3D Numerical Ray Tracing for the APS-Upgrade Storage Ring Vacuum System Design

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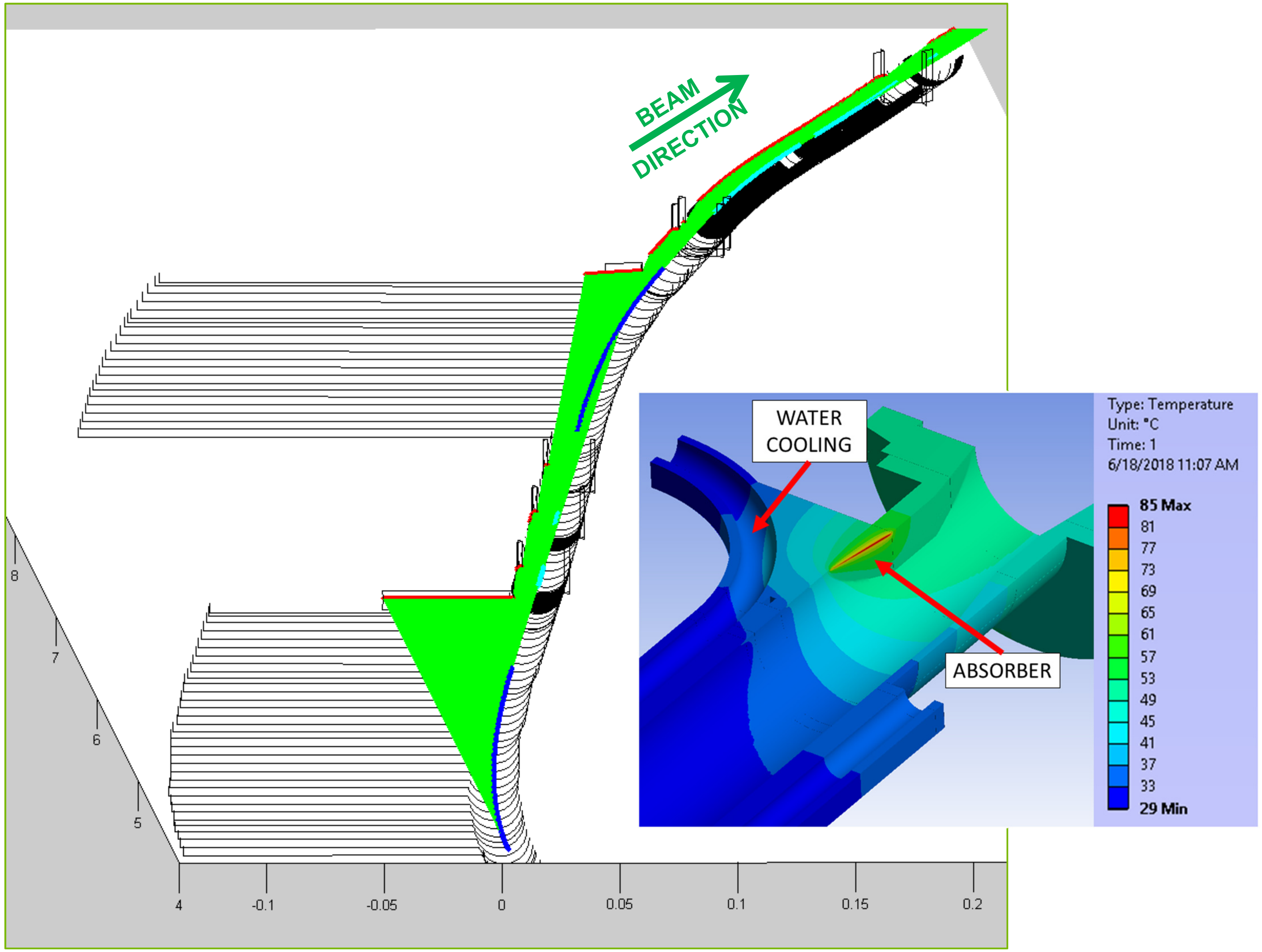
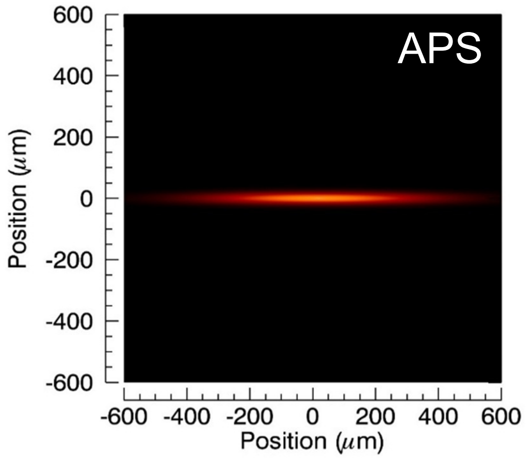
Agenda

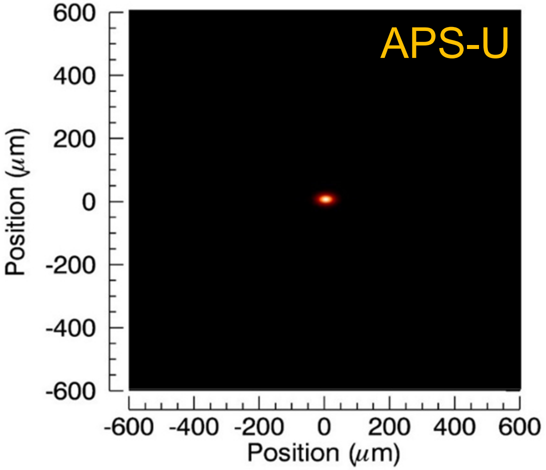
- APS Upgrade project
  - Project and storage ring vacuum system overview
- 2D ray tracing
  - Summary for APS-U
  - Limits of analysis
- 3D ray tracing
  - Motivations
  - New MatLab program for APS-U: Algorithm, theory, model geometry
  - Ray tracing results: thermal loads for ANSYS & informing beam position limits

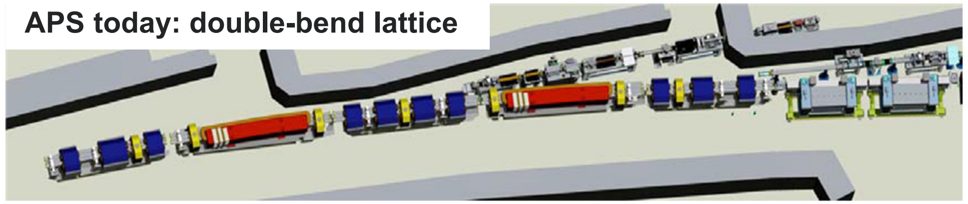


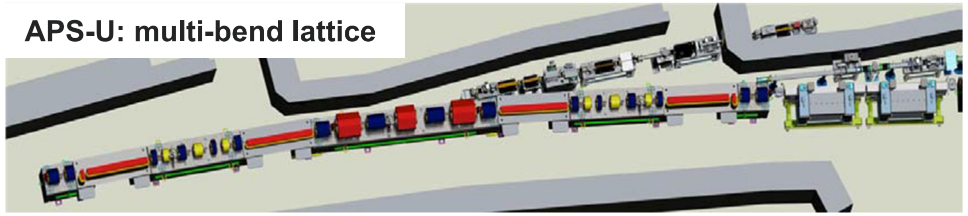
APS Upgrade Project - Overview

- Advanced Photon Source (APS)
  - 7 GeV, 100 mA, 1.1 km circumference synchrotron light source built in 1995
- APS-U multi-bend achromat lattice
  - 6 GeV, 200 mA beam current
  - Optimized for brightness above 4 keV
  - APS-U exceeds the capabilities of today's storage rings by 2 to 3 orders of magnitude in brightness, coherent flux, and nano-focused flux
  - 5000 hrs / year of beam to users at 95% availability
  - Anticipated operations ~2025
  - Powers entire beamline suit to meet needs of APS's >5000 users per year
  - 1 year APS down time (6-7 months installation)



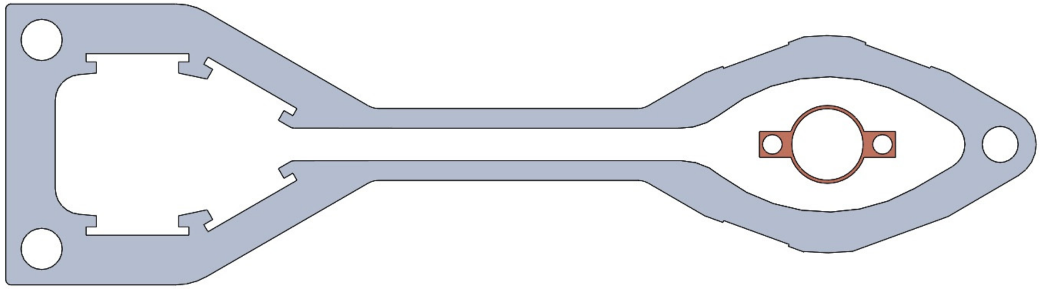




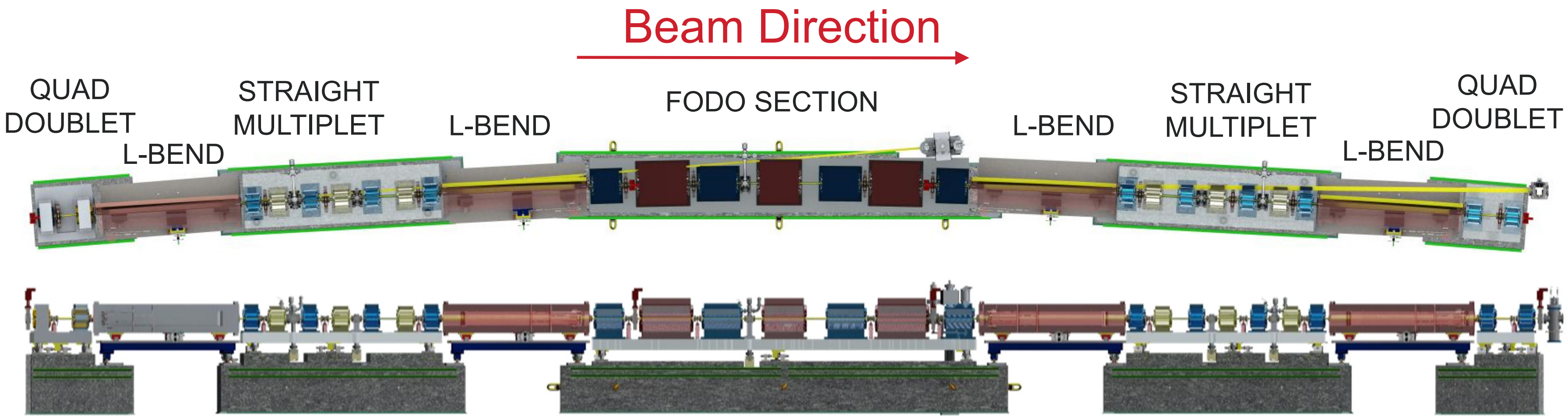


APS U Storage Ring Vacuum System - Overview

- 40x sectors, each ~27.6 meters in length
  - 22 m arc sections (our scope) + 5.6 m straight sections
- Small aperture vacuum chambers between narrow magnet gaps
- Hybrid vacuum system design
  - Discrete pumping with ion pumps and lumped NEGs
  - Distributed pumping with NEG strips and NEG coatings
- Low pressure design target for good beam lifetimes
  - 2 nTorr @ 200 mA by 1000 A*hrs conditioning (1E-11 Torr/mA)

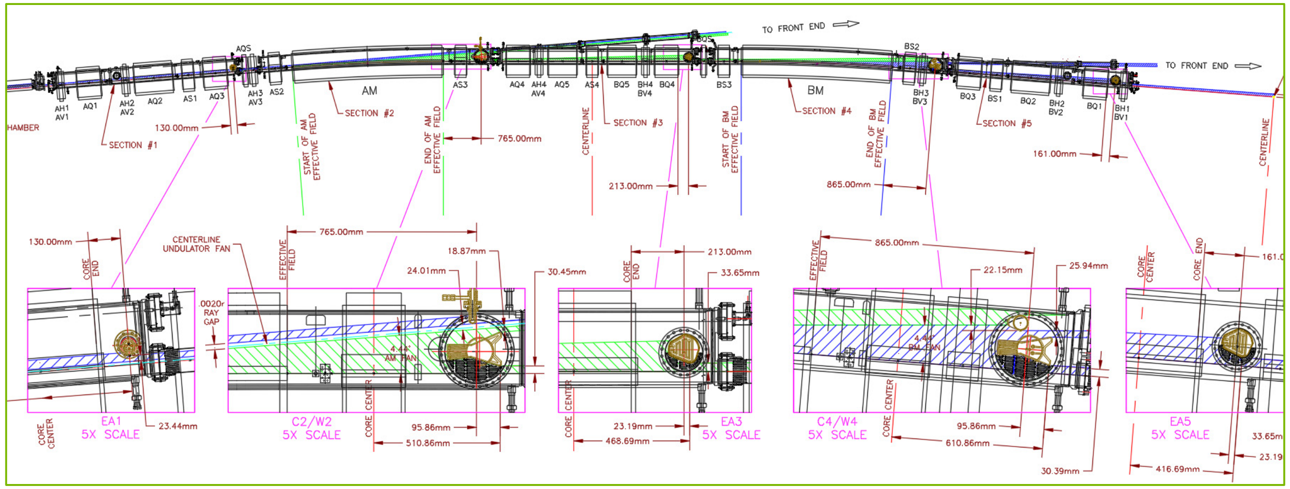


Existing APS storage ring chamber compared to new 22 mm ID APS-U style chamber

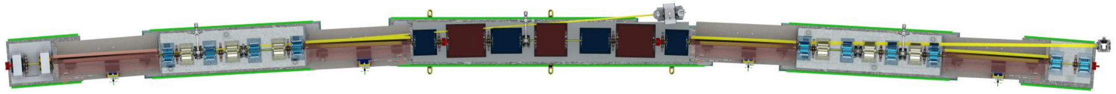


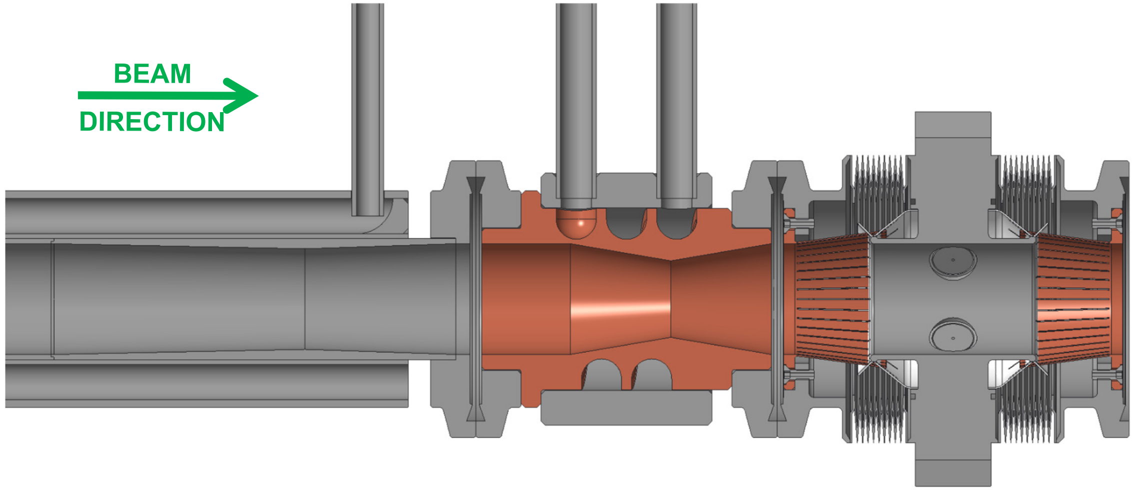
Top view ray tracing w/ 2D CAD

- Conventional 2D ray tracing with a top view layout in AutoCAD
  - For APS, 6x discrete photon absorbers take majority of unused photon heat load
- Smaller scale apertures of next-gen machines make more components participate in ray trace
  - For APS-U, 20x components including vacuum chambers participate in ray trace



Original APS storage ring vacuum system 2D ray trace using AutoCAD

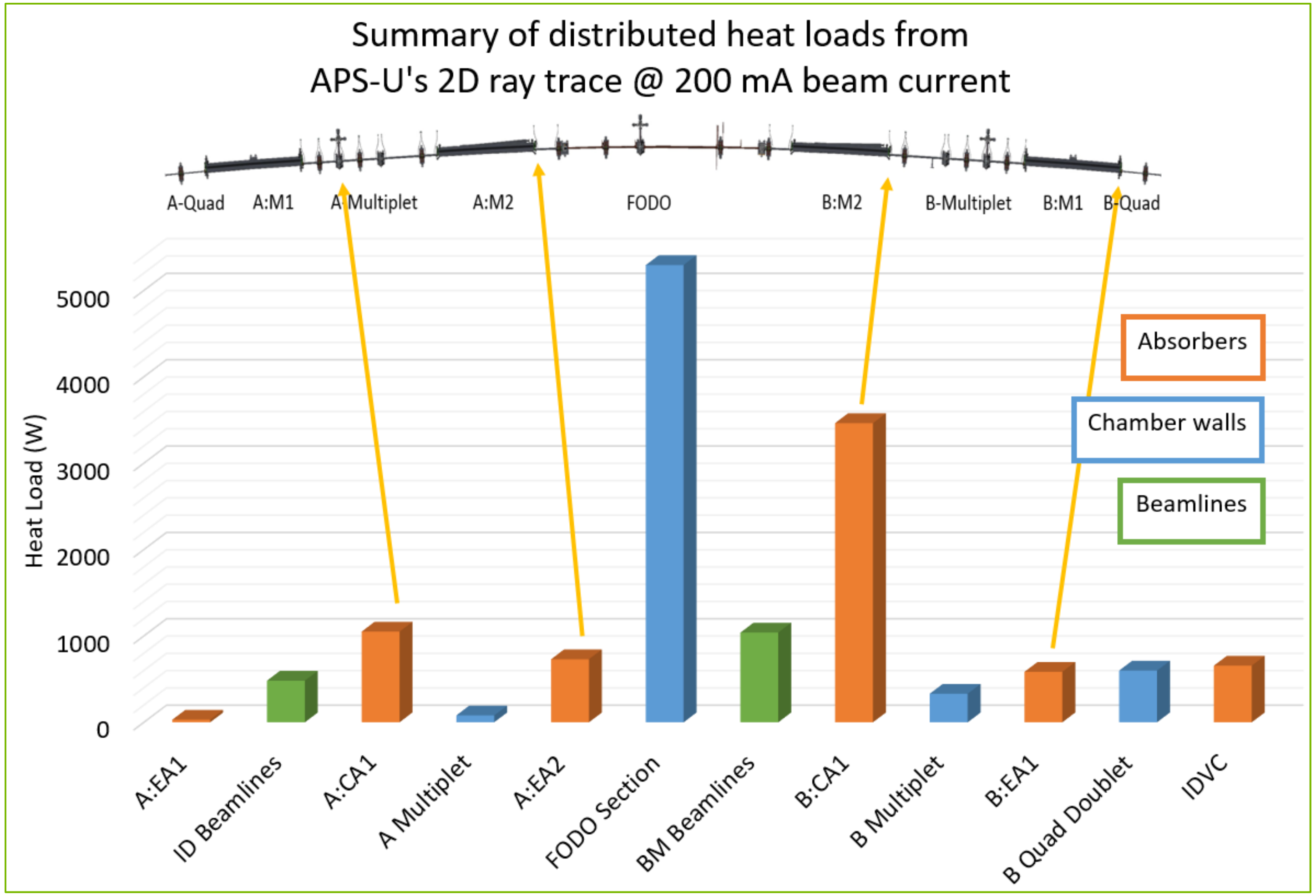




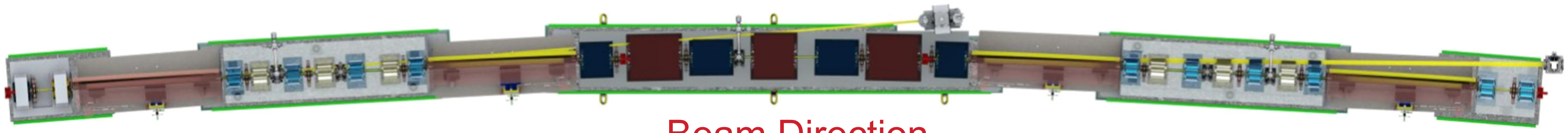
Typical APS-U storage ring vacuum sequence:
22 mm ID chamber protecting downstream flange joint,
inline absorber protecting length of downstream BPM

Summary of APS-U storage ring ray tracing

- 2D Ray Tracing for APS-U
  - Rays strike 20 separate vacuum components per sector and breakdown requires a complex 2D CAD layout
  - 14.3 kW generated per sector @ 200 mA
    - 5.3 kW on FODO section chambers
    - 3.5 kW on B-side crotch absorber
    - 600 W in B Quad Doublet
- Ray tracing compared and verified using 3 separate tools:
  - 2D CAD layout
  - SynRad, CERN's 3D ray tracing code
  - New 3D MatLab program for studying beam missteering



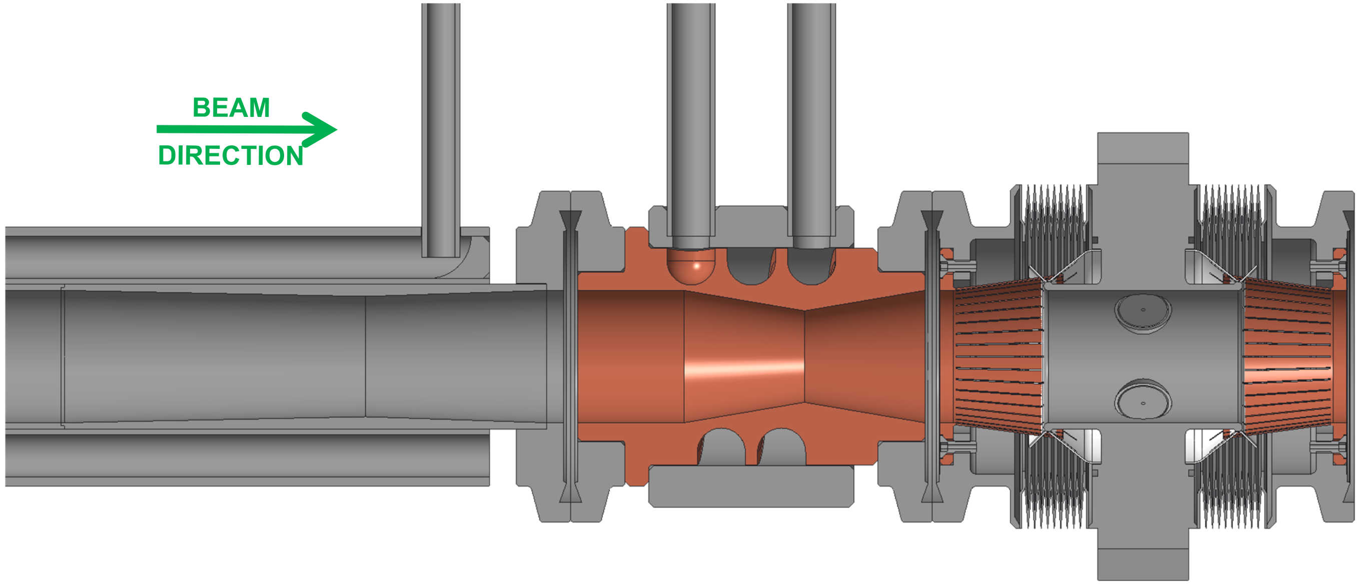
Summary of APS-U's 2D ray trace



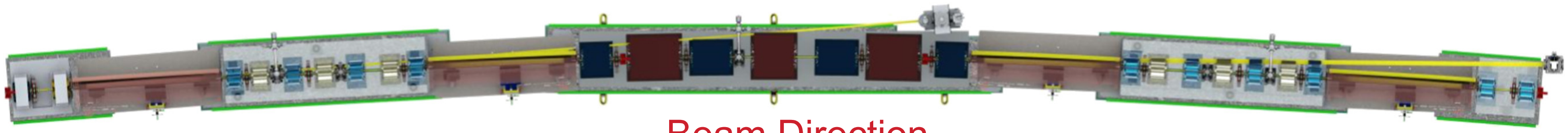
Beam Direction

Motivations for 3D ray tracing

- Difficult to ensure protection of new machines with small apertures, sensitive components, and more photon intercepting chambers and absorbers
- Beam missteering happens in 3D and presents too large of a set of possibilities to capture in 2D
- Absorbers and chambers need to be designed and analyzed to withstand worst-case radiation loads
- How to reasonably specify limits for beam position limit detection systems?



Typical APS-U vacuum sequence:
Chamber protecting downstream flange joint,
inline absorber protecting length of downstream BPM



Beam Direction

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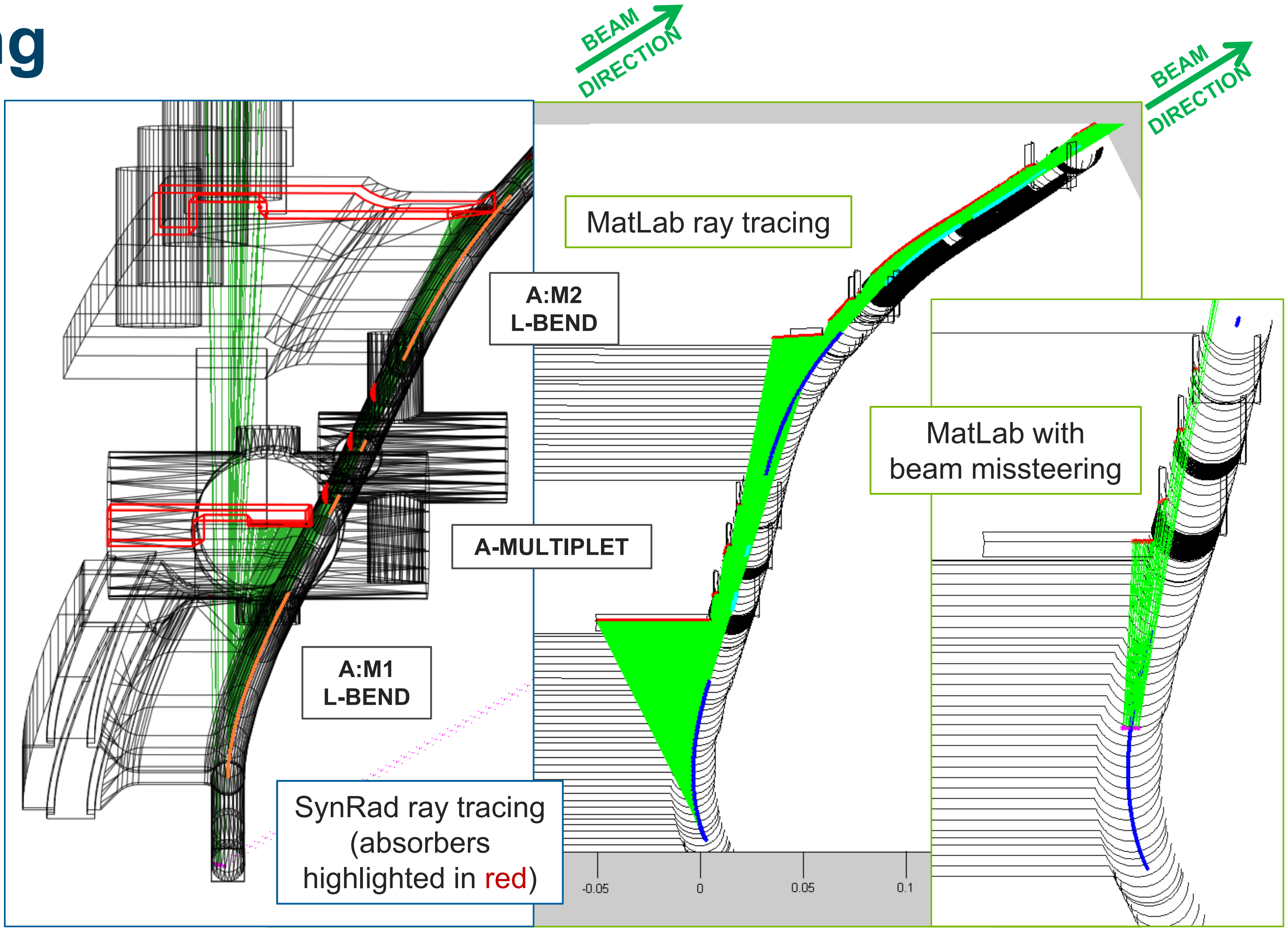
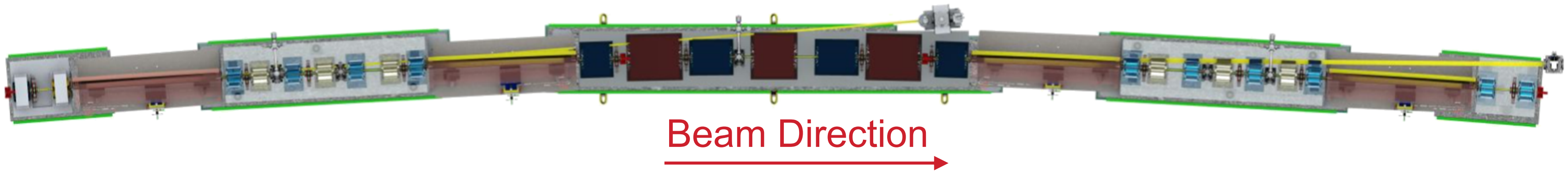
APS-U 3D ray tracing

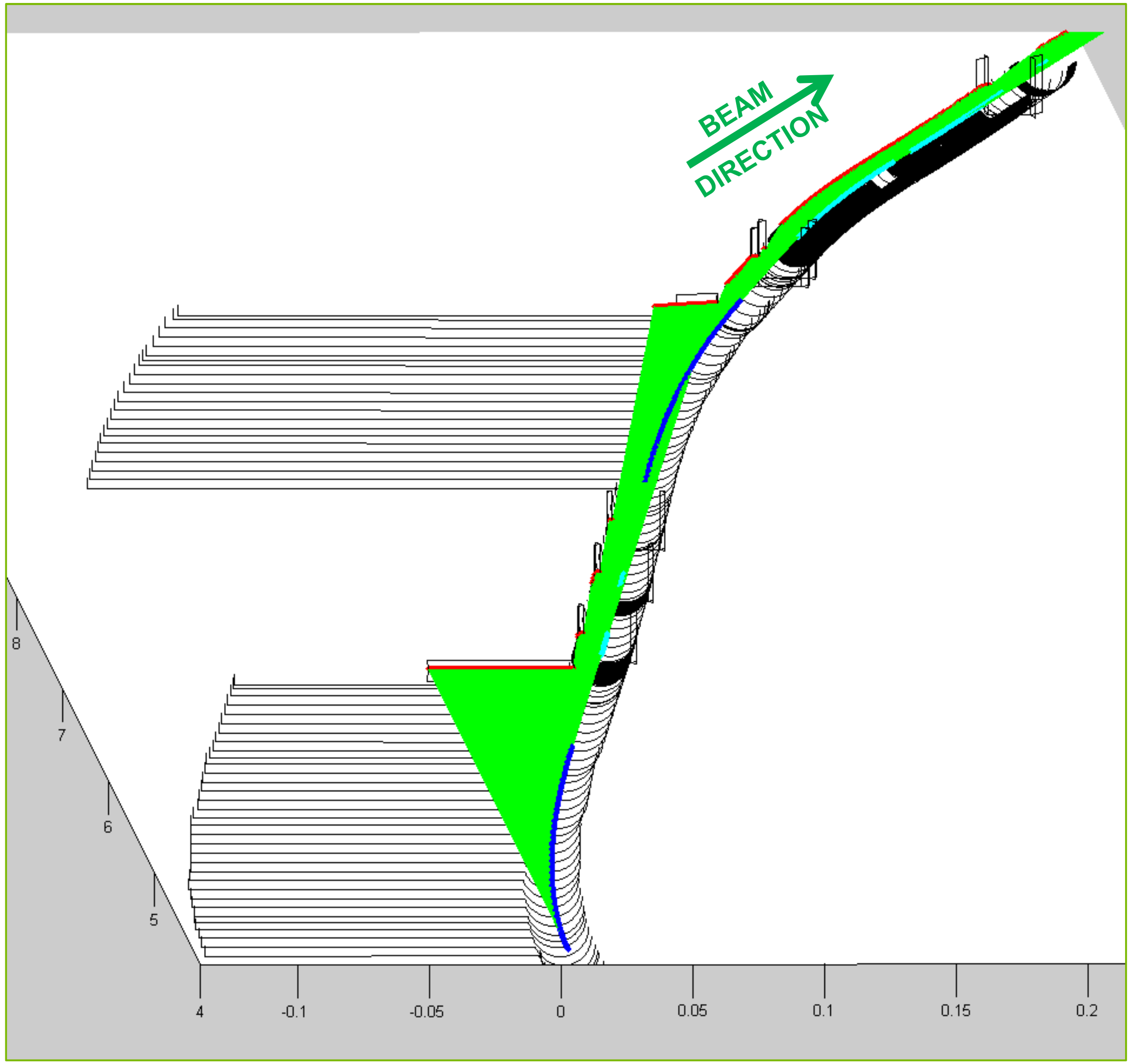
- Ray tracing compared with 3x separate tools:
  - 2D layout: takes time to create CAD layout and break down results, modify for scenario studies
  - SynRad (CERN code): 3D models extracted from full vacuum system CAD assembly, quick to modify with practice, difficult to compare results across vacuum system
  - Numerical 3D ray tracing with new MatLab code: explore beam
- Better understanding of ray tracing and missteering helps ensure robust shielding within narrow apertures





Overview of numerical ray tracing algorithm

1. Build geometry based on sequentially ordered geometric elements along beam path
2. Generate tangential rays from points along bend path
    1. If no missteering: just one ray per point
    2. If yes missteering: at each point, generate numerous rays with deviated positions and angles based on local phase space ellipses
3. Find where ray strikes by checking downstream geometry sequentially
4. Record data from strike on element: strike coordinates, total heat (W), intensity (W/mm, W/mm2), etc.
5. Use logic to find ‘worst rays’ on each element after many possible strikes



2D ray tracing model in MatLab
(E-beam bends in **blue**, photon ‘rays’ in **green**, strike points in **red**)

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Overview of numerical ray tracing algorithm

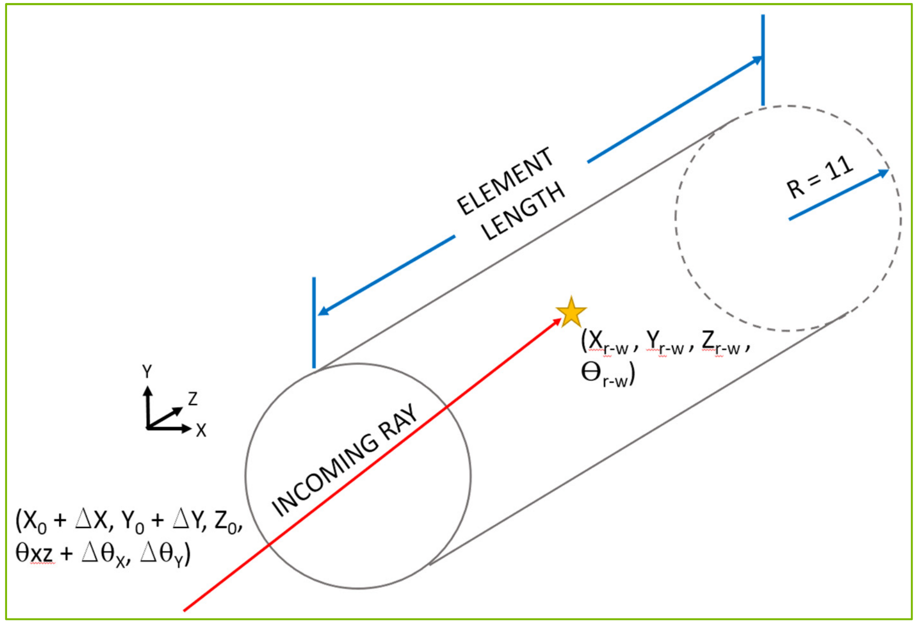


Diagram of ray traced to intercepting geometry

$$\overrightarrow{u_{ray}} = (x_{r-w} - (x_0 - \Delta x), y_{r-w} - (y_0 - \Delta y), z_{r-w} - z_0) \quad (5\text{-}1)$$

$$\theta_{r-w} = \sin^{-1} |\vec{n} \cdot \vec{u}| / (|\vec{n}| \cdot |\vec{u}|) \quad (5\text{-}2)$$

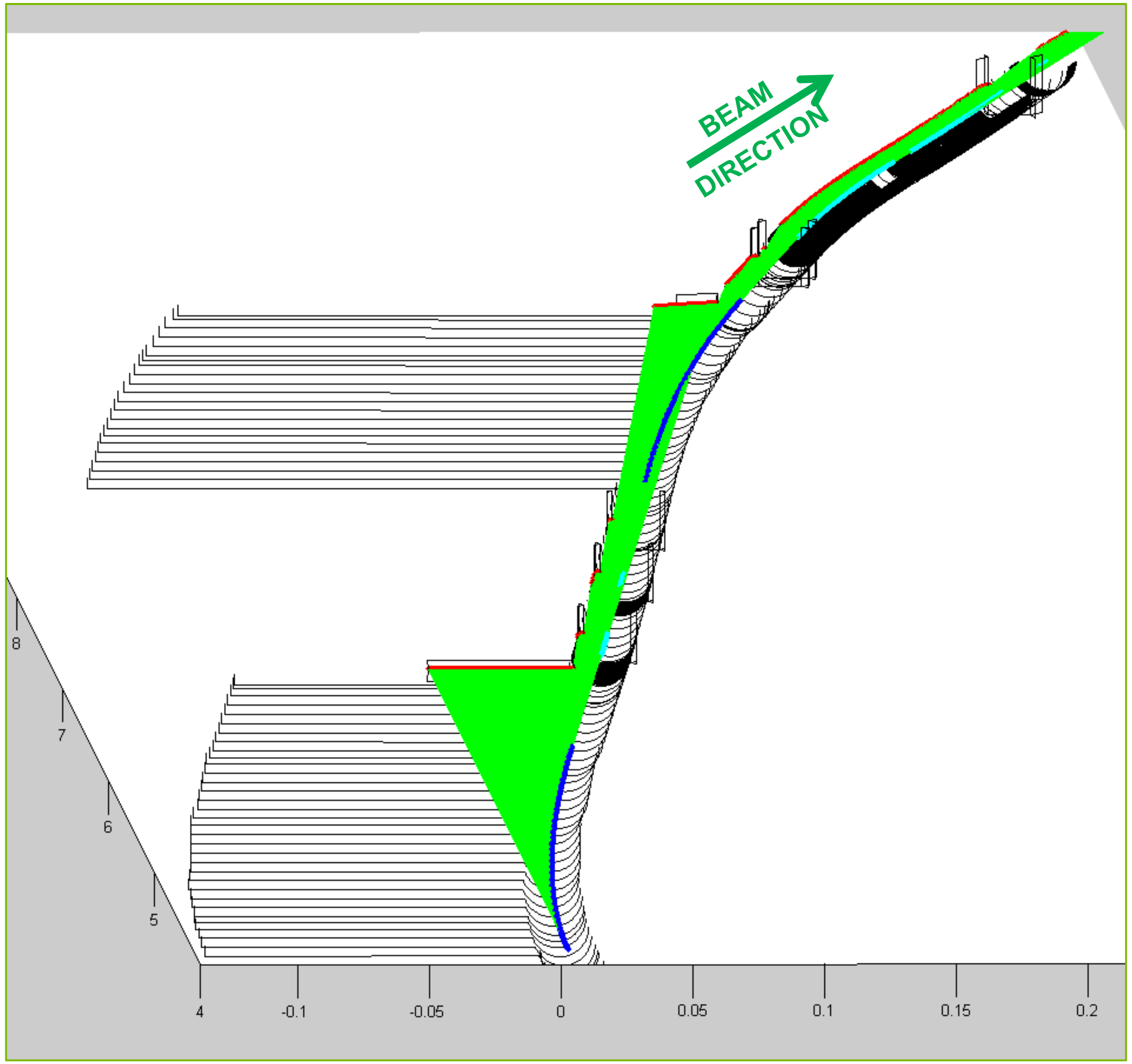
$$P_{d0}\left(\frac{W}{mrad^2}\right) = 5.421 * E_e^4(GeV) * I(A) * B(T) \quad (5\text{-}3)$$

$$P_{d0}\left(\frac{W}{mrad}\right) = 4.221 * E_e^3(GeV) * I(A) * B(T) \quad (5\text{-}4)$$

$$P_{d0}\left(\frac{W}{mm^2}\right) = P_{d0}\left(\frac{W}{mrad^2}\right) * \sin(\theta_{r-w}) / L_{r-w}^2 \quad (5\text{-}5)$$

$$P_{d0}\left(\frac{W}{mm}\right) = P_{d0}\left(\frac{W}{mrad}\right) * \sin(\theta_{r-w}) / L_{r-w} \quad (5\text{-}6)$$

Common synchrotron radiation heat load equations



2D ray tracing model in MatLab
(E-beam bends in **blue**, photon 'rays' in **green**, strike points in **red**)

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Beam orbits and lattice functions

- Spatial and angular beam deviation possibilities from local phase space ellipses in x,y planes
  - Phase space ellipse extents calculated with Courant-Snyder lattice parameters
  - APS-U physics provides parameters along finely spaced points across the sector
  - Maximum beam extents limited by a limiting aperture or beam position limit detection system
- Local ellipses discretized, large amounts of new ray paths with deviations tested in MatLab

Ellipse Equations:

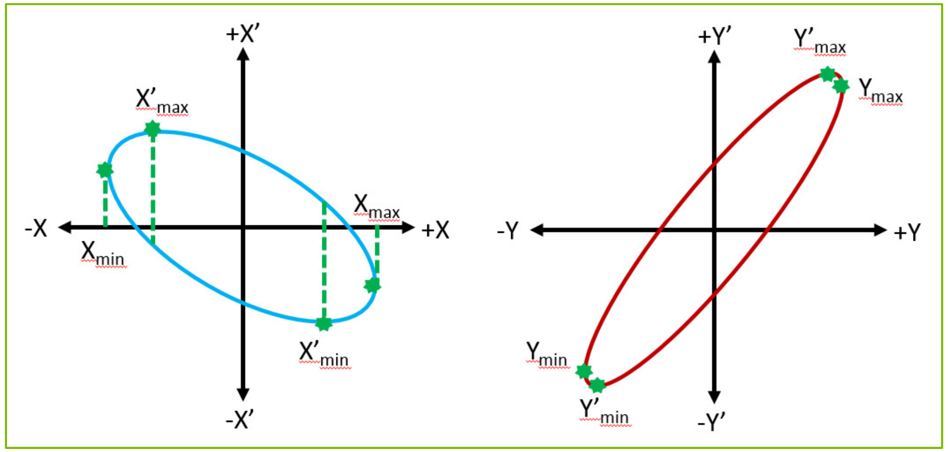
$$\mathcal{A} = \gamma(s)x^2 + 2\alpha(s)xx' + \beta(s)x'^2$$

$$x' = \frac{-2\alpha x \pm \sqrt{(2\alpha x)^2 - 4\beta(\gamma x^2 - \mathcal{A}_x)}}{2\beta}.$$

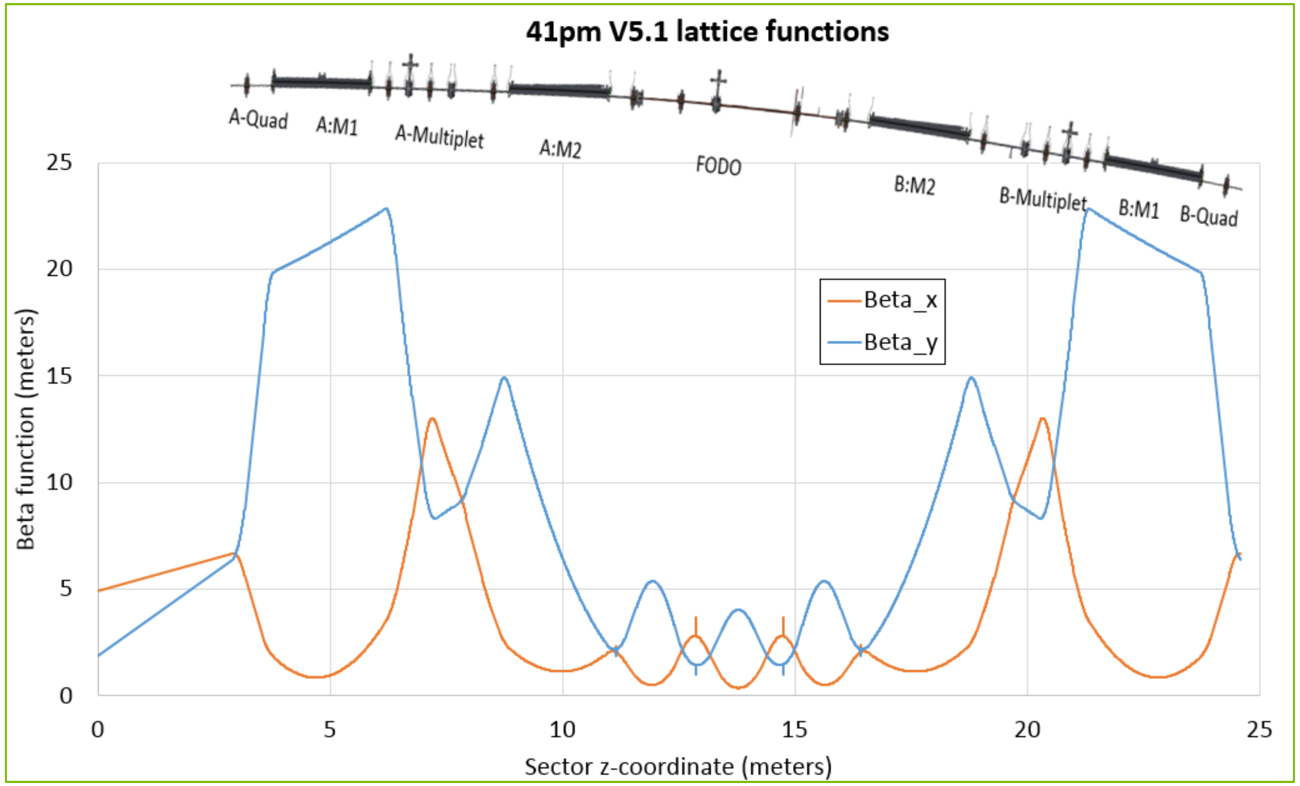
Spatial extents:

$$x_{max} = \pm\sqrt{A_x \beta_x}$$

$$y_{max} = \pm\sqrt{A_y \beta_y}$$



Example local phase space ellipses



APS-U lattice functions in the x and y plane

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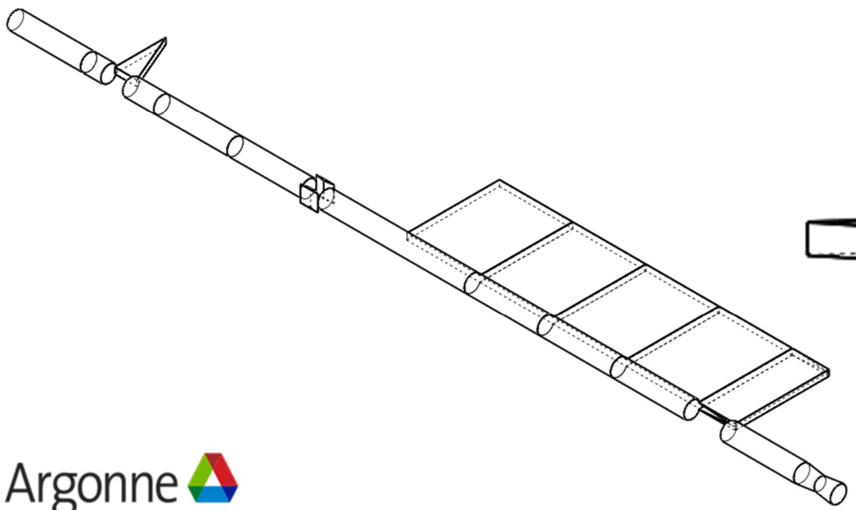
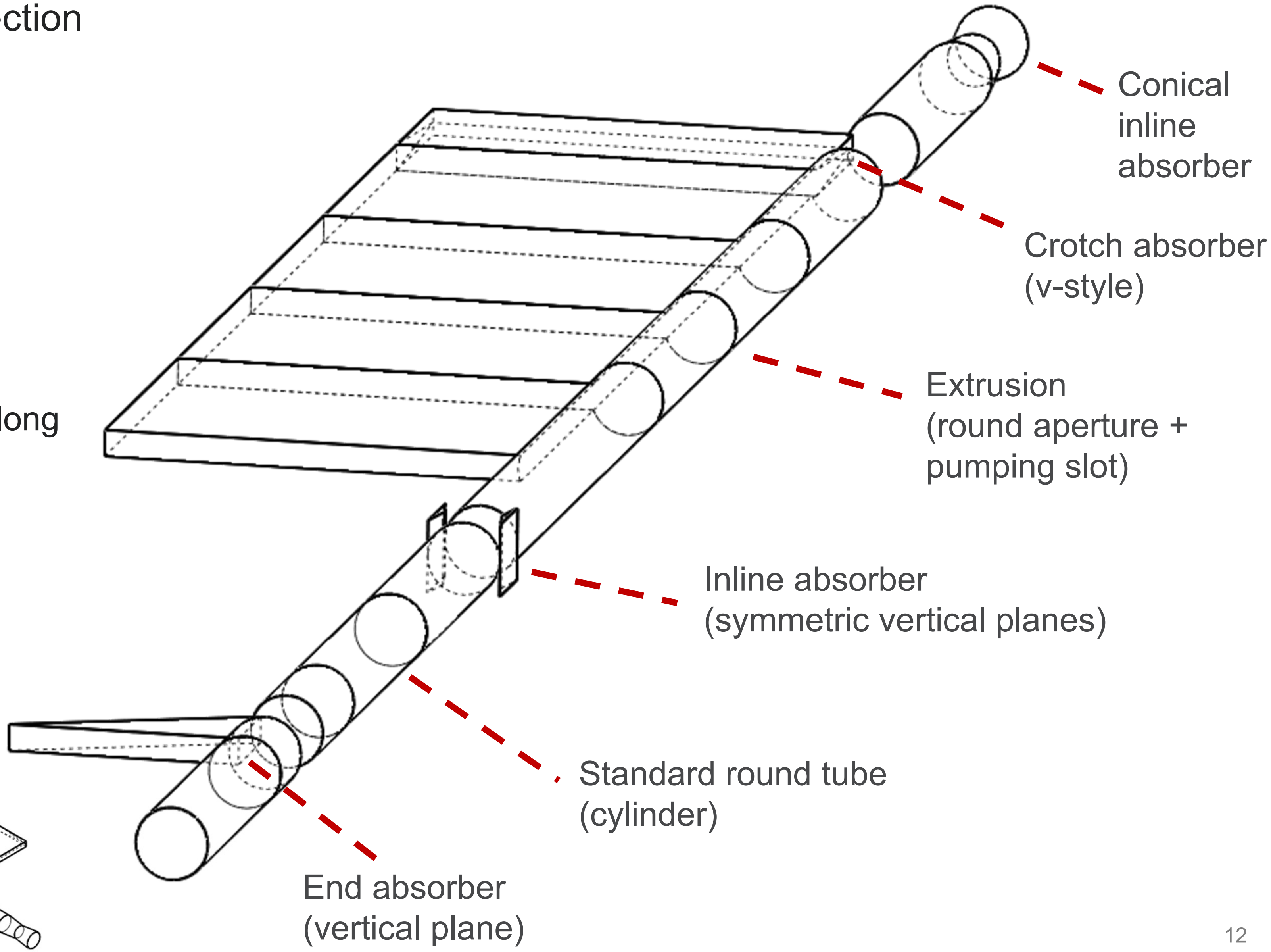
3D numerical ray tracing geometry

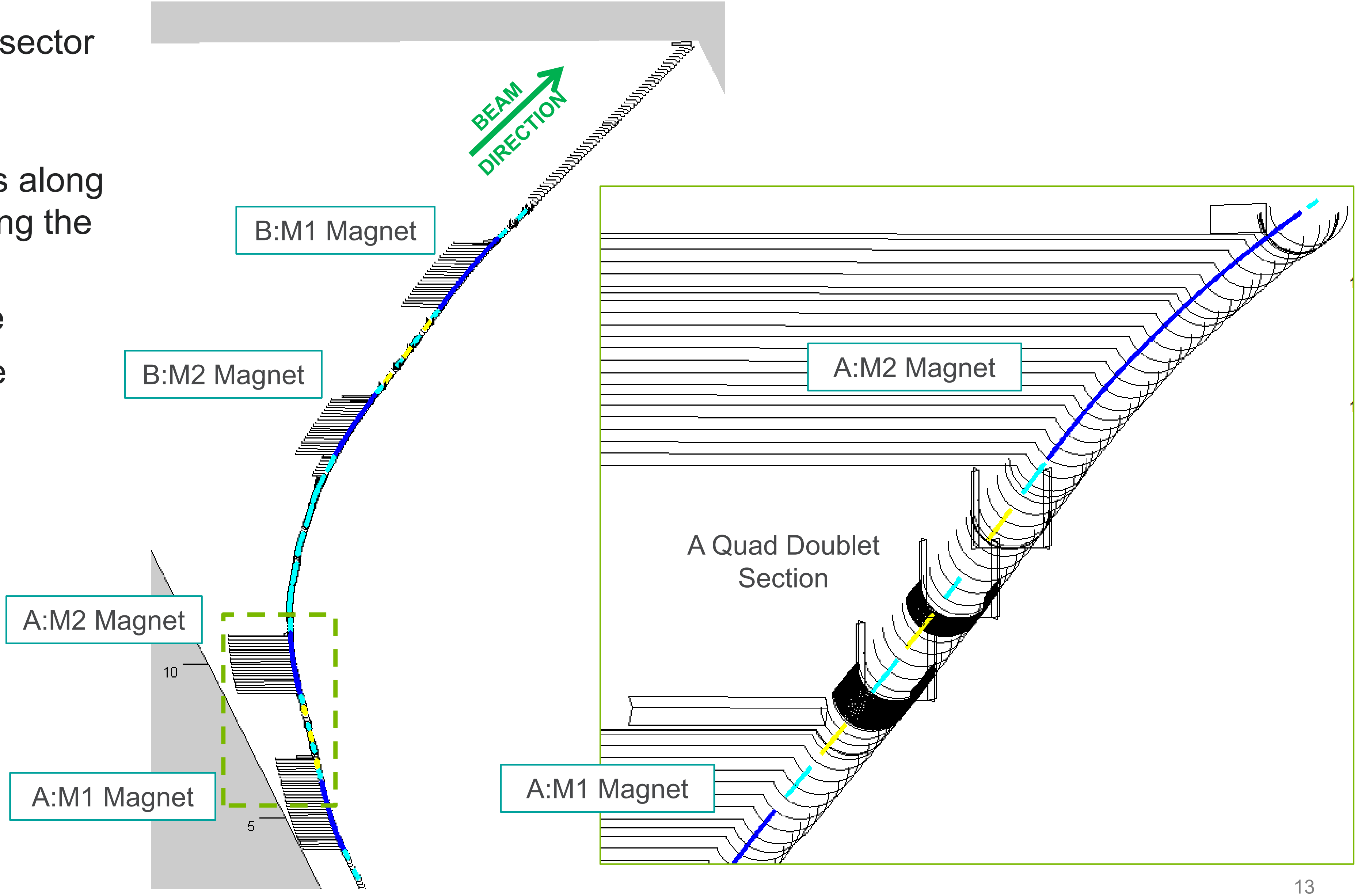
- Geometry programmed by cross section
  - Round tubes
  - Simplified extruded chambers with antechambers
  - Photon absorbers (planar, conical, and v-shaped)
- Photon extraction geometry not yet developed (future work!)
  - Current program follows geometry along the main beam path



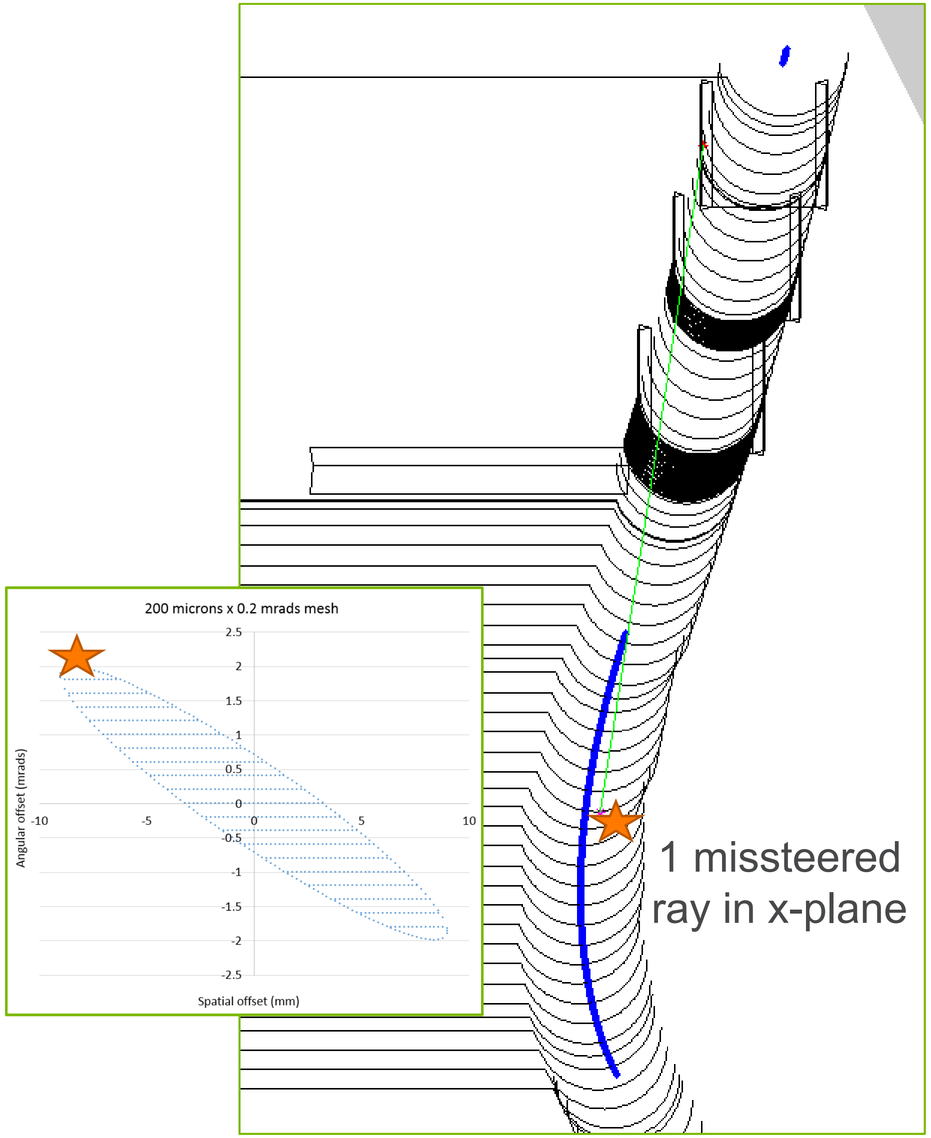


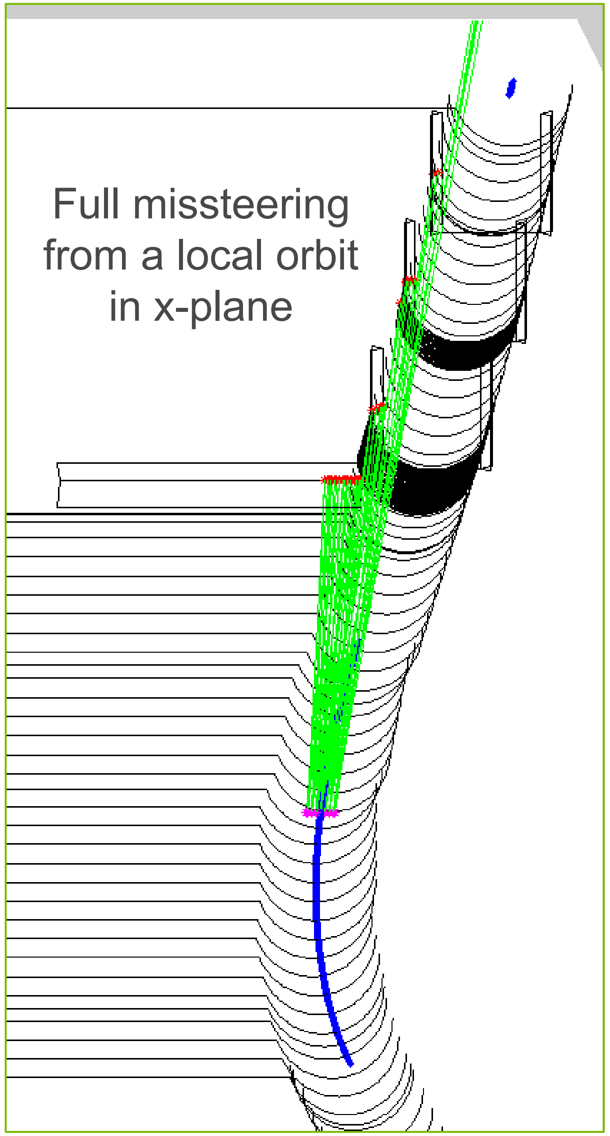
3D numerical ray tracing geometry

- Full scale 27.6 m length sector APS-U model built from sequential elements
- Rays generated at points along colored paths representing the magnet lattice
- Dipole paths in dark blue
- Quadrupoles in light blue
- Sextupoles in yellow

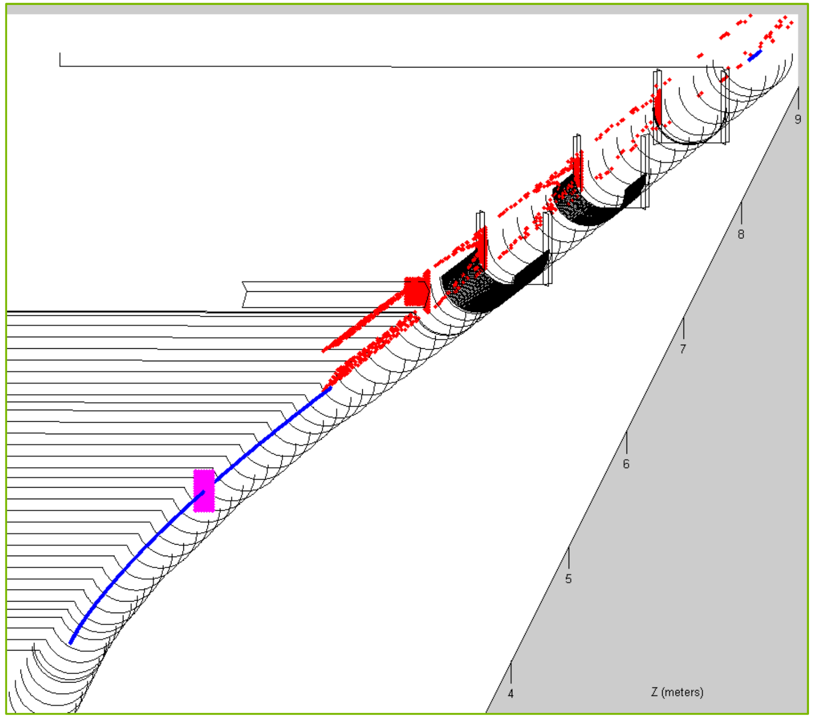


Beam missteering: X and Y planes



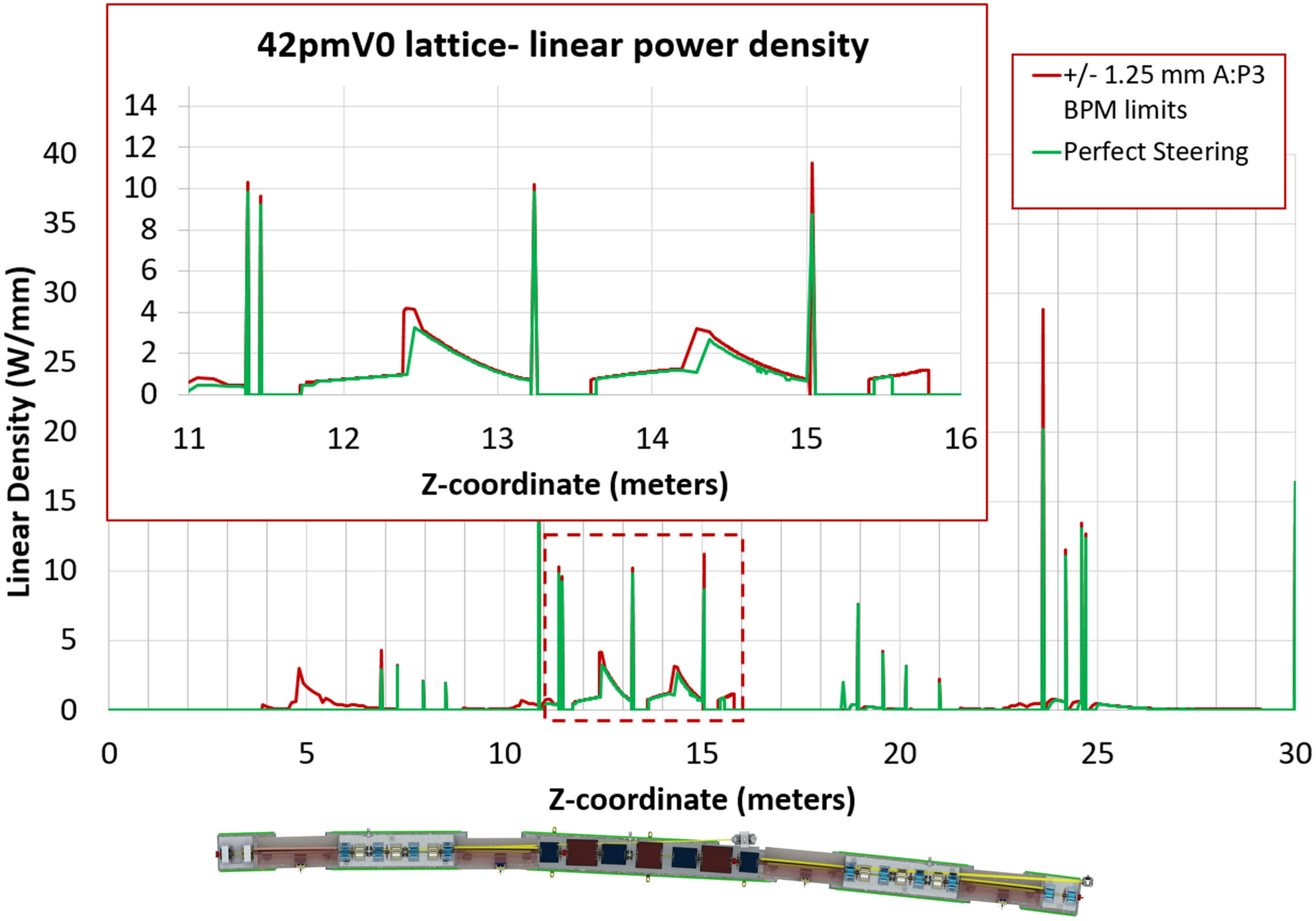


Full missteering from a local orbit in ***both*** x and y-planes
(green ray paths removed from image)



3D ray tracing results along length

- Linear power across sector compared for ideal steering (green) and worst cases of missteering with a BPLD limit (red)
- General nature of ray trace: spikes at compact absorber faces, high body loads on round chambers in FODO section, light body loads elsewhere
- Ideal steering case has been verified to 2D ray trace and SynRad's results



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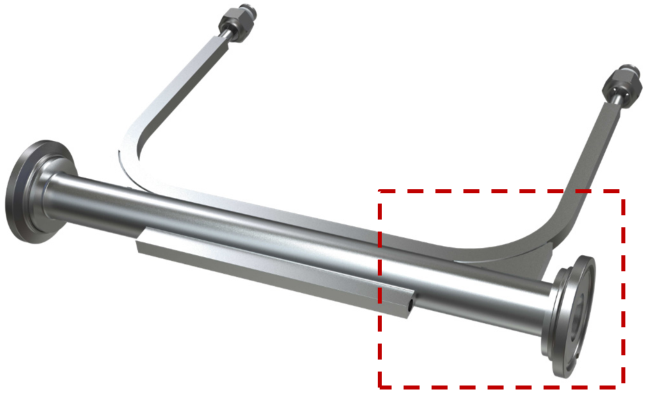
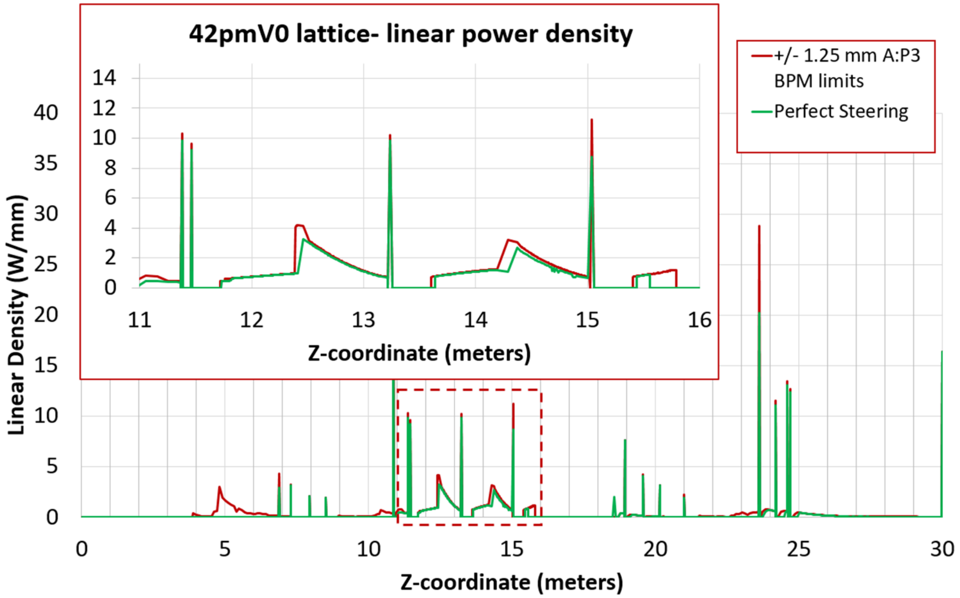
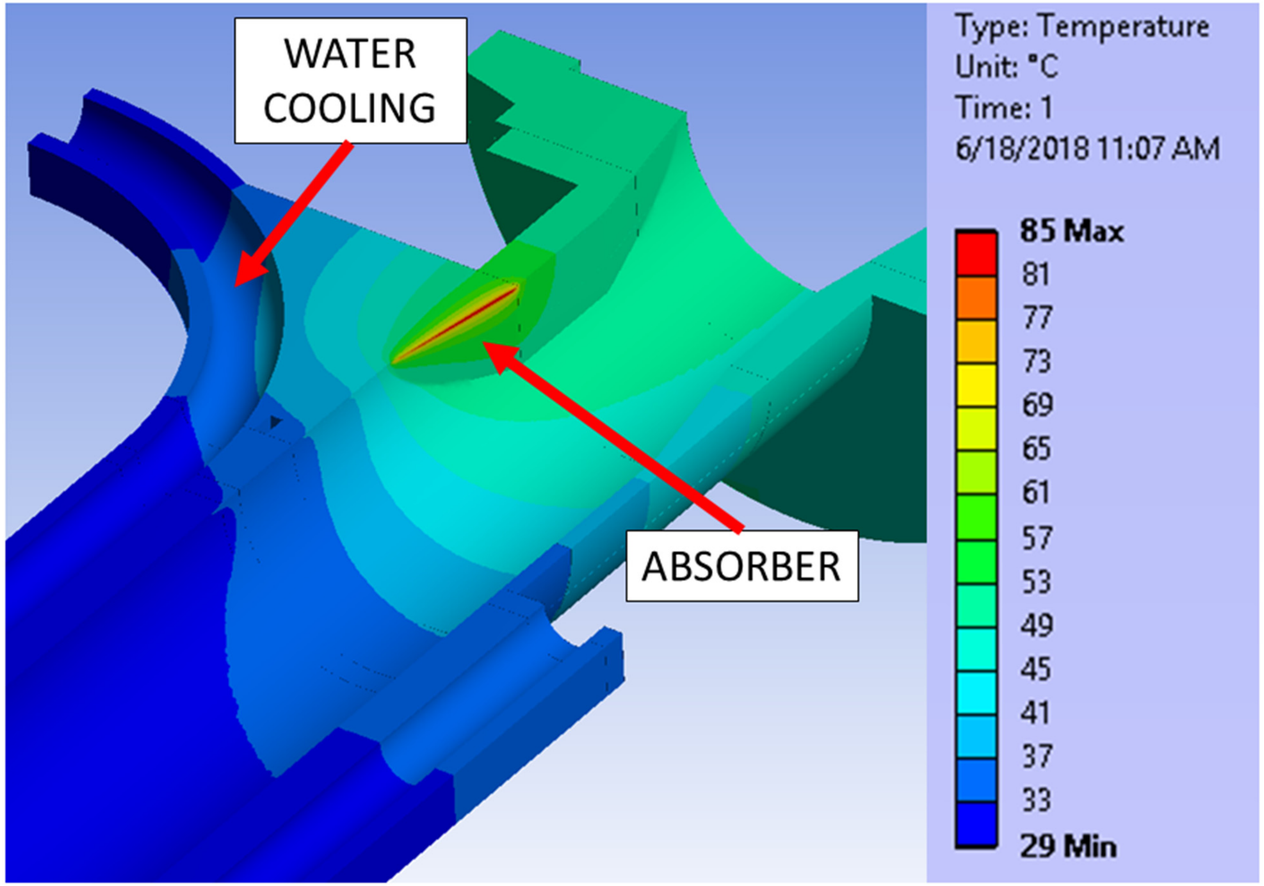
3D ray tracing results along length

- Integrated results across individual chambers used for conservative boundary conditions for thermal/structural analysis
- Typically ~10% higher loads than ideal case if a BPLD limit considered



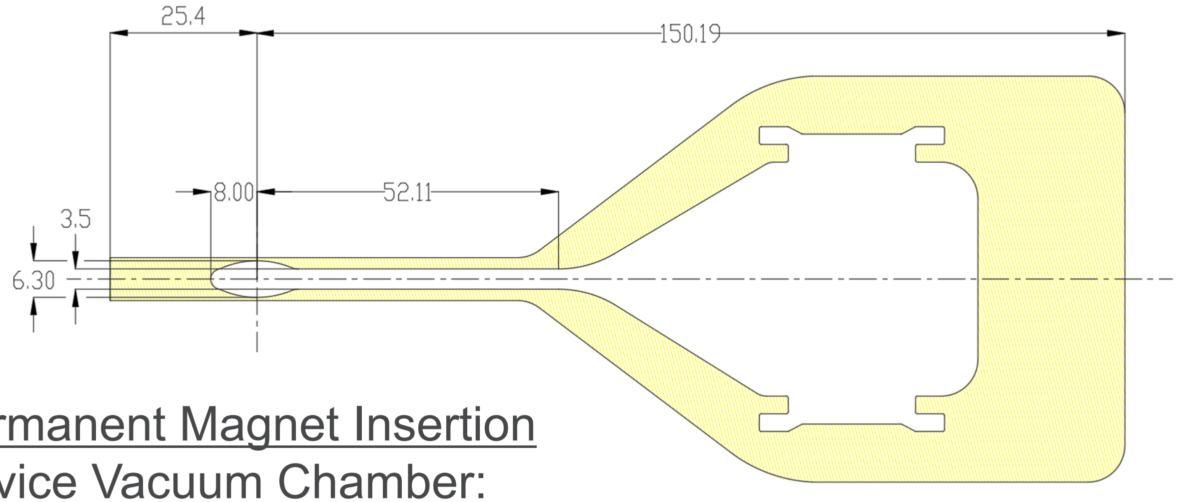




Typical ANSYS thermal analysis of water-cooled APS-U chamber with inline absorber

Informing BPLD limits

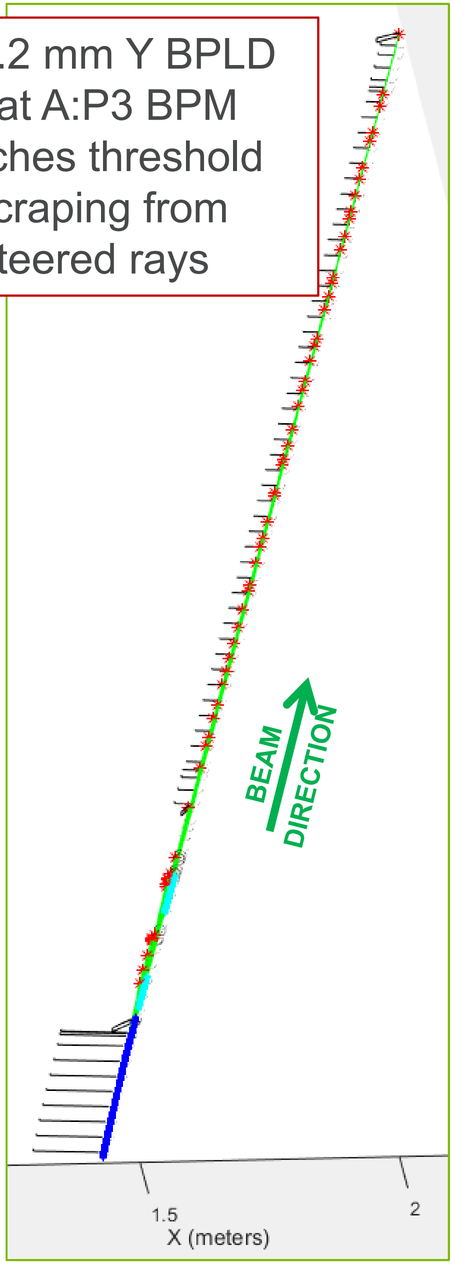
- Straight section chambers with long, narrow, uncooled apertures
- How to understand scraping possibilities and can a reasonable BPLD limit help minimize them?
- Simplified model with ideal machining and alignment
- Anticipate a full 200 mA BPLD limit of +/- 0.5 mm measured at a BPM
(less constrained for beam current < 1 mA)



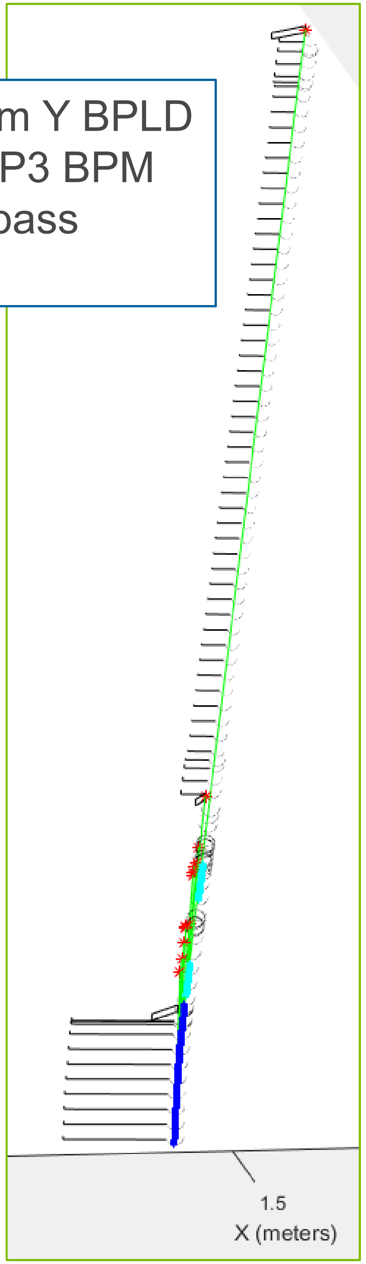
Permanent Magnet Insertion Device Vacuum Chamber:

- Length: 5.322m

+/- 1.2 mm Y BPLD limit at A:P3 BPM
*reaches threshold for scraping from missteered rays

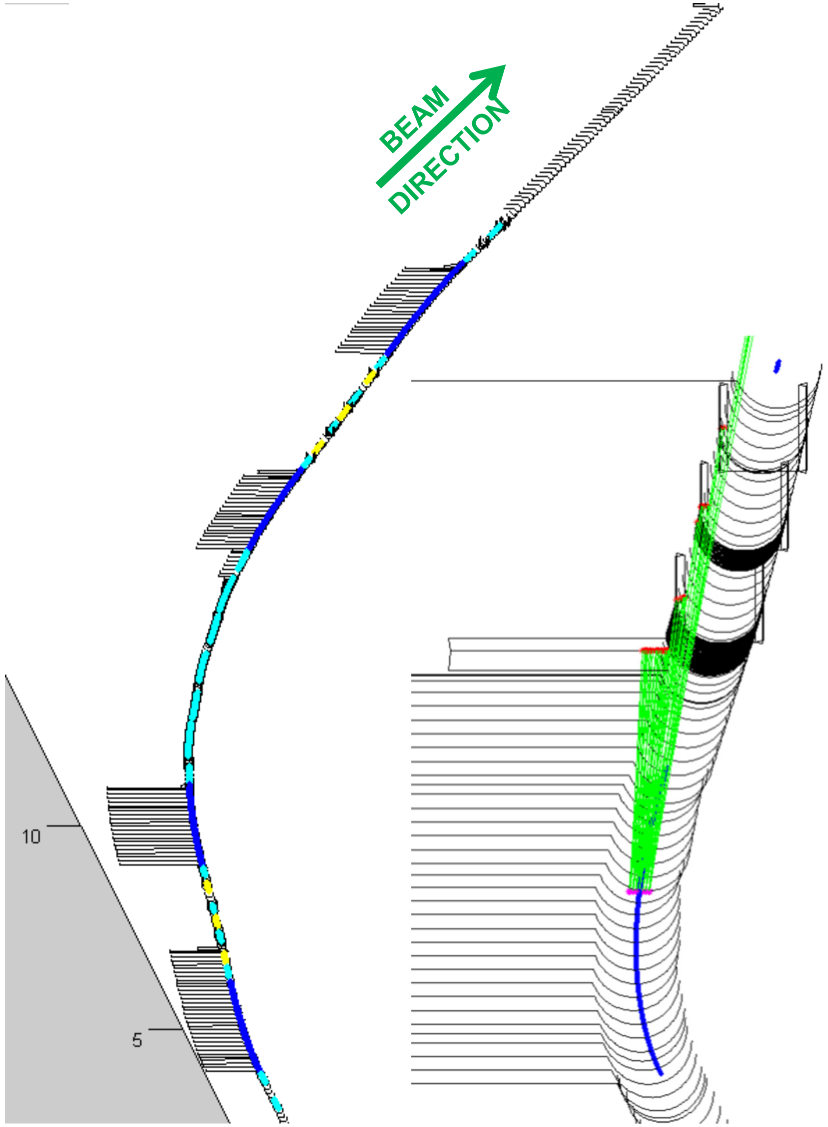


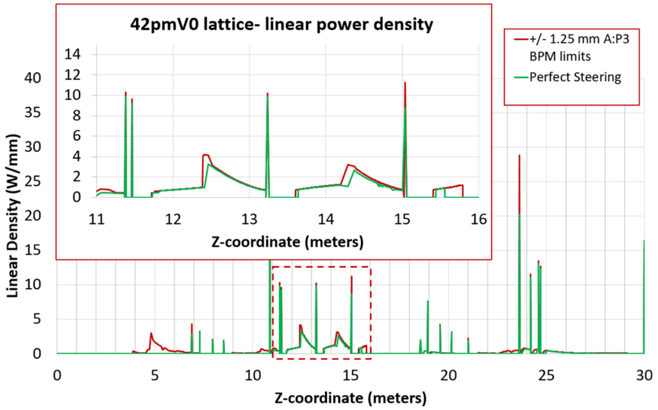
+/- 1.1 mm Y BPLD limit at A:P3 BPM
*all rays pass through

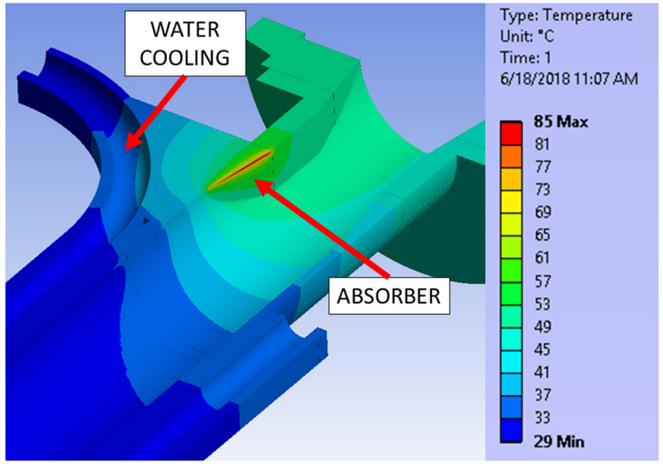


Conclusions and future work

- New MatLab program to investigate ray tracing with beam missteering
  - Models built off of adjustable geometric parameters for system analysis and scenario studies
  - Post-processed graphics help investigate results in 3D
  - Results used for conservative heat loads in thermal analysis
- Future work
  - Current program suited for chambers along the beam path, will develop program for extracted rays
  - Find efficient ways to model vacuum component misalignment
  - Import geometry from 3D CAD







Questions?