Scalloped Electron Beam FEL

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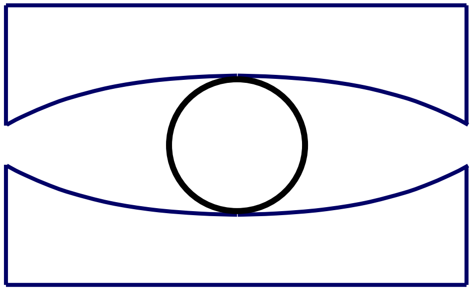
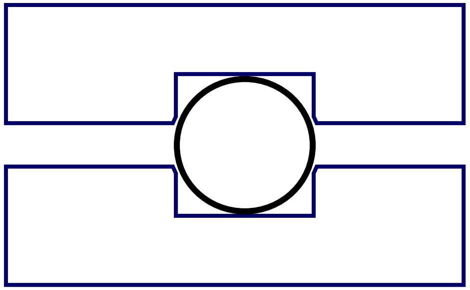
Betatron Motion in a Two-plane Focusing Wiggler

Wiggler field with parabolic pole face



$$B_y = B_0 \cosh(k_x x)\cosh(k_y y)\sin(k_w z)$$

$$B_y = B_0\left(1 + k_x^2 x^2 + k_y^2 y^2\right)\sin(k_w z)$$



Envelope equation

$$\frac{d^2\sigma}{dz^2} = -k_\beta^2\sigma + \frac{2I}{\gamma^3 I_A \sigma} + \frac{{\varepsilon_n}^2}{\gamma^2\sigma^3}$$

Betatron function

$$k_\beta = \left(\frac{eB_0}{2\gamma m_e c}\right) = \frac{k_w a_w}{\sqrt{2}\gamma}$$

Emittance-dominated matched beam radius

$$\sigma_0 = \sqrt{\frac{\sqrt{2}\varepsilon_n}{k_w a_w}}$$

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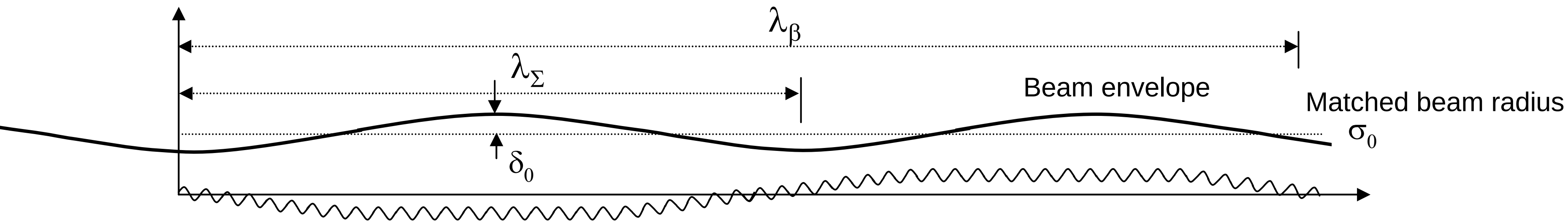
Scalloping Motion of Mismatched Beams



Modified envelope equation

$$\frac{d^2\delta}{dz^2} = -\delta\left(k_\beta^2 + \frac{K_S}{\sigma_0^2} + \frac{3\varepsilon^2}{\sigma_0^4}\right)$$

rms Envelope radius

$$\sigma = \sigma_0 - \delta_0 \sin(k_\Sigma z)$$

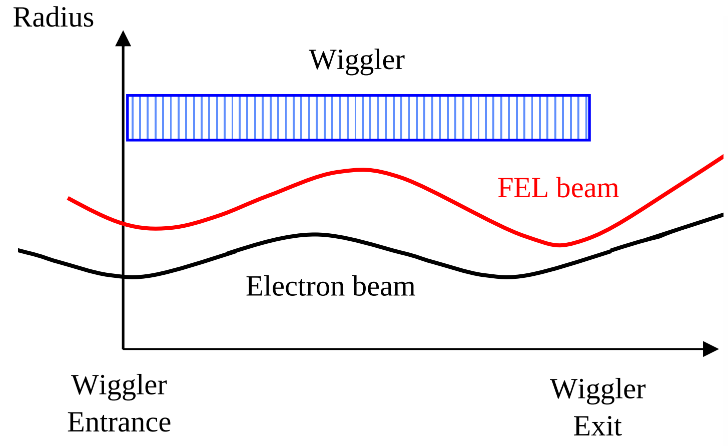
Scalloping frequency

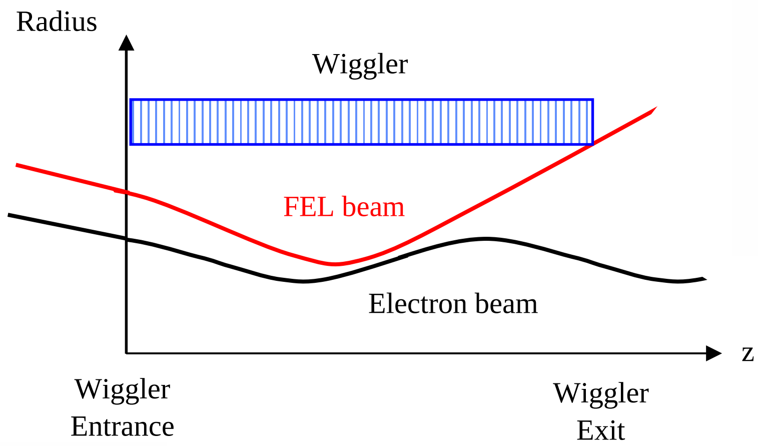
$$k_\Sigma = 2k_\beta \sqrt{1 - \frac{I}{I_A}\frac{1}{\gamma^2 k_\beta \varepsilon_n}}$$

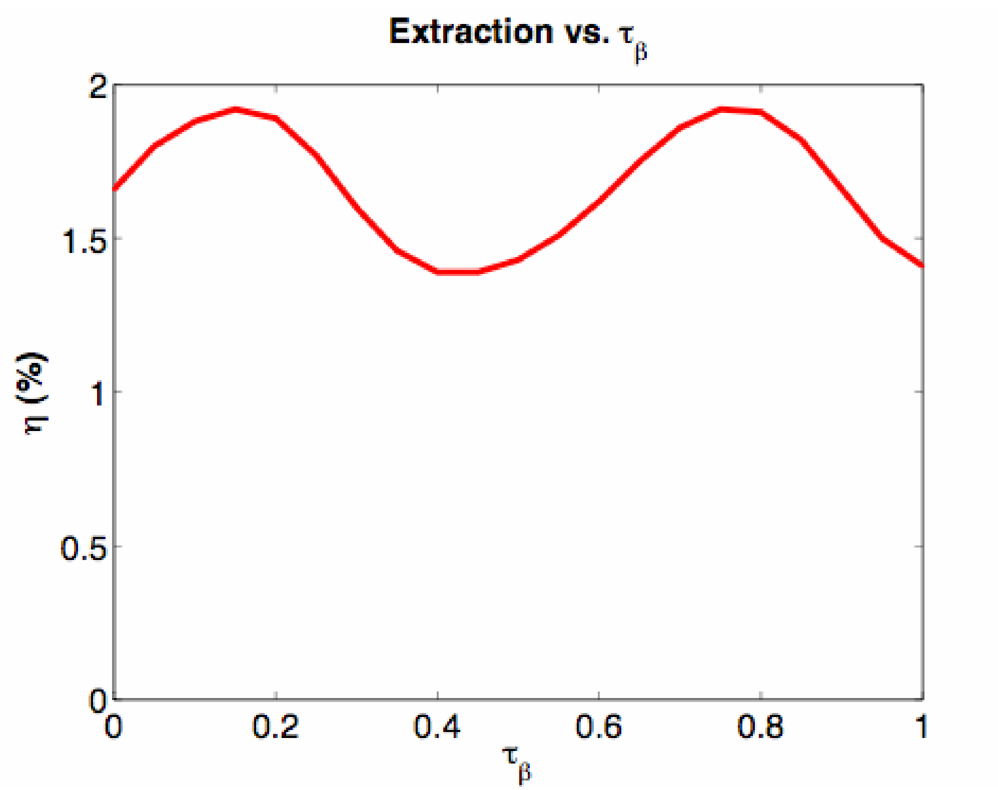
Scalloping wavelength

$$\lambda_\Sigma = \frac{2\pi}{k_\Sigma} \approx \frac{\lambda_\beta}{2}$$

Scalloped beam FEL performance depends on how the electron beam is initially focused







P.P. Crooker *et al.*, MOPPH075 Poster "Simulations of High-Power Amplifier FEL"

3-D gain length variation and FEL saturated power can be calculated analytically

1-D FEL Parameter

$$\rho = \frac{1}{\gamma}\left(\frac{a_w \lambda_w f_B}{4\sqrt{2}\pi\sigma}\right)^{2/3}\left(\frac{I}{I_A}\right)^{1/3}$$

1-D Power Gain Length

$$L_G = \frac{\gamma}{\sqrt{3}}\left(\frac{I_A}{a_w^2 f_B^2 k_w I}\right)^{1/3}\sigma^{2/3}$$

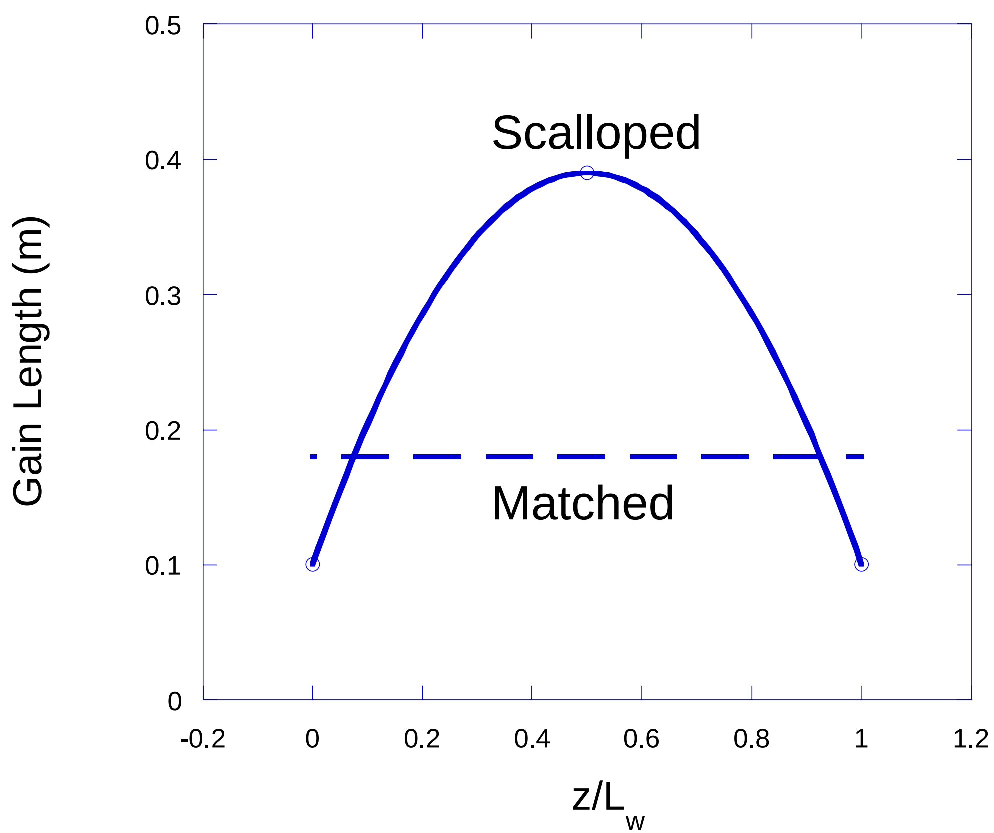
3-D Power Gain Length*

$$L_{3D} = L_{1D}\left(1+\Lambda_{3D}\right)$$

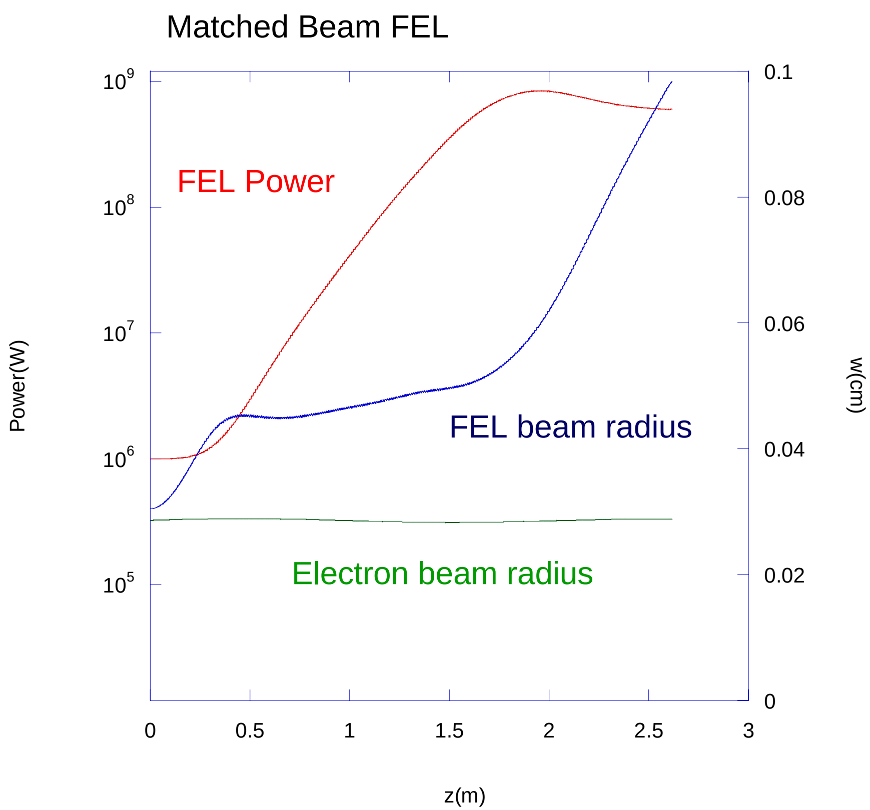
Saturated Power

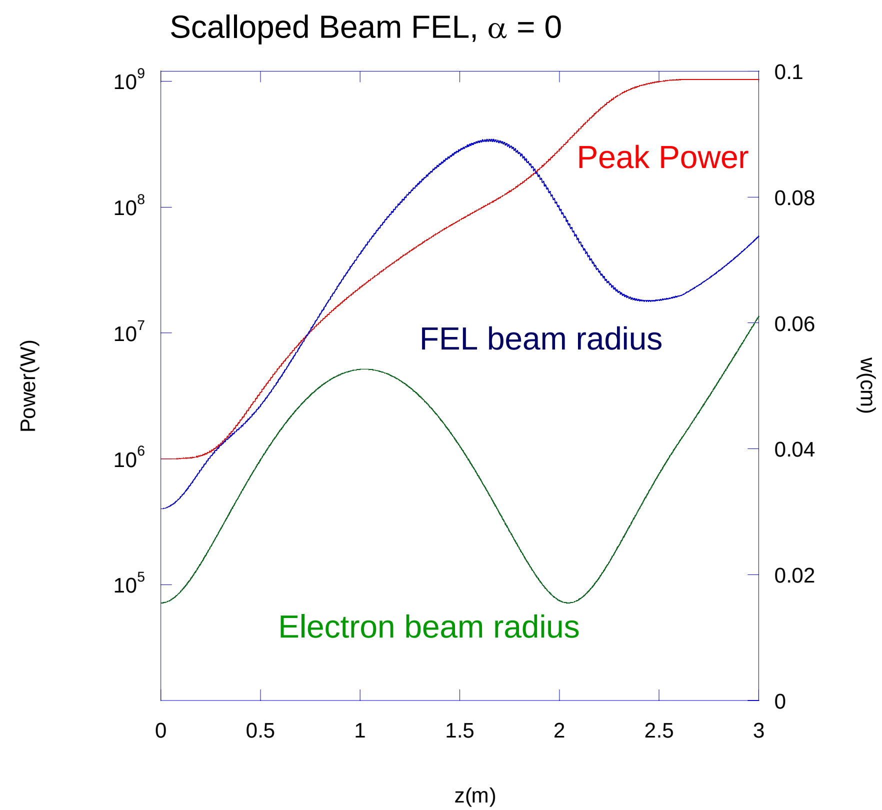
$$P_s = \frac{\rho P_{beam}}{\left(1+\Lambda_{3D}\right)^2}$$

* M. Xie's parameterization



MEDUSA simulations of scalloped beam FEL yield higher saturated power than matched-beam FEL





Scalloped beam FEL exhibits shorter lethargy region, longer saturation length, and higher saturated power compared to matched beam FEL.

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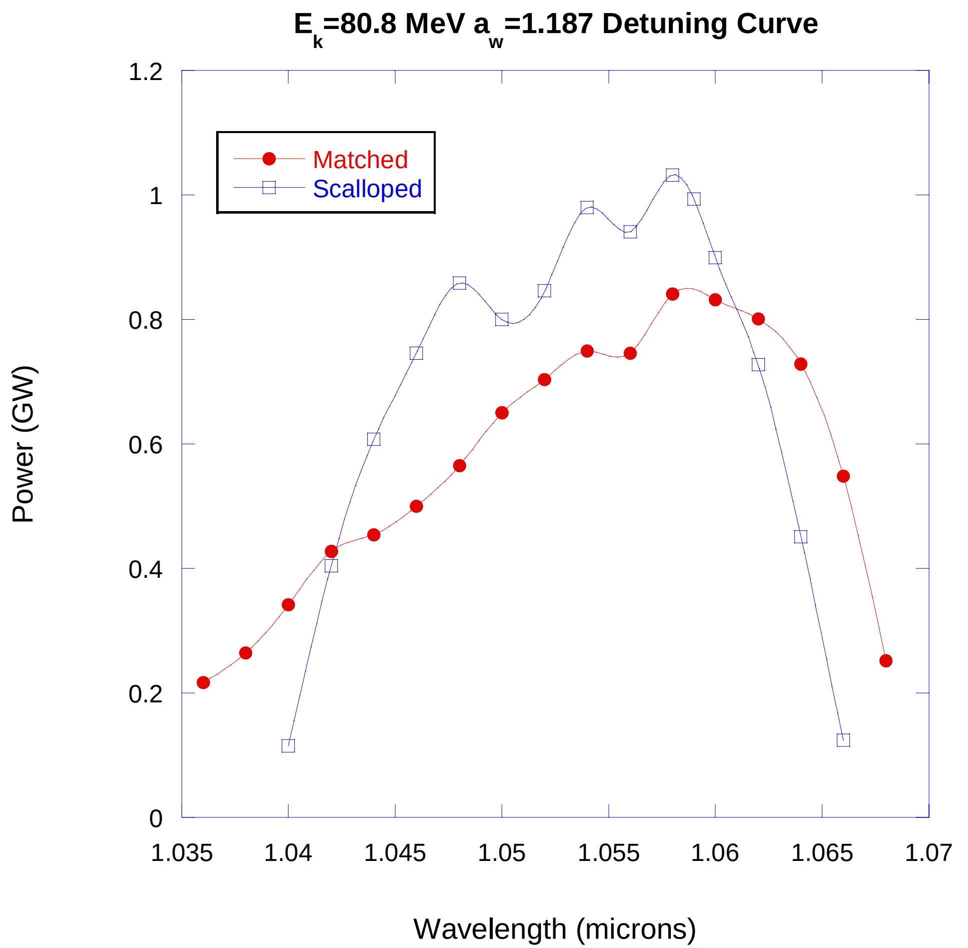
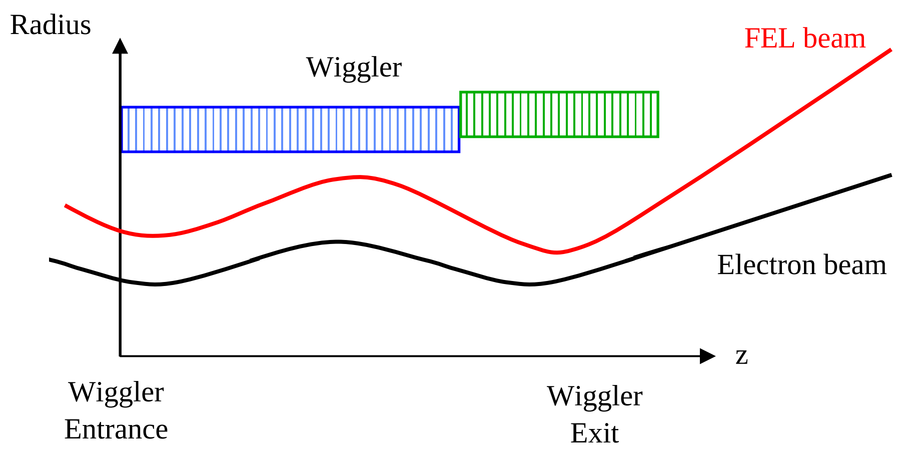
Scalloped beam has a narrower detuning curve & higher saturated power compared to matched beam



Modulation period is 5 nm, or 0.5% of central wavelength.

Scalloped Beam with Step-Tapered Wiggler



- Step-tapered wiggler provides additional gain and increases efficiency.
- Optical guiding in step-tapered wiggler strongly pinches the optical beam.
- The pinched optical beam diffracts rapidly, reducing intensity on mirrors.

D.C. Nguyen *et al*., Phys. Rev. ST-AB, 9, 050703 (2006).

Summary

- Scalloped-beam FEL uses natural betatron oscillations in electron beam envelope to modify the optical beam.
- Scalloped-beam FEL with electron beam waists near the entrance and exit produces higher power than matched beam.
- The optical beam can be strongly pinched near the wiggler exit and the resulting increase in diffraction reduces the FEL intensity on the first mirror (at a fixed distance).
- The main drawback with scalloped-beam FEL is a slight increase in the wiggler length needed to reach saturation.