Available online at www.sciencedirect.com
ScienceDirect
Nuclear Instruments and Methods in Physics Research A 592 (2008) 1–8
NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH Section A
www.elsevier.com/locate/nima

Lattice design and beam dynamics in a compact X-ray source based on Compton scattering

Peicheng Yu*, Wenhui Huang

Department of Engineering Physics, Tsinghua University, Beijing 100084, PR China

Received 15 October 2007; received in revised form 20 March 2008; accepted 21 March 2008
Available online 4 April 2008

Abstract

We present a feasibility study of a particular X-ray source based on Compton scattering. In particular, we focus on the pulse mode of its operation, in which electron beams are injected with the frequency of 50–60 Hz. We propose to construct a compact storage ring with a circumference of 12 m, as well as a lattice to provide stable operation in the pulse mode for electron–laser interaction. We develop a computer code to simulate beam dynamics in the pulse mode. Intra-beam scattering and Compton scattering are included in the simulation, and their effects on beam emittance and stability are discussed. This source provides X-ray beam in the pulse mode with an intensity of $\sim 1.7\times10^{12}$ photons/s and spectral brightness of $\sim 10^{10}$ photons/s/0.1%BW/mm^2/mrad^2 in the energy range from 20 to 80 keV. These parameters meet the requirements for angiography as well as other technological and scientific applications that require high brightness and pulse nature of X-ray.

Keywords: LESR; Compton scattering; X-ray; Beam dynamics; Lattice design

1. Introduction

Hard X-rays of 20–80 keV are now very useful for biological and medical applications. Currently, there is a growing interest in developing compact hard X-ray sources based on Compton scattering. The idea of utilizing the laser-electron storage ring (LESR) for the purpose of increasing frequency and luminosity of hard X-rays by means of Compton scattering was proposed by Huang and Ruth in 1998 [1]. The basic principle of this scheme is Compton scattering off a low-energy electron beam stored in a storage ring with an intense laser pulse stored in an optical storage system to produce the desired photon spectrum. In a head-on collision, the maximal scattered photon energy can be represented by $E_{\gamma,\ \max}=4\gamma^2E_{\rm las}$, where γ is the relative energy and $E_{\rm las}$ is the energy of the laser photon. The micropulse length of the scattered photon is almost the same as that of the electron beam. For its compactness and low construction cost, this scheme is an alternative proposal to the traditional method of generating X-ray photons using a superconducting wiggler on synchrotron radiation source.

In this proposal, the main dynamic features of the electron beam involve Compton scattering (CS), synchrotron radiation (SR), and intra-beam scattering (IBS). Due to the quantum nature of Compton scattering, quantum excitation which increases beam emittance should be taken into consideration in ring design. Likewise, IBS becomes a significant factor for emittance growth when the beam energy is a few MeV to a few hundred MeV.

There are two basic schemes for the LESR [2]. The first scheme keeps beams in the ring until steady-state parameters are reached [3,4]. In such a storage ring, the long-term stability of photon intensity can be achieved. The LESR in this scheme is designed with a controlled momentum compaction factor, by means of which one can achieve large energy acceptance and keep the long-term stable motion of electron beam with large energy spread. The intensity of the X-ray is stable due to the use of an electron beam with steady-state parameters.

The second scheme uses non-steady-state parameters of electron beams. In this scheme, beams are injected more frequently and dumped before steady parameters are

*Corresponding author.
E-mail address: tpc02@mails.thu.edu.cn (P. Yu).

0168-9002/$ - see front matter © 2008 Elsevier B.V. All rights reserved.
doi:10.1016/j.nima.2008.03.114

reached in the ring [5]. Due to periodic injections of electron beam, the ring produces X-ray in the pulse mode. Compared with the steady-state mode, the pulse mode has certain advantages. Damping time of such compact storage ring is of the order of 1 s, thus, the electron beam parameters are close to the initial values rather than steady-state values when they are dumped. Since electron beam parameters deteriorate in the ring, we obtain a higher intensity of scattered photon if beams are dumped long before they reach steady-state parameters. Another reason is that from the simulation results of this paper, longitudinal beam size is the bottleneck of stable operation. Hence, long-term stability requires low momentum compaction factor, which makes lattice design of LESR more difficult. The pulse mode is able to avoid this problem, because electron beams are dumped before their longitudinal size become too long for stable operation.

We discuss this pulse mode in this paper and present a lattice design for the scheme. We likewise present theoretical analysis and numerical simulation for beam dynamics involving Compton scattering, synchrotron radiation, and intra-beam scattering.

2. LESR lattice design

2.1. Main requirements

In the laboratory frame, the number of photons, N_x, generated in collision between a laser pulse and an electron pulse is determined by the following expression, assuming that electron beams and laser density have Gaussian distribution [13]:

$$N_x = \frac{\sigma N_e N_\gamma}{2\pi\sqrt{\sigma_{ey}^2 + \sigma_{ly}^2}} \times \frac{1}{\sqrt{(\sigma_{ex}^2 + \sigma_{lx}^2)\cos^2(\alpha/2) + (\sigma_{ez}^2 + \sigma_{lz}^2)\sin^2(\alpha/2)}} \quad (1)$$

where σ_{ex}, σ_{lx}, σ_{ey}, σ_{ly}, and σ_{lz} are the RMS transverse and longitudinal sizes of beam and laser pulse, respectively; N_e and N_γ are the number of electrons and the number of laser photons in a single pulse, respectively; α is the collision angle, with $\alpha = 0$ corresponding to head-on collision; and σ is the Compton Scattering cross-section.

We can see from Eq. (1) that in order to achieve a high quantity of scattered photons the transverse beam size at the interaction point (IP) should be adequately small, which means the beta function should be small at IP. Hence, with low beta insertion involved, the natural chromaticity of the storage ring becomes significantly large and strong sextupoles are placed in the dispersive area to correct chromaticity. The dynamic aperture of the ring is diminished as a result.

In order to implement a head-on collision, we have to place a hole in the center of each mirror of the optical system to allow the electron beam to go through it, which makes it more difficult to build the optical system. When head-on collision is difficult to realize, a small collision angle is necessary, which makes the term $({\sigma_{ez}}^2 + {\sigma_{lz}}^2)\sin^2(\alpha/2)$ a significant part that determines the total yield of scattered photons. Therefore, longitudinal beam size should necessarily be short for the optimization of the photon yield. Longitudinal beam size σ_{ez} is determined by the following expression [2]:

$$\sigma_{ez} = \sqrt{\frac{\alpha_c h E_e}{2\pi e V_{RF}|\cos\phi|}}\lambda_{RF}\delta \quad (2)$$

where α_c is the momentum compaction factor, h is the harmonic number, and δ is the total energy spread; λ_{RF} and V_{RF} are the wave length and voltage of the RF cavity, respectively; and E_e is the energy of electron. From Eq. (2), we can see that a small momentum compaction factor is important when designing the LESR lattice [2].

For on-axis single-turn injection, we plan to use a traveling wave design kicker and a Lambertson-style septum for the injection scheme [5]. As a result, we need one long dispersion-free straight section where we will place the injection system. The RF cavity as well as IP should also be placed into the dispersion-free section to achieve stability. Hence, the lattice should have long dispersion-free straight sections.

As such, the lattice designed for the LESR should have the following features:

- The IP should have low beta function.
- The lattice should have a long dispersion-free section in which to place the injection system, RF cavity and IP.
- Strong sextupoles are introduced to correct the natural chromaticity of the storage ring; therefore, the dynamic aperture should be compensated using harmonic sextupoles.
- The photon yield depends strongly on longitudinal beam size in non-head-on collision; hence, a small momentum compaction factor is necessary in order to achieve high yield of scattered photon.

2.2. The LESR lattice

The most common scheme for the LESR is a racetrack design with two long straight sections [2,5]. The placement for our LESR is illustrated in Fig. 1. This scheme is based on the lattice design for the NESTOR ring in Ukraine [2].

The injection system is placed in one straight section, while the IP and RF cavity are placed in the opposite one [5]. We use the typical DBA structure with two quadrupoles in the arc area, and in this way it becomes convenient to place sextupoles in the dispersive section.

The circumference of the ring is 11.92 m. There are 4 bending magnets, 16 quadrupoles, and 10 sextupoles. Bending radius is 0.38 m and bending angle is 90°. The