Axially Polarized Wiggler Radiation From A Toroidal Electron Beam Source

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Abstract - **Recent work has described wigglers in which the radiating electron beam circulates azimuthally within a toroidal tube where a surrounding permanent magnet structure keeps the beam on a mean circular path and simultaneously provides the field periodicity for wiggler action.[1,2] Both the mean field and the periodic one are in the axial direction so that the resulting synchrotron and wiggler radiations are both polarized in the principal toroidal plane. The present work analyzes a structure in which the synchrotron and wiggler polarizations are mutually orthogonal so that one or the other can be easily eliminated to provide essentially monochromatic radiation. This is accomplished by an azimuthally periodic arrangement of magic ring sections that form a toroidal tube. These are oriented with their axial field components constant and equal and their radial components equal but alternating radially outward and inward in direction. The constant axial field holds the electron beam in a circular path while the alternating radial field provides the wiggler action. The wiggler radiation has n times the frequency of the synchrotron radiation where n is the number of azimuthal periods per circuit.**

Index Terms - **Wigglers, Sychrotrons, Axial and Radial Polarization, Toroidal Magnets**

I. INTRODUCTION

Free electron lasers or wigglers are periodic magnetic arrays which provide an accelerating field to an electron beam, forcing it to oscillate transversely about its translational path, thereby causing it to radiate. [1] Various rectilinear arrangements of both the electromagnet and permanent magnet varieties are used for this purpose. In such devices, the emitted radiant energy is derived from the translational kinetic energy of the electron beam of which only a small portion is converted to radiation in a single pass of the beam through the array. It has been suggested [1] that in a circular array the beam might make multiple passes to afford longer exposure of the electron beam to the circumferentially alternating magnetic elements as in Figure 1.

The wiggler magnets produce an azimuthally periodic, radial magnetic field which causes the beam to vibrate parallel to the principal toroidal axis. The vibration gives rise to radiation with its electric vector polarized in the direction of electron oscillation. Because of the mean circular motion of the beam the wiggler radiation is accompanied by tangentially polarized synchrotron radiation with a frequency of $\omega_s = \gamma^2\omega_c$ where ω_c is the classical frequency of an electron circulating in a magnetic field and γ is the relativistic parameter $[1-(v/c^2]^{1/2}$. $\omega_w = n\omega_s$ where ω_w is the wiggler frequency and n the number of wiggler periods in a complete circuit. Both wiggler and synchrotron radiation are propagated tangentially through a circumferential slot cut through the toroidal shell in the equatorial plane.

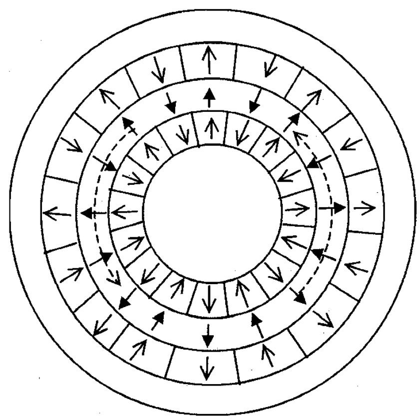

Fig 1. Circular wiggler configuration suggested in reference [1]. Magnetization ↑; Field ↑ Electron Beam - - - >

Such a structure requires an additional axial field source to keep the electron beam on the desired circular path. This source may consist of either electro-magnets or massive permanent magnets. Both options entail undesirable weight and bulk and the former also requires an electric power supply together with its cooling impedimenta.

In a previous paper [2] the authors described a toroidal wiggler in which the same permanent magnet source effectively provides both the synchrotron and wiggler functions, through the modulation of a single axial field. In figure 2 is pictured such an array. The cross section of its permanent magnet segments is that of a magic cylinder or ring which was chosen because the fields of such configurations are very high compared to other arrays of similar mass and bulk. [1-7]

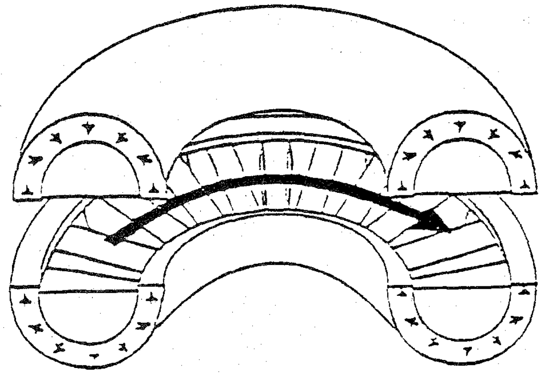

Fig 2. An expanded view of a single field-source for both synchrotron and wiggler fields. In this structure iron "teeth" are azimuthally spaced to modulate the field.

In such structures the synchrotron and wiggler radiations have the same equatorial polarizations as shown in Fig 3. It may be undesirable in some cases for the polarizations to be coplanar.

II. AXIALLY POLARIZED WIGGLER RADIATION SOURCES

To obtain mutually orthogonal polarization for the two radiations with a single field source as in Fig 3, appropriately beveled magic ring slices are fitted together to form a toroid, the successive slices of which are oriented as shown in figure 4. The axial field component remains constant from slice to slice, thereby providing the constant centripetal force needed to keep the electrons in orbit while they emit radially polarized synchrotron radiation. The axial field component reverses direction from slice to slice so that it provides the periodic acceleration along the principal toroidal axis that gives rise to the axially polarized wiggler radiation. Hence the two radiations are polarized orthogonally and easily separable by appropriate devices such as prisms. The ratio of the field components B_A/B_R can be adjusted by a change in the angle between the disks' polar axes and the principal toroidal axis.

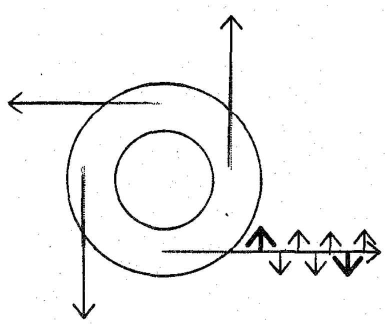

Fig 3. Coplanar polarizations of wiggler and synchroton radiations. Wiggler polarization ↑ synchotron polarization ⇑ Radiation directions ⟶

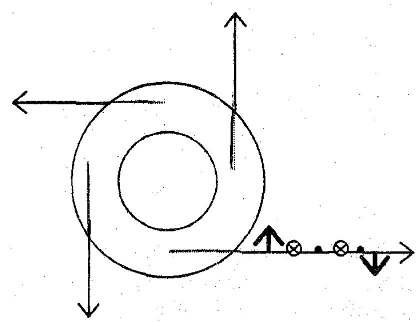

Fig 4. Orthogonal Polarizations. Wiggler. Polarization •⊗; synchrotron polarization ⇑ Radiation Direction ⟶

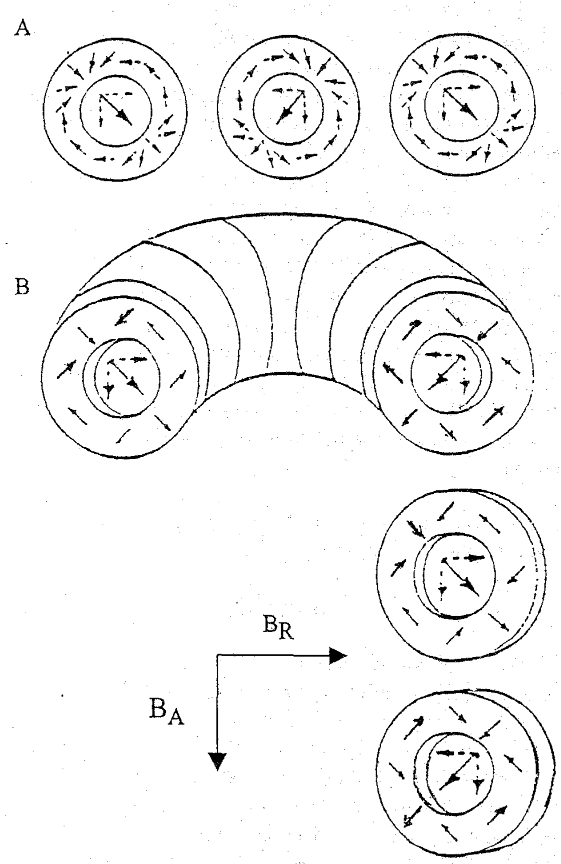

Fig 5. Construction of toroid with constant axial and periodic radial field. A. Orientations of successive magic cyclinder slices. B. Arrangement of slices in a toroid.

It might be necessary to provide an electric solenoid wound about the toroidal tube to furnish an azimuthal columnating field for the electron beams, although this might also be accomplished by judicious perturbations in permanent magnet shape.

III. ANALYSIS AND RESULTS

For analysis a structure of moderate size and plausible applicability was chosen. Figure 6 shows the given parameters and Table 1 shows required fields and resulting frequencies as functions of electron energy in the configuration of Figure 5.

Note the high wiggler accelerating fields of over 7kG in the militarily interesting giga and terahertz regions.

For lower electron beam energies the axial field can be made smaller to enhance the wiggler field amplitude at its expense through the change in slice orientation.

Bore Radius (r_i)	1 cm
Principal Toroidal Radius (r_T)	12 cm
Outer Radius of Toroidal Tube (r_o)	2 cm
magnetic Remanence	12 kG (1.2 T)

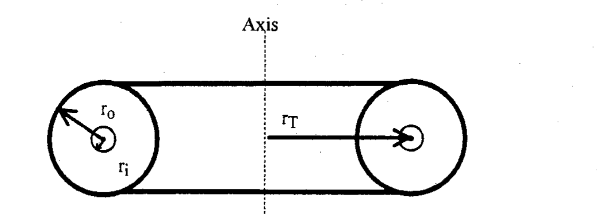

Fig 6. Dimensions and Parameters used in analytic calculations

TABLE 1
Fields and frequencies of axially-polarizing wigglers as functions of γ.

γ	KE (Mev)	B_y gauss	B^R_y gauss	$\cos\theta$	B^R_x	B_x gauss	ω_r Hz
1.0001	5.11E-05	2.01	1.45	0.121E-03	11.9	7320	$3.5(10_7)$
2	0.51	246	178	1.38E-02	11.9	7319	$1.7(10^{10})$
10	4.60	1414	1092	8.50E-02	11.9	7294	$2.5(10^{12})$
40	19.9	5685	4099	3.42E-01	11.3	6880	$1.6(10^{14})$
100	50.6	14216	10250	8.54E-01	6.3	3807	$2.5(10^{15})$
140	71.0	19903	14350	1.20			$69(10^{15})$

For structures in which the principal toroid radius is enough larger than the outer tube radius so that the wedge angle of the magic ring slices is small it might be practicable to approximate the wedged segments with pierced disks as in Fig. 7. If the inner segment is made to produce the same field as the outer. Mutual rotations in opposite senses can adjust the field to any value below maximum. Also the total field can be rotated thereby giving considerable flexibility in operational mode; ring twister, wiggler, and variable period and field strength.

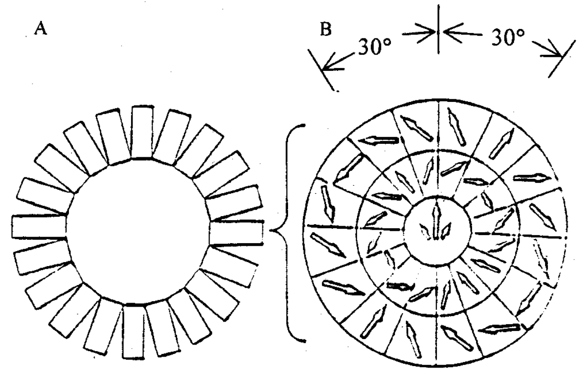

Fig 7. A. Approximation of wedged toroidal segments with disk like ones. B. Cross section of a disk set for a field of 0.867 of the maxium.

IV. CONCLUSIONS

The wiggler and synchrotron fields of a circular free electron laser can be provided and made orthogonal by a single permanent magnet source. The field strengths provided by such a source compare favorably with those of standard sources and offer multiple circuits of the electron beam. For some structures a field and mode adjustable toroid might be practicable.

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