

# OVERVIEW OF SHORT-PULSE X-RAY GENERATION USING CRAB CAVITIES AT SPRING-8

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## Abstract

We have been developing a system to generate short-pulse X-rays using superconducting crab cavities at the SPring-8 storage ring. In this scheme, the maximum repetition rate of the short-pulse X-rays is the same as the acceleration frequency of the ring; thus user experiments at other beam lines are not disturbed by the generation of short pulses. We are planning to install KEKB-type crab cavities as vertical deflectors. Suppression of phase fluctuation among crab cavities is essential for the generation. An overview of the short-pulse generation scheme and topics related to hardware development for the stabilization of rf phase fluctuation are described.

## INTRODUCTION

The SPring-8 storage ring is a third-generation synchrotron radiation source with four long straight sections, in which a typical X-ray pulse width of a few tens of picoseconds is obtained. Recently, X-rays with a shorter pulse width of around sub-picosecond have become required for time-resolved studies on structural dynamics. Although XFEL facilities [1] currently under construction are expected to satisfy this requirement, storage-ring-based light sources have the advantages of a high repetition rate and high stability. Many methods for obtaining short-pulse X-rays have been proposed and tested such as a laser-slicing method [2], circulating a short bunch in an isochronous ring [3], and bunch rotation with vertical kickers [4] and vertical rf deflectors [5] [6]. Among these methods, bunch rotation with vertical rf deflectors has an advantage over other methods in that it does not disturb the other users' experiments.

As rf deflectors, we can utilize superconducting crab cavities, which were developed for the KEK B-factory [7][8]. Their operation frequency of 508.887MHz is close to 508.58MHz, which is the acceleration frequency of the SPring-8 storage ring. Therefore, these crab cavities enable short-pulse generation with minimum R&D because of the small amount of modification required. We found that it is essential to reduce the relative rf phase fluctuation among the crab cavities to suppress emittance degradation at the other beam lines.

In this paper, we give an overview of the planned short-pulse X-ray generator at SPring-8 and the development of a high-power phase shifter and a cavity tuner to solve the

problem of phase fluctuation.

## OVERVIEW

The layout of the short-pulse generator in one of the long straight sections is shown in Fig. 1. At the first two cavities, the bunch is vertically deflected and tilted in the longitudinal-vertical plane. Then the tilted bunch radiates X-rays while it passes through a mini-pole undulator. The radiated X-rays are also tilted in the longitudinal-vertical plane similarly to the tilted bunch. As a result, short-pulse X-ray can be obtained when we slice out the head and tail parts of the X-rays. After the emission of X-rays, following third and forth cavities remove the tilt of the electron bunch in a similar way to the first two cavities. Two slits downstream of the undulator slice each X-ray into a short pulse. These slits prevent merging of photons from the head and tail electrons. The orbit is bumped so that the first slit can be placed as close to the undulator as possible.

The rf parameters of the short-pulse generator with the crab cavities are listed in Table 1. We optimized the loaded Q of the cavity to  $10^5$  in order that rf phase fluctuation can be controlled by a PLL. An rf power of 150 kW / cavity is selected as maximum value that can be achieved in the present crab cavities.

Table 1: Rf Parameters of Crab Cavity

cavity type	superconducting cavity
operating frequency	508.58MHz
deflecting mode	TM110
$R/Q$	46.7 $\Omega$
loaded Q	$10^5$
rf power	150kW / cavity
drift space between cavities	10m
deflecting voltage	1.67MV
phase stability	14mdeg (1 $\sigma$ )

## X-ray Pulse Width and Intensity

The obtainable pulse width of X-rays depends on the slit width. The shortest X-ray pulse width is obtained at a slit width of the zero limit and can be written as

$$2\sigma_{p0} = \frac{2\sigma_y^*}{c \tan \theta_{tilt}}, \quad (1)$$

$$\tan \theta_{tilt} = e V_{kick} \omega_{rf} L / c E, \quad (2)$$

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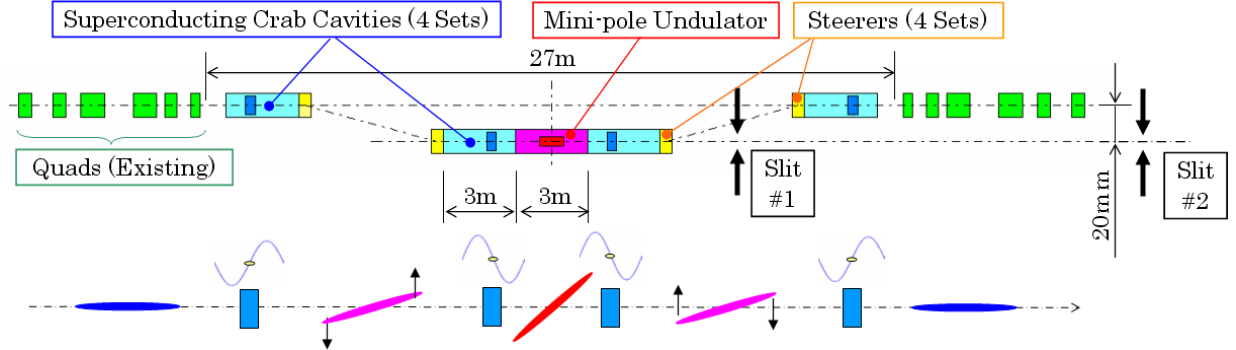


Figure 1: Planned layout of short-pulse generator at SPring-8.

$$\sigma_y^* = \sqrt{\sigma_y^2 + \sigma_D^2} . \quad (3)$$

where  $\sigma_{po}$  is the X-ray pulse width in time,  $\sigma_y$  is the vertical electron beam size,  $\sigma_D$  is the photon beam size due to diffraction,  $\sigma_y^*$  is the effective photon beam size including the diffraction,  $c$  is the speed of light,  $\theta_{ilt}$  is the tilt angle of the bunch,  $V_{def}$  is the deflection voltage of the crab cavity,  $\omega_f$  is the angular frequency of the deflection voltage,  $L$  is the length of the drift space and  $E$  is the beam energy.

Table 2: Calculation conditions and the results for the performance of the short-pulse generator

Beam Energy ( $E$ )	8GeV	4GeV
Effective Size ( $\sigma_y^*$ )	6.52 $\mu\text{m}$	3.59 $\mu\text{m}$
Photon Wavelength	0.0292 nm	0.116 nm
Tilt Angle ( $\theta_{ilt}$ )	22.3mrad	44.5mrad
Photon Flux Density <sup>(#)</sup>	$3.6 \times 10^{15}$	$3.1 \times 10^{15}$
Pulse Width ( $2\sigma_{p0}$ )	2.0ps	0.54ps

(#) : The flux density is for 100% extraction efficiency and is in the unit of photons / s / 1%BW @ 100mA.

Using the above formulae, we calculated and evaluated the pulse width at beam energies of 8GeV and 4GeV [9]. We plan to install the designed short-pulse generator in one of the long straight sections (LSSs) of the ring. The calculation conditions at the LSSs and results are shown in Table 2. In this table, the pulse width is for the zero-limit slit width. The pulse width and extraction efficiency are functions of the slit width, and these relations are shown in Fig. 2. As an example, when we choose an extraction efficiency of 0.1%, the pulse width ( $2\sigma$ ) and slit width are 2.2ps and 5.55 $\mu\text{m}$  at 8GeV and 0.8ps and 8.01  $\mu\text{m}$  at 4GeV, respectively.

The possibility of operating SPring-8 at a lower beam energy has been discussed and tested, since a smaller beam size is available at a lower beam energy, for example, the vertical beam size at a beam energy of 4GeV would be half that at 8GeV.

### Lower-Order Mode

The crab cavity has such a large beam pipe diameter that its higher-order modes propagate out of the cavity. A lower-order mode (LOM), the TM010 mode, however,

can remain in the cavity and cause longitudinal beam instability. At KEK, a coaxial coupler is attached to extract the LOM and avoid the instability. The coupler also works as a frequency tuner for the TM110 mode and its structure is complicated. The stored beam current of SPring-8 is 100mA and that of KEKB is 1.7A. The loaded Q of the LOM required to avoid the beam instability is less than 10,000 at SPring-8, and less than 70 at KEKB [7]. An input coupler for TM110 mode is also used as a LOM coupler at SPring-8 and the required value of loaded Q will be realized. Thus, the LOM does not cause the beam instability and moreover, we can simplify the tuner structure, which will lead to higher reliability.

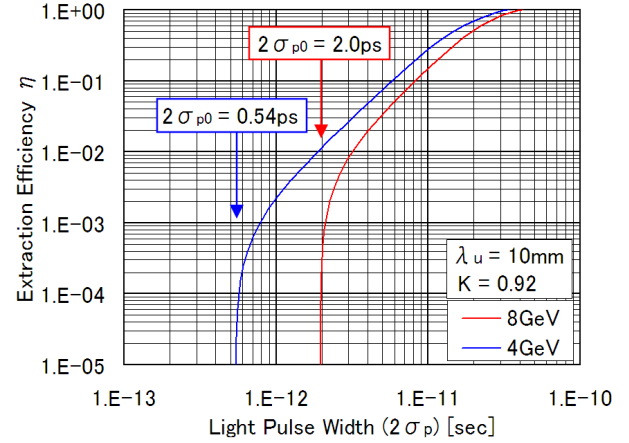


Figure 2: Obtainable X-ray pulse width ( $2\sigma$ ) and its extraction efficiency. Since the sliced X-ray pulse width depends on the effective photon beam size and the beam energy, the results for two values of 8GeV and 4GeV are shown.

## HARDWARE DEVELOPMENT

If the relative rf phase among cavities fluctuates, bunches oscillate in the vertical direction, which degrades the effective emittance and disturbs the experiments of other users. If we set the allowable center-of-mass oscillation to 1 $\mu\text{m}$ , the tolerance of the phase fluctuation is 14mdeg, which corresponds to an RMS jitter of 0.076ps. If we employ one rf source to drive four cavities, fast and common phase noise, mainly electrical noise, becomes ignorable because common phase fluctuation

does not contribute to the degradation of emittance. Consequently, the fluctuation of the cavity resonant frequency is the only source of the relative phase fluctuation.

To suppress the phase fluctuation, we have been developing a high-power phase shifter, its power supply and a frequency tuner for the cavity. The phase shifter has a fast response with small amount of phase shift, whereas the cavity tuner covers a large but slow phase shift.

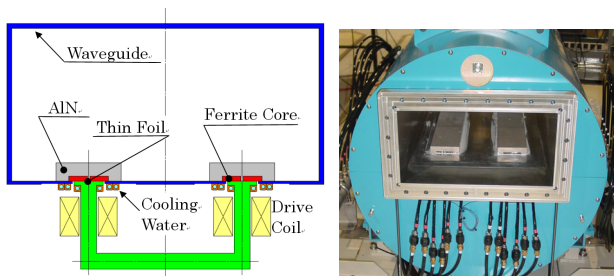


Figure 3: Schematic view and its picture of the high-power phase shifter.

### High-Power Phase Shifter

A fast and high-power phase shifter has been developed for the suppression of rf phase fluctuation. It can handle an rf power of 300kW under a full-reflection condition. It covers a phase shift of  $\pm 1.5$  deg with the frequency response of from DC to 1 kHz ( 3dB ). This frequency response was determined from the measured data on the phase fluctuation of the KEKB crab cavity, which was due to mechanical vibrations of the cavity and variations in LHe pressure in the cryostat.

The phase shifter consists of a waveguide and a couple of ferrite cores as schematically shown in Fig. 3. The phase of the rf is shifted by applying a magnetic field to the cores. Since the eddy current on the surface of the waveguide near the magnetic flux determines the frequency response, the thickness of the waveguide near the cores is 50  $\mu\text{m}$ . A high-power test of the phase shifter was carried out and the above specifications were confirmed. Also, the insertion loss deviation for the full range of the phase shift was less than 0.1dB.

The phase shifter requires a power supply to drive its cores. Its frequency range is DC to 10 kHz with a current of 60A and a voltage of 550V. Since this type of power supply is not commercially available, we have developed a proto type of power supply. It consists of DC power supplies whose voltages are powers of 2, such as 4 V, 8 V ... and 256 V, and power MOSFET switches. The frequency response of the power supply was measured in an offline test using a load with the same impedance, 50  $\mu\text{H}$  / 40 m $\Omega$ , as that of the phase shifter. Although tests on the stability and reliability of the power supply are still under progress, tests on the important parameters have already been completed. Specified frequency response has been achieved.

### Cavity Tuner

A frequency tuner suitable for SPring-8 (Fig. 4) has been developed. The cavity frequency is shifted by a deformation of the cavity in a beam direction. This tuner does not have the function of the LOM coupler, since the loaded Q value of the LOM is lowered by the input coupler. In its development, the following were taken into consideration. The crab cavity has high stiffness owing to its rib structure, because the cavity shape can be easily buckled by air pressure. Therefore, the tuner system which includes a cryostat must have high stiffness as well.

The tuner has two actuators; one is a piezo actuator for precise and rapid tuning and the other is a jack bolt for large but slow motion. For this tuner, smooth and linear motion is important. Also, a small backlash is essential. A proto-type of the tuner has also been tested with elastic loads that simulate the stiffness of the cavity and cryostat, and the cavity mass. Offline tests including precise motion of the tuner are under progress.

On the basis of the results of tests, we performed the PLL simulation, in which the characteristics of the cavity and the phase shifter were taken into consideration. The simulation indicated that the phase fluctuation among cavities can be suppressed to 14mdeg by the PLL control.

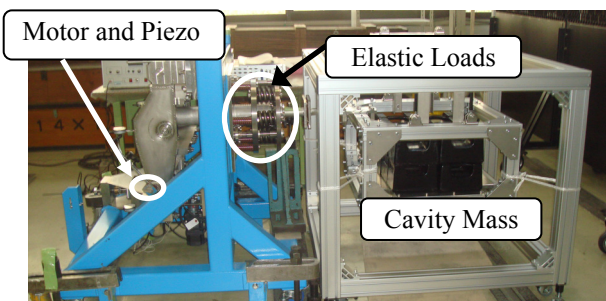


Figure 4: The proto-type of the cavity tuner. Elastic loads which simulate the crab cavity and cryostat stiffness are attached between the tuner and the cavity mass.

## SUMMARY

It is possible to realize a phase noise of less than 14mdeg using the high-power phase shifter and the tuner that we have developed. Issues requiring R&D have been resolved. We are now ready to install the short-pulse X-ray generator in SPring-8.

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