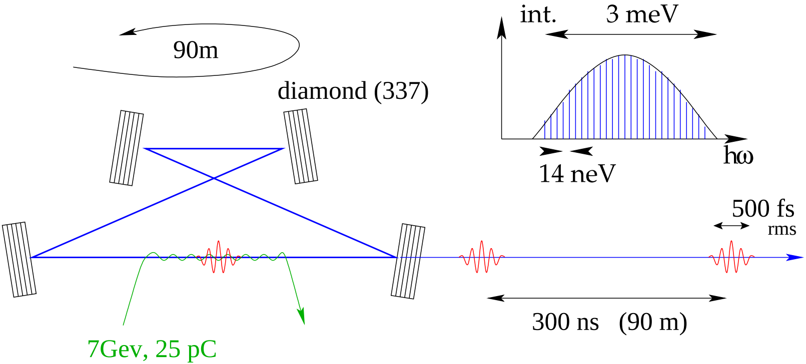
XFELO

Design example: XFELO for 14.4 keV



$6.5 \cdot 10^8$ photons/pulse

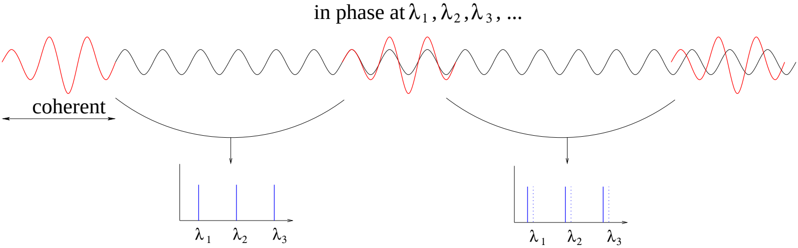
Kwang-Je Kim et al.: PRL **100**, 244802 (2008)
PRST-AB **12**, 030703 (2009)

parameters from R. Lindberg (ANL)

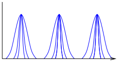
XFELO

XFELO has full longitudinal coherence within each pulse but no pulse-to-pulse coherence without cavity-length stabilization

of course one pulse is always coherent with the next at suitable λ_i
but different λ_i for next pulse pair ..



lines broaden as cavity length jitters



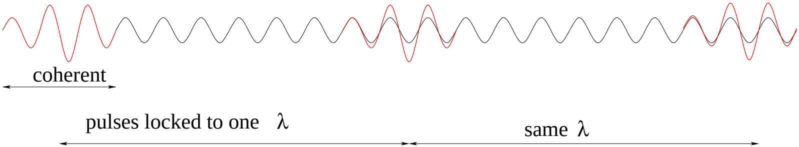
uniformly distributed for $t \to \infty$

$\to$ no coherence in the ensemble / ergodic average

XFELO

need an external reference to determine λ

so that pulses are phased to each other at this λ



How can we do that? – use nuclear resonance as external reference

With this, the XFELO can duplicate the coherence properties of optical lasers used in metrology

XFELO

example ^{57}Fe with 5 neV natural linewidth,

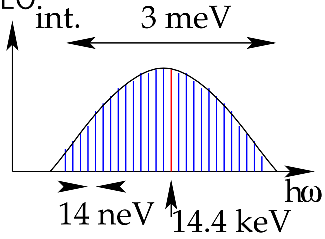
(or 8 neV after some inhomogeneous broadening ($FeK(CN)_6$))

can resolve 14 neV mode spacing of XFELO.

stabilize the cavity to make

one mode resonant with ^{57}Fe

→ stable frequency comb



→ intense coherent radiation for metrology, fundamental physics

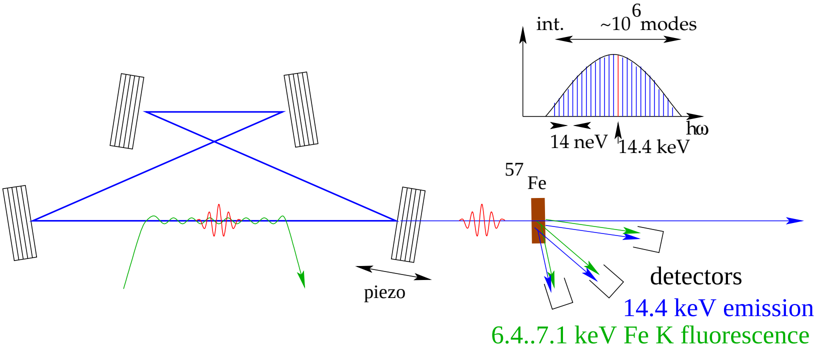
noise sources to address:

gain-related: spontaneous emission, gain fluctuation

cavity-length fluctuations: seismic, heat load fluctuations

Cavity Stabilization - I

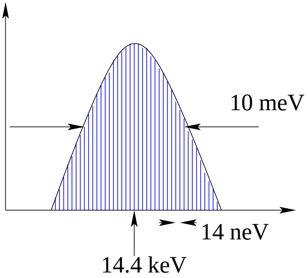
measure resonance of ^{57}Fe sample, adjust cavity length with piezo:

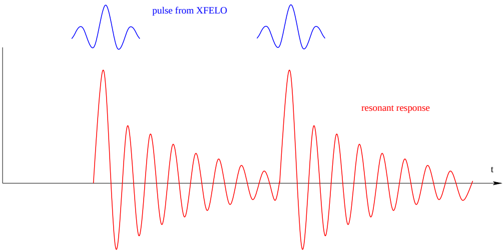


B.W. Adams, K.-J. Kim, Phys. Rev. ST-AB **18**, 030711 (2015)

Cavity Stabilization - I

frequency vs. time domain





longitudinal modes spaced at cavity round-trip frequency one in resonance with ^{57}Fe

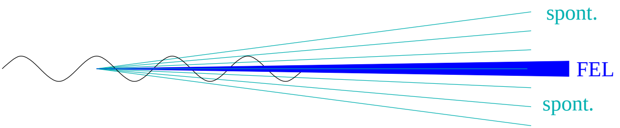
phase relation of wavepackets relative to previously excited free oscillation of nuclear dipoles

Sources of Phase Noise

electron bunches

1) spontaneous emission into lasing mode: 10^{-8} in intensity, 10^{-4} in amplitude

(classical spontanous undulator radiation)



linewidth from spont. emission: 10^{-12} eV

BWA & KJK, PRST-AB **18**, 030711 (2015)

noise in modulus is limited by loss/gain balance

only phase noise remains

2) fluctuations in electron bunches:

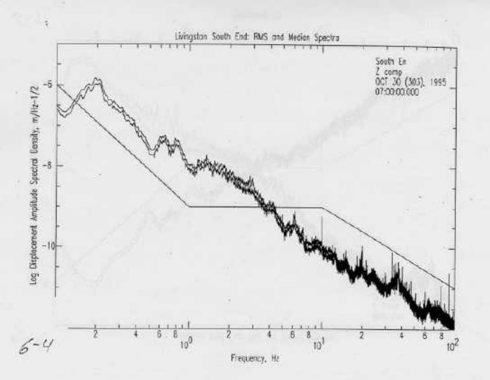
gain fluctuations due to bunch charge and electron energy

bunch arrival time fluctuations broaden comb lines

effect estimated at 10^{-3} level

Sources of Phase Noise

ground motion (seismic)



http://www.ligo.caltech.edu/docs/G/G010325-00.pdf

ground motion

amplitude $A(f)$

$$10^{-9}\frac{m}{\sqrt{Hz}}\left(\frac{10Hz}{f}\right)^2$$

so,

$$\sqrt{\int_{f_0}^{1/T} df\,\frac{A^2(f)}{Tf}} < \frac{\lambda}{100}$$

for $f_0 > 8kHz$

30-kHz feedback loop can handle this

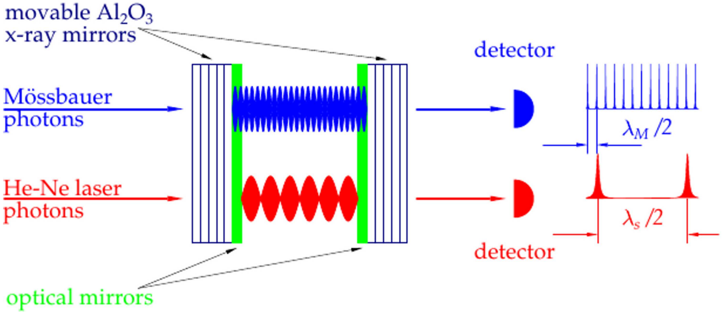
and better with mechanical damping

Applications: Length/Time Standard

Use NR as length standard: Shvyd'ko et al., PRL **85**, 495 (2000)

combined x-ray / optical Fabry-Perot interferometer (FPI)

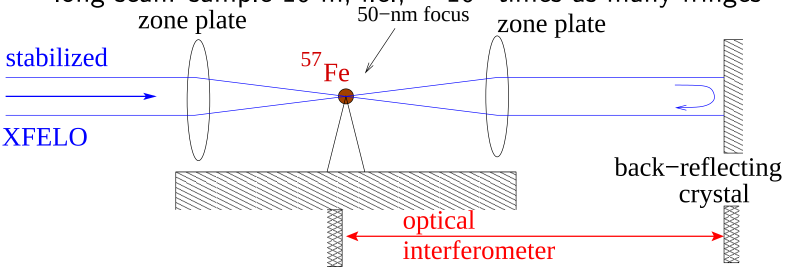
Yu. V. Shvyd'ko, 2004



Applications: Length/Time Standard

improvement:

long scan: sample 10 m, i.e., $\sim 10^4$ times as many fringes



Traveling assembly: focusing/collimating zone plates and
a single ^{57}Fe atom embedded in a crystal

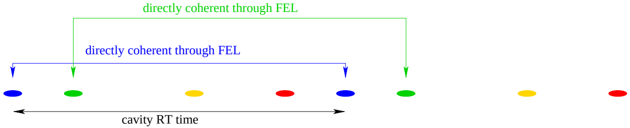
With 50-nm focus, abs. $\sigma = 10^{-22}\text{m}^2$, 1000 resonant photons / pulse

about 100 absorption events / sec.

Sparse sampling, using known λ to 7 places

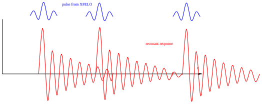
Weird Tricks on the Comb

inject bunches at a rate that is a harmonic or a sub-harmonic of the cavity round-trip time



first, get sub-populations of pulses related by cavity RT time

Then, the external NR reference will enforce coherence among them



strong NR response only if sub-populations are in phase

can do Fibonnacci sequences of bunch intervals, etc.