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OFF-ORBIT RAY TRACING ANALYSIS FOR THE APS-UPGRADE STORAGE RING VACUUM SYSTEM

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Abstract

A MatLab program has been created to investigate off-orbit ray tracing possibilities for the APS-Upgrade storage ring vacuum system design. The goals for the program include calculating worst case thermal loading conditions and finding minimum shielding heights for photon absorbers. The program computes the deviation possibilities of synchrotron radiation rays emitted along bending magnet paths using discretized local phase space ellipses. The sizes of the ellipses are computed based on multi-bend achromat (MBA) lattice parameters and the limiting aperture size within the future storage ring vacuum system.

For absorber height calculations, rays are projected from each point in the discretized ellipse to the locations of downstream absorbers. The absorber heights are minimized while protecting downstream components from all possible rays. For heat loads, rays are projected until they hit a vacuum chamber wall. The area and linear power densities are calculated based on a ray's distance travelled and striking incidence angle. A set of worse case local heat loads is collected revealing a maximum condition that each vacuum component must be designed to withstand.

MOTIVATION

The goal of performing off-orbit ray tracing calculations is to better understand missteering possibilities and their consequences for the APS-U vacuum system design. It is straight forward to construct the paths of perfectly steered synchrotron rays using a 2D CAD application and this provides an initial idea of both distributed heat loads and shielding requirements for critical vacuum system components. Introducing local orbit errors [1] increases the ray path possibilities which leads to higher local heat loads and requires more conservative shielding.

Spatial and angular deviation possibilities from an ideal beam path are dictated by local phase space ellipses and present a continuum of ray path possibilities. A worst case ray path within the vacuum system is not necessarily found by choosing extreme points on the local ellipses therefore 2D CAD is not an ideal tool for investigating missteering due to the large quantity of ray possibilities which need to be constructed. More ideal would be a numerical method which discretizes each local ellipse and tests the travel of all ray possibilities within a model of the vacuum system. The approximations of the worst rays should converge towards a unique solution with increased mesh density.

METHODS

Off-orbit ray tracing possibilities can be calculated from local phase space ellipses in both the horizontal (x,x') and vertical (y,y') phases spaces. The local ellipses are calculated for either phase space based on the Courant-Snyder parameters using equations (1) and (2) where A_x is calculated based on the half size of the limiting aperture in the storage ring and the beta function value at the limiting aperture's location. Figure 1 shows a schematic of a phase space ellipse and a corresponding mesh of ray deviation possibilities.

$$x' = -2\alpha x \pm \frac{\sqrt{(2\alpha x)^2 - 4\beta(\gamma x^2 - A_x)}}{2\beta} \qquad (1)$$

$$A_x = \frac{a^2}{\beta_u} \qquad (2)$$

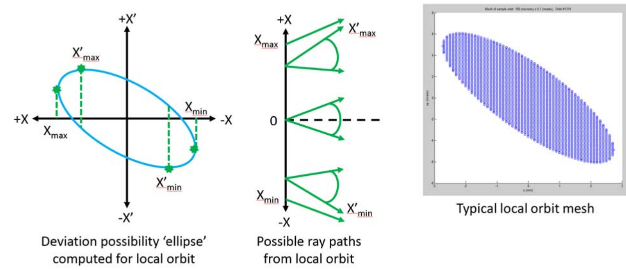

Figure 1: Local orbit ellipse concept and ray possibilities when meshed (top) and diagram of basic ray tracing schematic (bottom)

A MatLab program has been written to discretize both the horizontal and vertical local phase space ellipses along APS-U bending magnet paths and to trace out every ray in the mesh. The quantity of ellipses and their respective sizes are found using an input file containing both the global locations and Courant-Snyder parameters along finely space points of the APS-U magnet lattice. The rays are traced until they intersect geometric elements representing either vacuum system walls or photon absorbers.

Figure 2 shows maximum horizontal deviations from the (x,x') ellipses calculated along the APS-U bending magnet paths. The MatLab program computes the ray paths for all spatial and angular combinations within this envelope as determined by the ellipse mesh. The photon absorbers within APS-U's 22 mm I.D. multiplet vacuum chambers create an 18 mm limiting aperture for the vacuum system. The spatial deviations fit well within the typical 22 mm I.D. beam aperture found along most of the APS-U vacuum system.

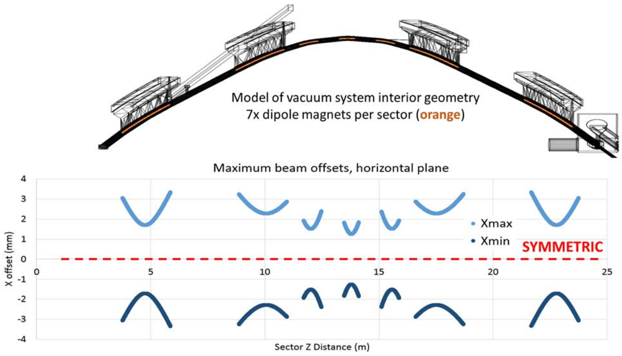

Figure 2: Maximum horizontal beam offsets computed along bending magnet paths

The program has two separate goals, each calculated in a unique way:

1. Minimize the shielding height for all photon absorbers within one of the APS-U vacuum system's 40 repeating sectors
2. Find a composite set of the worst local heat load possibilities along a sector

Figure 3 shows a schematic of the ray tracing concept for the first goal of minimizing photon absorber heights, where height indicates the distance from the vacuum chamber wall to the tip of the absorber. First, the global positions of photon absorbers are computed including conservative worst case alignment offsets. The program starts with a conservative initial guess of the absorber height. If the absorber can shield its respective downstream component from all possible rays, then the absorber height is reduced by an increment and the process is repeated. When the absorber height can no longer shield the downstream component from all possible rays then the previous solution is kept as the minimum.

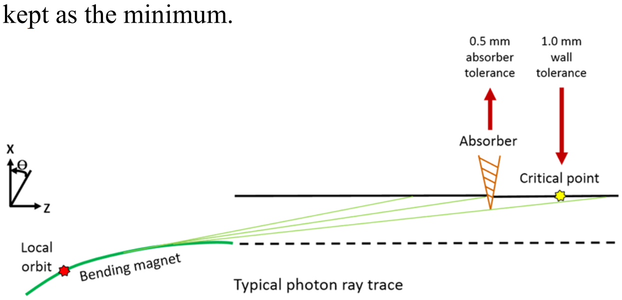

Figure 3: Local orbit ellipse concept and ray possibilities when meshed (top) and diagram of basic ray tracing schematic (bottom)

For the second goal, an array of connected wall elements is created representing the vacuum system walls. Rays are calculated until they intersect a downstream wall element where local area and linear power densities are calculated [2] using equations (3) and (4) based on the field strength of the photon producing magnet, the distance travelled, and the striking incidence angle.

$$P_a\left(\frac{W}{mm^2}\right) = 5.42 * E_e^4(GeV) * I(A) * \frac{B(T)}{L^2} * \theta_{ray} \quad (3)$$

$$P_l\left(\frac{W}{m}\right) = 4.22 * E_e^3(GeV) * I(A) * \frac{B(T)}{L} * \theta_{ray} \quad (4)$$

A composite set of the highest possible loads is then collected along the vacuum system walls. This set represents the worst case loading case that can be found for any point on the length of the vacuum system. If a vacuum chamber can be designed to withstand this composite set of worst local heat loads, then it will withstand any lesser case.

The program's meshing parameters include mesh sizing for both the horizontal (x,x') and vertical (y,y') phase spaces. For the first goal, a length increment is set for minimizing the absorber height. For the second goal, the full length of one sector's vacuum system walls are partitioned into collection bins for heat load calculations.

MINIMUM PHOTON ABSORBER HEIGHTS

Figure 4 shows the minimum absorber heights calculated for a sector of the APS-U storage ring. In this plot larger height values indicate more conservative shielding requirements at a particular location. The quantity of absorbers is based on the number of components per sector, including BPMs, bellows, and gate valves, that require shielding.

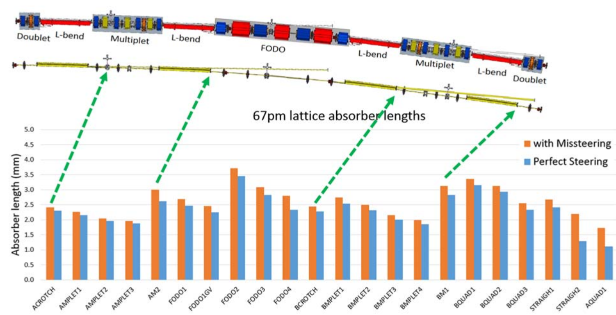

Figure 4: Minimum heights of photon absorbers for a sector of APS-U storage ring

Figure 5 shows how the calculations for each absorber converge towards a maximum solution with increasing mesh density.

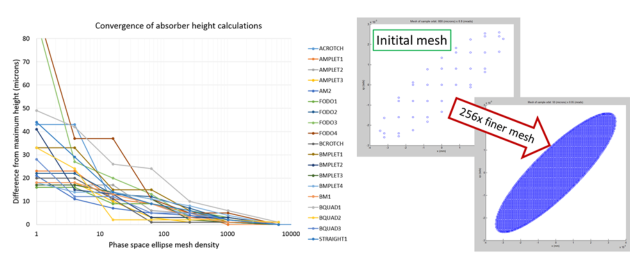

Figure 5: Convergence of minimum absorber height calculations with increasing local orbit mesh density

WORST CASE HEAT LOADS

A composite plot is shown in Figure 6 of the worst case local power densities along the vacuum system length. A simplified vacuum system model is used assuming a continuous 22 mm ID vacuum chamber with no photon absorbers. The model uses finely spaced points from the lattice file to follow the true curvature of the vacuum system. The results are only accurate in the Multiplet and FODO sections which match the uniform cross section assumption however.

A zoom in to the FODO section is shown at bottom of the figure indicating the worst case peaks along the 22 mm I.D. NEG-coated copper vacuum chamber walls. The plot indicates up to a 67% increase in local power densities when including beam missteering. This is because missteering allows the rays to find shorter paths and higher striking angles along the vacuum chamber walls which leads to higher power densities. The heat load results also converge towards a unique peak value with increasing mesh density and towards a smoother composite solution with decreasing length of the wall elements.

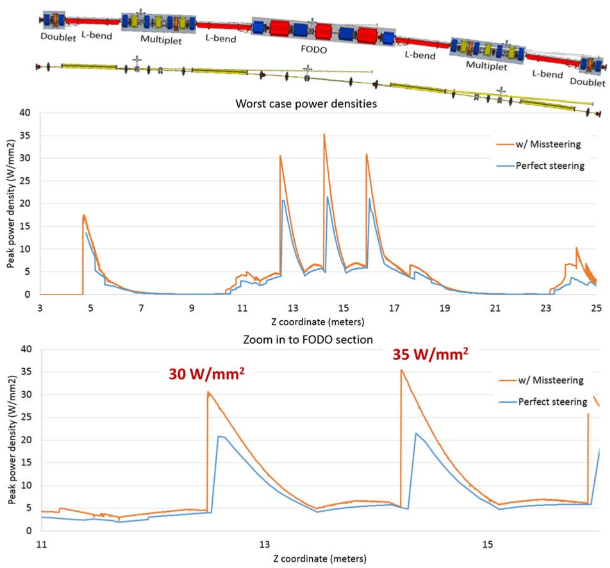

Figure 6: Worst case local thermal loads plotted along sector of APS-U storage ring (top) and zoom into load along copper FODO section chamber walls (bottom)

CONCLUSIONS

The new MatLab program for off orbit ray tracing provides APS-U with a flexible tool to better understand design challenges. Coarse mesh studies are quick to compute and provide preliminary insights while higher mesh solutions converge towards final values and smoother results with increasing mesh density. The program has also been verified to match 2D CAD ray traces when no missteering is applied.

The calculations for the minimum photon absorber heights show a variety of values along the sector indicating that a 'one size fits all' might be too conservative. While a uniform absorber design would be better for manufacturing and alignment, an optimized set of absorbers may reduce beam impedance.

The composite plot of worst case local heat loads reveals critical hot spots with greater than 30 W/mm^2 power densities on walls of the FODO section vacuum chambers. In one applied case, the program found an APS-U BPM and absorber intended for the FODO section to be in the path of an extreme heat load peak. These components were then moved downstream to a safer region. Future thermal/structural analysis will need to establish if vacuum chamber and photon absorber designs need to be altered to withstand these heat loads. If heat loads are found prohibitive for thermal/structural analyses, then beam orbit sizes may be reduced with a beam position limit detector.

NEXT STEPS

One goal to continue this work is to show the sensitivity of impedance calculations to the heights found for the absorbers. If the sensitivity is high, then a set of absorbers with unique, optimized heights will be designed. If sensitivity is low, then a uniform absorber height design may be suitable.

For heat load calculations, a post process will be created to map the spatial values of the heat loads similar to Figure 7 for use as a boundary condition in thermal/structural analysis. The model can also be improved by including higher angled absorber elements and openings for non-cylindrical chambers with fan outs such as in L-bend and straight section regions. Also, including cylindrical elements would allow for more accurate calculations of ray travel in the vertical plane. Vertical offsets are important to understand as this leads to less efficient cooling by water channels located on the central axis of vacuum chambers.

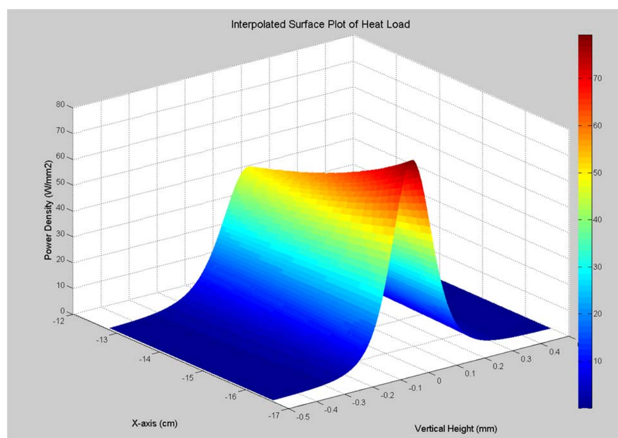

Figure 7: Example photon power density distribution mapped onto a surface

ACKNOWLEDGMENT

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REFERENCES

[1] V. Sajaev, private communication, 2016.

[2] R. Dejus, private communication, 2016.