GENERATION OF HIGH-ENERGY SYNCHROTRON RADIATION WITH A 10-T SUPERCONDUCTING WIGGLER INSTALLED IN THE SPring-8 STORAGE RING

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Abstract

A three-pole 10-T superconducting wiggler was installed in the 8-GeV electron storage ring at SPring-8 for generating high-energy synchrotron radiation. Beam tests were carried out to check its performance and to investigate the effects on a stored beam. A beam was successfully stored at magnetic fields of the wiggler up to 9.7 T. The beam current was limited to 1 mA to avoid unnecessarily high heat-load on photon absorbers and radiation damage to accelerator components. Beam parameters such as a horizontal beam size, a bunch length, betatron tune shifts were measured. A spectrum of high-energy synchrotron radiation from the wiggler was also measured with the NaI scintillator at an extremely low beam current of about 8 pA.

INTRODUCTION

There are some demands of using high-energy gamma rays in the energy range from a few hundred keV to several or ten MeV. Intense low-energy positron beams can be produced via the electron-positron pair-production process by high-energy gamma rays. The low-energy positron beam is a powerful probe of Fermi surface and defects in materials science[1]. In nuclear astrophysics, it becomes probable to measure photonuclear reaction cross sections of some key elements such as ^{16}O and ^{180}Ta in the scenario of nucleosynthesis[2]. High-energy photons of about a few hundred keV to 500 keV can be used in, for example, Compton scattering experiments. Another possibility is the generation of neutrons via photodisintegration of ^{9}Be[3].

To generate high-energy gamma rays Csonka[4] proposed to use a micropole undulator. We proposed[5] to use a high-field superconducting wiggler (SCW) since necessary techniques are ready in Budker INP to develop SCW and an 8-GeV electron storage ring is available at SPring-8. We designed and fabricated a 10-T superconducting wiggler at Budker INP[6, 7] and installed it in the SPring-8 storage ring in August, 2002. Beam tests were then carried out and the results are reported in this paper.

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THREE-POLE SUPERCONDUCTING WIGGLER

A design value of the maximum field of SCW is 10 T and the achieved maximum value is 10.3 T recorded in a test site at SPring-8[8]. A field distribution was measured on the median plane of the electron orbit by using a Hall sensor fixed on a carbon rod and calibrated with NMR probes. The measured dipole field distribution along the wiggler axis is shown in Fig. 1 by the solid line. The peak value is 10.136 T. A calculated distribution is also shown by the dashed line. Calculated and measured fields agree well. The maximum values of the position and angle of the electron orbit at 10 T are 7.3 mm and ±25 mrad, respectively.

The first integral of the measured magnetic field along the electron orbit was 0.011 Tm, which corresponds to a horizontal kick angle of 0.4 mrad for an 8-GeV electron beam. This kick can be compensated by tuning two independent power supplies connecting to central and side poles of SCW.

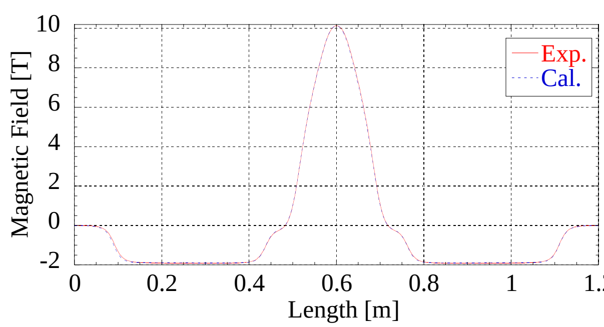

Figure 1: Dipole field distribution of SCW.

From the measured field distribution we evaluated quadrupole and sextupole components caused by non-uniformity of the fields. The integrated values of quadrupole and sextupole components are 0.50 T (defocusing) and 45 T/m (focusing), respectively, when the peak field is 10.136 T.

The details on SCW are described in Ref.[7].

BEAM TEST

For the purpose of beam tests, a stored current of 1 mA is enough to check the performance of SCW and to investigate the effects on a stored beam. Due to this limit of the beam current, we can avoid unnecessarily high heat-load on photon absorbers and radiation damage to accelerator components.

To perform efficient orbit corrections in both horizontal and vertical directions, we installed two horizontal and two vertical correction magnets upstream and downstream by SCW. Furthermore, we introduced two independent power supplies for two quadrupole magnets adjacent to SCW to compensate optics distortion. Though this scheme was found to be efficient to recover tune shifts, we did not routinely use it during a beam test.

Effects of SCW

Since the defocusing force becomes stronger as the field of SCW becomes higher, we changed a working point from a nominal point (ν_x, ν_y) = (40.15, 18.35) to (40.24, 18.35) at the beginning of the beam test, where ν_x and ν_y are the horizontal and vertical betatron tunes, respectively. The horizontal and vertical betatron functions at SCW are 25 m and 7 m, respectively.

In Fig. 2 we show the horizontal and vertical betatron tunes as a function of the peak field of SCW. Measured values are shown by solid circles (horizontal) and solid triangles (vertical). During excitation of SCW we changed the strength of the quadrupole magnets adjacent to it, and the betatron tunes were shifted by this change. The measured tunes in the figure are corrected by this amount. In Fig. 2 we show calculated tunes at 10.136 T by open symbols. The horizontal tune shifts can be explained by the quadrupole component of measured magnetic fields and the vertical ones can be explained by adding the effect of edge focusing.

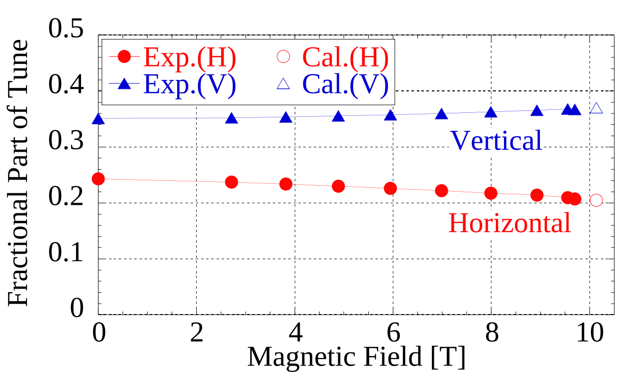

Figure 2: Betatron tunes as a function of the SCW peak field.

To study the effects on beam emittance, we measured the horizontal beam size at the point of beam injection in the following way[9]: we store a single-bunch beam, scrape it by firing bump magnets, measure a beam-loss rate and repeat this procedure by changing the height of a bump orbit. By assuming a gaussian density distribution for a circulating beam, we can obtain the root-mean-square beam size by fitting the data points of the beam-loss rate with the method of least squares. The results are shown in Fig. 3 by solid circles. Measured values are normalized by a value at 0 T to show relative change. The solid curve shows a calculation by using the field data shown in Fig. 1. We obtained good agreement between the experimental data and calculation results. An emittance is increased from 6.4 nmrad at 0 T to 13 nmrad at 10 T. This large increment is due to a large horizontal betatron function in a position of SCW.

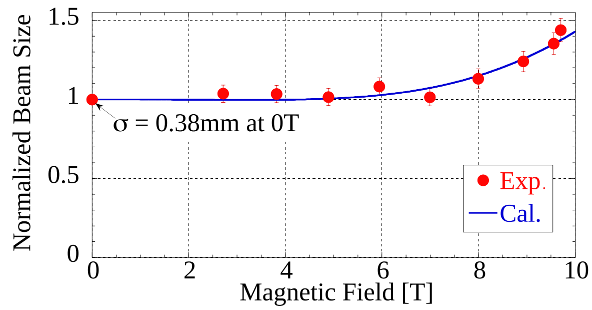

Figure 3: Horizontal beam size normalized by a value at 0 T.

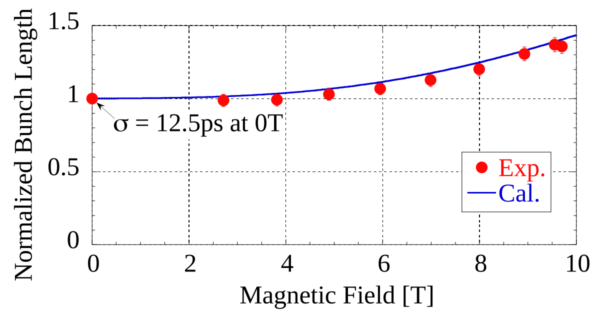

Figure 4: Bunch length normalized by a value at 0 T.

The normalized bunch length is shown in Fig. 4. An energy spread is increased from 0.11 % at 0 T to 0.15 % at 10 T due to emission of photons by SCW.

The sextupole field component of SCW mainly affects the dynamic aperture. (Though the sextupole as well as the quadrupole component changes chromaticities, a change in chromaticity is less than 0.1 and can be neglected.) The dynamic aperture was calculated by taking account of the sextupole components. The results show that the aperture is reduced in the horizontal direction. It is reduced typically from (-15 mm, +8 mm) to (-10 mm, +7 mm) at the point of beam injection. The injection efficiency was decreased by this reduction of the aperture.

Photon Energy Spectrum

We measured a spectrum of high-energy synchrotron radiation (SR) by using the NaI(Tl) scintillator and a photomultiplier (PM) when the SCW peak field was 9.5 T. A single-bunch electron beam of 0.11 mA was firstly stored and then scraped by firing bump magnets. The ratio of the number of electrons before and after scraping was estimated by the photon-counting method[10]. We then measured a photon spectrum at an extremely low beam current of 8 pA($\pm$20 %).

A schematic drawing of a photon beamline is shown in Fig. 5. All equipments for the spectrum measurement were installed in the storage ring tunnel. No experimental hutch was constructed and the photon beam was not extracted from the tunnel.

To separate ultra-high vacuum and atmosphere we put two windows in the photon beamline. One is made of Be with a thickness of 0.25 mm and the other Al with a thickness of 3 mm. A block of Pb with a thickness of 50 mm was set downstream from the windows to cut low-energy gamma rays.

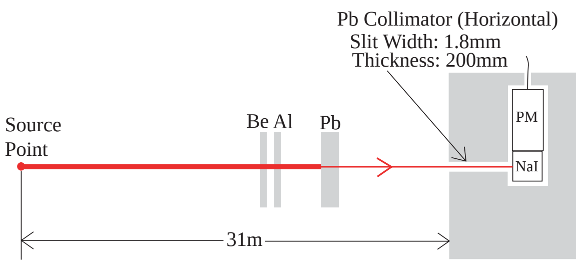

Figure 5: Experimental setup for spectrum measurement.

In Fig. 6 we show the measured photon-energy spectrum together with simulation results obtained by the GEANT3-code[11]. The energy calibration of the detector was done by using a radioactive source of ^{60}Co which emits gamma rays of 1.17 MeV and 1.33 MeV. The dashed lines in Fig.6 indicate the ambiguity of estimation of a total number of stored electrons. Reasonable agreement of the experimental data on the simulations was obtained. There is a possibiliy that a slight difference between the experimental data and the simulations comes from radiation damage of the detector during the spectrum measurement and/or from a systematic error of energy calibration. Alignment errors of a Pb collimator could also be a source of ambiguities in simulations.

SUMMARY

We installed a 10-T superconducting wiggler in the SPring-8 storage ring and carried out beam tests. Beam parameters and a photon spectrum were measured, and the results agreed well with calculations based on the measured field distribution.

The effects of SCW on the stored beam are not small. When the peak field of SCW is 10 T, the horizontal emittance becomes twice. The reason is that the SPring-8 storage ring is operated with a “high-beta” optics and the straight section where SCW was installed has a large horizontal betatron function.

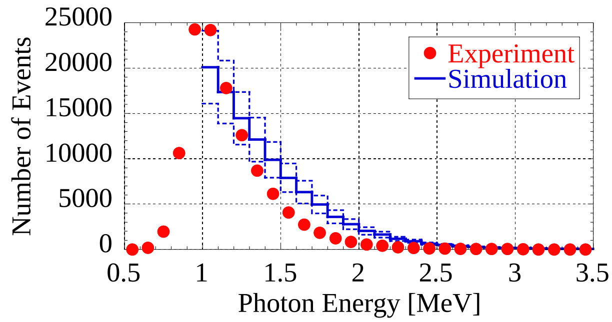

Figure 6: Photon spectrum at a magnetic field of 9.5 T.

When we consider the effects on the stored beam together with high heat-load, it is hard to use SCW in user-time since many SR users require highly brilliant and stable X-ray beams. Nevertheless, the applications of high-energy gamma rays generated by SCW are interesting and important, and we are now looking for a possible way of using SCW not for the beam test but for real applications.

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