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Sincrotrone
Trieste

Advanced experiments and facility plans at FERMI

Filippo Bencivenga

Elettra Sincrotrone Trieste

Outline

1) Experimental facilities at FERMI

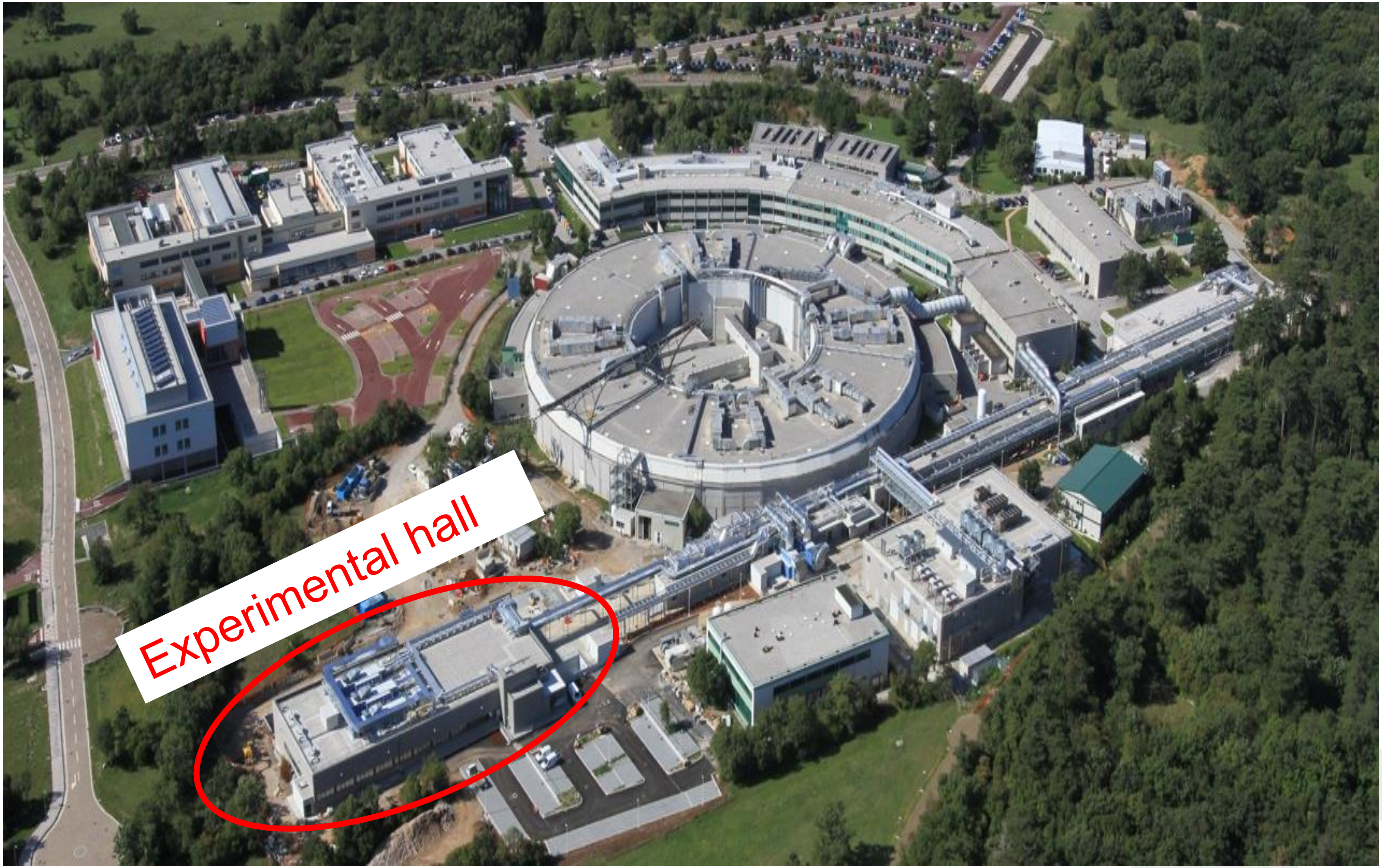
2) Multi-FEL pulses for advanced experiments

3) FEL-based four-wave-mixing

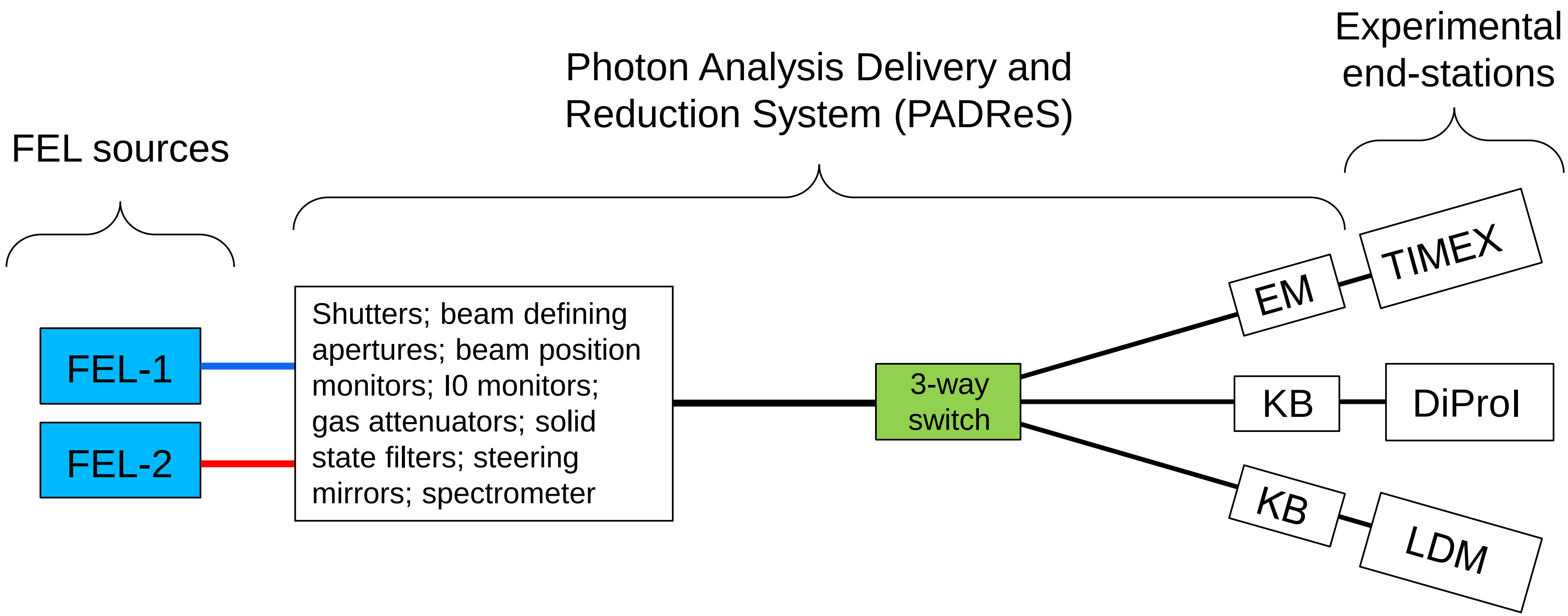
4) Short-term plans (2016-2018)

5) Mid-term plans

The FERMI facility



The FERMI beamlines
@ the beginning of user operation



Experimental end stations

1) **EIS-TIMEX** → solid-state samples under "extreme" and metastable conditions
Masciovecchio et al., JSR 2015

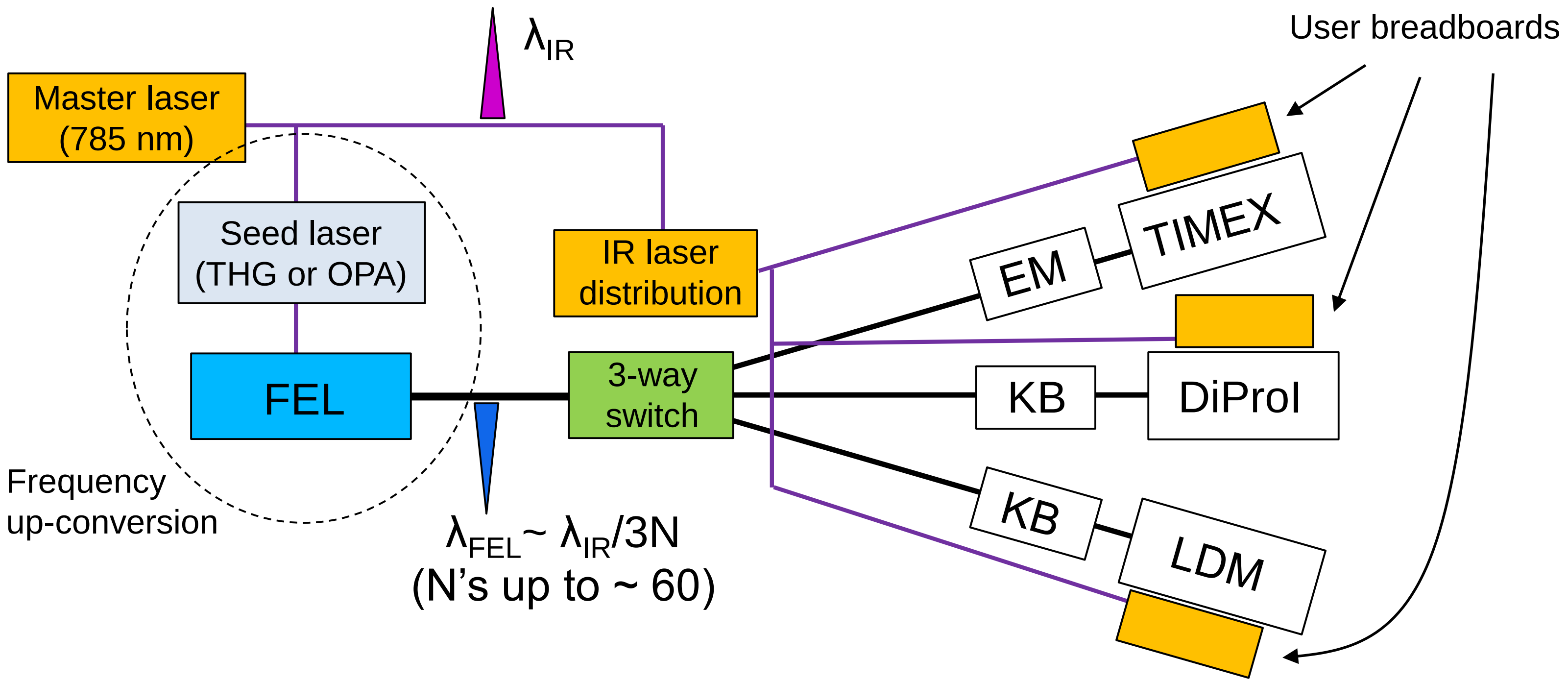
2) **DiProI** → Diffraction and projection imaging ("multipurpose" end-station)
Capotondi et al., RSI 2014

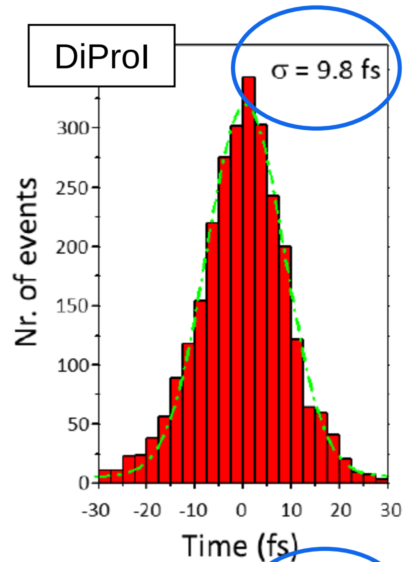
3) **LDM** → Low density matter: gas phase samples (atoms, molecules and clusters)
Svetina et al., JSR 2015

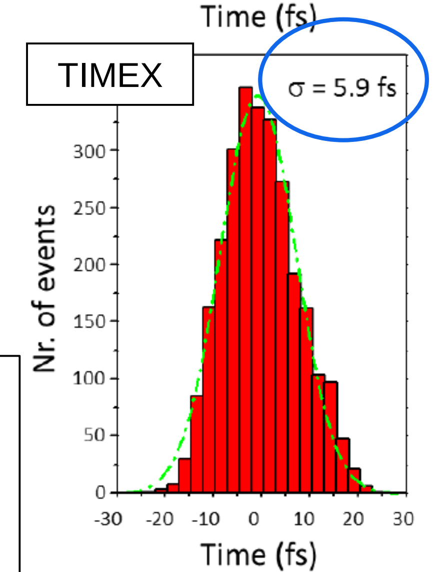
Ellipsoidal Mirror (EM): a few μm^2 focal spot size (fixed)
Kirkpatrick-Baez (KB): adjustable focal spot "HxV" with H,V=10-1000 μm

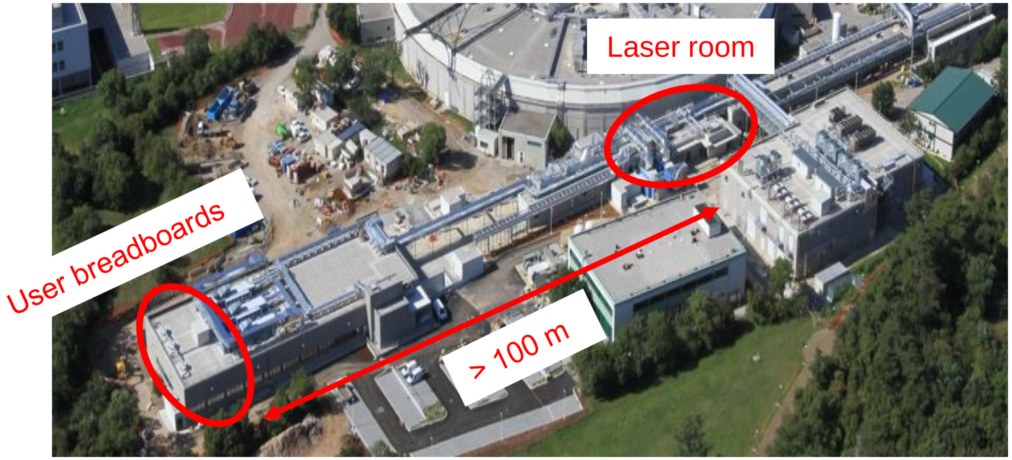
The FERMI beamlines

pump-probe capabilities







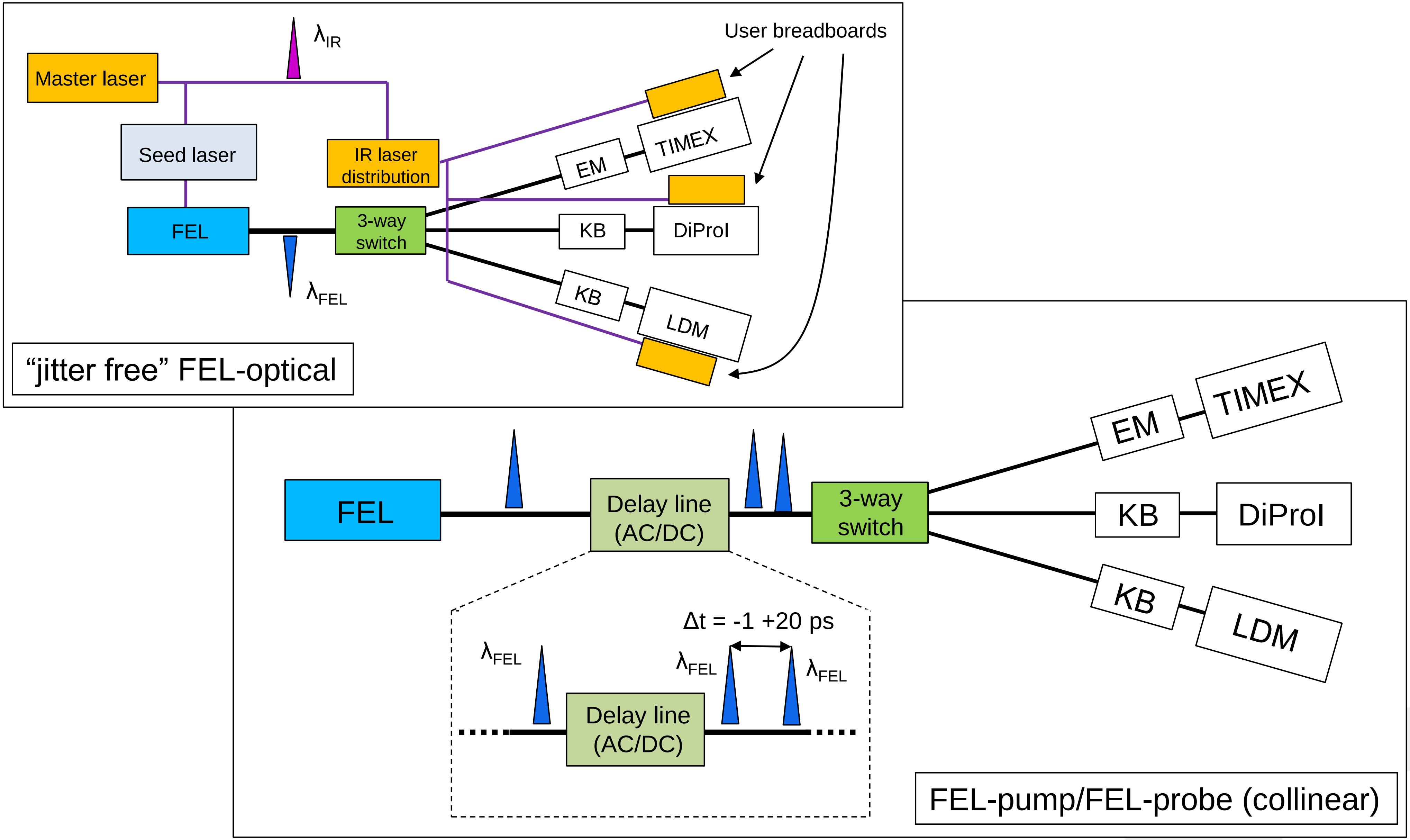


FEL-optical jitter < 10 fs (r.m.s.)
→ < 3 μm stochastic fluctuations in the optical path difference over more than 100 m

Danailov et al. Opt. Express 2014

"jitter free" FEL-optical pump-probe routinely used in almost all user experiments

The FERMI beamlines
pump-probe capabilities



FERMI: a “user driven” facility

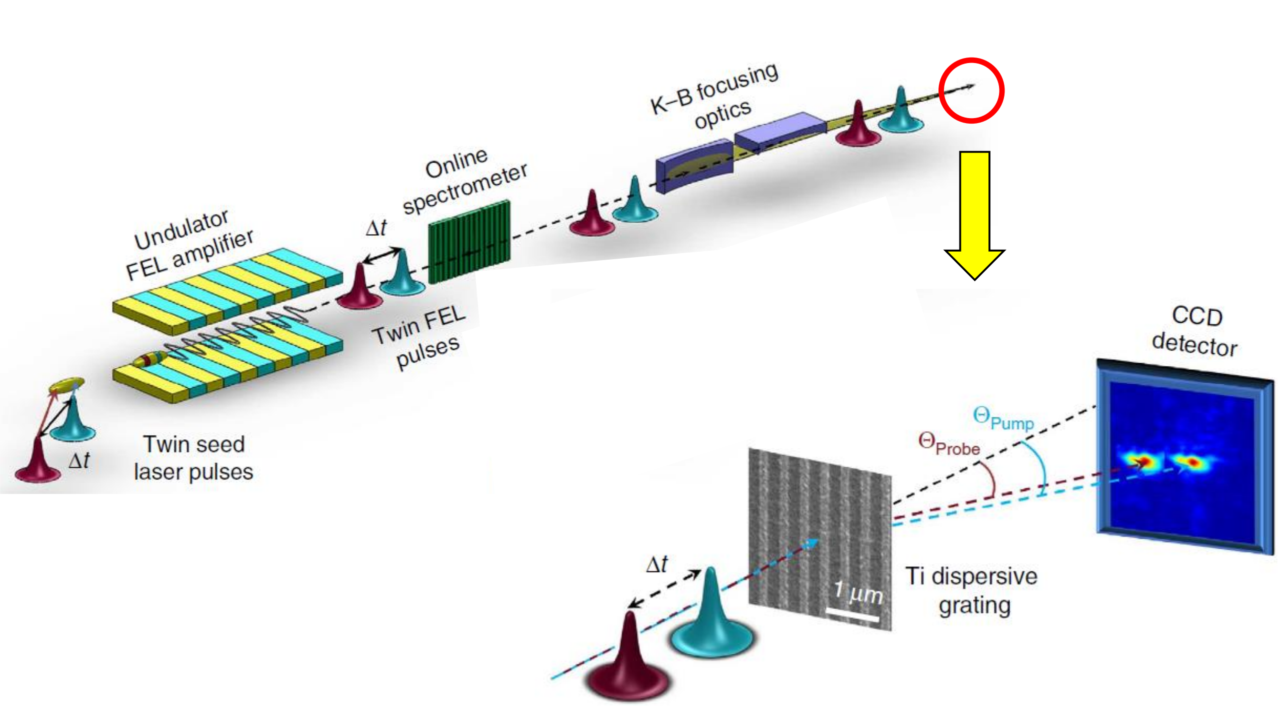
multi-FEL pulses for advanced experiments

The very first user activity of FERMI (Dec. 2012): the “twin-seed” experiment, a
fruitful collaboration between experimental, machine and laser physics teams

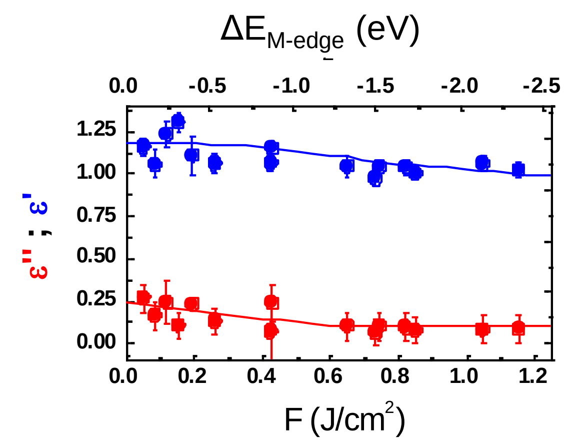
ARTICLE

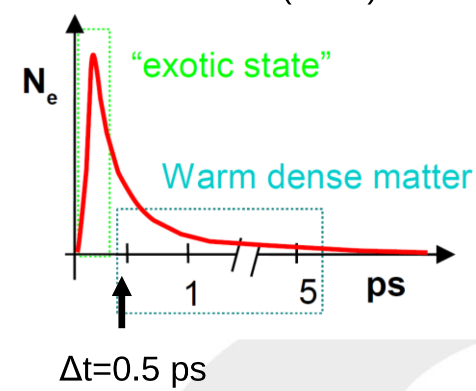
Received 24 May 2013 | Accepted 21 Aug 2013 | Published 18 Sep 2013 DOI: 10.1038/ncomms3476 OPEN

Two-colour pump-probe experiments with a twin-pulse-seed extreme ultraviolet free-electron laser



Follow-up experiment: lineshape analysis of the diffraction pattern vs FEL flux (@ Δt=0.5 ps)





Bencivenga et al, Faraday Discuss. 2014

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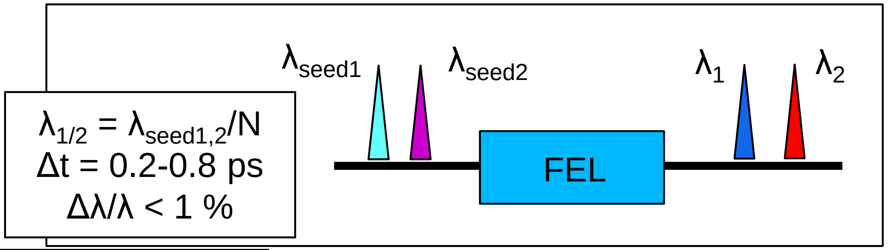
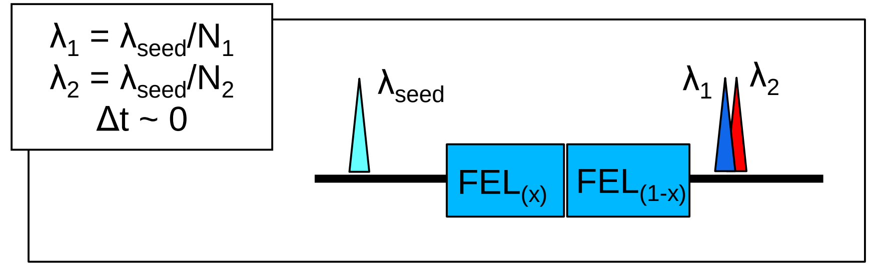
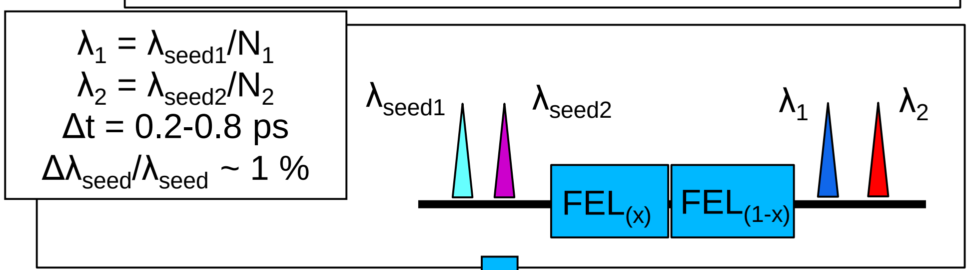
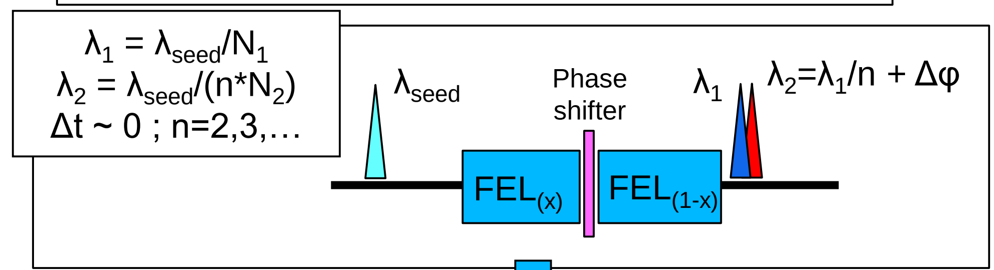
FERMI: a “user driven” facility

multi-FEL pulses for advanced experiments









ARTICLE

Received 21 Aug 2015 | Accepted 3 Dec 2015 | Published 13 Jan 2016 DOI: 10.1038/ncomms10343 OPEN

Widely tunable two-colour seeded free-electron laser source for resonant-pump resonant-probe magnetic scattering

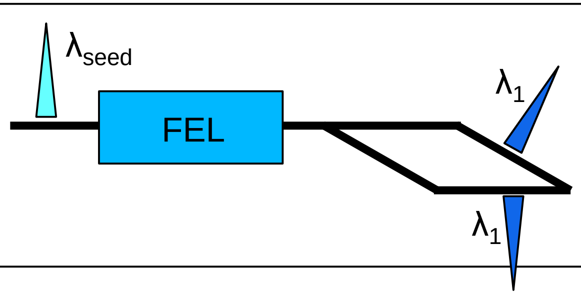
LETTERS

PUBLISHED ONLINE: 22 FEBRUARY 2016 | DOI: 10.1038/NPHOTON.2016.13

nature photonics

Coherent control with a short-wavelength free-electron laser

“conventional” FEL operation + setups to handle (**non-collinear**) FEL pulses

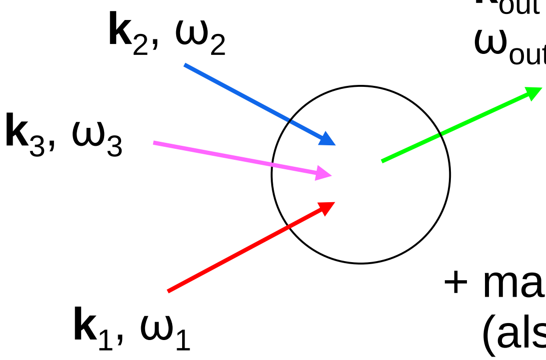


LETTER

doi:10.1038/nature14341

Four-wave mixing experiments with extreme ultraviolet transient gratings

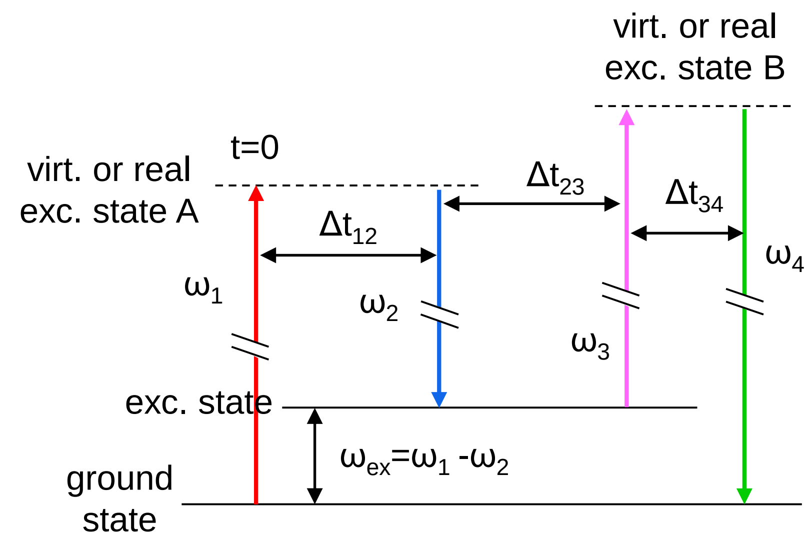
FEL-based four-wave-mixing (FWM)



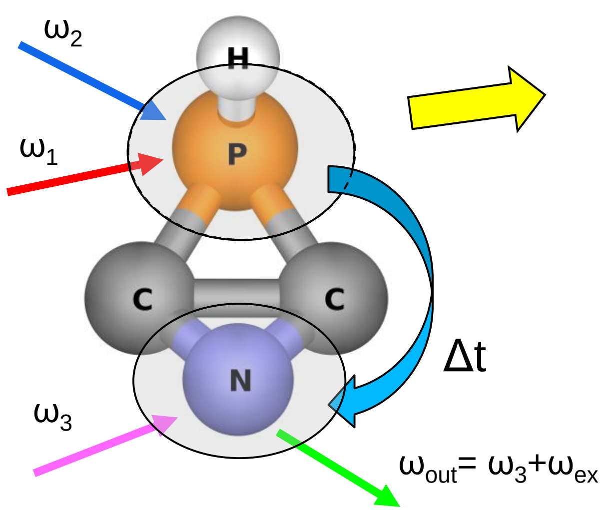
$\mathbf{k}_{out} = \mathbf{k}_1 - \mathbf{k}_2 + \mathbf{k}_3$
$\omega_{out} = \omega_1 - \omega_2 + \omega_3$

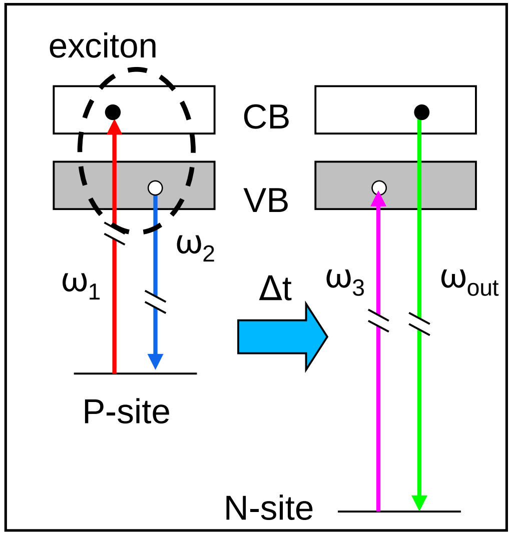
+ polarizzation, bandwith, etc

+ many other processes (also looking for $\mathbf{k}_1+\mathbf{k}_2-\mathbf{k}_3$ and $-\mathbf{k}_1+\mathbf{k}_2+\mathbf{k}_3$ signals)



XUV/soft x-ray coherent Raman scattering (XCRS)[1]





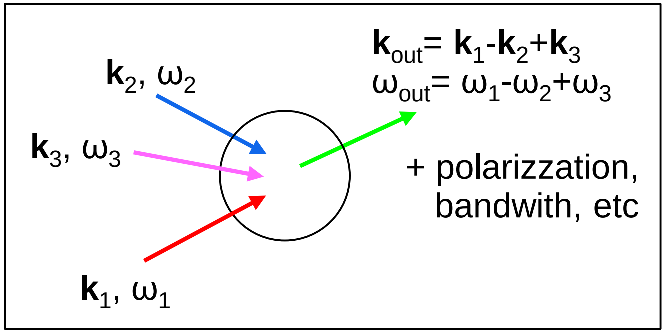
With respect to optical CRS:
i) Larger ω_{ex} range (up to several eV's) → high energy excitations, e.g. valence band excitons.
ii) Resonant enhancement of $\chi^{(3)}$ close to core resonances allows to localize the site at which the elected excitation is created and probed.
iii) Shorter wavelengths → larger wavevectors (FWM signal sensible to the structure) & relaxed dipole selection rules

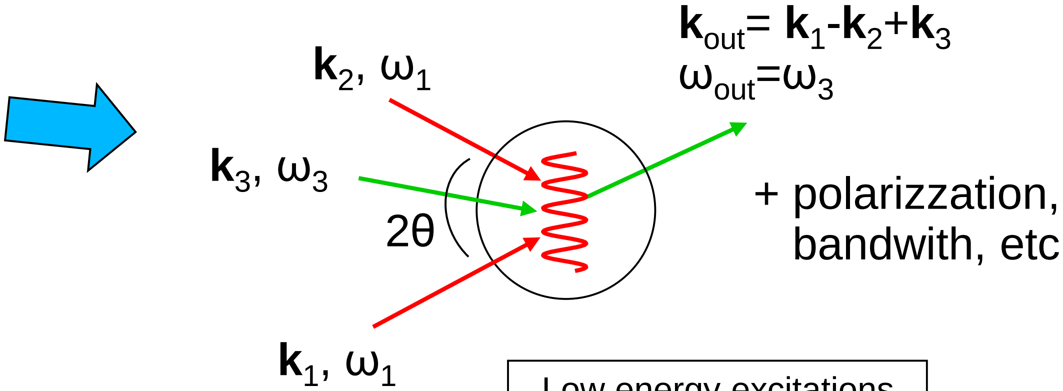
With respect to linear X-ray methods:
Multi-wave and coherent nature of the process → correlations and real-time dynamics between selected (and distinct) atomic sites, not possible in linear methods (light-matter interactions take place on a given atomic site). Plus other kind of selectiveness typical of FWM interactions.

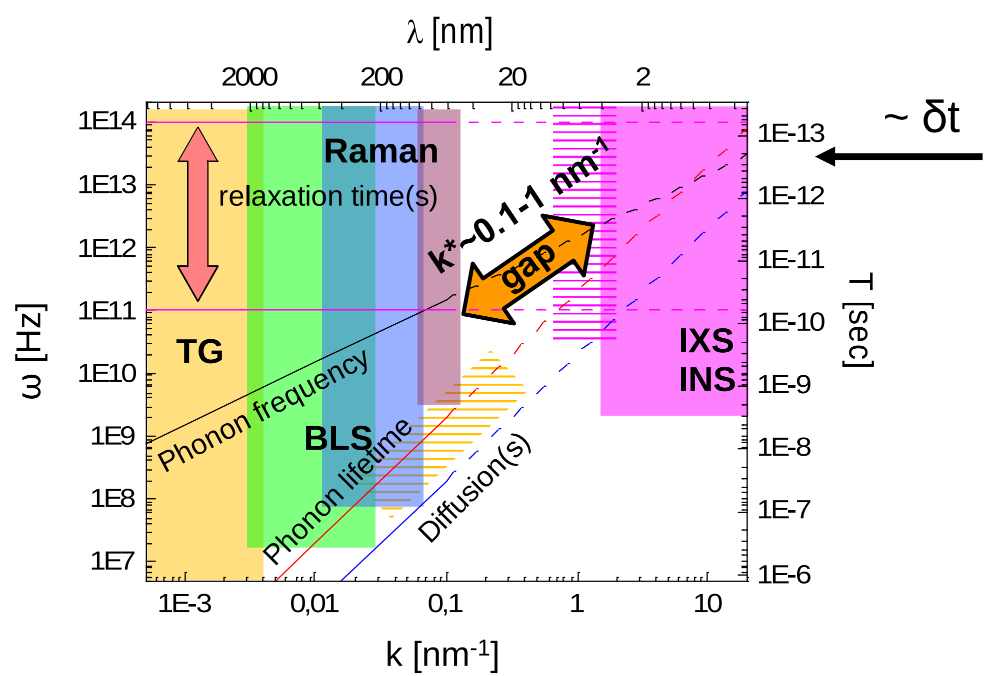
1) Tanaka and Mukamel, Phys Rev Lett 2002

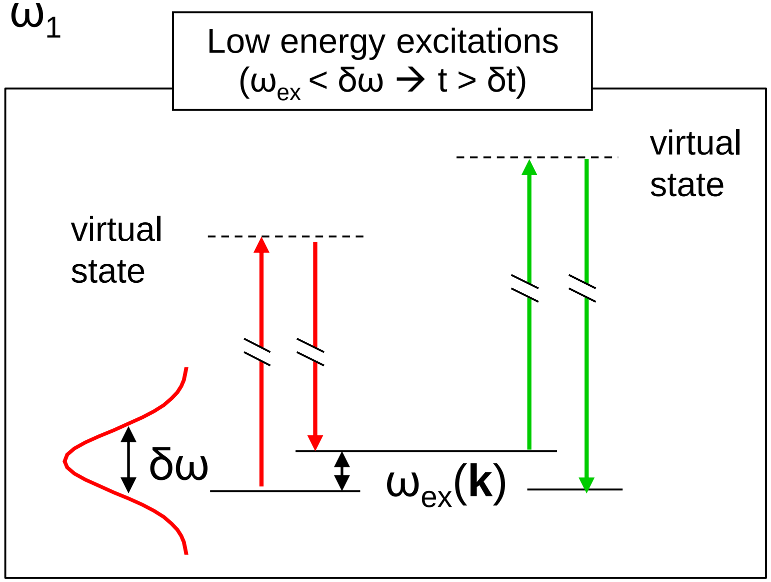
The first step: FEL-based TG

→ the ‘TIMER’ project









Goal: lattice dynamics at the nanoscale (transport phenomena, structural relaxations, acoustic and thermal properties, diffusion processes) on, e.g.: disordered systems (role of nm-sized elastic heterogeneities) and nanostructures (mechanics and thermodynamics)

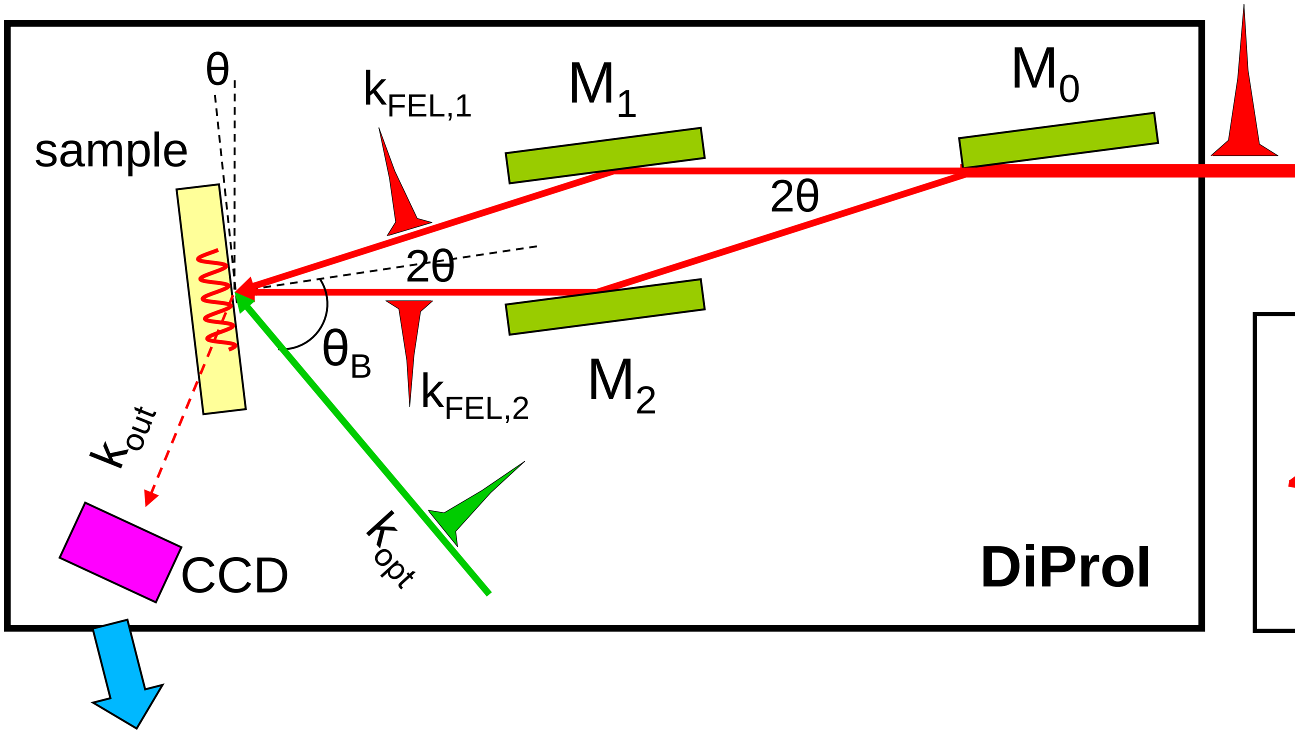
$\mathbf{k} = \mathbf{k}_1 - \mathbf{k}_2$

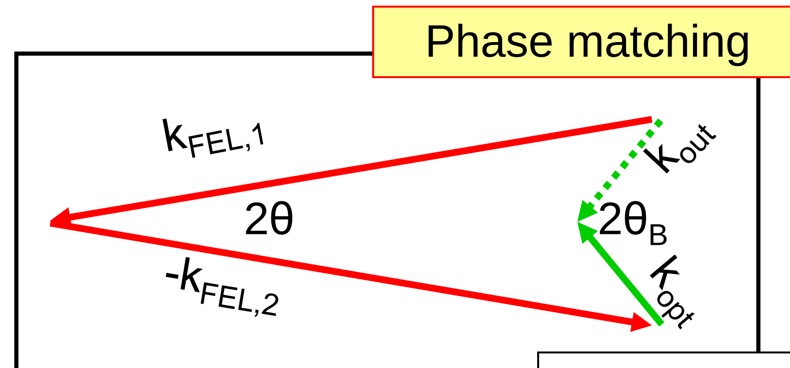
$|\mathbf{k}| = 4\pi \sin(\theta)/\lambda_1$

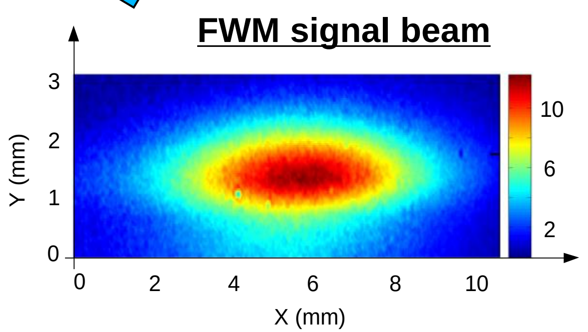
→ $|\mathbf{k}| = 0.02\text{-}2\ nm^{-1}$

(θ/λ_1 up to 50°/4 nm)

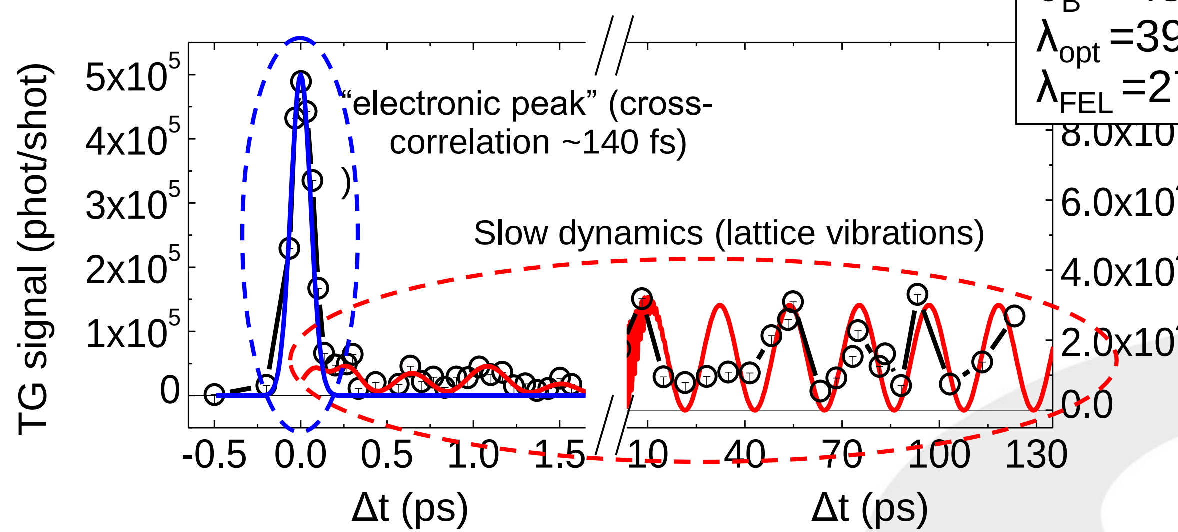
The first step: FEL-based TG
→ “mini-TIMER”(@DiProI)







First evidence of a **FWM stimulated by photons at sub-optical wavelengths**
Capability to **“read” the time evolution of the non-linear response**



$2θ = 5.9^o$
$θ_B = 48^o$
$λ_{opt}$ =393 nm
$λ_{FEL}$ =27 nm

Bencivenga et al, Nature 2015

The first step: FEL-based TG
→ “mini-TIMER”(@DiProI), one year later...

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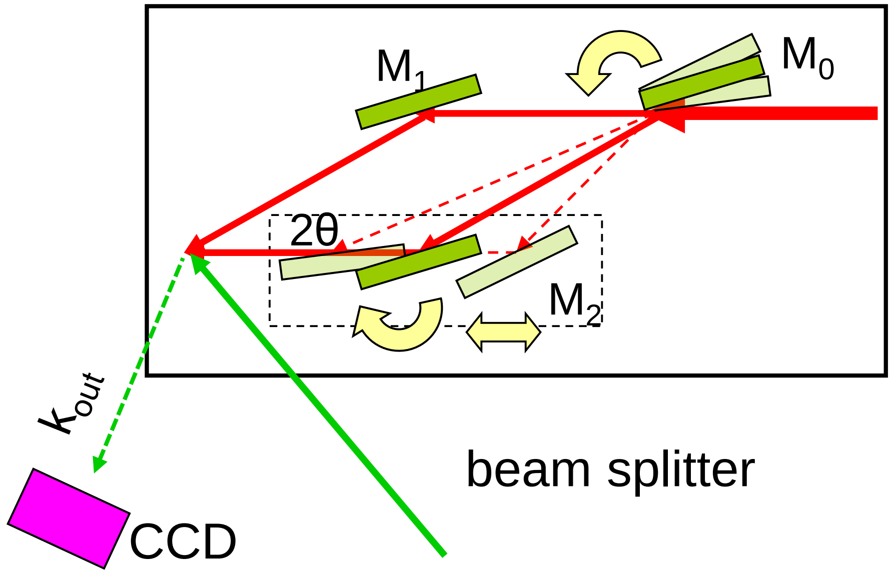
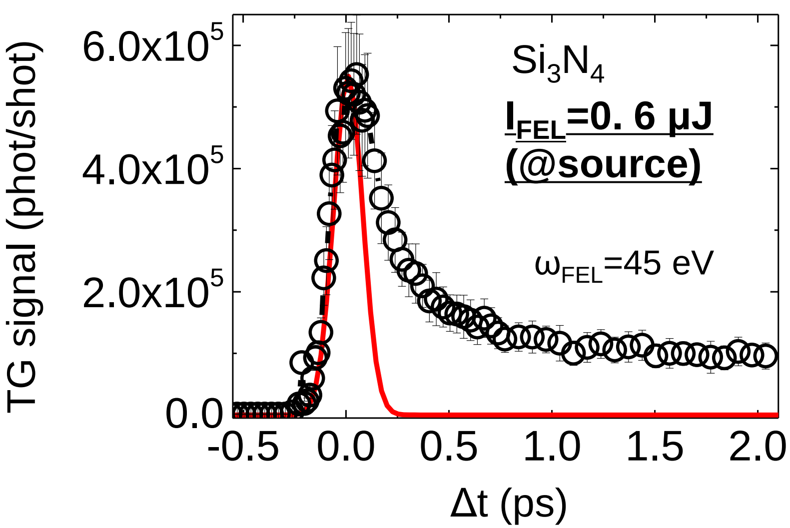
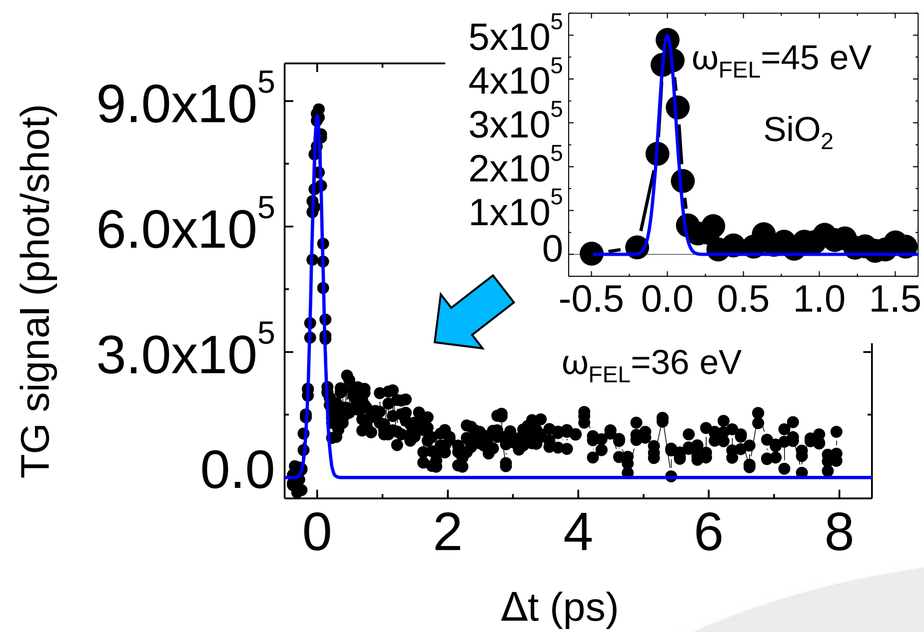


New features (implemented):
i) Larger range for CCD and sample angles and selectable sample-to-CCD distance (fully motorized)
ii) “asymmetric” configuration for larger FEL-FEL delay at fixed 2θ
…and improved experience…



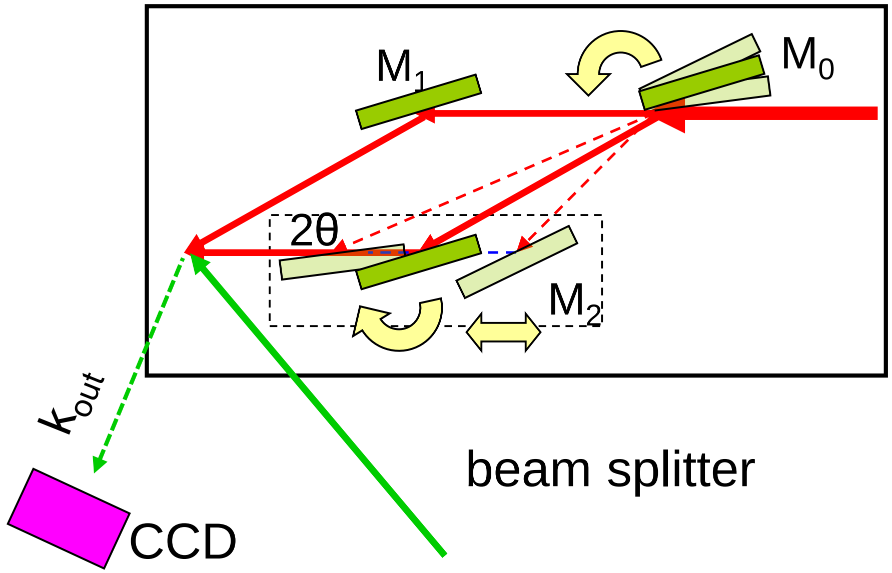
Measurements on other samples (Si_3N_4 and Diamond)

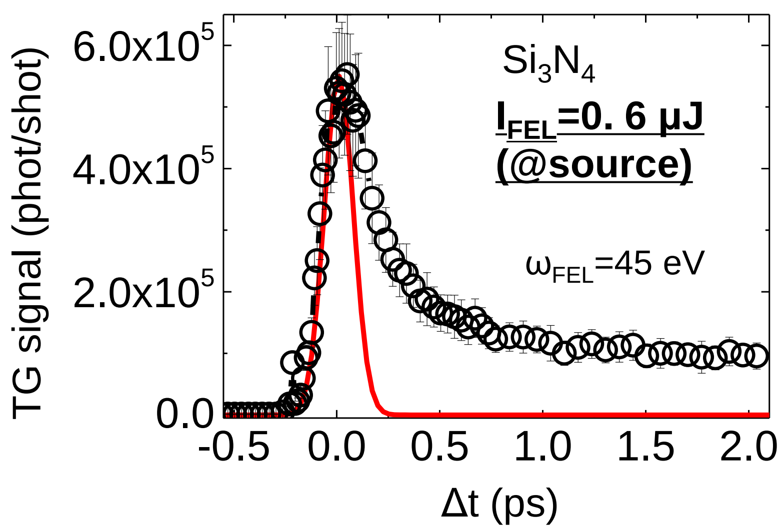


Improved quality of the data (double count rate with half of the FEL intensity, ~ 2 vs 5 μJ /pulse) and faster acquisition time (~ 120 vs 300 sec/point)

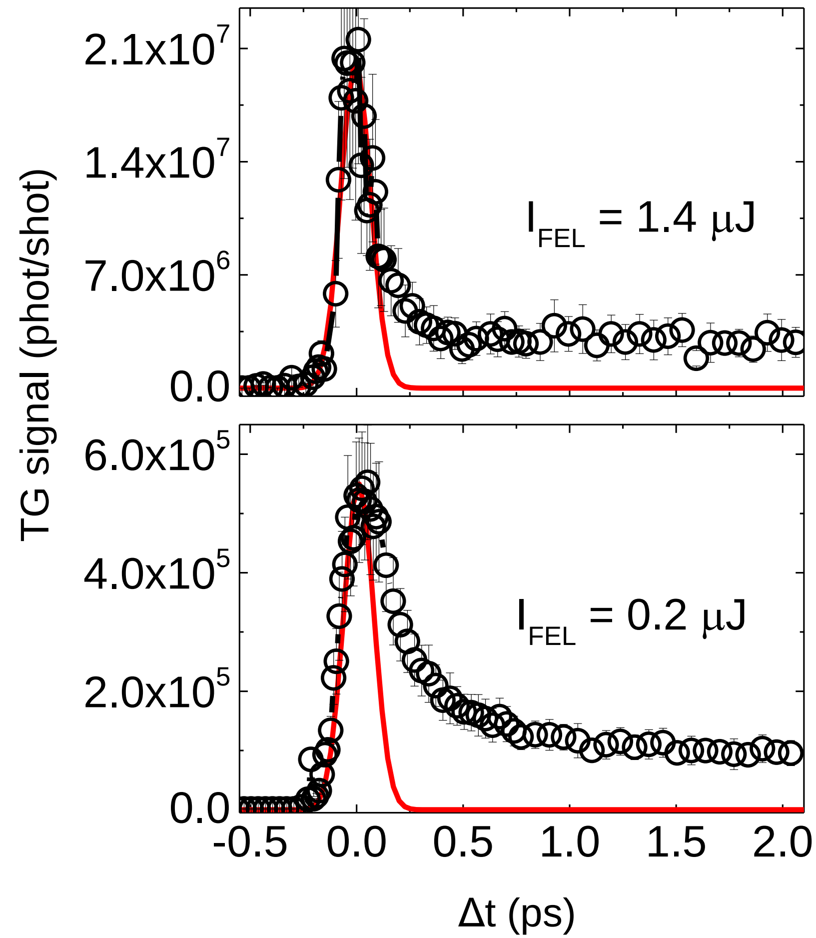
The first step: FEL-based TG

→ “mini-TIMER”(@DiProI), one year later...





Probed other samples (Si_3N_4 and Diamond)



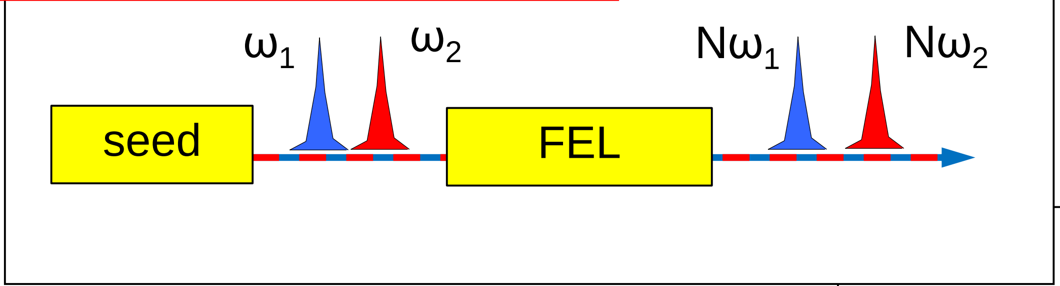
TG vs FEL fluence (on Si_3N_4) → evidence for a fluence dependent time decay → generation and relaxation of a free electron grating

Bencivenga et al., Faraday Discuss. (accepted)

The second step: FEL-based CRS

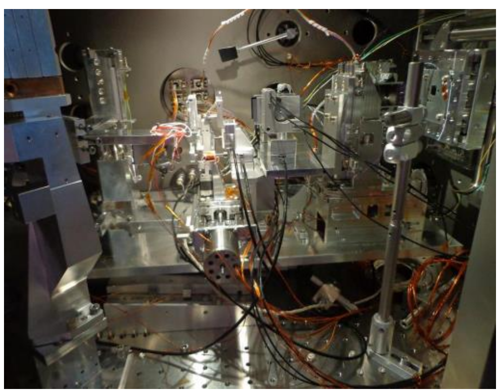
→ "color mini-TIMER" !

Twin-seed two-colour mode[1]

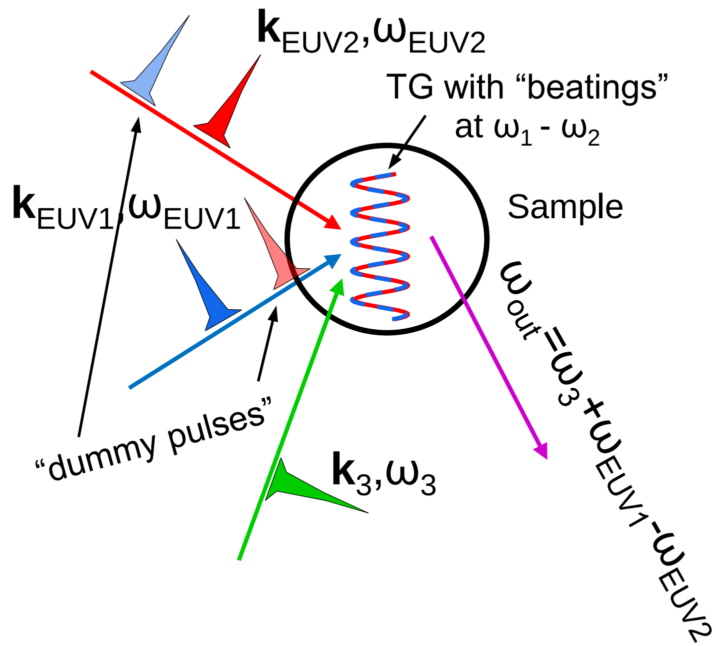


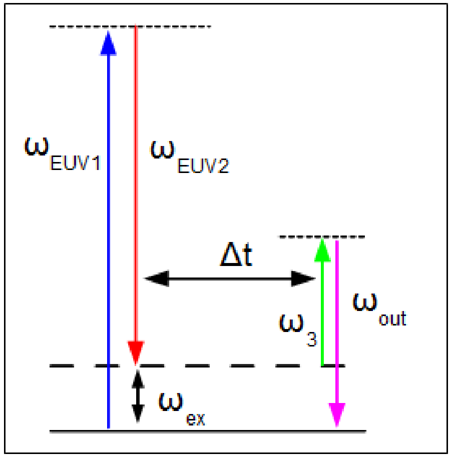
+

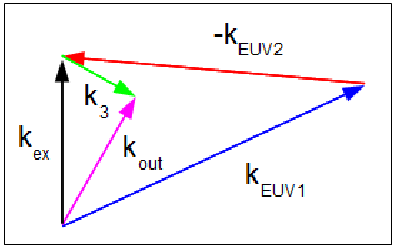
"mini-TIMER"



FEL-based EUV-CRS[2]
(non-resonant / low-ω_{ex})



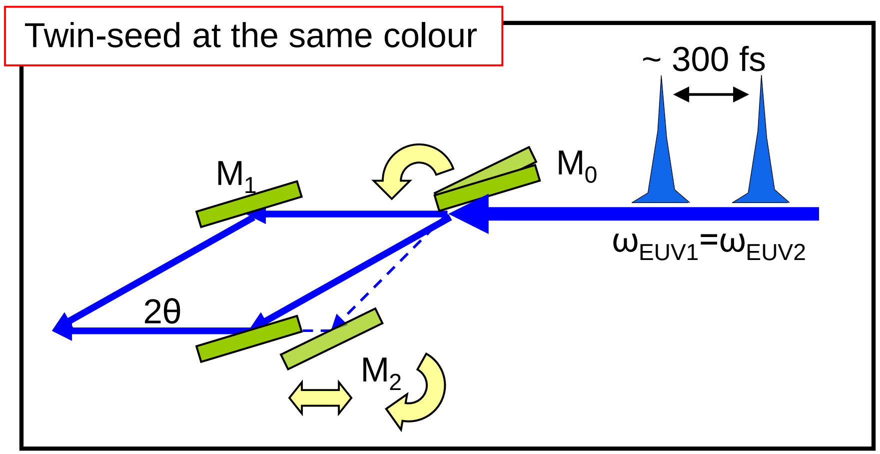


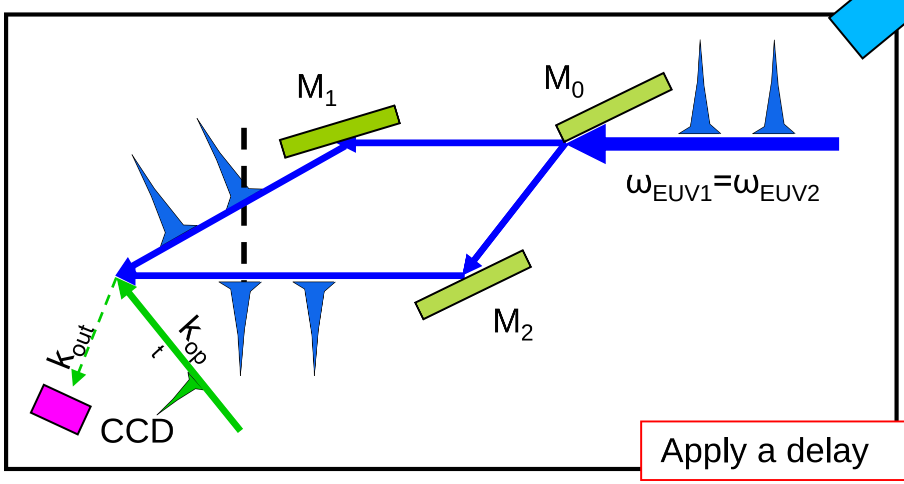


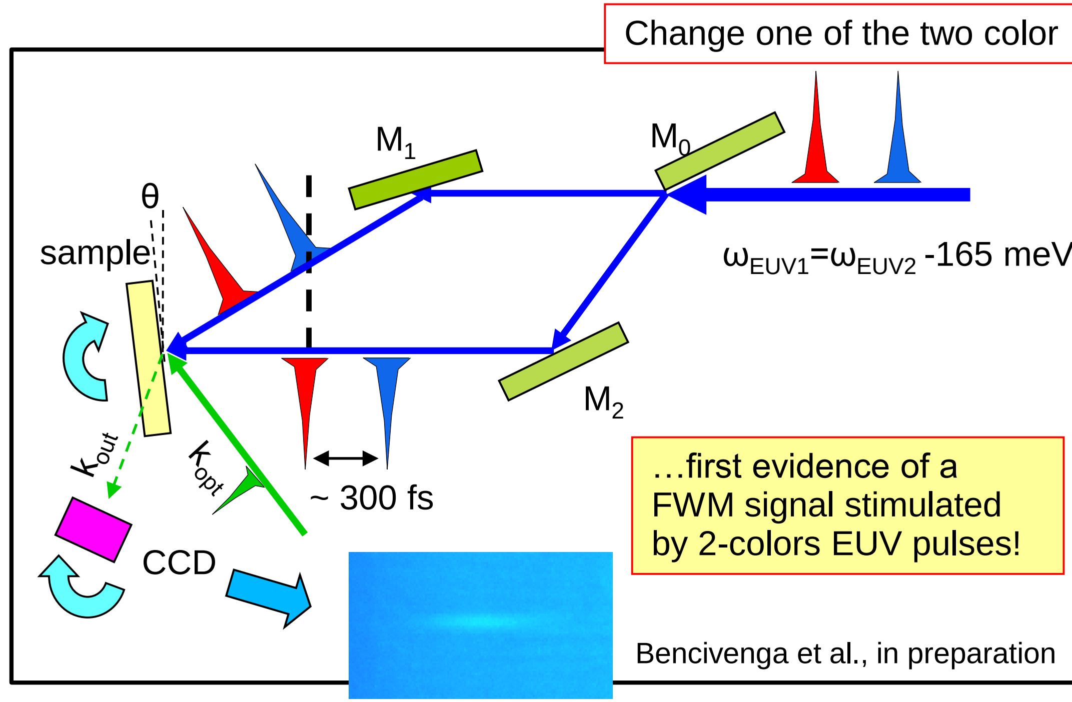
1) E. Allaria et al., Nat. Comm. (2013); 2) F. Bencivenga et al., faraday Discuss. (2014)

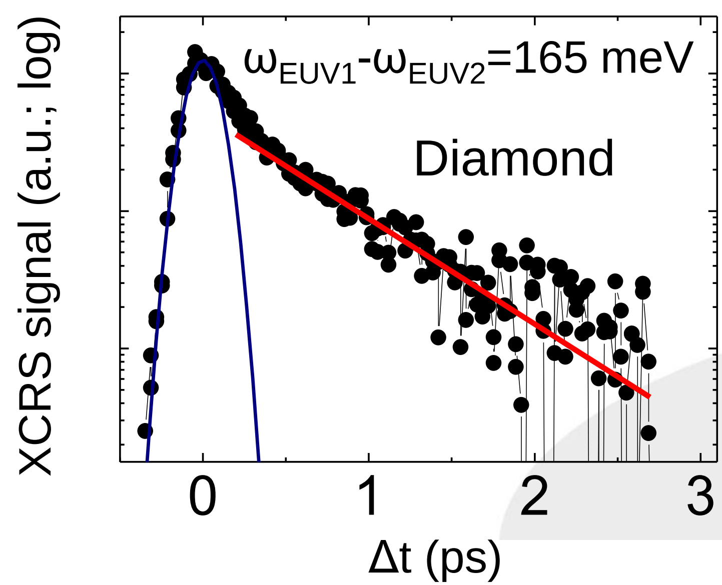
The second step: FEL-based CRS

→ "color mini-TIMER" !

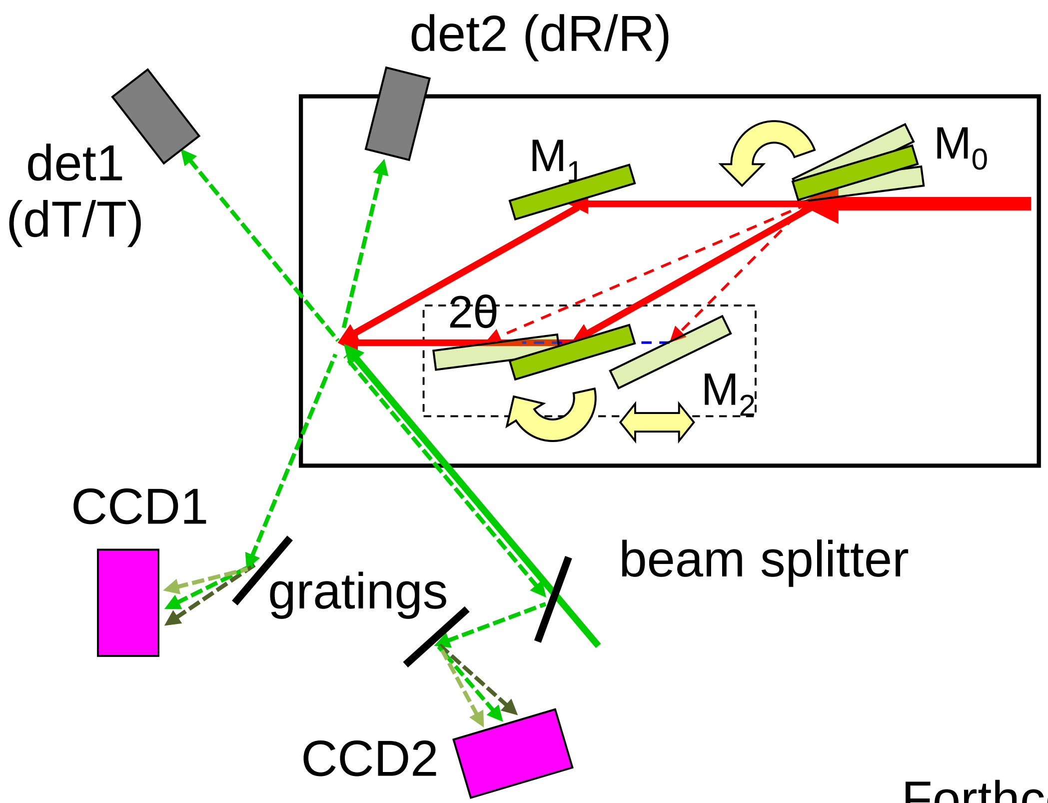


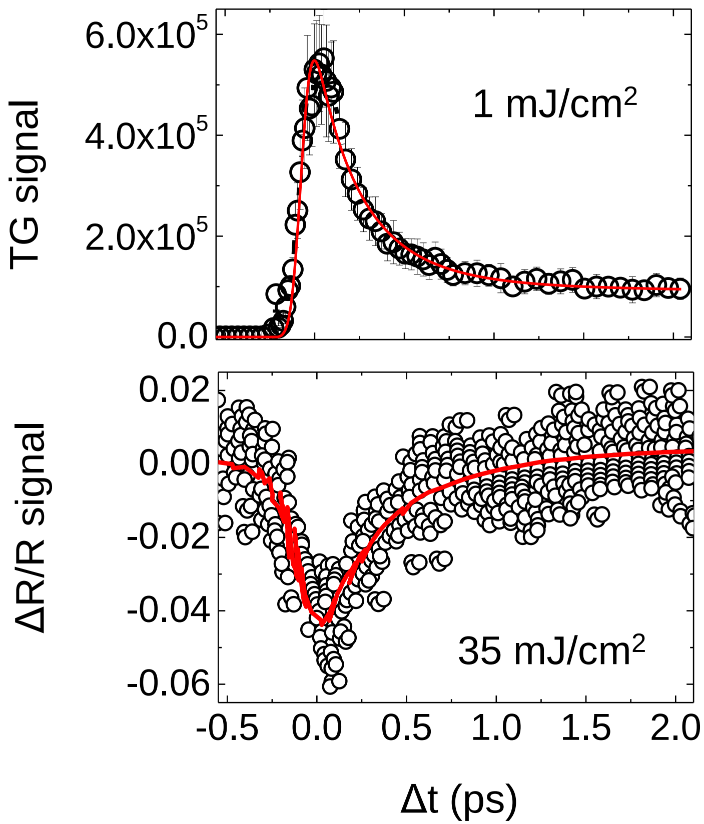






mini-TIMER: planned upgrades

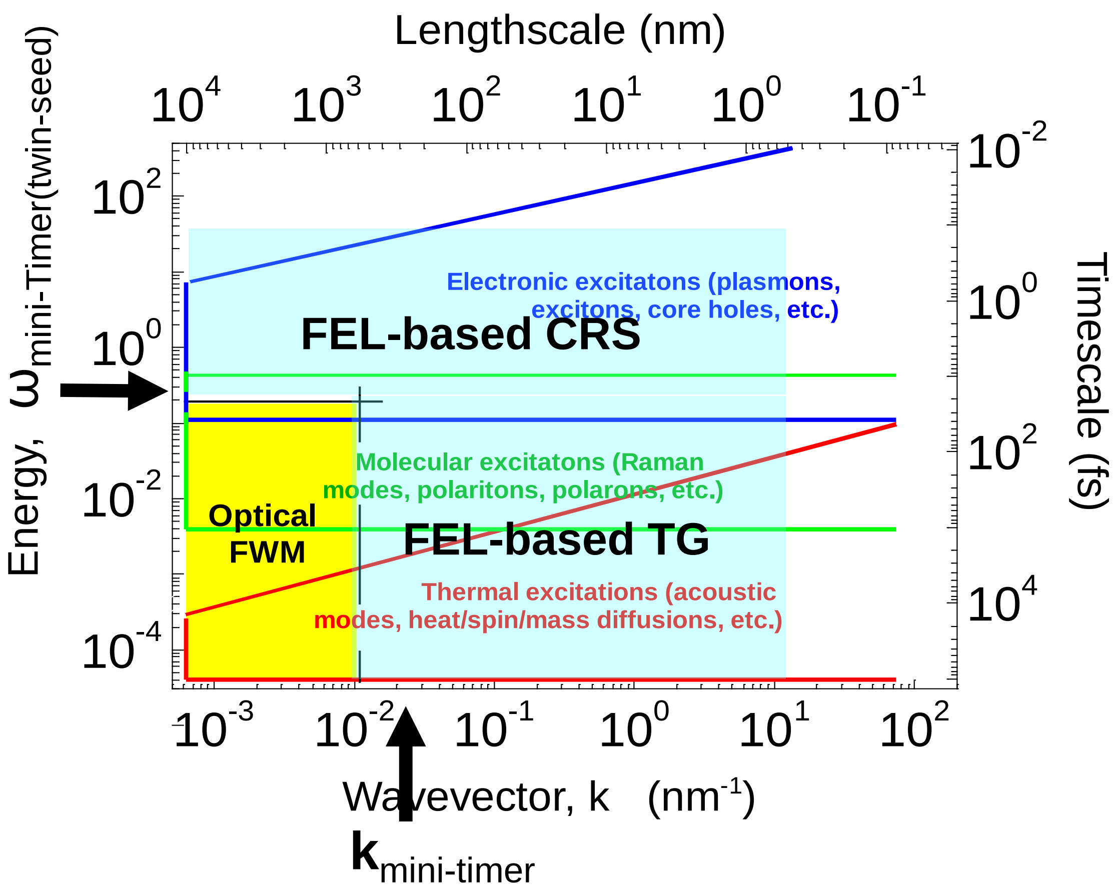


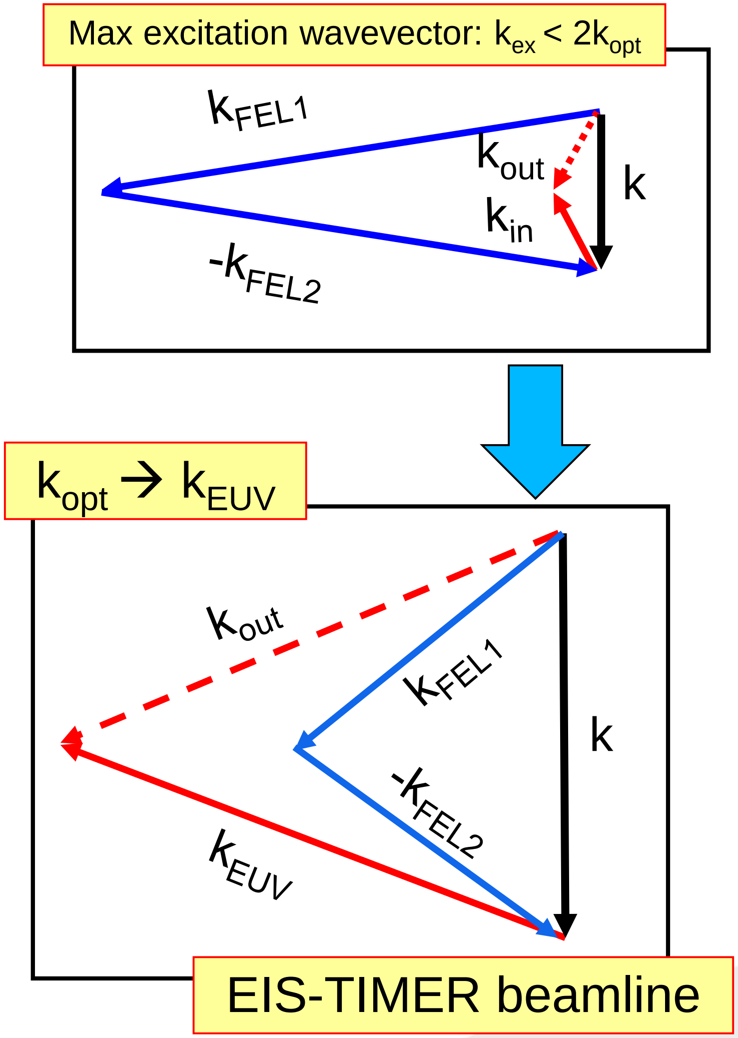


We decided to consider mini-TIMER as an instrumentation available for users → 11 proposals in the 4th call, 4 allocated beamtimes

Forthcoming upgrades (July 2016):
i) Fully encoded system (fast shift from TG to CRS)
ii) 2θ-scans or λ_{FEL}-scans at fixed $|k|=4\pi\sin(\theta)/\lambda_{FEL}$
iii) Parallel detection of transient reflectivity and transmissivity signals
iv) Spectral analysis of FWM signals
v) Parallel detection of the reflected FWM signal

The next step: all-EUV FWM

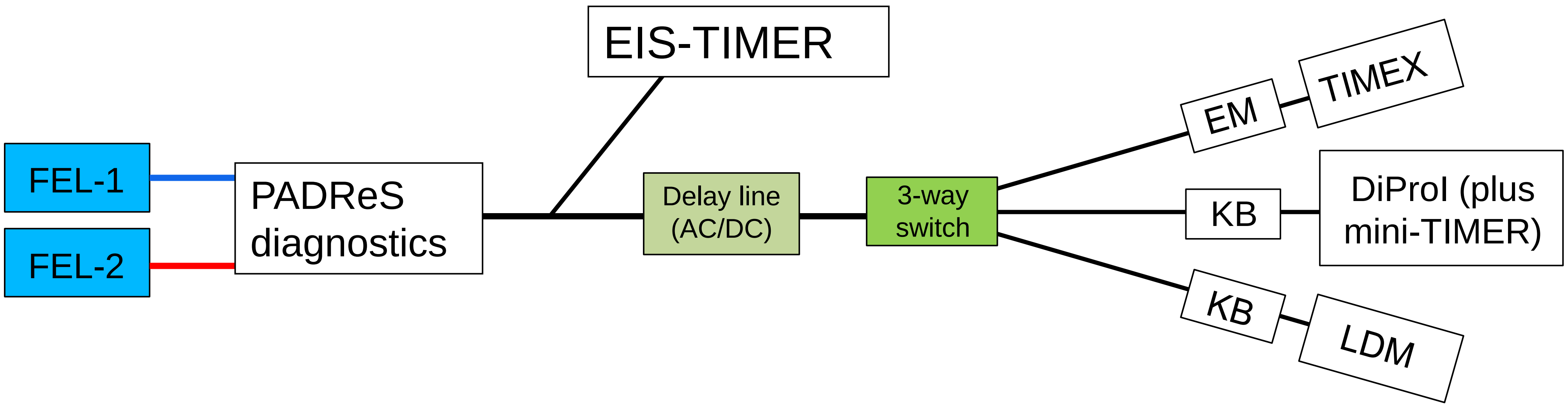




TIMER's goal: lattice dynamics at the nanoscale ($k \sim 0.1$-$1\ nm^{-1}$)

The FEL probe also allows to phase match FEL-pulses with ω_{EUV1}-ω_{EUV2} in the multi-eV range (e.g. valence excitations)

New experimental facilities
→ the TIMER family



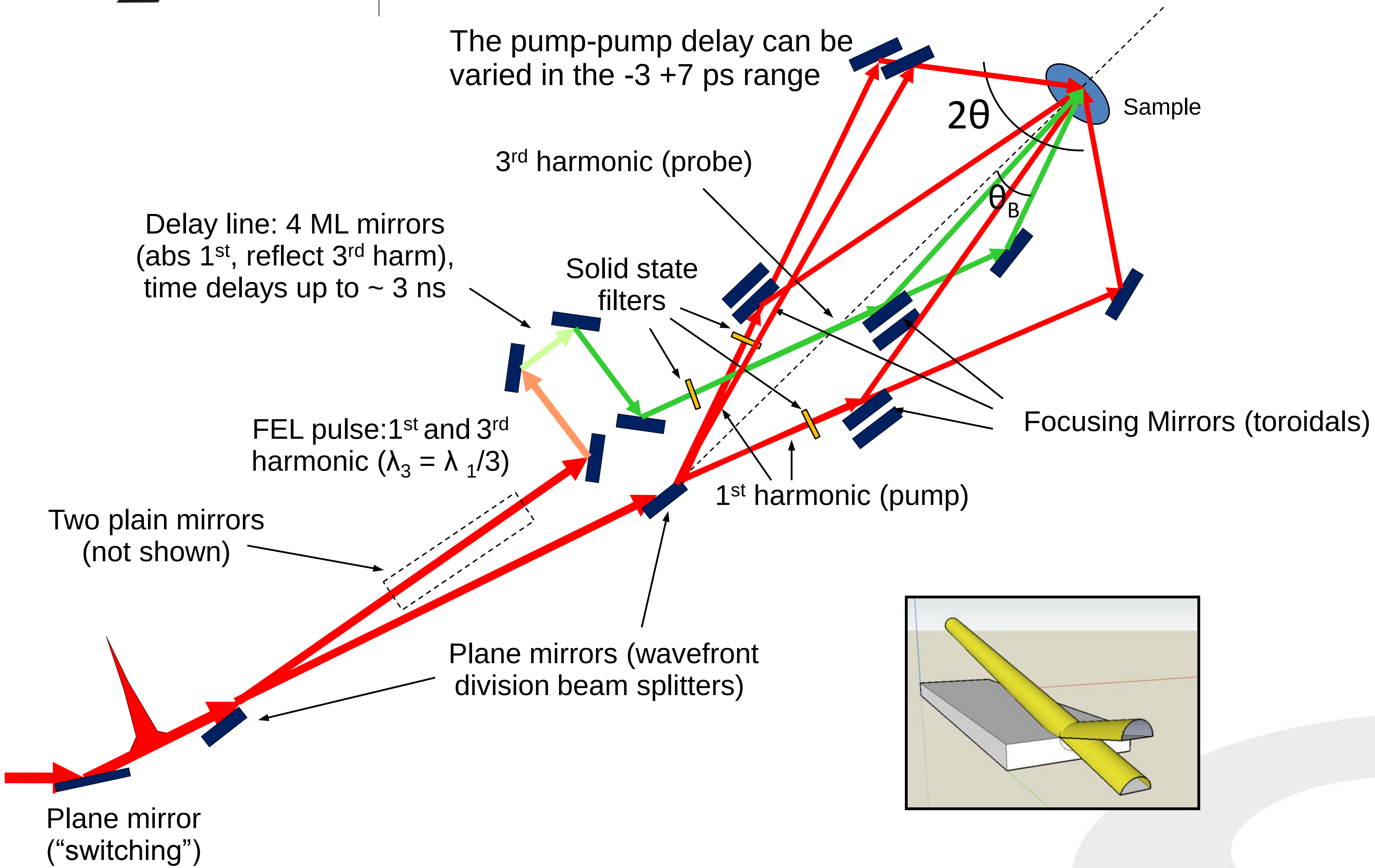
Experimental end stations

1) **EIS-TIMER** → "all FEL-based" FWM experiments, presently **under commissioning**: two commissioning weeks in 2015, two more foreseen in 2016, plus the first "real" experiment! **User operation will start in 2017** (13 proposal from the 5th call, plus 11 for mini-TIMER).
   Bencivenga et al., JSR 2015
2) **mini-TIMER@DiProI** → Highly requested setup (~ 30 % of DiProI's proposals), we are going to **upgrade the setup** in order to be as much complementary as possible with EIS-TIMER. If optical probing is acceptable, mini-TIMER is better than TIMER because of the possibility to continuously vary the FEL crossing angle
3) **nano-TIMER** → a test setup based on diffraction gratings, presently **under design** (Svetina and Bencivenga). The realization and the first test is foreseen in **late 2017**

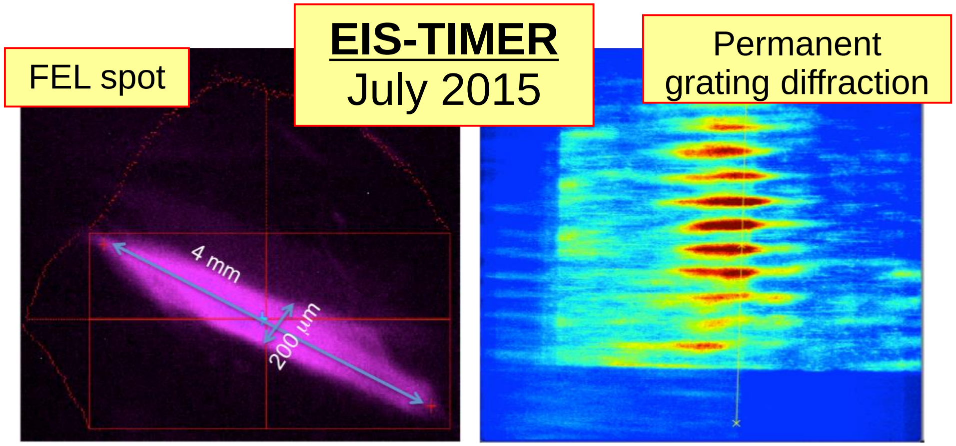
Bencivenga et al., NJP 2013; JSR 2015

New experimental facilities

→ EIS-TIMER

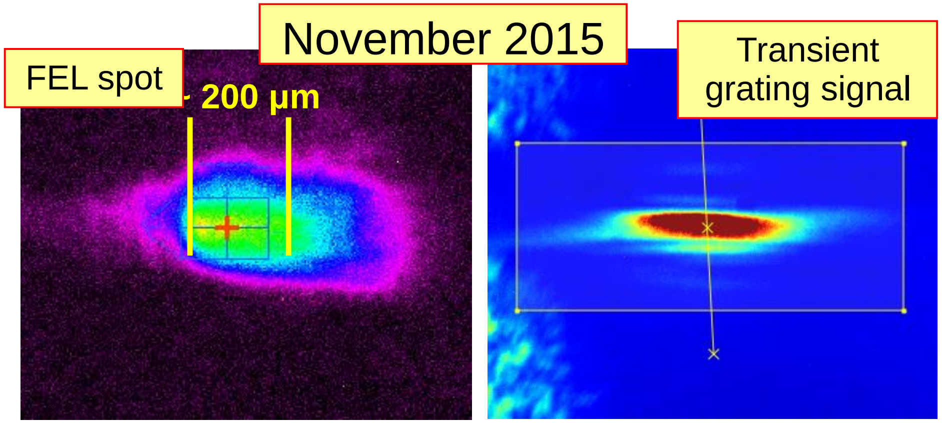


New experimental facilities
→ EIS-TIMER

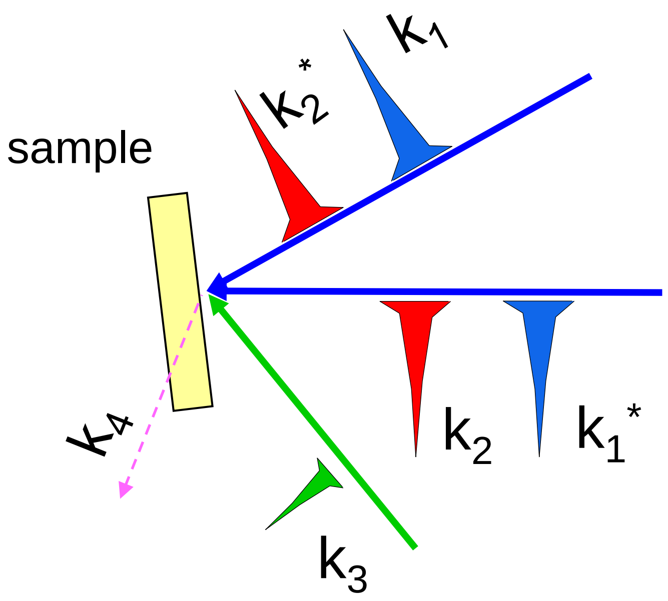


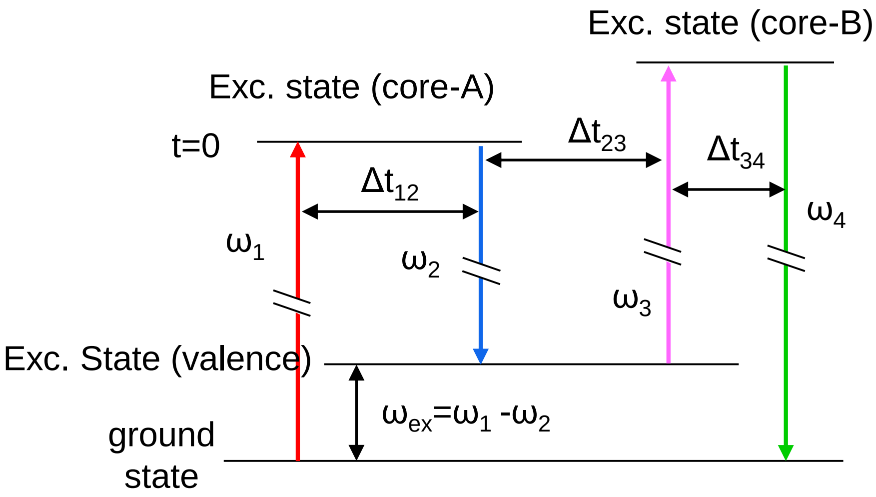
1) First commissioning week (July 2015): FEL “pump” beams at the sample, with an ameliorable focus but still enough to provide evidences of FEL-FEL interference (i.e. the generation of permanent gratings)

2) Second commissioning week (Nov. 2015): much better focus, better shape of permanent gratings and evidence for a TG signal



New experimental facilities
→ nano-TIMER





In principle one cannot ignore the (k_3,k_1^*,k_1) and (k_3,k_2^*,k_2) interactions, in particular if real excited states are involved...

3) **nano-TIMER** → a test setup based on diffraction gratings, presently **under design** (Svetina and Bencivenga). The realization and the first test is foreseen in **late 2017**

Bencivenga et al., NJP 2013; JSR 2015

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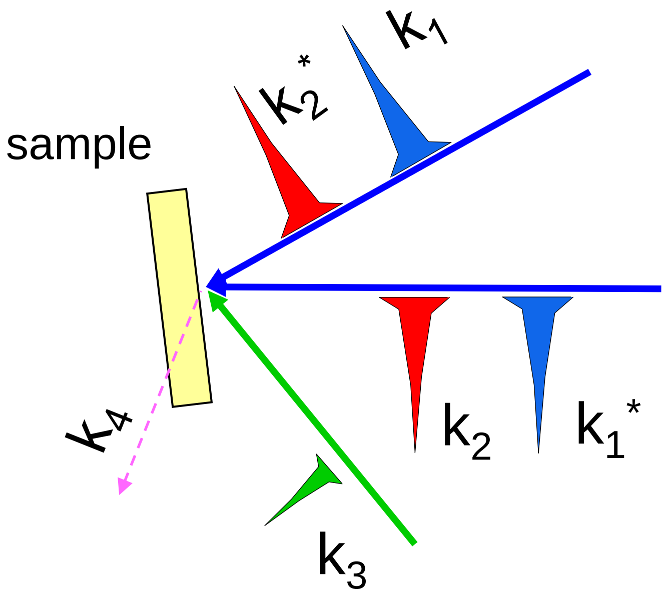
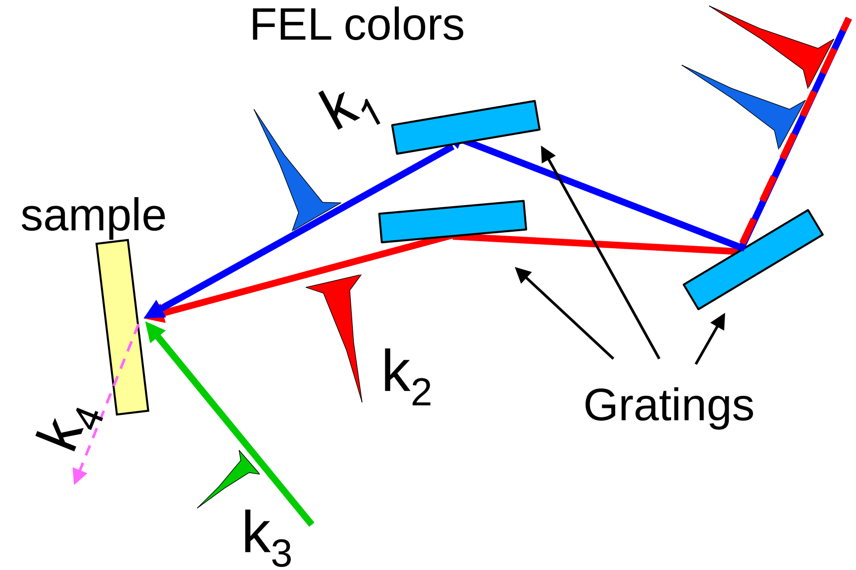
New experimental facilities
→ nano-TIMER

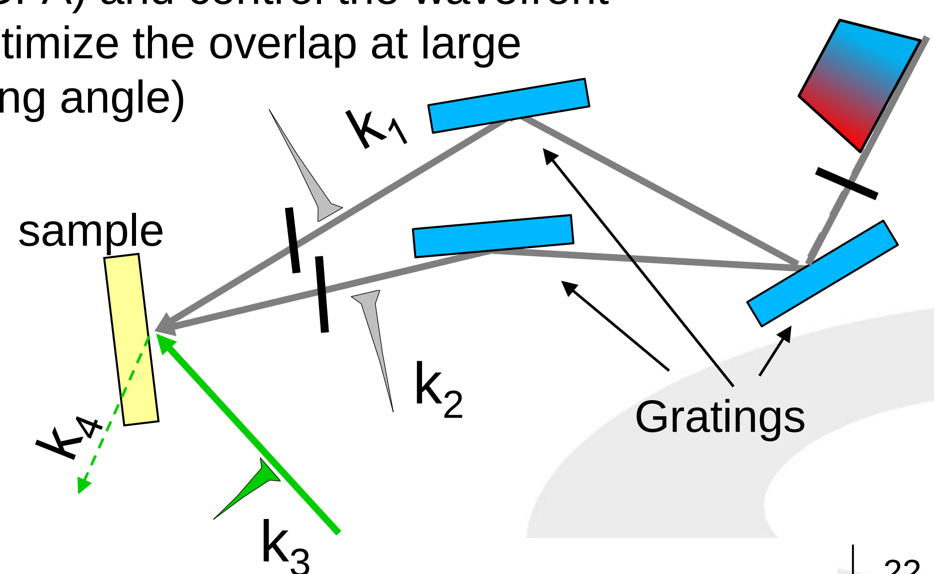
"wavefront division" beamsplitting (mirrors)



"clean" selection of the FEL colors



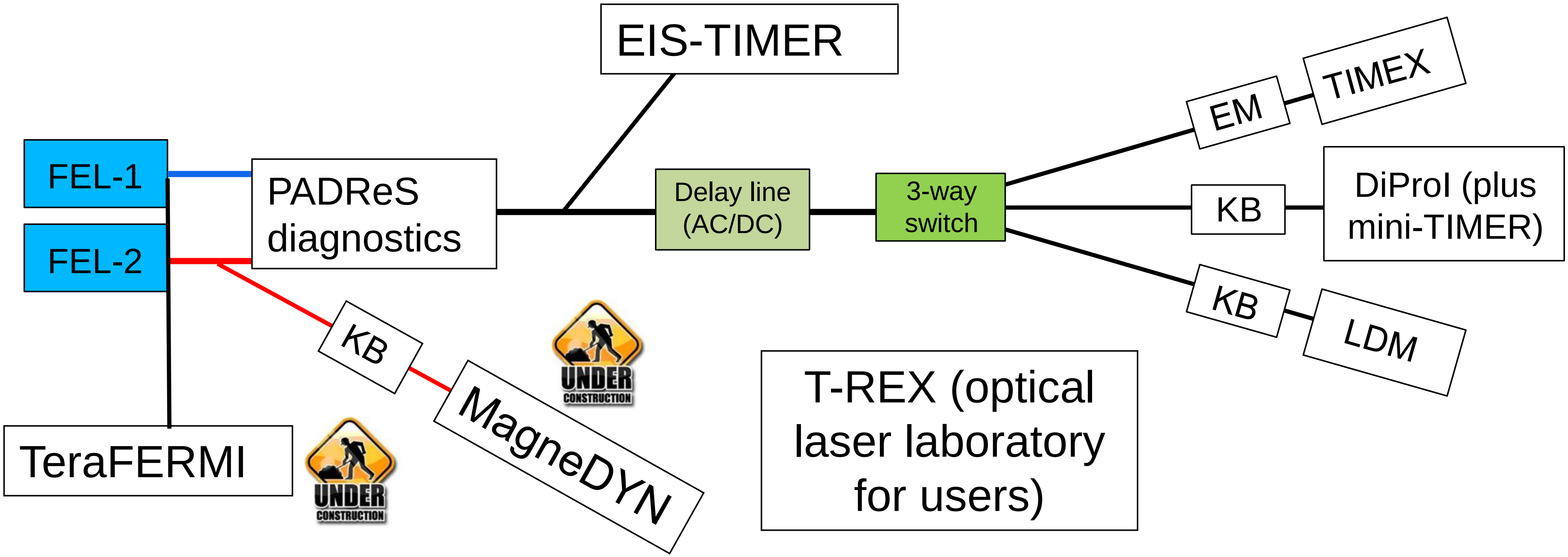
+ "compress" FEL "broadband" pulses (e.g. CPA) and control the wavefront tilt (optimize the overlap at large crossing angle)



3) **nano-TIMER** → a test setup based on diffraction gratings, presently **under design** (Svetina and Bencivenga). The realization and the first test is foreseen in **late 2017**

Bencivenga et al., NJP 2013; JSR 2015

New experimental facilities

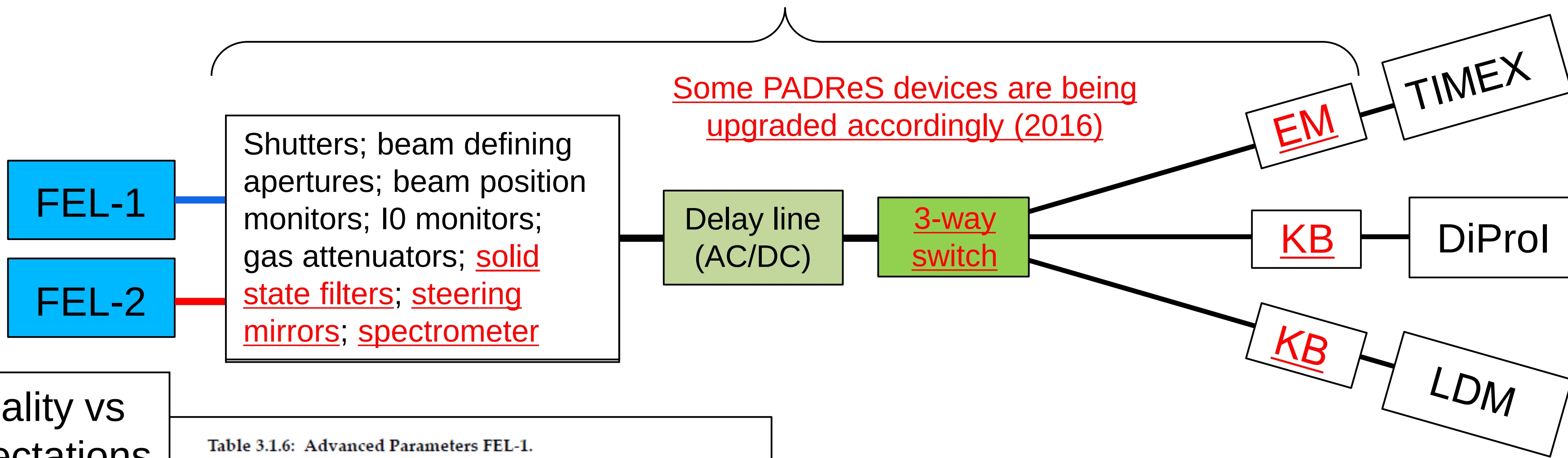


Experimental end stations

1) **MagneDyn** (magnetization dynamics and phase transitions in complex materials, ultrafast control of demagnetization); only FEL-2 beamline → **beamline assembling (Nov. 2016), commissioning in 2017**
2) **TeraFERMI** (THz pulses between 1 mm and 20 μm, with MV/cm fields); "parasitic" beamline that can work in parallel with the others → **first light in Dec. 2015, commissioning in 2016**
3) **T-REX** (user-dedicated ultrafast optical laboratory)

Elettra Sincrotrone Trieste

The “old” FERMI beamlines vs the actual performances of the source(s)



Reality vs expectations

Table 3.1.6: Advanced Parameters FEL-1.

Parameter	*Value*	*Comments*
Photon energy range	100 ÷ 40 nm	
Pulse length	50 ÷ 100 fs	Any value in between is acceptable
Bandwidth	About 20 meV (FWHM)	Close to TL
Polarization	Linear / Circular	Variable
Repetiton rate	50 Hz	
Peak power	1 ÷ 5 GW	+ multipulse

Table 3.1.7: Advanced Parameters FEL-2.

Parameter	*Value*	*Comments*
Photon energy range	40 ÷ 10 nm	
Pulse length	100 ÷ 1000 fs	Any value in between is acceptable
Bandwidth	> 5 meV	Closed to TL
Polarization	Linear / Circular	Variable
Repetiton rate	50 Hz	
Peak power	0.3 - 1 GW	

Now down to ~15 nm (most of the EUV range) and fully tunable (core-level spectroscopy)

Key parameters for FEL-1, limited experience with FEL-2 but this will come soon (the user operation will start in a few weeks)

Now down to ~4 nm

Expected ≈ 20 fs

PHYSICAL REVIEW X 4, 041040 (2014)

Control of the Polarization of a Vacuum-Ultraviolet, High-Gain, Free-Electron Laser

SCIENTIFIC REPORTS

OPEN **Single Shot Polarization Characterization of XUV FEL Pulses from Crossed Polarized Undulators**

Received: 22 April 2015
Accepted: 29 July 2015

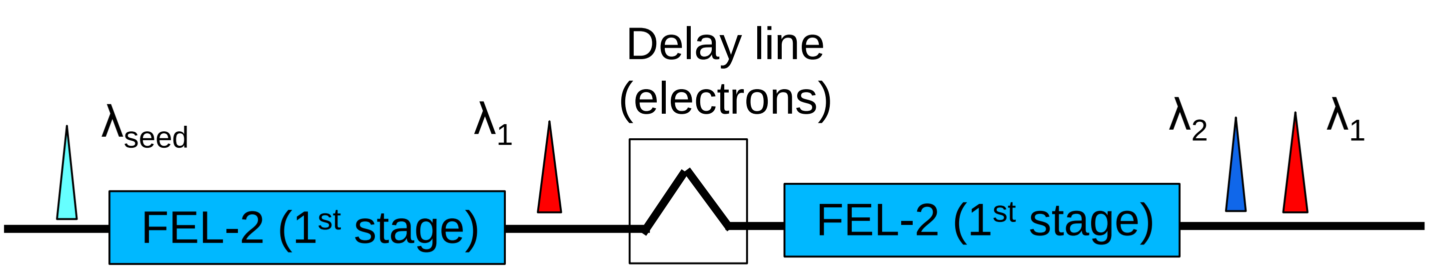
Coherent addition of FEL pulses with different polarizations

FEL sources

FEL-1: stable and reliable performances established

FEL-2: nominal performances established down to 4 nm

User experiments with FEL-2 are coming soon (**2016**)
To date **~30 % of user proposals** in the 4th and 5th calls;
among them another multi-pulse/multi-color approach
(FEL-2 is intrinsically a two-color source!)



$\lambda_1 = \lambda_{seed}/N1$
$\lambda_2 = \lambda_{seed}/(N1*N2)$
$\Delta t \sim 0.3$ ps

FEL sources (short-term plans)

FEL-1: stable and reliable performances established

FEL-2: nominal performances established (down to 4 nm!)

User experiments with FEL-2 are coming soon (**2016**)

Design, construction and test of a prototype for a new high gradient accelerator LINAC structure (**2018**)

Echo-Enabled Harmonic Generation experiment on FEL-2 (**2018**)

…but you already have some results!

FEL sources (mid-term plans)
4 points are under evaluation:

Shorter wavelengths (deeper in the soft x-ray)

Shorter pulse duration (CPA, towards the fs)

Improved multi-pulse operation (ECHO)

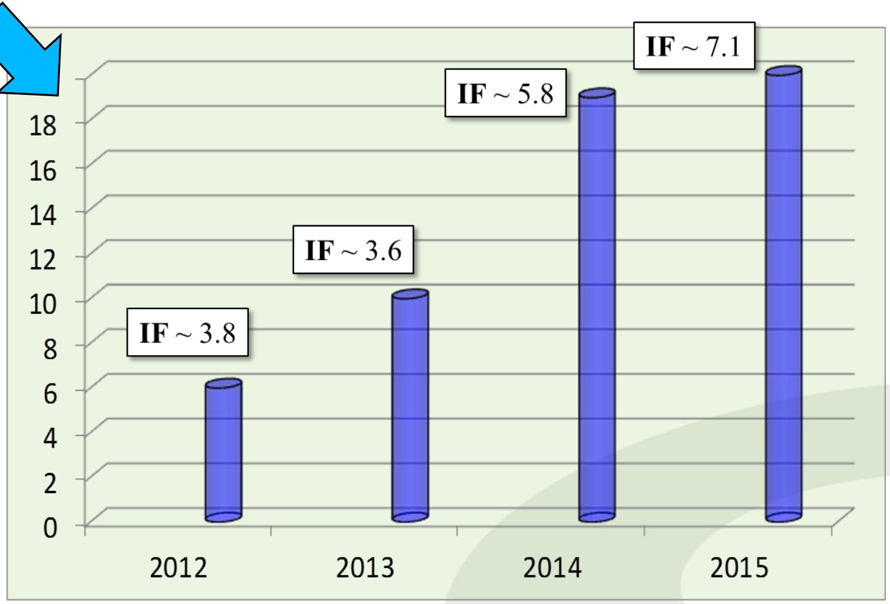
Beautiful options for soft x-ray FWM!

Parallel operation of FEL-1 and FEL-2

Submitted / allocated proposals	1st call	2nd call	3rd call	4th call
	2,14	2,25	3,13	3,24

Waiting time ~ **one year** between the decision on beamtime allocation and the experiment

Publications (~ one each exp…)



Conclusions

1) FEL-1 operations are stable and reliable, from the source down to the end stations. Multi-pulse/multi-color operation has permitted to achieve high-profile results
2) Short-term plans (machine):
   i) user operation with FEL-2 (from 2016), including multi-pulse operation (in 2017)
   ii) prototype of a new LINAC structure (2018)
   iii) "echo" experiment (2018)
3) Short-term plans (photon transport/end-stations):
   i) upgrade of the photon transport to allow reliable operation down to 4 nm (ongoing)
   ii) upgrade of the mini-TIMER system to meet user requirements (ongoing)
   iii) commissioning of EIS-TIMER (ongoing) and beginning of user operation (2017)
   iv) design (ongoing) and construction of nano-TIMER (2017)
   v) commissioning (ongoing) and user operation of TeraFERMI (2017)
   vi) construction (late 2016) and commissioning of MagneDYN (2017)
   vii) user operation at T-REX
4) The "future of FERMI" (in four points):
   i) shorter wavelengths (ideally down to ~1 nm, soft x-ray range)
   ii) shorter time duration (ideally down to the fs range, CPA)
   iii) multi-pulse operation (ECHO)
   iv) parallel operation of FEL-1 and FEL-2

Acknowledgements, an advertisement and a proposal

Our best results come from internal collaborations between experimental teams (C. Masciovecchio), laser team (M. B. Danailov), machine physicists (L. Giannessi) and photon transport team (M. Zangrando)

What about ATHOS-pump/ARAMIS-probe (or vice-versa)?

only 7 ns (2 meters!)

- Independently tunable
- Time-zero ok
- Spectral overlap at 1 nm
- In double pulse mode you can have 4 pulses
- Jitter ???