3D NUMERICAL RAY TRACING FOR THE APS-UPGRADE STORAGE RING VACUUM SYSTEM DESIGN

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Abstract

The APS-Upgrade project will build a diffraction limited storage ring requiring a vacuum system design with small aperture vacuum chambers passing through narrow magnet poles. The small apertures dictate that the walls of the vacuum chambers act as distributed photon absorbers. The vacuum chambers must be designed robustly so a thorough understanding of the synchrotron ray tracing with beam missteering is required.

A MatLab program has been developed to investigate 3D ray tracing with beam missteering. The program discretizes local phase spaces of deviation possibilities along the beam path in both the horizontal and vertical planes of motion and then projects rays within a 3D model of the vacuum system. The 3D model contains elements in sequence along the beam path which represent both chamber segments and photon absorbers. Ray strikes are evaluated for multiple worst-case criteria such as local power intensity or strike offset from cooling channels. The worst case results are plotted and used as boundary conditions for vacuum chamber thermal/structural analyses. The results have also helped inform decisions about practical beam position limits.

RAY TRACING FOR THE APS-U STORAGE RING VACUUM SYSTEM

The APS-Upgrade will retrofit the existing 40 sectors, 1.1 km circumference APS storage ring with a new 6 GeV, 200 mA storage ring optimized for brightness above 4 keV. The new storage ring vacuum system will feature 22 mm inner diameter vacuum chambers to fit between narrow magnet apertures, see Figure 1. Each sector will have 5x copper photon absorbers to both funnel extracted photons towards the front ends and to shadow downstream components. Each sector will also have 14x independently mounted beam position monitor (BPM) assemblies. The BPMs are not water cooled and have sensitive features including RF liners and BPM buttons and each will need shadowing by compact inline absorbers built into the immediate upstream chambers.

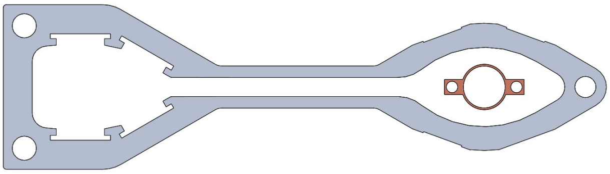

Figure 1: Cross section comparison of current APS-style vacuum chamber to new APS-U-style chamber.

In total the vacuum system will have 20x water-cooled vacuum components which will intercept synchrotron radiation either by design with a photon absorbing edge or along the chamber length as consequence of the small apertures. Figure 2 shows a cross section of three APS-U vacuum components in sequence. Here a slight taper on a vacuum chamber shadows a downstream flange joint of a compact copper inline absorber. The absorber then shadows the length of a BPM assembly past its downstream flange joint. The current APS has 6x total photon absorbing components compared to APS-U's 20x and this fits into a trend among diffraction limited light source vacuum systems with increasingly more compact vacuum chamber requirements. This increase in complexity leads to a need for more careful ray tracing constructions and calculations and considerations beyond the limits of conventional top view 2D ray traces.

A new MatLab program has been developed to investigate 3D ray tracing possibilities with missteering. Beam missteering possibilities and limits vary along the length of the lattice function and the ray tracing consequences differs from component to component in a complex system. Numerical methods are a more efficient approach to exploring missteering rather than individual CAD constructions. The new MatLab program calculates the local extents of missteering by discretizing local phase space ellipses and then projects the large quantity of rays downstream towards a model of vacuum elements. The quantity of ray strikes can be summarized to ensure the protection of sensitive components and to analyze worst case ray tracing outcomes unique to each vacuum component.

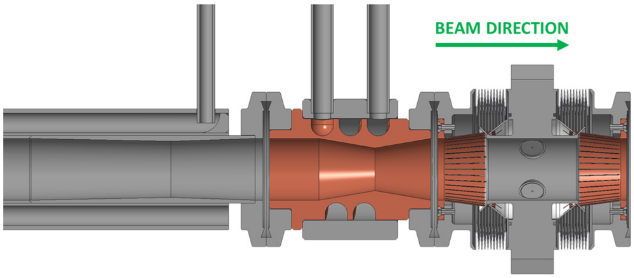

Figure 2: Top view cross section comparison of current APS-style vacuum chamber to new APS-U-style chamber.

SUMMARY OF APS-U'S 2D RAY TRACE

Building and analysing a conventional 2D ray trace remains critical as it sets the baseline for heat load distributions and shadowing of critical components. APS-U's storage ring ray trace is summarized in the table in Figure 3. APS-U's magnet lattice generates 14.3 kW per sector at 200 mA beam current. This excludes narrowly funnelled

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radiation produced in the straight sections that the storage ring vacuum system will not intercept. Only 10% of the bending magnet radiation is passed to the beamlines and the rest is intercepted by vacuum components. For the photon absorbers, the 'b-side' crotch absorber takes the most bending magnet radiation at 3.4 kW and the A-side crotch absorber takes 1 kW. For the vacuum chambers, 5.3 kW (or ~1 kW/m) is intercepted along the FODO section's copper vacuum chamber walls. 600 W (or ~700 W/m) are intercepted in the B-Quad Doublet. Lighter loads (~100 W/m) are intercepted along small aperture aluminium vacuum chambers in the Multiplets.

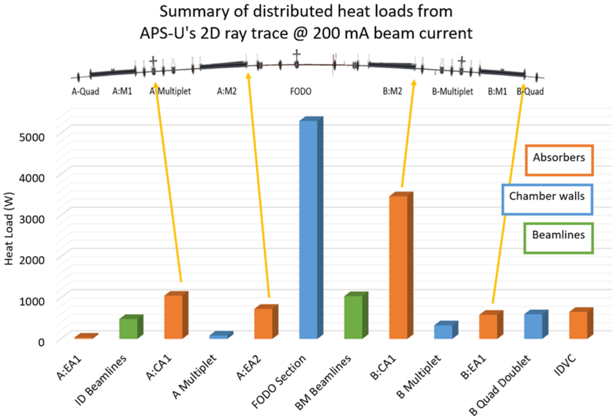


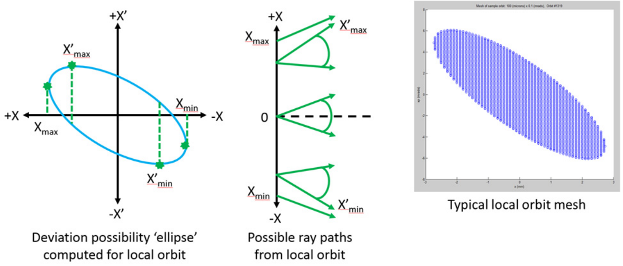
Figure 3: Summary of APS-U storage ring vacuum system 2D ray trace.

BEAM MISSTEERING LIMITS

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 4 shows a schematic of a phase space ellipse and a corresponding mesh of ray deviation possibilities.

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

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



Deviation possibility 'ellipse' computed for local orbit
Possible ray paths from local orbit
Typical local orbit mesh

Figure 4: Local orbit ellipse concept and ray possibilities when meshed (top) and diagram of basic ray tracing schematic (bottom).

The MatLab program discretizes the local phase space ellipses and uses each point to deviate the positional and angular path of rays from a given base point along the arcing beam path. The extents of the ellipses in both X and Y and thus deviation possibilities at any point along the arcing beam paths are determined using lattice functions provided by APS-U physics. The deviated ray is then projected out until it strikes a geometric element in a model of the vacuum system. Finally strike parameters of interest such as power intensity are calculated using equations (3) and (4).

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

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

ALGORITHM FOR 3D NUMERICAL RAY TRACING

The summary of the algorithm for the new 3D numerical ray tracing is as follows:

1. Build vacuum system geometry based on sequentially ordered geometry elements along the beam path. Figure 5 shows an example diagram of sequential geometric elements and the current types of elements allowed in the program.
2. Generate rays projected from finely spaced points where synchrotron radiation is generated along the arcing beam path
3. Determine where rays strike by checking if the intersection between a ray and a geometric element falls within the upstream and downstream extents of the element, see Figure 6.
4. Calculate data of interest from the strike including total power (W) deposited, power intensity (W/mm and W/mm^2), location of strike, etc.
5. Use logic to find the 'worst case' ray to strike any given element out of a large quantity of possible strikes.

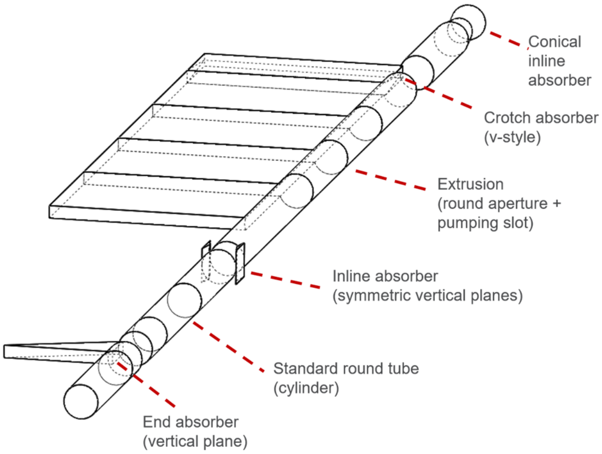


Figure 5: Diagram of a sequence of geometric elements and the element types currently available in the program.

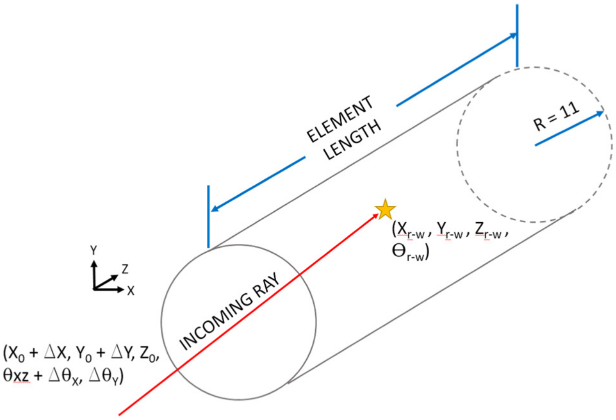


Figure 6: Diagram of a ray striking a geometric element.

The program imports lattice parameters across a typical sector. The format and types of lattice parameters were developed with input from APS-U physics and the program has now been used to quickly analyze multiple changes and iterations to APS-U's magnet lattice.

Geometry is built into the program as a sequence of geometric elements and typically requires the element's length, central global coordinates, and details of the cross section specific to each element. The input parameters are flexible and can be used to study design scenarios.

Results are provided in a large array with details of the worst ray strikes found on each geometric element. Examples of the ray strike details include ray origination and strike location, length travelled and angle of strike, and power intensity. Criteria for 'worst cases' are defined by logic with examples being 'highest power intensity' or 'furthest vertical offset from a cooling channel along the central plane'. The data is most easily viewed and manipulated in a spreadsheet program like MS Excel.

3D RAY TRACING RESULTS

The first benchmark of the program is to run it with no missteering and confirm that the results match both equivalent 2D CAD layout and 3D models in CERN's SynRad ray tracing program (part of the MolFlow+ Monte-Carlo Simulator package) [1]. Figure 7 shows a post process of numerous generated rays by the program within a top level cross section of the 3D geometry. The results are colored closely to those viewed in SynRad as a means of confirming that the calculations yield a highly similar result in 3D.

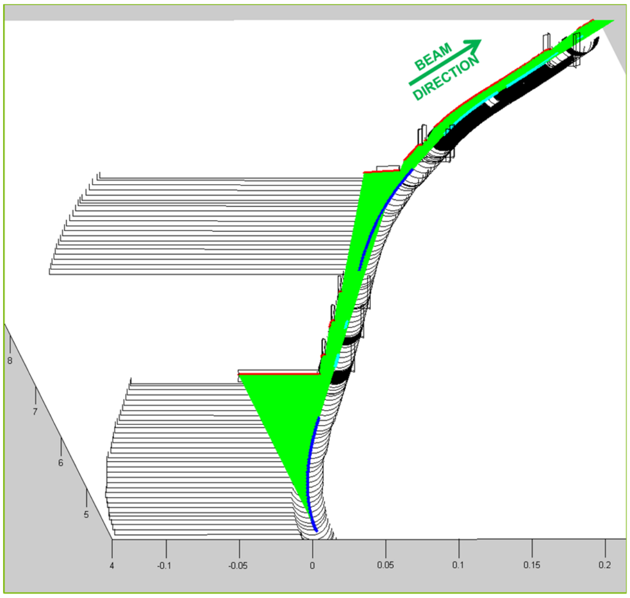


Figure 7: Angled view of an APS-U ray trace of the A-side of the vacuum system with no missteering from the new 3D numerical ray tracing program.

For APS-U the results of both individual rays and sweeping fans of rays have been found to match near equivalently between both 2D CAD and SynRad with differences usually being attributable to challenges in making equivalent geometric models between the three separate methods. Individual rays reconstructed in 2D CAD have been seen to travel the same distance and strike geometry at the same angle of incidence.

Beam missteering can be introduced following the confirmation of the 'ideal' ray trace. A user will enter a value for either a limiting aperture or a beam position limit detection system limit (BPLD limit) to determine the extents of missteering. Then discretization parameters for the local ellipses are chosen where finer rays will lead to more rays being tested during a run of the program. Figure 8 demonstrates the generation of both a single missteered ray and all of the rays generated from a discretized local x-plane ellipse.

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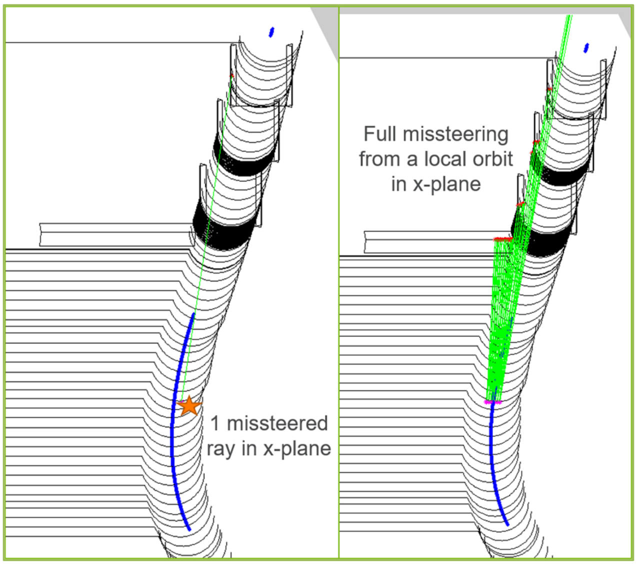

Figure 8: Comparison of one missteered ray (left) vs. all of the rays generated from a single local phase space ellipse in the X-plane (right).

When results such as linear power density and peak power density are compared across the length of the vacuum system, the set of ideally steered rays is always a lower bound to the set of 'worst case' rays as shown in Figure 9. Linear power is plotted across the sector and compared for both 'ideal' ray tracing and ray tracing with beam missteering confined by a BPLD limit. Local spikes in the results are due to tapered absorbers in the model. The figure shows a zoom in to the FODO section where copper vacuum chambers will receive high loads > 1 kW/m along their round bodies. The difference between a missteering result and a ideal steering result increases as the BPLD limit increases to an upper limit when the BPLD limit is equivalent to the limiting aperture.

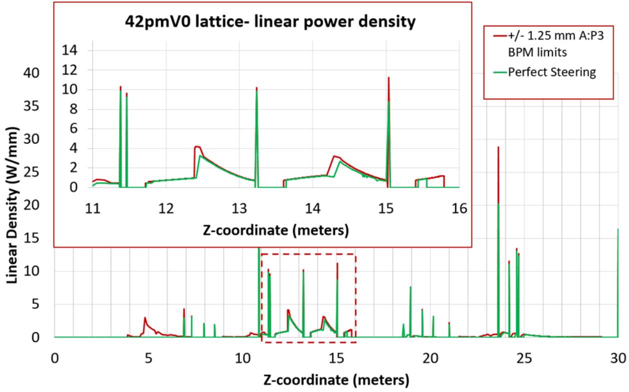

Figure 9: Comparison of linear power across a full sector for ideal steering vs missteering with BPLD limits with zoom in to the FODO section.

The results from the program can then be incorporated into a thermal/structural finite element analyses for vacuum chambers and absorbers. Figure 10 shows a typical ANSYS analysis for an APS-U vacuum chamber where a fine heat load across the water-cooled chamber is concentrated on a compact inline absorber face.

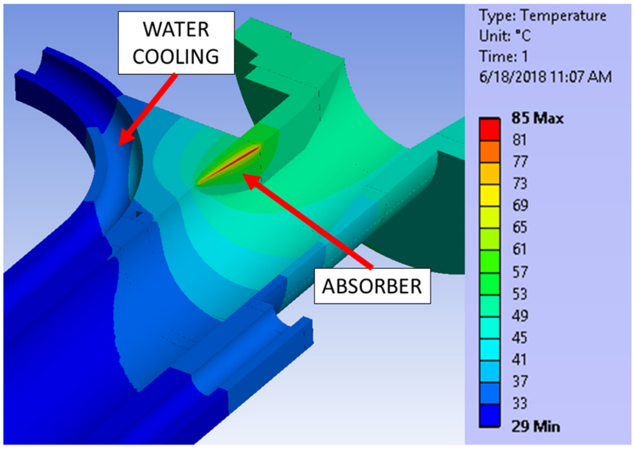

Figure 10: Typical ANSYS temperature result at downstream end of a water cooled vacuum chamber with narrow ray tracing heat load applied to an inline absorber.

Scenario studies were used to inform the BPLD limit for APS-U's storage ring. The vacuum system will include a number of extruded chambers with uncooled narrow pumping slots designed between small magnet gaps. Rays travelling with a vertical positional or angular offset may be found to strike the chamber if not carefully confined. Recent work found +/- 1 mm BPLD limits should be sufficient to protect 3.5 mm tall pumping slots spanning > 5 meter lengths in the straight sections from being struck by missteered rays.

CONCLUSIONS AND FUTURE WORK

The new 3D ray tracing program helps more efficiently explore the wide range of beam missteering consequences within a complex vacuum system. The program has been used to help ensure robust equipment protection and thermal/structural design for APS-U's storage ring vacuum system design. The program imports familiar lattice parameters and has now been used to analyze multiple iterations to the APS-Upgrade's magnet lattice. The program is also built on flexible geometric parameters which can be toggled to explore design scenarios.

The current program is primarily suited for calculations of vacuum components along the beam path. Future work should develop the program to explore missteering consequences down photon extraction lines towards front ends and beam lines. Geometric modelling can also be improved with the inclusion of more elements or more ideally finding a way to import external 3D CAD geometry.

ACKNOWLEDGMENT

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[1] R. Kersevan and M. Ady, "MolFlow+ - A Monte-Carlo Simulator Package developed at CERN," CERN VSC Group, 2015. [Online]. Available: http://test-molflow.web.cern.ch/.