Microwave Undulator to Generate Short-wavelength FEL Radiation

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***Abstract*- This paper presents the design and the measurement of a short section of a 36 GHz microwave undulator, as well as the electron beam dynamic and the spectrum of the FEL radiation based on the microwave undulator. The operation of the microwave undulator at a higher frequency of 94 GHz is also discussed.**

I. INTRODUCTION

The Free-electron laser [1] has the capability in producing high-power and spatially coherent radiation at ultrashort-wavelength. This opened revolutionary applications in biophysical and chemical science, medical and drug research, and solid-state physics [2, 3]. FELs operating at the X-ray frequency range have also been in operation recently in the last 10 years. More X-ray FELs are planned and will be constructed in the near future. In the UK, an XFEL science case was published in October 2020 to discuss the main scientific opportunities and identify the capabilities required to realize these opportunities [4].

The FEL radiation is produced in the insertion device called an undulator. Its radiation wavelength can be expressed as $\lambda = \lambda_u(1 + k^2/2)/2\gamma^2$, where λ_u is the undulator period, which is defined as the period of the magnet. γ is the relativistic factor representing the energy of the electron bunch. $k = 0.0931B_0(\mathrm{T})\lambda_u(\mathrm{mm})$ is the undulator strength parameter defined by the magnetic field strength and the undulator period.

The above equation shows at the fixed FEL radiation wavelength, reducing the undulator period can reduce the electron energy. However, it is challenging for the permanent magnet undulator (PMU), which is commonly used in the XFELs, due to the physical constraints. The magnetic field strength will decrease dramatically as the magnet period becomes smaller.

The Electromagnetic-wave (EM-wave) undulators have great potential to be used in a free-electron laser (FEL) when shorter undulator periods are required. The EM-wave undulators have the advantage of a large beam aperture to reduce the wakefield. They are also able to fast control polarization and magnetic field strength by varying the polarization and power level of the drive source. The EM-wave undulator has also been demonstrated in the experiment. In 2014, SLAC demonstrated the FEL radiation with an X-band microwave undulator driven by a 50 MW klystron. It achieved an equivalent Bu of 0.65 T and a period of 13.9 mm [5]. An EM-wave undulator operating at a higher frequency 36 GHz was designed to validate the concept and achieved a scalable design at different lengths and frequencies [6, 7].

This paper presents the design and the measurement of a short section of the 36 GHz microwave undulator and the electron beam dynamics inside the microwave undulator. The operation of the microwave undulator at a higher frequency of 94 GHz was also discussed.

II. MICROWAVE UNDULATOR CAVITY

Microwave undulators can be classified as the traveling-wave (waveguide) [8, 9] and the standing-wave (cavity) types. They both operate at a high-power level, therefore it is essential to achieve a high-quality factor for the cavity-type one to achieve a high equivalent magnetic field. The corrugated waveguide, as shown in Fig. 1, that supports the low-loss HE_{1n} modes was used. Fig. 2 shows the electric field pattern of the operating HE_{11} mode in the undulator cavity with 72 periods. The coupler structure was designed based on the near-field radiation pattern of the HE_{11} mode, to maintain the high Q factor at the cavity wall. The undulator period was 4.34 mm and the equivalent magnetic would be 1.27 T when a 1-meter structure is driven by 50 MWs of input power.

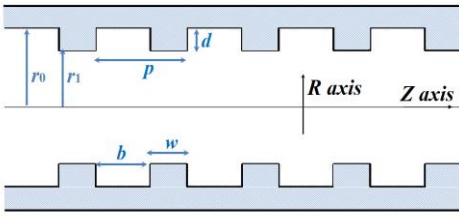

Fig. 1 Schematic drawing of the corrugated waveguide.

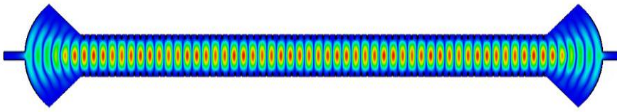

Fig. 2 The electric field pattern of the EM-wave undulator cavity with 72 periods of regular corrugation sections operating at 36 GHz.

The microwave undulator was manufactured and different machining methods were evaluated, including the direct machining and an electroforming method. The measurements showed both methods have closed resonance frequencies compared with the designed values, while the microwave undulator assembled by a few sections of corrugated waveguide machined directly has a better surface finish and therefore a higher Q factor, ~71940. The assembled undulator structure is shown in Fig. 3.

Fig. 3 Assembled structure of the microwave undulator by direct machining.

Further investigation of the potential of high-power microwave sources to drive the microwave undulator and the FEL radiation from the wiggling magnetic field were carried out. It showed that the maximum drift distance of the electrons in the transverse direction was larger for lower beam energy. However, the drift distance can be close to zero by synchronizing the phase difference between the electron bunch and the EM-wave at the entrance of the microwave undulator. This means a high-power amplifier as the drive source can be used to power the microwave undulator of electron beam energy less than 1GeV. At high beam energy, for example at a few GeV, the drift distance is within 1 mm and an oscillator may be used as the drive source [10]. SPECTRA was used to simulate the radiation spectrum from the microwave undulator, and the results are shown in Fig. 4. Soft X-ray radiation can be produced with an electron beam with an energy of less than 1 GeV.

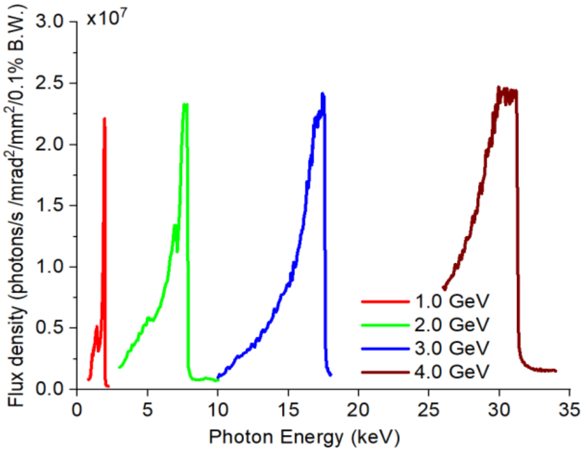

Fig. 4 Radiation spectrums of the microwave undulator at different electron beam energies.

III. THE W-BAND MILLIMETER-WAVE UNDULATOR

One of the unique advantages of the microwave undulator is there is no significant physical constraint on the undulator period, as it is mainly determined by the operating frequency, $\sim c/2f$. The MU can operate at higher frequencies which allows for achieving a shorter undulator period [11]. For example, a millimeter-wave undulator operating at 94 GHz can achieve an undulator period of ~1.70 mm. This is ~10 times shorter compared with the state-of-the-art PMUs. This allows producing a similar X-ray FEL radiation wavelength at a much lower electron bunch energy, ~1/3 of the electron beam energy is needed for the W-band millimeter-wave undulator as compared to the Ka-band microwave undulator. This could be of great interest to the future compact X-ray FEL facilities. Currently, the undulator cavity structure has been designed and is under construction. To maintain a large beam aperture at 94 GHz at a high-Q factor of the undulator cavity, a special design of the coupler structure is required to reduce the leakage power of the EM-wave. An over-moded Bragg reflector was therefore designed to achieve an ultra-high reflection (higher than -0.15 dB) and to maintain a large waveguide radius. The photo of the aluminum mandrel of the undulator structure is shown in Fig. 5. The measurement results will be reported in near future.

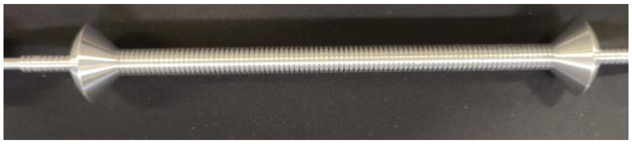

Fig. 5 The Aluminum mandrel of the 94 GHz millimeter-wave undulator.

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