Scalloped Electron Beam FEL

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FEL 2006
August 28 – September 1, 2006
Acknowledgments

Financial supports from the Office of Naval Research and the High-Energy Laser Joint Technology Office are greatly appreciated.

Los Alamos National Laboratory is operated by Los Alamos National Security, LLC for the Department of Energy.
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

\[ \sigma_0 = \sqrt{\frac{2\varepsilon_n}{k_w a_w}} \]
Scalloping Motion of Mismatched Beams

Scalloping frequency

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

Scalloping wavelength

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

rms Envelope radius

\[ \sigma = \sigma_0 - \delta_0 \sin(k_{\Sigma}z) \]
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
\[
P_s = \frac{\rho P_{beam}}{(1 + \Lambda_{3D})^2}
\]

* 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.
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.

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.