DESIGN OF A 2.1-GEV ELECTRON STORAGE RING*

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Abstract

A 2.1 GeV electron storage ring can serve as a third-generation light source for photon energies of 1-2000 eV. We design a ring with emittance of 1.5 nm-rad, circumference of 215 m, and twelve 5.5-m long straight sections. With a 100-MHz radiofrequency (rf) system, the computed Touschek current-lifetime product is 2800 mA-hr. Two passive fifth-harmonic cavities may be used to suppress longitudinal parasitic coupled-bunch instabilities while increasing the bunch length and lifetime by a factor of four. For stable operation with ring currents up to 600 mA, microwave-instability simulations indicate that the reduced longitudinal impedance should not exceed 1.5 ohms.

INTRODUCTION

A ring energy of 2.1 GeV will allow insertion devices to provide photons with energies of 1–2000 eV for the vacuum-ultraviolet and soft xray user communities [1]. We design a ring of this energy using combined-function magnets and a 100-MHz rf system, obtaining a design similar to that of the MAX-IV rings [2].

The MAX-IV design incorporates combined-function magnets in a 12-sided ring of length 287 m, with long straight sections of length 4.6 m. Our desired 2.1 GeV ring energy is 30% lower than the 3-GeV energy of the higher-energy MAX-IV ring. This enabled us to design a shorter 12-sided ring with longer straight sections for insertion devices, with nearly the same emittance as the MAX-IV 3-GeV ring. The low emittance allows the usage of small-aperture magnets and small-gap insertion devices with a reasonable amount of horizontal-vertical coupling.

Modeling of an rf system employing six 100-MHz cavities gives an adequate Touschek lifetime of 14 hours for a ring current of 200 mA. The computed dynamic aperture does not limit the lifetime. With the use of two passive 500-MHz cavities, the bunch length and Touschek lifetime are quadrupled while typical longitudinal parasitic coupled-bunch instabilities are suppressed. For stable operation with ring currents up to 600 mA, simulations of the microwave instability indicate that the reduced longitudinal broadband impedance should not exceed 1.5 ohms.

LATTICE DESIGN

We designed the ring with the MAD accelerator code [3]. Since MAD 8.22 doesn't model combined-function quadrupole/sextupole magnets, each magnet of this type was modeled as a quadrupole with three equal-strength thin sextupoles at the ends and center.

The MAX-IV superperiod contains 5 combined-function UNDIP bending magnets, flanked by MATDIP and SOFTDIP bending magnets. The SOFTDIP magnets have a weak dipole field to reduce the synchrotron radiation energy deposited on the long-straight-section vacuum tanks.

Using the MAX-IV design as a starting point, we designed a shorter 12-sided ring where each superperiod contains 3 combined-function UNDIP bending magnets, flanked by MATDIP and SOFTDIP bending magnets [4]. Figure 1 shows the lattice functions of our design, whose circumference is 215.13 m. The 12 long straight sections have length of 5.5 m, zero dispersion, and symmetric lattice functions with β_x = 8 m and β_y = 2.75 m in the center. This β_y value is ideal, equaling one-half of the long straight section length. The value of β_x is larger to allow injection into a long straight section.

The momentum compaction is 0.001066. The emittance of the 2.1-GeV ring is 1.468 nm-rad, which is 16% larger than the emittance of MAX-IV for 3-GeV operation. The tunes are (22.591, 6.368); natural chromaticities are (–33.83, –29.49). The relative energy spread is 7.75 x 10^{-4}, the synchronous voltage is 231.42 kV, and the longitudinal radiation-damping time is 8.75 ms.

By using two families of sextupoles for chromaticity correction and a single family of harmonic sextupoles, we achieved a horizontal dynamic aperture (for energy deviations up to ±3% and ideal magnets) of [–20 mm, +10 mm], which exceeds the desired vacuum chamber horizontal aperture of [–10 mm, +10mm]. The vertical dynamic aperture of ±3 mm exceeds the desired vertical vacuum chamber aperture of ±2 mm. Since reasonable

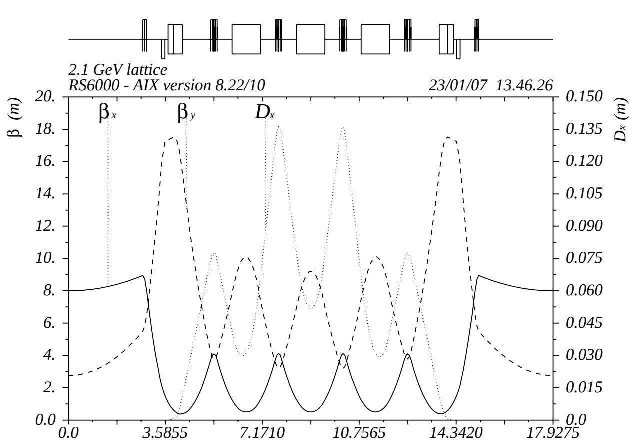

Figure 1: Lattice functions for one superperiod of the 2.1-GeV ring design.

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magnetic field errors and misalignments have little effect on the MAX-IV dynamic aperture [2], we expect that the dynamic aperture of our design is sufficient.

100-MHZ RF SYSTEM

We consider operation with a 100.4-MHz rf system. For rf voltage of 1.2 MV, the synchrotron frequency is 3.64 kHz, and the rms bunchlength is 10.774 mm.

To calculate the Touschek lifetime, we used the ZAP code [5] to model a horizontal physical half-aperture of 10 mm throughout the ring. To adequately sample the ring, ZAP was modified to use as many as 40,000 ring positions. We used a ZAP input file in which each drift space and dipole magnet is divided into ten pieces, while each quadrupole is divided into 20 pieces. For 200 mA in 72 bunches with 1.5% emittance coupling, the computed Touschek lifetime for an rf voltage of 1.2 MV is 14.76 hour, giving a current-lifetime product of 2952 mA-hours.

For greater accuracy, ZAP was modified to use a lifetime formula that doesn't assume nonrelativistic electron velocities in the beam frame [6]. This computation gives a slightly lower Touschek lifetime of 14.22 hours, with a current-lifetime product of 2844 mA-hour. Losses to physical apertures occur at the locations of maximum horizontal dispersion. The computed lifetime is unchanged if a larger dynamic aperture is specified, indicating that the computed dynamic aperture does not limit the lifetime.

By using emittance coupling larger than 1.5% and/or a fifth-harmonic cavity for bunchlengthening, the Touschek lifetime may be increased. Since a lifetime of several hours suffices for top-up injection, the ring lifetime appears to be long enough.

500-MHZ HARMONIC CAVITY

Using a passive fifth harmonic rf cavity to lengthen the bunch is expected to increase the lifetime and the Landau damping of parasitic coupled-bunch instabilities. Successful harmonic-cavity operation may prevent the need for a longitudinal feedback system and increase the current threshold of microwave instability. We consider the use of six 100-MHz and two 500-MHz cavities, with the parameters given in Ref. [4].

The methods used for analytic predictions and simulations are described in Ref. [7] and [8]. According to Ref. [8], accurate simulations of Robinson and parasitic coupled bunch instabilities require ≥ 1000 macroparticles in the ring, while accurate simulations of microwave instability require ≥ 1000 macroparticles per bunch. To complete hundreds of simulations using 4000 macroparticles per bunch, we performed simulations simultaneously by using the University of Wisconsin-Madison's CONDOR® pool for high-throughput computing. This pool performs computations by utilizing the otherwise idle time of networked workstations and personal computers [9].

Figure 2(a) shows analytic instability predictions where a parasitic higher-order mode (HOM) is considered with quality factor of 3000, resonant impedance of 10 kΩ, and resonant frequency of 0.9998605 GHz (717 times the revolution frequency). The HOM properties are chosen to approximate a typical mode in a 100 MHz cavity with HOM damping, whose frequency maximally excites non-Robinson coupled-bunch instability. For currents of 360–600 mA, optimal bunchlengthening is predicted to be stable, increasing the bunchlength by a factor of four. At currents of 200–320 mA, the analytic modeling predicts that near-optimal bunchlengthening is stable.

Figure 2(b) shows results from simulating 4000 macroparticles/bunch for 200,000 turns (16 radiation-damping periods). The relative energy spread and number of lost macroparticles at the end of each simulation were recorded. An energy spread that exceeds the natural value by more than 10% is taken as a sign of instability. In Fig. 2(b), a circle is plotted when the energy spread at the end of a simulation exceeds the natural value by more than 10%, while a solid square is plotted when macroparticles are lost in a simulation. The simulations shown in Fig. 2(b) are in approximate agreement with the analytic

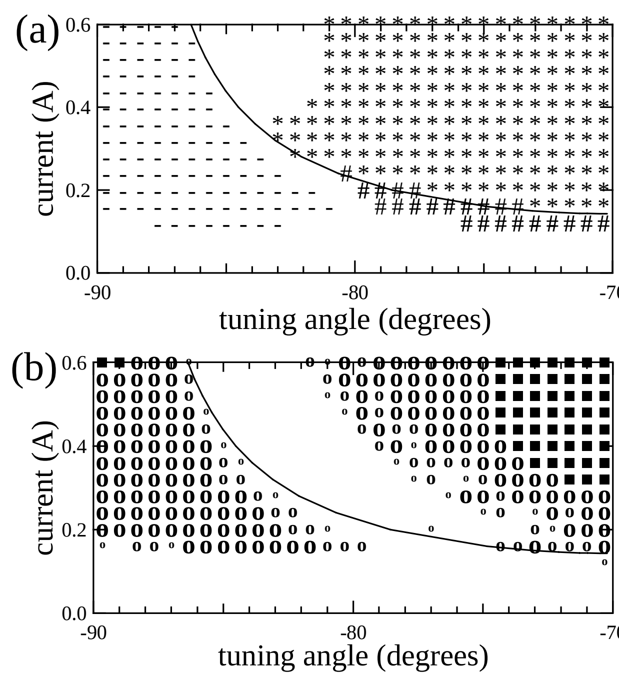

Figure 2: Modeling of a 100-MHz/500-MHz RF system with parasitic coupled bunch instability. A solid curve shows the parameters for optimal bunchlengthening. (a) Analytic predictions. –: parasitic coupled bunch instability; |: coupled-dipole Robinson instability; *: coupled-quadrupole Robinson instability; #: fast dipole-quadrupole Robinson mode-coupling instability. (b) Results of 200,000-turn simulations of 288,000 macroparticles. ◦ : mild instability, where the energy spread exceeds its natural value by 10–30%; o: moderate instability, where the energy spread has increased by 30–100%; **o**: strong instability, where the energy spread has increased more than 100%; ■: lost macroparticles.

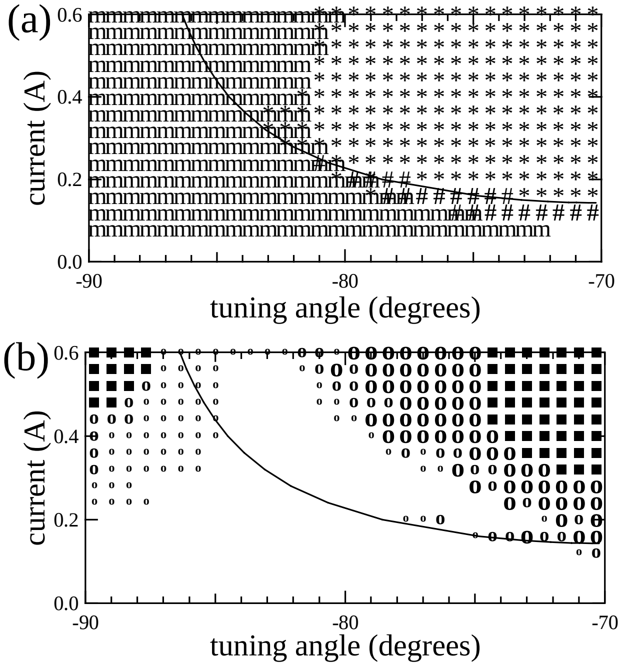

Figure 3: Modeling of a 100-MHz/500-MHz RF system with microwave instability from the broadband impedance $|Z_p/p|$ = 1.5 Ω. (a) Analytic predictions. m: microwave instability; |: coupled-dipole Robinson instability; *: coupled-quadrupole Robinson instability; #: fast dipole-quadrupole Robinson mode-coupling instability. (b) Results of 200,000-turn simulations of 288,000 macroparticles. ◦ : mild instability, where the energy spread exceeds its natural value by 10–30%; **o**: moderate instability, where the energy spread has increased by 30–100%; **o**: strong instability, where the energy spread has increased more than 100%; ■: lost macroparticles.

modeling of Fig. 2(a). The analytic modeling and simulations both indicate that optimal bunchlengthening provides sufficient Landau damping to suppress the parasitic coupled-bunch instability from a typical HOM.

To study the effect of broadband impedance from the vacuum chamber, the microwave instability is considered for a HOM with quality factor of one and resonant angular frequency of c/b, where c is the speed of light and b is the vacuum chamber radius. An analytic prediction, described in Ref. [8], considers whether the negative-mass instability of a coasting beam can overcome Landau-damping resulting from the longitudinal velocity spread caused by the beam's energy spread, as in the ZAP code [5]. Figure 3(a) shows analytic predictions for a broadband HOM with quality factor of one, resonant impedance of 5137.5 Ω, and resonant frequency of 4.77 GHz. This HOM models reduced longitudinal broadband impedance $|Zp/p|$ of 1.5 Ω in a chamber with radius of 10 mm. Microwave instability is predicted for sufficiently high ring current and low harmonic-cavity voltage.

Figure 3(b) shows results of 200,000-turn simulations of 4000 macroparticles/bunch for $|Zp/p|$ = 1.5 Ω. The simulations are in rough agreement with the analytic model. Comparisons with experiments on the Aladdin electron storage ring indicate that microwave instability thresholds determined by simulations agree with experiment [8]. According to Fig. 3(b), microwave-stable operation of the 2.1-GeV ring with currents up to 600 mA may be achieved by using the harmonic cavities to increase the bunch length, provided that the reduced longitudinal broadband impedance does not exceed 1.5 Ω.

SUMMARY

We have designed a 2.1-GeV ring with low emittance of 1.5 nm-rad and a circumference of 215 m. Twelve 5.5-m straight sections are provided — eleven for insertion devices and one for injection. The energy spread is 7.75 x 10^{-4}, the synchronous voltage is 231.42 kV, and the longitudinal radiation-damping time is 8.75 ms. With 1.5% emittance coupling, a vacuum chamber half-width of 10 mm gives a Touschek current-lifetime product of 2800 mA-hours with a 100-MHz rf system. Further details and a MAD lattice file may be found in Ref. [4].

Modeling of a passive fifth harmonic rf system predicts that the bunchlength and Touschek lifetime may be increased by a factor of four while suppressing typical longitudinal parasitic coupled-bunch instabilities. For stable operation with a ring current up to 600 mA, simulations of the microwave instability indicate that the reduced longitudinal broadband impedance $|Zp/p|$ should not exceed 1.5 Ω.

Our design of a low-emittance 2.1-GeV electron storage ring with circumference of 215 m appears to be a promising candidate for a third-generation light source.

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