PAUL SCHERRER INSTITUT PSI

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Rafael Abela

The SwissFEL X-ray Laser Project at PSI: Challenges and Opportunities

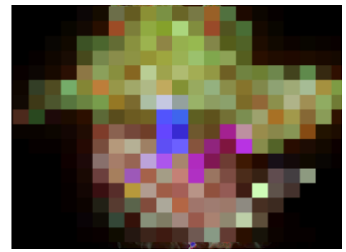
SwissFEL – a forefront research infrastructure for CH

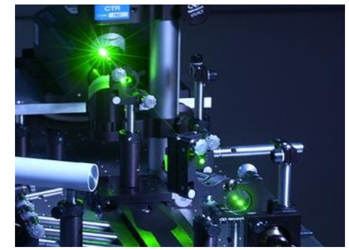
3rd gen. synchrotron

fine, slow

optical lasers

fast, coarse

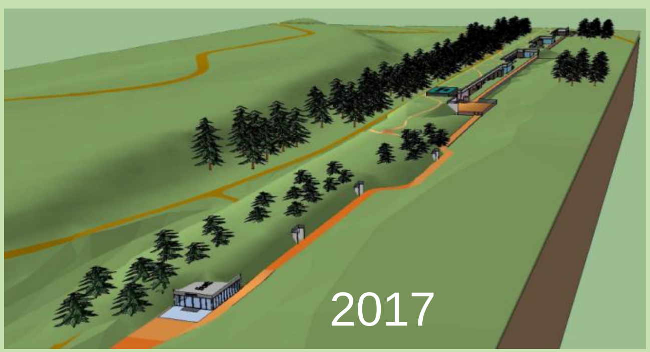


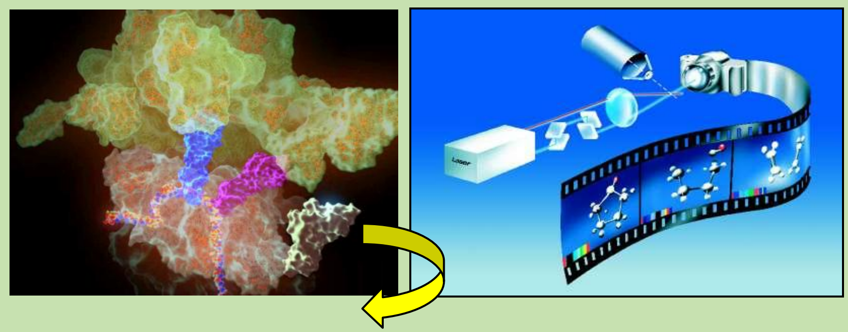


SwissFEL

fine **and** fast

at extreme high intensity



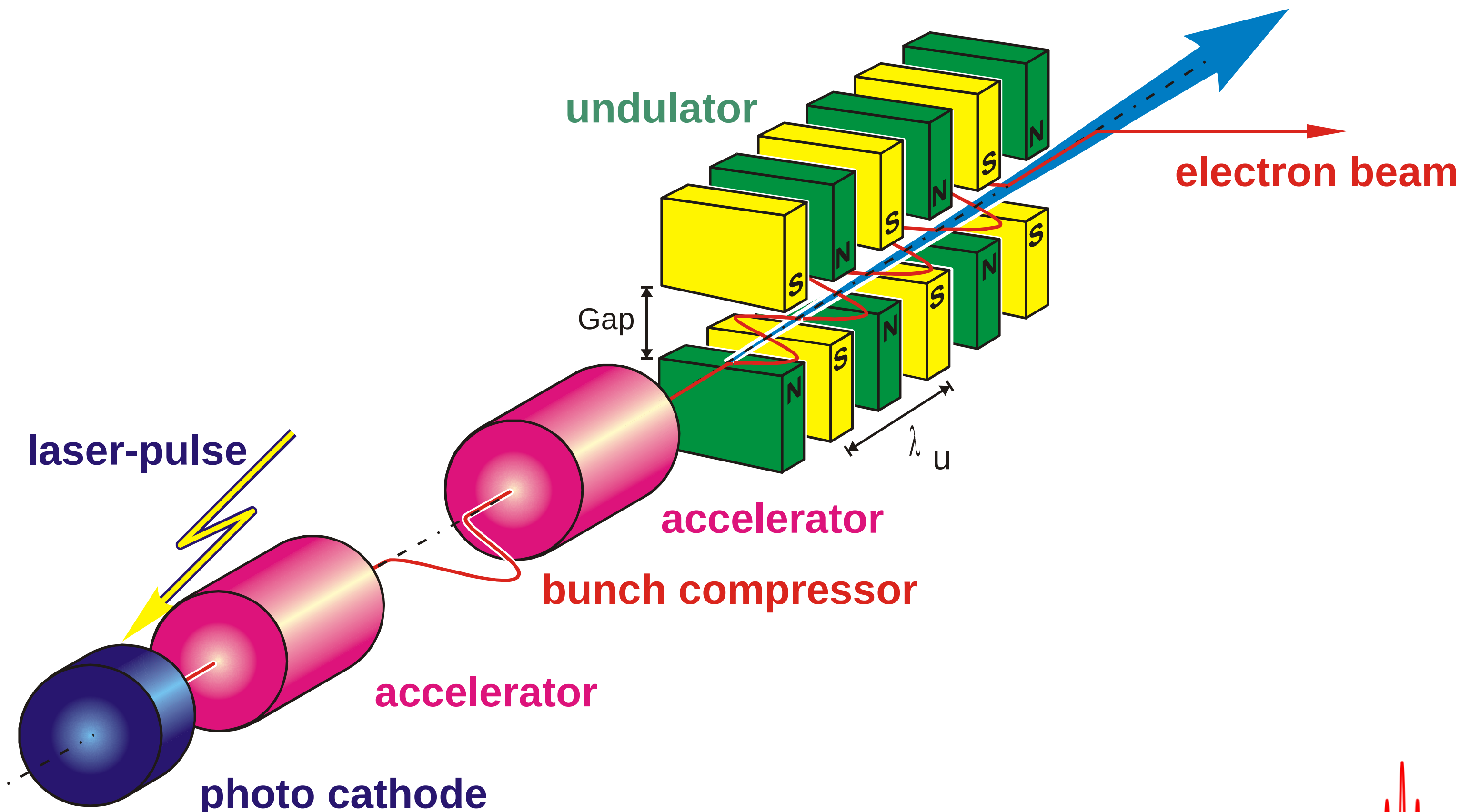


new direct insights into chemical, physical, biological mechanisms governing our daily-life

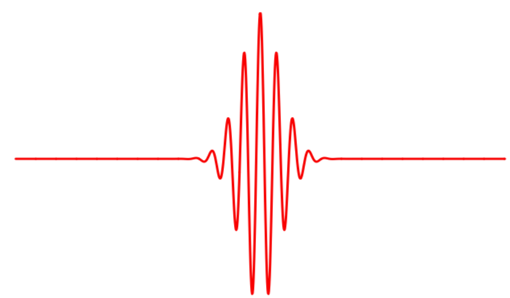
MOTIVATION

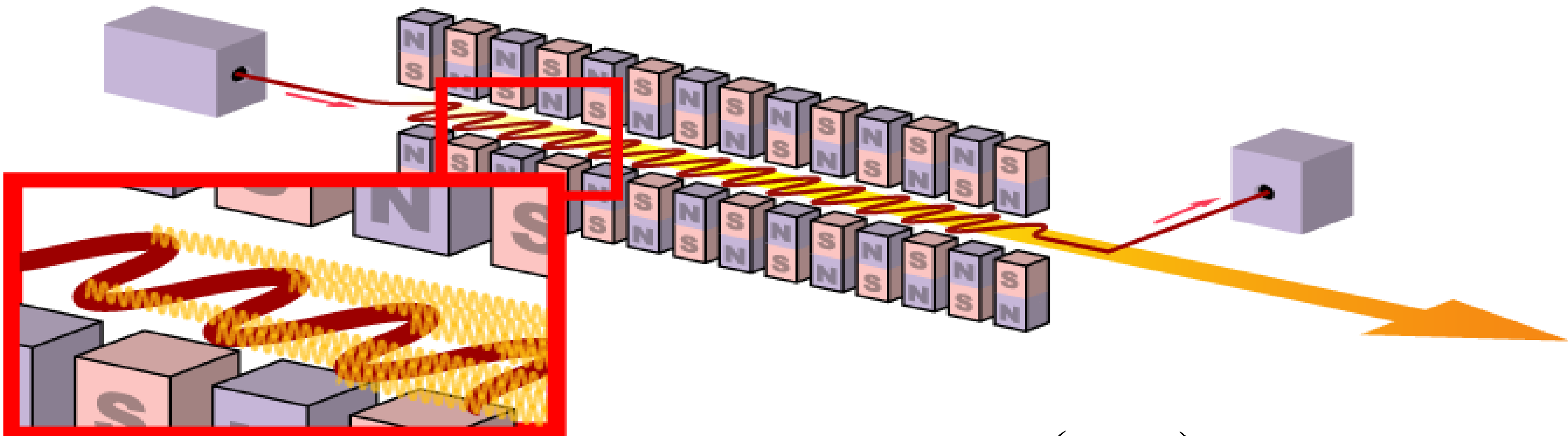
1. *Short wavelength* (0.1nm): atomic resolution
2. *Short pulses* (<20 fs – 2 fs): time-resolved measurements, avoid radiation damage
3. *Coherence*: lensless imaging
4. *High brilliance*: short (single-pulse „shot by shot“) measurements

FEL Basic Design



XFEL: fine and fast $\lambda = 0.1$ nm, $\tau = 10$ fs



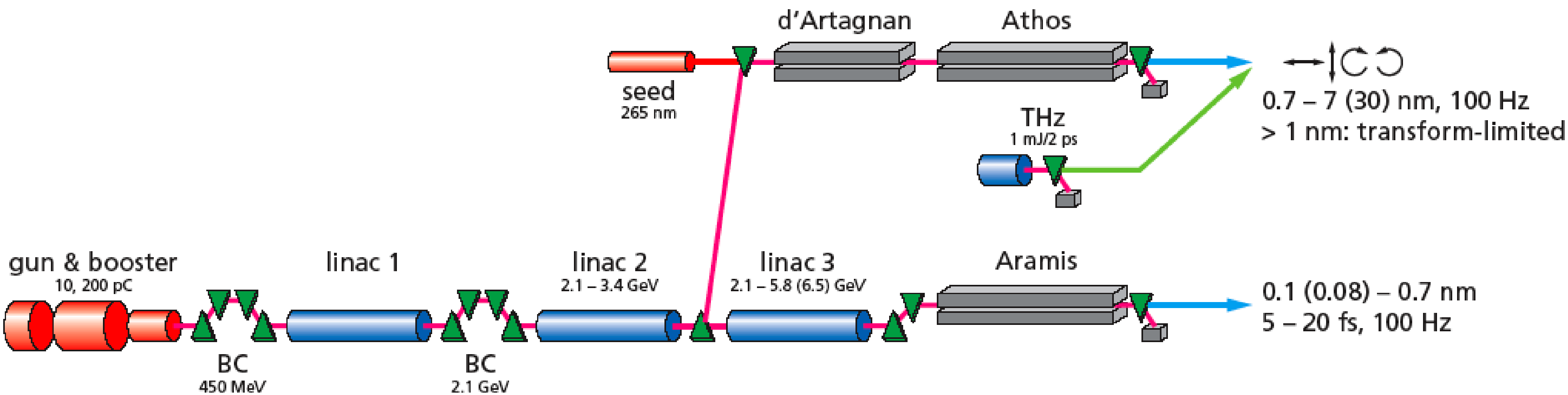


$$\lambda = \frac{\lambda_U}{2\gamma^2}\left(1+\frac{K^2}{2}\right)$$

$$\varepsilon_N \approx \gamma \frac{\lambda}{4\pi}$$

$$N_{\text{€}} \propto \gamma$$

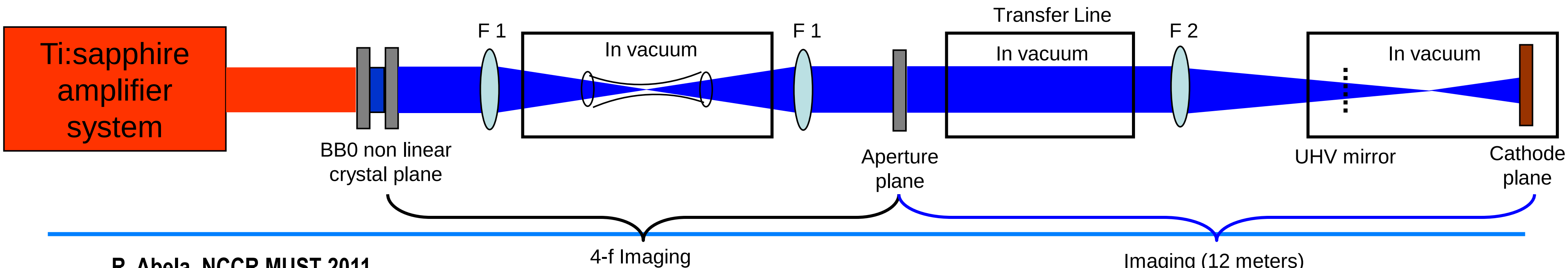
The SwissFEL



- hν: Mg L-edge (50 eV) - ^{57}Fe Mössbauer resonance (14.4 keV)
- Soft X-rays: circular polarization, transform-limited (seeding)
- Hard X-rays: 5-20 fs (low-charge mode)
- Synchronized THz pump source
- 100 Hz repetition rate ⇒ condensed matter applications

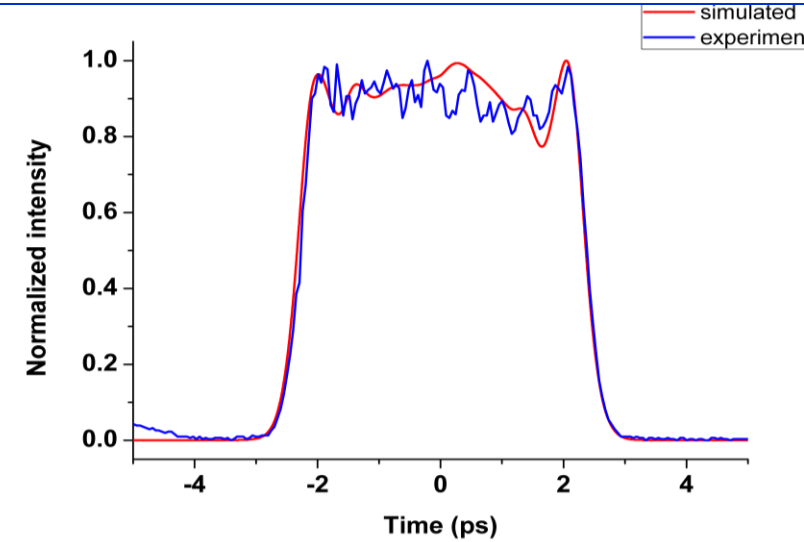
Photocathode Laser Requirements for SwissFEL

Gun Laser specifications	
Maximum pulse energy on cathode	up to 30 µJ
Central wavelength	250-300 nm
Bandwidth (FWHM)	1-2 nm
Pulse repetition rate	100 Hz
Double-pulse operation	yes
Delay between double pulses	50 ns
Laser spot size on cathode (rms) (10 pC / 200 pC)	0.1 / 0.27 mm
Minimum pulse rise-time	< 0.7 ps
Pulse duration (FWHM)	3-10 ps
Longitudinal intensity profile	flattop
Transverse intensity profile	flattop
Laser-to-RF phase jitter on cathode (rms)	<10 fs
UV pulse energy fluctuation	< 0.5% rms
Pointing stability on cathode	<3 µm



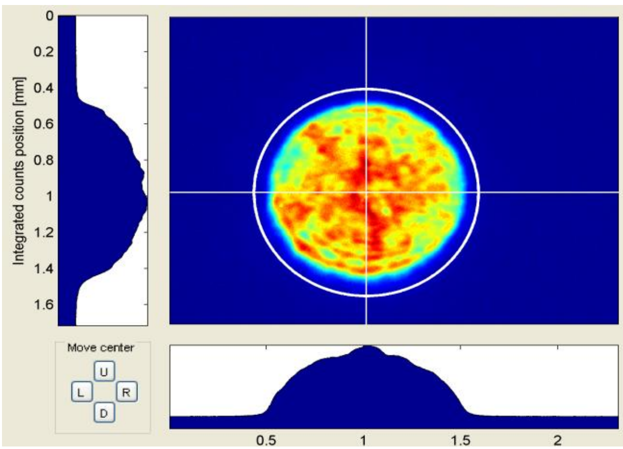
Photocathode Laser Requirements for SwissFEL

temporal flattop



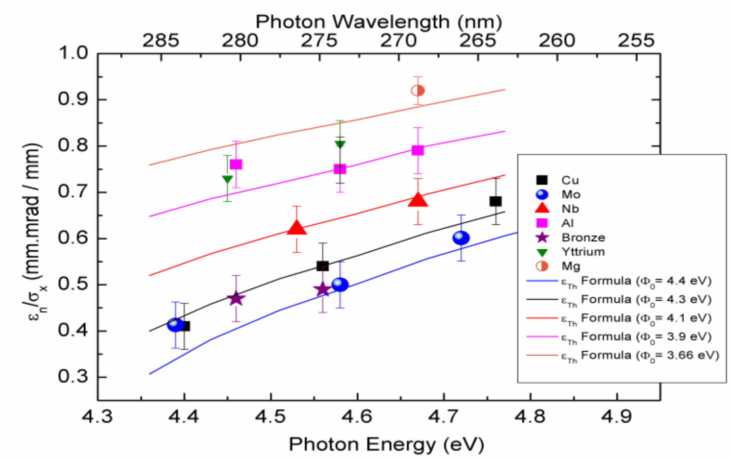
Trisorio et al. Appl. Phys. B 105, 255 (2011)

transverse flattop



On the cathode

low intrinsic emittance

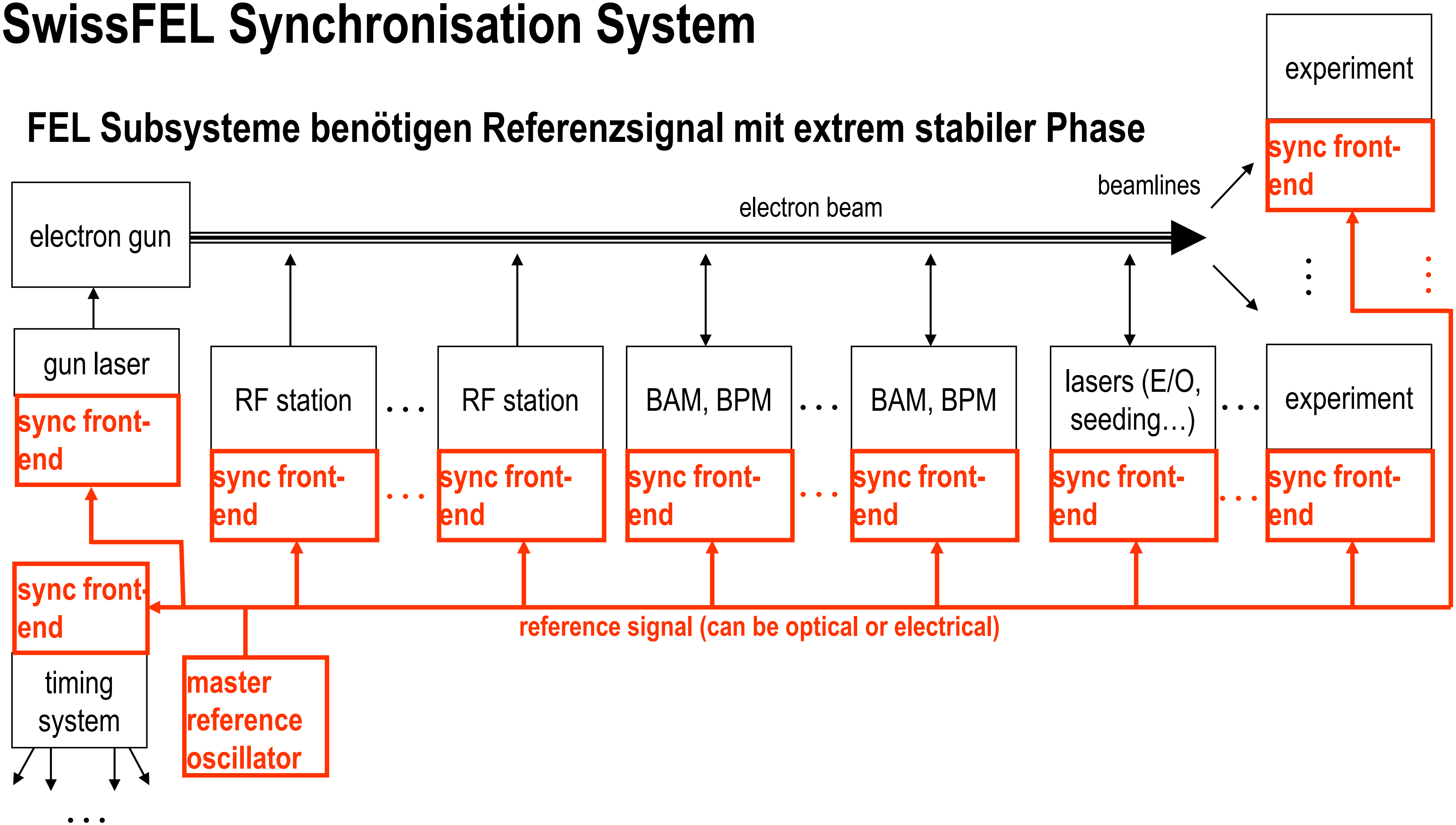


... a challenge for deep UV radiation

Hauri et al., PRL 104, 234802 (2010)

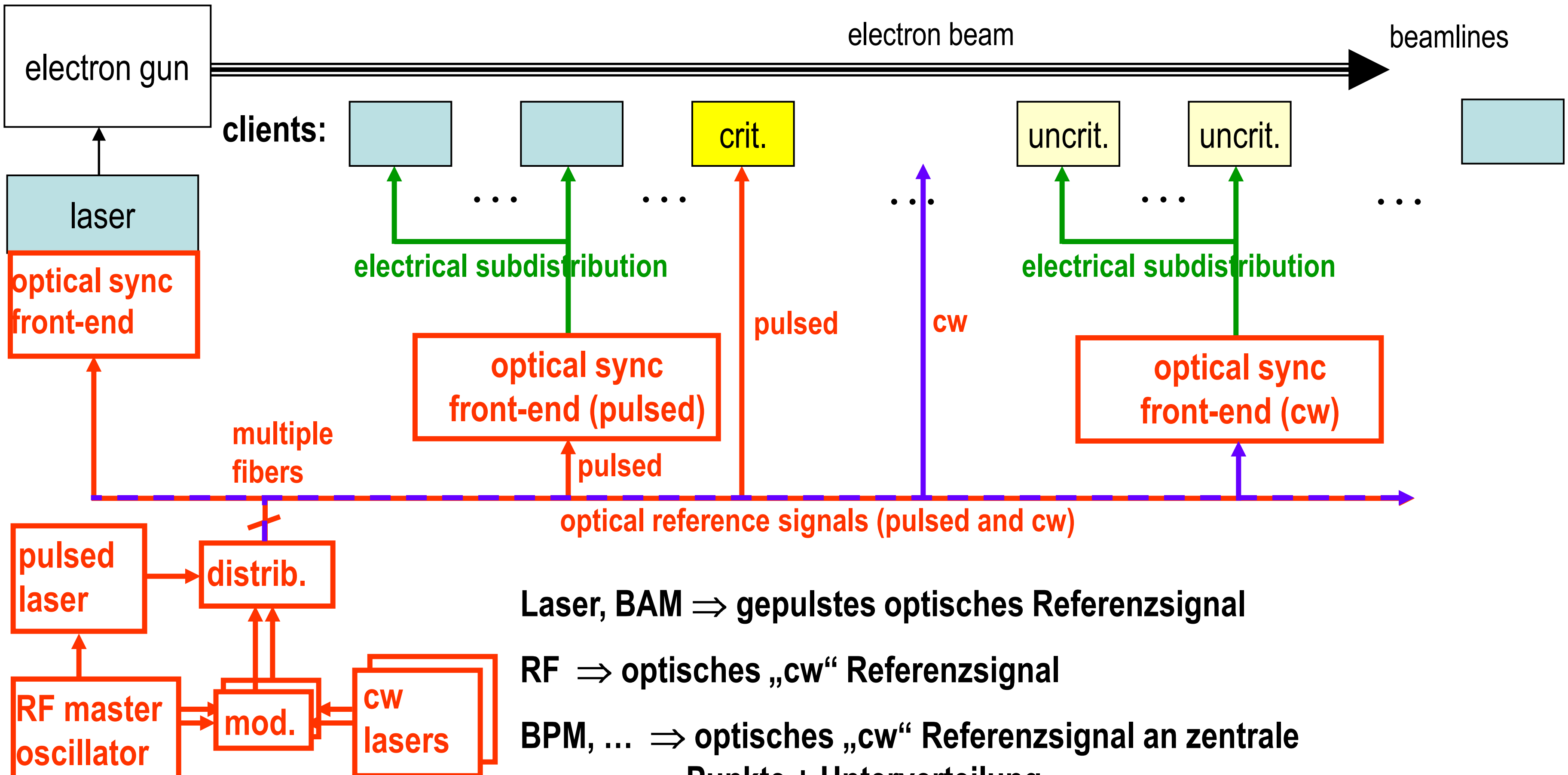
SwissFEL Synchronisation System

FEL Subsysteme benötigen Referenzsignal mit extrem stabiler Phase



Hybrid-Layout für SwissFEL

Unterverteilungen für weniger krit. Klienten



Laser, BAM ⇒ gepulstes optisches Referenzsignal

RF ⇒ optisches „cw“ Referenzsignal

BPM, … ⇒ optisches „cw“ Referenzsignal an zentrale Punkte + Unterverteilung

Pump and Probe Measurements

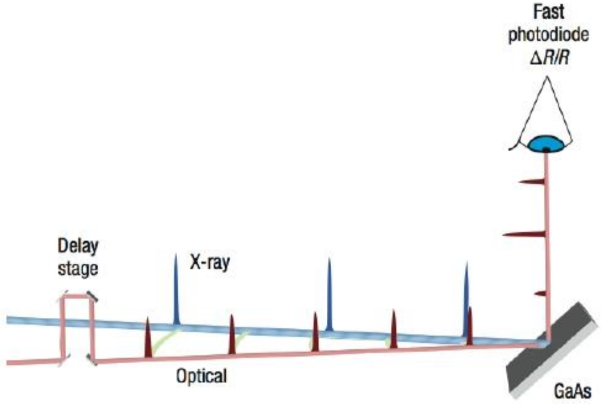
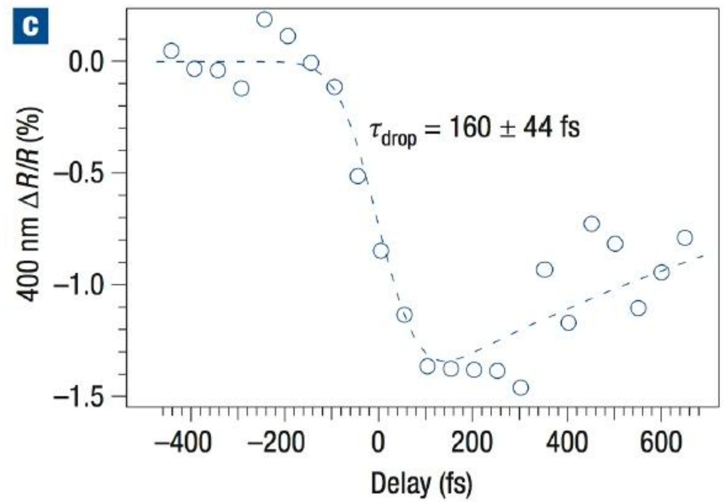


Figure 1 Transient X-ray-induced optical reflectivity ($\Delta R/R$) measurement: schematic overview. Extreme-UV FEL pulses (39.5 eV, <50 fs, <16 μJ)



Gahl, C. *et al. A femtosecond X-ray/optical cross-correlator. Nature Photon.* ***2, 165–169 (2008).***

Pump and Probe Measurements

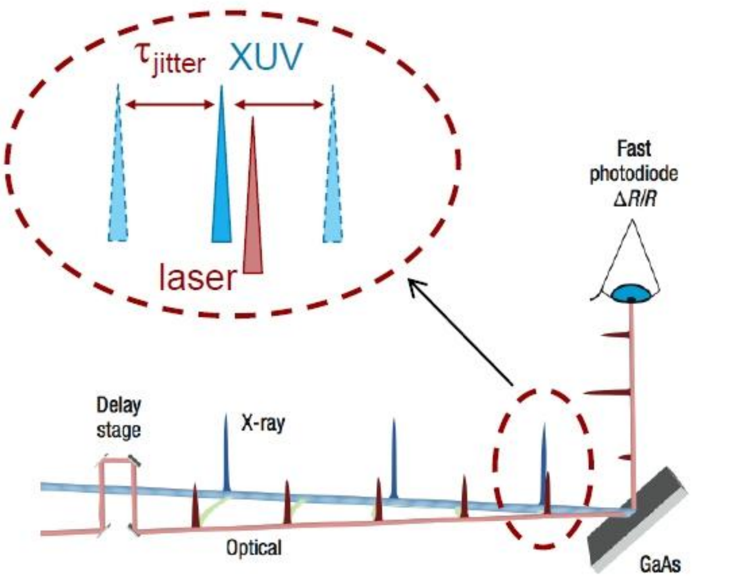
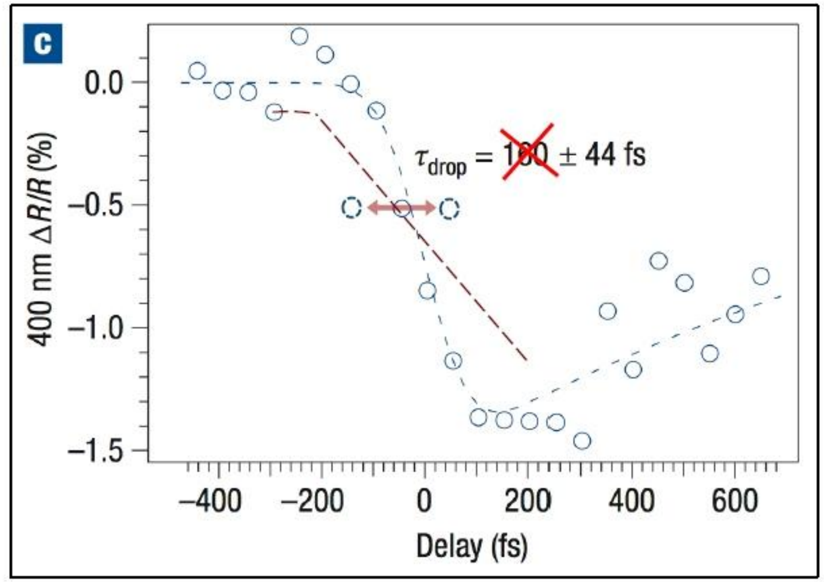
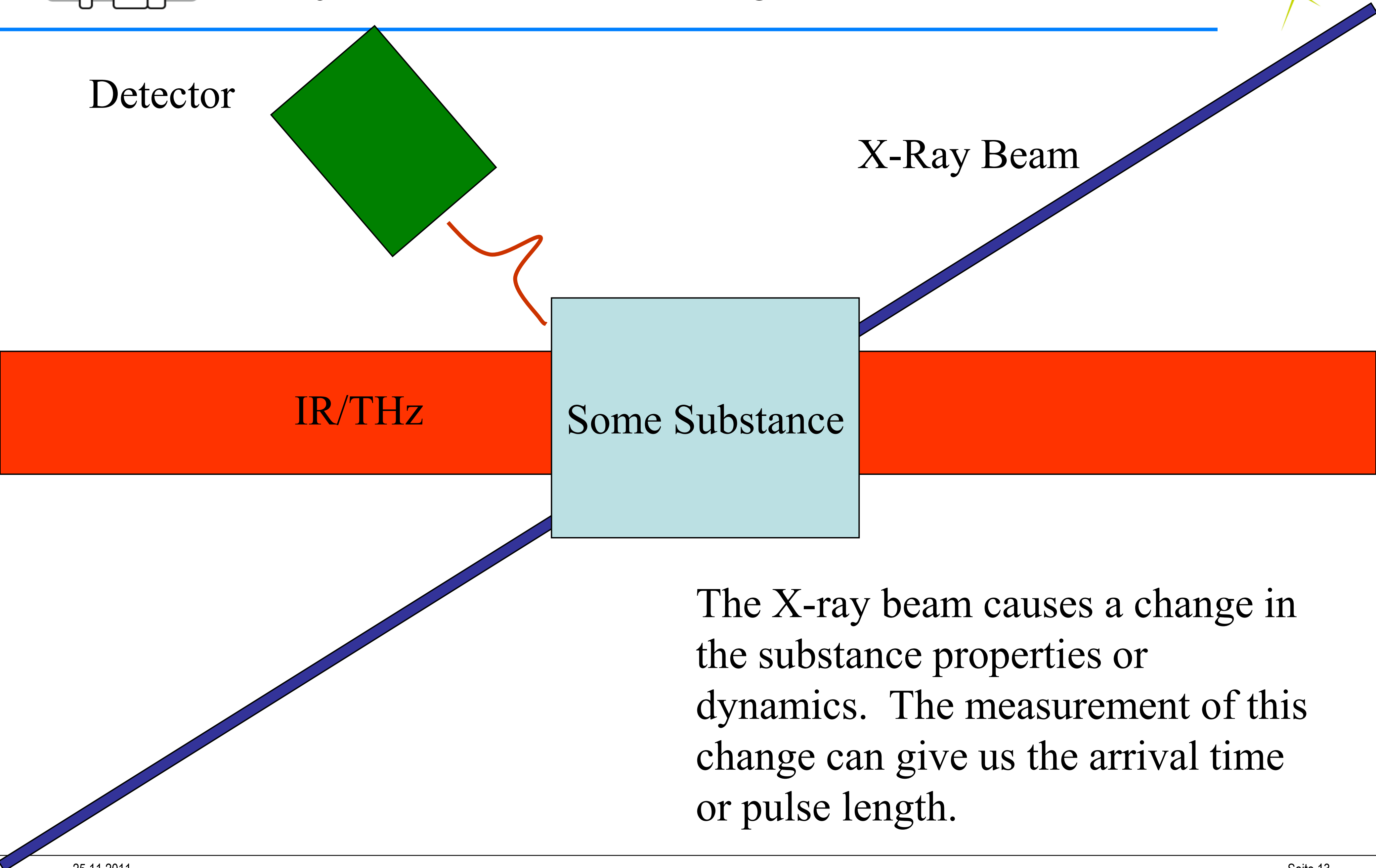


Figure 1 Transient X-ray-induced optical reflectivity ($\Delta R/R$) measurement: schematic overview. Extreme-UV FEL pulses (39.5 eV, <50 fs, <16 μJ)



Gahl, C. *et al. A femtosecond X-ray/optical cross-correlator. Nature Photon.* ***2, 165–169 (2008).***

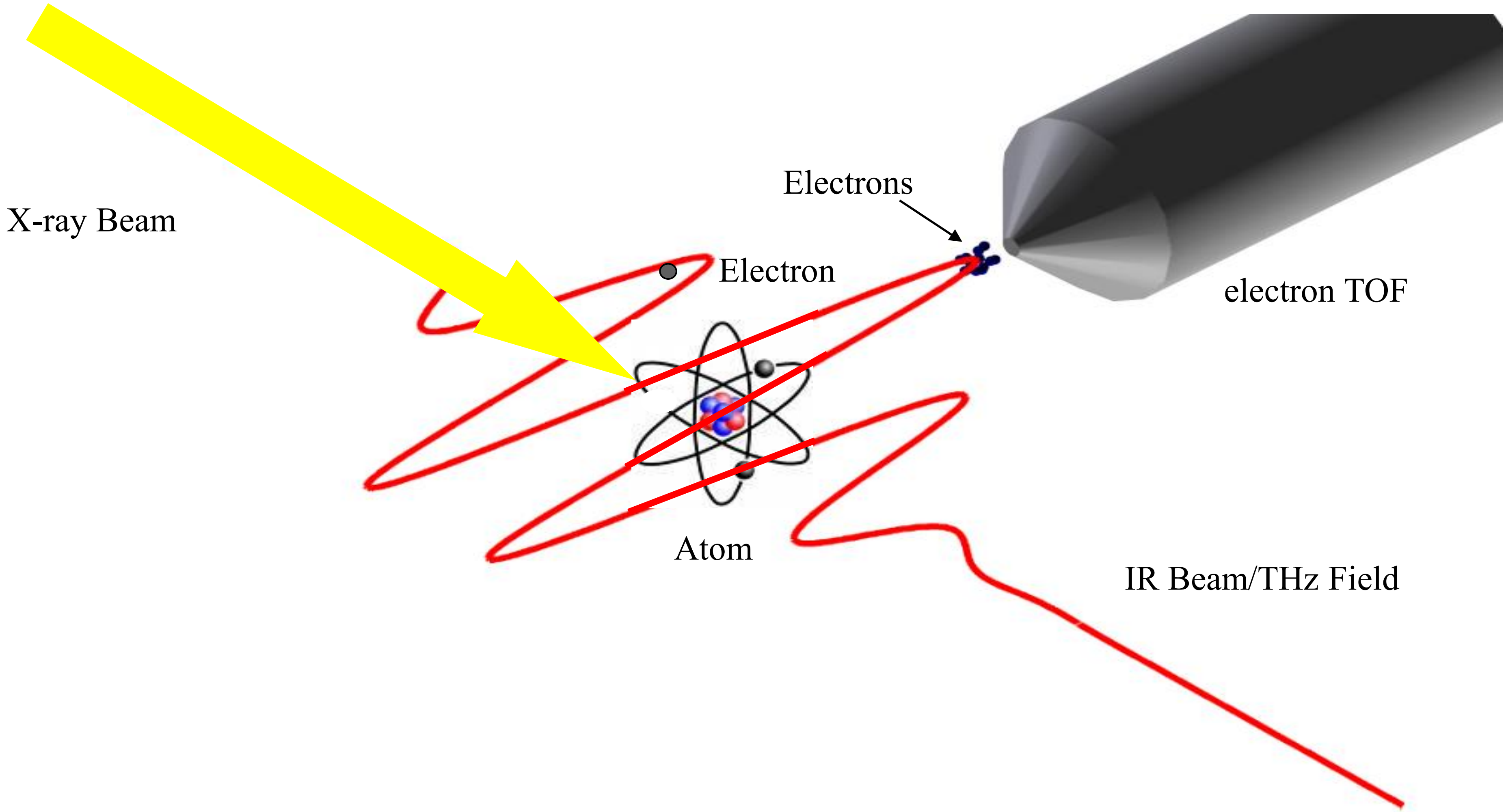
X-Ray Arrival Time and Pulse Length Measurement Concepts



The X-ray beam causes a change in the substance properties or dynamics. The measurement of this change can give us the arrival time or pulse length.

Pulse Arrival Time and Pulse Length

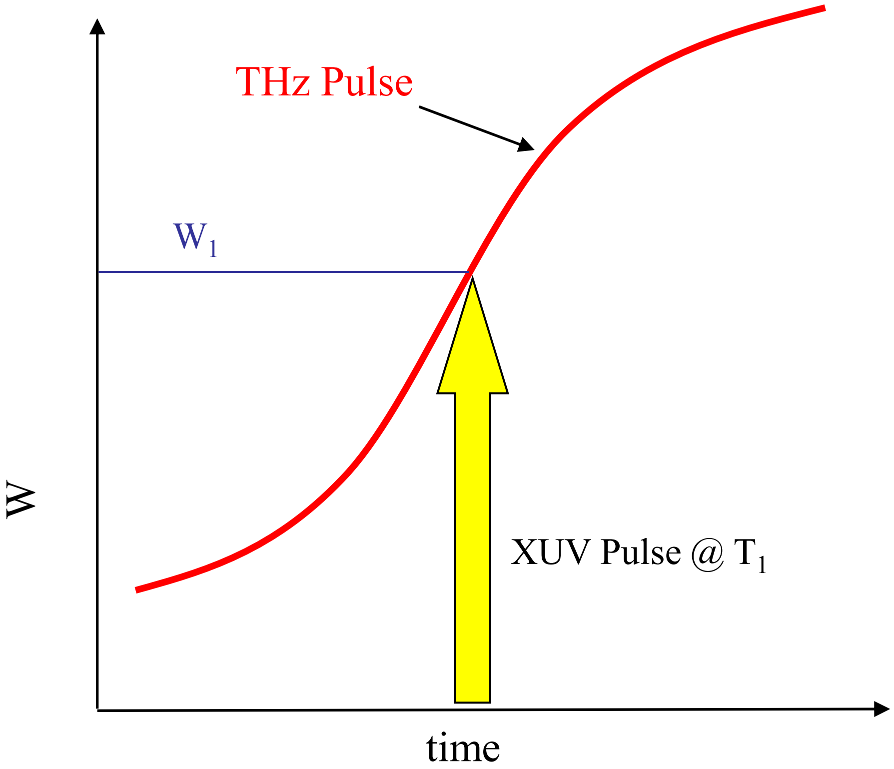
- Use a THz streak camera concept to measure the arrival time and length of the photon pulse.



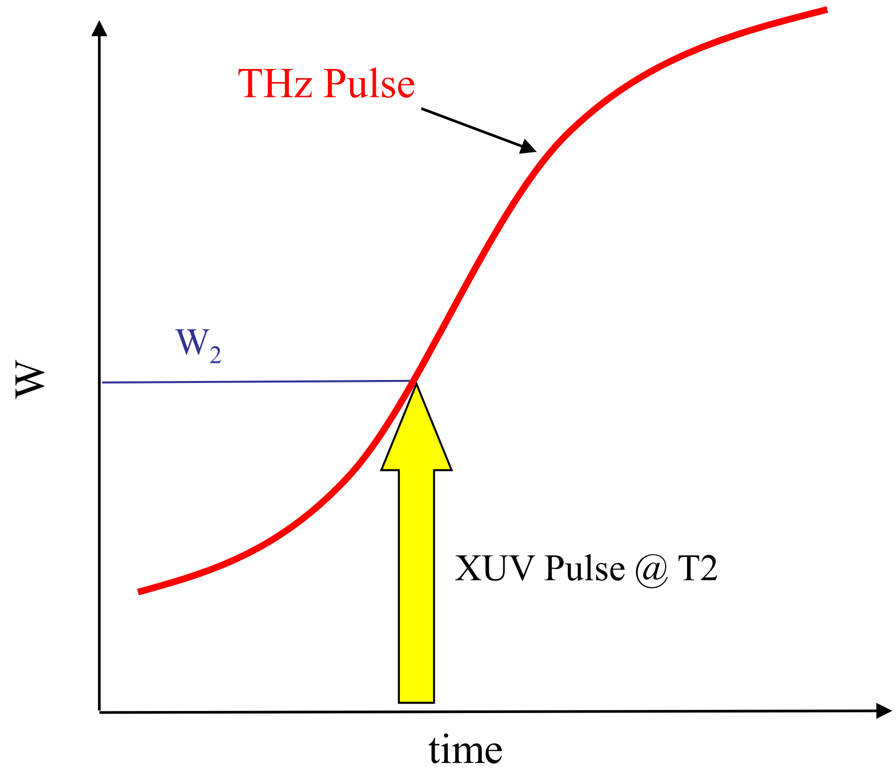
$$KE_{electron} = E_{photon} - \text{Binding Energy} \quad \pm W$$

Pulse Arrival Time and Pulse Length Measurements

XUV Pulse 1:



XUV Pulse 2:



$W_2 - W_1 \Rightarrow T_2 - T_1$

Past Results for Pulse Length at FLASH

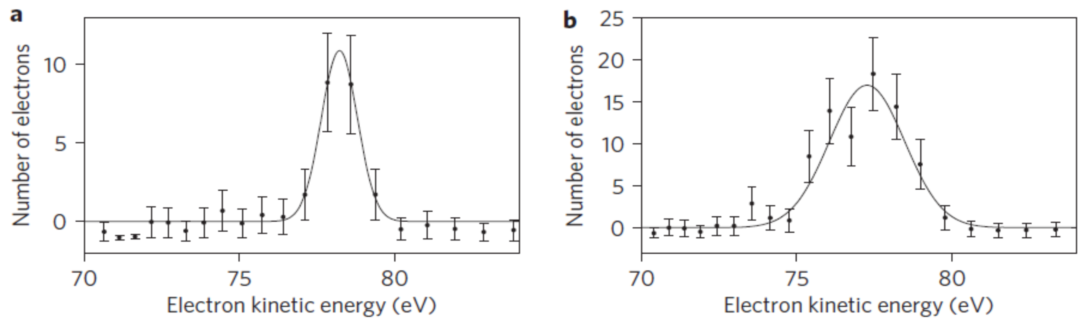


Figure 5 | Single-shot photoelectron spectra. a,**b**, Non-streaked (**a**) and streaked (**b**) single-shot photoelectron spectra with fitted Gaussian curves. The smooth profile with no observable substructure is typical for 90% of the spectra acquired in this work. The vertical bars indicate the statistical error given by the number of electrons detected within a 0.7-eV-wide kinetic energy bin.

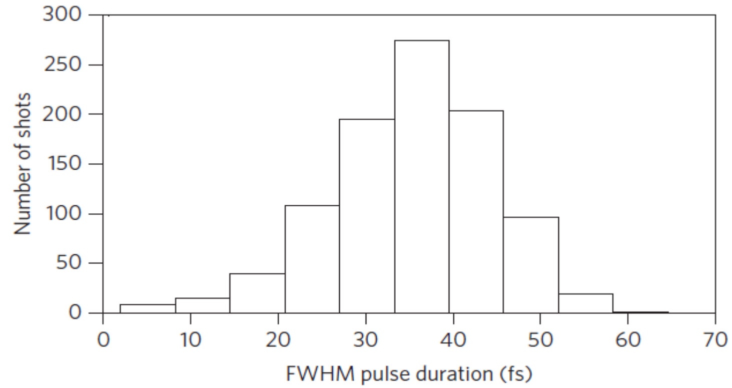
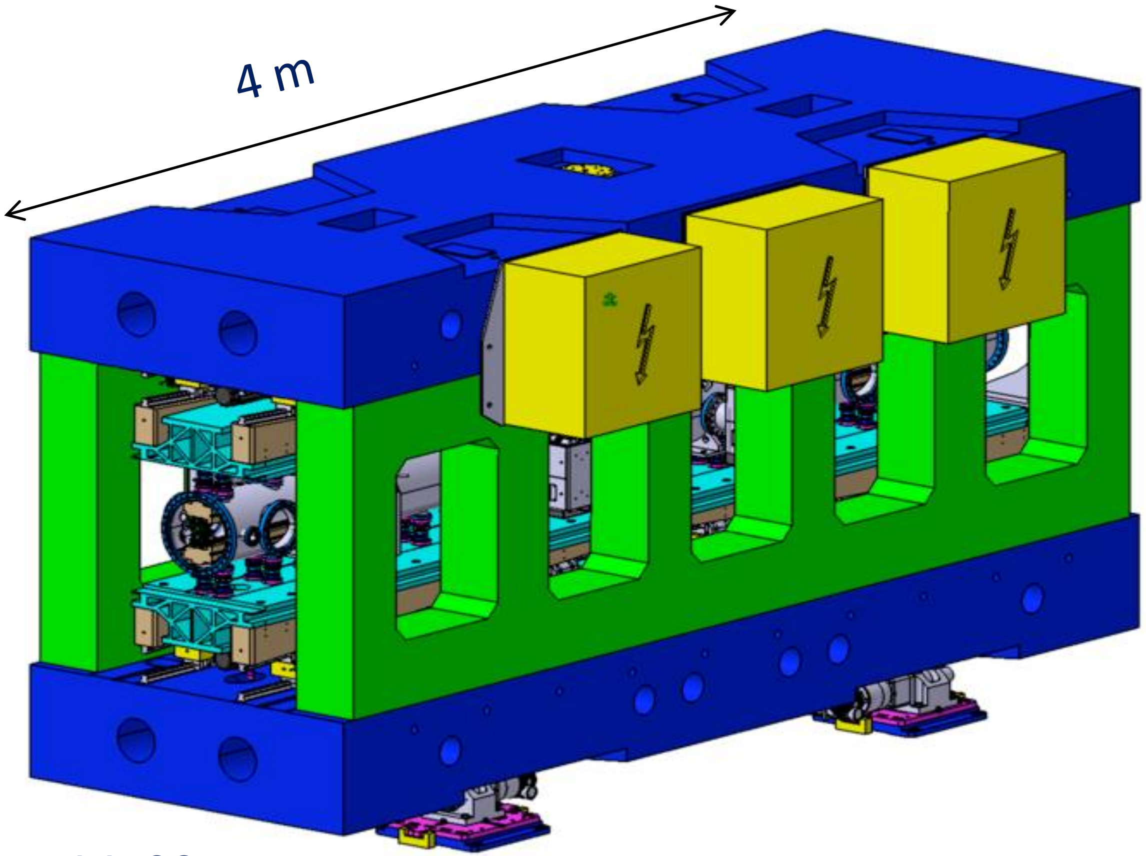
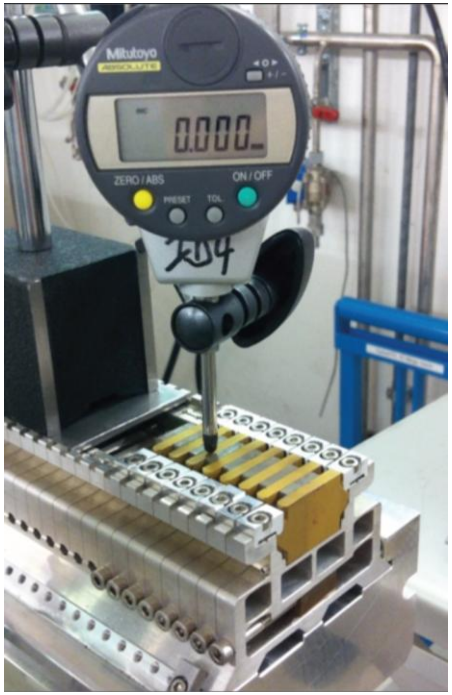


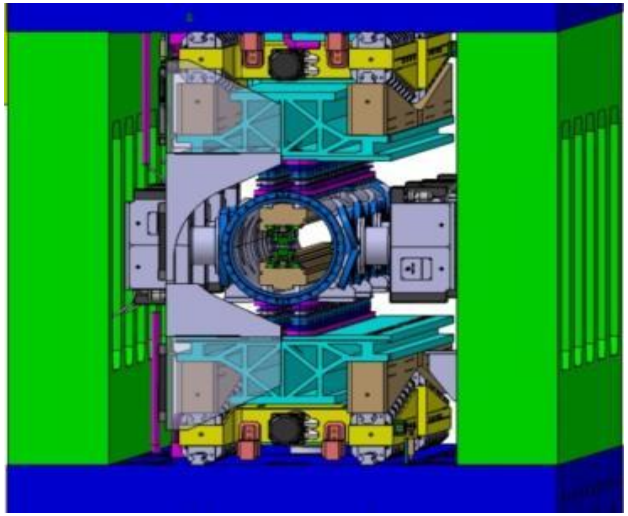
Figure 4 | Histogram of reconstructed pulse durations. Distribution of full-width at half-maximum (FWHM) durations of 13.5-nm pulses from FLASH, reconstructed from 1,000 individual shots by an analysis considering a Gaussian pulse profile.

U. Fruehling et al., Nature Photonics **3**, 523 (2009)

ARAMIS Undulator





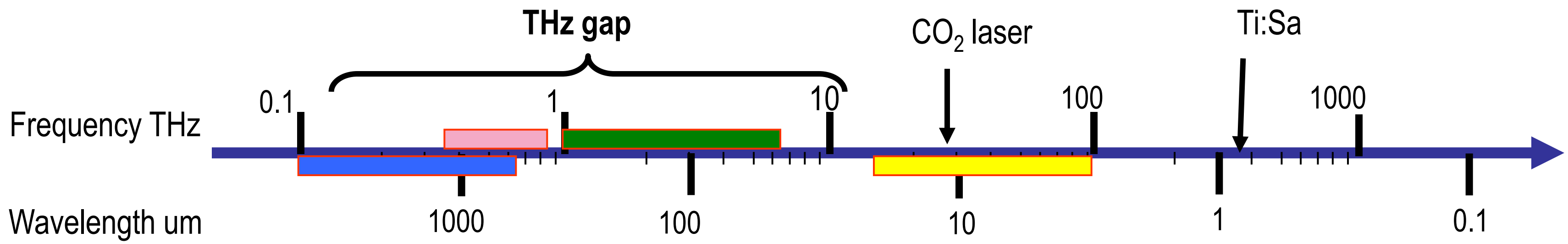


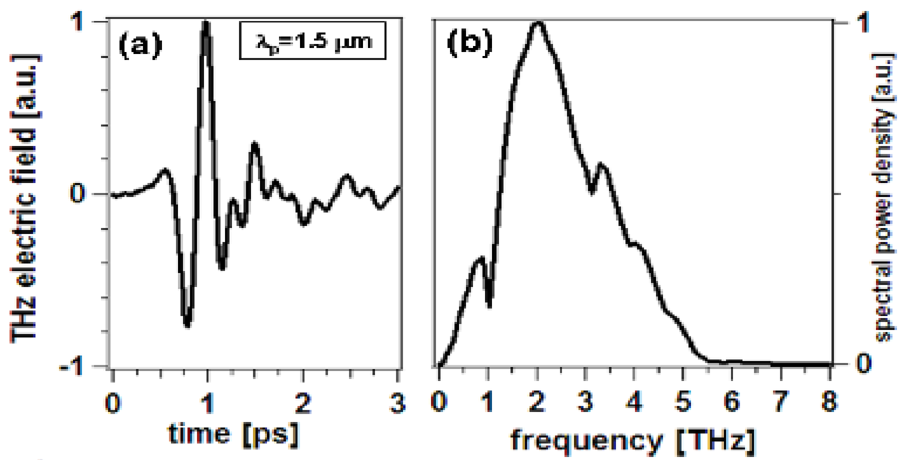
M=23 t

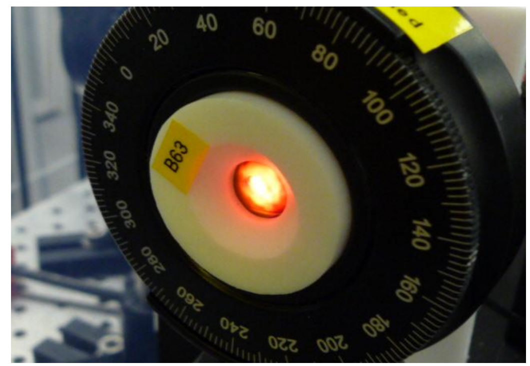
12 x für ARAMIS

First prototype: Dec. 2012

Laser-based THz source at PSI – R&D for SwissFEL



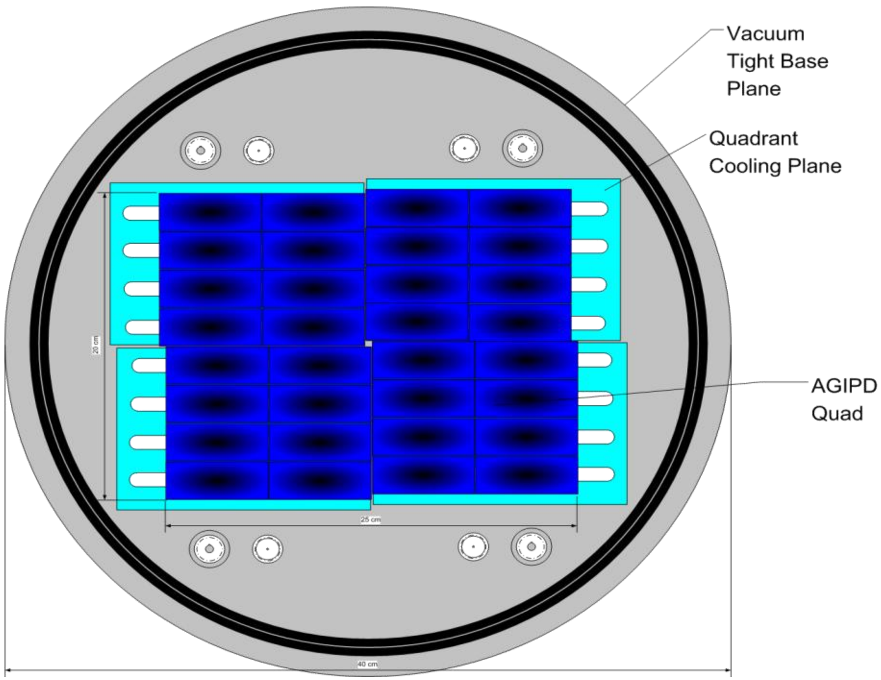




- **45 uJ THz pulse energy produced in DAST at 2.5 THz**
- **up to 2 MV/cm (or 0.6 Tesla)**
- **carrier-envelope phase stable electromagnetic fields**
- **good THz pulse energy stability (0.8% rms)**

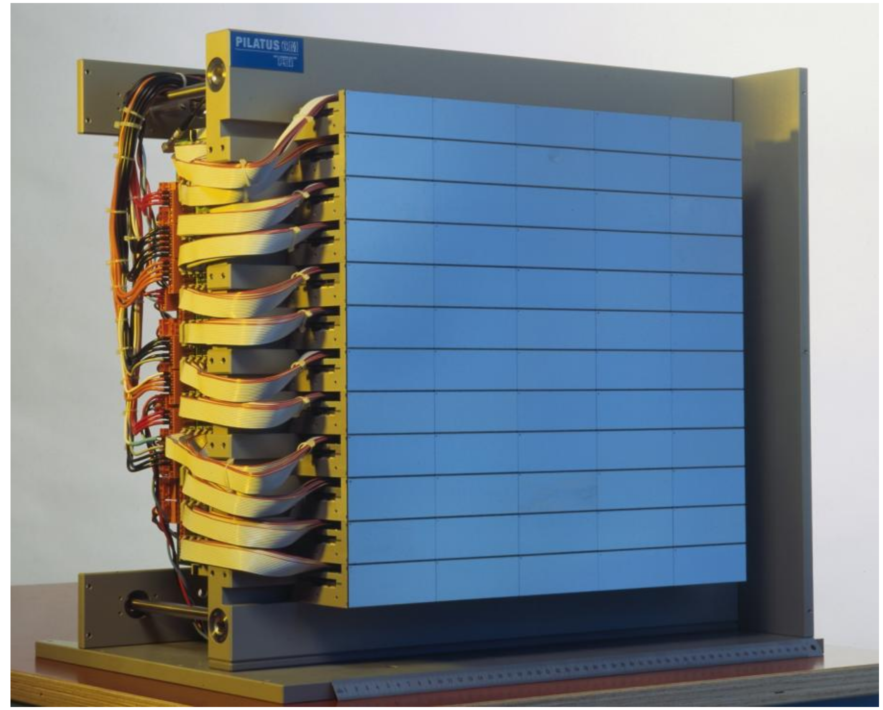
Hauri et al. APL 99, 161116 (2011)

Detector Development



PIXEL Detector for

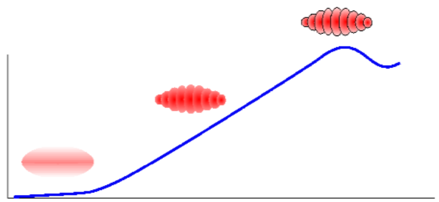
European XFEL AGIPD
SwissFEL

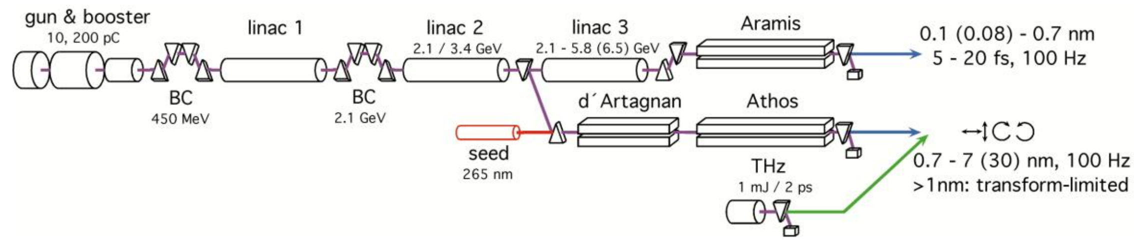


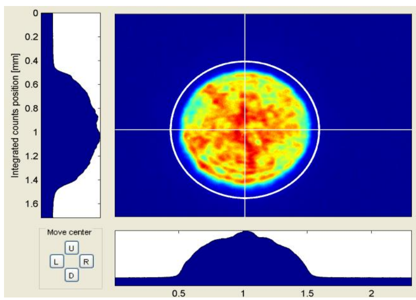
PIXEL Detector at the SLS

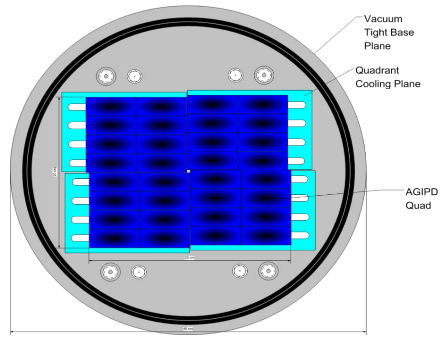
Proposed location on PSI - east site

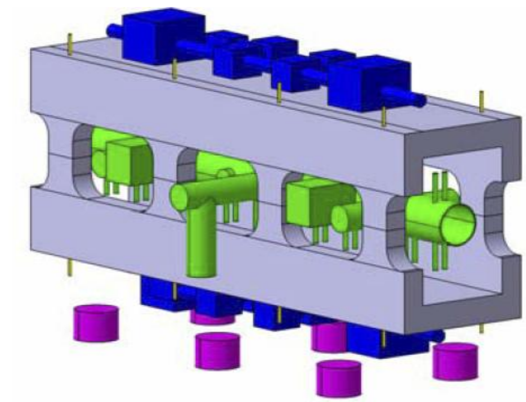
SUMMARY




gun & booster
10, 200 pC
BC
450 MeV
linac 1
BC
2.1 GeV
linac 2
2.1 / 3.4 GeV
linac 3
2.1 - 5.8 (6.5) GeV
Aramis
0.1 (0.08) - 0.7 nm
5 - 20 fs, 100 Hz
d´Artagnan
Athos
seed
265 nm
THz
1 mJ / 2 ps
0.7 - 7 (30) nm, 100 Hz
>1nm: transform-limited

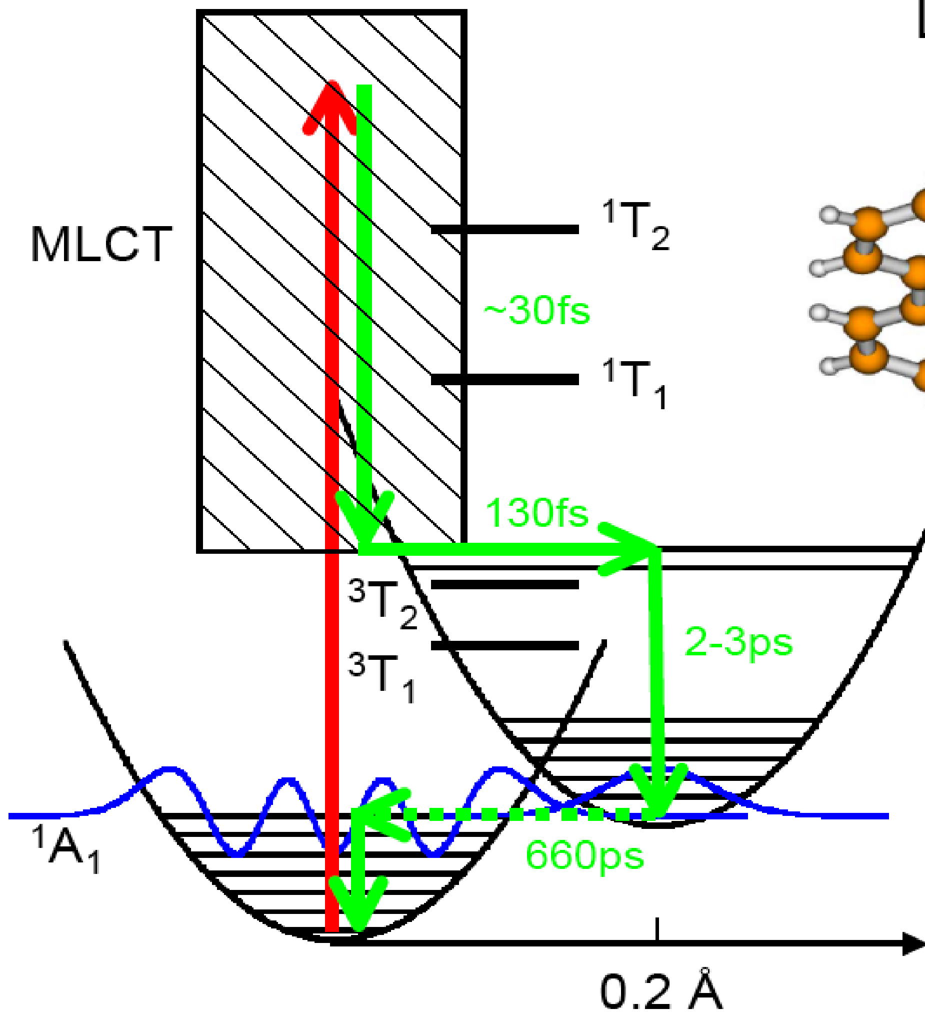

Integrated counts position [mm]
Move center
U
L
R
D


Vacuum Tight Base Plane
Quadrant Cooling Plane
AGIPD Quad

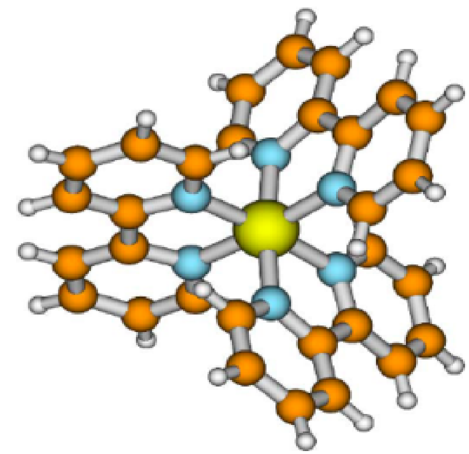


Photochemistry: Fundamental Steps

Iron tris-bipyridine photocycle



$[Fe^{II}(bpy)_3]^{2+}$



Model system for

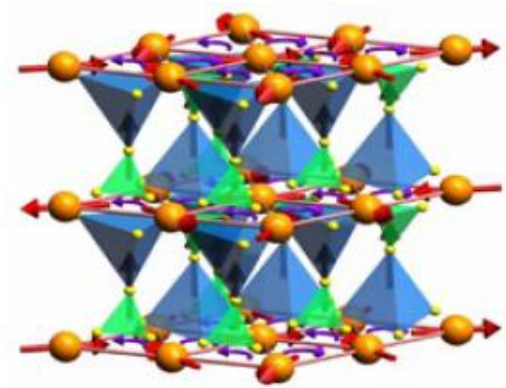
Biology: hemoglobin

Geochemistry

Solar Chemistry

Catalytic systems

Strong correlated electron systems



What is W?

Start off with the final velocity of the just-photoionized electron in the THz electric field:

$$v_f = v_0 + \frac{e}{m_e} A(t)$$

Where $E_{thz} = -\frac{dA}{dt}$ *A* being the vector potential of the electric field.

Knowing that $E_{thz} = E_0 \cos(\omega t + \phi)$

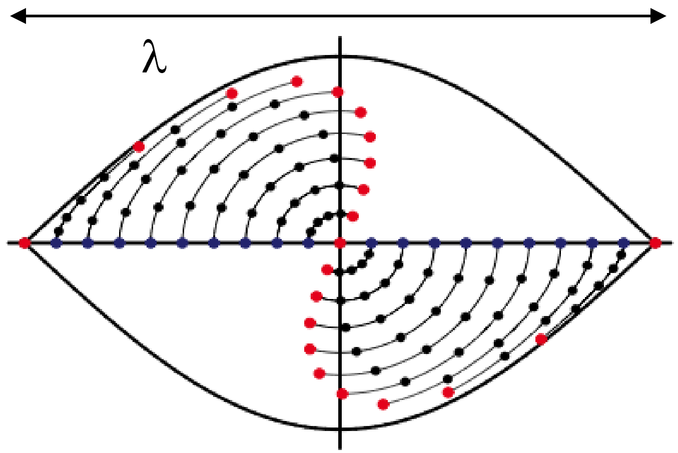
We get for the final kinetic energy of the electron:

$$K_f = K_0 + 2U_p \sin^2(\omega t + \phi) + \sqrt{K_0 U_p} \sin(\omega t + \phi) = W$$

(annotation: $2U_p \sin^2(\omega t + \phi)$ → 0)

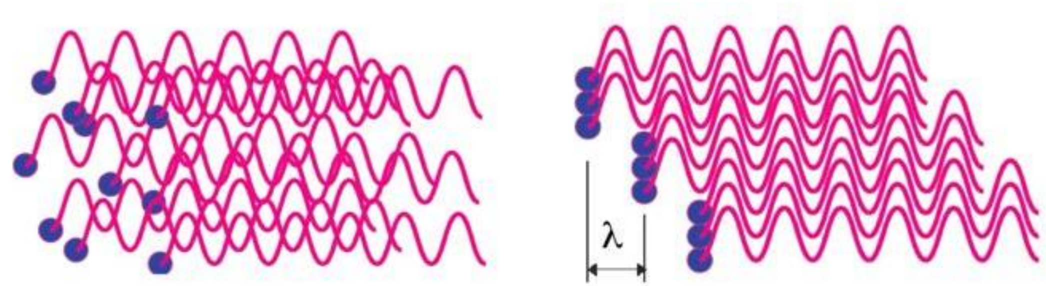
Where $U_p = \frac{e^2 E_0^2}{4 m_e \omega^2}$

Micro-bunching and coherent emission



Initially uniform e⁻ distribution (blue) evolves into microbunches (red).

Micro-bunches radiate coherently.

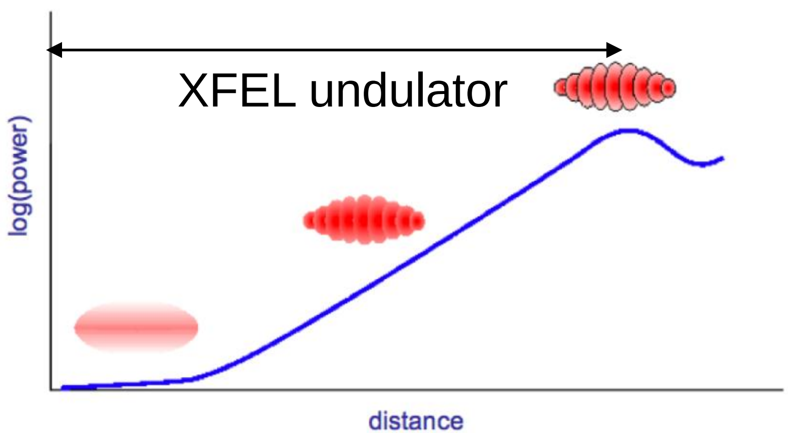


$$P_{incoh} = NP_1$$

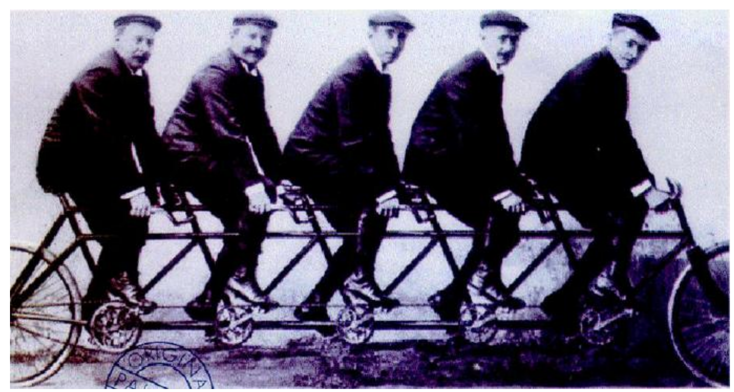
$$E = NE_1$$

$$P_{coh} = N^2 E_1^2 = NP_{incoh}$$

$$N \approx 10^9 \text{ !!}$$



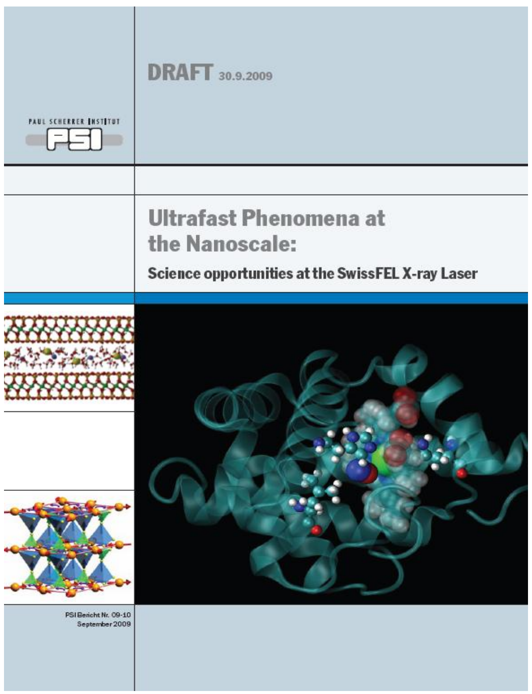
„Self-amplifying spontaneous emission“ (SASE)



The SwissFEL Scientific Case

Ultrafast Phenomena at the Nanoscale:

Science opportunities at the SwissFEL X-ray Laser



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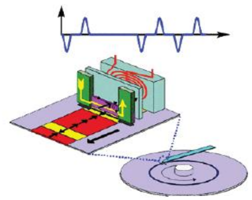
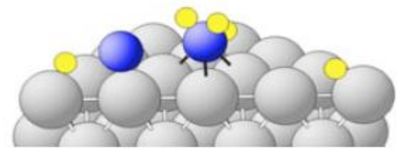
Scientific Challenges

Magnetism: materials and processes for tomorrow's information technology

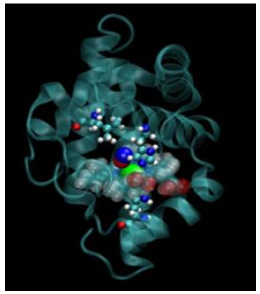


Catalysis and solution chemistry: for a clean environment and a sustainable energy supply

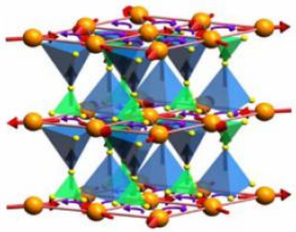


Coherent diffraction: flash photography of matter

Biochemistry:
shedding light on the processes of life

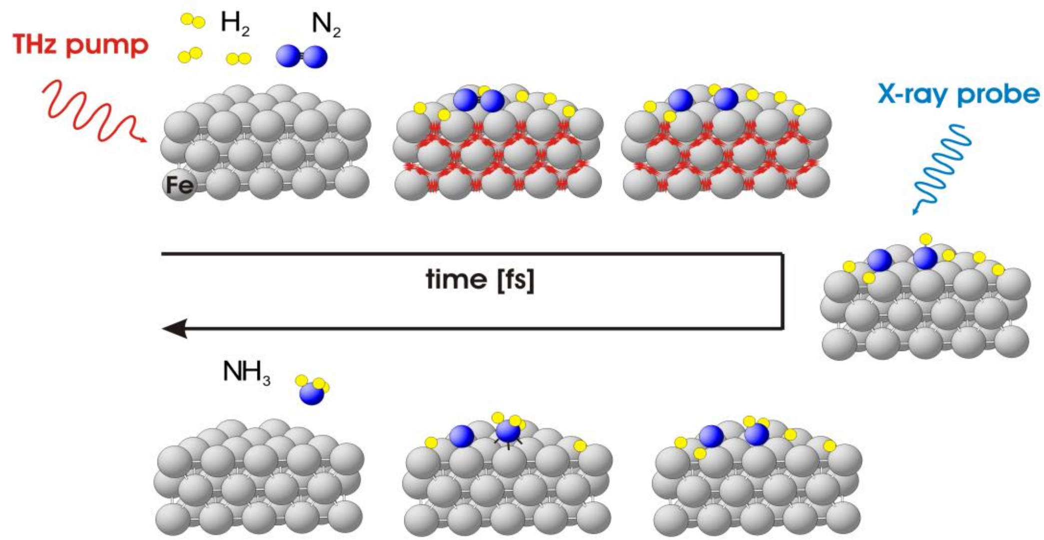


Correlated electrons:
the fascination of new materials



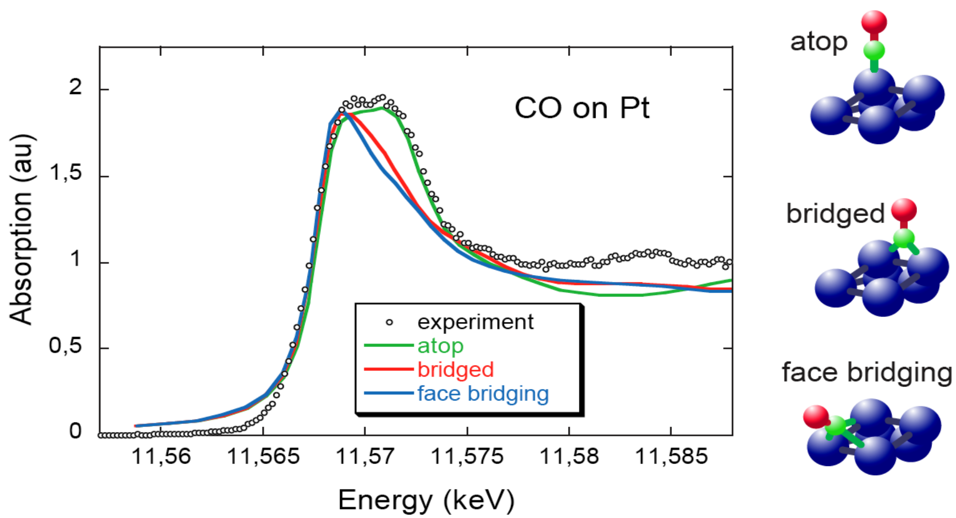
Pump-probe surface catalysis

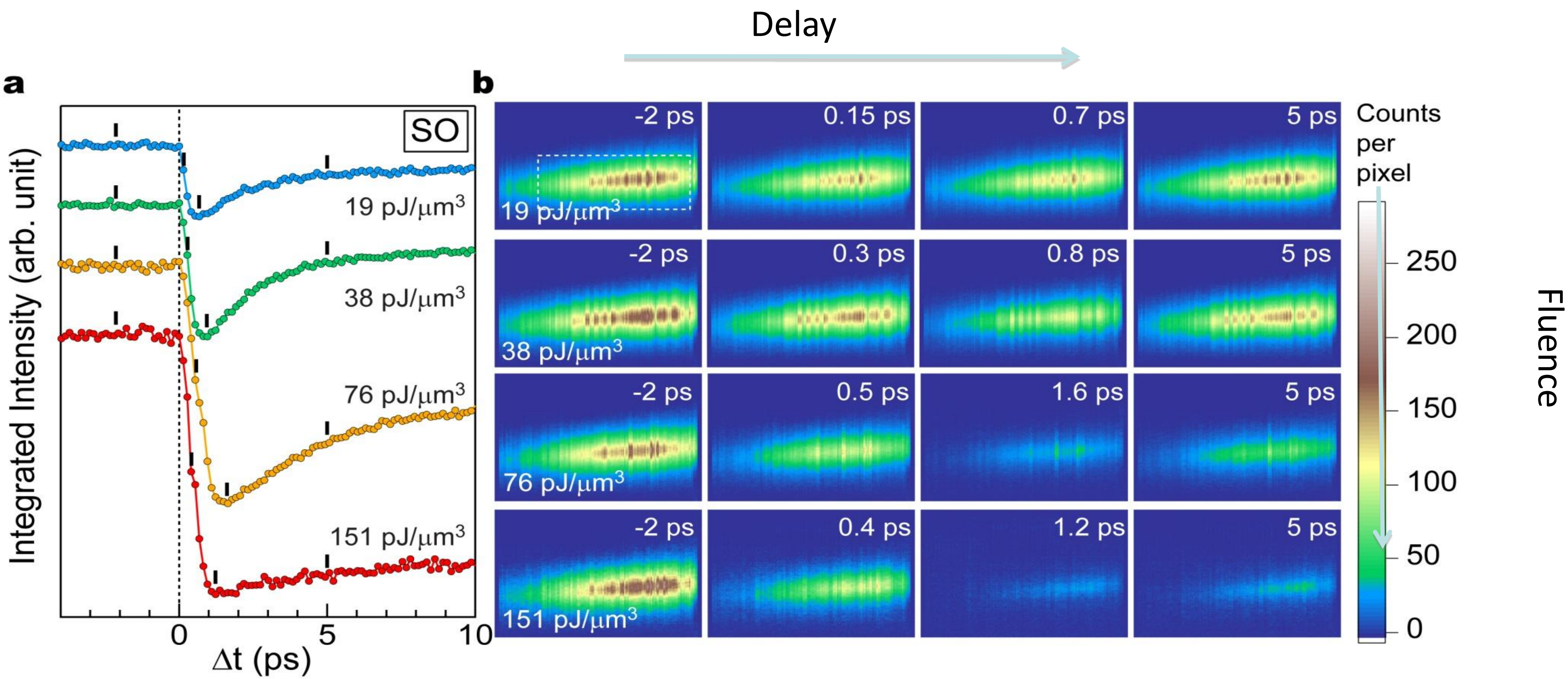
e.g., Haber-Bosch Process
$N_2+3H_2 \rightarrow 2NH_3$



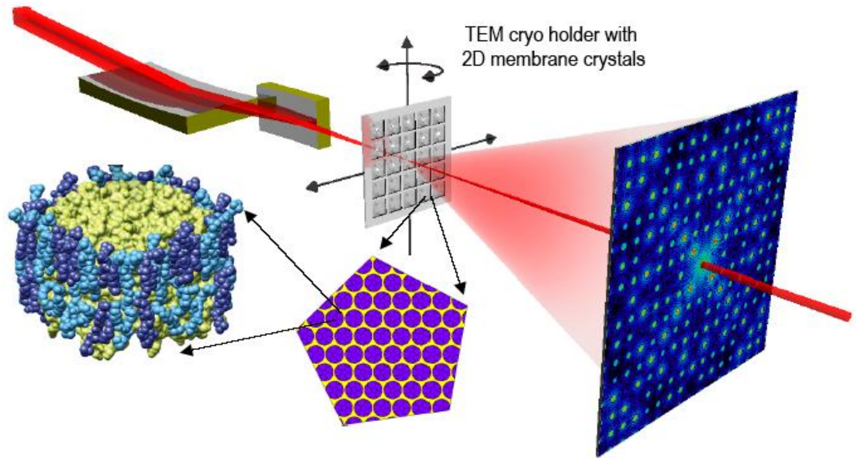
XANES (static)

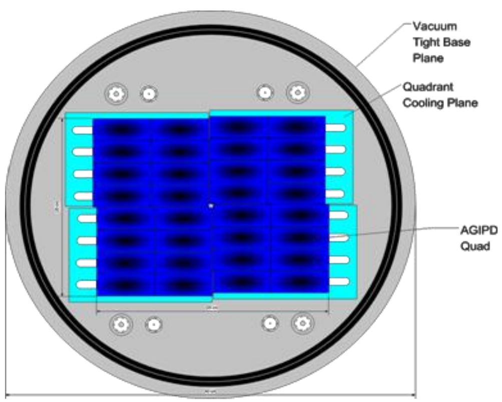
J. van Bokhoven (ETH)



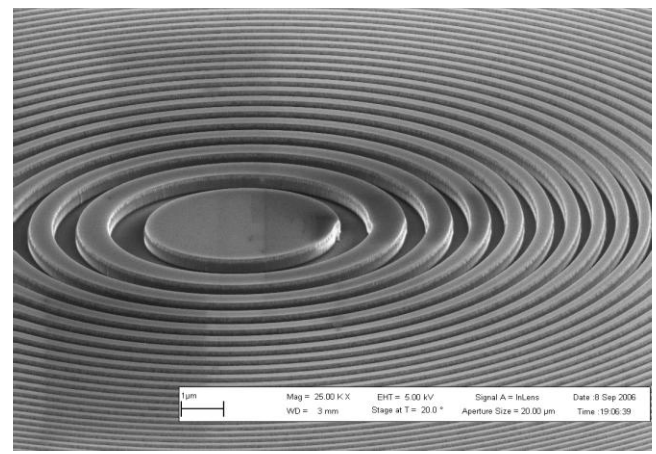

Delay
a
b
SO
Integrated Intensity (arb. unit)
19 pJ/μm³
38 pJ/μm³
76 pJ/μm³
151 pJ/μm³
0
5
10
Δt (ps)
-2 ps
0.15 ps
0.7 ps
5 ps
0.3 ps
0.8 ps
0.5 ps
1.6 ps
0.4 ps
1.2 ps
Counts per pixel
250
200
150
100
50
0
Fluence

Crystallography ??????????





PIXEL Detektor für SwissFEL



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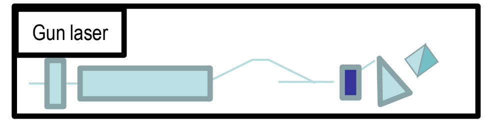
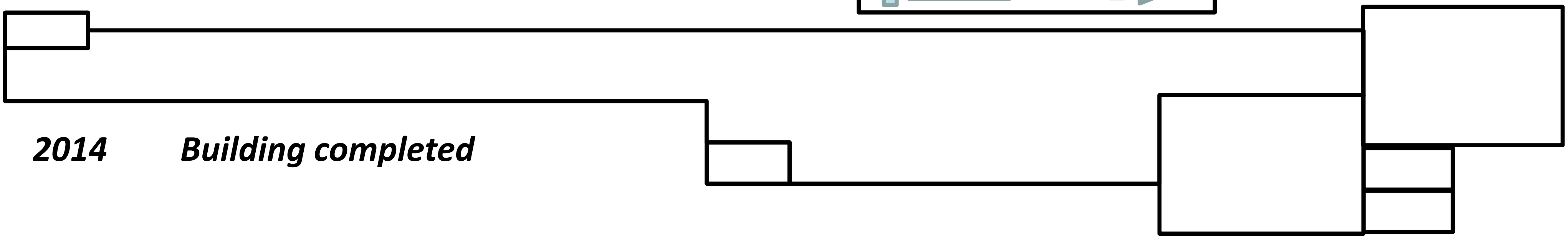
SwissFEL Phasing

must

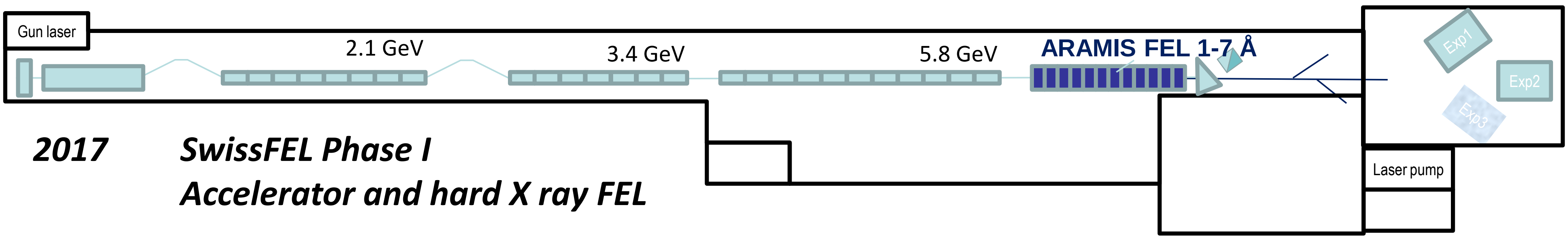
2010   250 MeV Injector facility



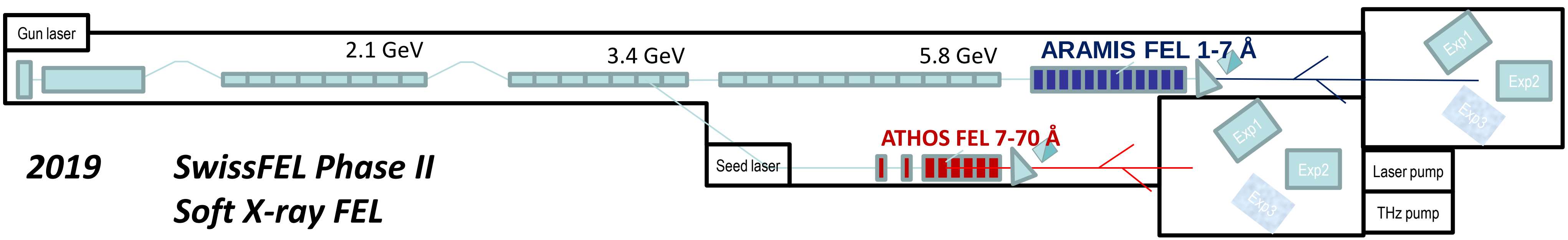
2014   Building completed



2017   SwissFEL Phase I
Accelerator and hard X ray FEL



2019   SwissFEL Phase II
Soft X-ray FEL



Budget

Quelle	Betrag	Anmerkungen
ETH Bereich	20 MCHF	Zugesagt für 2012
EDI Department	9 MCHF	Zugesagt für 2012
Kanton Aargau (Lotterie Font)	30 MCHF	Zugesagt 6 MCHF/y 2012-16
CH Bundesmittel	157 MCH	Parlamentsentscheid 2012 Zeitraum 2013-16
PSI budget	60 MCHF	8 MCHF/y 2012 13 MCHF/y 2013-16
Total	**276 MCHF**	

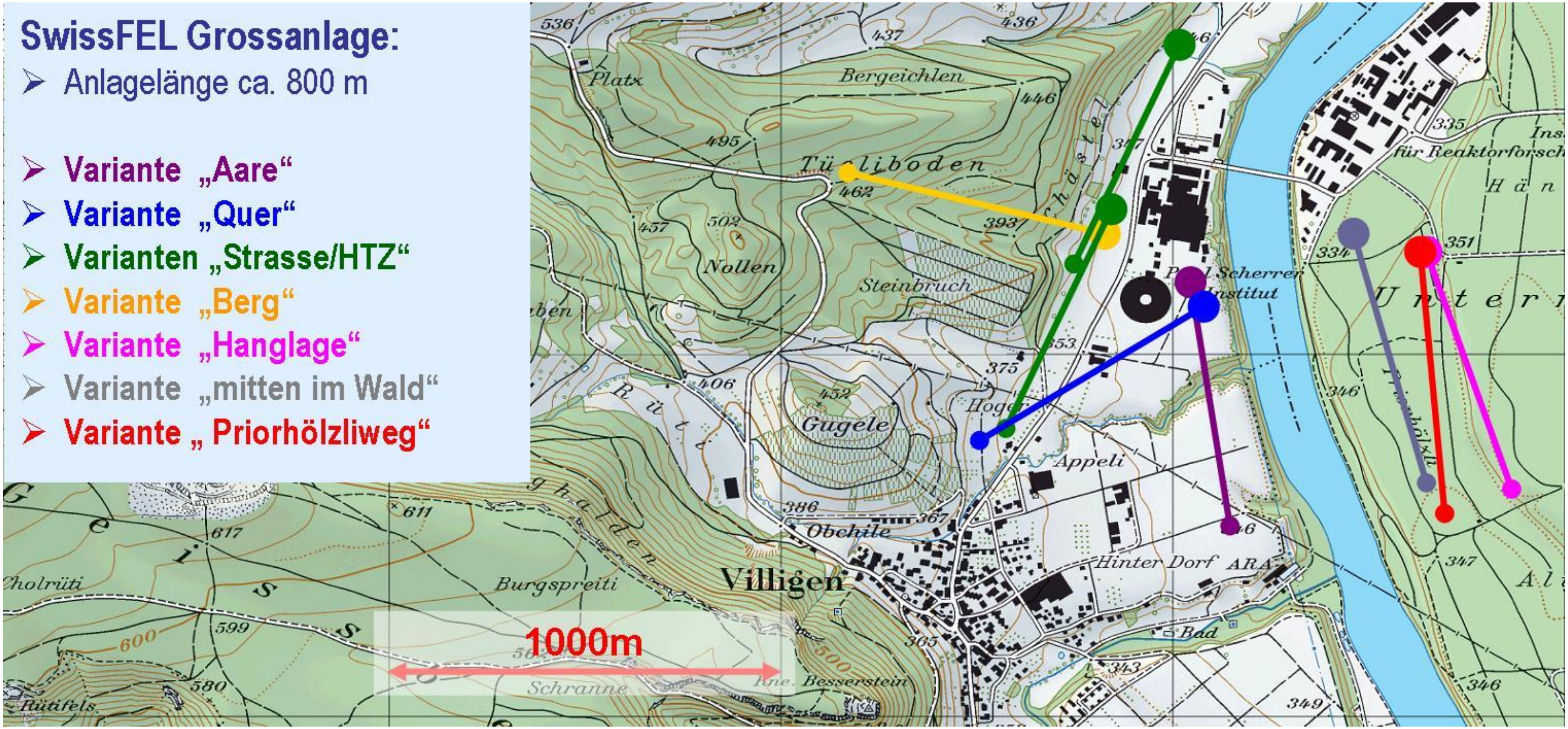
+ PSI Mitarbeiter

SwissFEL Site Evaluation

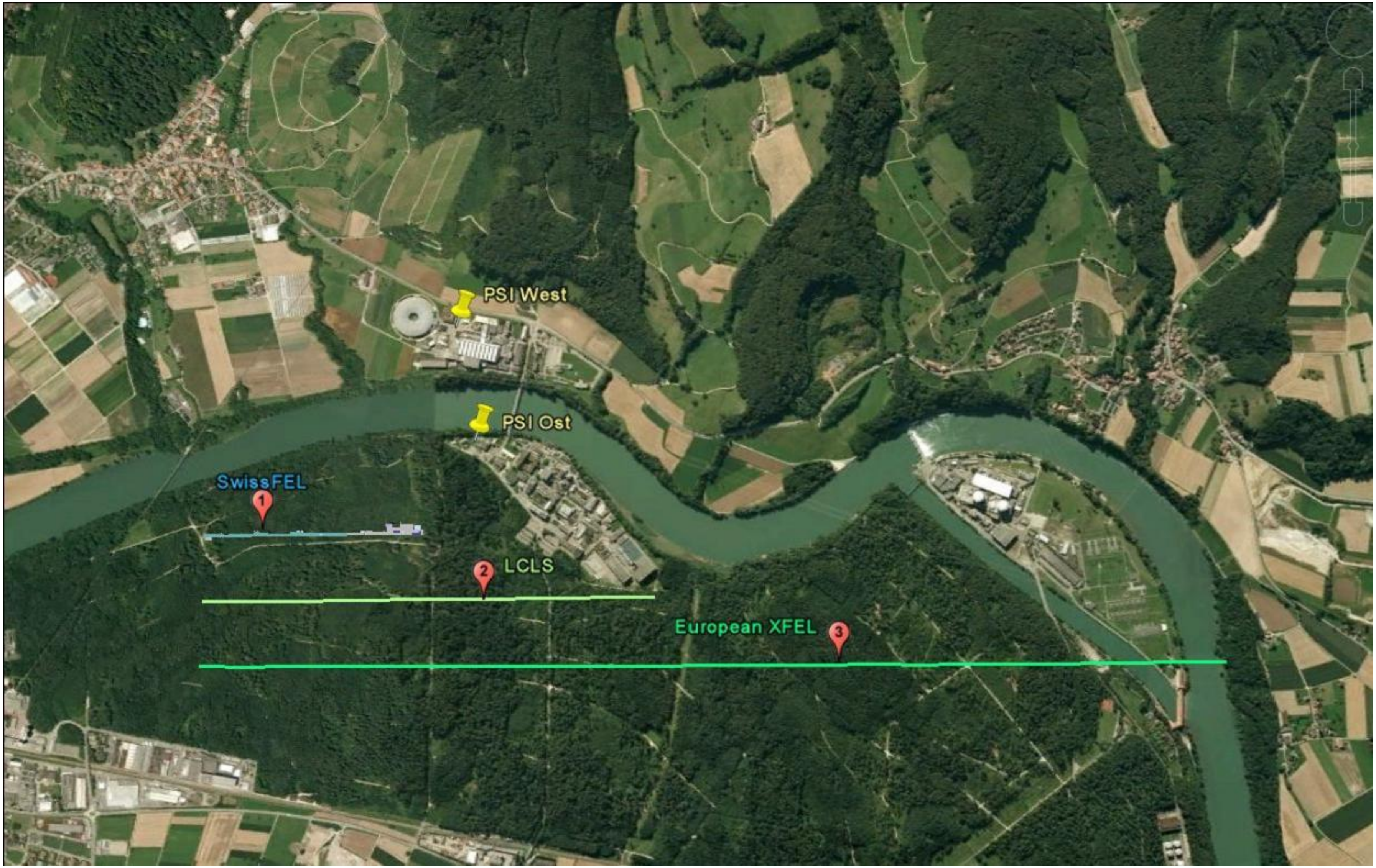
SwissFEL Grossanlage:

- Anlagelänge ca. 800 m

- Variante „Aare“
- Variante „Quer“
- Varianten „Strasse/HTZ“
- Variante „Berg“
- Variante „Hanglage“
- Variante „mitten im Wald“
- Variante „ Priorhölzliweg“



Selected site



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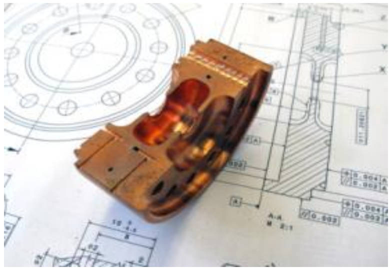
SwissFEL Milestones

4 MeV gun:	in operation
Scientific Case:	September 2009
Local community:	January 2010
ETH Board:	March 2010
Start „Bewilligungsverfahren“:	March 2010
250 MeV injector:	First beam March 2010
Inauguration 250 MeV inj.	August 24th 2010
Parliament decision:	2012
Start of construction:	2013
Aramis operation:	2017
Athos operation:	2019

http://fel.web.psi.ch

SwissFEL technical R&D for key items with Industry

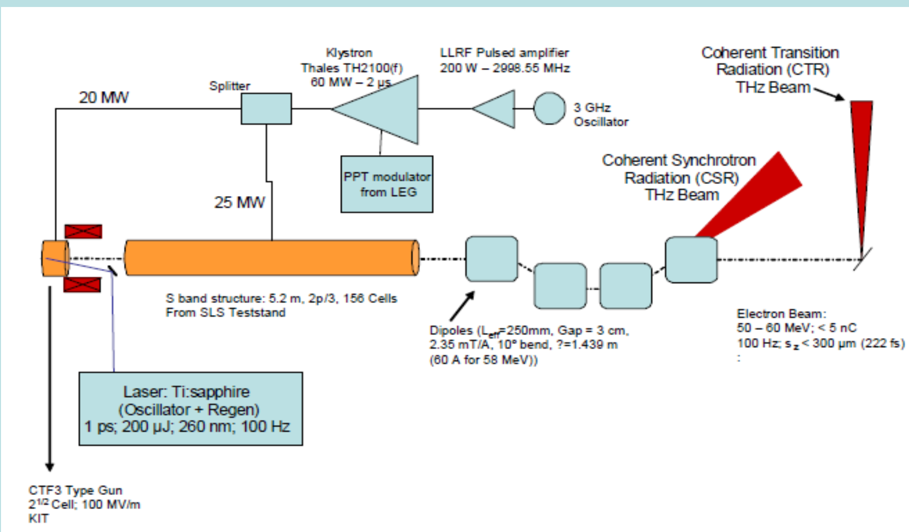
				
Item	**RF structures**	**Pulsed High voltage for RF sources**	**Undulator magnet systems**	**Real time data analysis and compression**
Key technologies	• Ultra precision machining • Ultra clean, ultra precision bonding	• High current, high voltage switching technology • Precision voltage measurement & control	• Heavy load precision positioning • Precision machining of large support structures	• FPGA electronic design and programming • Fast algorithms
Status	Industry study for a production line with ultra precision machining and brazing furnace	Collaboration agreement .	Engineering studies Contracts for functional model partly placed	Design study completed Contract for prototype placed

THz source, two prone approach

- **High field pump source for experiments**
  (see Bruce's talk)

Bend radiation from compact e⁻ accelerator
THz radiation with B > 1 T

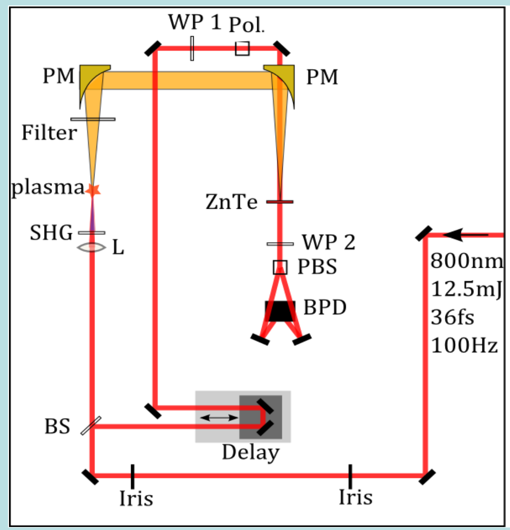
Collaboration with KIT Karlsruhe for
FLUTE THz source



- **Key diagnostic tool for X-ray timing and pulse length diagnostic**

(pioneered at FLASH/DESY, Nature Photonics 3 (2009), 523)

Laser generated THz
→ avoids synchronization problem for pump probe experiments. THz is produced from same laser beam as laser pump pulse



BS	Beam splitter R=2%
L	Lens f=75mm-500mm
SHG	BBO* crystal for SHG
Filter	Teflon low pass filter
PM	Off axis parabolic mirror
WP 1	half wave plate
Pol.	Polarizer
ZnTe	sampling crystal 2mm
WP 2	quarter wave plate
PBS	polarizing beam splitter
BPD	Balanced photo detector