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USING DECOHERENCE TO PREVENT DAMAGE TO THE SWAP-OUT DUMP FOR THE APS UPGRADE*

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Abstract

The Advanced Photon Source (APS) is pursuing an upgrade of the storage ring to a hybrid seven-bend-achromat design, which will operate in swap-out mode. The ultra-low emittance (about 30 pm in both planes) combined with the desire to provide high charge (15 nC) in individual bunches, entails very high energy density in the beam. Simple estimates, confirmed by simulation, indicate that interaction of such a bunch with the dump material will result in localized melting. Over time, it is possible that the beam would drill through the dump and vent the ring vacuum. This would seem to prevent extraction and dumping of bunches as part of swap out, and also suggests that transferring of bunches out of the ring carries significant risk. We devised an idea for using a pre-kicker to cause decoherence of the target bunch emittances, making it safe to extract. Simulations show that the concept works very well.

INTRODUCTION

The Advanced Photon Source (APS) is a third-generation, 7-GeV synchrotron light source that has been in operation for over two decades. In order to enhance scientific capabilities, we are pursuing an upgrade that involves replacing the existing storage ring with a hybrid seven-bend-achromat design [1] including reverse bending magnets [2, 3], operating at 6 GeV. Because the new design [4] is pushed to very low emittance, nonlinear dynamics is challenging, which necessitates use of swap-out mode [5, 6]. In this mode, when electron bunches are depleted due to the limited lifetime, they are replaced in their entirety by new, full-charge bunches from the injector. Rather than attempt to recover these bunches (e.g., in a high-energy accumulator [6]), we will discard them in a swap-out dump located in the storage ring.

To maximize the Touschek lifetime and provide quasi-round beams in x-ray beamlines, we will generally operate the ring with an emittance ratio κ of approximately unity. This results in emittances of about 30 pm in both planes. When combined with the desire to provide high charge (15 nC) in individual bunches, this entails very high energy density in the beam. Indeed, the energy density in a single 15-nC bunch hitting the swap-out dump in APS-U will be very similar to the energy density in the entire 100-mA beam in the APS today. That beam has been observed to create grooves in copper and tungsten [7].

Simple estimates, confirmed by simulation, confirm that interaction of a 15-nC APS-U bunch with the dump material will result in localized melting. Over time, it is possible that the beam would drill through the dump and vent the ring vacuum. Even if this did not occur, we would still have a concern about vacuum pressure bursts and clouds of material ejected every 5 to 15 seconds (the expected swap-out interval). This phenomenon would seem to preclude extraction and dumping of bunches as part of swap out, fatally undermining the operational scheme for the new ring. It also suggests that transferring of bunches out of the ring (e.g., into an accumulator ring) carries significant risk, since the bunches might hit a septum or other component, causing catastrophic damage.

After considering many other solutions, we adopted a concept using a pre-kicker to cause decoherence of the target bunch, inflating the emittances and making it safe to dump the beam into commonly-used materials. Simulations were performed using `elegant` [8] and `MARS` [9].

ESTIMATE OF TEMPERATURE RISE

The peak energy density in the beam is

$$d = \frac{N_e m_e c^2 \gamma}{2\pi\sigma_x\sigma_y}, \quad (1)$$

where N_e is the number of electrons, m_e is the electron rest mass, γ is the relativistic factor, and σ_x (σ_y) is the horizontal (vertical) rms beam size. For the present 7-GeV APS storage ring, the peak energy density for the full 100 mA beam is 0.13 TJ/m^2, using $\sigma_x = 280\,\mu$m and $\sigma_y = 11\,\mu$m. As mentioned above, dumping this full beam is known to make clearly visible grooves in copper and tungsten, even though the dumps take several turns. If kicked directly into the dump, the APS-U beam will have $\sigma_x = 6.5\,\mu$m and $\sigma_y = 24.5\,\mu$m, giving a peak energy density for a single 15 nC bunch of 0.09 TJ/m^2. Since the ejected bunch hits the dump all at once, rather than over several turns as in the APS case, we expect significant material damage.

We can make a rough estimate of the temperature rise by ignoring both the temperature dependence of the specific heat and the possibility of phase transitions. The latter is clearly appropriate since if such occur, there is already a serious problem. With these assumptions, the temperature rise is

$$\Delta T = \frac{D A_w}{C_m}, \quad (2)$$

where D is the dose in J/kg (or Gy), A_w is the atomic weight in kg/mole, and C_m is the molar specific heat in J/K/mole. The dose is obtained from

$$D = S_{pc}\frac{N_e}{2\pi\sigma_x\sigma_y}, \quad (3)$$

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where S_{pc} is the collisional stopping power. The collisional stopping power gives the energy loss into ionization, which directly results in heating of the material. The NIST database [10] gives values for S_{pc} in MeV $\cdot$ cm^2/g, which we multiply by $10^5 q_e$ (q_e being the electron charge) to covert to J $\cdot$ m^2/kg. The dose can be conveniently computed for many materials using the Android app TAPAs [11].

Table 1 shows estimates for some common materials that might be used in the dump. Empirically, we have found that when Eq. 2 predicts ΔT to exceed the melting temperature for a given material, that material will suffer damage. Examples in the present APS SR of materials damaged by beam dumps include copper and tungsten; however, aluminum components exposed to the beam have never shown beam-induced failure. In the former case, the melting temperatures were exceeded according to Eq. 2; whereas, in the latter it was not. Generally lower-Z, lower density material such as carbon or aluminum can survive a beam dump without mechanical failure; however, because of the very high energy densities of the APS-U beam, the collisional (local heating) component appears sufficient to damage essentially any solid material.

SIMULATION OF SWAP-OUT WITH DECOHERENCE

Because swapping a bunch is a deliberate act, we decided to investigate the possibility of using a transverse kick followed by decoherence as a way to inflate the emittance of the bunch before extracting it. To ensure that the beam cannot damage the dump, we need to decrease the electron density by a minimum factor of between 2 and 7, depending on the material. The magnitude of the kick must be sufficient to produce the desired reduction in beam density without loss of beam.

We used the parallel version of `elegant` [12, 13] to simulate the decoherence process using element-by-element tracking with canonically-integrated elements. Because the bunch has fairly high charge, we included the short-range longitudinal and transverse wakefields, using a model that includes nine impedance elements in each of the 40 sectors of the APS-U lattice [14]. The rf systems (harmonics 1296 and 5184) are included with the passive higher-harmonic cavity tuned so as to maximize the Touschek lifetime in the presence of a 48-bunch, 200-mA beam, using a method similar to [15]. We also included lattice errors and correction using the results of a commissioning simulation [16].

Each of the 48 bunches was modeled with 10,000 simulation particles. In order to make the simulation run times manageable, we tracked the multi-bunch beam to equilibrium using a simplified model that replaces the ring with a single element (`ILMATRIX`, or individualized linear matrix). After equilibrium is achieved, the model switches to element-by-element tracking. Shortly after this occurs, bunch 0 is given a vertical kick to initiate decoherence. Transverse and longitudinal bunch-by-bunch feedbacks are included to ensure stability of the other bunches; the transverse feedback kick is limited to 1 µrad so that it does not significantly interfere with the decoherence kick.

The decoherence kick is modeled as an idealized offset of the vertical slope centroid of bunch 0 at a location with $\beta_y = 1.88$ m and $\alpha_y = 0$. For kicks of 0.15 mrad and below, no beam is lost, while for 0.20 mrad and above, there is beam loss after a few hundred turns or less. From the dynamic aperture alone we would have expected no losses below about 0.8 mrad, indicating that the losses at these low kick angles are a result of single-bunch collective effects.

We used tracking data to compute the maximum particle density as a function of pass for several cases, as shown in Fig. 1. The density is seen to decrease but also to oscillate. In phase space, complex patterns with x-y correlations are seen to form, a result of operating on the $\nu_x - \nu_y = 59$ resonance. As these wash out, after about 250 passes, the oscillations in the density subside. After about 200 passes, the density is consistently below 1% of the original value. After waiting about 400 passes, a factor of 330 reduction is obtained. It appears that results are quite similar for kicks of 0.1 and 0.15 mrad. One could perhaps dump the beam as quickly as ~50 passes after the decoherence kick, but it seems prudent to wait about 250 passes.

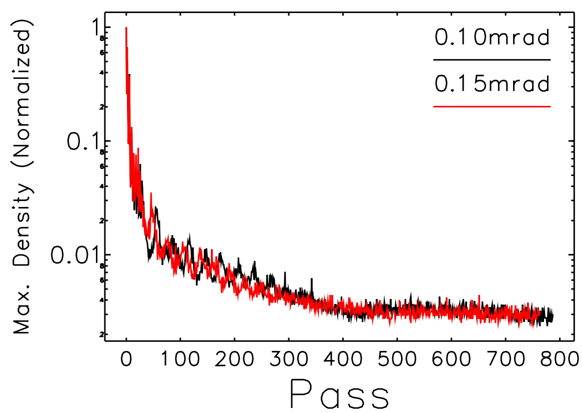

Figure 1: Maximum particle density in bunch 0 as a function of the number of turns since the vertical kick.

Figure 2 provides a more visual comparison of the particle density on the dump surface for two cases: when the beam is kicked onto the dump without decoherence and when the beam is kicked onto the dump 300 passes after an 0.15-mrad decoherence kick.

SIMULATION OF TEMPERATURE RISE WITH DECOHERENCE

Energy deposition is examined in various materials and different geometries using the matter-particle interaction program `MARS`. Simple rectangular block geometry is employed, assuming normal-incidence beam. Small-volume geometry arrays are required to accurately assess the dose and heating from APS-U beam loss. To facilitate this, the central 1.02-mm by 1.02-mm x-y region of the collimator

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Table 1: Temperature rise estimates for the swap-out dump for APS-U in the absence of decoherence, assuming a single 15-nC bunch is kicked into the dump. For commonly-used metals, we exceed the melting temperature by a significant margin. Note that graphite in vacuum does not melt, but rather sublimates at 3915 K.

Material	D	C_m	A_w	ΔT	T_{melt}	$\Delta T/(T_{melt}-298)$
	MJ/kg	J/mole/K	kg/mole	K	K	
Graphite	3.38	8.52	12×10^{-3}	4760	N/A	N/A
Beryllium	2.96	16.4	9×10^{-3}	1622	1560	1.3
Aluminum	3.23	24.2	27.0×10^{-3}	3600	933	2.5
Titanium	3.03	24.9	47.9×10^{-3}	5830	1941	3.5
Copper	2.94	24.4	63.5×10^{-3}	7650	1358	7.2
Tungsten	2.53	24.3	183.8×10^{-3}	19,000	3695	5.6

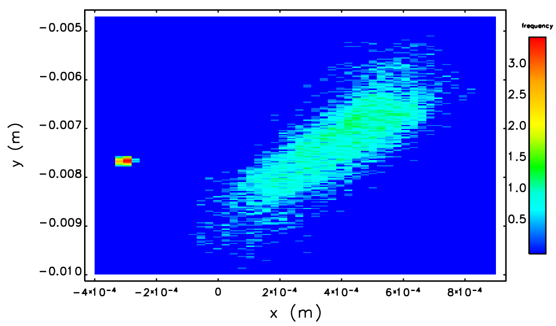

Figure 2: Density map (log scale) for two cases. Left: beam is kicked onto the dump without decoherence. Right: beam is kicked onto the dump 300 passes after receiving a 0.15-mrad decoherence kick. The beams are offset horizontally for clarity.

is divided into 51 by 51 equal 0.02-mm by 0.02-mm by 10 mm voxels.

Transverse distributions are read externally from `elegant` output; typical initial electron distributions employ 10^6 macroparticles. The maximum dose is obtained for several candidate materials including graphite, aluminum, and titanium alloy TiAl6V4 (TiA, containing by weight 6 percent Al and 4 percent V).

Figure 3 shows the peak ΔT profiles along the beam path assuming normal incidence without decoherence. The tungsten profile was not generated for this case. These results roughly agree with the estimates in Table 1.

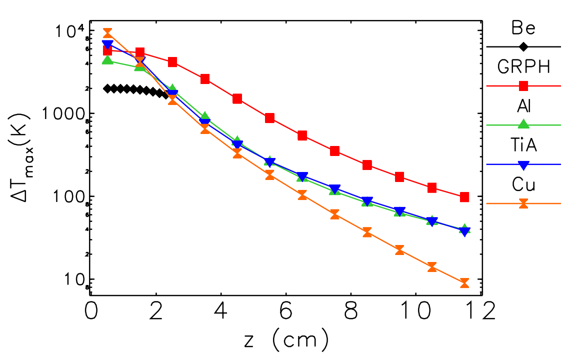

Figure 3: Longitudinal peak ΔT distributions for a single bunch without decoherence, based on MARS simulations.

If the swap-out bunch is kicked first by a weak stripline kicker (pre-kicker), then dumped after a delay of about 250 turns to allow decoherence, a significant reduction in the energy density results, allowing the bunch to be dumped without damaging the target. Using data from `elegant` for this case, MARS predicts peak ΔT values of 16.8K, 11.9K, 19.4K, 44.8K, and 269K in graphite, aluminum, TiA, copper, and tungsten, respectively. Peak axial ΔT profiles from MARS geometry regions for these five materials are plotted in Fig. 4. The peak temperature excursions after decoherence show a large reduction compared with those prior to decoherence listed in Table 1.

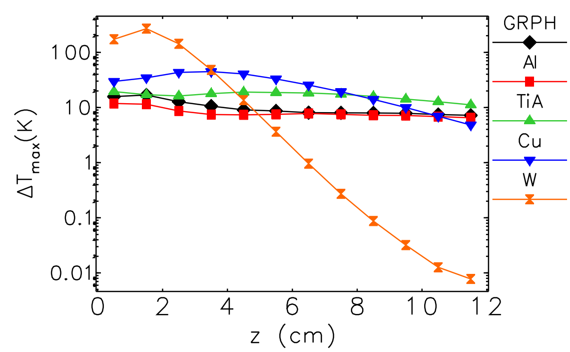

Figure 4: Longitudinal peak ΔT distributions for a single decohered bunch, based on MARS simulations.

CONCLUSIONS

Due to concerns about melting of the swap-out dump for APS-U, we modeled the effect of a pre-kick applied to one bunch out of 48 in a 200 mA fill, which we postulated would allow inflating the emittance through decoherence. We found that the magnitude of the kick was limited by the stability of the bunch in the presence of the short-range impedance. However, a vertical kick of about 0.15 mrad caused no beam loss and provided greater than 100-fold decreases in the particle density in a few hundred turns.

The APS-U swap out system will include a special kicker just for initiating decoherence. The swap out kickers will not fire unless the decoherence kicker is verified to have kicked the target bunch.

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