Some ideas for determining the f_0 of an x-ray comb produced via XFELO

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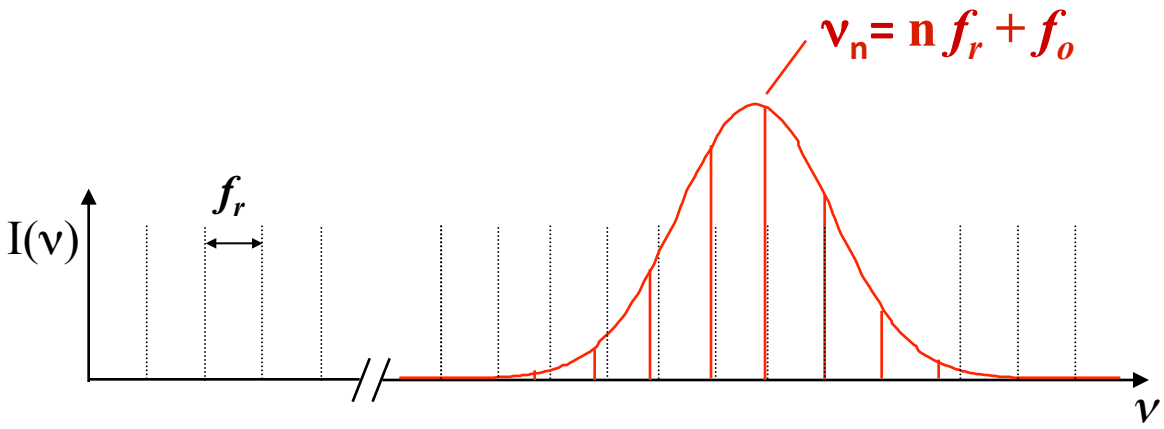
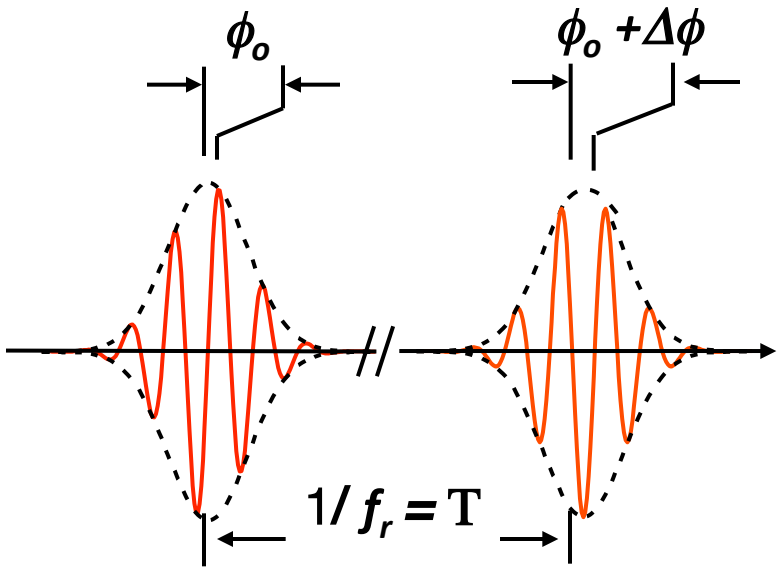
Frequency Combs



f_r = Comb spacing

$f_o = \Delta\phi \times f_r / 2\pi$, Comb offset from harmonics of f_r

$\Delta\phi$ = Phase slip b/t carrier & envelope each round trip



Directly relate optical frequencies to RF

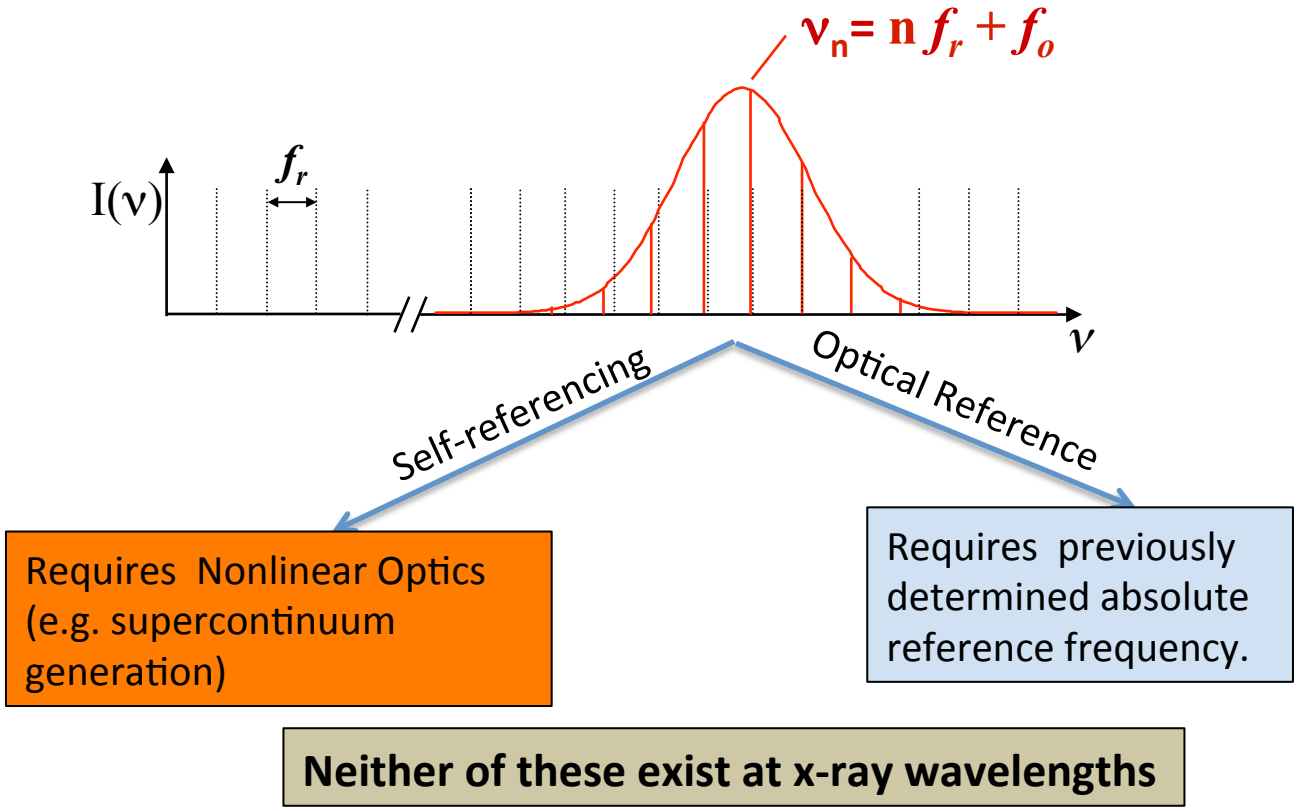
⇒ Optical clocks.

⇒ Precision measurement.

Also essential for attosecond physics through carrier envelope phase control.

Comb tooth linewidth determined by coherence time of pulse train, not the pulse duration!

- f_{rep} and f_0 are electronically countable frequencies. How do you measure them?
- f_{rep} is easy! Just count pulses arriving at detector.
- f_0 is related to the optical phase, and thus requires an interferometric measurement of the light wave's phase evolution, either by
  (1) beating the comb against itself (self-referencing)
  (2) beating the comb against an optical reference frequency previously linked to the Cs standard



Use Laser Physics?

- In principle, the f_0 of a comb is uniquely determined by the physics of the mode-locked laser that created it, so that in principle if one measured everything about the laser cavity and gain medium, one could predict the f_0 of the comb.

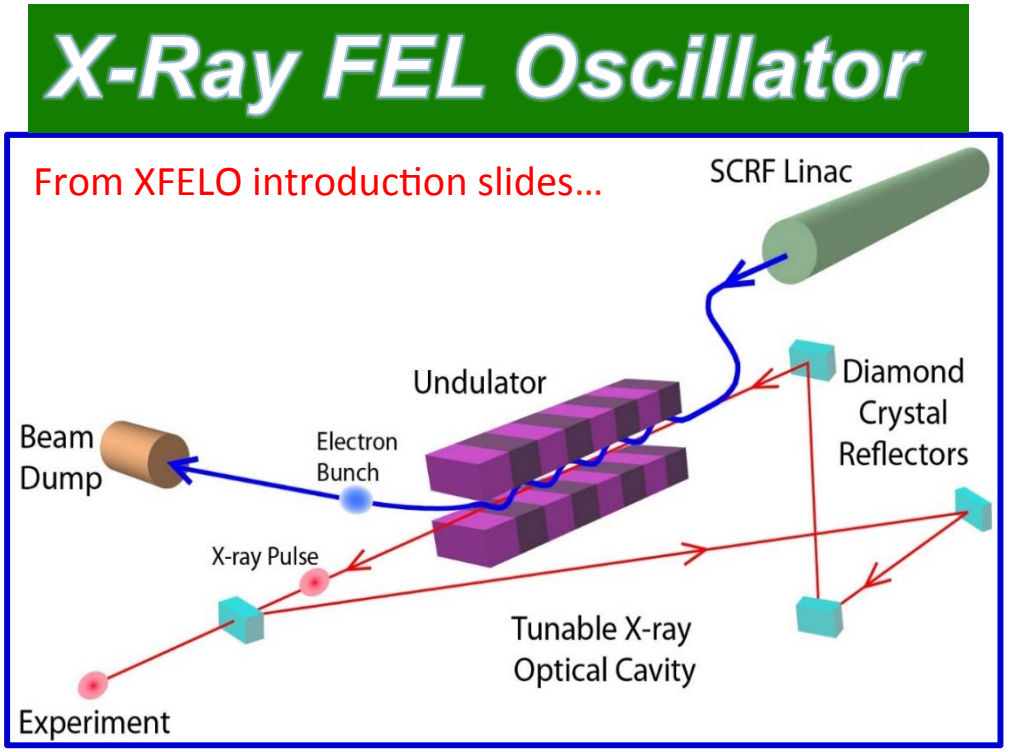
- But in practice this is impossible! Very subtle changes in the gain medium, optics, alignment, etc. can make large changes in f_0 (and this is commonly exploited for feedback and control.)

- However… perhaps the XFELO is different in that it's gain medium (the electron bunch) is spit out every round trip, and **the phase evolution of the microbunching pattern in the ejected electron bunches is the same as the intracavity light.**

This is the key idea to explore with the accelerator physics people.

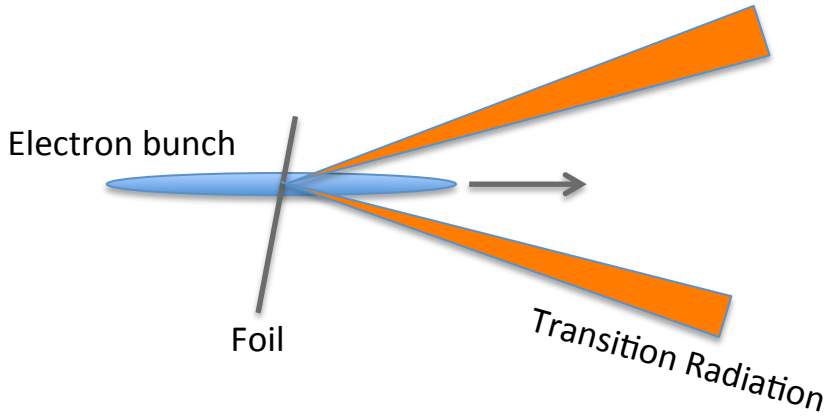
Can you measure the microbunching structure shot by shot or produce longer wavelength radiation using these ejected bunches with the same (or deterministically related) f_0 ?

Right now the electron bunch is just destined for a beam dump, but the x-ray phase information *is* encoded in this bunch.



Can you measure the microbunching structure shot by shot or produce longer wavelength radiation using these ejected bunches with the same (or deterministically related) f_0 ?

Coherent Optical Transition Radiation



- Relativistic electron bunches can produce long-wavelength radiation upon passing through foils, and this radiation is coherent!

Interference phenomenon in optical transition radiation and its application to particle beam diagnostics and multiple-scattering measurements

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(Received 24 March 1975)

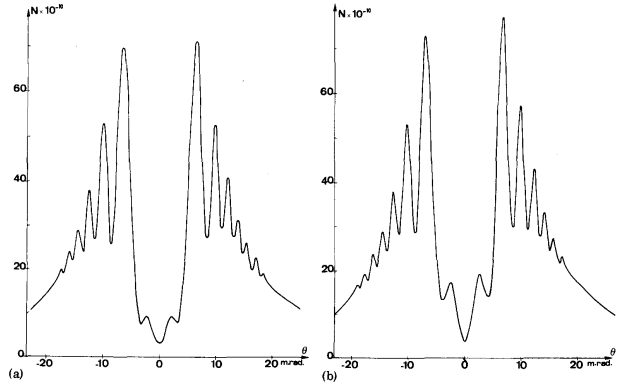

FIG. 10. Transition radiation patterns for the two-foil arrangement: $\gamma = 141.9$; $L = 13.5$ mm; $\lambda = 4530$ Å; $\Delta\lambda = 190$ Å; $\theta_0 = 0.5$ mrad. Foil I: (a) aluminum-coated Mylar. (b) Uncoated Mylar.

Coherent Optical Transition Radiation

- COTR is a commonly used accelerator diagnostic for measuring beam sizes and temporal profiles. Has been used for both conventional accelerators and wakefield accelerators.

- And it has been used to study microbunching in FELs…

PRL **110,** 094802 (2013) PHYSICAL REVIEW LETTERS week ending 1 MARCH 2013

Single-Shot Coherent Diffraction Imaging of Microbunched Relativistic Electron Beams for Free-Electron Laser Applications

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(Received 12 July 2012; published 1 March 2013)

PRL **96,** 014801 (2006) PHYSICAL REVIEW LETTERS week ending 13 JANUARY 2006

Temporal Characterization of Femtosecond Laser-Plasma-Accelerated Electron Bunches Using Terahertz Radiation

J. van Tilborg,[1,*] C. B. Schroeder,[1] C. V. Filip,[2] Cs. Tóth,[1] C. G. R. Geddes,[1] G. Fubiani,[1,†] R. Huber,[1] R. A. Kaindl,[1] E. Esarey,[1,2] and W. P. Leemans[1,2]

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(Received 1 July 2005; published 4 January 2006)

VOLUME 86, NUMBER 1 PHYSICAL REVIEW LETTERS 1 JANUARY 2001

First Observation of z-Dependent Electron-Beam Microbunching Using Coherent Transition Radiation

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(Received 21 July 2000)

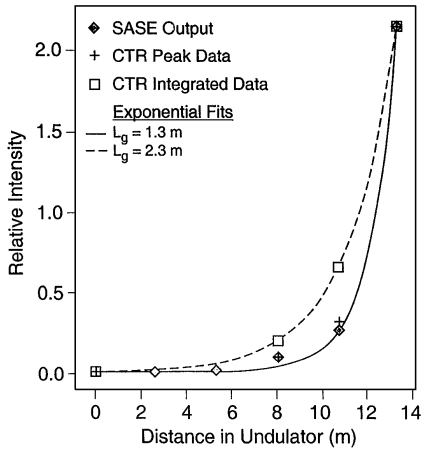

FIG. 4. Results of the z-dependent intensity measurements for UR (diamonds) and CTR. Both the UR and the peak CTR (pluses) have a similar exponential growth corresponding to $L_g = 1.3$ m. The angle- and wavelength-integrated CTR data (squares), however, have a growth consistent with $L_g = 2.3$ m.

Coherent Optical Transition Radiation

But… I think the COTR from the microbunched beam at x-ray wavlengths will again be at x-ray wavelengths (*not useful*). The COTR spectrum for a bunch is essentially the Fourier transform of the bunch profile.

Here is an example with an IR FEL:

VOLUME 81, NUMBER 26 PHYSICAL REVIEW LETTERS 28 DECEMBER 1998

Observation of Self-Amplified Spontaneous-Emission-Induced Electron-Beam Microbunching Using Coherent Transition Radiation

A. Tremaine, J. B. Rosenzweig, S. Anderson, P. Frigola, M. Hogan, A. Murokh, and C. Pellegrini
Department of Physics and Astronomy, UCLA, 405 Hilgard Avenue, Los Angeles, California 90095-1547

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(Received 9 July 1998)

We report the measurement of electron-beam microbunching at the exit of a self-amplified spontaneous-emission free-electron laser (SASE FEL), by observation of coherent transition radiation (CTR). The CTR was found to have an angular spectrum much narrower than spontaneous transition radiation and a narrow-band frequency spectrum. The central frequency of the fundamental CTR spectrum is found to differ slightly from that of the SASE, a finding in disagreement with previously invoked CTR theory. The CTR measurement establishes the uniformity of microbunching in the transverse dimension, indicating the SASE FEL operates in a dominant transverse mode. [S0031-9007(98)08027-2]

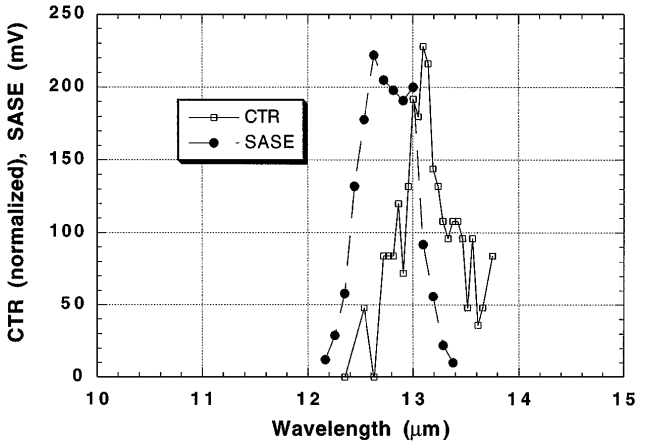


FIG. 3. SASE and CTR signals as a function of wavelength, with CTR scaled to SASE amplitude.

What to ask the accelerator people

1. Can you somehow measure shot by shot the microbunching structure of the electron bunch in a phase sensitive manner? Does not have to be absolute, just need phase differences pulse to pulse.

   My understanding from a quick literature search is that this is beyond the state of the art, but something accelerator physicists would love to do anyway.

2. Can COTR from the ejected microbunched electrons be used somehow to produce a comb with the same (or deterministically related) f_0, but at longer wavelengths?

   My understanding is that simply passing the electron macrobunch through a foil will not do this, but perhaps it can be decelerated or otherwise manipulated to do this.

What to ask the accelerator people

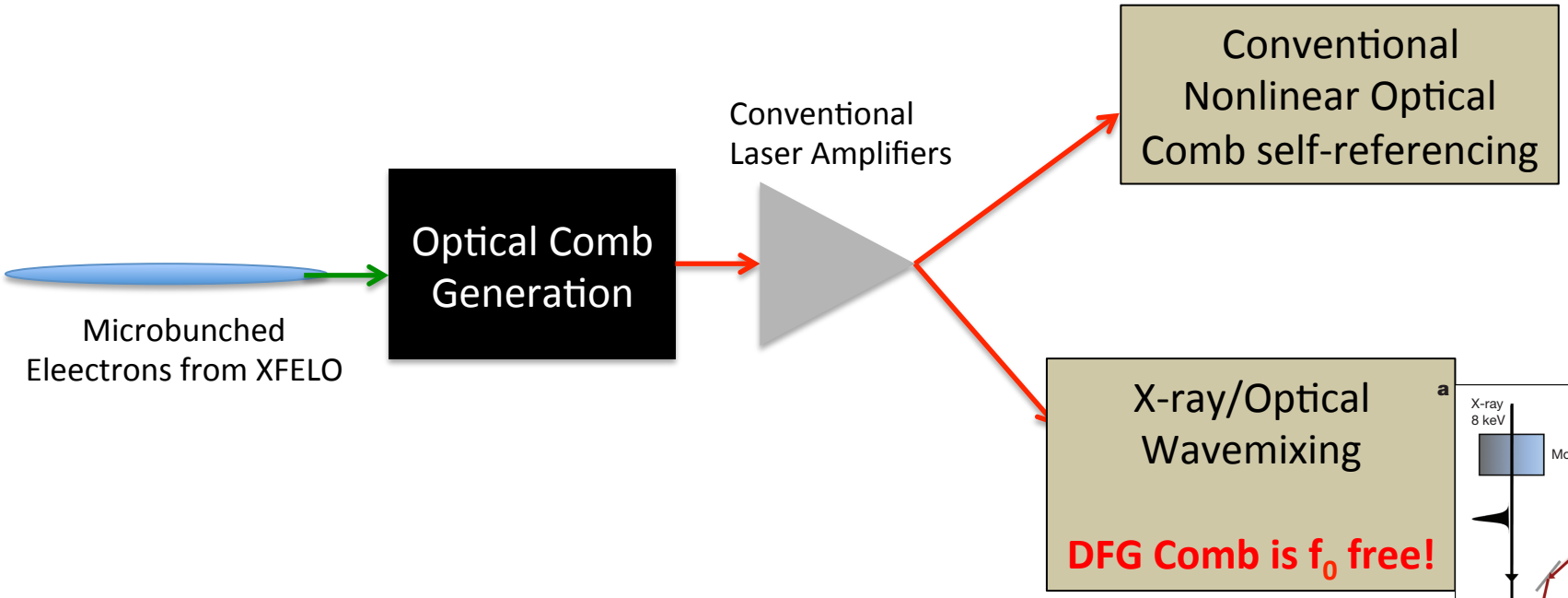
3. If not COTR, can an optical comb be made by using a longer wavelength FEL at a sub-harmonic of the microbunching pattern? (similar to injection locking).

My feeling is that this could be possible but challenging/expensive

4. X-ray energy of 15 keV will be the 5th harmonic of the microbunch, is it also possible to extract light from the fundamental of the microbunch (3 keV). This could be used for DFG or a heterodyne beat with stabilized laser HHG source.

HHG currently only demonstrated out to 1.6 keV

If you could…



ARTICLE

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X-ray and optical wave mixing

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