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USE OF SOLID XENON AS A BEAM DUMP MATERIAL FOR 4TH-GENERATION STORAGE RINGS*

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Abstract

Damage to tungsten, aluminum, and titanium beam dumps has been observed in the Advanced Photon Source (APS) due to the high charge (368 nC/store), high energy (7 GeV), and short loss time (~15μs). Owing to the higher charge (736 nC/store) and much lower emittance (42 pm vs 2.5 nm), this issue is expected to be much more severe in the APS Upgrade. This strongly suggests that carefully-designed dumps are necessary in 4th-generation electron storage rings to prevent catastrophic damage to vacuum systems when, for example, rf systems trip. However, it also implies that the dump will be damaged by each strike and will thus need to be "refreshed," perhaps by moving the dump surface vertically to expose undamaged material. Xenon, a gas that solidifies at 161K, is an intriguing possibility for a beam dump material. Calculations suggest that as the beam spirals in toward a dump in a high-dispersion area the tails of the electron beam would vaporize sufficient xenon to rapidly diffuse the beam and render it harmless. The dump surface could be periodically reformed without breaking vacuum. Issues with the concept include the need to protect the frozen xenon from wakefield heating.

INTRODUCTION

The electron beam in the existing APS storage ring has damaged copper, tungsten, aluminum, and titantium in various circumstances [1, 2]. The electron beam in the APS-U storage ring [3] will have even higher energy density, so that removing the beam requires either taking steps to inflate the emittance or else accepting damage to the dump. In the case of swap-out, we have proposed the use of a pre-kicker to inflate the emittance of the target bunch through decoherence, which takes about 250 turns to fully develop [4]. This provides a ~100-fold decrease in particle density for a single bunch out of 48.

Using this method for whole-beam aborts is problematical, primarily because when the rf systems trip it takes only 50 turns before the beam strikes the dump. Since the whole beam has 48 times as much stored energy as a single bunch, we would need to inflate the emittance by a much larger factor compared to the swap-out case. For these reasons, we assume that the whole-beam dump will have a sacrificial surface that is damaged and refreshed after each abort.

An alternative method of decohering and even aborting the beam is using a gas jet. As we'll show, with a high-Z gas of sufficient density, the angular scattering can be large enough to significantly decrease the electron beam density. However, creating the jet in a conventional way is problematical, since it seems to require a very fast-opening valve and high-pressure, high-temperature gas storage, as well as a way to collect the gas after the fact. This inspired the idea of using a cryocooled beam dump made of solid xenon, which might yield a gas jet when the tails of the beam begin to vaporize the surface; it would also cryopump the xenon after the event. We start by modeling a hypothetical xenon gas column, then discuss the implications for a solid xenon dump. Xenon seems attractive because it is relatively inert and has a relatively high Z of 54. It solidifies at 161.4 K and vaporizes at 165.0 K. In the solid form, it has a relatively high density (3640 kg/m^3) and thus a relatively short radiation length of 2.3 cm.

EFFECTS OF A GAS COLUMN

For an initial exploration, we assumed a local pressure bump that covers the entire beam-pipe aperture, ignoring for now the process of creating the bump.

The `MATTER` element in `elegant` [5–7] allows modeling scattering from a material given the thickness, mass density, atomic number, and atomic mass. We inserted a single `MATTER` element in the APS-U lattice [3] at the location of the whole-beam dump in Sector 37. This location was chosen because of the high horizontal beta function (which accentuates the effect of angle scattering) and for other reasons described below.

Tracking was performed starting with with $\epsilon_x = \epsilon_y = 30$ pm, $\sigma_\delta = 0.13\%$, and $\sigma_t = 100$ ps, using 100k particles in each of 48 bunches. Both the beam-loaded main and harmonic rf cavities were included. The areal mass density d of the gas column was varied over 0.003 to 0.3 kg/m^2. For reference, note that a 1-mm-long column at STP corresponds to $d = 0.0059$ kg/m^2. As Fig. 1 shows, the emittances inflate by three orders of magnitude in a few turns, which is faster and more effective than decoherence from a kicker. This gives a three order of magnitude decrease in transverse particle density.

These simulations demonstrate the potential of a xenon gas column for diffusing an intense electron beam. Several options might be considered for creating such a gas column. A gas reservoir with a fast-opening valve is a possibility for creating a gas jet. One could also vaporize solid xenon with a laser. The concern with such schemes is that the valve or laser might fail to operate when needed, allowing the undiluted beam to hit the vacuum chamber. Alternatively, one could vaporize solid xenon with an intense electron beam, which just happens to be available and cannot fail to be present when needed.

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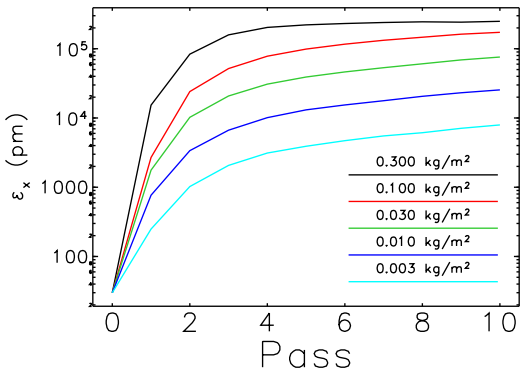

Figure 1: Emittance as a function of passes through a xenon column of various areal densities.

SOLID XENON DUMP

Xenon solidifies below 160 K and vaporizes at 165 K [8]. The vapor pressure at 44 K is 0.1 nT [9], which has a negligible effect on beam lifetime, so we'll assume that it is held at this temperature by a cryocooled metal substrate. To vaporize the xenon, we must first bring the temperature to 160 K, requiring 25.5 J/g, or 25.5 kGy. The heat of melting is 17.3 kGy [8]. Raising the temperature to 165 K requires 1.0 kGy [10]. Vaporizing the material requires 96.0 kGy [8]. The total dose required to take xenon from 44 K to vapor is 139.8 kGy. We'll assume that the heat capacity for the vapor is constant at 0.16 kGy K^{-1}, the value for STP [8].

Simulation of the beam abort was performed with `Pelegant` assuming 200 mA in 48 bunches, with each bunch represented by 100,000 particles. The simulation took under 10 hours on 640 Intel Broadwell cores. After letting beam equilibriate, we mute the generator power to the 12 beam-loaded rf cavities [11], following which the beam spirals toward the beam dump at a rate of 66 µm/turn, where one turn takes 3.68 µs. The rms beam sizes in the vicinity of the beam dump are $\sigma_x = 116$ µm and $\sigma_y = 16$ µm. Since the beam scrolls across the edge of the dump as the orbit decays, the footprint size on the beam dump differs from the rms sizes, and must be obtained from `Pelegant`'s record of lost-particle coordinates. The rms horizontal (vertical) footprint size is roughly (very close to) $0.25\sigma_x$ (σ_y).

Since the footprint is not gaussian in the horizontal plane, we analyzed the charge hitting $\Delta x = 5$ µm by $\Delta y = 5$ µm voxels that extend the full length of the dump. The collisional stopping power [12, 13] provides the dose D ignoring shower development, which is appropriate given the length of interaction. For solid xenon and a 6-GeV electron beam, we have

$$D[kGy] = \frac{0.223Q[nC]}{\Delta_x[mm]\Delta_y[mm]}. \quad (1)$$

The voxel length, typically ~ 15 mm, varies with horizontal position since the "speed-bump" dump has a vertically-oriented cylindrical surface with a 1-m radius. As Fig. 2 shows, vaporization begins at about 53.7 turns after the trip. (Use of 48 bunches in the simulation allows resolving fractional turns.) At this time, about 0.08% of the beam has interacted with the dump, implying that the beam centroid is about $3.15\sigma_x$ from the dump surface.

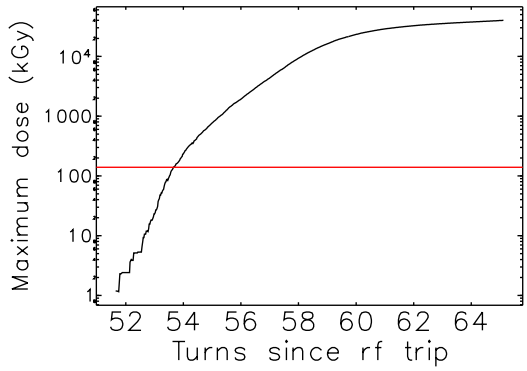

Figure 2: Maximum dose in the solid xenon versus turns since the rf trip. The red line shows the level required to vaporize xenon from a starting temperature of 44 K.

Knowing the dose also allows determining the temperature of the vapor and thus the rms velocity of the gas atoms. This allows us to estimate the size of the expanding gas cloud. In doing this, we incorrectly assume that the moving gas continues to be heated according to its original position in the solid. This is perhaps an underestimate, since the expanding gas cloud moves into a region of higher electron beam density. To compute the areal density of the cloud, we integrated the 90^{th}-percentile rms velocity versus time to obtain the radius of gas cloud, which is assumed to be semi-cylindrical. As shown in Fig. 3, the radius reaches $6\sigma_x \approx 0.7$ mm—encompassing more than 99% of the beam— at 55.6 turns after the rf trip, about 1.9 turns after vaporization begins. At this time, 1.1% of the beam has been intercepted by the dump. As shown in Fig. 4, the region of high dose extends about 50 µm below the surface. the areal density of the gas is 0.22 kg/m^2; consulting Fig. 1, this will inflate the emittance by three orders of magnitude in less than two turns. The dose map at this point (turn 57.6) is shown in Fig. 5.

The areal density will drop during this time as the gas cloud continues to expand, which will reduce the effect. However, the core of the beam has experienced even higher areal density at slightly earlier times in the expansion of the cloud. We've also ignored the 66 µm/turn motion of the beam toward the higher density gas near the dump surface.

ENGINEERING CONCEPT

The above simulations predict that about 0.4 mg of xenon will be vaporized between the rf trip and inflation of the emittance by three orders of magnitude. At this point, 57.6 turns after the rf trip, the beam will have made a channel ~ 100 µm deep and ~ 70 µm high.

The xenon gas is condensed onto a cold substrate such as copper that is cooled by a cryocooler. The substrate is cooled to below 44K, where the vapor pressure of solid Xenon is less than the vacuum pressure requirement for the

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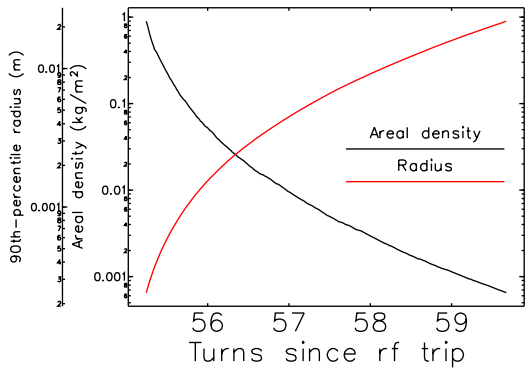

Figure 3: Estimated radius of the semi-cylindrical gas cloud and the areal mass density of the xenon atoms.

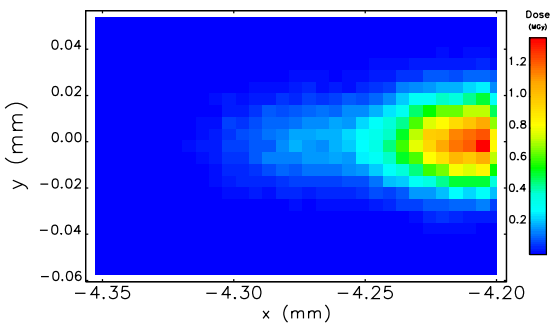

Figure 4: Dose imparted to solid xenon by tails of the electron beam at 55.6 turns after the rf trip.

stored beam chamber. The copper substrate is shaped as a blade that is inserted into the beam chamber similar to other collimators or absorbers. The thickness of the xenon layer should be several hundred microns to avoid damage to the copper substrate.

The process of charging the substrate with solid xenon is performed in an external chamber that is directly above the whole beam dump stored beam chamber. The coating thickness can be controlled carefully by allowing xenon gas to enter the chamber at a low partial pressure for a specific period of time period. All surfaces below the condensing point at that partial pressure will coat with xenon. The external processing chamber is isolated from the stored beam chamber with a gate valve. Once the substrate is coated with several 100 microns of xenon in the external chamber, UHV vacuum is restored and the load lock valve opened. Bellows on the external chamber allows enough motion of the external chamber to insert the substrate into the whole beam dump stored beam chamber. The bellows range of motion also allows indexing the substrate after beam dumps to expose fresh surface to the beam dump region.

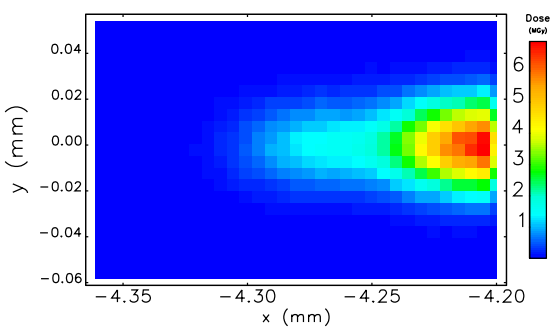

Figure 5: Dose imparted to solid xenon by tails of the electron beam at 57.6 turns after the rf trip.

The xenon surface can be restored after several series of stored beam dumps by retracting the system out of the stored beam chamber and above the load lock valve. Once the substrate is returned to the external chamber, the substrate can be warmed to vaporize all xenon from the substrate. The process to charge the substrate with xenon and insert back into the stored beam chamber is repeated on a periodic basis or after a predetermined number of beam aborts.

Design engineering challenges include developing a full thermal model with the thermal radiation load on the solid xenon surfaces and electron-beam induced thermal loads. Some temperature gradient through the xenon solid is acceptable since cryocooler capacities are sufficiently large to operate the substrate at temperatures below the required 44K to meet the vacuum performance requirements. The substrate operating temperature needs to be determined based on the total thermal load on the xenon. The electrical conductivity of the solid material needs to be determined to estimate the electron-beam-induced thermal loads. Providing an adequate rf seal between the xenon substrate and the stored beam vacuum chamber is perhaps the most significant challenge.

CONCLUSIONS

Due to the extremely low emittance and high charge, electron beams in fourth-generation storage ring light sources are expected to damage metal beam dumps, requiring the use of sacrificial surfaces to intercept aborted beams. A concept was explored for diffusing an intense electron beam in a fourth-generation storage ring using a gas cloud generated by the tails of the beam as it spirals toward a solid xenon dump. Simulations and estimates suggest that a dense cloud would envelop the beam in the APS-U after less than 0.1% of the beam was scraped off, resulting in a 1000-fold reduction in energy density in a few turns. An engineering concept was outlined for a system that allows reforming the xenon surface periodically.

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