Design Studies of Coherent Prebunching and Emittance Reduction for the MaRIE XFEL

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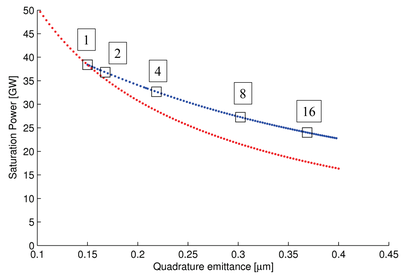
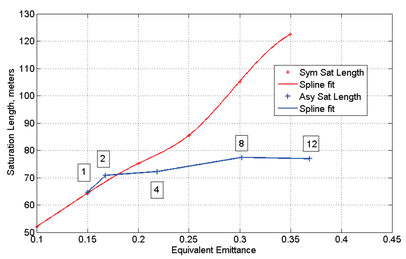
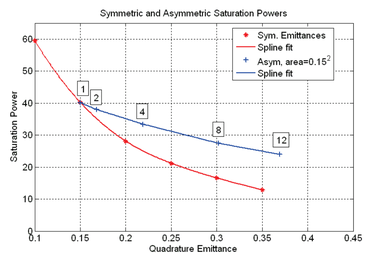
FEL performance with Asymmetric Emittances

There are currently several schemes being studied to reduce the normalized emittance of the electron beam after it has been accelerated to large energies, in order to reduce the gain length in the FEL. Some of these schemes will result in asymmetric emittances where one transverse emittance is much larger than the other [1]. We have done GENESIS [2] simulations of electron beams with asymmetric emittances, and seen that (1) the optimal focusing does not deviate far from symmetric focusing in the 2 planes, and (2) the saturation power does not decay as fast as one would expect from simply adding the induced energy spreads in quadrature. We have also developed a modified version of the Ming Xie [3] parameterization for estimating performance with asymmetric emittance, which agrees reasonably well with simulation.

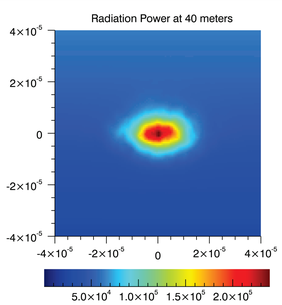


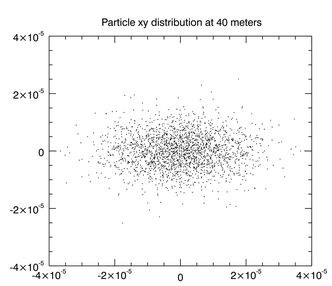
Ming Xie parameterization, with $\Delta\gamma/\gamma = 1.5\times10^{-4}$, AW0 = 1.47, undulator period = 2.4 cm. We kept the product of the emittances, $\epsilon_x{}^*\epsilon_y=(0.15\ \ m)^2$. The x-axis is the sum of the emittances in quadrature.





These results are from GENESIS simulations with $\Delta\gamma/\gamma = 1.5\times10^{-4}$, AW0 = 1.47, undulator period = 2.4 cm. We kept the product of the emittances, $\epsilon_x{}^*\ \epsilon_y=(0.15\ \ m)^2$. The x-axis is the sum of the emittances in quadrature.





Particle and radiation distribution in exponential section, with $\epsilon_x/\epsilon_y=4$

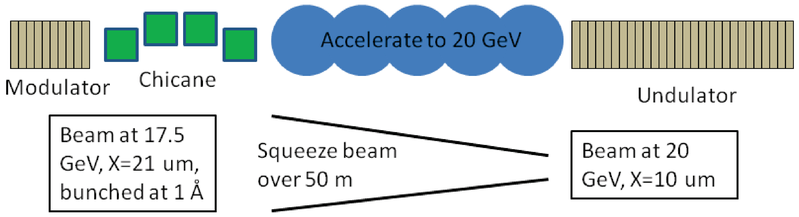
Nonlinear Debunching Effects on Harmonic Generation Schemes

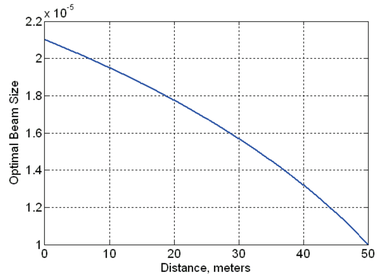
The effective energy spread introduced from the emittance of the beam is given by:

$$\sigma_\gamma = \frac{\gamma_0\epsilon_N^2}{\langle X\rangle^2} \qquad (1)$$

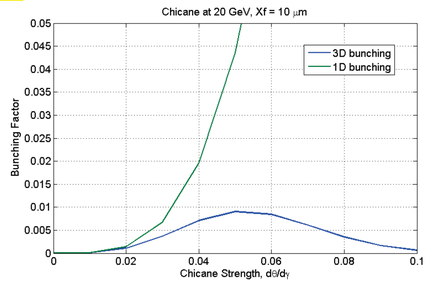
This effect will be large, comparable to ρ or greater for an XFEL. Harmonic generation schemes generally involve introducing an additional energy modulation ~2x the random energy spread in the beam, which will seriously degrade FEL performance. We are currently exploring different options for mitigating this effect by decreasing the effective energy spread from emittance. Eqn. (1) shows us that this energy spread can be decreased by either increasing the transverse size of the beam, or having harmonic generation located at lower electron energies than the final undulator, and attempting to preserve the electron bunching through accelerator sections.

Both of these possibilities have limitations: making the transverse size large will reduce the current density, and hence increase the gain length, while staging HGHG at low energies is limited because the linear R_{56} effect from the accelerator sections soon becomes too large and causes overbunching.

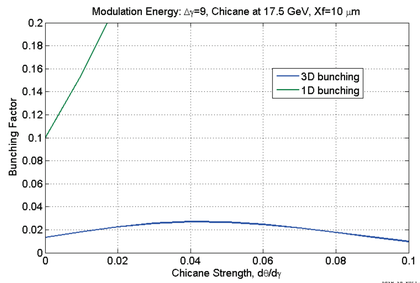




(left) Beam size vs. distance, optimized to reduce nonlinear debunching. Beam starts at 17.5 GeV and is accelerated to 20 GeV.



Bunching factor from HGHG, with (above): modulator chicane right before undulator, and (below) m-c 50 m before, with beam at 17.5 GeV



The bunching factor from standard HGHG is [7]:

$$b_n = 2\exp\left[-\frac{1}{2}n^2\sigma_\gamma{}^2\left(\frac{d\theta}{d\gamma}\right)^2\right]J_n\left(n\Delta\gamma\frac{d\theta}{d\gamma}\right)$$

Here σ_γ is the intrinsic energy spread of the beam, n is the harmonic number, $\frac{d\theta}{d\gamma}$ is the

dispersion from the chicane, and $\Delta\gamma$ is the modulation energy. If we include nonlinear effects and debunching in an accelerator section the bunching factor becomes:

$$b_n = 2\exp\left\{-\frac{1}{2}n^2\left[\sigma_\gamma{}^2 + \left(\frac{\delta\theta_{NL}}{d\theta/d\gamma} + \frac{\gamma_0\epsilon_N^2}{\langle x^2\rangle}\right)^2\right]\left(\frac{d\theta}{d\gamma}\right)^2\right\}J_n\left(n\Delta\gamma\frac{d\theta}{d\gamma}\right)$$

Here $\delta\theta_{NL}$ is the nonlinear debunching in the accelerator section. The two nonlinear terms are added directly because they come from the same source.

Nonlinear Debunching in Accelerator Sections

If the electron beam is accelerated after a harmonic generation section, the beam will debunch from nonlinear effects from the emittance of the beam. The RMS value of the angular spread of the beam is given by:

$$\langle x'^2\rangle = \frac{\varepsilon_n^2}{\gamma^2\boldsymbol{X}^2} + (\boldsymbol{X}')^2, \quad \boldsymbol{X}^2 = \langle x^2\rangle \qquad (1)$$

The typical particle debunching from an accelerator section (assuming a round beam) will then be given by:

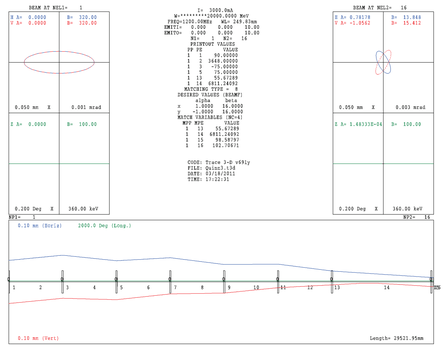
$$\delta z = \left[\int_{s_0}^{s_f}\frac{\varepsilon_n^2}{\gamma^2\boldsymbol{X}^2} + (\boldsymbol{X}')^2\right]ds$$

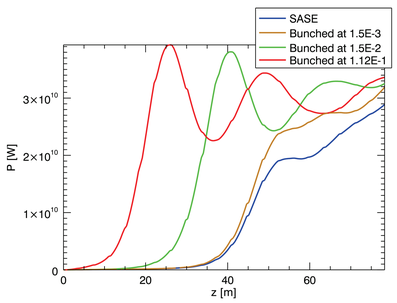
For constant acceleration, the minimized debunching along the accelerator will happen when the beam size follows a path given by:

$$\boldsymbol{X}'' = \frac{-\varepsilon_n^2}{(\gamma_0+\gamma' s)^2\boldsymbol{X}^3}$$

The optimized beam size is calculated numerically, which determines the minimum debunching from an accelerator section.

(below) Because it is impossible to squeeze beam down to 10 μm without significant nonlinear debunching, we are considering squeezing beam in undulator, where radiation from bunches will conserve signal



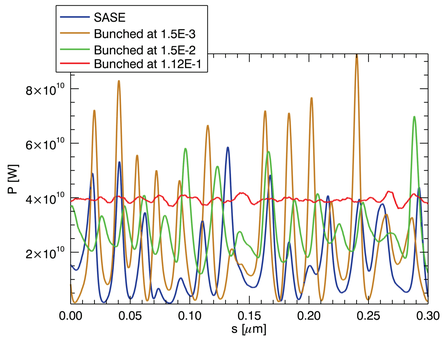


Coherent Bunching Needed to Overcome SASE

The SASE equivalent bunching factor for MaRIE is ~1×10^{-3}, corresponding to an equivalent energy of ~10 kW. Increasing the bunching factor from harmonic generation schemes involve increasing the energy modulation, which increases the effective energy spread in the beam. Because of this, we only want to bunch the beam enough to overcome SASE and reduce the bandwidth by a factor of 10-100. The output bandwidth from a seeded FEL can be estimated as [4]:

$$\frac{\Delta\omega_{new}}{\omega_1} \approx \frac{\Delta\omega}{\omega_1}\sqrt{\frac{P_1}{P_0+P_1}}$$

Here P_0 is the equivalent SASE power (either in the bunching or an EM field), and P_1 is the power in the coherent seed. Thus an input bunching factor of ~.01 should be enough to reduce the bandwidth by 10.



GENESIS simulations indicate that the SASE bandwidth of the MaRIE XFEL will be 3.6×10^{-4}, for an electron beam with 0.3 μm emittance and an energy spread of 5.0×10^{-5}. This is about 30% greater than 1D theory [5]. It is likely that wakefields will produce a bandwidth that is much larger than this. We are also investigating the transverse coherence of the MaRIE XFEL. Because the fundamental emittance criteria for an FEL, $\leq\lambda/4$ is violated, our FEL will not be fully transversely coherent [6]. Physically, this comes about because emittance limits how small we can squeeze the beam down. This in turn leads to very large Rayleigh lengths (50 m for the TEM_{00} mode). Thus the higher order transverse modes will not diffract away fast enough.

[1] N. A. Yampolsky, B. Carlsten, K. Bishofberger, S. Russell, R. Ryne, and A. Dragt "*Controlling electron-beam emittance partitioning for future X-ray light sources*", submitted to Phys. Rev. Lett.; http://arxiv.org/abs/1010.1558
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[4] B. Carlsten, et. al., *New x-ray free-electron laser architecture for generating high fluxes of longitudinally coherent 50-keV photons*, submitted to J. Mod. Optics, (2010)
[5] Huang, Z. and Kim, K., Review of x-ray free-electron laser theory, Phys. Rev. ST-AB **10**, 034801 (2007)
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