Argonne NATIONAL LABORATORY

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Thermo-Mechanical Design of FODO Module Vacuum Chambers of MBA Lattice at APS

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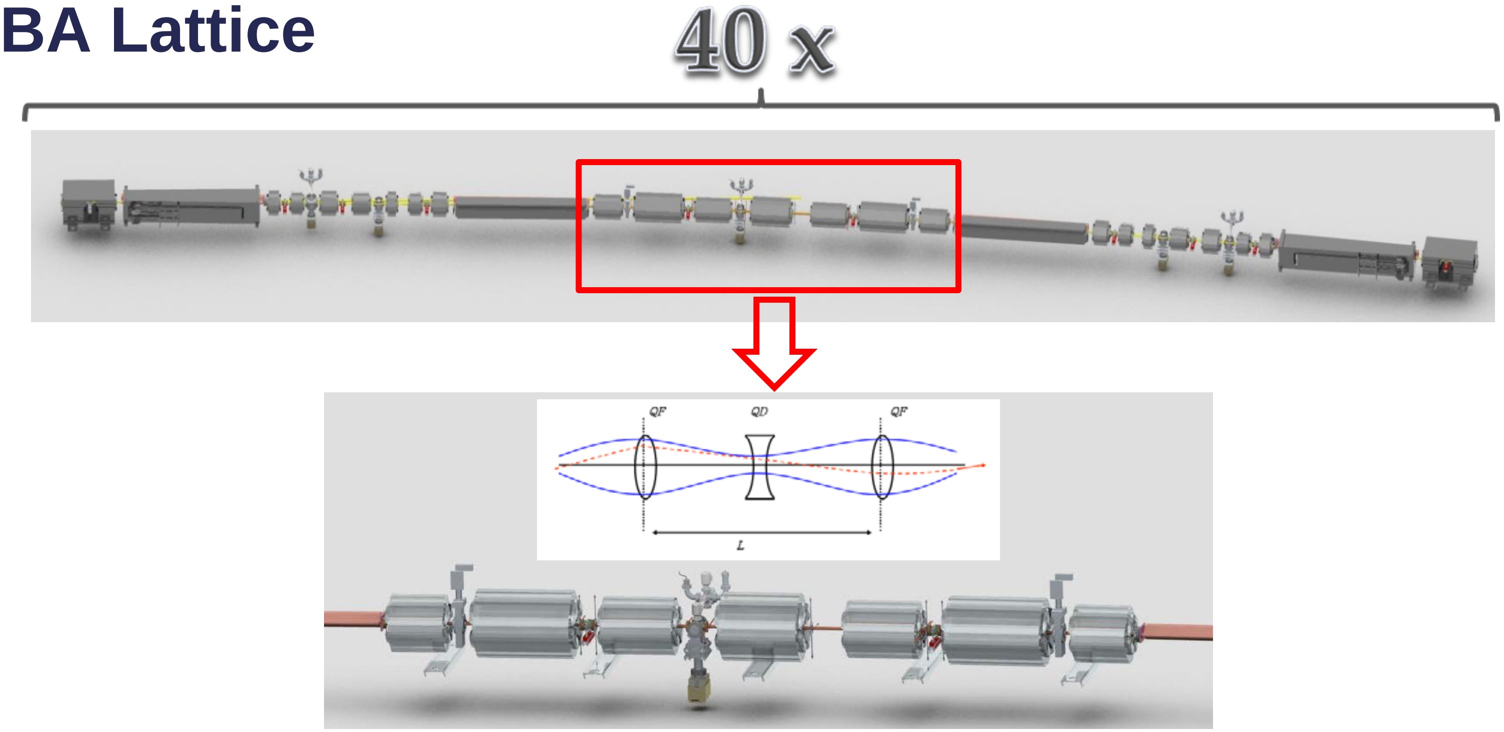
U.S. DEPARTMENT OF ENERGY

Outline

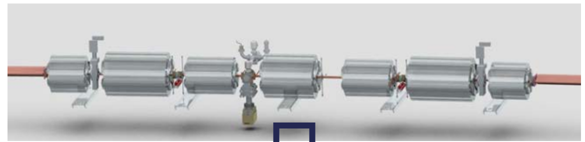
- FODO module of MBA Vacuum System
- FODO Module Design Process
- Thermo-Mechanical Optimization of the FODO Module Components
- The results (so far)

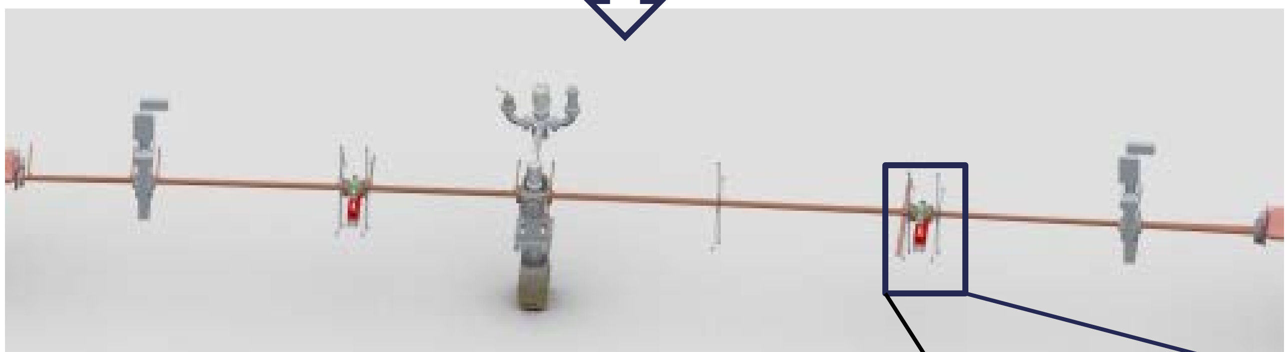
FODO (Focusing and Defocusing) Module of APS_U MBA Lattice

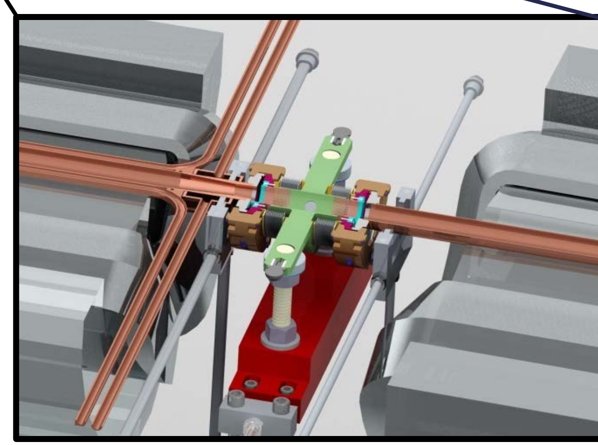


- FODO section is the central section of each of 40 identical sectors of APS_U MBA Lattice. It consist of
  - Focusing and defocusing quadrupole lenses in alternating order.
  - Vacuum sub-system that provides scattering free path for charged particles
  - Beam diagnostics

Vacuum sub-system of FODO Section

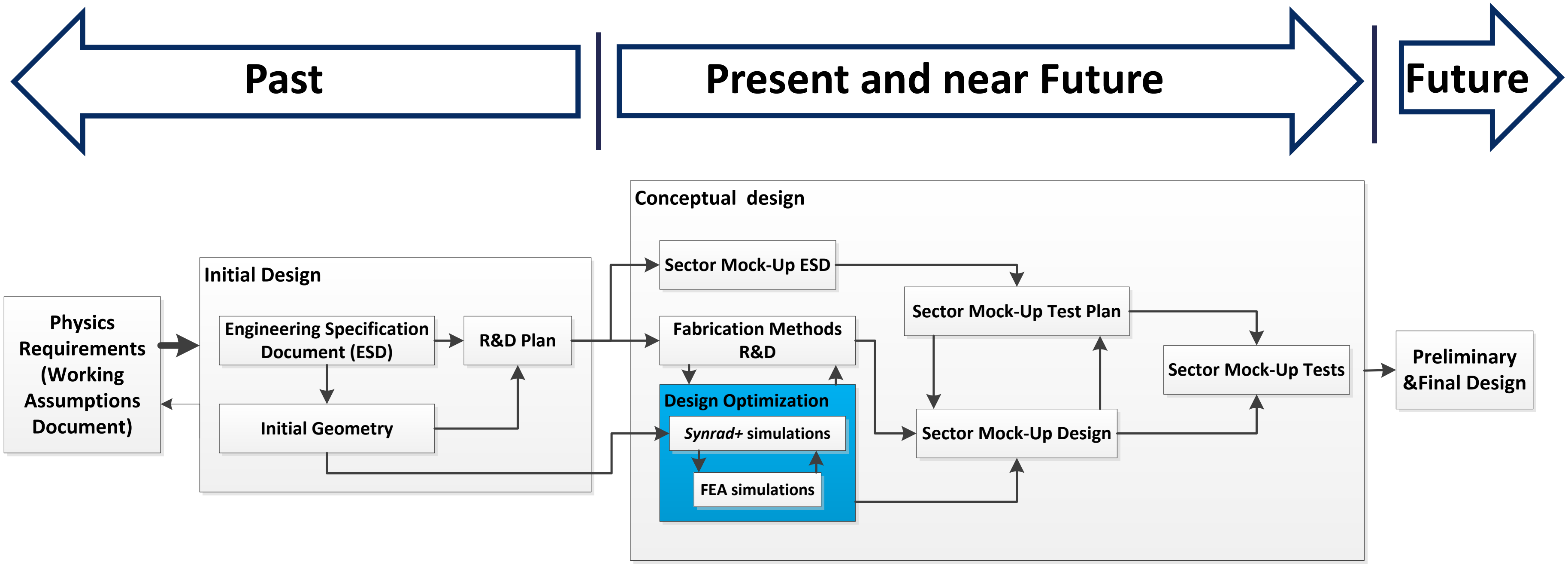






- Thermal budget of FODO vacuum chambers consists of synchrotron radiation, RF and eddy current heating
  - **OFS copper with excellent thermal and good structural properties was selected as the material of choice**
- Strict spatial limitations imposed by magnet design require
  - Compact and efficient cooling system design
  - Design that will maintain dimensional stability

FODO Section Vacuum Sub-System Design Process

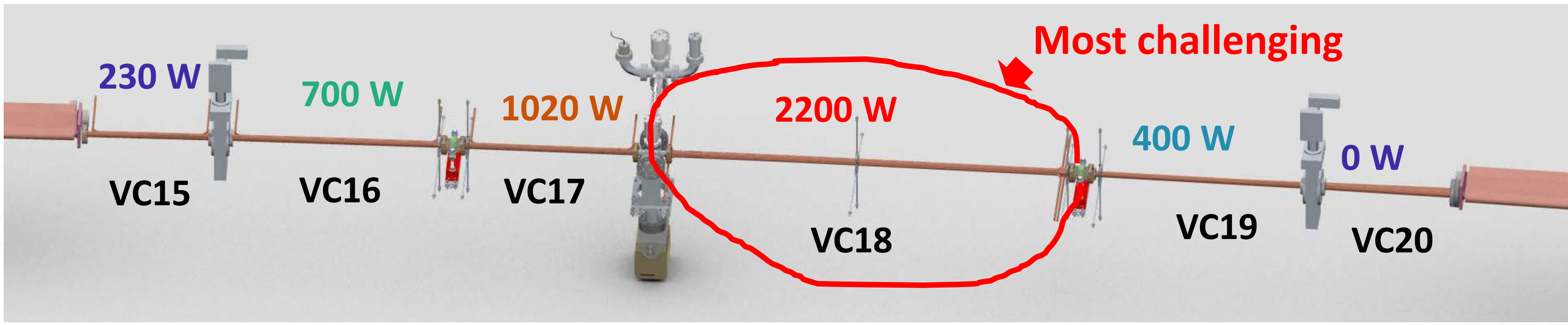


The questions that we are trying to answer with design optimization

- How to most effectively cool our vacuum chambers?
  - Vacuum chamber walls are exposed to synchrotron radiation, RF heating, and eddy current heating.
  - At the moment we are taking in consideration only synchrotron radiation in our analyses. Also, we assume that all incident SR power is absorbed.
- What materials we have to use?
  - OFS Copper is the material of preference. In its work hardened state it has considerable yield strength. Unfortunately certain fabrication processes will cause annealing. Can we use it safely?
- Will the deformation under operating conditions remain within acceptable limits of the tolerance budget?
  - The ID of magnet poles and ID of the vacuum chambers, combined with the requirement that chamber walls do not touch pole tips, leave us with 1 mm thick chamber walls and 1 mm gap between the pole tips and outside of the chamber walls.

How to effectively cool our vacuum chambers

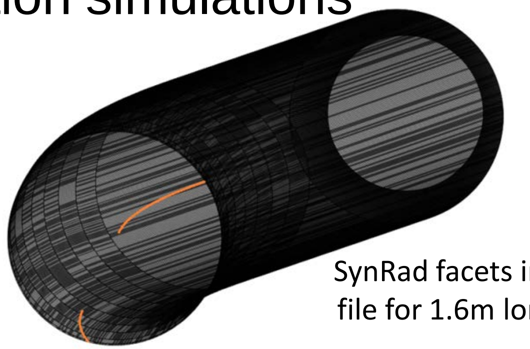
- SR Heat loads in FODO section based on preliminary ray-tracing and SR power calculations



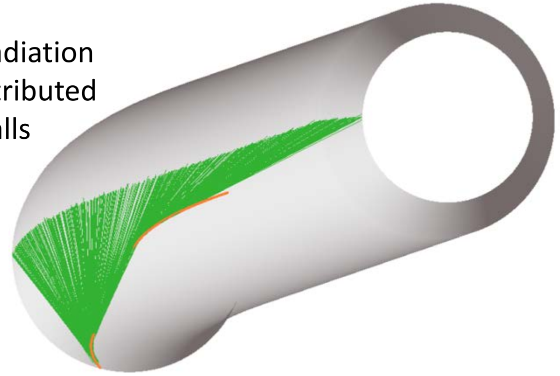
- Heat loads in VC18 calculated with *SYNRAD+*

Few words about *SYNRAD+*

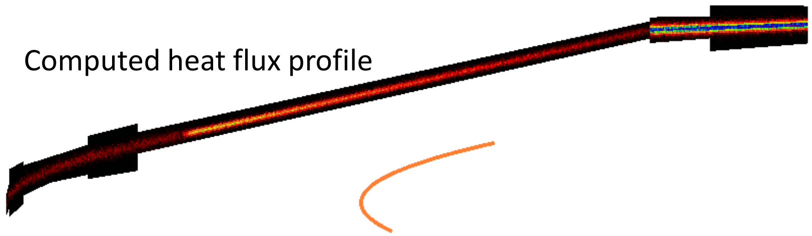
- *SYNRAD+* is the software package developed at CERN by Marton Ady and Roberto Kersevan and is meant to be used together with Molflow+ for coupled SR/photodesorption simulations
  - STL file of interior surfaces of the geometry of interest is generated by 3D CAD package (preferably at highest resolution as possible)
  - STL file is then imported into *SYNRAD*
  - 'magnetic regions' (**orange**) that generate radiation fan are brought into problem based on global lattice file
  - SYNRAD performs ray-tracing and computes spatial distribution of the load intercepted by the walls
  - Computed heat fluxes are exported 'point by point' with global coordinates (x, y, z) for ANSYS import
  - Data are imported into ANSYS using 'external data' module (requires very fine meshing of the load region)



SynRad facets imported from STL file for 1.6m long, 22mm ID pipe



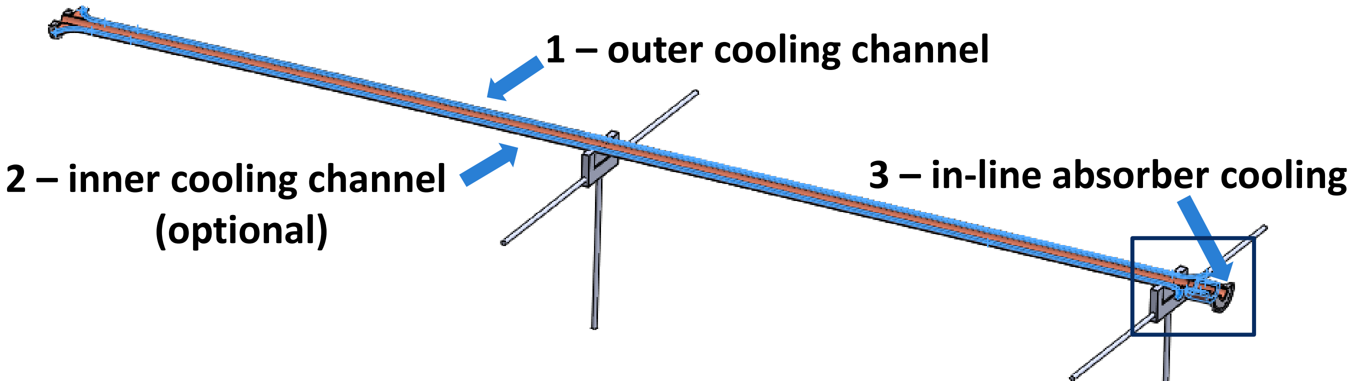
Sectioned view of radiation fan (**green** lines) distributed on chamber walls



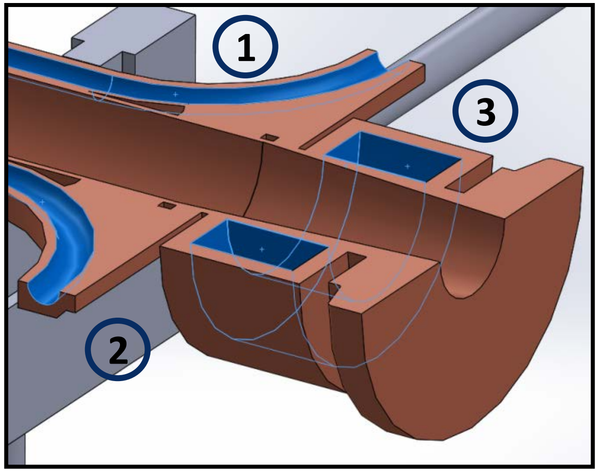
Computed heat flux profile

How to effectively cool our vacuum chambers

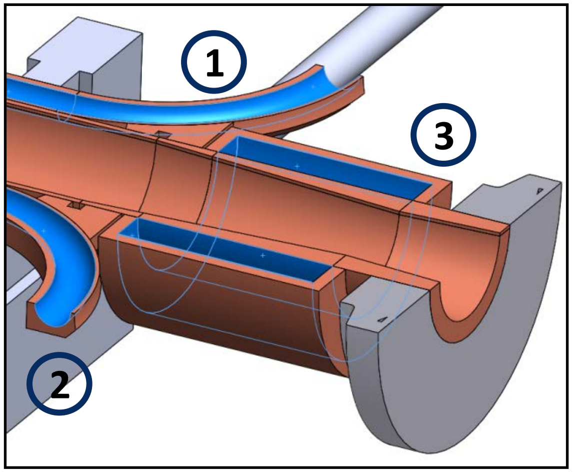
- Cooling system of VC18 is envisioned to have two longitudinal cooling channels and a separate cooling circuit for in-line absorber



Initial design



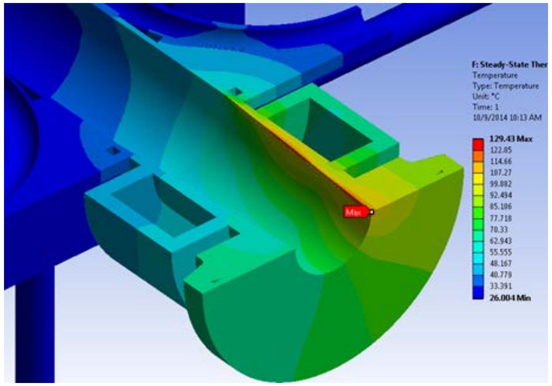
Impedance-optimized design



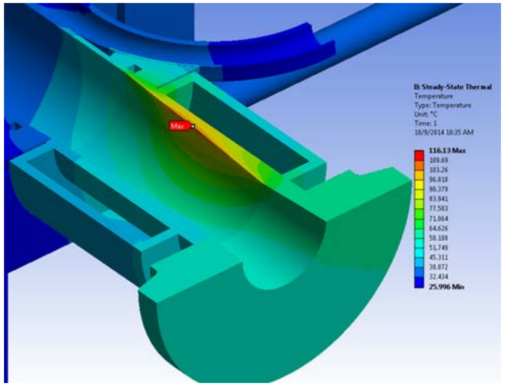
Optimization of in-line absorber design

- Temperatures

Initial design, T_{max}=129.4 °C

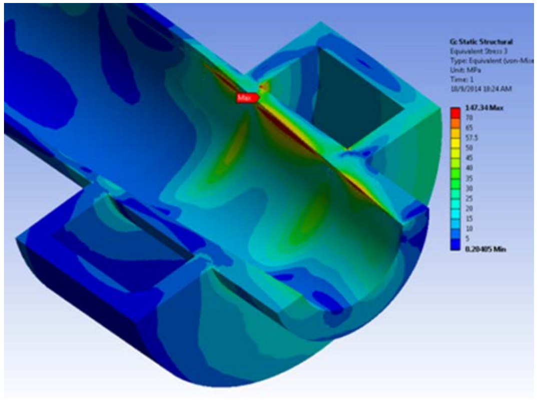


Impedance optimized design, T_{max}=116.3 °C

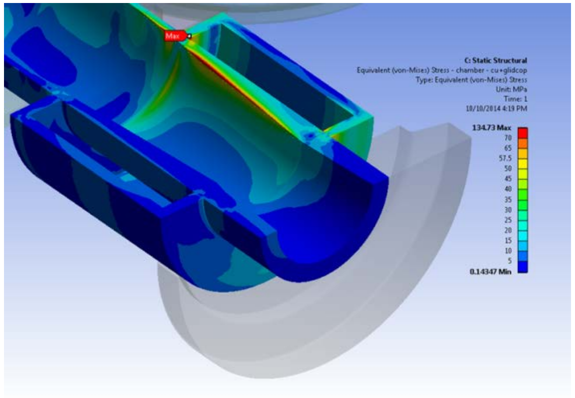


- Equivalent stress

Initial design, σ_{max}=147 MPa

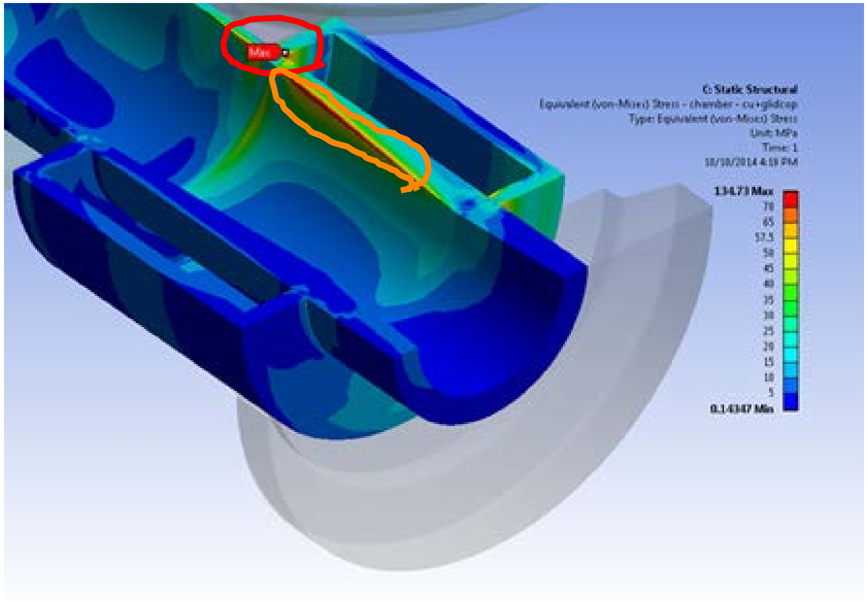


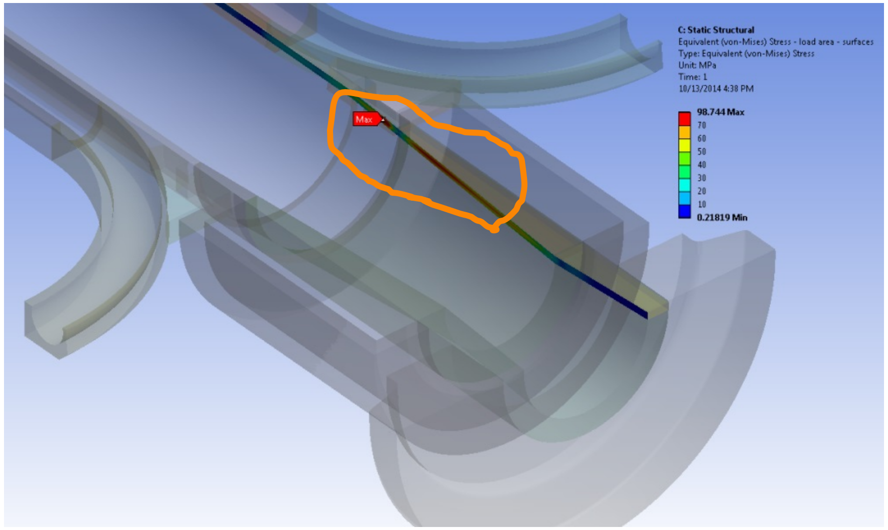
Impedance optimized design, σ_{max}=135 MPa



Material selection

- Areas with computed stress values over 70 MPa are evident
  - Maximum stress values are computed in the zone of the sudden change of geometry and with only moderately refined mesh and the computed values are most likely overestimated
  - However, the area of the beam footprint has uniform geometry and very fine mash so the stress values higher than 70 Mpa computed in that area are accurate

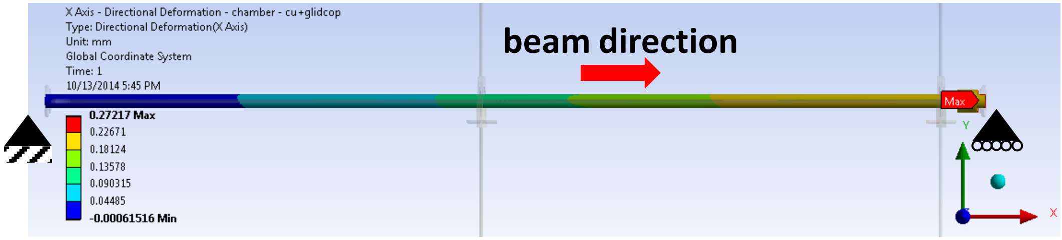




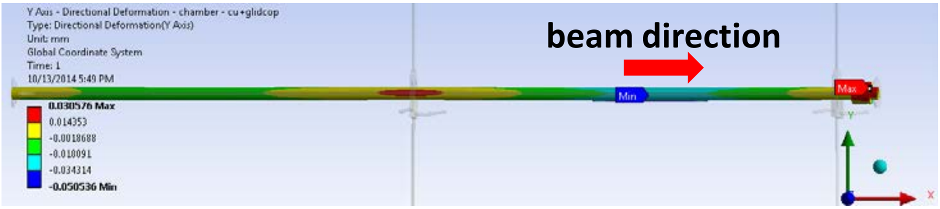
- At the moment we are planning to make in-line absorber stubs out of Glidcop. The rest of the vacuum chamber will be made out of OFS Copper

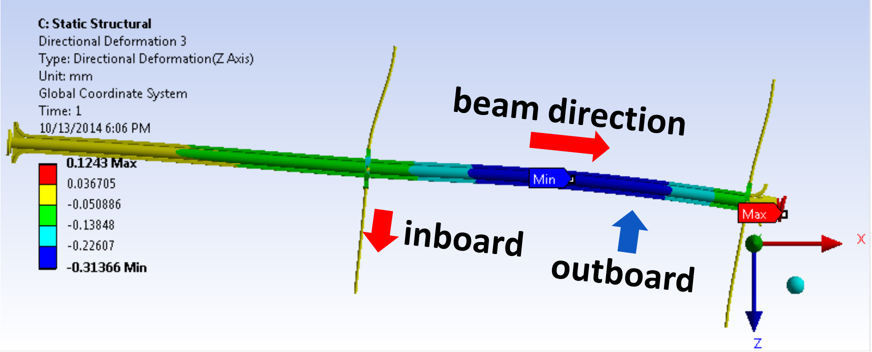
Will the deformation under the operating conditions be an issue?

- Deformation along the chamber axis is not a problem
  - Each chamber will have one fixed end and one end free to move in that direction



- Deformation in radial direction, both in vertical (sagging) and in horizontal plane is the concern because of tight available space and the requirement that the chamber walls do not touch pole tips.



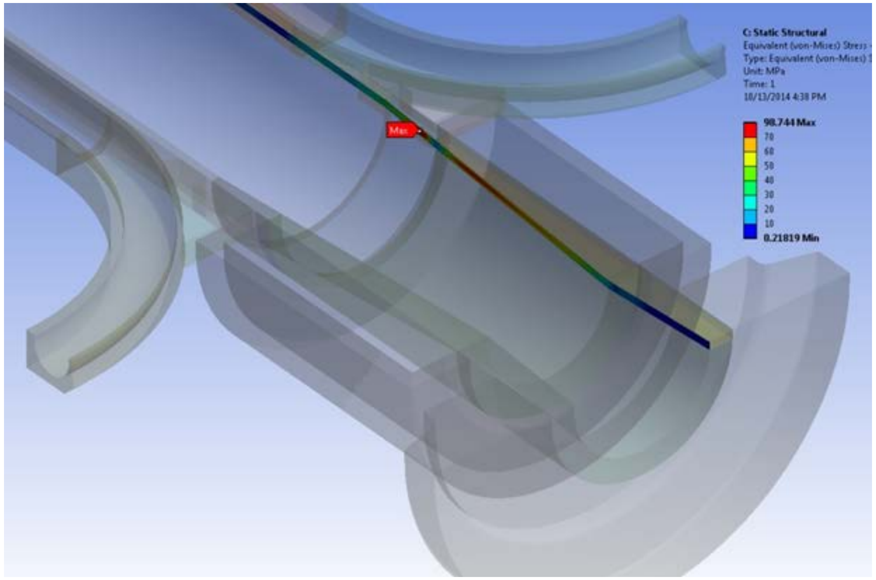


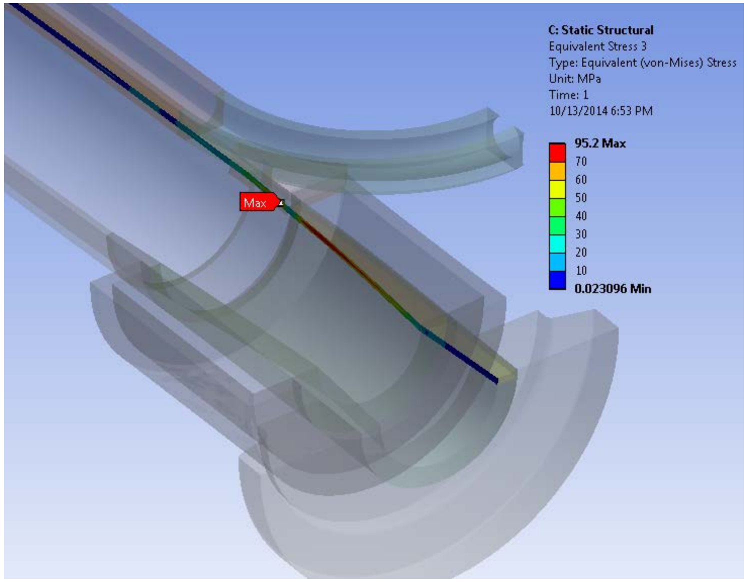
  - Maximum sag of 50 μm is acceptable. However, the results are preliminary as the location of supports is not final.
  - 315 μm (outboard) displacement in the horizontal plane takes 30% of the available gap.

Two cooling channels? Or one is enough?

- Analysis under the assumption that all the SR power is absorbed at the footprint (Table 1) indicates that the design with one cooling channel could be acceptable.
  - Larger value of max. equivalent stress computed for the geometry with 1 cooling channel is computed in the zone of sudden change in geometry. Stress values computed in the zone of the beam footprint are similar.

Table 1		no. of cooling channels	
		2	1
max. temperature	°C	116	118
max. eq. stress	Mpa	135	160*
max. x-deformation	μm	272	389
y-deformation (sag)	μm	-51	-41
inboard (+z) def.	μm	107	48
outboard (-z) def.	μm	314	219





The results of the Thermo-Mechanical design optimization

- The design of the in-line absorber is developed that satisfies both thermal/structural requirements and the requirements imposed by the APS-U MBA Lattice impedance budget
- High-strength copper alloy Glidcop AL-15 is considered for fabrication of in-line absorbers
- The inboard/outboard horizontal deformation of vacuum chambers is a concern due to the tight deformation budget
- The vacuum chamber design with only the outboard cooling channel looks like viable solution
  - Reduces inboard/outboard deformation
  - Reduces fabrication costs and simplifies the cooling water distribution
  - Final decision will be made only after analysis is performed with better defined levels and distribution of thermal load

Backup Slides

Two cooling channels? Or one is enough? - Continued

- We know that all the incident power does not get absorbed at the beam footprint. Part of the incident power (~5-10%) is reflected, mostly due to the Compton scattering and x-ray fluorescence.
- This reflected energy can not be considered as 'sidekick cooling' because it eventually ends up being absorbed elsewhere by chamber walls.
- Absorption of the power by the parts of the chamber walls that are not directly exposed to the synchrotron radiation could potentially change the temperature and stress distribution and the way that chambers deform.
- Unfortunately, at the moment we do not know either the exact amount of the reflected power or how it is spatially distributed.
- Nevertheless, we can perform sensitivity study based on assumed different levels of scattered power.

Two cooling channels? Or one is enough?
Sensitivity study

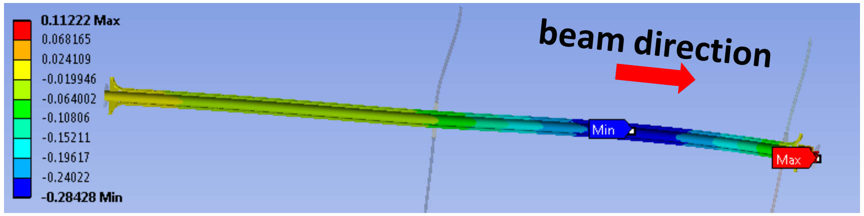
- Four different cases were analyzed
  - Reflected power was assumed to be 5, 10, 15 and 20% of the incident RF power
  - It was assumed that the power was uniformly reflected towards the remaining portion of the chamber wall (gross simplification)
- Results are shown in Table 2

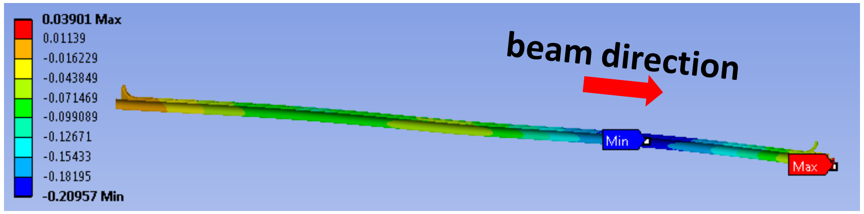
Table 2		Reflected RF power			
		5%	10%	15%	20%
2 cooling channels					
max. temperature	°C	116	113	111	108
max. eq. stress	Mpa	153	146	140	134
max. z-deformation	μm	112	106	100	95
min. z-deformation	μm	284	279	273	268
1 cooling channel					
max. temperature	°C	118	116	114	111
max. eq. stress	Mpa	156	149	143	137
inboard (+z) def.	μm	39	19	4	3
outboard (-z) def.	μm	210	180	150	127

Two cooling channels? Or one is enough?
Sensitivity study

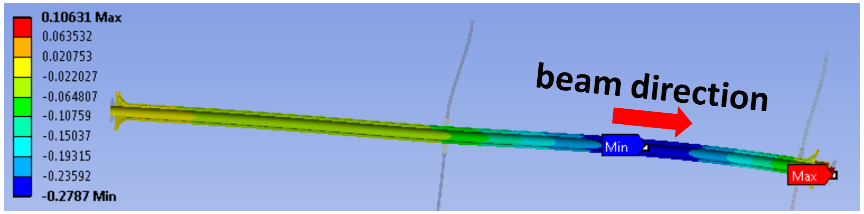
2 cooling channels

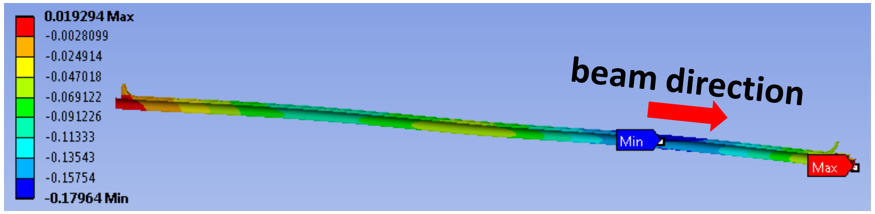
1 cooling channel



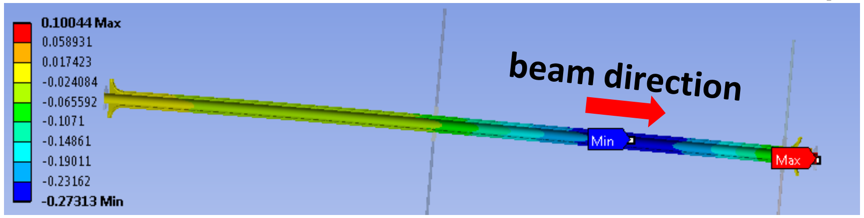


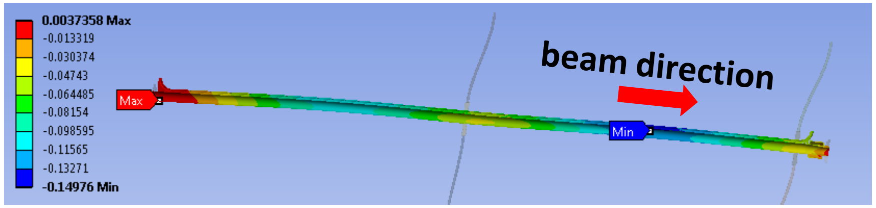
5% RF power reflected



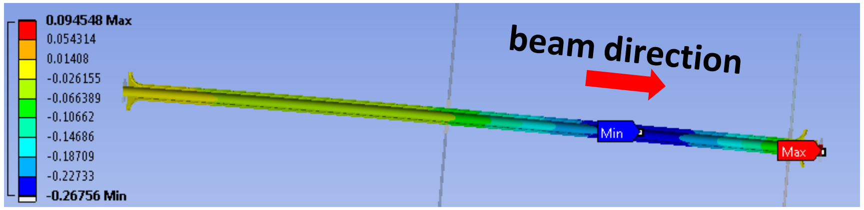


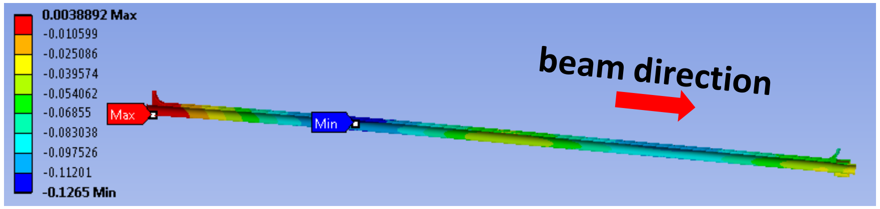
10% RF power reflected





15% RF power reflected

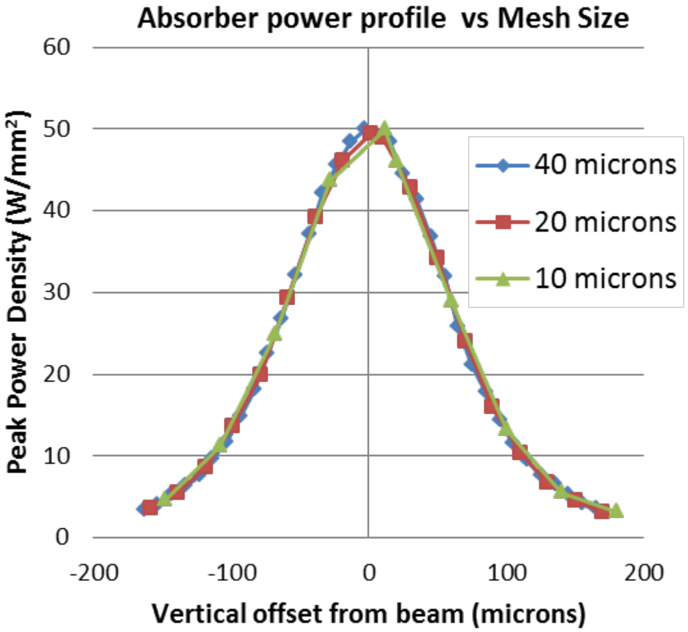


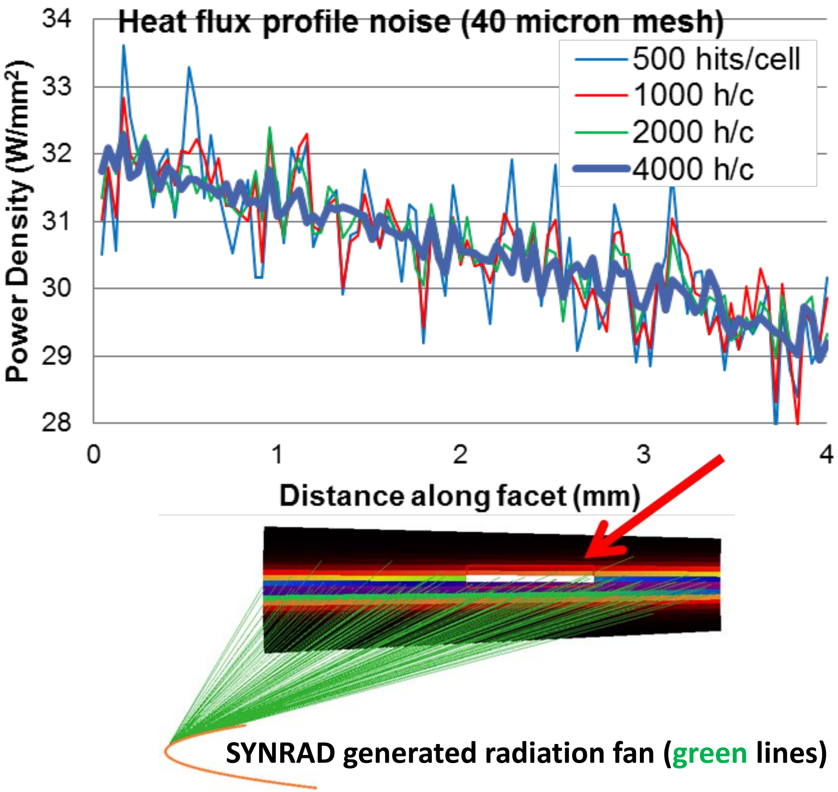


20% RF power reflected

Few words about *SYNRAD+*

- *SYNRAD+* is a Monte-Carlo based simulator package
  - high resolution of the mesh is required to accurately capture the SR power profile. 40 micron mesh proved to be suitable to capture beam power profile
  - large number of 'hits' per mesh cell needed to reduce the statistical noise (to achieve 4000 hits per cell 11 hours of computing on 16 core, 64 GB RAM computer)

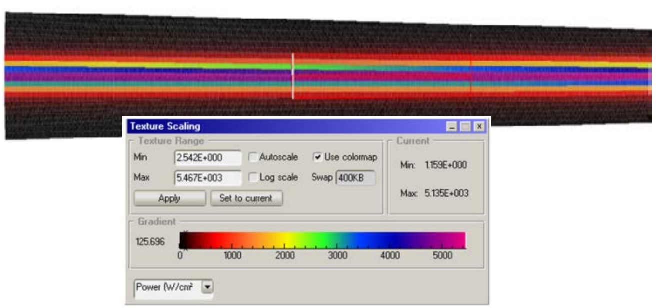




Few words about *SYNRAD+*

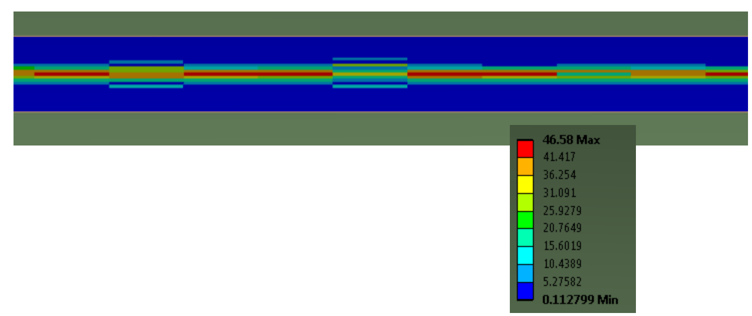
- Once RF power profile is accurately captured it has to be transferred to ANSYS
  - Global coordinate system has to be established and maintained in all 3 involved software packages (3D CAD, SYNRAD+ and ANSYS) to accurately transfer data.
  - ANSYS mesh has to be of the comparable size to accurately capture the power profile. Mesh cells with same/similar size in height proved to be optimal.
  - Good ANSYS mesh will capture power peaks within 5% accuracy and total power with 3-5% accuracy.
  - Such dense mesh in ANSYS requires lot of computer resources. Properly meshed VC18 model required 149 GB of RAM memory to run ‘in core’. Thermal analysis run in core needs 2-3 h, structural more than 6 h

SYNRAD+ output



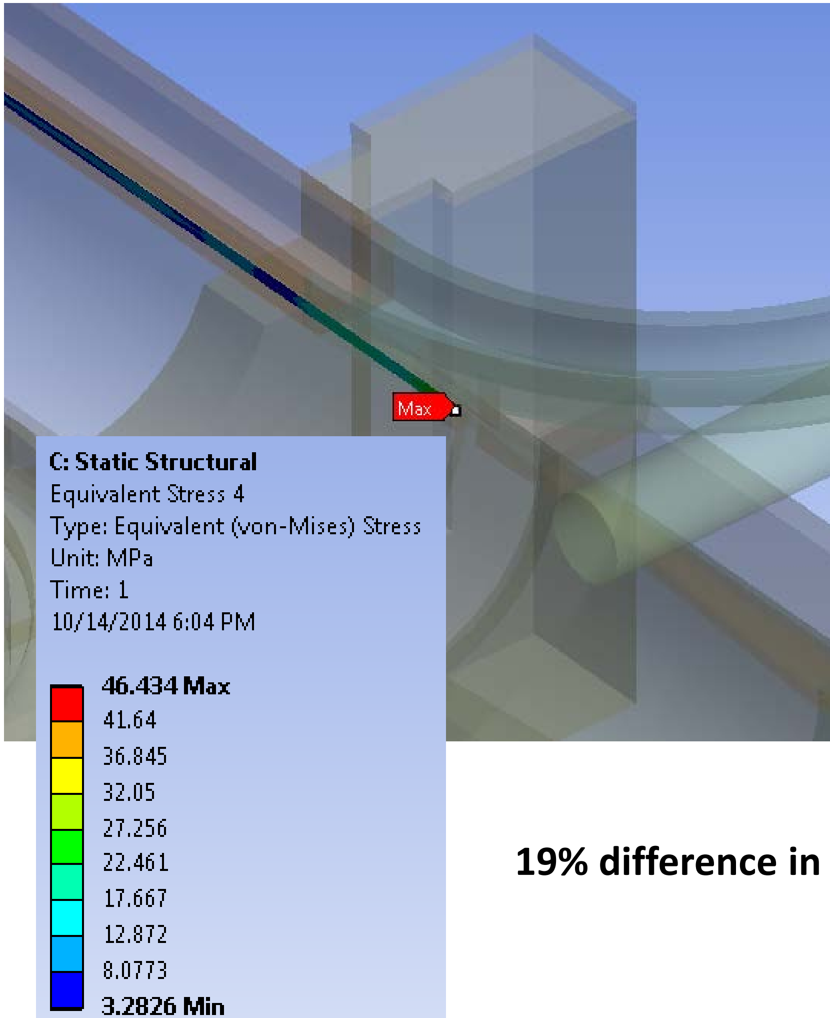
Inadequate ANSYS mesh

ANSYS output

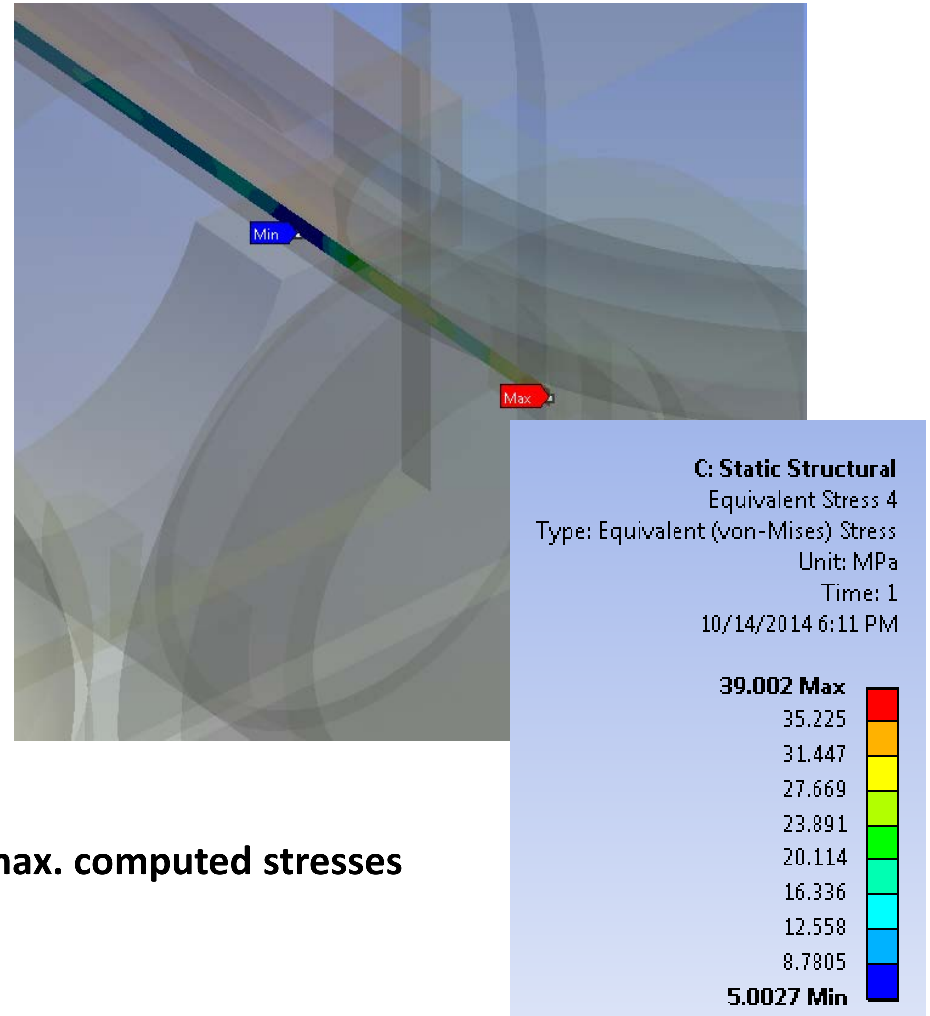


SYNRAD+, is it worth of trouble?

SYNRAD+ calculated power

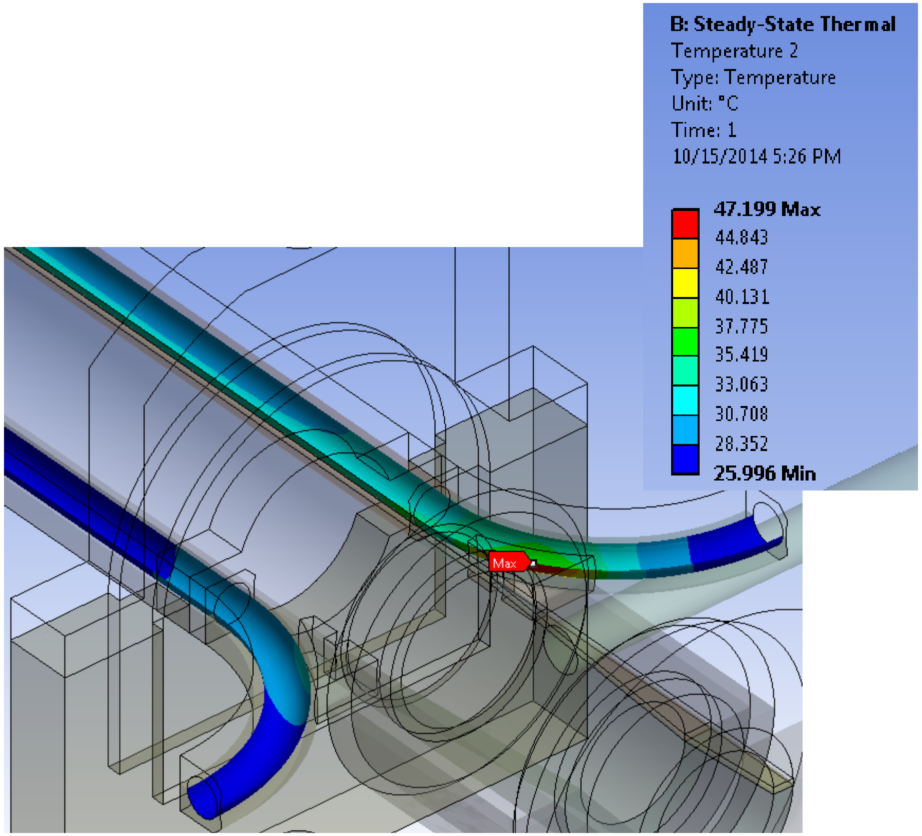


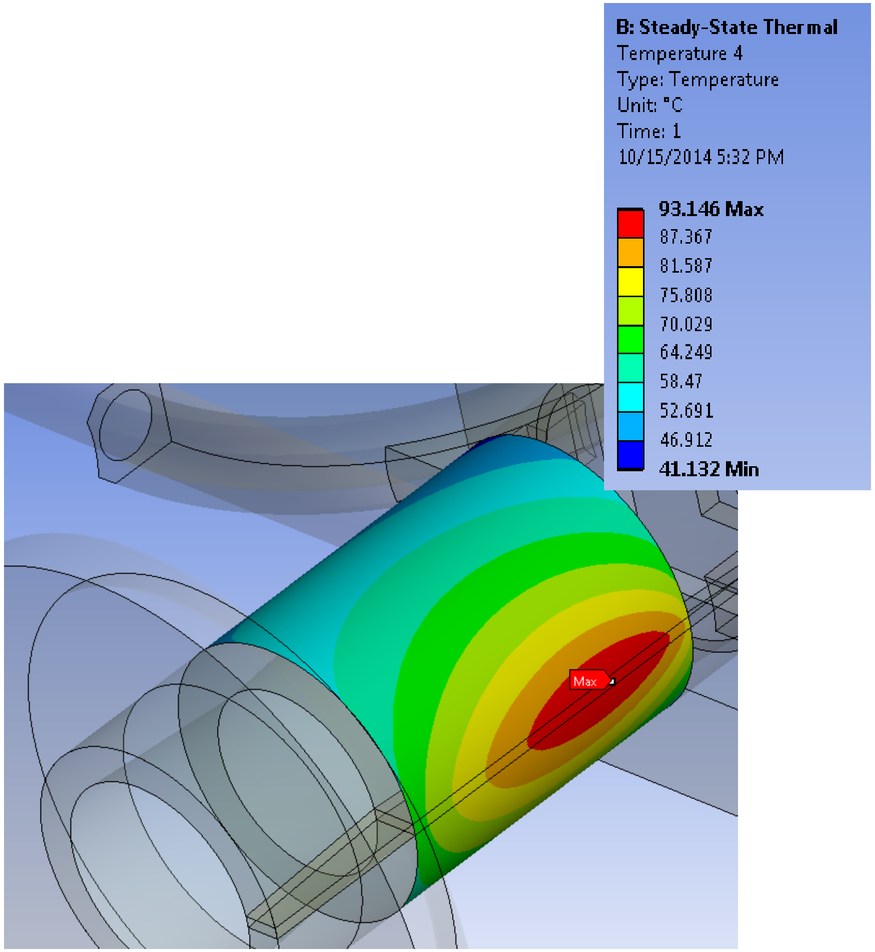
Same total power but uniformly distributed



19% difference in max. computed stresses

Cooling efficiency





- Cooling of the in-line absorber needs further work
  - As the temperature difference between the wall and the cooling water reaches almost 70 °C any disturbance in the flow can cause significant increase in the wall temperature