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TESTING OF A FAN-OUT KICKER TO PROTECT COLLIMATORS FROM LOW-EMITTANCE WHOLE-BEAM ABORTS IN THE ADVANCED PHOTON SOURCE STORAGE RING*

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Abstract

In the Advanced Photon Source Upgrade storage ring, the horizontal collimators protect the rest of the machine from whole beam aborts; however, as shown in previous experiments, the collimators themselves must also be protected from the full intensity of the lost store. The suitability of a vertically-deflecting fan-out kicker was evaluated experimentally. Aborted beam strikes the surface of the collimator with the expectation that the absorbed energy density or dose is reduced sufficiently to maintain the integrity of the device. We discuss the results from recent measurements where a fan-out kicker was employed to test this concept. 6-Gev, 200-mA (737-nC) APS stored beam is used to irradiate both aluminum and copper collimator test pieces.

INTRODUCTION AND MOTIVATION

Previous experiments in the Advanced Photon Source (APS) storage ring (SR) have shown that low-Z material such as aluminum will be damaged due to high-energy-density (HED) conditions created when struck during whole-beam loss events [1–3]. We have simulated these conditions which are anticipated for the APS upgrade (APS-U) [4] where electron beam horizontal emittance will be reduced by two orders of magnitude and brightness will increase by factors of 200-500. Though approaching the horizontal emittance reduction with the original APS lattice is impractical, horizontal beam size can be reduced along with minimization of the vertical emittance sufficiently to obtain APS-U-like energy density. Twiss parameters for a lattice minimizing both beta functions at the collimator location (s = 1023.78 m), is presented in Fig. 1; this position is at the downstream end of SR rf Sector 37 (S37).

EXPERIMENTAL DESCRIPTION

The collimator experiment was conducted during a studies period at the end of April 2023. The collimator test pieces were mounted to the end of a water-cooled scraper assembly housed within a 10-cm (4-in.) vacuum tee. Figure 2 shows a view from the upstream end of the assembly (beam into the page), with the scraper fully inserted into the chamber in the horizontal, x-direction. During user operations, the

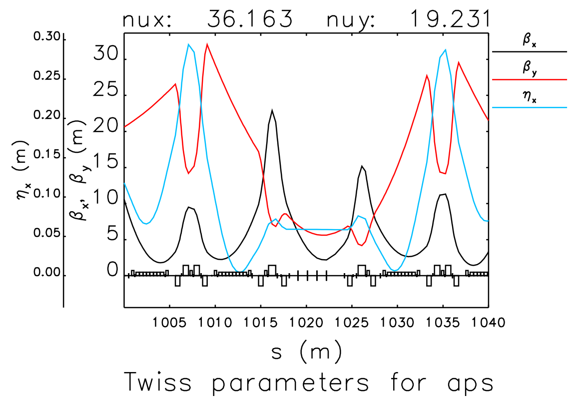

Figure 1: Reduced horizontal beta lattice for the S37 collimator experiment. Collimators are located at s = 1023.78 m.

assembly is retracted such that the apex of the collimators are parked 30.85 mm inboard of the beam centerline (x = −30.85 mm). During beam abort studies, the assembly is inserted to x = −4 mm for injection and x = −2 mm for aborts. A nominal radius of R = 800 mm has been machined on each test piece's beam-facing surface. Measurements indicate a ~ 6% smaller value of R in the machined pieces. As in earlier studies, a diagnostic imaging system was used capture emission and post-beam strike images [3].

The fan-out kicker (FOK) is a vertically-deflecting pulsed magnet installed in Sector 36 of the SR. The FOK produces

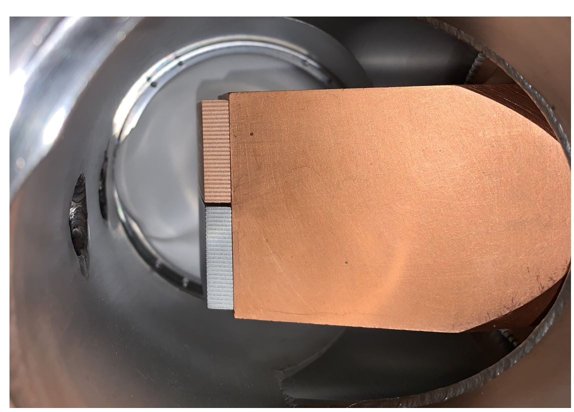

Figure 2: The water-cooled scraper assembly in S37. The collimator test pieces are mounted to the end of the assembly. The view is looking downstream.

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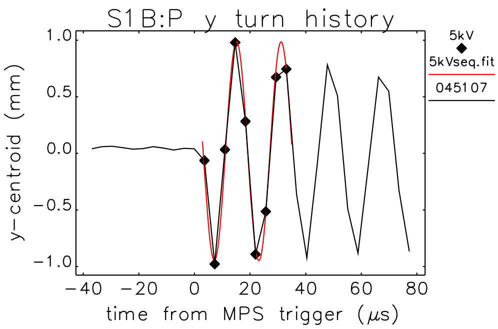

Figure 3: Vertical bunch centroid oscillation caused by the FOK.

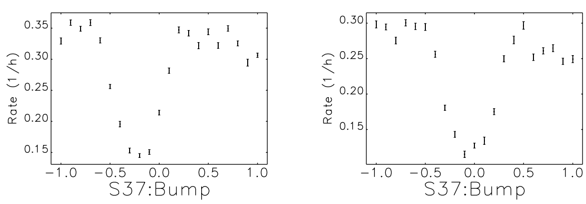

Figure 4: Gap localization from loss rate data. Left: before orbit correction; right: after orbit correction. H-scale: mm.

roughly a half-sine wave magnetic field lasting just over one SR turn (T_o = 3.68 μs). Charging the FOK capacitors to 2 kV yielded a 245 μrad kick and approximately a 2-mm amplitude displacement at the S37 collimator location. An example of bunch centroid betatron oscillations caused by the FOK and monitored with the turn-by-turn BPMs is presented in Fig. 3. Also shown is a sinusoidal fit to the first two oscillation periods after the FOK fires. The ratio of the oscillation frequency to the ring frequency is 0.23 in good agreement with fractional component of the vertical tune shown in Fig. 1.

COLLIMATOR STUDIES

Studies included conditioning at collimator injection and abort positions, gap localization, wakefield measurements, and beam aborts. Here we focus on the latter two items, but first a few words on conditioning and gap localization. Having the collimator-scraper assembly in the machine for the entire user run, allowed for faster conditioning at the injection ($x = -4$ mm) and abort locations ($x = -2$ mm). As in past studies, the gap center and beam reference height were determined by bringing the collimator apex to approximately $x = -1$ mm and scanning a low current beam vertically past the gap. The loss rate decreases when the beam is opposite the slot between the collimator pieces, due to increased quantum lifetime. Loss rate versus vertical position in mm, before and after orbit alignment, are plotted in Fig. 4.

Beam Aborts with the Fan-Out Kicker

Six separate beam aborts with 200-mA, 6-GeV beam were employed to strike the collimator test pieces; three on the copper and three on the aluminum. The six cases are summarized in Table 1.

Table 1: Beam Abort Case List

Case No.	Vertical Offset (mm)	Material	Fan-Out Kicker Voltage (kV)
0	+1.5	Cu	2
1	-1.5	Al	2
2	-2.0	Al	1
3	+3.0	Cu	0
4	-3.0	Al	0
5	+2.0	Cu	3

As in past experiments, visible-light emissions from the test pieces were observed with the diagnostic imaging system during beam strikes; an example from Case 0 is presented in Fig. 5. The beam moves from right to left. The emission is more diffuse than in previous experiments and a large amount of radiation “snow” is present on the full frame indicating the camera was irradiated.

Images of the collimator surfaces from the diagnostic imaging system after the planned beam strikes are shown in Fig. 6. The field of view at the collimator surface is 12 mm and the depth of field is approximately 2 mm. The gap between the test pieces is 0.87 mm. It is clear in the visible strike damage from Cases 1,2, and 4 on the Al, that the higher FOK voltages result in less damage.

Wakefield Effects

The goal is to explore whether wakefields [5] can be used to passively self-protect the APS-U collimators by expanding the beam during whole-beam aborts. Wakefield effects were studied by moving the scraper so that the beam was forced to pass within the 0.87-mm gap between the collimator test pieces. The gap depth is 6.35 mm (0.25"). The test pieces were fabricated with 1-mm spaced rulings; these rulings are visible in Fig 6 on the Cu test piece. The rulings serve as fiducial markings but may also be considered a chirping structure [6, 7]. An optimized structure in this case would be one maximally disruptive to the beam. The rulings are

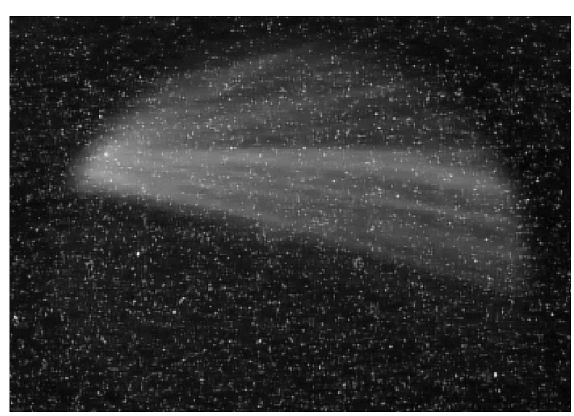

Figure 5: Emission from Case 0 beam abort. The collimator apex is positioned at $x = -2$ mm. See text for more details.

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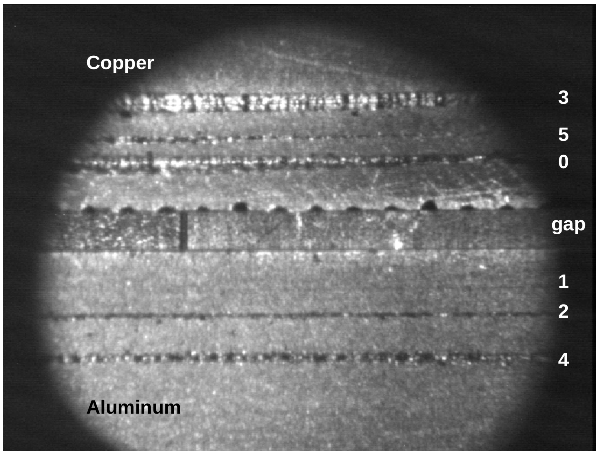

Figure 6: Image of the collimator test pieces after the beam abort study. The collimator apex position is $x = 4.15$ mm. Digits indicate the case number.

nominally cylindrical with a depth of 0.127 mm (0.005"); the depth of every fifth ruling is 0.254 mm (0.010"). The aluminum surface facing the gap did not have rulings.

Beams with varying charge per bunch were studied. With 10-mA of stored beam (circulating charge of 37 nC), cases of 3, 6, and 9 bunches were employed. A significant reduction in current was observed in the 3 and 6 bunch cases as the beam entered the gap region; however; little loss was seen for the 9-bunch case. A similar effect was observed with a 20-mA, 18-bunch beam: no loss was observed as the gap was moved over the beam; however, lifetime was reduced while the beam was in the gap. In Figure 7, the 3, 6, and 9-bunch current and collimator apex position waveforms are plotted versus time. The current waveforms are temporally aligned by overlaying the respective scraper position traces.

ANALYSIS

Peak dose levels in the collimators are determined from the transverse sizes of the circulating beam $\sigma_{x,y}$, collisional

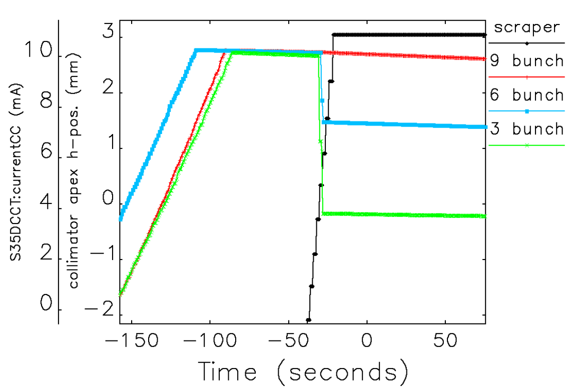

Figure 7: Current as the collimator gap is moved over 3, 6, and 9-bunch beams all with initially 10 mA.

Table 2: Beam Parameters and Peak Dose during 200-mA Beam Aborts. At 6 GeV, $S_{pc} = 2.153$ MeV-cm^2/g for Al and 1.959 MeV-cm^2/g for Cu. $\beta_x = 3.96$ m/rad, $\beta_y = 6.35$ m/rad, $\eta_x = 0.0584$ m

C. N.	Kick kV	ϵ_x (nm-rad)	ϵ_y (pm-rad)	σ_x (μm)	σ_y (μm)	D_G (MGy)
0	2	2.102	17.13	108.3	10.43	20.28
1	2	2.245	14.15	110.9	9.48	23.90
2	1	2.166	22.69	109.5	12.00	19.19
3	0	1.844	50.88	103.5	17.97	12.32
4	0	2.086	40.33	108.0	16.00	14.58
5	3	2.029	27.50	107.0	13.22	16.22

stopping power S_{pc} [8], and total number of electrons $N_e = I_b L/c$ where I_b is the beam current and $L = 1104$ m is the full length of the SR. The SR period, $T_o = L/c$. This method has been shown to be a reasonable approximation to more detailed calculations [3]. Assuming Gaussian bunches, the peak dose may be expressed as,

$$D_G = S_{pc} \frac{N_e}{2\pi\sigma_x\sigma_y} \tag{1}$$

Beam parameters and calculated peak dose values using Eq.1 for the six cases given in Table 1 are listed in Table 2. For the dispersion contribution, we assume a momentum spread $\Delta p/p = 0.001$. RMS spot size is determined as,

$$\sigma_{x,y} = \left(\beta_{x,y}\epsilon_{x,y} + \left[\eta_{x,y}\frac{\Delta p}{p}\right]^2\right)^{1/2} \tag{2}$$

Here we assume $\eta_y = 0$. The calculations ignore the effect of the FOK. Although the vertical emittance was not well controlled due to sextupoles inside the bump being inadvertently left on, it seems clear that the use of the fanout kicker significantly reduced the effective dose. For example, Case 5 (Cu, 3 kV) has higher nominal dose than Case 3 (Cu, 2 kV), but much less damage. Case 1 (Al, 2 kV) has much higher dose than Case 4 (Al, 0 kV), but no visible damage. Simulations are planned with the actual conditions to better understand the potential confounding effect of the variable vertical emittance.

CONCLUSION

We observed that the fan-out kicker can cause a reduction in damage to collimator surfaces. As expected, because of its longer radiation length, much less damage is observed in aluminum than in copper under similar conditions. A fan-out kicker is planned for APS-U to protect the collimators; it will fire whenever a beam abort is commanded.

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