Advances in the Principal Design of The Superconducting Toroid for the new International AXion Observatory (IAXO)

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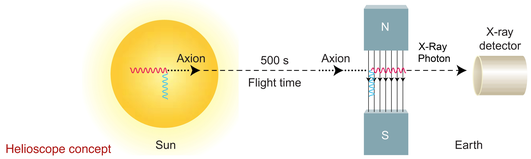
A new axions helioscope detector, utilizing a large superconducting toroidal magnet to increase the sensitivity to axion-photon coupling by 1 order of magnitude, with respect to the current state-of-the-art

Axions are hypothetical particles that presumably solve the strong CP problem in the standard model of physics

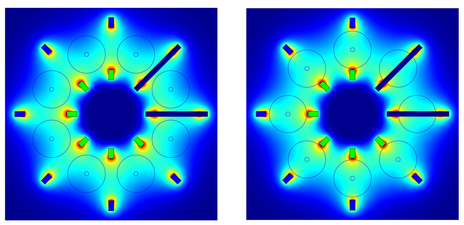
- Axions are amongst the most promising dark matter candidates in modern cosmology
- "Invisible" particles, but convert to and from photons in the presence of a strong magnetic field



Helioscope concept

Figure of merit and Lay-out optimization

- Magnet's Figure of Merit (MFOM) $f_M = L^2 \int B^2(x,y)dxdy \rightarrow L^2B^2A$
- Integration performed solely across the open area covered by the X-ray optics
- Two possible angular alignments for the telescopes: "area dominated" or "field dominated"

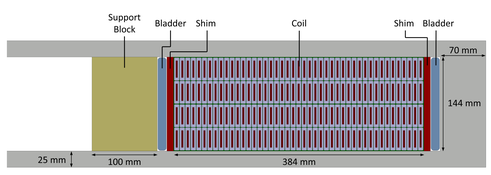


- Lay-out optimization favors the "area dominated" alignment

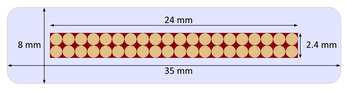
Conductor

- Based on a large Rutherford type NbTi cable embedded in Al-0.1wt%Ni substrate
- 40 strands of 1.3 mm diameter and Cu/SC ratio of 1.1
- Peak magnetic field in the windings is 5.4 T for 12 kA
- Net force on each racetrack coil is 18.8 MN, directed radially inwards
- At 4.5 K, the temperature margin is 2 K
- Two double pancakes windings with 180 turns
- Operational margin I_{op}/I_c at 4.5 K of 30%

Coil winding



Conductor cross-section



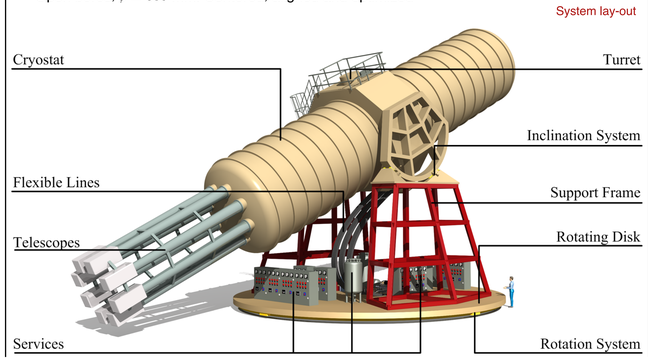
Main design parameters of the IAXO superconducting toroidal magnet

Property		*Value*	*Unit*
Cryostat dimensions:	Overall length	23.9	m
	Outer diameter (including central part)	6	m
	Cryostat volume	~ 530	m^3
Toroid size:	Inner radius, R_{in}	1.05	m
	Outer radius, R_{out}	2.05	m
	Inner axial length	21.0	m
	Outer axial length	21.8	m
Mass:	Conductor	65	tons
	Cold Mass	130	tons
	Cryostat	35	tons
	Total assembly	~ 250	tons
Coils:	Number of racetrack coils	8	-
Winding dimensions:	Winding pack width	384	mm
	Winding pack height	144	mm
	Length of inner turn	43.1	m
	Length of outer turn	45.5	m
	Turns/coil	180	-
Nominal Values:	Nominal current, I_{op}	12.0	kA
	Stored energy, E	660	MJ
	Inductance	9.2	H
	Peak magnetic field, B_p	5.4	T
	Average field in the bores	2.5	T
Conductor:	Conductor unit length per double-pancake	4.0	km
	Conductor length per coil	8.0	km
	Total conductor length (including reserve)	68	km
	Cross-sectional area	35×8	mm^2
	Number of strands	40	-
	Strand diameter	1.3	mm
	Critical current @ 5 T, I_c	58	kA
	Operating temperature, T_{op}	4.5	K
	Operational margin	40%	-
	Temperature margin @ 5.4 T	1.9	K
Heat Load:	at 4.5 K	$\sim$150	W
	at 60-80 K	$\sim$1.6	kW

Design concept

- Addresses all experimental requirements from the magnet
- Relies on known engineering solutions
- Feasible to manufacture using known techniques
- Magnet system and detector split
- Open bores, $\phi = 600$ mm. Centered, aligned and optimized

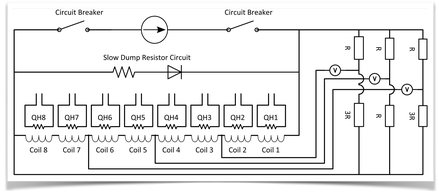
System lay-out



Electrical circuit and quench protection

- Adiabatic temperature rise due to a uniform quench spread is ~100 K
- Based on an active system and an internal dump of the stored energy

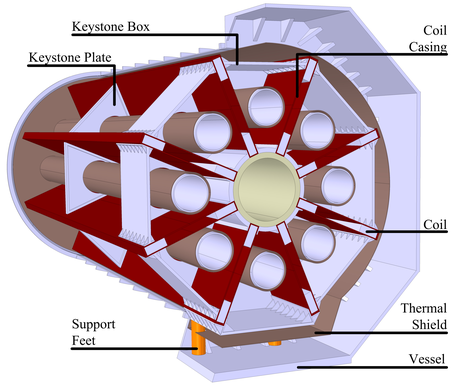
- Two dump modes
- High-T_c current leads
- Flexible superconducting cables
- Each coil is equipped with multiple quench heaters
- Quench detection relies on normal voltage growth across the magnet



Cold mass

- Weighs approximately 130 tons
- Operating temperature is 4.5 K
- Total length of 22 m with diameter of 5.1 m
- Two double pancakes, separated by a 1 mm layer of insulation

- Eight coils in star configuration supported by a central cylinder
- Additional structure elements to support magnetic and gravitational loads
- Coil windings embedded inside Al5083 casings attached to the support cylinder at their inner edge
- Coils impregnated for final bonding and pre-stressed within their casing



Cryostat and its Movement system

- Based on a rigid central part, placed at the center of mass of the whole system and serves as a fixed support point of the cold mass
- Two large cylinders and two end plates seal the vacuum vessel
- Eight cylindrical open bores are placed in between the end plates
- Vessel optimized to sustain atmospheric pressure and weight, while being as light and thin as possible
- The main cold mass supports are made of four G10 feet
- The support feet connect the reinforced bottom keystone box to the cryostat central part
- IAXO detectors need to track the sun for the longest possible period to increase data-taking efficiency: $\pm 25^\circ$ vertical inclination and 360° horizontal rotation
- An altitude-over-azimuth mount configuration was chosen to support and rotate the magnet
- The magnet services are placed on top of the rotating disk to couple their position to the horizontal rotation of the magnet
- The magnet services are connected via a turret aligned with the rotation axis, thus simplifying the flexible cables and transfer lines arrangement

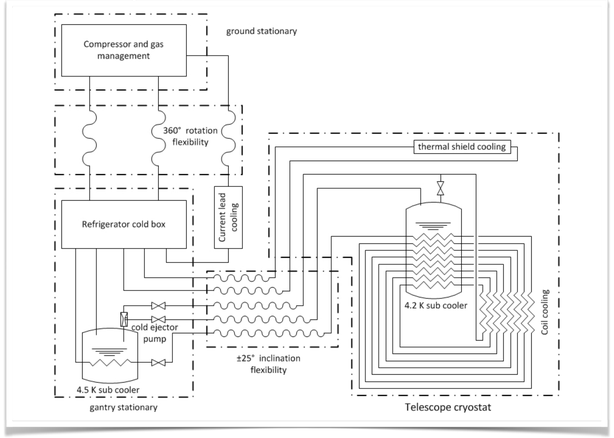
Cryogenics

Concept

- Coil windings cooled to 4.5 K via conduction
- Total heat load is 150 W at 4.5 K and 1.6 kW at 60-80 K
- Based on cooling with a forced flow of sub-cooled liquid helium at supercritical pressure, to avoid two-phase flow
- Coolant flows in a piping system attached to the coil casings, allowing for conduction cooling
- Total heat load is 150 W at 4.5 K and 1.6 kW at 60-80 K

Operation scheme

- Helium compression and gas managed are ground stationary
- Refrigerator cold box, current leads and a 4.5 K helium bath mounted on the rotating disk
- 4.2 K helium bath connected to the magnet cryostat
- Helium flow of 23 g/s, supplied at 300 kPa and 4.6 K and sub-cooled in the 4.5 K bath



- Before entering the cooling circuit of the first coil, the flow is cooled to 4.3 K in the 4.2 K bath
- After passing through the cooling channels of each coil, the helium is re-cooled in the sub-cooler of the magnet cryostat
- Part of the return flow is used to supply the 4.2 K sub-cooler
- The remaining gas supplies the 4.5 K bath
- Thermal shield is cooled by a flow of 16 g/s gas at 16 bar between 40 K and 80 K
- The cooling of the current leads is supplied at 20 K and 1.2 bar
- The total equivalent capacity of the refrigerator results in a 360 W isothermal load at 4.5 K
- The refrigerator cold box is compact enough to be integrated with the current leads cryostat on the gantry that is rotating with the helioscope

Conclusion

- The new design for the IAXO toroidal superconducting magnet features an increase of the solar axion searches sensitivity by at least 1 order of magnitude
- This design allows for maximum flexibility for the experimentalists and a maximized detection potential of the apparatus
- Magnet structure and detectors are separated by the inclusion of eight open warm bores for easy maintenance and upgrade when opportunity arrises
- The design of the magnet is also lead by the motivation to make IAXO a platform that can easily accommodate novel detection techniques and new equipment, when available

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