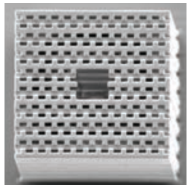
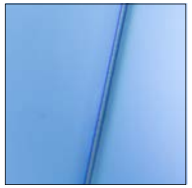
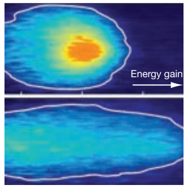
Accelerator on a Chip 2
PAM-2, ETH Zürich

Rasmus Ischebeck, Paul Scherrer Institut
2017-05-19

Accelerators on a Chip

Quick Recap: Last Week's Lecture

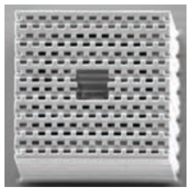
- Acceleration of relativistic particles needs an accelerating structure
- Structure size ~ wavelength of the radiation

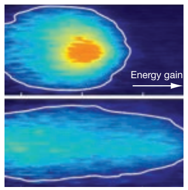
- Here: goal is to use lasers as radiation source
- Structures made with methods of the semiconductor industry, as well as advanced free-form techniques

- 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

Accelerator on a Chip 2
PAM-2, ETH Zürich



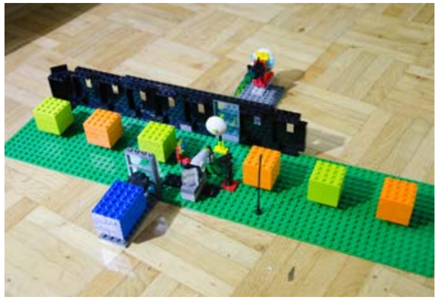


Rasmus Ischebeck, Paul Scherrer Institut
2017-05-19

Accelerators on a Chip
Today: Experiments
> Building blocks for an experiment
> Experimental results

Building Blocks for an Acceleration Experiment

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



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

Fabrication of Structures
Photolithography

ASML 5

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

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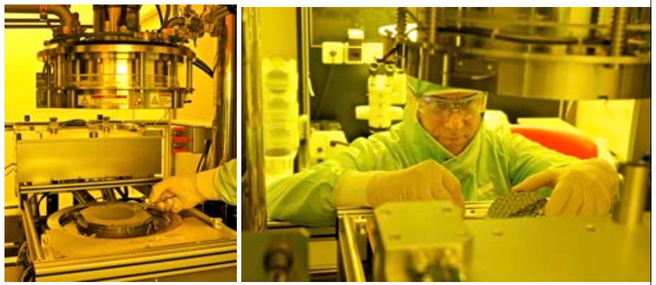
Fabrication of Structures
Electron Beam Lithography

Stanford 6

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

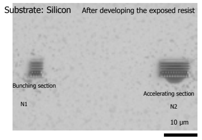
Fabrication of Structures
Wafer Processing and Etching

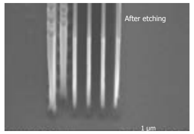


After exposure of the photoresist, the wafer is etched

Fabrication steps

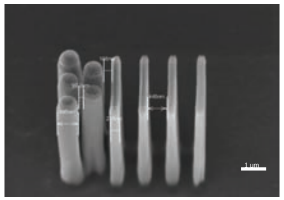
- Electron beam lithography (EBL)
  - EBL system: Raith150 Two (max. acc. voltage 30 kV)
  - Negative resist for faster exposure: ARN-7520 *(Thickness: 400 nm)*
  - Proximity effect still needs to be corrected
  - RIE system: Oxford instruments (PlasmaPro 100)
  - Up to 3 microns etching with the current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



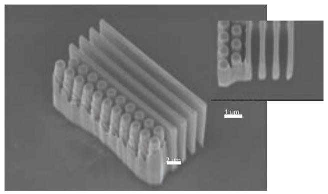


Electron beam lithography at the university of Erlangen

Corrections to be made

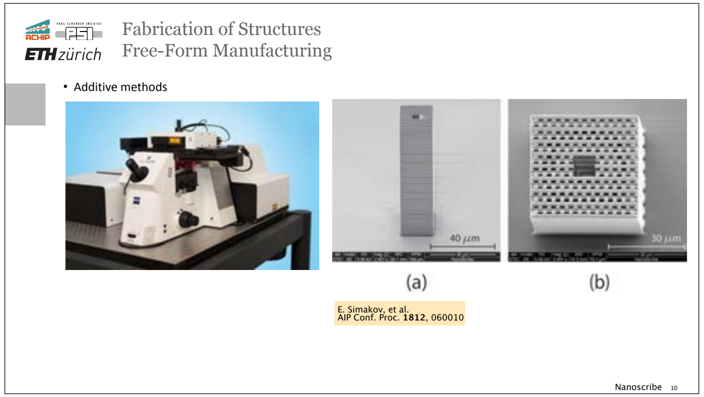


Making the electron path wider and correcting the other geometries



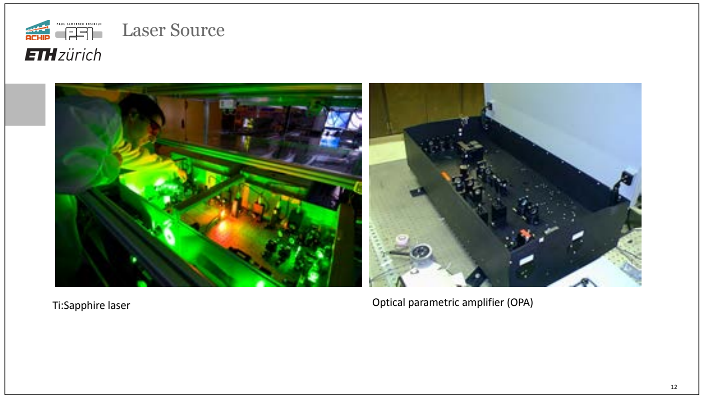
Correcting the electron dose distribution during the exposure to prevent blockage of the electron path

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

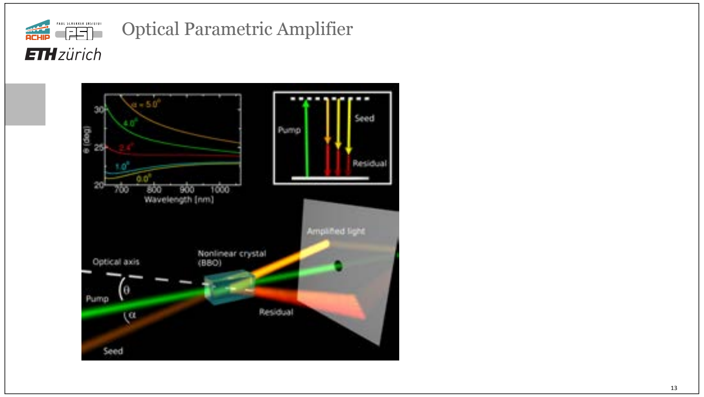


Additive methods: polymers
Hardening of resins by two-photon absorption
Sintering of powders

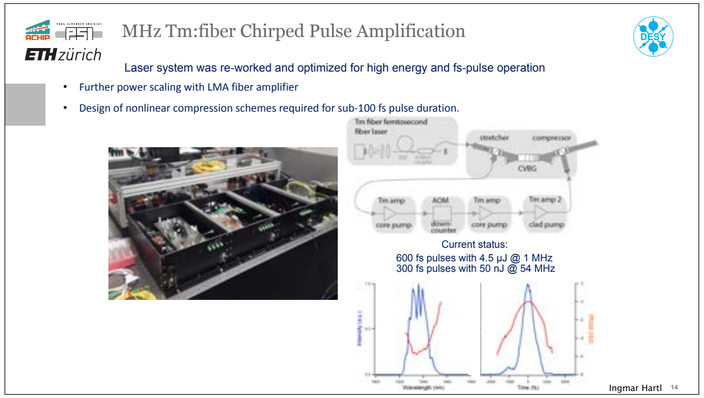
Subtractive methods: possibility to work on glasses (borosilicate, fused silica, …)
Ongoing research: crystalline materials



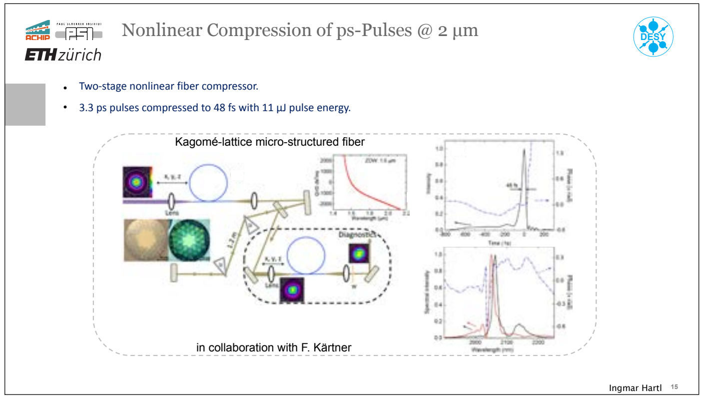
Laser source for first experiments: typically titanium sapphire laser
Well-established technology
Very broad spectrum allows for few-femtosecond pulses
Fundamental wavelength: 800 nm



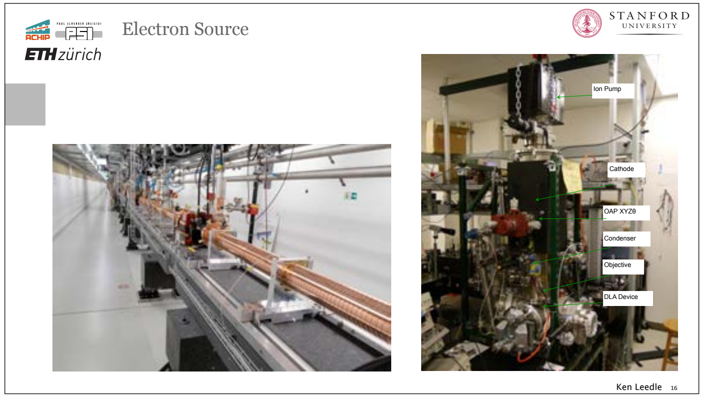
Optical parametric amplification allows to generate photons with longer wavelength
Wavelength can be tuned by rotating crystal



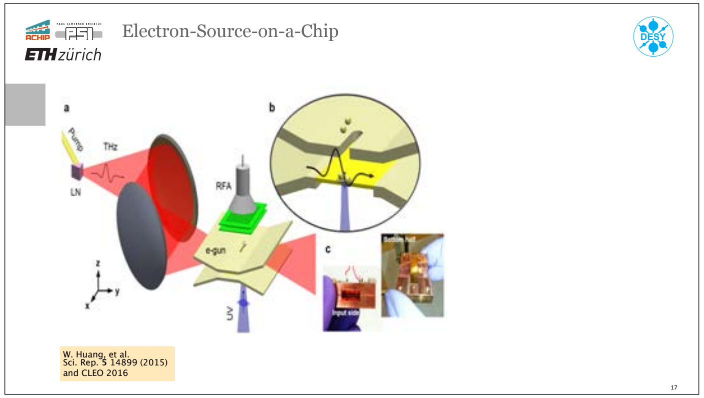
For an actual accelerator-on-a-chip, one would like a laser with better energy efficiency
—> Thulium doped fiber laser



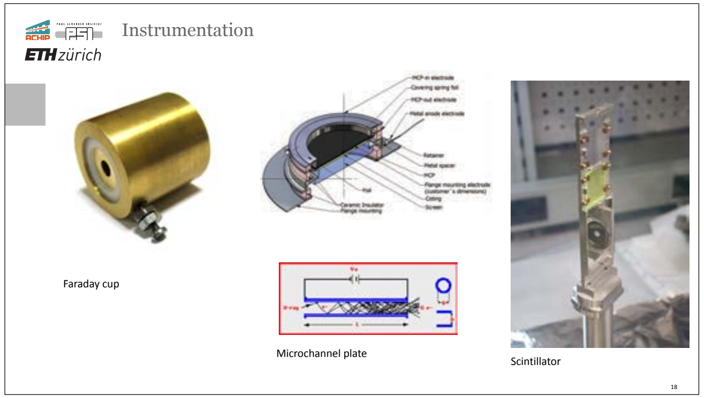
Compression of pulses required for highest accelerating fields



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



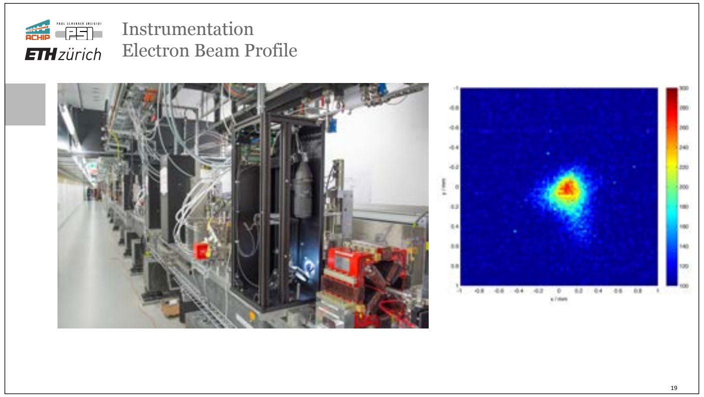
Instrumentation required to measure electron (and laser) properties after the acceleration

Electron detection

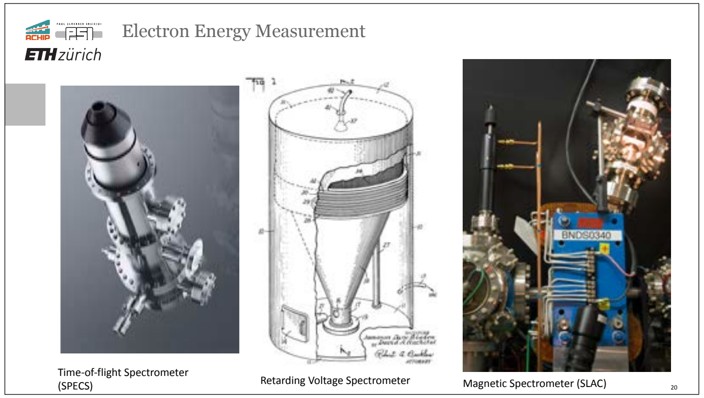
> Faraday cup

> Microchannel plate

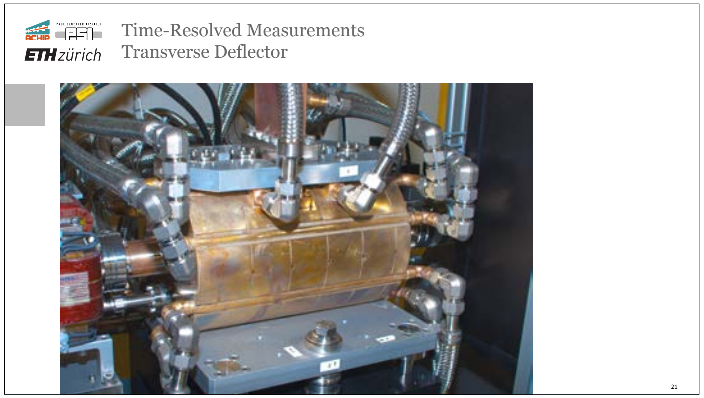
> Scintillator



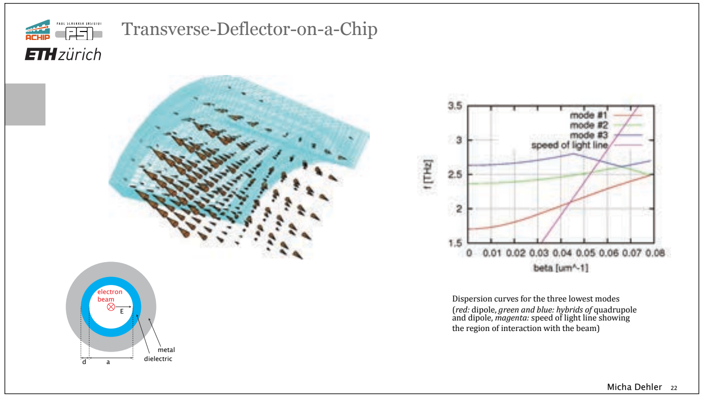
Scintillators allow for beam size measurement



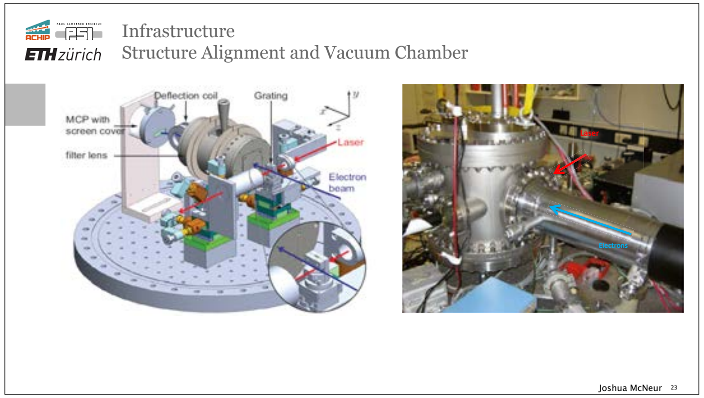
From lowest energy to highest:
> time-of-flight spectrometer: up to ~ 10 keV
> retarding voltage spectrometer: up to ~ 100 keV
> magnetic spectrometer: up to GeV (and beyond)



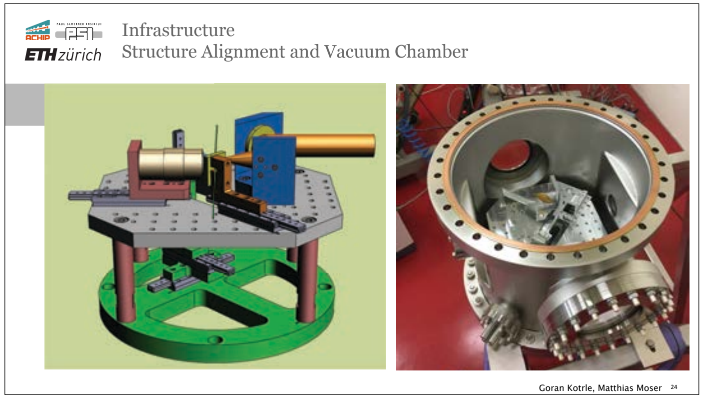
Transverse deflecting cavity



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

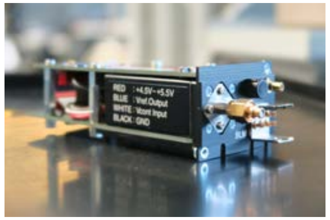


Need to align electron and laser beam with the structure
Micrometer precision is not easy to achieve…
The experiment needs to be performed in vacuum



Another setup for a 7 MeV transverse acceleration experiment

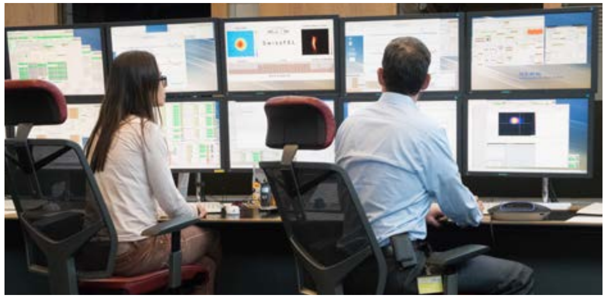
Infrastructure
Loss Monitors and Radiation Protection



Cigdem Ozkan Loch, Patrick Pollet 25

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

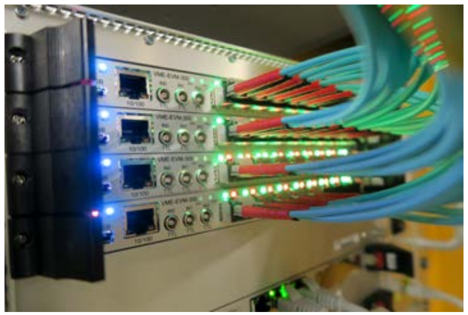
Infrastructure
Control System



Nicole Hiller, Thomas Schietinger 26

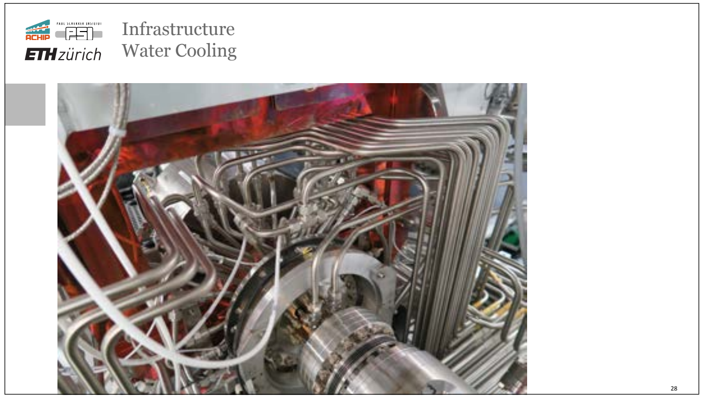
Control system

Infrastructure
Timing & Synchronization



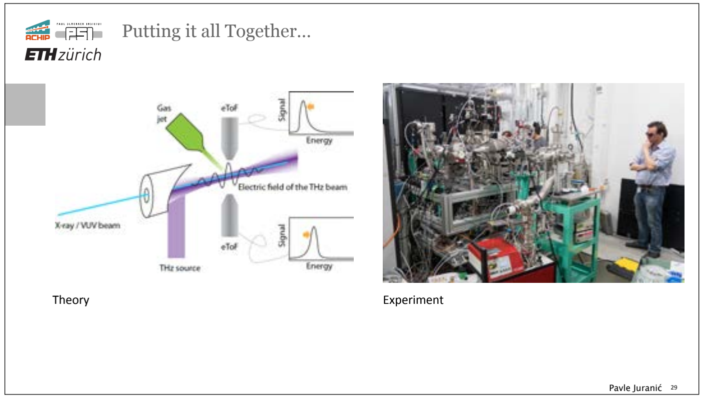
Babak Kalantari 27

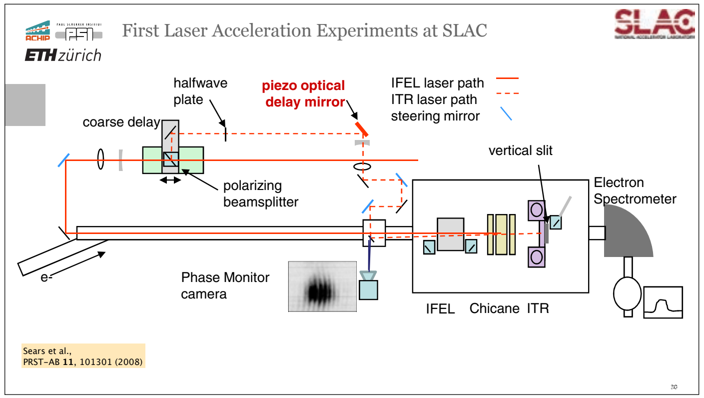
Timing system to ensure simultaneous readout of all devices



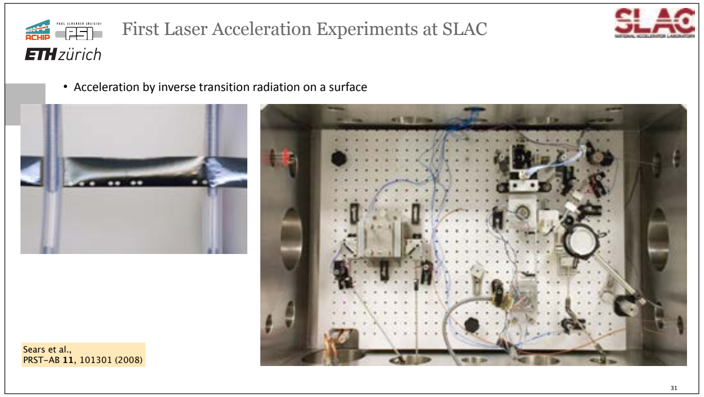
Water cooling

etc … etc …

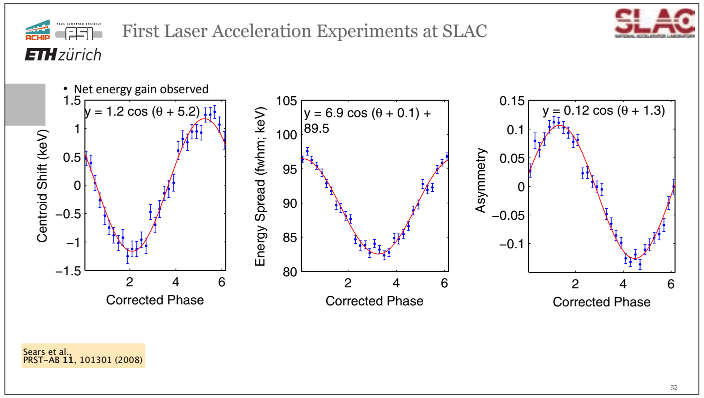




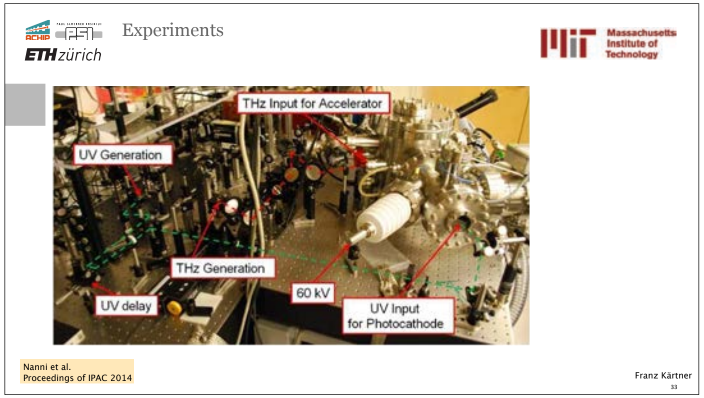
First laser acceleration experiments at SLAC
Set up with the 60 MeV beam in the Next Linear Collider Test Facility
Laser: 800 nm Ti:Sapphire



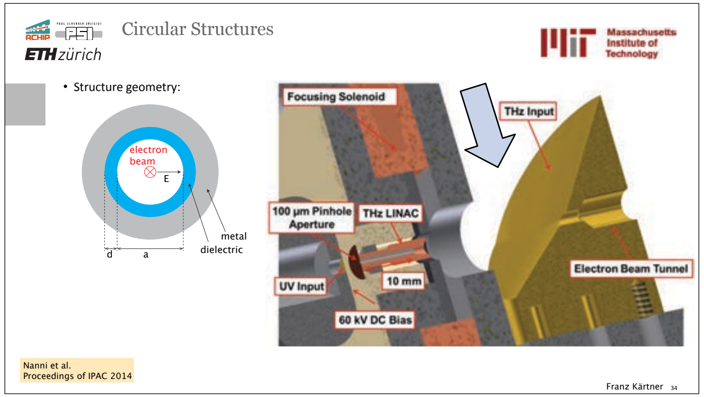
Not actually using a “real” accelerating structure yet
Instead: terminate electromagnetic fields at a boundary
Allows for half-a-wavelength acceleration
Boundary material is destroyed by the laser beam, but this takes hundreds of picoseconds
Electrons just pass through the material
Another way to describe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



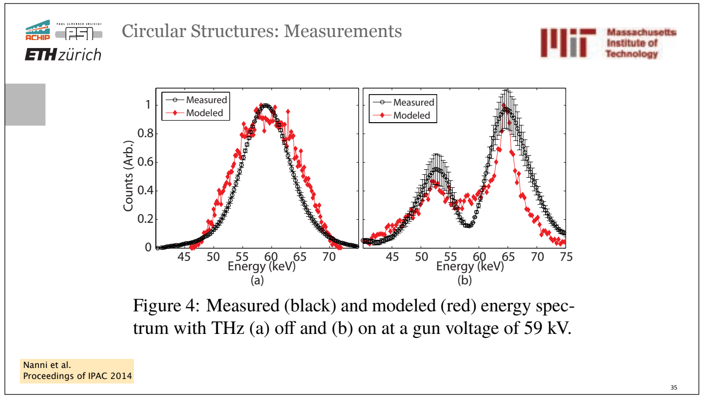
Note the magnitude of the acceleration: 1 keV
> while using a 90 keV energy spread
> initial energy: 60 MeV



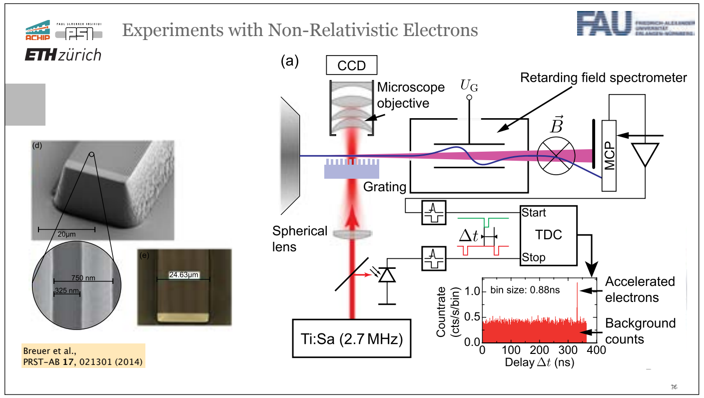
Experiments with low-energy electrons



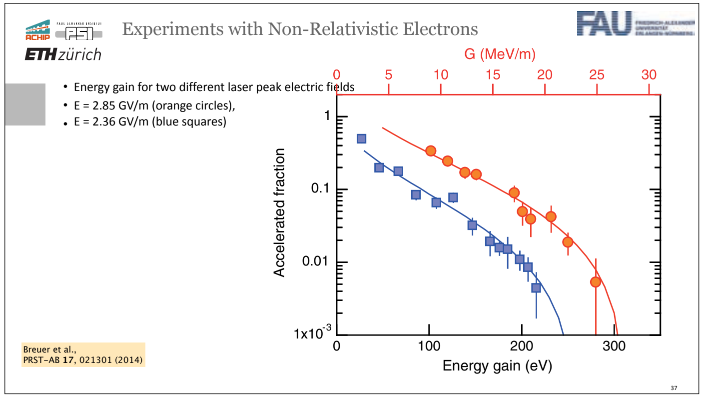
Dielectric-lined waveguide geometry



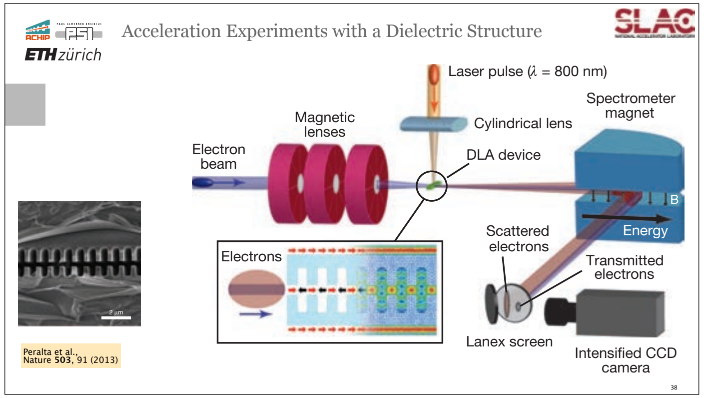
Energy spectrum has two peaks:
the electron beam is longer than the wavelength, thus some of the electrons are accelerated, others are decelerated



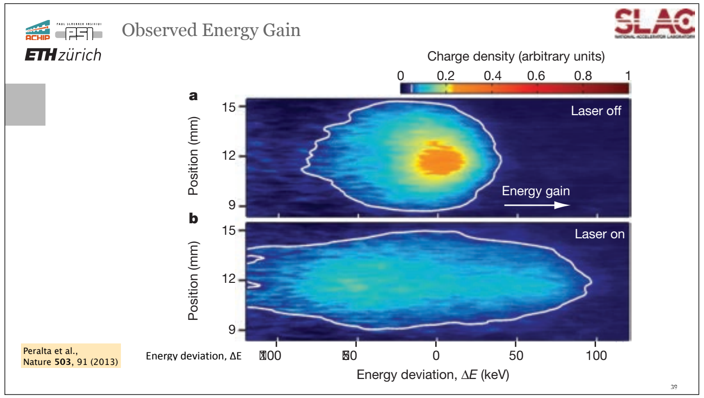
Experiments with grating structures performed at the University of Erlangen



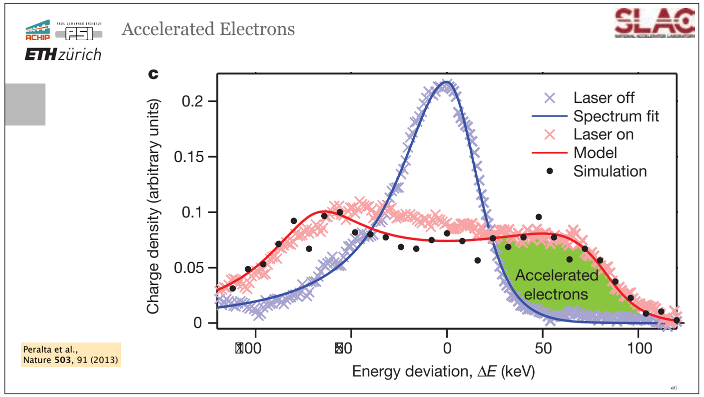
Note the low efficiency of acceleration of non-relativistic electrons!



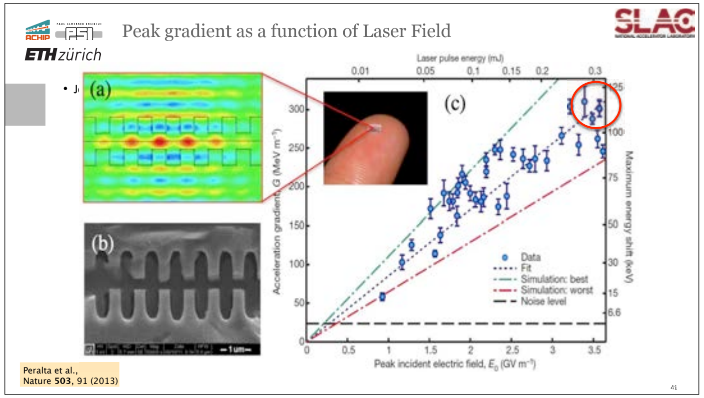
Same Next Linear Collider Test Facility as before
Now with “real” structures



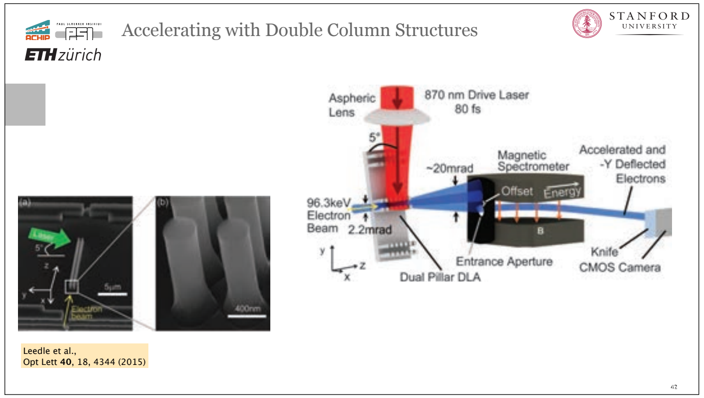
Depending on their phase, some electrons are accelerated, some are decelerated
Clear increase of energy spread
(again, the electron bunch is much longer than the wavelength)



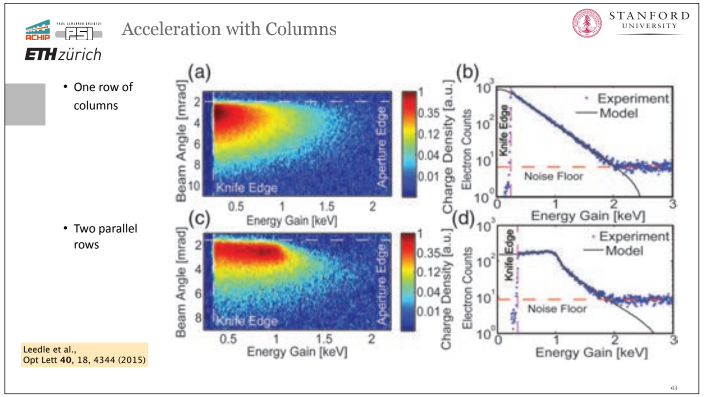
Electrons get accelerated by about 50 keV
(initial energy: 60 MeV)



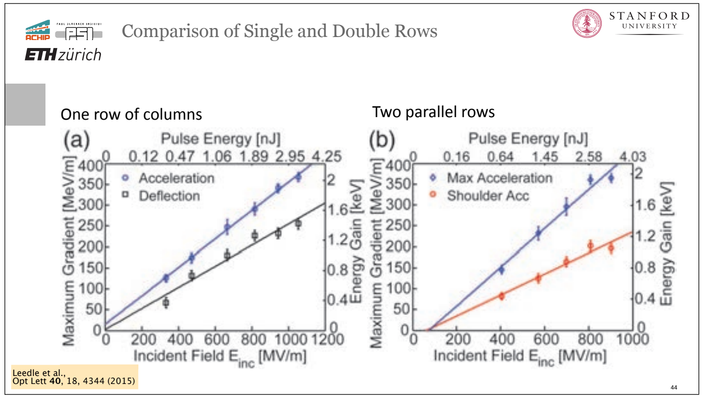
Acceleration gradient is a linear function of the incident field
Maximum energy gain: 100 keV



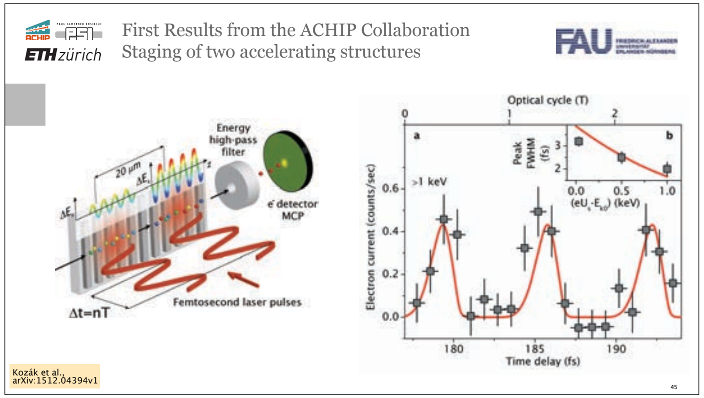
Double column structures are intrinsically aligned



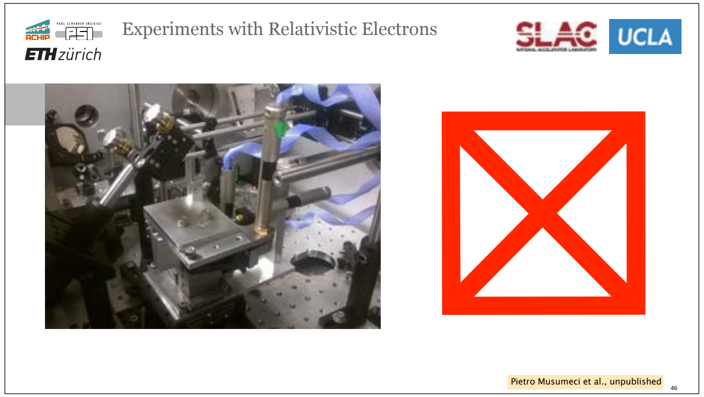
Accelerating non-relativistic electrons



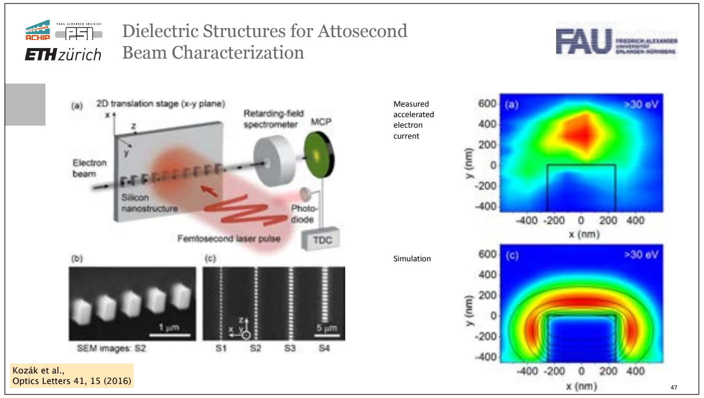
Double columns have more symmetric fields



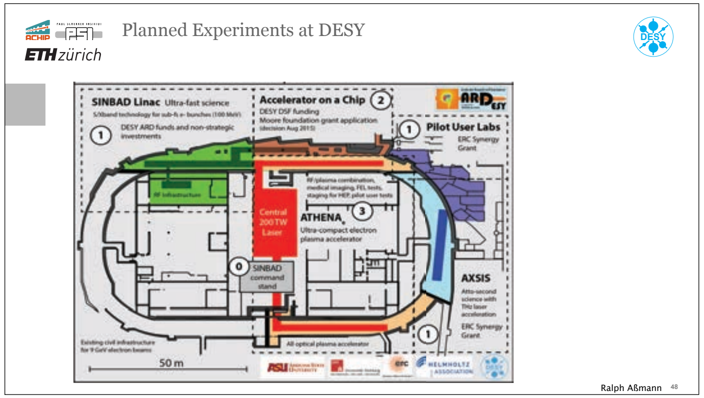
Important aspect: staging of multiple accelerating structures
First experiment: single grating, two laser pulses
Phase between the two laser pulses can be adjusted



Experiments using relativistic electrons

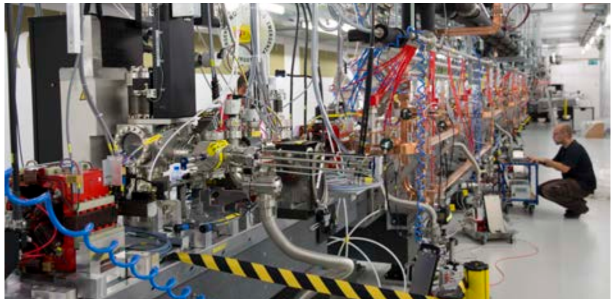


Devices-on-a-chip can also be used for beam characterization
Attosecond resolution



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

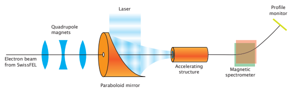
Planned Experiments at PSI
Installation of a Test Chamber in SwissFEL

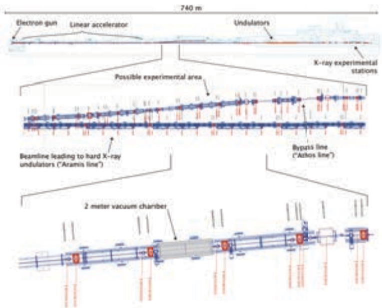


Goal: use this chamber to test for radiation hardness and for collective effects
No laser source available

Planned Experimental Setup in SwissFEL

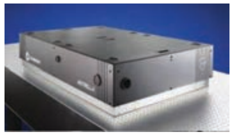
- Goal: Acceleration by 1 MeV





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

Dedicated Laser Room



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

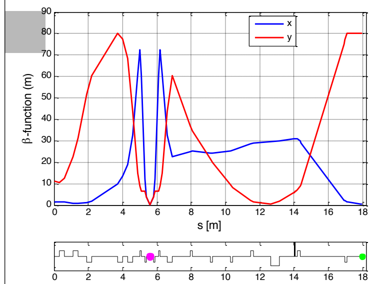
Eugenio Ferrari

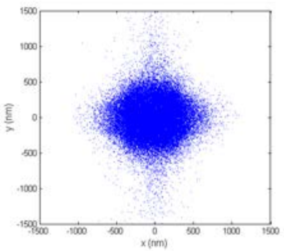
Laser transport system required

Possible Laser Accelerator Experiments at PSI

- **Ultra-relativistic particles**
  - Particle energy E = 3.4 GeV, Lorentz factor γ = 6700, Velocity v = 99.99999887% 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

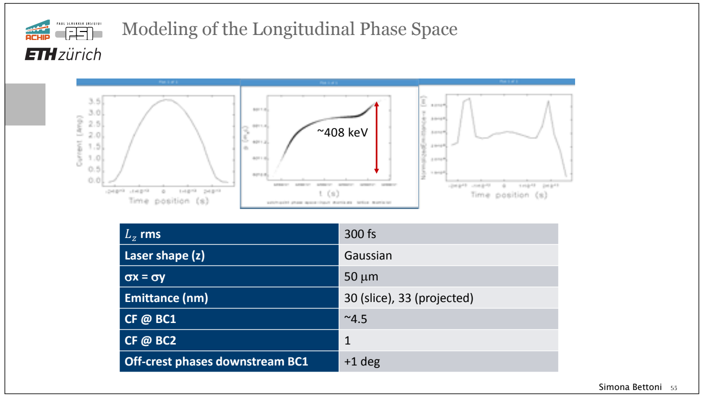
Focusing of the Electron Beam



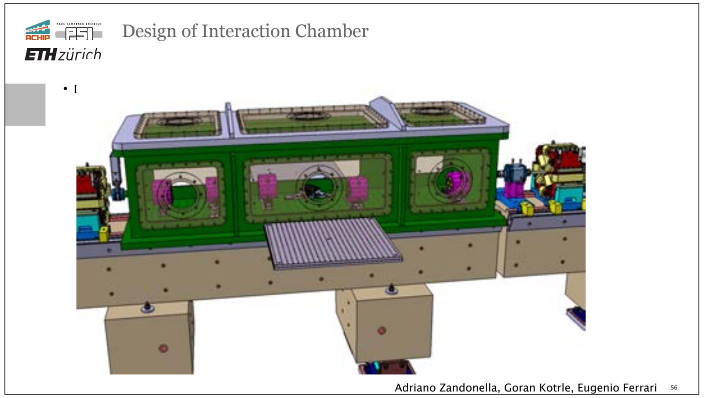


Eduard Prat

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

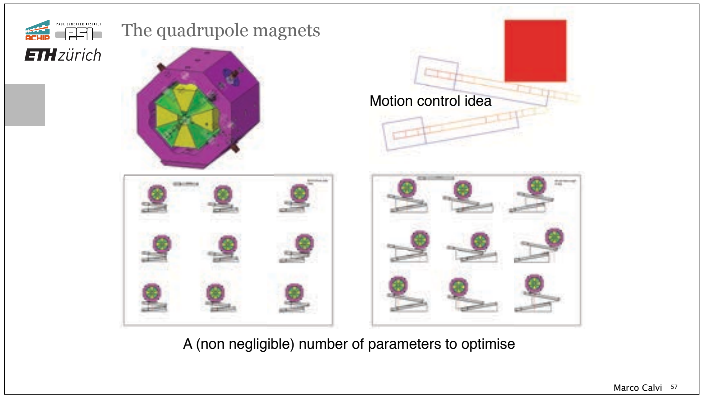


Low intrinsic energy spread allows for precise measurement of energy gain

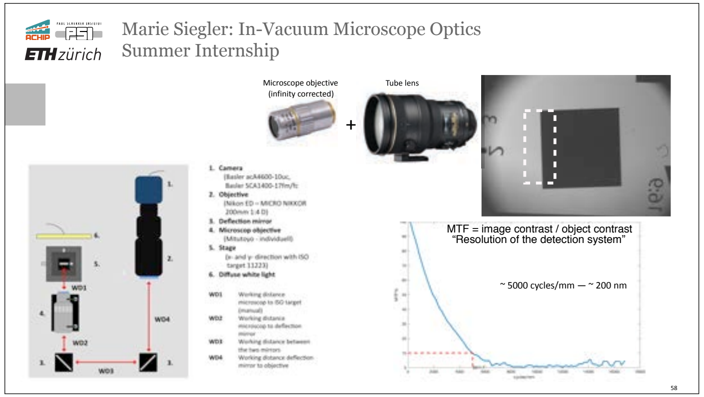


2-meter long interaction chamber

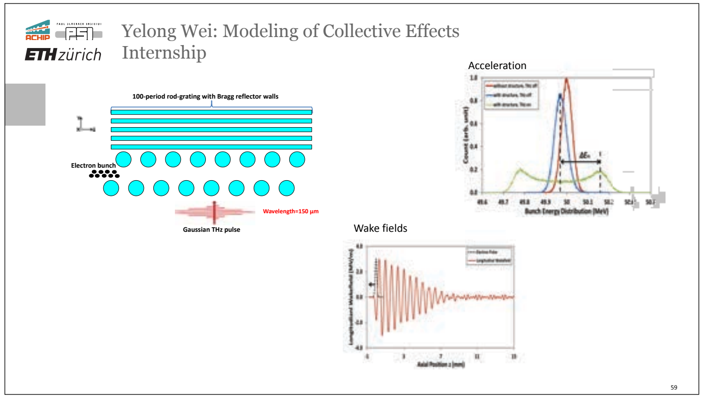
Includes quadrupole magnets for beam focusing



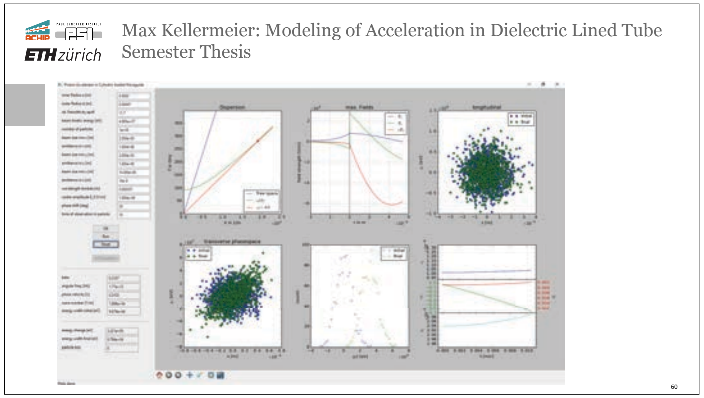
Permanent magnet quadrupoles for beam focusing



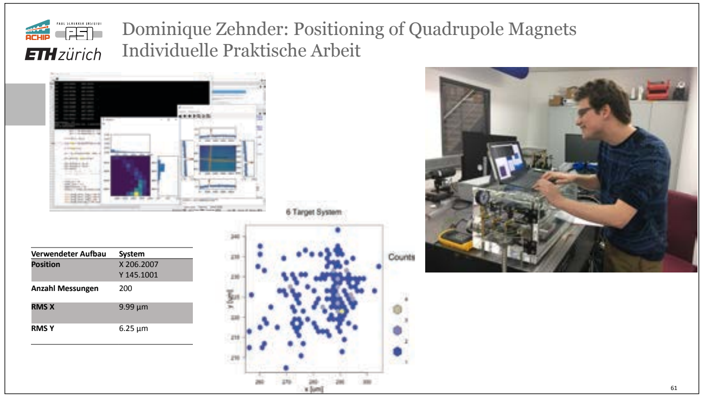
Finally, some student projects at PSI
Microscope optics required to image sub-micrometer beam
In-vacuum microscope objective, combined with tube lens and camera outside the vacuum
Collimated beam is transported through the window —> no spherical aberrations
Long distance requires large tube lens to avoid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



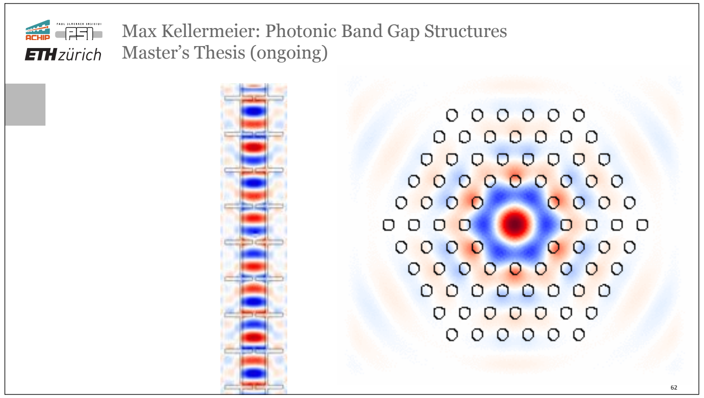
Modeling a scaled structure
Structure size compatible with beam in the SwissFEL Injector
(Resonant to 150 µm radiation)
Wake fields result in an increase of
> energy spread
> emittance
for the tail of the beam



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



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



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

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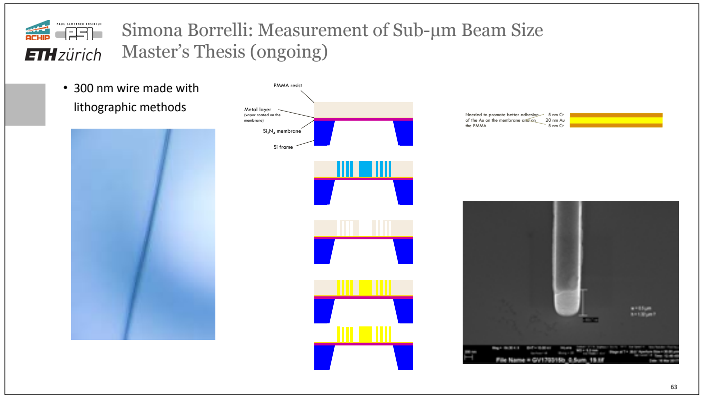

Measurement of sub-micrometer beam size with wire scanners
Traditional wires: only down to about 25 µm
Manufacture a wire using electron beam lithography

Questions?

Nick Veasey

Thank You

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