TRENDS IN THE DEVELOPMENT OF INSERTION DEVICES FOR A FUTURE SYNCHROTRON LIGHT SOURCE

C.S. Hwang*, C.H. Chang, NSRRC, Hsinchu, Taiwan

Abstract

An in-vacuum undulator with a permanent magnet near 295 K has become a mature technology and is widely used; it can adopt a short-period length in a medium-energy facility to provide an enhanced photon brilliance in the hard x-ray region. A cryogenic permanent magnet is applicable for an in-vacuum undulator. A superconducting wiggler with NbTi wire will provide great flux with a continuous spectrum for the extreme x-ray region. The wire of high-temperature superconductors will have the potential to be utilized for the superconducting undulator. There are also special technical algorithms to develop a extremely short period in small magnet gap. Some conventional planar undulators with special functions must also be fabricated to diversify applications in the various light source facilities. In this review we describe the current and future developments of insertion devices in storage-ring and free-electron laser facilities.

INTRODUCTION

The main purpose of the third- or fourth-generation facility is to enhance the output at the greatest photon energies, or to extend the range of tuning energy at a lower electron energy. It is important to obtain X-rays with a low harmonic order of radiation by adopting short-period undulators with a small gap in the advanced medium-energy facility. Insertion devices are the key instruments in an accelerator storage ring (SR), energy-recovery linac (ERL) and free-electron laser (FEL) facility. An out-of-vacuum has been the norm in operations since the past two decades, but the period length and magnet gap of these insertion devices are so large that the photon energy can't attain the higher photon energies in the medium-energy electron SR. For this reason the third-generation synchrotron accelerators SR with high energy, such as ESRF (6 GeV), APS (7 GeV), and SPring-8 (8 GeV), were constructed in years 1988, 1990 and 1991, respectively. Relative to a SR, the ERL- or FEL-based synchrotron radiation facilities have a smaller horizontal beam aperture that is the same as the size of the vertical one. Consequently, the out-of vacuum still remains generally used for ERL and FEL facilities.

The in-vacuum undulator (IU) [1] with a permanent magnet or hybrid structure at room temperature has become a mature technology and is widely used in last decade; it can adopt a short-period length in a medium-energy facility (less than 3 GeV) that has thus been planned in many institutes, such as, Soleil (2.75 GeV), SSRF (3.5 GeV), and the 3 GeV facilities of Diamond, ALBA , TPS, NSLS-II and MAX-IV. The photon energy can attain only up to 35 keV (brilliance $\geqq 10^8$) in a medium-energy facility with the IU at room temperature. A cryogenic permanent magnet is applicable for an in-vacuum undulator to enhance the remanence field and the coercivity force. In future, a cryogenic permanent-magnet undulator (CU) [2-4] will provide harder x-rays up to 66 keV (brilliance$\geqq 10^8$) in a 3 GeV SR. Figure 1 shows the possibility of the energy spectrum in the 3 GeV energy facility with a IU or CU. A 0.1% energy spread and 2^o rms phase error had been used to calculate the flux and brilliance in the TPS lattice parameters. Figure 2 reveals the possible peak field strength that is as a function of gap in the different period length of undulator.

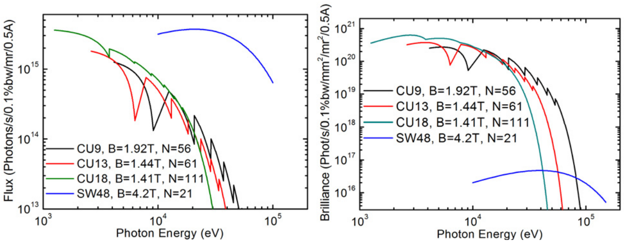

Figure 1: Possible hard x-ray spectrum of medium-energy accelerator facility in the various insertion devices.

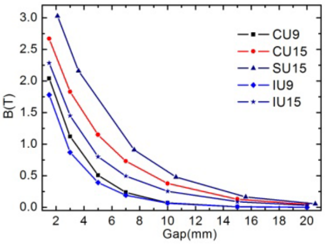

Figure 2: Maximum magnetic-flux density in different magnet gap of the various period-length undulators.

Superconducting wigglers (SW) [5-7] are also a mature technology to provide a high photon flux for hard x-rays in a facility with medium electron energy (see Fig. 1). A drawback of a SW is that much useless power radiated from the SW adversely affects the stability of optical components in the beam line and also requires more RF systems that increase the cost of the accelerator facility. The superconducting technology with high-temperature superconductor (HTS) wires will have the potential for the development of undulators in the coming decades. Several superconducting undulators (SU)[8-10] have been launched and some critical issues, such as the heat-load problem and the field-shimming method, must be solved

---

*cshwang@nsrrc.org.tw

of SU. The transitional planar undulators, such as APPLE-II undulators or the electromagnet elliptically polarized undulator (EPU), are still popular for use in a circular-polarization experiment with low- or high-frequency switching, respectively. Various special technical algorithms have been pursued to meet the strong desire for short period of insertion devices. A HTS bulk magnets [11] and a stacked layer of thin HTS tapes [12] are applicable even for a extremely short period (about 5 mm) SU, but these ideas are just rugged and not practical. The issue of extremely short period in a small magnet gap is also discussed here.

IN-VACUUM UNDULATOR

It is possible to pursue extremely small gaps with an IU in the SR, but the smaller gaps should depend on the results of beam dynamics for the Touschek lifetime. An optimized length of undulator at the minimum gap to maintain a reasonably great Touschek lifetime is hence necessary [13]. The in-vacuum technology has become mature currently, and many accelerator facilities have utilized an IU for their light source, especially the medium-energy facility. The risk of radiation damage to the permanent-magnet materials and the heat load on the magnet block from the weak-field effect in extremely small gap (smaller than 5 mm) of IUs is serious. An aging treatment for each magnet block through maintaining permanent magnets at temperature 145 ^{o}C for 24 h in vacuum to enhance a large coercive force [13] is therefore necessary. Hitachi-metal Neomax developed a high-performance NdFeB sinter magnet by deposition diffusion of Dy; the remanence field and coercivity force became enhanced to more than 400 G and 4 kOe near 295 K, respectively. To avoid the huge heat load on the magnet block from the resistive wall wake-field, the nickel copper sheet attached to the face of the magnet pole and the RF finger at both sides should be carefully installed in the IU. The design concept for a RF transition taper and CuNi sheet should allow a longitudinal degree of freedom for baking out. Most operational failures that occur on the IU are the issues [13] of vacuum, the installation of CuNi sheet, and the leak of water piping.

A length with a short period and a small gap of the IU are being applied for the medium energy SR. Three IUs, two with period length 12.5 mm and the other with period length18 mm, were installed in the NSLS synchrotron light source [3, 14], but the total length is only 0.36 m for period length 12.5 mm and 1 m long for period length18 mm with operating magnet gaps 3.3 and 5.6 mm, respectively. The lifetime decreases only marginally when they are operated at the vertical beta function 0.3 m (in the middle of a straight section) [15]. These IUs are also fabricated for SCSS XFEL (Japan-SPring-8). The magnet length and magnetic period of each segment are 5 m and 18 mm, respectively. The maximum K value, 2.2, is obtained at gap 3.5 mm and the magnet gap can be varied to tune the photon energy over a wide range. The phase shifters were used to adjust the optical phase between the two adjacent undulators.

For a medium-energy facility, an in-vacuum hybrid wiggler (IW) [16-17] was developed to replace the SW when a cryogenic system is lacking. SOLEIL facility decided to investigate the in-vacuum technology to attain the domain of large photon energy. The IW50 can produce 2.1 T at a minimum gap 5.5 mm, but a compensating mechanical system composed of springs had to be developed to minimize the large magnetic forces acting between the magnet arrays (10 tons) in the vacuum.

A cryogenic permanent magnet is applicable for an in-vacuum undulator to enhance the remanence field (B_r) beyond 1.58 T and the coercivity force beyond 3000 kA/m. In this case, the large remanence field enhances the magnetic-flux density and the large coercivity force resists radiation damage and demagnetization. Therefore, the CU will thus be the best potential used for the extremely short period undulator. A CU has been recently constructed for a smaller period length in a light source [2-4]. The optimized temperature for operation of magnet block of NEOMAX50BH should be 135 K so that the deviation of the remanence field and coercivity is less sensitive to the magnet block temperature. The PrFeB-based cryogenic undulator for a laser plasma accelerated e-beam is currently applied also for the Table-top Free-electron Laser (TT-FEL) at Ludwig-Maximilans University. The TT-FEL with 1-GeV electron source is associated with the CU9 [18] at magnet gap 2.5 mm to produce keV photons. The extremely short period with a thinner magnet would allow a greater photon energy but is easily demagnetized. An optimum period length 9 mm with magnet gap 1.2 mm is hence studied [19] and was considered for the FEL facility. A gap variation of the CU induced by thermal shrinkage of the supporting shaft should be adjusted. To compensate the temperature gradient and to correct the resultant increased phase error, a method is proposed at SPring-8 in which the gap variation is corrected by a differential adjuster of the out-vacuum shafts supporting the in-vacuum beam [20]. A measurement system called SAFALI [20], based on laser instrumentation and dynamic feedback of the magnetic sensor position, served to measure the CU. The preliminary results of measurements of the magnetic field show that the field errors are independent of temperature; there is hence no extra phase error when the magnet array is cooled to low temperature. The cryogenic temperature is obtainable with a cryogen-free cryocooler or the liquid nitrogen.

A prototype 2-m long CU16 has been operated at magnet gap 5 mm for more than two years with a beam in the ESRF SR [21]. Measurements of the magnetic field reveal that the field quality differs slightly with temperature gradient, which should be avoided. To maintain a small temperature gradient using a differential adjuster design is thus important so that will be useful to obtain a small phase error. In the future, it is possible to maintain a 2^{o} rms phase error for the construction of CU in a synchrotron light-source facility, and the CU will possibly replace the IU for a future light source.

SUPERCONDUCTING INSERTION DEVICE

Many SWs have been applied for a synchrotron light source. An advanced SW48 [7] with short period length was fabricated by BINP. One has been installed in the CLS and another will be installed in the Diamond light source. The field strength is 4.2 T with period length 48 mm in a pole gap 13.9 mm. Meanwhile, four SW60 [5] with 3.2 T were fabricated by NSRRC and have been installed in the 1.5-GeV Taiwan Light Source (TLS); the operational performance in TLS is excellent [5]. In addition, a SW60 with 3.5 T [6] was installed in Max-II. Three different design philosophies have been done at BINP, MAX-II and NSRRC. NSRRC selected the 100-K aluminium beam duct and an even pole number, whereas BINP and MAX-II selected the 4.2-K stainless-steel beam duct and an odd pole number. Figure 3 presents a schematic drawing of the 100-K aluminium chamber [5].The 100-K aluminium chamber improves the thermal conductivity and decreases the electric resistance of the beam duct. Another benefit of the 100-K aluminium beam duct is that the number of re-absorbed molecules is small and H_2 and CO are not then frozen on the surface when the beam duct is kept over 100 K, but the end-tapered transitions with stainless steel is required to decrease the thermal conductivity. The even pole design prevents a trip of the electron beam when the magnet quenches [5]. The 4.2-K stainless-steel beam duct of the BINP SW was designed with a liner copper strip that was kept at 20 K to reduce the heat load on the beam duct, but MAX-II lacks the liner copper strip. However, the $20\,\mu$m thickness of copper was coated in the S.S. beam duct at MAX-II. The beam-duct design of BINP and MAX-II has a small magnet gap that is 1 mm less than that of NSRRC.

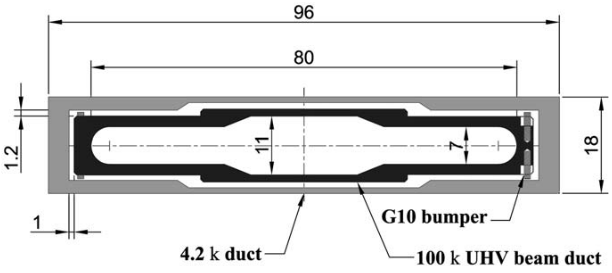

Figure 3: Schematic drawing of the beam-duct design for the NSRRC superconducting wiggler.

Although the technique of a SW with NbTi wire is mature, but for SU it is still a problem. A SU [10] has been installed in the ANKA storage ring. The operating problem is that the SU quenched when the magnet gap becomes small; this quench arises from the induced heat load that heats the coil. NSRRC [9,22] and APS [23] have also launched a feasibility study of a SU. A HeLiCal collaboration in UK has a R&D programme to develop the superconducting helical undulator [24] for the ILC project. The helical SU with period length 11.5 mm at winding bore 6.35 mm can attain 0.86 T. These designs all concentrated to use NbTi wire with an iron pole for the SU. Another helical undulator concept [25] using superconducting wire or a staggered structure is also adopted to provide a helical field.

The heat load on a SU was studied to survey the relative operational issues in the SR. It includes not only power dissipated [9] from the bending magnet radiation but also from the image current of the electron beam and the electron bombardment , and the scattering light on the beam duct [26]. In the long-bunch machine, the main contribution to heat load on the beam duct comes from the electron bombardment [24,26], but the main contribution to heat load on the beam duct in the short-bunch length and the few-bunch operation machine [9,27] will come from the image current. The bending magnet radiation can be decreased with a scraper before an ID and a soft-end design on the dipole magnet. High RRR of the beam duct operated at the long bunch length with a low-frequency RF cavity and the Landau cavity will reduce heat load. A uniform cooling power from a cryogenic system is necessary in the small-gap SU. A recondensing LHe bath cryostat is an effective method of cooling a SU such that the heat load on the beam duct can be rapidly removed by the liquid helium. Present commercial HTS wires including BSCCO and YBCO material have been improved and have the potential to solve the heat-load problem. Although the 1-G and 2-G HTS wire can be operated at the liquid-nitrogen temperature, the critical current density is not comparable to the present LTS wire. The HTS wire still has challenges to improve the critical current density, length of wire, small bending radius, cost and so on. The bending radii of most superconducting wires are larger that creates a problem to make the extremely short period undulator.

The other issue of a SU is the field-shimming problem. Shimming methods were developed at ANKA [28] and NSRRC [29]. The SU of NSRRC was shimmed using iron-shim pieces and a low temperature trim coil. The maximum field correction with this shimming method of iron-shim pieces and trim coil is approximately 2 %. The trim-coil method is much easier in situ to find the optimal current because the current is remotely variable and without opening the cryo-chamber. The method of trim iron pieces is, however, more cost-effective in hardware and no heat loss is caused by the additional current leads of the trim coils from 4.2 K to 295 K, but this method entails a complicated task to execute the warming and cooling of the magnet. The SU of ANKA was shimmed with an array of coupled high-temperature-superconductor (HTSC) loops attached to the surface of the SU. The maximum field correction by the shimming method of HTSC is approximately 1 %. These methods require additional advanced testing to perform the more practical field-shimming tasks.

TRANSITIONAL INSERTION DEVICES

Few transitional out-of vacuum planar insertion devices are still used for recent advanced light sources, such as the planar elliptically polarized undulator (EPU) of the Apple-II structure. The operational performance [30] of the APPLE-II device is satisfactory. The largest APPLE II device UE65 [31] worldwide (5m long) was already installed in the 6-GeV light source PETRA III at DESY, with a small gap 11 mm, to modify the state of polarization. To obtain circularly polarized light, most APPLE II EPU undulators were designed to be operated in a universal mode [32], in which only three rows are moved and provide for any state of polarization [32] and can also vary the field strength [33]. This scheme can be instead of the magnet gap varying to tune the photon energy. This function was successful for the ADRESS beam line at SLS.

Most of the new accelerator facilities have planned the APPLE II EPU, including the institutes of SLS, Soleil, Diamond, ALBA, SSRF, and TPS. Although the APPLE II EPU has the greatest rate of circular polarization, the field roll-off of the two transverse field components decreases rapidly, which is known to be the source of decreased dynamic aperture. A thin shim at the magnet block edge [34] or a non-zero magnetized angle with respect to the vertical axis [35] of the magnet block was thus used to improve the vertical field (B_y) roll-off. The method of an end shim at the magnet edge controls the magnet block performance more easily than the non-zero magnetized angle magnet, but the non-zero magnetized angle magnet provides greater magnetic-flux density. Neither method can improve the field roll-off of the horizontal field (B_x). The other issue of the APPLE II EPU that there is a huge force between two adjacent rows when the phase is altered. The pole number of each sector unit of magnet array will thus have magnet block numbers 5 and 7 to decrease the total force of each sector unit and to install and remove of each sector magnet array easily.

Another issue is that the APPLE II device can't be used to perform the switching of opposite polarization state more rapidly than 1 Hz. The planar electromagnet undulator [36] with an electromagnet/permanent magnet undulator using copper sheets as coil is thus selected for rapid switching to the opposite polarization in insertion devices. In addition, the circularly polarized mode with first harmonic energy of the EPU can provide a small heat load for the beam line if the polarization mode is immaterial for the experiment, but a circularly polarizing quasi-periodic undulator [36] is necessary for circularly polarized light with high harmonic energy. The circularly polarizing quasi-periodic undulator uses electromagnets to generate the vertical field and permanent magnets to generate the horizontal field. Quasi-periodicity can be introduced in the vertical electromagnet field on decreasing the current at the quasi-periodic poles so as to decrease the heat load of the horizontal linear polarization.

Several out-of vacuum planar undulators are still utilized for the energy-recovery linac (ERL) and FEL facility, such as SPARC, FLASH, LCLS. It allows a small electron beam aperture in the horizontal and vertical axes in the ERL and FEL. Each 3.4-m long segment undulator with period length 30 mm (k=3.5) [37] was operated at fixed magnet gap 6.8 mm for LCLS FEL. The taper shims serve to correct the horizontal and vertical trajectories between each segment. The undulator strongbacks are large, highly precise objects made from titanium forgings. The magnets are slightly canted with a 4.5-mrad opening angle, allowing for some k tunability. SPARC XFEL has an undulator (maximum k=2.2) with six permanent sections with 2.8-cm period; the magnet gap can be varied between 25 and 6 mm. The transitional planar undulators are still used in the FEL facility currently.

ADVANCED DEVELOPMENT OF INSERTION DEVICES

The taper undulator can be used to compensate FEL gain degradation that is caused by the energy chirp in a single-pass seeded FEL, such as the NSLS SDL undulator [38]. The difference of magnetic-field strength at both end of the undulator was 5 %. A taper undulator can also provide a greater spectrum bandwidth for x-ray diffraction to obtain more reflection points. However, it seems a difficulty to create a large taper in the in-vacuum undulator. A pure permanent-magnet structure of a Delta undulator [39] with 24-mm period length and 5-mm magnet gap is designed for the Cornell ERL to produce a universal polarization mode on varying the phase to tune the photon energy. To satisfy the vacuum condition, four 0.5-mm wide slits between the magnet arrays provide enough conductance for high-vacuum pumping speed, and the blocks were soldered to copper holders in the vacuum that the outgassing rate is 2.77×10^{-7} Torr litr/s.

A novel concept was proposed to generate an undulator field on stacking in series several HTS superconductor tapes [12]. A flat $YBa_2Cu_3O_{7-\delta}$ (YBCO) tape conductor can be patterned in the superconductor that maintains the current in a defined path using micromachining, lithography or laser techniques. The HTS superconductor tape thereby becomes a competitive application for a short-period undulator with small gap. In addition to the HTS tape, the bulk with HTS superconductor [40,41] was applied for the development of an undulator. The HTS bulk magnets represented by YBaCuO bulk can trap a magnetic field stronger than a permanent magnet, but the magnetization mechanism is the main issue in using HTS bulk magnets. A special mechanism for magnetization must be developed to magnetize the HTS bulk such that the magnetic flux persists inside the bulk material and becomes a permanent magnet through the ‘pinning’ effect.

Either the HTS superconductor bulk or the HTS tape conductor still requires much time to improve the performance of a HTS material to meet the applications in undulator.

CONCLUSION

There are many IUs that have been applied for present insertion devices. CU was developed successfully and will be a mainstream for the advanced medium-energy facility. To match the requirement of high brilliance and wide energy spectrum in the advanced medium-energy facility, the ID design strategy is to use the extremely short-period CU with short-length in the low betatron function section and the long-period CU with long-length in the long straight section. The SU with HTS wire might be used to solve the heat-load problem, but it will depend on the development timetable of the HTS wire. Much time to attain the purpose using LTS wire, HTS wire and HTS tape or bulk is required. Conventional planar helical undulators are still popular for the circularly polarized radiation in the SR, ERL and FEL facility.

ACKNOWLEDGMENT

We thank Dr. H. Kitamura (SPring-8), Dr. T. Tanabe (NSLS-II), Dr. J. Bahrdt (BESSY) and Dr. J. Chavanne for discussing useful concepts and status, and Dr. J. C. Jan, Mr. C. Hs. Chang, Mr. C. M. Wu, and Mr. S. D. Chen for providing valuable information.

REFERENCES

[1] S. Yamamoto, T. Shioya, M. Hara, H. Kitamura, et al., Revi. Sci. Instrum. 63, p. 400 (1992).
[2] T. Tanaka,T. Hara, T. Bizen, T. Seike, et al., New J. Phys. 8, p. 287 (2006).
[3] T. Tanabe, J. Ablett, L. Berman, D. A. Harder, S. Hulbert, et al., AIP Conf. Proc. 879 (2006) p.283.
[4] J. Chavanne, C. Penel, P. Elleaume, Synchrotron Radiation News, Vol. 22, No. 4, p. 34-37 (2009).
[5] C. S. Hwang, C. H. Chang, H. H. Chen, et al., Nucl. Instrum. Meth. A 556, p. 607 (2006).
[6] E. Wallen, G. LeBlanc, and M. Eriksson, Nucl. Instrum. Meth. A 467, p. 118 (2001).
[7] S.V. Khrushchev, V.K. Lev, N.A. Mezentsev, et al., Nucl. Instrum. Meth. A 603, p. 7 (2009).
[8] S. H. Kim, et. al., IEEE Trans. Appl. Supercond., vol. 15, no. 2, p. 1240 (2005).
[9] J. C. Jan, C. S. Hwang, P. H. Lin, and F. Y. Lin, IEEE Trans. Appl. Supercond. Vol.18 , NO.2, p. 427(2008).
[10] S. Casalbuoni, M. Hagelstein, B. Kostka, et al., Phys. Rev. ST Accel. Beams 9, 010702 (2006).
[11] T. Tanaka, et al., Phys. Rev. ST Accel. Beams, vol. 7, 090704 (2004).
[12] S. Prestemon, R. Schlueter, Proceedings of FEL2009, Liverpool, UK, p. 726 (2009).
[13] Private communication with Dr. H. Kitamura.
[14] T. Tanabe, A. Blednykh, D. Harder, M. Lehecka, et al., Proceeding of PAC2005, p.1949 (2005).
[15] Private communication with Dr. T. Tanabe.
[16] X. M. Marechal, T. Bizen, T. Hara, T. Seike, et al., Nucl. Instrum. Meth. A 467-468, (2001) 138-140.
[17] F. Marteau, C. Benabderrahmane, et al., Proceeding of PAC2009, 4–8 May 2009, Vancouver, Canada.
[18] J. Bahrdt, W. Frentrup, A. Gaupp, et al., Proceeding of SRI2009, 28 Sep.–2 August, Australia (2009).
[19] F. O'Shea, G. Marcus, et al. , Proceeding of PAC2009, 4–8 May 2009, Vancouver, Canada.
[20] Takashi Tanaka, Takamitsu Seike, et al., Phys. Rev. ST Accel. Beams 12, 120702 (2009).
[21] J. Chavanne, C. Penel, P. Elleaume, Synchrotron Radiation News, Vol. 22, No. 4, p. 34 (2009).
[22] C. S. Hwang, J. C. Jan, P. H. Lin, et al., IEEE Trans. Appl. Supercond. Vol. 16, NO.2, p. 1855 (2006).
[23] R.L. Kustom, E.R. Moog, et al., Proceeding of PAC2009, 4–8 May 2009, Vancouver, Canada.
[24] Y. Ivanyushenkov et al., Proceedings of PAC07, Albuquerque, New Mexico, USA, p. 2862 (2007).
[25] C. S. Hwang, P. H. Lin, Phys. Rev. ST Accel. Beams Vol. 7, 090701 (2004).
[26] S. Casalbuoni et. al., http://care-hhh.web.cern. ch/CARE-HHH/ECL2/Proceedings/Casalbuoni_ECL 2_1.pdf.
[27] Erik Wallen and Greg LeBlanc, Cryogenics 44, p.879 (2004).
[28] D. Wollmann et al., Proceeding of PAC2009, 4–8 May 2009, Vancouver, Canada.
[29] J. C. Jan, C. S. Hwang, F. Y. Lin, C. H. Chang, P. H. Lin, IEEE T. APPL. SUPERCON. 19 , p.1332 (2009).
[30] C. S. Hwang, C.H. Chang, F. Y. Lin, H. H. Chen, et al., Rev. Sci. Instrum., 73, p. 1436 (2002).
[31] J. Bahrdt, H.-J. Bäcker, et al., proceeding of SRI2009, 28 Sep.–2 August, Australia (2009).
[32] C. S. Hwang, Shuting Yeh, January, Nucl. Instrum. Meth. A 420, p. 29 (1999).
[33] C. S. Hwang, C.H. Chang, T.C. Fan, F.Y. Lin, et al., Nucl. Instrum. Meth. in Physics A399, p. 463 (1997).
[34] C. S. Hwang, C.H. Chang, T.C. Fan, Ch. Wang, et al., Nucl. Instrum. Meth. A 467, p. 114 (2001).
[35] C. S. Hwang, C. S. Chang, et al., IEEE Trans. Appl. Supercond. Vol.18 , NO.2, p. 423 (2008).
[36] R. Dejus, M. Jaski, S. Sasaki, Proceeding of PAC2009, 4–8 May 2009, Vancouver, Canada.
[37] James L. Bailey, Thomas Barsz, et al., Proceedings of FEL08, p. 460 (2008).
[38] T. Watanabe, X. Wang, et al., Proceedings of PAC07, Albuquerque, New Mexico, USA, p.1371 (2007).
[39] A. Temnykh, Phys. Rev. ST Accel. Beams 11, 120702 (2008).
[40] Takashi Tanaka, Toru Hara, and Hideo Kitamura., Phys. Rev. ST Accel. Beams, vol. 7, 090704 (2004).
[41] R. Kinjo, T. Kii, H. Zen, et al., Proceedings of FEL08, Gyeongju, Korea, p.473 (2008).