Abort Interlock Diagnostic for Protection of APS Vacuum Chamber*

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The Advanced Photon Source (APS) vacuum system has been designed to be passively safe from bending magnet radiation heating at positron beam currents up to 30 mA. Above this value, certain components may be damaged from vertical beam missteering, although work is proceeding to raise the safe current threshold. Because of this, a system for preventing the misalignment of high power density beams is required. This report details a system for protection from dipole radiation only. Work on a system for ID radiation is continuing.

I. INTRODUCTION

Radiation from bending magnets is emitted in fans emanating from the positron beam as it follows a nominally circular trajectory through each of the 80 dipole magnets in the storage ring. The nominal power emitted due to bending magnet radiation is 1.6 MW at a beam current of 300 mA. The distribution of radiated power with vertical angle above the accelerator midplane is quite accurately described by a Gaussian distribution with an rms width given by $\sigma = 0.608/\gamma$, where γ is the relativistic factor, equal to 13,700 for the APS beam energy of 7 GeV. Therefore $\sigma = 44$ μrad, and the power per unit solid angle in the midplane, averaged over horizontal angles is $dP/d\Omega = 1.6\,\mathrm{MW}/2\pi/1000/(2\pi)^{1/2}\sigma = 2.3\ \mathrm{kW/mrad^2}$ at 300 mA.

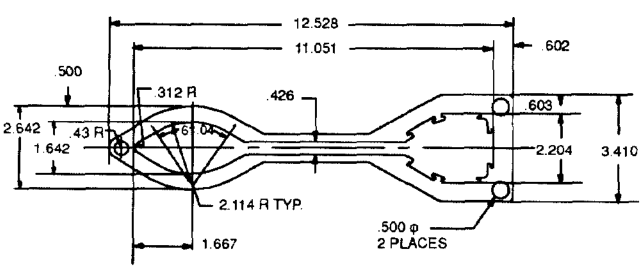

Figure 1. Cross Section of Storage Ring Vacuum Chamber.

The positron beam is confined to move within the storage ring vacuum chamber extrusion, whose cross section is shown in Figure 1. Each sector is broken down into six vacuum chamber sections. Bellows are located between storage ring vacuum chamber sections and allow a certain amount of mechanical compliance between chambers to facilitate small motions for alignment purposes. Located within each bellows assembly is an rf liner which yields a smooth electrical transition from one vacuum chamber section to the next and must be shadowed from synchrotron radiation at all power levels. The shadowing is accomplished by small tapered spacers which are attached inside the upstream and downstream flanges of all chambers. These spacers will be subjected to synchrotron radiation heating during beam missteering conditions and, in fact, are responsible for the beam intensity limitation during commissioning. Above 100 mA curved vacuum chamber sections can be damaged by synchrotron radiation. This occurs when the beam is parallel–translated vertically by an amount greater than 5 mm (see Figure 1). The bellows spacers and curved chambers are the only components at risk from vertically missteered dipole radiation.

Shown in Table 1 are values for horizontal and vertical acceptances for various phases of storage ring operation. For commissioning, the entire storage ring vacuum chamber will by and large have the cross section shown in Figure 1. Following commissioning, insertion devices will be installed in two stages. Initially, chambers with a 6–mm vertical half aperture will be installed (Phase I), and mature operation (Phase II) entails the installation of insertion device vacuum chambers with a 4–mm half aperture.

Once one has the values for the acceptances given in Table 1, it is a simple matter to find the maximum position and angle caused by a global closed orbit distortion anywhere around the ring .

II. BEAM ABORT INTERLOCK

The beam abort interlock associated with beam missteering is part of the overall machine protection system (MPS), which encompasses all mechanisms which can potentially damage the machine. Common to all MPS input is a method for turning off the beam; at the APS the chosen method is to momentarily interrupt the rf system. This ensures that the beam will lose energy and spiral inwards, to be totally lost in less than 300 microseconds [1]. This process can be made even faster and the loss localized by placing a horizontal aperture limitation, or scraper, at a location of large horizontal dispersion [2].

Table 1. APS Storage Ring Acceptances

	Acceptance A, mm–mrad	Limiting Aperture a, in mm	β (m) at limiting aperture
Vertical, commissioning	20.4	20.85	21.3
Vertical, Phase I	3.36	6	10.7
Vertical, Phase II	1.50	4	10.7
Horizontal	74.2	42.3	24.1

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The proposed diagnostics for detecting a potentially damaging beam missteering condition are tungsten wires strung inside the vacuum chamber in pairs, one wire above and one below the beam axis. Bringing the wire ends out of the vacuum system through a vacuum feedthrough, a resistance measurement can easily be made and translated directly into a temperature measurement. Shown in Figure 2 is a plot of resistivity vs. temperature for tungsten. At high temperatures, the dependence is almost linear.

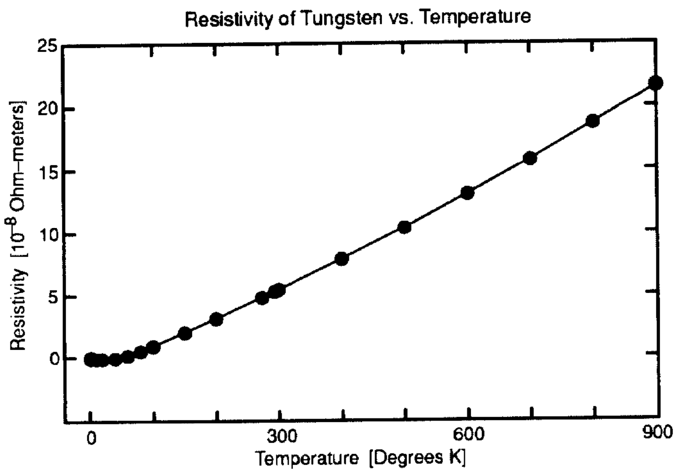

Figure 2. Variation of Tungsten Resistivity with Temperature.

The tungsten wires will be incorporated into a total of 80 accelerator absorbers located downstream of dipole sources. Shown in Figure 3 is a schematic of a radiation absorber assembly with two tungsten wires strung behind it such that the radiation strikes the wires at an angle of 4.5 degrees, approximately 80 mrad. The figure indicates that the wires will heat up if photons strike the absorber between 3.5 and 5 mm vertically from the nominal positron beam midplane. Because the beam has some width, the centroid of the photon beam will be effectively limited to lie between 3.0 and 5.5 mm, since 2 σ is about 0.5 mm

Shown in Figure 4 is a positron phase space plot showing the limitations imposed by the wires. The figure is a projection of vertical phase space as viewed from the downstream end of a dipole magnet. One can extend this concept and map all 80 pairs of wires onto the same plot. What results is the 160–sided polygon producing an effective vertical acceptance limit of A = 0.45 mm–mrad. This means that global orbit distortions will be limited by the interlock system to vertical displacements no larger that $\sqrt{\beta A} = 2.9$ mm at $\beta = 19.0$ meters and angles no larger than $\sqrt{\gamma A} = 0.2$ mrad inside the dipole. What remains are the effects of purely local orbit distortions, which are generally too weak to cause the beam to strike any at risk components without first striking a downstream wire monitor.

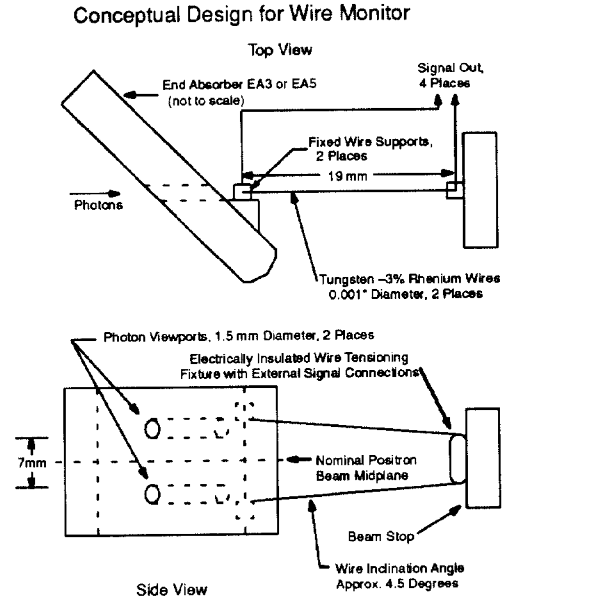

Figure 3. Concept for Interlock Diagnostic Built into a Radiation Absorber.

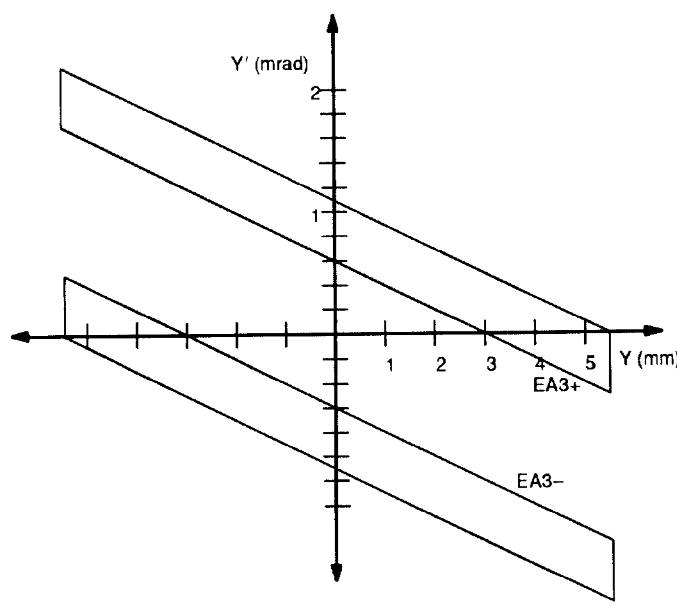

Figure 4. Projection of EA3 Wires onto Positron Phase Space at Downstream End of AM.

III. CALCULATION OF WIRE TEMPERATURE

Recall that the accelerator vacuum system is deemed to be passively safe from dipole radiation at beam currents below 30 mA. At currents less than this, it is desirable to inhibit the action of the interlock, e.g. for the purpose of orbit studies. Therefore, in order to have a margin of safety, the tungsten wires must be able to withstand direct irradiation from bending magnet sources for sustained periods of time at beam currents up to 30 mA, and much higher if possible.

The primary mechanism for cooling of the wire is black body radiation. One can solve for the equilibrium wire temperature, arriving at

$$T^4_{\text{wire}} = T^4_{\text{ambient}} + \frac{A_P}{A_s}\frac{1}{\sigma\ \varepsilon\ L^2}\frac{dP}{d\Omega}\ , \qquad (1)$$

where T_{wire} and $T_{ambient}$ are the wire and ambient temperature in degrees Kelvin respectively, σ is the Stefan–Boltzmann constant, and ε is the wire surface emissivity. For reference, $(1/L^2)\ dP/d\Omega$ = 27.2 Watts/cm^2 peak for each milliamp of positron beam current at L = 5.3 meters, corresponding to the typical source – wire distance.

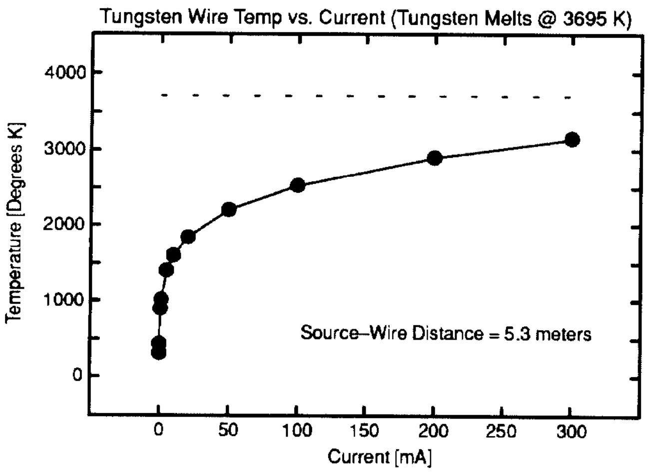

Figure 5. Wire Temperature vs. Positron Beam Current.

One interesting aspect of the above result is that the wire temperature is independent of the wire gauge, depending only on the ratio A_p/A_s which, for a round wire inclined at an angle θ, is just $A_p/A_s = (\sin\theta)/\pi$. Shown in Figure 5 is a plot of wire temperature vs. positron beam current, inclined with respect to the nominal positron orbit midplane at an angle of 80 mrad. In generating Figure 5, a linear dependence of the emissivity ε with temperature, approximating measured values, was used, resulting in a fifth–order polynomial for T. Despite the variation of power with vertical angle, it turns out that the peak temperatures for beam currents exceeding 30 mA very closely follow the behavior shown in Figure 5 in a simulation including a Gaussian distributed power density and conductive cooling. This is due to the fact that heat conduction through the wire ends has a relatively small effect.

IV. TIME RESPONSE

In addition to the ability to withstand high photon fluxes without being damaged, the wire monitors must have the capability to respond very quickly. Although no components can be damaged in times shorter than a few seconds, the potential exists for the photon beam to sweep past the wire monitors so quickly that not enough energy gets deposited to produce a measurable resistance change.

The worst case situation occurs when a global orbit distortion moves the photon beam close to a wire and then a maximum amplitude local bump is applied. The maximum value of a vertical parallel translation bump inside a dipole magnet is 3.6 mm, and from Figure 4 it can be seen that the beam must move 2.5 mm to get past the viewport, i.e. 69% of a full strength local bump. The L/R time constant of the vertical correctors is 82 ms to reach (1–1/e) = 63% of full strength. In other words, the wires must respond significantly faster than 82 ms to prevent a local bump from sweeping the photon beam past the wire undetected.

The relation determining the time rate of change of temperature does not depend on radiative heat loss at all, since we are most concerned with the time period when the wire is still relatively cool. The relation is given by

$$\frac{dT}{dt} = \frac{1}{\varrho\, C_p\, L^2}\,\frac{dP}{d\Omega}\,\frac{4\sin\theta}{\pi d}\ , \qquad (2)$$

where ϱ = 19.3 g/cm^3 is the density of tungsten, C_p= 0.133 J/g/°K is the heat capacity, and d is the wire diameter, assuming the wire is uniformly illuminated.

For a 50–micron–diameter wire, Eq. (2) yields 6500 °K/sec at a beam current of 30 mA, otherwise known as 216 °K/sec/mA, for θ = 80 mrad, L = 5.3 meters. A 100 °K temperature rise at 30 mA thus requires a time period of 15.4 milliseconds. Because the wire is not uniformly heated along its entire length, one should conservatively use the total volume of the wire rather than just the volume of wire being hit by radiation, as was done in Eq. (2). This reduces the response time by at most a factor of 5, i.e. a 100 °K temperature rise in 72 milliseconds. This is still faster than the L/R time constant of the magnets.

For the resistance measurement, care must be taken to limit ohmic heating. For a 35–mm–long, .002"–diameter tungsten–3% rhenium alloy wire, the room temperature resistance is 1.7 ohms, but rises rapidly if ohmic heating exceeds a few milliwatts. This limits the applied current to between 20 and 30 mA, producing 50 to 100 millivolts of signal, which should be easily detected.

V. CONCLUSIONS

A simple method for the detection of vertical missteering of dipole magnet radiation in the APS storage ring for use in a beam abort interlock has been developed. The method uses 50–micron–diameter tungsten alloy wires as resistive temperature sensing devices to directly detect the presence of photon beams off axis. These wires can withstand direct irradiation from bending magnet radiation conservatively at beam currents up to 100 mA, and are significantly below their melting temperature even at 300 mA. Their response time is faster than 72 milliseconds at 30 mA of beam current, the lowest current at which the interlock will be activated. By integrating the wires into the design of water–cooled radiation absorbers, their alignment with respect to the beam is simplified. The wire resistance is in the range of 1 to 2 ohms and can be measured with an applied current between 20 and 30 mA without causing an unacceptable temperature rise from ohmic heating.

VI. REFERENCES

[1] L. Emery, private communication, APS Internal Note.
[2] L. Teng, private communication, APS Internal Note.