X-Rays and Extreme Ultraviolet Radiation: Principles and Applications

Chapter 6. FEL Homework Problems (Aug. 2018)

6.1 Imagine you are participating in the first hard x-ray FEL experiments. What is the name of this lasing process? Describe how it emerges from fluctuations of electron density. How does this affect the spectral content of the emerging FEL radiation. In what sense is this statistical?

6.2 Name thirteen (13) important parameters that characterize an x-ray FEL beam for scientific experiments.

6.3 What controls the spatial coherence of an FEL? How is this achieved? What are three primary electron beam and undulator parameters that lead to FEL lasing? What peak x-ray FEL laser power is achieved? Compare these parameters to undulator radiation at a hard x-ray synchrotron facility. How is spatial coherence measured for x-ray pulses?

6.4 You are participating in the first hard x-ray free electron lasing experiments. Various undulator modules will be moved into place and the resultant radiation observed. What equation describes the expected wavelength? What are two crucial observations, both relatively simple, that you can make that will convince you that lasing has occurred as the number of added undulator modules increases? What observations do you expect to make?

6.5 You are participating in the planning of a seeded FEL. At this time the strongest at-wavelength seed available is high harmonic generation (HHG) driven by a Ti:sapphire laser. What are some general guidelines that would allow you to set a required power threshold for the requisite laser harmonic? How would this compare to the noise driven undulator radiation which naturally occurs in the first undulator modules? Is your estimate based on peak electron current averaged over the electron bunch, or based on anticipated fluctuations that would drive the competing SASE process?

6.6 Explain how energy transfer between the radiated field (wave) and the electron beam leads to bunching and gain in the FEL lasing process. What is the relationship between the electron beam velocity and the x-ray or EUV phase velocity? What is v/c in terms of the electron beam's γ?

6.7 Describe the 'slip condition'. How is related to the undulator equation?

6.8 What is the 'bunching advantage' of an FEL vis á vis an unmodulated electron beam as in undulator radiation? How many orders of magnitude greater might the peak power of an FEL pulse be relative to the peak power radiated by a similar undulator at a synchrotron facility? What are other examples of the N^2 effect in physics and daily life?

6.9 The one-dimensional FEL equations are very helpful in quantitatively understanding the FEL process. What are some resulting parameters that one deduces from the 1-D theory. What non-linear affects are not included in the linearized 1-D equations? What important 2-D and 3-D effects are not included in the 1-D theory? How do these omissions affect one's ability to accurately predict performance that can be achieved in the laboratory?

6.10 How is the radiated spectrum of a hard x-ray FEL measured? How many spectral spikes might be observed in a current SASE experiment? Describe how the number of such spectral spikes might be reduced? For what type of experiments is the relative spectral bandwidth important? For what type of experiments is the longitudinal (temporal) coherence length important? What are typical examples of both?

6.11 Describe how the spatial coherence of FEL radiation is measured. What might this reveal about the electron beam phase space?

6.12 How is temporal (longitudinal) coherence length related to spectral bandwidth? How is spectral bandwidth measured? How might longitudinal coherence length be measured directly?

6.13 The one-dimensional relative spectral width for FEL gain is shown in slide 6.39 to be $2\Delta\omega/\omega\big|_{FWHM} = 1/2\pi N_G$, where $N_G \equiv L_G/\lambda_u$ is the number of undulator cycles in one gain length. Estimate the relative spectral bandwidth, and its more convenient inverse, for LCLS, SACLA, PAL, SwissFEL, and the EU XFEL. Relevant parameters for LCLS are given in Table 6.1, p.249 of the text (see updates in the errata and slide 6.34). For other FEL facilities check their web pages for relevant parameters at wavelengths of interest. How might these 1D relative spectral bandwidths compare to laboratory observations. What might be the cause of these differences?

6.14 Self-seeding is used with SASE FELs to narrow the radiated spectral bandwidth. Explain how this works. How narrow a relative spectral bandwidth can be generated? What does this imply regarding the number of cycles in the electron microbunch in the FEL region downstream of the monochromator? Give a numericle example? What are the two roles played by the electron deflecting chicane? How does self-seeding affect pulse-to-pulse amplitude variations? Consult references 44 & 85 in chapter 6; D. Zhu et al., Appl. Phys. Lett.**101**, 034103 (2012) and J. Amann et al., Nature Photonics **6**, 693 (October 2012).

6.15 Intense, fully coherent EUV/SXR FEL pulses generated at FERMI are used for both dynamical studies and non-linear studies. Direct laser seeding, using crystal doubling, tripling and quadrupling techniques (see R.W. Boyd, Nonlinear optics, Academic Press) can transfer the spatial and temporal coherence of the conventional, well controlled laser, to the FEL. The FEL then amplifies the highly coherent seed pulse. Assuming the seed pulse is bandwidth limited (see the text, p.110) its duration $\Delta\tau$ will determine its spectral bandwidth $\Delta\hbar\omega$. For a sufficiently long seed pulse its relatively narrow spectral width will fit within the FEL spectral bandwidth and be fully amplified. An interesting possibility is to seed with a very short duration pulse, perhaps using HHG techniques as discussed in chapter 7. However there is a limit set by Heisenberg's Uncertainty Principle, Eq.4.4b, p.115. For a shorter duration seed pulse the spectral bandwidth may be too broad for the FEL spectral bandpass. That is, the FEL bandpass may be too narrow to amplify the broad spectrum of very short duration pulses. What is the FERMI FEL bandwidth according to the formula in slide 6.39? For this spectral bandwidth, what is the Uncertainty limited pulse duration, assuming a bandwidth limited seed pulse? What would be the effect of seeding with a shorter duration pulse? What type of experiments would be affected by this limitation? What types of experiments provide unique opportunities using the intense, spatially and temporally coherent EUV/SXR pulses available at FERMI? Consult the paper by E. Allaria et al.,Nature Photonics **6**, 699 (October 2012) for FERMI operational details. See the papers F. Bencivenga et al., Nature **520**, 205 (9 April 2015),and L. Foglia et al., Phys. Rev. Lett. **120**, 263901 (26 June 2018), and references therein, for ideas regarding nonlinear investigations.

Allaria, J. Synchr. Rad. **22**, 485 (2015).

6.16 What important parameter is critical to achieving a pump-probe capability with significant difference in the probe and pump energies? Give an example of a pump probe experiment that has been performed, or you would like to perform?

6.17 Give five examples of science that have made significant progress with the availability of EUV and x-ray FELs.

6.18 Why is it important that the Rayleigh range (see pp. 110, 259, and the online errata) be equal to many gain lengths?