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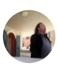

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Study of a Superconducting Magnetic Diverter for the ATHENA X-Ray Space Telescope

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***Abstract*—The advanced telescope for high energy astrophysics (ATHENA) is an X-ray telescope of the European space agency which is planned to be launched in 2028. It will carry out observations in the X-ray band, exploiting two focal plane detectors where X-ray photons will be focused by silicon pore optics. Previous X-ray missions have shown a serious issue with soft protons and ions (below 150 keV/n), which could enter the telescope mirror aperture and be concentrated toward the focal plane. These particles must be blocked or diverted to avoid excess background loading on the detectors. The proposed solution is to deflect protons away from the instruments field of view by means of magnets located between the optics and the focal plane. A 160000 amp-turns HTS superconducting toroidal magnet, composed by three or four round coils located between 0.6 and 1.2 m from the focal plane, can efficiently deflect most of the incoming particles. The rejection rate for protons till 120 keV is better than 99%, to be compared with about 80% of a previously proposed diverter based on permanent magnets. The magnetic field requirement at the detectors level (B < 1 mT) is widely satisfied, as well as the mass budget of 110 kg. Challenging aspects related to the operation and reliability of the superconducting magnet will be discussed.**

***Index Terms*—Advanced telescope for high energy astrophysics (ATHENA), ESA, genetic algorithms, HTS, magnetic diverter, MgB_2, superconductors.**

I. Introduction

The Advanced Telescope for High ENergy Astrophysics (ATHENA) is an X-ray telescope of the European Space Agency which is planned to be launched in 2028. It will be placed in a halo orbit around the Lagrangian point L2. The space-based observations in the X-ray band will be performed by the WFI (Wide Field Imager) and X-IFU (X-ray Integral Field Unit) detectors, where X-ray photons will be focused. Previous missions [6]–[10] have shown the necessity to block or deflect low energy particles concentrated by the mirrors, which may affect the sensitivity of the detectors or a induce radiation damage. So far, the proposed existing solution is the magnetic deflection using permanent magnets [2]. We studied a magnetic diverter based on superconducting magnets, using optimization tools and sweep parameters analysis for the geometry and Monte Carlo particle tracking simulations for the particle fluxes.

The proposed solution is a toroidal magnet composed of 3 or 4 round coils, located between 0.6 m and 1.2 m from the focal plane.

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TABLE I
General Requirements

Requirement	Value
Overall Mass	≤110 kg
Dipole Moment	$\sim$0 A·m^2
Photon Flux Block	= 0%
$\|\boldsymbol{B}\|$ on the WFI detector	$B_{WFI} < 10^{-3}$ T
$\|\mathbf{B}\|$ on the X-IFU detector[a]	$B_{X-IFU} < 10^{-3}$ T

[a] During the detector cool down, the magnetic field must be $B_{X-IFU} < 10^{-4}$ T.

II. Design Requirements

A. Mission and Technical Requirements

Table I shows the ATHENA mission requirements that directly impact the diverter design. The overall mass of the diverter and its ancillaries must be less than 110 kg, and the incoming photon flux must not be blocked by the diverter materials. The residual magnetic dipole moment must be minimized to avoid any possible torque due to the interaction with the geomagnetic field.

Requirements on the residual magnetic flux density are instead due to the on board instrumentation. The sensitivity of the detectors, in fact, can be affected by the presence of a magnetic field at the focal plane level.

The diverter must operate in a thermal environment where the main source of heat is the radiation from the mirrors, which are kept at about 300 K.

B. Efficiency Requirements

The requirements for the rejection efficiency are described in [1], [2]. Regarding the soft protons background, the largest uncertainty is due to the external fluxes impacting on the mirrors. In fact, the low energy environment in L2 is not well-known and it is highly dynamic, making hard to predict the impact on the mission.

However, the latest study on the particle background expected on X-IFU instrument is carried out in [6] with Monte Carlo

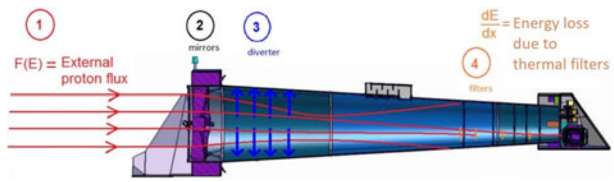

Fig. 1. Schematics of the path followed by the soft protons through the telescope. The filters shown (identified with the number 4) are thermal filters, which can absorb the lowest energy protons. In the work reported in [6], any magnetic field has been taken into account.

TABLE II
MAX. PARTICLE ENERGY TO BE DEFLECTED FROM FOCAL PLANE IN keV

Particles	WFI	X-IFU
Protons	75 keV	74 keV
Electrons	31 keV	21 keV

simulations, where the proton interactions with different parts of the telescope have been mapped without considering any magnetic field acting on their trajectories (see Fig. 1).

The result is the estimation of an energy threshold below which it is necessary to remove more than 96.5% of the incoming flux [6]. In Table II the thresholds are reported for protons and electrons.

III. Design Solutions

In order to fulfill the mass requirement as well as to guarantee a high stability margin to the magnet, the choice of the superconductor is naturally led either to HTS or to MgB_2 cables [3], [4]. We made a comparative analysis between Ti-clad MgB_2 conductor and ReBCO tapes for each design, in order to identify which one most minimizes the mass of the winding and ancillary equipment at the same operative current density, here set at 80 A/mm^2. The operating temperature is set respectively to 20 K for the Ti-MgB_2 conductor [4] and to around 70 K for the ReBCO, with a margin of about 50% on the critical current density @1 T in perpendicular field. The Ti-MgB_2 conductor density is about 2.1 times lower than ReBCO: 4000 kg/m^3 compared to 8500 kg/m^3.

As regards ancillary equipment (mechanical structure, power supply, cryogenics, quench detector and protection system), the choice of the conductor mainly affects cryogenics as it is related to the operating temperature. The magnet cryogenics could be based on a passive cooling system as already used in PLANK NASA satellite [5]: cryogenic heat pipes connect the payload to radiators. Only four fluids are available to operate heat pipes below 70 K: hydrogen, deuterium, neon, and nitrogen. For ReBCO, it is possible to use liquid nitrogen while for MgB_2 the only suitable fluid is hydrogen. Respect to a ReBCO magnet operating at 70 K, the MgB_2 option requires larger radiators. Indeed, the power radiated toward the deep space is 1.2 W/m^2 at 70 K while it is only 8 mW/m^2 at 20 K. The low radiating power at 20 K implies large panels or the use of a cryocooler. The consequent mass penalty and impact on the payload design steers the choice to a ReBCO magnet.

IV. Conceptual Designs and Optimization Tools

In order to consider all the requirements, we developed a series of optimization tools that allow us to minimize the mass, dimensions and total current (*Ampere·turns)*. We decided to apply two different approaches to two slightly different designs. Basically, the design explored is a toroid with a low number of coils in order not to intercept the incoming photon flux and to limit the mass. On the other hand, the fringe field would be higher than in the usual toroidal configurations and the bending power lower. The optimization has been carried out taking care of those aspects, exploiting the parameters we considered critical for the diverter. For both designs, Monte Carlo simulations have been performed in order to estimate the entity of the particles rejection performance, a leading parameter of the design quality.

As the activity was devoted to a preliminary magnetic design, no hypothesis was done about the conductor dimension and, consequently, about the operating current. Therefore, some aspects of the magnet design, like quench protection, will be analyzed during further developments of the project.

A. *Genetic Algorithms Optimization*

One of the proposed designs is a toroidal diverter made of 3 racetrack coils, at which we applied an optimization process through the Evolutionary Algorithms (EAs). EAs are population-based meta-heuristic optimization algorithms that use biology-inspired mechanisms and survival of the fittest theory in order to refine a set of solution $\{x_k\}$ iteratively, that always converge to one solution. Genetic algorithms (GAs) are a subclass of (EAs) where the elements of the search space are binary strings or arrays of other elementary types [11].

For this work, we wrote a custom GA MatLab based code. First, it calculates the magnetic field obtained by the 3 coils toroidal diverter with COMSOL engine, then it tracks the particles in the calculated field (COMSOL). Through MatLab LiveLink the GA communicates with COMSOL on purpose to obtain solutions and parameters that the GA needs to calculate the Fitness Function (FF), then decides how to proceed in the evolution. The FF to minimize is defined as $\alpha_{det} = N_{det}/N_{inc}$: the fraction of particles intersecting the detectors N_{det} ratio the incident particles N_{inc}. The smaller α_{det} is, the greater is the efficiency of deflecting particles.

The design variables considered are geometrical and electrical: the coil dimensions, the distance from the field of view (z coordinate) and number of Ampere·turns.

The constraints for the FF come from the design requirements, namely the total mass and distance of the diverter from the detector (which is related to the constraint Bpeak on the detectors). In Table III we report the design parameters and in Fig. 2 the GA concept design.

As results of this analysis, we found that with MgB_2 the mass of the winding is 14 kg, to which we have to add roughly 100 kg with the ancillaries, while with ReBCO the mass of the winding is 26 kg for the diverter and 50 kg with the ancillaries.

TABLE III
THREE COIL TOROID SPECIFICATIONS

Coil length	350 mm	Coils aperture	120°
Coil height	450 mm	Ampere.turns	160000
Cross-section	600 mm^2	B_{max} over conductor	1.07 T
x^b	30 mm	Energy stored	4300 J
y^b	200 mm	Dipole Moment	0 Am^2
z^b	1205 mm	SC mass (MgB_2)	14 kg
		SC mass (REBCO)	26 kg

[a]Inner and outer radius of the toroidal magnet.
[b]Coordinates of the diverter center of mass respect to the axis of the telescope and the detector's plane.

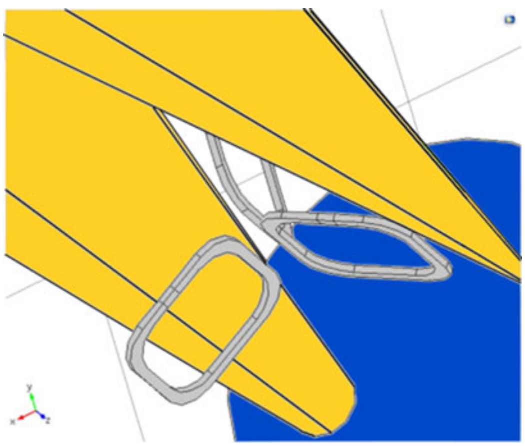

Fig. 2. First concept design of the diverter with the photons flux incident on the detectors. The blue surface is the plane where detectors lie, meanwhile the yellow cone are the particle fluxes.

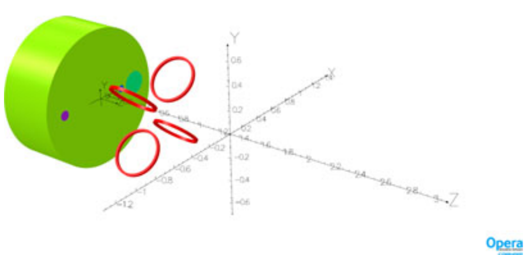

Fig. 3. Second concept design of the diverter.

B. Sweep Parameters Analysis

The second diverter proposed is a 4 coils toroid (see Fig. 3) which design has been selected through a parametric model of 10 degrees of freedom. They are respectively the Cartesian coordinate x, y, z needed to find the best position of the diverter center of mass respect to the axis of the telescope and the detectors plane; the geometric dimensions of each coil (inner and outer radius r_i, r_e of the toroid, width w of the coil); two Euler angles $\hat{x}, \hat{y}$ related to the x, y axis, to identify the best rotational position of the center of mass; and two angles $\hat{c}_1, \hat{c}_2$ that identify the azimuthal position of each coils respect to the detectors position, in order to avoid any block of the photons flux.

The model has been prepared using OPERA by Cobham, swapping the parameters to find the best configuration using an in-house code. As results, the mass of the diverter with MgB_2 is 9.5 kg, while for YBCO is 20.2 kg. Also for this design, the

TABLE IV
FOUR COIL TOROID SPECIFICATIONS

DoFs		Specifications	
r_i	150 mm	Ampere·turns	160000
r_e	330 mm	B_{max} over conductor	0.74 T
w	25 mm	Energy stored	2100 J
x	80 mm	Dipole Moment	0 Am^2
y	80 mm	SC mass (MgB_2)	9.5 kg
z	600 mm	SC mass (YBCO)	20.2 kg
$\hat{x}$	0°		
$\hat{y}$	0°		
$\hat{c}_1$	45°		
$\hat{c}_2$	45°		

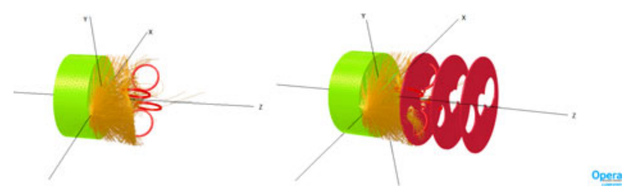

Fig. 4. Reverse tracking simulations without filters on the left, with filters on the right.

mass for the ancillary systems are evaluated as about 100 kg for the MgB_2 and 50 kg for the ReBCO configuration. Both analyses point out that a good solution for the diverter can be the ReBCO; in fact, low mass and a cryocooler free system is more suitable for this application. The design specifications are reported in Table IV.

V. MONTE CARLO PARTICLE TRACKING SIMULATIONS

Charged particles rejection performances of both designs have been estimated through Monte Carlo simulations. We used respectively COMSOL for the 3-coils and OPERA for the 4-coils designs. For both softwares, we wrote a dedicated code to perform the simulations in order to consider the transportation properties and the interactions with the magnetic field for protons. Being those simulations used to estimate and not to validate the designs performances, other particles and nuclear interactions have not been considered, as well as secondary particles production. For both designs we used at first a Monte Carlo direct particle tracking: the simulated proton beam hitting the detectors from the telescope mirrors is modeled as a uniform angular spread with the same *rms* width in the sagittal and meridional planes. Simulations have been carried out with different *rms* and energies, then tracked under the effect of the magnetic field produced by the diverter. For these simulations, no thermal filter (Figs. 1, 4) has been modeled. In order to have a better statistics and a more reliable validation including the effects on the particles produced by the thermal filters of the telescope, for the 4-coils design we used also the reverse particle tracking: particles have been released from the detectors with a certain solid angle, the magnetic field was inverted and the particles were tracked in order to see which ones were effectively coming from the mirror aperture of the telescope. The results are presented afterward.

TABLE V

rms	20 keV	75 keV	120 keV	500 keV
0.5	$< 1 \cdot 10^{-5}$	$< 1 \cdot 10^{-5}$	$< 1 \cdot 10^{5}$	$< 1 \cdot 10^{5}$
1	$< 1 \cdot 10^{-5}$	$3.53 \cdot 10^{-5}$	$< 1 \cdot 10^{5}$	0.001
2	$< 1 \cdot 10^{-5}$	$3.22 \cdot 10^{-4}$	$2.01 \cdot 10^{-4}$	0.0028
4	$< 1 \cdot 10^{-5}$	$1.56 \cdot 10^{-4}$	$2.23 \cdot 10^{-4}$	0.0035

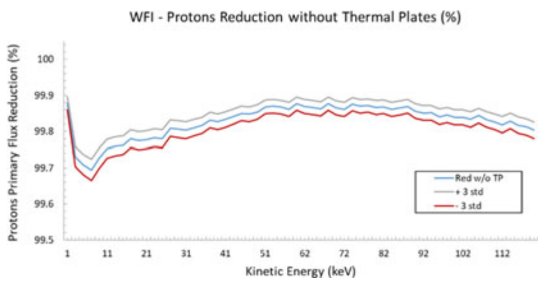

Fig. 5. Protons reduction in percentage for the WFI detector without thermal plates as a function of the kinetic energy of the entering spectra. The grey and red lines are respectively the statistical uncertainties at $\pm 3\sigma$.

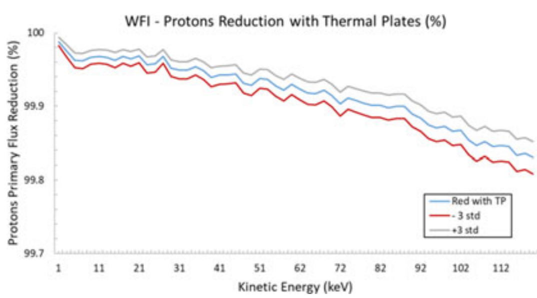

Fig. 6. Protons reduction in percentage for the WFI detector with thermal plates as a function of the kinetic energy of the entering spectra. The grey and red lines are respectively the statistical uncertainties at $\pm\, 3\sigma$.

A. 3-Coils Diverter

In order to be consistent with the efficiency evaluations reported in [2], the simulations were carried out with $3{\cdot}10^5$ particles directed to the focal plane of the detectors with energies from 20 keV to 500 keV and rms from 0.5 to 1. In the simulations, no thermal filters were considered. In Table V, it is reported the efficiency of the diverter obtained with GA optimization for the detector WFI, which present higher value of α_{det} because of his size. From α we calculate the efficiency rejection as $\eta = 100 \cdot (1 - \alpha)$. In some cases, the efficiency at lower energy seems less than at higher energy, e.g., at 75 keV for $rms = 2$ the efficiency is lower than at 150 keV. Even if the number of particles is not high enough to get a good statistic we may suppose that this is due to particles that swirl around the diverter because of the intensity of the field. Those particles may be deflected radially inward and directed to the detectors instead of being deflected radially outward. Due to computational limits, it was not possible to achieve a better statistics.

B. 4-Coils Diverter

We simulated in more details the proton spectra entering the WFI and X-IFU detectors in the energy region of 0–120 keV, considering also the effects of the thermal filters (see Fig. 4).

Simulations were carried out with $4.1{\cdot}10^7$ protons each one, in order to achieve a significant statistic. Results for the WFI, the worst one in terms of reduction, are shown in Fig. 5, 6. The results obtained without thermal plates show that a small fraction of protons (especially at the energy of few keV) follows the external lines of the magnetic field, swirling around the diverter and hitting the detectors. With thermal plates, this effect is suppressed because those protons are absorbed by the materials.

VI. Conclusion

After an initial trade-off analysis, a 160000 amp-turns HTS superconducting toroidal magnet, composed of 3 or 4 round coils has been chosen and a preliminary conceptual design. The magnet can be wound with a high-temperature superconductor (MgB_2 or preferably ReBCO). Differently, from the permanent magnet, positioned close to the mirrors, the proposed superconducting diverter is located between 0.6 m and 1.4 m from the focal plane.

Challenging aspects are related to the operation and reliability of the superconducting magnet, namely cryogenics, stability and quench protection. Nevertheless, these solutions are, at this level of study, really competitive with the other proposed for ATHENA in terms of both efficiency and mass. The rejection rate for protons at 120 keV is better than 99.8%, to be compared with the about 80% of the diverter based on permanent magnets. The requirements on the magnetic field on the detectors and the mass are widely satisfied.

This feasibility study has revealed that a superconducting diverter could be an efficient and interesting solution for the ATHENA X-rays telescope.

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