A Proposal for a Superconducting Space Magnet for an Antimatter Spectrometer

Riccardo Musenich, Stefania Farinon
(INFN – Genoa)

Oscar Adriani, Paolo Papini
(INFN – Firenze)

Bertrand Baudouy, Valerio Calvelli
(CEA – Saclay)

Bruna Bertucci
(Università di Perugia and INFN – Perugia)
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 of space experiments like AMS-01, PAMELA, AGILE, FERMI, AMS-02, CALET, and DAMPE.
Next generation of particle physics experiments in space

(full characterization of cosmic radiation, including antimatter nuclei)

Reliable charge sign separation above 1 TV

Rarity of antimatter signals

High bending power (1-3 Tm)

Precision tracking

Long-term mission (3-5 years)

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

O. Adriani\textsuperscript{1,2}, G. Ambrosi\textsuperscript{3}, B. Baoudoy\textsuperscript{4}, R. Battiston\textsuperscript{5,6}, B. Bertucci\textsuperscript{7,3}, P. Blasi\textsuperscript{8}, M. Boezio\textsuperscript{9}, D. Campana\textsuperscript{10}, L. Derome\textsuperscript{11}, I. De Mitri\textsuperscript{8}, V. Di Felice\textsuperscript{12}, F. Donato\textsuperscript{13}, M. Duranti\textsuperscript{3}, V. Formato\textsuperscript{12}, D. Grasso\textsuperscript{14}, I. Gebauer\textsuperscript{15}, R. Iuppa\textsuperscript{5,6}, N. Masi\textsuperscript{17}, D. Maurin\textsuperscript{11}, N. Mazziotta\textsuperscript{17}, R. Musenich\textsuperscript{18}, F. Nozzoli\textsuperscript{6}, P. Papini\textsuperscript{2}, P. Picozza\textsuperscript{19,12}, M. Pierce\textsuperscript{20}, S. Pospíšil\textsuperscript{21}, L. Rossi\textsuperscript{22}, N. Tomassetti\textsuperscript{6,3}, V. Vagelli\textsuperscript{23}, X. Wu\textsuperscript{24}

1. University of Florence, Italy
2. INFN-Florence, Italy
3. INFN-Perugia, Italy
4. CEA Saclay Ifcu/SACM, France
5. University of Trento, Italy
6. INFN-TIFPA, Trento, Italy
7. University of Perugia, Italy
8. GSSly & INFN-Laboratori Nazionali del Gran Sasso, Italy
9. INFN-Trieste, Italy
10. INFN-Napoli, Italy
11. Università Grenoble Alpes and IN2P3 LSPC, France
12. INFN-Roma Tor Vergata, Italy
13. University & INFN Torino, Italy
14. INFN Pisa, Italy
15. KIT, Karlsruher Institut für Technologie, Germany
16. University and INFN Bologna, Italy
17. INFN-Bari, Italy
18. INFN-Genova, Italy
19. University of Roma Tor Vergata, Italy
20. KTH Royal Institute of Technology, Sweden
21. CTU, Czech Technical University, Czechia
22. CERN, Switzerland
23. ASI, Italian Space Agency, Italy
24. University of Geneva, Switzerland
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 ($\sim$3 m$^2$ sr in combination with the calorimeter);
- time of flight (ToF) system to measure the particle velocity and charge magnitude;
- large acceptance ($\sim$9 m$^2$sr) 3D imaging calorimeter to measure particle energy and discriminate electromagnetic from hadronic components.
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### Key performance parameters of the ALADINO apparatus

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calorimeter acceptance</td>
<td>~ 9 m² sr</td>
</tr>
<tr>
<td>Spectrometer acceptance</td>
<td>&gt;10 m² sr (~ 3 m² sr w/i CALO)</td>
</tr>
<tr>
<td>Spectrometer Maximum Detectable Rigidity (MDR)</td>
<td>&gt; 20 TV</td>
</tr>
<tr>
<td>Calorimeter depth</td>
<td>61 $X_0$, 3.5 $\lambda_I$</td>
</tr>
<tr>
<td>Calorimeter energy resolution</td>
<td>25% ÷ 35% (for nuclei)</td>
</tr>
<tr>
<td></td>
<td>2% (for e+/e-)</td>
</tr>
<tr>
<td>Calorimeter e/p rejection power</td>
<td>&gt; 10^5</td>
</tr>
<tr>
<td>Time of Flight measurement resolution</td>
<td>~100 ps</td>
</tr>
<tr>
<td>High energy $\gamma$-ray acceptance (Calorimeter)</td>
<td>~ 9 m² sr</td>
</tr>
<tr>
<td>Low energy $\gamma$-ray acceptance (Tracker)</td>
<td>~ 0.5 m² sr</td>
</tr>
<tr>
<td>$\gamma$-ray Point Spread Function</td>
<td>&lt; 0.5 deg</td>
</tr>
</tbody>
</table>
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High Earth orbit

> $3.6 \cdot 10^4$ km
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Lagrangian point L2

1.5 \cdot 10^8 \text{ km}

1.5 \cdot 10^6 \text{ km}
## Space-borne superconducting magnets

<table>
<thead>
<tr>
<th>Magnet Type</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>Astromag</td>
<td>designed, never built</td>
</tr>
<tr>
<td>ADR magnet for SXS</td>
<td>satellite destroyed 2 weeks after launch</td>
</tr>
<tr>
<td>AMS02</td>
<td>built, integrated, tested, not launched</td>
</tr>
</tbody>
</table>

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*  MgB₂ toroid
MAARS**  ReBCO solenoids
SR2S***  MgB₂ toroids

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

$\text{B}_4\text{C}$-Aluminum composite, high strength aluminum and titanium alloys, aramid fibers

Low mass, simple cryogenics, high stability
### MAIN CHARACTERISTICS OF THE MAGNET

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of coils</td>
<td>10</td>
</tr>
<tr>
<td>Total current per coil</td>
<td>440000 A</td>
</tr>
<tr>
<td>Operating current</td>
<td>200 A</td>
</tr>
<tr>
<td>Inductance</td>
<td>180 H</td>
</tr>
<tr>
<td>Average magnetic flux density</td>
<td>0.8 T</td>
</tr>
<tr>
<td>Average bending power</td>
<td>1.1 T·m</td>
</tr>
<tr>
<td>Peak field at the conductor</td>
<td>3 T</td>
</tr>
<tr>
<td>Cold mass</td>
<td>1200 kg</td>
</tr>
</tbody>
</table>
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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$_3$Sn 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

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.

\[ E/V \approx 20 \text{ MJ/m}^3 \quad \iff \quad E/V > 50 \text{ MJ/m}^3 \]

CMS: \( E/V \approx 25 \text{ MJ/m}^3 \)
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 ceramic reinforced alloys and aramid fibers for the mechanical structure.

• Use of pulsing heat pipes, never applied in space at low temperature, to increase the heat exchange efficiency, saving mass.

• Design a non-protected magnet to get rid of the quench protection system and pushing up the overall current density, in such a way to limit the magnet mass.