FEMTO Station: From SLS to SwissFEL

G. Ingold

- for the FEMTO group -

Paul Scherrer Institut

Laboratory for Synchrotron Radiation

SwissFEL Workshop
ARAMIS Endstation B

Villigen, Switzerland

March 27, 2012

FEMTO

FEMTO: Activities & Scientific Team

(I) Femtochemistry: fs & ps Absorption

→ time-resolved XAS in solution (Chergui Group, EPFL & PSI / R. Abela)

(II) Condensed Matter: fs & ps Diffraction

In house group⋆

P. Beaud	Scientist
G. Ingold	Scientist
S.L. Johnson [start August 1, 2011: ETHZ faculty position]	Scientist
A. Oggenfuss	Technician

⋆ [responsible for FEMTO source: design (2001 - 2003) & construction (2003 - 2005) & operation (2006 - 2011) / funds: ETH Council]

S. Mariager	Postdoctoral Fellow
A. Caviezel	PhD Student
S. Grübel	PhD Student
J.A. Johnson	Postdoctoral Fellow
F. Krasniqi, D. Abramsohn, E. Möhr-Vorobeva	previous members

collaborations: U. Staub (SLS RESOXS team), C. Milne (EPFL), CH. Quitmann (SYN)
R. Feidenhans'l (U Copenhagen), Ch. Back (U Regensburg)

Outline:

- Lessons from FEMTO

- Towards SwissFEL (ARAMIS)

FEMTO ⇒ SwissFEL: Strongly Correlated Electron Systems

Hard X-ray Instrumentation Workshop, Bern, November 21, 2011

poster # 15: Ultrafast Structural Dynamics in Strongly Correlated Electron Systems: Timing Specifications (PSI / ETHZ)

poster # 16: Vibrational Control of Quantum Materials: Ultrafast X-ray Diffraction Studies (MPI/CFEL)

poster # 17: Coherent Control of Microscopic Order - High Field THz and X-ray Experiments at the SwissFEL (PSI / ETHZ)

poster # 18: Time-resolved Diffuse X-ray Scattering (ETHZ)

poster # 20: Probing Magnetic Phase Transitions (PSI / ETHZ)

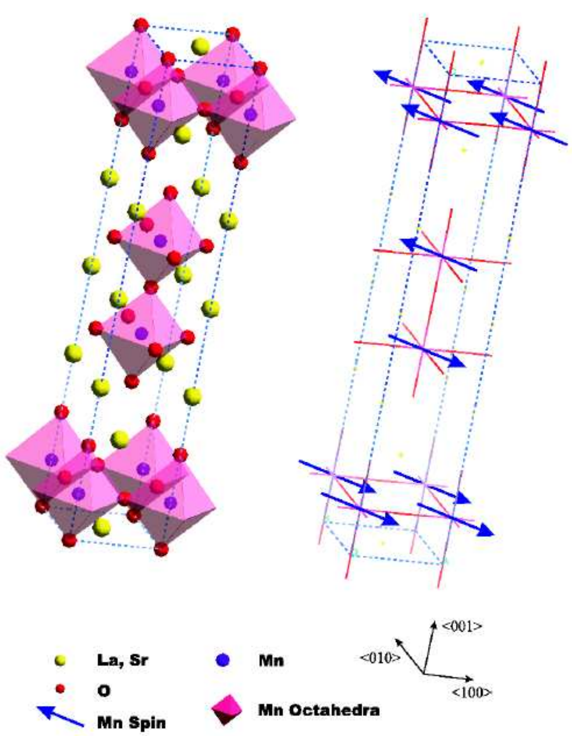
Deadline ARAMIS Endstation-B: start commissioning end 2016

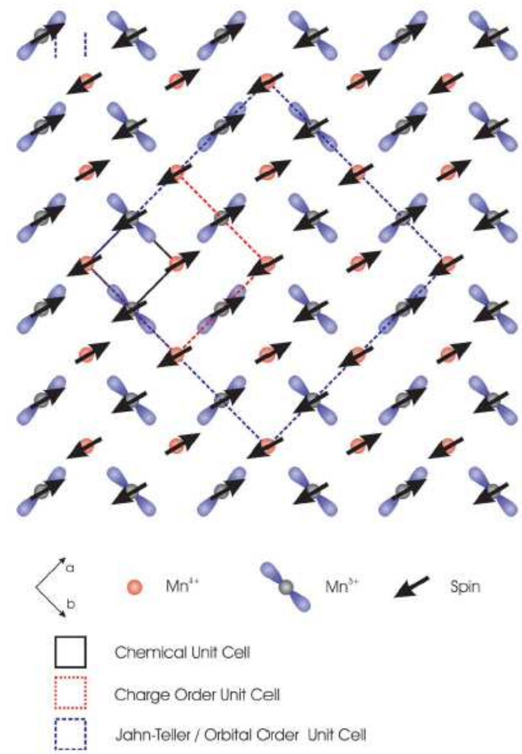
(10 years after commissioning FEMTO in 2006)

Correlated Structural and Electronic Dynamics in Complex Materials

Goal: Resolve correlated dynamics: lattice, charge, orbital and spin order

real time & atomic resolution





- **Lattice dynamics:** **(time domain & atomic resolution): $\tau_{vib} \simeq$ 100 fs (vibrational period)**
- **Electron dynamics:** **(charge-, orbital-, spin-order): $\tau_{e-ph} \simeq$ 1 ps (e-phonon); $\tau_{e-e} \simeq$ 10 fs (e-e scattering); $\tau_{e-corr} \simeq$ 0.1 fs (e-correlation)**

FEMTO

FEMTO → SwissFEL:
Stimulated Transient Phenomena in the Solid State

Method

⇒ **pump - probe**

⇒ **atomic resolution**

⇒ **femtosecond time scale**

Topics

- **coherent phonon dynamics**
  ongoing
- **non-equilibrium phase transitions**
  ongoing
- **switching in multiferroics**
  started

FEMTO

FEMTO Project: Design 2001 - 2003 / Construction: 2003 - 2005

10 Research focus and highlights – Synchrotron light | PSI Scientific Report 2006

Seeing matter within a picosecond

A tuneable undulator source for femtosecond X-rays in the range 4 – 12 keV is now in operation at the SLS storage ring. The source combines accelerator and laser technology relevant for the next generation light sources. It provides an inherently synchronized femtosecond laser 'pump' and X-ray 'probe' to enable time-resolved absorption and diffraction experiments. Observation of coherent optical phonons in bismuth single crystals via X-ray diffraction demonstrates the excellent spatial and temporal stability of the source that allows direct quantitative measurement of ultrafast lattice dynamics and associated phase transitions.

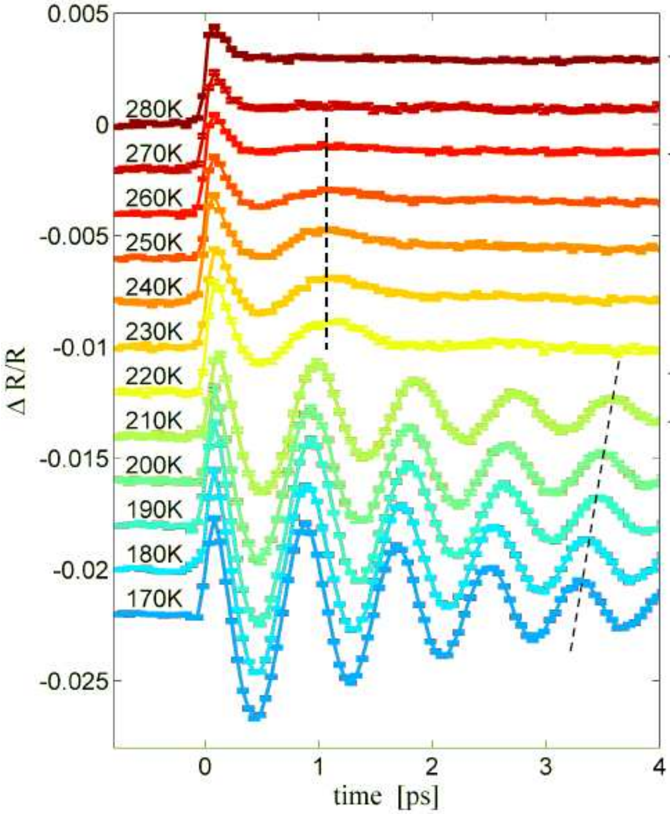
FEMTO

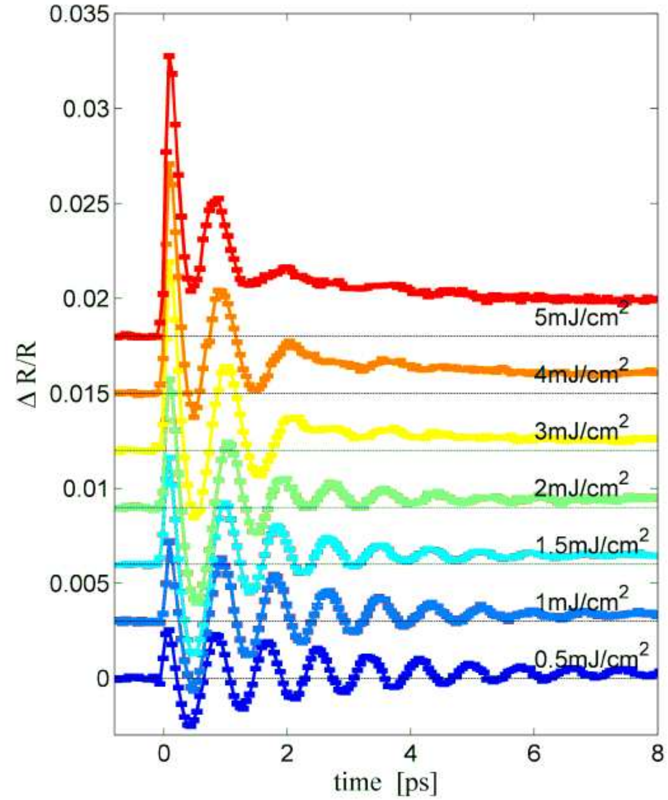
Phonons & (Martensitic) Phase Transition - MSMA Ni_2MnGa

optical reflectivity measurements 800 nm

pre-martensitic phase → T_M = 215 K → martensitic phase

fluence 1 mJ/cm^2 **temperature 200 K**





[S. Mariager et al., to be published]

FEMTO

Crystalline Solids: Femtosecond Phonon Dynamics

- **Spatio-temporal stability and coherent control** — FEMTO / slicing
  (coherent phonons in Peierls system Bi)
  [P. Beaud et al., Phys. Rev. Lett. 99 (2007)]

- **Grazing-incidence X-ray diffraction** — FEMTO / slicing
  (nanoscale depth-resolved coherent lattic motion in Bi)
  [S.L. Johnson et al., Phys. Rev. Lett. 100 (2008)]

- **Strain-wave dynamics** — FEMTO / slicing
  (excited carriers & lattice heating in InSB)
  [F.S. Krasniqi et al., Phys. Rev. B 78, (2008)]

- **Squeezed phonon states** — FEMTO / slicing
  (measurement of the variance of the atomic displacement in Bi)
  [S.L. Johnson et al., Phys. Rev. Lett. 102, (2009)]

- **Femtosecond unit cell dynamics** — FEMTO / slicing
  (Peierls system Te)
  [S.L. Johnson et al., Phys. Rev. Lett. 103, (2009)]

FEMTO

Crystalline Solids: Non-Equilibrium Phase Transitions & Long-Range Order

- **Metal-to-Insulator (MIT) transition in manganite** — FEMTO / slicing
  (half doped LCMO; Jahn-Teller stabilized; CO/OO melting)
  [P. Beaud et al., Phys. Rev. Lett. 103 (2009)]

publication in 2010 ?

- **Dynamics of Charge-Density-Wave (CDW)** — FEMTO / slicing
  (CDW transition in $TiSe_2$; Jahn-Teller effect $\leftrightarrow$ exciton condensation)
  [E. Möhr-Vorobeva et al., Phys. Rev. Lett. 107 (2011)]

- **Magnetic phase transition in multiferroics** — LCLS / FEL
  (cupric oxide CuO; collinear-to-spiral AFM phase transition)
  [S.L. Johnson et al., Phys. Rev. Lett., 108 (2012)]

- **Magneto-structural phase transition** — FEMTO / slicing
  (magneto-structural AFM $\longrightarrow$ FM transition in FeRh; phase coexistence)
  [S. Mariager et al., Phys. Rev. Lett. 108, (2012)]

”2009 FEMTO annus mirabilis” : 3 PRL + 1 Science paper

publication in 2010 ? No, but another one in 2009 . . .

- **Femtosecond XANES study in liquid system** — FEMTO / slicing

  (light-induced spin crossover dynamics in an iron(II) complex)

  [CH. Bressler et al., Science 323 (2009)]

⇒ **SwissFEL Scientific Case: Femtochemistry**

⇒ **SwissFEL Workshop: ARAMIS Endstation-A**

(Villigen, March 13, 2012)

FEMTO

FEMTO 2006-2012: Experiments Successfully Exploited . . .

- **fs grazing incidence diffraction & fs scanning absorption spectroscopy**

  - high harmonic operation: 5 - 10 keV & 2.4 GeV

- **stability & diagnostics** — SwissFEL:

  - SLS storage ring: controlled operation → SASE inherently unstable
  - diagnostics: pulse averaging → single shot: intensity, wavelength, time
  - trans. ⊕ long. feedback systems & top-up → feedforward systems
  - THz slicing diagnostics → e-beam coherent radiation

- **pump-probe timing stability**

  - intrinsic synchronization → arrival time stamping
  - time resolution: 200 fs FWHM → 20 fs FWHM

- **best medium is no medium**

  - propagate beams in vacuum

- **repetitive measurements & low flux**

  - stroboscopic scanning → "diffraction without distruction"
  - 2 x 10^2 ph/pulse/0.1% bw & 2 kHz → 8 x 10^{10} ph/pulse/0.1% bw & 100 Hz

⇔ profit: high flux & shorter pulses

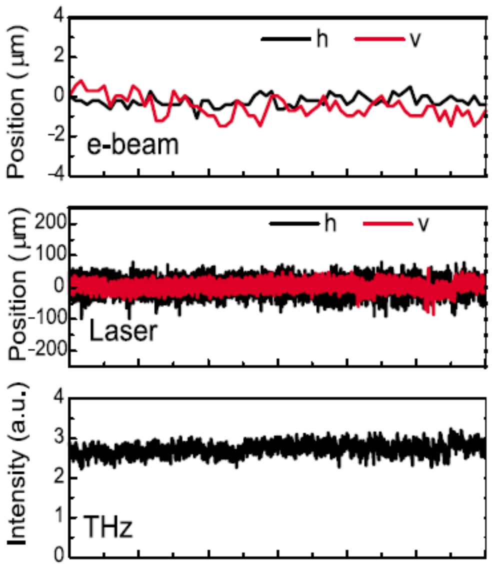
price: instability

FEMTO

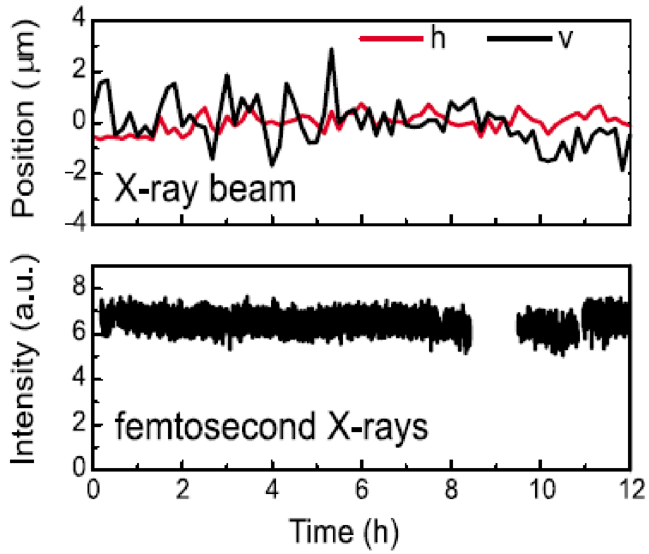
Lessons from FEMTO: Spatiotemporal Stability

- DIAGNOSTICS -

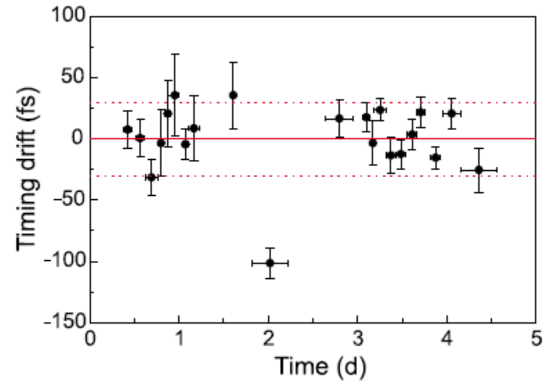
slicing operation



X-ray beam

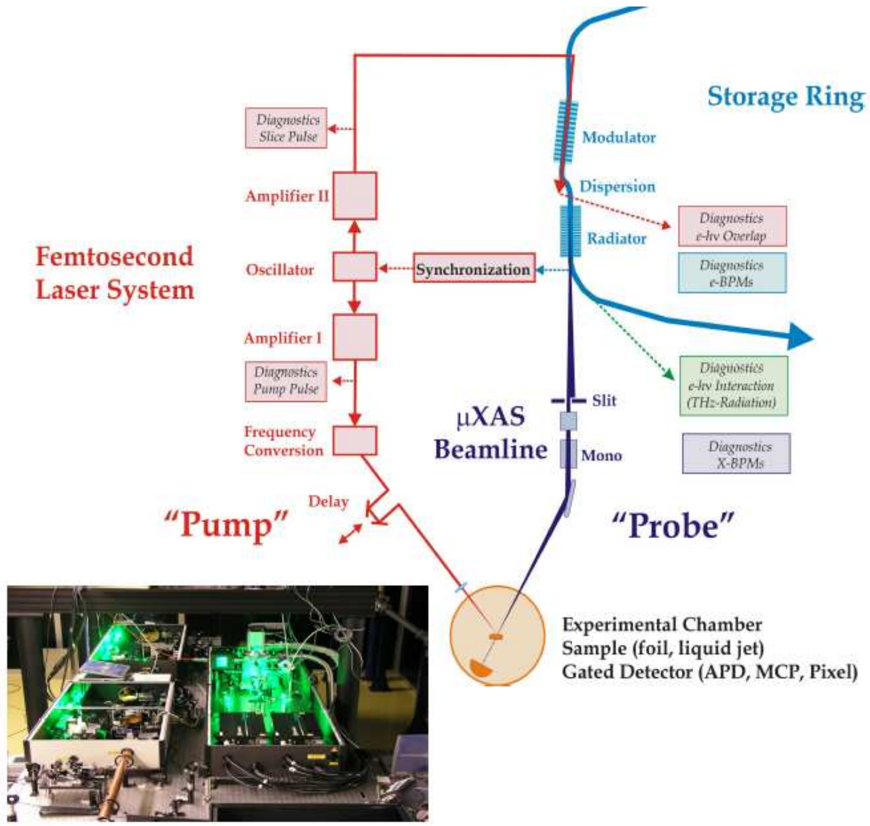


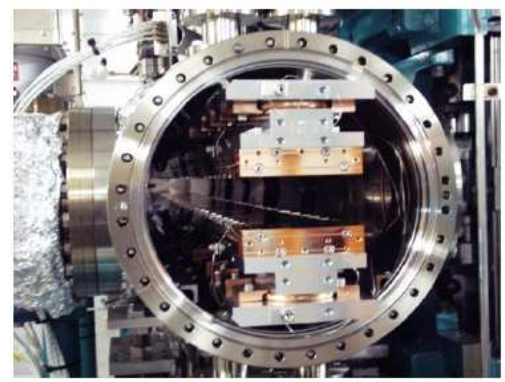
timing stability



Longterm temporal stabiliy: 30 fs (rms) $\Leftrightarrow$ spatial X-ray stability on sample: $\leq 5\ \mu$m

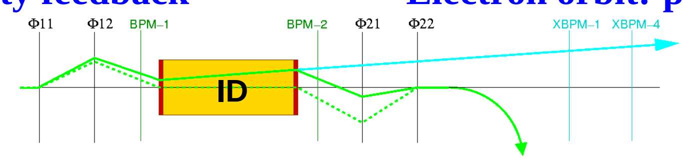
Intrinsic Synchronization & Feedback Systems & Top-up Operation





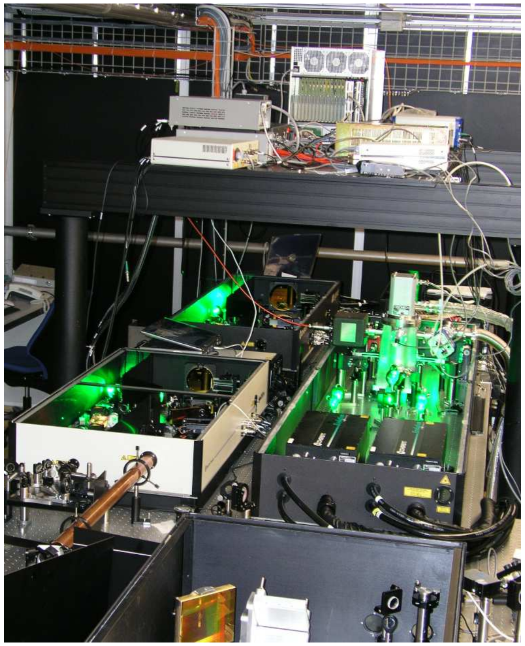
Laser-synchronization: cavity feedback

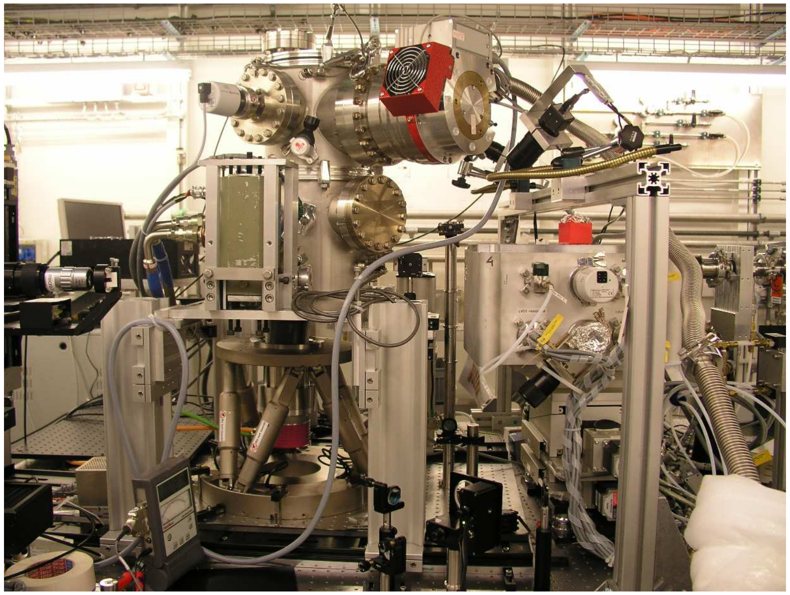
Electron orbit: position feedback & top operation

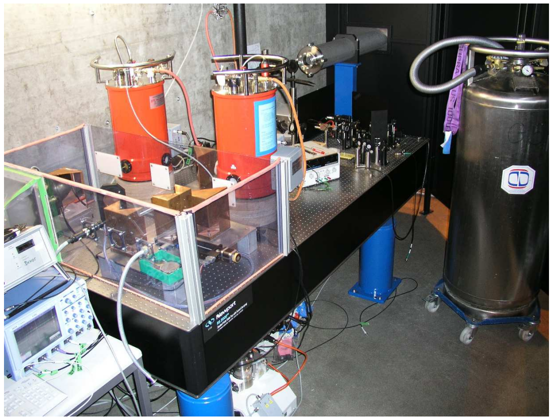


Feedback systems ⇔ Spatiotemporal stability [G. Ingold, AIP Conf. Proc. 879 (2007)]

FEMTO Station: Laser System - Exp Chamber - Diagnostics

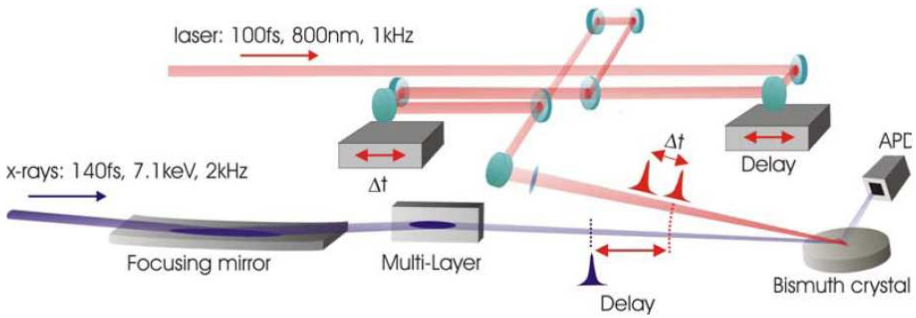






Laser-pump / X-ray-probe experiments: time resolution 200 fs

Pump-probe setup (2-pulse excitation)

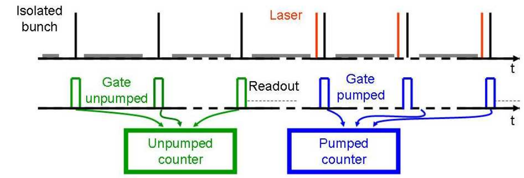


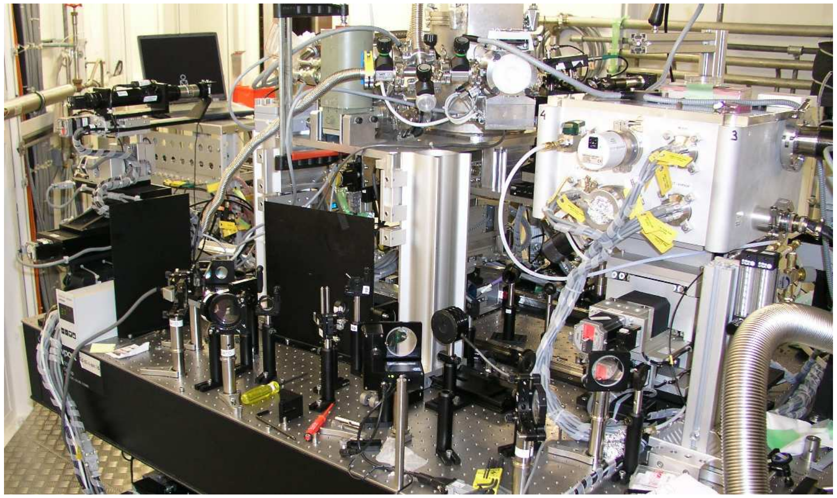
Pixel detector (gateble)

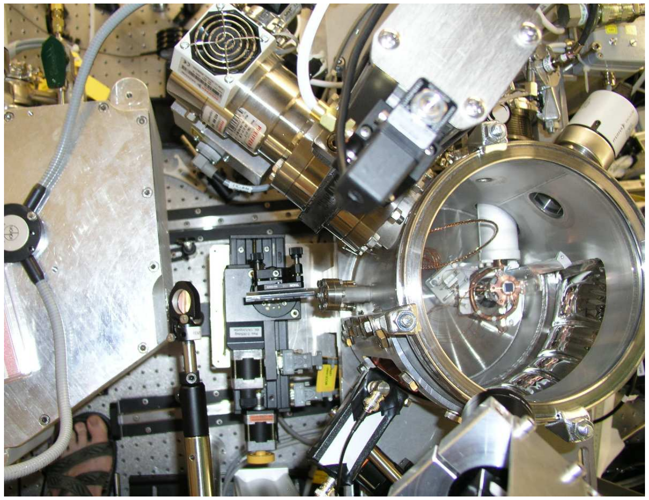
(PSI Detector Group)

Pilatus pixel detector

- 487 x 195 pixels = 94965 pixels
- Active Area 83.8 x 33.6 mm²
- Pixel size: 0.172x0.172 mm²
- Dynamic range/pixel: 20bits
- Readout time: 4 ms
  - Longer than FEMTO bunch period



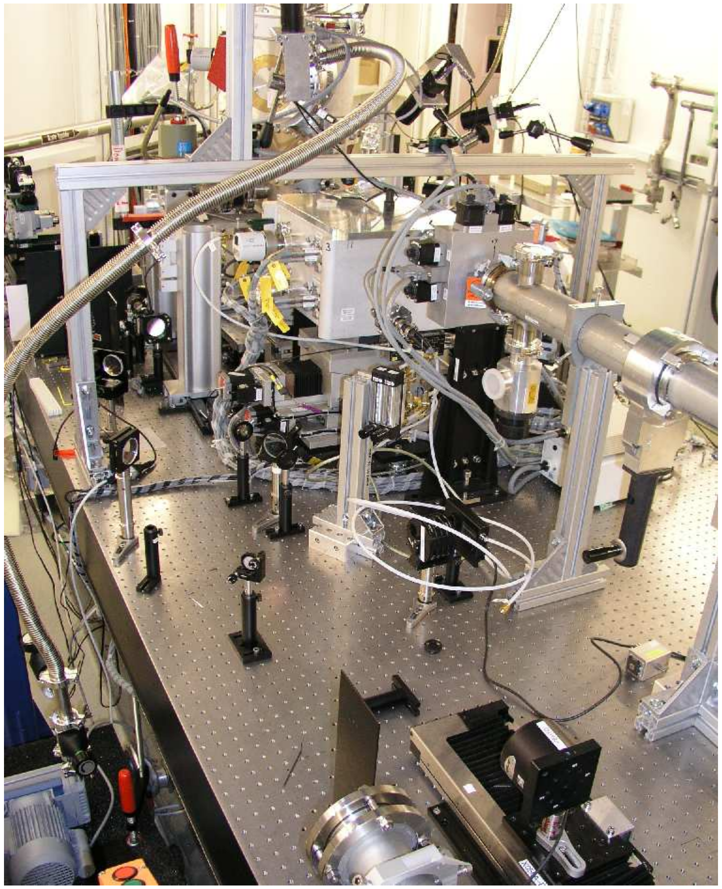


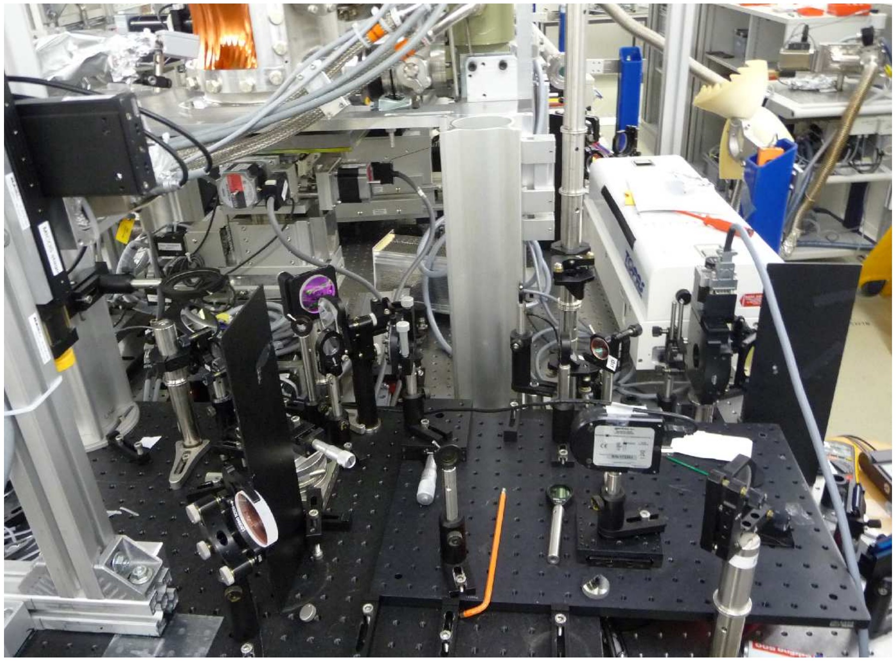


FEMTO

FEMTO Endstation: Laser Setup at the Experiment

Laser (bottom) & X-ray (top)

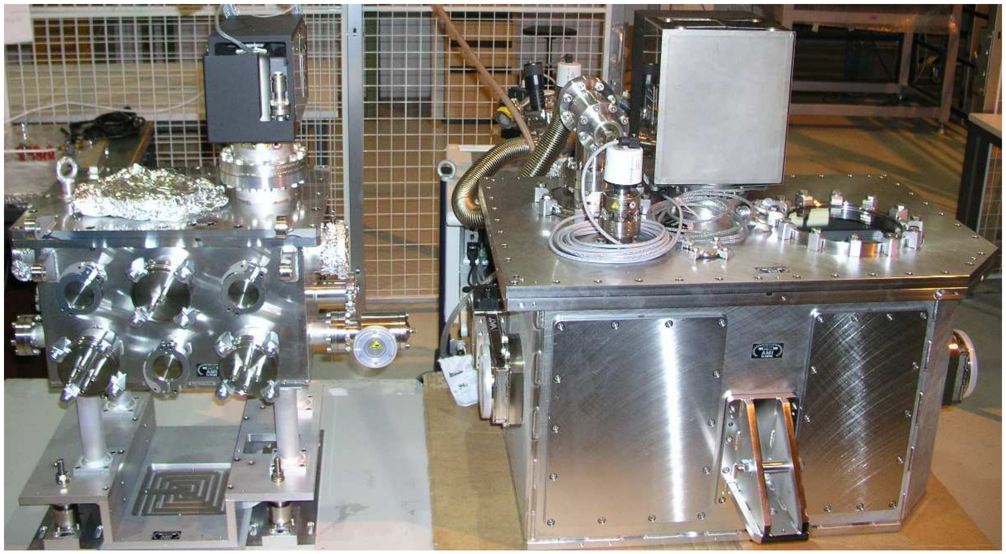




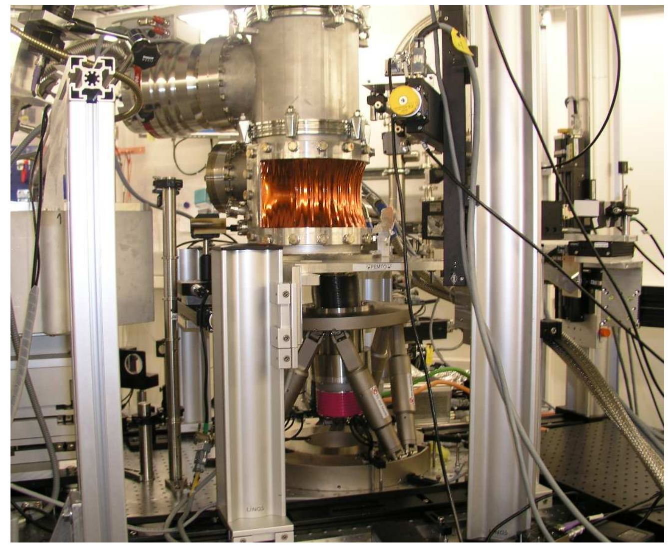
Lesson: really bad - there is no permanent installation of the FEMTO endstation

New FEMTO Endstation: Phase I - Status Feb 2012

ML Monochromator KB Optics



HV Hexapod Cryo Goniometer
T = 40 - 300 K

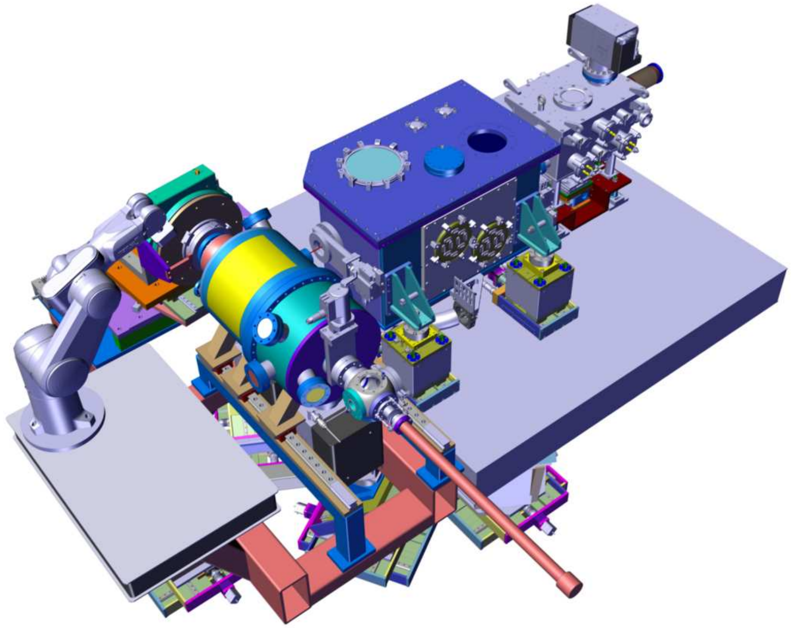


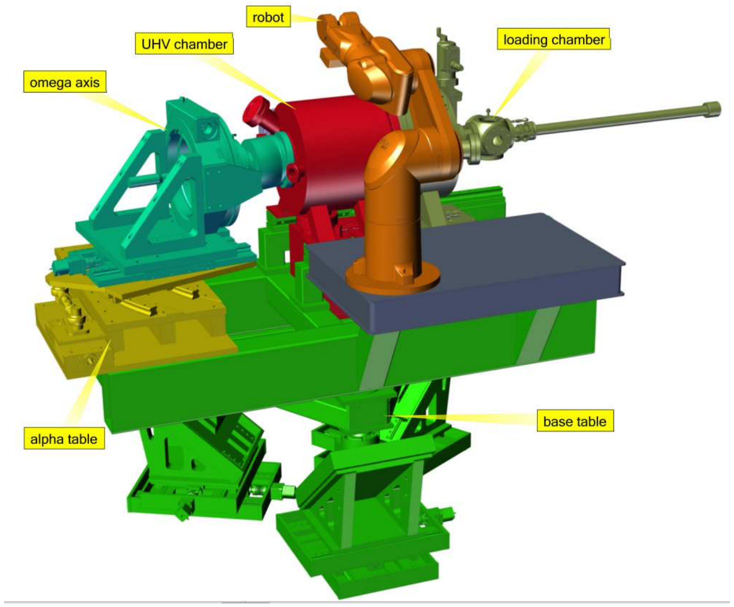
Installation at μXAS beamline: summer 2012

approach:

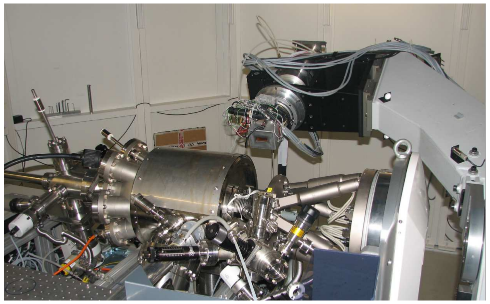
- 2D pixel detector: out vacuum
- cryo-cooled sample: in vacuum (5 x 10^{-8} mbar & 40 K & 6 days)
- speckle-free exit window (Kapton, Be)
- no bake-out: installation of LN_2 cold traps

Phase II: Design New FEMTO Cryo-Diffraction Endstation





MS - Diffractometer & Be - Chamber



FEMTO

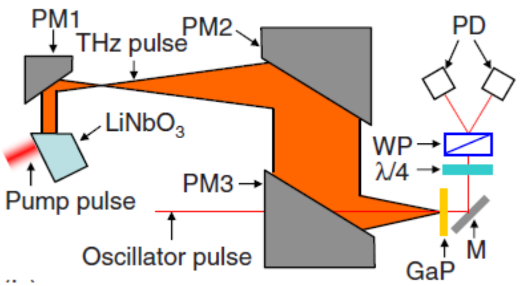
Phase II: UHV Cryo Diffractometer & THz-pumping

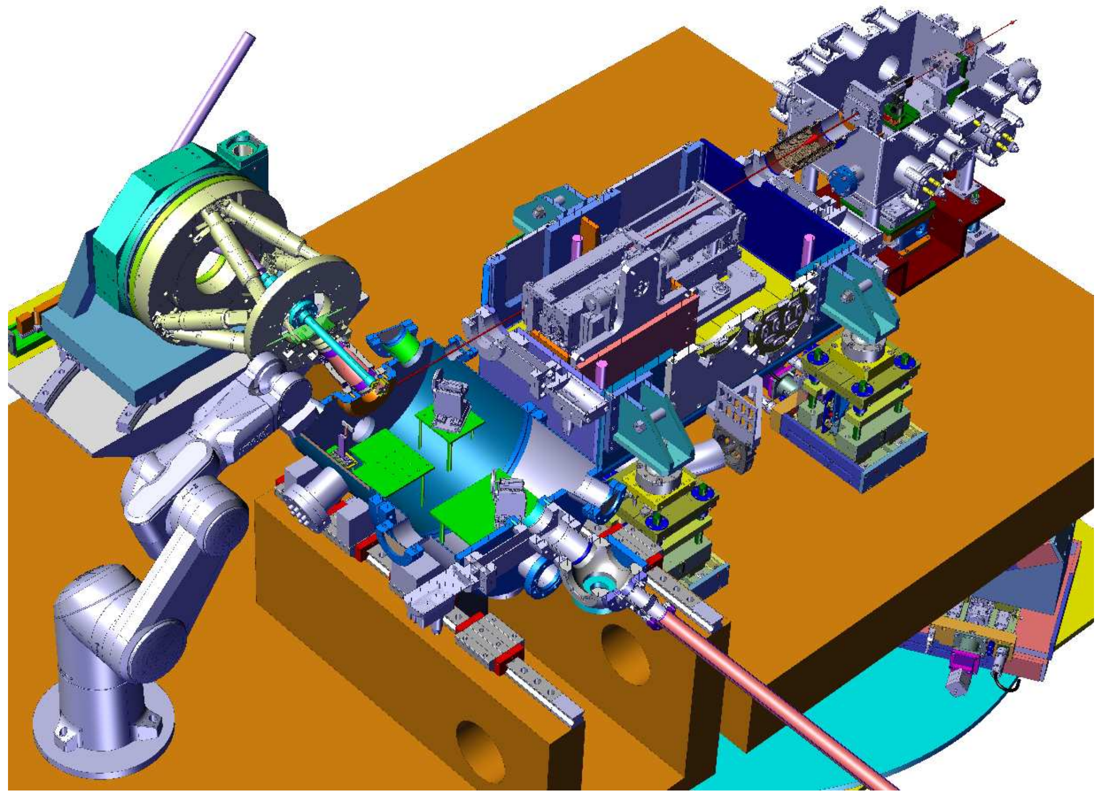
THz pumping

Laser: 85 fs, 1 kHz, 4mJ

UHV Cryo Diffractometer

20 - 700 K





Demonstrated electrical field: 1.3 MV/cm

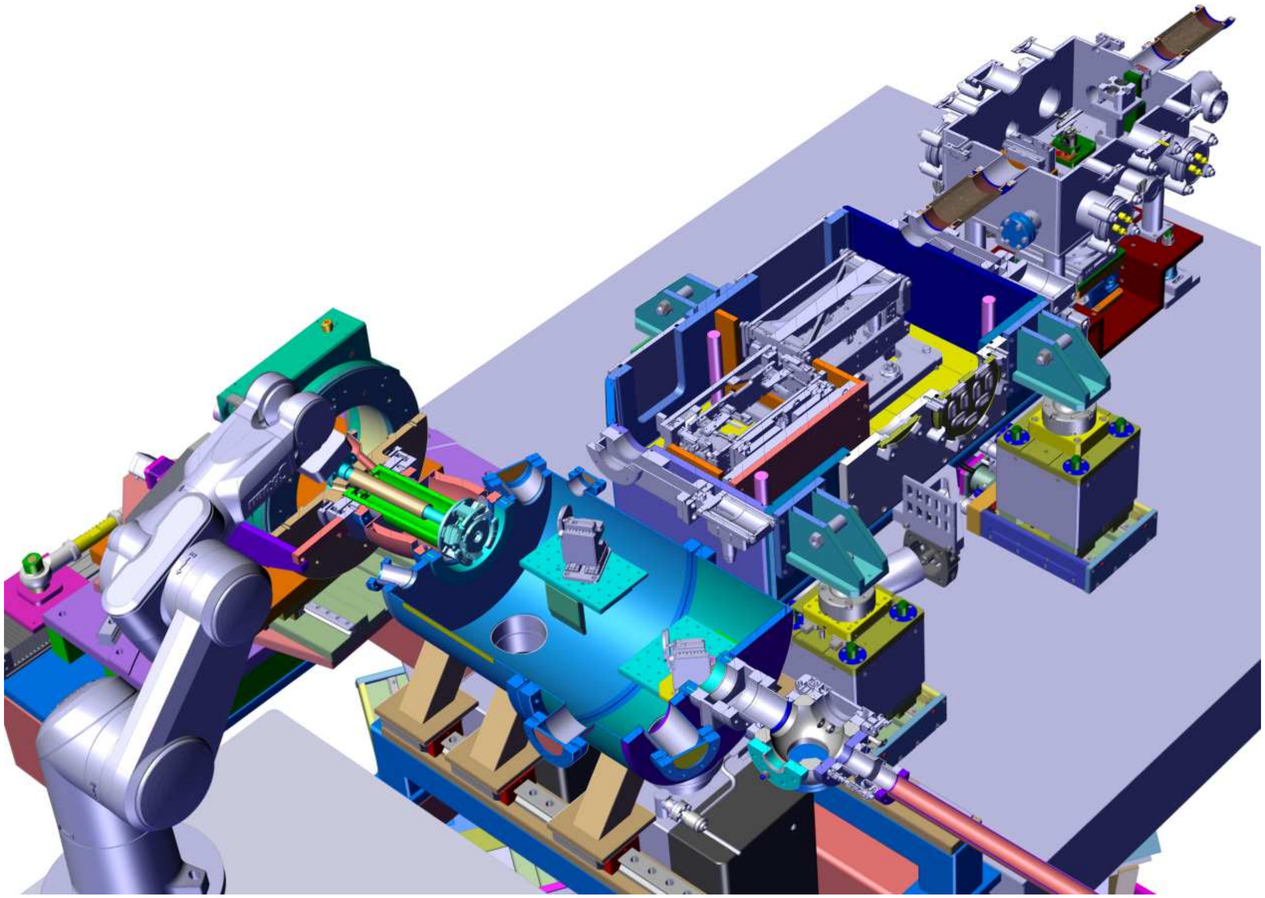
[Hirori et al., APL 98 (2011)]

Funds: SNF (R'Equipe) + FOKO + SYN

⇒ compact speckle-free cryo diffractometer for SwissFEL

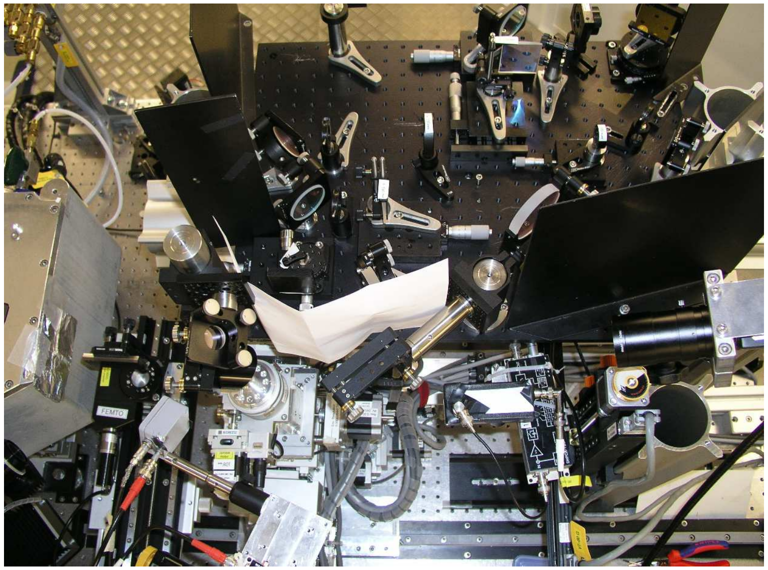
FEMTO Endstation: Conceptual Design - Status September 2011

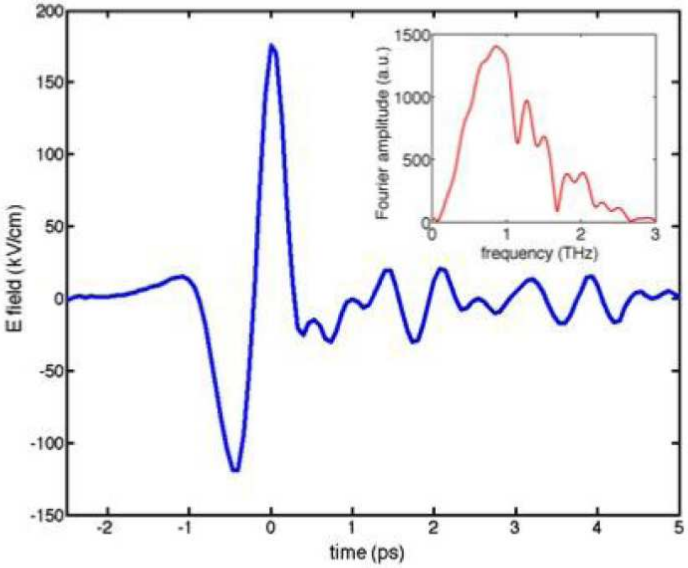
In-vacuum sample alignment $\leftrightarrow$ angular accuracy 0.001°

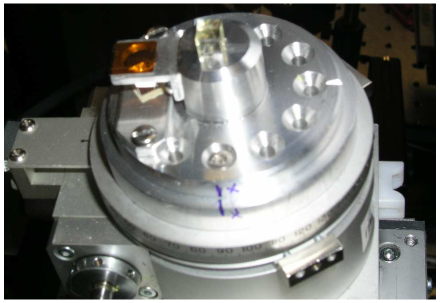


FEMTO Dec 2011: THz-pump / X-ray diffraction

→ THz-switching of ferroelectrics, status: 160 kV/cm (laser: 110 fs, 1kHz, 1-2 mJ)







[J. Johnson, S. Gruebel, S. Johnson, P. Beaud et al.]

funds: NCCR MUST

Towards SwissFEL: ARAMIS Endstation-B

(1) long-range order in correlated materials:

- structural dynamics: diffraction (tr-XRD) — lattice
- electronic dynamics: resonant diffraction (tr-RXRD) — charge, orbital, spin

(2) non-equilibrium phase transtions:

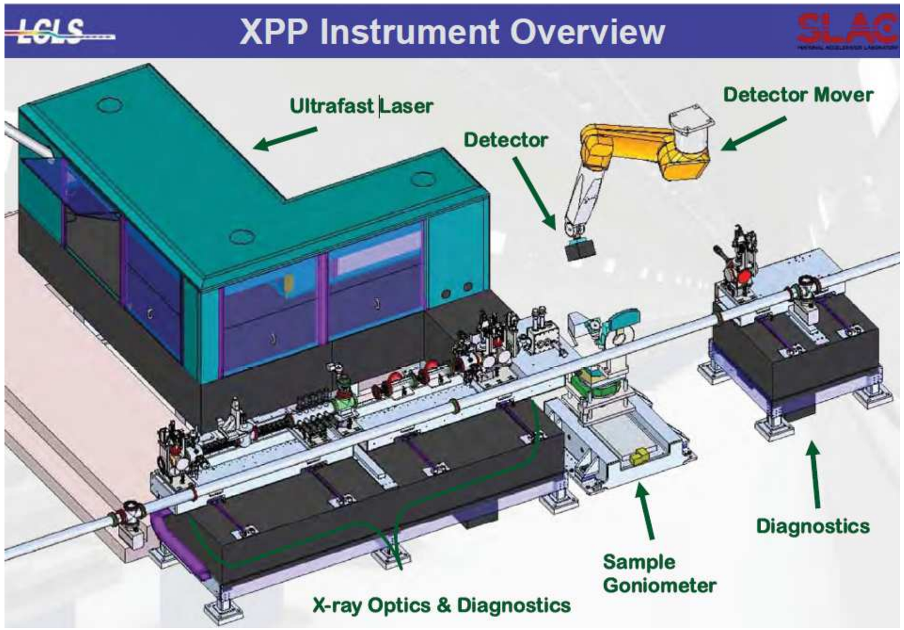
- phases can be tuned by varying external parameters: — B, E, S/P, T
  (and chemical or ”photo-doping”)
  (B: magnetic, E: eletric, S/P: strain/pressure, T: temperature) — → ’B E S/P T’ sample environment
- coherent scattering (domain dynamics): — → speckle-free sample environment
  (trans. & long. coherence)

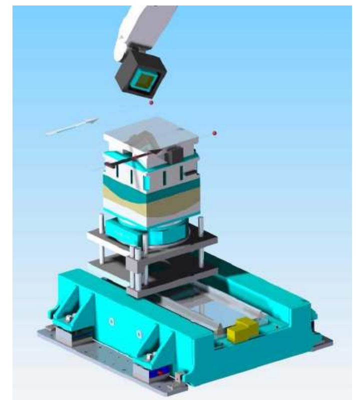
(3) switching in multiferroics:

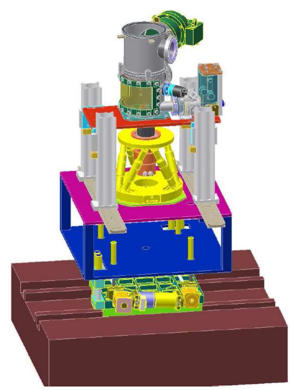
- flexible pump & probe beams: — wavelength / intensity / pulse length / polarization
  pump-beam — wavelength: THz / IR / UV / X-ray
  probe-beam — wavelength: tunability / polarization: lin & circ

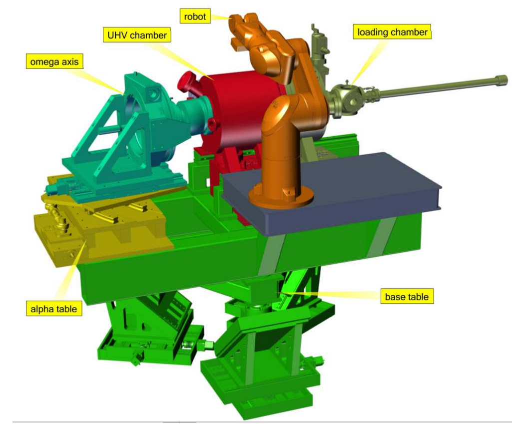
FEMTO

2012: How would Endstation-B look like today ? . . . probably similar to XPP endstation at LCLS . . .









2016/17: What do we need/want at SwissFEL ?

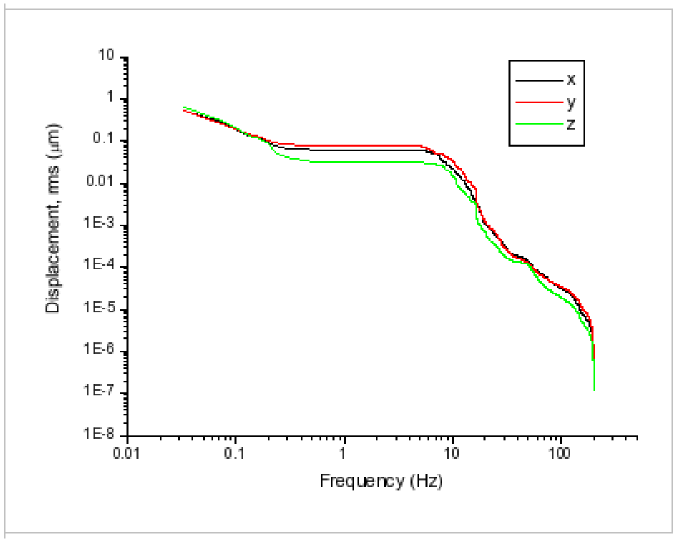
Pump-probe time resolution: 200 fs FWHM → 20 fs FWHM

(1) e-beam arrival measurement: ≤ 60 fs FWHM

Installation e-BAM after undulator: e-beam ↔ X-ray arrival time correlated within SASE jitter

(SLS storage ring: integrated vibrational displacement caused by any component: 100 nm rms

[∼ 1 fs FWHM] for f ≥ 5 Hz)



(2) X-ray beam arrival measurement: ≤ 20 fs FWHM

Installation X-ray BAM in front exp. station: non-destructive, wavelength & intensity independent

⇒ (1) & (2) provide redundancy & cross checking

X-Ray Probe Beam: Flexible Polarization

Installation of diamond phase retarders after the monochromator

crystal phase retarders (CPR) $\leftrightarrow$ circular polarized undulator (CPU)

circular polarized flux: fom = $(\mathrm{S}_3/\mathrm{S}_0)^2$ x S_0

[S_3: circular polarized flux density; S_3: unpolarized flux density]

spontaneous radiation: fom(CPR) $\simeq$ fom(CPU) for energies $\geq$ 3 keV

$\leftrightarrow$ if valid for fs SASE: no need for polarized afterburner

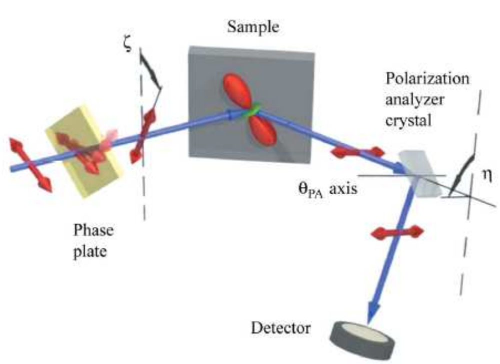
---

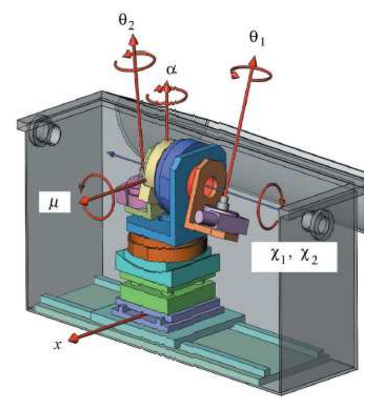
Journal of
Synchrotron
Radiation
ISSN 0909-0495

Received 23 June 2009
Accepted 31 August 2009

Linear polarization scans for resonant X-ray diffraction with a double-phase-plate configuration

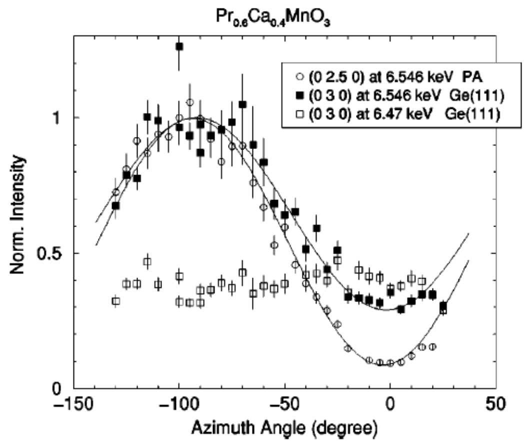
Valerio Scagnoli,* Claudio Mazzoli, Carsten Detlefs, Pascal Bernard, Andrea Fondacaro, Luigi Paolasini, Federica Fabrizi and Francois de Bergevin



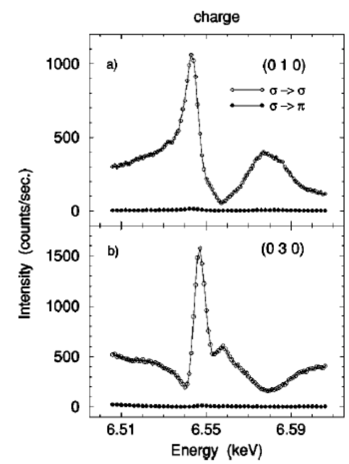


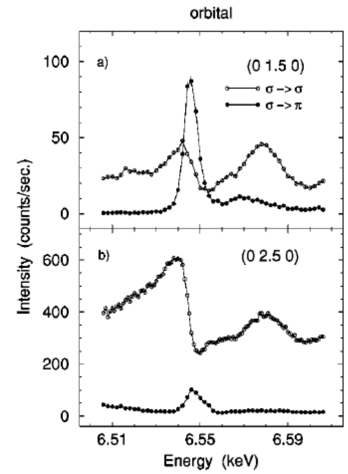
Scanning - Resonant & Non-Resonant Diffraction: Example PCMO

azimuth - scan

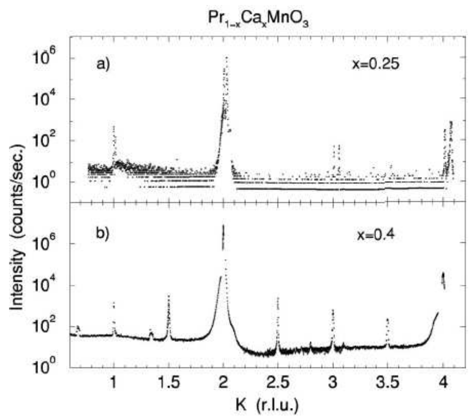


energy - scan (polarization resolved)

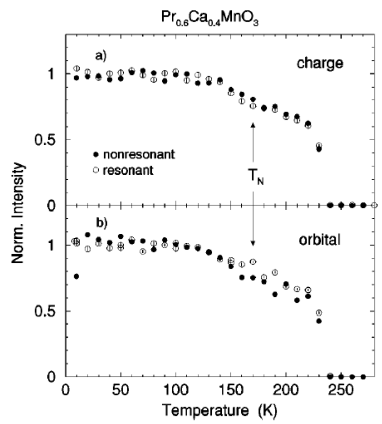




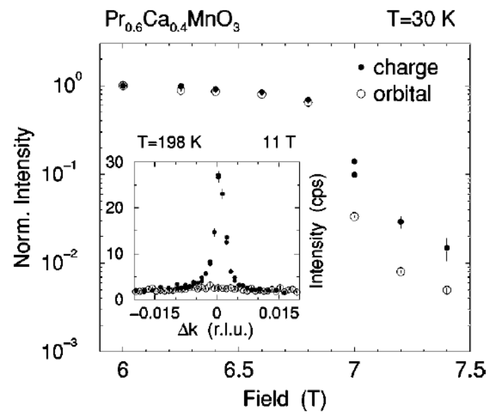
q - scan



T - scan



B - scan



[Brookhaven Group: Zimmermann et al., PRB 64, 2001]

FEMTO

SwissFEL ARAMIS: Hard X-Ray TR-(R)XRD Endstation

(I) Speckle-free XPP UHV diffractometer for condensed matter

$\rightarrow$ flexible pump & probe beams [wavelength (THz, IR, UV, X-ray); polarization; fluence]

$\rightarrow$ integrated diagnostics [pulse arrival; intensity; polarization]

$\rightarrow$ flexible sample environment [$\vec{B}$, $\vec{E}$, S/$\vec{P}$, T]

[B = 0 - 10 (12) T (static); E = 0 - 100 kV/cm (static) & 1 MV/cm (THz); S: strain; T = 15 - 700 K]

(i) in air: B = 0 - 1 T (PM) & T = 100 - 400 K, ΔT = $\pm$ 5 K (LN2 cryo-jet)

(ii) UVH: B = 0 - 10 (12) T (SC) & T = 15 - 700 K, ΔT = $\pm$ 0.5 K (He-flow cryostat)

T = 400 - 2000 K, ΔT = $\pm$ 2 K (Laser heater)

(II) Large area pixel detector operated in air / He- atmosphere

$\rightarrow$ detector arm: industrial robot [position accuracy in 1 m^3 $<$ pixel size]

(small angle scattering: large sample - detector distance)

(III) Integrated Diagnostics

$\rightarrow$ X-ray pulse arrival [high pressure THz - streaking]

$\rightarrow$ polarization: crystal analyzer [polarizer: crystal phase retarders (after Mono)]

(IV) Laser Set-Up at Exp Station

$\rightarrow$ talk by P. Beaud

FEMTO

Static Magnetic Field: "1/2 Split Coil SC Magnet" ∼ 6 - 7 Tesla

Oxford Instruments **14T Recondensing UHV XMCD System**

System description:	
14 T fast-ramping (15 min to field) horizontal field split pair in UHV cryostat, with interchangeable VTI and ^{3}He inserts, and fully automated sample height and rotate movement	
Status:	
In progress	
OI ref. 39175	

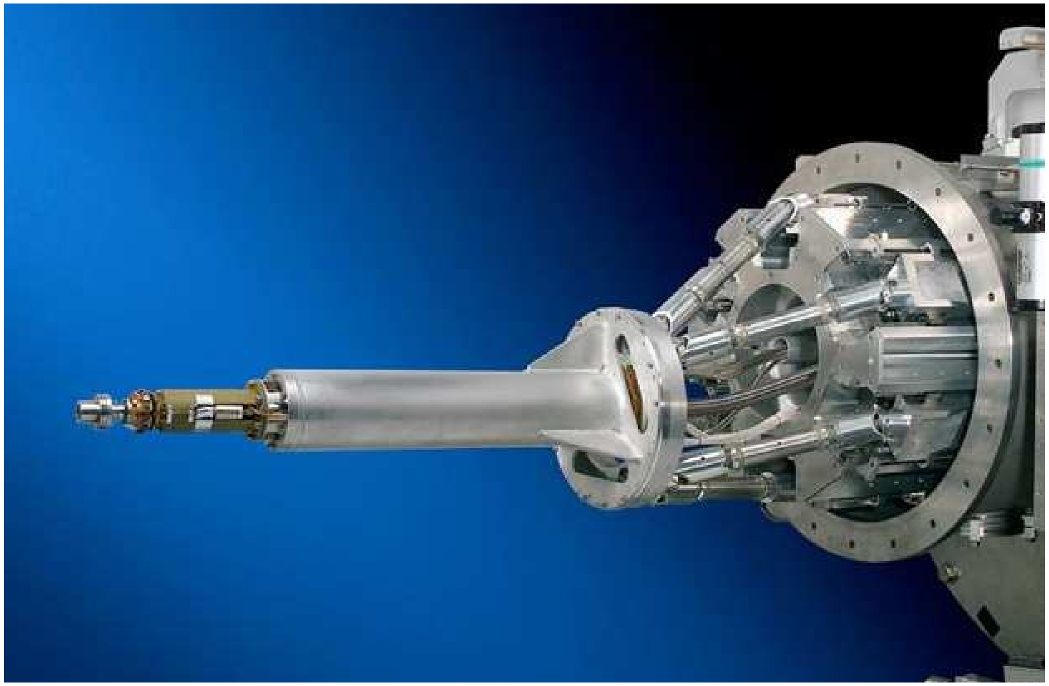
OXFORD INSTRUMENTS
The Business of Science®

proposal: space constraints ↔ SC coils mounted above midplane only

FEMTO

Custom Sized SC Magnets & Hexapod Sample Manipulators

[http://www.oxford- instruments.com]



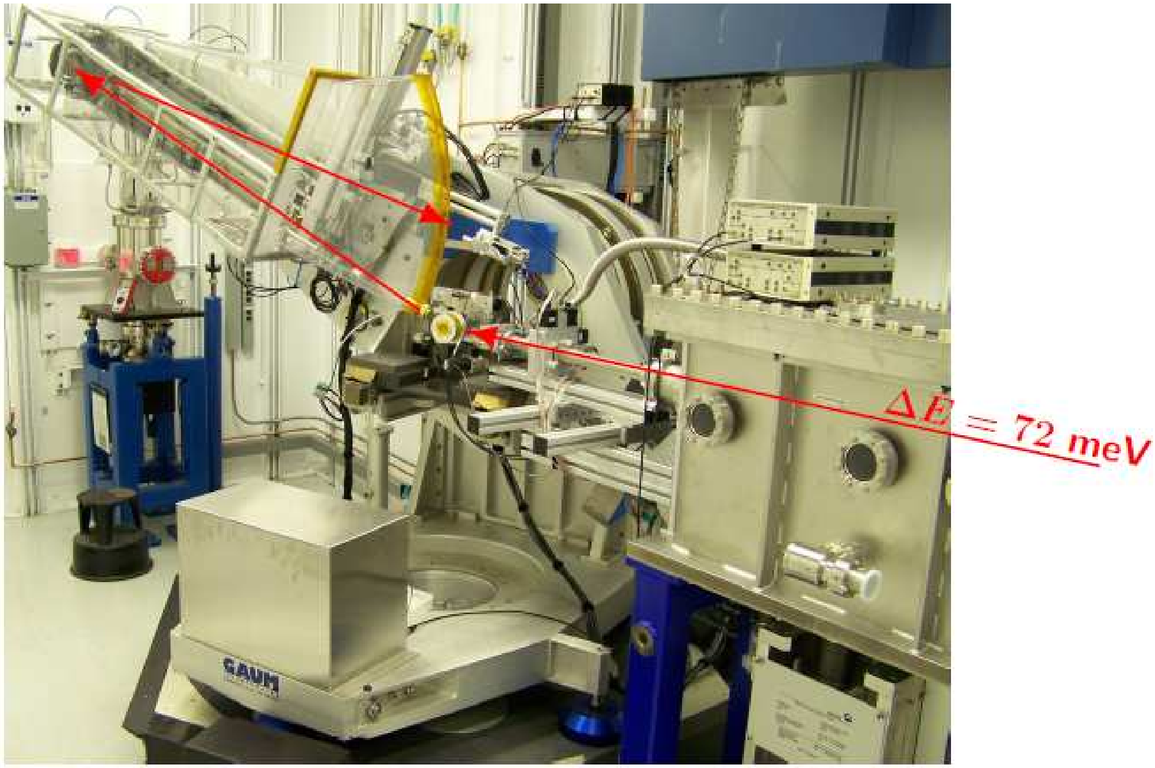
[http://www.symetrie.fr/en/]

⇒ non-magnetic cryogenic in-vacuum precision manipulators have to be developed
insertion into small bore ($\sim$ 40 mm) split pair SC magnet

↔ opposite approach: pulsed magnets ?
demonstrated (BL19LXU/SPring8): 38 T & 30 msec duration, 50 T could be feasible
rep-rate & lifetime ?

FEMTO

Outlook: Electronic Excitations - Hard X-Ray tr-RIXS & Self-Seeding



MERIX RIXS spectrometer at APS 30-ID

energy: 4 - 12.4 keV → **K-edges 3d elements & L-edges 5d elements (Ir)**
self-seeding: 10^{-5} bw → **energy resolution $\sim$ 100 meV & flux 10^{12} ph/s & 60 fs**
sample environments: **low & high T, magnetic field**
polarization dependence: **scattering in H & V plane**