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COMPACT ACCELERATOR LIGHT SOURCE FOR INDUSTRIAL APPLICATIONS *

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Abstract

Synchrotron radiation has great application potential in industry. However, the large scale of modern light source has limited it from popular use. Compact accelerator light source has many virtues such as small scale, cost effectiveness, maintenance convenience, etc., which make it a main solution of light source application in industry. The idea has attracted great interests from many institutes, and much effort has been put into its research and development. In this paper we present a design of compact accelerator light source with very small scale. The lattice is very simple to ensure its compactness, while the beam parameters remain flexible to industry needs.

INTRODUCTION

Synchrotron radiation was considered as byproduct of colliders in the past and turned to be a powerful tool in scientific research after the discovery of its merits in light spectrum, brightness, polarization, collimation, etc. Light sources have been widely used as a large research platform for scientists, and numerous achievements have been made with the help of synchrotron radiation.

A light source typically consists of an injector, a storage ring, some beamlines and experiment stations. To satisfy the needs of users, light sources are usually built in a large scale to accommodate various types of beamlines for research in different scientific fields. Such a large facility costs rather great, and funding from government is a routine approach.

Industrial applications of synchrotron radiations attract great interests as well. And some compact light sources were built in a research institute for industrial users or in an industrial enterprise. Most industrial applications are in medicine, pharmacy, chemistry, mechanics, and food industry. Some new applications such as EUV lithography are under exploration.

INDUSTRIAL APPLICATIONS

Industrial application is a direct way for synchrotron radiation to benefit the society and improve people's life quality. With rapid growth of industrial demand, various applications of synchrotron radiation have been developed.

Medical Applications

High energy photos can be used in the medical industry in many aspects including physical examination, cancer treatment, pharmacy and so on. X-ray is one of the most common ways for health checkup, and it is also a main part in the spectrum of synchrotron radiation. Gamma ray, which can be radiated from a compact accelerator using techniques such as Compton backscattering, has been used to break the DNA inside cancer cells, stop cancer from growing and cause its death eventually.

In hospitals synchrotron radiations from compact accelerators can be used for medical treatment, while pharmacy industry can use high intensity synchrotron radiations to improve efficiency of medicine research and development. X-ray has been used for protein structure analysis, and new medicine can be developed more efficiently. Another application of X-ray in medicine industry is to reform the drug particles and to conduct a proper distribution of different components.

Chemical and Mechanical Industry

Catalyst plays an essential role in chemical industry, and synchrotron radiations can help to develop and manufacture high-efficiency kind. Other important applications of synchrotron radiation in chemical industry include material characteristics improvement etc. Using X-ray to detect flaws in solid object is a common approach for its merits such as flexibility, damage-free, and so on.

Radiation Sterilization

Sterilization can help to preserve food for a long time. Radiation can be used to sterilize the products of food industry in a rather quick and easy-to-tune manner. Compact accelerator is a good option to provide radiations the food industry needs.

EUV Lithography

Synchrotron radiation as a solution of light source for EUV lithography has been under exploration for years. Comparing to LPP (Laser-Produced Plasma) and DPP (Discharge Produced Plasma) light sources, compact accelerators can provide EUV light with high density and high collimation without pollution from metal particles or plasma ions.

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TYPICAL FACILITIES

The scale of light sources for industrial applications varies from tens to hundreds of meters. And here we focus on the compact accelerators below 50 meters.

A typical compact accelerator light source is the Metrology Light Source (MLS) [1], open to users since 2008, mainly for applications of radiometry and technological development. The 48-m storage ring consists of 4 DBA cells. The injection is accomplished with an orbit bump covering half of the storage ring.

COSAMI [2] was proposed in 2017 as an EUV metrology source. The storage ring has a circumference of 25.8 meters and consists of two 5BA cells. High flux EUV light is radiated from an undulator with 16-mm period and 0.42-T magnetic field.

Here we present a compact accelerator light source with tow DBA cells (Fig. 1). The circumference of the ring is less than 30 meters, and two 5-m straights can be used to accommodate undulator, RF cavity and injection complex. The general design principles of compact accelerator and specific choice of our design is discussed in the following sections.

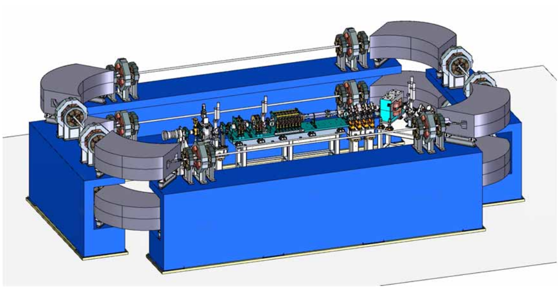

Figure 1: A design of compact accelerator light source.

COMPACT RING LATTICE

The double bend achromat (DBA) has been the most successful and widespread lattice used for third generation synchrotron-based light sources. Using a DBA structure in a compact storage ring light source will result in significant horizontal dispersion due to the large bending angle of each dipole. Large horizontal dispersion generally leads to smaller energy acceptance, resulting in lower Touschek lifetime. However, a larger dispersion is beneficial for reducing the strength of sextupoles used for chromaticity correction, thereby weakening the nonlinearity introduced by sextupoles.

The emittance of the electron beam is proportional to the cube of the bending angle of the dipoles. Therefore, the triple bend achromat (TBA) lattice has the potential for lower natural emittance than the DBA lattice. Under the same conditions, TBA produces smaller dispersion than DBA, which will result in a greater intensity of the sextupoles used to correct chromaticity.

Small emittance demands strong focusing quadrupoles for stable beam dynamics and strong quadrupoles provoke large natural chromaticity in both transverse planes. Correcting large chromaticity demands strong sextupoles which produce strong nonlinear effects leading to issue such as shrunken dynamic aperture (DA) and reduced beam lifetime. To mitigate the strong nonlinear effects, two classic lattice types have emerged, a hybrid MBA (HMBA) and a higher-order achromat (HOA). In the HMBA cell, the sextupoles are located in the two dispersion bumps at both sides of the cell, with sextupoles of each family separated by a −I transformation to cancel part of their nonlinear effects. While, in the HOA cell chromaticity-correcting sextupole magnets are distributed in each unit cell with strict phase advances over the cell such as to cancel basic geometric and chromatic resonance driving terms.

In ref.[3], a torus knot type storage ring that the beam orbit is not closed with one turn but return to the starting point after multiple turns around the ring has been proposed. If this type of lattice is adopted for a light source ring, many insertion devices can be installed for the use of synchrotron radiation and some new experimental techniques become available which could not be used in a small storage ring.

In our design, we used the simplest DBA structure, with only four focusing quadrupoles (two families) in a cell, and the defocusing force was provided by the edge field of the dipoles. Thanks to the low energy of the electron beam and large bending angle of the dipoles, the edge field of the dipoles is sufficient to provide the defocusing force required for stable beam motion. Due to the use of weaker focusing in DBA resulting in small phase advance, the correction of chromaticity between sextupoles does not meet the -I transformation. Therefore, we used two additional sets of harmonic sextupoles to optimize nonlinearity effects. Finally, the optimized dynamic aperture and beam life meet the design requirements.

INJECTION

For compact storage rings, injection must be accomplished in a small space under a simple scheme with cost-effective considerations. Available methods involve pulse quadrupole/sextupole magnet (PQM/PSM) [4,5], non-linear kicker (NLK), strip line kicker, deflecting cavity, etc. Here we give a possible approach using NLK.

The NLK injection scheme (Fig. 2) is somewhat like traditional orbit bump injection except there is no orbit bump. The NLK injection scheme typically consists of one NLK instead of four kickers in traditional orbit bump injection scheme, hence the NLK injection requires less space for the kicker and removes the complication of synchronizing four pulsed kicker magnets.

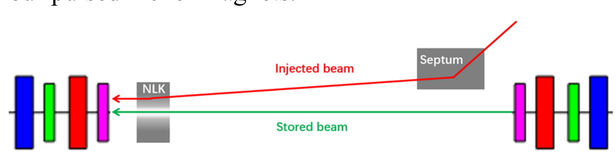

Figure 2: NLK injection scheme for compact test ring.

The NLK provides a nonlinear distribution of magnetic fields which has a maximum value off axis where the injected beam arrives and a zero or near-zero value at the centre where the stored beam passes by. Therefore, the injected beam will receive a kick from NLK and lose its transverse momentum and will be eventually captured by

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the storage ring. In the meantime, the stored beam at the centre will receive no kick or slight kick, which significantly reduces the injection perturbations on the stored beam.

TRANSPORT LINE

The transport line of the compact light source is used to transfer the beam from the injector or pre-accelerator to the storage ring or the next accelerator with more similar design comparing to general light source transport lines. The design goal is to minimize the loss of the beam on the transport line. Unlike general light source, the compact light source has greater restrictions on space layout. It is necessary to have high transport efficiency and high matching flexibility in a limited space, which is the main challenge of compact light source transport line design. When designing a compact light source transport line, the requirements must be put forward according to the actual situation and the beam conditions. The optimization calculation method is then used by appropriately adjusting the geometric and/or electromagnetic parameters of the transport line element. In order to reduce the difficulty of engineering implementation, the transport line design needs to control the magnet strength within a certain range. According to fit the requirements, the long transport line can be divided into multiple segments by different functions. The common magnetic focusing structure of the transport line is usually FODO or FODO-like, containing horizontal or vertical dipoles, several focused and defocused quadrupoles, which matches the beam twiss parameters. To achieve compact layout, high magnetic field strength and tight dividing space is a common choice.

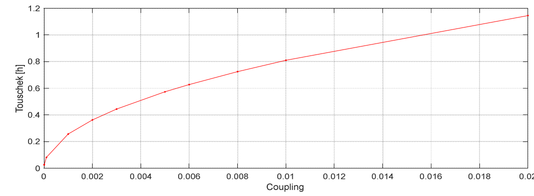
COLLECTIVE EFFECTS

High beam current improves efficiency for industrial applications. However, collective effects will be a challenge, especially for a low-energy compact accelerator.

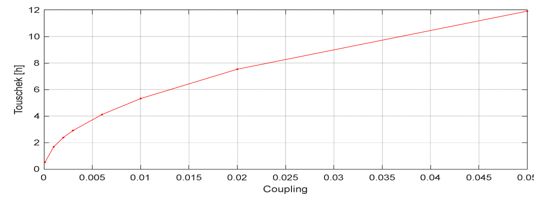
Touschek effects dominate the beam lifetime. As the beam current increases, the Touschek scattering gets stronger and reduces beam lifetime significantly. Compromise between high beam current and sufficient beam lifetime must be considered. A common way to increase the beam lifetime is to increase the beam size. High hormonic cavity can be used to lengthen the beam in longitudinal plane. Coupling between horizontal and vertical plane can also significantly affect the beam lifetime. Figure 3 illustrates the calculation of Touschek lifetime under different coupling.

The intra-beam scattering (IBS) effect can cause growth in emittance and energy spread, which decreases the performance of a light source. A proper design should involve comprehensive considerations including IBS effect. For the 30-m test ring, the growth rate due to IBS effect is shown in Fig. 4.

Other effects should also be examined carefully. For example, coherent synchrotron radiation (CSR) effect can cause micro-bunch instability (MBI). Various measures such as Landau damping are used to handle these collective effects.



(a)



(b)

Figure 3: Touschek lifetime under different coupling (a) 30-m test ring with 100mA beam current (b) 100-m test ring with 1000mA beam current.

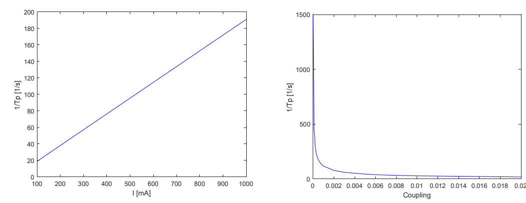


Figure 4: Growth rate of IBS effect (a) coupling 0.6% (b) beam current 200mA.

CONCLUSION

We give a brief review of the industrial needs and applications of synchrotron light sources based on compact accelerators. Typical facilities and a design with simple DBA lattice is presented. The general design principles and specific design choice of the simple-DBA one are discussed, including storage ring lattice, injection scheme, transport line design and collective effects.

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