J. Synchrotron Rad. (1998). **5**, 162–167

SPring-8 Program

H. Kamitsubo

JAERI-RIKEN SPring-8 Project Team, Kamigori, Ako-gun, Hyogo 678-12, Japan.
E-mail: kamitsub@sp8sun.spring8.or.jp

(*Received 4 August 1997; accepted 1 December 1997*)

SPring-8 is a third-generation synchrotron radiation source operating in the soft and hard X-ray region. It consists of an injector linac of 1 GeV, a booster synchrotron of 8 GeV and a storage ring with a natural emittance of 5.9 nm rad. The storage ring can accommodate 61 beamlines in total, and 26 of them are under construction. The project has been carried out jointly by JAERI and RIKEN and construction of the facility started in 1991. Commissioning of the injector linac was started in August 1996 and an 8 GeV electron beam was injected into the storage ring in March 1997. The first synchrotron radiation from a bending magnet was observed at the front end of the beamline on 25 March and radiation from an undulator was observed on 23 April. On-beam testing of seven beamlines, four of them from in-vacuum undulators and three from bending magnets, started in July. The maximum stored current is currently fixed at 20 mA and the lifetime at maximum current is longer than 20 h. The dedication is scheduled for October 1997.

Keywords: hard X-rays; low-emittance ring.

1. Introduction

The SPring-8 (super photon ring of 8 GeV) facility is one of the world's most brilliant synchrotron radiation sources in the energy range from 0.3 keV to several hundred keV (SPring-8, 1991). It is composed of a 1 GeV electron/positron linac, an 8 GeV booster synchrotron and a low-emittance storage ring with a circumference of 1436 m. The storage ring is designed to have a super period of four with 40 straight sections of length 6 m and four long straight sections. It can accommodate 38 beamlines from insertion devices (IDs), including four long IDs. In addition to these ID beamlines, 23 beamlines from the bending magnet (BM) can be installed. The maximum length of the beamlines is 80 m from the exit of the ID or BM. However, we can extend nine beamlines to 300 m and three beamlines to 1000 m. The radioactive isotope (RI) experimental hall is built adjacent to the experimental hall to accommodate three beamlines for radioactive samples.

The energy of 8 GeV allows us to obtain high-brilliance X-rays continuously in the energy range from 5 keV (fundamental) to 60 keV (fifth harmonic) from a standard in-vacuum undulator with a period length of 32 mm. Fig. 1 shows the spectral brilliance of SPring-8 bending magnets, wiggler and undulator with 6 nm rad emittance, 10% coupling and 100 mA.

The Spring-8 project has been carried out jointly by the Japan Atomic Energy Research Institute (JAERI) and the Institute of Physical and Chemical Research (RIKEN). The facility is constructed at Harima Science Garden City which is located 100 km west of Osaka. Construction started in 1991 and is now one year ahead of the initial schedule. The linac, the synchrotron and the storage ring, together with seven beamlines, have been successfully commissioned (Kamitsubo, 1997).

Due to the geographical features of the SPring-8 site, the storage ring is built around a small hill and the injectors are built apart from the storage ring. The injector linac is to be used to supply an electron beam to a second storage ring, *i.e.* the 1.5 GeV synchrotron radiation source named 'New SUBARU' which is being constructed by Hyogo Prefecture for Himeji Institute of Technology.

By now, five public beamlines, one RIKEN beamline and one R&D beamline have been completed, and 19 beamlines are under construction. Ten beamlines will be available for outside users in October, and the dedication is scheduled for 6 October 1997.

Spring-8 has the legal status of a national user facility and is open for use by researchers not only from Japan but worldwide. The Japan Synchrotron Radiation Research Institute (JASRI) will have the responsibility for the operation, maintenance and improvement of SPring-8 after the dedication in October.

2. SPring-8 accelerators

Fig. 2 shows an aerial view of the Spring-8 facility. The injector linac and the booster synchrotron are built at a level 10 m below the level of the storage ring. An 8 GeV electron beam is transported from the synchrotron to the storage ring through the underground tunnel and injected into the storage ring from the inside of the ring. Electrons circulate clockwise in the synchrotron whereas they circulate counterclockwise in the storage ring. The major specifications of the SPring-8 accelerators are given in Table 1; all the figures are design values.

2.1. *Injectors*

The injector linac consists of a 250 MeV high-current linac, an electron/positron converter and a 900 MeV main linac. When we started work on the design, positrons were expected to be more appropriate than electrons in overcoming instabilities in the storage ring. Considering the experience at the ESRF, however, we decided to start commissioning with electrons and remove the e^-/e^+ converter. The linac has 26 accelerator columns which are of the $2\pi/3$ travelling-wave and constant-gradient type. The average accelerating field is designed to be higher than 16 MV m^{-1}. One high-power klystron of 80 MW (Toshiba E3712) supplies microwaves to two accelerator columns. A modulator provides the klystron with a pulsed electric power of 190 MW of 4 μs width and at a repetition rate of 60 Hz. The beam commissioning started on 1 August and we succeeded in accelerating the beam to the final energy of 1 GeV on 8 August. However, the final energy of the beam was reached when the beam was injected into the synchrotron in December.

The booster synchrotron has 64 bending magnets, 80 quadrupole and 60 sextupole magnets and 80 steerers. The integrated field strength was measured for all bending magnets and the r.m.s. distribution is 8×10^{-4}. All the magnets were aligned within an accuracy of 0.2 mm. Power supplies for these magnets are operated at 1 Hz. The typical time structure of the output current is as follows: 0.15 s flat-bottom for beam injection, 0.4 s ramping, 0.15 s flat-top for beam extraction, and 0.3 s falling. The tracking accuracy of the bending-magnet power supply is better than 1×10^{-4}.

The RF system of the synchrotron consists of eight five-cell cavities, waveguides, two 508.58 MHz klystrons (Toshiba E3786) and their power supplies. The required maximum RF power is 1.69 MW at 8 GeV. The RF voltage changes from 8 to 18.7 MV during electron acceleration from 1 to 8 GeV. The five-cell cavity is made of OFHC copper and has an effective shunt impedance of 21 MΩ. The beam-position monitors are located at upstream positions of 80 quadrupole magnets. Four signal-processing systems are used for 80 beam-position monitors and it takes less than 30 ms to obtain all position data.

Installation of the synchrotron was completed in October and commissioning was started on 10 December 1996. We succeeded in extracting the 8 GeV electron beam to a beam dump on 27 January 1997.

Table 1
Major parameters of the Spring-8 accelerators.

Injector linac		
Energy	Electron	1.15 GeV
	Positron	0.9 GeV
Repetition rate		60 Hz
RF		2856 MHz
Total length		140 m
Electron gun	Cathode	Y 796
	Voltage	200 kV
Accelerator columns	Number	26
Klystron	Number	13
	Maximum power (peak)	80 MW
Booster synchrotron		
Injection energy		1 GeV
Maximum energy		8 GeV
Circumference		396.12 m
Repetition rate		1 Hz
Number of cells	FODO lattice	40
Super period		2
RF		508.58 MHz
No. of klystrons	1 MW output	2
No. of cavities	Five-cell type	8
Harmonic number		672
Storage ring		
Energy		8 GeV
Lattice type		Chasman–Green
No. of cells	Normal cell	44
	Straight cell	4
Super period		4
Circumference		1436 m
Stored beam current	Single bunch	5 mA
	Multibunch	100 mA
Harmonic number		2436
RF		508.58 MHz
No. of cavities	Single-cell cavity	8×4
Revolution period		4.79 ms
Natural emittance		5.9×10^{-9} mrad
Coupling constant		<10%
Source point data		
No. of straight sections	High-β sections	19
	Low-β sections	15
	Long sections	4
Number of BM sources		23
Electron beam size	High-β sections	0.35×0.078
($\sigma_x \times \sigma_y$) (mm)	Low-β sections	0.069×0.052
Beam divergence	High-β sections	0.015×0.007
($\sigma'_x \times \sigma'_y$) (mrad)	Low-β sections	0.073×0.01

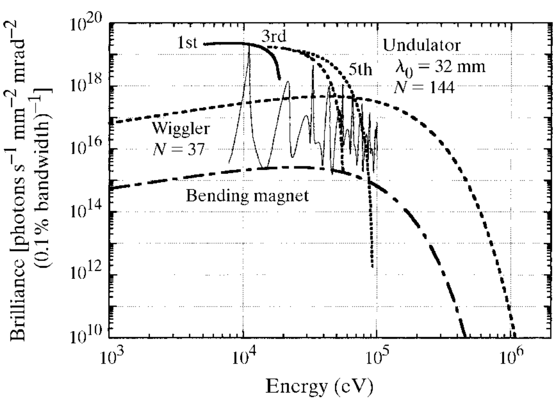

Figure 1
The spectral brilliance of the Spring-8 bending magnet, wiggler and undulator, calculated assuming 6 nm rad emittance, 10% coupling and 100 mA stored current.

2.2. *Storage ring*

The storage ring is a fourfold symmetric ring in its final form and the magnet lattice is of a Chasman–Green type with the modification of the inclusion of four long straight sections. In order to realize this ring we designed the storage ring to be composed of two types of unit cell, *i.e.* the normal cell and the straight cell. As shown in Fig. 3, the former consists of two bending magnets, ten quadrupole magnets and seven sextupole magnets and has a dispersion-free space of length 6 m (Fig. 3*a*). On the other hand, the latter has no bending magnet but has the same arrangement (Fig. 3*b*) of the focusing magnets as that of the normal cell; thereby both cells have approximately the same beam-dynamical property. In the first phase of operation, the storage ring will have a lattice structure of 4 × (11 normal cells + 1 straight cell) and be approximately 48-fold symmetric from a beam dynamical point of view. In this case, the operating mode of the storage ring is such that the β-function has low and high values alternately at neighbouring straight sections. In the second phase we will change the magnet arrangement of the straight cell to achieve a long dispersion-free space (Fig. 3*c*).

The storage ring has 88 bending magnets, 480 quadrupole magnets and 336 sextupole magnets. Their measured r.m.s. distributions of integrated field strength and gradient are better than 5×10^{-4}. The performance of the low-emittance ring depends strongly on the high quality of these magnets and their precise alignment. The magnetic centres of all the focusing magnets on the common girder are aligned within an accuracy of 0.05 mm. All bending magnets and common girders are aligned within 0.1 mm accuracy around the whole ring. The final surveying was completed in January 1997 and the standard deviation of the alignment errors found to be 0.04 mm. This accuracy was confirmed by using the injected electron beam during commissioning of the storage ring.

Three RF stations are installed. Each station is composed of eight single-cell cavities of the bell-shape type. The frequency of the higher-order mode (HOM) for each cavity can be controlled using two movable tuners and a plunger, keeping the fundamental frequency of 508.58 MHz constant. Then, HOM frequencies which could generate coupled-bunch instability can be well separated from cavity to cavity, so that the threshold current for coupled-bunch instability becomes higher than 200 mA.

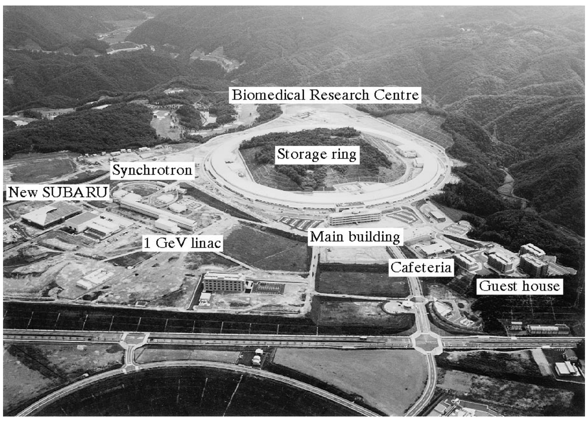

Figure 2
An aerial view of the SPring-8 facility. The storage ring is built around a small hill. The injectors are built at a level 10 m below the level of the storage ring.

A precise timing system coupling the injectors and the storage ring is needed for single-bunch or for few-bunch operation. By using optical fibres with low temperature-dependence and newly developed E/O (electrical to optical) and O/E modules, precise timing with time jitter of less than 10 ps is achieved.

The vacuum system for each unit cell consists of two bending-magnet chambers, three straight-section chambers, each of which is for the focusing magnets on one girder, two crotch chambers, one dummy chamber for an insertion device to be built in the future, and other components. All the chambers are made of aluminium alloy. The pumping system is based on non-evaporable getter strips, and sputter-ion pumps and distributed ion pumps are used as supplementary pumps. The final vacuum pressure reaches below 10 nPa.

Two beam-position monitors are welded directly to each straight-section chamber, giving a total number of 288. The beam-current monitors and a tune monitor are installed in the straight sections, together with absorbers, in order to avoid unnecessary irradiation by synchrotron radiation. Two types of current monitors are developed: one is a DC monitor of parametric current transformer type and is used to measure the DC component of the stored current with a resolution of 5 μA; the other is a pulse transformer with a signal processor to measure the charge of one bunch. The tune monitor consists of a beam shaker and its signal source, an amplifier, pick-up electrodes, signal-processing circuits and a spectrum analyser. All these monitors have been shown to work extremely well during storage-ring commissioning.

3. SPring-8 beamlines

3.1. *Beamlines*

As can be seen in Fig. 3, SPring-8 has 44 straight sections, 40 of which are standard straight sections of length 6 m and four are long straight sections. One standard straight section is used for the injection of the electron beam, and four are used for the installation of RF stations. One standard straight section is reserved for the future installation of harmonic RF cavities to make the bunch width shorter. Therefore, 38 straight sections can be used to accommodate IDs, four of which will be long IDs. In addition to the beamlines from these IDs, we decided to build 23 beamlines from the bending magnets, so that 61 beamlines can be installed at SPring-8. Table 2 lists the beamlines at SPring-8.

A beamline is composed of three parts: a front-end channel, a transfer channel with the optical system, and the experimental stations. The front-end channels of all beamlines are installed in the storage-ring tunnel, whereas the transfer channels and the experimental stations are

Table 2
Spring-8 beamlines.

Total number of beamlines	61
Classification by source type	
Insertion device beamlines	38
BL from normal straight sections (high β)	(19)
BL from normal straight sections (low β)	(15)
BL from long straight sections	(4)
Bending magnet beamlines	23
Classification by users	
Public beamlines	>30
Contract beamlines	10–20
JEARI/RIKEN beamlines	<10
R&D and machine study	5

installed in hutches in the experimental hall. Most of the components of the front-end channels and the transfer channels are standardized.

The beamlines are divided into four groups according to the source types and source points, *i.e.* beamlines from IDs installed at low-β sections, those from IDs at high-β sections, those from IDs at the long straight sections, and beamlines from bending magnets.

The beamlines are also classified by users into four groups: public beamlines, contract beamlines, JAERI/RIKEN beamlines, and beamlines for R&D and machine study. The public beamlines are constructed by SPring-8 and are open for use by general users not only from Japan but worldwide. Institutions and industries can have their own beamlines, which are classified as contract beamlines, individually or in groups at Spring-8. In this case about 30% of the beam time should be open for general users. On the other hand, JAERI and RIKEN have the privilege as the constructor of Spring-8 to have beamlines (JAERI/RIKEN beamlines) for their own use. The Research Centre for Nuclear Physics, Osaka University, is proposing to build a 'laser electron photon beamline' to study quark-nuclear physics using Compton backscattered laser photons from 8 GeV electrons.

In Table 3 are listed the beamlines under construction at SPring-8. There are 26 beamlines, *i.e.* 11 public, five contract, six JAERI/RIKEN, two R&D and two for machine study, and outlines of them are listed in Table 3.

3.2. *IDs*

IDs are the key technology for third-generation synchrotron radiation sources, especially for SPring-8. Most of the excellent features of synchrotron radiation, such as high brilliance, tunability over a wide energy range, polarization, coherence, small beam size, and short time structure of the beam, are also realized by IDs, in particular by undulators. New types of IDs have been developed at Spring-8 (Kitamura, 1998), as listed in Table 3.

The development of in-vacuum undulators has allowed us to obtain X-rays of energy up to 100 keV so that the serious problems of excessive heat-load can be substantially overcome. For example, an in-vacuum undulator with a period length λ_u = 32 mm can generate X-rays in the energy ranges 5.2–18 keV (first), 15.5–45 keV (third), and 26–60 keV (fifth) with brilliance higher than 10^{18} photons s^{-1} mm^{-2} $mrad^{-2}$ (0.1% bandwidth)$^{-1}$ by changing the gap from 25 mm to 8 mm. The performance of the first in-vacuum undulator shows that the brilliance of seventh harmonics is 80% of that calculated for the ideal undulator. As listed in Table 3, in-vacuum undulators are employed in the beamlines BL09XU, BL10XU, BL39XU, BL41XU and BL41XU.

An in-vacuum undulator has a vertical magnetic field and provides X-rays linearly polarized in the horizontal plane. A second type of in-vacuum undulator which

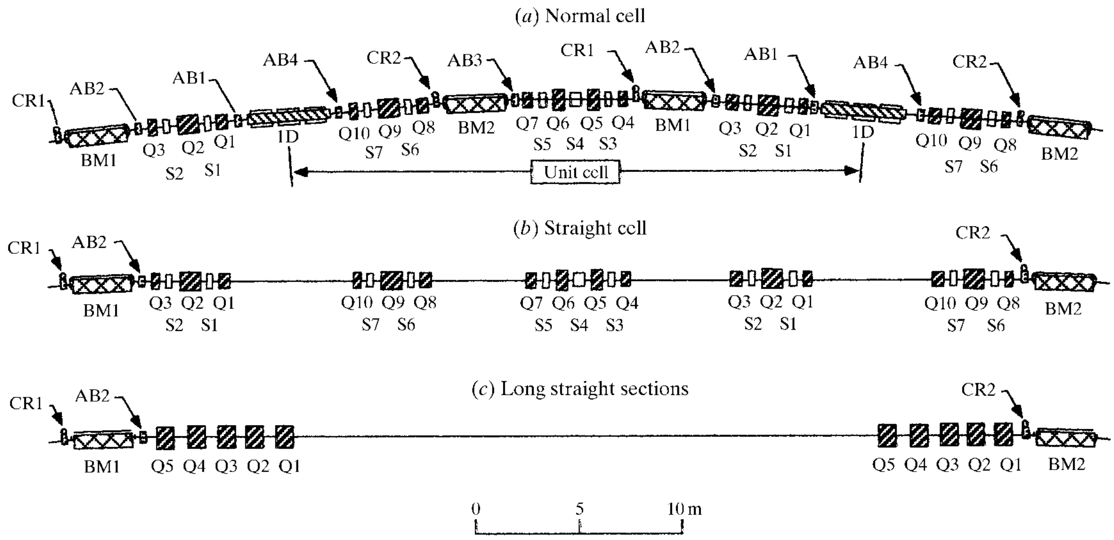

Figure 3
The arrangement of the magnets in (*a*) a normal cell and (*b*) a straight cell of the storage ring. The straight cell will be converted into a long straight section by rearranging the focusing magnets. (*c*) An example of a magnet arrangement in a long straight section. BM1–BM2: bending magnets; Q1–Q10: quadrupole magnets; S1–S7: sextupole magnets; ID: insertion device; CR1–CR2: crotches; AB1–AB2: absorbers.

Table 3
List of beamlines (under construction).

Beamline number	Name	Source
Public beamlines		
Insertion device beamlines		
BL08W	High-energy inelastic scattering	Elliptical multipole wiggler
BL09XU	Nuclear resonant scattering	In-vacuum undulator
BL10XU	Extremely dense state	In-vacuum undulator
BL39XU	Physicochemical analysis	In-vacuum undulator
BL41XU	Biocrystallography	In-vacuum undulator
BL25SU	Soft X-ray spectroscopy of solid	Twin-helical
BL27SU	Soft X-ray photochemistry	Figure-8 undulator
Bending-magnet beamlines		
BL01B1	XAFS	Bending magnet
BL02B1	Crystal structure analysis	Bending magnet
BL04B1	High-temperature research	Bending magnet
Contract beamlines		
BL15IN	WEBRAM (NIRIM)†	Insertion device
BL16XU	Industrial consortium insertion device‡	In-vacuum undulator
BL16B2	Industrial consortium bending magnet	Bending magnet
BL24XU	Hyogo beamline	In-vacuum undulator
BL44XU	Macromolecular assemblies (IPR, Osaka University§)	In-vacuum undulator
JAERI/RIKEN beamlines		
JAERI		
BL11IN	Surface science	Insertion device
BL25SU	Actinide science	Variably polarizing undulator
BL14B1	High-pressure science	Bending magnet
RIKEN		
BL29IN	Coherent X-ray	Insertion device
BL44B2	Structural biology II	Bending magnet
BL45XU	Structural biology I	In-vacuum undulator
R&D and machine study		
BL05In	Machine study I	Insertion device
BL38B2	Machine study II	Bending magnet
BL46XU	R&D II	In-vacuum undulator
BL47XU	R&D I	In-vacuum undulator

† Wide-energy-range beamline for research in advanced materials; National Institute for Research in Inorganic Materials. ‡ Industrial consortium insertion device for materials research. § The Institute for Protein Research, Osaka University.

generates a horizontal magnetic field has been developed at Spring-8 (BL45XU). A helical undulator, on the other hand, applies vertical and horizontal magnetic fields with an equal period length, and the electron beam therefore makes a spiral trajectory generating circularly polarized photons. It should be pointed out that the fundamental radiation travels along the axis of the helical undulator while higher harmonics radiation travels in off-axis directions. In the case where higher harmonics are not needed, it is an advantage to use this type of undulator. At Spring-8 the helical undulator is mainly applied to generate soft X-rays of several hundreds of eV. A twin-helical undulator, which consists of two identical helical undulators having opposite helicities and five kicker magnets, is used in BL25SU. In this undulator the helicity of the radiation is changed at a frequency of 10 Hz by switching five kicker magnets. Figure-8 undulators are another type of helical undulator used in BL27SU. This undulator is composed of horizontal and vertical undulators with period lengths of λ_u and $2\lambda_u$, respectively. Then the radiations with opposite helicities interfere with each other to give linear polarization in the horizontal plane. The advantage of the Figure-8 undulator is that only the fundamental radiation travels along the undulator axis.

A variable-polarization undulator used in BL23SU is another type of undulator. In this undulator the upper and lower arrays of permanent magnets are split into two parts and each diagonal pair can be moved independently. The polarization of resulting radiation depends on the relative phase of the two pairs, whereas the energy can be changed by changing the gap. The relative phase is altered mechanically so that the helicity can be changed rapidly.

4. First results of commissioning

4.1. *Accelerators*

Commissioning of the storage ring commenced on 14 March 1997. Test operation of the whole accelerator system had been carried out for a week before the commissioning. On 14 March we injected the beam from the synchrotron to the storage ring. Soon after, we observed the first turn of the beam in the ring. Then we spent five days for fine adjustment of the beam-transport line from the synchrotron to the injection section of the ring. On 21 March we started again with on-axis injection and, after a beam-energy correction and tune survey, the sextupole magnets were excited. We observed 24 turns of the beam. On 25 March we started operation of the RF system. After a fine adjustment of the phase and frequency we succeeded in storing a beam of 0.05 mA. The lifetime of the beam was 7 h. On the next day, 26 March, we succeeded in observing the first synchrotron radiation from the front end of BM beamline BL02B1. We then made efforts to correct the closed orbit distortion (COD) and to increase the stored current. A target current of 20 mA was achieved on 17 April with a lifetime of 3 h.

Test operation of the in-vacuum undulator (BL47XU) was started on 22 April and we succeeded in observing the first radiation from the front end of BL47XU on 23 April. The spot size of the photon beam was ~1 mm and did not move when the gap was changed from 50 mm to 20 mm.

The test operation of the accelerators for machine studies was continued during May and June. The beam lifetime at 20 mA has reached 30 h and it is now clear that the performance of the machine is extremely satisfactory.

4.2. *Beamlines*

The with-beam test of two beamlines, BL02B1 and BL47XU, was undertaken in June and we succeeded in extracting radiation direct to the experimental stations. In addition, two BM beamlines, BL01B1 and BL04B1, and three ID beamlines, BL09XU, BL41XU and BL45XU, were subsequently commissioned in July. We succeeded in extracting the photon beams to the experimental stations in all the beamlines and began performance testing of the monochromators. Preliminary data have now been obtained on BL02B1 and BL04B1 (Noda, 1998).

5. Conclusions

So far the commissioning of SPring-8 has been carried out very satisfactorily and we have found that the performance of the accelerators and of the insertion devices is very close to the design prediction. Insertion devices and front-end components for three more beamlines, BL08W, BL39XU and BL10XU, will be installed in August. We will continue to extract photon beams from these beamlines to the mirrors and monochromators in the optical hutches and to the experimental hutches. The dedication of Spring-8 is scheduled for 6 October and after that the public beamlines will be open for general use.

References

Kamitsubo, H. (1997). *Proceedings of the 1997 Particle Accelerator Conference*, Vancouver, BC, Canada. To be published.

Kitamura, H. (1998). *J. Synchrotron Rad.* **5**, 184–188.

Noda, Y., Ohshima, K., Tonaya, H., Tanaka, K., Terauchi, H., Maeta, H. & Konishi, H. (1998). *J. Synchrotron Rad.* **5**, 485–487.

SPring-8 (1991). *SPring-8 Project Part 1, Facility Design*. SPring-8, Kamigori, Ako-gun, Hyogo 678-12, Japan.