Coherent free-electron laser pulses:

the user perspective

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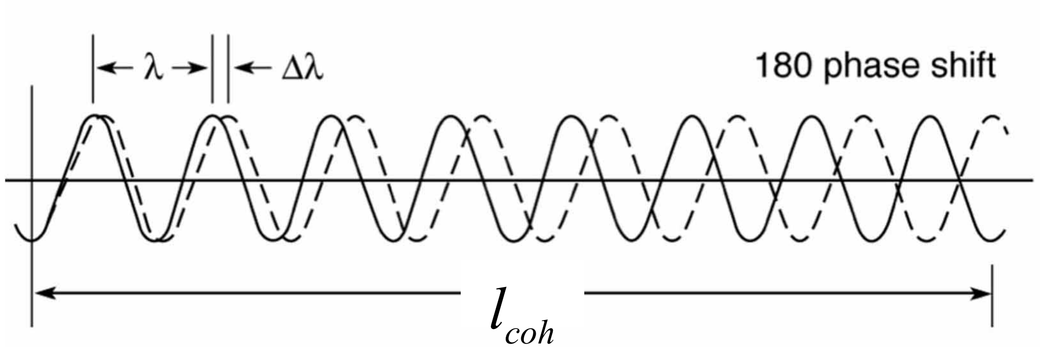
Classical coherence

Coherence quantifies the stability of the relative phase between two waves at different points, either in time or in space. Coherence expresses the potential for the waves to interfere.

Temporal coherence



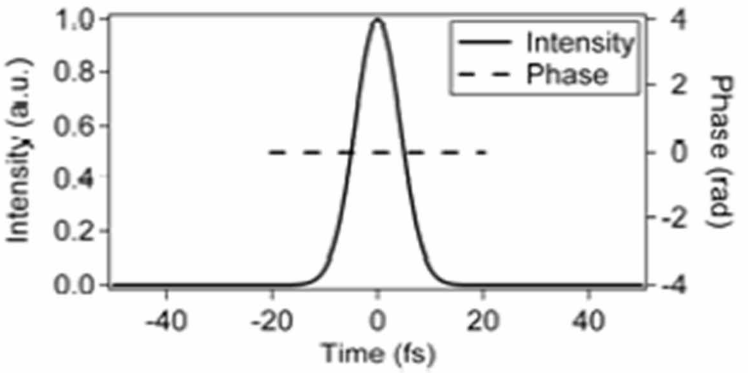
Coherence length and coherence time

$$\tau_{coh} = \frac{l_{coh}}{c}$$

Time-bandwidth product

$$\tau_{coh}\Delta\nu = const$$

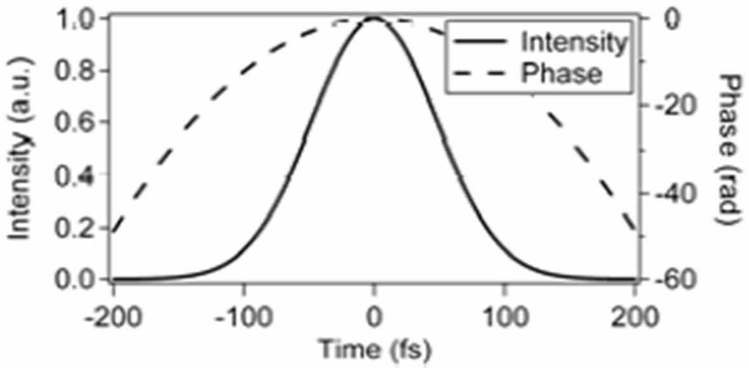
Classical coherence



Flat temporal phase, pulse duration coincides with coherence time

TRANSFORM-LIMITED FULLY COHERENT PULSE

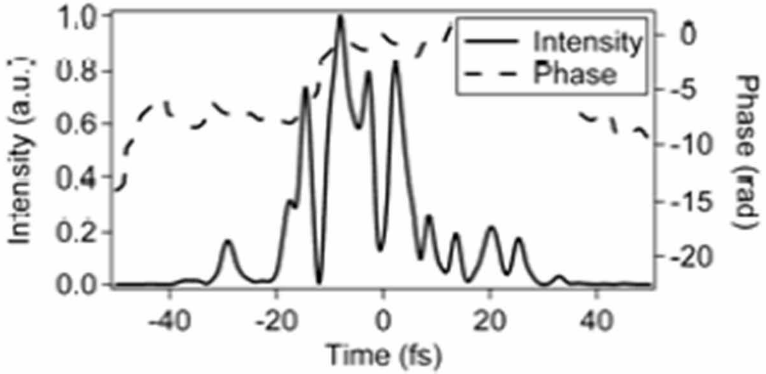
Seeded FEL



Chirped temporal phase, pulse duration is <u>shorter</u> than coherence time

Partially coherent pulse

SASE FEL



Stochastic temporal phase, pulse length <u>much shorter</u> than coherence length

Partially coherent pulse

Focus

Needs of “standard” and “advanced” FEL users in terms of longitudinal coherence

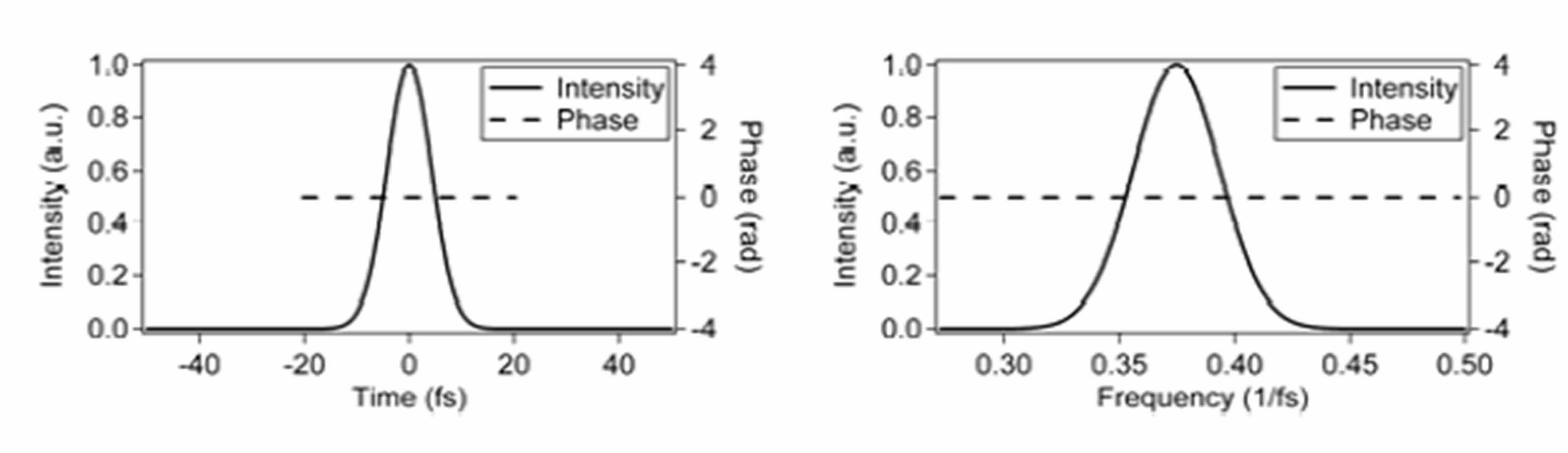
Representative experiments and hints about perspectives

Only longitudinal coherence and femtosecond pulse duration

What really matters, about coherence, to a FEL user?

”Standard users” of a coherent FEL says:

Give me a transform-limited pulse!

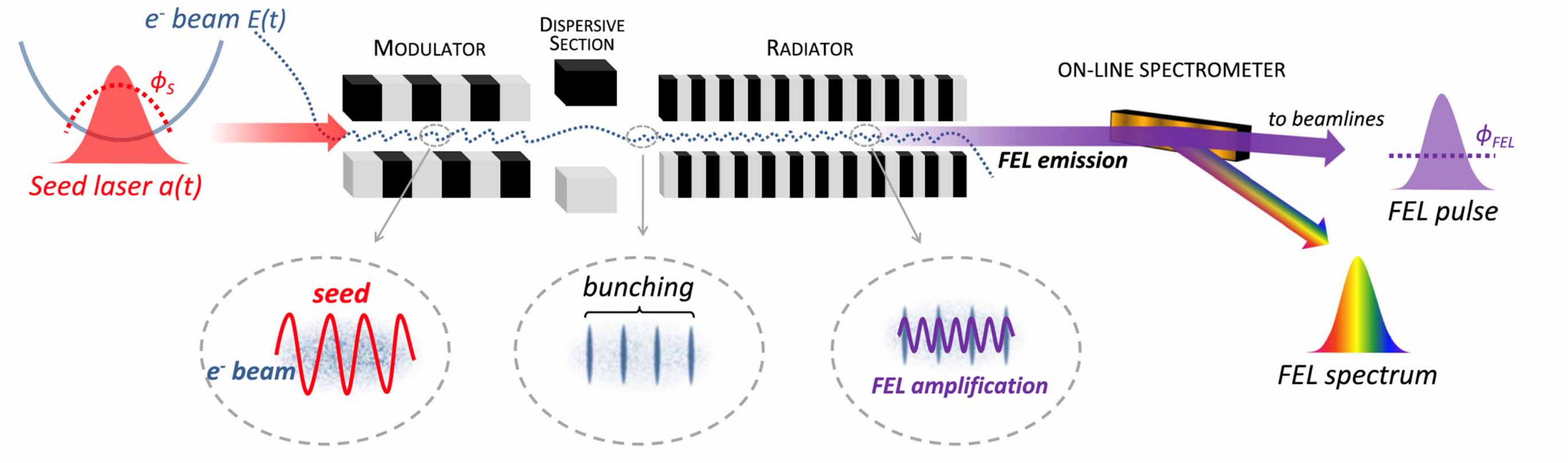


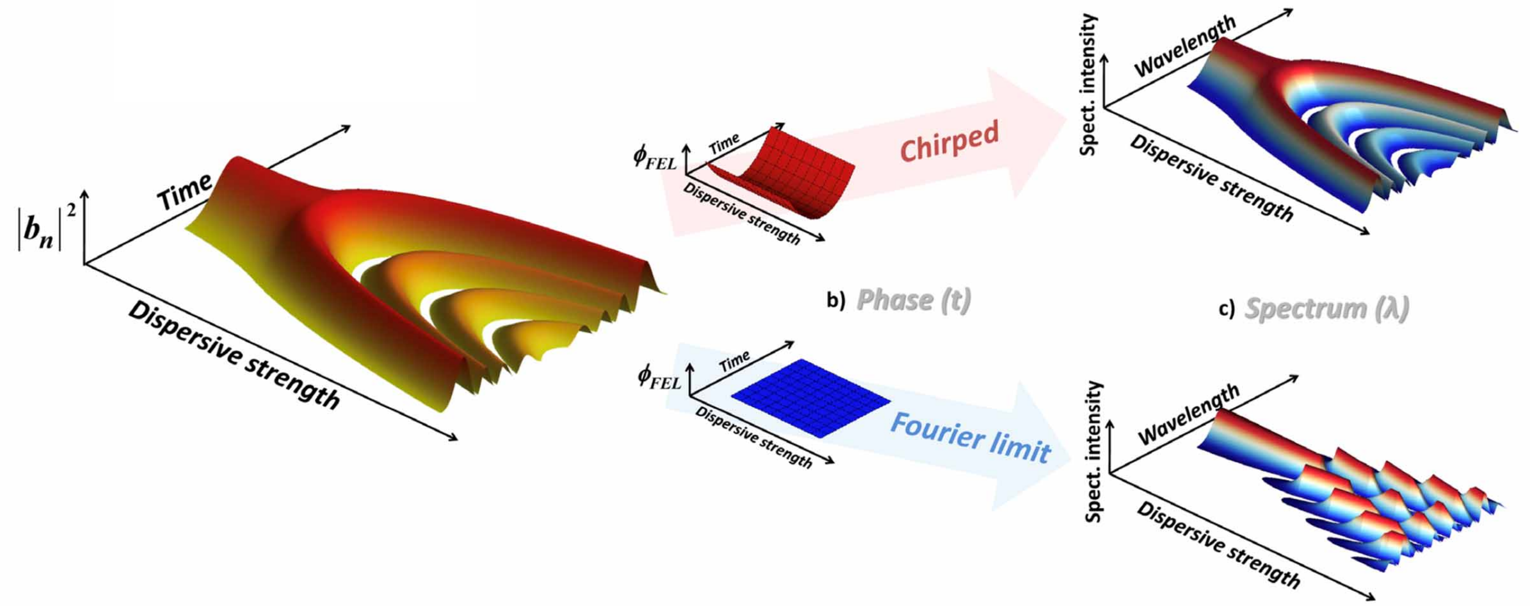
FERMI seeded FEL:

Pulse durations : tens of femotseconds

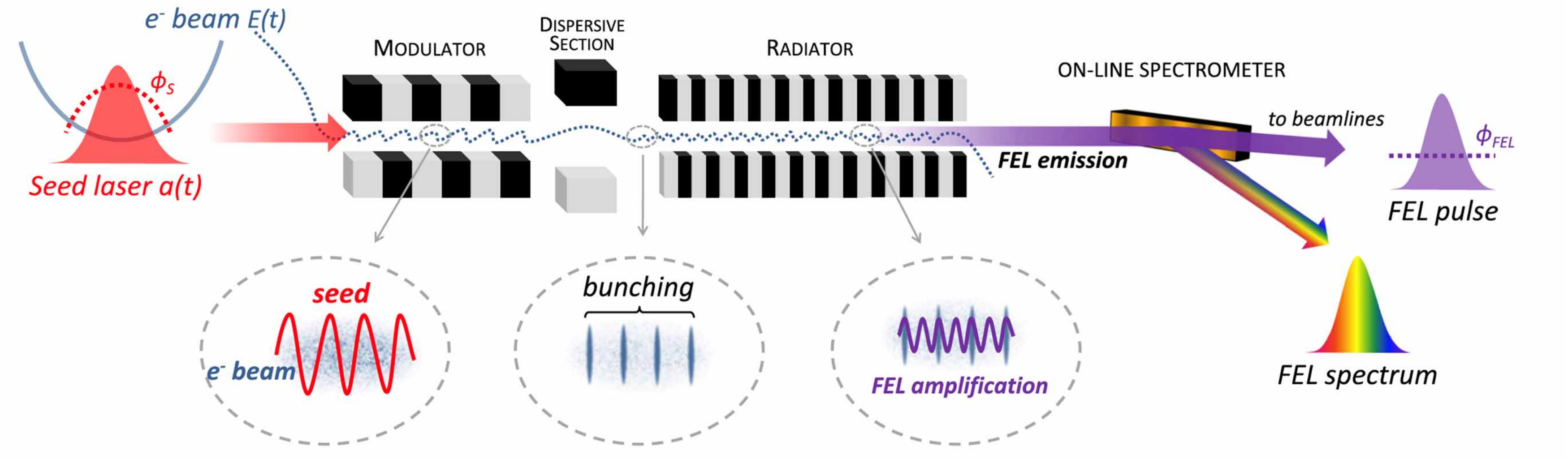
Spectral width : about 10^{-4}

How to generate and diagnose a transform-limited FEL pulse

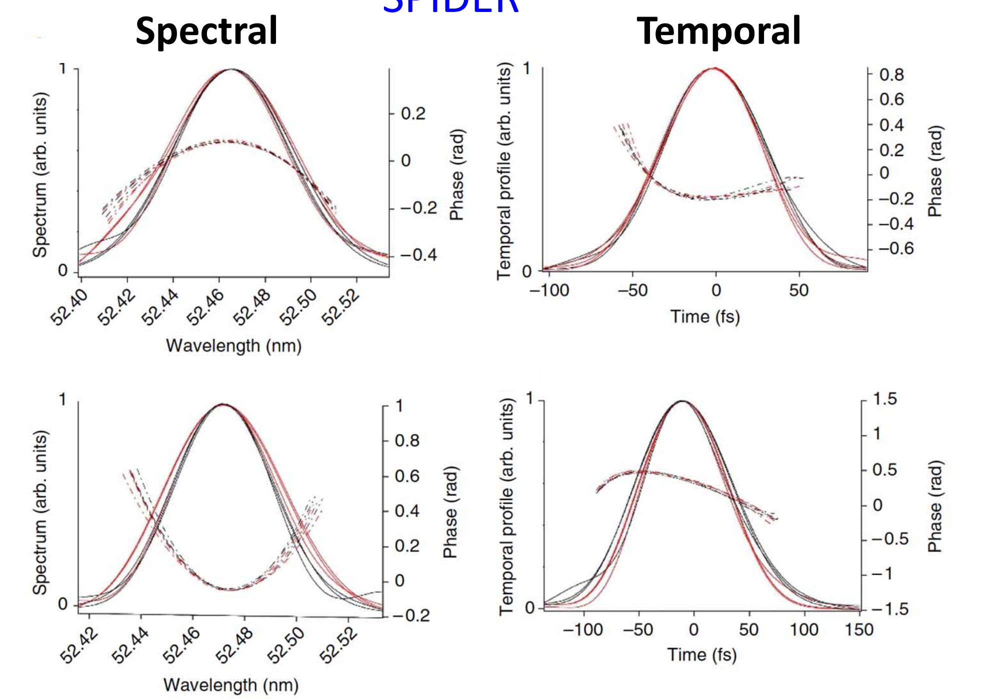




How to generate and diagnose a transform-limited FEL pulse



SPIDER

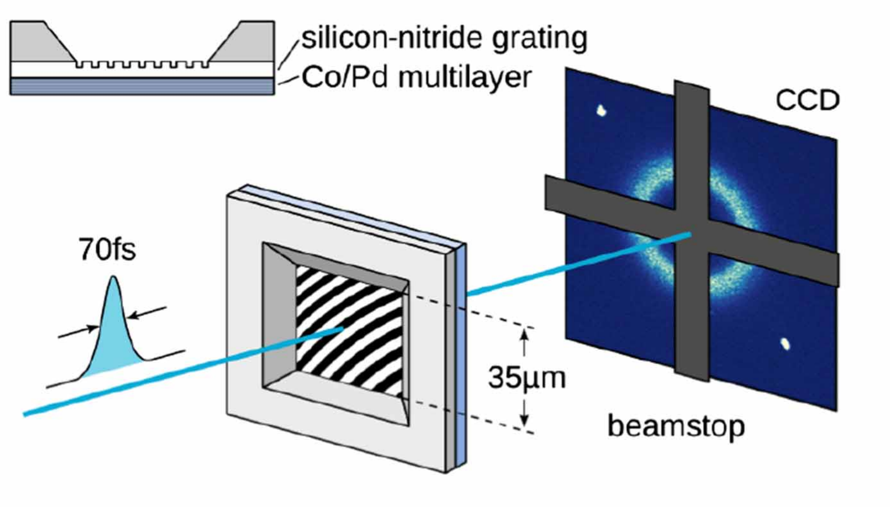


Disentangle coherent and incoherent effects in light-matter interaction

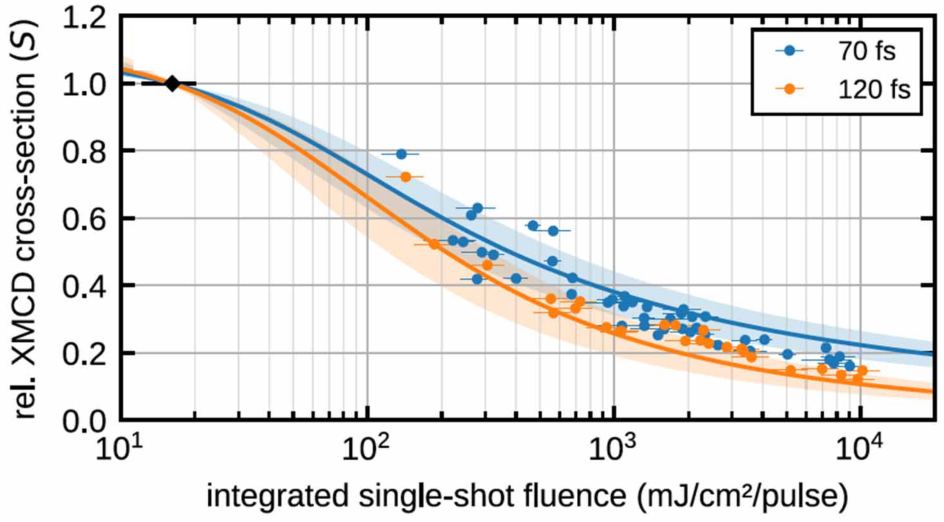
Short-pulse duration is essential, e.g., when:

Trying to disentangle coherent (stimulated emission) and incoherent (demagnetization) effects in resonant diffraction or transmission experiments, at different edges (M vs L) of 3D transition metals.

Schneider et al, PRL 2020



XMCD cross section at Co $M_{3;2}$ edge



Long (70 and 120 fs) FEL pulse at Co <u>M edge</u>: XMCD cross-section quenching with fluence dominated by demagnetization

Short (2.5 and 5 fs) FEL pulses at Co <u>L edge</u>: XMCD cross-section quenching with fluence dominated by coherent stimulated emission *[Chen et al, PRL 2018]*

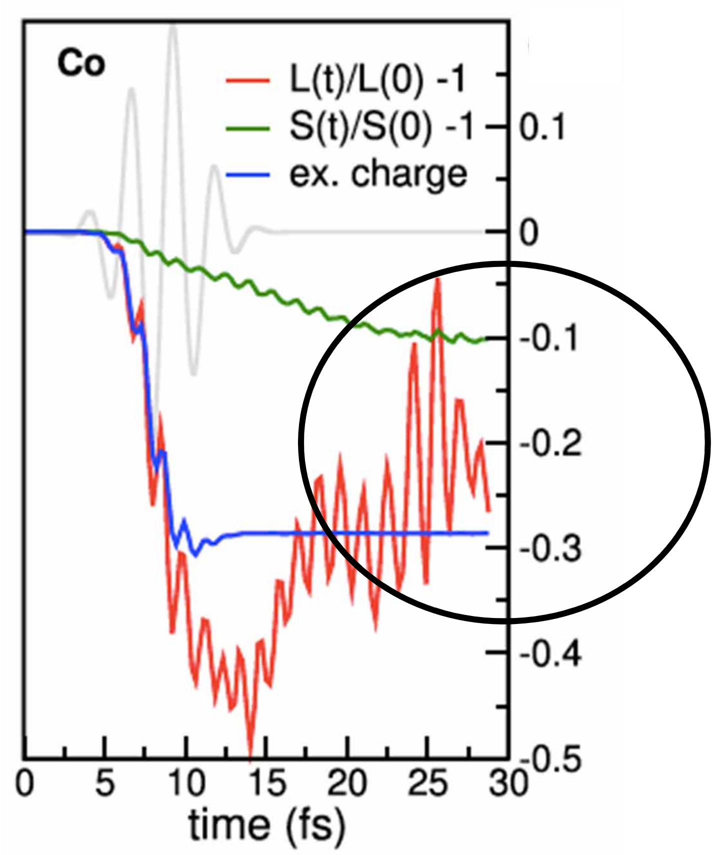
Disentangle the physics of angular momentum redistribution in laser-matter interaction

Short pulse durations are essential, e.g., when:

Trying to disentangle physics of angular momentum redistribution in laser-induced demagnetization

Spin-orbit coupling at femtosecond timescale drives a transfer of spin angular momentum into orbital angular momentum, which via the Coulomb term eventually transfers to the lattice.

Dewhurst et al, PRB (2021)



Simulated XMCD at Co L edge

Pump and probe pulses as short as **5 fs**.

Spin angular momentum decreases

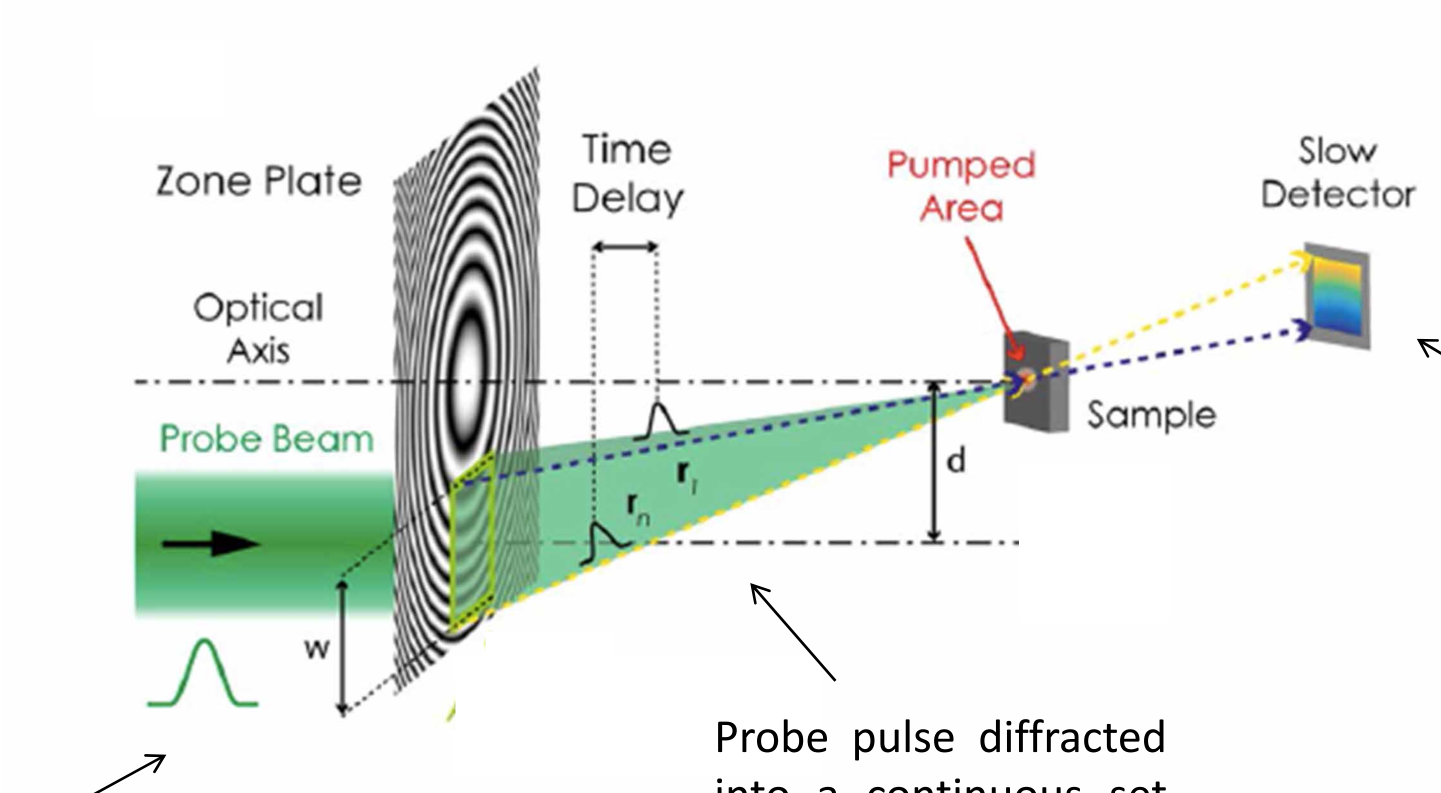
Orbital angular momentum increases

X-ray streaking

Retrieving, with a single x-ray pulse, the time evolution of an ultrafast process, over an extended time window

Buzzi et al., Scientific report 2017

Jal et al., PRB 2019
Rösner et al., Strct. dyn. 2020



Arrival time of each sub-pulse to the sample is encoded into the spatial coordinate at the detector

Probe pulse diffracted into a continuous set of spatially separated sub-pulses

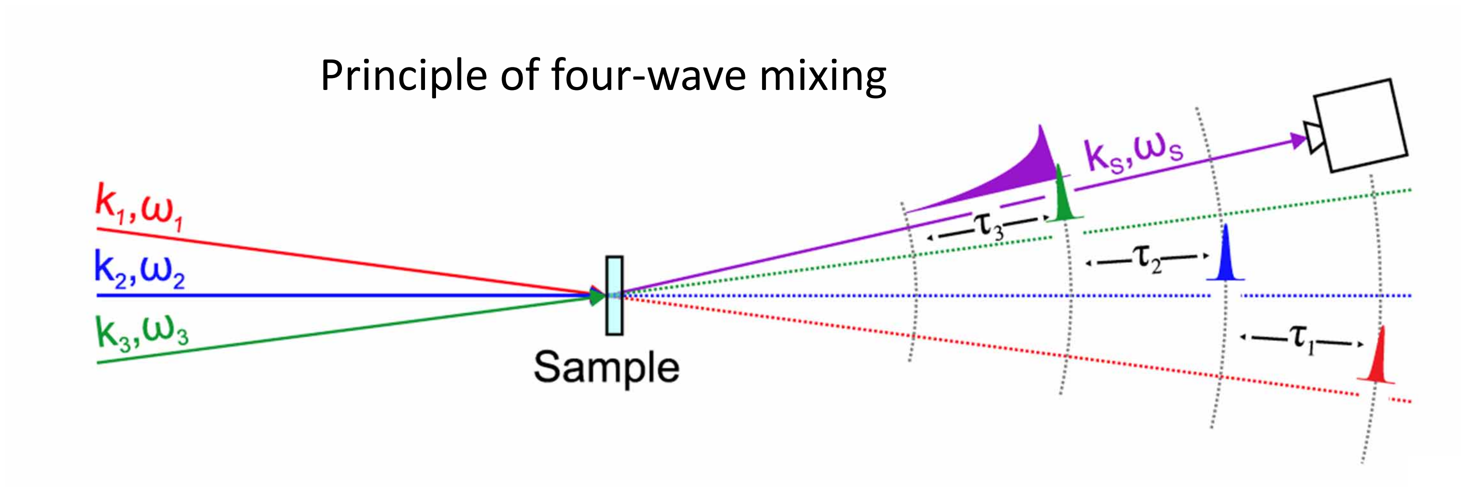
Need a **monochromatic** probe pulse

Are transform-limited pulses the Holy Grail for all user experiments?

Four-wave mixing

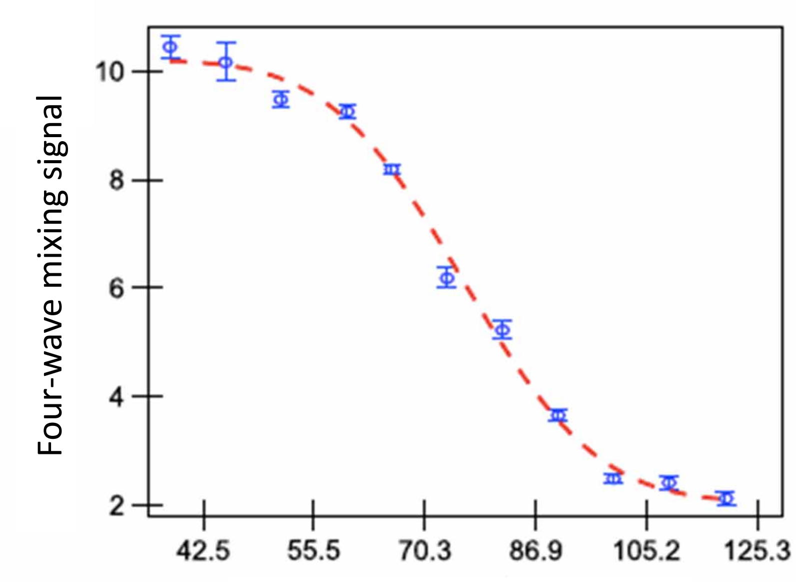
Nonlinear response of matter due to interaction of strong fields through the nth order susceptibility of a material

Principle of four-wave mixing



Foglia et al., Struct. Dyn. 2019

Four-wave mixing signal vs coherence length →

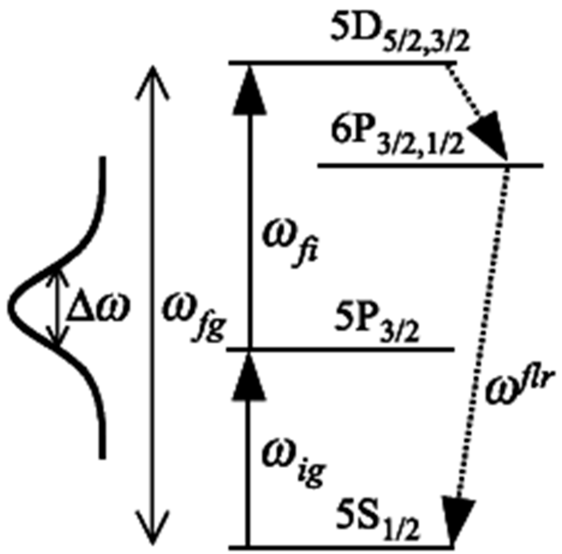


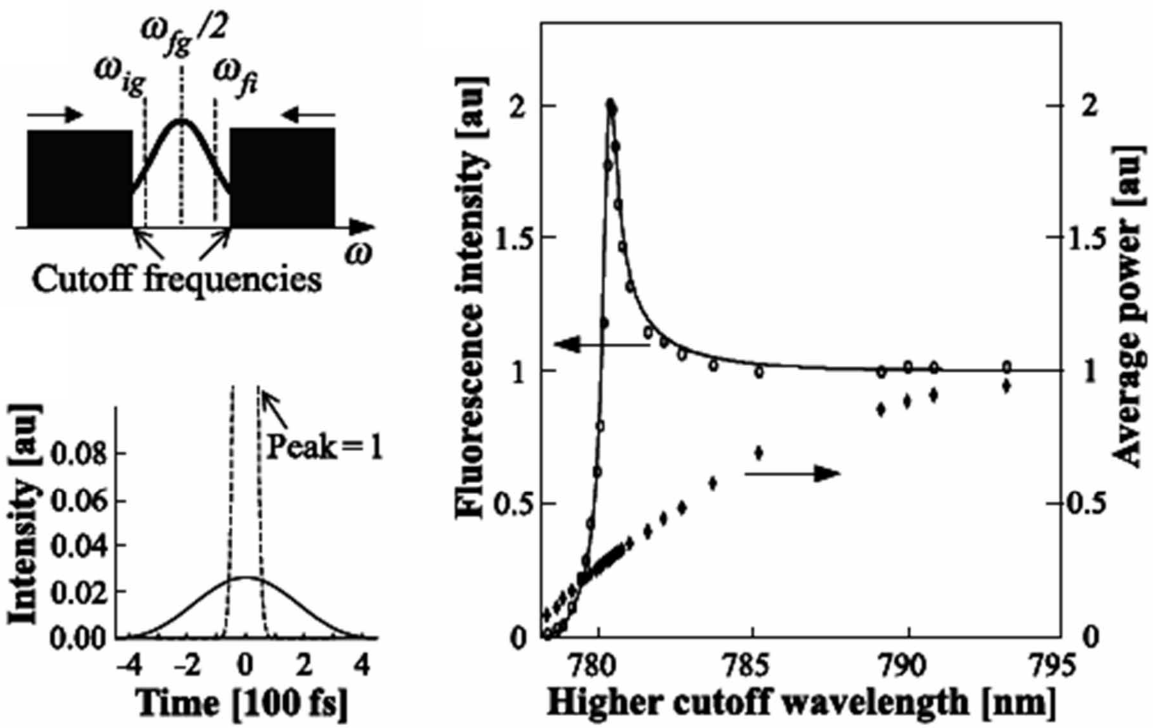
Coherent quantum control

Ability of steering quantum systems by coherently manipulating the interacting light

Dudovich et al., PRL 2001

Resonant two-photon absorption in Rb





Enhancement of the two-photon absorption rate by shaping light pulses in a way that exploits the spectral response of the interaction around the resonance

Are transform-limited pulses the Holy Grail for all user experiments?

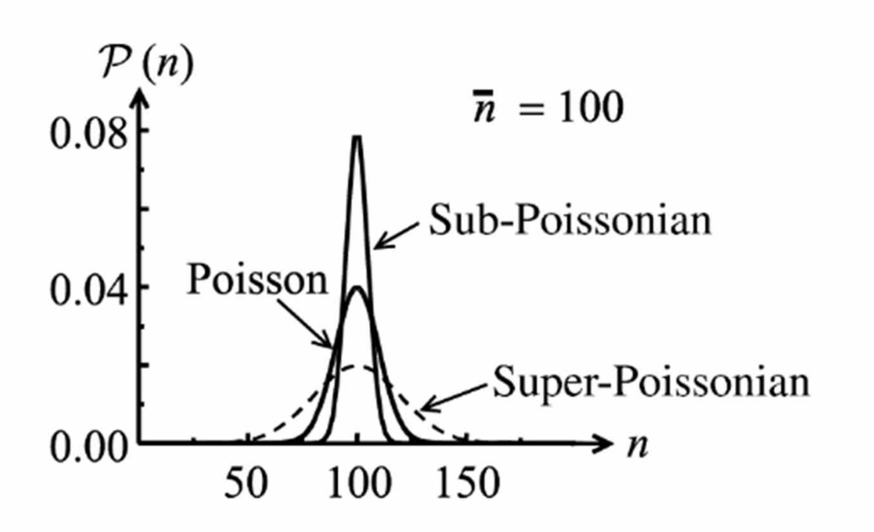
… not for experiments requiring **pulse shaping**

“Advanced” FEL users say:

Give me pulses with adjustable spectro-temporal shapes!

Quantum coherence

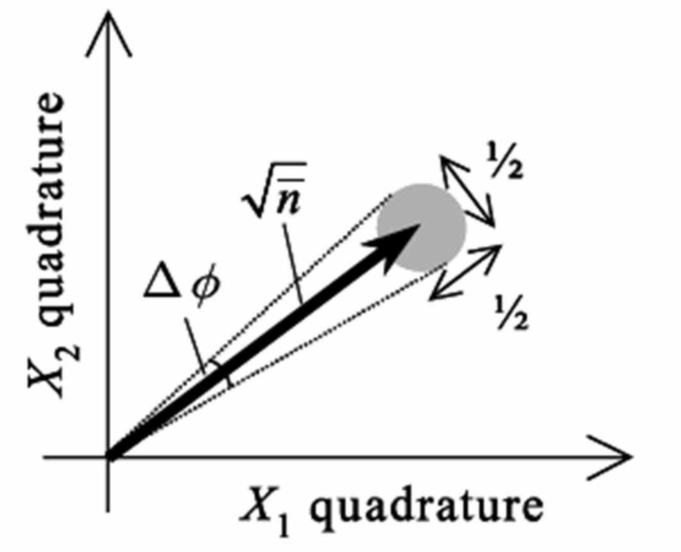
Coherent states have Poissonian statistics



Number-phase uncertainty

$$\Delta n \Delta \phi \geq \frac{1}{2}.$$

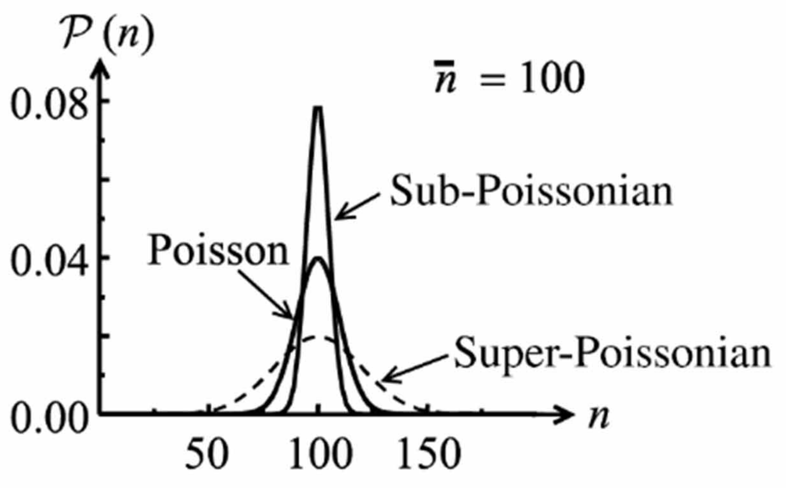
Quantum coherent state



Pictures taken from: M. Fox, Quantum Optics, Oxford university press 2006

Quantum coherence

Coherent states have Poissonian statistics



Number-phase uncertainty

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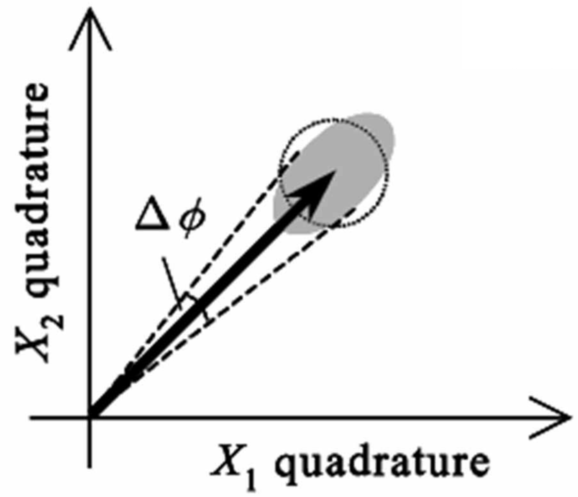
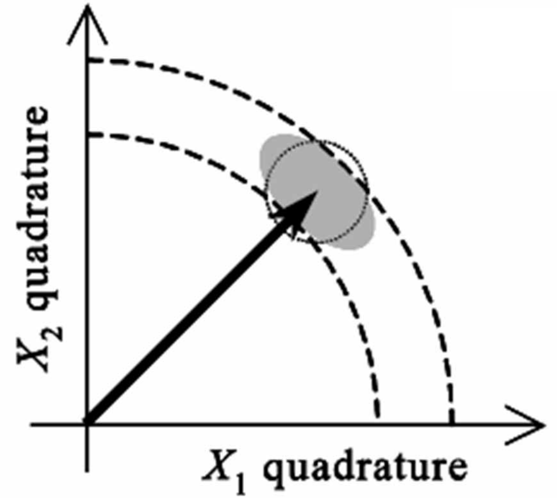
Phase squeezed state



Amplitude squeezed state

Sub-Poissonian light !



Pictures taken from: M. Fox, Quantum Optics, Oxford university press 2006

Conclusions

Large majority of users happy with ultra-short or monochromatic pulses

Advanced techniques require pulse shaping

Quantum “super-coherent” states possible and useful?