

DESIGN OF THE TRANSVERSE C-BAND DEFLECTING STRUCTURE FOR MEASUREMENT OF BUNCH LENGTH IN X-FEL

Hiroyasu Ego, JASRI, XFEL Joint Project /SPring-8, Hyogo, 679-5198, Japan
Yuji Otake, RIKEN, XFEL Joint Project /SPring-8, Hyogo, 679-5148, Japan

Abstract

In SPring-8, the 8 GeV X-FEL with a short length of about 700 m is under construction. An electron beam with a bunch length having a duration of less than 200 fs is indispensable for stable and brilliant X-ray radiation. We planned to measure the short bunch length with a transverse RF deflector. A bunch measuring system including a deflector must be located within 15 m of 3-stage bunch compressors at a beam energy of 1.45 GeV. To install the system in such a restricted space, we need a deflector generating a transverse deflecting voltage of over 40 MV. Therefore, a new C-band deflecting structure was designed. It is a periodic disc-loaded structure with a racetrack-shaped iris in the centre of each disc. The deflecting resonant mode is the HEM11- $5\pi/6$ mode of a backward travelling-wave. The racetrack-shaped iris serves as both a cell-to-cell coupler and a beam-passing hole, prevents rotation of the deflection plane of the HEM11 mode, and makes the deflecting mode stably resonant. We represent the details and merits of the C-band structure along with the demanded performance in this paper.

INTRODUCTION

The 8 GeV X-ray free-electron laser in SPring-8 (XFEL) is based on the self-amplification of spontaneous emission. It was designed to be compact coherent X-ray source, owing to high-gradient C-band choke-mode accelerating tubes and in-vacuum undulators [1]. The total length of XFEL, including experimental sections, is approximately 700 m. To radiate stable, brilliant, and coherent X-rays, we generate an electron beam with an emittance of less than 1π mm-rad and a short bunch length having a duration of 200 fs. The bunch length is attained by adiabatic velocity-bunching with multiple sub-harmonic RF cavities and three-stage bunch compressors [2]. To diagnose the longitudinal structure of a bunch after compression, we use transverse RF deflecting structures (deflectors) as shown in Fig. 1. Recently, the practicality of the deflectors to the diagnostics is reported in Refs [3-6]. The deflectors are indispensable components for XFEL.

DEMANDED PERFORMANCE

In XFEL, the deflectors are located within 15 m of the last bunch compressor at a beam energy of 1.45 GeV. Since we must set a Q-scan monitor downstream of the deflectors, the diagnostic system comprising the deflectors and a beam-profile monitor should be less than 10 m long. Therefore, we need a high transverse voltage

of over 40 MV, assuming that the drift length of the bunch through the deflectors is 5 m.

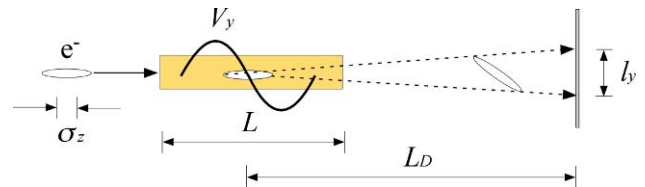


Figure 1: Schematic of an RF deflector.

A bunch with the zero-crossing RF phase in the deflectors is pitched or “crabbed” by the transverse fields in the vertical direction. Then, the longitudinal bunch shape is projected in the vertical direction on the profile monitor set behind the deflectors. The relation between the deflection voltage, V_y , and the projected bunch length on the monitor, l_y , is given by

$$V_y = \frac{l_y}{L_d} \frac{cp_z}{ek_a\sigma_z}, \quad (1)$$

where L_d is the drift length between the deflector and the monitor, k_a the wave number of the deflector, σ_z the bunch length, and p_z the longitudinal momentum of the bunch. Putting the parameters in Table 1 into Eq. (1), V_y must be 40 MV in the planned case of $L_d = 5$ m and $l_y = 1$ mm. Then, by using a beam-profile monitor with a spatial

Table 1: Deflector Specifications

Total Deflecting Voltage	V_y	40	MV
RF deflecting phase	ϕ_a	0	degree
Fractional bunch length for X-ray oscillation	σ_z	200	fs
Beam energy at the deflector	$p_z c$	1.45	GeV
Resonant frequency	f_a	5712	MHz
Type of structure		CZ	
Resonant mode		HEM11	
Phase shift per cell	βD	$5\pi/6$	rad
Group velocity	v_g/c	-2.16	%
Filling time	T_f	0.27	μ s
Unloaded Q	Q_a	11500	
Transverse shunt impedance	z_y	13.9	M Ω /m

resolution of less than 10 μm [7], we can examine the bunch length at a resolution of a few fs.

An S-band LOLA is one of the most important RF structures used as a deflector for FEL [4-6, 8]. The RF deflecting structures of a disc-loaded cylindrical waveguide, such as LOLA, were vigorously developed in the 1960's as a mass separator, and the beam-deflecting HEM11 (or TM11-like) mode was analyzed both theoretically and experimentally [8-12]. V_y of LOLA is expressed by

$$V_y \approx 1.6(MV / m / MW^{1/2})L\sqrt{P_0}, \quad (2)$$

where L is the length of LOLA and P_0 a peak input power fed into LOLA [4, 5]. Assuming that two 2.5 m long LOLAs were used in our XFEL, a total RF peak power of over 50 MW is needed to generate the demanded deflecting voltage. In consideration of the installation space and the RF power consumption, the S-band LOLA doesn't fit for our system unfortunately. Therefore, a new RF deflecting structure has been researched and designed with simulation codes, MAFIA and HFSS.

C-BAND DEFLECTING STRUCTURE

Figure 2 shows a cut-off view of the newly designed C-band deflecting structure. It is a periodically disc-loaded cylindrical waveguide with an iris shaped like a racetrack. The iris shape consists of two semicircles with a radius of R_a and two straight lines with a length of L_a , connected alternately. The structure is called "RAIDEN", which is an abbreviation of "racetrack-shaped iris-coupling deflection structure".

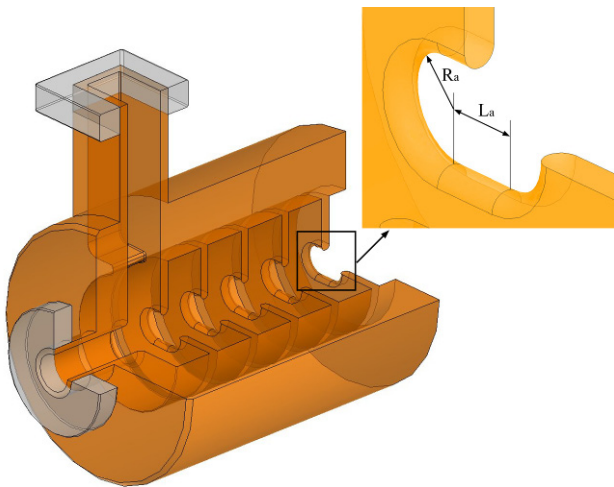


Figure 2: Cut-off view of the C-band RAIDEN.

In general, C-band RF structures can generate a higher acceleration voltage than S-band structures. Furthermore, the C-band RF (5712 MHz) system is adopted for the main accelerators in XFEL and contributes to the compactness of XFEL [13]. A 50 MW klystron, a power supply and waveguides delivering stable RF power have

been developed, and are available for the deflector. Therefore, we decided to develop a compact C-band deflecting structure. On the other hand, it is a demerit of the C-band structure that cell-to-cell coupling irises become smaller than those of the S-band one. However, the inevitable reduction in size of the iris fortunately becomes no vital problem in the case of XFEL, since no deflection of the bunch centre is required differently from the case of the mass separator.

The HEM11 mode of a backward travelling-wave is excited in RAIDEN and pitches a bunch passing through. The HEM11 mode in an axis-symmetric structure degenerates in twofold. To solve the degeneracy and to prevent rotation of the deflecting plane, LOLA has suppressor holes. Considering manufacturing, we judged it difficult to bore the suppressor holes to the discs of a small C-band RF structure. Therefore, we adopt the racetrack-shaped iris instead of the suppressor holes. The iris breaks the axis symmetry and cancels the degeneracy of the HEM11 mode. Then, two HEM11 modes appear with a different deflecting plane mutually crossing at right angles. The horizontally aligned iris of RAIDEN gives a stronger cell-to-cell coupling to the perpendicularly deflecting mode (y-mode) than the other horizontally deflecting mode (x-mode). Therefore, only the pass-band of the y-mode becomes wide, and the overlap between the pass-bands of the y-mode and x-mode is small. Figure 3 shows MAFIA simulations on the pass-bands of the HEM11 modes in RAIDEN with irises of $R_a = 6$ mm and $L_a = 8$ mm. In this case, the y-mode resonances with a cell-to-cell phase shift of more than $\pi/12$ are outside of the pass-band of the x-mode, and have a large group velocity. Thus, they can be stably excited without mixing with the x-mode resonances. The cell-to-cell phase shift of the y-mode is set to $5\pi/6$ at a resonant frequency of 5712 MHz. Then, the cell length, or disc spacing, is

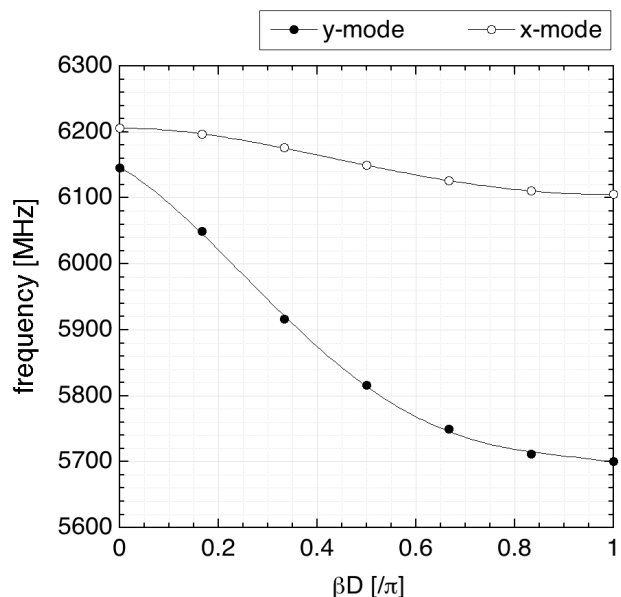


Figure 3: Pass-bands of the split HEM11 modes.

21.8686 mm. This results in a reduction of the number of cells and bonding points, and is inexpensive to manufacture. We selected and fabricate RAIDEN of the constant-impedance type by considering the development period and structure simplicity.

Figure 4 shows the simulated deflection efficiency and the group velocity of the HEM11 $5\pi/6$ y-mode as a function of (a) R_a at $L_a = 1$ mm and (b) L_a at $R_a = 6$ mm in the case of a 1.7 m long RAIDEN. The results represent that the iris flattened moderately with a suitable L_a causes the greater efficiency and group velocity than that with a long R_a . The vertically narrowed iris concentrates the electrical fields and generates a high gradient, similarly to the nose-cone of an RF cavity used for a high-gradient accelerator. In consideration of the demanded voltage, power consumption, and vacuum conductance, we chose an iris with $R_a = 6$ mm and $L_a = 8$ mm. The RF properties of RAIDEN with the iris size are listed in Table 1. Thus, V_y of RAIDEN is expressed by

$$V_y \approx 3.0(MV/m/MW^{1/2})L\sqrt{P_0}, \quad (3)$$

where L is the length of RAIDEN. As a result, two 1.7 m long RAIDENs fed with an RF power of 16 MW each generate a total deflecting voltage of 40 MV, and meet the demands as deflectors for XFEL. The maximum output power of the C-band klystron is 50 MW, and is therefore sufficient to drive the RAIDENs.

SUMMARIES

A transverse C-band deflecting structure of a disc-loaded waveguide has been designed and optimized for XFEL in SPring-8. The coupling iris of each disc is shaped as a racetrack and contributes much to fixing the deflecting plane, the stable resonance of the HEM11 mode, and a high-gradient deflection. The deflecting HEM11 mode of the 1.7 m long structure has a filling time of 0.27 μ s, and generates a deflecting voltage of over

20 MV. We can then measure the bunch length with a time resolution of a few fs by using this high gradient deflector, called RAIDEN.

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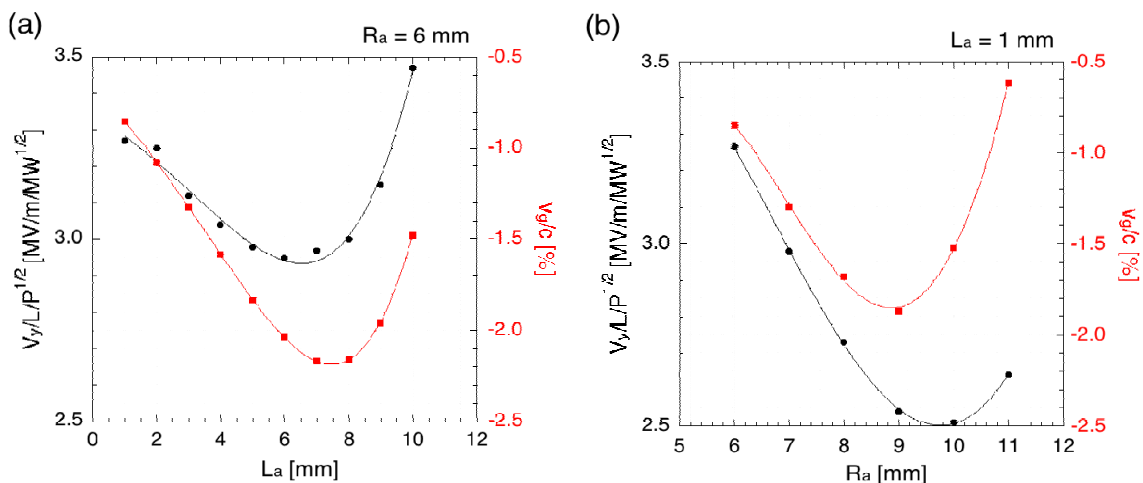


Figure 4: Deflection efficiency and group velocity of the HEM11 $5\pi/6$ y-mode.