Introduction

At 18-ID, the power in the reflected beam (pink beam) from the collimating mirror (CM), which is the first optical component, can be as much as 956 W at 500 mA storage ring current. The safe capture of this pink beam under mis-aligned mirror conditions is addressed in TN 2655, ‘FXI Mis-steered Pink Beam’. The approach relies on the use of hard-stops to limit the motion of the CM. This technical note presents the case that if the storage ring current is limited to 10 mA, and the FOE photon shutter is closed, the hard stops for the CM are not necessary due to the significantly reduced power in the pink beam.

Approach

At 500 mA stored beam current, the power reflected by the mirror at its nominal incidence angle of 4.4 mrad is 956 W (from XOP). This power is within 3% of the maximum power that can be reflected by the mirror for all incidence angles. If the mirror incidence angle is higher than 4.4 mrad, then the reflected power will be reduced due to the lower cut-off energy. If the mirror incidence is less than 4.4 mrad, the length of the mirror will limit the reflected power. The mirror is 1450 mm long and the beamsize at the mirror is 6.2 mm x 6.2 mm. For convenience, we shall assume this beamsize for our calculations; i.e; we do not account for the beam divergence. This is a conservative assumption in terms of power density. For these calculations, we assume that at 10 mA stored beam current, the pink beam power is 956 W/50 = 19 W. The issue is thus to see what this 19 W beam of size 6.2 mm x 6.2 mm (power density of ~ 0.5 W/mm²) can hit in the FOE.

Based on the absolute total travel range (from zero) of the CM vertical stages, the maximum angle that the mirror can attain is about 30 mrad. This is based on the length of the actual stages and ignores limit switches and hard stops.

Based on the size and location of the CM exit flange, in order for the pink beam to hit the CM tank, the mirror would have to have an incidence angle of about 35 mrad. This is beyond the absolute angular limit of the mirror, as mentioned above. Furthermore, at 35 mrad incidence angle, the pink beam would only have 0.34 W at 10 mA. Thus, we only need to consider the case where the pink beam exits the CM tank exit flange.

Figure 1 is a ray-trace of all possible pink beam through the pink beam aperture. Figure 2 considers the two representative rays where the pink beam does not go through the pink beam aperture, but is mis-steered to very high angles. The two rays drawn: (1) pink beam hits the white beam stop/pink beam mask (WBS/PBM) at near normal incidence and (2) pink beam exits the vacuum environment and hits secondary bremsstrahlung shield – II (SBS-II). These figures show that under all CM conditions, the mis-steered pink beam will have to first hit either (I) cooled copper (WBS/PBM or Pink beam stop), either on the sloped surfaces or near normal incidence, (II) tungsten secondary bremsstrahlung stop – IV (SBS-IV) at near normal incidence (III) stainless steel pipe at grazing incidence or (IV) the toroidal mirror (TM). We consider each of these four cases separately.

Although the focus of this technical note is on the thermal aspects, we have also confirmed with XOP that radiation-wise, the CM reflected pink beam (at 4.4 mrad incidence angle) is fully
stopped within the FOE, even at 500 mA ring current, by FOE downstream wall of 50 mm Pb or the two 18 mm thick tungsten blocks of the FOE Photon Shutter. As seen from Figures 1 and 2, for the pink beam to make it downstream of the pink beam stop, the CM incidence angle must be > 4.4 mrad; thus, the assumption of 4.4 mrad incidence angle for the XOP calculations is conservative.

**Figure 1**: A ‘ray trace’ of mis-steered pink beam through the pink beam aperture. This shows that the pink beam hit either the pink beam stop or SBS-IV or the TM.
Figure 2. Two mis-steered pink beam rays: one that hit the WBS/PBM at near-normal incidence and one that exits the vacuum pipe and hits SBS-II.
Results

Case I: Pink beam hits cooled copper, either on the sloped surfaces or at near normal incidence
The pink beam hits either the water-cooled WBS/PBM or the water-cooled PBS either on the sloped surfaces or at near normal incidence. The FEA on the WBS/PBM shows that with a surface power density of 5.62 W/mm² and 10 kW total power, the maximum temperature is 154 °C. The FEA for the PBS shows that with a surface power density 7.66 W/mm² and a total power of 956 W, the maximum temperatures is 174 °C respectively (see FXI Toyama FDR report). Thus, even if the pink beam (19 W total power and 0.5 W/mm² power density) hits these components at normal incidence, it will not cause any damage.

Case II: Pink beam hits uncooled tungsten in vacuum:

The pink beam hits tungsten SBS-IV at near-normal incidence. This piece is not cooled and resides in vacuum. We can do a simple overly conservative estimate using only black body radiation from the beam footprint to show that this beam cannot damage the tungsten. Thermal conductivity is ignored. The equation for black body radiative heat loss is:

\[ q = \varepsilon \sigma A T^4 \]

where
- \( q \) = radiative heat loss in W
- \( \varepsilon \) = emissivity of the material (tungsten)
- \( \sigma \) = Stefan-Boltzmann constant = 5.7 x 10⁻⁸ Wm⁻²K⁻⁴
- \( A \) = surface area in m² = 6.2 mm x 6.2 mm = 38 x 10⁻⁶ m²
- \( T \) = temperature in K

The melting point of tungsten is 3422 °C. The emissivity of tungsten increases with temperature. If we assume the temperature is 2500 °C (considerably below the melting point), and using the emissivity value at 2000 °C, we get \( q = 35.9 \) W, which is > 19 W. Thus, in this overly conservative estimate, the pink beam cannot damage the tungsten.

Alternately, we performed FEA using the actual SBS-IV dimensions. The results (Figure 3) show that the maximum temperature reached is only 339 °C. The difference between the FEA and the simple analytical model above is that the FEA includes thermal conductivity that heats up the entire block and thus, the effective surface area for radiative loss is much larger.

Figure 3: FEA of the SBS-IV 75 mm x 28 mm x 75 mm (thick) subject to normal incidence heat load of 19 W over 6.2 mm x 6.2 mm area. Emissivity is 0.15 (see www. MatWeb.com)
Case III: Pink beam hits a stainless steel vacuum pipe at grazing incidence:

In this case, the pink beam hits the walls of the stainless steel pipe at grazing incidence. The relevant locations are the penetration pipes through SBS-I, SBS-II and the primary bremsstrahlung stop. For this case, we assume the highest possible grazing incidence angle (2x30 mrad) in order to obtain the highest power density. We round down 1/0.06 to 16 and assume that the beam footprint is 6.2 mm x (6.2 mm x 16) = 6.2 mm x 99.2 mm. Because there are several possible locations for this to occur, we modeled a fictitious worst case by combining the thinnest wall and smallest pipe, namely, the pipe through the primary bremsstrahlung stop with the shortest pipe (200 mm), namely, the pipe through SBS-II. The primary bremsstrahlung pipe has a square cross-section with 13 mm inner side dimensions. Thus, our fictitious worst case model is a plate of 52 mm (W) x 200 mm (L) x 1.5 mm (thick). We assumed convective air cooling on one large planar surface (52 mm x 200 mm) and the two small edges (1.5 mm x 52 mm). The vacuum side large surface (heat load on this surface) and the two long edge surfaces are insulated (no heat loss). An air convection heat transfer coefficient of 50 Wm^-2°C^-1 is assumed (see www.engineeringtoolbox.com). A centered heat load of 19 W is spread across the 6.2 mm x 99.2 mm footprint. The maximum temperature reached is 80.4 °C (Figure 4). This is much lower than the stainless steel melting temperature of > 1400 °C and also below the melting point of lead (327 °C) that surrounds the pipe.

Figure 4: FEA of a piece of stainless steel 52 mm (W) x 200 mm (L) x 1.5 mm (thick) with a heat load of 19 W over a 6.2 mm x 99.2 mm area. The maximum temperature is 80.4 °C, which is much lower than the stainless steel melting point of > 1400 °C.

Case IV: Pink beam hits the toroidal mirror (TM):

There are two possible scenarios here: (a) the TM is damaged, (b) the TM reflected beam hits the FOE photon shutter at near normal incidence. The photon shutter has consists of dual Copper-Tungsten blocks, with the copper facing upstream (see PD-COM-PSH-1000).

Scenario (a) is not a concern because the downstream SBS-IV (tungsten) will stop all rays if the TM is not there (Case II).

Scenario (b) is also not a safety concern because even if the copper fails, the tungsten block will not be damaged (Case II). Nonetheless, we performed FEA for the beam hitting the copper block. The results show that the maximum temperature reached is 184.5°C (Figure 5).
Figure 5: FEA of a piece copper 80 mm (W) x 50 mm (L) x 16.5 mm (thick) with a heat load of 19 W over a 6.2 mm x 6.2 mm area. The maximum temperature is 184.5°C. Emissivity is 0.78 (www.EngineeringToolbox.com).

Conclusions

At 10 mA stored beam current, with the FOE photon shutter closed, the FXI collimating mirror does not require any hard stops or limits on its motion because the maximum power in the reflected beam under all possible mirror conditions is safely captured within the FOE.
Details of the primary bremsstrahlung stop showing the tube dimensions
Details of SBS-II, showing the details of the pipe.