DESIGN OF MICROWAVE UNDULATOR CAVITY*

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Abstract

Static magnetic field undulators are capable of producing quasi-monochromatic synchrotron radiation of very high brightness. However, it is not possible to quickly change the properties such as polarization of the radiation in a static undulator. It is possible to construct an undulator using microwaves instead of static magnets where the electron beam is undulated by both electric and magnetic fields of an rf wave. A major advantage with a microwave undulator is that the radiation properties can be changed very quickly. The biggest challenge in developing a microwave undulator is in keeping the rf losses low. We are designing a microwave undulator with the aim of achieving at least a tenth of the flux obtained by the BL13 static magnetic field Elliptical Polarized Undulator in the SPEAR ring. We have considered circular waveguide modes and hybrid HE_{11} mode in a corrugated waveguide as possible candidates for the microwave undulator. It is found that a corrugated waveguide has the lowest rf losses with a very desirable field profile. It is also possible to use this device for a linac driven FEL. Our analysis of the corrugated waveguide cavity for the rf undulator will be presented.

INTRODUCTION

In general, an undulator consists of a highly relativistic electron beam wiggled in the presence of a periodic undulating magnetic (or electromagnetic) fields producing synchrotron radiation. Highly successful modern undulator based synchrotron sources are based on periodic permanent magnetic fields. However, due to the intrinsic limitations of magneto static fields the polarization of the radiation fields and the undulator period cannot be controlled. These limitations can be overcome if high power rf waves are used instead of static magnetic fields in the undulator. However, the necessary rf power sources required to realize a microwave undulator capable of delivering synchrotron radiation comparable to a magneto static undulator was not available in the past. Recently a 500 MW X-band rf source was developed for the Next Linear Collider [2]. Combined with the advances in overmoded rf components and systems [3] led to the idea of the possibility of a practical rf undulator presented in this work. The same idea can be extended to LINAC driven rf FEL.

We are designing a microwave undulator for the SPEAR3 storage ring at SLAC. In a storage ring a static undulator would be *on* all the time giving rise to higher brightness. In order to be competitive, the microwave undulator we are designing should generate at least a tenth of circularly polarized radiation flux that can be generated by a static undulator. We have considered smooth wall circular waveguide structures operating in the TE_{11} and TE_{12} modes and a corrugated waveguide operating in the HE_{11} - mode as possible candidates for the design of the undulator [4]. Our study has shown that the HE_{11} - mode offers superior loss characteristics compared to other modes and can be operated at relatively lower power levels.

In order to generate the necessary field strength to undulate the 3 GeV electron beam in the storage ring, the rf power flow in the waveguide would be in the order of giga watts. To achieve such power levels rf energy can be stored inside a waveguide cavity to obtain the required levels of field strength by only compensating for the waveguide losses which can be within achievable power levels. It is a computationally intensive problem to design a corrugated waveguide cavity using numerical methods such as Finite Element Methods (FEM). As the corrugated waveguide can be regarded as a series of smooth cylindrical waveguides with discontinuities in radius, it can be analyzed using mode matching techniques that require moderate computational resources which is presented in this work.

RADIATION IN A MICROWAVE UNDULATOR

In a Circularly Polarized Standing Wave (CPSW) microwave undulator, due to the fact that the rf energy is confined in a cavity, the electron beam interacts with both the forward and backward wave with respect to the electron motion inside the cavity. The transverse electron velocity (normalized to speed of light in free space) is given by [1],

$$\beta_x(z) + i\beta_y(z) = -\frac{K}{\gamma}\sum_{n=-\infty}^{\infty}\left[J_n(\delta) + J_{n+1}(\delta)\right] \cdot \exp\left\{i\left[k/\bar{\beta}_{||} + (2n+1)k_{||}\right]z\right\}, \quad (1)$$

where

$$\delta = \frac{K^2}{2\gamma^2}\frac{k}{k_{||}}, \quad (2)$$

$K = eE_w/m_0c^2k_{||}$ is the normalized amplitude of the rf wave, E_w is the amplitude of the rf wave, m_0 is the mass of an electron, c is the speed of light in free space, γ is the relativistic factor, k is free space wave number and $k_{||}$ is the axial wave number of the rf wave inside the waveguide.

From Eq. (1) we see that a CPSW microwave undulator, in general, is a combination of several harmonic motions and would radiate in several harmonics unlike a static

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undulator. However, for a highly relativistic electron beam, such as one in the SPEAR3 ring, the value of δ (Eq. (2)) would be small when operated far from cutoff and higher order terms may be neglected and only $n = 0$ and $n = -1$ terms which are the contributions of the backward and forward wave respectively are dominant. If these conditions are not met, then the beam would radiate in higher harmonics also. Propagation far from cut-off necessitates the use of waveguide cavities with very large transverse dimensions. An advantage of large waveguide dimension is that the surface heat density will be low. However, a large waveguide will be highly overmoded and it will be challenging to excite only the required rf mode in it.

CHOICE OF WAVEGUIDES AND MODES

The microwave undulator should have a very strong transverse field strength (both electric and magnetic) near the axis of the waveguide where the electron beam is placed to undulate the beam. At the same time the waveguide losses of the rf field should be low as the feasibility as well as cost of the rf source is critically dependent on keeping the waveguide losses low.

The microwave undulator we are designing is required to produce at least a tenth of radiation flux of the proposed BL13 static magnetic undulator. To be conservative we are designing the microwave undulator to produce a fifth of the radiation flux as the BL13 static undulator. A circular cylindrical waveguide operating in the TE_{11} - mode, which is the easiest to excite, satisfies the condition that the field near the axis is strongest. For the undulator we are designing, the power loss per meter length of the waveguide for a TE_{11} - mode is over 5 MW to produce a fifth of the radiation flux with a radiation energy of 700 eV of the BL13 static undulator [4]. A TE_{12} - mode in a cylindrical waveguide has the same field structure near the axis of the waveguide as a TE_{11} - mode. The loss per meter length of the waveguide for a TE_{12} - mode would be 1.6 MW to produce the same radiation as a TE_{11} - mode. We see that there is a significant reduction in waveguide loss if the undulator is operated in the TE_{12} - mode instead of the TE_{11} - mode.

We have also considered another waveguide structure and mode, a hybrid HE_{11} - mode in a corrugated waveguide. This mode is typically used in transporting high power millimeter waves in applications such as Electron Cyclotron Resonance Heating in tokomaks due to their low attenuation characteristics. The corrugated waveguide is a cylindrical waveguide with periodic corrugations as shown in Fig. 1a. The HE_{11} - mode which is a cylindrical waveguide TM_{11} - mode (with $H_z = 0$) near cutoff undergoes a transformation due to the corrugations in the waveguide in to a rf field with both an electric and magnetic field ($E_z \neq 0, H_z \neq 0$)in the axial direction as we move away from the waveguide cutoff. Under conditions known as the "balanced hybrid conditions", when the axial electric field is equal to the axial magnetic field times free space

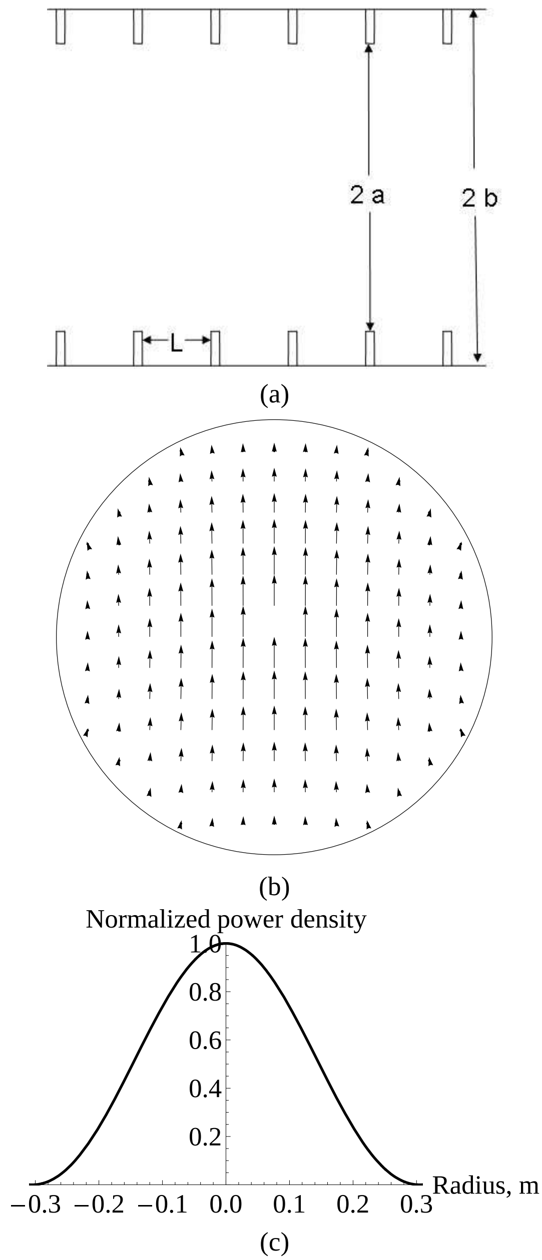

Figure 1: (a) Corrugated waveguide, (b) Cross section of transverse electric field in a HE_{11} - mode in a corrugated waveguide under balanced hybrid conditions, (c) Normalized power density of a balanced hybrid HE_{11} - mode.

impedance, the transverse electric field is strongly polarized as shown in Fig. 1b. Figure 1c shows the normalized power density as a function of radius over a cross section of the corrugated waveguide which approximates a gaussian curve under balanced hybrid conditions. As can be seen from Fig. 1c the power density is very low near the waveguide walls which lead to very low attenuation for this mode. As can be seen from Fig.1b the rf field is strongest near the axis of the corrugated waveguide as required for undulator operation. Another significant advantage of a HE_{11} - mode in a corrugated waveguide over the TE_{11} and TE_{12} modes

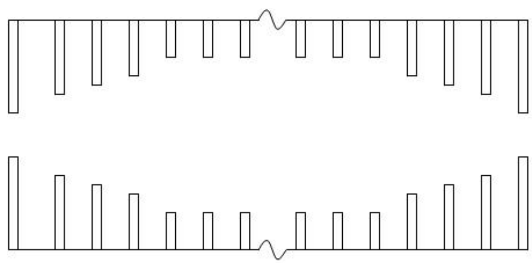

Figure 2: Schematic of a corrugated cavity with non uniform end corrugations for mode conversion and reflection of a HE_{11} - mode.

in a smooth cylindrical waveguide is that the fields are very strongly polarized in one direction. Therefore, cross polarization in a HE_{11} mode is very low.

MODE MATCHING ANALYSIS OF A CORRUGATED WAVEGUIDE

To study the feasibility of using a corrugated waveguide working in the HE_{11} - mode in a microwave undulator, we used boundary matching analysis of the corrugated waveguide neglecting space harmonics. This analysis was presented in [4] and verified with simulations in HFSS. Our studies show that a corrugated waveguide HE_{11} - mode is a promising mode for the microwave undulator.

The foregoing analysis assumed that the corrugated waveguide is uniform and matched on both ends of the waveguide. However, we are designing a standing wave undulator in which the rf energy should be reflected at both ends of the corrugated waveguide cavity. Moreover, the cavity would include a mode converter in order to excite the HE_{11} - mode. Hence, corrugations in the ends of the corrugated waveguide cavity will necessarily be not uniform. A rough schematic of how the corrugated waveguide cavity would be is shown in Fig. 2. Note that the end corrugations shown in Fig. 2 are only for illustration purposes to show the corrugation dimensions vary near the ends of the cavity and not necessarily how the final design would be.

The analysis and design of a corrugated waveguide cavity with a mode converter is a computationally intensive problem for numerical techniques such as FEM. The corrugated waveguide cavity can be treated as a series of uniform waveguides with discontinuities in wall radius at each corrugation. Therefore, the structure can be analyzed using Mode Matching (MM) techniques (for example see [5]) which can be much less computationally intensive than FEM techniques. Moreover, the MM techniques include space harmonics in the analysis making it more accurate than the analysis given in [4].

RESULTS AND DISCUSSION

In [4] we have estimated that a corrugated waveguide with an outer radius of 34 cm and a corrugation depth of 3.4 cm gives the lowest waveguide loss for the undulator being

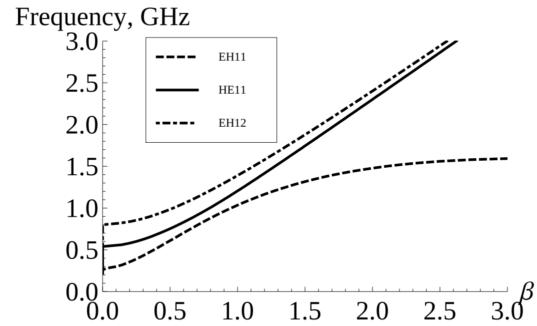

Figure 3: Dispersion curves calculated using mode matching method for a corrugated waveguide. β is the product of the axial wave number and the pitch of corrugations.

designed. We have now developed a mode matching code to design the complete cavity including mode conversion from a mode in a smooth cylindrical waveguide to a HE_{11} - mode. Figure 3 shows the dispersion curves for the EH_{11}, HE_{11} and EH_{12} modes for the above dimensions. Near cutoff, the EH_{1n} - mode is the same as a TE_{1n} - mode while a HE_{1n} - mode is the same as a TM_{1n} - mode in a circular cylindrical waveguide. Therefore, our approach to excite a HE_{11} - mode in the corrugated waveguide is to transform a TM_{11} - mode in a smooth cylindrical waveguide through a mode converter. At present we are in the process of designing such a mode converter by gradually tapering the corrugations from a smooth waveguide to the corrugation depth required. Results of the design will be published in a future work. After designing this mode converter, we will work on the excitation of a TM_{11} - mode in a smooth cylindrical waveguide suitable for the microwave undulator we are designing. The design will also include reflection of this mode to confine the power inside the waveguide cavity.

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