Low energy electron storage ring with tunable compaction factor

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A low energy electron storage ring is designed to have many desirable properties, such as varying momentum compaction factor, damping partition numbers, favorable betatron tunes for multturn accumulations, and excellent dynamic aperture. This storage ring can be used for debunching rf linac beams in one turn, for compression of linac pulses, and more importantly for a compact photon source based on inverse Compton scattering of laser beams. © 2007 American Institute of Physics. [DOI: 10.1063/1.2754393]

I. INTRODUCTION

The cooler injector synchrotron (CIS), built in 1998 and decommissioned in 2002 at the Indiana University Cyclotron Facility (IUCF), could accelerate proton beams from 7 to 240 MeV. The CIS was made of four-dipole magnets in fourfold symmetry with a circumference of $C=17,364$ m. The dipole magnets had a vertical gap of 58.2 mm and an effective length of 2 m, or the bending radius of $\rho=1.273$ m. The horizontal focusing was derived from $1/\rho^2$, and the vertical focusing was attained from the $12^\circ$ edge angles on each dipole. This concept of accelerator design was extended beyond a proton kinetic energy of 300 MeV in a racetrack design to accommodate both slow and fast extractions in a compact medical synchrotron (CMS) design.

After the decommissioning of the CIS, the four-dipole magnets were stored in a warehouse. Recently, there is a call for using these magnets for the design of an electron storage ring, which can provide radiation effect experiments for NASA, and more importantly, it can also provide a compact x-ray photon source based on inverse Compton scattering with high power laser pulses. There are a number of projects on inverse Compton scattering x-ray (ICSX) sources (see Ref. 3 for a review of this subject). Many ICSX sources use rf linacs as a driver for electron beams which have the desirable properties of short bunch length and small emittances. The difficulties with the linac driver is that the orbit jitter becomes important when the beam size is squeezed to the order of $10 \mu m$ in order to achieve its x-ray flux and brilliance.

On the other hand, an electron storage ring will provide a more stable, higher efficiency driver for the ICSX. The difficulties in a low energy electron storage ring are a long damping time, a negative horizontal damping partition, space charge effect, and beam lifetime issues. The advantages of the low energy electron storage ring are its low cost, easy operation, and availability to a local science community for electron beam and photon beam experiments. The success of this design can serve as a prototype accelerator for other similar facilities.

This article provides a detailed design concept, issues, and their technical solutions for using the existing CIS dipoles for a compact electron storage ring. Typical operational electron beam energy is between 20 and 100 MeV, while the maximum achievable electron energy of this accelerator is 600 MeV. In Sec. II, we discuss the properties of the basic magnetic lattice, rf cavity requirements, properties of the available cavity in house, effect of the vacuum pressure on the beam emittances, beam lifetime, and dynamic aperture. The expected performance of the compact x-ray photon source is given in Sec. III. The conclusion is given in Sec. IV.

II. THE STORAGE RING DESIGN

Using the four existing CIS bending dipole magnets ($\rho=1.273$ m, $L=2$ m), we design an electron storage ring that can debunch rf linac beam bunches in the steady state mode of operation and compress linac pulses in the transient mode of operation. The horizontal and vertical focusings of the beam motion in the original CIS are derived from $1/\rho^2$ and edge angle of $12^\circ$, respectively. The difficulty of using this accelerator as an electron storage ring is its negative horizontal damping partition number, i.e., the horizontal betatron motion becomes unstable. Modification is needed in order to change the horizontal damping partition.

The damping partition can be changed by (1) redesigning the main dipole magnets with a defocusing gradient, (2) using Robinson wigglers, (3) adding focusing quadrupoles to modify the dispersion function in the dipoles, or (4) adding focusing wigglers in the straight sections. It would be costly to build new dipole magnets, and even more for new combined function dipoles, and thus we give up this path. The Robinson wigler can change the damping partition, however, it is not very effective. Adding quadrupole magnets in a straight section can also change the damping partition. But, the most effective method of changing the damping partition is installing focusing damping wigglers in the straight sections. An advantage of using damping wigglers is that the dispersion function can be changed in the main dipoles and thus create a lattice with a tunable momentum compaction factor. If properly designed, the damping time of the horizontal motion can be reduced to less than 1 min at 25 MeV and less than 10 s at 50 MeV.
A. The accelerator lattice

The lattice with just the four bending dipoles has unstable horizontal motion with a negative horizontal damping partition $J_x = -0.3$. Two sets of three-magnet wigglers are inserted in the ring at opposite sides to provide a negative dispersion function in the dipoles so that the horizontal damping partition can be varied from a negative to a positive number.

The resulting lattice is composed of four dipoles at the four corners interconnected by four straight sections of length of 3.0 m, and two sets of focusing damping wigglers in the center of opposite sides. The set of damping wigglers is made of three gradient rectangular dipoles with $B_1/B_0 = 1.9$ m$^{-1}$, where $B_1 = (dB_z/dx)_{x=0}$ and $B_0 = B_z(x=0)$. The circumference is 20 m. The revolution period is 66.6 ns. Figure 1 shows the betatron amplitude functions of the lattice, where the bending radius of the damping wigglers is $\rho_w = 0.75$ m. At this wiggler field strength, the momentum compaction factor is nearly 0. The damping times, damping partition, and momentum compaction factor are functions of the field strength of the damping wigglers.

The choice of the accelerator circumference arises from the need of ease of injection and extraction of electron beams, available chicane magnets for ICSX photons, and enough space for the CIS cavity, which is of the order of 1 m in length. With a circumference of 20 m, all conditions are met. A small betatron amplitude function at IP can provide higher photon flux and brilliance, and for our machine the horizontal betatron amplitude function is about 0.82 m at the IP.

The accelerator lattice functions can be tuned by changing the wiggler field strength. Figure 2 shows the $\nu_x$, $\nu_z$, $J_x$, and $\alpha_c$ versus the bending radius of the damping wigglers. The focusing gradient of the wiggler magnets $B_1/B_0$ is chosen so that the betatron tunes do not encounter major linear and nonlinear resonances. In particular, we would like to avoid resonances at $\rho_w = \infty$, i.e., the condition that the wiggler field is off. When the focusing gradient is larger the vertical betatron tune will be pushed near the half-integer; when the gradient is smaller, the vertical tune will be pushed to the integer unit at small $\rho_w$ values. The value of $B_1/B_0 = 1.9$ m$^{-1}$ is obtained by these conditions with dynamical aperture trackings.

The momentum compaction $\alpha_c$ can vary from $-1$ to 0.58 by changing the field strength of the damping wigglers; in particular, the momentum compaction factor is nearly zero at $\rho_w = 0.7-0.8$ m. By adjusting the momentum compaction factor to a value $|\alpha_c| \geq 0.5$, a linac beam can be effectively debunched of its rf structure in one turn. In this mode of operation, the entire storage ring works as an $\alpha$ magnet for beam debunching.

Since the horizontal betatron tune is about 1.75–1.8, electrons can be accumulated from linac pulses, if the orbit bumpers are properly programed. Our numerical simulations show that a 10–15 injection-turn accumulation is possible depending on the septum thickness and the horizontal aperture of the electrostatic kickers. Accumulation of linac beams can provide high charge electron bunches.

Since the momentum compaction can be adjusted to 0, we can study the beam dynamics at the quasisynchronous condition, which is relevant to future high energy and condensed matter physics projects. The vertical damping time is reduced by about a factor of 2 with the damping wigglers at $\rho_w = 0.5$ m. The horizontal damping partition $J_x$ is positive at the $\rho_w \leq 2.0$, i.e., the horizontal damping time can be adjusted by varying the field strength of the damping wigglers. The resulting damping times and the horizontal natural emittance at 25 MeV is shown in Fig. 3. The energy scaling of the damping time and the natural emittance are $1/\gamma^3$ and $\gamma^2$, respectively, where $\gamma$ is the Lorentz factor of the electron beam.

B. Beam injection and extraction

Since the horizontal phase advance across a straight section has been designed to be $\pi$, one can use two kickers to
The accumulated beam can be extracted up to about 50 ns, where a 10 ns kicker rise time is assumed. Tron bunches can also be accumulated. In this scheme, one can debunch the rf structure of the rf linac beam.

Traveling wave kickers and electrostatic kickers are both feasible. These kickers can have a rise/fall time within 10 ns. Thus the injected beam can have a bunch length up to about 50 ns. Using electrostatic kickers, the kicker angle is given by

$$\theta = \frac{E_{\text{kick}} L_{\text{kick}}}{\beta c (B \rho)}$$

where $L_{\text{kick}}$ is the length of the kicker and $\beta c$ and $B \rho$ are the speed and the momentum rigidity of the beam, respectively.

For injection and extraction, the beam must clear the adjacent dipole magnets and the Lamberton magnet must provide 0.53 rad angular kick, i.e., $B_0 \ell_{\text{sept}} (T \text{m}) = 1.6 [\text{pc GeV}]$. For electron beam at 60 MeV, the integrated septum field strength is less than 0.10 T m.

### C. The rf system and lifetime

For a circumference of 20 m, the revolution frequency of the beam is 15 MHz. In the operational mode of rf linac debunching or beam compression (accumulation), no cavity is needed. For beam physics studies with quasi-isochronous condition, we can use an available cavity with harmonic number $h=1$, i.e., the cavity operates at a frequency of 15 MHz.

The original CIS cavity was built for proton acceleration with frequency from 2 to 10 MHz. The quarter-wave-like cavity is loaded with ten ferrite rings with quadrupole field bias. Major rf tuning is achieved by parallel external capacitors. With an external capacitance $C_{\text{ext}}=290 \text{ pF}$, the cavity was tested up to 11.4 MHz where the resulting shunt impedance was about 1 kΩ. For 15 MHz operation, we need to reduce the external capacitance to about 120 pF or the number of ferrite rings in the cavity. By reconfiguring the ferrite rings, we may maximize the shunt impedance for a possible 3 kV cavity voltage. In the future, we will build a 90 MHz rf cavity for harmonic $h=6$ in order to achieve a bunch length of the order of 10 ps for short-pulse x rays.

The Touschek lifetime is an important issue for all low energy electron storage rings. The Touschek lifetime is sensitive to the parameter

$$\xi = \left( \frac{\Delta \rho}{\gamma \sigma_{px}} \right)^2,$$

where $\Delta \rho$ is the bucket height and $\sigma_{px}$ is the horizontal momentum width. The operational parameters of the accelerator can be varied to change the $\xi$ parameter from order 1 to order.
10\(^{-3}\). Since the Touschek lifetime has a minimum at \(\xi=0.03\), this accelerator is a sensitive laboratory for detailed study of the physics relevant of the Touschek lifetime.

For normal operation of this storage ring, we will need a lifetime of 1 h or more. Figure 5 shows the expected Touschek lifetime and the bunch length as a function of the rf voltage for harmonic numbers \(h=1\) and 6. However, since \(\xi \sim V_{\text{rf}}/\left(\left|\alpha_c\right|g\epsilon_s\right)\), the Touschek lifetime can also be varied by changing the momentum compaction factor \(\alpha_c\).

**D. Vacuum**

Beam gas scattering is another source of emittance dilution. The emittance evolution equation can be expressed as

\[
\frac{d\epsilon}{dt} = -4\alpha_e + G + gP,
\]

where \(\alpha\) is the radiation damping rate or the inverse of the damping time, \(G\) is the quantum excitation due to photon emission, \(P\) is the vacuum pressure, and the constant \(g\) depends on the vacuum decomposition, energy of the particle, and betatron amplitude functions. The damping rate is proportional to \(\gamma^2\), the quantum fluctuation is proportional to \(\gamma^2\), and the pressure diffusion rate is proportional to \(\gamma^2\).

The equilibrium emittance is achieved at \(d\epsilon/dt=0\):

\[
\epsilon = (\gamma/\gamma_0)^{\frac{\alpha}{2}}\epsilon_0 + \frac{g_1}{(\gamma/\gamma_0)^{\frac{1}{2}}}P_g \text{ (nTorr),}
\]

where \(\epsilon_0\) is the natural emittance at \(\gamma_0\) and \(g_1 = 9.2 \text{ \mu m}\), assuming a vacuum composition of 60% H\(_2\) and 40% CO\(_2\). Choosing \(\gamma_0 = 48.9\) for 25 MeV electron beam energy, we can calculate the equilibrium emittance as a function of energy. Figure 6 shows the equilibrium emittance with \(\epsilon_0 = 11 \text{ nm at 1% vertical emittance coupling}\). The emittances are dominated by the vacuum pressure at low energy and become the natural emittances at high energy.

**E. Dynamic aperture**

Generally, the dynamic aperture depends on the betatron tunes and nonlinear magnetic fields. Since the betatron tunes are far from major systematic resonances, we expect that the dynamic aperture will not be a problem. Since the betatron tunes are far from major resonance lines, the dynamic aperture is more than ±10 cm. All of our dynamic aperture calculations include typical systematic sextupole strengths in dipoles.

**III. COMPACT PHOTON SOURCE**

We have designed the storage ring with varying momentum compaction factor, which can be used as a debuncher for rf linac beams and as a compressor of linac pulses. The high brightness electron beams can also provide the important function of an ICSX photon source.

The x-ray source is derived from the scattering of a laser beam pulse by relativistic electrons at the chicane magnet system shown in Fig. 1. The energy of the scattered photon is

\[
E_x = E_l \frac{1 - \beta \cos \theta^*}{1 + \Delta - \beta \cos \theta},
\]

where \(E_l\) is the laser beam energy, \(\beta c\) is the speed of the electron beam, \(\theta^*\) is the crossing angle of the laser and electron beams, \(\theta\) is the angle of the scattered x-ray photon with respect to the electron beam direction, \(\Delta = E_l (1 - \beta \cos (\theta - \theta^*)) / E_x\) is a small correction term, and \(E_x\) is the electron beam energy. For a head-on collision, \(\theta^* = \pi\). The scattered x-ray photons are confined to a cone of 1/\(\gamma\) with respect to the electron beam direction and have tunable energy by changing the electron beam energy or the angle of the x-ray photon with respect to the electron beam direction.

The bending angle of the chicane magnet can vary from zero to 110 mrad. The scattered x ray can easily be separated from the circulating electron beam at a distance 25 cm from the collision point.

The x-ray flux is given by
\[
\frac{dN_x}{dt} = \mathcal{L} \sigma_T,
\]
where \(\sigma_T = (8\pi/3)\epsilon_0^2\) is the Thomson scattering cross section and \(\mathcal{L}\) is the luminosity of the electron-photon scattering. For head-on collisions, the luminosity is
\[
\mathcal{L} = \frac{N_e N_l}{4\pi \sigma_T \epsilon_0^2},
\]
where \(f\) is the encountering rate, \(N_e\) is the number of electrons per bunch, \(N_l\) is the number of photons in a laser pulse, and \(4\pi \sigma_T \epsilon_0^2\) is the effective overlap area where laser and electron beams interact.

For x-ray production, we will consider the \(h=6\) cavity operation so that the bunch length of the electron beam is of the order of 5–10 ps, shown in Fig. 5. For a 10 nC electron bunch, we find \(N_l = 6.24 \times 10^{10}\) electrons per bunch. For a \(\lambda = 1\) \(\mu\)m laser, the emittance of the laser beam is about 79 nm which is comparable with that of the electron beam, assumed to be about 50 nm in our flux estimation. Assuming 1 mJ of total energy for each laser pulse at 90 MHz frequency with 1 \(\mu\)m wavelength, the number of laser photons per pulse is \(N_l = 5.0 \times 10^{15}\).\(^3\) The luminosity becomes \(\mathcal{L} = 4.2 \times 10^{35} \text{ cm}^{-2} \text{s}^{-1}\) assuming the beam radius is given by the horizontal beam size. The flux of x-ray photons is \(dN_x/dt = 2.8 \times 10^{11}\) photons/s. These x-ray photons are emitted in an angular cone of \(\sigma_{\text{th}} = \sigma_{\text{th}} < 1/\gamma\) with transverse size \(\sigma_{x',z'} = \sqrt{\beta_{x'}^2 \epsilon_{x',z'}}\), where \(\beta_{x'}^2\) and \(\beta_{z'}^2\) are the values of the betatron amplitude functions at the IP.

The brilliance of the backscattering x-ray photon is
\[
B = \frac{dN_x}{dt} = \frac{\mathcal{L}}{\pi \sigma_T \epsilon_0^2} \int_{\Delta \omega < 0.1^\circ} \int_{\sigma < 1/\gamma} F_{\Delta \omega < 0.1^\circ} F_{\sigma < 1/\gamma},
\]
where \(F_{\Delta \omega < 0.1^\circ}\) is the fraction of photons with frequency within a bandwidth 0.1% of frequency spread and \(F_{\sigma < 1/\gamma}\) is the fraction of photons within the angular spread of the scattered x-ray photons. At 50 MeV electron beam energy, we find \(\sigma_{\text{th}} = \sigma_{\text{th}} = 6\) mrad and \(\sigma_{\text{th}} = 210\) \(\mu\)m at the IP. Assuming \(F_{\sigma < 1/\gamma} = F_{\Delta \omega < 0.1^\circ} = 0.5\), we find \(B \approx 9 \times 10^9\) photons/(mm\(^2\) mrad\(^2\) 0.1% \(\Delta \omega/\omega\)). Both the flux and the brilliance of the x-ray photon are proportional to the bunch charge and the laser intensity. The x-ray photon brilliance will slightly increase with higher energy electron beam because the backscattering angle is proportional to \(\gamma^{-1}\). One may also design horizontal focusing optics at the IP to enhance the x-ray brilliance at a virtual focal point where experimental samples would be located.\(^9\) With 600 MeV maximum energy and tunable momentum compaction, this storage ring may also provide useful coherent terahertz radiation.\(^10\)

**IV. DISCUSSION**

We find that the combined function damping wigglers can effectively change the momentum compaction factor and the damping partition of a low energy electron storage ring. We use this property to design a low energy electron storage ring with tunable momentum compaction factor. This accelerator can debunch the rf linac beams in one revolution. We design the injection and extraction systems to accommodate this function. The betatron tunes of this storage ring are favorable for multiturn accumulations. The accumulated beam charge can be extracted in one shot for high-energy-density radiation-effect experiments.

A low energy electron storage ring is useful for the studies on the Touschek lifetime, collective beam instabilities, nonlinear beam dynamics, and space charge physics.\(^9\) Since the compaction factor of the storage ring is tunable, beam dynamics studies of quasi-isochronous physics will be of great interest to accelerator physics community.\(^6\)

With high bunch charge accumulated in the storage ring, the resulting bunch has high beam brilliance after the damping time. The high brightness electron beams can be used as the driver for the x-ray photon source by employing the inverse Compton scattering process. We have provided a conservative estimate of the x-ray photon flux and its brilliance. The flux is comparable, but the brilliance is three to four orders lower than that estimated from a linac photocathode source of Ref. 3.

We used the existing CIS dipoles in our design. However, if one tries to build a new storage ring, one can optimize the damping time by making the dipoles shorter, e.g., 1.25 m dipole length, while keeping the length of each straight section at 2.5–3 m so that the circumference is about 15 m. This will shorten the damping time by 60%. Beam dynamics of this smaller storage ring are similar to what we have discussed in this article.

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