THE COMPOSITE WIGGLER FOR THE ELFA PROJECT

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Abstract : the solution of a composite wiggler (an hybrid section coupled with an electromagnetic section), whose parameters are determined by ELFA experiment requirements is described in details. The parameter choice and a preliminary design of the two sections are presented and discussed.

Introduction

The aim of the ELFA (Electron Laser Facility for Acceleration) [1] experiment is to study the physics of a single pass FEL amplifier operating in the high gain Compton regime using short electron pulse beams. The experimental purpose is the production of high peak power (0.3-1 GW) of microwave radiation, with a basic wavelenght of $\lambda_r = 3$ mm, with the possibility to tune from $\lambda = 1$ cm to $\lambda_r = 0.1$ mm. In order to achieve this goal an electron beam of very high current (400 A) in short pulses (6 cm) and with a maximum energy around 10 MeV will be injected into the wiggler midplane .

Three different modes of operation will be explored: Steady State, Weak and Strong Superradiance [2], only the first of which has been experimentally observed, and only with long pulse electron beams.

The FEL interaction will take place in a waveguide. Different waveguides will be inserted into the wiggler in order to control the group velocity of the radiation; with a 10 mm high waveguide ($v_g = v_e$) it will be possible to verify whether the SS regime can be achieved with short electron pulses while with a 30 mm high waveguide ($v_g > v_e$) we are going to verify the existence of the theoretically predicted SR regimes. Finally in the SS regime, it is necessary to taper the magnetic field in the wiggler in order to maintain the resonance condition after saturation and to continue extracting energy from the electron beam; this allows to increase extraction efficiency from $4 \div 6\%$ to $20 \div 30\%$. In table I we summarize the basic parameters for the wiggler.

Table I - Wiggler Parameters

wiggler parameter	$a_w = 2.85$
period	$\lambda_w = 12$ cm
peak magnetic field	$B_w = 3.6$ kGauss
minimum gap	$g = 3\ 6$ mm
minimum number of periods	$N_w = 50$

The wiggler parameter B_w and λ_w has been chosen in such a way to obtain the desired output wavelength λ_r with beam energies in the range reachable by our accelerating system, and to keep large enough the gain parameter ρ (maximizing the extraction efficiency and minimizing the wiggler length). This field level (with $g/\lambda_w = 0.3$) is easily reached with an hybrid wiggler and is reasonable for an e.m. device. To ensure the necessary flexibility for radiation wavelength tuning, we should be able to lower the field level B_w down to 1.2 kGauss.

Some preliminary calculations on the SS FEL process (fig.1) show that about 30–35 wiggler periods are necessary in order to reach saturation without tapering and about 15 additional periods to obtain the maximum output level of operation with tapering.

The resulting wiggler length is several meters ($\simeq 6$ m), and this requires the beam focusing in both transverse planes. Focusing in the vertical plane is assured by the "natural" property of the plane wiggler field configuration, while in the horizontal plane it can be provided by proper pole geometry (canted poles or parabolic shaped poles).

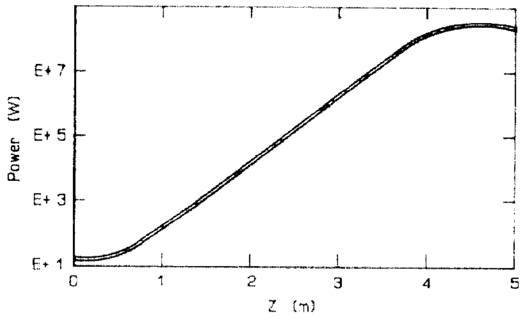


Fig. 1: Steady state FEL process simulation

In order to satisfy all this requirements, the more flexible solution is represented by an e.m. wiggler but its construction and operation could be very expensive. Another solution can be a composite wiggler, consisting at two coupled sections:

- the first part, approximately 35 periods, is made with an hybrid structure(iron poles + permanent magnets); this part shall have constant peak field to let the radiation produced in the FEL process grow up from the lethargy to the high gain regime. At the end of this section the radiation should reach the S.S. saturation.
- a second part, approx. 15 periods, is made with a e.m. structure which allows to obtain easily a steering free and rapidly tunable tapering of the magnetic field.

In this paper a preliminary design of the composite wiggler will be presented by emphasizing those aspects and problems which are characteristic of the system.

Magnetic Structure

The hybrid configuration has been chosen because of the several advantages over the e.m. and pure permanent magnet design: in the range of dimensions of our interest it grants a considerable higher field level and has lower construction and operation costs than the e.m. wiggler, while, still giving a higher field, it has the major advantage over the pure PM solution of being by far less sensitive to errors in PM blocks magnetization strength and direction.

It is worth noticing that the maximum field level for the wiggler of 3.6 kGauss has been fixed because of the limit of the e.m. section (due to saturation effects in iron poles); our hybrid wiggler is quite far from upper field limit; this reflects upon the wiggler costs and gives margin for flexibility in geometrical and structural choices.

The magnetic design has been performed in 2-D with PANDIRA,[3]. The dimensions of permanent magnets blocks and poles have been optimized in order to minimize the field harmonics components on the wiggler axis.

The field harmonic content is determined via Fourier analysis assuming that the y–component (vertical) of the field in a infinitely long and wide period structure is described by:

$$B_y(y,z) = B_1 \sum b_{2m+1} cos[(2m+1)kz] cosh[(2m+1)ky]$$

where k=2 π/λ_w, B_1 is the amplitude of the fundamental and $b_{2m+1} = B_{2m+1}/B_1$ is the normalized amplitude of the $2m+1$ field component.

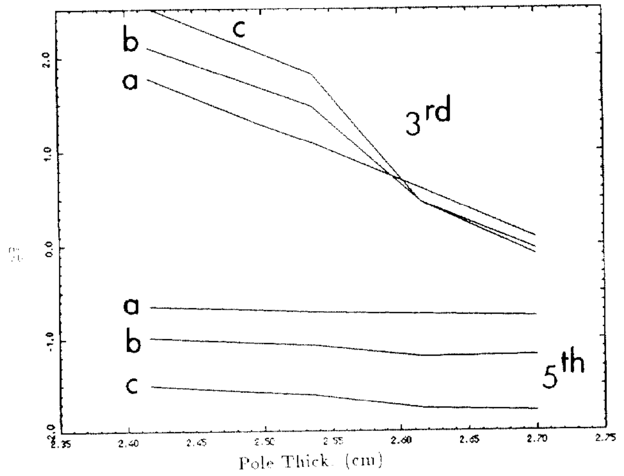


Fig. 2: 3^{rd} and 5^{th} harmonic components at: a) $y = 0$ cm, b) $y = 0.4$ cm, c) $y = 0.6$ cm as a function of pole thickness.

In fig.2 the 3^{rd} and 5^{th} harmonic components at different values of y, in % of the fundamental, as a function of the pole thickness are shown. The 3^{rd} and 5^{th} harmonic (b_3 and b_5) can be reduced respectively to 0.2% and 0.7% of the fundamental whereas the higher harmonics are negligible ($< 0.1\%$). The dependence of the peak magnetic field and the harmonic component contribution on the wiggler gap has been investigated.

We have evaluated the 3-D effects with a semianalytical model which takes into account all 3-D contributions to the magnetic field flux in the pole [4]. The real field level we can expect for our geometry is lower than the one predicted by the 2-D code PANDIRA but should be still higher than our goal of 3.6 kGauss.

The final set of parameters for the hybrid section is given in Table II and the fig.3 shows the geometry of the poles and permanent magnets blocks which will be used in the model tests.

Table II - Hybrid Wiggler

	poles	magnets
T (mm)	27	33
H (mm)	45	40
W (mm)	100	120
material	soft iron (Ca <0.05%)	Nd-Fe-B
periods	35 (minim.)	

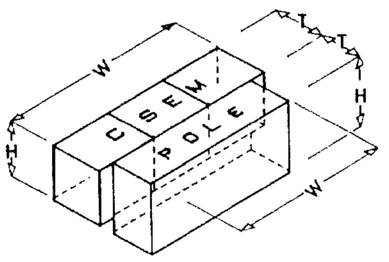


Fig. 3: Hybrid wiggler geometry.

As shown in fig.3 the magnet has not overhang at the top and presents a step of 0.5 cm (useful for fine tuning coils), and the CSEM material is divided in 3 blocks of squared cross sections (useful for block sorting).

The possibility to use Samarium Cobalt instead of Nd-Fe-B for PM blocks is still not precluded. The decision will be based not only on performance limit and costs, but also on radiation hardness properties and temperature effects evaluation.

End Poles Magnetic Design

To avoid steering perturbations of the beam as it travels through the wiggler, it is necessary to design a special configuration for the field at the ends of the wiggler.

Following Halbach's binomial configuration [5] the relative magnitude of the scalar potential (absolute value) should be zero for the first pair of up-down poles, and 0.25, 0.5, 0.75, 1., 1., ... for the following pairs. The zero scalar potential of the first pole pair is maintained by direct magnetic linkage of the upper pole to the lower pole. The scalar potentials of the other poles are controlled by their geometry and the amount of Nd-Fe-B between them. In fig.4 the results of PANDIRA calculations for the end configuration described before is shown.

No end coils will be used in this design. Instead, we shall use a system of Nd-Fe-B rotors for fine tuning of the wiggler end field [4].

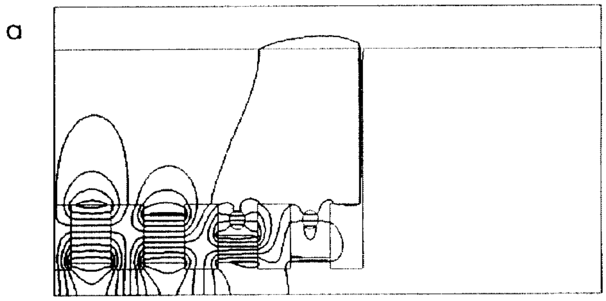
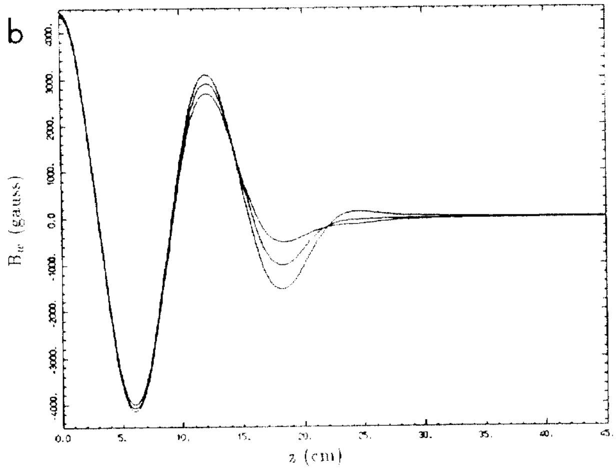


Fig. 4:
a) Configuration and magnetic field pattern for wiggler ends, showing PM blocks dimensions needed to obtain the binomial potential pattern, and the two round PM rotor tuners for fine tuning of the field;
b) Magnetic field level for wiggler end configuration, showing tunability level reachable using PM rotor tuners.



Electromagnetic Section

The design of the electromagnetic section has been carried out by using the same procedures adopted for the hybrid section. The fig.5 shows the magnetomotive force as a function of the wiggler gap and the peak magnetic field and the curves of the maximum field level in the iron poles. From this graph it is evident that the saturation effects (which become large above 18 kGauss) determine the working region of the electromagnetic section. The main parameters of this section are reported in Table III.

Table III - Electromagnetic Wiggler

Pole thickness	27 mm
Coils section (H×T)	40×16.5 mm^2
Overall current density	$\geq 1000\ A/cm^2$
Power/period	$\simeq 3$ kW
Max. field in the poles	$\simeq$16 kGauss
Periods	14 (minimum)

Model studies will show if it is necessary to use a PM assisted configuration. This can help to reach the desired field level and lower current density and power consumption.

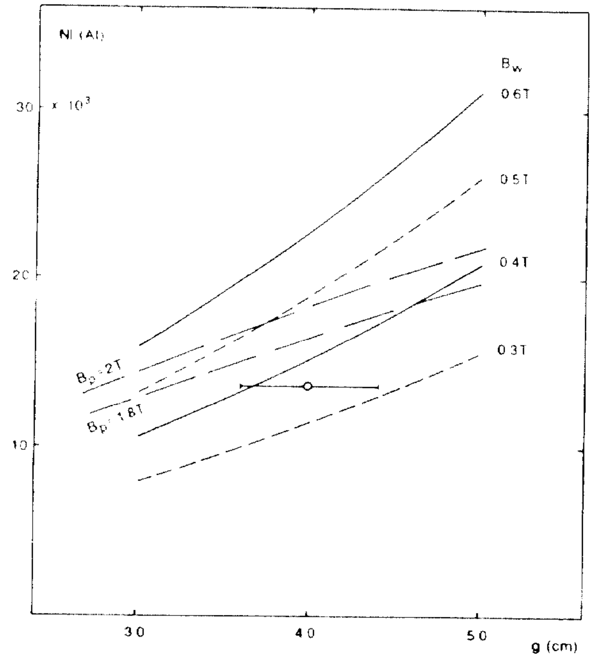


Fig. 5: Magnetomotive force as a function of gap and peak magnetic field in an e.m. wiggler. Maximum field level in the iron and working region of ELFA e.m. wiggler section are shown.

Hybrid-Electromagnetic Section Coupling

The transition section between the hybrid and electromagnetic part of the wiggler can present some problems not only from the point of view of the realization but also from the point of view of the quality of the field. In fig.6 we show the preliminary proposed configuration and the PANDIRA output corresponding to it.

Conclusion

The composite wiggler solution seems to be, at the present stage of the project, the one that fits best all the ELFA experiment requirements. A preliminary design has been defined, and the results are going to be tested on a full scale model of a few periods of the wiggler. In particular we are going to test:

- peak field level and harmonic content;
- transverse uniformity of the field;
- tolerances;
- end configuration of the wiggler;
- transition region between the hybrid and the e.m. sections;
- tapering.

The study on the model will be also useful for the definition of the focalization on the horizontal plane.

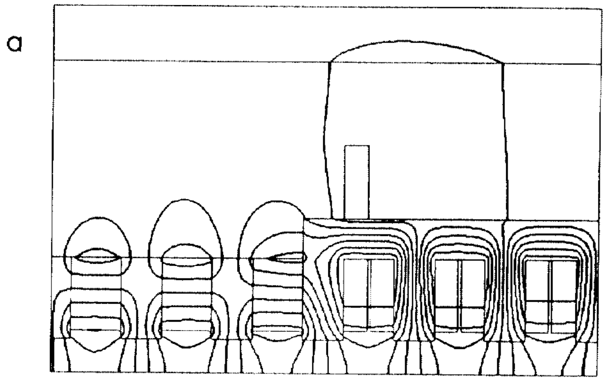
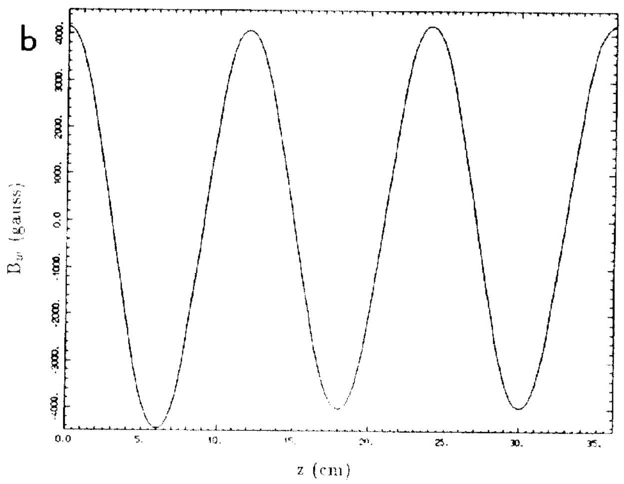


Fig. 6: Geometry and magnetic field pattern (a) and field level (b) in the transition region.



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