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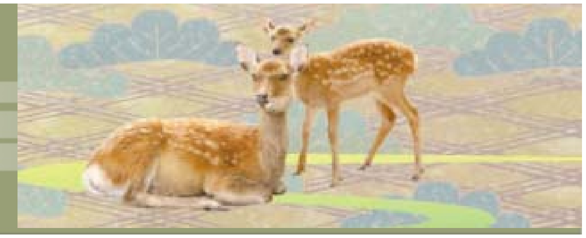

Progress towards X-ray FELO and Concept for Sub-Å Stabilization for Nuclear Resonance Metrology

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ANL & U of C

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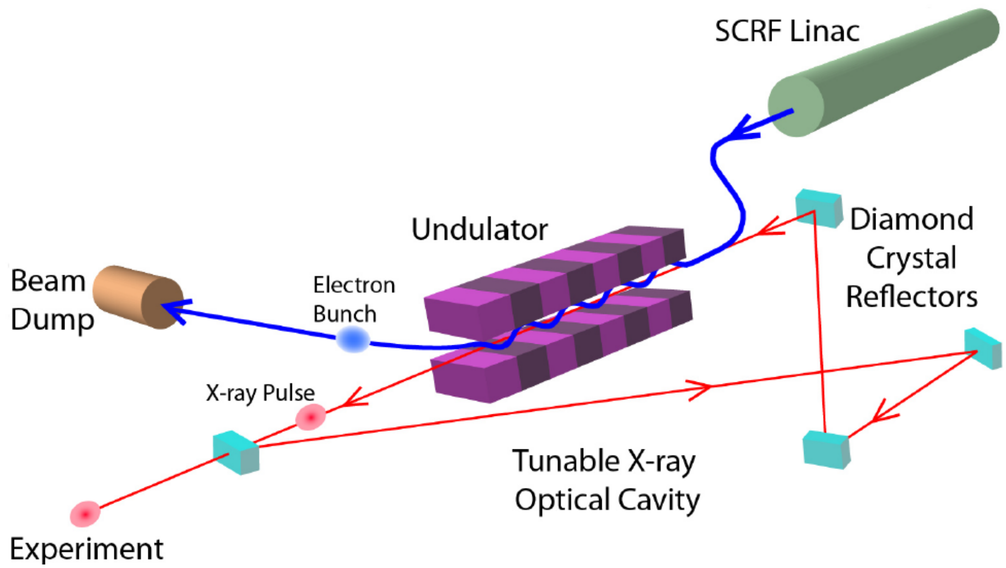
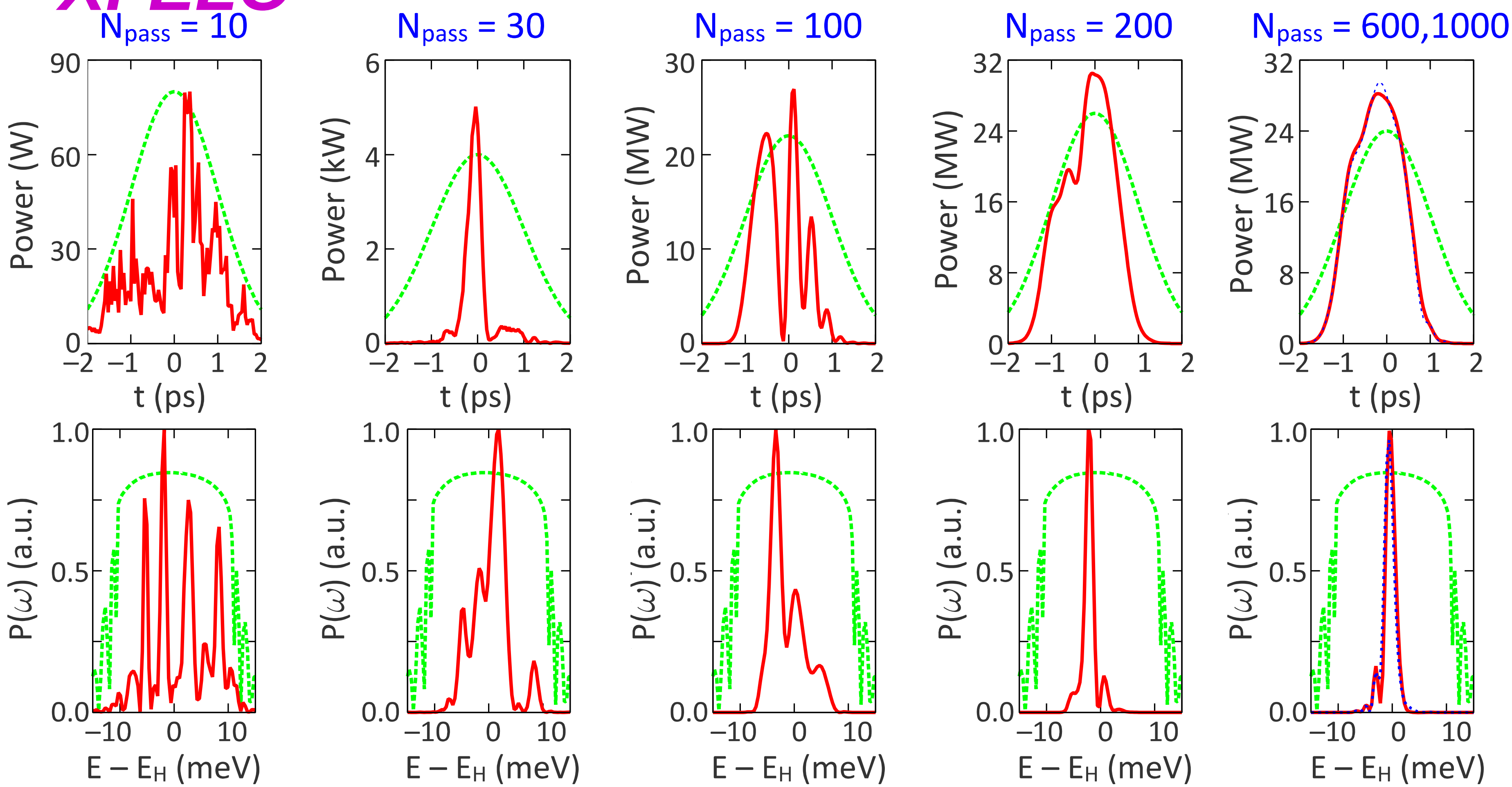
U.S. DEPARTMENT OF ENERGY

X-Ray FEL Oscillator (XFEL-O)



- **X-ray FEL oscillator is feasible by using Bragg mirrors**
  - R. Collela and A. Luccio, 1984; KJK, Y. Shvyd'ko, and S. Reiche, 2008)
- **Tuning is possible with a four mirror configuration**
  - R. M.J.Cotterill, (1968)KJK & Y. Shvyd'ko (2009)
- **Crystal choice becomes independent from Bragg planes→ choose diamond for its best mechanical and thermal properties**

Temporal and spectral evolution of XFELO



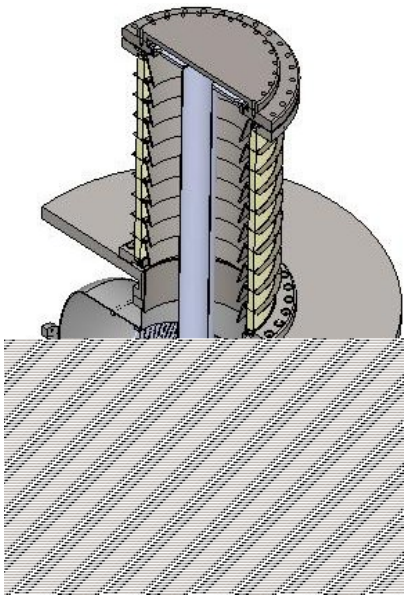
R.R. Lindberg, K.-J. Kim, Yu. Shvyd'ko, and W.M. Fawley, *Phys. Rev. ST-AB.* **14**, 010701 (2011)

Example Parameters

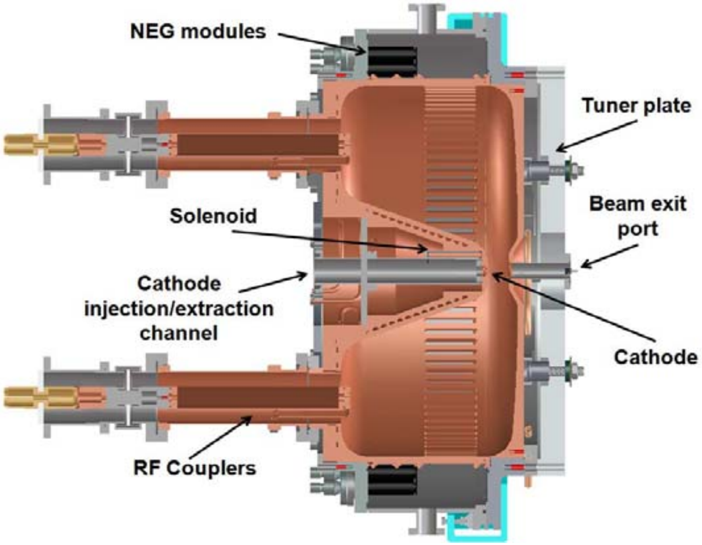
- **Electron bunches: 7 GeV, 25 pC, 0.5 ps (rms)**
- **Undulator: K=1.38, λ_U=1.65 cm, L_U=30m**
- **X-ray cavity roundtrip length: 90 m**
- **Diamond (337) crystal**
- **30% gain=15% RT loss+5% out-coupling+10% net gain**
- **Output x-ray pulse characteristics—complementary to high-gain XFEL:**
  - **$\hbar\omega$=14.4 keV, > 5% tuning range**
  - **6.5×10^8 photons/pulse,**
  - **Full coherence and high stability**
  - **BW : $\Delta\hbar\omega \sim$ 3 meV (FWHM)→ 700 fs(FWHM)**
  - **Rep rate 3 MHz (RT length=90m)**
- **See R. R. Lindberg and KJK (WEPD27), J. Zemella, et al.,(WEPD29), R. Hajima, et al., (WEPD30)**

Accelerator technology: Injector

- **Injectors for ERL projects (KEK/JAEA, Cornell) at the soft x-ray FEL NGLS at NGLS will meet the XFELO requirements**



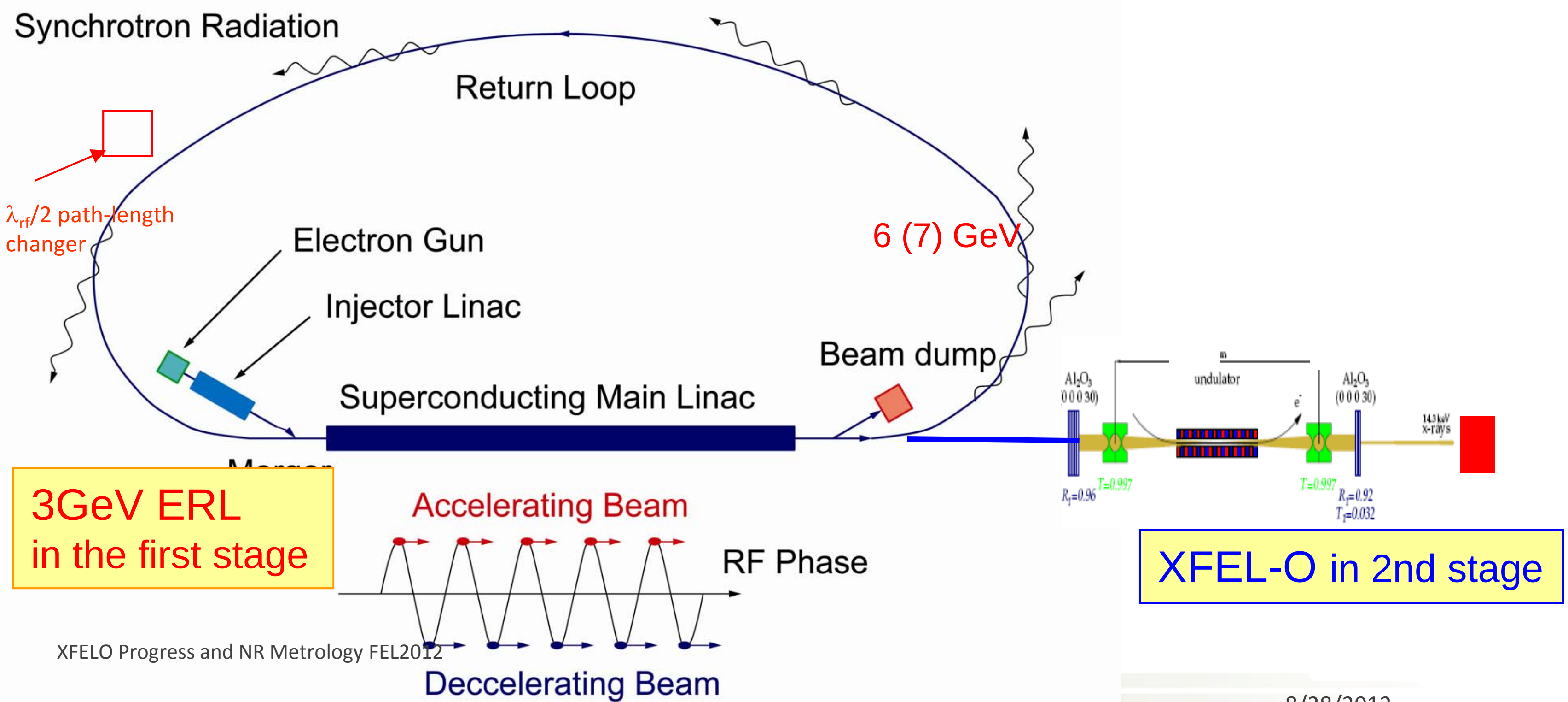
N. Nishimori, et al, WEPD51



C. Papadopoulus, et al., MOPD31

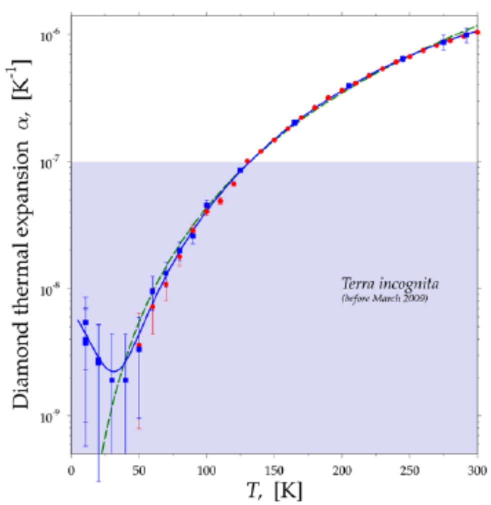
Main accelerator

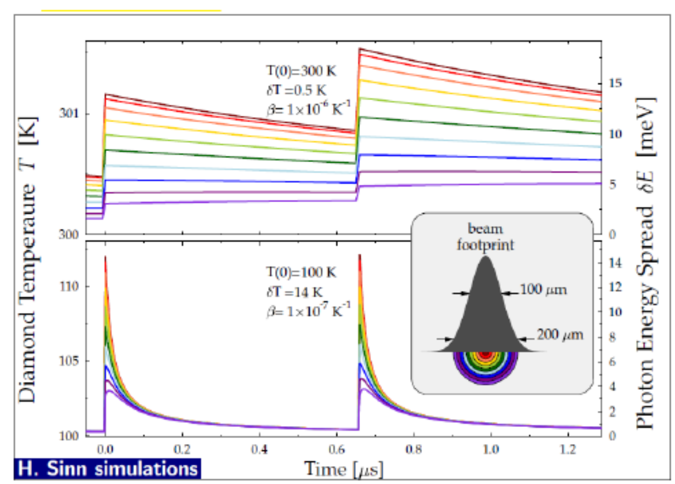
- CW SCRF accelerators for >5 GeV is feasible with or without recirculation passes: ERLs at KEK/JAEA, Cornell
- A pulsed mode XFELO can be operated at European XFEL (**J. Zemella, et al., WEPD29)**
- Most parameters of an ultimate storage ring retrofitted to large HEP rings (PEP, Tevatron, PETRA<>>) are compatible except for the longitudinal emittance



Synthetic diamond for an XFELO appears feasible

- **High reflectivity >99% has been demonstrated**
  - **Yu. V. Shvyd'ko, S. Stoupin, V. Blank, and S. Terentyev, Nat. Photonics 5, 539 (2011)**
- **Intra- and inter pulse heating/expansion can be avoided by cooling the diamond crystals to T < 100K**
  - **S. Stoupin and Yu. V. Shvyd'ko, Phys. Rev. Lett. 104, 085901**
- **The charge imbalance due to photo-emission may be avoided in high-purity crystal (BNL diamond amplifier gun)**





XFELO applications

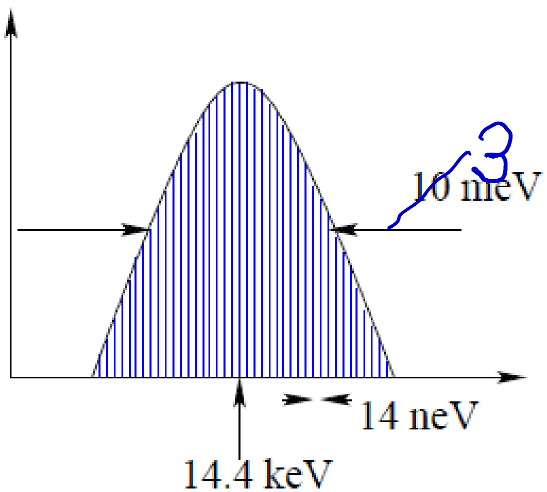
- **High resolution spectroscopy**
  - **Inelastic x-ray scattering**
- **Mössbauer spectroscopy**
  - **10^3/pulse, 10^9/sec Moessbauer γs (14.4 keV, 5 neV BW)**
- **X-ray photoemission spectroscopy**
  - **Bulk-sensitive Fermi surface study with HX-TR-AR PES**
- **X-ray imaging with near atomic resolution (~1 nm)**
  - **Smaller focal spot with the absence of chromatic aberration**
- ***Capture coherent atomic motion (< 1 ps resolution) in real space***

Further opportunities for an XFELO: Extreme temporal coherence length from sub-mm→ km→10^8 m(spontaneous emission limit)!

- **The XFEL-O output pulses, being a copy of the same circulating intra-cavity pulse, are phase-coherent**
- **If the pulse spacing *T* is controlled accurately, $\Delta T \ll \lambda/c$, the spectrum of XFELO output has a comb structure**
- **The stabilized XFEL-O may establish x-ray-based length standard and have applications in some fundamental physics**

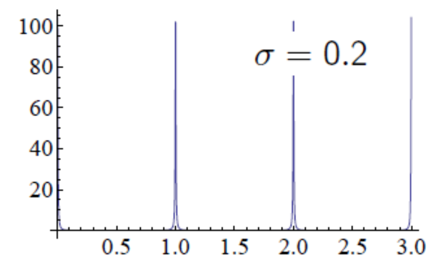
Comb structure of a stabilized XFELO

- **Comb spacing: $\hbar\omega_T = \hbar 2\pi/T = 14$ neV is well-matched to ^{57}Fe resonance: $\hbar\omega = 14.4$ keV, $\Gamma = 4.8$ neV**
- **There are ~2×10^5 lines (modes) in the FEL BW: $\hbar\Delta\omega = 3$ meV**
- **The integer n is centered around $n_R = \omega_R/\omega_T = L/\lambda_R \rightarrow$ the comb line moves one unit if the cavity length L is changed by λ_R**
- **$6.5 \times 10^8 / 2 \times 10^5 = 3000$ photons/mode**

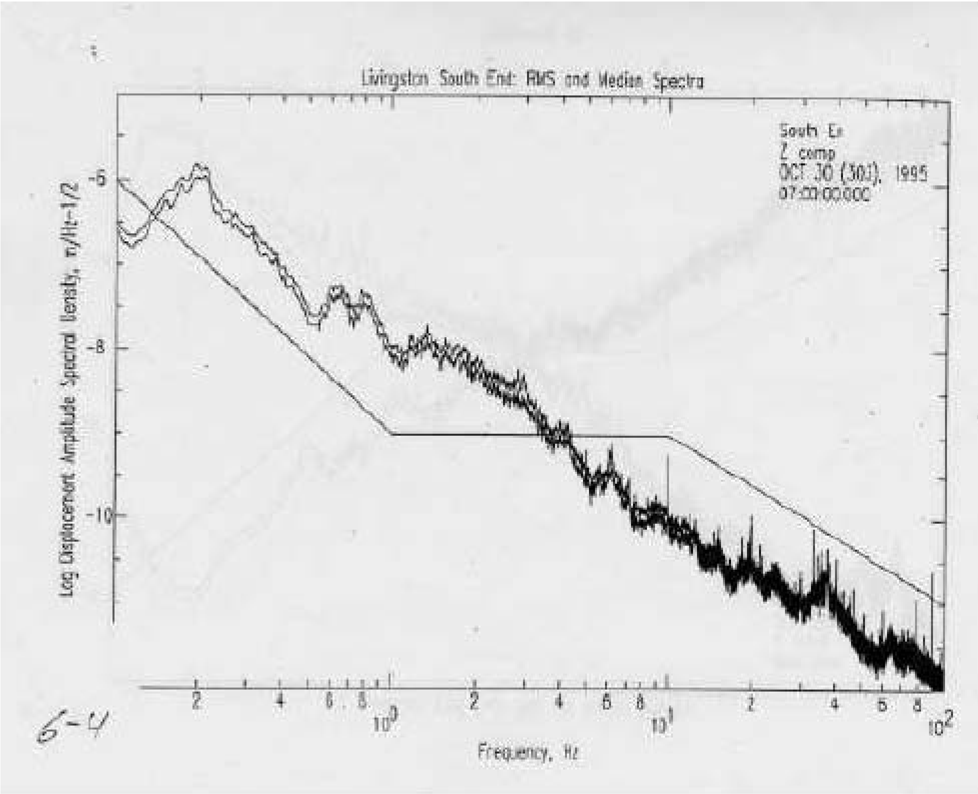


Line broadening due to phase noise

- $E(t) = \sum_n e^{i\psi_n} E_0(t - nT)\Big)$ $\qquad \psi_n = \varphi_n + \sum_{k=0}^{n} \phi_k$
- **Uncorrelated:** φ_n **& cumulative:** ϕ_k
- **Gaussian random variables:** $\langle \varphi_k^2 \rangle = {\sigma_\varphi}^2$, $\langle \phi_k^2 \rangle = \sigma^2$
- $\tilde{E}(\omega) = \frac{1}{\sqrt{2\pi}} \int dt e^{i\omega t} E(t) = \sum_{n=1}^{N} e^{i\psi_n} e^{in\omega T} \tilde{E}_0(\omega)\Big)$
- **Without phase error, this is a spectral comb with envelope** $\tilde{E}_0(\boldsymbol{\omega})$ **with peaks at** $\omega = n\omega_T$; $\omega_T = 2\pi/T$
- $\langle |\tilde{E}(\omega)|^2 \rangle = NF(\sigma_\varphi^2, \sigma^2, \omega) |\tilde{E}_0(\omega)|^2$
- $F(\sigma_\varphi^2, \sigma^2, \omega) = \left(1 - e^{-\sigma_\varphi^2} + e^{-\sigma_\varphi^2} \frac{\sinh(\sigma^2/4)\cosh(\sigma^2/4)}{\sinh^2(\sigma^2/4) + \sin^2(\pi\omega/\omega_T)}\right)$
- $\sigma << 1,\ \sigma_\varphi << 1,\ \omega \approx n\omega_T \Rightarrow F = \frac{\sigma^2}{\sigma^2 + (2\pi(\omega - n\omega_T))^2}$
- **Spontaneous emission:** $\sigma \sim \mathbf{10^{-4}}$



Ground motion(seismic)



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

- **Empirical formula for spectral power:**

$$SP = 10^{-18}\left(\frac{10Hz}{f}\right)^4\left[\frac{m^2}{Hz}\right]$$

- **Require**

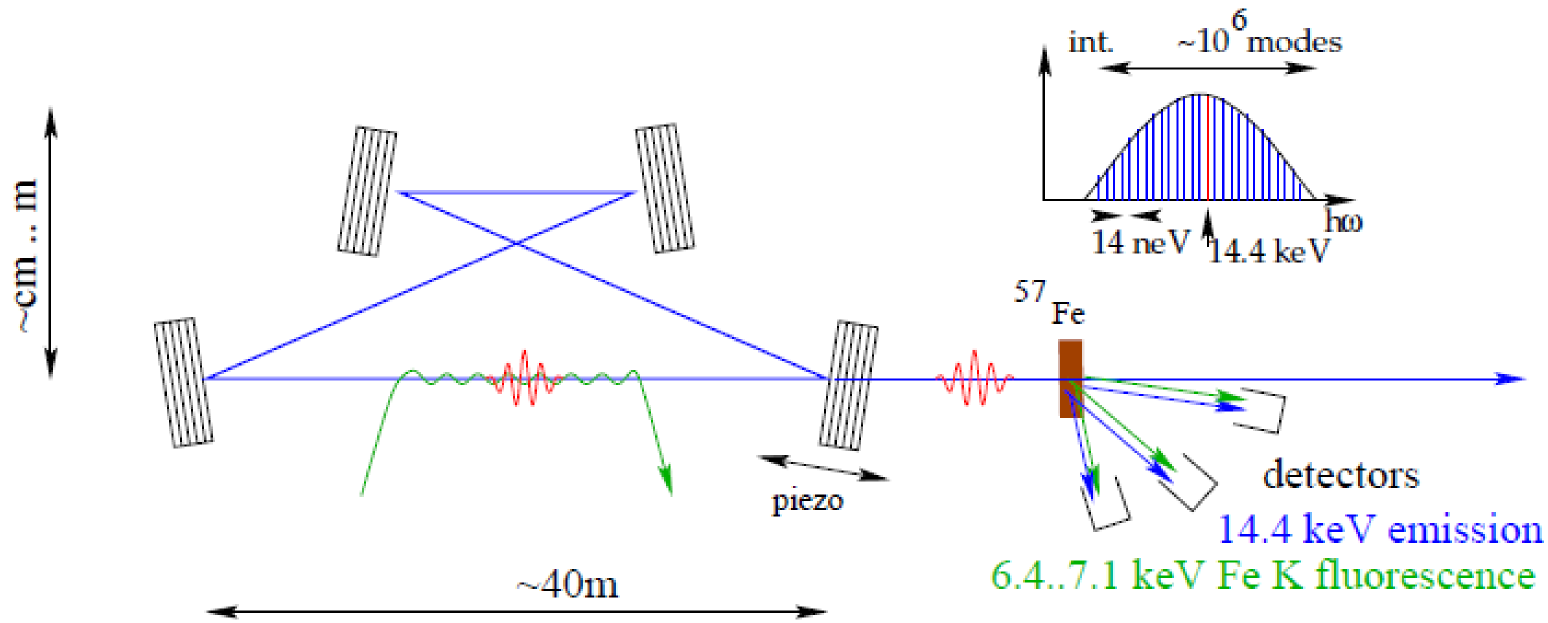
$$\sqrt{\int_{f_0}^{\infty} df\, SP} \leq \frac{\lambda}{100}$$

→f_0 >2 kHz for λ~ 1 Å

- **Feedback for f_0 < 2 kHz**

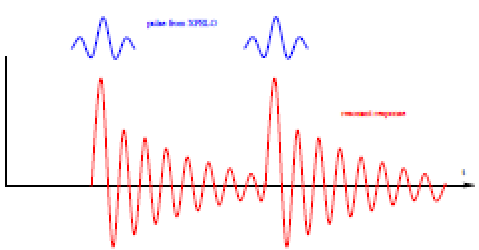
Cavity stabilization by tying one of the comb lines to a nuclear resonance line (B.W. Adams and K.-J. Kim, WEPD31)

Find the signal maximum by changing the cavity length ~1 Å and lock to it

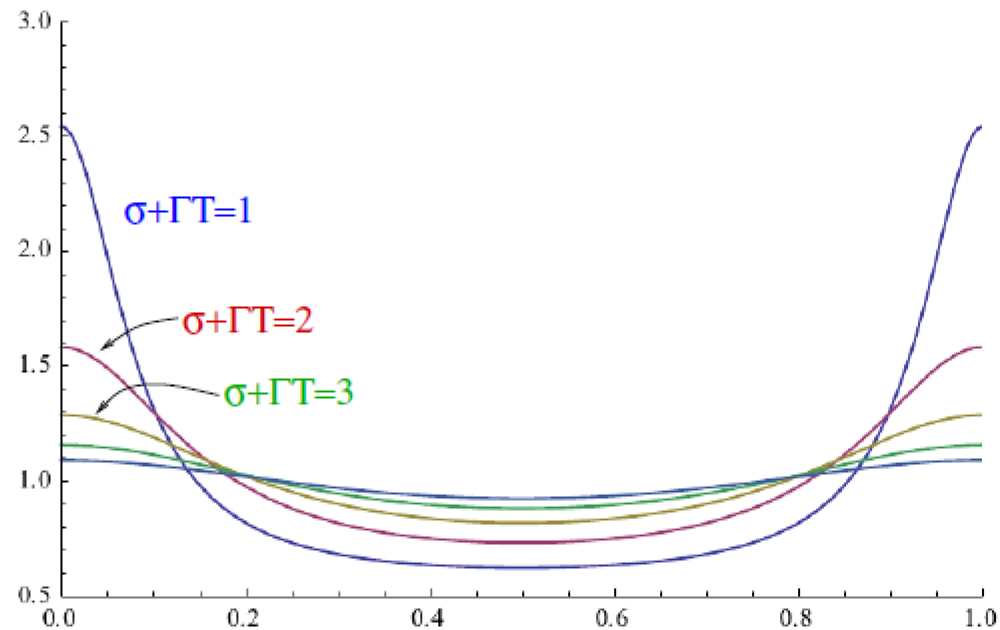


Excitation of nuclear resonance at ω_R of width Γ

- $$n_{abs}(\omega_R, \Gamma) = \kappa \int d\omega \frac{(\Gamma/2)^2}{(\omega-\omega_R)^2+(\Gamma/2)^2} \langle |\tilde{E}(\omega)|^2 \rangle$$
$$= N n_0 F(\sigma_\varphi^2, \sigma^2 + \Gamma T, \omega_R)$$
- **For ΓT =2.14 (corresponding to ^{57}Fe and *T*=300 ns) the contrast is still sufficient**



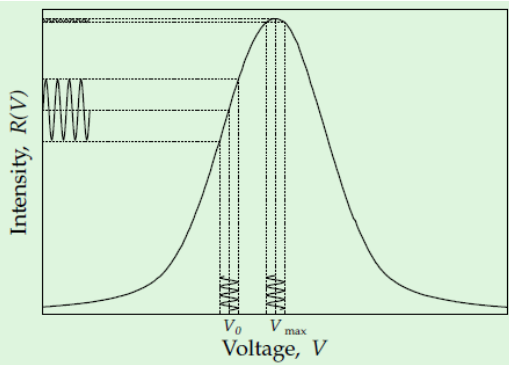
Contrast reduction due to ring-down between pulses



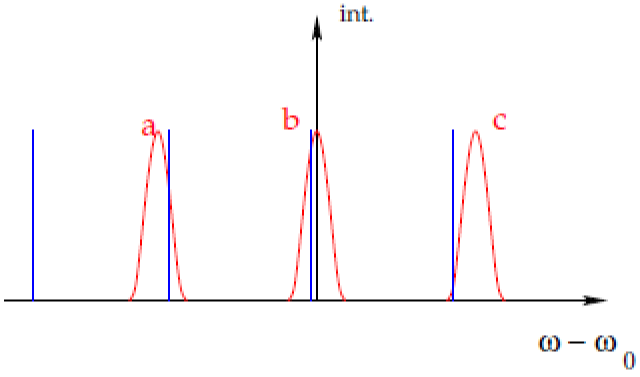
Feedback to prevent line drift at time scale $t > \tau = 1/f_0$

Methods to detect the tuning signal

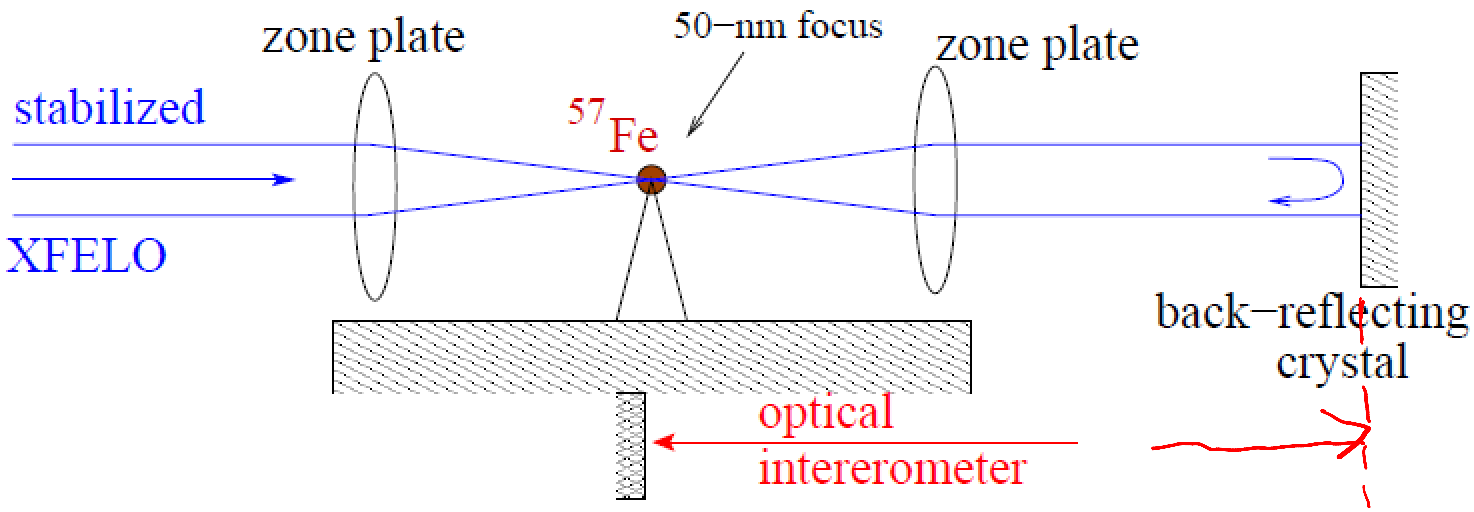
- **Null-detection FB used at LIGO—dithering the crystal position**



- **Employ three samples slightly off-tuned to each other by relative motion**



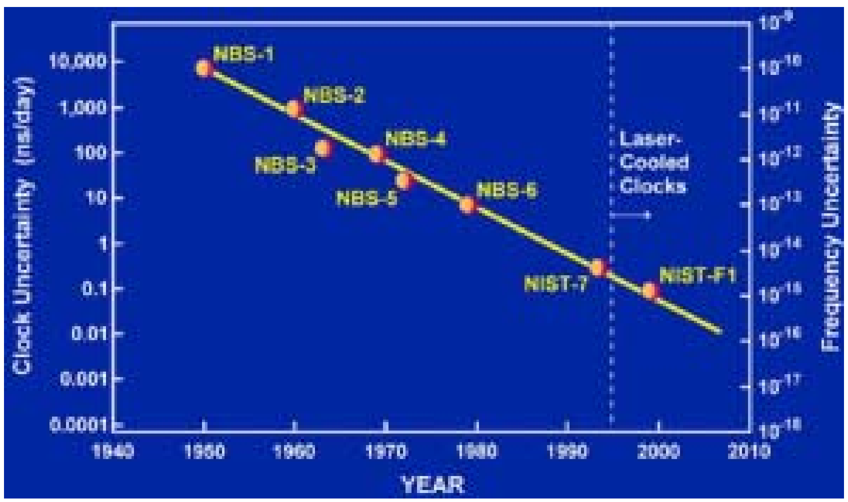
Precision measurement of NR wavelengths

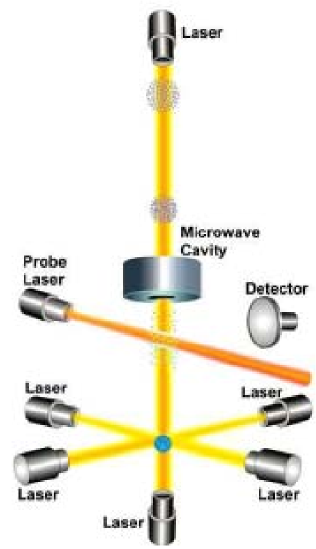


- **Stabilization does not determine absolute value of NR wavelength**
- **Form standing wave pattern using the output of the stabilized XFEL-O using ^{57}Fe resonance**
- **Count the interference peaks with a single ^{57}Fe atom fixed to a travelling assembly travelling a distance Δz (< cT/2) precisely determined by optical length standard. Assume Δz =10 m.**
- **Not necessary to probe all of the 10^{12} peaks! Sparse sampling with pre-existing knowledge of λ**

X-ray time standard

- **Measure ^{57}Fe λ_R to 10^{-11} accuracy (currently known to 10^{-7}), even to 10^{-13} by interpolation.**
- **Other NR isotopes for higher accuracy, eg., ^{45}Sc (10^{-22})**
- **Replace atomic–clock standards with NR standard**
- **Nuclei are much better isolated from environmental perturbations than the electronic transitions used in atomic clocks**





most accurate: Al+ ion in trap: $8.6 \cdot 10^{-18}$ (arXiv:0911.4527)

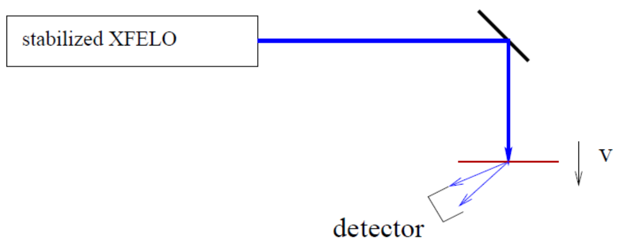
http://www.nist.gov/pml/div688/grp50/primary-frequency-standards.cfm

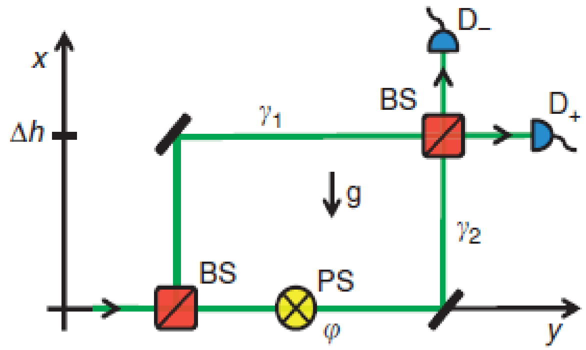
Characteristics of NR-stabilized XFEL-O enabling applications for technology and fundamental sciences

- **Higher wavelength accuracy**
  - **as small as 10^{-22}**
- **Small dimension of moving clock**
  - **one NR atom ~ 1 pm**
  - **A cm-size atomic clock is feasible but with less accuracy~ 10^{-11}**
- **X-rays can be focused to a smaller spot-size**

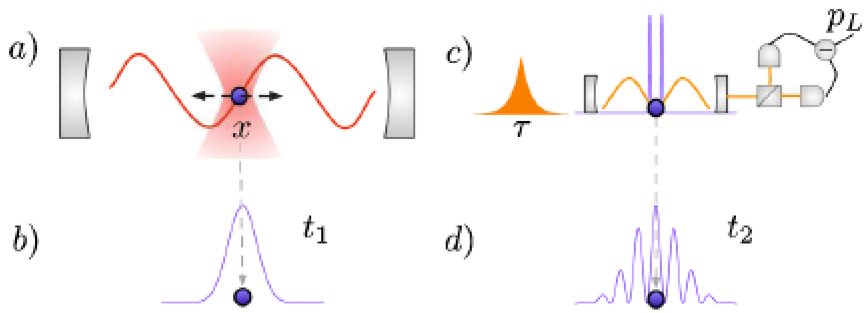
Some possible applications

- **Precision measurement of B- and g-field→ "find oil !"**





- **The role of proper time in quantum gravitation**
  - M. Zych, F. Costa, I. Pikovski, C. Brukner, Nature Comm. (2011)
- **Macro-particle aspects in collapse of quantum wavefunction (the fate of Schrödinger cat)—improve the resolution of experiment proposed by Kaltenbaek, et al., PRL 107, 020405 (2011);**



Conclusions

- **An XFELO produces fully coherent, meV BW radiation, complimentary to high-gain XFEL**
- **Accelerator technology for an XFELO is available**
- **Diamond optics appears feasible/promising**
- **An XFELO will drastically improve experimental techniques developed for the 3rd generation sources**
- **Extending the XFELO to produce x-ray comb stabilized by locking to NR**
- **A stabilized XFELO may have application in nanotechnology and fundamental sciences**