TRANSVERSE C-BAND DEFLECTING STRUCTURE FOR LONGITUDINAL PHASE SPACE DIAGNOSTICS IN THE XFEL/SPRING-8 "SACLA"

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Abstract

In SPring-8, the 8 GeV compact XFEL "SACLA" is under commissioning. A single bunch of electrons is compressed down to about 30 fs for brilliant SASE X-ray lasing. It is an important key of stable lasing to investigate the longitudinal phase space and the sliced emittance of a lasing part of the bunch by using a transverse RF deflector. We developed a high gradient C-band deflecting structure operated at 5712 MHz for the bunch diagnosis with a resolution on a femtosecond scale in a limited space in SACLA. The backward travelling-wave of the HEM11-5π/6 mode is excited in the cylindrical structure periodically loaded with racetrack-shaped irises. The featuring irises suppress rotation of the deflection plane and generate strong cell-to-cell coupling for stable resonance. Two 1.8m-long structures were fabricated and installed in SACLA. They successfully generated a deflection voltage of 60 MV and pitched the bunch at the zero-crossing RF phase.

INTRODUCTION

SACLA, XFEL/SPring-8, is a compact SASE X-ray laser owing to high-gradient C-band choke-mode accelerating tubes and in-vacuum undulators [1]. The total length of SACLA including experimental halls is approximately 700 m. It had been constructed at the end of February in 2011 and succeeded in laser amplification with an X-ray wavelength of 0.12 nm after commissioning for three months. The commissioning continues and a highly intense and stable X-ray laser will be provided to users in the FY 2011.

SACLA demands an electron bunch having a part with a normalized emittance of less than 1 π mm-mrad and a peak current of more than 3 kA in a duration of about 30 fs for laser amplification. The extremely short bunch is formed by means of adiabatic velocity bunching with multiple sub-harmonic cavities and three-stage magnetic bunch compressors until the bunch is accelerated up to 1.4 GeV [2]. The practicality of a transverse RF deflecting structure (deflector) for longitudinal bunch diagnosis was reported in Refs [3-5]. The deflector is an indispensable component for XFEL. In order to measure bunch lengths less than 100 fs and verify the bunch compression, we developed high-gradient C-band deflectors and built a longitudinal diagnostic system with a resolution of a few fs in a drift space with a length of about 15 m downstream of the bunch compressors. This paper presents the fabrication and performance of the deflectors and the measurements in the process of bunch compression for the laser amplification of SACLA.

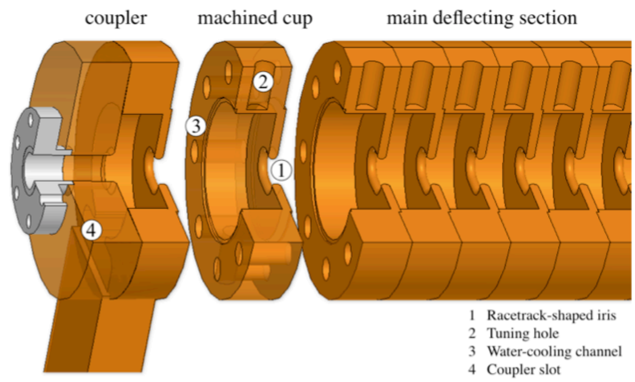

Figure 1: Schematic cut-off view of the C-band deflector, RAIDEN.

C-BAND DEFLECTOR

RAIDEN

Figure 1 shows a schematic cut-off view of the developed C-band deflector. It is a cylindrical waveguide periodically loaded with irises shaped into a racetrack. The iris shape consists of two semicircles with a radius of 6 mm and two straight lines with a length of 8 mm, connected alternately. The structure is called "RAIDEN", which is an abbreviation of "racetrack-shaped iris-coupling deflection structure". The backward-travelling wave of the vertically deflecting HEM11-5π/6 mode is excited at 5712 MHz to pitch a bunch. The iris breaks the axis symmetry and suppresses rotation of the deflection plane [6]. The horizontally aligned irises of RAIDEN give strong cell-to-cell magnetic coupling to the vertical mode. Figure 2 shows MAFIA simulations on the pass-bands of the horizontal and vertical HEM11 modes in RAIDEN. Only the vertical mode has a wide pass-band of 423 MHz resulting in clear mode-separation, high group-velocity

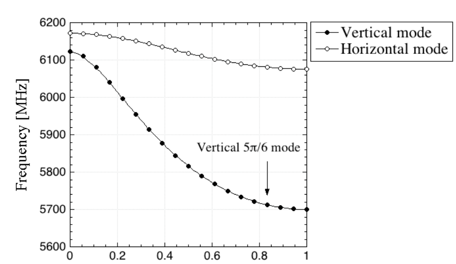

Figure 2: Pass-bands of the split HEM11 modes.

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and low sensitivity to fabrication tolerances. The vertical 5π/6 operation mode is far away from the pass-band of the horizontal mode and has a group velocity of -0.021c sufficient for stable operation. We selected RAIDEN of the constant-impedance type in consideration of its development period and structure simplicity.

Fabrication and RF tuning

Two 1.8-m long RAIDENs were formed with class-1 OFHC-copper cups and couplers stacked together with a period of 21.869 mm as shown in Fig. 1. Seventy-seven cups as deflecting cells were machined with CNC lathes and milling machines. An ultra-precise lathe gave a specular finish of less than 0.1 μm in roughness to the inner surface of each cup except its iris. The axially asymmetric iris was firstly milled and filleted with a radius-end mill to a surface roughness of about 1.6 μm and then electro-polishing generated a specular finish of about 0.5 μm on the iris surface. The machined cups were jointed by silver brazing in a vacuum atmosphere to form a main deflecting section.

Since imperfect fillets of the irises yielded a random frequency deviation to the amount of -10 MHz, the cells were needed to be RF tuned by exerting a mechanical pressure to make permanent dimples on the cell walls through tuning holes in Fig. 1. We were, however, impossible to carry out adequate RF tuning by the nodal shift technique because the strong cell-to-cell coupling and transverse field distributions prevented a movable metal rod from shorting each individual cell. Therefore we used the tuning method developed at DESY and based on the bead-perturbation measurement [7, 8]. Perfectly tuned input and output couplers are unnecessary for this tuning. Couplers were cramped to the main deflecting section and temporally tuned with a movable plunger. The scattered wave from an imperfect cell was calculated with the measurements and related to an S11 parameter. When S_n and θ_n respectively represent the amplitude and phase of the scattered wave from the n-th imperfect cell, the relation is given by

$$\frac{|\Delta S_{11}|}{|S_{11}^*|} = \frac{\Re\left[jS_n e^{j\theta_n}\right]C_n}{a_2}, \qquad (1)$$

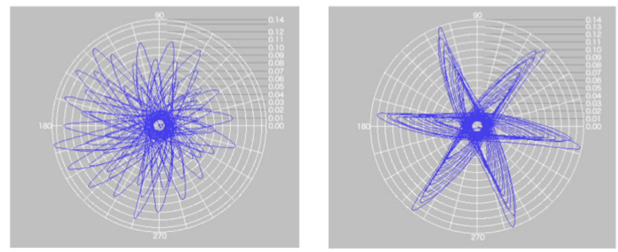
where ΔS_{11} is a change of S11 to be given by tuning, S_{11}^* the reflection after detuning of the input coupler, C_n the attenuation from the coupler to the n-th cell, a_2 the amplitude of deflecting wave in the second cell.

The couplers were matched after the RF tuning above. The slot into a rectangular waveguide and the inner radius of each coupler were adjusted so that the input VSWR could be less than 1.1:1 at 5712 MHz. Then the matched couplers were brazed to the main section.

Figure 3 shows the phasors of the deflecting fields in one of the fabricated RAIDENs by bead-perturbation measurement with a metal bead of 3 mm in diameter and pulled in steps of 0.4 mm. The six-hold symmetry of 5π/6 mode was clearly attained by the tuning. The RF properties of the RAIDENs were measured with a network analyser and listed in Table 1. Though the Q-values deteriorated into about 79% of the MAFIA calculation mainly owing to the dimples, we can generate a sufficient deflection voltage with the RAIDENs and given by

$$V_T \approx 4.0\left(MV/m/\sqrt{MW}\right)L\sqrt{P_0} \times 2, \qquad (2)$$

where L is the deflection length and P_0 the peak input power fed into each.



(a) (b)

Figure 3: Phasors of deflecting fields within one of the RAIDENs by bead-perturbation measurement (a) before tuning and (b) after tuning.

Table 1: RF properties of the fabricated RAIDENs

		#1	#2
Operation frequency [MHz]	f_a	5712	
Resonant mode		HEM11-5π/6	
Body length (deflection length) [m]		1.808 (1.706)	
Unloaded Q	Q_a	8809	8948
Group velocity	v_g/c	-0.0214	-0.0214
Filling time [μs]	T_f	0.269	0.269
Attenuation parameter	τ	0.548	0.539
Transverse shunt impedance [MΩ/m]	r	20.8	21.0
VSWR		1.12	1.09
Maximum accumulation of errors in phase-advance [°]		7.5	2.8

High-power Test

The RAIDENs were tested and conditioned at high power in a test stand of the RIKEN Harima institute. Substantial outgassing as a byproduct of electrically multipactoring discharge was observed within the RAIDENs during the initial process. After conditioning for about 40 hours, operation was possible with negligible outgassing or arcing at any power up to a rated klystron output of 50 MW with a pulse length of 1 μs and a repetition of 60 Hz. The vacuum level in them at the end of the conditioning was less than 1×10^{-6} Pa at full operating power. They under the conditioning were cooled with eight longitudinal water-cooling channels shown in Fig. 1. Heat generation of a constant impedance structure gradually decreases from the input to the output. Thus temperature uniformity within 0.1ºC was met by flowing a cooling water of 20 *l*/min in the channels along the main section from the input to the output. A constant wall temperature could be maintained by varying the temperature of cooling water in the range from 26.5ºC to 30.0ºC. After satisfactory completion of the high-power test, they along with vacuum manifolds, rectangular waveguides, and water lines were mounted on support girders in the accelerator tunnel of SACLA.

LONGITUDINAL DIAGNOSIS

Figure 4 shows the schematic of the built diagnostic system. A bunch with the zero-crossing RF phase in the RAIDENs is pitched with a deflection voltage of 60 MV. The bunch is extended in the vertical direction according as drifting and the longitudinal bunch structure is projected on a Ce:YAG beam-profile monitor set behind them. The projected bunch length, l_y, related to the deflection voltage, V_T, is given by

$$l_y \approx \frac{eV_T L_d}{cp_z} k_a \sigma_z \cos\varphi_a , \quad (3)$$

where L_d is the drift length between the middle of the RAIDENs and the monitor, k_a the RF wave number, σ_z the bunch length, φ_a the deviation from the zero-crossing RF phase and p_z the longitudinal momentum of the bunch. Putting the parameters V_T = 60 MV, L_d = 12.5 m, k_a = 119.7 φ_a = 0º and cp_z = 1.4 GeV into Eq. (3), σ_z /l_y becomes 52 fs/mm. The profile monitor has a spatial resolution of less than 10 μm [9, 10] and we can examine the bunch length at a resolution of fs. We measured the longitudinal structure of compressed bunches by using this system in the commissioning of SACLA. Figure 5 shows some digitalized beam-profiles obtained in the process of bunch compression: (a) a profile without deflection voltage, (b) the profile of a bunch of about 1 ps at V_T = 19 MV and (c) the profile of a bunch of about 40 fs at V_T = 60 MV. Bunches under deflection voltage were extended in the vertical direction and their longitudinal structures were projected as designed. The lasing part in a bunch was successfully formed through this diagnosis.

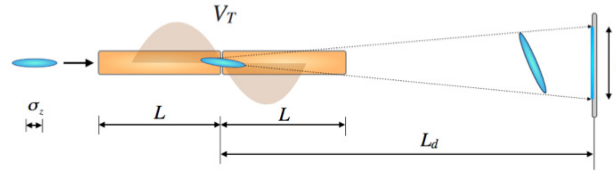


Figure 4: Schematic of the longitudinal diagnostic system.

SUMMARY

We developed a high-gradient C-band deflector in order to measure the longitudinal structure of a bunch in SACLA. The fabricated 1.8-m long deflectors generated stably a vertical deflection voltage of 60 MV without rotation of their deflection plane. The longitudinal structure of a bunch compressed to several tens fs was successfully projected on a screen at an expansion ratio of about 50 fs/mm. We will measure the longitudinal phase space and the sliced emittance of the bunch for stable laser amplification by using this system.

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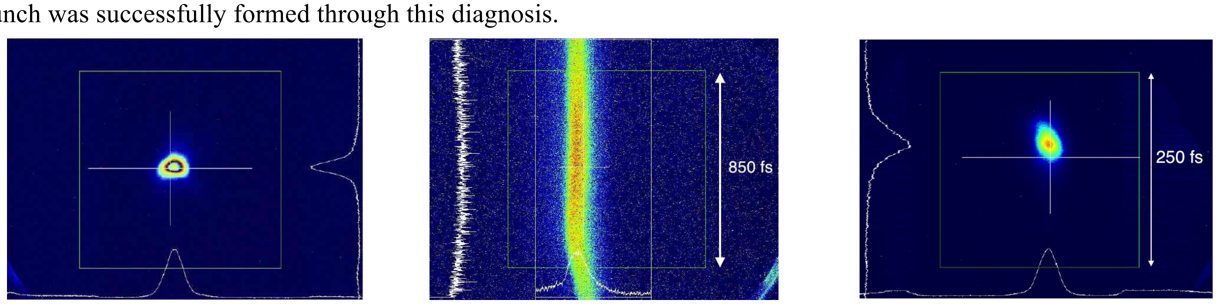

(a) (b) (c)

Figure 5: Bunch profiles on a Ce:YAG screen. (a) A bunch profile without deflection voltage; (b) the profile of a bunch of about 1 ps at V_T = 19 MV; (c) the profile of a bunch of about 40 fs at V_T = 60 MV.