Part 3: The current state of research and an outlook on future developments in various selected fields of accelerator physics and technology:

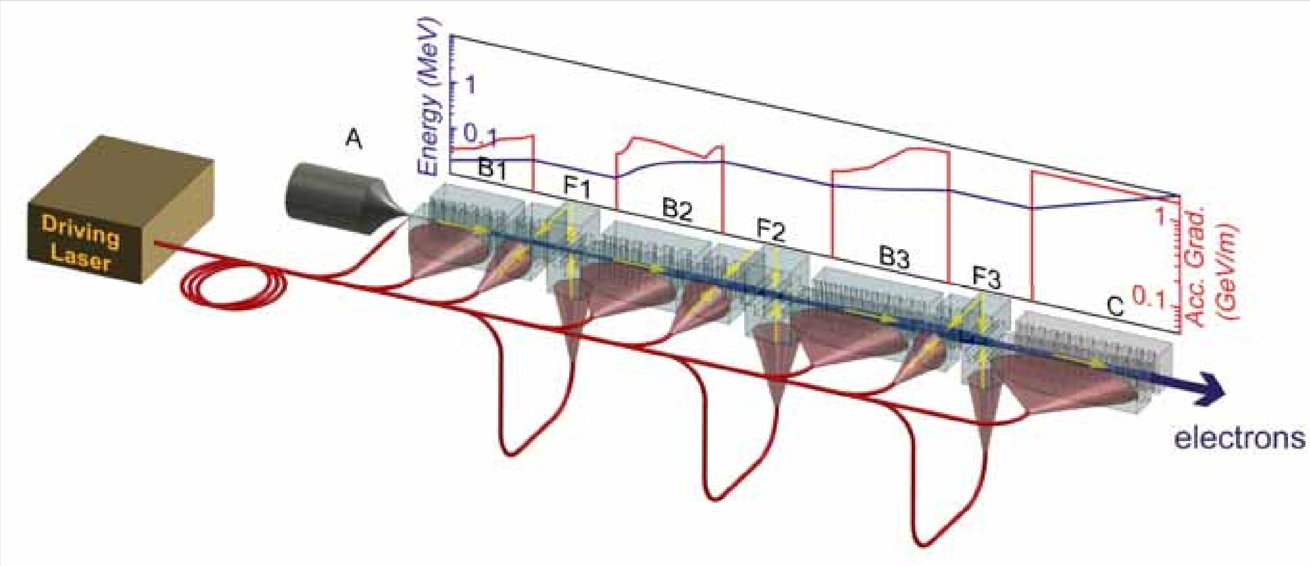
Accelerator on a chip

Taking advantage of photonics technology

Peter Hommelhoff

Friedrich-Alexander-Universität Erlangen-Nürnberg (FAU), Erlangen, Germany

Max-Planck-Institut für die Physik des Lichts (MPL), Erlangen



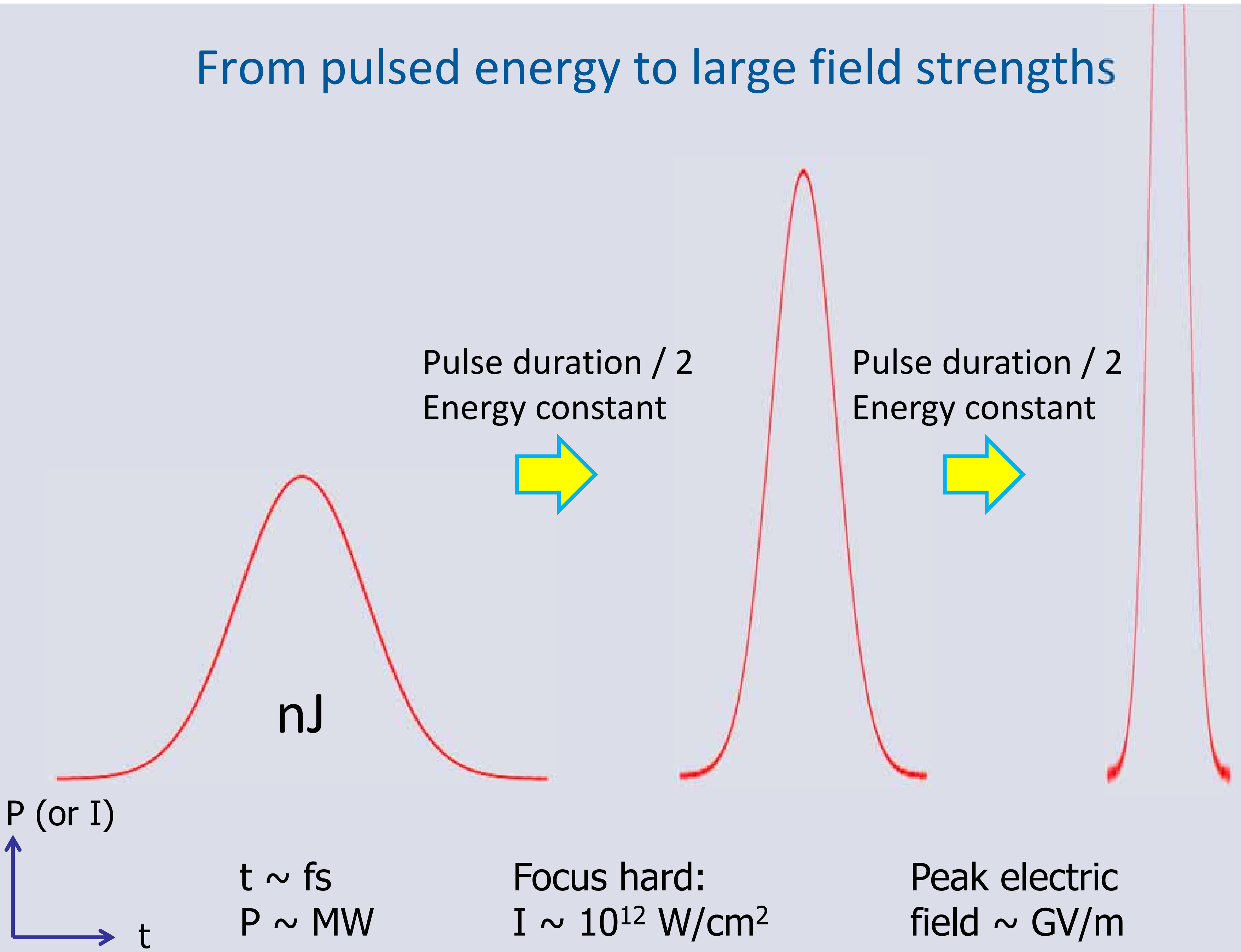
GORDON AND BETTY MOORE FOUNDATION

ACHIP Accelerator on a Chip International Program

bmb+f Bundesministerium für Bildung und Forschung

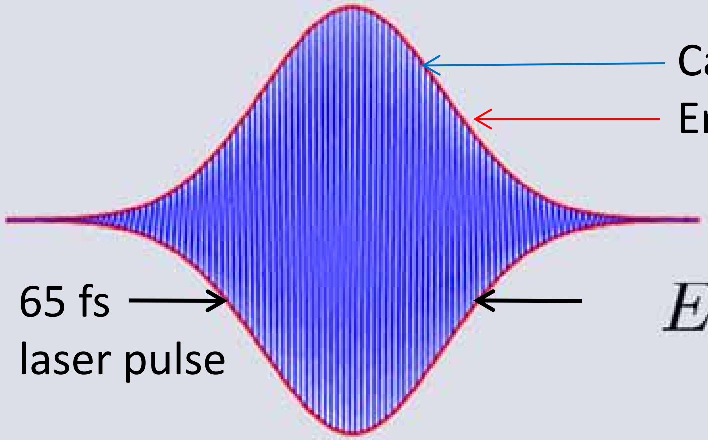
KfB Workshop: Perspectives for Accelerator Physics and Technology, TU Darmstadt 16.-17.Feb. 2017

From pulsed energy to large field strengths



FRIEDRICH-ALEXANDER UNIVERSITÄT ERLANGEN-NÜRNBERG

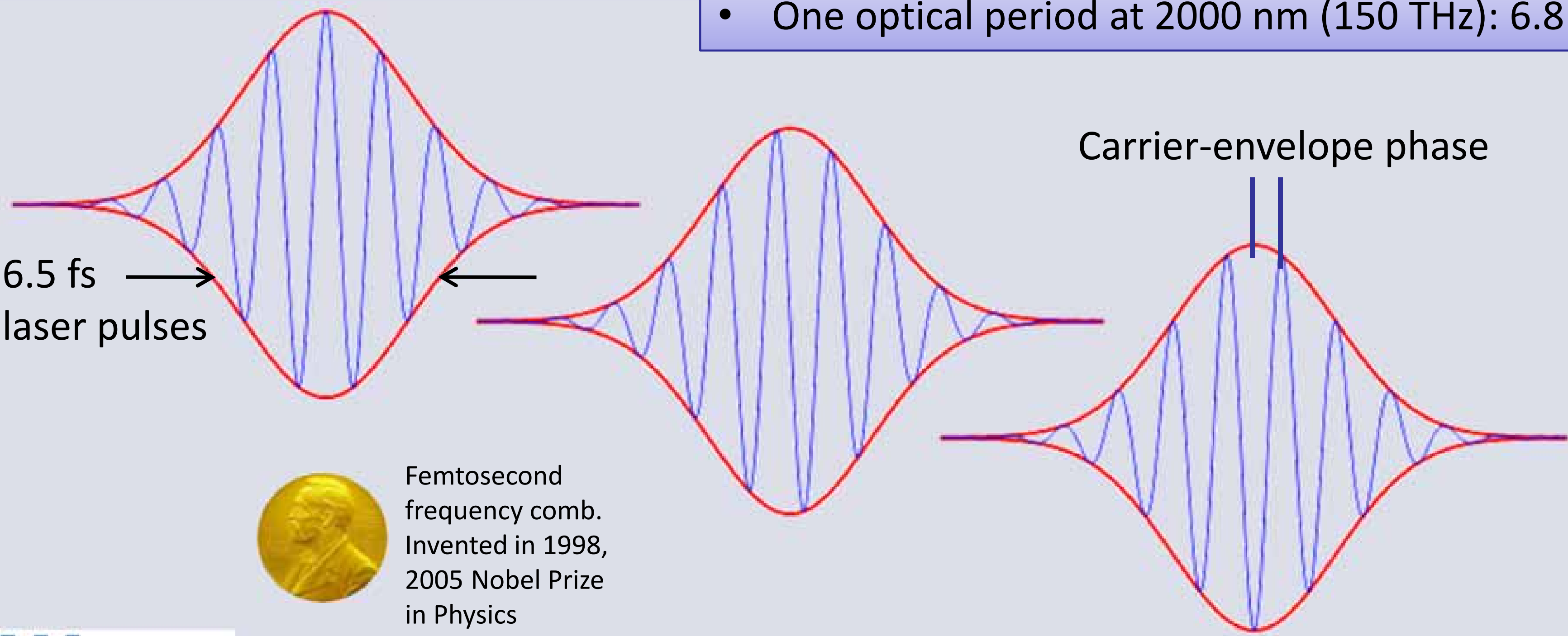
Femtosecond and few-cycle laser pulses



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

- Field strengths of GV/m easily attainable
- Peak intensities of 10^{15} W/cm^2
- Peak power: MW, GW, up to PW today

- One optical period at 800 nm (375 THz): 2.7 fs
- One optical period at 2000 nm (150 THz): 6.8 fs



Femtosecond frequency comb. Invented in 1998, 2005 Nobel Prize in Physics

Technology perspective: ***photonics***

- Power and cost efficient laser technology
  - high average power
  - rugged turn-key fiber technology

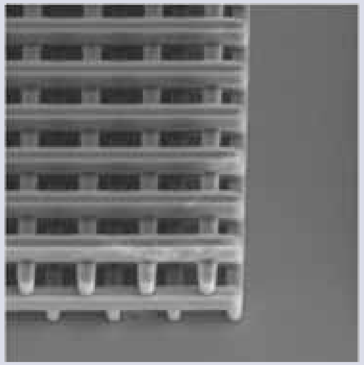
- Optical field control available

- (Silicon) nanostructuring capabilities

➡ ***Photonics technology!***

World market for photonics: $481 billion in 2012, expected $620 billion in 2020 (Nat. Phot. 11, 1, 2016)

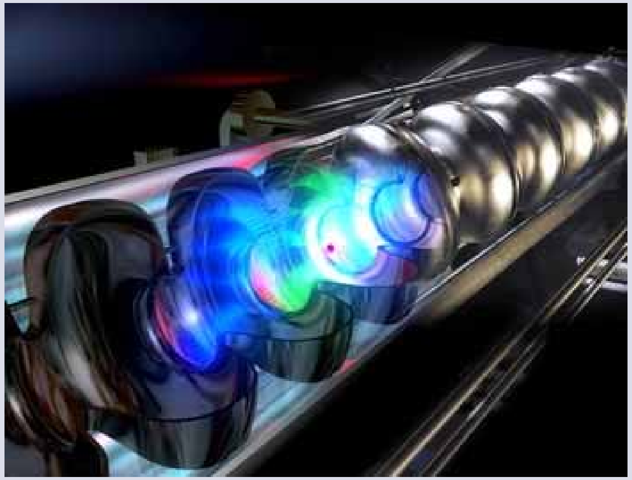
Similar story to radar klystrons driving accelerator technology in the 1940s?



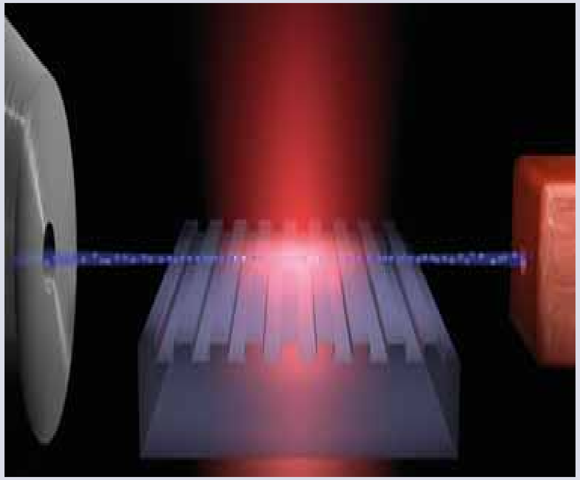
Even 3-dimensional structures

McGuinness et al., J. Mod. Opt. 2009

Particle accelerators: from RF to optical/photonic drive?

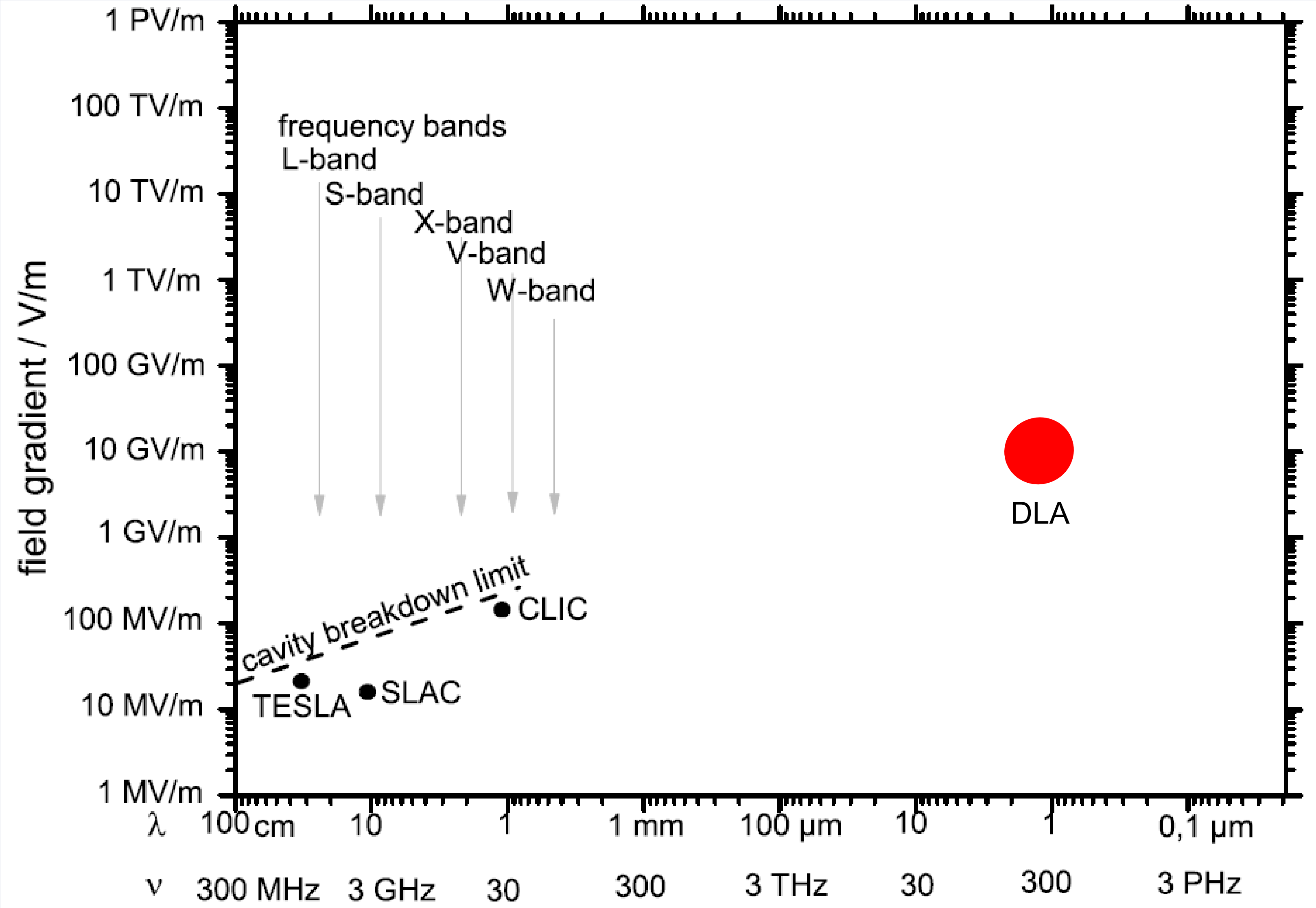


RF cavity (TESLA, DESY)



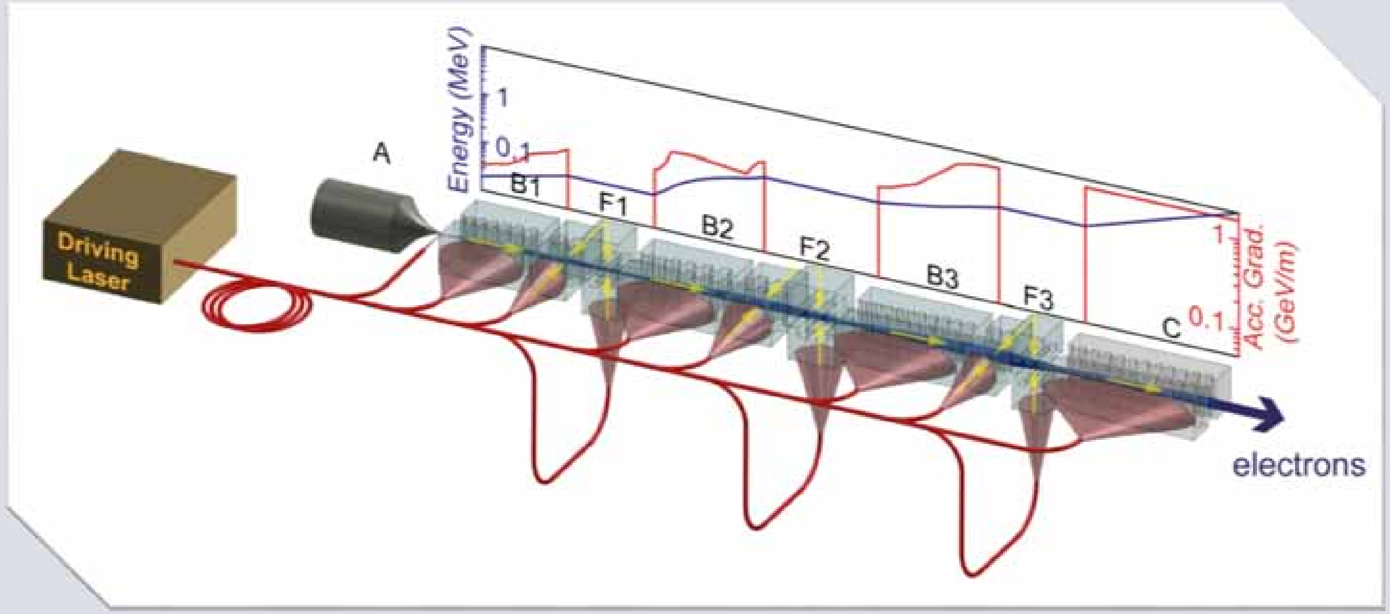
	Conventional linear accelerator (RF)	Laser-based dielectric accelerator (optical)
Based on	(Supercond.) RF cavities	Quartz grating structures
Peak field limited by	**Surface breakdown: 200 MV/m**	**Damage threshold: 30 GV/m**
Max. achievable gradients	**100 MeV/m**	**10 GeV/m**
Drive period	**~300 ps**	**~5 fs**

Breakdown limits



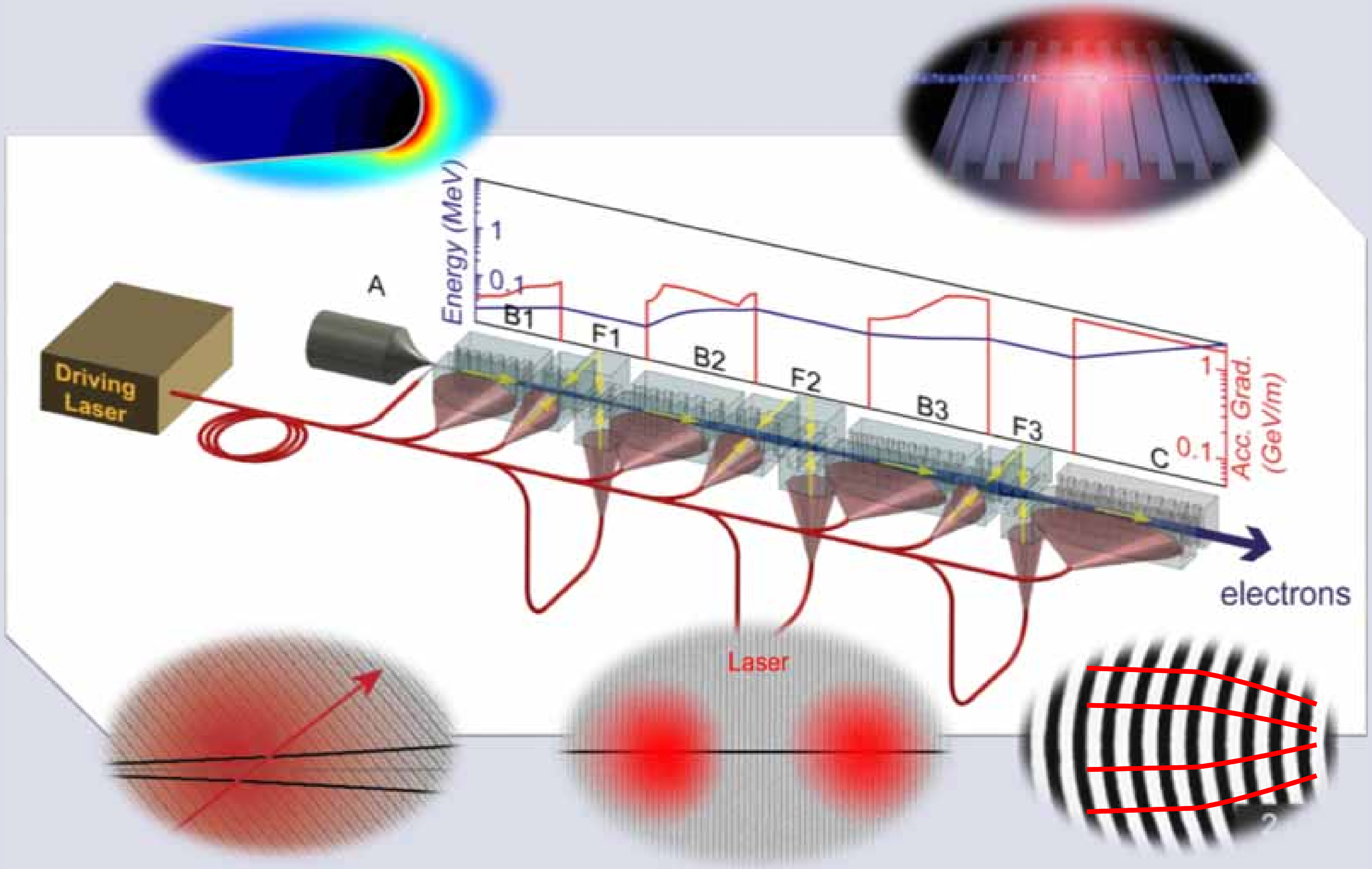
adapted from B. Hidding et al., Phys. Plasmas 16, 043105 (2009)

Laser acceleration of electrons at photonic structures
Dielectric laser acceleration (DLA)
Structure loaded vacuum acceleration of electrons



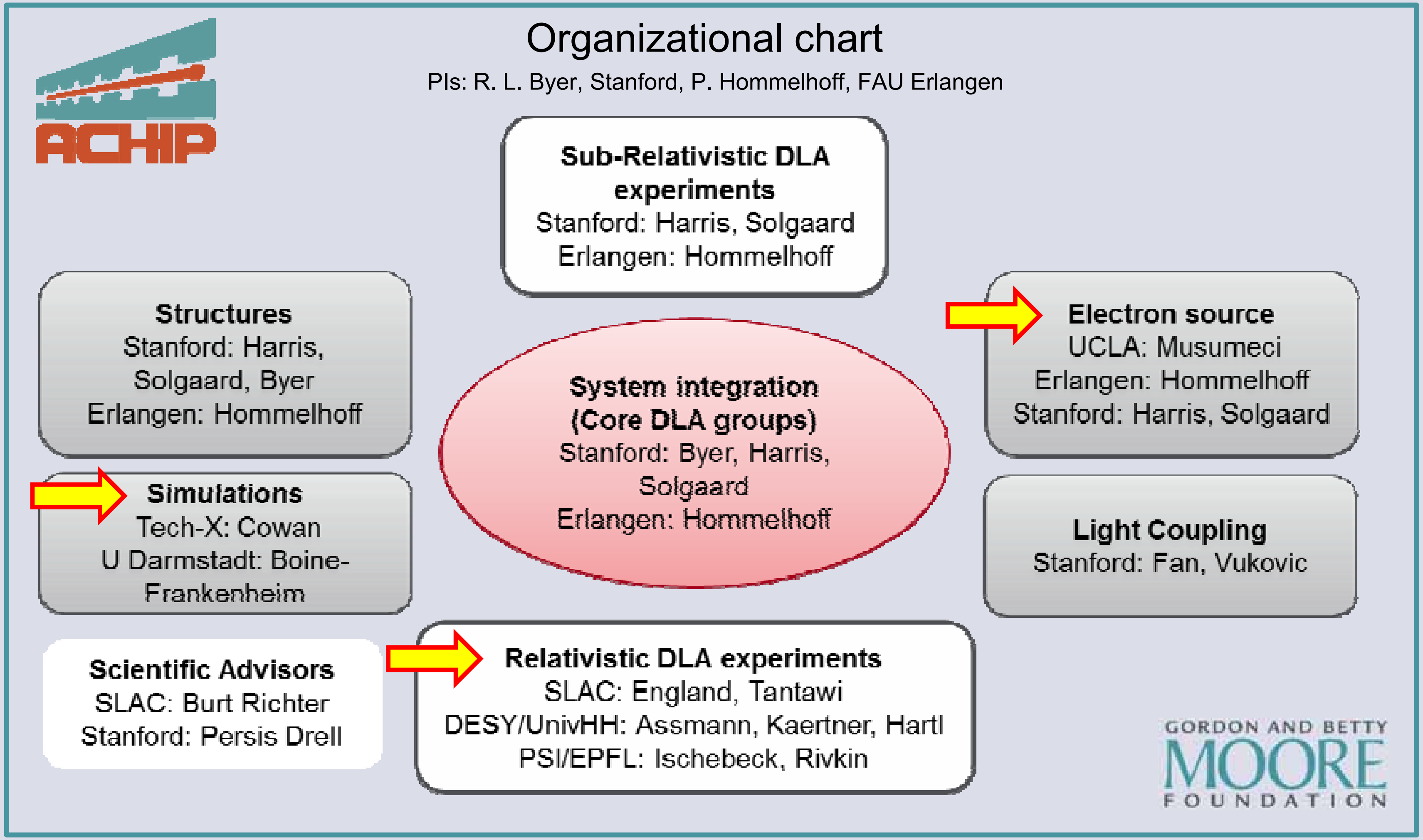
J. McNeur, M. Kozák, J. Breuer, Li Ang, N. Schönenberger, J. Illmer, A. Mittelbach, PH

Accelerator on a chip



FRIEDRICH-ALEXANDER UNIVERSITÄT ERLANGEN-NÜRNBERG

ACHIP: Accelerator on a Chip International Program



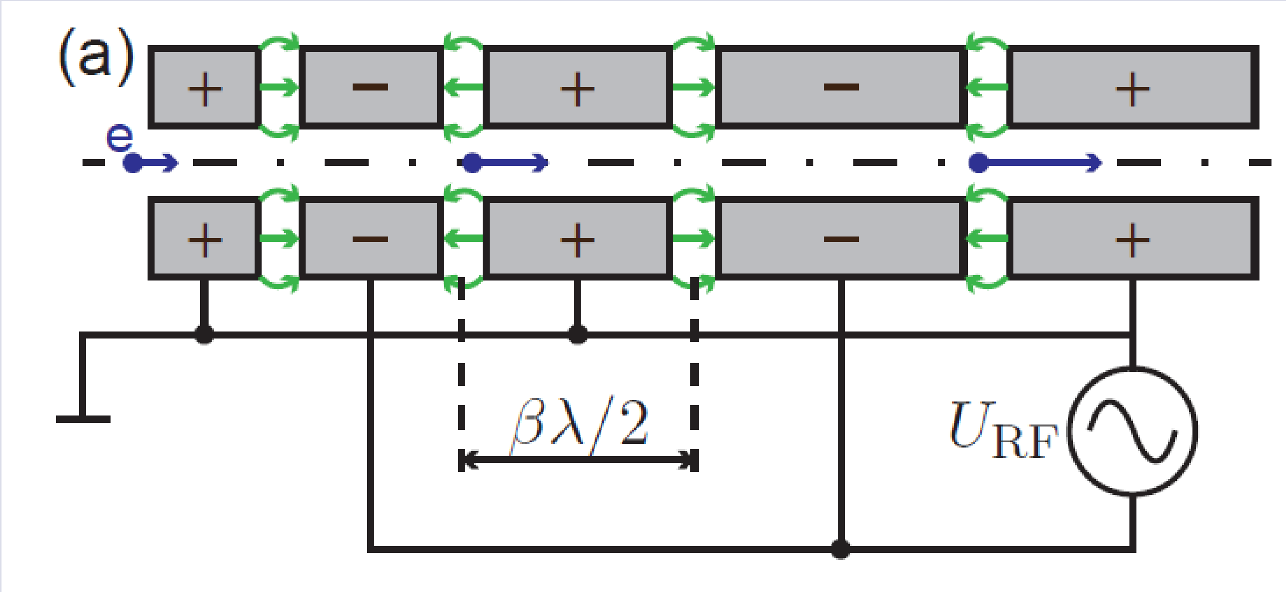
ACHIP Scientific Advisory Board: Chan Joshi, UCLA, Lia Merminga, SLAC, Reinhard Brinkmann, DESY

Program start: Dec. 2015

Erlangen meeting of ACHIP collaboration (Sept. 2016)

FRIEDRICH-ALEXANDER UNIVERSITÄT ERLANGEN-NÜRNBERG

Widerøe linac

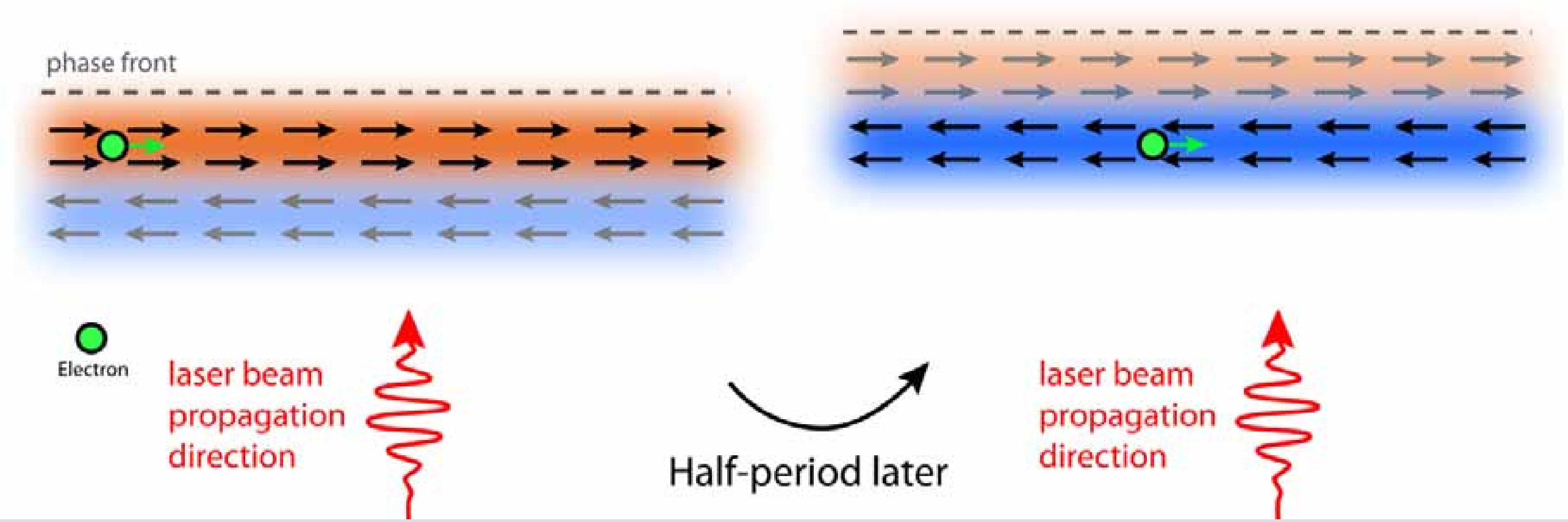


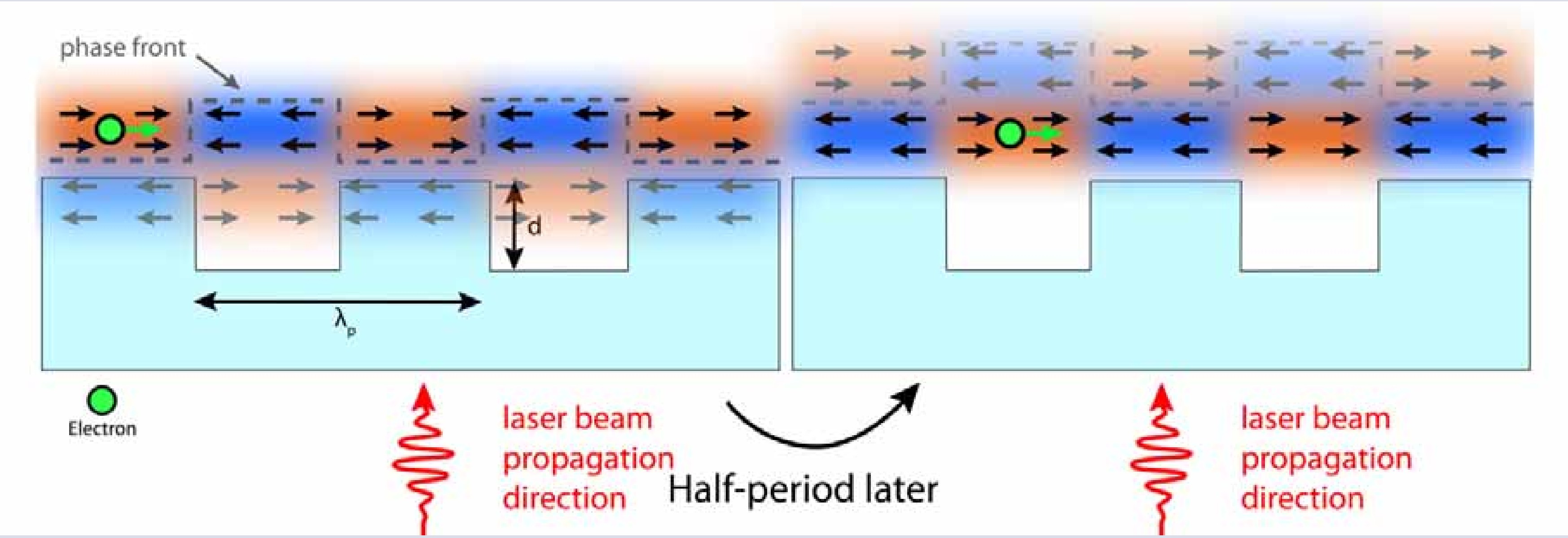
taken from J. Breuer's thesis

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

Wideroe, 1928
Ising, 1924

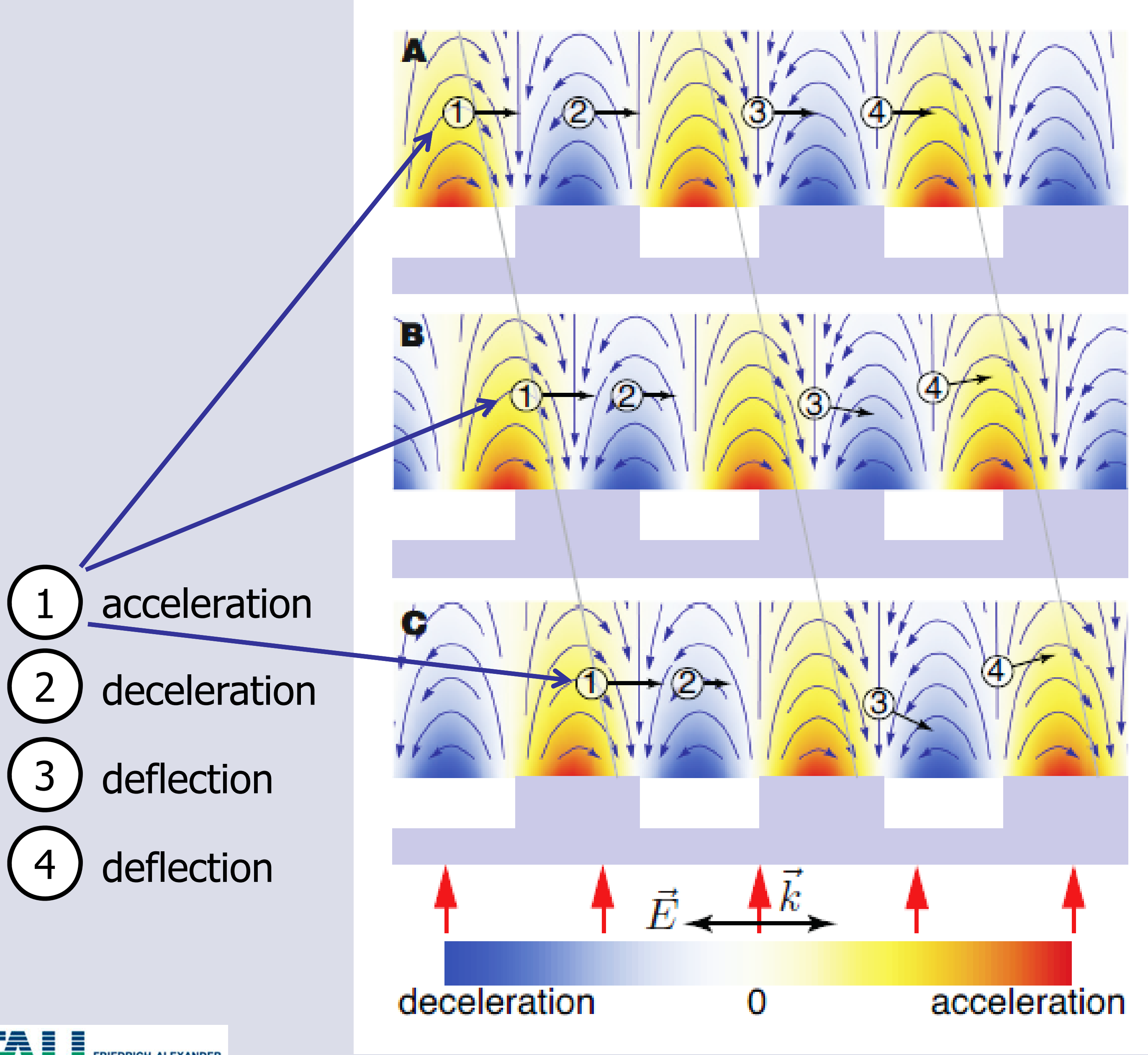
Acceleration at a dielectric structure / phase mask





Hommelhoff, KfB, TU Darmstadt, Feb. 2017

Acceleration by phase-synchronous propagation



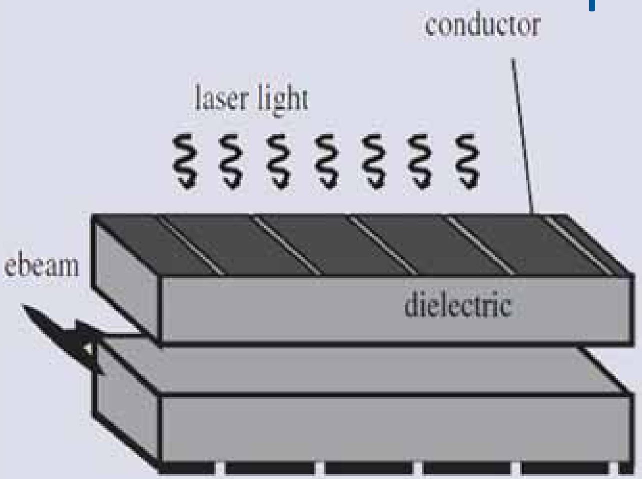
t = 0

t = π/2

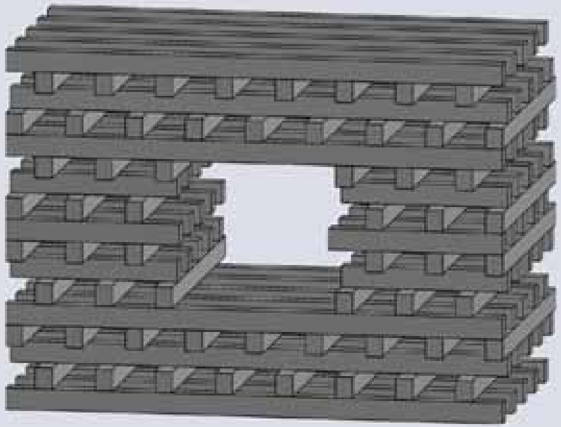
t = π

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

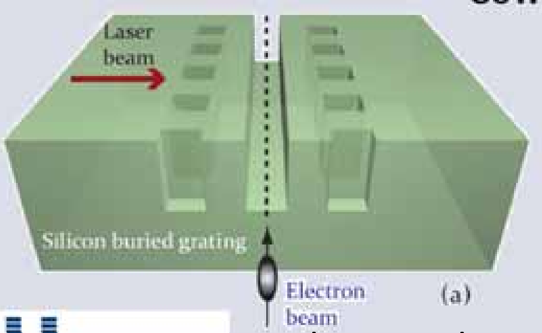
Proposed dielectric structures



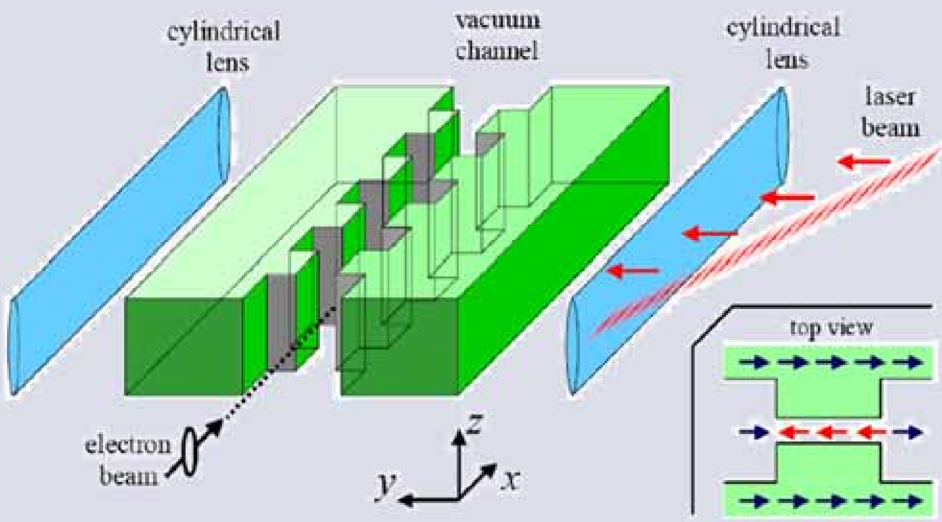
Yoder Rosenzweig, 2005



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)

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

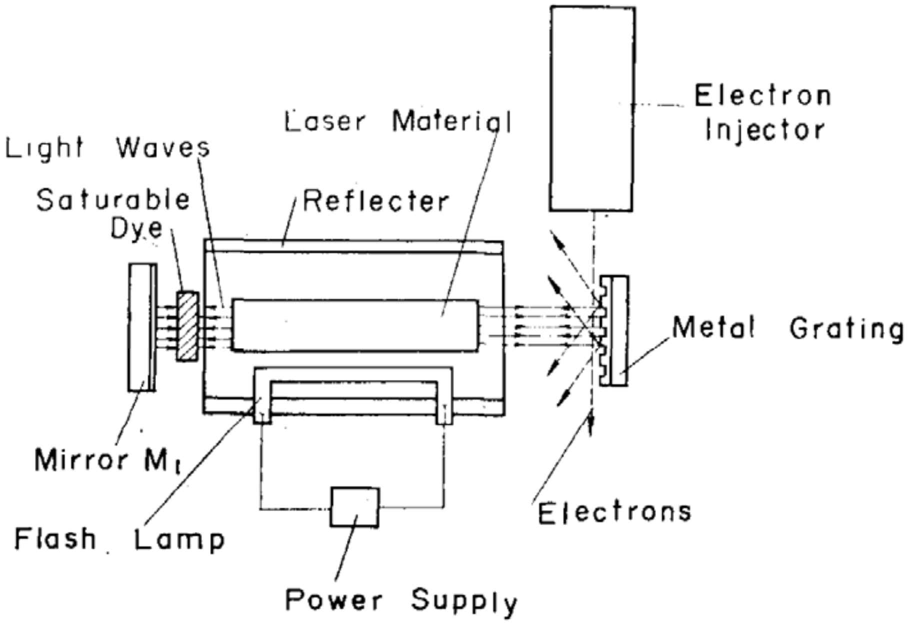


Fig. 1. Schematic diagram of "laser linac with grating".

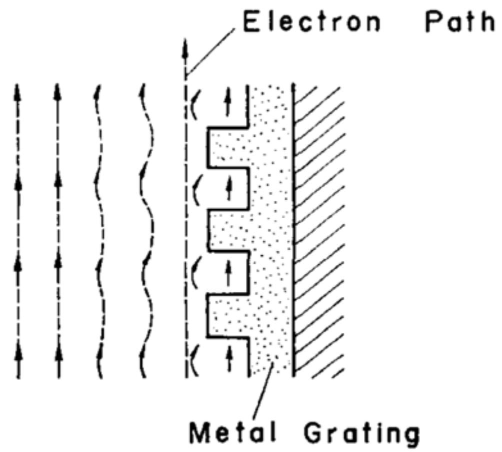


Fig. 2. Configuration of electric-field near grating surface.

Exp. demonstration with mm radiation (keV/m): Mizuno et al., Nature Nature 328, 45 (1987).

FRIEDRICH-ALEXANDER UNIVERSITÄT ERLANGEN-NÜRNBERG

In the 90s: dielectrics!

VOLUME 74, NUMBER 13 PHYSICAL REVIEW LETTERS 27 MARCH 1995

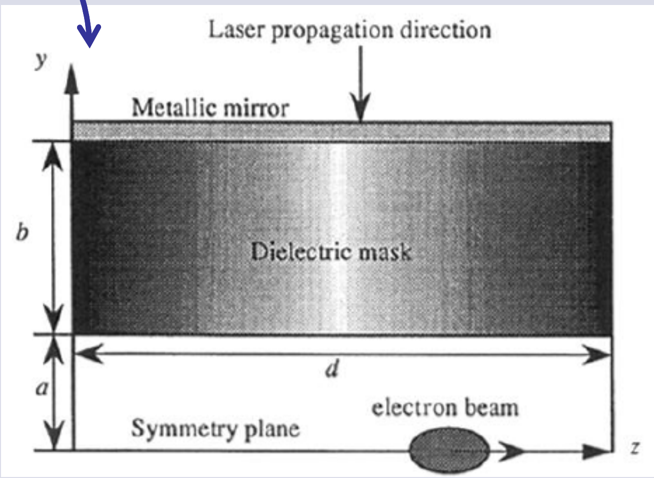
A Proposed Dielectric-Loaded Resonant Laser Accelerator

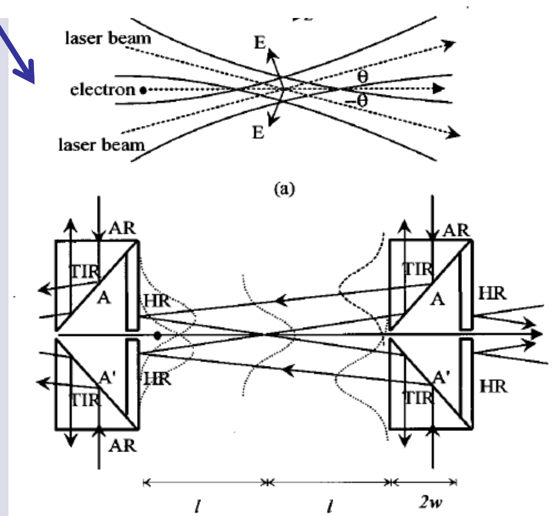
J. Rosenzweig, A. Murokh, and C. Pellegrini
Department of Physics, University of California, Los Angeles, 405 Hilgard Avenue, Los Angeles, California 90024
(Received 2 September 1994)

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)

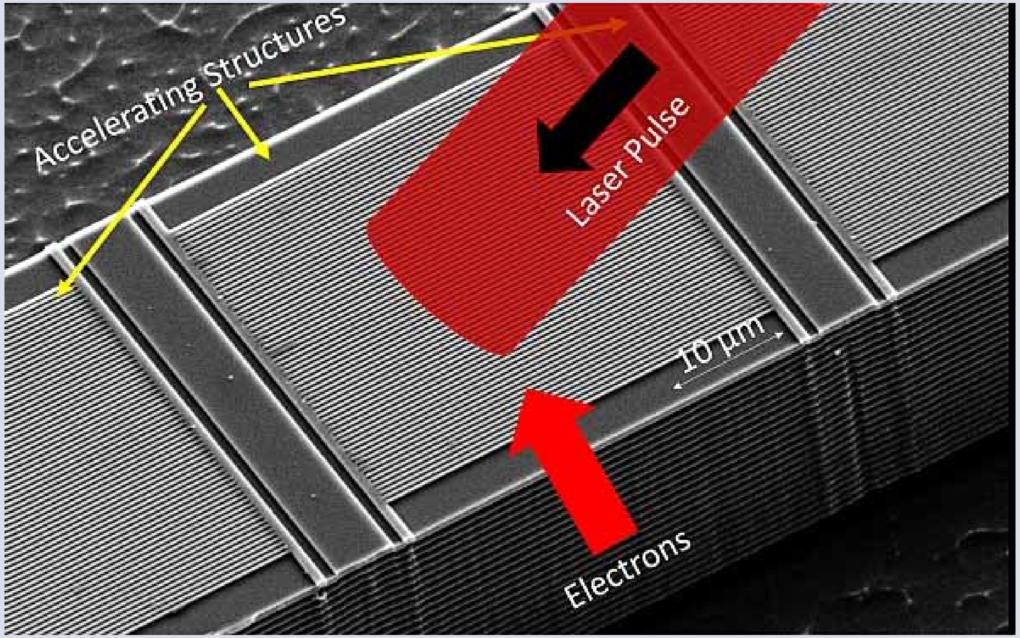




Other longtime players: Sieman group (SLAC), Travish (UCLA), Yoder (Manhattan) …

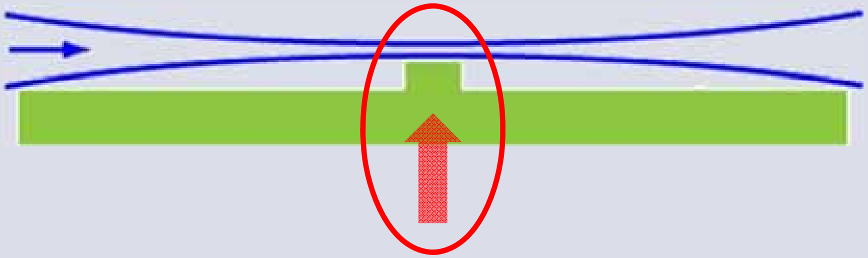
Grating structure

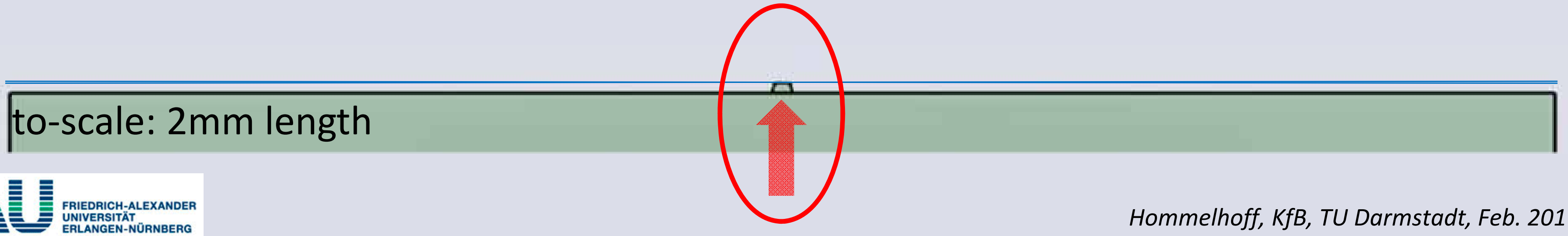
- Grating period: 620nm
- Grating depth: 450nm
- **Challenge:** get close enough (<200nm) to the grating surface without clipping the beam
  → put grating on 20µm high mesa structure



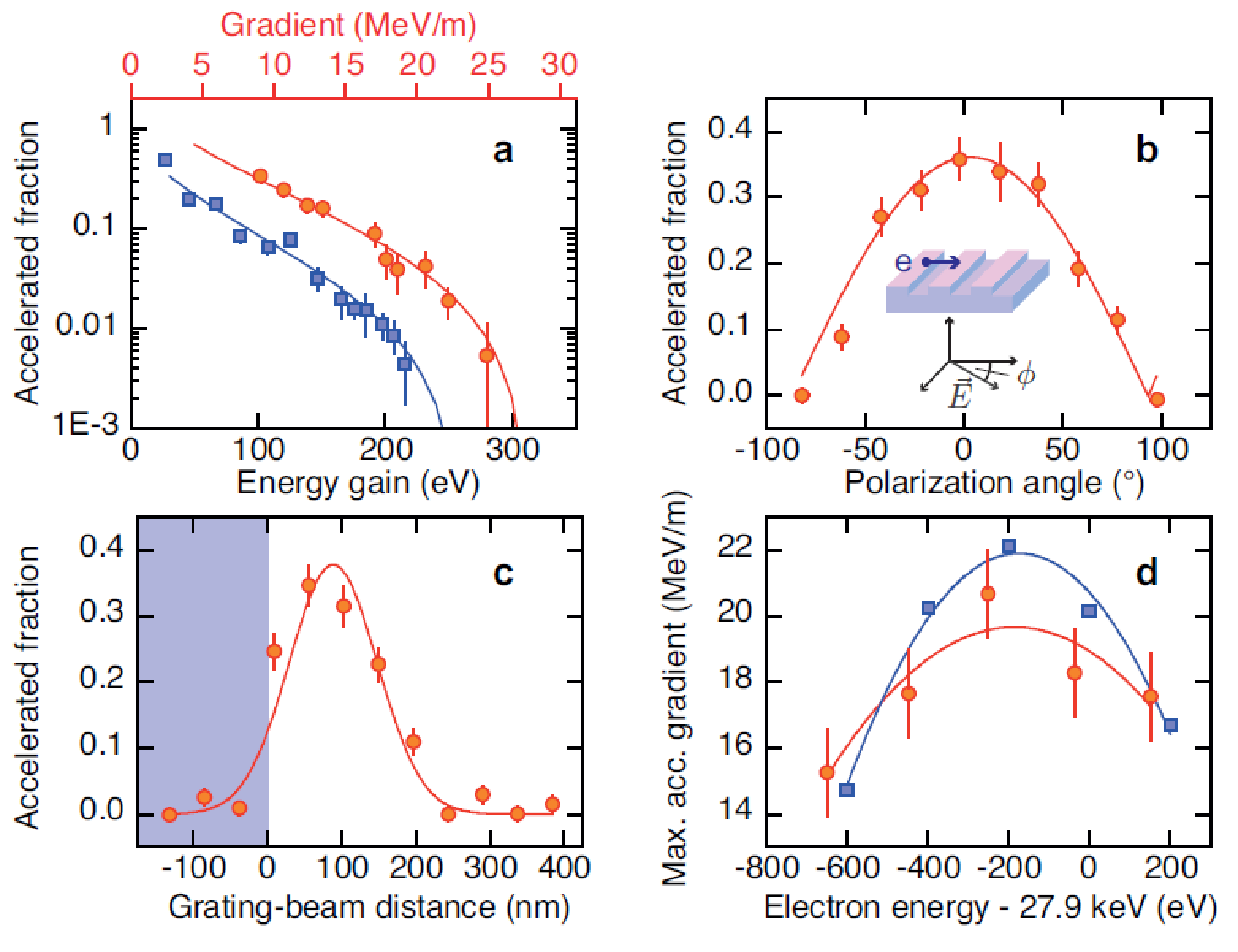
Silicon structures made by K. Leedle, H. Deng (Harris & Byer groups, Stanford)

electron beam focus





Dielectric laser acceleration results



Max. observed gradient (2012): 25 MeV/m

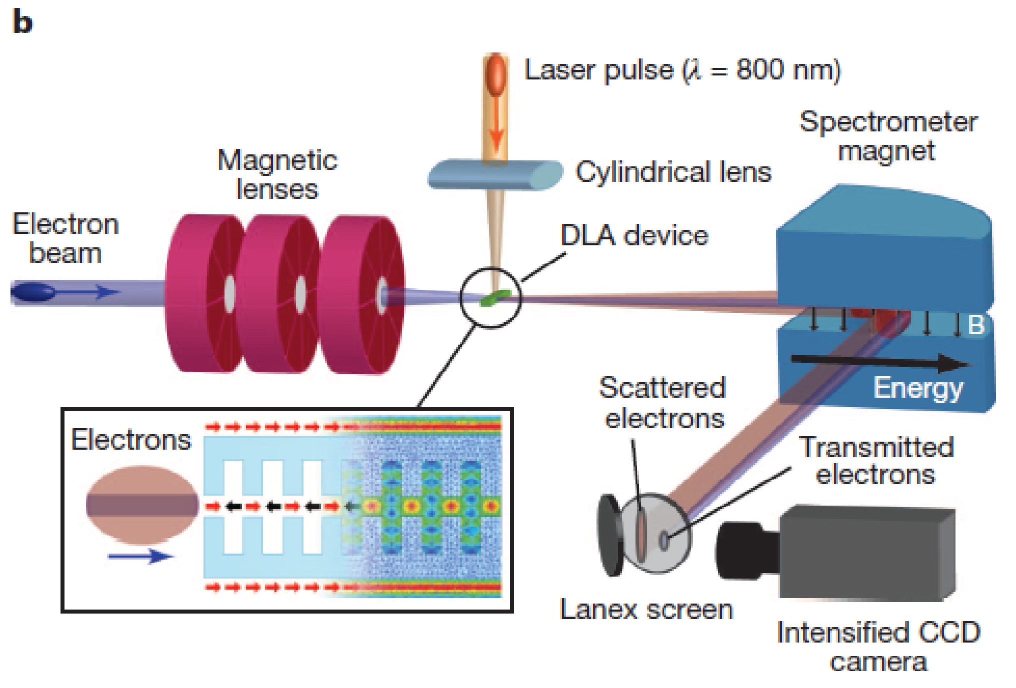
2016: 200 MeV/m, expected soon: 700 MeV/m **all at non-rel. energies (β = 0.3)!**

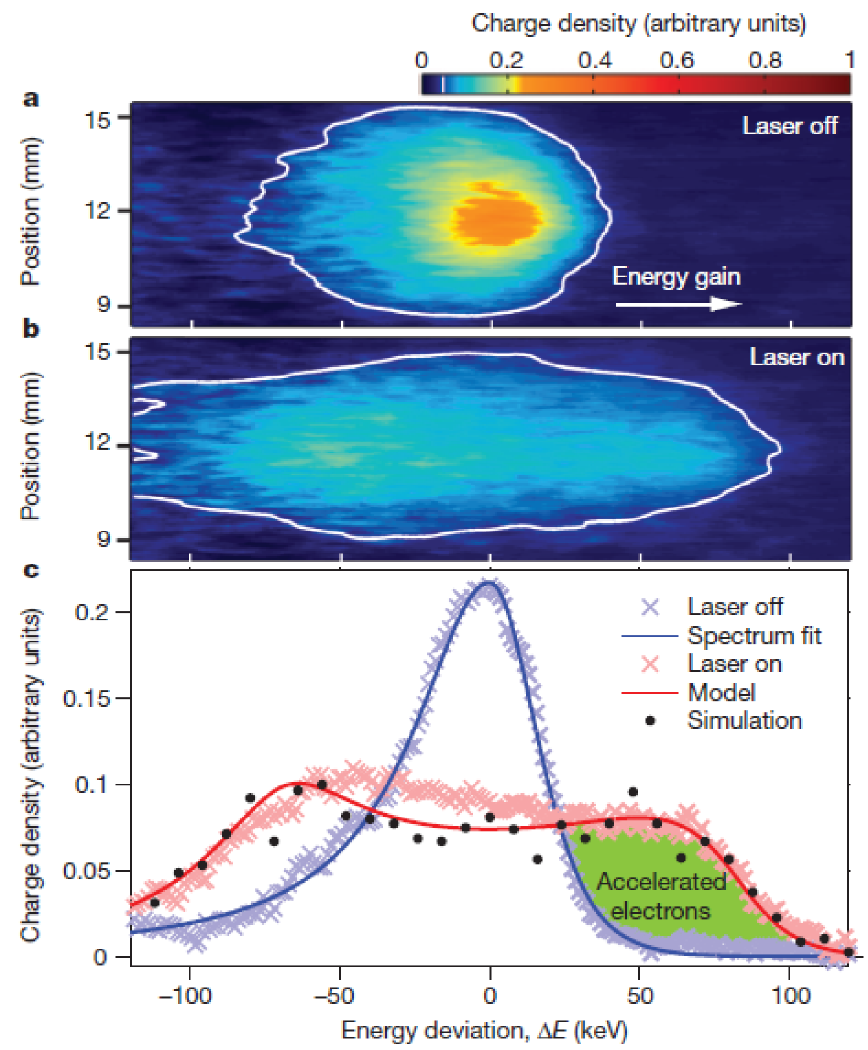
FRIEDRICH-ALEXANDER UNIVERSITÄT ERLANGEN-NÜRNBERG

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

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

Group of R. L. Byer at NLCTA





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)

DLA results so far

- ✓ **Proof-of-concept demonstration** of DLA:
- ✓ 25 MeV/m at β = 0.3; at β ~ 1: > 1GeV/m

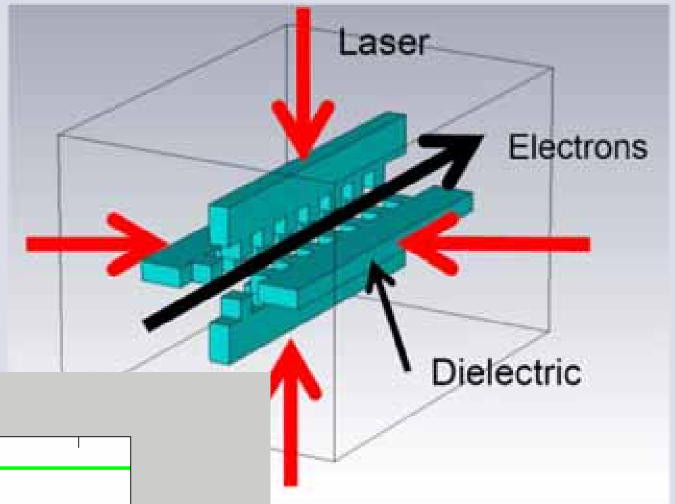
- ✓ **New structures**
  - ✓ **two-stage acceleration**
  - ✓ **optical focusing**
  - ✓ **optical deflection**
  - ✓ **beam position monitor**
  - ✓ **(sub-) femtosecond bunching**

- ✓ **200.4 MeV/m** with few-cycle NOPA-DFG (with β = 0.3 electrons!)

- ✓ **850 MeV/m** with 8 MeV electrons

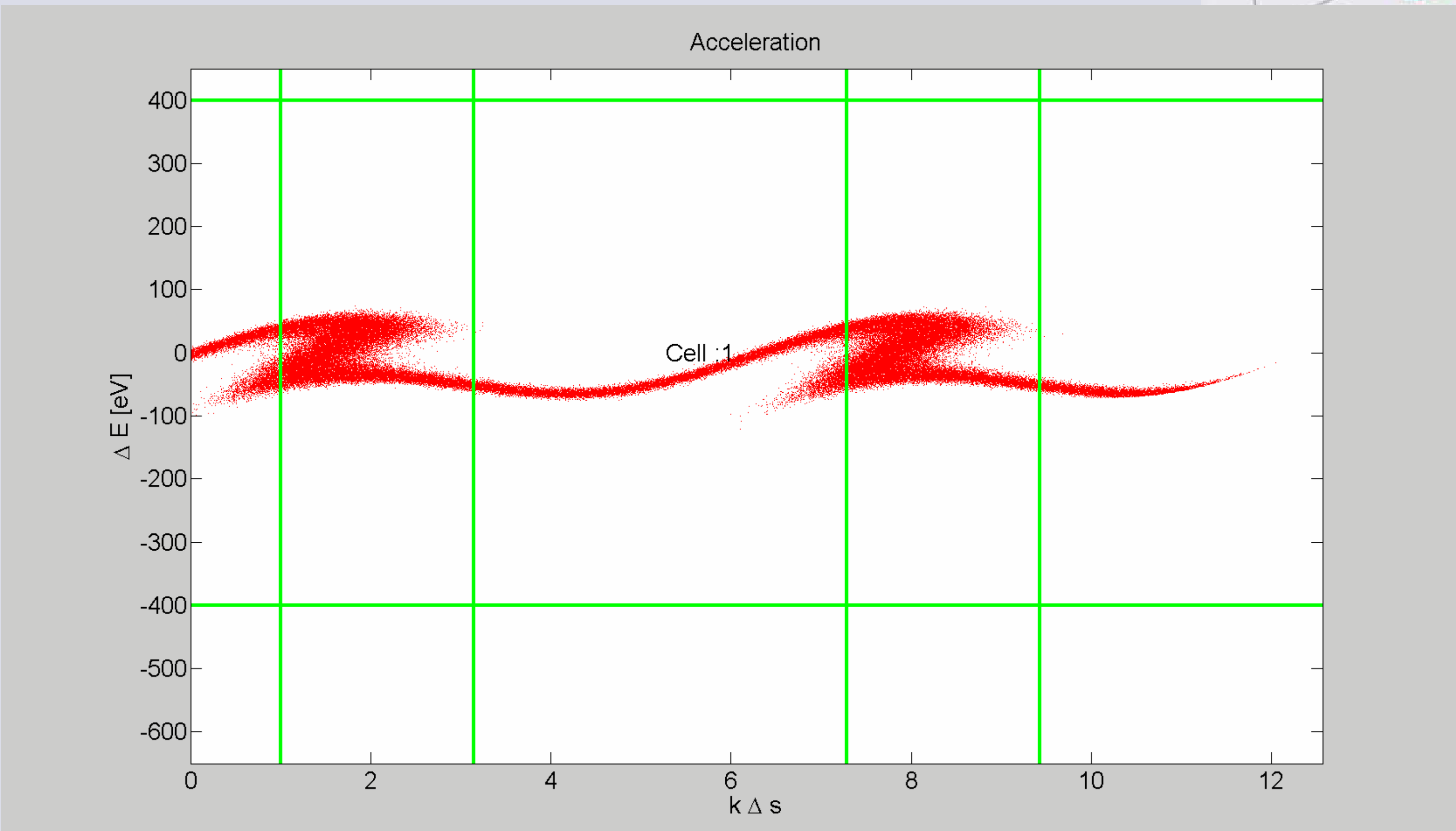
Breuer, Hommelhoff, PRL 2013
Plettner et al., PR-STAB 2009
Breuer et al., PR-STAB 2014
Breuer et al., J. Phys. B. 2014
McNeur et al., J. Phys. B. 2016
England et al., Rev. Mod. Phys. 2015
Kozak et al., Nat. Com. 2017
McNeur et al., MS in preparation
Hohmann et al., Opt. Lett. 2012 (NOPA)
Kozak, McNeur et al., to follow
England et al., to follow

TU Darmstadt: simulation group



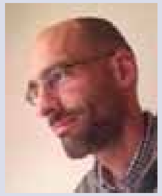
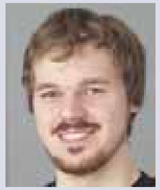
O. Boine-Frankenheim, Uwe Niedermayer & co.

- *Beam dynamics simulations*
- *components*

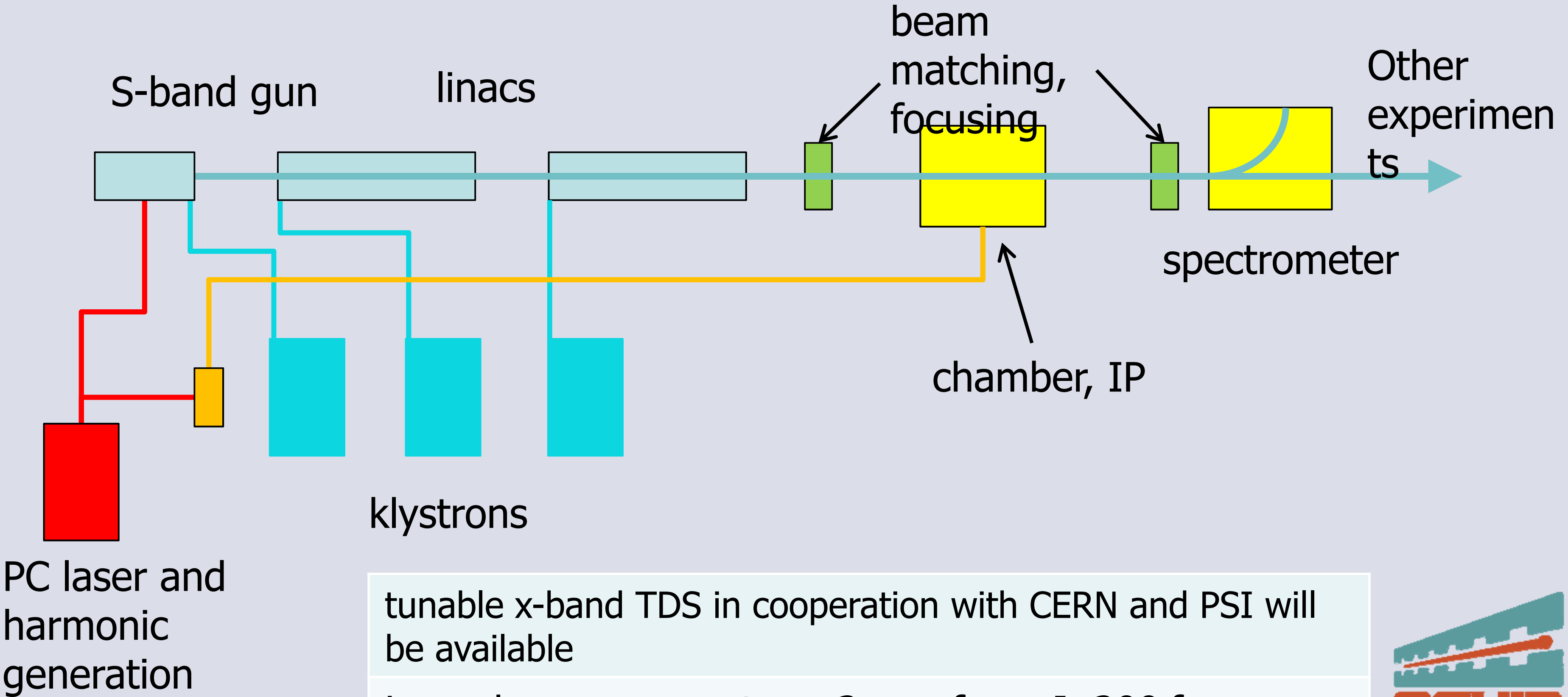


DESY: SINBAD

- Concept for stage 0 experiments
  - IR overhead from photo cathode laser converted to 2 µm wavelength as laser source for ACHIP experiments
  - Chamber and diagnostics similar to SLAC/FAU/PSI


Ralph Assmann
Ulrich Dorda
an team



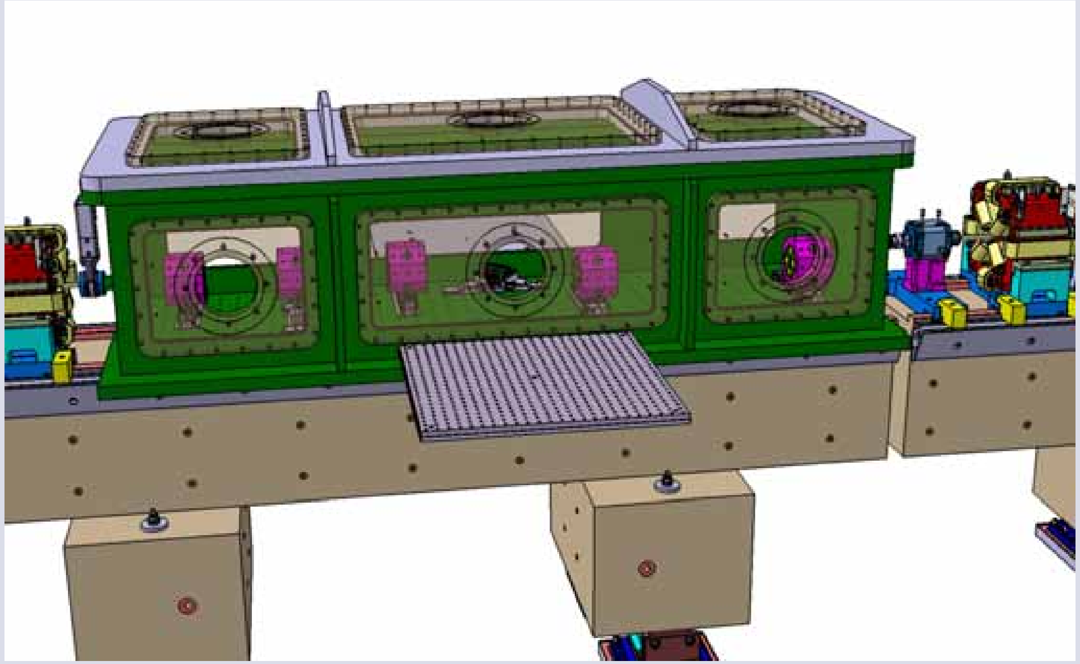
tunable x-band TDS in cooperation with CERN and PSI will be available

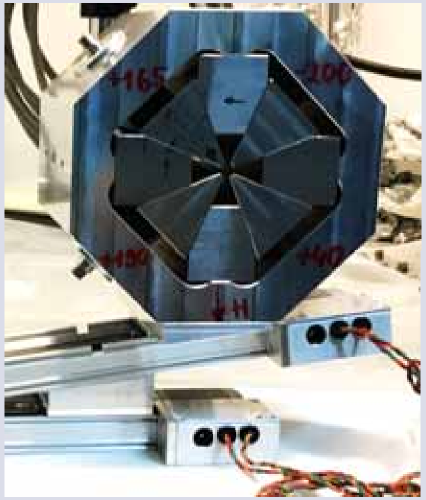
Laser beam parameters: 2 µm, few µJ, 200 fs

PSI: Dedicated DLA chamber in Swiss-FEL

- Experiments with an ultra-relativistic beam (3 GeV)
- Optical undulation: hard X-ray generation
- Beam monitoring (longitudinal)

Lenny Rivkin
Rasmus Ischebeck
Franziska Frei
Eugenio Ferrari
and team





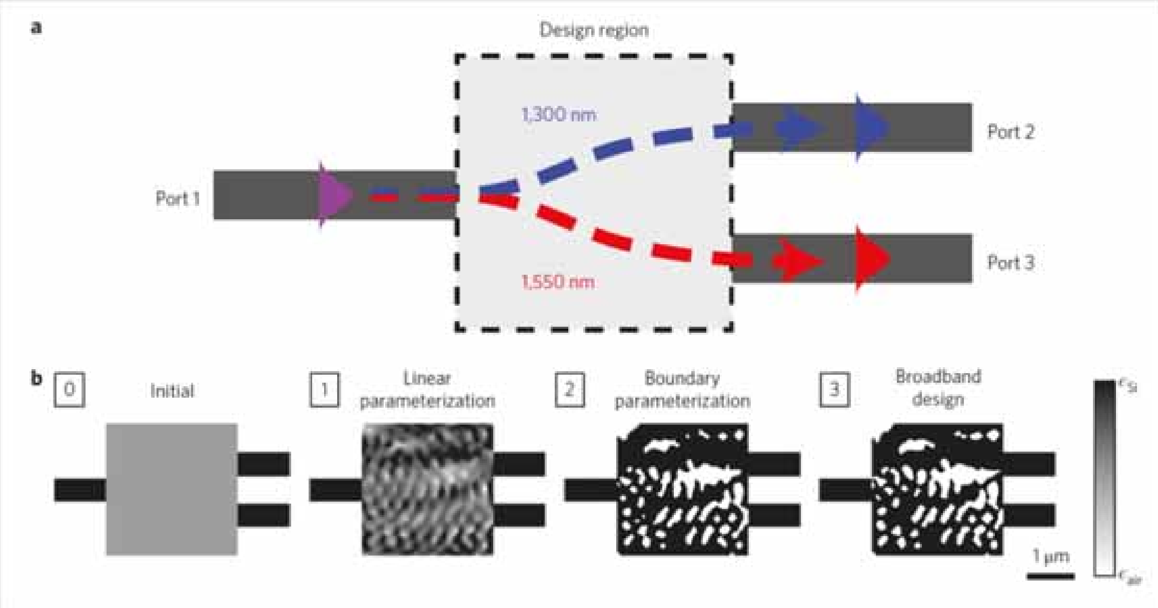
Current status: around *„first beam“*

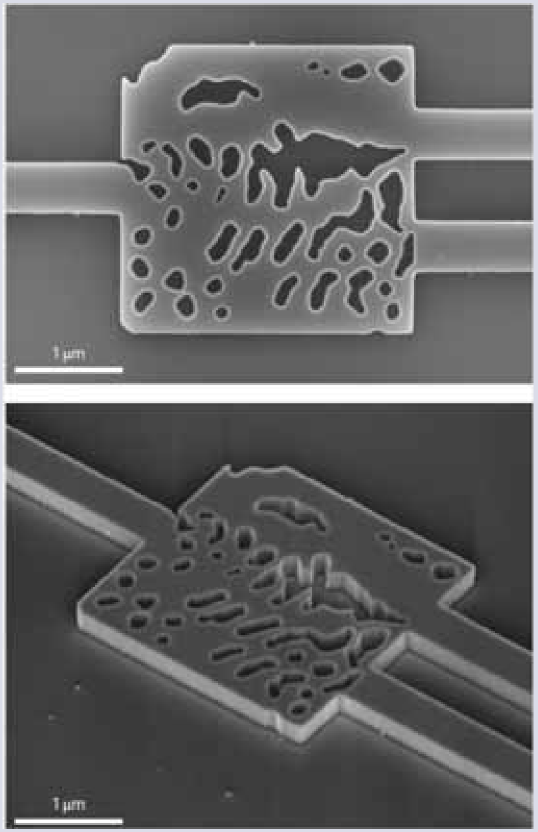
Vuckovic, Fan (Stanford): Photonics simulation groups

LETTERS
PUBLISHED ONLINE: 11 MAY 2015 | DOI: 10.1038/NPHOTON.2015.69
nature photonics

Inverse design and demonstration of a compact and broadband on-chip wavelength demultiplexer

Alexander Y. Piggott, Jesse Lu, Konstantinos G. Lagoudakis, Jan Petykiewicz, Thomas M. Babinec and Jelena Vučković*





Example device: dielectric 1550nm -1300 nm demultiplexer. Size: 2.8 x 2.8 μm^2

Challenges

Brightness: smallness of beam pipe requires ultra-high brightness beams (small available phase space volume)

New sources; source array and parallel beams?

Electron dynamics: to achieve large energy gains, control of electron dynamics over long distances is required. Special: $\boldsymbol{\alpha = \frac{q\,E_0}{k_z\,mc^2} \approx \frac{1}{10^4}}$ (similar to proton acceleration)

New elements

Alternating focusing-defocusing schemes

Diagnostics: smallness of beam requires new methods

New schemes

Coulomb repulsion effects: transverse and longitudinal phase space issues!

New sources; source array and parallel beams?

High repetition rate drivers

Relation to laser plasma schemes

Photonics-based dielectric (DLA)

- *linear in the driving field*
- extremely low bunch charge
- high rep. rate
- excellent beam needed
- scalability easy
- all-optical beam control
- gradients of up to 10 GeV/m
- new devices for classical accelerators?

Laser-plasma scheme

- *non-linear in the driving field*
- large bunch charge ok
- low rep. rates
- beam parameters
- scalability?
- classical beam control
- gradients of TeV/m

Very different requirements and pros and cons

⇒ *complementary in nature*

Philip Dienstbier
Michael Förster
Christian Heide
Takuya Higuchi
Martin Hundhausen
Johannes Illmer
Martin Kozak
Ang Li
Joshua McNeur
Stefan Meier
Anna Mittelbach
Timo Paschen
Jürgen Ristein
Constanze Sturm
Alexander Tafel
Norbert Schönenberger
Philipp Weber
Peyman Yousefi
Robert Zimmermann

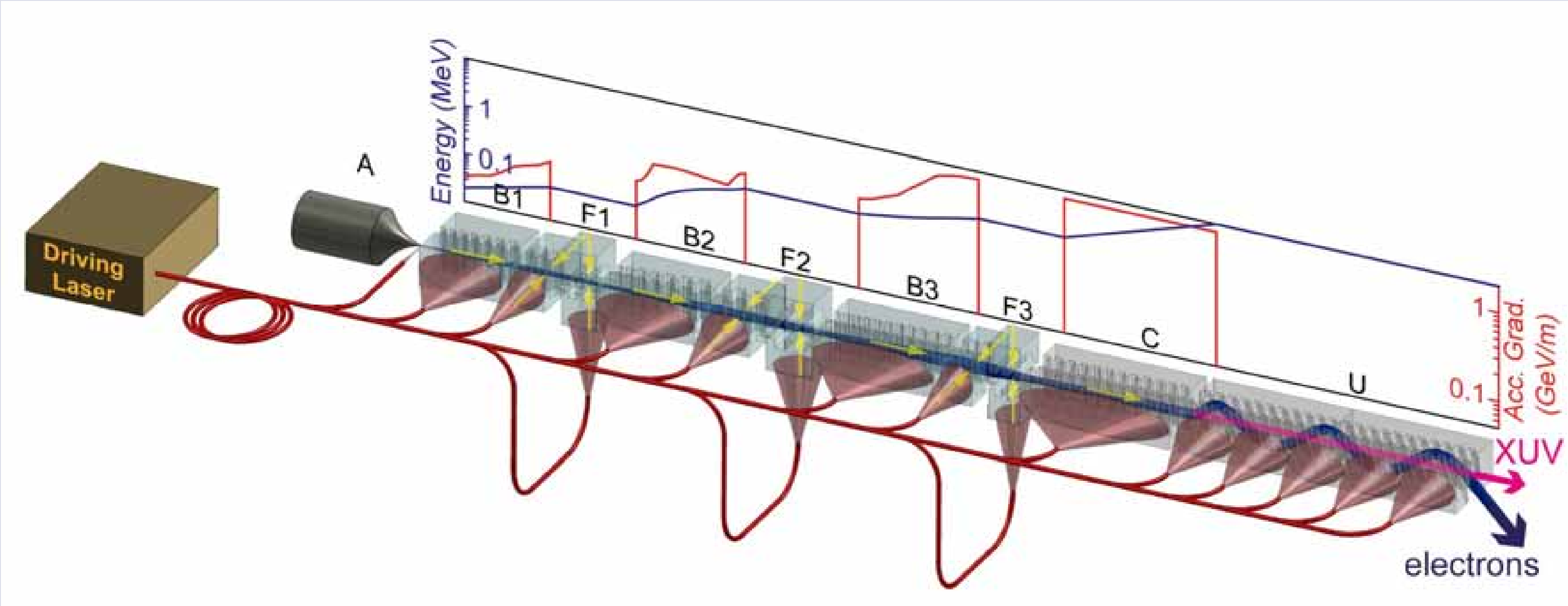
Former members:
A. Aghajani-Talesh ***J. Breuer*** P. Dombi D. Ehberger M. Eisele R. Fröhlich ***J. Hammer*** S. Heinrich ***J. Hoffrogge*** H. Kaupp ***M. Krüger*** A. Liehl L. Maisenbacher F. Najafi H. Ramadas T. Sattler Ella Schmidt ***M. Schenk*** L. Seitz J.-P. Stein H. Strzalka Y.-H. M. Tan ***S. Thomas*** Di Zhang

Partners/ collaborations:
QEM collaboration
ACHIP collaboration
D. Bykov, P. Russell, MPL
R. L. Byer + coll., Stanford / SLAC
I. Hartl, F. Kärtner, R. Aßmann, DESY
R. Holzwarth, MenloSystems
Chr. Lemell, J. Burgdörfer, TU Vienna
M. Kling, F. Krausz, LMU/MPQ
G. G. Paulus, Jena
J. Rosenzweig, P. Musumeci, UCLA
M. Stockman, Georgia State

GORDON AND BETTY
MOORE
FOUNDATION

FAU FRIEDRICH-ALEXANDER UNIVERSITÄT ERLANGEN-NÜRNBERG

Research toward a new kind of laser-driven particle accelerator based on photonics technology



Photonics-based technology is ripe (and cheap)

Sources! Brightness! Phase space! Dynamics! Photon generation!...

⇨ ***Much to be demonstrated. Clearly: accelerator research***

FRIEDRICH-ALEXANDER UNIVERSITÄT ERLANGEN-NÜRNBERG