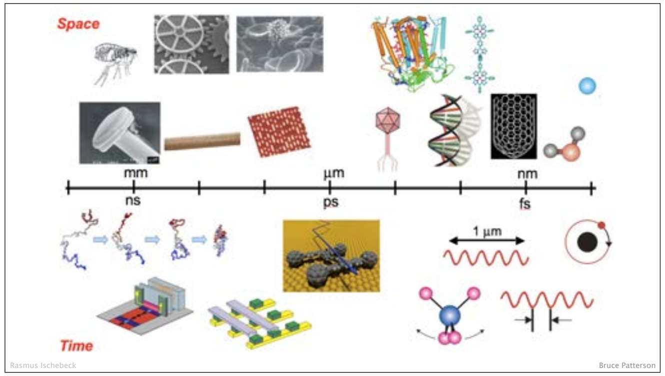
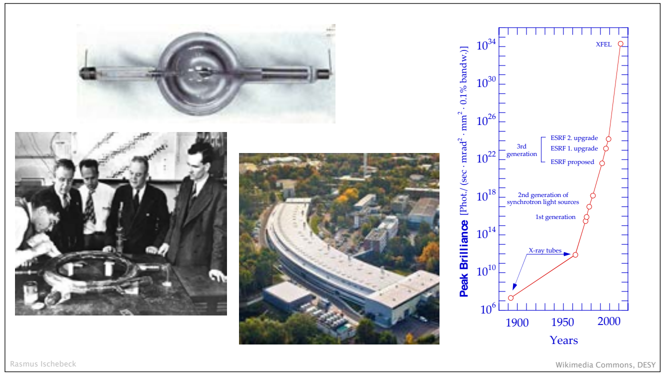
To make movies of the inner workings of a cell, to take snapshots of the reactions between molecules, we need to achieve appropriate resolution in space and time: welcome to Synchrotron Light Machines and Free Electron Lasers II!

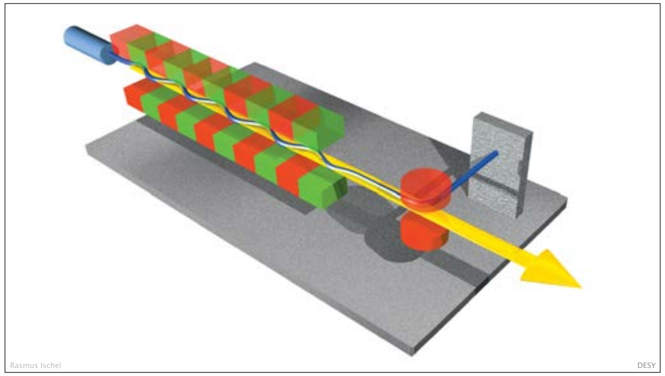
> Motivation
> Physical processes in a free electron laser
> Free electron lasers for XUV and X-Rays
> Components of a free electron laser



We need a source that emits photons of a wavelength smaller than the size of the molecules, and short in comparison to the dynamics that we want to study

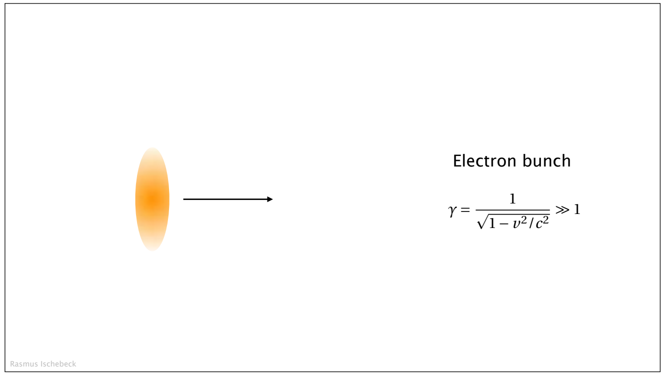


At the same time, we need enough photons for our experiments
—> Need to increase the brilliance by 9 orders of magnitude

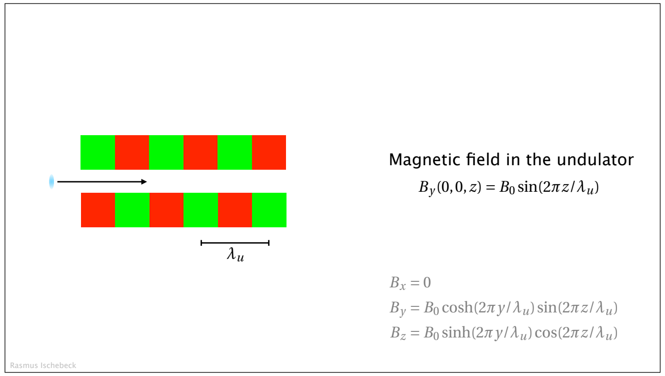


Start with the same ingredients as in a traditional synchrotron radiation source:

> free electrons
> magnetic undulator

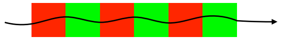


Start with a relativistic electron bunch…



…and a sinusoidal magnetic field
[Strictly speaking, the curl and divergence of the static magnetic field vanish in vacuum,
$\nabla \times B = 0$ and $\nabla \cdot B = 0$
Thus, the field acquires a z component for $y \neq 0$

Motion of the electrons in the lab frame



$$m_e \gamma \frac{\mathrm{d}\vec{v}}{\mathrm{d}t} = \vec{F} = -e\vec{v} \times \vec{B}$$

$$m_e \gamma \frac{\mathrm{d}v_x}{\mathrm{d}t} = e v_z B_y = e v_z B_0 \sin(k_u z)$$

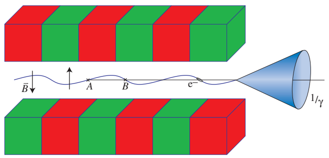
$$\Longrightarrow v_x(z) = -\frac{Kc}{\gamma}\cos(k_u z)$$

$$\text{with } K = \frac{eB_0}{m_e c k_u}$$

$$x(z) = -\frac{K}{k_u \gamma \beta_z}\sin(k_u z)$$

Rasmus Ischebeck

—> sinusoidal motion of the particles



The electrons emit in a narrow cone with opening angle

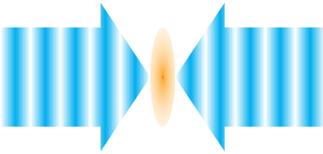
$$\vartheta = \frac{1}{\gamma}$$

The fundamental harmonic of this radiation is given by:

$$\lambda = \frac{\lambda_u}{\gamma^2} \cdot \frac{(1 + K^2/2)}{2}$$

Rasmus Ischebeck

The electrons emit X-rays in a narrow cone
Radiation from a single electron from multiple periods adds up coherently if a resonance condition is met; this is the fundamental wavelength of the undulator



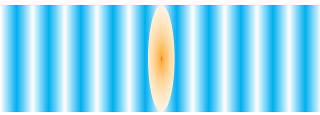
mean speed of the electrons:

$$\bar{\beta}_z = 1 - \frac{2+K^2}{4\gamma^2}$$

external electromagnetic wave:

$$\vec{E} = \vec{u}_x \tilde{E}_x \cos(kz - \omega t + \psi_0)$$

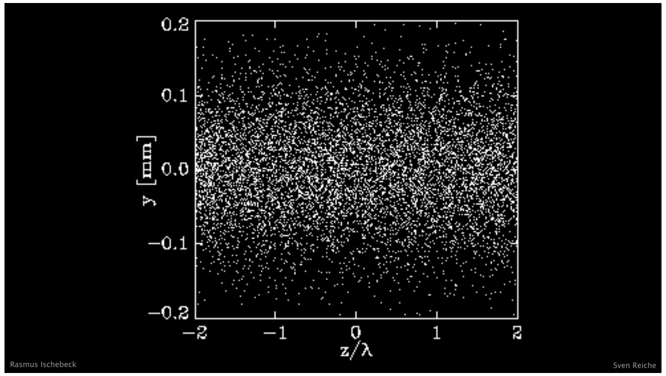
Now, we look at the effect of the radiation on the electron bunch
Two fields:
> undulator field
> radiation field
in the rest frame of the bunch, these fields have the same frequency



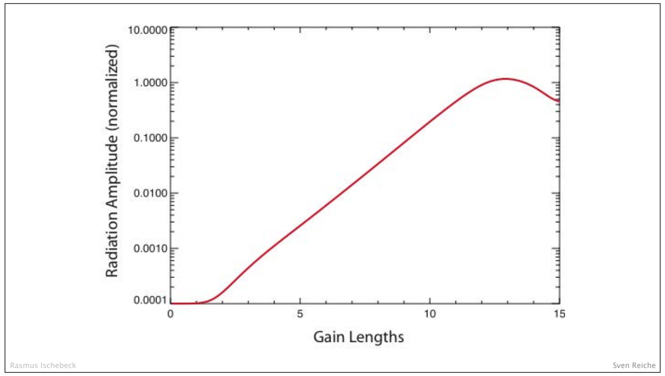
Energy gain:

$$\begin{aligned}\frac{\mathrm{d}W}{\mathrm{d}t} &= -e\vec{E}\cdot\vec{v} \\ &= e\tilde{E}_x \cos(kz - \omega t + \psi_0)\frac{cK}{\gamma}\cos(k_u z) \\ &= \frac{e\tilde{E}_x cK}{2\gamma}\left[\cos((k+k_u)z - \omega t + \psi_0) + \cos((k-k_u)z - \omega t + \psi_0)\right]\end{aligned}$$

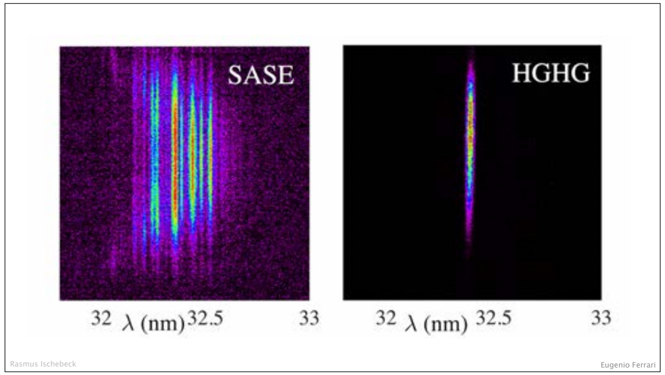
Addition of two traveling waves:
standing wave!



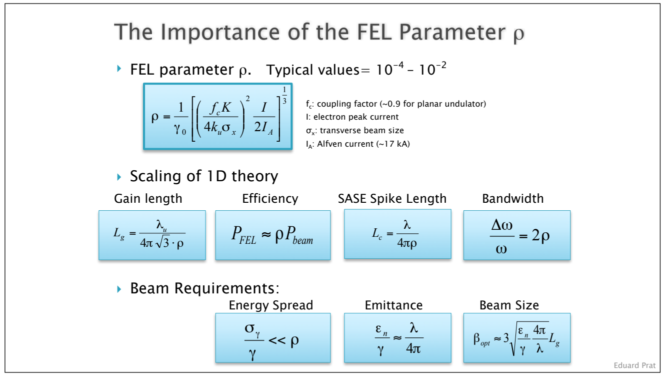
Results: some electrons gain energy, some lose energy, depending on their phase
(In conjunction with the transverse motion of the particles)
—> energy modulation
—> spatial modulation (in conjunction with the dispersion)



Multiple electrons are bunched to a region smaller than the wavelength:
Coherent emission!
Exponential gain of the radiation



No seed available?
Use spontaneous radiation!
Startup of the process
right: external seed
left: spontaneous radiation (SASE)

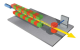


Pierce parameter rho
Important for many effects in a free electron laser
—> More about this in any advanced FEL course!

Synchrotron Light Machines and FELs II

Rasmus Ischebeck, Paul Scherrer Institut

>Motivation



>Physical processes in a free electron laser

>Free electron lasers for XUV and X-Rays

>Components of a free electron laser

FELs in operation:
> LCLS

> SACLA

FERMI@ELETTRA

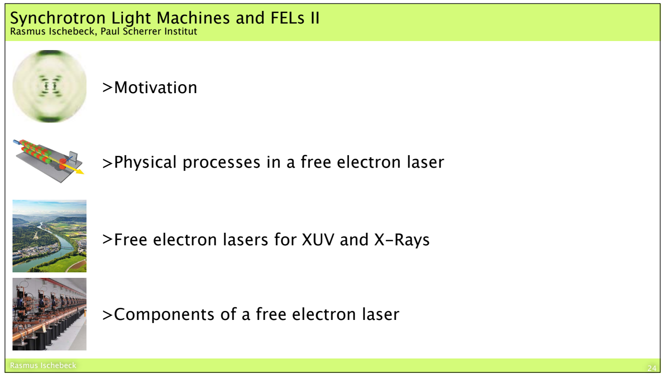
> FLASH

FELs in construction:
> PAL-XFEL

> SXFEL @ SINAP

> XFEL.EU

> SwissFEL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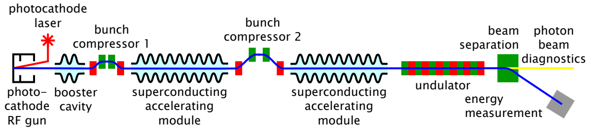
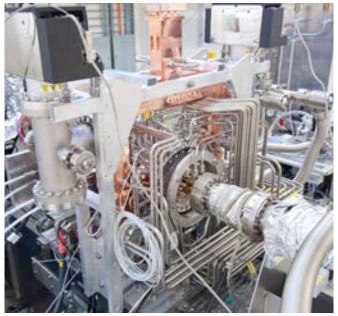


Rasmus Ischebeck

Components of a Free Electron Laser

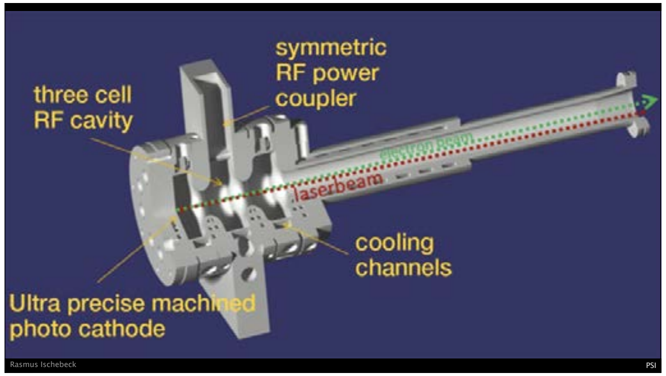


Rasmus Ischebeck

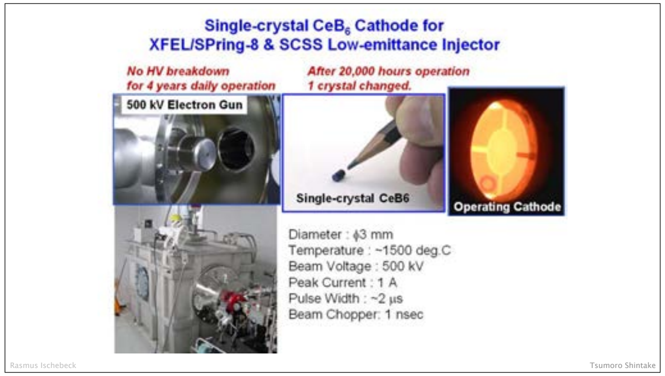
Tsumoro Shintake

Electron Source:

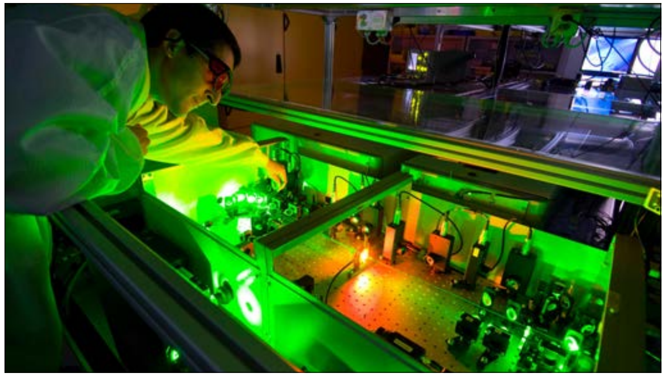
a) Photoemission
b) Thermionic emission



Electron bunches are generated inside a radiofrequency cavity
—> large accelerating fields at the photocathode are necessary to counteract the space charge forces which would otherwise reduce the charge density

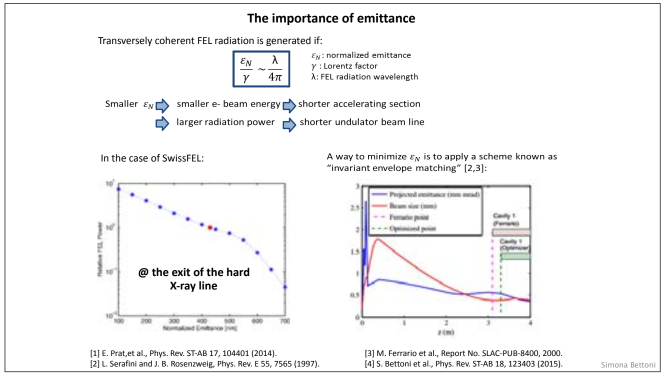


In the case of a thermionic source, the current density is somewhat lower
—> multiple compression stages necessary!

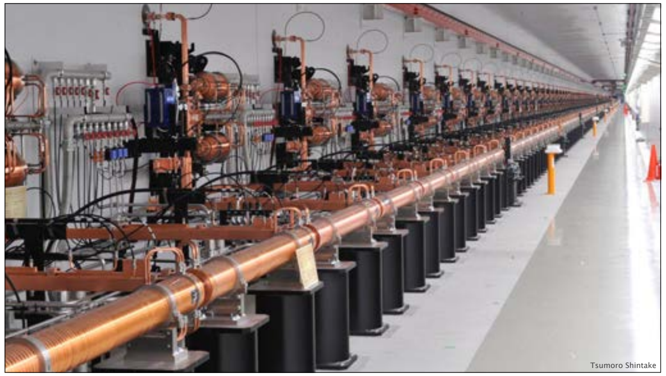


Photocathode laser: stability is of paramount importance for the operation of the FEL
Frequency-tripling or quadrupling is used to generate UV photons for efficient electron extraction from the cathode

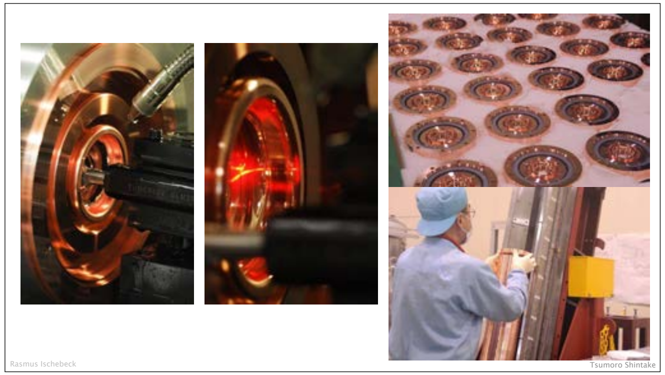
Significant effort: increase the brightness of the source
Normalized emittance cannot be improved after the source
The initial emittance is generated in the gun, and it is degraded for example by mis-alignment of the accelerating structures, causing wakefields, and by self-forces during pulse compression.



The importance of emittance



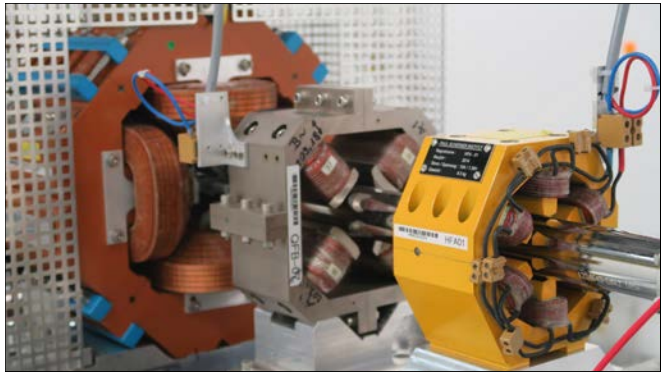
Acceleration: radiofrequency cavities in a linear accelerator



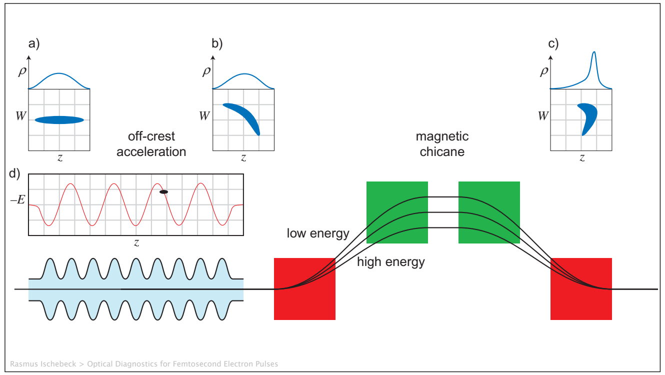
Series production of RF structures

Industrial process to assemble each cavity from individual discs
Micrometer precision required to control the resonant frequency

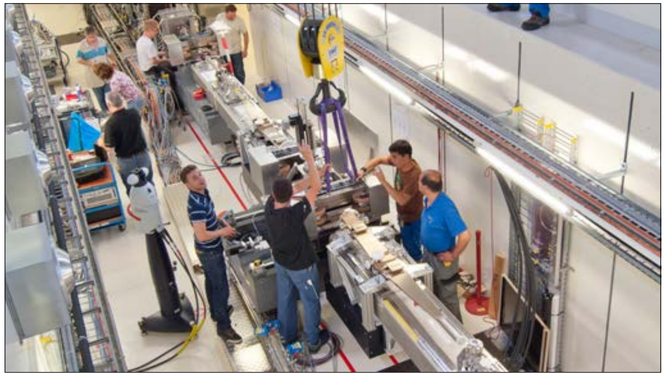
Focusing: quadrupole magnets



Higher order optics correction: skew quadrupoles and sextupoles

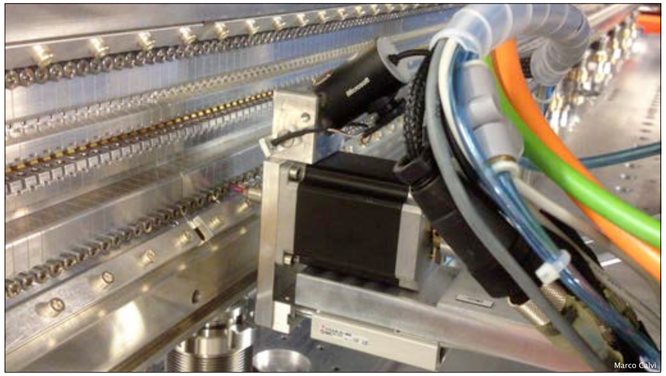


Bunch compression: off-crest acceleration, followed by a magnetic chicane
Particles in the head of the bunch travel a longer path —> this allows the particles in the tail to catch up
Non-linear compression can be avoided by higher harmonics of the accelerating frequency

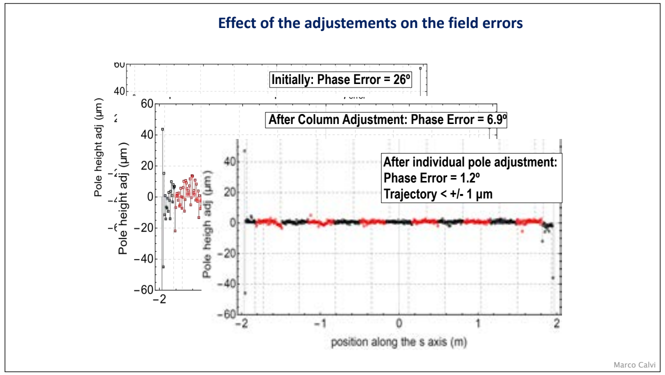


Bunch compressor: macroscopic object, 10 meters long
Used to compress bunches with 10 micrometers diameter!

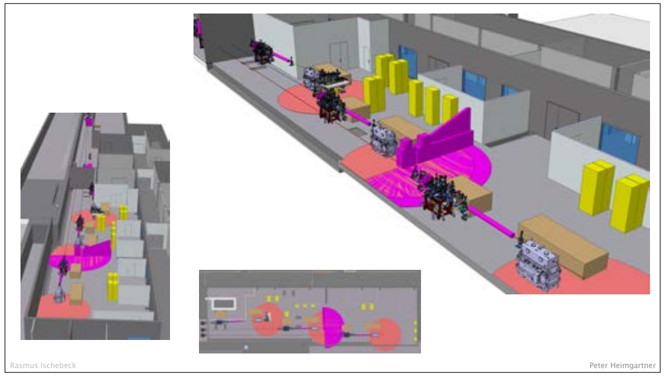
Undulators: long series of permanent magnet undulators allows for saturation of the FEL process



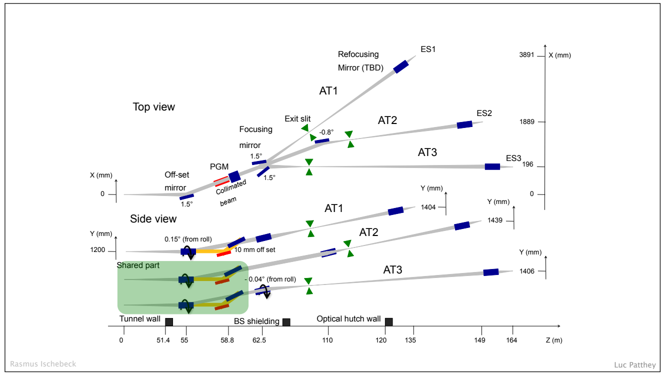
Alignment of undulator poles to sub-micrometer precision
14’000 magnets



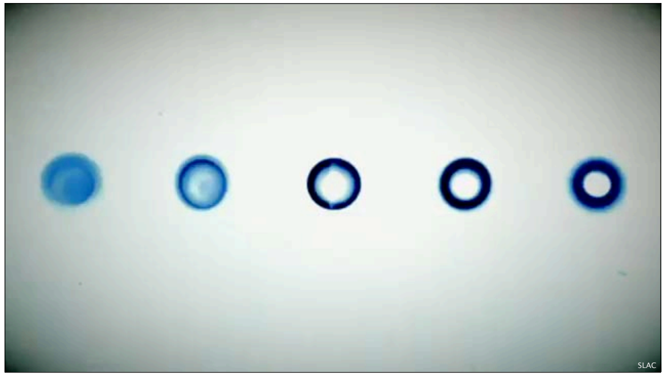
Importance of adjusting each magnet pole individually



Photon beamline: beam transport to the experiment
> Focusing
> Monochromator
> Photon beam diagnostics



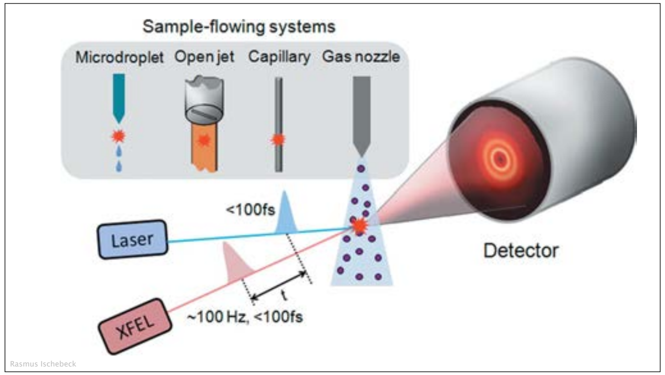
Schematic layout of the photon beamlines in SwissFEL ATHOS



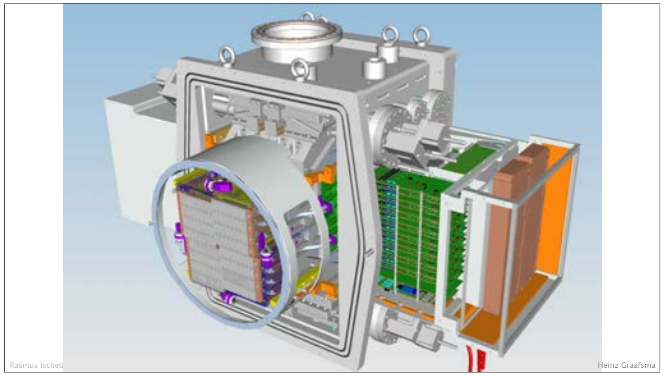
Necessary on the experimental side: sample delivery
Challenge: hold the sample into the beam:

- > as little material as possible around the sample
- > FEL beam destroys most materials

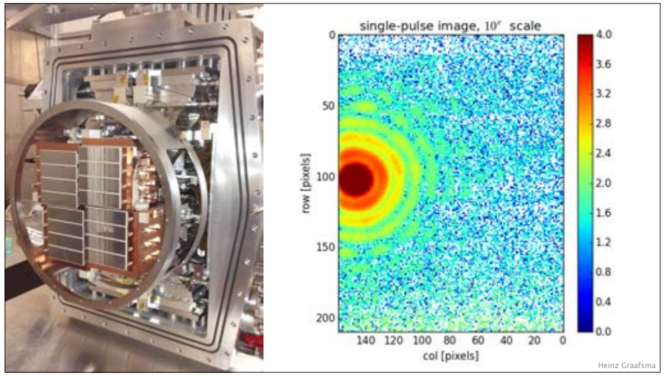
Shown here: effect of the LCLS on water droplets



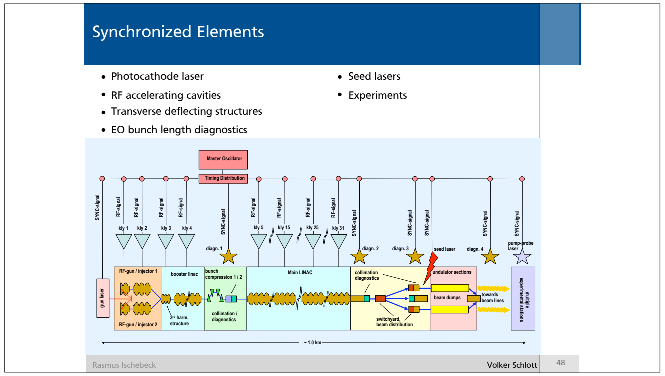
Micro-droplets or jets suitable to deliver nanocrystals into the beam



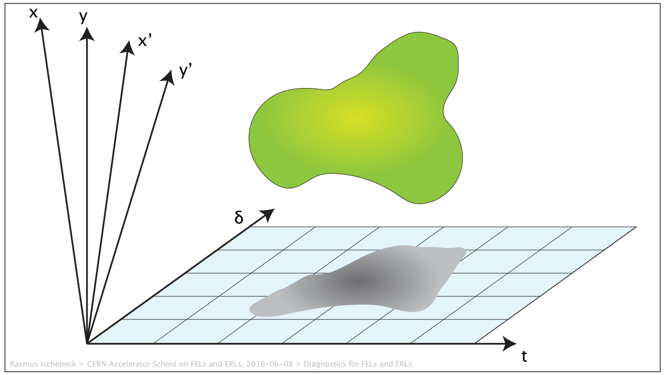
Detector: semiconductor pixel detector
Adjustable hole for the undeflected beam
Fast readout of the data required



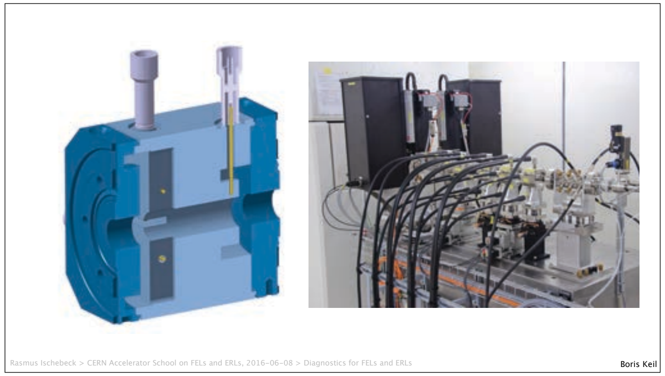
Detector prototype
single-shot diffraction image of a pinhole



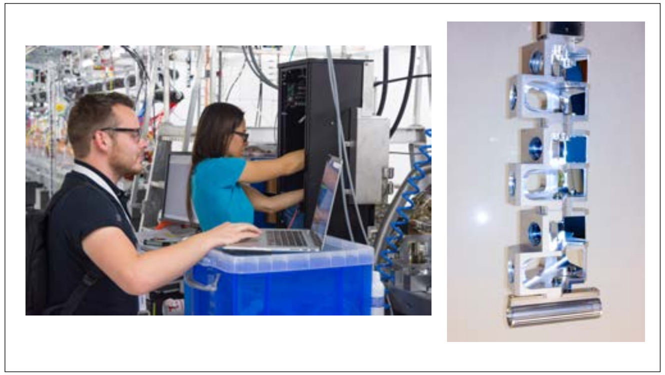
Synchronization of all components to femtosecond accuracy
Distributed system of kilometer size



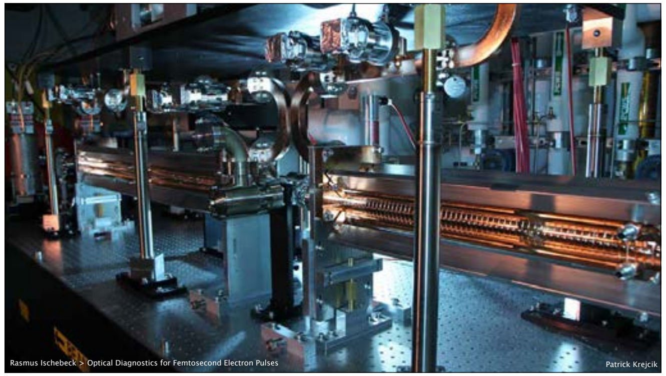
Instrumentation for FELs
Let's first have a look at the object of study, the beam.
This beam can be represented by the particle distribution in the six-dimensional phase space, extended by transverse coordinates x and y, transverse angles x' and y', time t and energy delta.
When we speak about the longitudinal phase space, we mean the projection on these last two dimensions, and in particular the time, which is very difficult to measure with femtosecond accuracy.
No diagnostics exists for the entire distribution.
We can only measure projections into one or two of these dimensions.
Additional beam line elements, such as quadrupole magnets and transverse deflecting RF cavities can then be used to do phase space transformations, which allow us to see dimensions that are not easily accessible, and we can use mathematical reconstruction algorithms to infer 3d information.



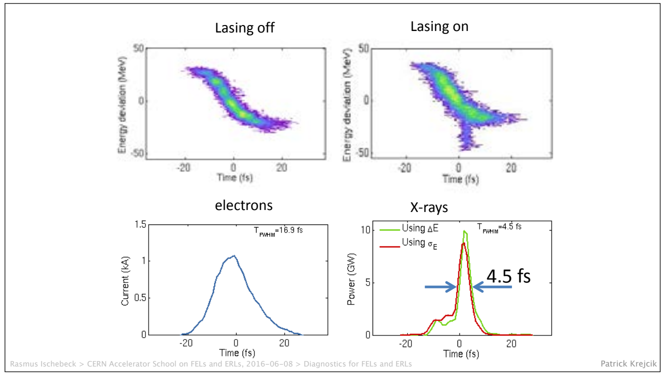
Beam position monitors: cavity pickups



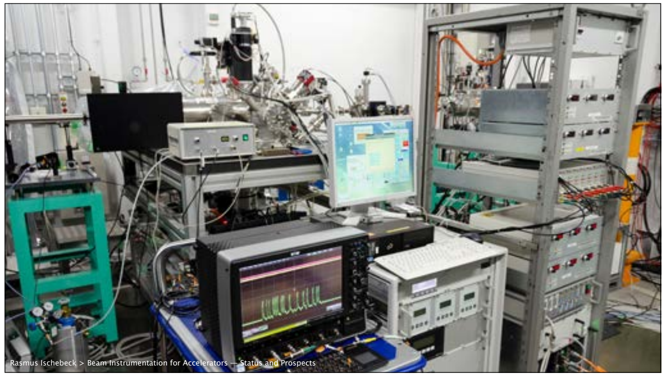
Beam profile monitor: scintillating screens
Be careful: coherent transition radiation may spoil the images for highly compressed beams!



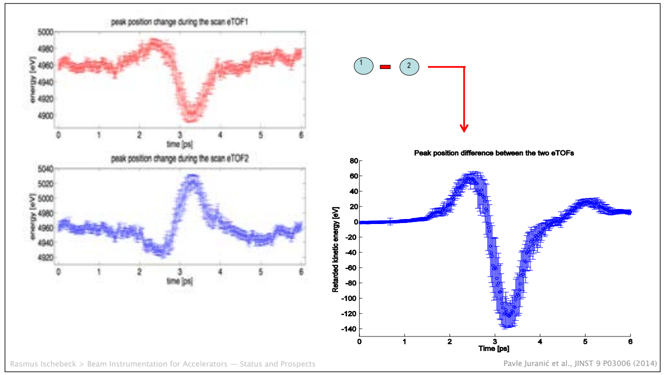
Phase space transformation with RF deflecting cavity
Reference for all longitudinal diagnostics
Shown here: installation in LCLS



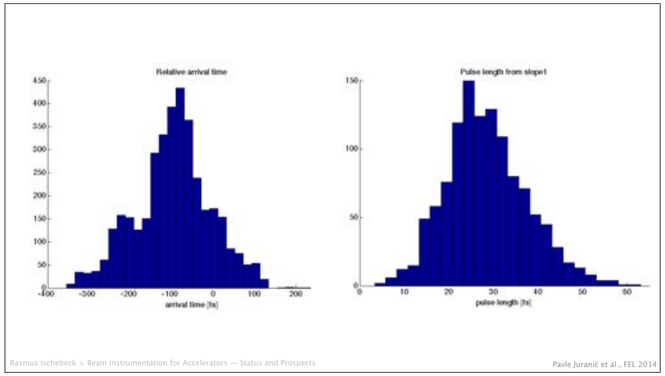
Measurements of full phase space possible!
Femtosecond resolution, depending on:
— emittance
— streak strength



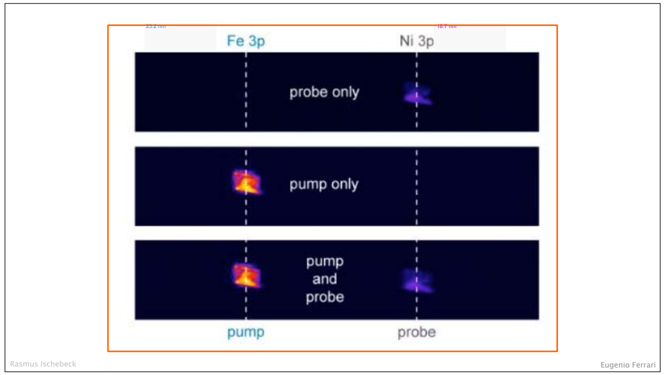
Measurement of X-ray pulse length:
ionize Xenon clusters, measure photoelectron spectrum.
Modulation of this spectrum by terahertz field derived from the pump laser



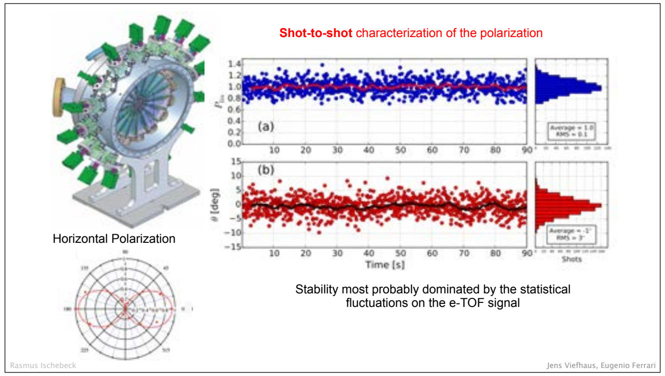
Two electron spectrometers.
Opposite effects for upper and lower electron spectrometer —> measurement of arrival time of X-rays with respect to terahertz



Measurement of arrival time and pulse length possible



Two-Color mode: use two parts of the undulator for two distinct wavelengths
This can be used for pump-probe experiments



Polarization: generation in undulators that use four magnets which can be shifted along the optical axis
Measurement by observing the ionization of gas atoms possible
Arrange 16 electron time of flight spectrometers around the interaction zone

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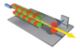
>Motivation



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Thank you for slides, illustrations, photos and movies:
> BioVisions, Harvard University
> Bruce Patterson
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