DESIGN OF HYBRID MAGNET UNDULATORS WITH NON-CONSTANT PARAMETERS FOR HIGH GAIN, HIGH EFFICIENCY FREE ELECTRON LASER

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Abstract

A suitable undulator design for a high gain-high efficiency FEL in the Master Oscillator Power Amplifier configuration is discussed.

1. Introduction

One of the crucial parameters of any free electron laser (FEL) experiment is the efficiency [1]. High efficiency, i.e. large output laser to e-beam power, requires tapered undulator devices. Efficiencies larger than 35% have been experimentally achieved [2].

A high power FEL can be therefore realized combining the performances of accelerators with high current to those of devices with large efficiency. A good candidate as e-beam source for this kind FELs is the induction linac, which produces short (10-100 ns) widely spaced pulses, with high peak current (several kiloamperes) and energy of the order of tents of MeV (i.e. an e-beam power of tents of GW). Furthermore the already specified beam qualities are in general good enough so that the induced inhomogeneous broadenings do not severely affect the gain. The electron pulses of an induction linac are too far apart to permit synchronization with single optical pulse in a resonator. Furthermore they are too short to allow intracavity oscillations during an individual pulse. A suitable configuration for a FEL driven by this type of e-beam structure is that of an amplifier for a signal provided by an external source i.e. the ***master oscillator***. Such configuration is usually named MOPA (Master Oscillator Power Amplifier).

Undulators for this operation are of the multicomponent type and consist of a non tapered (A) and tapered (B) sections. In A the input master oscillator field is brought up to the onset of saturation. In B a large fraction of the e-beam power is converted to the optical field.

In this contribution we discuss a possible design scheme for a multicomponent undulator for high gain - high efficiency FELs.

2. The Non-Tapered Section

FEL operating in the very high gain regime exhibits exponential gain depending on the longitudinal coordinate z, namely [3]

$$G(z) = 1/9 \exp(2\alpha z/\lambda_U), \quad \alpha = 4\pi\rho(\sqrt{3/2}) \qquad (2.1)$$

being ρ the Pierce parameter, specified in Tab. 1. The e-beam energy spread and emittances cause a reduction of the peak values of the gain, so that the factor $\sqrt{3/2}$ in eq.(2.2) should be replaced by [4]: $\sqrt{3/2} \rightarrow \eta(\mu_e, \mu_x, \mu_y)$ where η describes the gain depression through the inhomogeneous broadening parameters $\mu_{e,x,y}$ related to the energy spread (σ_e) and normalized emittances ($\gamma\epsilon_{x,y}$) by the relations

$$\mu_e = 2\sigma_\epsilon/\rho, \quad \mu_{x,y} = \sqrt{2}/\rho \cdot K/(1+K^2) \cdot \gamma\epsilon_{x,y}/\lambda_U \qquad (2.2)$$

TABLE I

$I_0 = ec/r_0 \equiv$ Alfvén current (1.7×10^4 A)

$I \equiv$ e.b. current

$(\Delta\omega/\omega)_0 = 1/2N$ = homogeneous bandwidth

$N \equiv$ number of undulator periods

$\lambda_u \equiv$ undulator period

$L_u \equiv N\lambda_u \equiv$ undulator length

$\lambda_0 = \lambda_u/2\gamma^2(1+k^2), \quad \gamma \equiv E/m_0c^2$

$K = e B_0 \lambda_u/\sqrt{2}\, 2\pi m_0 c^2 \equiv$ undulator parameter

$\sigma_\epsilon \equiv$ r.m.s. relative energy spread

$\gamma\epsilon_{x,y} \equiv$ e.b. normalized emittances

$(\Delta\omega/\omega)_0 = \sqrt{2|h_{x,y}|} \cdot K\gamma\epsilon_{x,y}/\lambda_u(1+K^2)$

$\mu_i = 1/\rho\,(\Delta\omega/\omega)_i, \quad i = \epsilon, x, y$

$\rho = \left[1/4\pi\gamma\left[(2\pi\lambda_u k)^2\ I/\Sigma_L I_0\right]F_1(\xi)\right]^{1/3}$

$F_1(\xi) = \xi[J_0(\xi) - J_1(\xi)]^2, \quad \xi = K^2/2(1+K^2)$

The function η is well reproduced in the range $\mu_e \in (0,3)$ and $\mu_{x,y} \in (0,1)$

$$\eta(\mu_x, \mu_y, \mu_e) = \frac{\eta(0,\mu)\exp(-0.034\,\mu_e^2)}{[1 + 0.185\,\eta(0,\mu)\,\mu_e^2]}$$

$$\eta(0,\mu) = 0.866\,\frac{1 + 0.636(\mu_x^2 + \mu_y^2) - 0.264(\mu_x + \mu_y)}{(1+\mu_x^2)(1+\mu_y^2)} \qquad (2.3)$$

The efficiency of the non tapered section is given by the Pierce parameter. The maximum power extracted from the electron beam in the A-region is just ρP_e where P_e is the e-beam power. According to ref.[5] we can evaluate L_A as the length necessary to bring the master oscillator power P_0 up to ρP_e, thus getting (see eq.(2.1))

$$L_A = \sqrt{3/2}\ \frac{L_A^0}{\eta(\mu_e, \mu_x, \mu_y)}, \quad L_A^0 = \frac{\lambda_U}{4\pi\sqrt{3}} \ln(9\rho P_e/P_0) \qquad (2.4)$$

where L_A^0 is the length of the non tapered region without inhomogeneous broadening contributions. The energy factor $2/\sqrt{3}\ \eta$ specifies the influence of the energy spread and emittances on the undulator length. In fig. 1 LA is plotted vs the peak current I. In the range 500-1500 Amperes the length of the non tapered region is strongly reduced. The dependence on the inhomogeneous broadening parameters is finally shown in fig. 2.

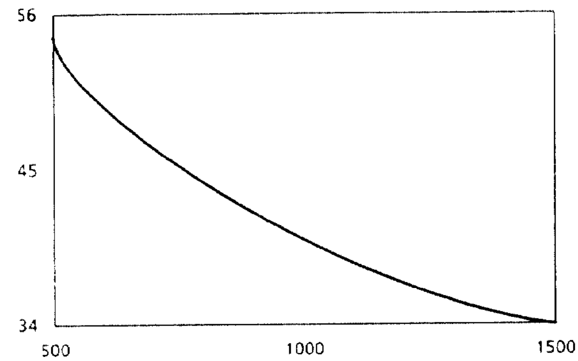

Fig. 1 - UM number of periods for saturation vs peak current (A)

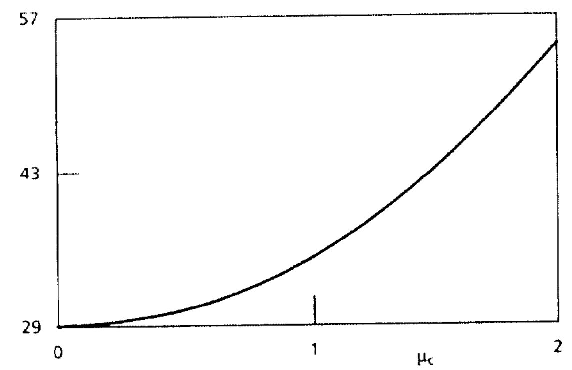

Fig. 2 - UM number of periods for saturation vs μ_e

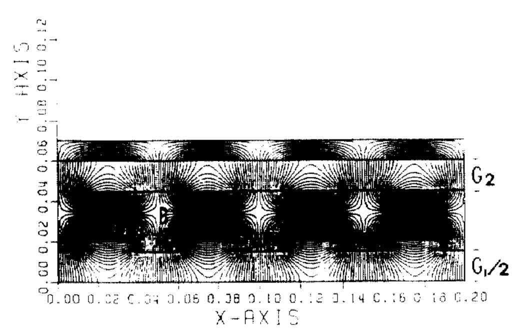

Fig. 3 - **Undulator geometry for the non tapered section. A) permanent magnet; B) iron.**

A convenient undulator geometry for the non tapered region may be that of fig. 3, where the upper section of two UM periods is shown. The undulator consists of a combination of hybrid REC plus iron insertions arranged as in the figure. A superimposed iron bar provides on axis field intensity variations just tuning the gap G2, as shown in fig. 4.

The advantage of this configuration is that of getting an extra tunability of the laser output wavelength without changing the main gap G1 or the electron beam energy.

3) The Tapered Section

The tapering can be achieved changing the on axis field, changing the undulator wavelength or combining both effects.

A general theory of the FEL dynamics in non uniform undulators is reported in ref.[6]. Here we will use some arguments only to fix design constraints. We

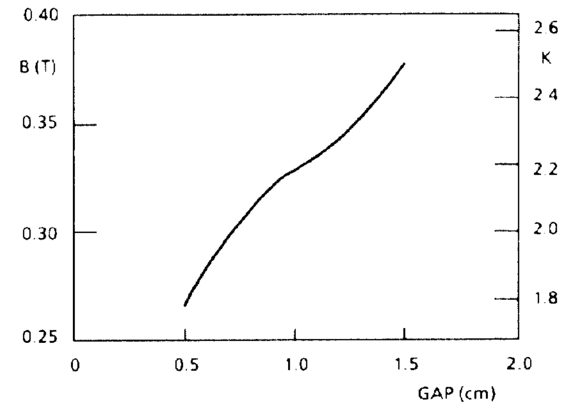

Fig. 4 - **On axis magnetic field and K parameter vs gap G2**

must therefore fix what is the range of K variation and what is the length of the tapered section.

Recalling that

$$K(z) = \sqrt{2\gamma^2(z)\,\lambda/\lambda_U - 1} \tag{3.1}$$

And denoting with $\eta = (\gamma_A-\gamma_B)/\gamma_A$ the fractional energy change from region A to the undulator output, we get that K_B (i.e. the K parameter at the end of the undulator), reads

$$K_B = (1-\eta)\,K_A\,\sqrt{1-(2\eta-\eta^2)/(K_A^2\,(1-\eta)^2)} \tag{3.2}$$

Requiring a relative energy variation of 40% we get $K_B \approx 1$.

The mechanism of energy transfer between electrons and radiation is symilar to the accelerating process in synchrotron. The electrons are trapped in a bucket and those with the phase near to the synchronous one Φ_R exchange the maximum energy with the optical field. The energy variation of the electrons can be written in the form

$$d\gamma/dz = -\,e\,K(z)\,E_L(z)\sin(\phi_R)/\gamma m_0 c^2 \tag{3.3}$$

where E_L is the laser electric field amplitude which can be related to the energy variation just by energy conservation, i.e.

$$\frac{e\,E_L}{m_0c^2} = \frac{e}{m_0c^2}\sqrt{\frac{4\,P_L}{c\,R^2}} \approx \frac{2}{R^2}\,[\delta\, I/I_0\,(\gamma_0-\gamma)]^{1/2} \tag{3.4}$$

δ is the fraction of trapped current, R is the mode radius and P_L is the laser power. Eq. (3.3) yields

$$\int_{\gamma_A}^{\gamma_B}\frac{d\gamma\,\gamma}{\{(\gamma_0-\gamma)\,[(\gamma/\gamma_0)^2\,(1+K^2)-1]\}^{1/2}} = \frac{2}{R}\left(\frac{\delta\, I}{I_0}\right)^{1/2}(z_B-z_A)\sin(\phi_R) \tag{3.5}$$

The quantity z_B-z_A is the length of the tapered section and can be cast in the more convenient form

$$z_B - z_A = \left|\frac{R}{\sin(\phi_R)}\right|\left|\frac{I_0\gamma_0^3}{I\,\delta}\right|^{1/2}\{g(\eta_B,K_0) - g(\eta_A,K_0)\} \tag{3.6}$$

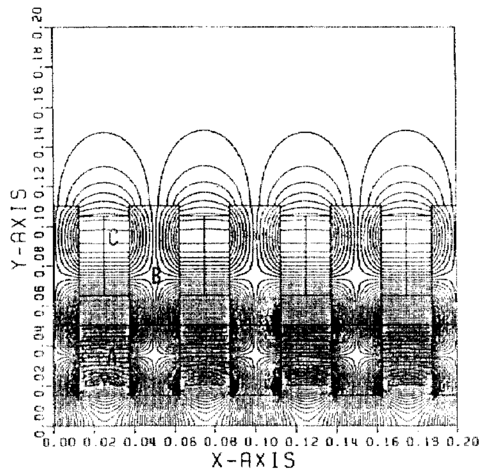

Fig. 5 - Scheme of the tapered section. The on-axis magnetic field is given by permanent magnets with electromagnetic tuning achived by coils. A) permanent magnet; B) iron; C) coil.

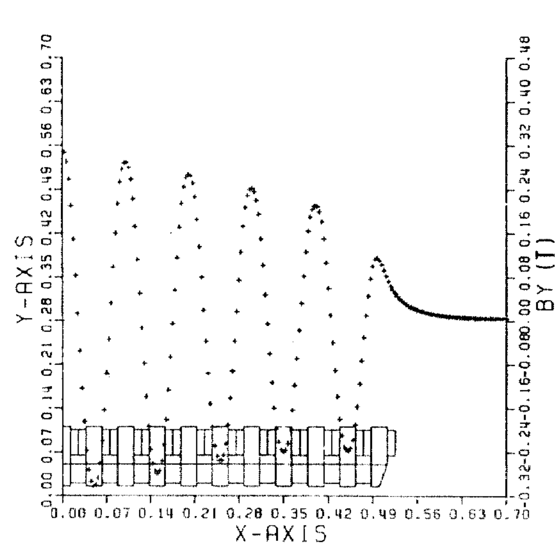

Fig. 6 - Example of on-axis magnetic field tuning for the last five periods of the tapered section.

where

$$g(\eta,K_0) = \int_0^{\eta} (1 - z^2)\,dz/[(1 - z^2)^2(1 + K_0^2) - 1]^{1/2} \qquad (3.7)$$

Assuming that $\Phi_R < \pi/2$ and with the parameters of tab.1, we get ($R \approx 1$cm) that the number of periods of the tapered section is larger than 10 and the efficiency ($\delta\eta$) is less than 40%.

A convenient tapering scheme is that proposed in fig. 5. The REC and iron parts are arranged in the same way of the non tapered section.

According to the previous discussion we require for the tapered section an undulator with a number of periods on the order of 20 and a K ranging from 2 to 1. We need therefore an on axis peak magnetic field varying from 0.15 to 0.075 T. We have however found particularly convenient the solution offered by hybrid UM with an electromagnetic tuning. In this case the possibility of getting a large K tunability is not authomatic and the geometrical arrangement of REC + COILS allowing the best performances must be carefully studied.

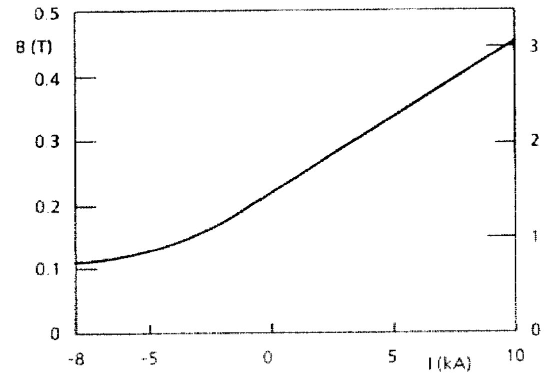

Fig. 7 - On-axis magnetic field and K parameter as functions of the current in the coils.

Among the configurations we have analyzed, the one offering the largest K tunability is that presented in fig. 6. The K and B_0 behaviour vs the current of the coils is shown in fig. 7. It is important to stress that the field exhibits an almost linear dependence over a wide range of currents and this allows a rather straightforward tapering. We can operate with large fields and relatively low current densities because the on axis field is essentially due to the permanent magnets and not to the coils as it happens in REC assisted undulators [7].

Footnote and References

* ENEA Guest

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