A PLAN OF SYNCHROTRON LIGHT SOURCE DEDICATED TO MEDICAL APPLICATIONS AT NIRS

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Abstract

A synchrotron light source dedicated to medical applications for practical use at a hospital is planned at NIRS. The system was designed for medical imaging with the synchrotron radiation (SR) for diagnosis of coronary arteries, coronary angiography, with monochromatic x-rays of 33 and 50 keV. The coronary angiography requires higher photon flux than the other applications, such as monochromatic x-ray computer tomography (CT). The conceptual design of the synchrotron light source is based on an electron storage ring with maximum energy of 2.3 GeV and beam current of 420 mA. Combination of the storage ring and a superconducting multipole wiggler is necessary to produce high photon flux required for the angiography. An electron linac of C-band has high electric field gradient. So it could be a good candidate of a injector for downsizing the whole system. Two beamlines of the insertion devices are planned to be used for clinical diagnoses, and other beam lines of bending magnets are prepared for basic experiments to support and develop the medical applications.

1 BASIC IDEAS OF DESIGN

Synchrotron radiation has great advantages of advancing medical diagnostic imaging. We have a plan of construction of a synchrotron light source dedicated to the medical applications at the National Institute of Radiological Sciences. Final goal of the plan is a compact light source to install in a hospital to utilize for medical diagnoses. A typical application of the SR is an intravenous coronary angiography (CAG) using energy subtraction method which has been clinically applied to examinees[1]. Monochromatic x-ray CT plays an important role in advancing heavy ion radiotherapy being done at the NIRS[2]. Advancing x-ray imaging using the SR will help us not only find out a cancer at the early stage, but know the characteristics of the tumor *in vivo* by obtaining more accurately diagnostic information.

One of the most important factor for the design is photon flux required for the various medical applicaitons. We showed estimations of the photon flux required for a few applications as typical cases in Table 1. The photon flux for the x-ray CT and the radiography are estimated based on the entrance surface dose suggested by IAEA[3]. The estimation of the photon flux required for the CAG was reported in detail in the reference[4]. As shown in the table 1, the CAG application requires higher flux than the other applications. The CAG does not require a very small beam emittance. The small beam emittance is necessary for advanced imaging techniques, such as phase contrast imaging. But in the medical applications, most cases require rather than large radiation fields. This requirement is contrary to that of the small beam emittance. Our concepts of design are summarized as follows. The light source should provide enough photon flux for the CAG, which requires higher flux than the other. It is compact as much as possible for practical uses at a hospital. And a small beam emittance is not necessary.

Table 1 Photon flux required for a few applications

Applications	Photon flux (ph/cm^2/sec)	Energy(keV)
X-ray CT	1.7×10^{11}	70
X-ray radiography	1.4×10^{9}	50
CAG (Iodine)	7.8×10^{12}	33
(Gadolinium)	4.3×10^{12}	50

2 DESIGN AND SYSTEM LAYOUT

3.1 *Design parameters and Layout*

The design parameters are listed in Table 2. The system layout is shown in Figure 1.

Table 2 Design parameters

Items	*Designed values*	
Beam energy	2.3	GeV
Beam intensity	420	mA
Circumference	79.7	m
Bending magnet (×8)		
bending angle	45°	
radius	5.11	m
maximum magnetic field	1.5	T
Beam emittance	3.8×10^{-7}	m·rad
Energy loss per turn (total)	1140	keV
RF frequency	508	MHz
RF voltage	3.2	MV
Injector (Linac)		
beam energy	500	MeV
peak current	100	mA
Multipole wiggler (×2)		
number of pole	9	
maximum magnetic filed	7	T
period length	420	mm

The main ring has an electron linac operated in C-band as an injector. The ring has four free straight sections. Two of them are occupied by multipole wigglers, and the other are occupied by beam injection device and acceleration RF cavities, respectively. There are two beam lines from the wigglers and a few lines from bending magnets.

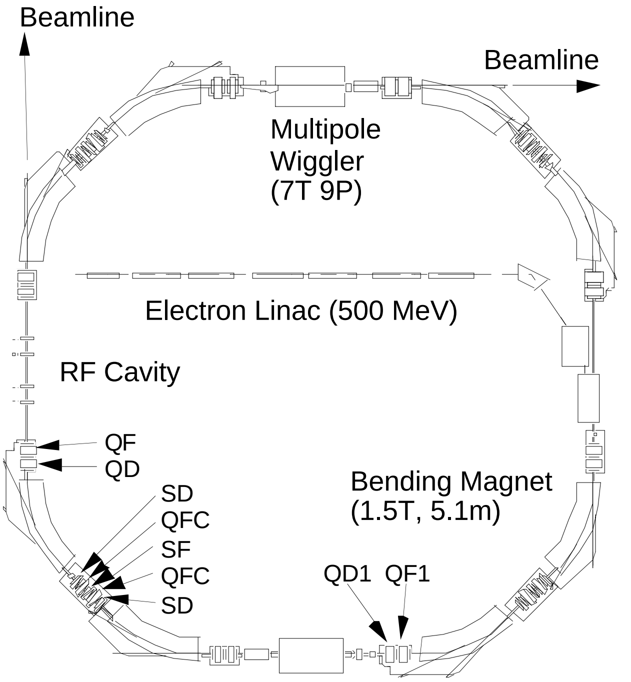

Figure: 1 System layout of the compact synchrotron light source for the medical applications.

3.2 *Electron Storage Ring*

The storage ring has a hexagonal shape with a circumference of 79.7 m. The bending magnets and quadrupole magnets form a double bend achromatic lattice and make a dispersion free at the straight sections in order to make beam size minimum at the superconducting multipole wigglers. The beta functions and dispersion are shown in the figure 2. The wigglers generate strong magnetic field, and they give strong edge focus effect to the electron beam at the straight sections. The quadrupole magnets located at both sides of the wiggler are operated independently with those located at the both sides of another straight section with no wiggler in order to keep β functions symmetry. Their edge effect also changes the beam tunes during increasing the wiggler excitation currents. The strength of quadrupole magnets have to be continuously varied to keep the tunes constant following the wiggler excitation currents. The operating point was searched to find out the best case for stable operation of the ring with exciting no or one or two wigglers. The operating point of $\nu_x=\nu_y=3.25$ gives the minimum changes of the strength of the quadrupole magnets in three different cases of operation mentioned above. This operating point is on a difference resonance line, but this resonance does not affect beam loss. The dispersion is maximized at the short straight sections between the bending magnets, so sextupole magnets are installed there to correct chromaticities of ξ_x / ξ_y = -5.81/-10.1.

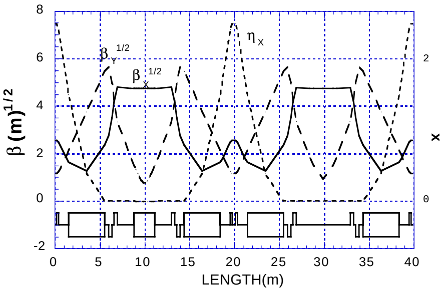

Figure: 2 Beta functions and dispersion of the storage ring.

Dynamic apertures at the multipole wiggler estimated by beam tracking simulation are wider than the physical aperture of the wiggler hatched in the figure 3. The figure is showing in a case of two wigglers operation. In a case of only one wiggler operation, the dynamic apertures become narrower than those in the case of two wigglers operation, but they are still much wider than the physical aperture.

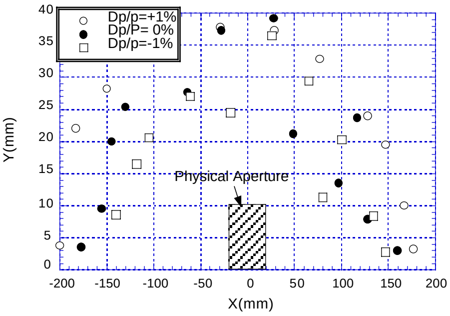

Figure: 3 Dynamic apertures in a case of two wigglers operation.

When the wigglers are operated, the beam emittance will become 0.38π mm·mrad due to radiation dumping. The vertical emittance is 0.04π mm·mrad with assuming the coupling constant to be 10 %. The beam size is estimated to be 2.8 mm × 0.3 mm in the straight sections. A quantum life time is more than 40 hours when the RF peak voltage is more than 3.2 MV. Touchek life time is about 14 hours at 420 mA of 2.3 GeV operation. A life time due to collisions with the residual gases in the ring is about 50 hours under an average pressure of 1.3×10^{-7} Pa. So the beam life time is limited by the Touchek effect.

The radiation loss is 482 keV/turn at the bending magnets and 656 keV/turn at the wigglers. Power density can be estimated about 1.5 kW/cm^2 at the bending sections. In the wiggler magnets the radiation horizontally fans out about 60 mrad. Using a 300 mm wide vacuum chamber of the wiggler, the radiation passes through it without giving any thermal loading to the wall of the chamber. But a thermal dumper must be installed after the exit of the wiggler.

3.2 Multipole wiggler and photon flux

The multipole wiggler is an important component to obtain high flux. The superconducting multipole wiggler is necessary for downsizing the whole system. The design parameters of the wiggler are determined to generate the flux required for the CAG, and to give less contamination of higher harmonic components of 33 and 50 keV which are K-edge energies of x-ray absorption of Iodine and Gadolinium used in contrast materials, respectively.

The wiggler has 9-pole with period length of 420 mm and maximum field 7 T, that gives a critical energy ε_C=24.6 keV at the electron energy of 2.3 GeV. The energy spectra generated by the electron beam of 420 mA at the wiggler and the bending section are shown in the figure 4. The flux densities of 33 and 50 keV x-rays are 1.3×10^{14} photons/sec/mrad/0.1%b.w. and 7.8×10^{13}, respectively. The third harmonic components of 12 % and 3 % are mixed with the 33 keV and 50 keV x-rays, respectively. The contamination of 99 keV x-ray is too much to keep an image quality good for clinical diagnosis. The higher harmonic components of the 33 keV x-ray are rejected by using a mirror as mentioned later.

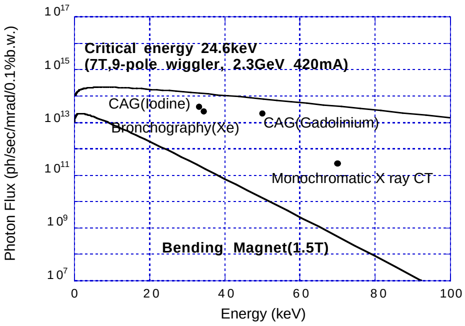

Figure: 4 Energy spectrum of the photon flux generated by the insertion device and the bending magnet.

The magnetic field of the wiggler is increased up to the maximum in about 20 min when the electron beam is accumulated. If we use a superconducting wire which has Nb_3Sn filaments of a few µm diameter, total amount of heat due to AC loss is about 4 W. This is a resonably small number to be cooled down without a large refrigeration system.

3.3 Beam lines for medical use

A beamline from the multipole wiggler is optimized for the CAG. A few beamlines from the bending magnets is planned to be used for basic researches and developments of new technique.

The CAG beamline is composed with a mirror coated with platinum, a monochromator, beam shutter and so on. The Pt coated mirror is installed upstream from the monochromator. It is used to remove the higher harmonic components of 33 keV x-ray. Large silicone crystal of (311) with asymmetry reflection plane can make the fan beam 40 times wider vertically, as well as monochromatize the white light. In this design, the transmission efficiency is about 30 % for 33 keV X ray.

4 SUMMARY

The medical applications of the SR are requiring high energy and high flux of x-rays. The light source designed here is optimized to the energy subtraction CAG using the contrast materials of the iodine and gadolinium. This light source can generate enough photon flux for the other applications, such as the monochromatic x-ray CT. The superconducting multipole wiggler is an important device for the medical applications. But the wiggler makes the ring operation complex due to the strong edge focus of the wiggler. The beamline transmit less than 30 % of x-rays. Therefore the highly efficient beamline may be able to downsize the whole system.

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