

Accelerators on a Chip

 Accelerator on a Chip 2
PAM-2, ETH Zürich



Rasmus Ischebeck, Paul Scherrer Institut
2017-05-19

3

 Quick Recap: Last Week's Lecture

- Acceleration of relativistic particles needs an accelerating structure
- Structure size \sim wavelength of the radiation
- Here: goal is to use lasers as radiation source
- Structures made with methods of the semiconductor industry, as well as advanced free-form techniques
- Numerical modeling of the structures
 - Eigenmodes of the structures
 - Accelerating fields, effect on individual particles
 - Collective effects
 - Tolerance studies
- Accelerator-on-a-Chip International Program

3

Accelerators on a Chip

- Today: Experiments
 - > Building blocks for an experiment
 - > Experimental results

 Accelerator on a Chip 2
PAM-2, ETH Zürich



Rasmus Ischebeck, Paul Scherrer Institut
2017-05-19

3

Building Blocks for an Acceleration Experiment

ETH zürich

- Fabrication of structures
- Laser source
- Electron source
- Instrumentation
- Infrastructure



Here is a “how-to” to build a working experiment on laser-based accelerators.

Fabrication of Structures
Photolithography

ETH zürich



Photolithography with UV photons is the standard manufacturing technology of the semiconductor industry
Smaller (older) processing equipment can be found at many universities

Fabrication of Structures
Electron Beam Lithography

ETH zürich



Electron beam lithography allows to write individual structures
Large writing time is not an issue for first prototypes


 Fabrication of Structures
 Wafer Processing and Etching



PSI 7

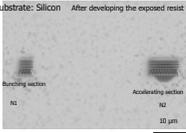
After exposure of the photoresist, the wafer is etched


 Fabrication steps



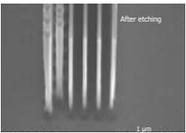
- Electron beam lithography (EBL)
 - EBL system: Raith150 Two (max. acc. voltage 30 kV)
 - Negative resist for faster exposure: ARN-7520 (Thickness: 400 nm)
 - Proximity effect still needs to be corrected
 - RIE system: Oxford instruments (PlasmaPro 100)
 - Up to 3 microns etching with the current resist

Substrate: Silicon After developing the exposed resist



Bunching section
 Accelerating section
 10 µm

After etching



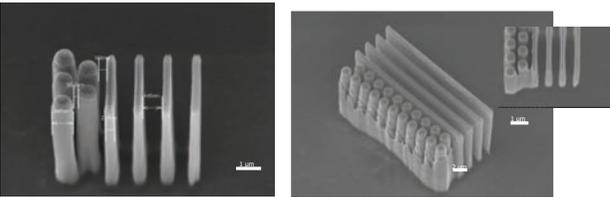
1 µm

Peyman Yousefi
 Laser physics institute at the university of Erlangen-Nürnberg

Electron beam lithography at the university of Erlangen


 Corrections to be made





Making the electron path wider and correcting the other geometries

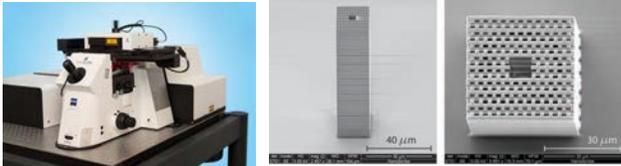
Correcting the electron dose distribution during the exposure to prevent blockage of the electron path

Peyman Yousefi
 Laser physics institute at the university of Erlangen-Nürnberg

This process, while well established, is by no means trivial
 Many parameters need to be controlled
 Particular challenge for the shown structures: large aspect ratio


 Fabrication of Structures
 Free-Form Manufacturing

• Additive methods



(a) (b)

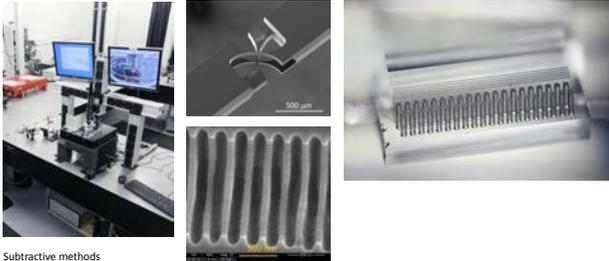
E. Simakov, et al.
 AIP Conf. Proc. 1812, 060010

Nanoscribe 10

Additive methods: polymers
 Hardening of resins by two-photon absorption
 Sintering of powders


 Fabrication of Structures
 Free-Form Manufacturing

Subtractive methods



Yves Bellouard, Femtoprint 11

Subtractive methods: possibility to work on glasses (borosilicate, fused silica, ...)
 Ongoing research: crystalline materials


 Laser Source

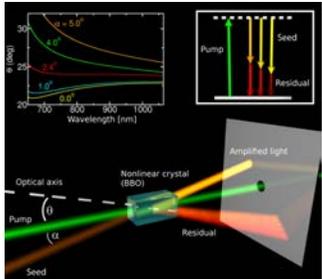


Ti:Sapphire laser Optical parametric amplifier (OPA)

12

Laser source for first experiments: typically titanium sapphire laser
 Well-established technology
 Very broad spectrum allows for few-femtosecond pulses
 Fundamental wavelength: 800 nm


Optical Parametric Amplifier



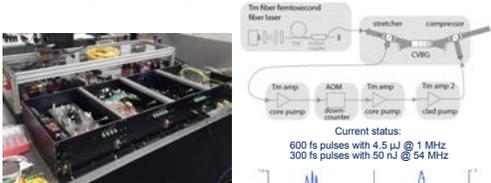
33

Optical parametric amplification allows to generate photons with longer wavelength
Wavelength can be tuned by rotating crystal

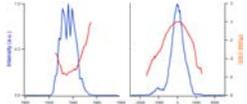

MHz Tm: fiber Chirped Pulse Amplification

Laser system was re-worked and optimized for high energy and fs-pulse operation

- Further power scaling with LMA fiber amplifier
- Design of nonlinear compression schemes required for sub-100 fs pulse duration.



Current status:
 600 fs pulses with 4.5 μJ @ 1 MHz
 300 fs pulses with 50 nJ @ 54 MHz

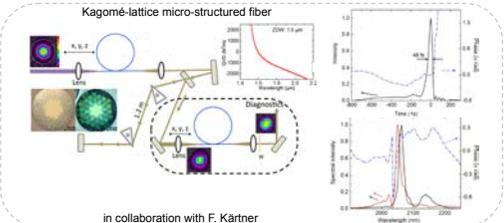


Ingmar Hartl 14

For an actual accelerator-on-a-chip, one would like a laser with better energy efficiency
→ Thulium doped fiber laser


Nonlinear Compression of ps-Pulses @ 2 μm

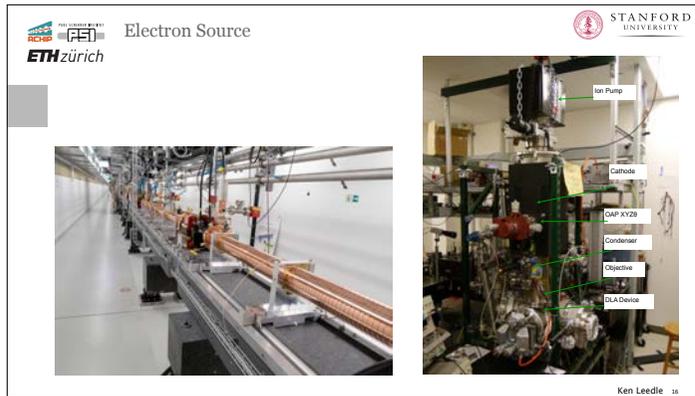
- Two-stage nonlinear fiber compressor.
- 3.3 ps pulses compressed to 48 fs with 11 μJ pulse energy.



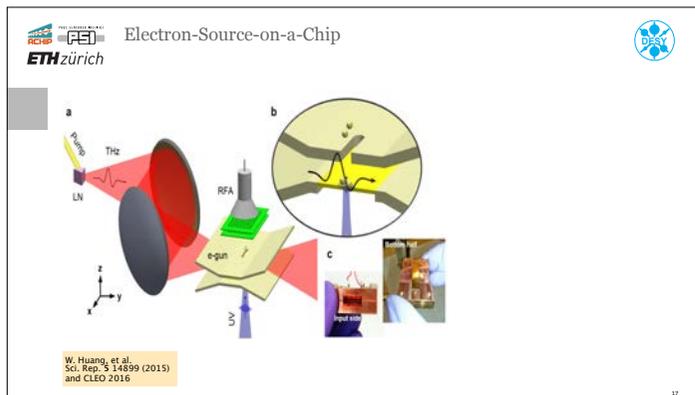
In collaboration with F. Kärtner

Ingmar Hartl 15

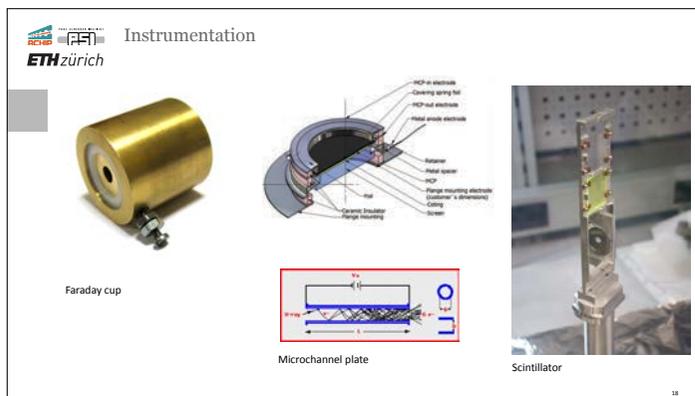
Compression of pulses required for highest accelerating fields



Scientists are presently preparing experiments with a wide array of electron sources from refurbished electron microscopes to high-energy particle accelerators



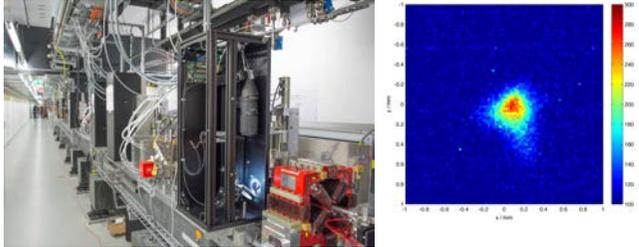
Again, for a working accelerator-on-a-chip, one would need an electron source on a chip



Instrumentation required to measure electron (and laser) properties after the acceleration

- Electron detection
- > Faraday cup
 - > Microchannel plate
 - > Scintillator

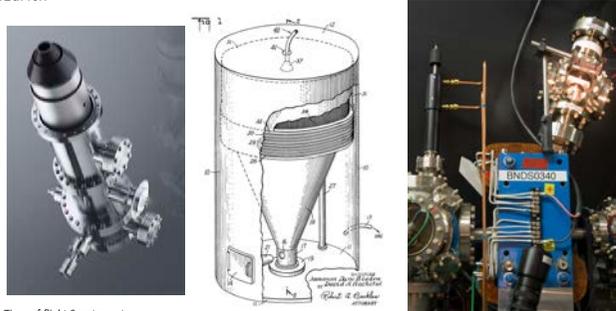

 Instrumentation
 Electron Beam Profile



19

Scintillators allow for beam size measurement


 Electron Energy Measurement

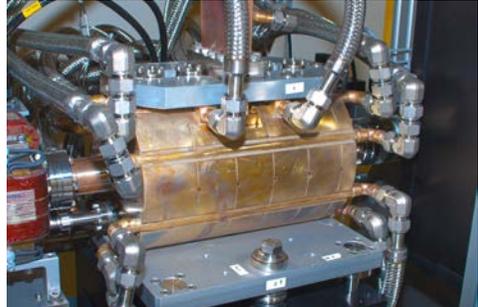


Time-of-flight Spectrometer (SPECs) Retarding Voltage Spectrometer Magnetic Spectrometer (SLAC)

20

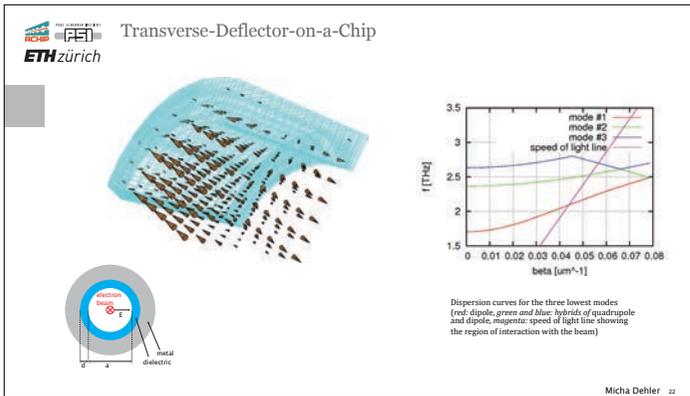
From lowest energy to highest:
 > time-of-flight spectrometer: up to ~ 10 keV
 > retarding voltage spectrometer: up to ~ 100 keV
 > magnetic spectrometer: up to GeV (and beyond)


 Time-Resolved Measurements
 Transverse Deflector

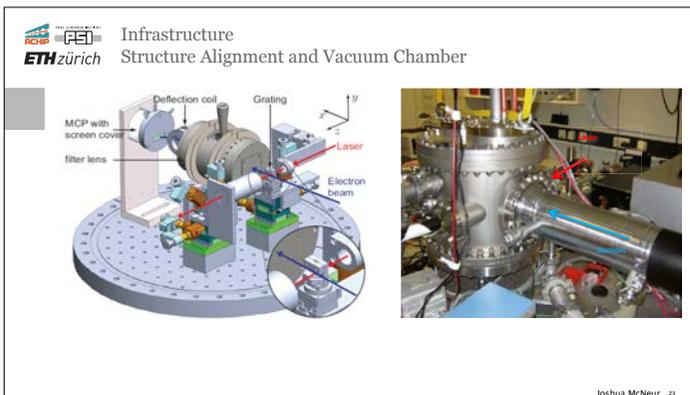


21

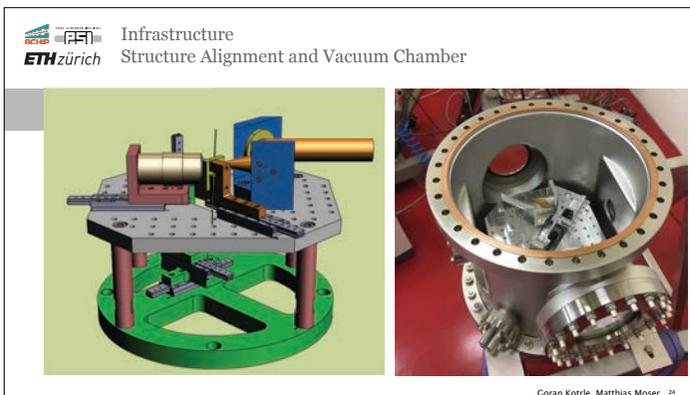
Transverse deflecting cavity



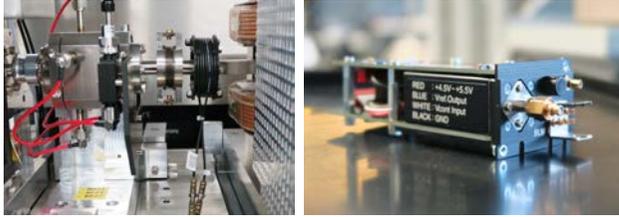
Repeat this success with laser-based structures
 Dielectric lined waveguide has also a deflecting mode
 Work on more sophisticated structures is ongoing...



Need to align electron and laser beam with the structure
 Micrometer precision is not easy to achieve...
 The experiment needs to be performed in vacuum

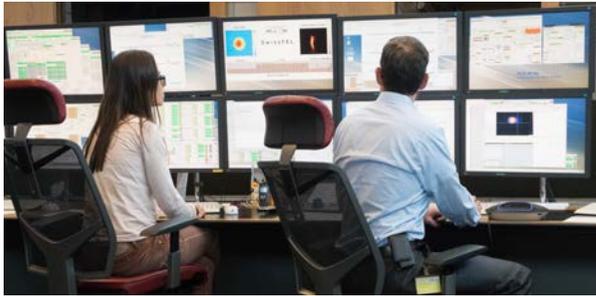


Another setup for a 7 MeV transverse acceleration experiment



Cigdem Ozkan Loch, Patrick Pollet 25

Don't forget all the necessary infrastructure:
> Loss monitors



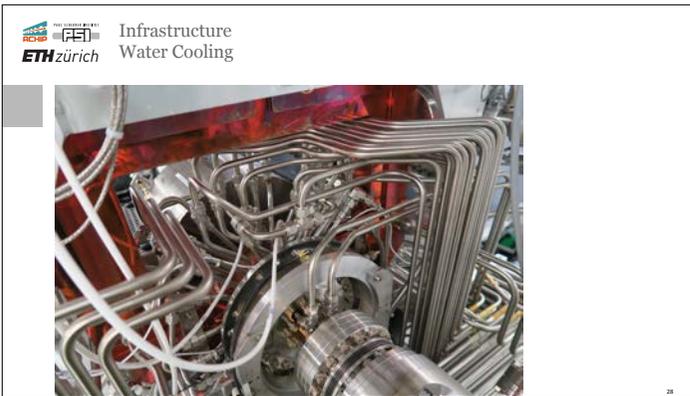
Nicole Hiller, Thomas Schietinger 26

Control system



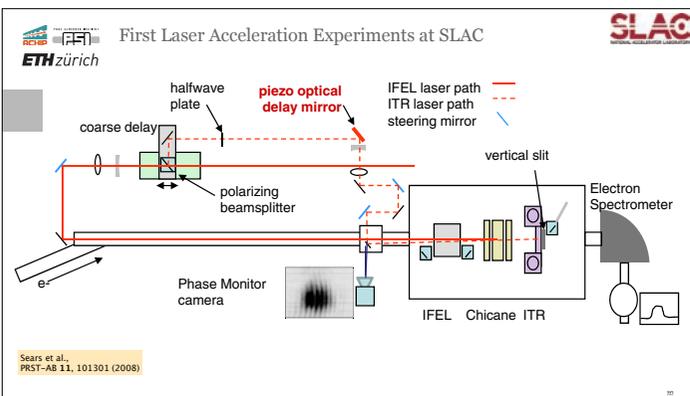
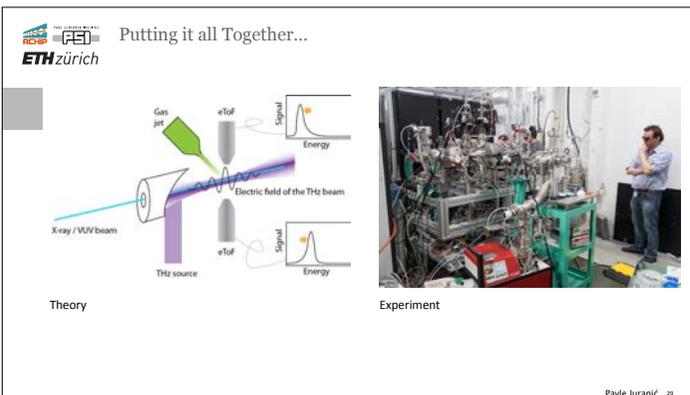
Babak Kalantari 27

Timing system to ensure simultaneous readout of all devices



Water cooling

etc ... etc ...



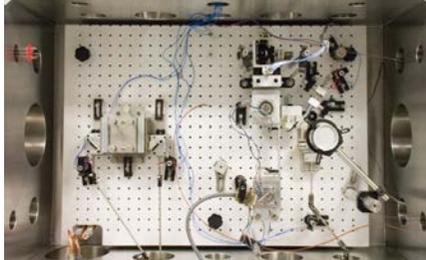
First laser acceleration experiments at SLAC

Set up with the 60 MeV beam in the Next Linear Collider Test Facility

Laser: 800 nm Ti:Sapphire

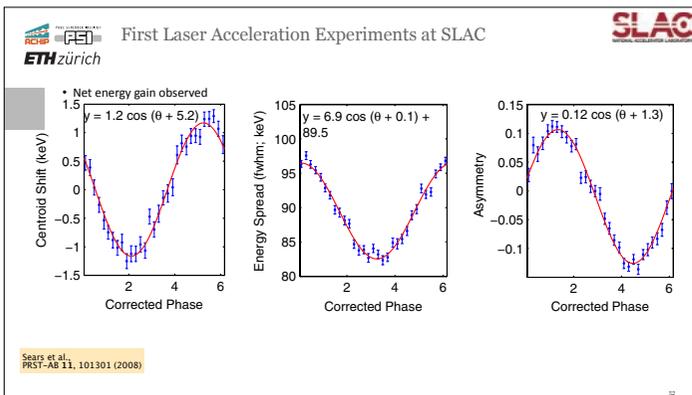

 First Laser Acceleration Experiments at SLAC

• Acceleration by inverse transition radiation on a surface

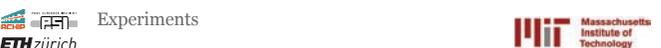


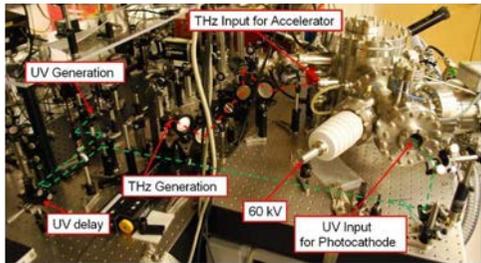

Sears et al.,
 PRST-AB 11, 101301 (2008)

Not actually using a “real” accelerating structure yet
 Instead: terminate electromagnetic fields at a boundary
 Allows for half-a-wavelength acceleration
 Boundary material is destroyed by the laser beam, but this takes hundreds of picoseconds
 Electrons just pass through the material
 Another way to describe this: inverse transition radiation



Note the magnitude of the acceleration: 1 keV
 > while using a 90 keV energy spread
 > initial energy: 60 MeV

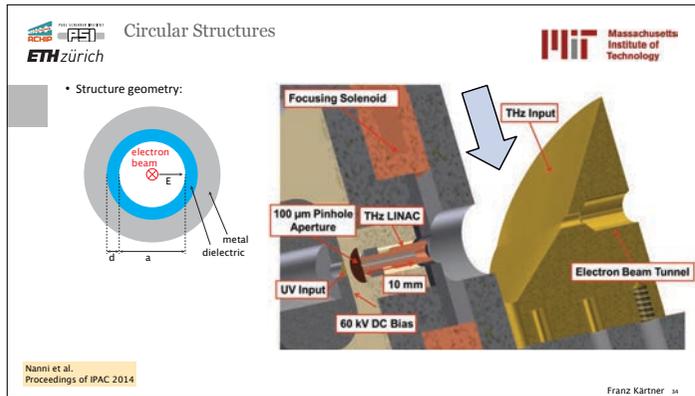

 Experiments



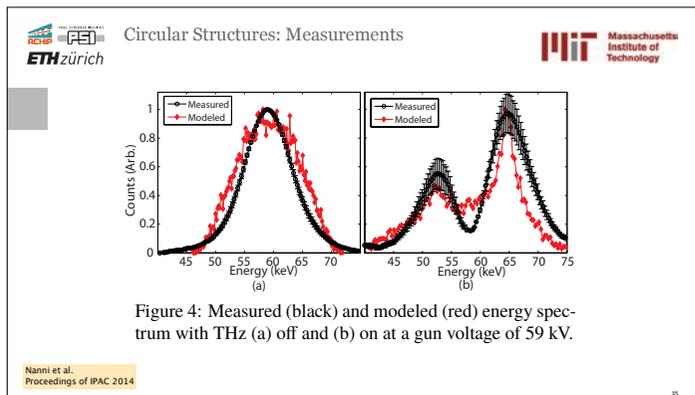
Nanni et al.,
 Proceedings of IPAC 2014

Franz Kärtner

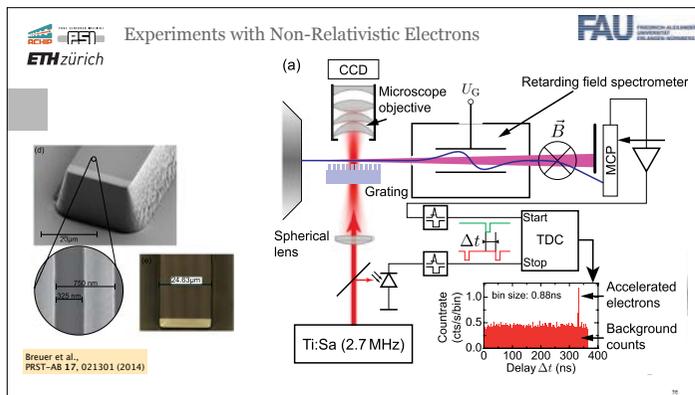
Experiments with low-energy electrons



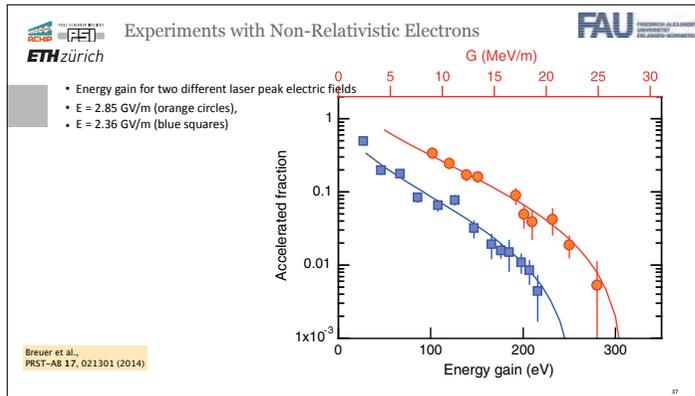
Dielectric-lined waveguide geometry



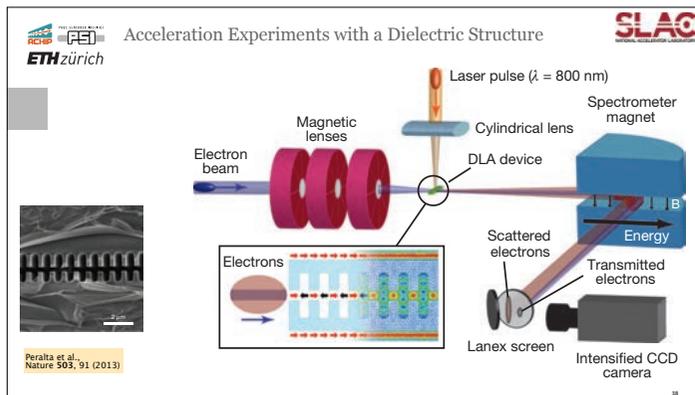
Energy spectrum has two peaks:
the electron beam is longer than the wavelength, thus some of the electrons are accelerated, others are decelerated



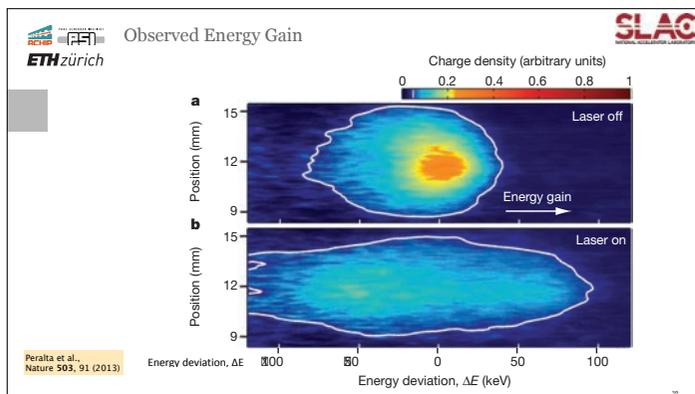
Experiments with grating structures performed at the University of Erlangen



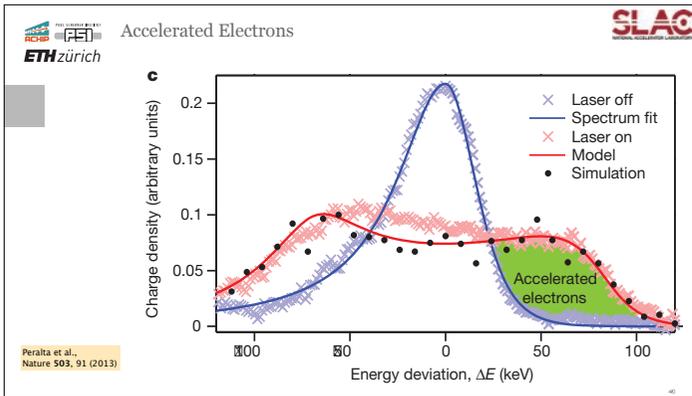
Note the low efficiency of acceleration of non-relativistic electrons!



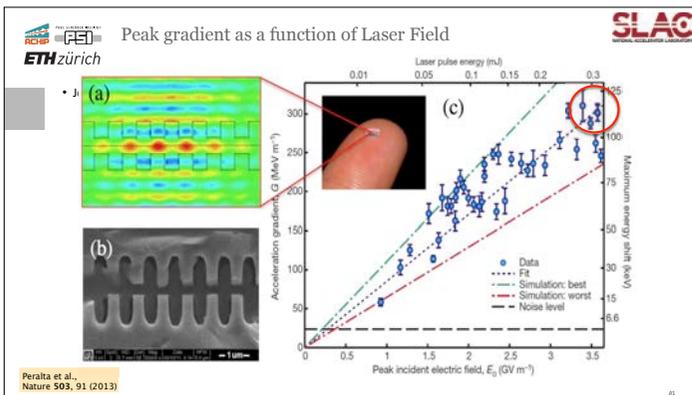
Same Next Linear Collider Test Facility as before
Now with “real” structures



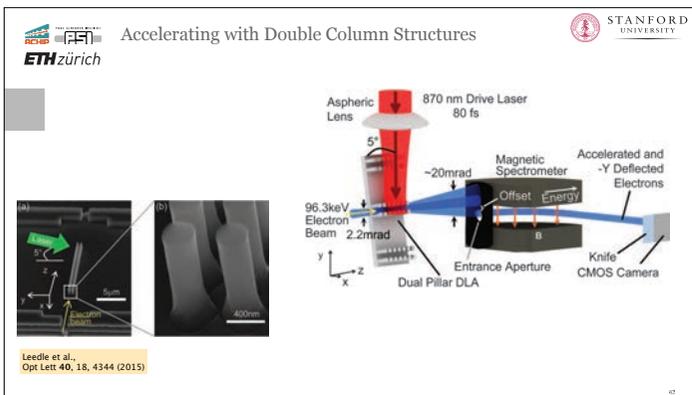
Depending on their phase, some electrons are accelerated, some are decelerated
Clear increase of energy spread
(again, the electron bunch is much longer than the wavelength)



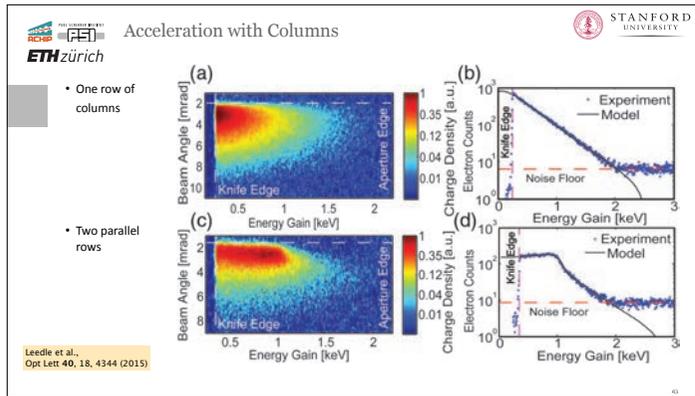
Electrons get accelerated by about 50 keV (initial energy: 60 MeV)



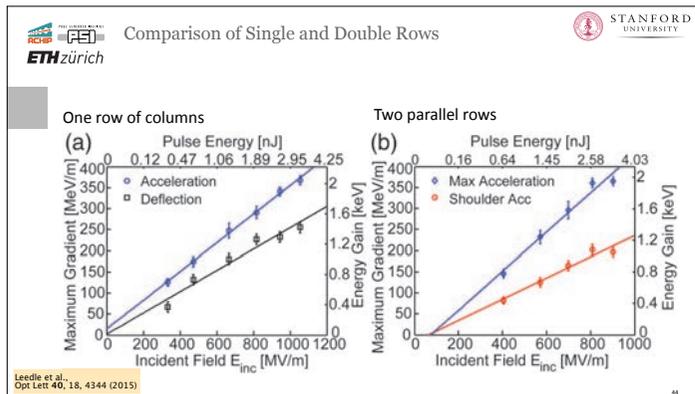
Acceleration gradient is a linear function of the incident field
Maximum energy gain: 100 keV



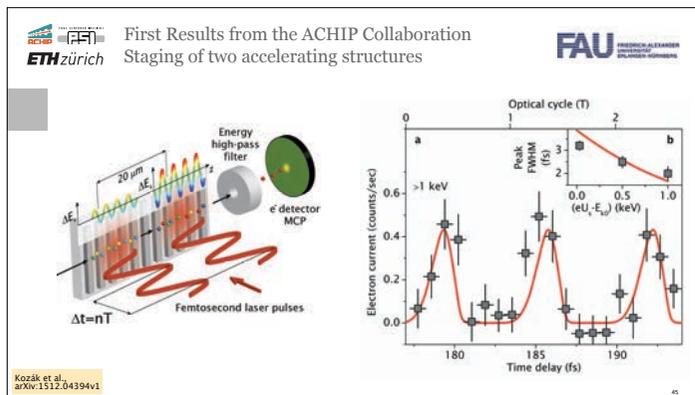
Double column structures are intrinsically aligned



Accelerating non-relativistic electrons

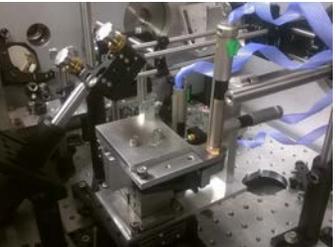
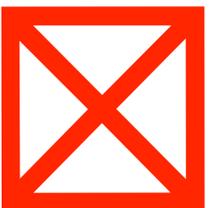


Double columns have more symmetric fields



Important aspect: staging of multiple accelerating structures
 First experiment: single grating, two laser pulses
 Phase between the two laser pulses can be adjusted

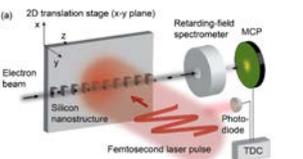
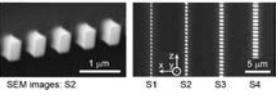
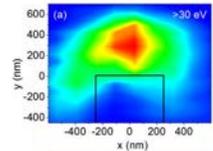
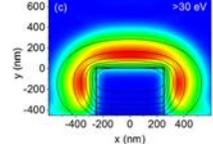

 Experiments with Relativistic Electrons

Pietro Musumeci et al., unpublished

Experiments using relativistic electrons


 Dielectric Structures for Attosecond Beam Characterization

Kozák et al., Optics Letters 41, 15 (2016)

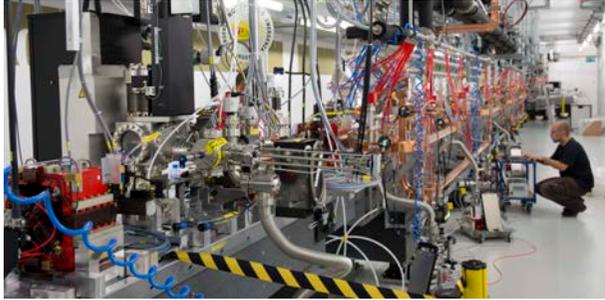
Devices-on-a-chip can also be used for beam characterization
Attosecond resolution


 Planned Experiments at DESY



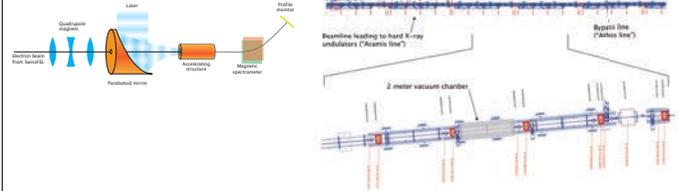
Ralph Abmann

DESY (Hamburg) is setting up a dedicated accelerator research facility

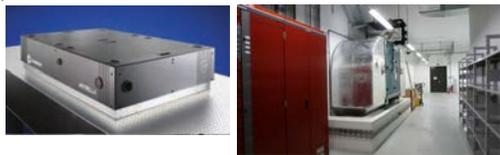


Goal: use this chamber to test for radiation hardness and for collective effects
No laser source available

- Goal: Acceleration by 1 MeV



A second setup is planned using the 3.4 GeV beam in the ATHOS beamline in SwissFEL
Ti:Sapphire laser with OPA

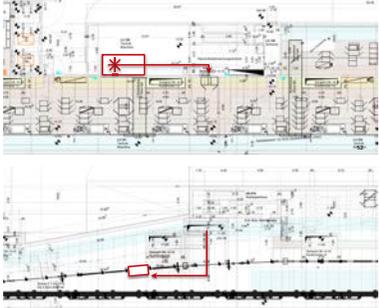


Ti:Sa laser (800 nm) with OPA (2 μm)
Provided by collaboration partners
Beam transport ~ 20 m
Laser safety:
Hutch in L3.120
Hutch in accelerator tunnel

Laser room is outside the accelerator tunnel
Laser is provided by collaboration partners

Laser transport system required


Laser transport



Eugenio Ferrari 52

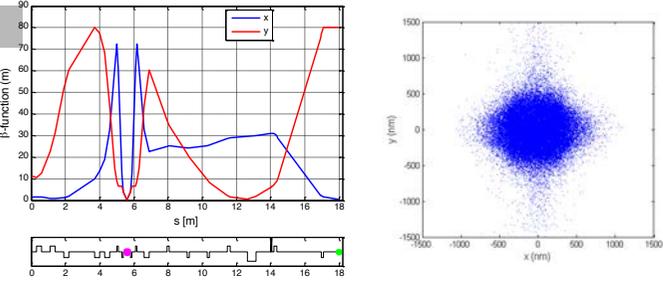

Possible Laser Accelerator Experiments at PSI

- Ultra-relativistic particles**
 - Particle energy $E = 3.4$ GeV, Lorentz factor $\gamma = 6700$, Velocity $v = 99.9999887\% c$
 - Velocity does not change significantly with acceleration
 - Control dephasing and direction change
 - High charge densities are possible
 - Study wake fields
- Low emittance beams**
 - Small focus, long Rayleigh length
- Short bunches**
 - Shorter than laser wavelength
 - Real acceleration of bunches
- Instrumentation for low-charge beams**
 - Measurement of slice emittance of a 30 fC bunch demonstrated

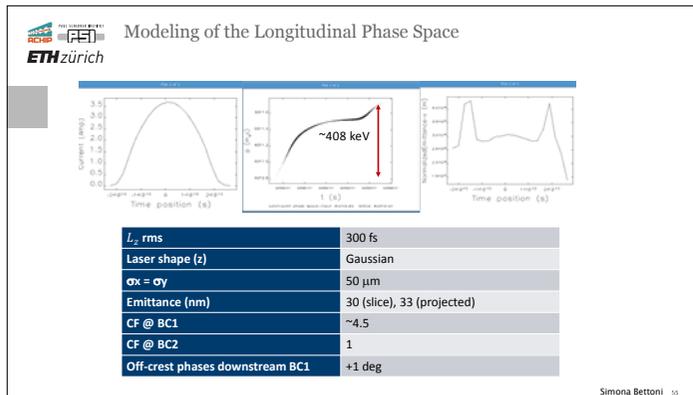
53

Modeling of the beam optics ongoing
 Expect sub-micrometer beam spot
 → the entire electron beam can pass through the structure

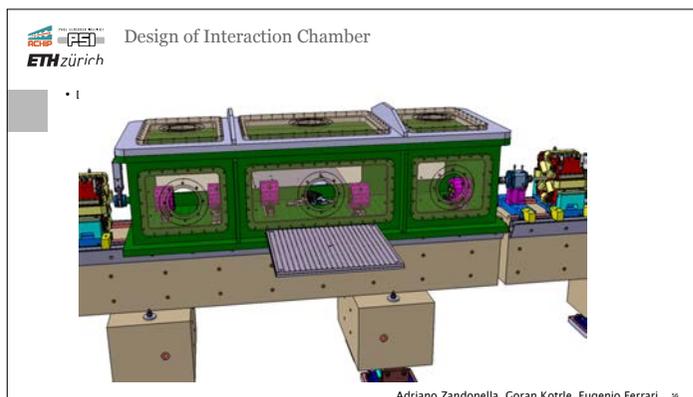

Focusing of the Electron Beam



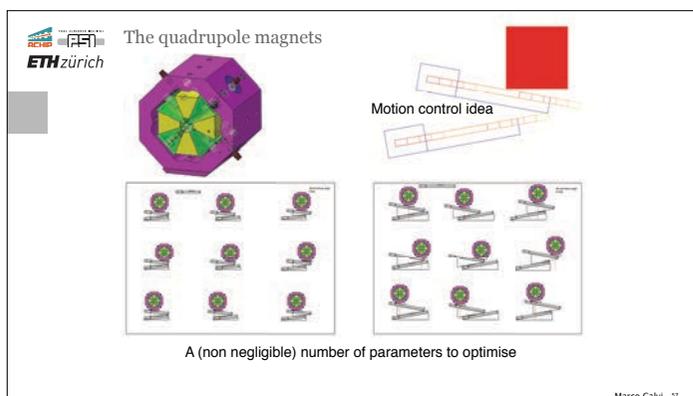
Eduard Prat 54



Low intrinsic energy spread allows for precise measurement of energy gain

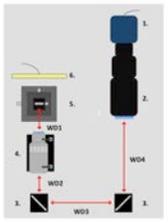


2-meter long interaction chamber
Includes quadrupole magnets for beam focusing



Permanent magnet quadrupoles for beam focusing


 Marie Siegler: In-Vacuum Microscope Optics
 Summer Internship

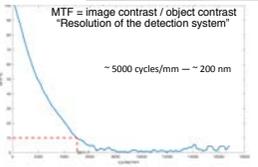


Microscope objective (infinity corrected) + Tube lens



- Camera (Eos 50D with M500 120x, Seler SCA3800-1.75m/f)
- Objective (Nikon ED - MICRO NIKKOR 200mm 1.4 D)
- Deflection mirror (individual)
- Microscope objective (individual)
- Stage (in any direction with ISO target 1.22)
- Diffuse white light

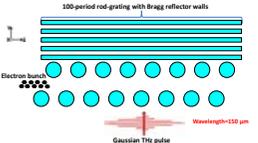
W01 Working distance microscope to ISO target (manual)
 W02 Working distance microscope to deflection mirror
 W03 Working distance between the two mirrors
 W04 Working distance deflection mirror to objective



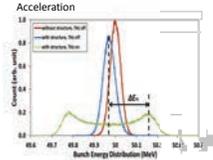
MTF = image contrast / object contrast
 "Resolution of the detection system"
 ~ 5000 cycles/mm — ~ 200 nm

Finally, some student projects at PSI
 Microscope optics required to image sub-micrometer beam
 In-vacuum microscope objective, combined with tube lens and camera outside the vacuum
 Collimated beam is transported through the window —> no spherical aberrations
 Long distance requires large tube lens to avoid vignetting

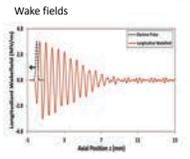

 Yelong Wei: Modeling of Collective Effects
 Internship



100-period rod-grating with Bragg reflector walls
 Electron bunch
 Gaussian Tpe pulse
 Wavelength = 150 μm



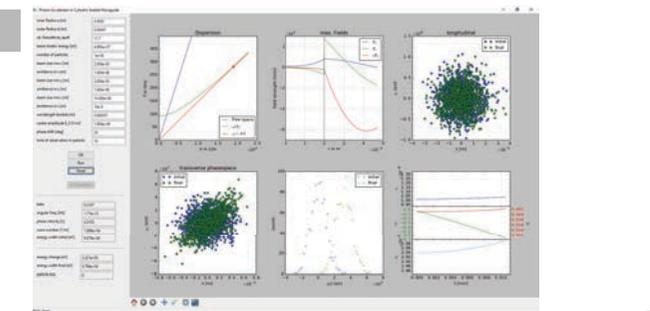
Acceleration
 Current [Arb. units]
 Bunch Energy Distribution [MeV]



Wake fields
 Longitudinal Wake Field [V/m]
 Axial Position [mm]

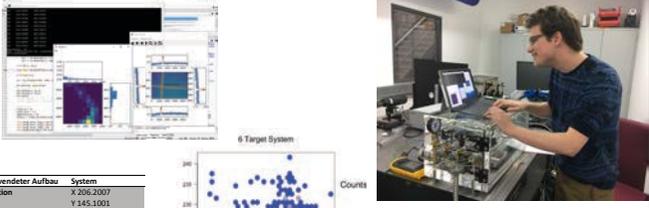
Modeling a scaled structure
 Structure size compatible with beam in the SwissFEL Injector
 (Resonant to 150 μm radiation)
 Wake fields result in an increase of
 > energy spread
 > emittance
 for the tail of the beam


 Max Kellermeier: Modeling of Acceleration in Dielectric Lined Tube
 Semester Thesis

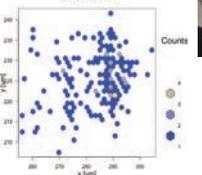


Modeling a dielectric lined circular waveguide
 Acceleration of particles with $\beta < 1$ (e.g. protons)
 Software to model the fields inside the structure, and to track particles

ETH zürich **Dominique Zehnder: Positioning of Quadrupole Magnets**
Individuelle Praktische Arbeit



Verwendeter Aufbau	System
Position	X:206.2007 Y:345.1001
Anzahl Messungen	200
RMS X	9.99 μm
RMS Y	6.25 μm



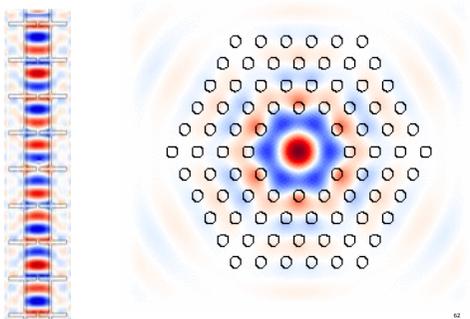
6 Target System

Counts

61

Quadrupole alignment system for the ATHOS vacuum chamber
Accuracy of the positioning: 10 μm

ETH zürich **Max Kellermeier: Photonic Band Gap Structures**
Master's Thesis (ongoing)

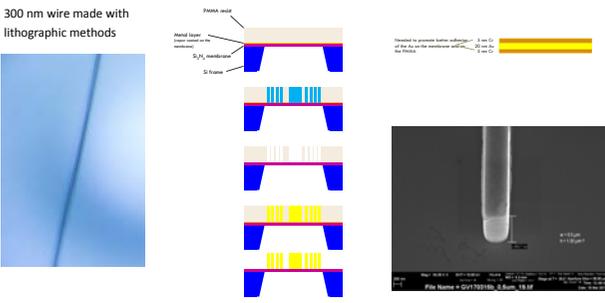


62

Modeling of a photonic band gap structure
Idea: concentrate the fields on the beam axis
To come: fabrication of this structure from fused silica using a free-form process

ETH zürich **Simona Borrelli: Measurement of Sub- μm Beam Size**
Master's Thesis (ongoing)

- 300 nm wire made with lithographic methods



300 nm wire

Metal layer
Photoresist
 Si_3N_4 underlayer
Si frame

63

Measurement of sub-micrometer beam size with wire scanners
Traditional wires: only down to about 25 μm
Manufacture a wire using electron beam lithography

Questions?



Nick Veasey

 **Thank You**

- Thank you for Simulations, Measurements, Illustrations, Animations and Photos:
 - Adriano Zandonella
 - Chris Sears
 - Dominique Zehnder
 - Edgar Peralta
 - Eduard Prat
 - Franz Kärtner
 - Goran Kotrle
 - Gordon and Betty Moore Foundation
 - John Breuer
 - Joshua McNeur
 - Ken Leedie
 - Marco Calvi
 - Marie Siegler
 - Martin Kozak
 - Matthias Moser
 - Max Kellermeier
 - Micha Dehler
 - Nick Veasey
 - Peter Hommelhoff
 - Paul Scherrer Institut
 - Peyman Yousefi
 - Pietro Musumeci
 - Ralph Aßmann
 - Ronny Huang
 - Simona Bettoni
 - Simona Borrelli
 - Stanford University
 - Wikimedia Commons
 - Yelong Wei
 - Yves Bellouard
- Download this talk in the file format of your choice:
 - <https://schebeck.net>
- More information on the Accelerator-on-a-Chip International Program at PSI:
 - <http://achip.ch>

 © 2017 Paul Scherrer Institut 65