

THE GROOVE GUIDE: A NON-CONVENTIONAL INTERACTION STRUCTURE FOR MICROWAVE FEL EXPERIMENTS

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Abstract

We discuss the use of a groove guide as the FEL interaction structure for the ELFA experiment: the groove guide confines the 100 GHz radiation and controls the slippage, permitting to investigate different FEL regimes. The groove guide is a laterally open structure: it supports a *single* guided mode even if its dimensions are large compared with the wavelength, as required in the experiment to accommodate the beam. Thus, differently from conventional oversized rectangular waveguides, the groove guide allows the beam to interact with a single mode, simplifying the design of the structure. The lateral openings ease the beam diagnostics as well, and overcome pumping problems.

1. INTRODUCTION

ELFA [1] is a high gain FEL designed to operate in the millimeter wavelength range ($\lambda = 3$ mm). One of the main goal of ELFA is to study the different regimes of the FEL interaction, i.e. the steady-state (SS) and the superradiance (SR) [2]. This is accomplished by controlling the slippage due to the different propagation velocities of the radiation and of the electron beam. Thus the structure that guides the radiation along the beam path is one of the critical component of the experiment. A rectangular waveguide operating in the TE_{01} mode is the solution considered in previous FEL experiments [3,4,5]. The rectangular waveguide that could be used for the ELFA experiment would have a width of 50 mm and a height of 8.7 mm (SS regime) or 9 mm (SR regime). The width of 50 mm depends on the amplitude of the transverse motion of the bunches and on the necessity of providing a suitable clearance for alignment purposes. These dimensions are very large compared to λ , and about 300 modes, many of them having

potential interaction with the beam, could propagate at the operating frequency of ELFA (100 GHz). Thus the use of such an oversized waveguide would lead to many problems related to the control of unwanted modes excited by the beam itself and by any waveguide discontinuity. Moreover, the high operating frequency and the huge number of high order modes would preclude the use of standard waveguide components (e.g. directional couplers, detectors, attenuators, loads, transitions and so on) in the design of the microwave circuitry connecting the FEL waveguide to the generator and to the output diagnostics.

To overcome these problems we considered a different guiding system, the so called "groove-guide" (GG), which is a typical low-loss transmission structure in the 3 mm band [6,7,8]. It is an open waveguide, consisting of two parallel conducting planes (see Fig. 1), where two longitudinal grooves permit to trap the electromagnetic energy. In general, the field inside the GG can be considered as the sum of some trapped modes, plus a continuous eigenfunction spectrum [9]. When the GG is suitably designed, only one mode remains trapped in proximity of the grooves: this mode is suitable for FEL interaction, since it has a field distribution that resembles the TE_{01} pattern in a rectangular waveguide (see Fig. 2). Differently from a rectangular waveguide, however, in a GG the beam interacts only locally with the fields associated with the continuous eigenfunction spectrum, that in any case are excited by the waveguide discontinuities and by the beam itself. In fact, the electromagnetic energy associated with these fields is radiated laterally, and thus it is effectively removed from the beam region. For this reason, when dealing with the electron/radiation interaction in a GG, only the trapped mode can be considered, since its field is the only one which gives rise to a continuous interaction along the whole structure.

The use of a GG in FEL experiments appears very attractive also because the lateral openings make feasible a number of sensing devices to be placed along the beam path to monitor the beam/radiation interaction.

2. THE GROOVE GUIDE

Fig. 2 shows the geometry of a GG and the electric field pattern of its dominant mode. The GG offers single-mode propagation up to a spacing b of the order of some wavelengths, provided the depth d of the grooves is about $b/4$ and their width a is of the order of b [10]. Since the fields of the dominant mode decay exponentially in the transverse direc-

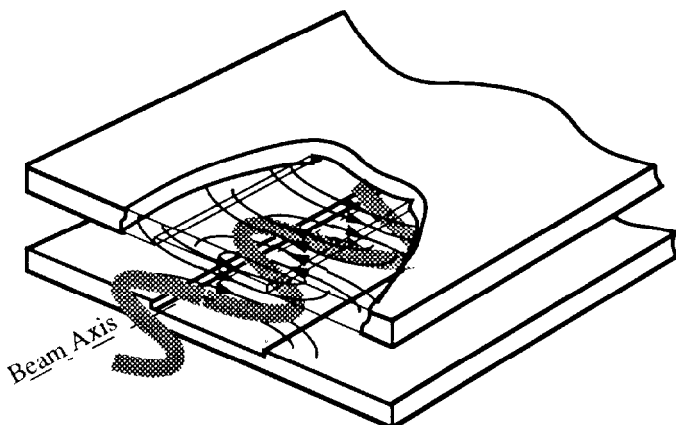


Fig. 1

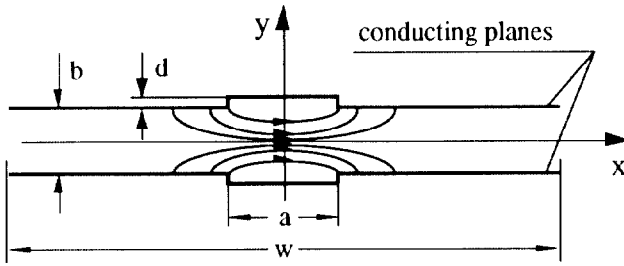


Fig. 2

tion, the propagation properties of the GG do not depend on the overall width w , provided it is sufficiently large. Thus the dimension w of the structure is not critical, and a value of about 6 times b is adequate [10].

The group velocity can be adjusted by a suitable choice of the dimensions a , b and d of the GG. In particular, for given dimensions a and d of the grooves, the spacing b affects mainly the group velocity. This fact suggests that it is possible to use the same structure to experiment both SS and SR regimes, provided the mechanical design allows one to trim the spacing b . Moreover, the dimensions of the groove affect the amount of the confinement of the electromagnetic energy. We can take advantage of this feature to increase the density of the electromagnetic energy in the region spanned by the beam and, consequently, the efficiency of the FEL interaction.

3. DIMENSIONING OF THE STRUCTURE

The actual dimensioning of the GG is performed with the aim of increasing as much as possible the coupling between the beam and the field, keeping the spacing b adequate to allow the beam alignment. To this end we carried out many numerical tests on different structures, considering different values of the dimensions a and b , and adjusting the groove depth d to obtain the group velocity suitable for SS regime. The resulting values of d are plotted in Fig. 3 as a function of the groove width a for values of the plane spacing b ranging from 5 mm to 7 mm (larger values of b result in poor confinement of the field, whereas 5 mm was considered to be the minimum allowable plane separation). The calculations

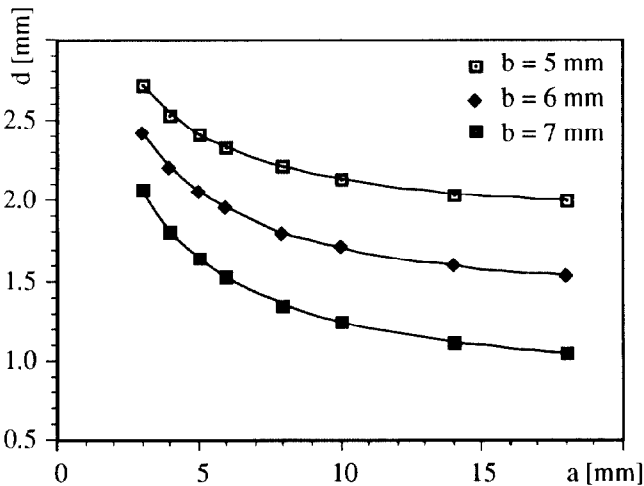


Fig. 3

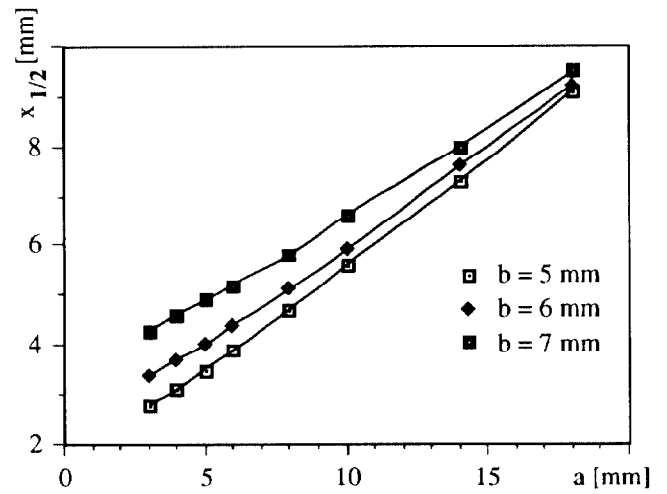


Fig. 4

were performed using the code PAGODA [11] that gives propagation constants and modal field of arbitrarily shaped waveguides.

From the modal field we calculated the coupling C of the wiggling electrons with the propagating electric field, normalized to the coupling in a reference rectangular waveguide:

$$C = \frac{\langle \mathbf{E}^{GG} \cdot \mathbf{v} \rangle_{\lambda_w}}{\langle \mathbf{E}^{RW} \cdot \mathbf{v} \rangle_{\lambda_w}} = \frac{\langle E_x^{GG} v_x \rangle_{\lambda_w}}{\langle E_x^{RW} v_x \rangle_{\lambda_w}} \quad (1)$$

where \mathbf{E}^{GG} and \mathbf{E}^{RW} are the (normalized) modal electric field of the groove guide and of the rectangular waveguide respectively. \mathbf{v} is the velocity of the electrons and the average is performed on the wiggler period λ_w ($\lambda_w = 10$ cm for ELFA). When evaluating (1) it is possible to expand the electric field around the beam axis ($x=0$, $y=0$, see Fig. 2), and to truncate the expansion at the second order. It has been verified that this approximation is very accurate up to a distance $x_{1/2}$ from the beam axis where the field is 1/2 of its maximum value. The distance $x_{1/2}$ is of the order of $a/2$ and increases for increasing b , as shown in Fig. 4; in any case it is comparable or larger than the amplitude Γ of the wiggling motion of the electrons ($\Gamma = 3.18$ mm for ELFA). From (1) it is obtained:

$$C = \left[E_x(0,0) + \frac{\partial^2 E_x}{\partial x^2} \frac{\Gamma^2}{4} \right] \sqrt{\frac{a^{RW} b^{RW}}{2}} \quad (2)$$

where the derivative is evaluated at the beam axis and $a^{RW} = 50$ mm, $b^{RW} = 8.7$ mm are the dimensions of the reference rectangular waveguide (see the Introduction). Fig. 5 reports the values of C as a function of the groove width a for different values of the plane spacing b : in all the considered cases C is greater than 1, i.e. the coupling in the GG is larger than in the reference rectangular waveguide. Moreover, it is noted that for each value of the spacing, it is possible to maximize the coupling by choosing a suitable value of a . Since the maximum values of C are only slightly different for the

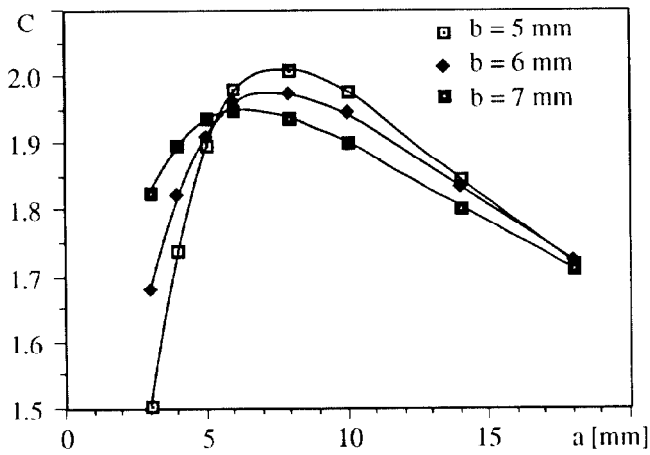


Fig. 5

three curves, the largest spacing, more convenient to accommodate the beam, can be used. For these reason the dimensions of the GG best suited for ELFA are: $a = 6 \text{ mm}$, $b = 7 \text{ mm}$, $d = 1.52 \text{ mm}$.

In order to verify the sensitivity of the slippage to the dimensional tolerances, some numerical evaluations have been carried out, considering small variations of the above mentioned values. Defining the normalized slippage parameter l_s/L_w as

$$\frac{l_s}{L_w} = \frac{v_g - v_{\parallel}}{v_{\parallel}}$$

where l_s is the "slippage length", L_w the length of the wiggler, v_g the group velocity and v_{\parallel} the longitudinal velocity of the electrons, the following sensitivity values were found:

$$\begin{aligned} \partial(l_s/L_w)/\partial a &= 1.2 \cdot 10^{-3} \quad [\text{mm}^{-1}] \\ \partial(l_s/L_w)/\partial d &= 5.6 \cdot 10^{-3} \quad [\text{mm}^{-1}] \\ \partial(l_s/L_w)/\partial b &= 5.5 \cdot 10^{-3} \quad [\text{mm}^{-1}] \end{aligned}$$

Since the length of the ELFA wiggler is 8 m, and assuming that the slippage length must be controlled with an accuracy of the order of 1 mm, the obtained sensitivities show that the dimensional tolerances required in the manufacturing of the GG are not very critical, and precision milling of metal blocks appears to be adequate. Moreover, the last sensitivity value shows that it is possible to change the slippage length from 0 (SS regime) to 15 mm (SR regime) by increasing the plane spacing b from 7 mm to 7.34 mm.

4. INFLUENCE ON THE FEL GAIN AND ON THE OUTPUT POWER

According to the 1-D FEL model [12], the enhanced coupling between the guided mode and the electron beam gives rise to an increase of the FEL gain parameter ρ , which determines all the relevant scaling laws and operating constraints for a FEL [12]. Introducing the coefficient C , defined in the previous section, in the FEL universal scaling of Ref. [13], it can be seen that the FEL gain parameter ρ is multiplied by a factor $C^{2/3}$. Considering a value of $C = 1.95$ for the preferred GG (see Fig. 5), the gain parameter ρ increases approximately by a factor of 50%. All the quantities related to ρ changes ac-

ordingly. In particular, the gain length, i.e. the e-folding length of the exponential growth of the radiation power along the wiggler, is given by:

$$L_{\text{gain}} = \frac{\lambda_w}{4\pi\rho}$$

Thus, the increase in the gain parameter ρ leads to a reduction of the gain length by a rough factor of 30%, allowing for a significantly shorter wiggler length required to saturate the emitted radiation. Moreover, the emitted FEL power at saturation is given by

$$P_{\text{out}} \approx \rho P_{\text{beam}}$$

where P_{beam} is the electron beam power. Again, the increase in ρ due to the coupling enhancement predicts an increase of the emitted FEL power of nearly 50%.

Also considering these 1-D scaling laws, the groove guide appears to be a very promising interaction structure, having superior characteristics with respect to the standard rectangular waveguide used for previous FEL microwave experiments. A more careful 3-D analysis of the FEL interaction in the groove guide is under way in order to verify these attractive features of the use of this structure for microwave FEL experiments.

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