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# THE CONCEPTUAL DESIGN OF A 36 GHz RF UNDULATOR *

D. Zhu†, Y. R. E. Tan, Australian Synchrotron, Clayton, Australia
L. Zhang, A. Cross, Department of Physics, University of Strathclyde, Glasgow, UK

*Abstract*

The CompactLight project supported by European H2020 is to design a hard X-ray FEL facility beyond today's state of the art. The project integrates photo injector, X-band acceleration and innovative compact short-period undulators together to make the machine more compact. RF undulator has an extraordinary advantage working at very short undulator period. A conceptual design for a RF undulator at 36 GHz using a corrugated cylindrical waveguide operating in the $HE_{11}$ mode is presented in this paper. Based on beam dynamics simulation and photon beam radiation simulations, the advantage of RF undulator to be used in CompactLight is presented.

## INTRODUCTION

During the past decades Synchrotron Radiation facilities have seen a fundamental tool for the study of materials in a wide spectrum of sciences, technologies, and applications. The latest generation of light sources, the Free Electron Lasers, capable of delivering high-intensity photon beams of unprecedented brilliance and quality, provide a substantially novel way to probe matter and have very high, largely unexplored, potential for science and innovation [1–3]. Currently, most of the worldwide existing FELs use conventional normal conducting 3 GHz S-band or 6 GHz C-band linac technology. The machine can reach to kilometres long. The CompactLight intends to design a hard X-ray FEL facility beyond today's state of the art, using the latest concepts for bright electron photo injectors, very high-gradient X-band structures at 12 GHz, and innovative compact short-period undulators.

RF undulators, suggested long time ago, has the advantage of very short undulator period, fast dynamic control of polarization, undulator strength and wavelength, large aperture, and cheap in comparison with the permanent magnet undulators [4–6]. Conventional permanent magnet undulator has undulator periods on the order of a few centimetres, but RF undulator can easily reach to micrometer periods and produce X-ray energies with lower energy electron beam. With the development of higher power RF sources in high frequency band, Rf undulator is becoming short-period alternatives to traditional undulators. It is a potential candidate to be used in CompactLight.

In this paper, we present a prototype of a RF undulator for CompactLight. A one metre long corrugated cavity sets up electromagnetic fields by pumping in 50 MW RF power with frequency 36 GHz to be used as a RF undulator. Firstly, a brief review of the parameters of RF cavity structure is presented. Then, a further investigation of the electron beam dynamics inside the cavity is given. Later, the RF undulator radiation spectrum as it is installed in our storage ring is evaluated.

## THE 36 GHz RF CAVITY STRUCTURE

It's critical for a RF undulator cavity to build up higher transverse electromagnetic fields along the centre axis to wiggler electrons in transverse direction. The high Q cavity with desired operating mode is needed to maintain a high field in the cavity centre area. A corrugated waveguide structure with a low loss $HE_{11}$ mode in a cavity is studied [5, 6]. In which the microwave power is mostly concentrated in the central region of the cavity and the electric field at the cavity wall is much smaller. It operated in X-band achieved a quality factor of 91000. When driven by a 50 MW klystron at 12 GHz, an equivalent $B_u$ of 0.65 T and a equivalent undulator period of 13.9 mm were achieved in the experiment. Based on this, a 36 GHz corrugated waveguide structure RF undulator is suggested [7].

The corrugated waveguide is a cylindrical waveguide with periodic corrugations as shown in Fig. 1.

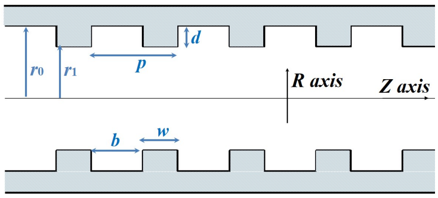


Figure 1: Schematic drawing of the corrugated waveguide.

The hybrid $HE_{11}$ 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 they 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 impedance, the transverse electric field is strongly polarized as shown in Fig. 2.

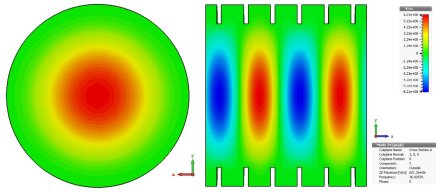

Figure 2: Electric field patterns of the $HE_{11}$ mode.

* Work supported by European Horizon 2020 CompactLight project.
† dajunz@ansto.gov.au

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As can be seen from the figure, the fields and power density is very low near the waveguide walls which lead to very low attenuation for this mode, but this will decrease the wall loss dramatically. Using this kind of structure and mode, a high Q factor cavity can be achieved.

Figure 3 and Fig. 4 are the electric field and magnetic field profile on the longitudinal axis. The peak electric field is $3.8 \times 10^8$ V/m, the peak magnetic field is 1.27 T. The cavity Q factor can research to 94344.

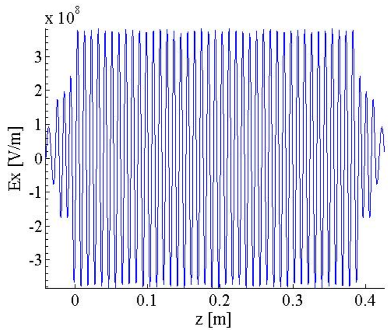


Figure 3: RF undulator cavity on-axis electric field profile.

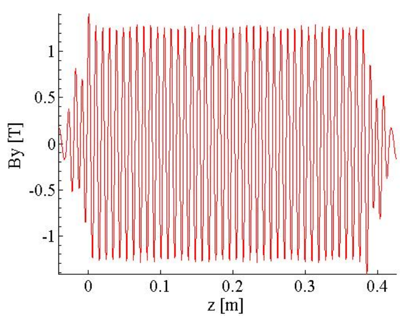


Figure 4: RF undulator cavity on-axis magnetic field profile.

## BEAM DYNAMICS IN THE CAVITY

When an electron beam interacts with a guided co-propagating and a counter-propagating deflecting EM wave, the equivalent undulator period $\lambda_u$ is given by the following equation [8]

$$\lambda_u = \frac{\lambda_0}{1 \pm \frac{\lambda_0}{\lambda_g}} \tag{1}$$

where $\lambda_0$is the free space wavelength, and $\lambda_g$ is the waveguide wavelength. The plus sign corresponds to the EM wave counter-propagating with the electrons, and the minus sign corresponds to the EM wave co-propagating with the electrons. These two cases are referred to as short-period and long-period undulation respectively. In the RF undulator cavity, the standing wave can be decomposed in a co-propagating and a counter-propagating EM waves, hence both short and long-period undulation mechanisms are present. Depending on the RF phase of the cavity fields when the beam is injected, the long-period undulation may cause the beam to drift.

The relativistic electrons in an RF cavity will interact with both the electric field $E_x = E_0 sin(2\pi z)/\lambda_g).sin(\omega t)$ and magnetic field $B_y = B_0 cos(2\pi z)/\lambda_g).cos(\omega t)$. The Lorentz force on electron can be rewritten in the form

$$F_x = \frac{eE_0}{2}(\frac{\zeta}{Z_\omega}+1)cos(2\pi z(\frac{1}{\lambda_0}+\frac{1}{\lambda_g})) + \frac{eE_0}{2}(\frac{\zeta}{Z_\omega}-1)cos(2\pi z(\frac{1}{\lambda_0}-\frac{1}{\lambda_g})) \tag{2}$$

where e is the charge of electron, $E_0$ and $B_0$ are the peak electric and magnetic field strength in the RF undulator cavity, respectively. $Z_\omega$ is the wave impedance in the cavity and $\zeta$ is the wave impedance in free space. The second term leads to a long wavelength and is undesirable in the undulator of a short wavelength FEL. The second term can be ignored if the wave impedance is close to the free space impedance, which means the operating frequency is far away from the cut-off frequency of the waveguide. In this case, the equivalent magnetic field $B_u$ of the RF undulator is given by

$$B_u = \frac{E_0}{2c}(\frac{\zeta}{Z_\omega} + 1) \tag{3}$$

For the designed 36 GHz RF undulator with 50 MW RF input power, the cavity Q factor can reach to 94344. In this condition, the equivalent magnetic field $B_u$ is 1.27 T, the equivalent undulator period $\lambda_u$ is 4.34 mm.

There is electron beam drift due to the long-period undulation. It need to perform beam dynamics simulations for different RF phases. The maximum drift is small compared to the beam apertures of the undulator and could be corrected by beam optics. [6]

## RADIATION SPECTRUM IN ASLS RING

To evaluate the advantage of this RF undulator, we used SPECTRA to do synchrotron radiation [9]. SPECTRA has built-in models for permanent magnet undulators, as well as user defined static magnetic field undulators. To simulate the RF undulator, we used the user defined undulator model with the equivalent undulator magnetic field profile. The validation of the correctness of this approximation is proved by performing single electron beam dynamics simulation with SPECTRA and solving the equations of motion in Mathematica using the on-axis RF electric and magnetic fields can get the same orbit.

The ASLS storage ring electron beam parameters is used in the radiation simulation. If the RF undulator is installed in our storage ring, what's kind of photon beam can be produced. The ASLS is a medium-energy third generation synchrotron facility running in Melbourne since 2007. The storage ring specifications are shown in Table 1.

Fig. 5 shows the radiation flux density for the first (blue), the third (red) and the fifth (green) harmonics on the photon energy map. The plot was obtained from SPECTRA far field calculation assuming an ideal permanent magnet undulator

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Table 1: ASLS Beam Parameters at the Straight Section

| | | |
|---|---|---|
| Energy | 3 | GeV |
| Circumference | 216 | m |
| Average Current | 200 | mA |
| Horizontal Emittance | 10.4 | nm rad |
| Coupling Constant | 0.012 | |
| Energy Spread | 0.001 | |
| $\beta_x$ | 8.92 | m |
| $\beta_y$ | 2.42 | m |
| $\sigma_x$ | 0.32 | mm |
| $\sigma_y$ | 17.5 | um |
| $\sigma_z$ | 9.0 | mm |

of 230 periods, 10 m from the undulator centre. The other parameters for the photon beam is listed in Table 2.

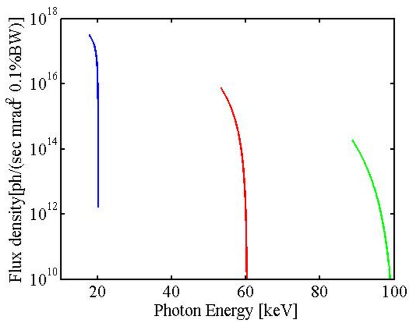


Figure 5: Radiation flux from the 1 m long RF undulator

Table 2: Photon Radiation Parameters with RF Undulator.

| | | |
|---|---|---|
| $B_u$ | 1.27 | T |
| $\lambda_u$ | 4.34 | mm |
| Total Length | 1.0 | m |
| Number of Periods | 230 | |
| K Value | 0.52 | |
| First Harmonic Energy | 17.8 | keV |
| First Harmonic Flux | $7.24 \times 10^{14}$ | |
| First Harmonic Flux Density | $3.2 \times 10^{17}$ | |
| Total Power | 1.87 | kW |

In Table 2, the unit for flux is $photon/s/0.1percent.B.W.$, The unit for flux density is $photon/s/mr^2/0.1percent.B.W.$.

The simulation results show that a very narrow band high energy and intense density photon beam emits from the RF undulator. The first harmonic energy is 17 keV with flux density $3.2 \times 10^{17} photon/s/mr^2/0.1percent.B.W.$. Comparing with our conventional 2 m long in-vacuum undulator, the flux density increases 20 times at 17 keV. This advantage makes it possible to use low energy electron to produce high energy photon beam. It is possible to use RF undulator as insertion device in synchrotron beamlines.

## CONCLUSION

We presented a new type of RF undulator which working at 36 GHz $HE_{11}$ mode with corrugated waveguide structure. In this structure, a high equivalent magnetic field $B_u$ and a short equivalent undulator period $\lambda_u$ are achieved. We investigated the beam dynamics inside the RF undulator. We get the radiation spectrum using ASLS storage ring electron beam parameters. The results show that we can produce high energy and high brilliance photon beam from the RF undulator.

## ACKNOWLEDGEMENTS

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