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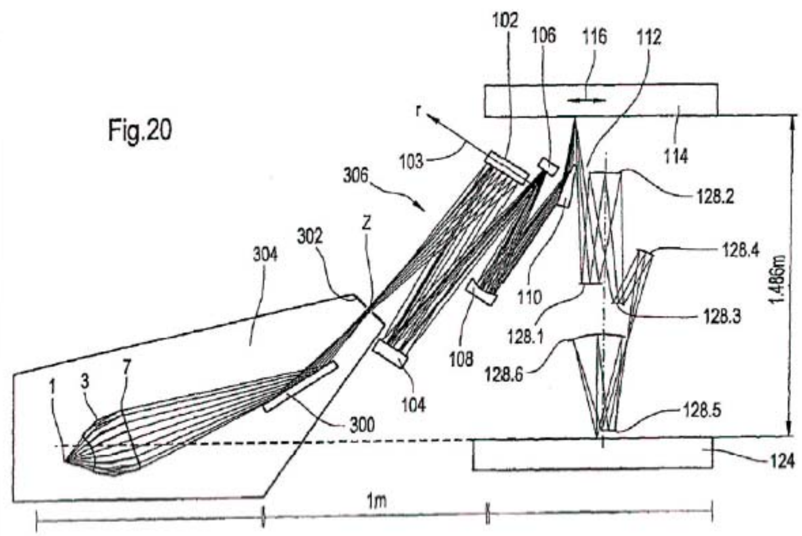
CERN EUGM 07 September 26-27, 2007

Thermal Load replication: Induction Heating with OPERA

Background:

The productivity demands of the EUV (Extreme Ultra Violet) lithography beta exposure systems require considerable source power levels in order to deliver 15 W in-band power at the intermediate focus (IF).

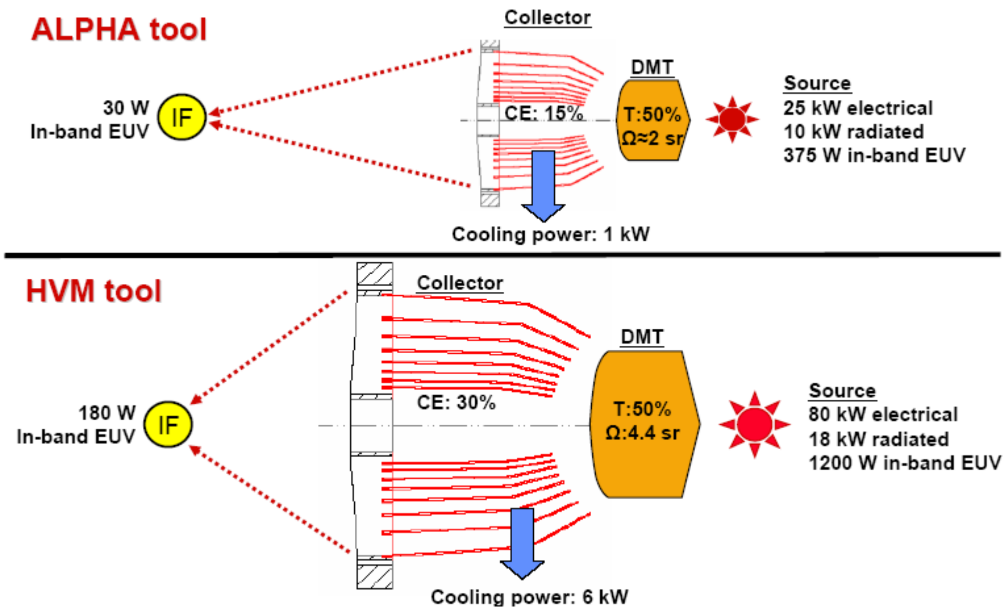
- Source: A gas discharge produced plasma (GDPP) source fueled with Xenon [**Error! Reference source not found.**] capable of delivering high power levels.
- DMT: debris mitigation technology is used to protect the collector optics from the debris emitted from the source.
- Collector focuses the radiated power to the IF



Source: U.S. Patent 7,015,489.

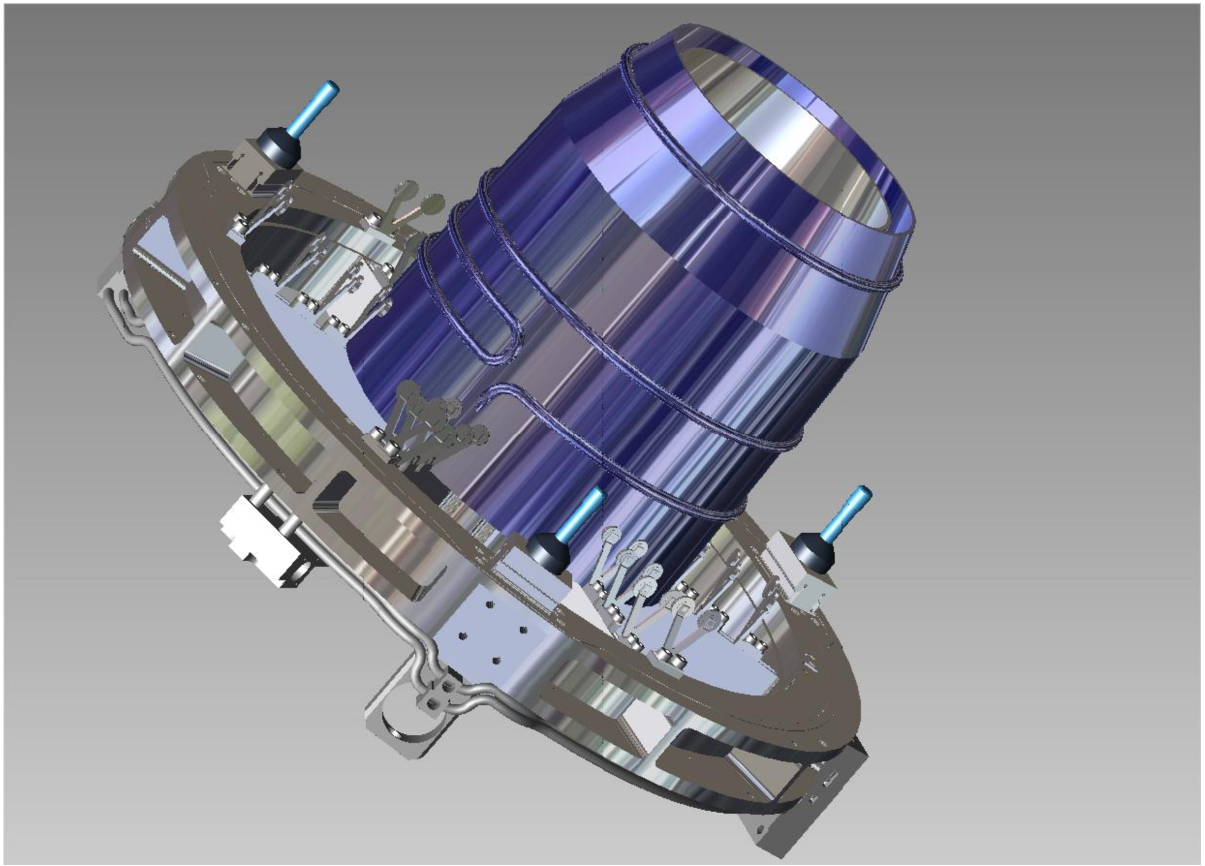
Collector and illuminator of EUV system.

- The purpose of the grazing incidence collector is to collect the light from an EUV source and to focus it in a defined location:
- Considering the transmission budget of the debris mitigation tool (DMT) and of the grazing incidence collector (GIC), this corresponds to about 10-12 kW total radiated power in 2π sr.
- This amount of radiated power, bound to increase considerably for high volume manufacturing exposure systems, requires effective, stable, and reliable thermal management design for the entire source-DMT-collector subsystem.



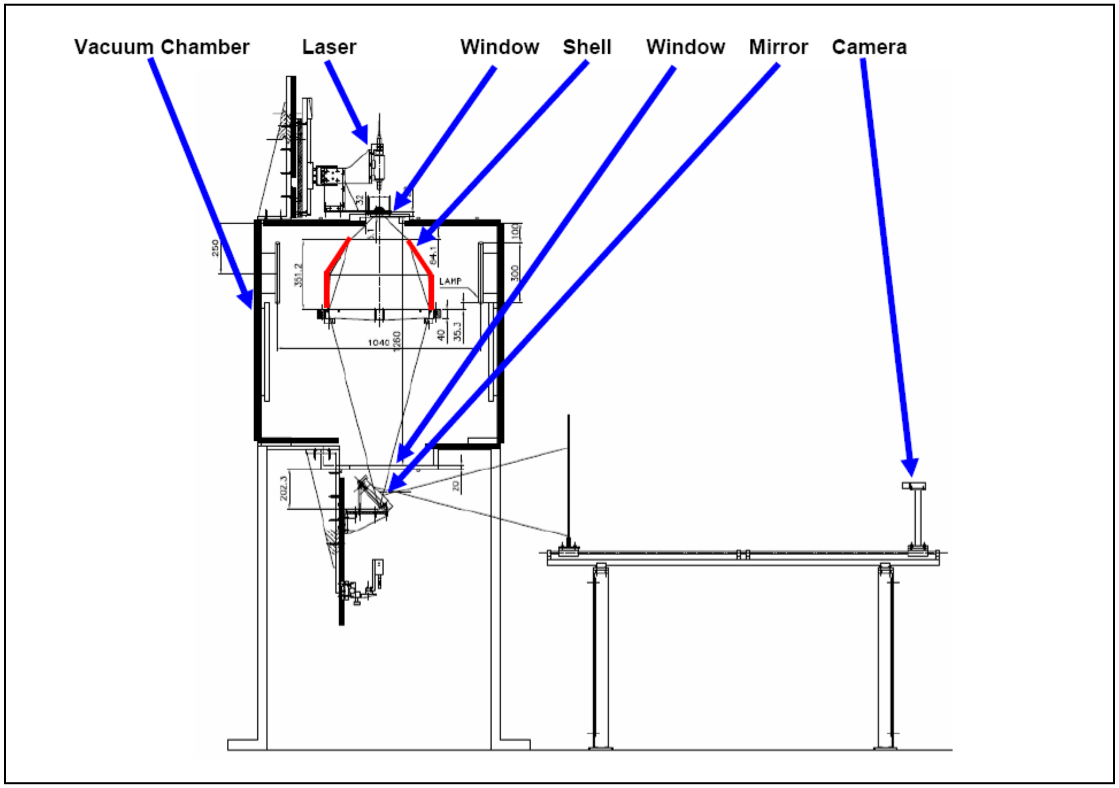
Collector:

- The typical optical collector consists in an assembly of concentric nested Nickel shells (mirrors) attached to a stiffening base (Spider) through flexible steel clips.
- The grazing incidence collector is subjected to a high thermal load through exposure to a EUV source: As the light falling on the collector shells partly consists of thermal radiation, heat is transferred to the collector shells.
- In order to maintain the optical integrity of the reflective surface material and overall performance of the unit, the collector shells must be cooled by water supplied through pipes located on the back of the mirrors.



Purpose 1: Emulate the source exposure on the optical bench

- In order to effectively remove the absorbed power from the collector optics, several cooling circuits are integrated into the backside of the EUV mirrors.
- The design guidelines are to provide optical performance stability through proper optimization of geometrical layout, flow and pressure drop parameters, and interference-free design with respect to the optical path.
- The effectiveness of the cooling layout is ultimately validated by means of thermo-structural analysis based on finite element models (FEM), resulting in estimation of the mechanical deformation data. This is then used to simulate the far field image stability by means of ray tracing calculation techniques.

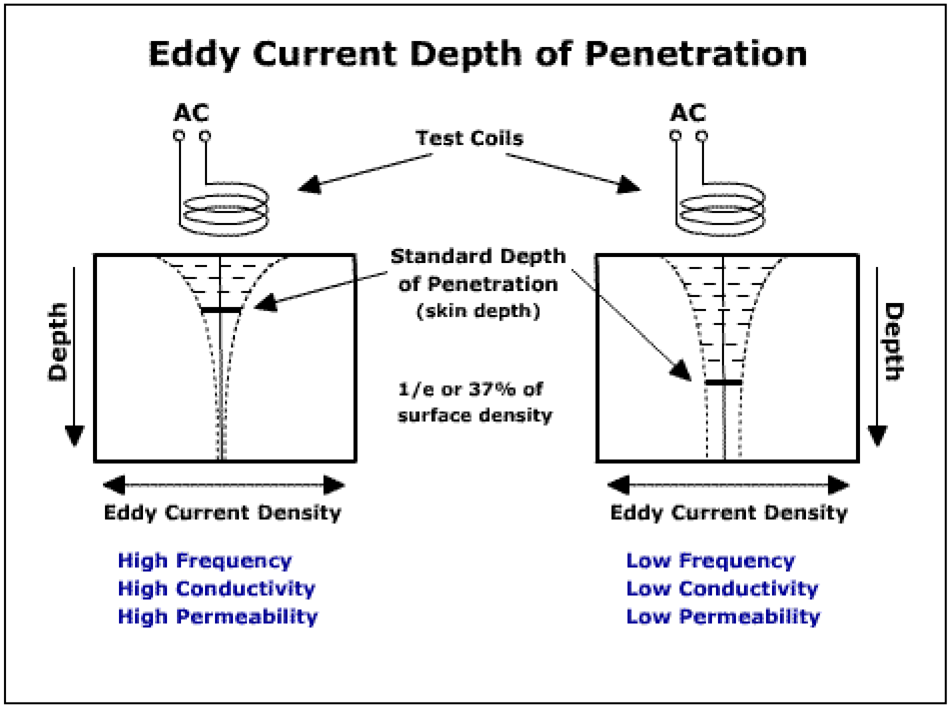


The goal is to develop an easy way to implement heating technique and apparatus that can be used with any size shell to produce heat distributions matching those generated by EUVL sources and DMTs. Such method and apparatus to allow optical (visible light) measurement of the effects of thermal distortion and be adaptable to both the existing optical bench (atmospheric) and to the vacuum thermal test chamber (under development). Said method / apparatus to be capable of producing the desired heat distributions without impeding actual real-time measurements of transient thermal response via thermocouples, LCD / video and other appropriate techniques.

Theory:

- Eddy currents are closed loops of induced current circulating in planes perpendicular to a magnetic flux.
- They normally travel “parallel” to the coil's winding and their flow is limited to the area of the inducing magnetic field.
- Eddy currents concentrate near the surface adjacent to an excitation coil. Eddy current density decreases exponentially with depth. This phenomenon is known as the skin effect. The depth that eddy currents penetrate into a material is affected by the frequency of the excitation current and the electrical conductivity and magnetic permeability of the specimen. The depth at which eddy current density has decreased to 1/e, or about 37% of the surface density, is called the standard depth of penetration (δ). The word 'standard' denotes plane

wave electromagnetic field excitation within the test sample (conditions which are rarely achieved in practice). Although eddy currents penetrate deeper than one standard depth of penetration, they decrease rapidly with depth.



The equation for the calculation of the standard depth of penetration (skin depth) is:

$$\delta \approx \frac{1}{\sqrt{\pi f \mu \sigma}}$$

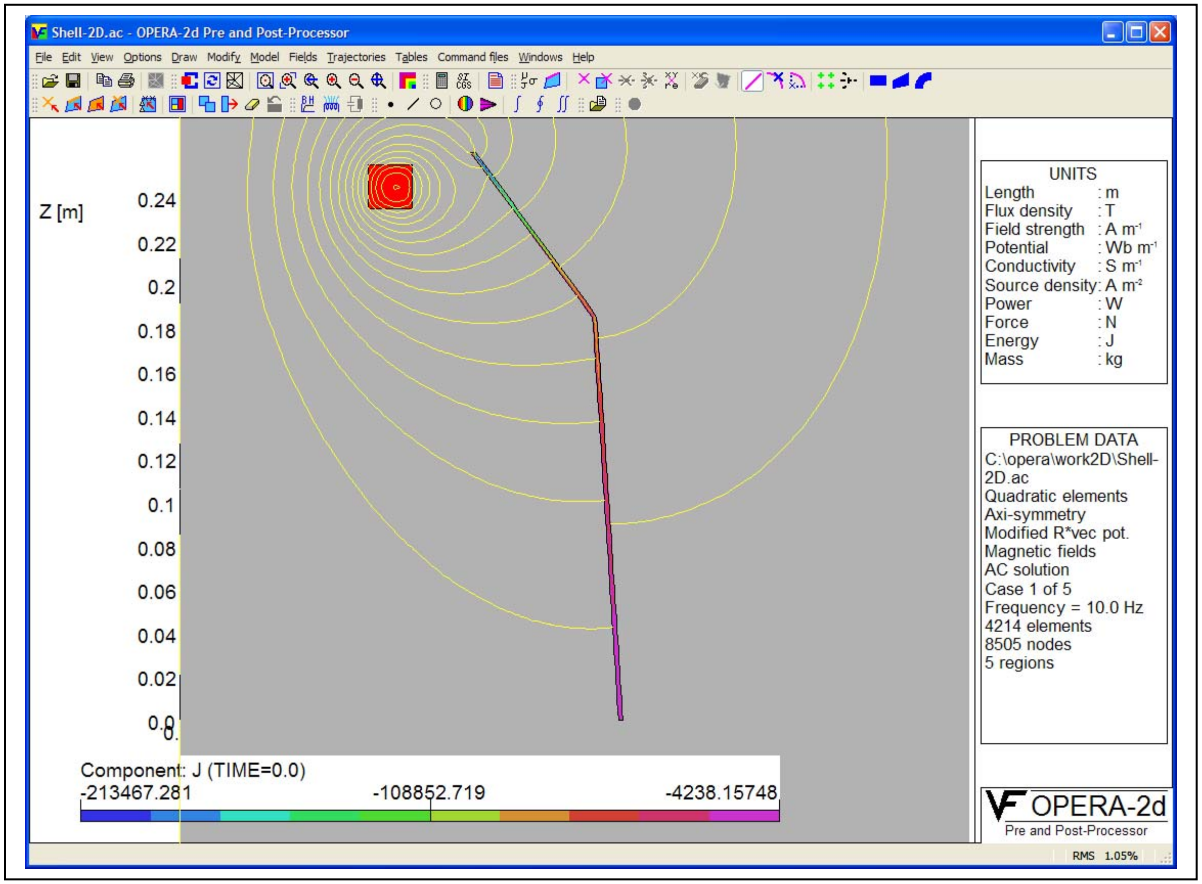
Where:

δ = Standard Depth of Penetration (mm)
π = 3.14
f = Test Frequency (Hz)

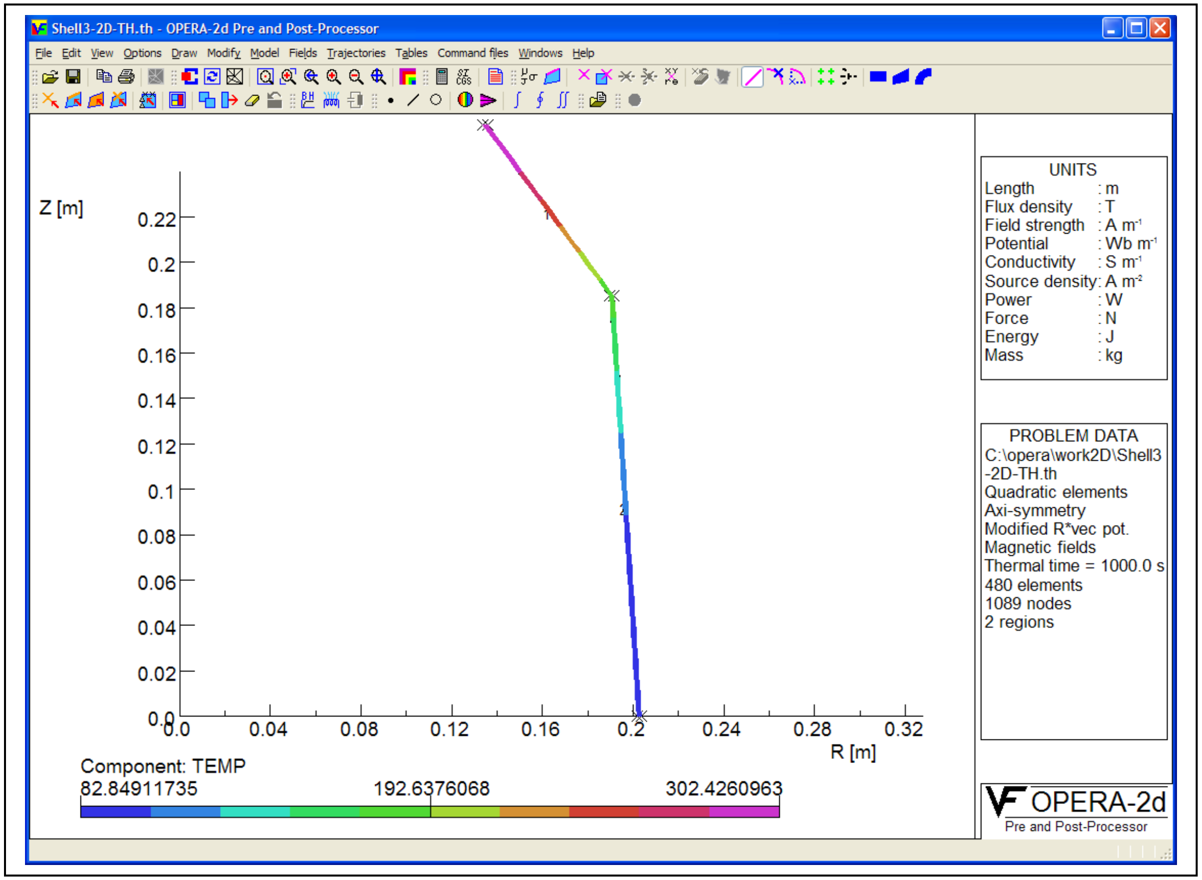
μ = Magnetic Permeability (H/mm)
σ = Electrical Conductivity (% IACS)

Concept:

- Establish a time-varying magnetic field at proximity of one collector shell in order to generate by induction some electrical currents (eddy currents) “on the surface” of the shell, which will subsequently produce some heat by Joules effect.
- Heat generated on or near the surface of the mirror
- Optical path shall not be obstructed, and back of shell shall be available for temperature data collection and optical observation.



Induced currents and magnetic flux lines for one coil

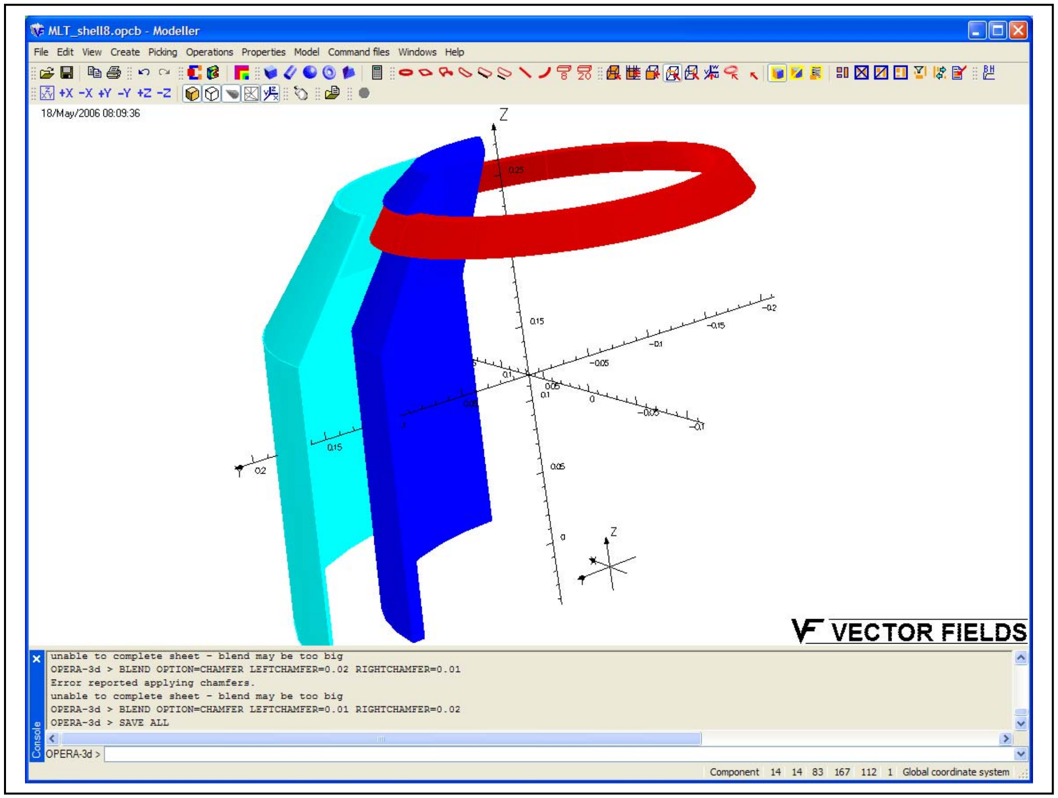


Temperature profile without any

cooling 1000 sec into the transient

Model:

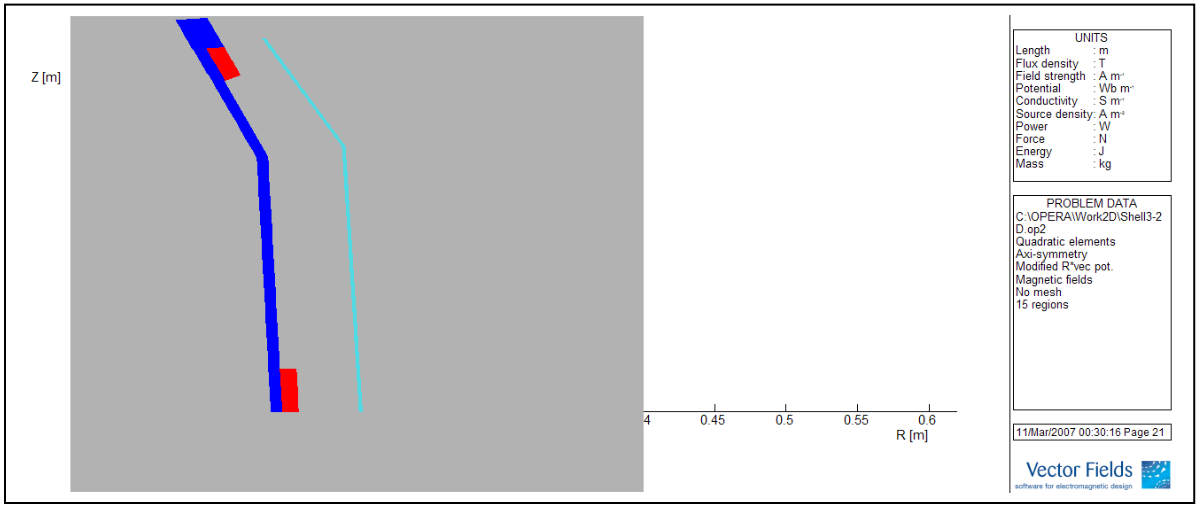
- Practically a series of water cooled copper wires (red, only one shown) are wound around powered iron (darker blue) (or magnetic steel) body serving as a magnetic return path.
- Because the coil is cooled there wouldn't be any IR perturbation.
- Conductivity of Powered iron (darker blue) is very low, very little eddy currents would be generated within.



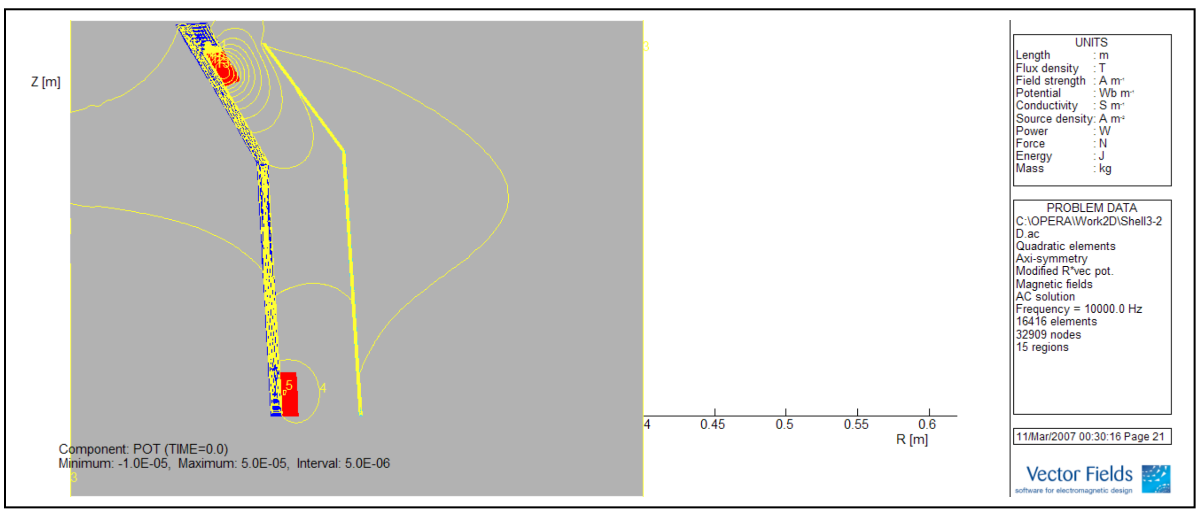
3D model of a one-coil structure (red) wound around the modified interior shell (darker blue) serving as the magnetic return path.

Note that the interior shell can be advantageously replaced with a part made of powered iron or other magnetically conductive material with very low inductive losses.

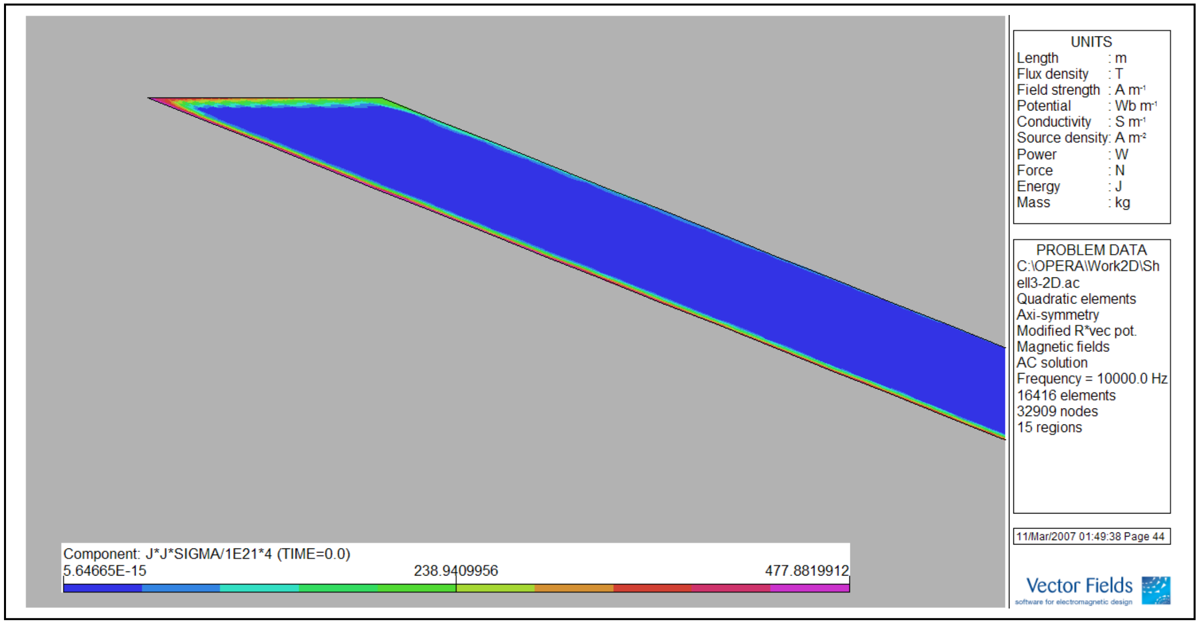
Data:



2D (axisymmetrical) model with two (2) coils (in red) with various current densities

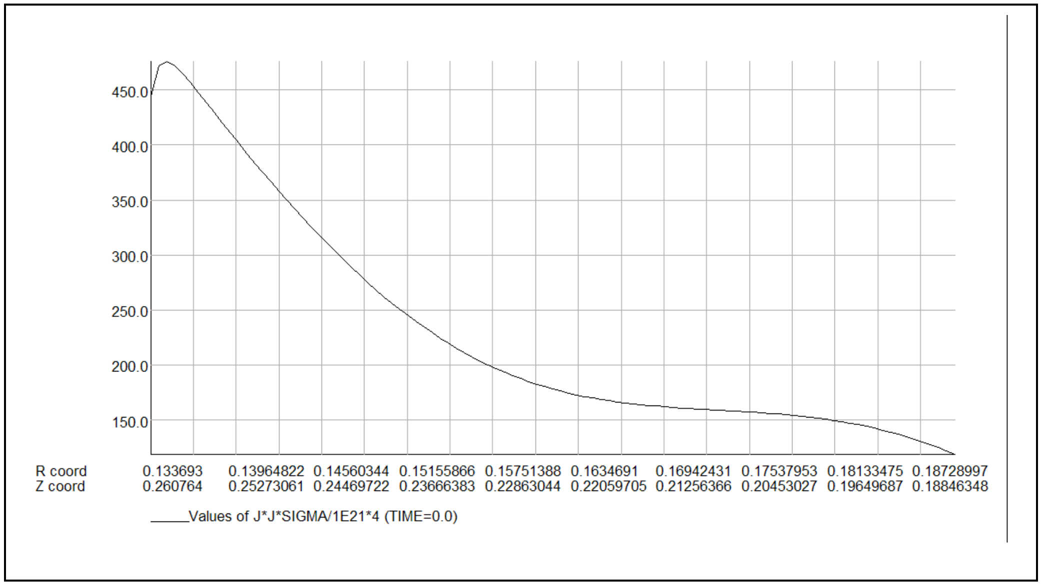


Magnetic flux lines for coils at top and at the bottom excited respectively with 100 Amp-Turns at 500,000 Hz.

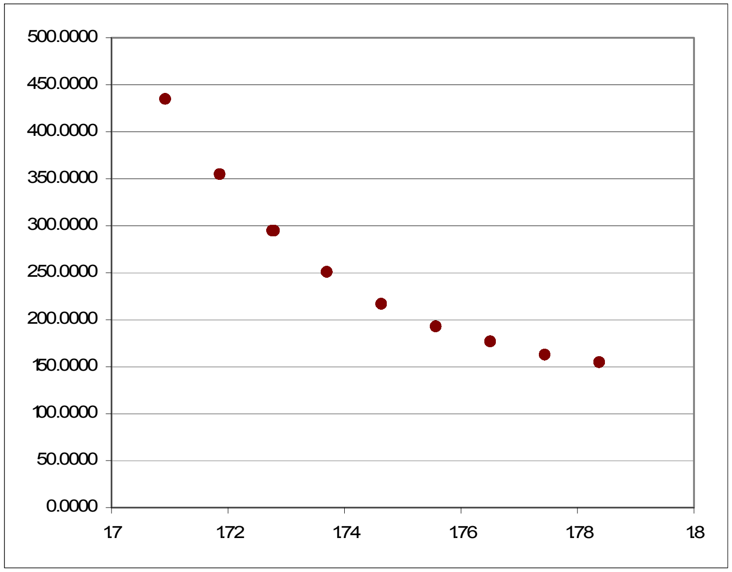


Induced power density near the tip of the shell:

- Note that most of the heat in generated within the skin depth of the material (in red)



Power density induced on mirror

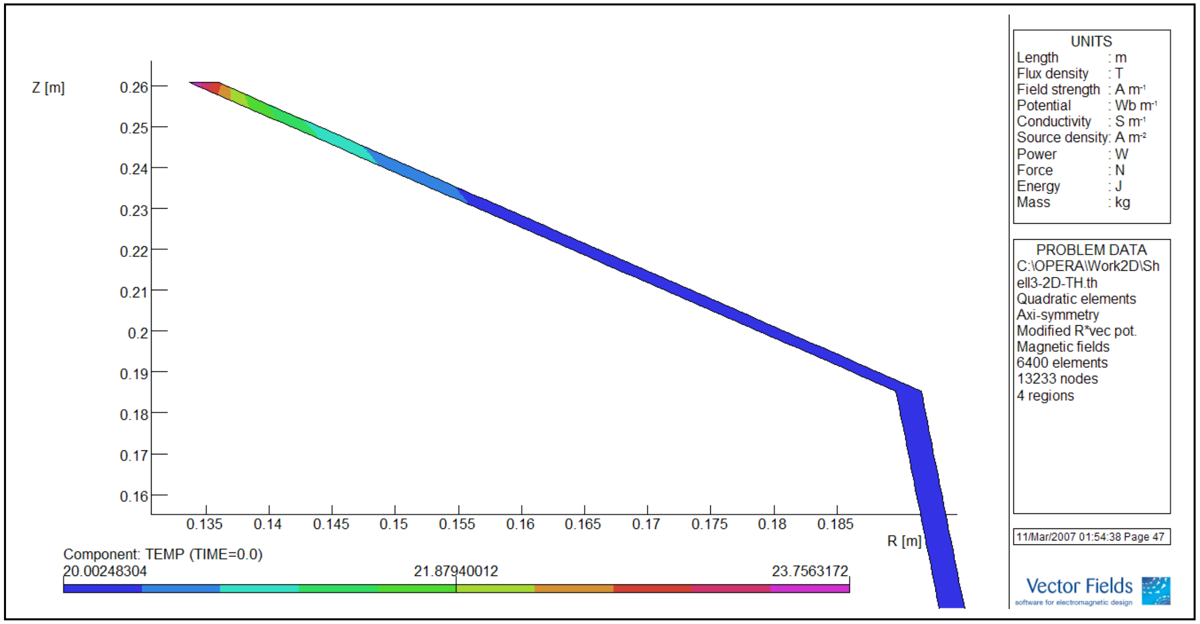


Radiative power distribution absorbed on mirror

- By adjusting the respective current of the various coils, nearly any (within range of current interest) heat source profile can be emulated.
- Force due to manufacturing and assembly asymmetries between the coil structure and the Nickel shell is quite small and is not expected to produce any significant deformation of the optical surface.

Coupled Electromagnetic and Thermal Analysis:

- A steady state AC or transient electromagnetic field analysis is performed to calculate the distribution of power loss in the plate.
- The power loss caused by eddy currents will be used as a heat source for a transient thermal analysis.
- The Pre and Post-Processor's TABLE command provides the method of taking information from one analysis and using this data as input to a subsequent analysis. Tables may be exported, imported and processed using different models, thus making it possible to use a different mesh for each analysis.
- COMI file can be used to automate the data transfer process



Example of the SS temperature profile at 500 kHz, 100 AT near tip of a cooled mirror in vaccum.

Pictures from IR camera

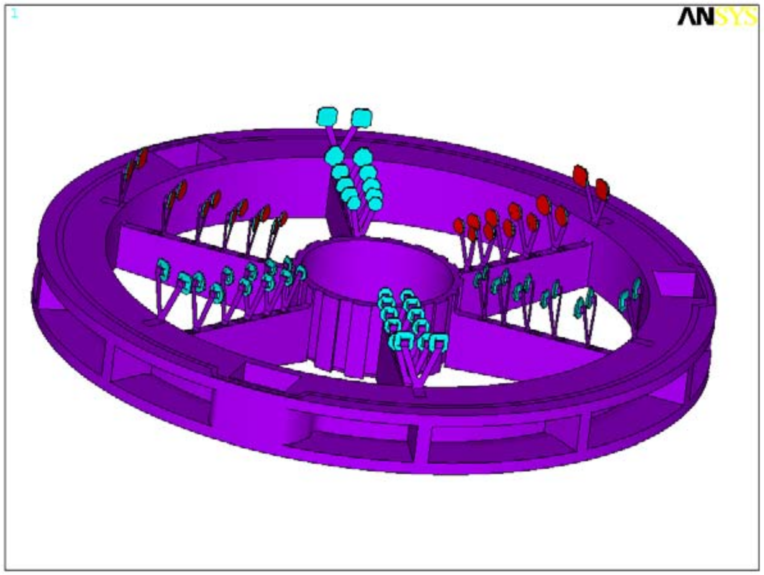
A comparison between measured values and analysis results is summarised in the following table:

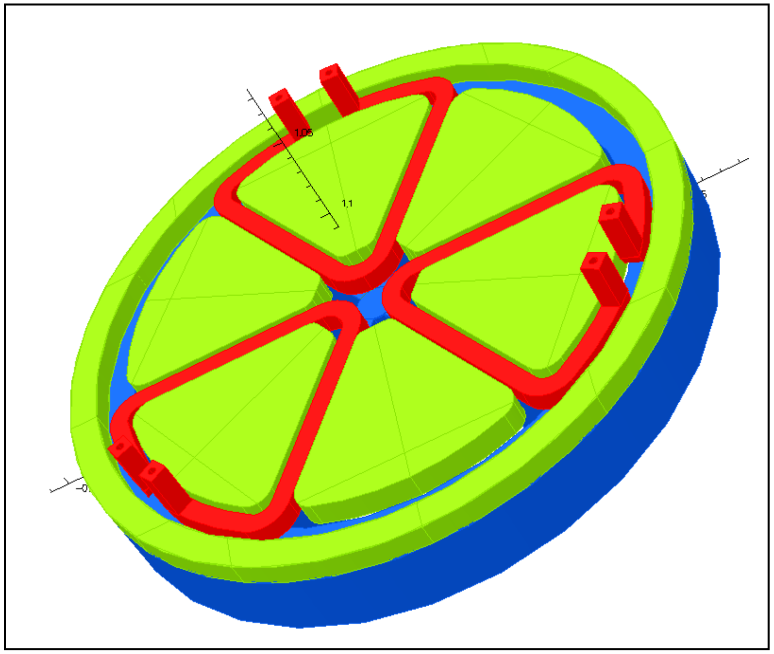
The temperature profiles from both analysis and measurement have been plotted in the graph below for comparison. The differences are mainly due to the simplified model adopted in the analysis, in particular slightly different axial location of the cooling lines. The peak temperature in the mirror is very similar comparing test and FEA.

Load Cases	Temperature [°C]					
	Water In-let		Water Out-let		Mirror Tube	
	Test	Calculated	Test	Calculated	Test	Calculated
a	21.1	21.1	23.1	22.8	22.1	22.8
b	21.0	21.0	24.4	24.3	23.4	24.2
d	19.9	19.9	26.1	25.3	25.7	24.9
e	22.0	22.0	24.5	23.8	23.4	23.8

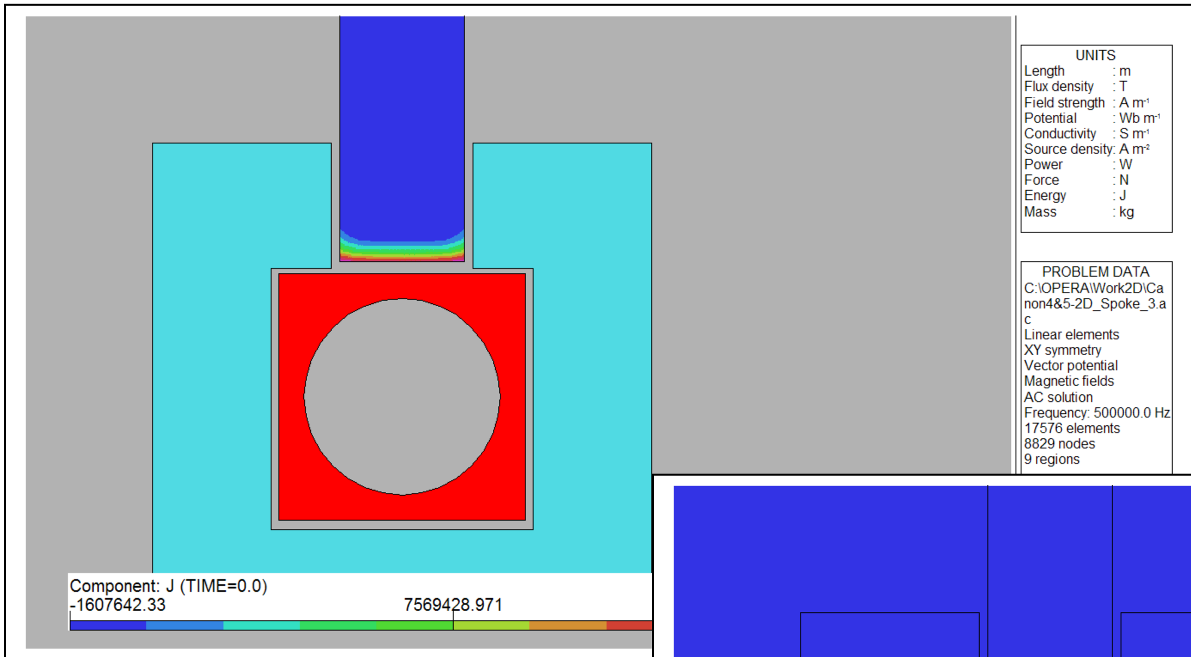
Table: Comparison between measured and calculated temperature.

Purpose 2: Heat the spider, or part of, in vacuum order to create a thermal gradient to quantify the conductance and the strength of the welds holding the clips to the shells and to the spider

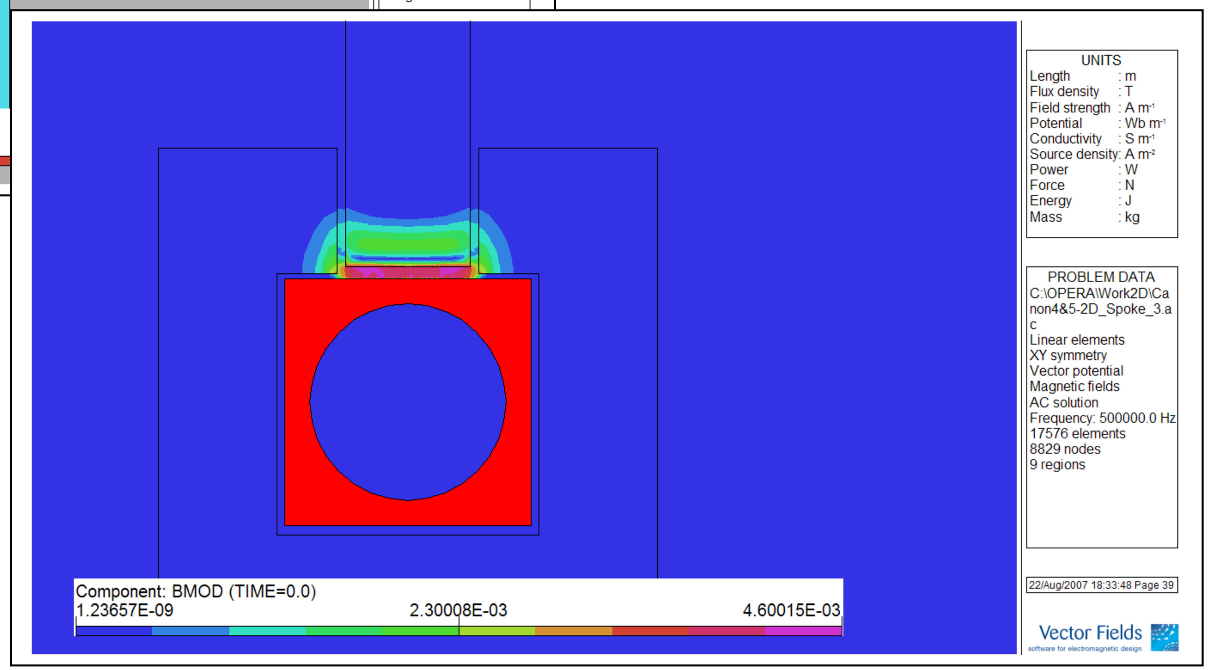




Spoke heating:
Heating elements (3) are place on the back of the spokes



- Power (avg) induced in Spoke 25 W per spoke.
- Power losses (avg) in copper 11 Watts per coil.
- Current 44A amplitude for 30 Volts (peak)

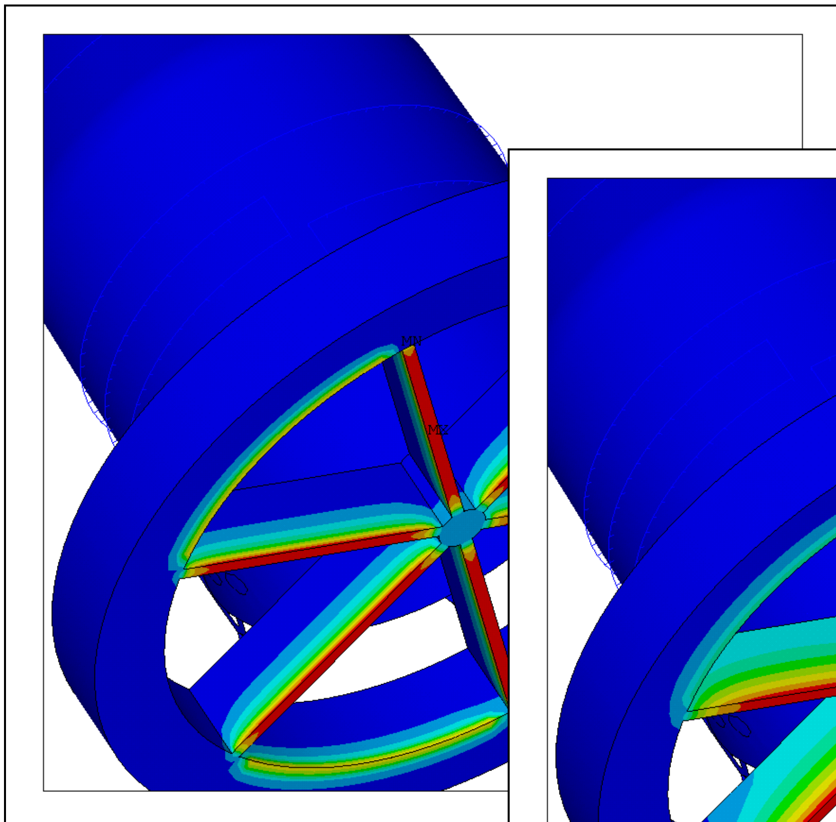


B-field magnitude over cross-section of device.

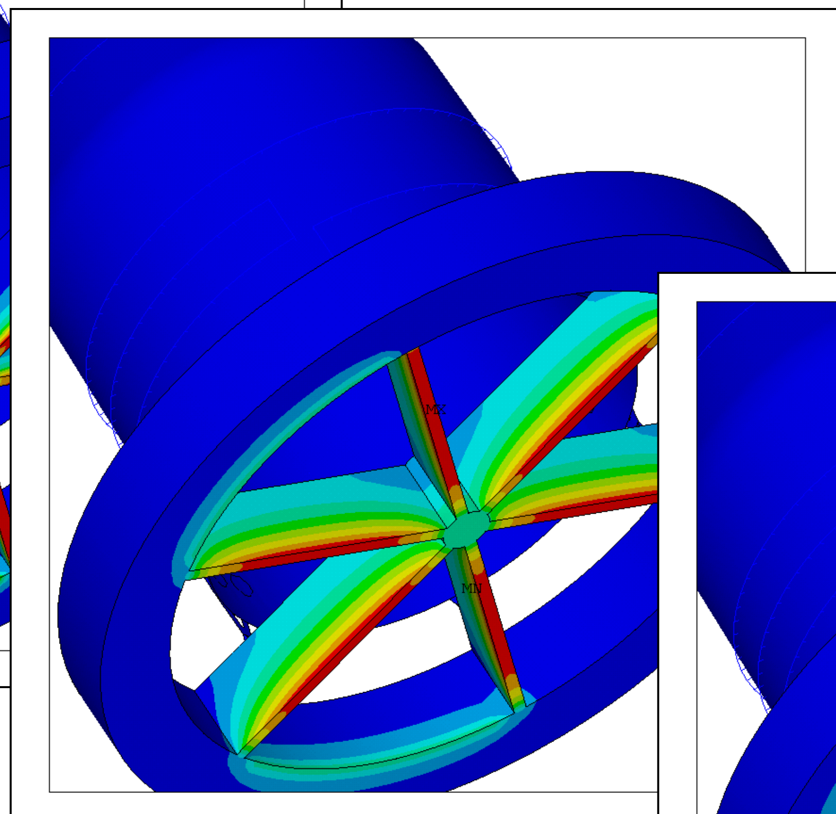
- Metrology elements are shielded from fields.

Thermal response when spokes are subjected each to 25 Watts:

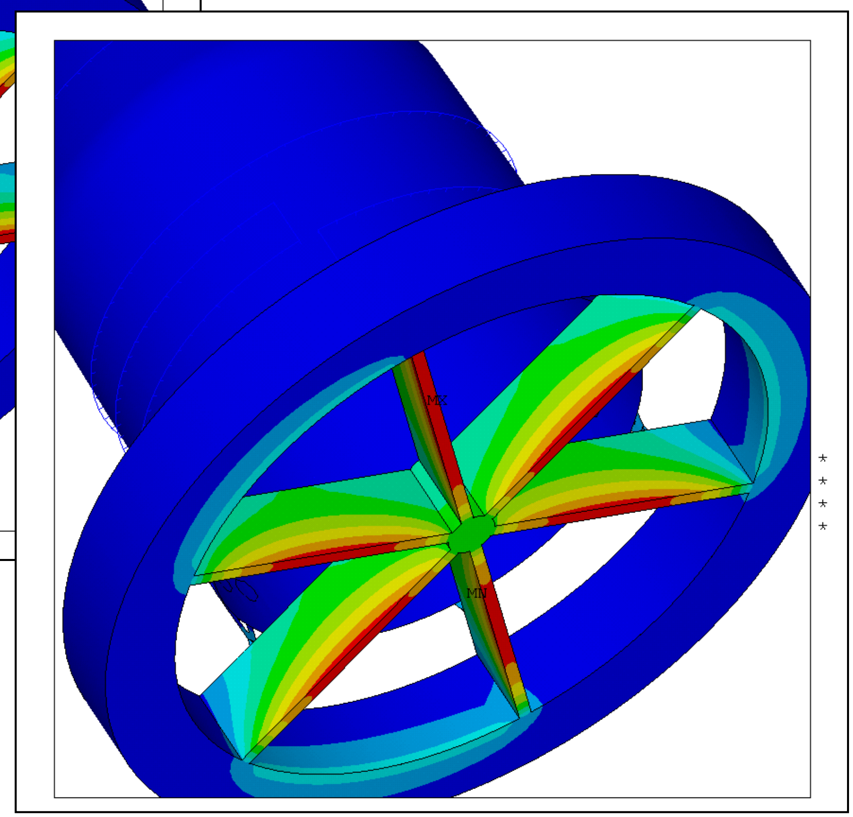
10 seconds into transient

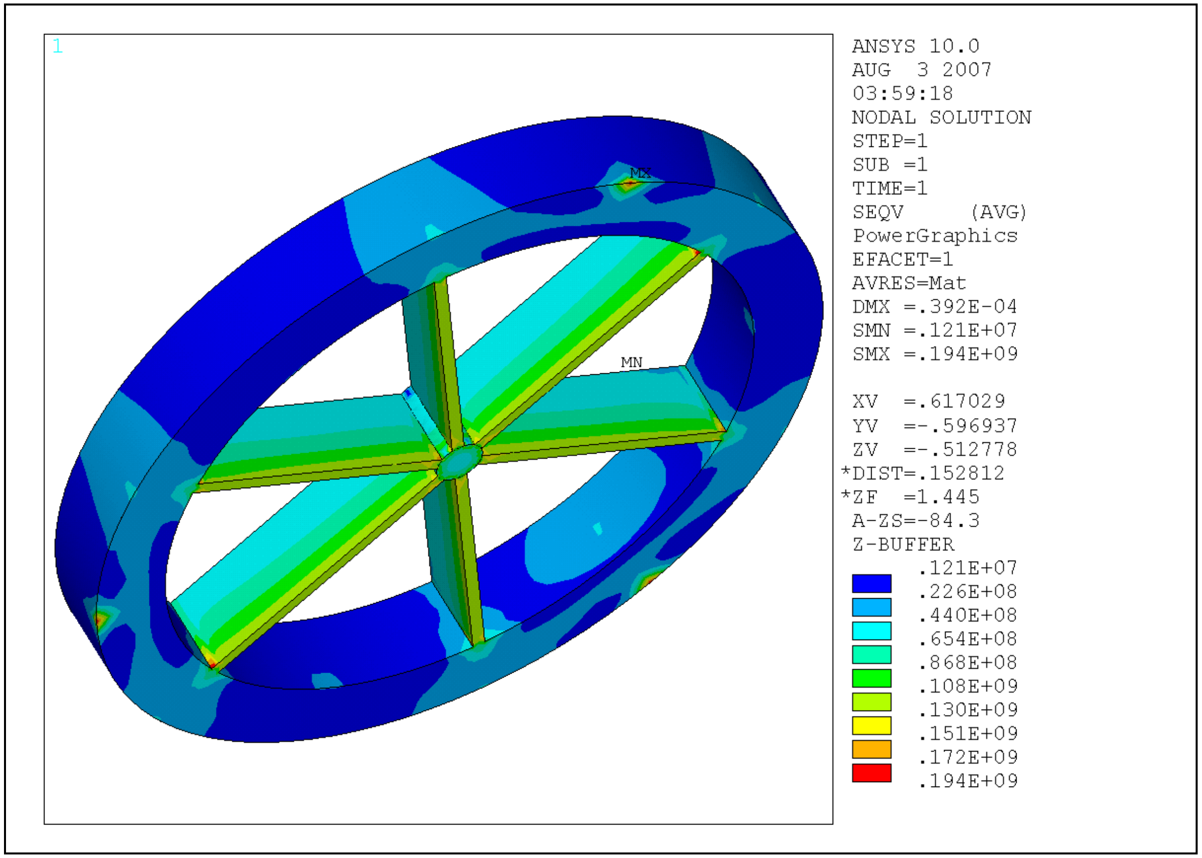


100 sec into transient



200 sec into transient





Coupled Thermal Analysis and structural Analysis: Future at Vector Fields?

Spider VM equivalent stress at 200 sec into transient.