USPAS FEL 2021 Final Exam

1. You're asked to design an X-ray FEL operating at 5 keV with a 4-GeV electron beam. Below is a list of electron beam parameters at two different bunch charges.

Bunch charge	rms bunch length, σ_z	Norm. rms emittance
40 pC	2.5 μm	0.3 mm-mrad
177 pC	15 μm	0.5 mm-mrad

   a) For an undulator period of 2.6 cm, calculate the undulator *K* to achieve resonance at 5 keV
   b) In the FODO lattice with average beta function of 18 m, calculate the rms electron beam radius for both bunch charges
   c) Calculate the peak current for both bunch charges, using the approximation $I_p = \frac{q_b}{FWHM}$
   d) Calculate the rho parameters for both bunch charges
   e) Calculate the 1D gain lengths for both bunch charges
   f) Analyze whether this X-ray FEL would be significantly affected by the electron beam emittance based on the normalized emittance numbers provided.

2. On slide 48 of FEL_3 lecture, the expression for the small-signal gain is given as

$$G_{ss} = (0.0675)\ 4(4\pi\rho N_u)^3$$

If we impose the condition that the undulator is one-third of the radiation Rayleigh length

$$L_u = N_u\lambda_u = \frac{1}{3}z_R$$

and approximate the $1/e^2$ radius of the radiation beam in the center of a helical undulator as

$$w_0 = 2\sigma_x = 2\sigma_y$$

Rederive the above expression for the small-signal gain to show that it scales with N_u^2 in this case.

3. Consider the LCLS copper S-band electron gun operating at 2,856 MHz with laser injection phase centered at -60° from the peak (30° from zero field if using sine convention). We will assume the laser pulse is a cylinder with uniform (top-hat) transverse intensity profile and constant power along a flat temporal pulse with full-width of 10.3 ps (10° RF phase). The electrons emitted at the two ends of the laser pulse occur at -65° (25° from zero field if using sine), and -55° (35° from zero field).

   a) Calculate the gamma and phase of the electrons emitted at -65° at the distance of 6 cm from the cathode, ignoring image charge and space charge effects.

b) Calculate the gamma and phase of the electrons emitted at -55° at the distance of 6 cm from the cathode, ignoring image charge and space charge effects.

c) What is the phase difference between these two groups of electrons in degrees?

d) How does this compare to the initial 10° phase difference? Explain what happens.

4. A freshly made Cs_2Te photocathode has a quantum efficiency of 10% at 266 nm when it is inserted into the photoinjector. After a few days of use, the cathode Q.E. decays to 1%.

   a. If you are to produce 100 pC electron bunch charge at 1 MHz, calculate the 266 nm laser power needed at the initial Q.E. of 10%.

   b. Calculate the 266-nm laser power needed after the Q.E. decays to 1%.

   c. To achieve very low emittance, the design calls for having a 1 mm diameter laser spot side on the photocathode. Calculate the image charge field assuming a uniform laser transverse profile.

   e. If the applied field is 20 MV/m, what is the cathode accelerating field at -60° (cosine convention) emission phase, including the image charge field?

5. You are to design a harmonic-generation (both HGHG and EEHG) FEL with to produce 5 nm using an input laser beam with wavelength at 205 nm and electron beam energy of 1 GeV, rms energy spread of 20 keV, and maximum allowable energy modulation of 100 keV.

   a. What is the maximum HGHG bunching factor for this harmonic?
   b. What is the expected EEHG bunching factor for this harmonic?
   c. For EEHG with rms input energy spread of 20 keV, compute the A_1 value that will produce a 60 keV energy modulation in the first modulator, and the A_2 value that will produce an 80 keV energy modulation in the second modulator.
   d. Calculate the R_{56} of the chicane that would provide a B_1 value of 11.