W-BAND ELECTROMAGNETIC WAVE UNDULATOR FOR AIST 800 MEV ELECTRON STORAGE RING TERAS

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Abstract

An electromagnetic-wave undulator based on a quasi-optical resonator operated in higher order TE mode is proposed to generate monochromatic X-rays. We plan to install it to an 800MeV electron storage ring TERAS of AIST. Mode propagation in the resonator was analysed with an electromagnetic-wave simulation code MAFIA and HFSS. Design parameters for the undulator operated in W-band (95 GHz) was presented. The peak electric field along the electron orbit was estimated to be 130 kV/m when we fed 95 GHz electromagnetic wave of. 1 kW. The estimated X-ray flux density was 3×10^{12} photons/sec/mrad^2/0.1% b.w. /A for 2.8 keV X-rays.

INTRODUCTION

An undulator generates monochromatic light using a static magnets and electron beam [1]. As the pitch of the undulator magnets becomes small, it becomes difficult to fabricate a stack of small magnets with a good magnetic field distribution, mainly because of mechanical precision on fabrication.

An electromagnetic-wave undulator uses electric and magnetic fields excited by the electromagnetic wave for the undulator. There is no limitation for pitch due to the technical limitation, in principle. So, the wavelength of the undulator light can be shortened with an electromagnetic-wave undulator than a conventional one. We are interested in a hard X-ray undulator using a compact electron accelerator and electromagnetic-wave undulator.

Electromagnetic-wave undulator was demonstrated by Shintake et al. in 1982 [2, 3]. They used 300 kW S-band microwave and a standing-wave ridge cavity to generate 400 nm visible light. Kawamura et al. built an electromagnetic-wave undulator with a high-power CO2 laser [4]. They focused the high-power CO2 laser in 10 GW/cm^2 onto 0.65 – 0.85 MeV electron beam to generate 500 nm photons.

A proposal to use superconducting cavity as an electromagnetic-wave undulator was made by Boni et. al in 1988 [5]. They pointed out that fast switching of the polarization of the undulator light was possible. It is

another advantage of the electromagnetic-wave undulator over the conventional magnetic undulator.

A unique proposal was reported by Kang et al. to enhance the peak electromagnetic field at the interaction region [6]. They proposed an electromagnetic-wave undulator to generate 100 keV hard X-rays using 7 GeV electron of Advanced Photon Source (APS) of Argonne National Laboratory using 34 GHz electromagnetic wave of 1 MW-peak. Magnetic field strength was 0.25 T along the electron beam orbit [7]. The electromagnetic wave counter-propagates to the electron beam in higher-order TE mode using a ring resonator based on a unique waveguide, so-called a quasioptical-resonator waveguide.

QUASIOPTICAL-RESONATOR WAVEGUIDE

The quasioptical-resonator waveguide [8, 9, 10] has been studied as a low-loss waveguide with side-open structure, which propagates only a specific mode. We designed a quasioptical-resonator waveguide operated in an over-mode of W-band (95 GHz) to generate X-ray undulator light using the high-quality electron beam of electron storage ring.

A quasioptical-resonator waveguide consists of a pair of cylindrical mirrors facing each other. There is an open slits on both side of the waveguide. The waveguide is operated in higher-order TE_{mn} mode. Figure 1 shows a schematic view of the Over-mode quasioptical-resonator waveguide in the vacuum chamber of the storage ring.

As the wavelength of the electromagnetic wave becomes shorter, dimension of the waveguide becomes small. It is on the order or its some fraction, and is 1.3 x 2.7 mm for WR-10 used for W-band waveguide. The size limitation can be relaxed if we use the oversize waveguide operated in higher-order mode.

Figure 2 shows the electric field distribution in transverse plane for TE_{mn} mode (m=7, n=0). As an undulator field, m should be an odd integer, and n should be even. The mode is formed as a result of the interference of the two bouncing waves by the reflector. As an effective undulator, these waves should counter-propagates to the electron beam. Higher order TE_{mn} modes of n>0 attenuates with the open structure of the side slits as they propagate.

The side slits width should be large enough to keep

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clearance to the electron beam during a perturbation on injection. In our case, the electron orbit dislocates 40 mm in horizontal at maximum. The vertical beam size is approximately 0.5~1 mm at maximum. Taking various effects for beam orbit distortion such as misalignments of the waveguide, septum and kicker coils and magnets into account, the opening slit size should be a few mm or more. We set it 5 mm.

Several important parameters on the design of the quasioptical-resonator waveguide are the radius of curvature (r) and the distance of the cylindrical reflector plates (d), which decide the peak electric field strength around the electron beam orbit. Figure 3 to 5 show peak electric field strength, attenuation constant, and guide wavelength of various size and modes for various r and d as a function of mode number m in TE_{m0}. With those results, we have chosen r, d and m for 18 mm, 20 mm and 7, respectively.
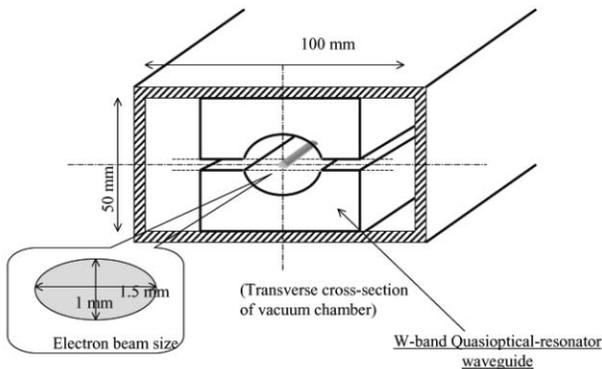

Figure 1: W-band quasioptical-resonator waveguide installed in the vacuum chamber of the storage ring TERAS of AIST.
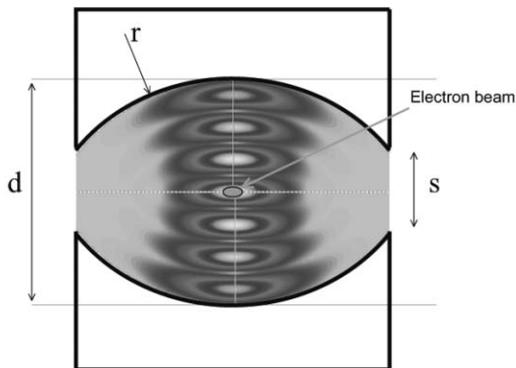

Figure 2: Electric field strength of TE_{70} mode calculated for W-band quasioptical-resonator waveguide. Radius of curvature; r, plate distance; d, and slit width; s are 18 mm, 20 mm, and 5 mm, respectively.

W-BAND ELECTROMAGNETIC-WAVE UNDULATOR

We have calculated the undulator spectrum using the electric and magnetic fields calculated for TE_{70} for the quasioptical-resonator waveguide. The x-ray flux density spectrum is shown in Figure 6, together with the synchrotron radiation spectrum from one of the bending magnets of TERAS of AIST.
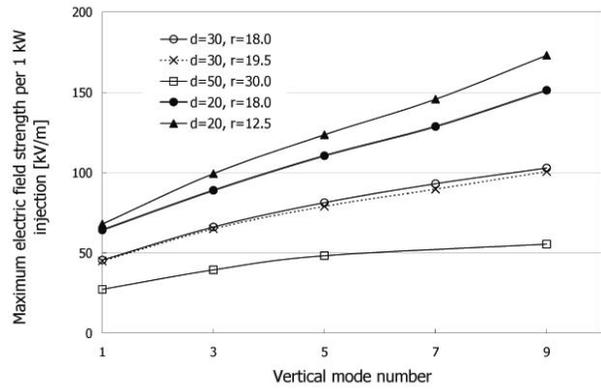

Figure 3: Electric field strength along electron beam axis as a function of the vertical mode number; m, of TE_{mn}, for various sizes.
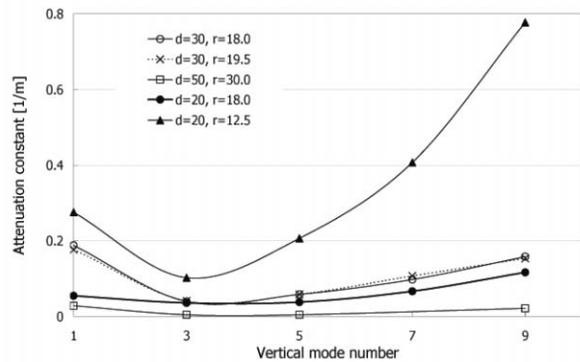

Figure 4: Attenuation constant of the W-band electromagnetic wave propagating in the quasioptical-resonator waveguide, shown as a function of the vertical mode number; m, of TE_{mn}, for various sizes.
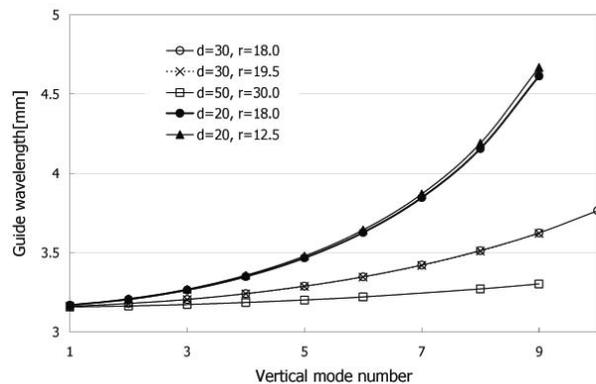
Figure 5: Guide wavelength of the W-band electromagnetic wave propagating in the quasioptical-resonator waveguide, shown as a function of the vertical mode number; m, of TE_{mn}, for various sizes.

Table 1 summarized various parameters and undulator light properties using this electromagnetic-wave undulator design.

Table 1: Parameters for the W-band electromagnetic-wave undulator.

Electromagnetic-wave (GHz)	95
Peak power (kW), [duty]	1, [1%]
Operation mode	TE_{70}
Electron energy (MeV)	760
Interaction region (cm)	80
Equivalent undulator pitch (mm)	1.93
Peak electric field (V/m)	1.29×10^5
Effective magnetic field density (T)	4.29×10^{-4}
K-value	6.41×10^{-5}
Undulator light wavelength (m), [Energy (keV)]	4.36×10^{-10}, [2.84]
Line width ($\Delta\lambda/\lambda$)	0.2 %
Peak photon flux density (photons/sec/mrad^2/0.1% b.w./A)	3×10^{12}
Synchrotron radiation flux density (photons/sec/mrad^2/0.1% b.w./A)	1.55×10^{11}
Attenuation (dB/m)	0.066

CONCLUSION

W-band electromagnetic-wave undulator using the quasioptical-resonator waveguide operated in TE_{70} mode was presented. We find 2.8 keV x-rays are generated in the order of 10^{12} photons/sec/mrad^2/0.1%b.w./A, assuming the emittance of the electron beam zero. We have been discussing how to feed the electromagnetic wave into the quasioptical-resonator waveguide and excite TE_{70} mode, most effectively. One of the choices is a multihole directional coupler. We designed a 15 dB directional coupler. Table 2 summarized the design parameters for the directional coupler. The simulation is being undergone using HFSS.

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Table 2: Design parameters for directional coupler.

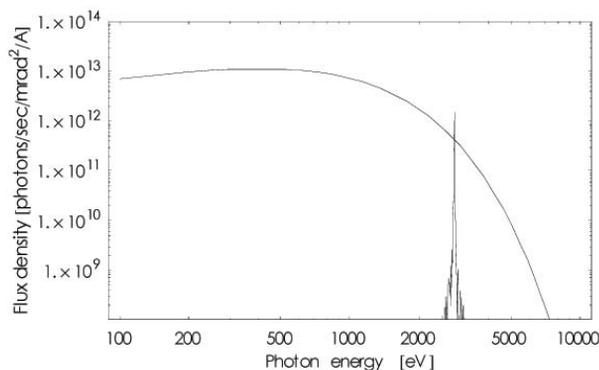|	
Coupling (dB)	15
Number of coupling holes	20
Coupler period (mm)	4.80866
Guide wavelength (mm)	3.846
Free-space wavelength (mm)	3.158

Figure 6: X-ray flux density of the undulator light. Synchrotron radiation from the bending magnet of TERAS is also shown in comparison.

REFERENCES

[1] H. Motz, J. Appl. Phys 22 [5] (1951)527-535.
[2] T. Shintake, K. Huke, J. Tanaka, I. Sato, and I. Kumabe, Jpn. J. Appl. Phys. 21[10](1982)L601-L603.
[3] T. Shintake, K. Huke, J. Tanaka, I. Sato, and I. Kumabe, Jpn. J. Appl. Phys. 22[5](1983)844-851.
[4] Y. Kawamura, D. Li, S. Rushin, T. Tanabe, K. Toyoda, Nucl. Instrum. and Meth. A445(2000)241-246.
[5] R. Boni, et al., Rev. Sci. Instrum. 60(1989)1805-1808.

[6] Y. W. kang, R. L. Kustom, P. J. Matthews, and A. Nassiri, EPAC 1994 Proceedings, pp.657-659, 1994.
[7] Y. kang, J. Song, and R. Kustom, 1999 PAC Proceedings, pp.168-170, 1999.
[8] T. Nakahara, N. Kuramochi, IEEE Trans. Microwave Theory and Techniques MTT-15[2](1967)66-71.
[9] J. R. Sirigiri, Ph D. thesis of MIT, 2003.
[10] P. F. Goldsmith, Quasioptical Systems, IEEE press.