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A SILICON TRACKER FOR THE ANTI MATTER SPECTROMETER ON THE INTERNATIONAL SPACE STATION ALPHA

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A SILICON TRACKER FOR THE ANTI MATTER SPECTROMETER ON THE INTERNATIONAL SPACE STATION ALPHA

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We present the design of the Silicon Spectrometer for the AMS experiment on the International Space Station ALPHA. We review the design principles and some of the issues related to the construction af a large, high precison silicon microstip tracker for a space born experiment.

1. INTRODUCTION

The AMS experiment[1] is designed to measure the antimatter components of the cosmic rays, in particular anti-nuclei with $|Z| > 1$, with a sensitivity of 10^4 to 10^5 better than the current limits. It comprises a large acceptance (about 1 m^2sr) magnetic spectrometer in space with of a new type of permanent Nd-Fe-B magnet and a precision spectrometer (precision tracker, time of flight counters, etc.) with a large analyzing power of $BL^2 = 0.15\ Tm^2$. The AMS experiment is scheduled for a two weeks Shuttle flight in 1998 and to be installed during the year 2000 on the International Space Station Alpha (ISSA) where will be operated for three years.

The aim of the AMS tracker is to measure the charged particle momentum vector, including the sign of the charge, and to provide an absolute measurement of the particle charge. In the AMS proposal we have considered two alternatives for the precision tracker filling the 1 m^3 magnet bore: a TPC and a Silicon Tracker. Both options have a sensitivity to antinuclei of better than 10^{-10}.

In this paper we present the design of the silicon version of the AMS tracker, and we discuss the principles we have introduced to solve the issues related to the use of a large, precise silicon tracker in an experiment in space. This design is based on many years of experience in designing, building and operating the 73,000 channel L3 Silicon Microstrip Detector (SMD) at LEP [2,3] and on the results of a R&D effort to build and operate long silicon ladders[4,5] exploiting recent advances in very low noise front end electronics[6,7].

For more details on the AMS experiment and on the Silicon Tracker we refer to the the AMS proposal [1].

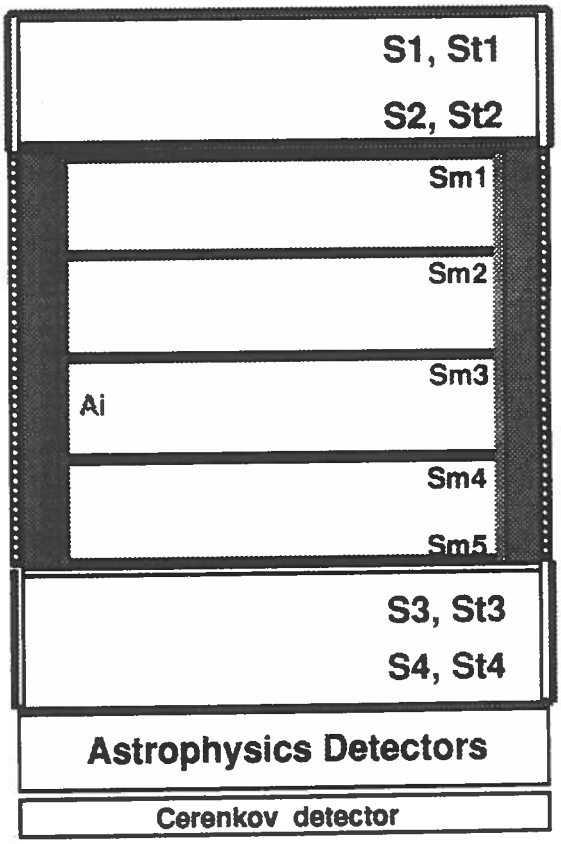

Figure 1 : The AMS Silicon option

2. THE AMS DETECTOR

Figure 1 shows a sketch of the AMS Silicon Tracker option, in the configuration with 5 high resolution tracking layers (minimal configuration). It consists of four components.

1. Five layers of high precision silicon detectors are located inside the magnet (Sm1 to Sm5); they give a precise measurement of the rigidity (i.e. total particle momentum divided by its electric charge), and allow a sensitivity (background rejection) for anti-He of below 10^{-10}. With six layers it would be possible to further improve the sensitivity. Each silicon layer provides a dE/dx measurement sufficient to separate Z = 1 from Z = 2 particles.
2. Four layers of scintillators, S1 to S4, for a first level trigger, TOF and dE/dx and four strip planes, St1 to St4, to measure the deflection angle are located outside the magnet.
3. A Cerenkov system to reject albedo background.
4. Possible additional detectors for astro-particle physics could be added

Table 1 : Main parameters of the AMS Silicon Tracker (minimal configuration)

Silicon Tracker Main Parameters	
Number of planes	5
Accuracy (bending plane)	10 μm
Accuracy (non bending plane)	30 μm
Number of channels	267K
Power consumption (W)	355
Weight (Kg)	30

The instrument will be surrounded with multi-layer insulation and a thin aluminium shell to shield against micro-meteorites and space debris, and will be operated at a temperature close to 290 K. The interior does not require pressurization.

The main parameters for the minimal configuration of the AMS silicon spectrometer are listed in Table 1.

2.1. Performance of the AMS spectrometer.

In order to establish the performance of the silicon version of the AMS spectrometer, we have performed detailed Monte Carlo simulations, using both protons and heavier nuclei. A simulation has been performed for 10^{10} Carbon events to study the scattering with the silicon detector and its support structure.

The momentum dependence of the resolution at 90°, for different particles, is shown in Figure 2, where we have used the standard analytical formulas[8] which agrees with the Monte Carlo calculations. Multiple scattering limits the resolution at low velocity to about 6%. For higher momentum, the silicon detector has an excellent resolution, with a Maximum Detectable Rigidity (P/Z) of about 500 GV. This tracker will be able to resolve the hydrogen and helium isotopes at low energy.

The five layer silicon spectrometer has a sensitivity to anti-carbon nuclei of better than 10^{-10}, in the range 0.5 - 10 GeV/c per nucleon matching the AMS primary goal. The computed charge confusion probability for carbon nuclei is shown in Figure 3b, together with the corresponding detection acceptance (Figure 3a).

This result is based only on the quality of the track fitting consistency of the path observed through the five silicon planes.

3. THE AMS SILICON TRACKER

The tracker is built from ladders. Each ladder is up to 60 cm long, composed of several double sided silicon sensors at the center of a thin, 5 cm radius carbon fiber tube support (Figures 4 and 5). This solution allow for a very transparent mechanical support, i.e. $X = 6\times10^{-3}\ X_0$/Layer. Each silicon sensor has 50 μm pitch readout strips on each side : the p-side strips run orthogonally to the n-side strips. The design of the double sided sensors will be similar to those used for the L3 Silicon Microvertex Detector (SMD)[2,3].

Two hybrids carry the front end electronics for the p- and n-sides, respectively. On the p-side, there are 1028 channels read by eight 128 channels, AC coupled, charge sensitive preamplifier chips, followed by eight flash analog to digital converters (FADC). On the n-side, there are 384 channels, read accordingly. The hybrids are placed at 90° with respect to the ladder plane and connected to the silicon strips through copper plated microlithographed kapton routers (Figure 5).

3.1 Electronics

To read the long AMS ladders we plan to use a new generation of front-end electronics,

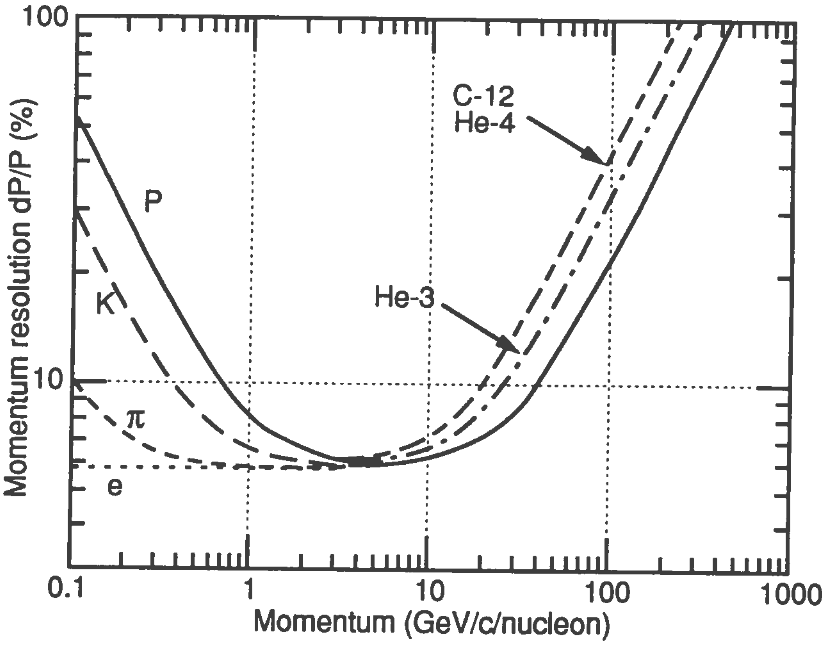

Figure 2 : Momentum resolution of the Silicon Tracker

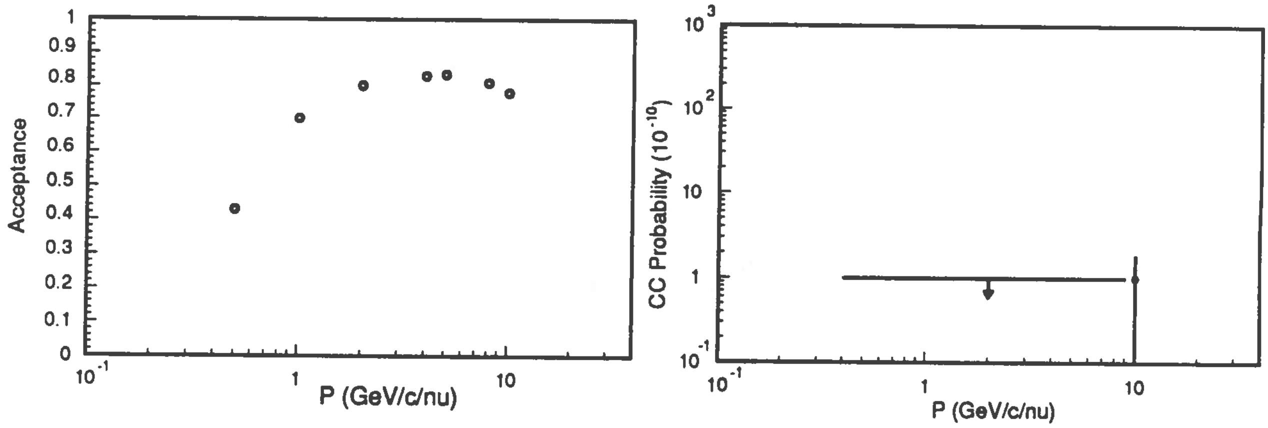

Figure 3 : The (a) acceptance and (b) charge confusion probability for carbon at different momenta

derived from the 'Viking' chip [6]. The Viking Equivalent Noise Charge (ENC) for the large input capacitance corresponding to 50-60 cm of microstrip detectors (≈ 80 pF) is still well below 1500 e^- electrons and this chip can be used to readout 60 cm long ladders with an expected S/N larger than 10. Starting from this observation we built several 63 cm long ladders which were exposed to a high energy test beam [4-5].

The S/N for 63 cm long microstrips is shown in Figure 6: the peak of the distribution is at ≈ 11, as expected.

An improved readout chip, the VA1, based on the same principle as the Viking, can handle much higher capacitive load (> 100 pF). An

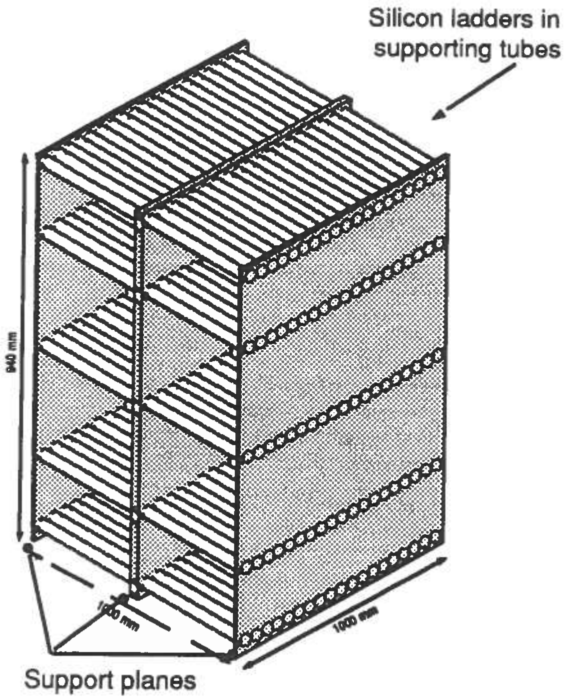

Figure 4 : Silicon tracker mechanical structure

equivalent noise charge (ENC) = 200 e^- + 5.4 e^- C (C in pF) for the prototype[9] and ENC = 165 e^- + 6.1 e^- C for the full 128-channel chip has been measured at 2 μs shaping time. With a power consumption of 1.2 mW/channel, the VA1 has a voltage gain of 12.5 mV/fC and is linear within ±10 Minimum Ionising Particle (MIP) input signal range (1 MIP = 3.6 fC)[10].

Since the VA1 is derived from the Viking design, we expect to reach a factor of two better S/N (> 25). A S/N ≥ 15 would be adequate for our application, since this corresponds to an intrinsic resolution of 7 μm.

4. MECHANICAL AND THERMAL ANALYSIS

In order to exploit the intrinsic accuracy of the silicon microstrip detectors (< 10 μm), the detectors have to be precisely assembled in units (ladders) which need to be very rigid as well as transparent to incident particles. Based on previous experience with the assembly of SMD and prototype ladders for the L3 experiment, we have developed a silicon ladder assembly method based on precisely cut silicon wafers[11]. Figure 7 shows the metrology results for a 63 cm long ladder composed of 10 (63 x 40 x 0.300 mm^3) silicon wafers. Our procedure does not require complicated positioning devices nor intensive use of a microscope which considerably reduces the fabrication time. The results indicate that the wafers are aligned typically to better than ±10 μm. The precision, dominated by the precision of the wafer cut, is satisfactory for this type of assembly where the final positional accuracy is given by the metrology (±5 μm).

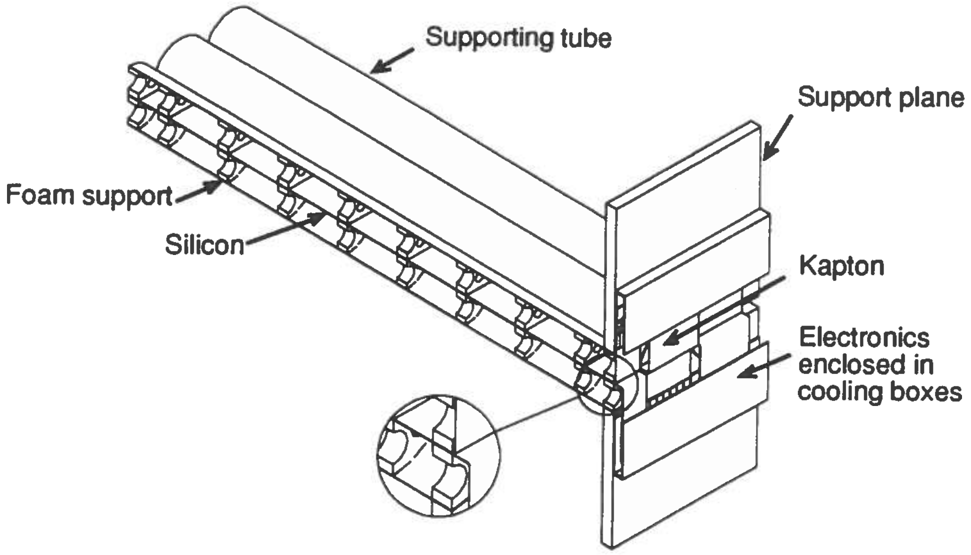

Figure 5 Position of front end electronics

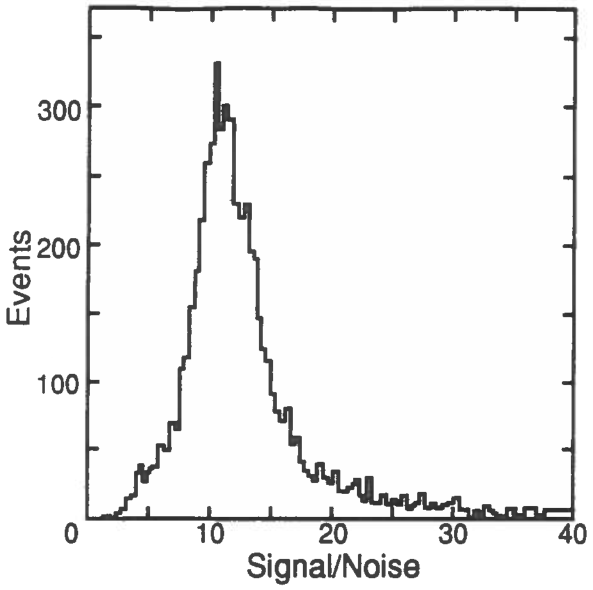

Figure 6 : The signal-to-noise ratio for a 63 cm long silicon ladder

The ladders will be assembled in five (or six) planes, supported by three rigid frames. Figure 4 shows a sketch of multilayer mechanical structure which would fit inside a square magnet. Once assembled, the overall mechanical structure should resist the loads induced at different launch phases, and it should tolerate moderate changes of temperature (± 40 K) and a large change of pressure without significant dimensional changes. The design of the ladders and of the overall mechanical support has been directed towards the requirements for both the Shuttle and ISSA missions[12].

The Spacelab Payload Accomodation Handbook for the Space Shuttle states that two types of adverse mechanical environment have to be considered:

- Static and low frequency transient accelerations.
- High frequency random and acoustic excitations.

As a consequence, the first design rule is to decouple the Silicon Tracker supporting structure from the excitation frequencies during the launch phase. This implies that the design of the structure

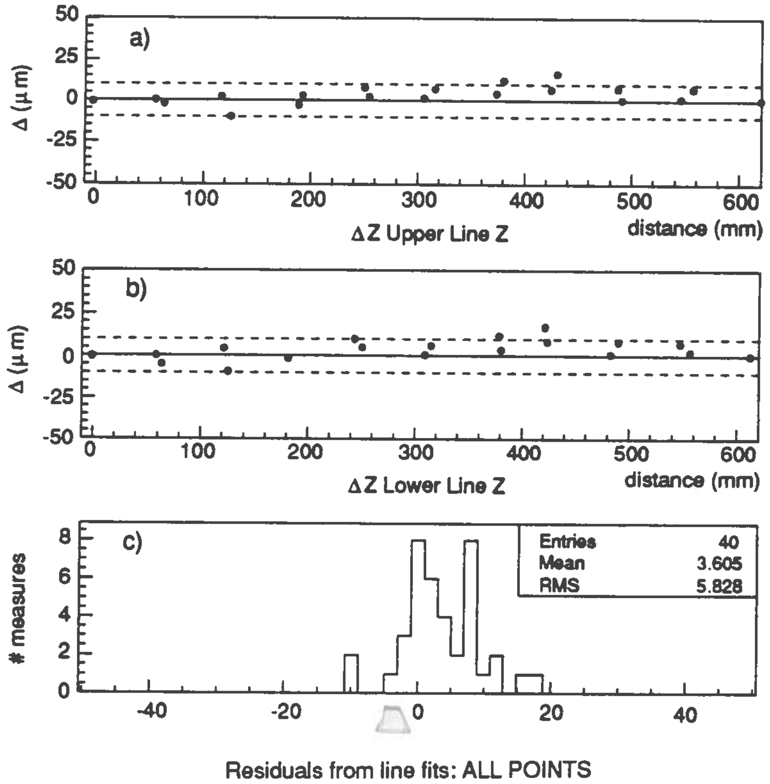

Figure 7 : The metrology results for the 63 cm long ladder: a) point-by-point deviations from straight line (solid line) defined by the first and last reference crosses on upper edge of ladder, b) same distribution as a) for the lower edge crosses, and (c) the residual distribution for all measured points

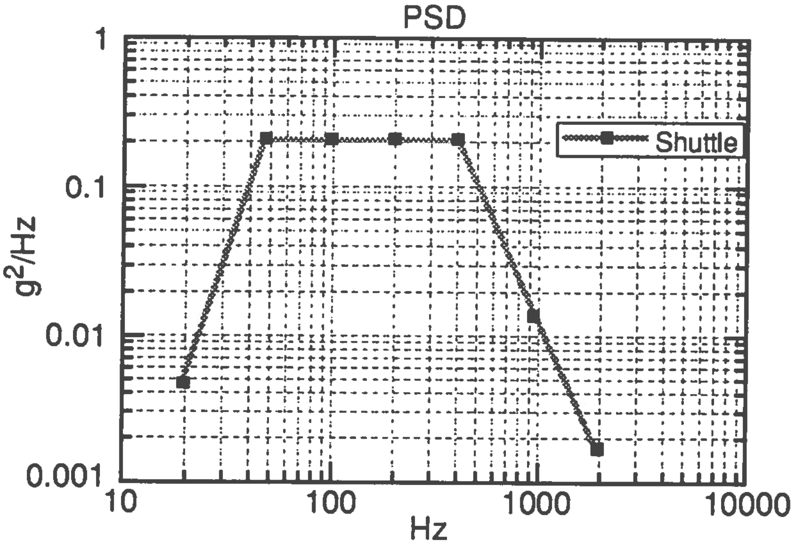

Figure 8 :Power Spectral Density of the high frequency random excitations

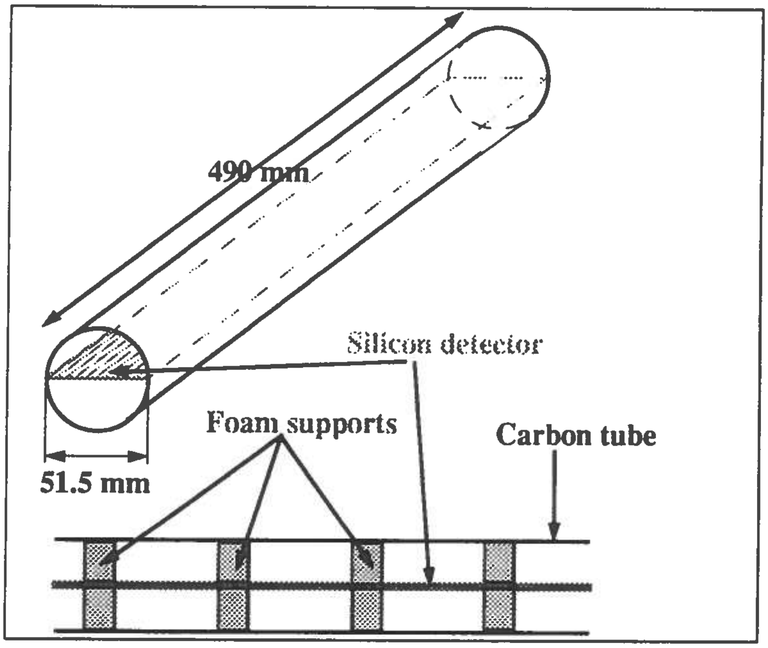

Figure 9 : Description of the structure of a tube used in the mechanical analysis

must ensure that the frequency of the first natural mode is higher than the structure excitation frequencies. This is not a problem for the low frequency transient accelerations (between 0 and 20 Hz) since it is not difficult for relatively small structures, like the one we are studying here, to have natural modes higher than 20 Hz.

A more difficult case concerns the random and acoustic excitations, which are present with the Power Spectral Density shown in Figure 8. Since we cannot get all eigenfrequencies higher than 2000 Hz, we have found a compromise between cost, mass and eigenfrequencies. We have chosen 0.02 g^2/Hz as the upper limit for the Power Spectral Density of vibration corresponding to the eigenfrequencies of the structure. This implies that all structural eigenfrequencies must be higher than 850 Hz.

This can be obtained by using very light and rigid materials, such as carbon fiber composites

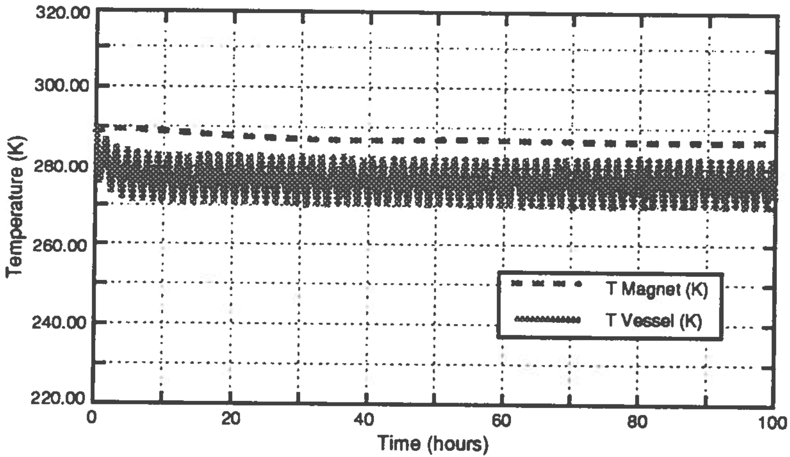

Figure 10 : Temperature of the magnet and vessel for $\varepsilon_V = \alpha_V = 0.6$ paint (Lower curve vessel temperature. Higher curve magnet temperature)

and sandwich structures[13]. For the tube supporting structure shown in Fig. 9 we have obtained the first eigenfrequency above 1400 Hz.

A modal analysis of the full structure has given the first eigenfrequency of the structure at 916 Hz.

A static load analysis with a $80\ ms^{-2}$ acceleration gave 3 μm as maximum displacement, and maximum Von Mises stress of 2.2 MPa.

This is negligible compared with the yield strength of the carbon fibre composites : between 620 and 800 MPa. A shock analysis has also been carried out and showed maximum Von Mises stress of 16 MPa, far below the limit for carbon fiber composites. These results confirm that it is possible to build a very stable, strong and light supporting structure satisfyig the needs of the AMS Silicon spectrometer.

We have also studied the thermal performance of the structure, assuming that the tracker is located inside a square section magnet surrounded by a cylindrical vessel. We have taken into account the known heat sources and heat fluxes and the parameters of the AMS design and we have iteratively solved the thermal equations.

There are several means of controlling the temperature of the vessel: We have found through finite elements simulations that the optimization of the emissivity and the absorptivity of the outer vessel coating it is sufficient to efficiently control the AMS thermal behaviour without active elements. A good approximation has been found using $\varepsilon_V = \alpha_V = 0.6$, which corresponds to ordinary white paint (see Figure 10). We notice that the magnet rapidly reaches the ±5 K range around its equilibrium temperature. In this study we have also verified that for the purpose of thermal equilibrium the role of a gas inside the AMS vessel is of negligible importance, due to the absence of gravity and of convective motions.

5. CONCLUSIONS

We have presented the design of the Silicon Tracker for the AMS experiment on the ISSA station. Thermal and mechanical properties of the fiber carbon support proposed for this detectors satisfy the requirements of a space mission, ensuring the protection of the silicon detectors during the lauch phases and an order of a few micron mechanical stability during AMS operation. Tests performed on 63 cm long silicon microstrip protoype ladders, show that both the front end electronis performances and the ladder mechanical accuracy are well within the requirements. This silicon tracker would have a sensitiviy to antinuclei of better than 10^{-10}, matching AMS primary physics goal with a technology which is attractive for an experiment in space.

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