MICROWAVE HELICAL UNDULATOR BASED PRODUCTION OF POLARIZED PHOTONS AND POSITRONS

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Abstract

Linac-driven undulator technology capabilities are evaluated for production of polarized positrons and polarized high-brightness γ- and X-rays. Challenging requirements for production of polarized positrons reveal a number of benefits of a microwave undulator for meeting them. Two novel approaches are introduced here for open and closed structures: cross-polarized excitation of a rectangular waveguide, and a twisted structure. For the CLIC project the microwave undulator could become an integrated part of the TBA and be naturally powered by a standard decelerator section. Other applications include emittance dampers, synchrotron radiation sources, and FELs. The twisted undulator provides unique opportunities for circular dichroism study as well as novel vector analysis in protein crystallography based on two-wavelength anomalous diffraction.

INTRODUCTION

Polarized positron source development is among important requirements for linear colliders [1]. One method is irradiation of a thin (with respect to radiation length) target with circularly polarized gamma rays produced by a helical undulator [2]. Conventional hybrid or electromagnet technology, however, imposes severe limitations on the undulator gap and the attainable field. The estimated active length of a superconducting (SC) undulator [2] is about 150m, and the physical length (~790m) is considerably longer than the LCLS undulator. Another promising method for gamma radiation is spontaneous undulator radiation via Compton backscattering using guided microwaves. In this paper we consider production of polarized gamma radiation using a microwave undulator.

Let us define here a dimensionless parameter N_p as the energy radiated in an ID by an ultrarelativistic electron divided by the e^-e^+-pair rest-mass-energy $2m_ec^2$. There are two conditions for a potentially "good" undulator for a positron source [7]: the energy flux and the γ-quanta energy both to be sufficient to form e^-e^+-pairs: N_p^2>>1, $\frac{ch2\gamma^2/e\lambda_w}{1+K_w^2+\gamma^2\theta^2} > 2m_ec^2$, where $N_p = \frac{1}{3} r_e\gamma^2 \int_0^L \left(\frac{\langle F_\perp\rangle}{m_ec^2}\right)^2 dz$, h is the Plank's constant, θ is the target angular size, $\lambda_w=L/N_w$ is the effective period of an equivalent undulator, r_e is the classical electron radius, $\langle F_\perp\rangle(z) = K_w m_e c^2 2\pi/\lambda_w$ is the rms deflecting EM force, K_w is the equivalent rms undulator factor, and L is the effective interaction length.

Unlike FEL or IFEL, the beam quality and K_w-factor are much less important for a spontaneous incoherent source and tapering is not required. We consider a realistic design goal for a polarized positron source ID in terms of the equivalent helical field B_w≥0.7T at a sufficiently large gap (2a>4-5mm) to address vacuum pumping, alignment, beam transport, secondary radiations and wakefield issues in a long insertion device.

CONVENTIONAL ID TECHNOLOGY

Conventional magnetic undulators for polarized positron source are compared in Table 1. The last two rows correspond to a hybrid variant at the same gap/period ratio for two PM materials: conventional, and the best commercially available. Since the twisted variant of a new hybrid topology [3] can give circular polarization along with comparable or even higher fields (unlike common helical design), the Halbach limit [8] for a planar hybrid design is used for estimation only.

Table 1: Comparison of Undulator Designs for Polarized Positron Source and Halbach Limits for Hybrid Design

EM ID	**Tested** [9]		**Tested** [10]	**Goal** [2]
Type	Pulsed		SC	SC(?)
∅2a=g, mm	0.889	1.067	4	6
Period λ_w, mm	2.52	2.43	14	10
Field B_w, T	0.71	0.54	0.8	1.07
$2a/\lambda_w$	0.353	0.439	0.286	0.6
Halbach limit, T	**Hybrid technology capabilities**			
NdFeB [8], T	0.694	0.5	0.914	0.284
NEOMAX47[11]	~0.78	~0.56	~1.0	~0.32

Taking into account the fundamental fact that the gap-to-period ratio determines the field amplitude, one can see from Table 1: a) Hybrid technology is very competitive with electromagnet at least within the given range $2a/\lambda_w$; and b) Great progress has been made, but the goal is still well beyond state-of-the-art technology – both hybrid PM and EM.

MICROWAVE UNDULATORS WITH CIRCULARLY POLARIZED RADIATION

We consider here a microwave ID concept of two types – cross-polarized and twisted IDs. The deflecting force in $B_w = \langle \vec F_\perp \rangle / e\beta c$ is related to the generalized Panofsky-Wenzel theorem in modal formulation (see [12] at $h_s \rightarrow -h_s$) as follows:

$$\frac{\vec F_\perp}{e} = i\sum_s \frac{\gamma_s^2}{h_s}\left[(1+\beta\beta_s)\nabla_\perp E_{sz} + (\beta+\beta_s)Z_0\vec e_z\times\nabla_\perp H_{sz}\right], \quad (1)$$

where $\gamma_s^2 = 1/(1-\beta_s^2)$, $\beta=\sqrt{1-\gamma^{-2}}$, $\beta_s=\omega_s/h_sc$. Different polarizations are included in the summation. Hybrid coupling occurs for dielectric-coated, periodic, or anisotropic surfaces. TE, TM, or hybrid HEM dipole modes can be used. Formulae (1) is valid for any beam/wave velocity and any type of structure (fast- or slow-wave, periodic or loaded by dielectric, *etc*.). The wiggler period in a backscattering scheme is shorter than the wavelength $\Lambda_s = 2\pi/h_s$: $\lambda_w = \Lambda_s/(\beta+\beta_s)$.

Cross-Polarized Microwave Undulators

Microwave analog of the helical undulator requires 90° phase and angular shifts between two waves. An FEL based on a tapered X-band TW deflector was evaluated by Pellegrini [13]. For a linearly polarized single source, a quadratic guide can be fed via a 3dB splitter, two bended waveguides, and a two-port coupler (see Fig. 1a). Transverse series impedance $R_\perp = |\vec{E}_\perp|^2/2P$ is $2Z_0\beta_s/a^2$ for TE_{01} mode and $B_w = <\vec{E}_\perp>(1+\beta/\beta_s)/c$. A circularly symmetric waveguide cannot be used directly because of uncorrelated perturbations of polarization and uncertain mode transformation/hybridization during propagation.

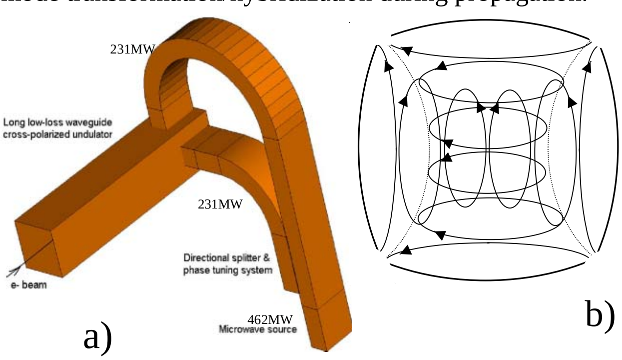

Figure 1: Conceptual layout of cross-polarized closed TE_{01+10} (a) and open TE_{50+05} (b) microwave undulators.

On the other hand, cross-polarized mode can be produced directly in a Rectangular Cross-Section Gyrotron Device [14]. Only a phase shifter is needed to provide proper phasing between the orthogonal waves.

We found that for a quadratic guide operating TE_{01}+TE_{10} modes at 30GHz, the optimal dimension is ~5.6×5.6mm^2. For a section having the same length as a CLIC accelerating/decelerating module (~2.23m) but fed by only one deceleration section (462MW) it gives an equivalent *helical* field B_w=0.76T and a period λ_w=6.9mm. For a smooth-wall copper guide we have α=1.1dB/m leading to N_p=3.1 (including the factor $(1-\exp(-2\alpha L))/2\alpha L$) and 42% power utilized.

Attenuation as low as α=0.2-0.01dB/m is attainable with several means well known in experimental cm-mm-wave technique: i) insertion of ~$\Lambda_s/4$ corrugations, ii) dielectric coating, and/or iii) to make it open (see Fig. 1b). With improved α=0.2dB/m transmission, the unit becomes longer, and N_p=16.5 for L=12m in the example above. For this attenuation, the estimated power budget is ~39MW/m (assuming no recuperation) which is ~10 times less than that for the CLIC main linac.

Twisted Microwave Undulator

The crossed-polarized option implies a two-port rectangular (or similar) geometry, which might not be the best in terms of impedance or attenuation. Phase and modal stability in a real, long guide remains to be proven as well. Another possibility is to introduce helicity directly as shown in Fig. 2, similar to the "bow-tie" low-overvoltage accelerating structure proposed by Kang [15].

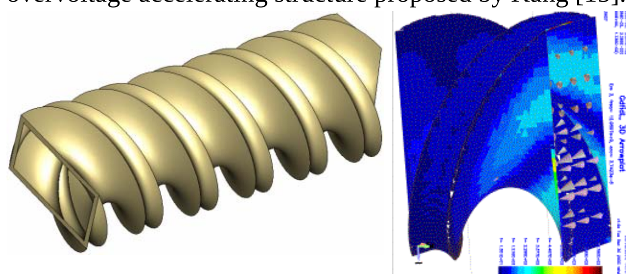

Figure 2: Strongly twisted "rectangular" waveguide. On the right: GdfidL simulation of microwave helical ID.

However, the 2π phase-advance-per-period results in a slow-wave structure with strong deformation, low group velocity, and higher attenuation. Fortunately, there is no need to have an exactly helical undulator in order to emit circularly polarized spontaneous radiation. The twisting configuration can have a much longer "helical" period compared to the undulator period λ_w [3]. Examples of adiabatically twisted structures are shown in Fig. 3. A twisted elliptical waveguide can be used as well.

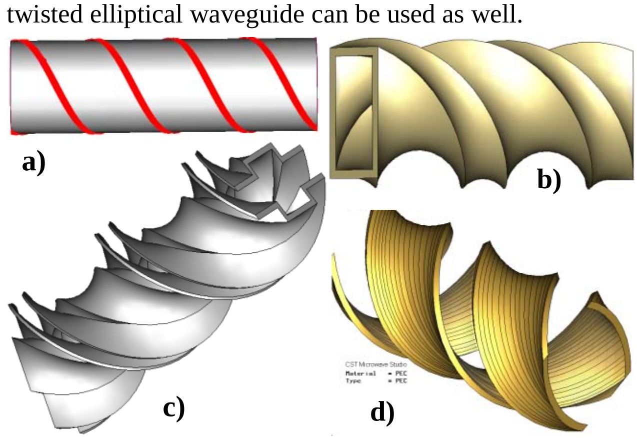

Figure 3: Closed (a,b) and open (c,d) twisted waveguides.

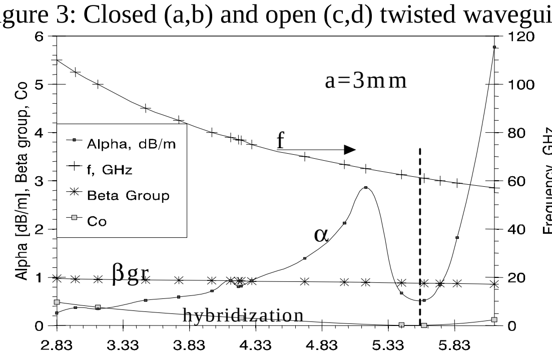

Figure 4: Attenuation, group velocity, frequency and hybridization as a function of wavelength Λ for the waveguide shown in Fig. 3a.

The simplest representation of a twisted undulator is a circular guide with azimuthal anisotropy (Fig. 3a). Lewin's approach [16] gives analytical solution of the corresponding boundary problem. We found that the smooth-wall attenuation is $\alpha \approx 0.52$dB/m, $\beta_{gr}=0.88=1/\beta_s$, Λ=5.6mm, and λ_w=2.62mm for 2a=6mm, f=61GHz, and pitch angle=45°. The hybrid HEM_{11} mode turns into a TE_{11} mode at the minimum α (see Fig. 4). For 200MW power, the equivalent twisted undulator field maximum amplitude is B_w=0.71T. This power level can be produced with an FEM: a front-end level of 2GW has been achieved at 20ns [17]. For section length $L=1/2\alpha$=8.35m (63% utilized power) we have N_p=4.1 and a pulse length $t_p = L(1+\beta/\beta_{gr})/c = 60ns$ at a moderate 171W/m heat deposition (120Hz rep rate).

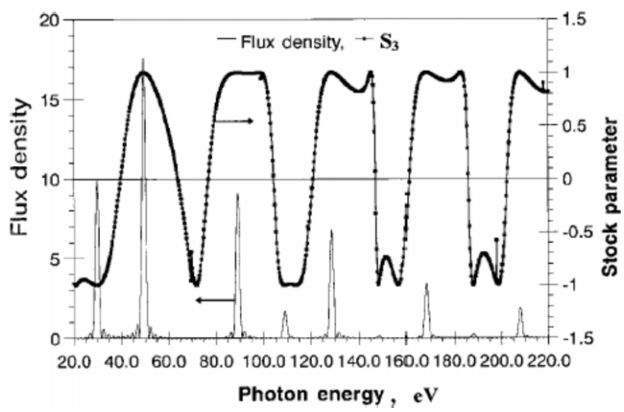

Figure 5: Numerical simulation of spectral flux and polarization for a twisted undulator of ref. [3].

In addition to a polarized positron source for linear collider, potentially important applications of the twisted topology are in molecular biology and condensed matter physics. If a source radiates simultaneously both polarizations with slightly different wavelengths, as a twisted undulator does (see Fig. 5), the flipping can be done much faster with monochromator and common optical instrumentation, rather than slow switching with undulator coils. Circular polarization of X-rays enhances protein crystallography imaging and increases contrast between the main radiated line(s) and spurious satellites when an efficient filtering technique [4] is applied.

One of the key challenges in X-ray imaging is the determination of the phase of the diffracted waves, which would give the absolute spatial position of each diffracting atom in the crystalline lattice. However, the X-ray detector measures only the diffracted intensity. Therefore additional information is required to determine the phase in order to perform a 3D inversed Fourier transformation. A suitable technique could be a Two-Wavelength Anomalous Diffraction [5], as a practical realization of the Multi-Wavelength Anomalous Diffraction [6], using the natural spectral split of a twisted-type radiator.

CONCLUSION

For a normal-conducting linac or linear collider the microwave undulator is a suitable and effective approach to a long, circularly polarized radiator: it is within state-of-the-art technology, cost effective, and very robust. It is naturally integrable into a TBA scheme using available power from a decelerator (*e.g.* at exactly the same cm-wavelength and pulse rate as CLIC).

In mm-wavelength region, a dedicated Two-Beam Generating-Undulating system based on multi-section FEM can be an effective alternative to the decelerator.

The physical length of a microwave undulator can be made much shorter compared with a magnetic undulator due to better focusing (at about the same active length and maximum deflecting force). Along with a large gap, it gives a significant advantage.

Twisted ID radiator can be used also in self-amplified FEL for molecular biology and condensed matter studies.

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