EXPLORATION OF A TEVATRON-SIZED ULTIMATE STORAGE RING *

M. Borland†, ANL, Argonne, IL 60439, USA

Abstract

With the Tevatron now shut down and slated for decommissioning, it is only natural to think about other possible uses for the 6.3-km tunnel. Given that the brightness of electron storage rings naively scales as radius cubed, one exciting possibility is to build a so-called ultimate storage ring light source. This paper describes a somewhat speculative exploration of this idea, showing the potential for a storage ring x-ray source of unprecedented brightness.

OPTIMIZATION OF EMITTANCE

The zero-current equilibrium emittance ϵ_0 scales as $\gamma^2\theta^3$, where $\theta = 2\pi/N_d$ is the angle of each of N_d dipole magnets, and γ is the relativistic factor [1]. For example, one way to achieve lower emittance is to build a large ring with double-bend cells identical to those in the Advanced Photon Source (APS) storage ring, but with weaker dipoles. Scaling the 3.1-nm, 7-GeV, 1.1-km circumference APS design to Tevatron (C=6.28 km) size gives $\epsilon_0 = 17$ pm. A more effective approach is to use multi-bend achromat (MBA) cells [2], as in MAX-IV [3], which permits decreasing θ to a much greater degree.

The vertical emittance is $\epsilon_y = \kappa\epsilon_0$, where typically $\kappa \sim 0.01$. For photon wavelength λ, having $\epsilon_y < \lambda/(4\pi)$ is pointless. The threshold is $\sim$ 10 pm for 10-keV photons. Thus, when $\epsilon_0 \leq 10$ pm we can take $\kappa \sim 1$ in order to decrease the effects of Touschek and intrabeam scattering.

In storage rings with small vertical undulator gaps, the large x-y coupling typically associated with $\kappa \sim 1$ results in difficult injection, since residual injection oscillations couple into the vertical plane. Hence, we must inject on-axis [4], as done in TANTALUS, the first dedicated synchrotron radiation ring [5]. This implies using swap-out injection, wherein an existing bunch or bunch train is removed from the ring and replaced with a fresh bunch or bunch train. Significantly, requirements for dynamic acceptance (DA) decrease dramatically, allowing DA of $\sim$ 1 mm and we can use insertion devices with small apertures in *both* planes.

DESIGN CONCEPT

In this exploratory work, we made no attempt to match the detailed Tevatron geometry, but kept the basic symmetry with six arcs and six long straight sections. We used optics modules from the PEP-X design [6], with $N_c = 30$ seven-bend-achromat cells per arc, giving $C = 6.21$ km and $N_d = 1260$. Since this is an exploratory design, we relaxed concerns about magnet strengths, since analysis of these is complicated owing to the use of combined function quadrupoles and sextupoles in the PEP-X modules.

The choice of cell tunes and N_c is influential for nonlinear dynamics [7]. We want each arc to provide a $+I$ transformation in both planes, requiring $\nu_q = n_q + m_q/N_c$, where q is x or y, and n_q and m_q are non-negative integers. We started with $n_x = 2$, $n_y = 1$, and $n_q = m_q = 5$, since this is close to the PEP-X cell tunes, but had nonlinear dynamics issues. Figure 1 shows the sextupole strengths and ϵ_0 as a function of the cell tunes, assuming beam energy of 9 GeV. Taking $\nu_x = 1.900$ and $\nu_y = 0.900$ reduces sextupole strengths by 40 to 50%, while increasing ϵ_0 by only 40%. This is acceptable since $\epsilon_0 \ll 10$ pm.

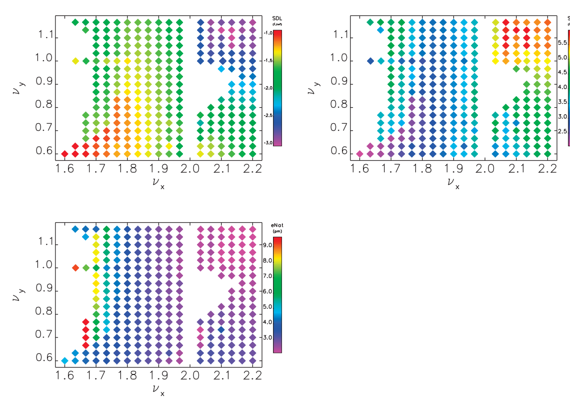

Figure 1: Integrated SD and SF sextupole strengths (top left and right) in $1/m^2$ and natural emittance (bottom right) in pm as a function of cell tunes at 9 GeV.

Figure 2 shows typical lattice functions starting from the arc and including half of a long straight. At 7 GeV, $\epsilon_0 = 1.8$ pm, about twice what's expected from $1/N_d^3$ scaling of APS. However, the momentum compaction factor, at 6×10^{-6}, is five times larger than the naive $1/N_d^2$ scaling indicates, which is welcome news for collective instabilities.

MICROWAVE INSTABILITY

The microwave instability (MWI) threshold in modern light sources is significantly higher than the naively applied Boussard criterion would indicate. This is not without theoretical justification. As discussed in section 2.5.6 of [8], the threshold can be very large if the impedance is in the upper part of the complex plane. For this reason, we look to experimental data for guidance. For the APS, we estimate $|Z/n| = 0.28\ \Omega$ from measurements of bunch length

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† borland@aps.anl.gov

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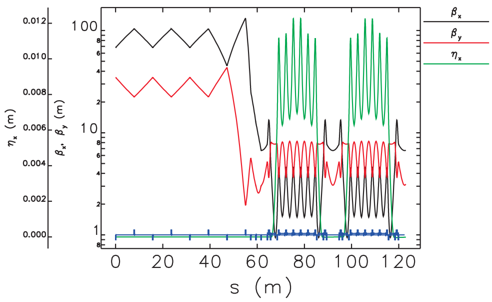

Figure 2: Typical lattice functions, showing half of the long straight section along with two arc cells.

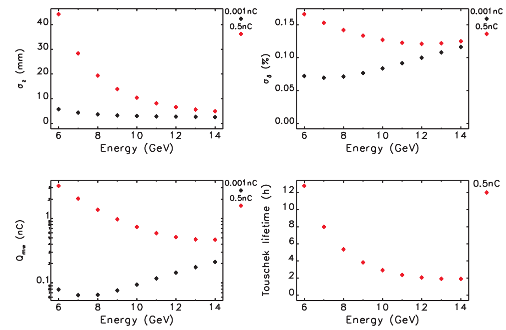

Figure 3: Collective effects as a function of beam energy for two different levels of bunch charge.

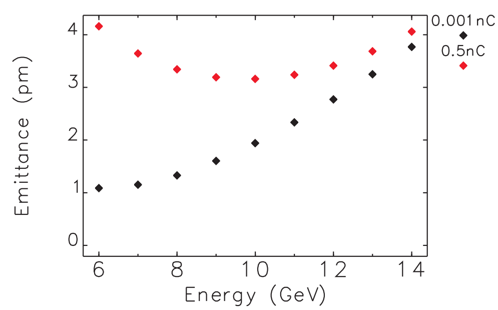

Figure 4: Emittance as a function of beam energy for two values of bunch charge, assuming full coupling.

vs current. Using this with the simple MWI threshold formula and taking into account measured bunch lengthening due to potential well distortion, gives a threshold of 0.9 mA, whereas the observed threshold is 4.9 mA. Given that similar high thresholds are measured in other large light sources [9], we included this five-fold empirical correction in our analysis.

To perform this analysis, we need values of energy spread and bunch length, including potential well distortion and intrabeam scattering. Using the APS value of $|Z/n| = 0.28\ \Omega$, this is conveniently modeled using the programs `haissinski` [10] and `ibsEmittance` [11]. Using these results, we then computed the MWI threshold (with the five-fold empirical adjustment) and the Touschek lifetime.

More specifically, we scanned the beam energy from 6 GeV to 14 GeV for bunch charge values of 0.001 and 0.5 nC, assuming an rf frequency of 500 MHz and $\epsilon_x = \epsilon_y = \epsilon_0/2$ at zero current. The results, shown in Figure 3, are surprising. For example, the MWI threshold for 0.5-nC bunches generally *decreases* with increasing energy, contrary to expectations. The reason is that at lower energy, the beam lengthens significantly and also suffers a significant increase in energy spread. These combine to provide a significantly increased MWI threshold. Our conclusion is that over a wide range of operating energies, we should be below the microwave threshold if we store 0.5-nC bunches. This implies a current of 200 mA if 80% of the 500-MHz buckets are filled. Figure 4 also shows the Touschek lifetime, which is computed under the assumption of $\pm 2\%$ momentum acceptance and $\kappa = 1$ using the program touschekLifetime [12]. It may be surprising that the lifetime is so long, but this owes much to the high energy and the lack of transverse momentum in the low-emittance beam.

The emittance is shown in Figure 4, from which we see that it is relatively flat as a function of energy, with a broad minimum around 9 to 11 GeV. Near this energy, IBS roughly doubles the emittance compared to the zero-current value. For the remainder of the present study, we'll assume operation at 9 GeV.

NONLINEAR DYNAMICS

In this section, we show results of preliminary nonlinear dynamics optimization using a multi-objective genetic algorithm (MOGA) that directly optimizes the dynamic acceptance and the Touschek lifetime [13]. Errors were set using the methodology of [13] to give approximately 1% beta and dispersion beats and an emittance ratio of 0.2. We also included insertion device apertures with horizontal (vertical) half-gaps of 18 mm (3 mm). Note that we did not perform the optimization with fully coupled emittances, which is inconsistent with our analysis above. Methods of producing $\kappa = 1$ remain to be explored.

The optimizer varied the integer and fractional tunes (keeping the cell tunes fixed), as well as the strengths of three SF families, five SD families, and three harmonic sextupole families. The chromaticity was fixed at 1 in both planes. Although the SF and SD magnets were split into several families, the optimization so far has not produced a significant variation in strengths, so that one family of each is apparently sufficient. The harmonic sextupole strengths are 1% or less of the chromatic sextupole strengths, which seems to indicate that they are not in fact needed. Of course, it may be that continued optimization would make use of these knobs to improve results.

Figure 5 shows the best dynamic and momentum acceptances achieved so far. Given that errors are included and that MOGA has explored less than 500 configurations,

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these are promising. The dynamic aperture is small, but more than adequate for on-axis injection provided the injector emittance is less than about 2 nm (a normalized emittance of 35 μm), which should be no issue. The predicted Touschek lifetime for 0.5-nC bunches is about 4 h. The estimated gas-scattering lifetime assuming 0.5-nT vacuum pressure is only about 4.5 h, a result of the small dynamic acceptance. Hence, the total lifetime is about 2 h.

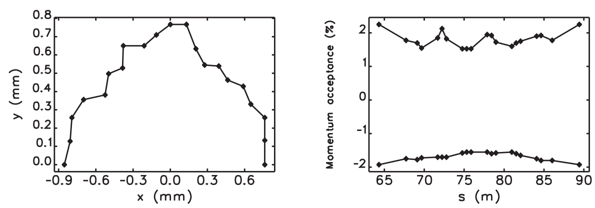

Figure 5: Preliminary MOGA optimization results, showing the dynamic acceptance (left) and the momentum acceptance (right) for one arc cell.

For 200-mA stored beam current, this lifetime implies an average injector current of only 0.6 nA. If we have 208 trains of 40 bunches, well have to deliver 20 nC per shot every 35 s with kicker rise and fall times of 10 ns. Figure 6 shows predicted x-ray brightness at 200 mA for superconducting undulators extrapolated from present APS designs [14, 15]. Depending on the photon energy of interest, the brightness is several orders of magnitude above what can presently be achieved with storage ring x-ray sources.

Table 1: Parameters of Optimized Lattice

C: 6.21 km	E: 9 GeV	U_0: 1.5 MeV/turn
ϵ_0: 2.9 pm	σ_δ: 0.096%	α_c: 6×10^{-6}
J_x: 2.66	J_y: 1.00	J_δ: 0.34
τ_x: 91 ms	τ_y: 243 ms	τ_δ: 713 ms
ν_x: 344.10	ν_y: 171.17	
$\xi_{x,nat}$: -480	$\xi_{y,nat}$: -275	
$\beta_{x,max}$: 131 m	$\beta_{y,max}$: 43 m	$\eta_{x,max}$ 12 mm
$\beta_{x,ave}$: 12.8 m	$\beta_{y,ave}$: 8.2	

Table 1 lists various parameters of the optimized lattice. Even at 9 GeV, the damping times are very long, the longest being 0.7 s in the longitudinal plane. This naturally creates concern about collective instabilities. The energy loss is only 1.5 MeV/turn, which could be increased by addition of damping undulators, thus improving the damping times dramatically. However, this will also shorten the bunch, thus reducing the MWI threshold.

CONCLUSION

We've explored the possibility of a 200-mA, 9-GeV Tevatron-sized storage ring light source with extremely low emittance in both planes. The emittance including IBS for 0.5-nC bunches is under 4 pm in both planes. At this point, no serious problems have been found, even though optimization of nonlinear dynamics is in a very early stage. The microwave instability is not an issue, owing to bunch lengthening from potential well distortion and intrabeam scattering. Brightness is well above what can be offered today with a storage ring light source and can perhaps be improved further, for example, through the use of damping wigglers. These would also reduce the damping times and presumably reduce issues with some collective effects.

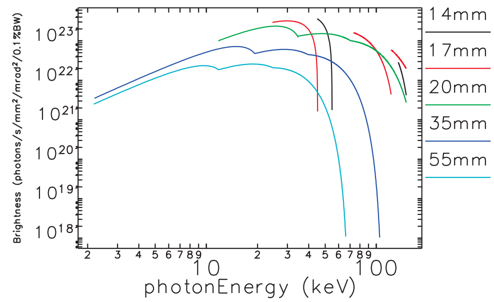

Figure 6: Curves of brightness in ph/s/mm^2/mrad^2/0.1%BW for various undulators.

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