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VACUUM CHAMBER THERMAL PROTECTION FOR THE APS*

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Introduction

The addition of undulators and wigglers into synchrotron storage rings created new problems in terms of protecting the integrity of the ring vacuum chamber. If the photon beam from these devices were missteered into striking an inadequately cooled section of the storage ring vacuum chamber, the structural strength might be reduced sufficiently that the vacuum envelope could be penetrated, resulting in long downtime of the storage ring. The new generation of high-energy synchrotron light sources (e.g., ESRF and APS) will produce photon beams of such high power density that cooling of the vacuum chamber will not prevent a potential penetration of the vacuum envelope, and other methods of preventing this occurrence will be required. Since active methods will be used to ensure that the beams are delivered to beam lines for users during normal operation, there is a need for passive protection methods during non-routine operation, such as turning on new beam lines, injection, etc., when the active systems may be disabled. In addition, the passive methods could prevent the problem from arising and provide the rapid time response necessary for the highest power beams, a property that might not be easily and reliably provided by active methods during the early operation of these machines.

This paper summarizes the results of a task group that studied the problem and outlines passive methods of protection for the Advanced Photon Source (APS).

Thermal Sources in the APS

Table I summarizes the main sources of thermal power in the APS storage ring, together with the power density typical of an electron beam welder for aluminum (vacuum chamber material for the APS). Not included in this table are additional low-power thermal sources, such as higher mode losses due to electromagnetic heating of the vacuum chamber components, since they are less than 100 watts and are widely distributed over many vacuum chamber components. From Table I it is clear that the undulator beams, if missteered into the ring vacuum chamber, could easily start to melt the aluminum chamber (if normally incident) in a time interval of a few milliseconds, independent of the available cooling. However, the grazing angle of the photon beam relative to the chamber surface will normally be quite small, decreasing the power density by the grazing angle. If the grazing angle is less than 20 mrad, there will be a sufficient decrease of the power density to prevent the rapid melting of the vacuum chamber surface. Otherwise the thermal risk to the vacuum chamber becomes a question of the capacity of the available cooling to handle the average incident power.

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Table I
Sources of Thermal Energy Posing Potential Risk to the Vacuum Chamber

Thermal Source	Power* or (Energy)	Size ($\Delta X \times \Delta Y$) or $\Delta\theta \times \Delta\phi$ HWHM	(Energy Density) or Power Density	Absorb Power Density on Surface Normal Incidence
e^+ beam	(7.5 kJ) pulsed	0.3 × 0.09 mm^2	(0.3 MJ/mm^2)	13 kW/mm^2 pulsed for Δt = 2.5 msec beam loss
Undulator A K = 2.5	30 kW DC	135×60 μrad^2	0.93 $MW/mrad^2$	9.3 kW/mm^2 DC (L=10 m)
Undulator B K = 1.1	10.7 kW DC	70×60 μrad^2	0.64 $MW/mrad^2$	6.4 kW/mm^2 DC (L=10 m)
Wiggler K=9	70 kW DC	525×75 μrad^2	0.45 $MW/mrad^2$	4.5 kW/mm^2 DC (L=10 m)
Dipole Magnet Radiation	20 kW DC	40×0.075 $mrad^2$	1.7 $kW/mrad^2$	67 W/mm^2 DC (L=5 m)
Electron Beam Welder-Al	-	-	-	0.3 kW/mm^2 DC

*All values based on E_0 = 7 GeV, I_0 = 300 mA operation of storage ring.

The APS vacuum chamber is an extruded aluminum chamber with a narrow slot for vacuum pumping and photon beam extraction.[1] The vertical height of this slot is the smallest aperture for the photon beam and therefore the major point of concern. Figure 1 shows this vertical aperture as a function of longitudinal distance (starting from the middle of the undulator) along the photon beam direction. The photon beam is generated by a circulating beam centered in the beam chamber of the undulator. For a vertical deflection angle, ϕ, of the circulating beam and therefore of the photon beam centroid, the photon beam will strike the surface of the slot for $0.45<\phi<0.55$ mrad. The footprint of the undulator beam on the surface of the slot will be approximately (1500 x 2 mm^2) with a grazing angle of about 0.5 mrad, well below the 20-mrad limit. Consequently, the instantaneous power density is small enough that melting of the chamber should not be a problem, if adequate cooling is available to handle the total incident beam power. If the circulating beam is

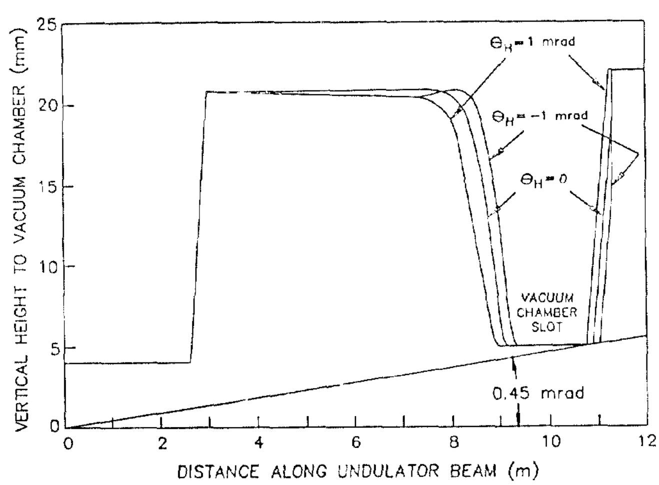

Fig. 1. The vertical vacuum chamber height as a function of distance along the undulator photon beam. The height is shown for horizontal closed-orbit divergence angles of +1, 0, and -1 mrad.

missteered vertically by ϕ>0.55 mrad, the photon beam enters the beam ellipse at approximately 42 mrad into the bend angle of the subsequent dipole magnet (total bend angle of 78 mrad). At this point the beam size is about (20 x 2 mm^2) and has a grazing angle to the vacuum chamber surface of about 42 mrad. In this case, cooling of the vacuum chamber does little to prevent melting of the aluminum chamber. Therefore, this condition must be prevented from occurring whenever the storage ring operates with undulators and at high beam current.

Potential Sources of Vertical Missteering

The APS task group studied a large number of potential sources of vertical beam missteering arising from accidental and intentional events. The event considered to be most likely to occur was a change of the vertical bend angle of one of the 360 vertical correction magnets. With a total of 1.25 mrad of bend possible (at 7 GeV), a single correction magnet could easily illuminate the beam ellipse. Each of these magnets is powered by a separate pulse-width-modulated power supply which could trip off or go to full power either intentionally or accidentally, steering the circulating beam and therefore the photon beam into the ellipse of the beam vacuum chamber.[2]

Although the vertical missteering of the circulating beam is necessary for the photon beam to illuminate the ellipse, the circulating beam must be able to continue to circulate unimpeded in the beam chamber for periods of time longer than one millisecond (~300 revolutions). The vertical gap of the undulator itself introduces a small aperture, which naturally restricts the magnitude of the closed orbit distortions to rather small values before the circulating beam hits this aperture and extinguishes the photon beam in several revolutions (<100 µs). Figure 2 shows the vertical closed orbit distortions (position, Y_{co}, and vertical angle, Y'_{co}) of the circulating beam at the center of the undulator resulting from one vertical correction magnet changing its value (from the corrected closed orbit value). The closed orbit distortions at all undulators will fall on the circle (ellipse in unnormalized units) with radius r_{co}, which is proportional to the strength of the vertical bend angle change and the square root of the beta function at the correction magnet. Also shown are the apertures for the undulator vacuum chamber and the vacuum chamber slot. The shaded area indicates where the range of values of potential risk to the vacuum chamber is greatest. In that region, the undulator beam will illuminate the beam ellipse and the circulating beam will continue to circulate unimpeded by the undulator vacuum chamber aperture.

Figure 3 shows the actual closed orbit distortions in all 40 undulator regions for each of several correction magnets changing their value by 0.5 mrad. It is clear that the condition can occur where the photon beam illuminates the surface of the beam ellipse and the circulating beam does not hit the undulator aperture itself. The likelihood of this occurring is reduced if more undulators or their vacuum chamber apertures are added to the ring, but even with all straight sections filled with undulators the risk to the vacuum chamber is still not zero. The risk remains because the undulator aperture and the beam chamber ellipse aperture for the photon beam occur at different betatron phases, and their restrictions don't fully overlap. The condition of overlapping aperture can be improved if the vertical betatron function in the undulator is increased to greater than 16 m, but most undulator sections must still have the same vacuum chamber aperture in order

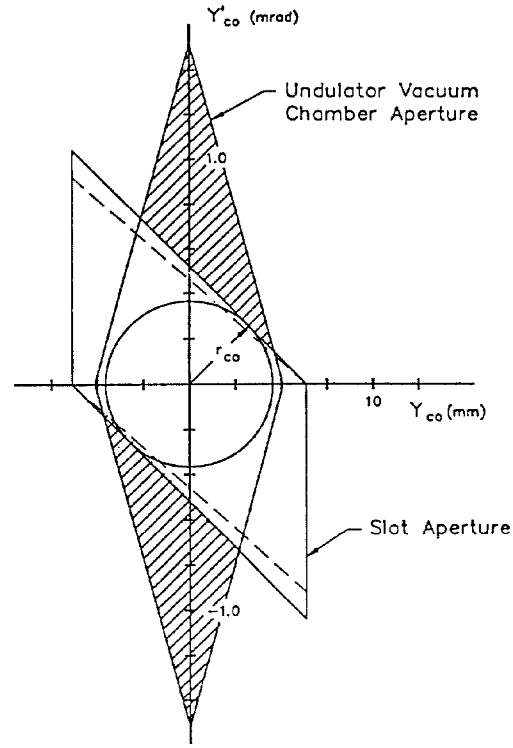

Fig. 2. The vertical closed orbit distortions in all undulators, resulting from a single vertical kick, lie on a circle of radius r_{co}. The trapezoids shown are the aperture seen by the beam for the undulator vacuum chamber gap and the vacuum chamber slot. The shaded area is the region of potential risk to the ellipse of the beam vacuum chamber.

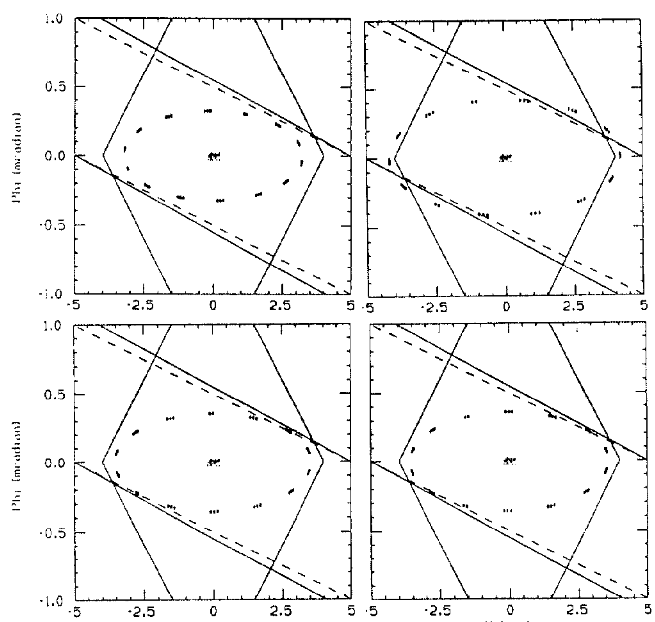

Fig. 3 Phase space plots for all 40 undulator regions with one vertical correction magnet at a time changing its value by 0.5 mrad. The points near the origin show the residual closed orbit distortions after correction and indicate the initial spread of the photon beam steering.

to reduce the risk to zero for an arbitrary number of installed undulators.

Passive protection methods

During normal operation of a fully commissioned storage ring, the primary protection will be an active detection circuit that identifies large excursions from the closed orbit in either the horizontal or vertical planes. Whenever the closed orbit excursion exceeds a safe value, the circulating beam will be aborted to a beam dump using a single-turn extraction system. However, during initial operation and subsequent tuning of new undulator beam lines, this active circuit will probably be disabled, and some method of passive protection will be required if undulators are installed and operating. The previously defined method of increasing the vertical betatron function in the undulator section is one example of a passive method of protecting the vacuum chamber from the risk of melting from a missteered undulator beam. This, however, restricts the minimum beta function in the undulator and also requires that all undulator straight sections have the same aperture restriction, even if no undulator is installed in that section.

The task group studied two other methods of passive protection that are less restrictive. The first method is to restrict the maximum vertical corrector strength to less than 0.25 mrad during times when the storage ring is operating at high current. This can be done easily by tapping down the voltage to the correction magnet power supplies such that corrections above 0.25 mrad are not possible. This range of corrections was found to be sufficient to handle the closed orbit corrections for quadrupole alignment errors up to the specified tolerance level of 0.1 mm. In case additional correction is required, the adjacent quadrupoles will have remotely controlled vertical jacks capable of providing an additional +0.4 mrad of correction. With the input current to the power supplies limited, even if one power supply goes to its maximum unregulated value, the circulating beam closed orbit distortions will still be less than a 0.4-mrad bend angle. This protection is sufficient to eliminate the possibility of the centroid of the photon beam illuminating the surface of the vacuum chamber slot, making additional cooling capacity unnecessary. In addition to individual correction magnets changing their value, studies of correlated changes have also been performed, and for those studied, the closed orbit of the circulating beam either failed to remain inside the undulator aperture or the photon beam failed to illuminate the surface of the vacuum chamber slot. For example, if all correction magnets in one period of the storage ring trip off from their value used to correct the initial closed orbit, the worst-case effective change was equivalent to a 0.25-mrad vertical bend angle, and the beam circulated inside the undulator aperture and did not illuminate the slot's surface.

The second method studied is to use beam scrapers to limit the amplitude of the closed orbit distortions allowed in the storage ring. The advantage of this method is that, although the location of the magnet causing the closed orbit distortion cannot be predicted, the location of the thermal problem can be, and therefore excursions in that region can be prevented. The ideal location for such a scraper would be in the middle of the dipole magnet immediately downstream of the installed undulator. Since the vertical beta function is actually larger there than in the undulator, the aperature of the scraper can be larger than the undulator gap. The only problem with this approach occurs if the corrector magnet that causes the closed orbit distortion is between the undulator and the scraper. In that case, a second scraper placed ahead of the undulator will ensure protection. If scrapers cannot be placed in the ideal locations, alternative locations can be used, in which case a pair may be required to adequately overlap the aperture of the vacuum chamber slot shown in Fig. 1. At this time, the APS does not plan to implement this method due to the increase in the transverse beam impedance budget of the ring caused by the scrapers. However, this method could easily be used to retrofit those regions with the most intense photon beams, since the scrapers only need to be added in those regions, not in regions without undulators installed. This would then ensure adequate protection for all sources of vertical missteering.

Conclusions

The high-power-density photon beams in the proposed next generation of synchrotron light sources will introduce new risks to the integrity of the ring vacuum chambers. In these machines, power densities will be such that vacuum chamber cooling will be unable to reduce the risk of rapid penetration of the chamber. Two general methods have been studied for providing passive protection of the vacuum chamber. These include: limiting of the power supplies that could missteer the beam and insertion of limiting apertures using beam scrapers that prevent the photon beam from illuminating the vacuum chamber. The APS will use the former during construction and will be able to implement the latter at a future time if the potential risk to the chamber warrants additional protection.

References

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