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S-BAND TRANSVERSE DEFLECTING STRUCTURE DESIGN FOR CompactLight

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Abstract

The CompactLight project is currently developing the design of a next generation hard X-ray FEL facility, which is based on high-gradient X-band (12 GHz) structures. However, to carry out pump-and-probe experiments in the project, two-bunch operation with a spacing of 10 X-band rf cycles is proposed. A sub-harmonic transverse deflecting structure working at S-band is proposed to direct the two bunches into two separate FEL lines. The two FEL pulses will have independently tunable wavelengths and can be combined in a single experiment with a temporal delay between pulses of +/- 100 fs. The rf design of the transverse deflector is presented in this paper.

INTRODUCTION

Two-bunch operation for the pump-and-probe experiments is part of the baseline specification of the CompactLight project. The spacing between the two bunches is 10 X-band rf cycles, which is determined by sufficient higher-order-transverse mode suppression in the accelerating structure. An S-band splitter is used to separate the two bunches and feed them into a septum before magnets guide the bunches to the two FEL lines. The distance between the two beam positions of the septum is 2.5 mm. The specification of the splitter design is to separate the two bunches by 2.5 mm after the drift, as shown in Fig 1. A sub-harmonic deflector system is proposed to split the two bunches [1–3]. This deflector is a transverse deflecting structure working at S-band.

In contrast to the accelerating structure which operates in the TM_{010} mode, the transverse deflecting structure operates in the TM_{110} mode. The magnetic field of TM_{110} mode creates a transverse kick to the beam. The bunch will then follow an angled trajectory downstream of the deflector. The relation between transverse movement and longitudinal movement is given by Eq. (1):

$$\frac{x}{y} = \frac{V_{\perp} e}{E}, \tag{1}$$

where x is the transverse displacement, y is the drift length, $V_{\perp}$ is the transverse deflecting voltage, e is the charge of the electron, and E is the electron energy. The S-band deflector operates at 2.998 GHz. The spacing between the two bunches, 10 X-band rf cycles, is 2.5 rf cycles at S-band. Thus the two bunches can be placed at the crest and trough of the rf cycle of the sub-harmonic deflector. Then the kicks applied to the two bunches are in opposite directions and the separation is maximized for a given kick voltage. The bunch energy in the hard X-ray mode is 5.5 GeV. The required deflecting distance for one bunch from the beam axis after drifting is 1.25 mm. The deflecting voltage can be calculated from Eq. (1). The longer the drift length, the less deflecting voltage is needed from the sub-harmonic deflector system. Both traveling-wave and standing-wave deflecting structures are designed for the sub-harmonic deflector system. Firstly we present the power capability for the deflector system, followed by the details of the traveling-wave and standing-wave structure designs.

POWER SOURCE CAPABILITY

The klystron for the sub-harmonic deflector system is CPI S-band klystron (VKS8262G1) [4]. It is capable of reaching a maximum power of 7.5 MW and a maximum pulse width of 5.0 µs. The maximum repetition rate of this klystron is 400 Hz. This type of klystron has already been applied at IFIC S-band test-stand in Valencia. According to the manufacturer this klystron has the potential of operating at 1 kHz. An S-band spherical pulse compressor is proposed to increase the peak power to the deflecting cavity. An average power gain of 5.29 is achieved by compressing the 4.5 µs klystron pulse to a 300 ns compressed pulse. The intrinsic quality factor of the spherical cavity is 100,000. The coupling factor is set at 7. We assume that the available power for the structure in 1 kHz operation is 6 MW with consideration of the losses.

TRAVELING-WAVE TRANSVERSE DEFLECTOR DESIGN

The traveling-wave transverse deflecting structure works at $\frac{2\pi}{3}$ mode. The single cell electrical field is shown in Fig. 2. Two rods are placed in the cavity to fix the polarization of the mode. A constant impedance design is chosen for easy fabrication. The length of the whole traveling-wave structure can be easily modified by adding or reducing cells to achieve the required deflecting voltage at the same input power.

To prevent the excitation of the modes with polarity rotated at 90°, two longitudinal rods (radius = 9.525 mm) crossing the cells off-axis have been inserted, as shown in Fig. 2. The resonance frequencies of such modes are shifted far enough from the operating mode frequency to be negligible. The calculated frequency shift for the rotated modes due to the rods is about +17.3 MHz, while the working mode is practically unperturbed. The main rf parameters are summarized in Table 1.

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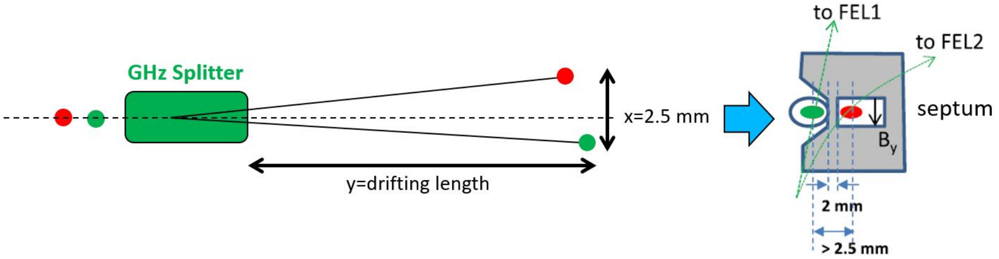

Figure 1: Schematic figure of the S-band splitter system.

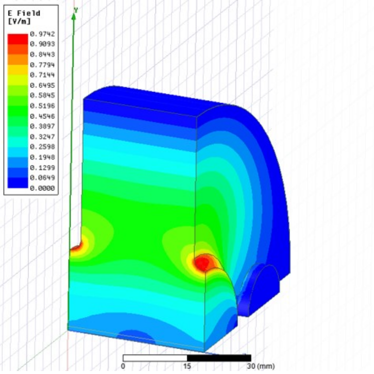

Figure 2: The electrical field of single cell of traveling-wave transverse deflecting structure.

Table 1: The RF Parameters of the Single Cell of the Traveling-Wave Transverse Deflecting Structure

Parameter	Value
Cell length [mm]	33.3
Operating frequency [GHz]	2.998
Shunt impedance [MΩ/m]	20.25
Quality factor	12369
Group velocity [v_g/c_0]	0.027

The deflecting voltage increases when increasing the cell number at the same input power. As discussed previously, the required deflecting voltage decreases when the drift length increases, Eq. (1). The required length of the traveling-wave deflecting structure to separate two 5.5 GeV bunches as a function of drift length is shown in Fig. 3.

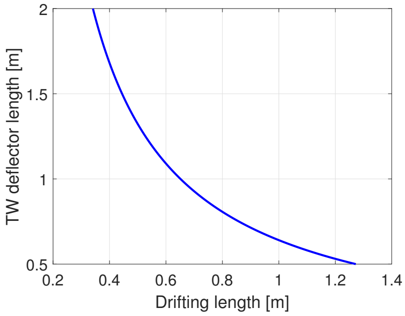

Figure 3: Traveling-wave deflecting structure length versus drifting length. The input power is 31.74 MW.

The schematic figure of the traveling-wave deflector system is shown in Fig. 4. The structure consists of 15 cells, with a total length of 0.5 m. The filling time is 62.5 ns. The pulse compressor compresses 6 MW, 1.09 µs klystron pulse to 31.74 MW, 72.5 ns output pulse which includes rise time of the system and the fill time of the structure. The deflecting voltage of the structure with 31.74 MW input power is is 5.4 MV.

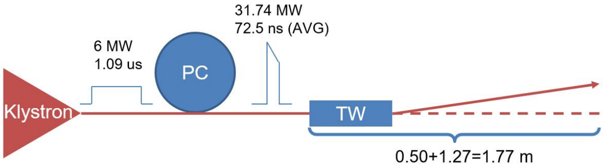

Figure 4: Schematic figure of the traveling-wave deflector system. PC is the pulse compressor and TW is the traveling-wave structure. The length of the structure is 0.5 m and the drifting length is 1.27 m.

STANDING-WAVE TRANSVERSE DEFLECTOR DESIGN

The single cell shape of the standing-wave transverse deflecting structure is similar to that of the traveling-wave structure, as shown in Fig. 5.

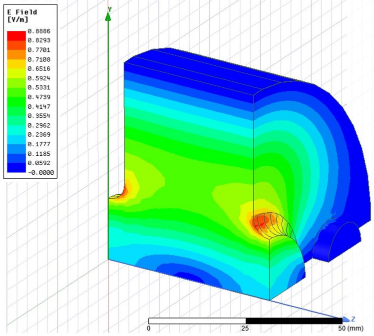

Figure 5: The electrical field of single cell of standing-wave transverse deflecting structure.

Two longitudinal rods (radius = 8 mm) crossing the cells off-axis have been inserted to suppress the excitation of the polarizing modes. The resonance frequencies of such modes are shifted far enough from the operating mode frequency to be negligible. The calculated frequency shift for the rotated modes due to the rods is +9.1 MHz. The rf parameters are summarized in Table 2.

Table 2: The RF Parameters of the Single Cell of the Standing-Wave Transverse Deflecting Structure

Parameter	**Value**
Cell length [mm]	50
Operating frequency [GHz]	2.998
Shunt impedance [MΩ/m]	21.1
Quality factor	15642

Two standing-wave deflecting structures consisting of 3 cells and 5 cells have been designed. The structures are designed for critical coupling. The filling time is defined as $\frac{2Q_L}{\omega}$ is 830 ns. The time to fill 99 % of the maximum electrical field in the structure at a constant input power is 3776 ns. There is high reflection from the standing-wave structure during the filling period of the pulse, especially in the initial part, that represents a risk of damage to the klystron. One solution to deal with the reflected power is to use a circulator to isolate the power source and the reflection from the structure. The schematic figure of the standing-wave deflector system with circulator is shown in Fig. 6. The pulse width of the klystron is 3.78 µs. Figure 7 shows a schematic of the standing-wave deflector system with 3 dB hybrid coupler.

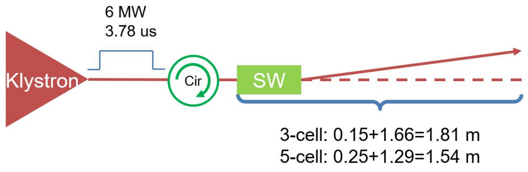

Figure 6: Schematic figure of the standing-wave deflector system with circulator. The length of the 3-cell standing-wave structure is 0.15 m and the drifting length is 1.66 m. The length of the 5-cell standing-wave structure is 0.25 m and the drifting length is 1.29 m.

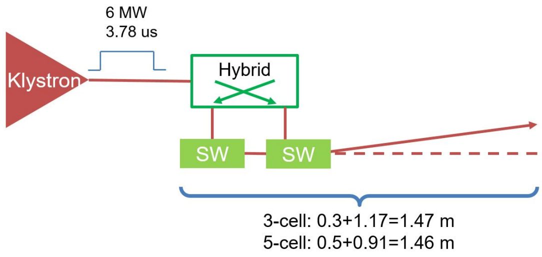

Figure 7: Schematic figure of the standing-wave deflector system with 3 dB hybrid coupler. The length of the two 3-cell standing-wave structures is 0.3 m and the drifting length is 1.17 m. The length of the two 5-cell standing-wave structures is 0.5 m and the drifting length is 0.91 m.

Another scheme to eliminate the reflection is to use two identical standing-wave structures and a 3 dB hybrid coupler. When the two structures are filled with a relative 90° phase shift, the 3 dB hybrid coupler can separate the wave from the klystron from the wave that leaves these cavities. The input power of each structure is 3 MW.

CONCLUSION

The CompactLight project is currently developing the design of a next generation hard X-ray FEL facility. One of the baseline specifications of the CompactLight project is two-bunch operation with a spacing of 10 X-band rf cycles. A sub-harmonic deflector system working at S-band is proposed to separate the two bunches before the FEL lines. Traveling-wave and standing-wave deflecting structures are studied. The traveling-wave deflector system can separate the two bunches with one 0.5 meter structure and 1.27 meter drift length. The standing-wave deflector system can separate the two bunches with two 0.15 meter structures and 1.17 meter drift space.

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