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ISOCHRONOUS INDUCTION CELL STORAGE RING*

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Abstract

A challenge in realizing a steady-state microbunching (SSMB) light source is achieving a high average current from a stored beam with a peak current low enough to avoid collective effects that spoil the longitudinal phase space. We are investigating a potential solution to this challenge that combines recent advances in isochronous transport and induction cells. We adapt anti-bend unit cells to yield an arc whose R_{56} can be adjusted near-zero on a per-arc basis. This fine control of momentum compaction allows for better mitigation of effects that spoil the longitudinal phase space. A consequence of RF technology is that high average current can only be achieved in a storage ring by pushing peak current, as only 1-2% of the circumference actually stores current. High peak current drives other design considerations which result in a fast churning of the longitudinal phase space. A ring with low peak current to avoid this churning has an average current too low to be a useful light source. Induction cells with a reset time of 10 ns have recently been developed for cinematographic radiography. An induction cell could allow over 95% of the ring to store current, yielding a high average current and low peak current. Here we outline an investigation to explore the beam dynamics and technology of such an isochronous induction cell storage ring.

INTRODUCTION

As a potential path to a steady-state microbunching (SSMB) light source [1], we are investigating an isochronous storage ring with a continuous beam. A ring that is isochronous to high order on a per-arc basis is obtained by adapting the anti-bend cell design proven in the recently commissioned SLS upgrade [2]. A continuous beam is obtained by replacing the RF system with active-active reset induction cells, a technology that has advanced significantly in recent years [3].

Depicted in Fig. 1, the beam in a conventional light source storage ring is bunched so that only a few percent of the ring circumference contains charge. This is a consequence of the RF system, which is used to restore energy to the beam that is lost in the bend magnets and insertion devices. Without the RF system, the beam energy would decay, and the beam would quickly be lost.

The fraction of the RF cycle where charge can be stored is called an RF bucket, whose height is given by the RF voltage. A high RF voltage is necessary for a long beam lifetime but the sharp slope focuses the beam into a short

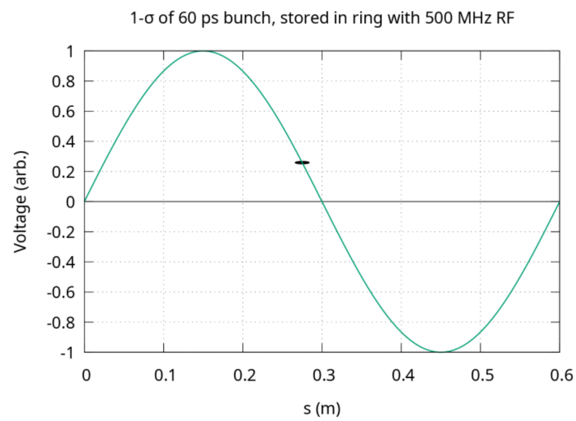

Figure 1: Voltage waveform in a 500 MHz RF cavity. The abscissa is drawn to scale with 1-σ of a 60 ps bunch. Particles can only be stored slightly off the zero-crossing of the RF, leaving most of the waveform devoid of charge.

bunch. In the commonly used 500 MHz RF system, the wavelength is 60 cm long, but the bunch is only about 1 cm long. Thus only about 1.7% of the ring contains charge. Third-harmonic cavities are often used to flatten the potential well and lengthen the bunch, but this yields only a factor of 2 or 3 in lengthening.

Recent advances in active-reset induction cell technology raise the possibility of using induction cells in place of RF cavities. An induction cell is essentially a transformer, where one loop of the core is attached to a ramping power supply and the other loop is the beam itself. The power supply is ramped during the beam passage, which generates a dB/dt and delivers an accelerating E-field to the beam. The ramp profile can be shaped to provide barriers at the ends of the ramp. Once per revolution the induction cell must be reset, necessitating a gap in the beam on the order of 10 nanoseconds. In a 100 m storage ring, all but 10 nanoseconds of the ring could contain charge, a greater than 90% fill. More sophisticated ramp profiles, perhaps spanning multiple cells and turns, may be considered to yield a truly continuous beam with 100% of the storage ring containing charge. Thus induction cells raise the possibility of unbunched, continuous-beam electron-storage rings. Assuming a Gaussian profile, each bunch in a 500 mA beam in a 100 m ring has a peak current of 10 A, or about 25×10^7 e$^-$/mm. A continuous beam would have a peak current of about 1×10^7 e$^-$/mm.

Continuous electron beams in induction storage rings have not yet been extensively studied. Induction cells have been tested successfully in proton rings [4, 5]. Recent consideration of induction cell rings is available at [6]. The University

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of Maryland operates UMER, a 10 keV induction storage ring [7].

Steady-state microbunching relies on structuring the longitudinal phase space using powerful drive lasers. In conjunction with a compression scheme, it aims to enable coherent emission at interesting wavelengths. To prevent the spoiling of the longitudinal phase space, it is necessary that the momentum compaction be near zero. In conventional storage rings, momentum compaction is necessarily large due to finite positive dispersion in the bend magnets. Additionally, these machines need large momentum compaction to wash out instabilities driven by high peak current. With a continuous beam facilitated by an induction cell, we hope to avoid the instabilities driven by a high peak current. By removing the necessity of having a large momentum compaction, we hope to remove one of the obstacles towards realizing an SSMB light source. Additionally, a continuous beam with a low peak current would suffer less from the effects of Touschek and intrabeam scattering.

STORAGE RING

The recently commissioned SLS upgrade uses anti-bend cells to manipulate dispersion independently of the β-function to achieve a smaller $\mathscr{H}$. The presence of anti-bending in dispersive regions contributes a negative quantity to the momentum compaction,

$$\alpha_c = \frac{1}{L}\int_0^L \frac{\eta(s)}{\rho(s)} ds, \tag{1}$$

where L is the circumference, η is the dispersion, ρ is bending radius. $\rho < 0$ for reverse bending. The SLS upgrade project ultimately chose to tolerate a larger emittance in return for a larger momentum compaction. Instabilities driven by peak current contributed to this decision. To our ends, we envision a machine with a very low peak current and deliberately target a near-zero momentum compaction. In doing so, we obtain a storage ring that is isochronous per arc and maintains small R_{56} excursions throughout the ring.

The concept isochronous storage ring we present here is intended to demonstrate our design principles and facilitate early simulation studies of continuous beams. Figure 2 shows the optics of one unit cell of this ring. Each of the 4 arcs is composed of 10 such unit cells. During cell design, R_{56}/C_0 is constrained such that its global value is 10^{-6} m. The arcs include 3 families of chromatic sextupoles, set to correct chromaticity to +1 in both planes and constrain second-order momentum compaction R_{566} to zero. Higher orders of momentum compaction can be controlled using chromatic multipoles. Table 1 shows the essential properties of the ring. The three lowest orders of momentum compaction through one arc are plotted in Fig.3. The betatron phase advances of the unit cells are such that the lowest-order resonant driving terms cancel over a sequence of 5 cells. This yields a good starting point for the optimization of the dynamic and momentum apertures. Further optimization includes adjusting the phase advance through the straights to set the working point, and minimization of the first-order geometric driving terms using 3 families of harmonic sextupoles. The resulting frequency map and dynamic aperture are shown in Figs. 4 and 5. The momentum aperture requires more consideration in the context of an induction cell and has not yet been extensively evaluated.

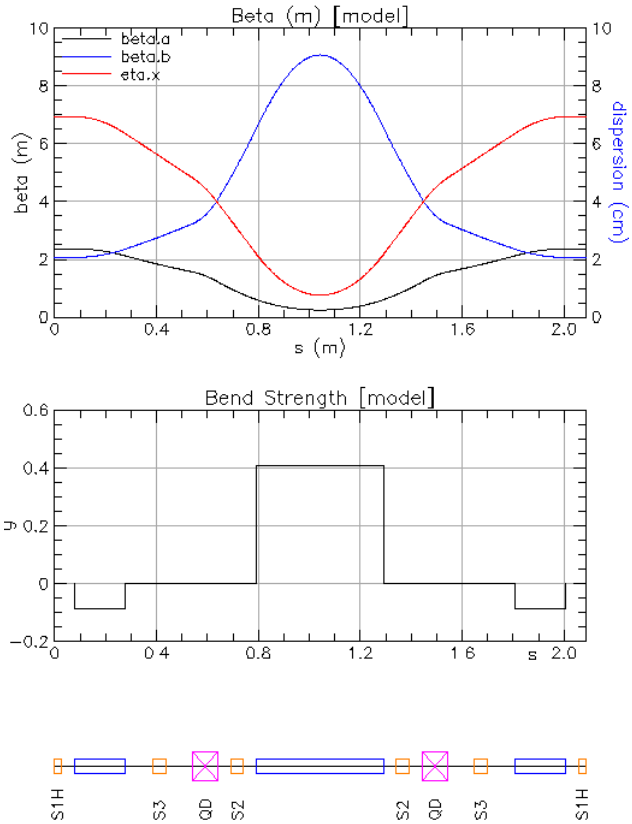

Figure 2: Optics and layout for the anti-bend cell used in the isochronous storage ring.

Table 1: The concept isochronous storage ring targets "4th gen" light source parameters along with zero momentum compaction.

Parameter	**Value**
C_0	119.6 m
E_0	1.0 GeV
Q_x	17.56
Q_y	5.18
ϵ_{nat}	429 pm·rad
σ_p	6.310^{-4}
U_0	46.7 keV
Σ |bend angle|	506 degrees
χ_x	−27.4
χ_y	−33.8
R_{56}/C_0	10^{-6}
R_{566}/C_0	$< 10^{-9}$

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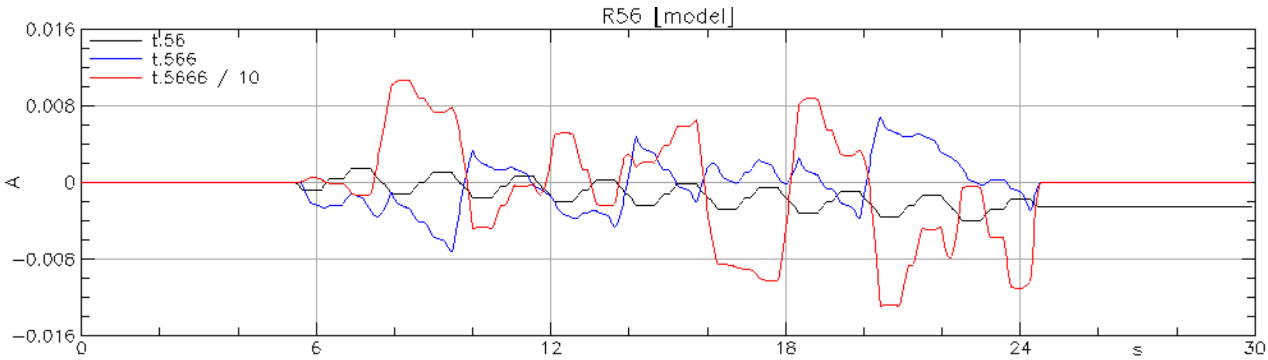

Figure 3: Momentum compaction and higher orders through one arc of the periodicity 4 storage ring.

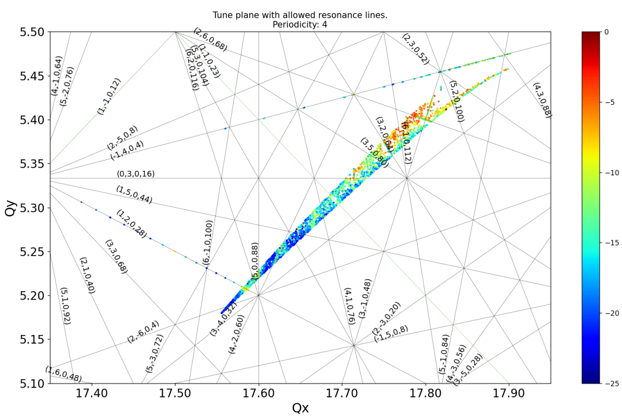

Figure 4: Frequency map for the concept storage ring.

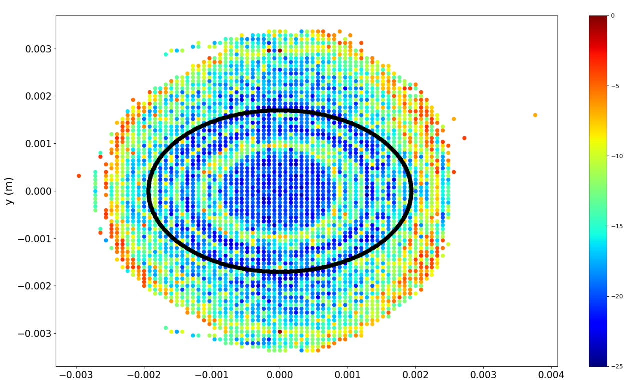

Figure 5: Dynamic aperture of the concept storage ring. The ellipse represents 25σ of the beam dimensions.

INDUCTION CELL

Prototype cells developed for the Scorpius project to enable cinematographic x-ray radiography have been tested at approximately 1 MHz with an approximately 10 ns reset time [3, 8]. These cells can deliver up to 100 kV or more to a 1.5 kA beam. The storage ring presented here would require developing an induction cell with repetition rate of 3 MHz that delivers 50 kV to a beam of 500+ mA. Additional design challenges include vacuum engineering and HOMs. Storage rings typically maintain 1 nT, whereas induction linacs maintain 100 nT. Induction cells expose structure to the vacuum chamber which may need to be optimized. Furthermore, storage ring light sources are nominally 24x7 facilities, whereas induction linacs are typically operated on a shot-by-shot, per-experiment basis.

RESEARCH OUTLINE

The first task is to develop a modeling environment for simulating continuous beams in a relativistic electron storage ring. We plan to develop a new element within the *Bmad* subroutine library [9] which can be programmed with a $\Delta E\,(t)$ contour representing the ramp of the induction cell. A second challenge is establishing an efficient multi-particle tracking simulation that captures the effects of ion trapping and chamber impedances on a continuous beam.

We also plan to reconsider the theory on wake fields. Existing treatments divide impedances into short-range (meaning within one bunch) and long-range (meaning bunch-to-bunch). These distinctions do not exist in the context of a continuous beam.

The viability of longitudinal feedback implemented by shaping the induction cell ramp profile in the presence of a finite (though small) R_{56} will be investigated.

The goal of these studies is to determine whether a continuous beam with a sufficiently flat current profile can be maintained in a storage ring, and determine the limitations on the total stored current. Additionally, we will simulate techniques for inducing steady-state microbunching, and for dealing with the energy spread induced by coherent photon emission.

CONCLUSION

By adapting the recently proven anti-bend cell design for storage ring arcs with recent advances in induction cell technology, we have come up with a new concept for storage ring light sources. We have presented our initial work on this project and outlined our plans to investigate the viability of this new ring.

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