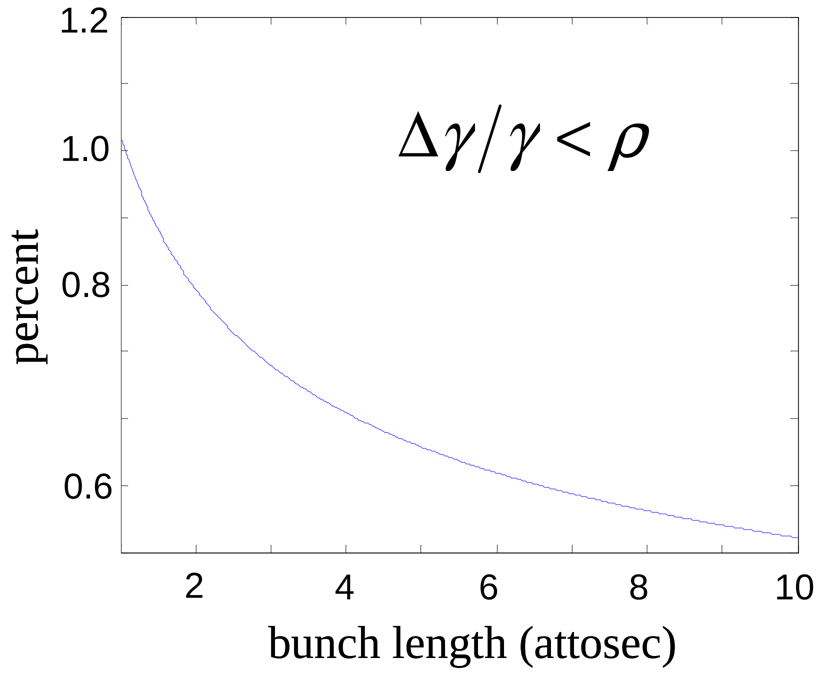
→

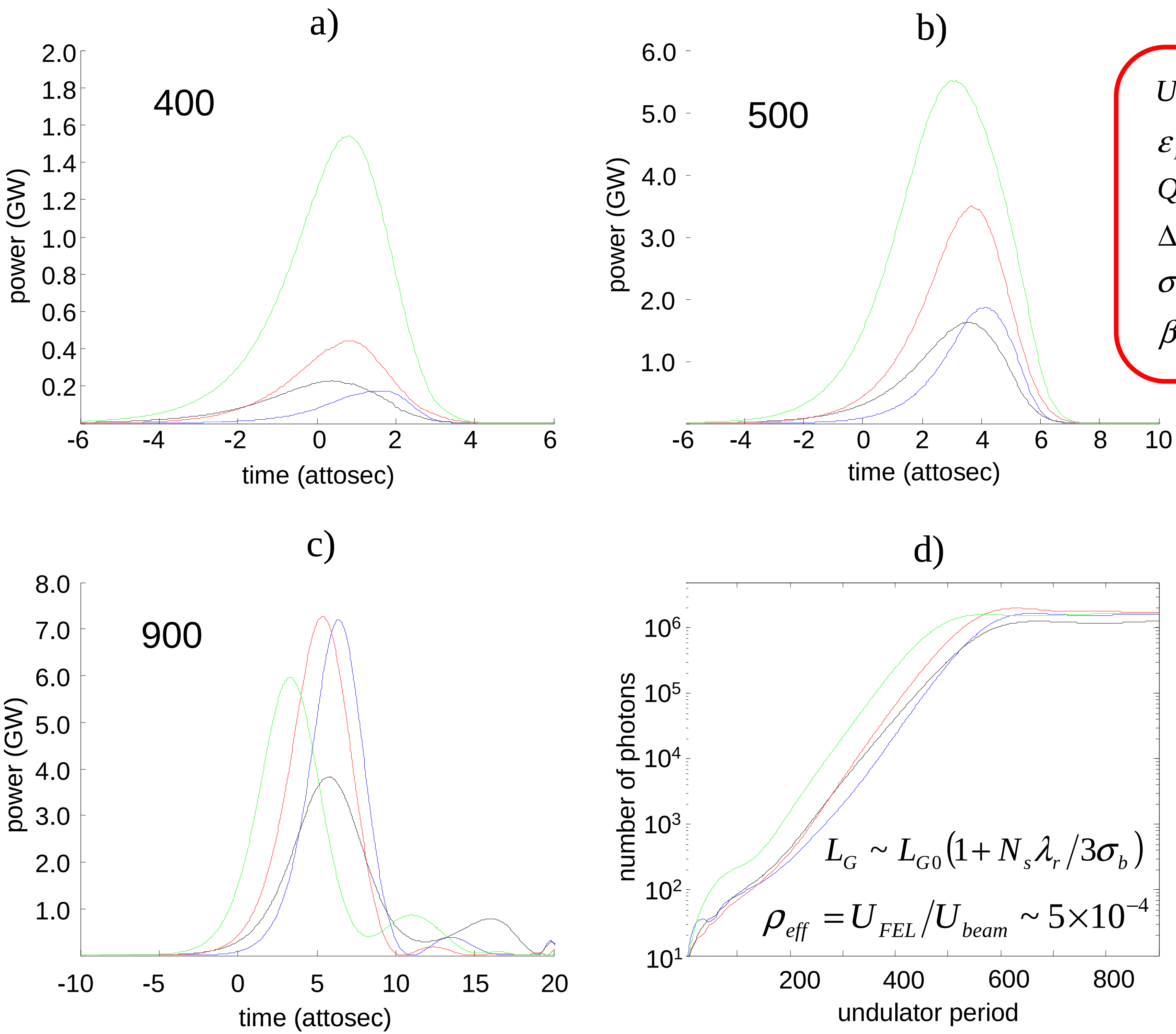
$L_G < L_R$ → $\lambda_u < 0.5\ \mathrm{mm}$

$\varepsilon < (\lambda_r / 4\pi)\gamma$ → $\lambda_u > 0.01\ \mathrm{mm}$

$\lambda_u = 0.3\ \mathrm{mm}$







$U_b = 2\,\mathrm{GeV}$

$\varepsilon_N = 10^{-9}\ \mathrm{m\text{-}rad}$

$Q_b = 20\ \mathrm{fC}$

$\Delta\gamma/\gamma = 0.1\%$

$\sigma_r = 200\ \mathrm{nm}$

$\beta^* = 4\ \mathrm{cm}$

$L_c \sim 21\lambda_r$

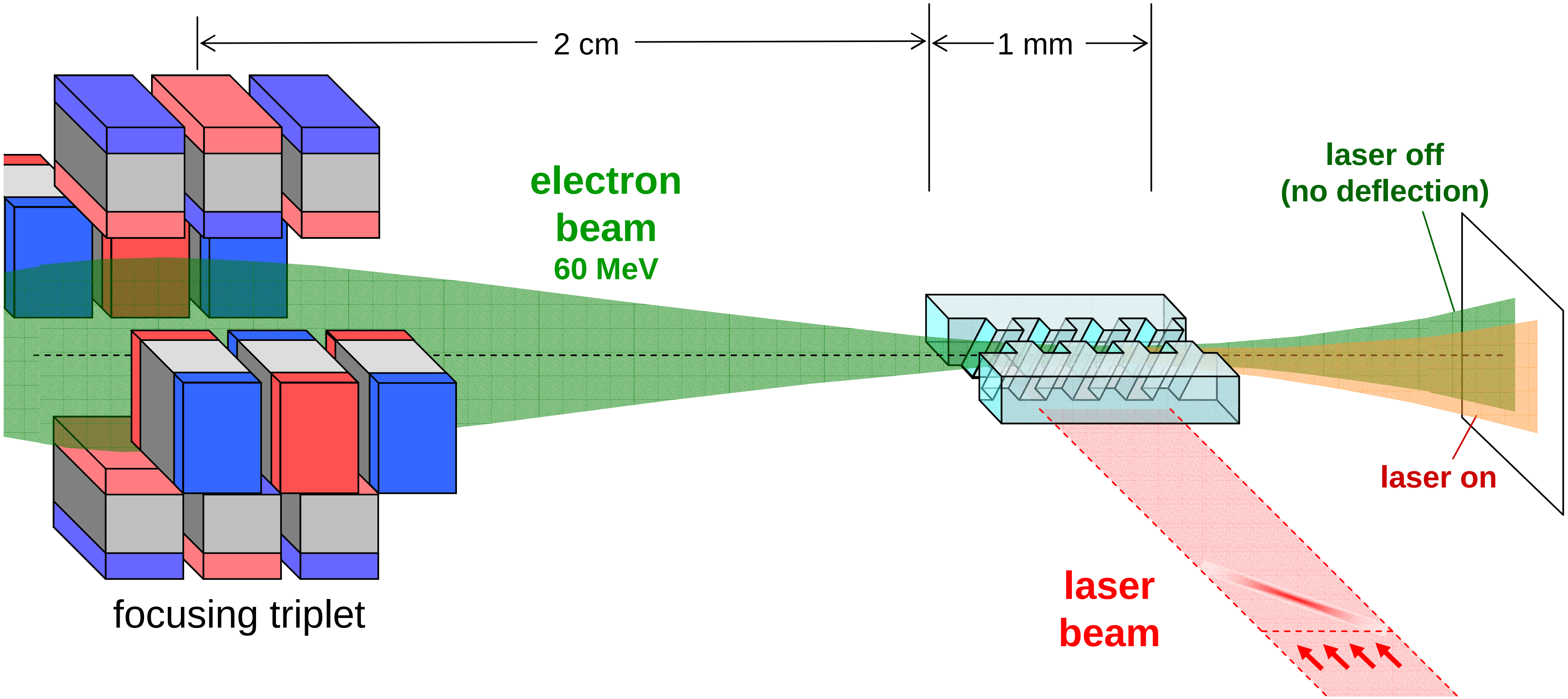
$\sigma_b \sim 136\lambda_r$

$\sigma_b/L_c \sim 6$

G. Dattoli, L. Giannessi, P.L. Ottaviani, C. Ronsivalle, J. Appl. Phys. 95, 3206 (2004)

Experiments

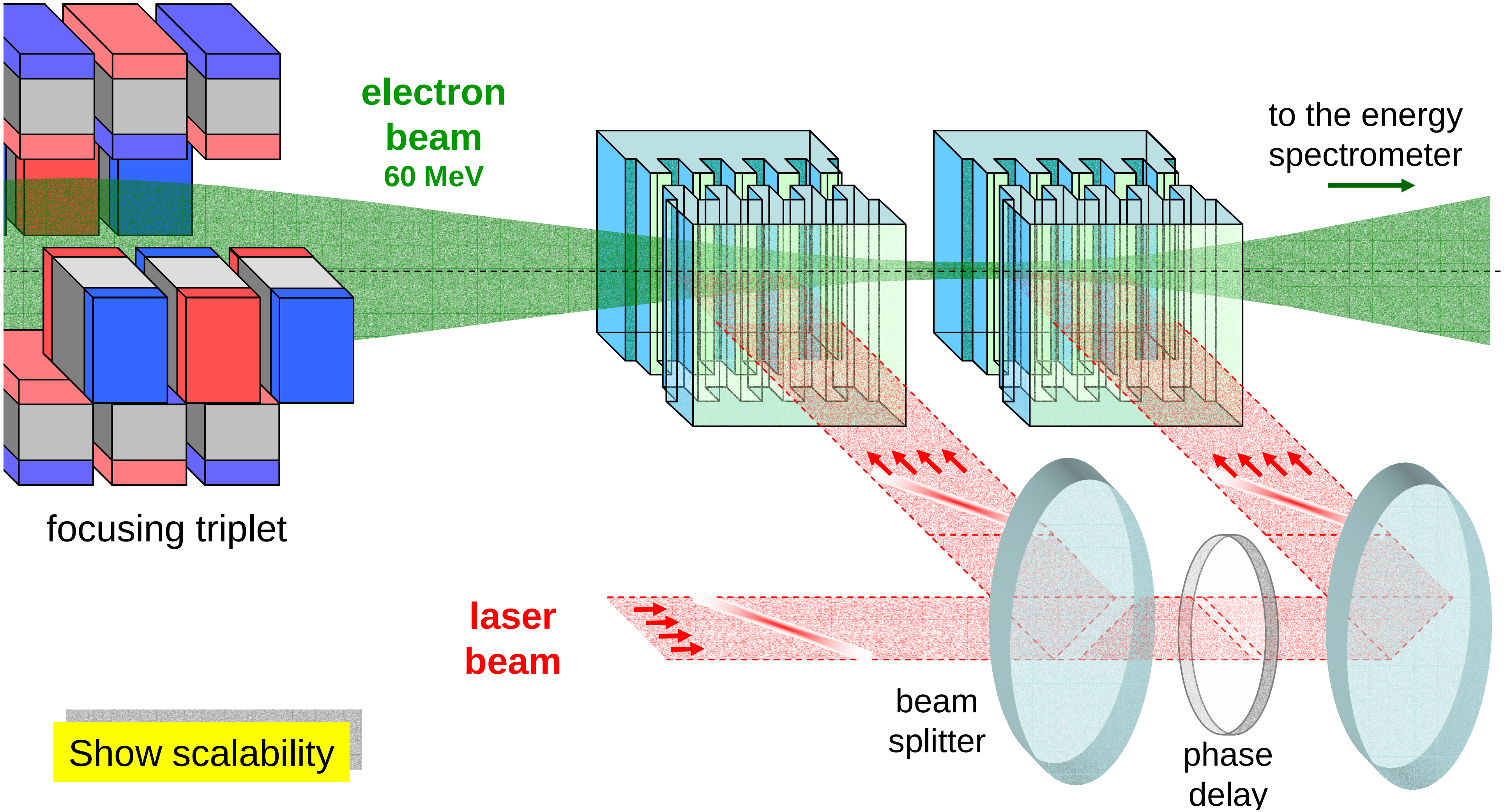
Test of laser-deflection



Prove the concept of a phase-synchronous deflection force

Experiments

Cascading of microstructure accelerators



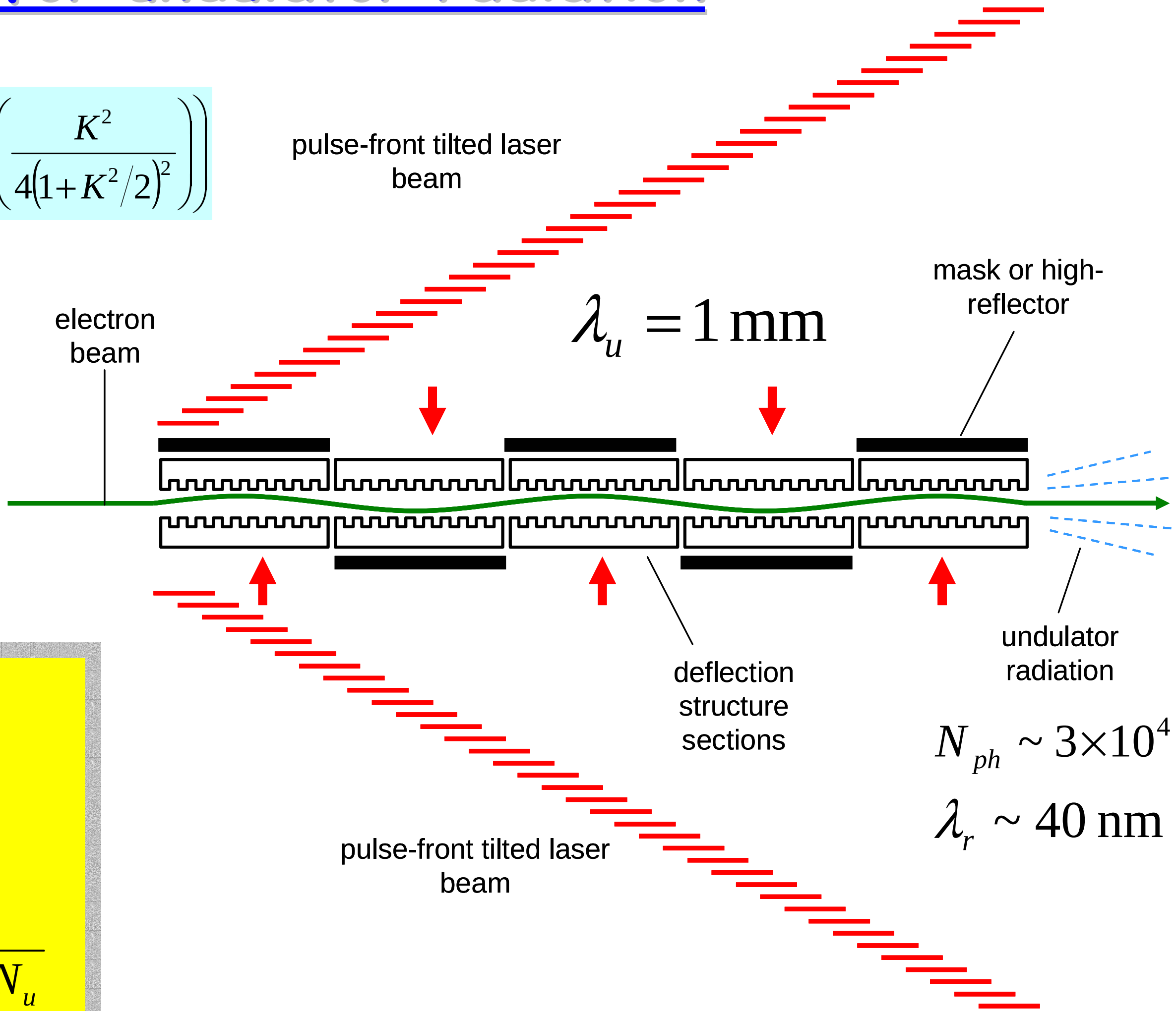
Show scalability

Experiments

E-163

Look for undulator radiation

$$N_{ph} = \pi\alpha \frac{K^2}{\left(1+K^2/2\right)^2}\left(J_1\left(\frac{K^2}{4\left(1+K^2/2\right)^2}\right) - J_0\left(\frac{K^2}{4\left(1+K^2/2\right)^2}\right)\right)$$



Prove the concept

measure

$$\begin{cases} K \propto \lambda_u \\ \Delta\omega/\omega = 1/N_u \\ \Delta\theta = \sqrt{2\lambda_r/\lambda_u N_u} \end{cases}$$

Long-term experiments

Inject higher density of optically bunched electrons into the structure

- search for small-signal gain
- verify predicted beam loading and wakefield effects

Test other materials for dielectric structures

- verify index of refraction and transparency window
- perform laser-damage threshold tests
- radiation damage tests

Integration of the components

- cascading of ~10^3 mm-long accelerator sections
- cascading of ~10^2 sub-mm long deflection sections
- beam transport: steering and periodic focusing
- beam diagnostics: BPMs, etc

Refinement of the idea

- undulator optimization: periodic focusing, tapering, etc.
- seeding, resonator configuration
- harmonic generation

Summary

Dielectric structure FEL
- injector
- accelerator
- undulator

Laser-driven

properties
1. photon energy of tens of keV
2. ~10^5 photons/pulse
3. 80 MHz → 10^{12} photons/sec

initial work
- laser-particle accelerators (LEAP/E163)
- field-emission injector
- modeling of the undulator and FEL process

future
- dielectric structure accelerators
- test a laser-driven deflector
- construct a low-energy pre-accelerator

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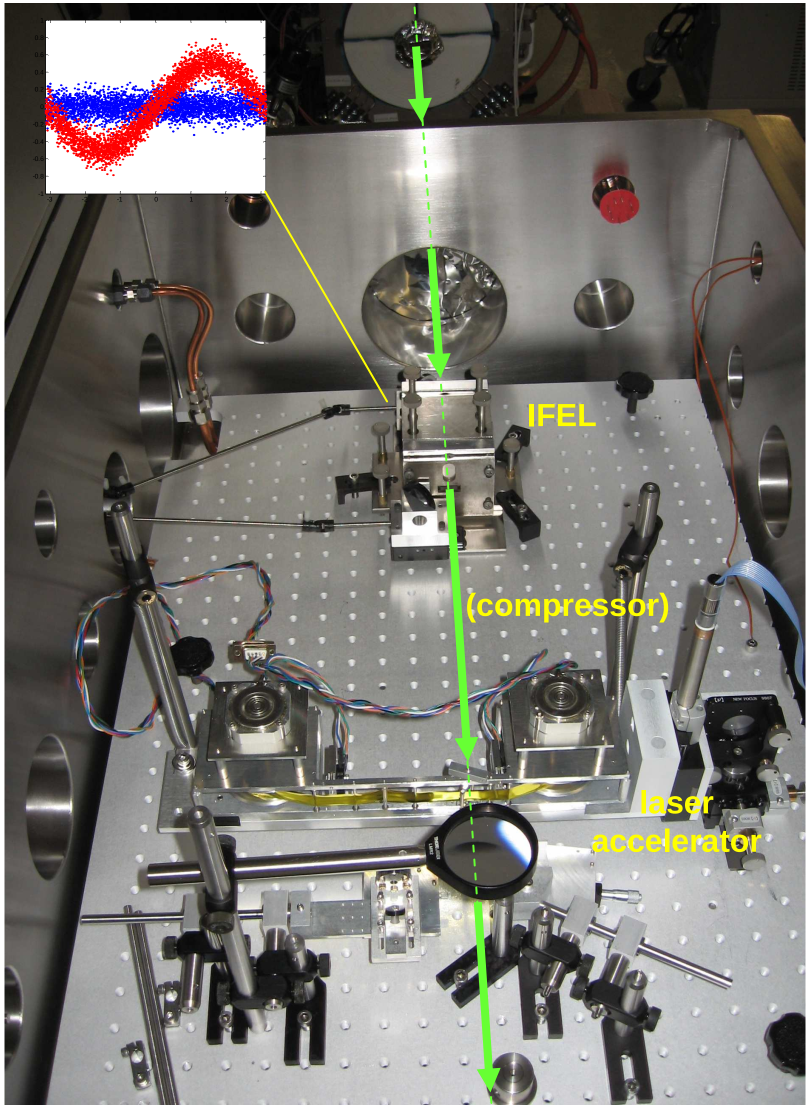
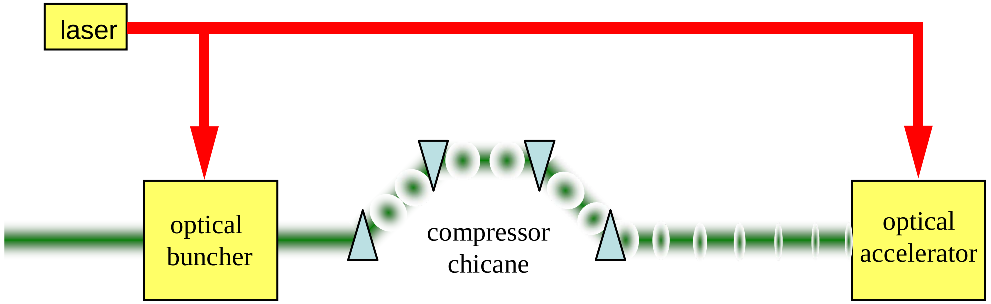
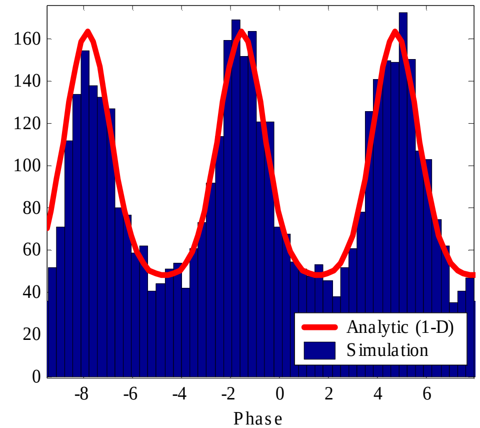
Buncher-accelerator two-stage experiment

(C. M. Sears)

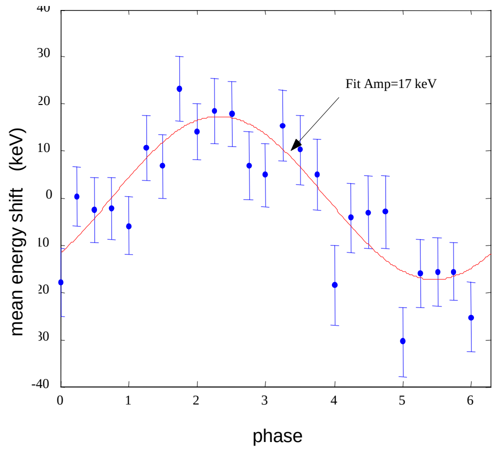




Expected bunching



Expected energy gain



Experiment features

- IFEL modulates energy spread
- electron drift creates optical bunches
- second accelerator → net acceleration

Architecture of a laser-driven free-electron X-ray source