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A Proposal for a Superconducting Space Magnet for an Antimatter Spectrometer

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1. What is the origin of the matter-antimatter asymmetry in our Universe?
2. What is the particle nature of dark matter and does it contribute to the cosmic radiation?
3. Which is the origin and the acceleration and propagation mechanism of cosmic *rays?*

During the last 25 years, these questions have been addressed with increasing accuracy and experimental performances by a number space experiments like

AMS-01
PAMELA
AGILE
FERMI
AMS-02
CALET
DAMPE

Next generation of particle physics experiments in space

(full characterization of cosmic radiation, including antimatter nuclei)

Reliable charge sign separation above 1 TV → high bending power (1-3 Tm)

Reliable charge sign separation above 1 TV → precision tracking .

Rarity of antimatter signals → long-term mission (3-5 years)

Rarity of antimatter signals → large detector acceptance

High precision particle astrophysics as a new window on the Universe with an

Antimatter Large Acceptance Detector In Orbit

Originally proposed in 2016
In 2019 submitted in response to ESA's Call for the VOYAGE 2050 long-term plan

Core Team members

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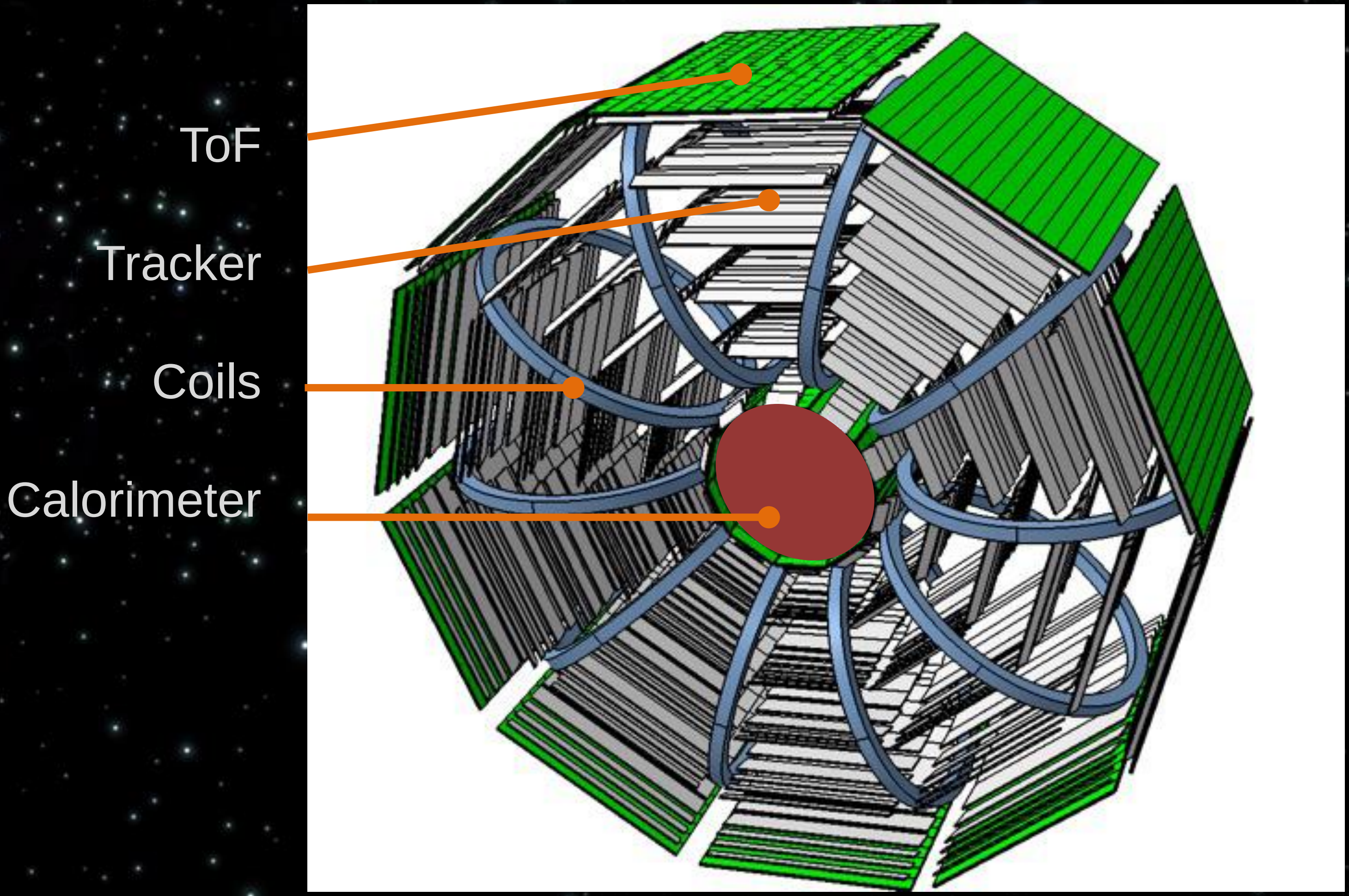
Three key elements:

- superconducting magnetic spectrometer to measure particle rigidity, charge magnitude and sign, with a maximum detectable rigidity exceeding 20 TV and an acceptance higher than 10 m^2 sr (~3 m^2 sr in combination with the calorimeter);

- time of flight (ToF) system to measure the particle velocity and charge magnitude;

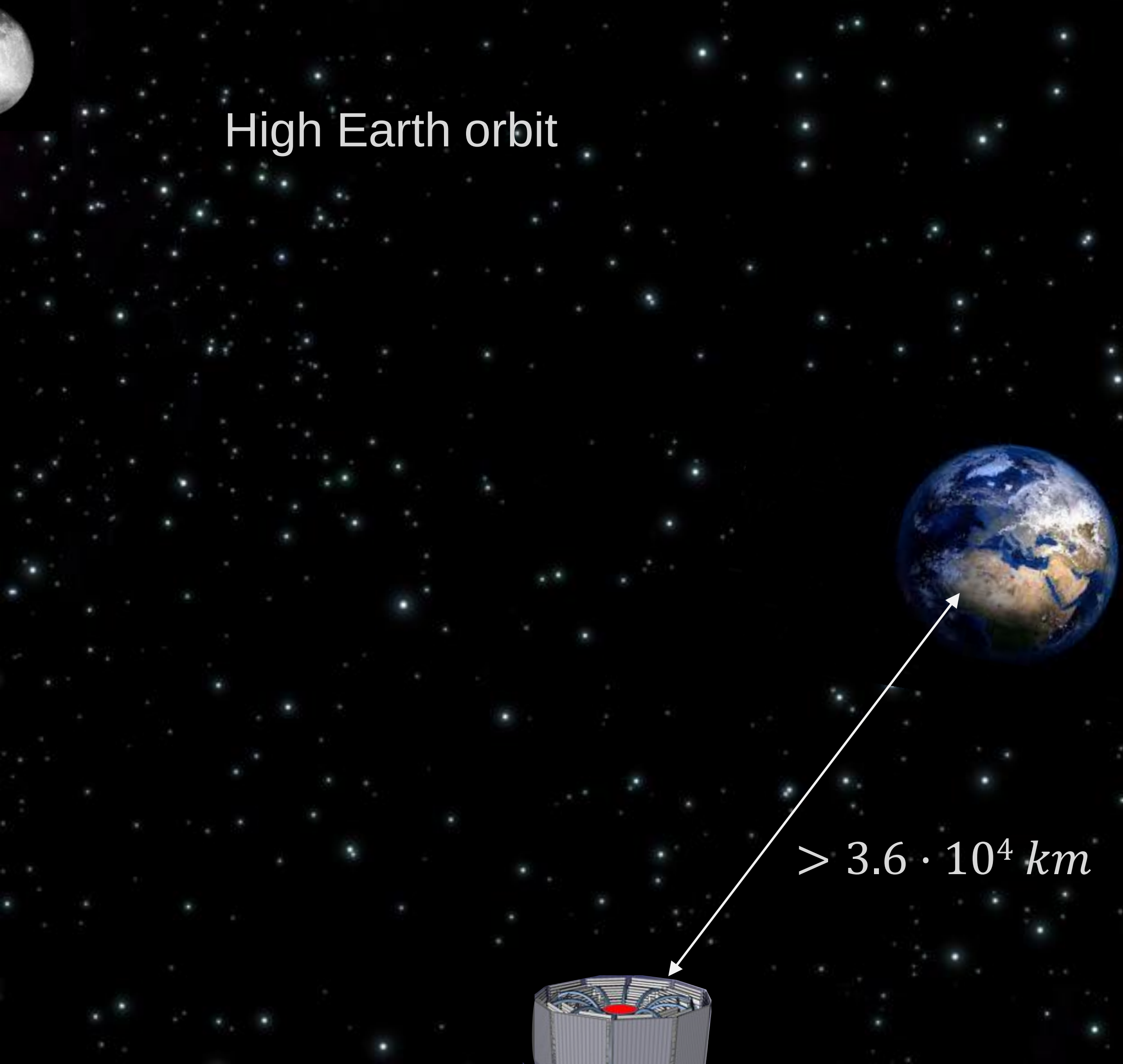
- large acceptance (~9 m^2sr) 3D imaging calorimeter to measure particle energy and discriminate electromagnetic from hadronic components.


ToF
Tracker
Coils
Calorimeter

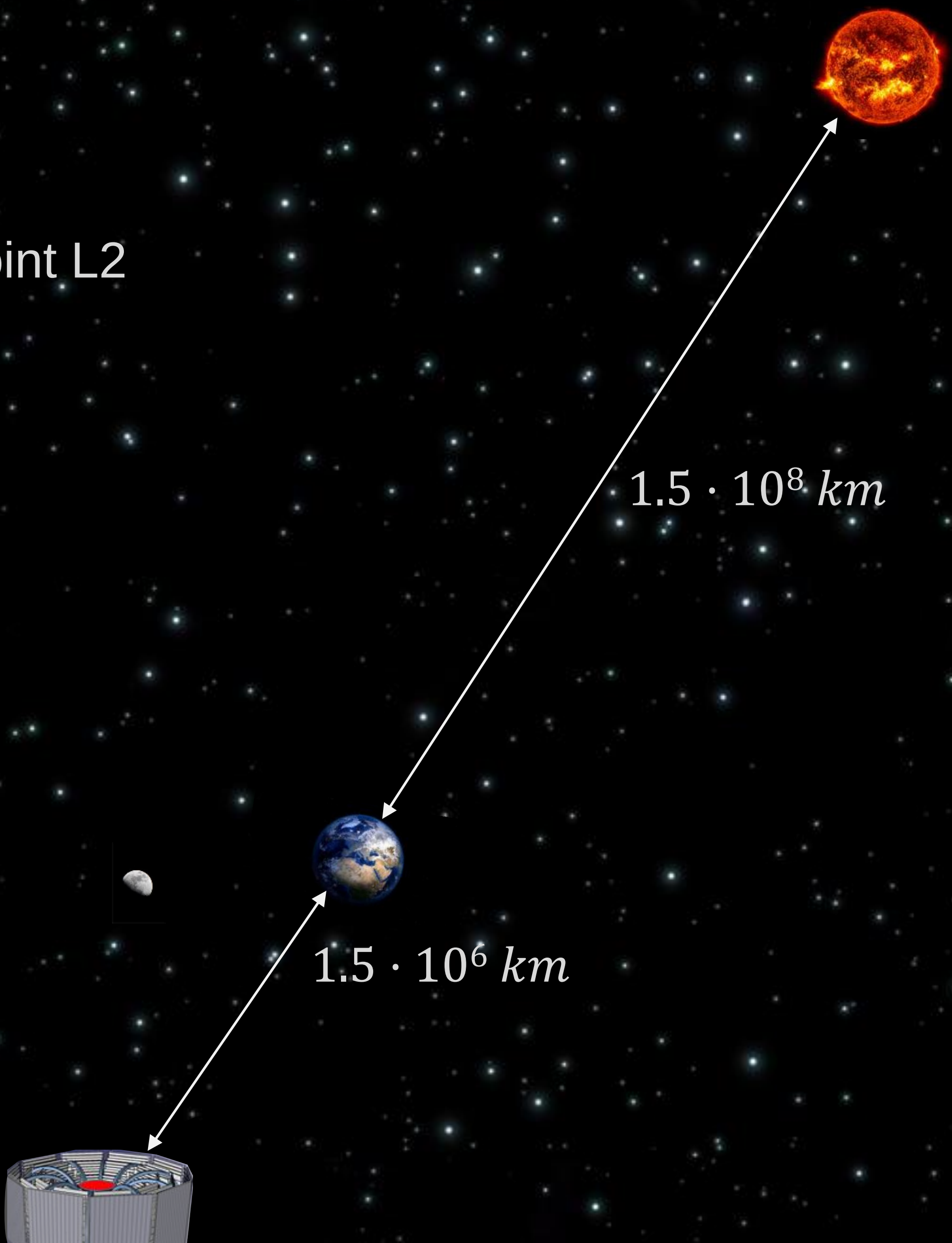
Key performance parameters of the ALADINO apparatus

Calorimeter acceptance	~ 9 m^2 sr
Spectrometer acceptance	>10 m^2 sr (~ 3 m^2 sr w/i CALO)
Spectrometer Maximum Detectable Rigidity (MDR)	> 20 TV
Calorimeter depth	61 X_0, 3.5 λ_I
Calorimeter energy resolution	25% ÷ 35% (for nuclei) 2% (for e+/e-)
Calorimeter e/p rejection power	> 10^5
Time of Flight measurement resolution	~100 ps
High energy γ-ray acceptance (Calorimeter)	~ 9 m^2 sr
Low energy γ-ray acceptance (Tracker)	~ 0.5 m^2 sr
γ-ray Point Spread Function	< 0.5 deg

High Earth orbit



Lagrangian point L2



$1.5 \cdot 10^8\ km$

$1.5 \cdot 10^6\ km$

Space-borne superconducting magnets

Astromag	designed, never built
ADR magnet for SXS	satellite destroyed 2 weeks after launch
AMS02	built, integrated, tested, not launched

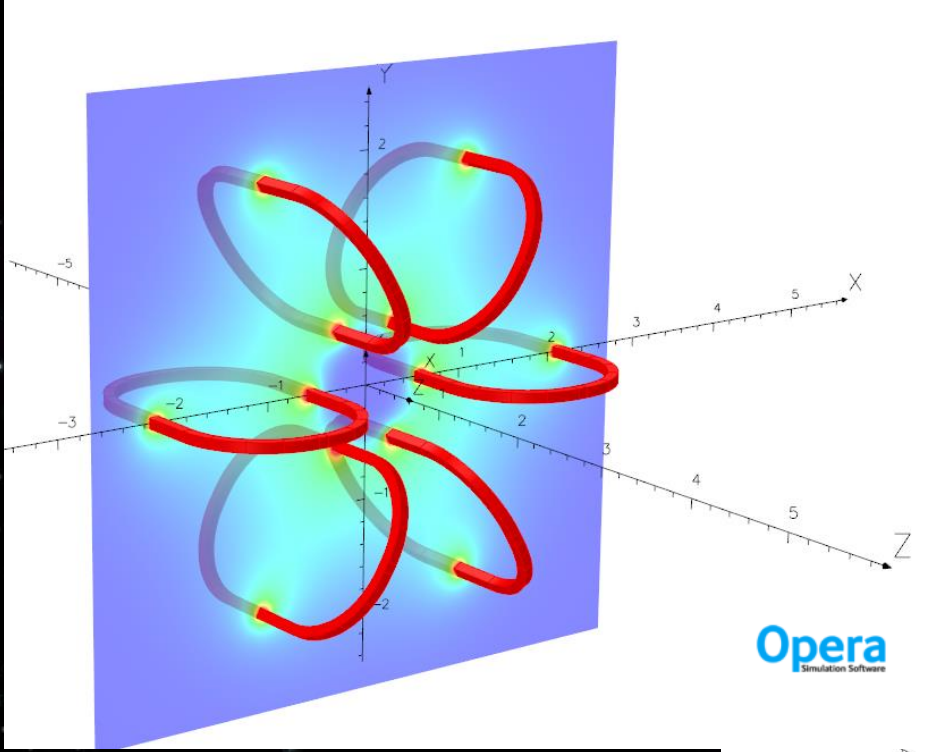
Stability and helium cryogenics hindered the use of superconducting magnet in space

Space-borne superconducting magnets

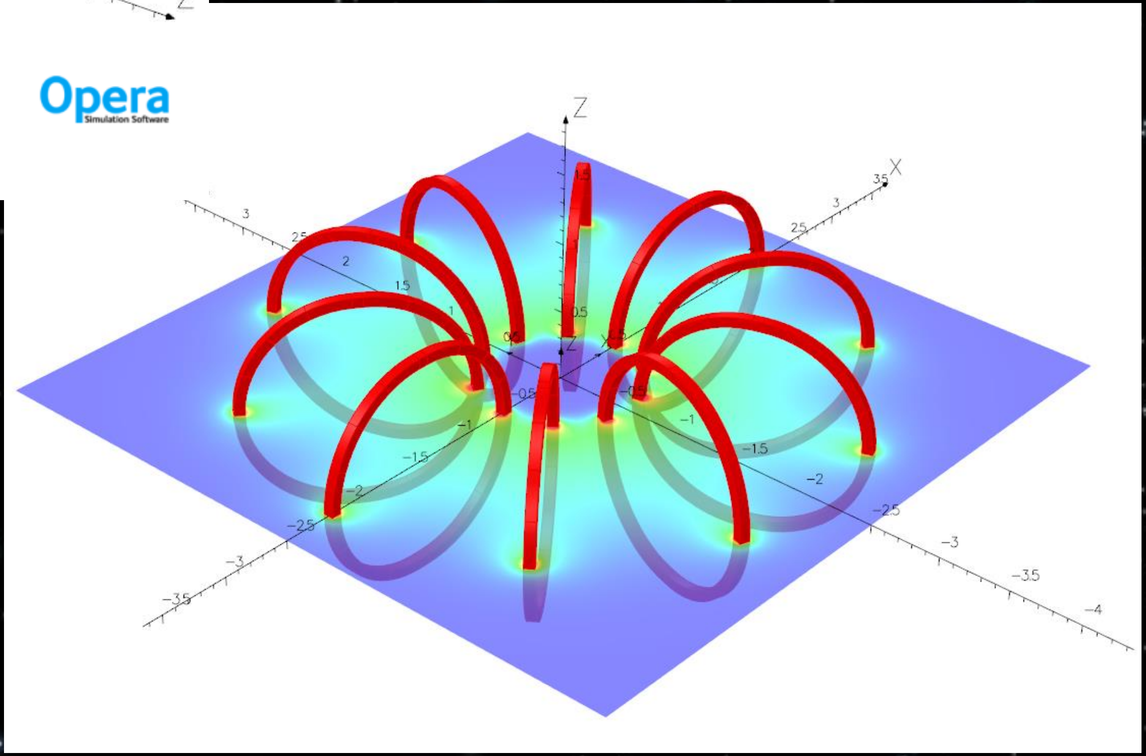
Studies on HTS/MgB2 space magnets for GCR shielding

ARSSEM*	MgB_2 toroid
MAARS**	ReBCO solenoids
SR2S***	MgB_2 toroids

*	INFN (co-funded by ESA)
**	NIAC
***	INFN – CEA – TAS-I – Columbus Superconductors – CERN (co-funded by EU)



Opera
Simulation Software



Superconducting magnets for space applications

Main requirements :

1. low mass budget, i.e. high stored energy to mass ratio and low density materials;
2. low power consumption, i.e. efficient cryogenics;
3. very high stability.

Besides, the presence of liquid helium tanks is a drawback.

HTS (ReBCO) toroid indirectly cooled @ 30 K

Light structural materials:

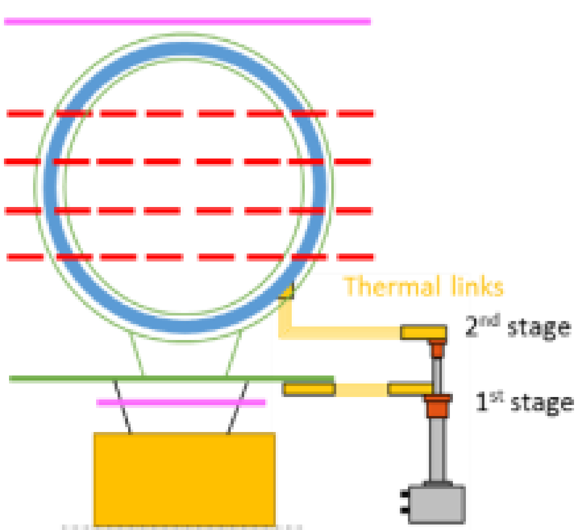
B_4C-Aluminum composite, high strength aluminum and titanium alloys, aramid fibers

⇩

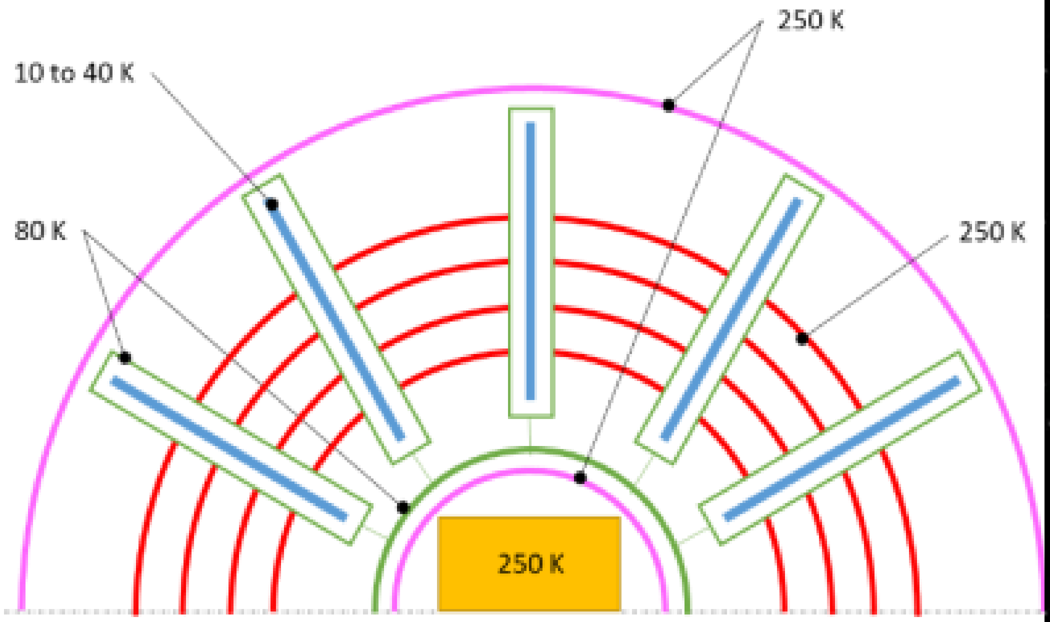
Low mass, simple cryogenics, high stability

MAIN CHARACTERISTICS OF THE MAGNET	
Number of coils	10
Total current per coil	440000 A
Operating current	200 A
Inductance	180 H
Average magnetic flux density	0.8 T
Average bending power	1.1 T·m
Peak field at the conductor	3 T
Cold mass	1200 kg

Side cross-sectional view



Top cross-sectional view



ToF + trigger

Superconducting coil

Tracker

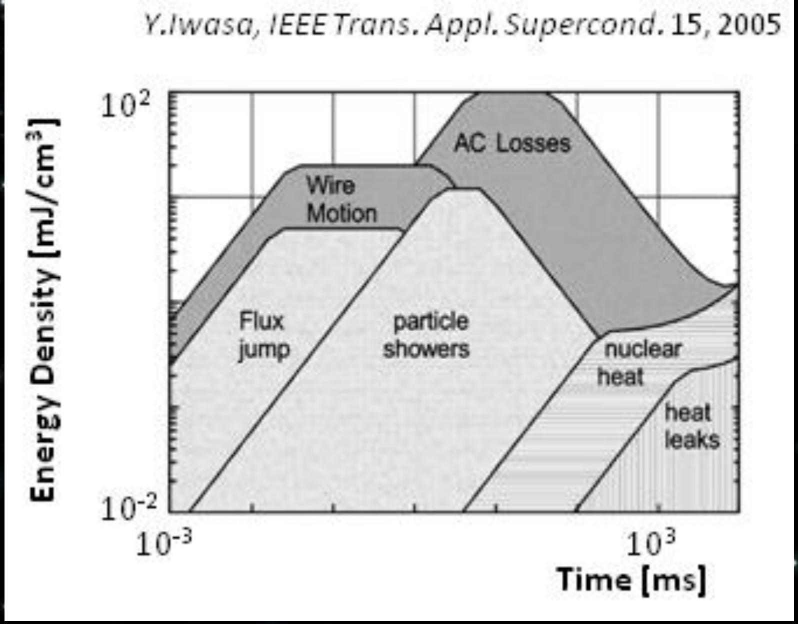
Cryogenic shield + thermal link

Cryocooler

Mechanical support

Calorimeter + trigger

Stability

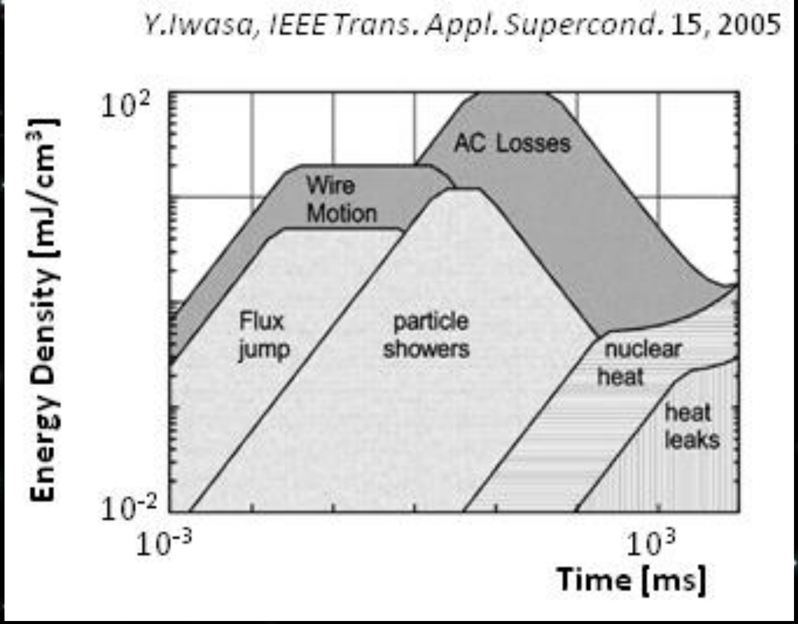


HTS magnets, operating at 30 K, are orders of magnitude more stable than low temperature magnets, wound with NbTi or Nb_3Sn conductors.

Energy releases sufficient to initiate quenches in low temperature magnets, do not affect the operation of a ReBCO magnet.

Slow charging/discharging, no leaks in vacuum insulation

Stability


Y.Iwasa, IEEE Trans. Appl. Supercond. 15, 2005

Only catastrophic events (structural failure, debris impact, heating due to degraded joint) can induce a quench.

Such a high stability makes magnets wound with ReBCO, reliable and consequently suitable for space application.

Quench protection (?)

Quench protection is generally a major issue in designing HTS magnets, due to the low propagation velocity of the normal zone.

No-insulated or partial-insulated coils could be a solution (but mechanical design must take into account unbalanced forces and torques.)

However, a quench in a HTS magnet operating at 30 K is unlikely.

If a quench occurs due to catastrophic events, the magnet does not require protection (mission aborted anyway).

Quench protection (?)

Considering that magnet protection strategies conflict with the mass budget requirements, the choice of a non-protected magnet must be seriously evaluated.

Current density can be pushed up and the cold mass can be further reduced.

$$E/V \approx 20\ MJ/m^3 \Longrightarrow E/V > 50MJ/m^3$$

CMS: $E/V \approx 25\ MJ/m^3$

Conclusions

ALADINO is a detector proposed for a long term mission, to be scheduled in the 30's, so, despite the fact that magnet preliminary design is based on the state of the art of the various components, some of the hypothesis are challenging and require a specific R&D program:

- Use of <u>ceramic reinforced alloys and aramid fibers</u> for the mechanical structure.
- Use of <u>pulsing heat pipes</u>, never applied in space at low temperature, to increase the heat exchange efficiency, saving mass.
- Design a <u>non-protected magnet</u> to get rid of the quench protection system and pushing up the overall current density, in such a way to limit the magnet mass.