Design of the BabyIAXO superconducting detector magnet

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Mon-Af-Or5-05

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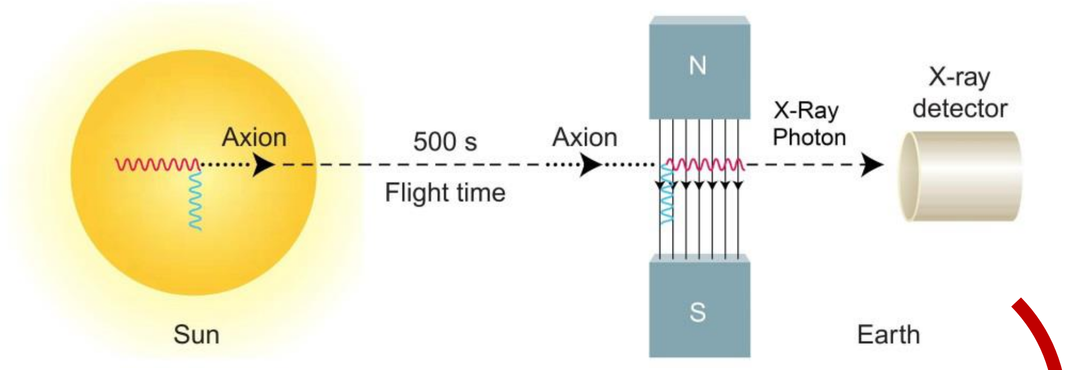
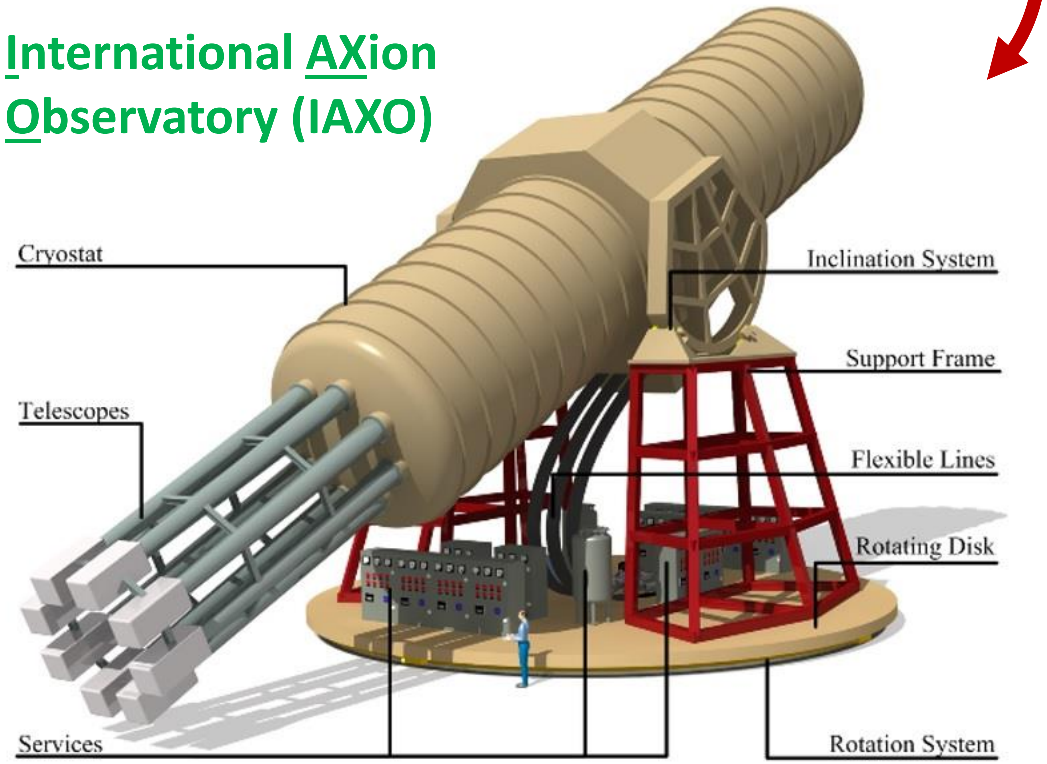
1 Introduction – axion helioscope concept - IAXO



- A high magnetic field oriented transversely to the solar flux of axions in a large bore magnet, tracking the sun, with photons concentrating optics and X-ray detectors.
- Magnet Figure Of Merit (MFOM) scales as L^2B^2A, thus design drivers are **magnetic field B**, **area A** and **length L.**

The feasibility and readiness of the required technologies will be demonstrated in the sub-scale demonstrator called **BabyIAXO.**

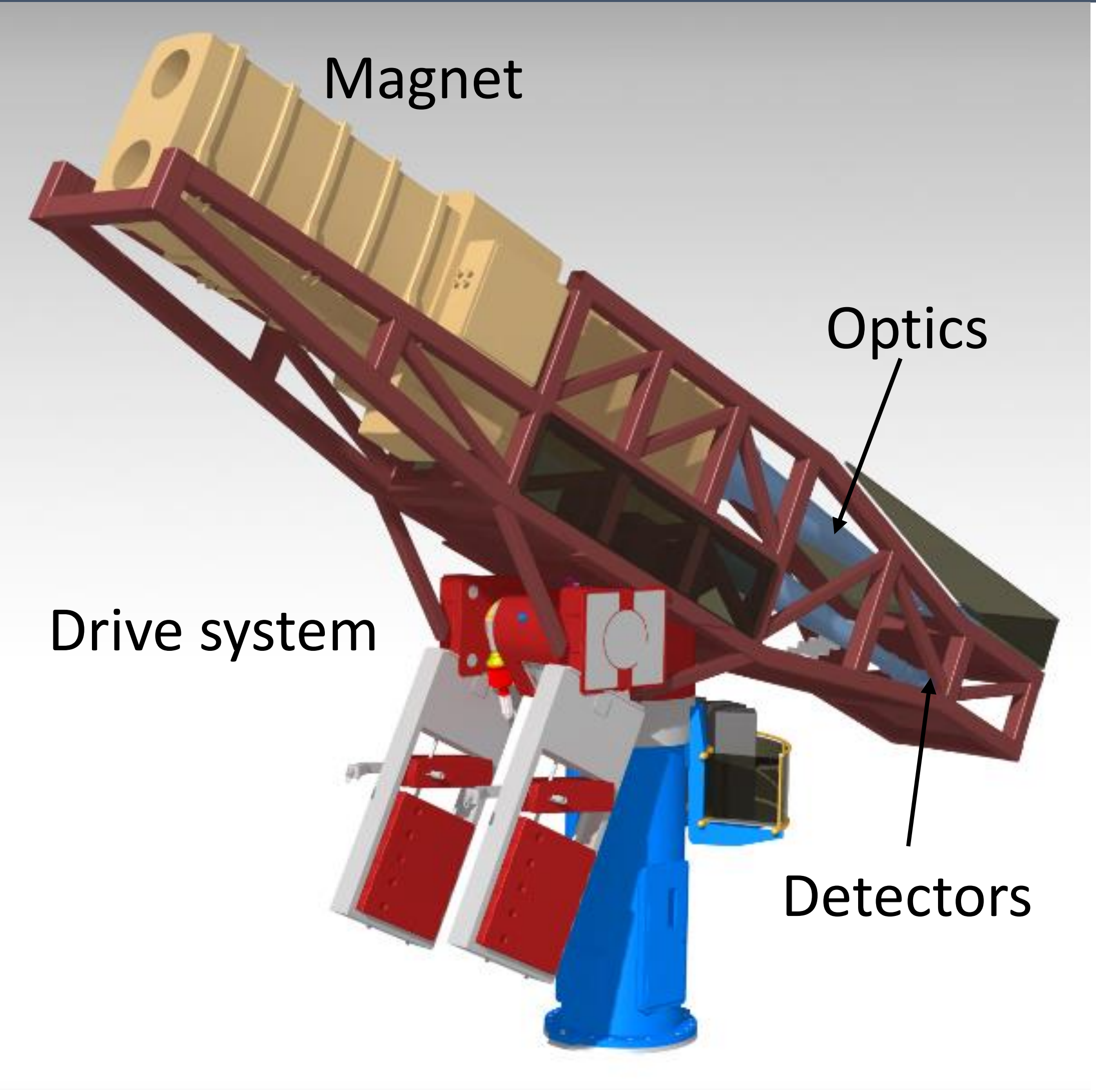
International AXion Observatory (IAXO)



Main features of the IAXO magnet:

- MFOM estimate 6000 T^2 m^4, average bore field 2.5 T
- 8 flat racetrack coils assembled in a toroidal geometry
- Operating current 12 kA, total conductor length 68 km
- Stored magnet energy 660 MJ, inductance 9.2 H
- Drive system provides 360° rotation and ±25° inclination
- Conduction cooling by a helium forced flow
- Outer diameter 6 m, length 25 m
- Overall mass 250 tons

1 Introduction – BabyIAXO



The BabyIAXO Experiment foreseen to be hosted by DESY (Hamburg)

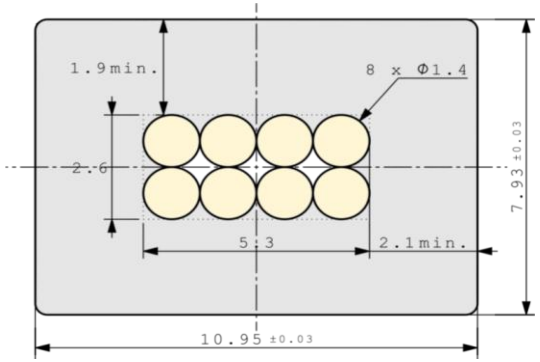
Main requirements for Baby-IAXO's magnet:

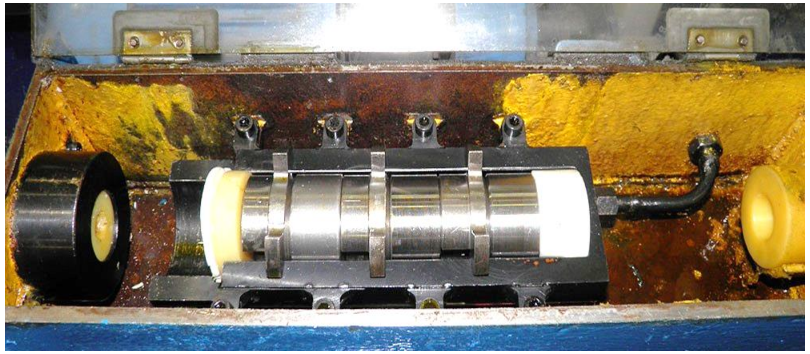
- Magnet performance **at least 10 times CAST's** magnet MFOM
- **Simple & Robust** design, allowing construction in 3 to 4 years
- **Lowest-cost** design within a magnet budget of some 3.5 M€.

Consequences:

- **Conductor:** NbTi Rutherford cable co-extruded with a pure Aluminum matrix with 2 K temperature margin
- **Coil windings:** two flat racetrack coils of 10 m length arranged in a common-coil layout
- **Detection bore:** two 700 mm diameter free-bore tubes
- **Electrical operation:** persistent current mode with power supply switched off after charging
- **Cooling mode:** conduction cooled at 4.2 K using gas-circulators
- **Cryogenics:** cryocoolers for cool down and stationary operation, thus dry cooling condition.

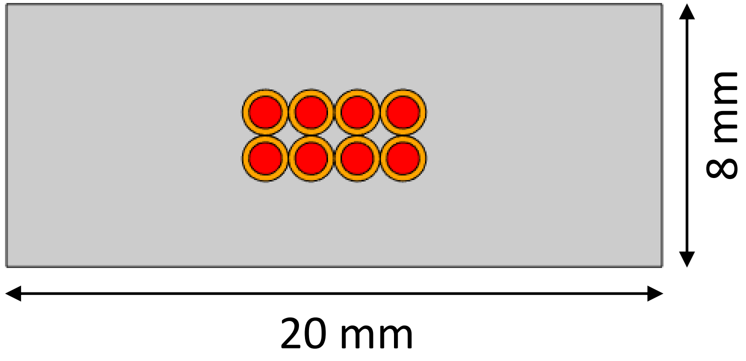
2 Cold mass – conductor specification



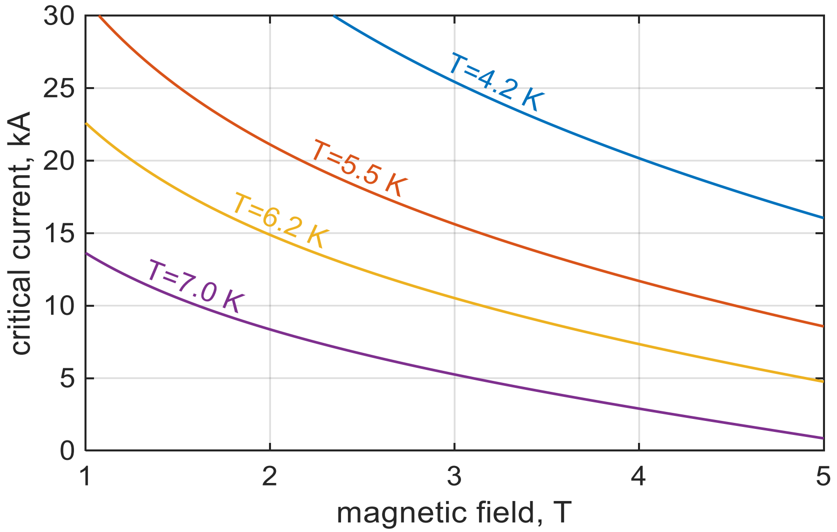


Panda conductor production trials at Sarko company, organized by BINP in 2018-19.

Al-stabilized
Rutherford cable

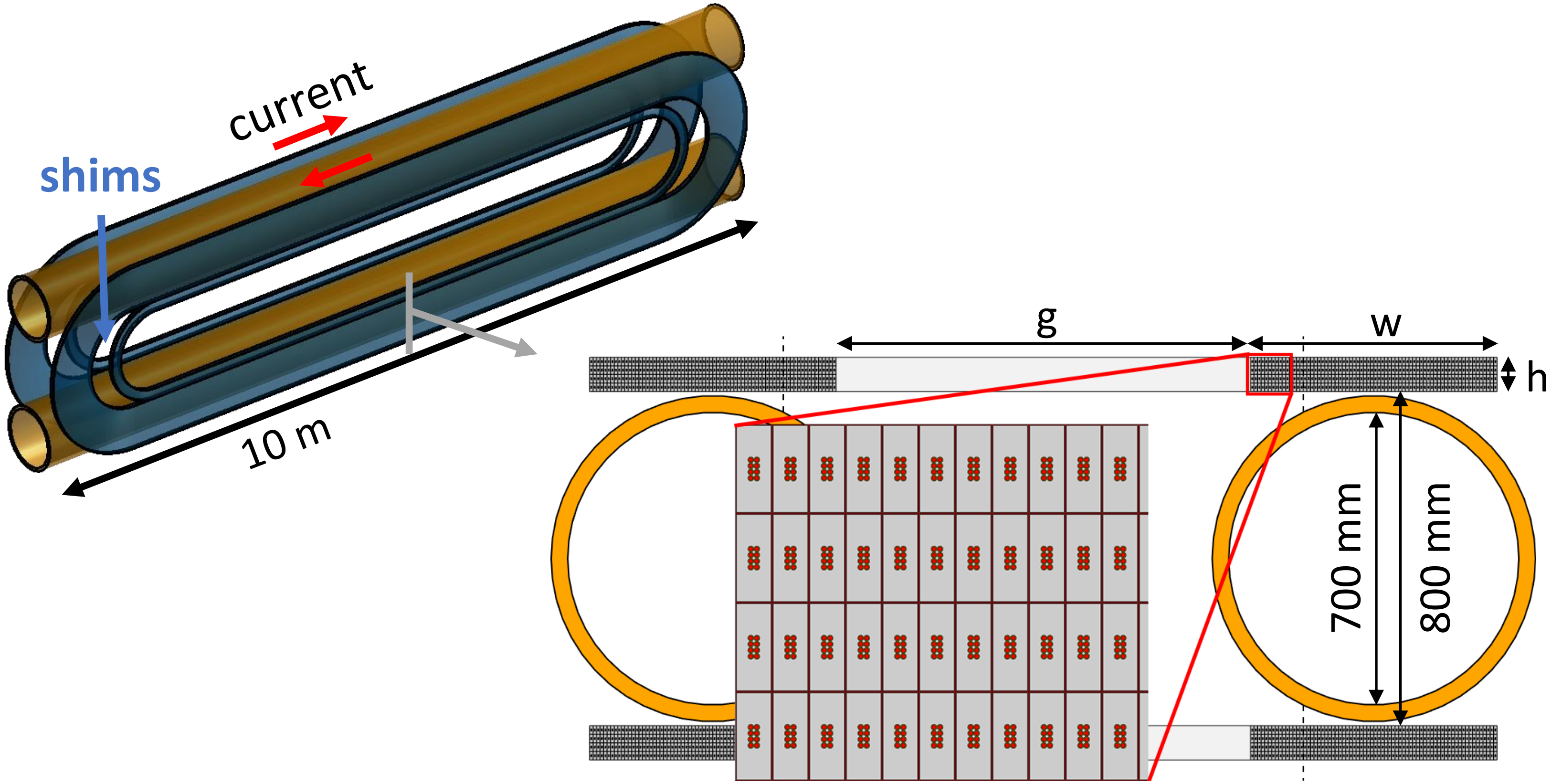


Number of strands	8
Strand diameter	1.40 mm
NbTi cross-section	≈ 6 mm^2
Copper cross-section	≈ 6 mm^2
Aluminum section	≈ 148 mm^2



- ✓ Saving time and budget by making use of the on-going R&D and production start-up of the FAIR-Panda conductor.
- ✓ Use the same cable, but with slightly adjusted Al cross section: 10.95 mm × 7.93 mm **---> 20 mm × 8 mm.**

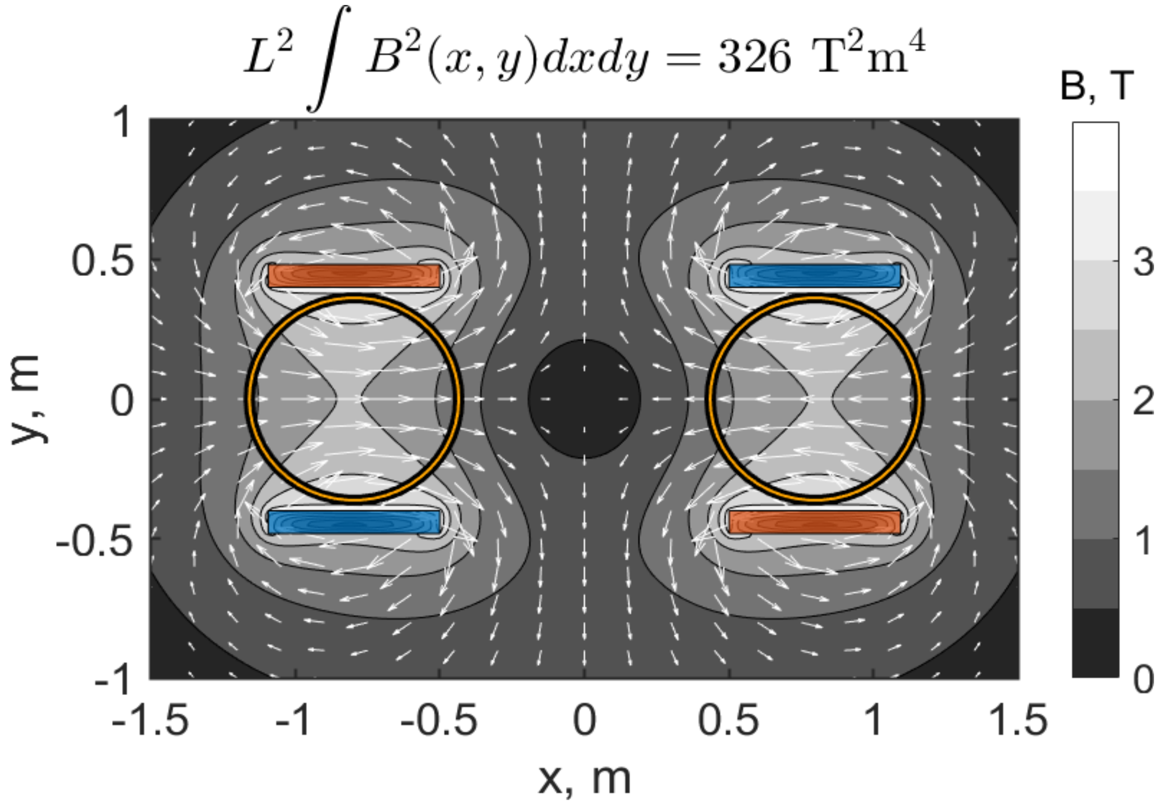
2 Cold mass – winding pack design

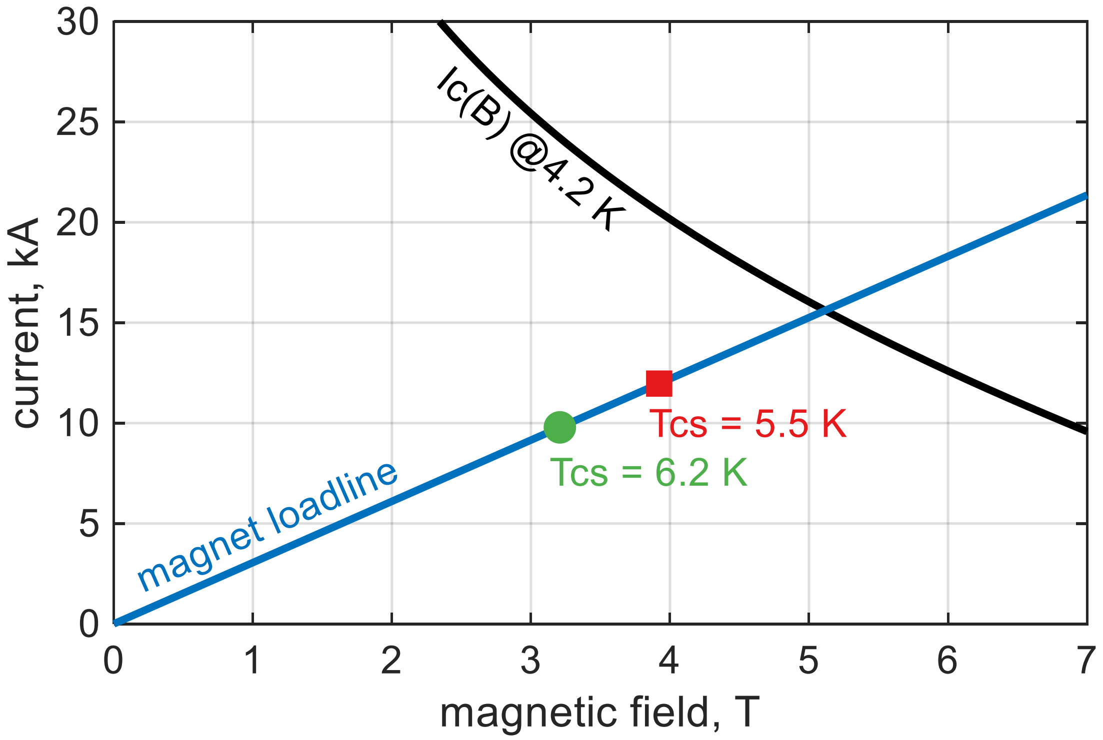


Winding width, w	595 mm
Winding height, h	82 mm
Pole gap, g	1000 mm
Magnet energy	50 MJ
Inductance	1.0 H
Peak magnetic field	**3.2 T**
Current density	56 A/mm^2
Operating current	**9.8 kA**
Conductor length	**11.4 km**
MFOM 3-D	232 T^2 m^4
MFOM 2-D	**326 T^2 m^4**

- **Conductor with pre-impregnated glass tape insulation (avoiding expensive vacuum impregnation).**
- **2-double pancake windings for BabyIAXO corresponds to the baseline design of IAXO windings.**
- **Free user bore tubes can be filled with air/gas/vacuum, at 300 K or at cold (staged option).**
- **Heaters on bore tube to stabilize temperature and avoiding condensation.**

2 Cold mass – working point, temperature margin, MFOM

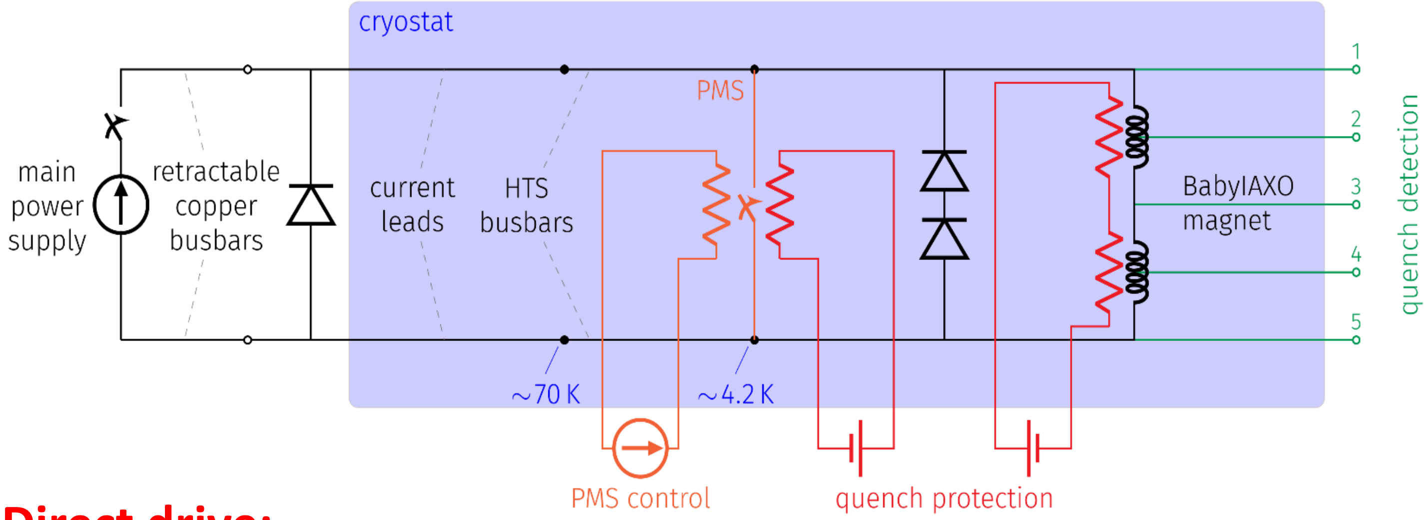


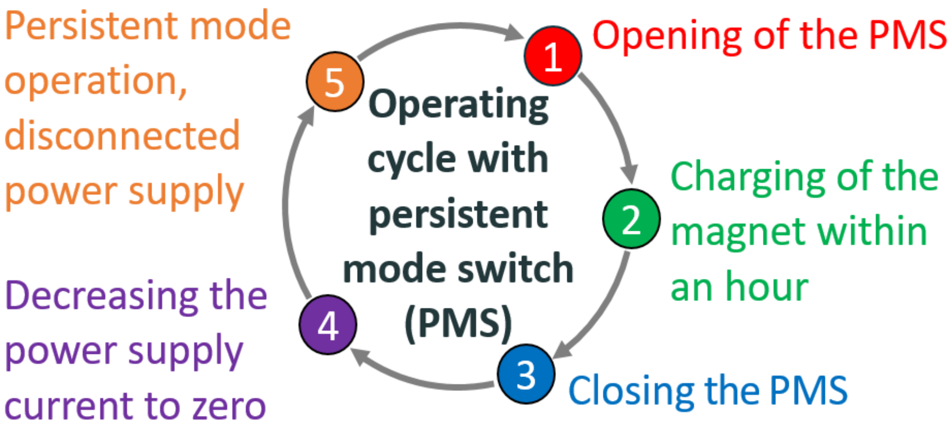


- **Average magnetic field in bore tubes 2.0 T, using shims provides increase of MFOM by ≈10 %.**
- **Nominal Operating current 9.8 kA, temperature margin 2.0 K, MFOM of 326 $\mathrm{T^2m^4}$.**
- **Ultimate performance may be ≈ 20% more in current, 12 kA maximum, mechanical design suits this.**

3 Electrical circuit – persistent mode vs simple direct drive

Persistent mode: reduced heat loads and simplified drive system, but **10 kA PMS** is the challenge.





Operating cycle with persistent mode switch (PMS)

1 Opening of the PMS

2 Charging of the magnet within an hour

3 Closing the PMS

4 Decreasing the power supply current to zero

5 Persistent mode operation, disconnected power supply

Direct drive:

- Persistent mode switch removed (no development, less risk, but higher operation cost).
- Power supply always connected through flexible 10 kA cables.
- Stable and simplified operation, however:
  - Higher voltage on copper bus bars
  - Higher heat load in stationary operation due to current leads, cold end temperature at ~70 K.

Common circuit parameters:

Power supply voltage	5 V to 10 V
Maximum current	12 kA
Operating current	9.8 kA
Ramp rate	3 A/s
Field decay rate	<0.3%/month
Regulation	$< \pm 10^{-3}$
Run-up time	55 min
Voltage during ramp-up	≈ 5 V

3 Quench Protection

Slow dump:

- Failure of external components requiring magnet shut-down.
- Stored magnet energy is released in diodes installed at room temperature; no active heating of the cold mass.
- Electrical circuit is unaffected and readily available for further operation.

Fast dump:

- Quench protection heaters are fired to speed-up the energy release by turning entire coil into the normal state, caused by a quench in either:
  1. **Main magnet**
  2. **HTS busbars**
  3. **PMS**

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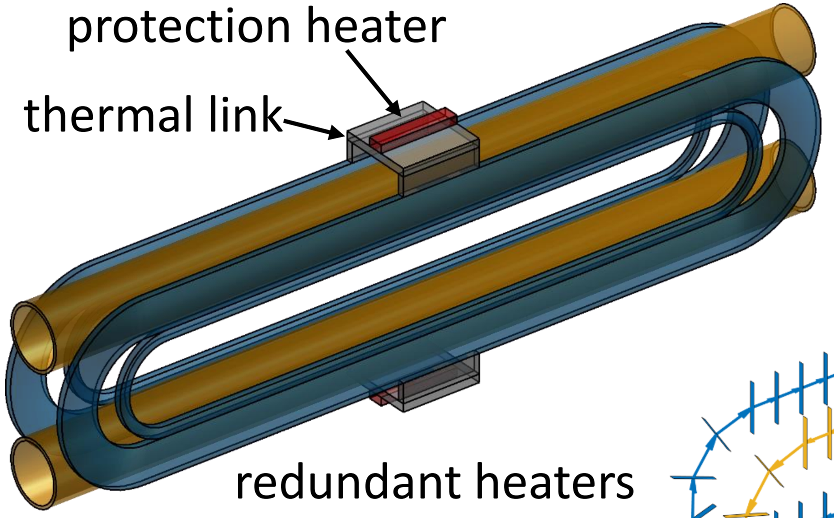
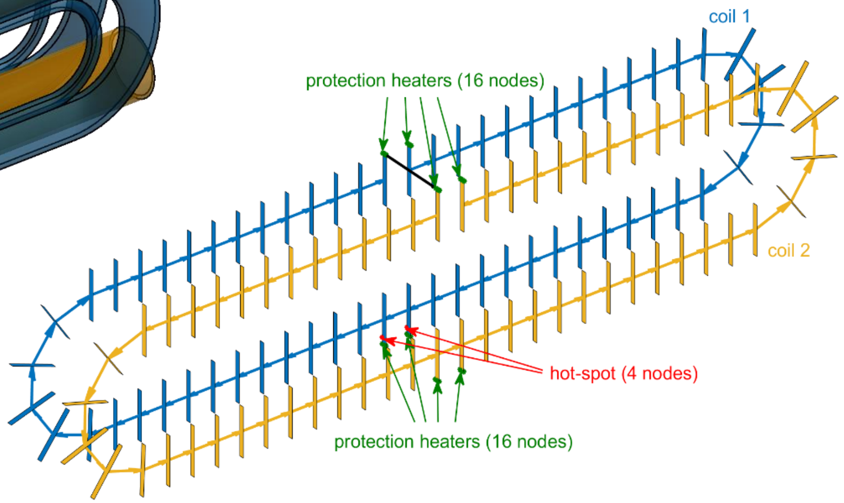


protection heater

thermal link

redundant heaters installed for more uniform fast dump heat distribution



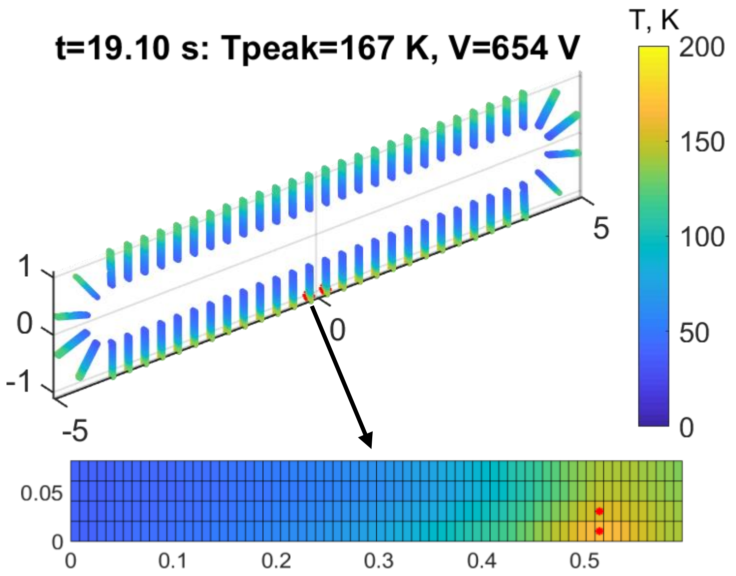
Simulation model features:

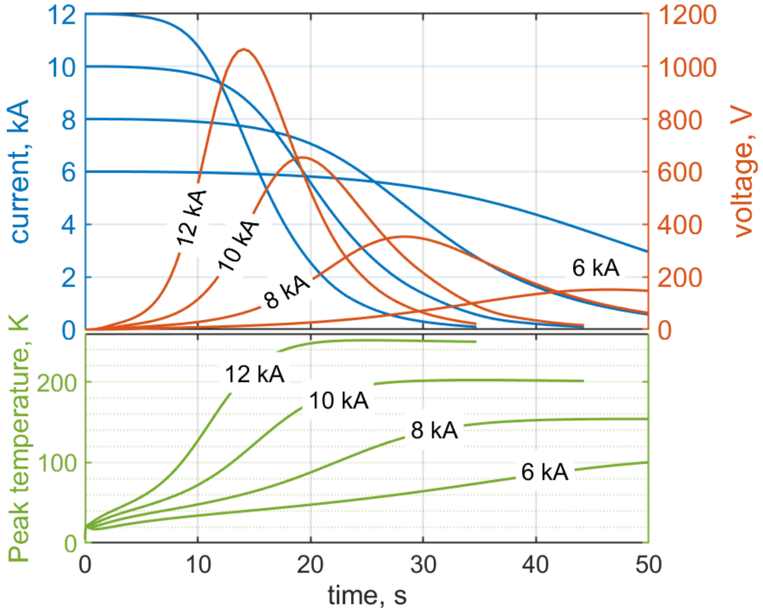
- Heat propagation along conductor and across windings cross-section.
- Magnetic field varies along the conductor.
- Adiabatic conditions, cooling not applied.
- Coils casing included: about 3 t of Al alloy.
- Quench detected using 0.5 V threshold.

* conservative approach, as number of support components are not included in the analysis.

3 Quench Protection – peak voltage and temperature

worst case: quench in 1 winding pack only, no casing, quench detection off:





- Stored energy dumped in the coil windings, taken up by its enthalpy.
- Coil-internal peak voltage reached when entire winding is normal state, **in worst case some 650 V**.
- Normal zone propagates with ≈ 7 m/s along the conductor and ≈ 2 cm/s across turns.

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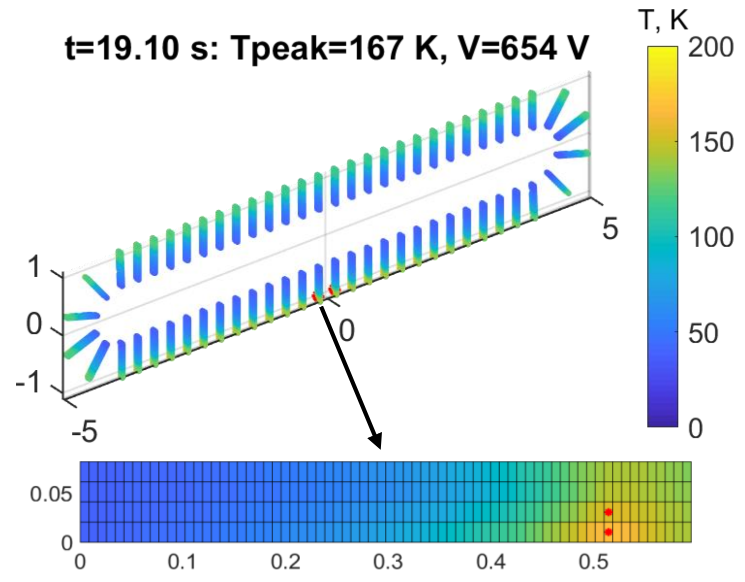

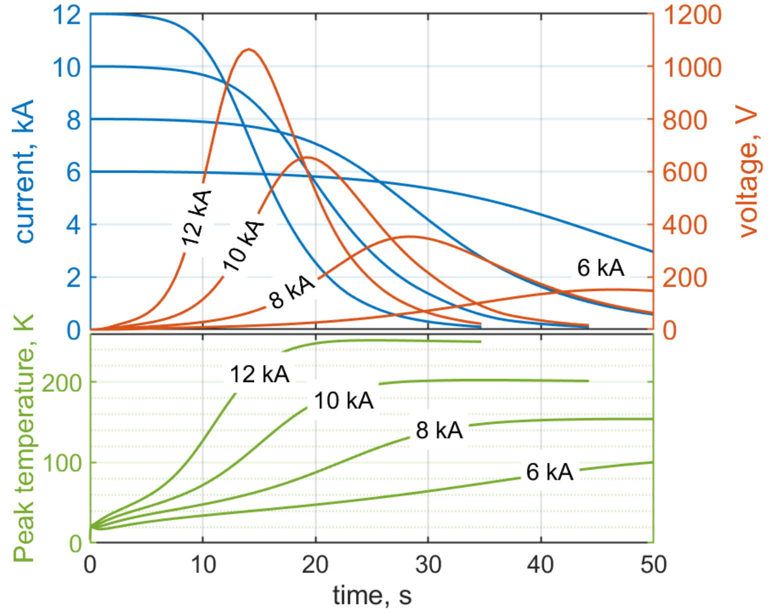

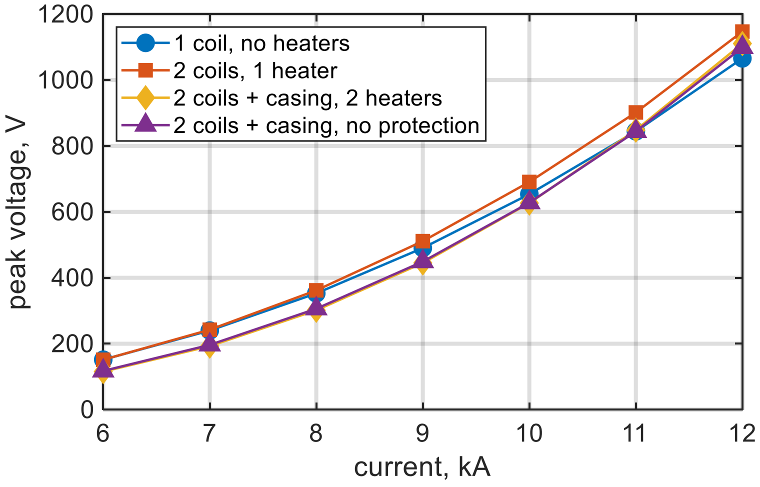

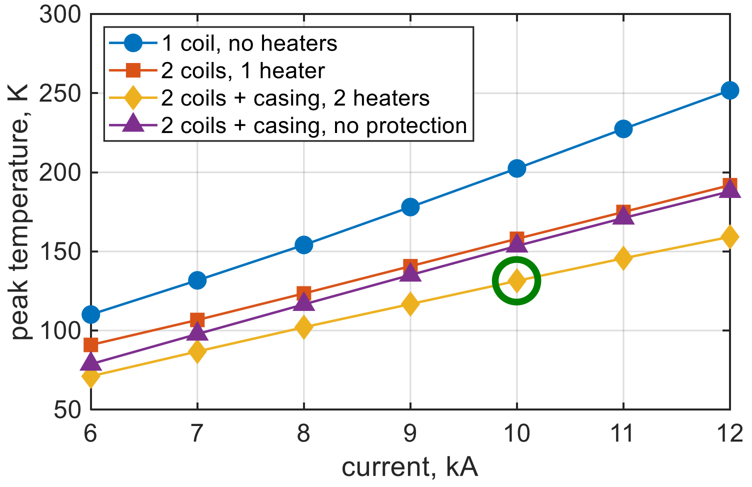

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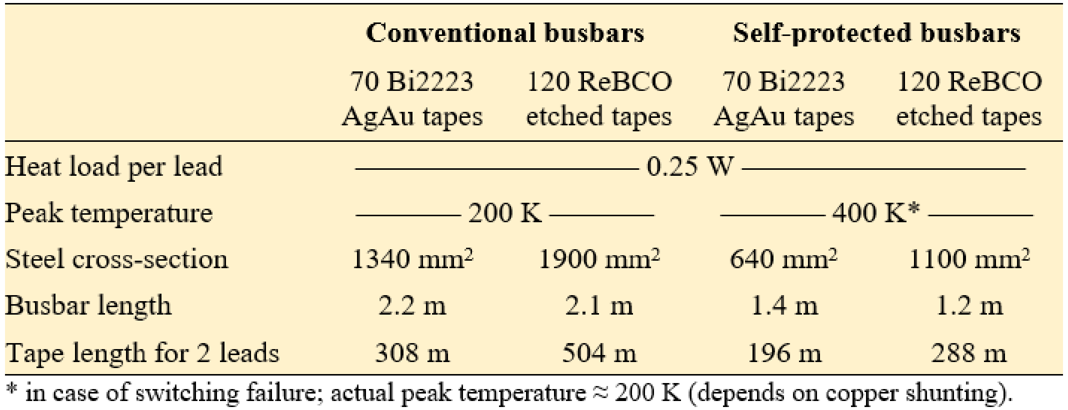
- Coil-internal peak voltage reached when entire winding is normal state, **in worst case some 650 V**.
- Normal zone propagates with ≈ 7 m/s along the conductor and ≈ 2 cm/s across turns.
- Peak voltage as a function of current practically independent of cases considered, **all < 0.7 kV at nominal.**
- Tmax **of 130 K** at nominal is safe. In realistic scenario of 2 coils and using heaters, the requirement is fulfilled for all currents.
- Tmax ≈ 15 % higher, if protection fails, still OK.

3 Quench Protection – HTS busbars and PMS



	Conventional busbars		Self-protected busbars	
	70 Bi2223 AgAu tapes	120 ReBCO etched tapes	70 Bi2223 AgAu tapes	120 ReBCO etched tapes
Heat load per lead	0.25 W			
Peak temperature	200 K		400 K*	
Steel cross-section	1340 mm²	1900 mm²	640 mm²	1100 mm²
Busbar length	2.2 m	2.1 m	1.4 m	1.2 m
Tape length for 2 leads	308 m	504 m	196 m	288 m

* in case of switching failure; actual peak temperature ≈ 200 K (depends on copper shunting).

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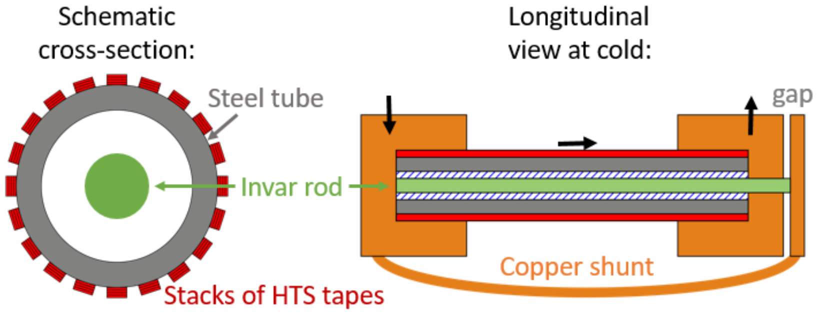
Wed-Mo-Or12-04

Conceptual layout of the self-protected busbars:



1. Assembly at RT: copper shunt preloaded to HTS section by tensioning invar rod, gap closed.
2. Normal operation at cold: open gap due to thermal shrinkage of HTS section, heat load minimized.
3. Quench: steel tube expands due to Joule heating, closing the gap thereby preventing further heating.

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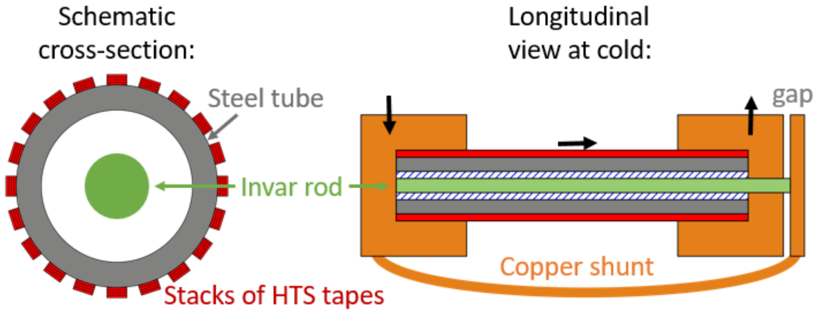

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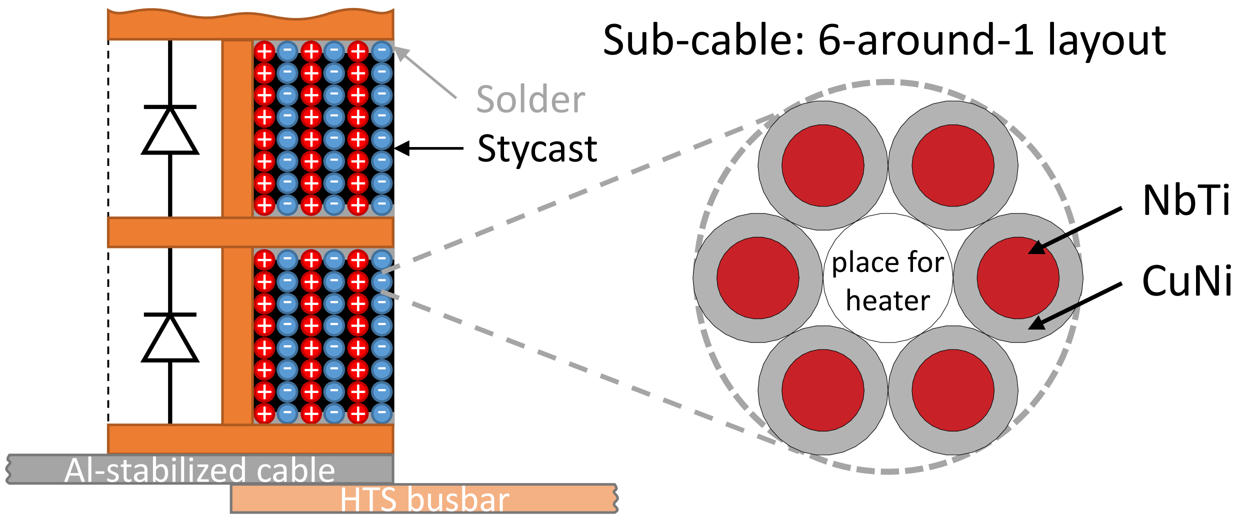
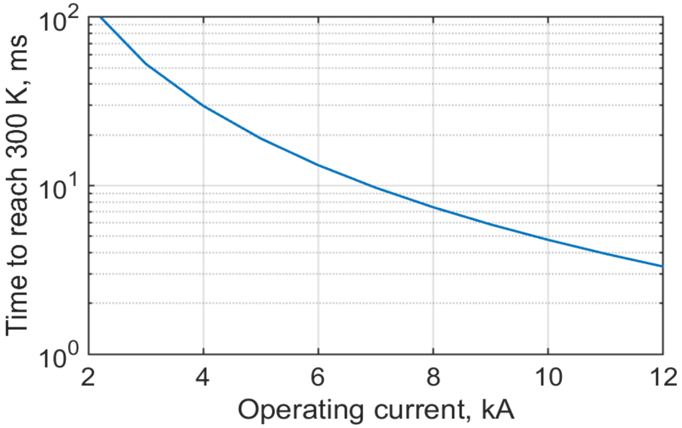
Sketch of 2 sections:



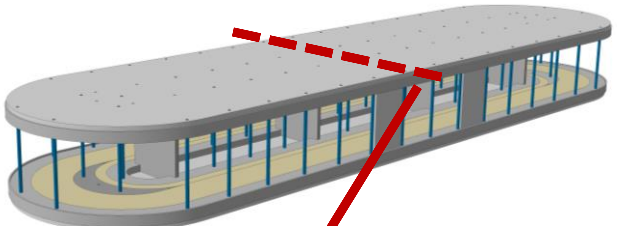
Total number of wires	36
Single wire length	180 m
Total wire length	6.6 km
Tcs @10 kA, 1.5 T	6.6 K
PMS Resistance	4.5 Ω
Power loss @3 A/s	2 W

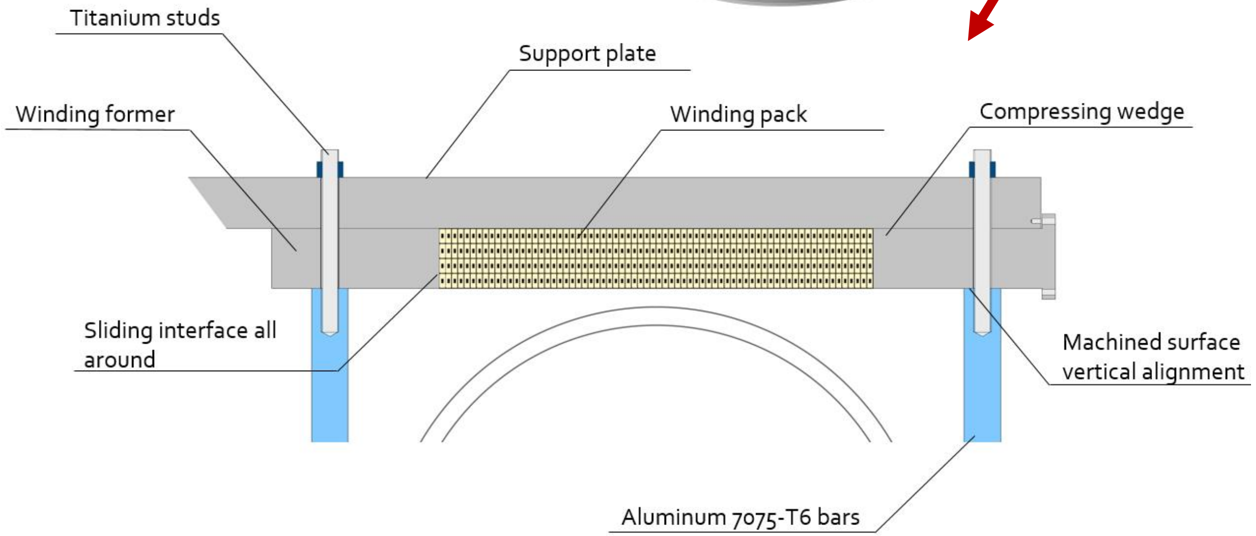


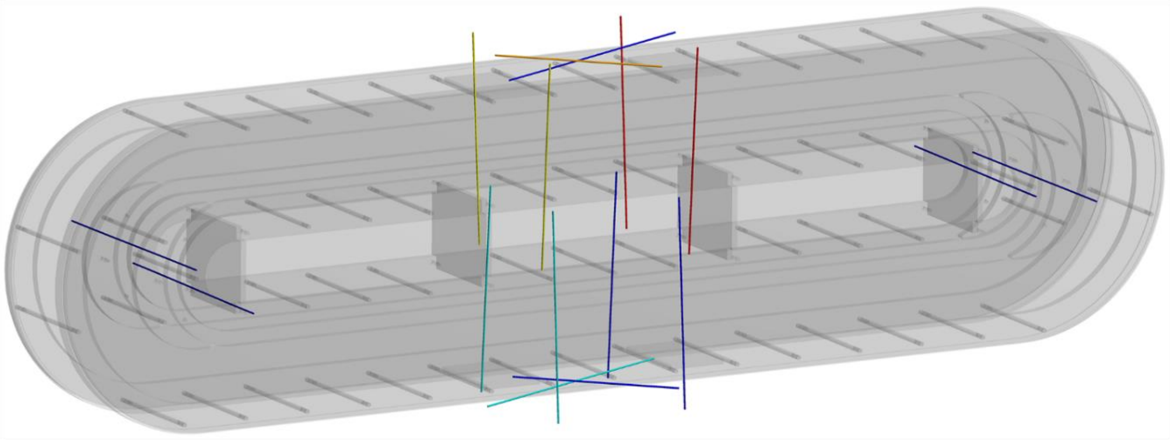
- Sub-cables split in sections, each shunted by a diode.
- The normal zone of 6 mm is sufficient to open the diode with 1.5 V forward voltage drop.

4 Cold mass – mechanical structure and integration

H.F.P. Silva et al
Wed-Af-Po3.17-03







- Coil layout and manufacturing process is a mimic of the full IAXO coils.
- Casing made of Al6061-T651, light while resisting a repelling load of up to 30 MN.
- Top plate is used as coil winding table as well, so simple tooling.
- Simple plate like assembly and few mm tolerance.
- Dowel pins and extra bolts used for alignment and manufacturing, before installing supporting rods.

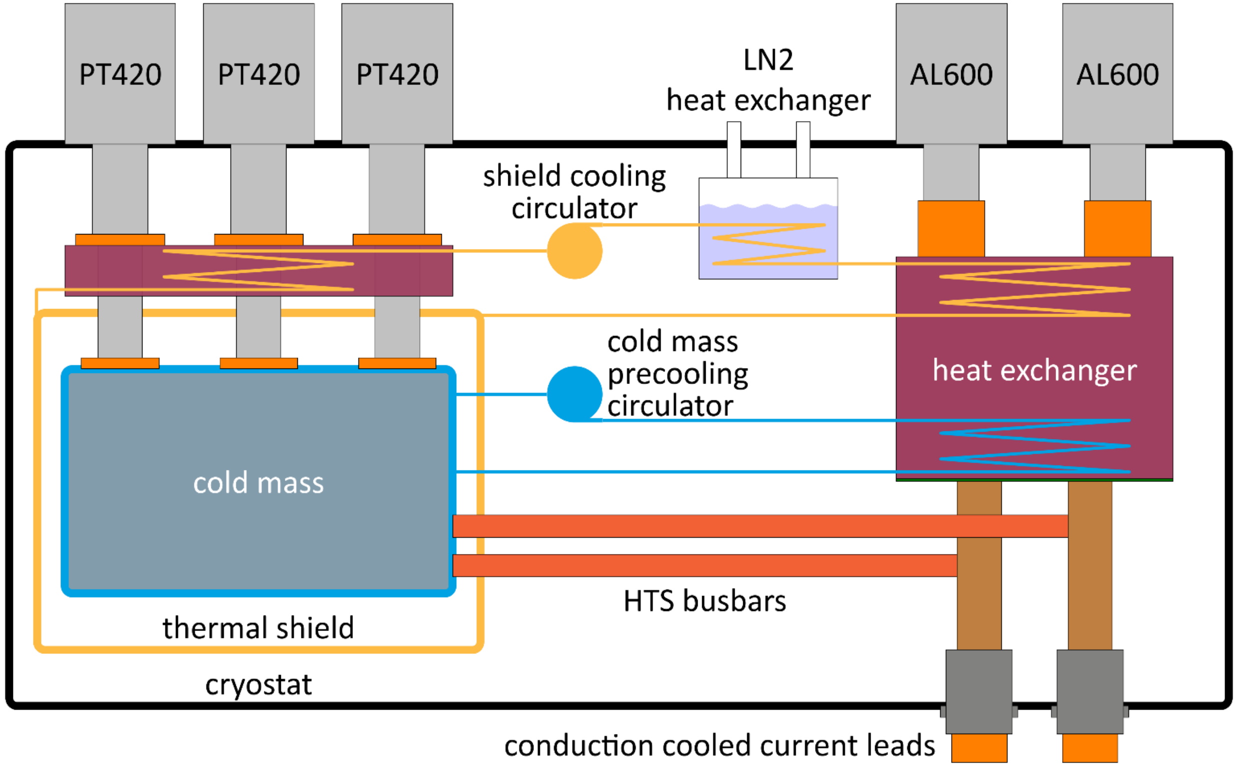
Location of rods	Material	Diameter	Function
Top vertical x 4	Ti alloy	12 mm	Gravity support
Bottom vert. x 4	Permaglas	24 mm	Vert. centering
Longitudinal x 8	Permaglas	26 mm	Inclin. support
Side transverse x 4	Ti alloy	≈10 mm	Transport

* Length of rods ≈ 2 m

4 Cryogenics – heat loads and cooling layout

Source	Heat load, W @thermal shield	 @cold mass
Radiation	160	2.2
Support structure	2.1	0.2
Current leads	260* / 800**	1.0
Total Net	**420* / 960****	**3.4**

* persistent mode operation. ** direct drive mode.

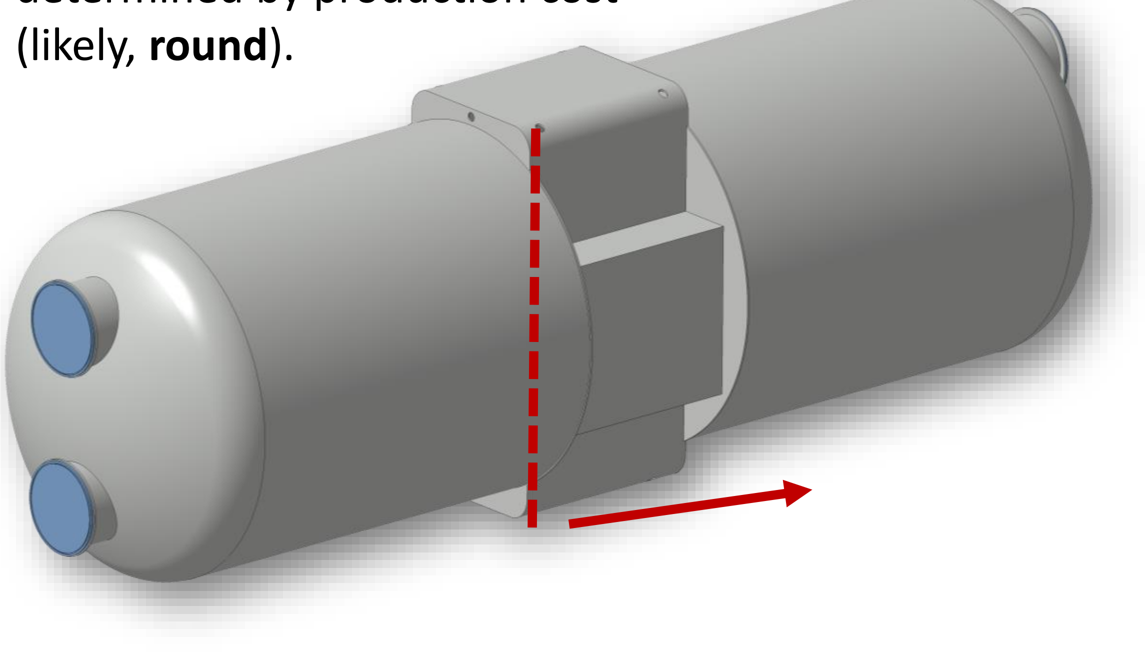


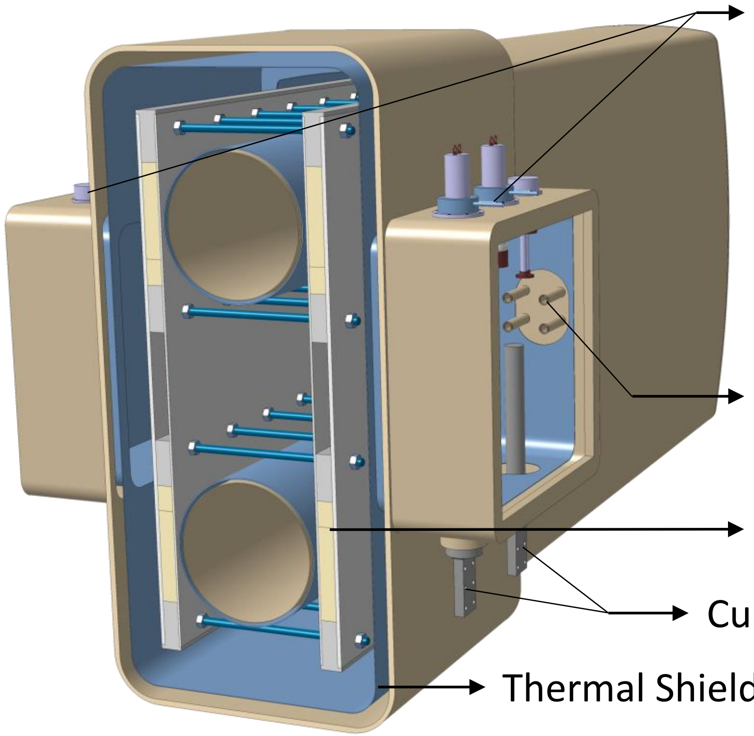
- 2 cryocoolers AL600 for shield and current leads at 45 K, deliver power for cooling down.
- 3 cryocoolers PT420 maintain cold mass at 4 K and help to cool down the cold mass.
- 2 He gas circulators transport the cooling power from source to cold mass and shield.
- A LN_2 heat exchanger, normally off, can support the AL600, for faster cool down or backing-up.

1. Cooling down from 300 to 45 K running all cryocoolers and circulators.
2. When at 45 K, 2nd circulator is isolated (gas pumped out).
3. Continued cooling down from 45 to 4 K and nominal operation with all cryocoolers on.
4. Cool down takes 17-20 days depending on choices of cold mass material.

4 Cryostat – cross section and service ports

* shape of cryostat **end-caps** will be determined by production cost (likely, **round**).





5 Cryocoolers:
- 3 x PT420 (6-8 W@4.5K)
- 2 x Al600 (700W@50K)

2 Helium Gas Circulators:
1. 300 - 45 K precooling
2. 300 - 45 K precooling + steady state shield cooling

Cryogenics and instrumentation interface

Cold Mass at 4.5 K

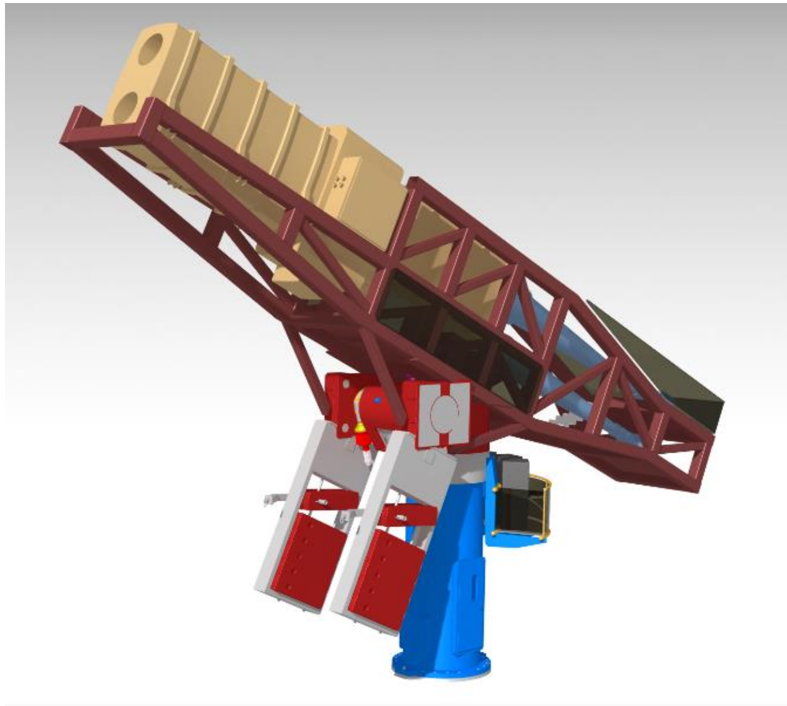
Current Leads

Thermal Shield at ≈ 40 K

- **Cryostat** made of SS304 is preferred since weight is not an issue for the tower and drive system.
- **Central post** provides main support of the cold mass using cold-to-warm tie rods.
- **Bore tubes** are made of 1 mm thick SS-304L, 0.4 t mass and equipped with heaters to prevent condensation and ice formation.
- The overall mass of the BabyIAXO magnet **≈25 t.**

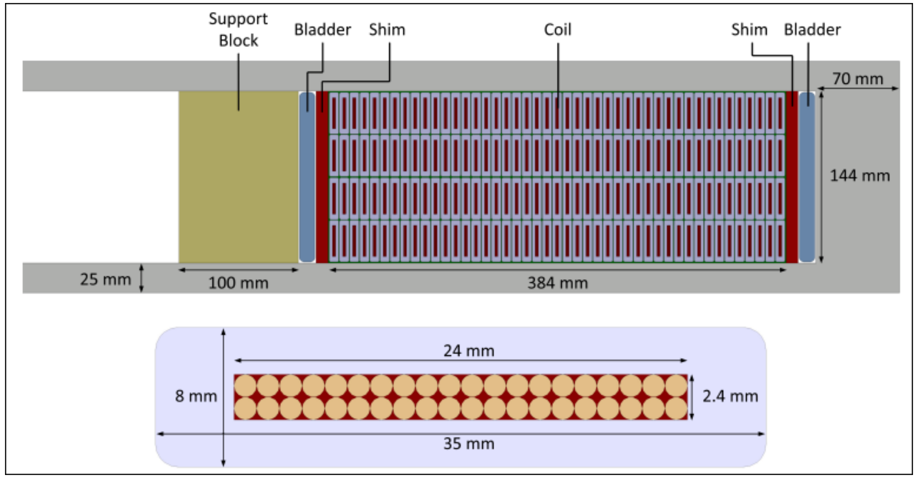
5 Conclusion

- IAXO Conceptual Magnet Design completed in 2014 satisfying requested axion sensitivity (300xCAST). As demonstration of the feasibility and readiness of the required technologies:
  - The fully functional sub-scale experiment BabyIAXO born early 2017, predesigned ever since.
  - Design relying on known manufacturing techniques featuring minimum risk and cost.
  - Conceptual design completed, practical low-cost manufacturing is now under study.
- A dry magnet of 10xCAST performance with minimum services is proposed, perfect for the anticipated installation site.
- Al-stabilized conductor is usually on critical path, here as well, design adjusted to add on to ongoing production qualification.
- The magnet operation, either direct drive or in persistent mode, to be decided following a feasibility study of the 12 kA switch.
- Construction kick-off is awaited once minimum funding for hardware is secured (≈ 3.5 M€), foreseen for early 2020.
- Anticipated installation at DESY, starting physics in 2025.

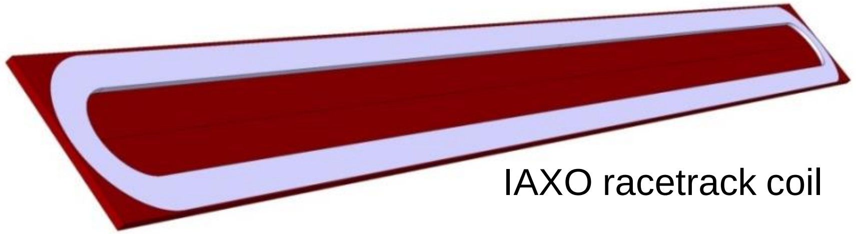


A1 IAXO Magnet – Conductor and Cold mass

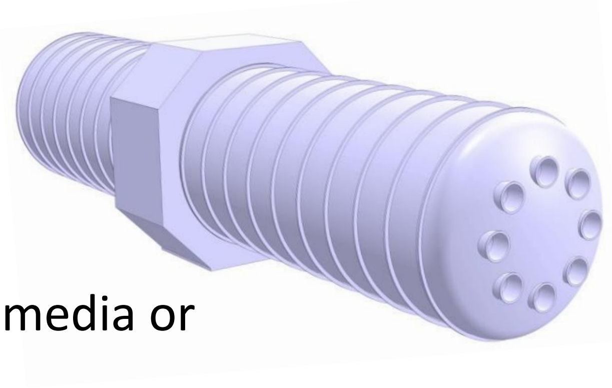
- Using “work horse” NbTi/Cu, Critical current 58 kA @ 5.4 T.
- 40 strands Cable, 1.3 mm diameter strands, Cu/NbTi ratio 1.1.
- Al-0.1%wtNi stabilizer, size 35 mm x 8 mm.
- Peak magnetic field in windings 5.4T@12kA, 60% on the load line.
- 1.9 K temperature margin @ 5.4 T.
- Two racetrack double pancakes, 2 x 90 turns per coil.
- 8 coils of size 21 m x 1 m, glued in an Al5083 casing.
- Al alloy cooling pipes glued on the casings.
- Central support cylinder to react magnetic forces.
- Keystone boxes and plates supporting the warm bores.
- Rigid central part of Al 5083, 70 mm thick.
- Reinforced bottom plate, 150 mm thick.
- 2 x 20 mm thick Al5083 reinforced cylinders.
- 8 thin cylindrical bores, to allow insertion of gas or other media or detectors.

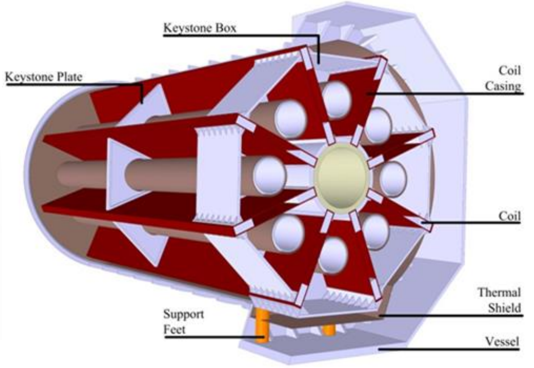


IAXO conductor and coil winding pack

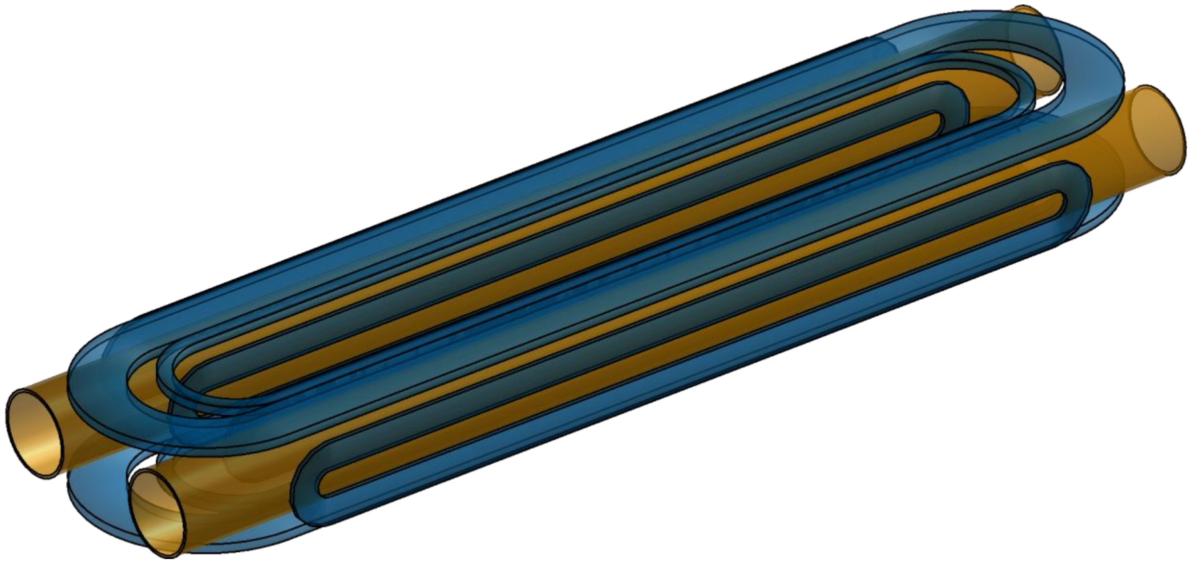


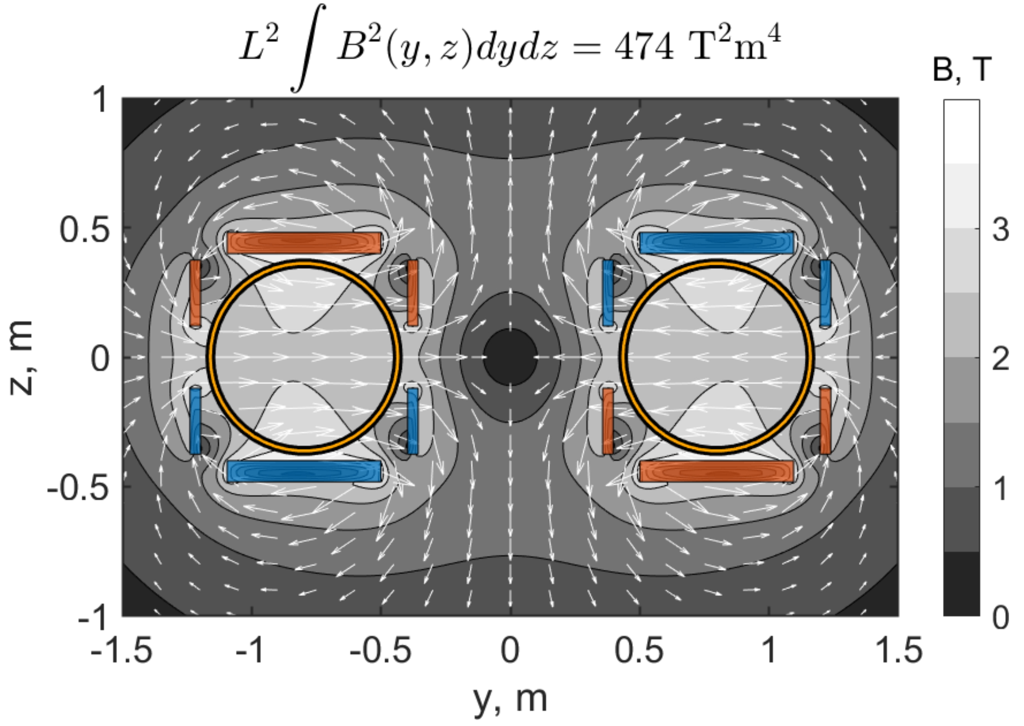
IAXO racetrack coil





A2 Boosting of MFOM by extra side coils

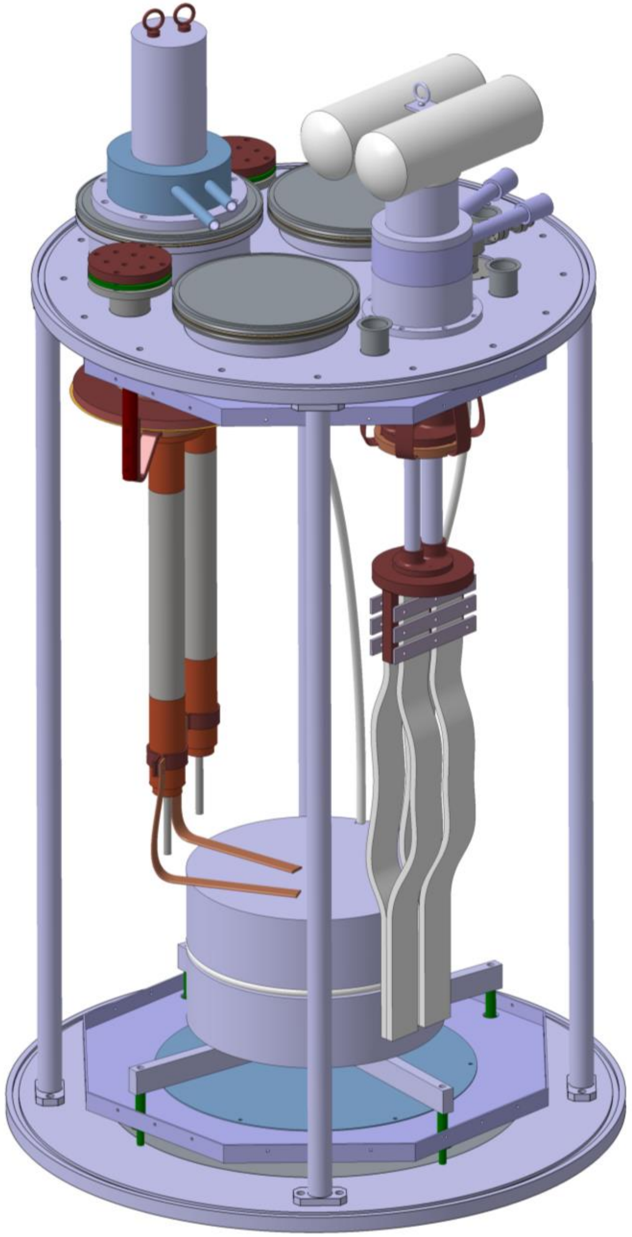




With little impact on structure, extra 4 racetrack coils can be added.

- More uniform field distribution, **MFOM increased by 40% to 474 T^2m^4**
- Partly mitigating the impact of optics blind spot on the MFOM
- Extra coils incorporated in side plates, replacing support rods (mechanics to be checked)
- 4 extra coils of 60 turns each, extra 4 km of conductor required, then 15 km conductor in total
- But of course has moderate impact on cost (some 700-900 k€)!

A3 Cryogenics – mini demonstrator



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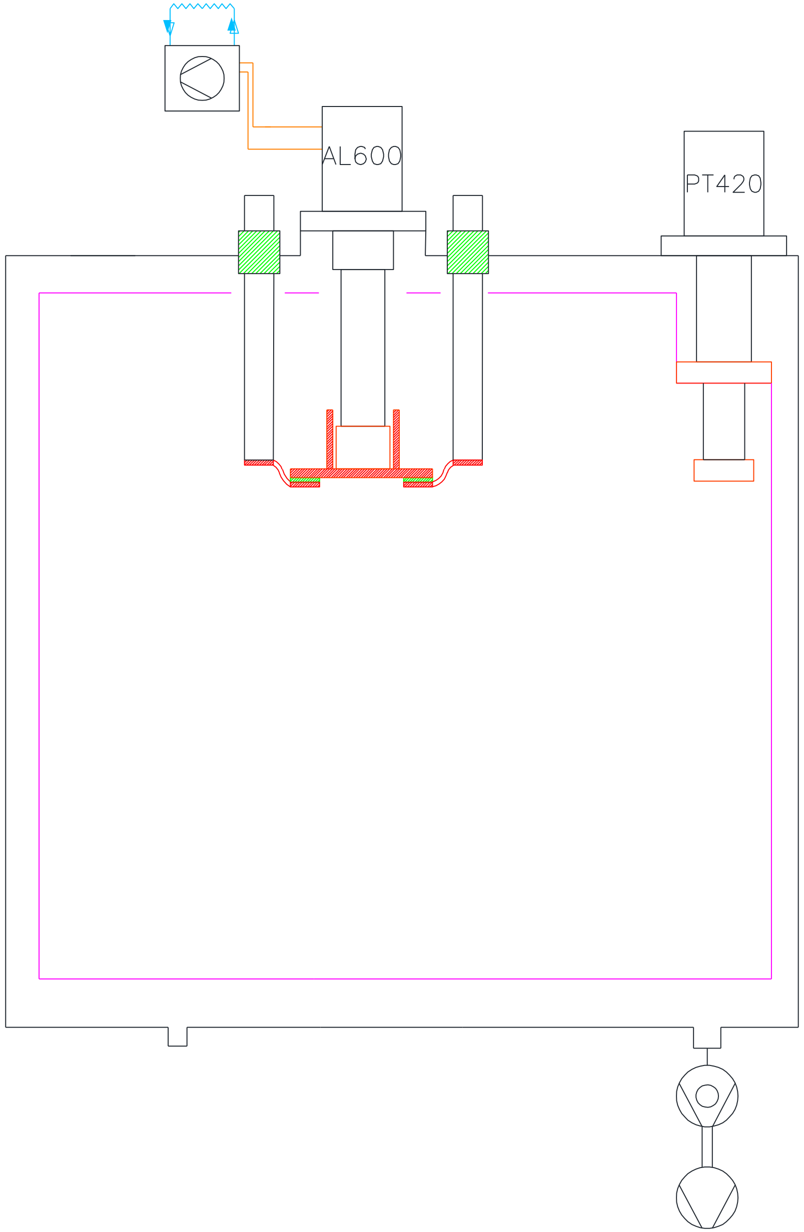
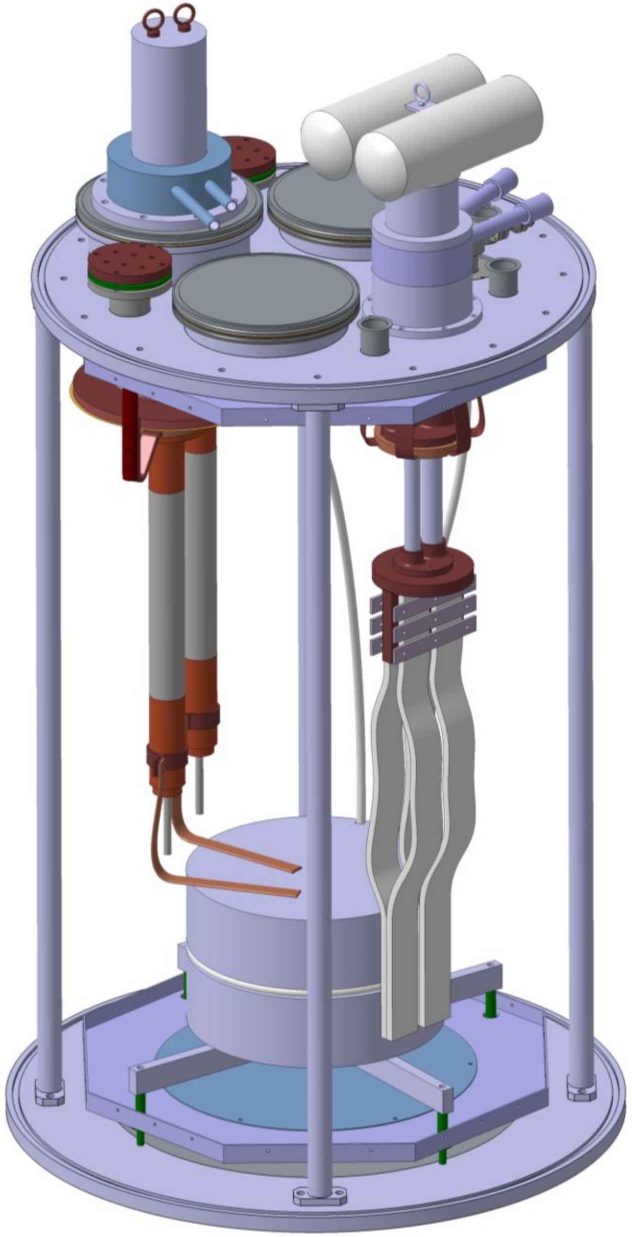


The proposed cooling concept to be tested in **a lab-scale demonstrator** in multiple stages of the experiment:

Stage 1:

- Heat loads from conduction cooled currents leads and to the shield
- Thermal interface to AL600
- Gradients along Al thermal links

A3 Cryogenics – mini demonstrator



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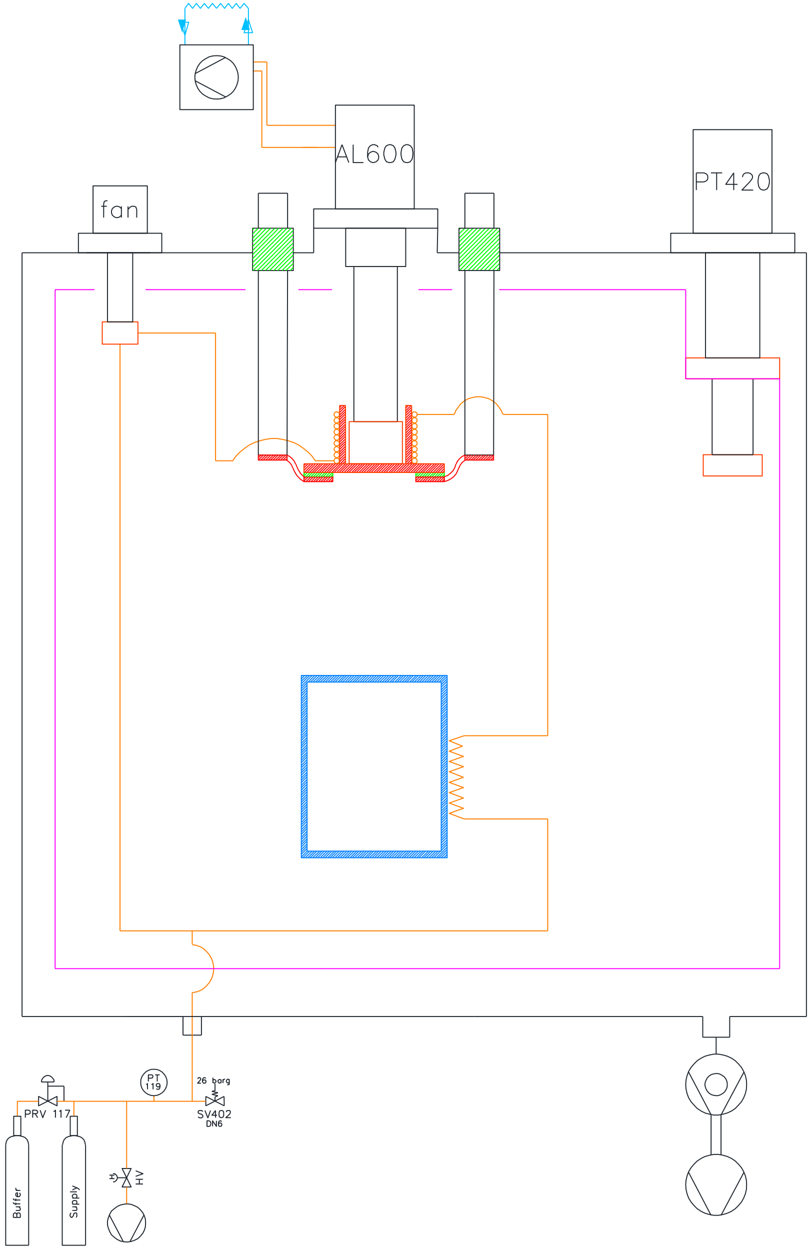

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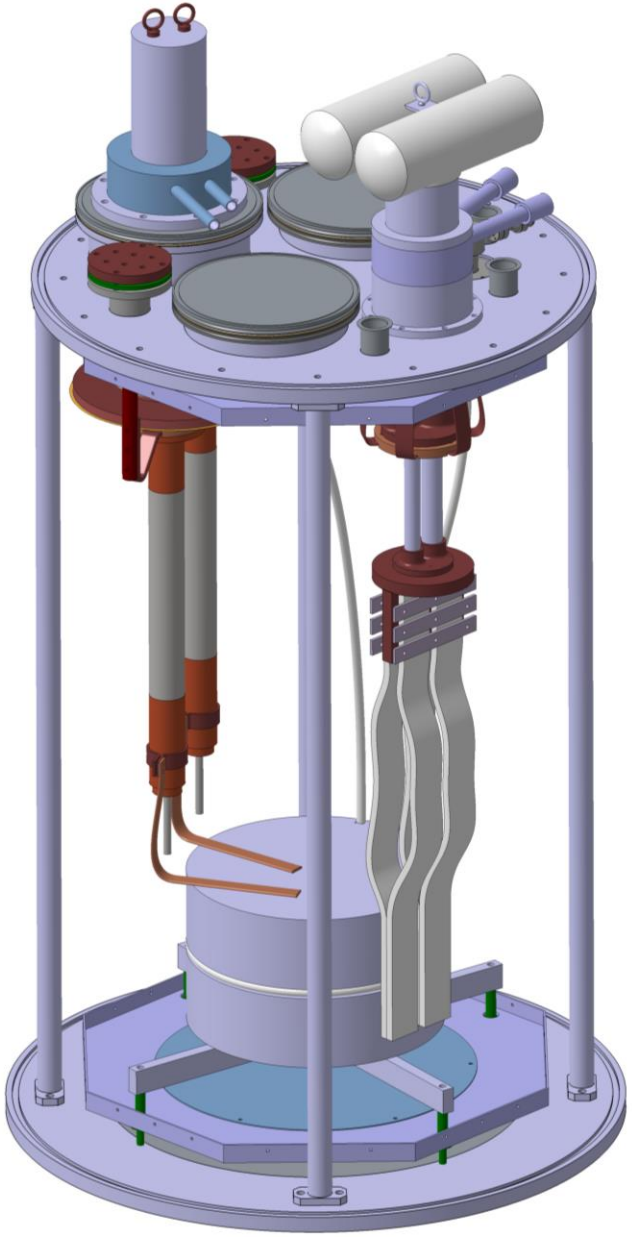
A3 Cryogenics – mini demonstrator



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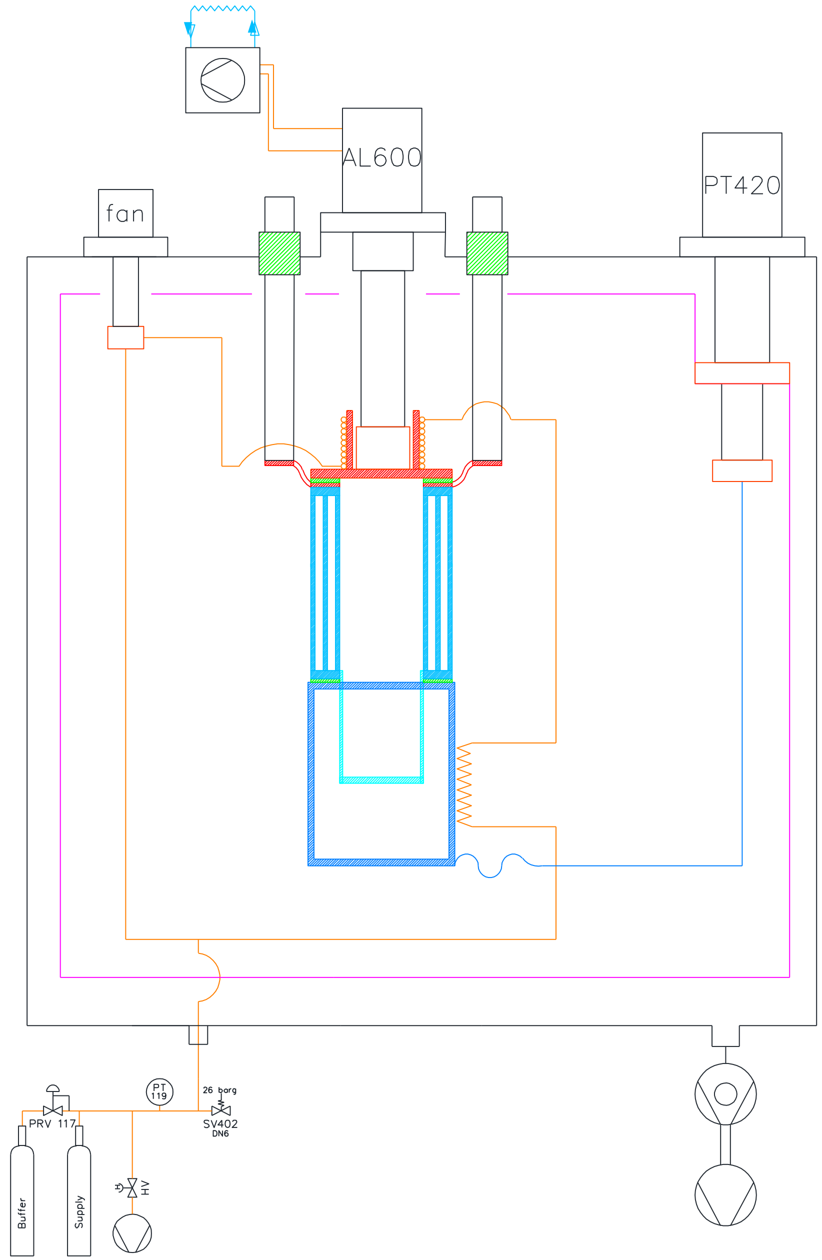

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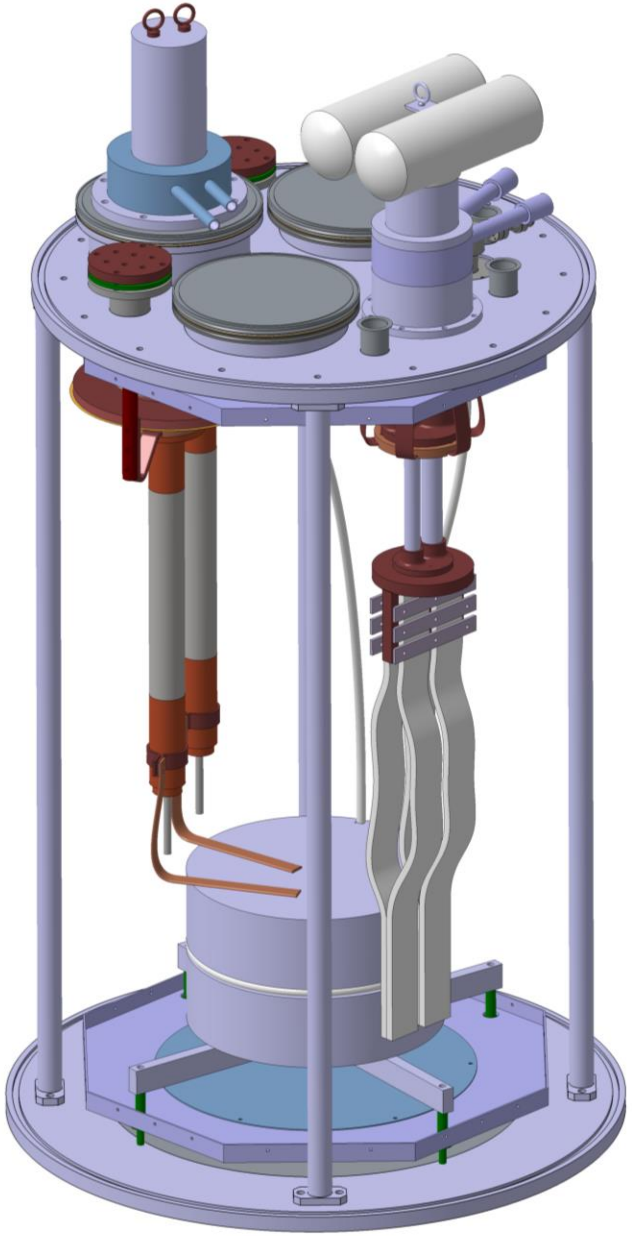
A3 Cryogenics – mini demonstrator



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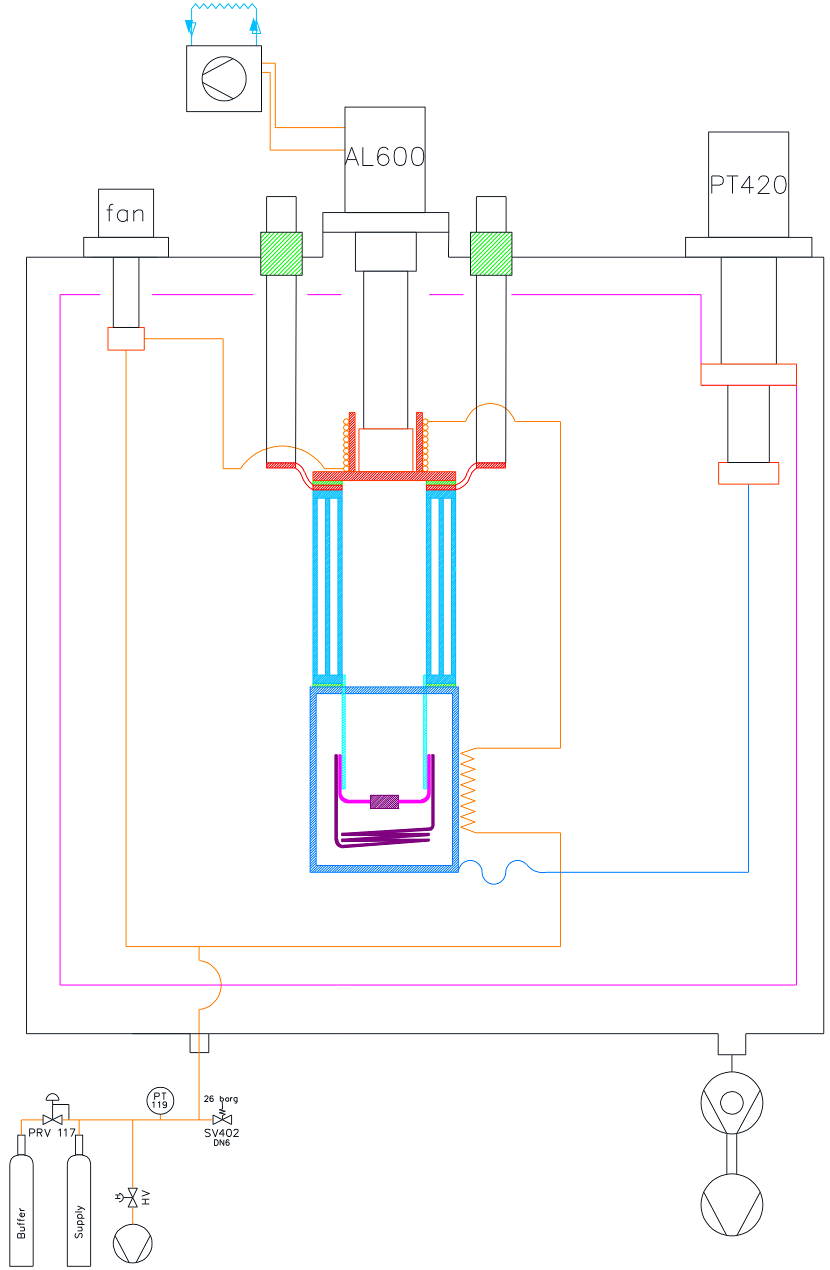

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Stage 4:

- Operation of the persistent mode switch