Thermal Analysis of the Cold Mass of the 2 T Solenoid for the PANDA Detector at FAIR

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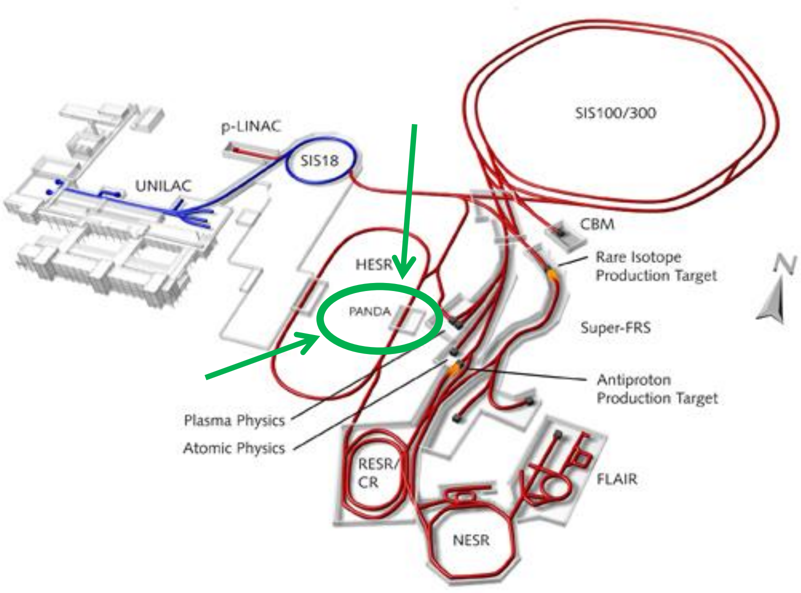
The PANDA experiment

- The Facility for Antiproton and Ion research (**FAIR**) under construction at GSI, Darmstadt (Germany) is one of the largest research project worldwide.
- panda anti-**P**roton **AN**nihilations at **Da**rmstadt.
- The **PANDA** collaboration is composed by more than 450 scientists from 17 countries.

- The PANDA experiment intends to do basic research on weak and strong forces, exotic states of matter and the structure of hadrons.
- Antiprotons produced by a primary proton beam is transferred to the High Energy Storage Ring (HESR).
- Antiprotons will collide with the fixed target inside the PANDA Detector.

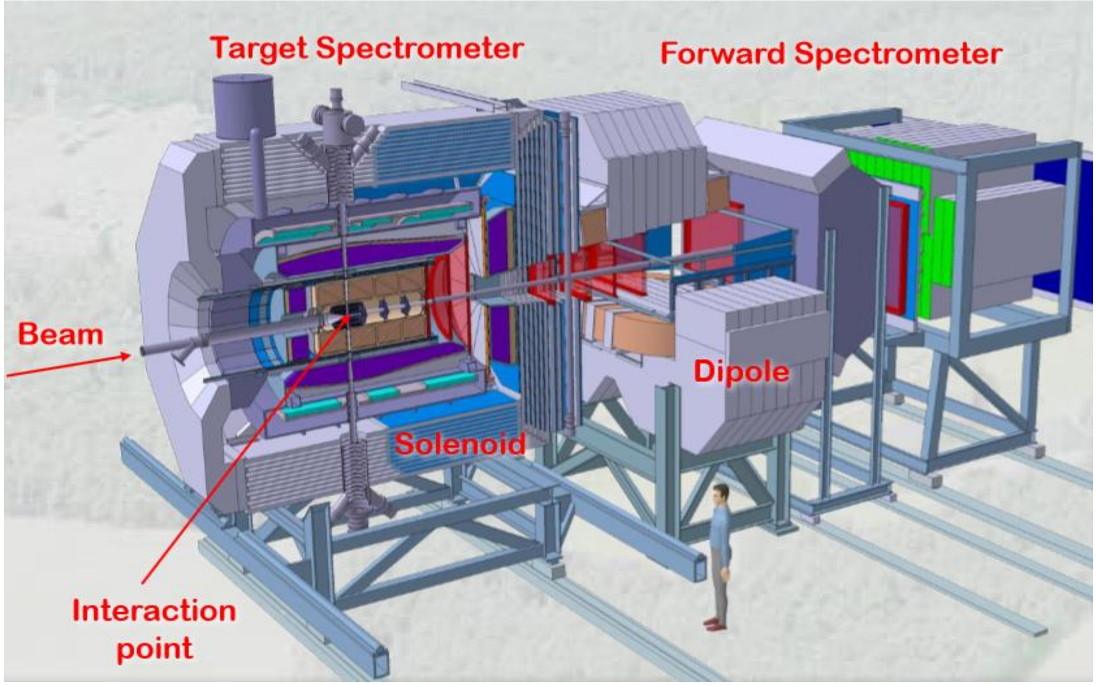


The PANDA detector

Panda is a **fixed target magnetic spectrometer experiment**.

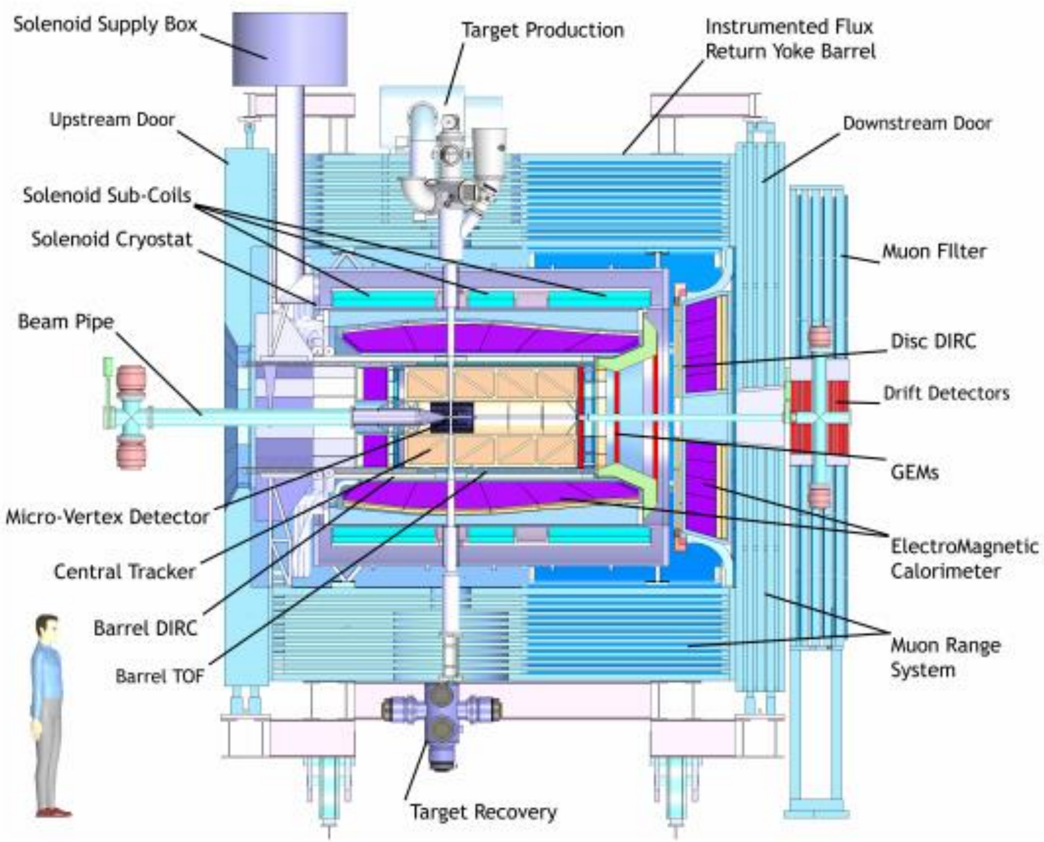
To achieve full coverage of the solid angle together with good particle identification and high energy and angular resolutions, the detector is **subdivided in two magnetic spectrometers**:

- **Target Spectrometer** based on a superconducting solenoid around the interaction point for large angles tracks.
- **Forward Spectrometer** equipped with a dipole magnet for small angle tracks.



The PANDA solenoid

- The Target Spectrometer is the core of the PANDA detector.
- The **Solenoid** features a warm bore of 1.9 m diameter around the interaction point with 4 m free length.
- The interaction point is located at 1/3 of the length of the coil. The solenoid is at this point and the cryostat exhibits a warm bore of 100 mm.
- The flux-return yoke is made of 13 layers of iron and incorporates mini-drift tubes for muons detection.



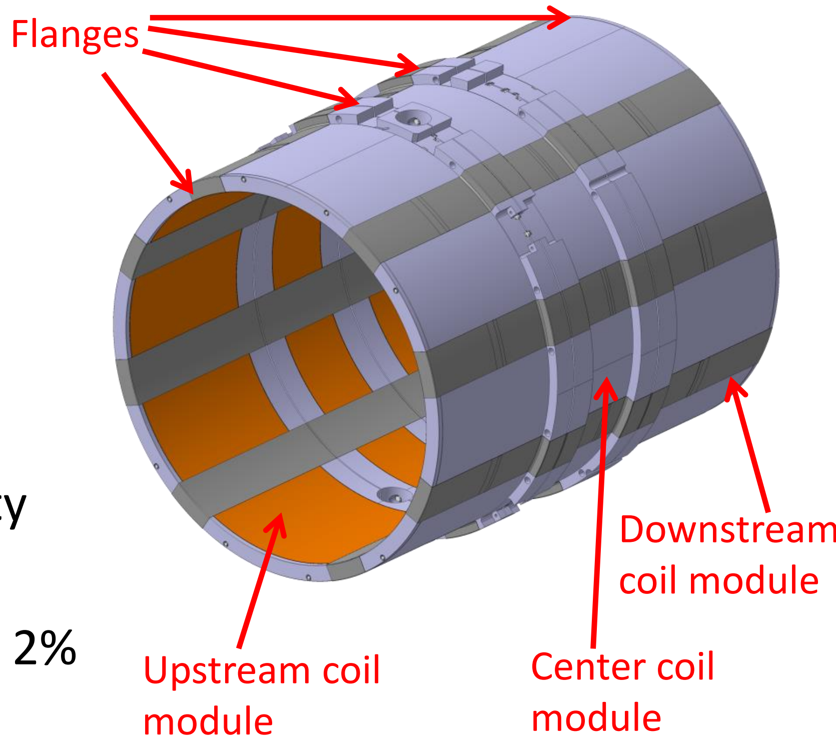
- Both ends of the return are fabricated as opening doors, and is also part of the muon system.

The PANDA solenoid

- For balancing forces and guaranteeing the required field homogeneity the coil is split in 3 parts.

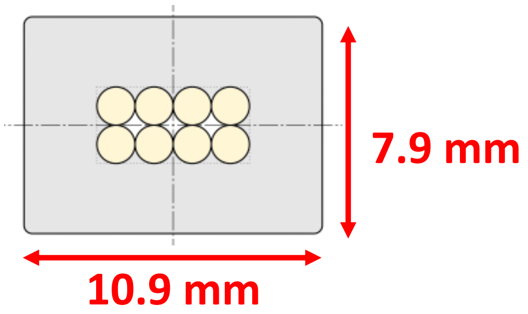
- The solenoid will thus be manufactured as 3 independent coil modules connected by flanges. The modules will be enclosed in a common cryostat.

- **Advantages**:
  - Easier coil manufacturing (winding, handling, etc…)
  - Reduced production cost
  - Possibility to correct errors due to winding using shims between coil modules. Very relevant as field quality requirements are tight:
    1. Central field homogeneity 2 T ± 2%
    2. Radial field integral < 2 mm



Conductor

Parameter	Value
Conductor type	Al-stabilized Rutherford cable
N. of strands	8
Strand diameter [mm]	1.4
Filament diameter [μm]	20
Cu : nonCu ratio	1.0
Cable dimensions [mm]	2.6 x 5.3
Conductor bare dimensions [mm]	7.9 x 10.9
Insulation type	Fiberglass
Insulation thickness [mm]	0.4
Temperature margin [K]	2.4



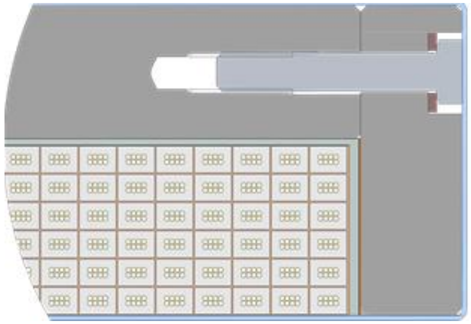
Rutherford cable with **low height-to-width-ratio**.

Advantages:

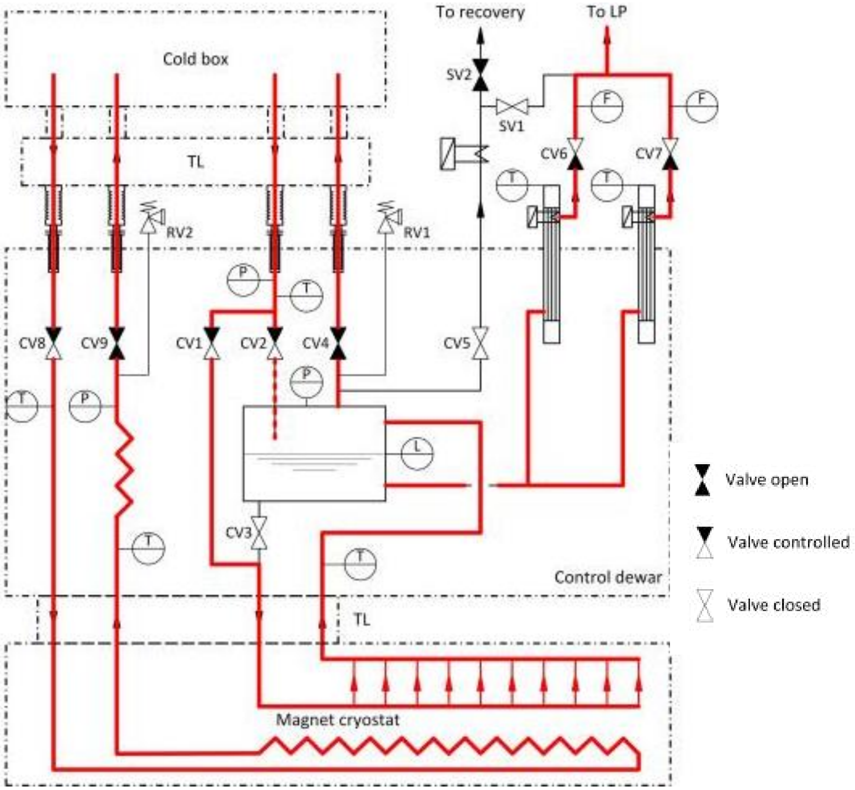
- Easy to wind
- Low eddy current loss

(Possible) disadvantages:

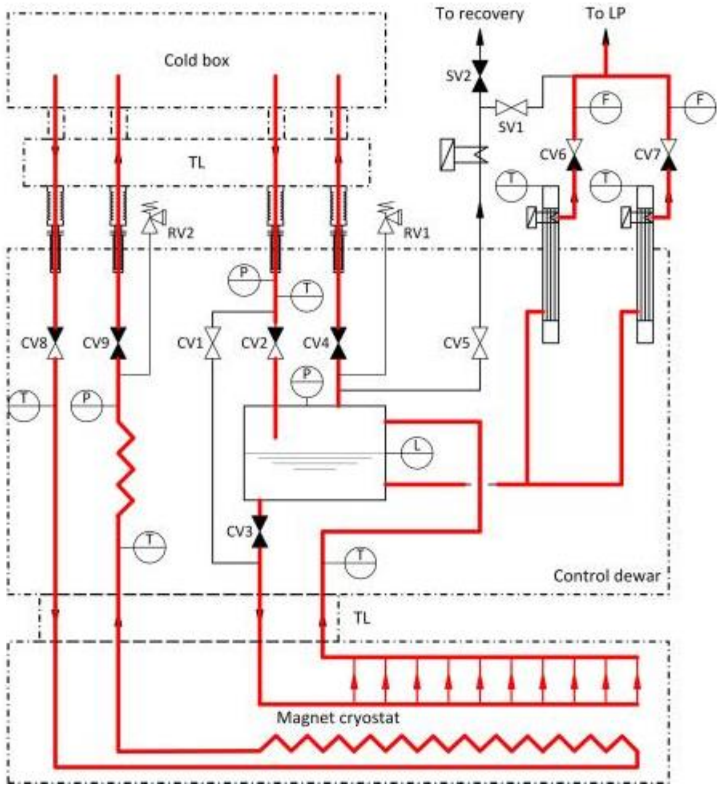
- 6-layers coil is needed to fulfill magnetic and dimensions constraints. This could lead to higher temperature gradients across the coils.



Cooling scheme



Cool down forced flow



Nominal operation thermosiphon

- Thermal shields cooled with He gas coming from the cold box.
- Current leads cooled with liquid He from control dewar.
- Control dewar volume ~ 300 l.

Heat load to cold mass

- Heat load to cold mass is 17 W.
- Heat load from cryogenic chimney and control dewar add other 10 W.

- The total heat load is thus (safety factor 2 included) **54 W**.

Component	Q [W]	Model details
Eddy current* in casing	11.5	3D FEM
Eddy current* in conductor	0.09	Mixed (FEM + analytic)
Radiation**	1.5	Analytic
Residual gas***	0.5	Analytic
Conduction** in Axial & Radial supports**	2.8	Analytic
6 joints (1 m length)	0.5	2D FEM

** Current ramp time = 2000 s.*

*** For a thermal shield temperature of 60 K and no superinsulation.*

**** Operating pressure of 2 10^{-6} mbar.*

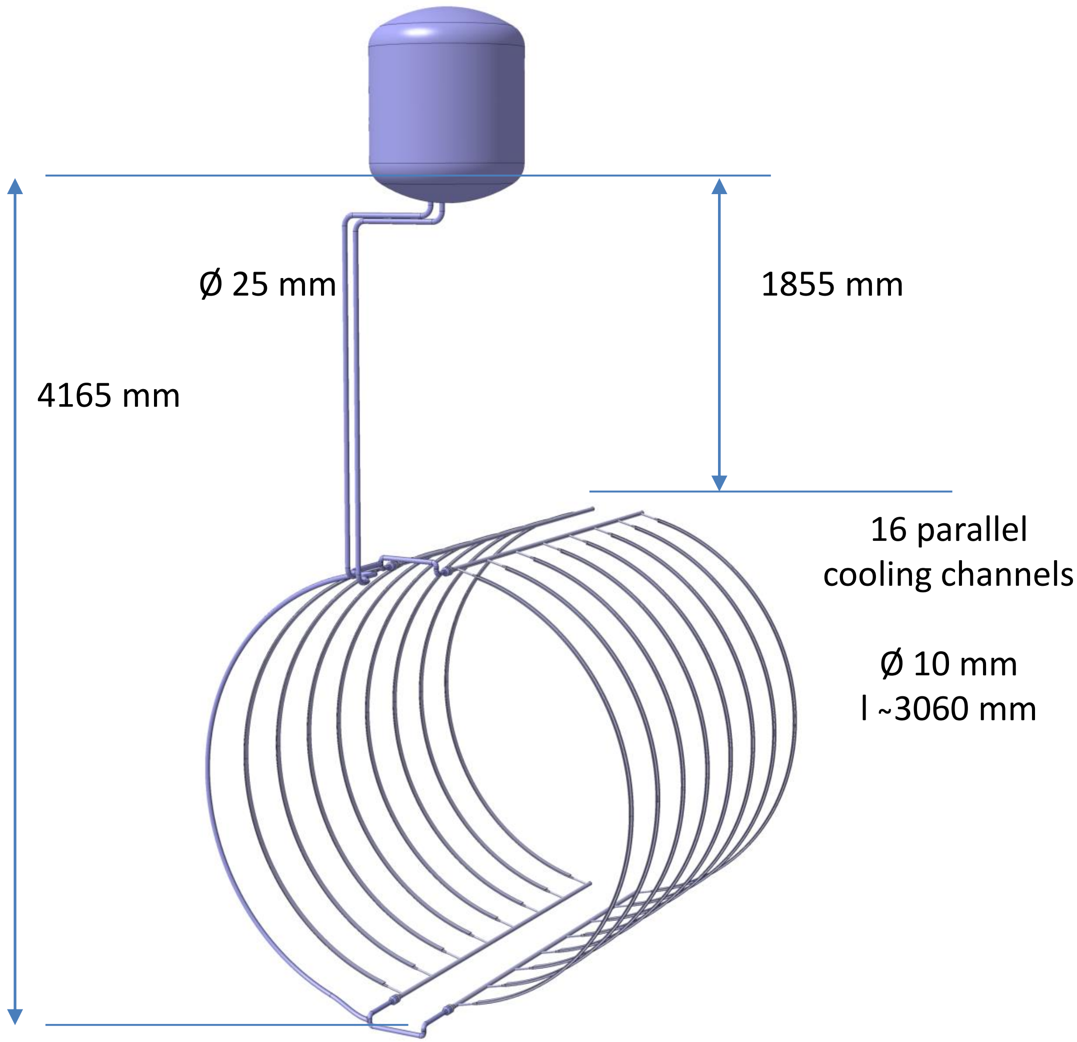
***** 12 radial + 8 axial rods, thermalized at 77 K at 2/3 of their length.*

Thermosiphon – preliminary assessment

Preliminary assessment of the feasibility of thermosiphon cooling of the PANDA solenoid [1].
Main approximations:

- Pressure drop at singularities neglected. It could lead to a reduction of the order of ~30% in the computed mass flow (and consequent increase in vapor fraction)
- Difference between outflow flow and liquid level in the dewar neglected

Heat load	Q = 54 W
Mass flow rate	$\dot{m}$ = 110 g/s
Vapor fraction	x = < 3%

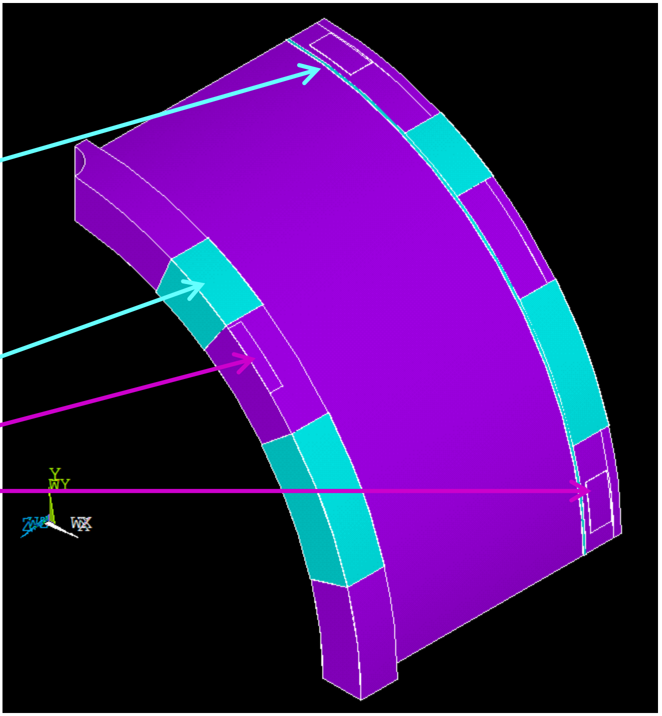


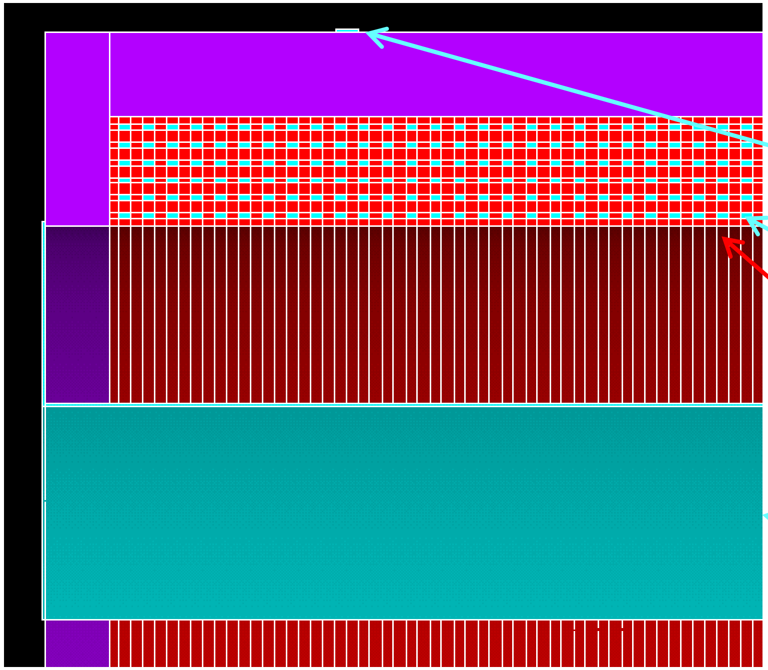
[1] *Experimental and theoretical study of a two phase helium high circulation loop, P. Bredy et al. AIP Conf.Proc. (2006) 496-503*

3D FE thermal model

¼ **3D model** of the **Upstream** coil module including:

- Conductor -> **pure Al** RRR = 500 and B = 3 T
- Insulation -> **fiberglass - epoxy**
- Casing -> **Al-5083**
- Cooling pipes (Ø 10 mm)
  -> **pure Al** RRR = 500 and B = 3 T
- Pure Al-strip -> **pure Al** RRR = 500 and B = 3 T
- Axial and radial support blocks -> **Al-5083**





Cooling pipe

Conductor

Insulation

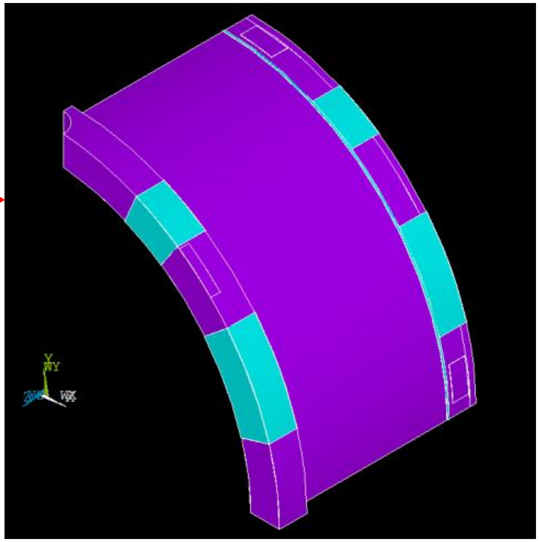
Al-strip

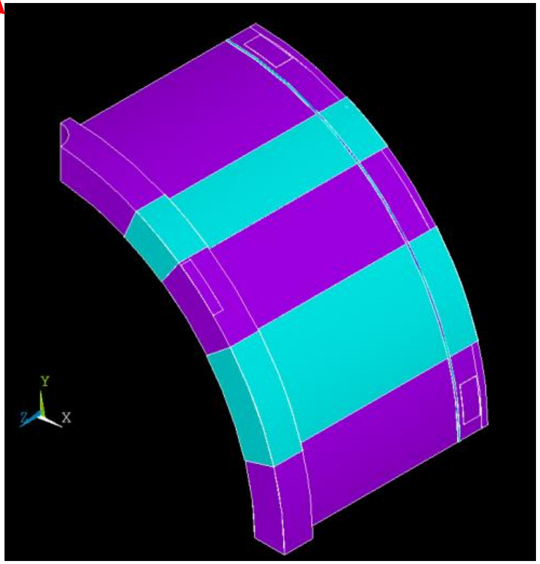
3D FE thermal model

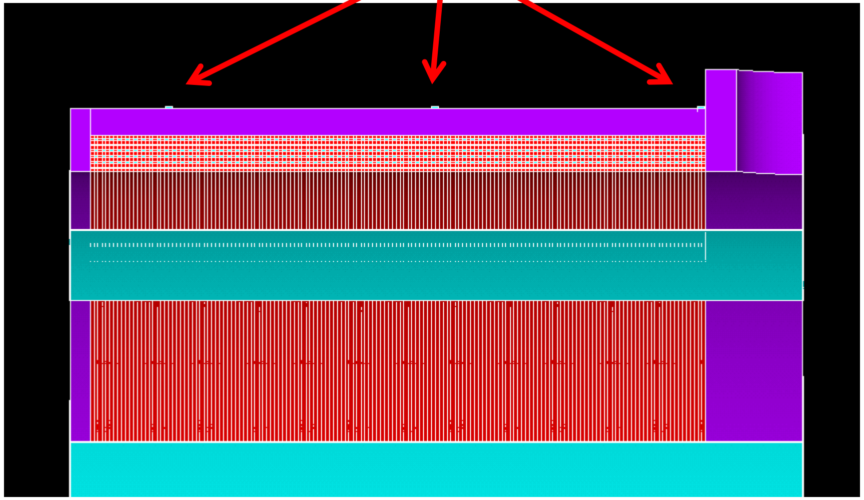
- **Radiation** in-leak on all the outer surfaces of the model.
- **Heat conduction** along the axial and radial supports.
  - The heat conduction along the axial support is equally divided between the upstream and center coil modules.
- **Eddy current** loss in the **conductor** based on the conservative assumptions:
  - $B = B_{peak} = 3$ T
  - $\rho_{Al} = \rho_{Al}$ (RRR = 1000 and B = 0 T).
- **Eddy current** loss in the **casing.**
- Cooling pipes @ **T = 4.5 K.**
- Since the three coil modules are separated by **shims**, they can be assumed **thermally decoupled.**
- The **azimuthal position** of the pure **Al-strips** is **determined by** the location of the axial- and radial **supports** connection blocks as well as of the holes for the **bolts in** the **flange** between upstream and center coils.

3D FE thermal model

Case	Number of cooling pipes	Pure Al strip position
1	2	Inner radius
2	3	Inner radius
3	2	Inner & outer radius
4	3	Inner & outer radius

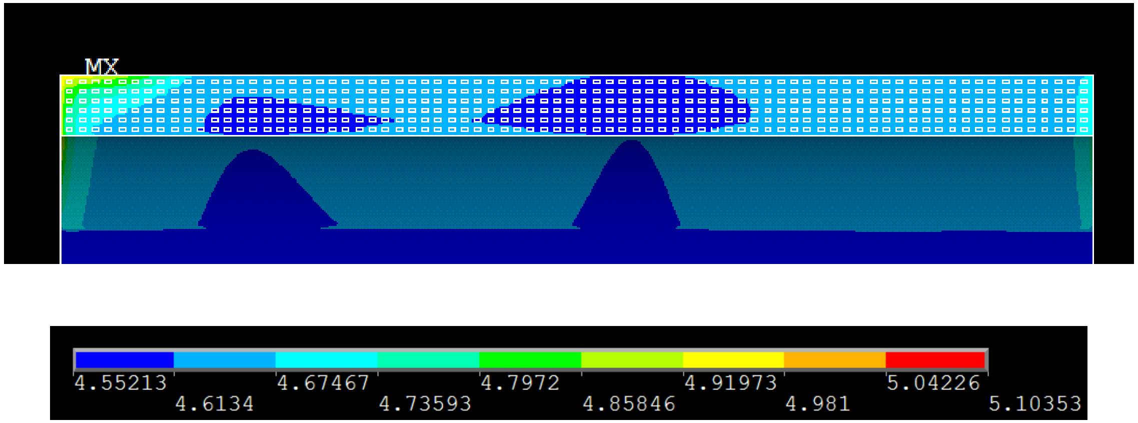






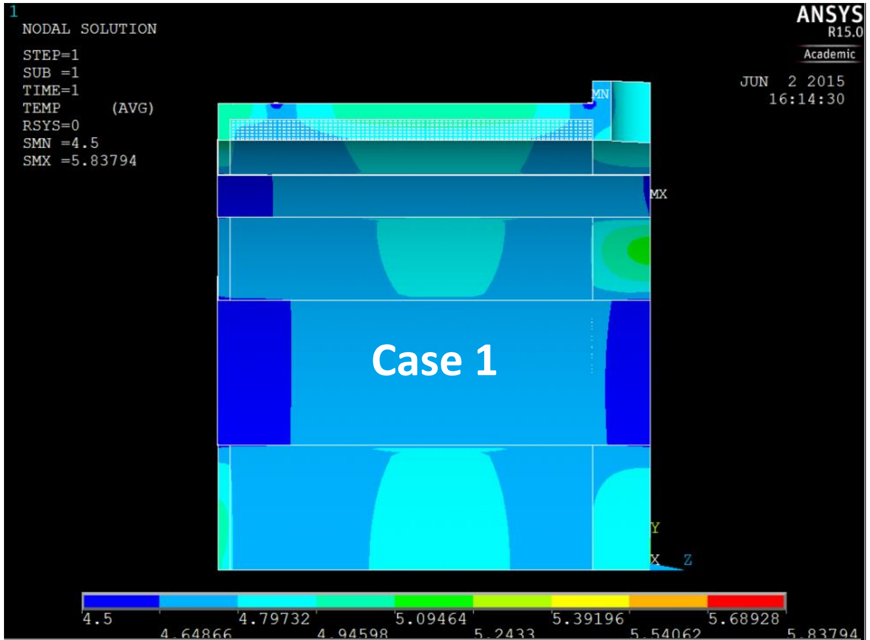
3D FE thermal model

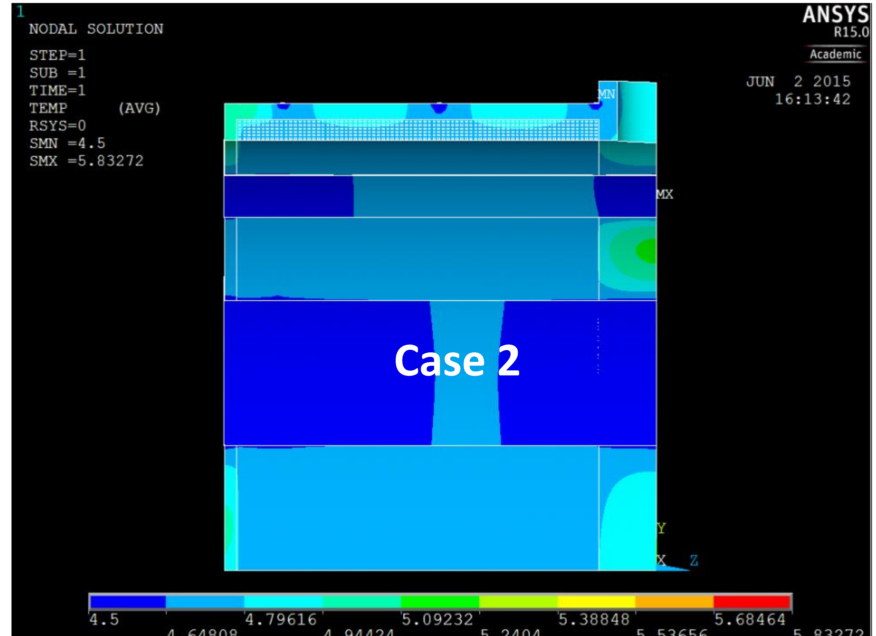
Case	Number of cooling pipes	Pure Al strip location	T_{peak} conductor [K]
1	2	Inner radius	5.03
2	3	Inner radius	4.92
3	2	Inner & outer radius	4.90
4	3	Inner & outer radius	4.90

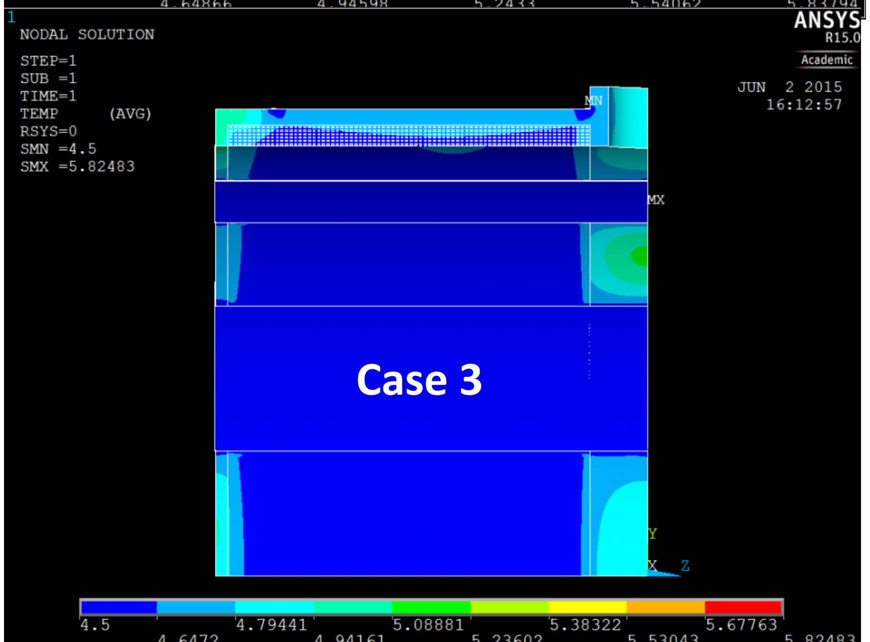


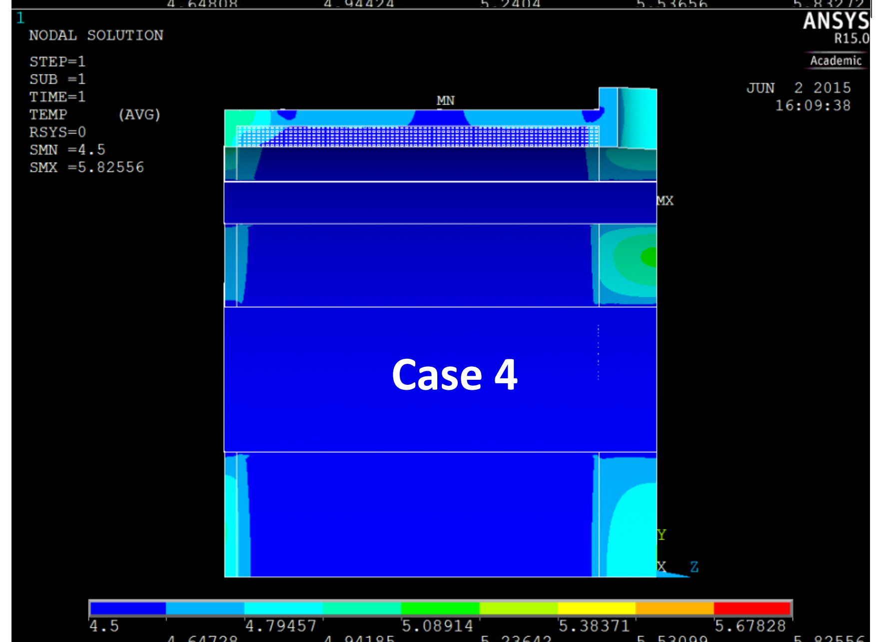
- **Peak temperature** on conductor is localized in correspondence of the radial supports connections, i.e. corner conductors in the outer layer.
- At **this location** B_{peak} < 3 T, thus the **temperature margin** is **larger than 2.4 K**.
- $\mathbf{T_{peak}}$ is **overestimated** as the model assumes perfect heat conduction from supports to cold mass.

3D FE thermal model









Conclusions

- Preliminary assessment of thermosiphon confirms that natural convection can be used for cooling of the PANDA Solenoid during nominal operation.

- The 3D thermal analysis confirms that 2 cooling pipes and 2 pure Al-strips glued to the inner layer of the coil are sufficient to guarantee a minimal temperature increase in the 6-layers coils (5.0 K) even in the presence of eddy current loss during current ramps up or down.

- The peak temperature is located in the corner of the outer layer close to the connection block of the radial supports. This temperature is likely overestimated as the model assumes perfect thermal contact between support rods and cold mass.

- The temperature distribution in the conductor can be easily improved by extending the pure Al-strips on the outer radius surface.

- A third central cooling pipe will be added for redundancy for the longest coils, i.e. upstream and downstream coils.