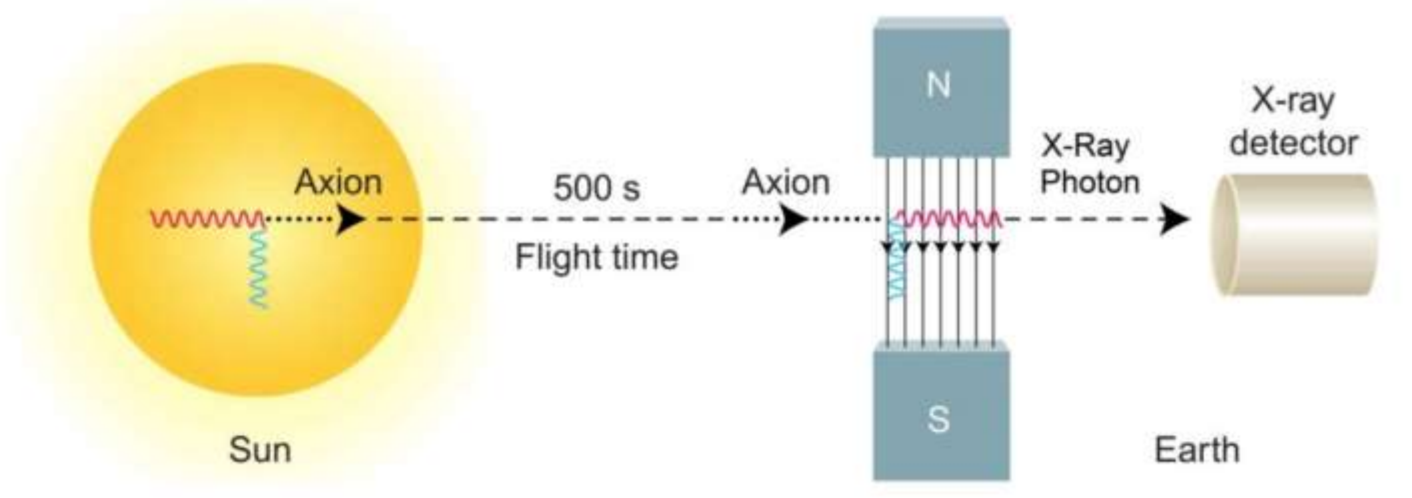
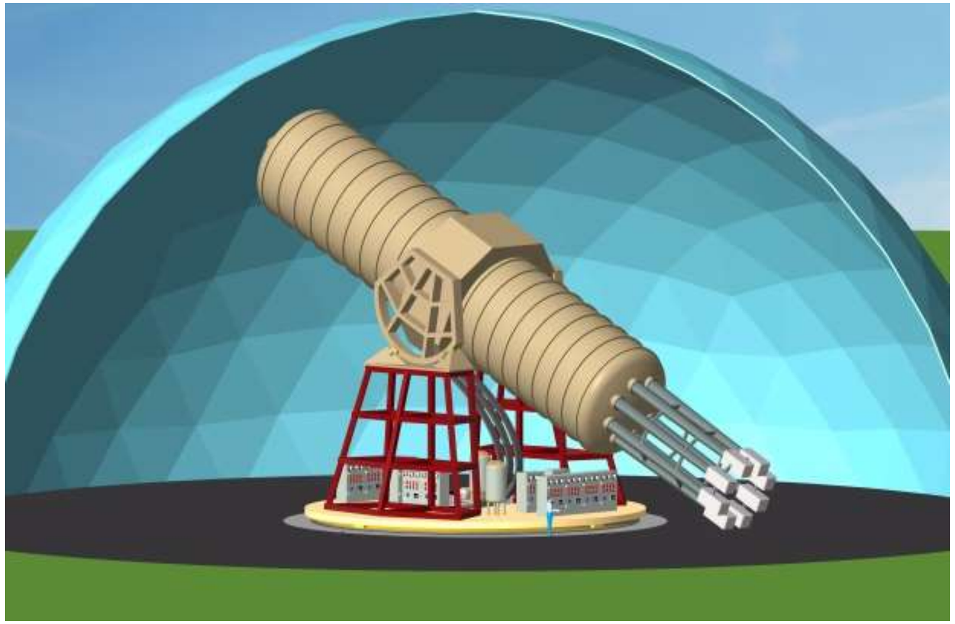
Thermal Analysis and Cryogenics of the Baby-IAXO detector magnet

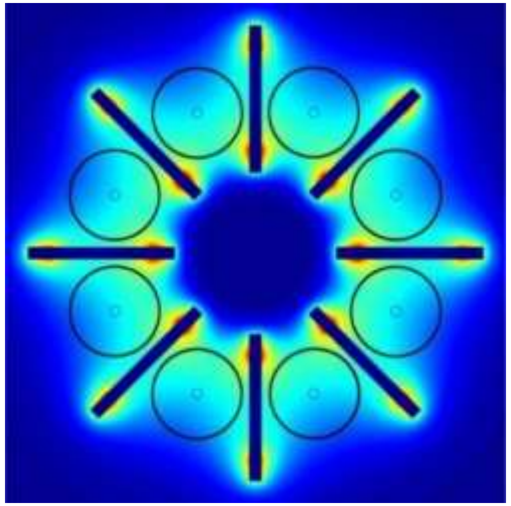
Helder F P Silva , Alexey Dudarev , Nikolay Bykovskiy, Patricia Sousa Borges & <u>Herman ten Kate</u>

Content:

1. IAXO – A new International AXion Observatory





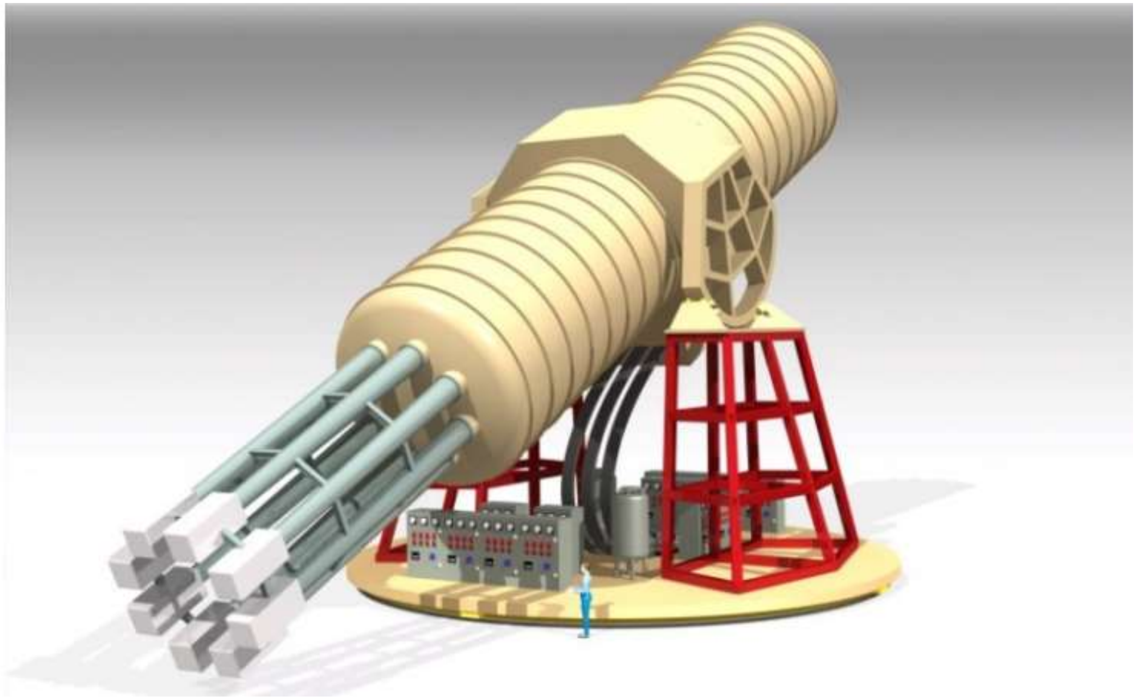


- Axions and axion like particles (ALP's) may be converted into X-ray photons in the presence of a transverse magnetic field.
- The sun is hypothesized to be a source of these particles.
- The Magnet Figure of Merit of an axion helioscope yields:

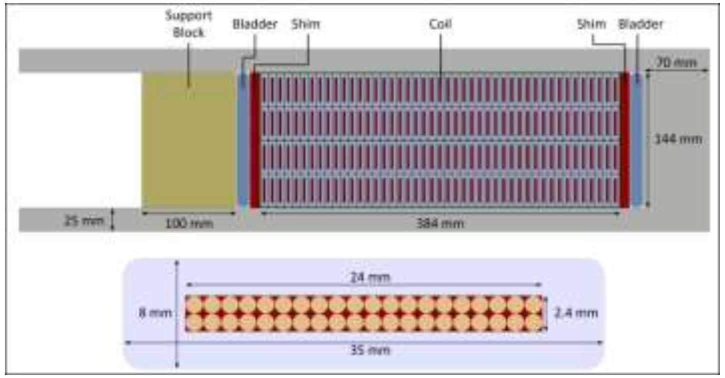
$$\boldsymbol{f_M \propto L^2 \int B^2(x,y)dx\,dy \;\rightarrow\; L^2B^2\mathrm{A}}$$

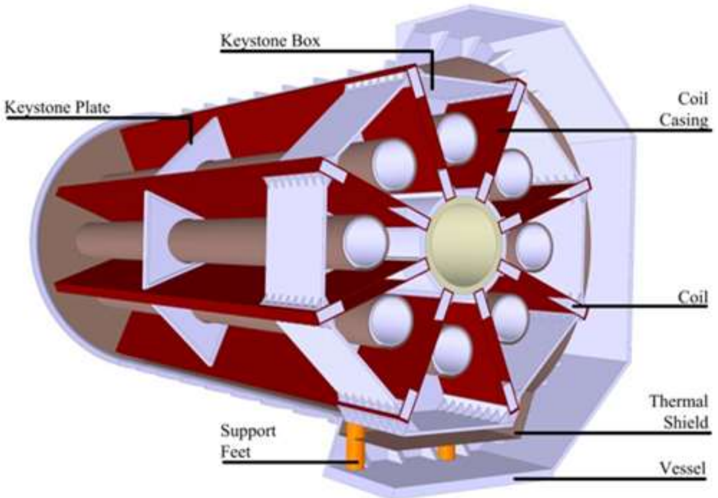
- Magnet design goal: maximize f_M while keeping cost down.

IAXO Full-size – Conceptual design



- Magnet Figure of Merit requested at least 300 times the present CAST magnet.
- Superconducting toroid with 8 racetrack coils, 2 double pancake coils per coil:
  - Well-know technique
  - Flat windings, easy tooling
  - Risk-minimizing design.
- 8 detector bores followed by optics and X-ray detector
- Characteristics:
  - 20-m long magnet
  - 8 detector bore tubes Ø 600 mm
  - Average magnetic field 2.5 T
- Cost: some 60 M€
- Conceptual design has been finalized.





2. Baby-IAXO – A down-scaled IAXO demonstrator

- A stepping stone towards the IAXO experiment.
- A fully functional demonstrator and development system, 2 bores, (only) 10 m long.
- Experiment requirements:

  Sun tracking capabilities:

  360° rotation

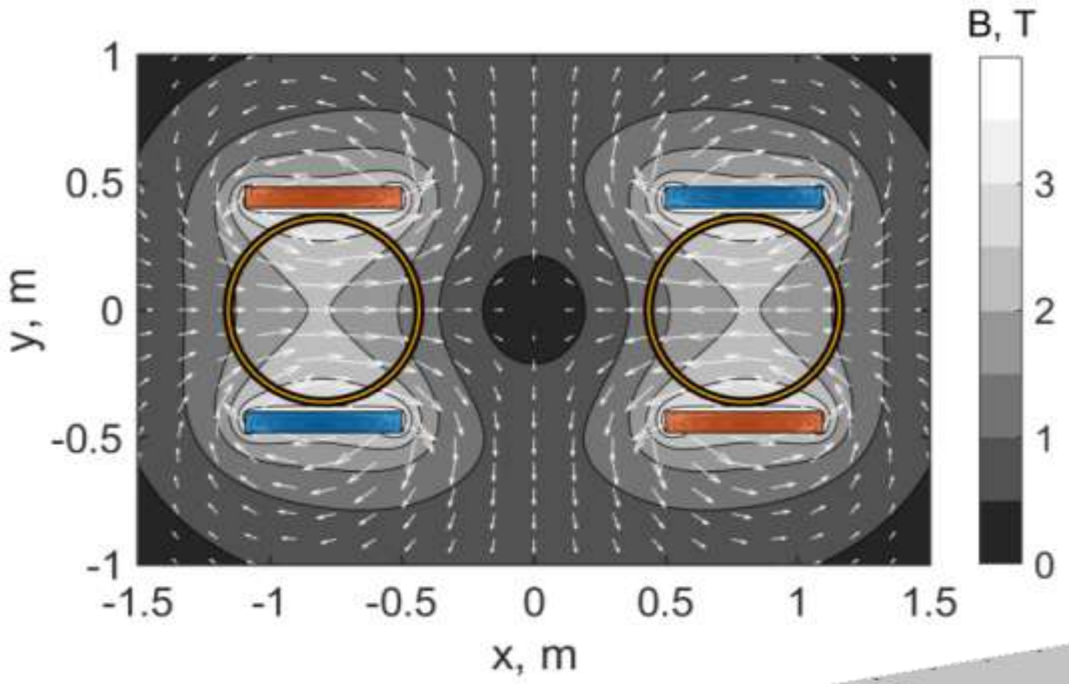
  ± 25° inclination.
- Anticipated site is South Hall at DESY, no cryogenics infrastructure, decided for a <u>dry cooling of magnet using cryocoolers.</u>
- Figure of merit set to 10 times the CAST magnet.
- Simple and robust design compliant with:

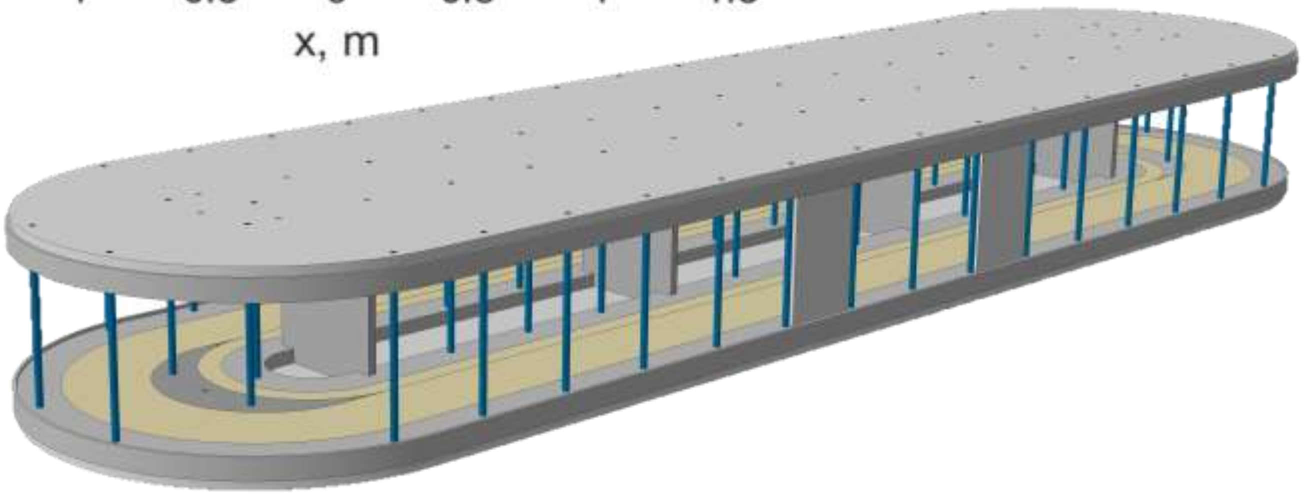
  - Construction timescale of 3 to 4 years

  - Low budget < 10 M for entire system.

Baby-IAXO – Detector magnet parameters

Racetrack coil width [mm]	595
Racetrack coil height [mm]	82
Coil length [m]	10
Gap between poles [mm]	1000
Gap between coils [mm]	800
Magnet stored energy [MJ]	50
Self-inductance [H]	1.0
Peak magnetic field [T]	3.2
Windings current density [A/mm²]	56
Nominal operating current [kA]	9.8
MFOM 3D [T^2m^4]	232

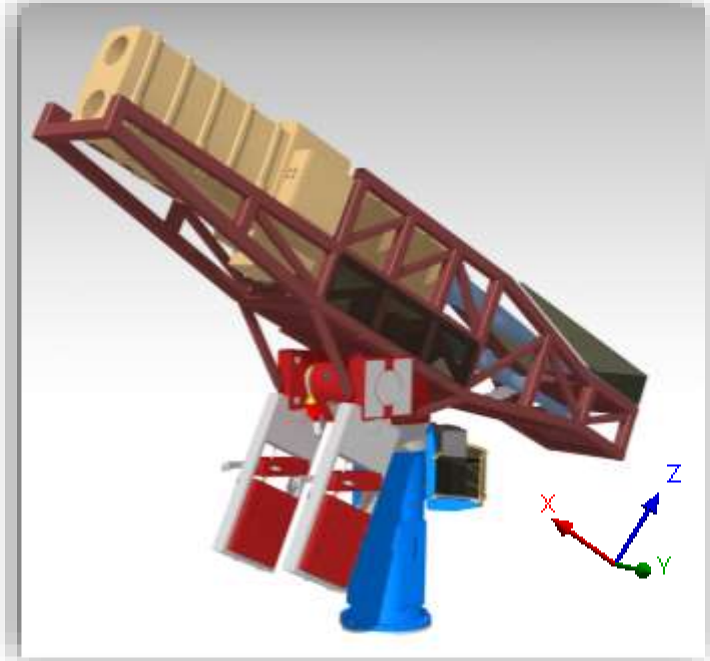




Design shows two racetrack coils in quadrupole layout, allowing for 2 free bore tubes of Ø 700 mm.

3. Baby-IAXO Cold mass suspension system – Forces

- Minimize conduction through the supports
  - Use slender supports in tension (rods)
  - Find material with the best strength to thermal conductivity ratio
- During transport cold mass locked vertically and transversely.
- Loads to be supported:
  - Weight of the cold mass
  - Magnetic force pulling cold mass towards the supporting system
  - Acceleration of lifting and transport.



	Fx [kN]	Fy [kN]	Fz [kN]	My |kN.m]
Tilted -25° [2]	-18.6	0	-239	71.6
Horizontal [2]	-5.5	0	-249	87.7
Tilted 25° [2]	-11.7	0	-271	160
Transport[1]	±170	0[1]	-210[1]	0

[1] Locked during transport
[2] When operated at 12kA

Baby-IAXO Cold mass supports - Comparison of materials

What is the best material for the rods?

$\frac{\sigma_a}{q} \longrightarrow$ higher values mean lower heat load for the same material strength

$\frac{E}{q} \longrightarrow$ higher values mean lower heat load for the same material stiffness

$$q = \int_{4.5K}^{50K} \lambda(T) \cdot dT$$

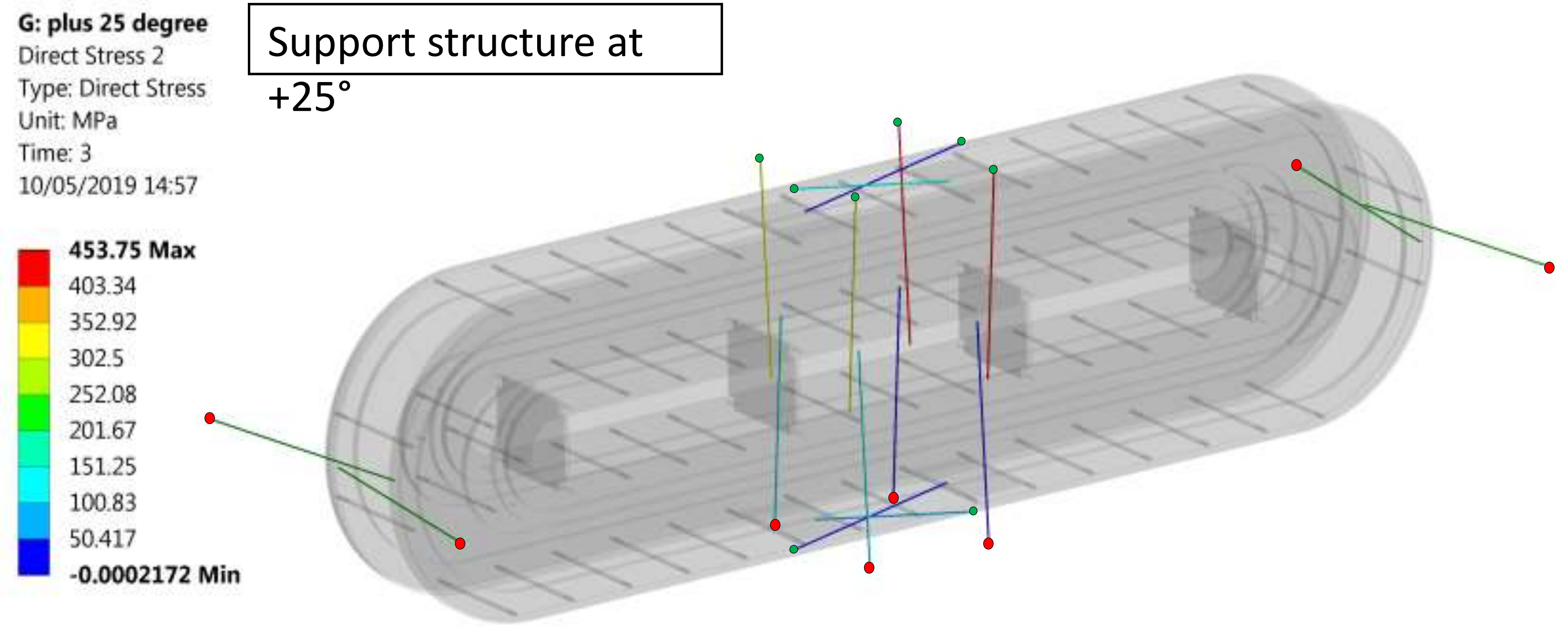
Material	Young modulus (E) [GPa]	Thermal contraction [%] [1]	Allowable stress (σ_a) [MPa] [4]	q $[W/m]$	$\frac{\sigma_a}{q}$ $\left[\frac{MPa \cdot m}{W}\right]$	$\frac{E}{q}$ $\left[\frac{MPa \cdot m}{W}\right]$
Inconel	200	0.19	710	154	4.5	1.3
Ti6Al4V	114	0.14	465	58	**8.0**	**2.0**
Permaglas	20	0.15	100	8.0	13	2.5
GFRP uniaxial	34	0.07	135 [3]	8.0	17	4.3
CFRP uniaxial	134	0.03	550 [3]	7.2 [2]	75 [2]	1.8

[1] Thermalized at 50K at 40% of length
[2] 4 times higher than permaglass between 300K - 50K
[3] Weak point is the bonding between the fibers and the metal interface
[4] Safety factor of 3 for the composite materials

The initial calculation where done using Ti6Al4V given the complexity / limitations of using composite materials.

Baby-IAXO Cold mass supports – System of rods

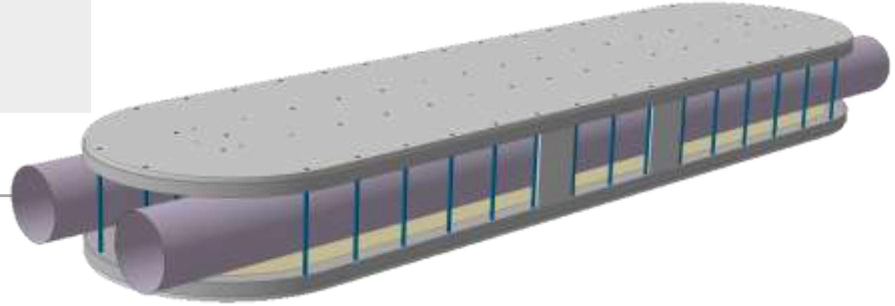
- Self centering support structure
- Rods used only in tension
- No pre-stressing of rods during installation
- Pre-stress occurs during cool down
- Rods marked in red are limited by displacement $(max\ {}^{E}/_{q})$
- Rods marked in green are limited by their strength $(max\ {}^{\sigma_a}/_{q})$
- Given the low heat load, there is no need to use composite materials



Condition	Material	Length [m]	Diameter [mm]	Number of rods	Heat load @50K [W]	Heat load @4.5K [mW]
Vertical rods	Ti6Al4V	1.8	16	8	1.9	90
Longitudinal	Ti6Al4V	1.6	16	4	1.1	50
Transverse	Ti6Al4V	2.0	16	4	1.3	40
Total					4.3	180

4. Baby-IAXO Cryogenic heat load – Radiation

	MLI layers	q_{MLI} [mW/m²]	$Area$ [m²]	Q_{MLI} [W]	Q_{limit} [W] (<u>20% margin</u>)
Thermal shield @50K	30	1200	~135	**<u>165</u>**	**<u>200</u>**
Cold mass @4.5K	1	25 - 50	~130	**<u>4.9</u>**	**<u>5.9</u>**



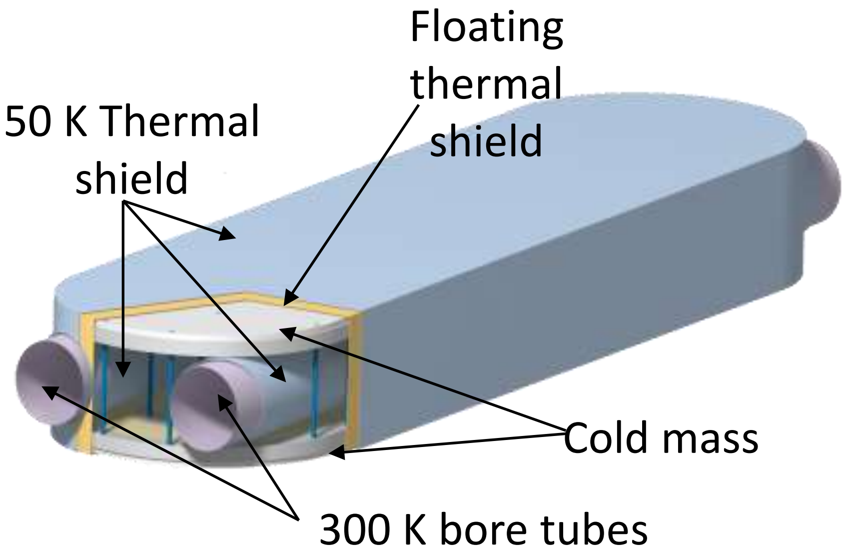
Thermal shield made mostly of large flat surfaces

- Easier installation of MLI
- No limitation in packing factor, except between bore tubes and cold mass
- Floating thermal shield around cold mass (not on bore tubes)
  - 25% heat load reduction

Direct line of sight between bores and outer shield

- View factor < 1

Cooled using Cryocoolers paired with a He gas circulator

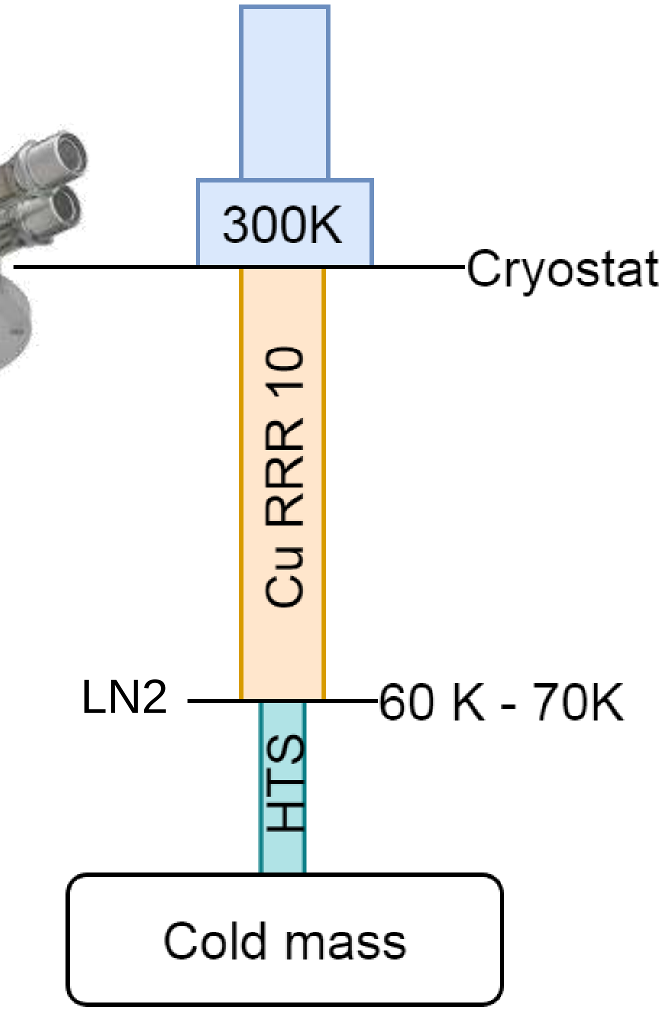


5. Baby-IAXO Heat load – 10 kA HTS Current Leads

- Heat load for two Cu, RRR10, conduction cooled current leads at 60 K:

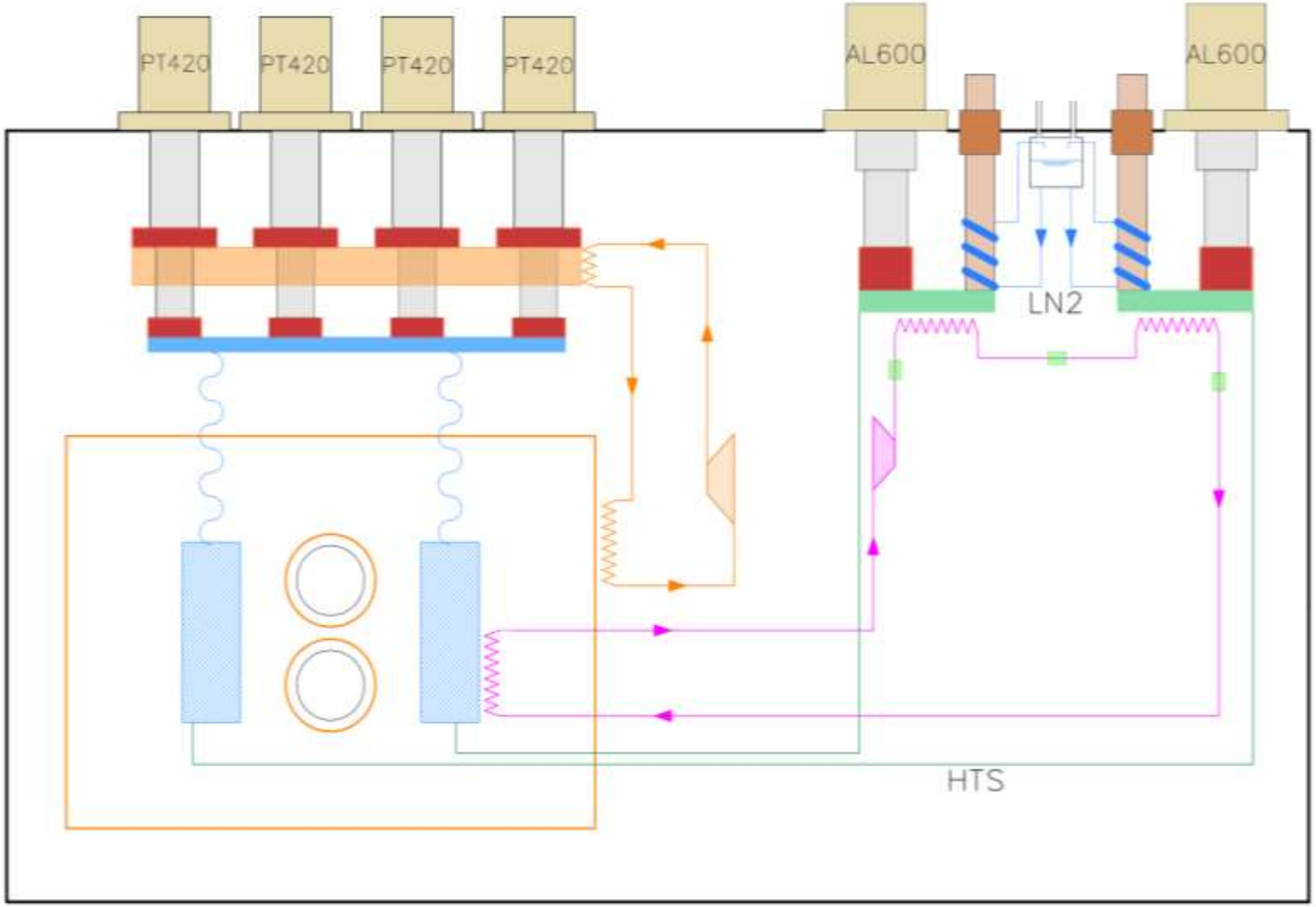
$$Q = 2 \cdot I \cdot \sqrt{2 \int_{60K}^{300K} \lambda(T) \cdot \rho(T) \cdot dT} = 840\ W$$

- For simplicity and lower thermal shield temperature:
  - Decoupled copper current lead and thermal shield
  - 2 Al 600 cryocoolers
  - Total cooling power @70 K is 1kW
  - 20% margin for covering losses
- When in overcurrent (12kA), liquid nitrogen will be used in combination with the cryocoolers to keep the temperature below 78 K.
- Expected heat load from HTS part < 1 W



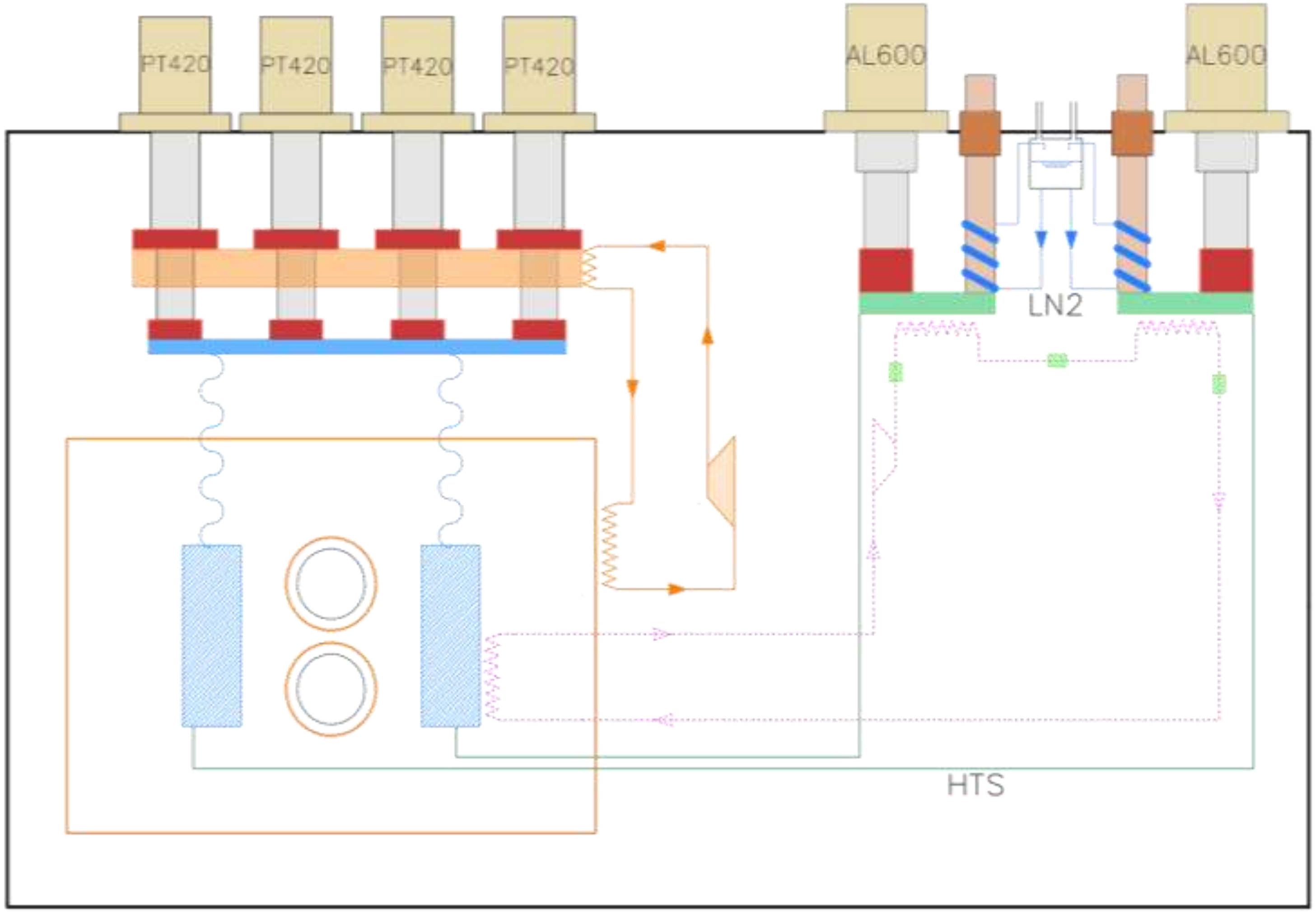
6. Baby-IAXO Cryogenic Concept – Cool Down

- Two independent He gas circulators:
  - Thermal shield and supports' intercepts cooled by 4 PT420 1st stage
  - Cold mass cooled down to 50 K by 2 AL600 cryocoolers
  - Decoupling of cold mass and AL600 cryocoolers by purging of the He gas circuit
- LN2 heat exchanger coupled to the AL600 cryocoolers adds the possibility of speeding up the cold down

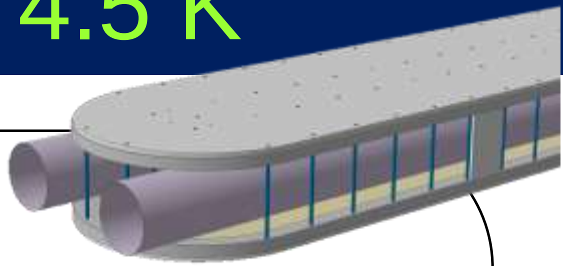


Baby-IAXO Cryogenic concept – Stationary operation

- Helium gas circuit coupled to AL600 cryocoolers purged.
- Current leads directly coupled to Al600 cryocoolers:
  - Lowest loss of cooling power
  - Cryocoolers electrically floating
  - Flexible interface on the cryostat
- Back-up LN2 heat exchanger for >10 kA operation.
- Cold mass cooled by 2nd stage of the PT420 cryocoolers:
  - Cool down from 50 K
  - Cold mass has high thermal conductivity
  - No need for a gas cooling circuit.



Baby-IAXO Cryogenic heat load – At 50 and 4.5 K



	Heat load @50K [W]	Heat load @4.5K [W]
Radiation	165	4.9
Supports	4.3	0.18
Current leads	840 (2)	1
Joints	-	1
Cryofan	35	
Total	1000	7.1
+20% margin	1200	8.5

4 Cryomech PT420 1st stage:

- All heat loads except current leads
- Cooling down of thermal shield

2 Cryomech AL600:

- Intercept current leads @ 60 – 70 K
- Cool down of cold mass down to 50 K

4 Cryomech PT420 2nd stage:

- All heat loads at 4.2K
- Cool down of cold mass down from 50 K.

(1) Temperature 45K
(2) Temperature 70K

	PT420	AL600	Total
Number of cryocoolers	4	2	6
Cooling power 1st stage[W]	55 (1)	500 (2)	1275
Cooling power @4.5K [W]	2.5	-	10

7. Baby-IAXO Conclusion

- New and original magnet system for solar axions search.
- A fully functional technology development system.
- Dry cooling system for 10 kA operation

  2 GM single stage + 4 double stage PT cryocoolers.
- Cool-down of 20 t cold mass using cryocoolers in 20 days.
- 1st stage of current leads independently cooled.
- Conduction cooled cold mass.
- He gas circulators (cryofan) circuits for cool down of cold mass and keeping thermal shield $\Delta T < 5$ K.
- Back-up LN2 heat exchanger for I>10 kA and faster cool down.
- **Project construction approval expected late 2019 for start of construction in 2020**.