بسم الله الرحمن الرحيم

Effects of ion-channel guiding on saturation mechanism of a single-pass FEL

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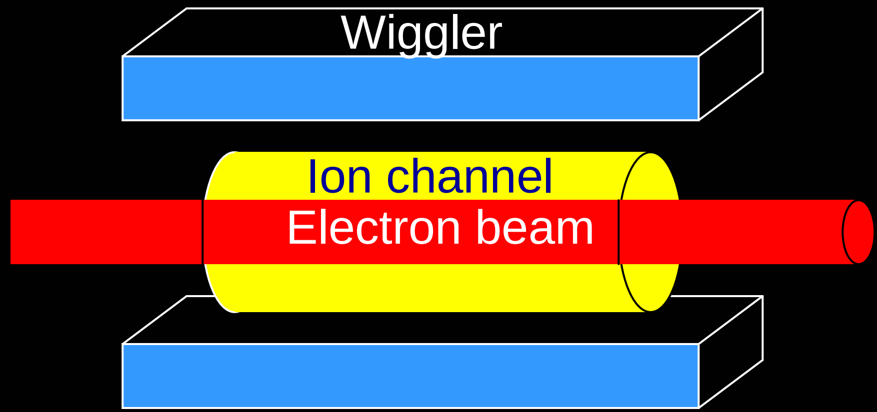
Outline

- Ion-channel guiding concept
- Ion-channel benefits and detriments
- The physical configuration
- Theoretical model
- Numerical results
- Conclusion

Ion-channel guiding concept

An ion-channel can be produced inside the FEL structure by ionizing a neutral gas either by using the electron beam itself or a high power laser pulse.

The electrons of the ionized gas are expelled from the beam value either by self-field of the electrons or ponderomotive force of the laser pulse and remains a channel of heavy ions.


Wiggler
Ion channel
Electron beam

Ion-channel guiding benefits

- Ions neutralize the space-charge of electrons and reduce the electron beam divergence.
- It permits beam currents higher than vacuum limit.
- It is a less expensive alternative to other guiding methods.
- It helps the radiation guiding.

Detriments

- Beam head erosion
- Ion-hose instability
- Ion-channel collapse

Physical configuration

- Helical Wiggler $\vec{B}_w = B_w(\hat{e}_x \cos k_w z + \hat{e}_y \sin k_w z)$
- Ion-cannel electrostatic field $\vec{E}_i = 2\pi e n_i(\hat{e}_x x + \hat{e}_y y)$
- Radiation field $\delta\vec{A}(z,t) = \delta\hat{A}(z)\left[\hat{e}_x \cos\alpha_+(z,t) - \hat{e}_y \sin\alpha_+(z,t)\right]$

  $\delta\Phi(z,t) = \delta\hat{\Phi}(z)\cos\alpha(z,t)$
- Electron beam $E = \gamma m_e c^2$

Equations of motion in the wiggler frame

$$\frac{du_1}{dz} = u_2 + \frac{d\delta a}{dz}\cos\psi - \omega_p^2 \frac{x_1}{\beta_3}$$

$$\frac{du_2}{dz} = -u_1 - \frac{d\delta a}{dz}\sin\psi - \omega_p^2 \frac{x_2}{\beta_3} - a_w$$

$$\frac{du_3}{dz} = a_w \frac{u_2}{u_3} + k_+ \delta a \frac{u_1 \sin\psi + u_2 \cos\psi}{u_3} - \frac{1}{\beta_3}\left(k\delta\varphi \sin\psi_{sc} - \frac{d}{dz}\delta\varphi \cos\psi_{sc} \right)$$

$\vec{u} \equiv \vec{p} / m_e c,$ $\quad \omega_p^2 = 2\pi n_i e^2 / m_e k_w^2 c^2,$ $\quad \omega_b^2 = 4\pi n_b e^2 / m_e k_w^2 c^2$

$a_w = eB_w / m_e k_w c^2,$ $\quad \delta a = e\delta\hat{A}(z) / m_e c^2,$ $\quad \delta\varphi = e\delta\hat{\varphi}(z) / m_e c$

$k \equiv k / k_w,$ $\quad \omega \equiv \omega / k_w c,$ $\quad \beta \equiv v / c$

$$\frac{d\psi(z)}{dz} = k_+(z) + 1 - \frac{\omega}{\beta_3}$$

$$\frac{d\psi_{sc}(z)}{dz} = k(z) - \frac{\omega}{\beta_3}$$

$$\frac{dx_1}{dz} = \frac{u_1}{u_3} + x_2$$

$$\frac{dx_2}{dz} = \frac{u_2}{u_3} - x_1$$

Field equations

- Maxwell equations in Coulomb gauge

$$\left(\frac{\partial^2}{\partial z^2}-\frac{\partial^2}{\partial t^2}\right)\delta\vec{a}(z,t)=-4\pi\delta\vec{J}_{\perp}(z,t)$$

$$\frac{\partial^2}{\partial z\partial t}\varphi(z,t)=4\pi\delta J_z(z,t)$$

$$\delta\vec{J}(z,t)=-\frac{1}{4}\omega_b^2\int_{-\infty}^{\infty}dt_0\vec{\beta}(t,t_0)\frac{\delta[t-\tau(z,t_0)]}{\left|\beta_z(t,t_0)\right|}$$

$$\frac{d}{dz}\delta a = \Gamma_+ \delta a$$

$$\frac{d}{dz}\Gamma_+ = k_+^2 - \omega^2 - \Gamma_+^2 + \frac{\omega_b^2 \beta_{z0}}{\delta a}\left\langle \frac{u_1 \cos\psi - u_2 \sin\psi}{|u_3|} \right\rangle$$

$$\frac{d}{dz}k_+ = -2k_+\Gamma_+ - \frac{\omega_b^2 \beta_{z0}}{\delta a}\left\langle \frac{u_1 \sin\psi + u_2 \cos\psi}{|u_3|} \right\rangle$$

$$\frac{d}{dz}\delta\varphi = -2\frac{\omega_b^2 \beta_{z0}}{\omega}\left\langle \sin\psi_{sc} \right\rangle$$

$$k = -2\frac{\omega_b^2 \beta_{z0}}{\delta\varphi\omega}\left\langle \cos\psi_{sc} \right\rangle$$

$$\langle\langle(\cdots)\rangle\rangle \equiv \frac{1}{2\pi}\int_{-\pi}^{\pi} d\psi_0 (\cdots)$$

$$\psi_0 = -\omega t_0$$

Numerical analysis

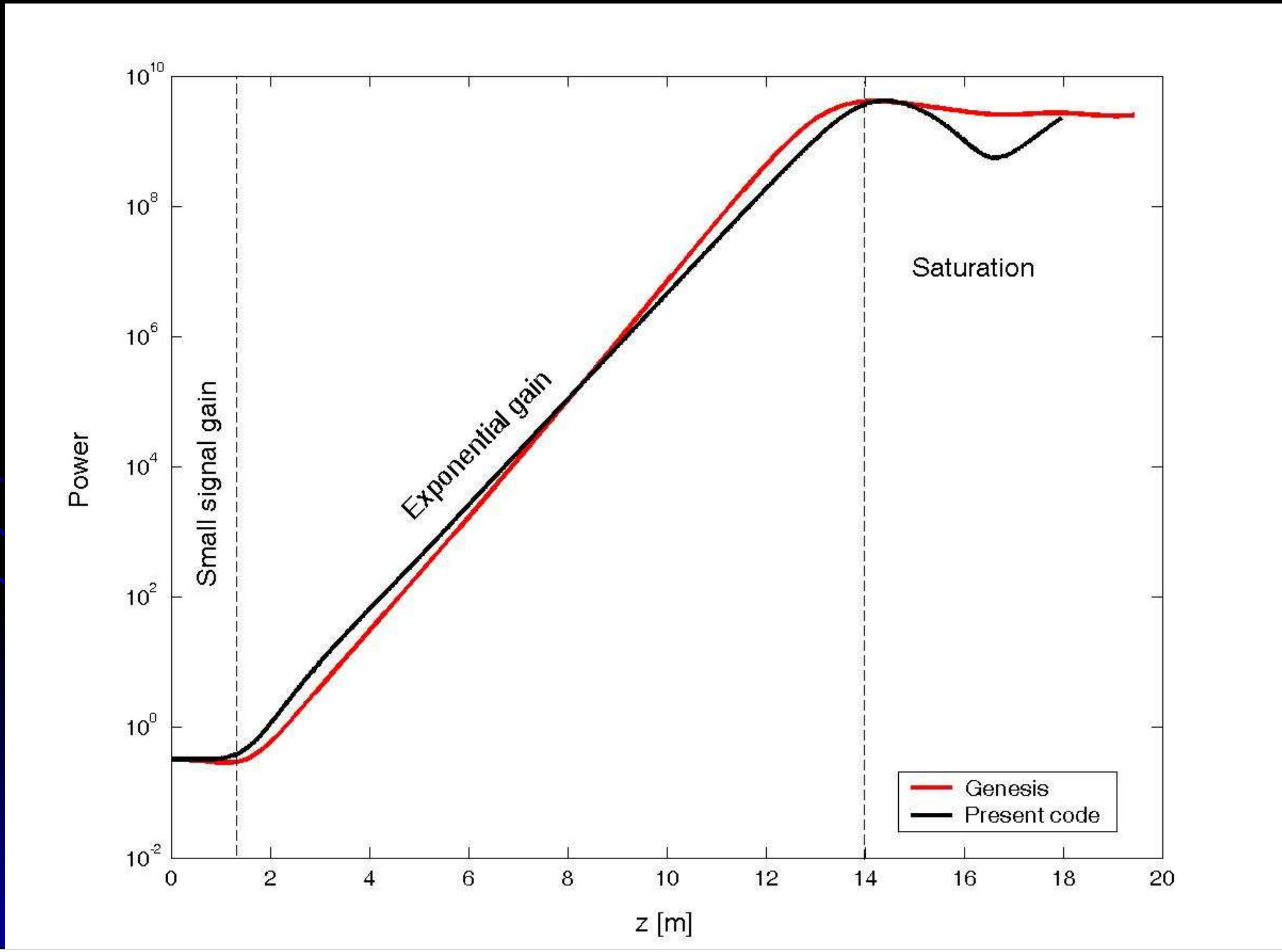
The first example is corresponding to a 1.2GeV electron beam, a_w=4 and without ion-channel

(Fermi@Elettra at 100 nm)

$$\gamma_0 = 1250, \qquad \omega_b = 47.5$$
$$K = 4, \qquad \omega_p = 0$$

There is 4N+7 first order differential equations which must to be solve self consistently

The output power versus axial position without ion-channel



Ion-channel affects the ordinary FEL parameter. An effective FEL parameter could be defined as:

$$K = \left| \frac{\gamma_0 \beta_{0z}^2 a_w}{\gamma_0 \beta_{0z}^2 - \omega_p^2} \right|$$

The output wavelength has its ordinary formula

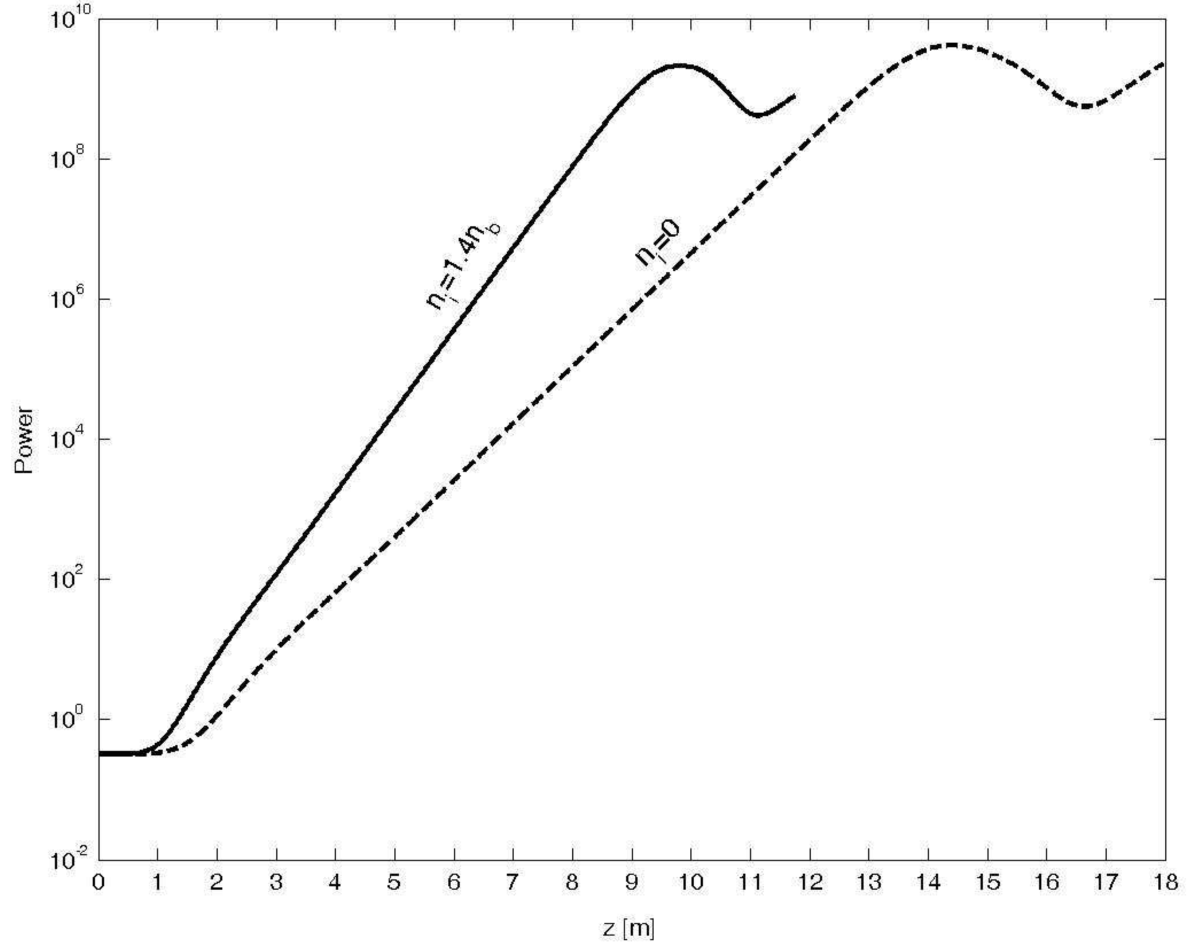
$$\lambda = \frac{\lambda_w}{2\gamma_0^2} \left[1 + K^2 \right]$$

Consequently, ion-channel acts as a tuning parameter for the standard FELs.

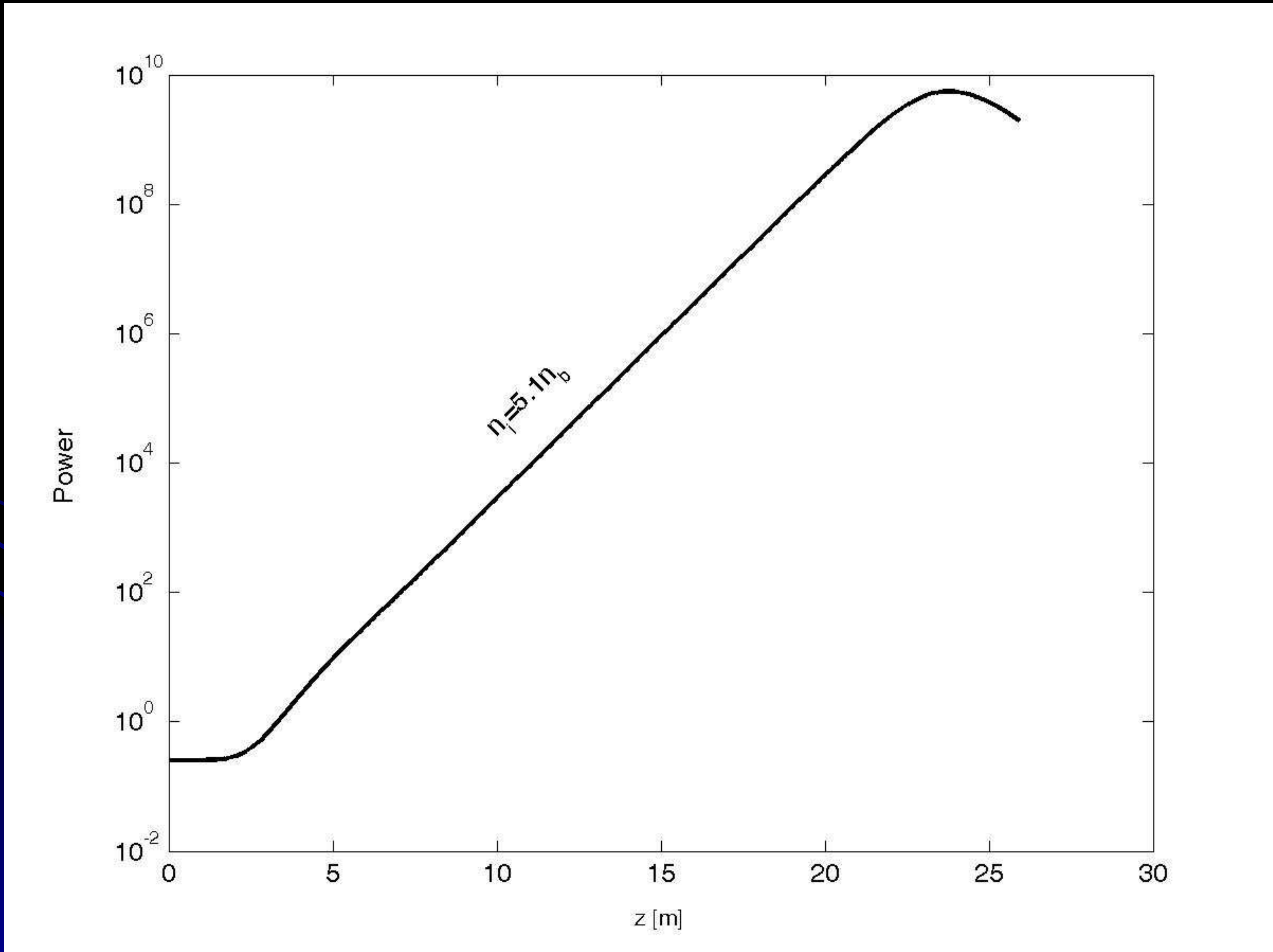
It can be used in two different schemes:

1. Changing the output wavelength for a fixed FEL structure
2. Getting to the same output wavelength with different structures

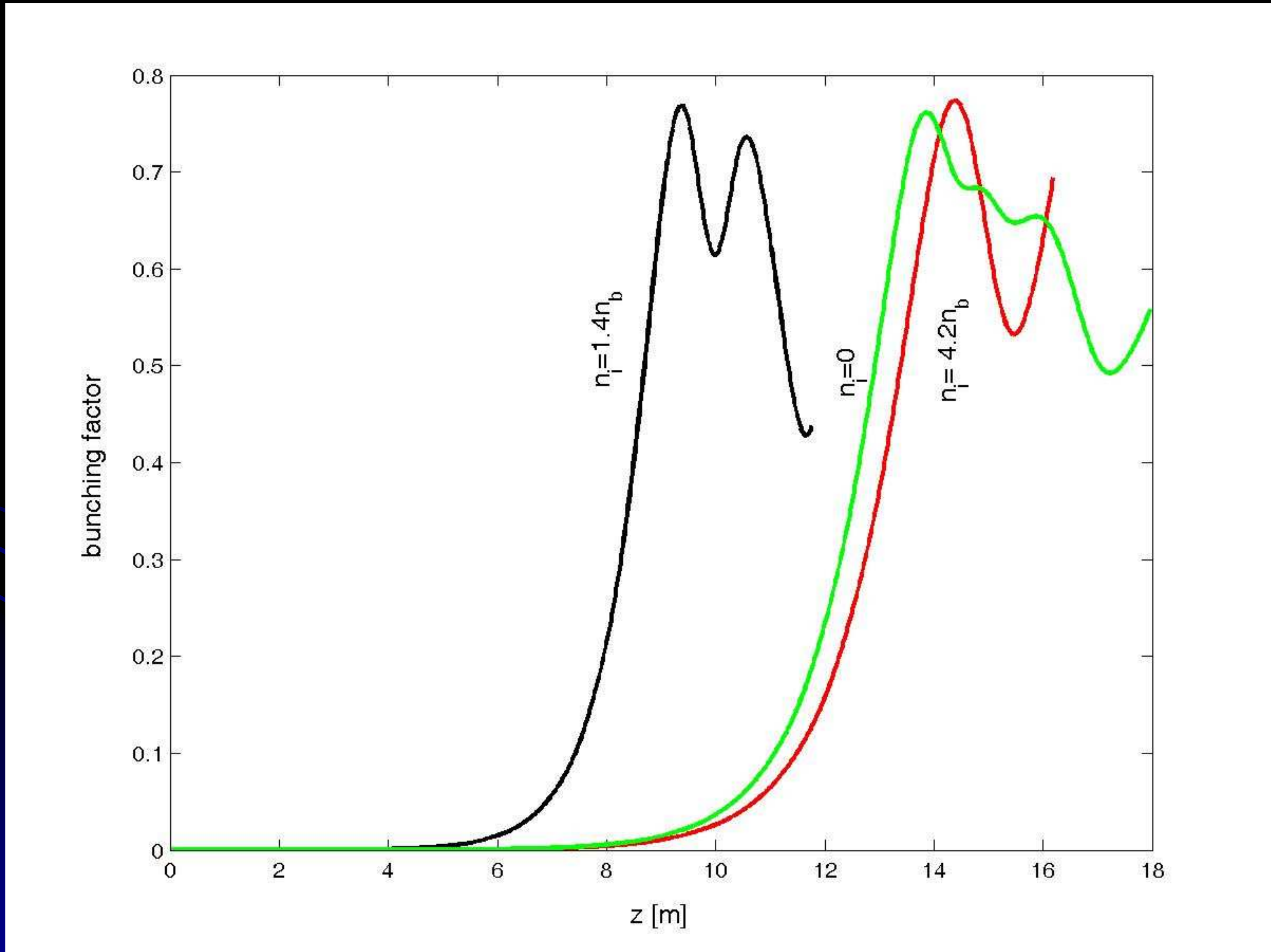
Output power for a FEL with a_w=1.27, ion-channel density n_i=1.4n_b and λ=100nm (K=4)



Output power for a FEL with, a_w=4 ion-channel density n_i=5.1n_b and λ=50nm (K=2.74)



Bunching parameter for different ion-channel densities



Conclusion

In addition to this evident fact that ion-channel guiding allows higher electron currents and less divergence;

- The ion-channel affects the ordinary FEL parameter in a way which can be used as a tuning parameter to control the output characteristics of the FEL.

- It is possible to reduce the saturation length for a fixed wavelength by reducing the ordinary FEL parameter and compensating it by an appropriate value of ion-channel.

Thank you for your attention