Chapter II

The Construction of AMS-01 for the First Flight

According to the NASA-DOE Agreement, before installation on the Space Station, AMS would perform a system check on the Space Shuttle to ensure that:

(i) the AMS experiment can function properly in the vacuum of space, with orbital temperature changes from -65^0 C to 40^0 C, and intense radiation background (which contains heavy nuclei causing single event latch-up in chips).

(ii) the detector can withstand the tremendous vibrations (150 Db) at launch, acceleration to 3 g at launch, and de-acceleration to 6.5 g at landing;

(iii) the AMS team can work in real time with the very large NASA staff at Johnson Space Center and Kennedy Space Center during the mission following NASA's mission protocol.

In addition, we wanted to use this opportunity to perform a limited measurement of cosmic ray spectra so as to be able to optimize the detector performance on the Space Station.

For the Space Shuttle flight, the configuration of AMS-01 is shown in Figure 4 below.

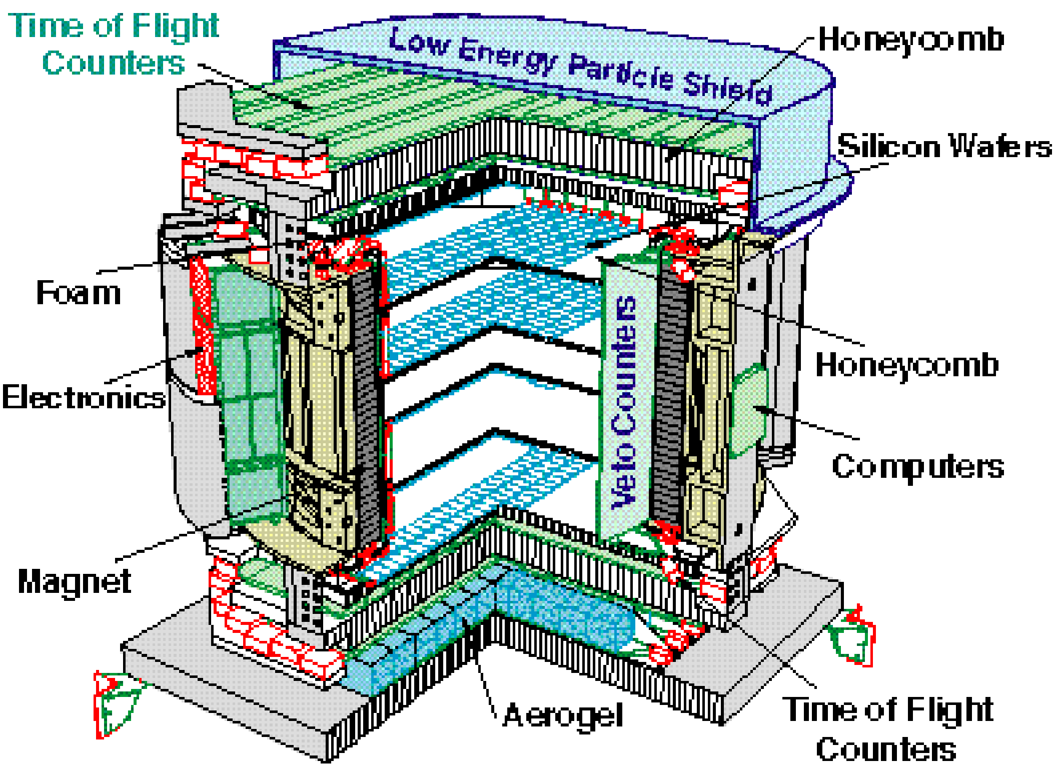

Figure 4 : AMS-01 configuration for the Space Shuttle flight.

I. The Construction of AMS-01 Magnet.

The AMS-01 magnet was made from 64 high-grade Nd-Fe-B sectors. Each sector was composed of 100 x (2” x 2” x 1”) blocks.

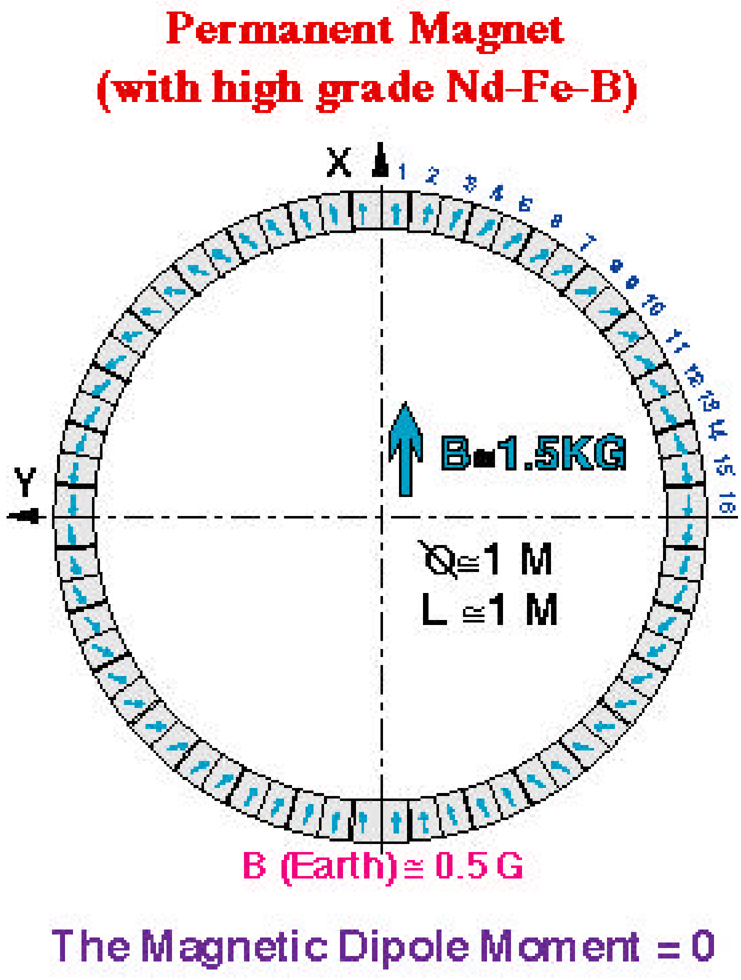

Figure 5 : Magnetic field orientation of the AMS-01 magnet

Figure 5 shows the arrangement of field direction of the 64 sectors. We used the highest grade Nd-Fe-B blocks with an energy level of $(BH)_{max} = 50 \times 10^6$ GO_e. This configuration produced a dipole field of 1.5 KG and a negligible dipole moment. [1] In addition, the flux leakage at 2 meter distance from the center of the magnet is 3G. [2]

Before the construction of the full scale magnets, a 1:3 scale magnet was built to confirm and measure the field inside the magnet, the dipole moment and the flux leakage.

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[1] The earth’s magnetic field is 0.5G. A strong dipole moment would result in an uncontrollable force on the shuttle and space station.

[2] NASA requires the leakage field to be < 300G so as not to interfere with the life support system of the astronauts.

Figure 6 shows the dimensions of the AMS-01 flight magnet :

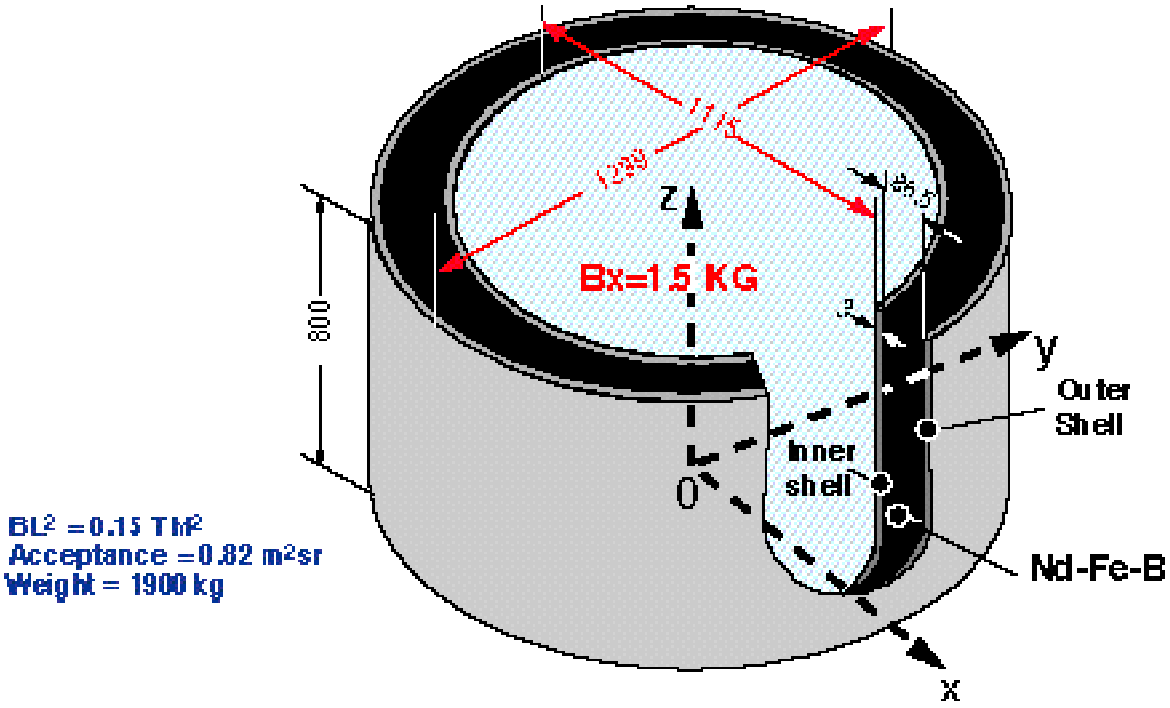


Figure 6 : **Properties of the AMS flight magnet**

Three full scale magnets were built:

(i) the first magnet was used in acceleration and vibration tests for space qualification;

(ii) the second magnet was the flight magnet;

(iii) the third magnet was built without glue for NASA safety tests.

The design of the AMS magnet was carried out by MIT together with the Institute of Electrical Engineering of the Chinese Academy of Science, Beijing. The magnet, the supporting structure and space qualification testing were completed by the Institute of Electrical Engineering and the Chinese Academy of Launch Vehicle Technology (CALT) under close supervision from NASA and Lockheed Martin.

Figure 7 shows the first magnet undergoing vibration testing.

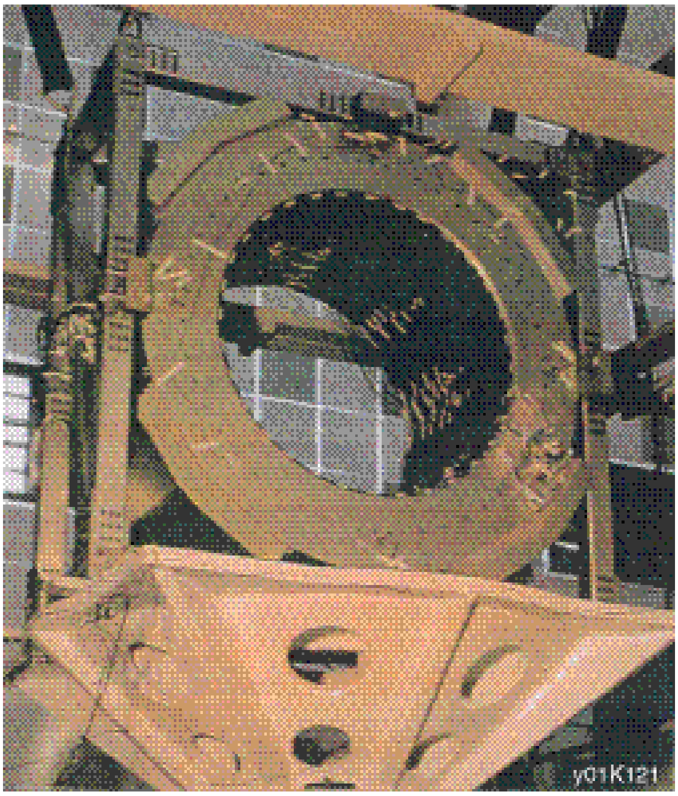


Figure 7 : **AMS magnet being subjected to vibration tests at the Beijing Institute of Spacecraft Environment and Engineering in Beijing, China, as part of the magnet's program of space qualification testing.**

Figure 8 shows the first magnet undergoing centrifuge testing up to 17.7g.

Figure 8 : **AMS magnet being subjected to centrifuge testing at the Laboratory for Centrifugal Modelling in Beijing, China, as part of the magnet's space qualification testing.**

Figure 9 shows the comparison of the sine sweep test results before and after 17.7g centrifuge tests. The test results indicate that there is no deformation in the detector before and after the 17.7g centrifuge test and that the eigenfrequency for the magnet is above the shuttle eigenfrequency of < 50 Hz.

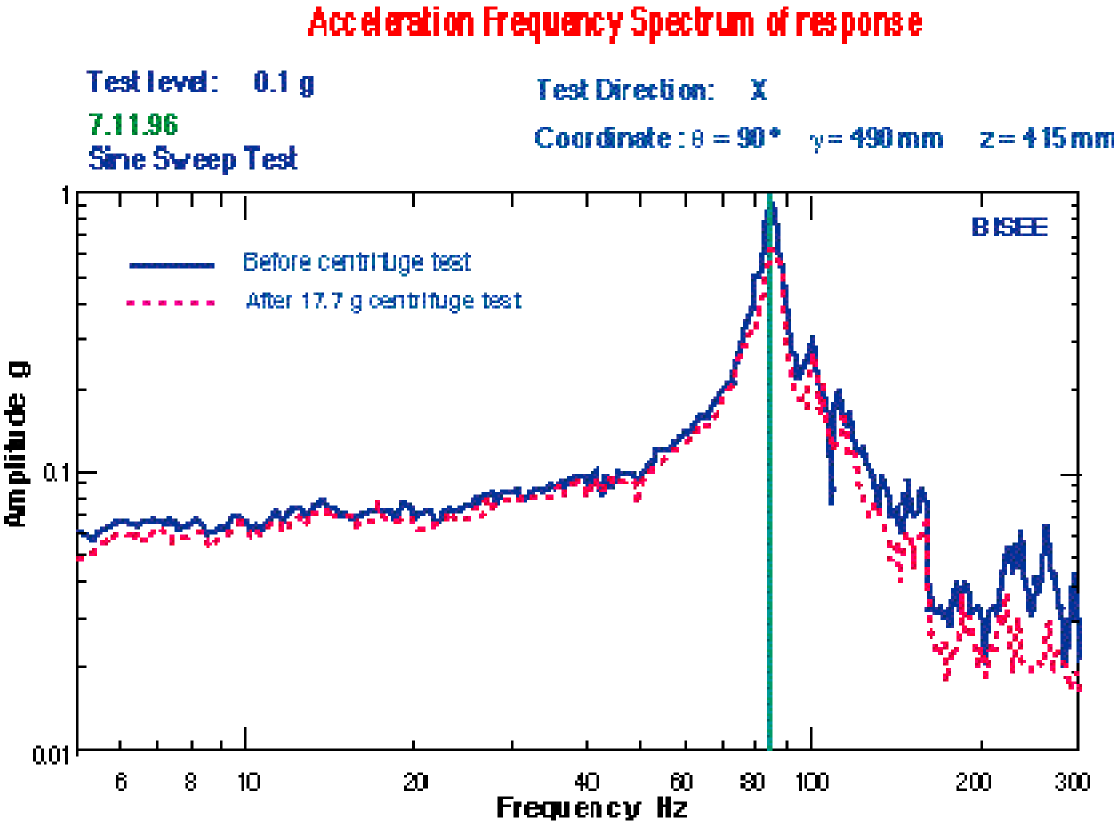


Figure 9 **Sine sweep test frequency spectrum response of AMS magnet before and after 17.7 g centrifuge test.**

The AMS-01 flight magnet was completed and transported to the Swiss Federal Institute of Technology (ETH), Zürich, for integration on 15 March 1997.

An independent team of specialists from CERN, together with ETH physicists, mapped the entire volume of the AMS-01 flight magnet and determined that the field agreed with the design value to within a 1% level.

The third full scale magnet was built because of the lack of knowledge of the glue performance over an extended period of time in a space environment. We built the magnet without using any glue to be tested to destruction to ensure that AMS could be returned on the Shuttle to Earth even if the glue completely failed.

Figure 10 shows a schematic of the test procedure on the third magnet.

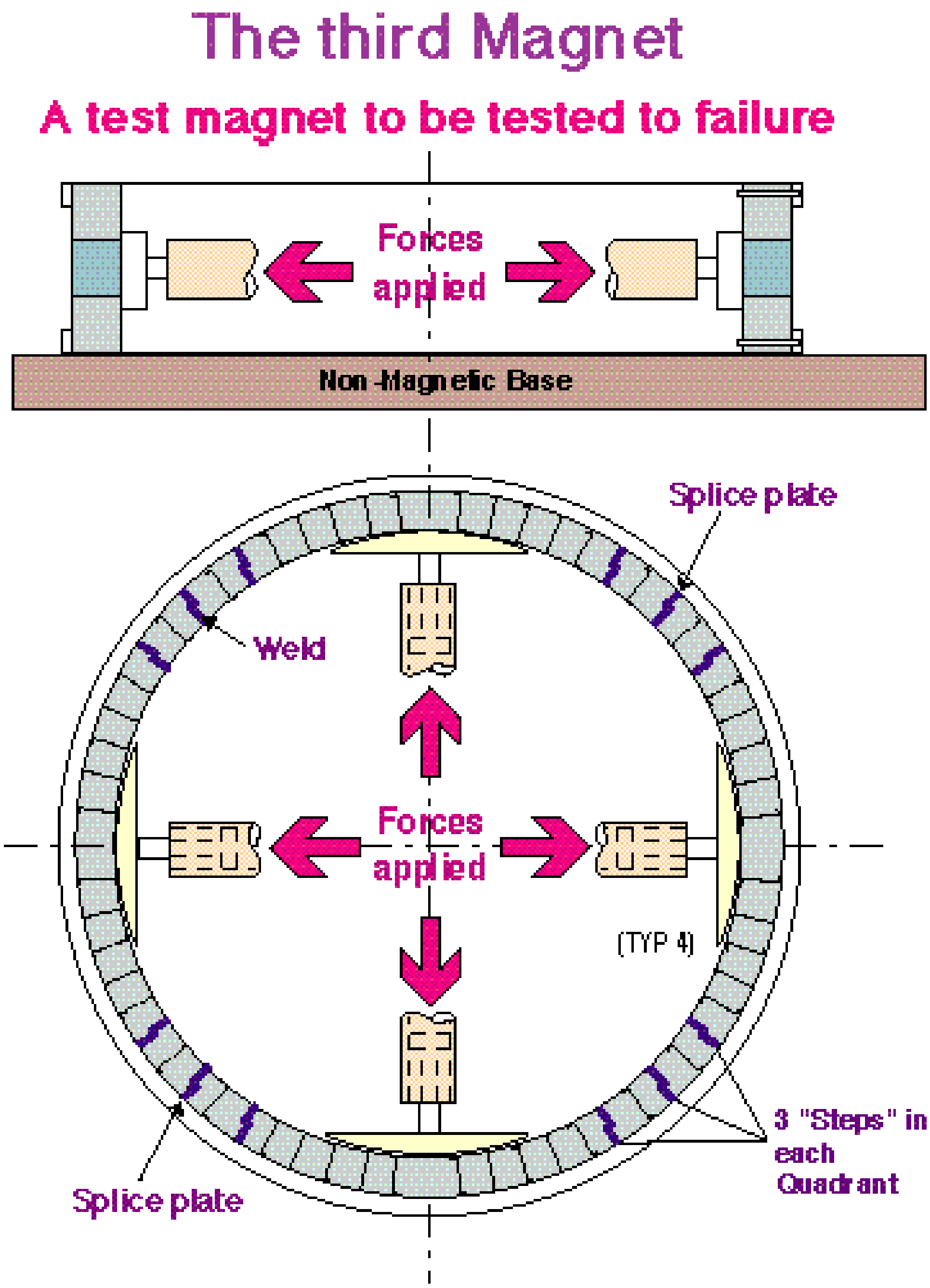


Figure 10: Schematic of the third magnet to test to destruction.

Table 5 below is a portion of the test report indicating that the AMS-01 magnet can withstand ten times higher stress conditions than what analysists indicated would cause failure.

In August 1997 we successfully completed a static test on a segment of the AMS magnet support structure.
This segment is similar to the flight magnet structure except that it was intentionally made weaker and no glue was installed to retain the magnets.

It was our intention to cause a catastrophic failure of the structure under internal loads exceeding those induced by the flight magnet material and external loads GREATLY exceeding launch and landing conditions.

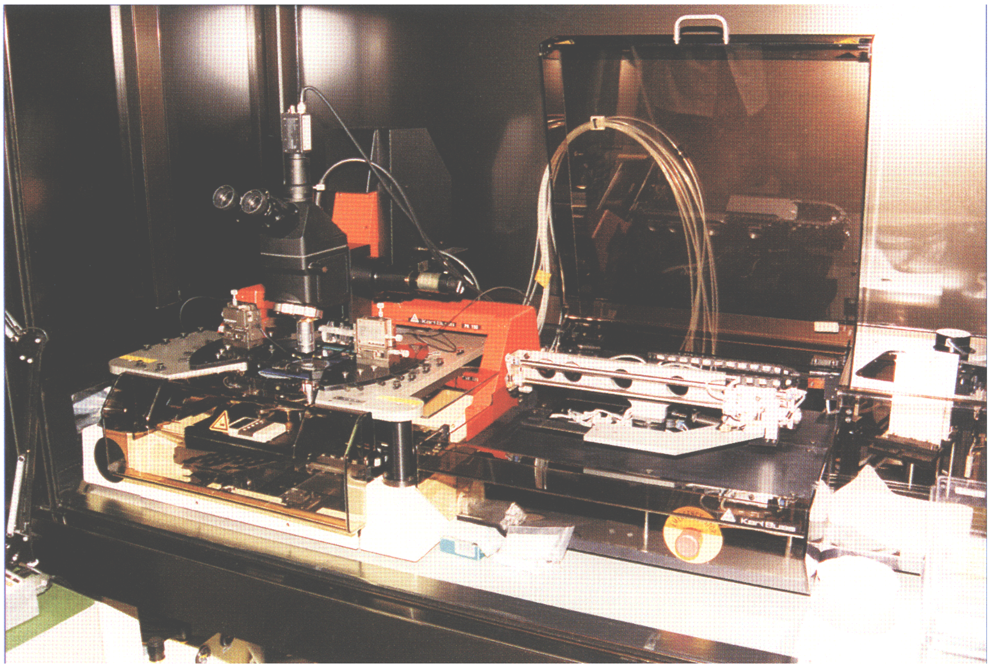
In this way we could get a better handle on the structure margin of safety as well as the failure mode if the shells were breached and the magnets were somehow allowed to escape.

We applied loads that were 3 to 10 times higher than what the stress analysists indicated were required to fail the structure. ...*IT WOULDN'T BREAK!*

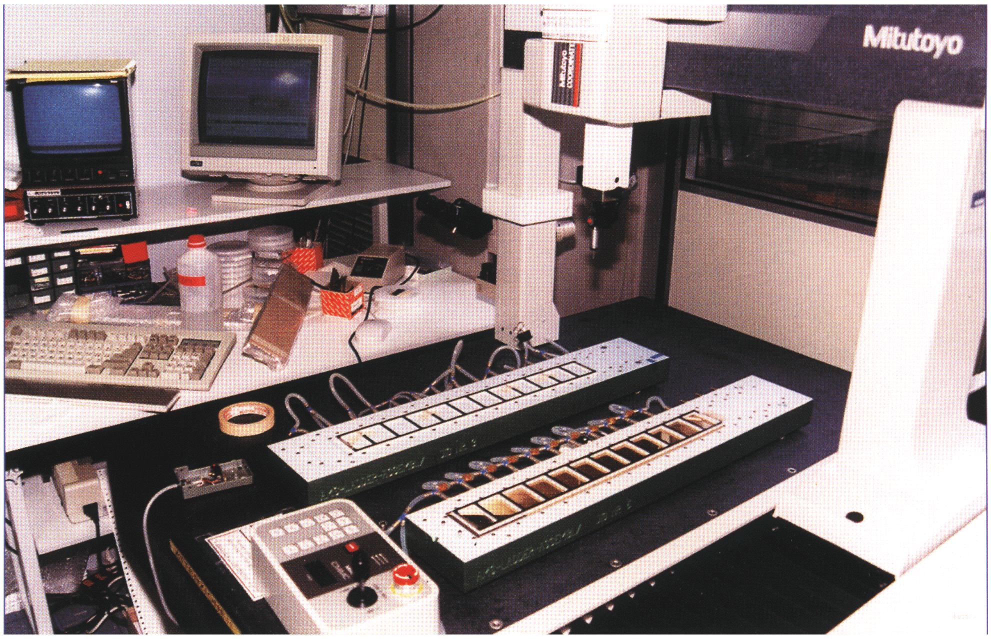
We finally ran out of load application hardware capability and yet the test article was still intact. We then reconfigured the hardware to cause even higher stresses. ... the stucture finally yielded, but still wouldn't break.
Therefore, the AMS flight magnet structure is way more than adequate even if there were a complete glue failure.

The design could even be used to house stronger magnets in the future if they became available before the ISS flight.

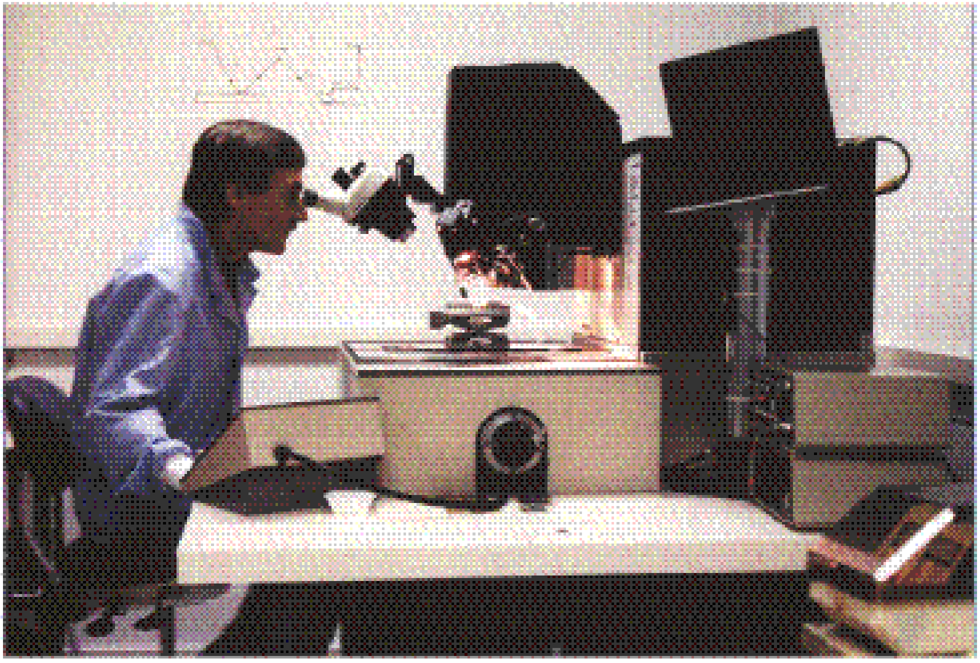
Table 5 : NASA Report of stress test on the AMS-01 magnet .



A total of about 3 million diode elements have been tested at Perugia using a specially developed high-speed testing machine operating 24 hours a day and recording all data on a database.



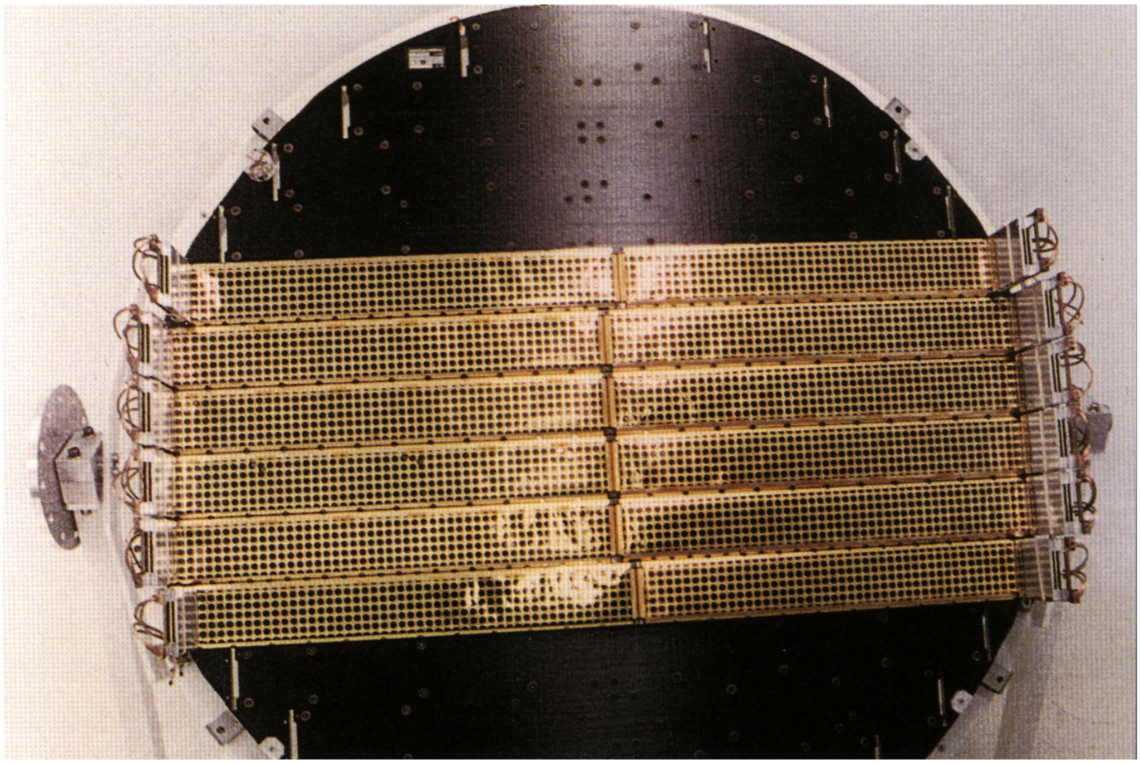
High precision tri-dimensional metrology machine used at the University of Perugia.



Wire bonding of silicon microstrip sensors under microscope at the University of Geneva.

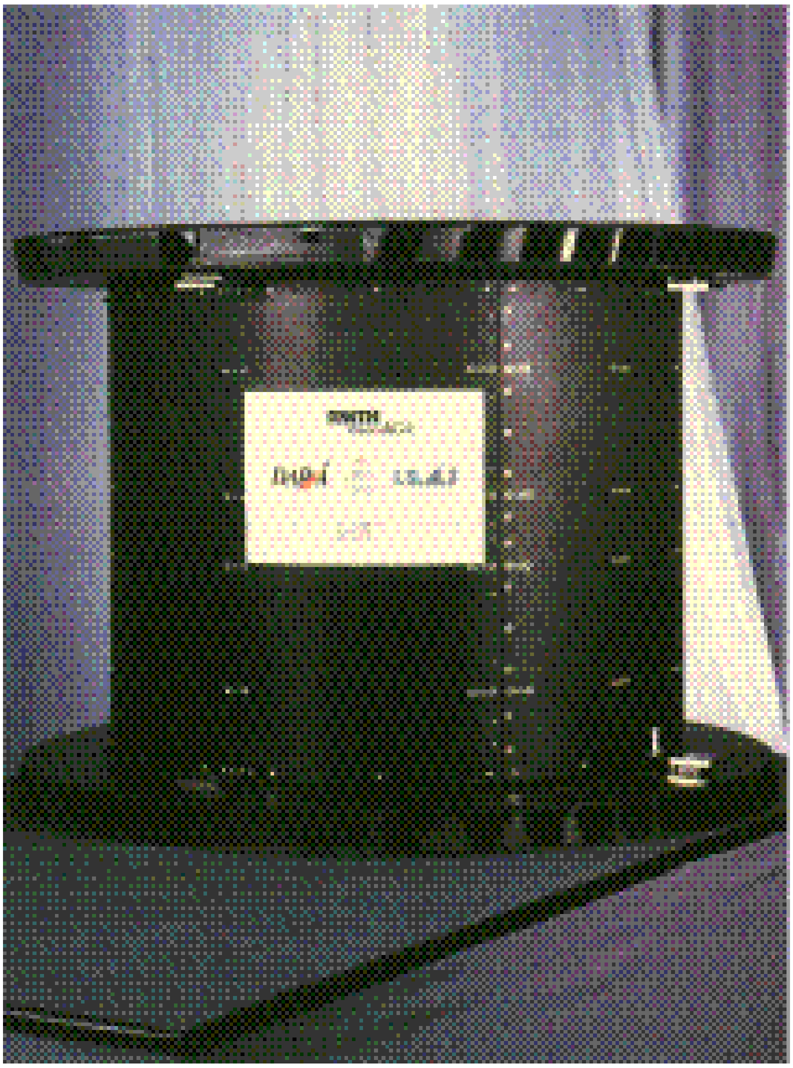
Gluing and metrology work at ETHZ.

The silicon ladders were wrapped in an ultra-thin copper coated electromagnetic shield. The ladders went through electromagnetic compatibility tests in range of KHz, MHz and GHz to establish EM immunity levels. The completed ladders were assembled on six thin honeycomb plates with a combined thickness X/Xo < 3.2%. Each of these, measuring 1 m in diameter, contained precision holes for attaching the silicon ladders and ensuring their flatness to 80μm. They were designed to allow the ladders to be aligned independently of temperature, humidity and air pressure changes. The photograph below shows the integration of the silicon ladders on one of the six plates.



Integration of silicon ladders by the University of Geneva team on one of six ultralight plates.

The support structure for the six planes was made from a carbon composite material to be light-tight and equipped with a cooling system that removes heat produced by the Tracker's front-end electronics. This is shown in the photograph below.



Final preassembled silicon tracker carbon-fiber composite (CFC) mechanical structure including the CFC upper and lower support flanges.

To ensure that the AMS-01 detector had the desired accuracy, we developed an infrared laser alignment system. The laser beams partially ionize the silicon as they traverse the Tracker structure. The system provides positional accuracy of a passing particle through each of the six planes to within a few microns. This system is shown in Figure 12 below.

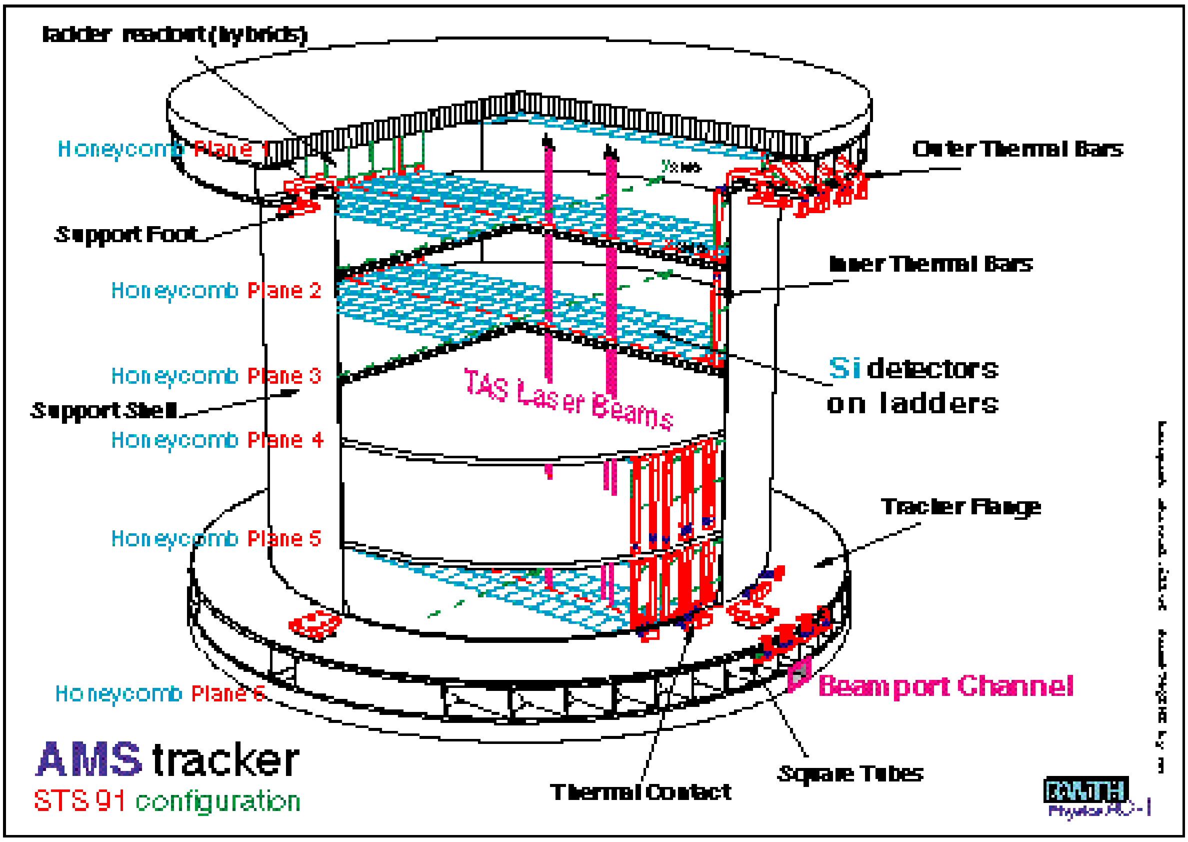


Figure 12 : Laser alignment system for AMS-01 Tracker.

The front-end electronics of the Tracker were made of very low noise VLSI units. Each channel consists of a sample and holds low-noise charge preamplifier, readout sequentially at a speed up to 5 MHz. The Data Reduction Electronics for the Tracker were specially designed to be light weight and use minimum power. The ladders and all the Data Reduction Systems went through vigorous space qualification testing including acceleration, vibration, thermal vacuum and temperature tolerance.

The ladders were tested in a heavy ion test beam at Gesellschaft für Schwerionenforschung (GSI) Darmstadt, Germany, with H, He, Li and C. Figure 13 demonstrates the dE/dX response linearity.

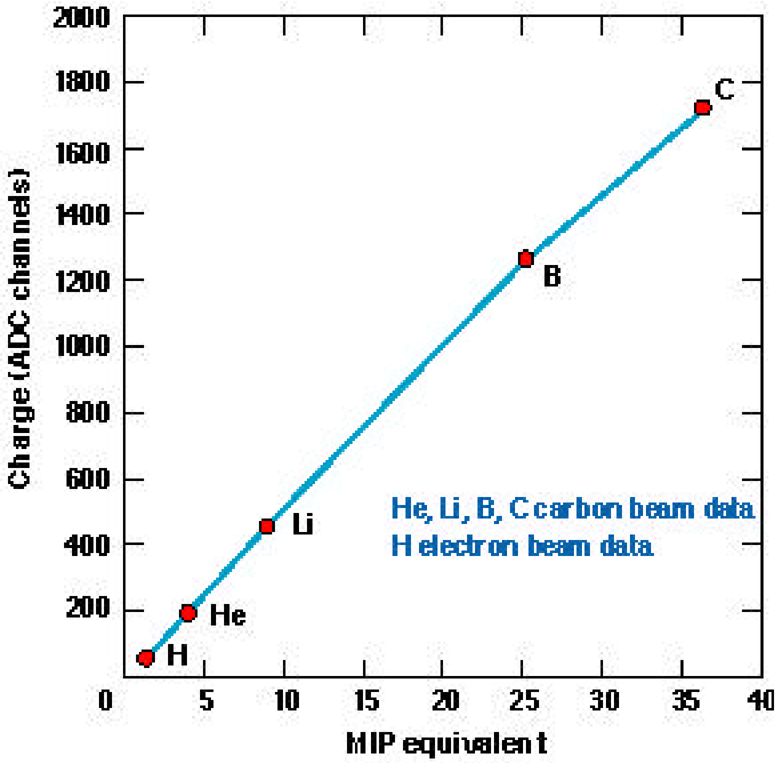
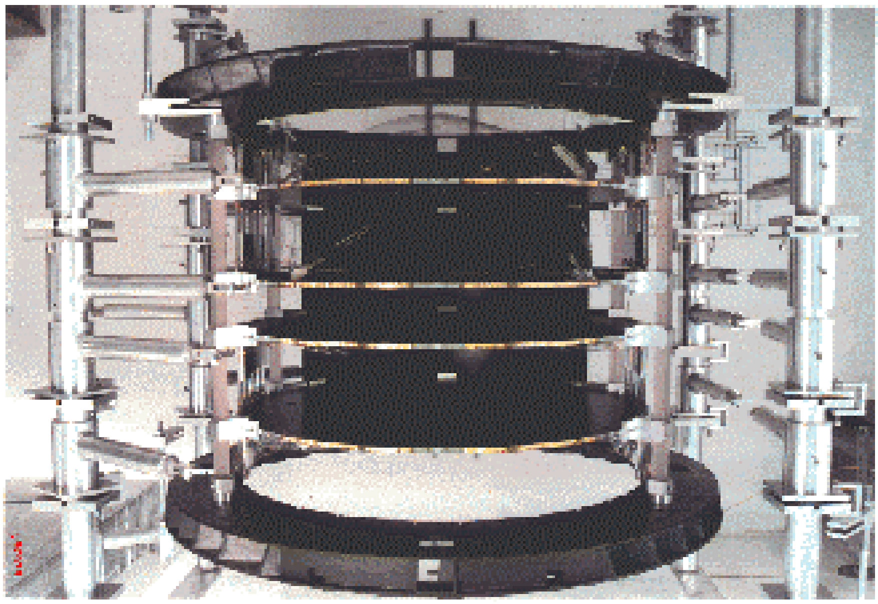


Figure 13 : Linear Response of Silicon Ladder.

The AMS-01 Tracker system was integrated and surveyed within the magnet during the late summer of 1997. To maintain the designed accuracy, a careful procedure was implemented during the assembly sequence. The photograph below illustrates one of the steps in the Tracker assembly procedure.



Silicon tracker in the assembly stage at ETHZ after installation of the upper flange, plate 2, plate 3, plate 4, plate 5 and lower flange. The tracker was supported during this assembly stage by four highly precise quartz bars.

3. AMS Counter System.

There are three types of counters in the AMS-01 detector.

(i) **The veto counters** are a wall of 16 modules of plastic scintillators surrounding the Silicon Tracker inside the magnet. Their function, in conjunction with the Time of Flight Counters, is to provide anti-coincidence protection against background particles entering the sides of the AMS apparatus or generated within AMS. Such events can create confusion in the event reconstruction or timing from the Time of Flight System. There is one phototube at each end of the scintillator. Because of the very limited space available and to maintain structure stability, very special thin fibers were used to guide the light to the phototubes (see photo hereafter). Much effort was spent to ensure the veto counters were 100% efficient. Figure 14 shows the measured number of photoelectrons from the top and bottom of one of the veto counters. As seen, the measured value is 32 photoelectrons where the designed value is 10 photoelectrons.

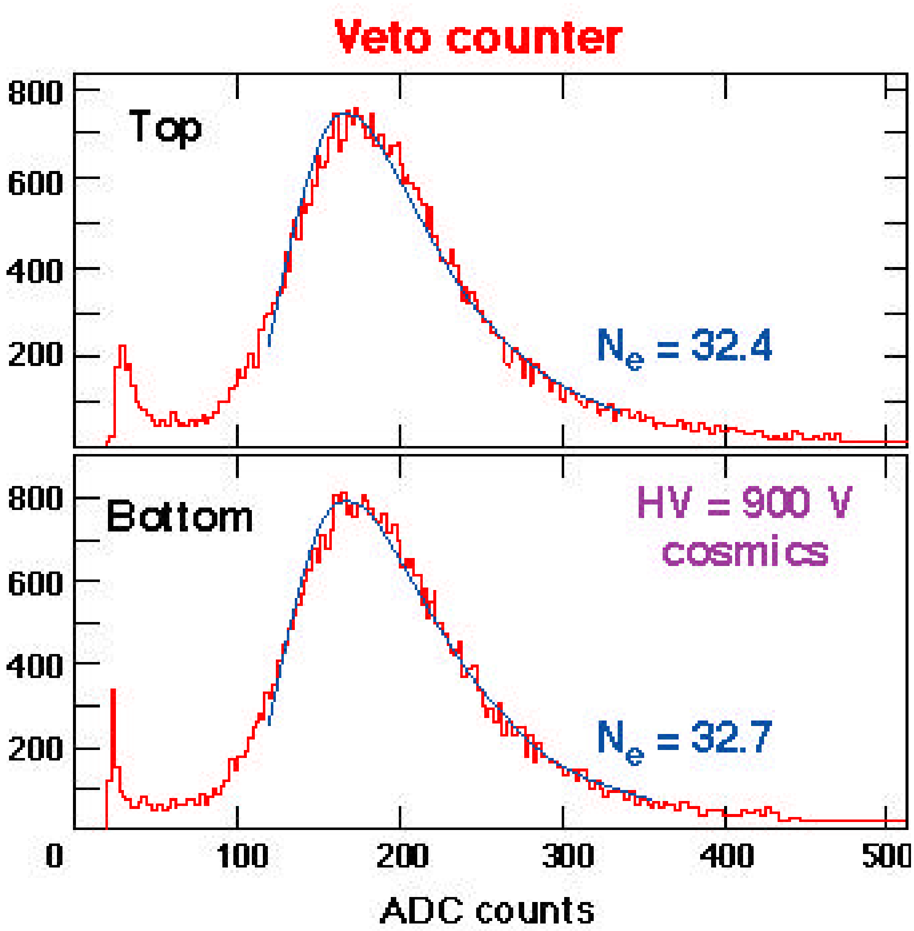
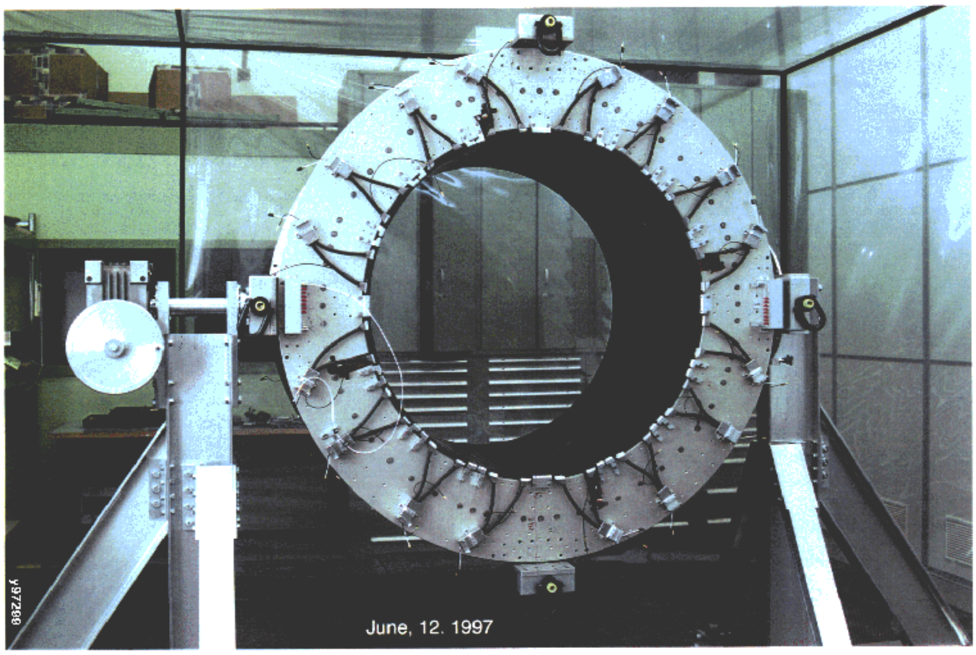


Figure 14: Measurement of number of photoelectrons from the top and bottom photomultiplier tubes.

The counters are supported in a specially made carbon-composite reinforced cylinder. The photograph below shows the final assembly of all 16 modules of veto counters inside the AMS-01 magnet.



Final Flight Assembly of all 16 modules of the anti-coincidence counter system in the AMS-01 magnet at ETHZ. The Carbon Fiber reinforcement cylinder is visible inside.

(ii) The AMS-01 Time of Flight Hodoscopes :

The purpose of the Time of Flight System is as follows:

- provide the first-level trigger;
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The four layers of Time of Flight Counters (S1-S4) contain 14 scintillator hodoscopes each. Each hodoscope is viewed by three photomultipliers at each end, as shown in Figure 15 below.

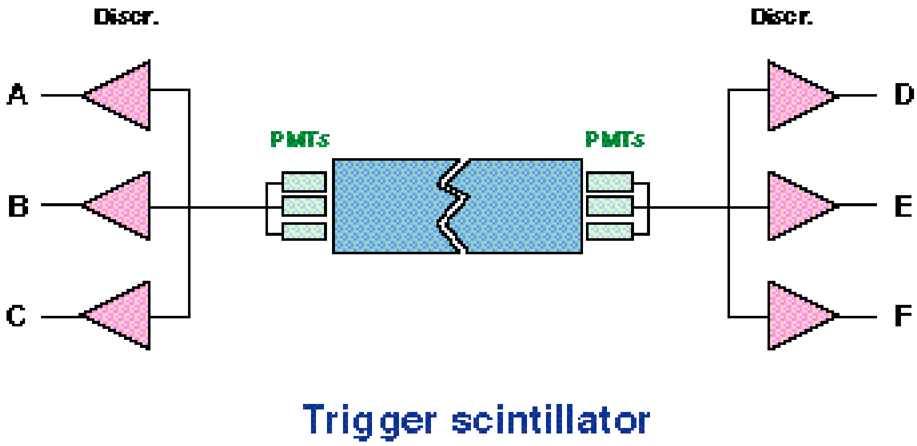

Figure 15 : Schematic of AMS-01 Time of Flight counters design.

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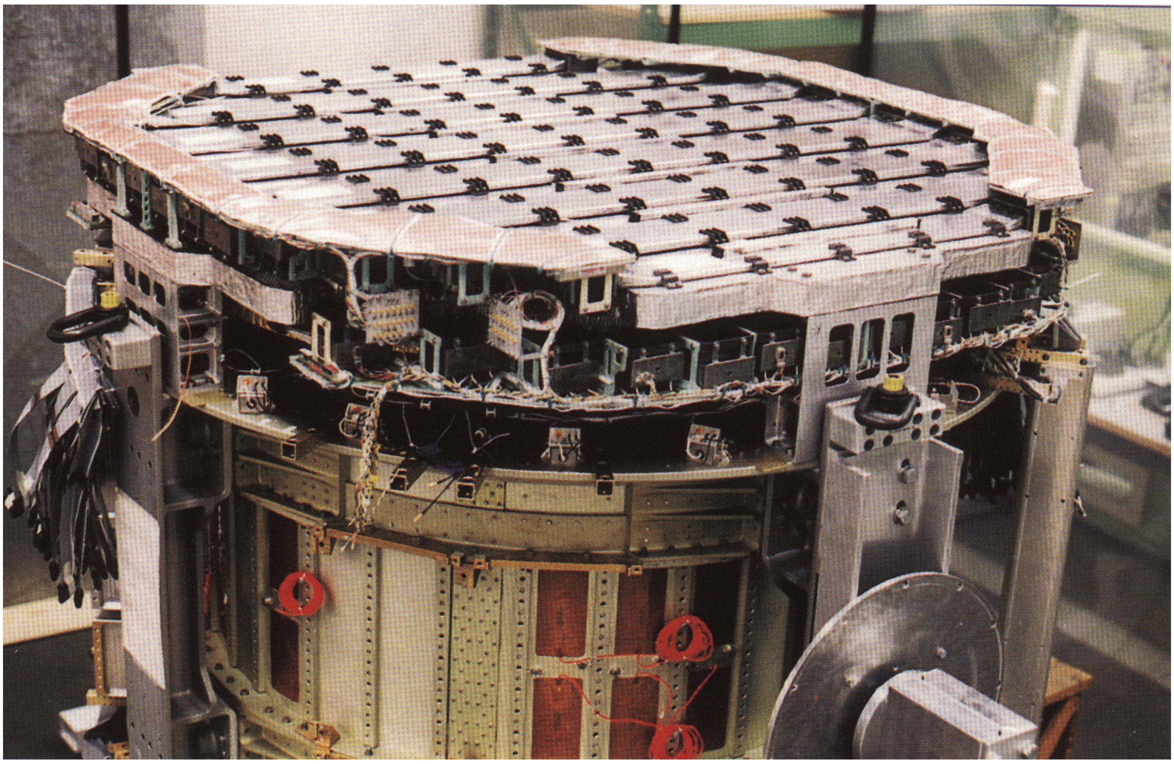


Mounting of Time of Flight on AMS-01 detector during detector integration at ETHZ (end of October 1997).

(iii) Aerogel Cerenkov Counters:

For the AMS-01Shuttle flight we replaced the RICH and ECAL with Aerogel Cerenkov Counters which had a refractive index n = 1.04. The Aerogel counters were made out of two superimposed layers of cells 11 x 11 cm^2, each layer consisting of 80 (top) and 88 (bottom) cells of aerogel blocks. Each block was individually coupled to two photomultiplier tubes which detect Cerenkov light from electrons (from 2.1 MeV), pions (from 560 MeV) and protons (from 4.05 GeV). This information enabled us to identify antiprotons up to 4 GeV.

Figure 16 shows the design of an aerogel counter cell.

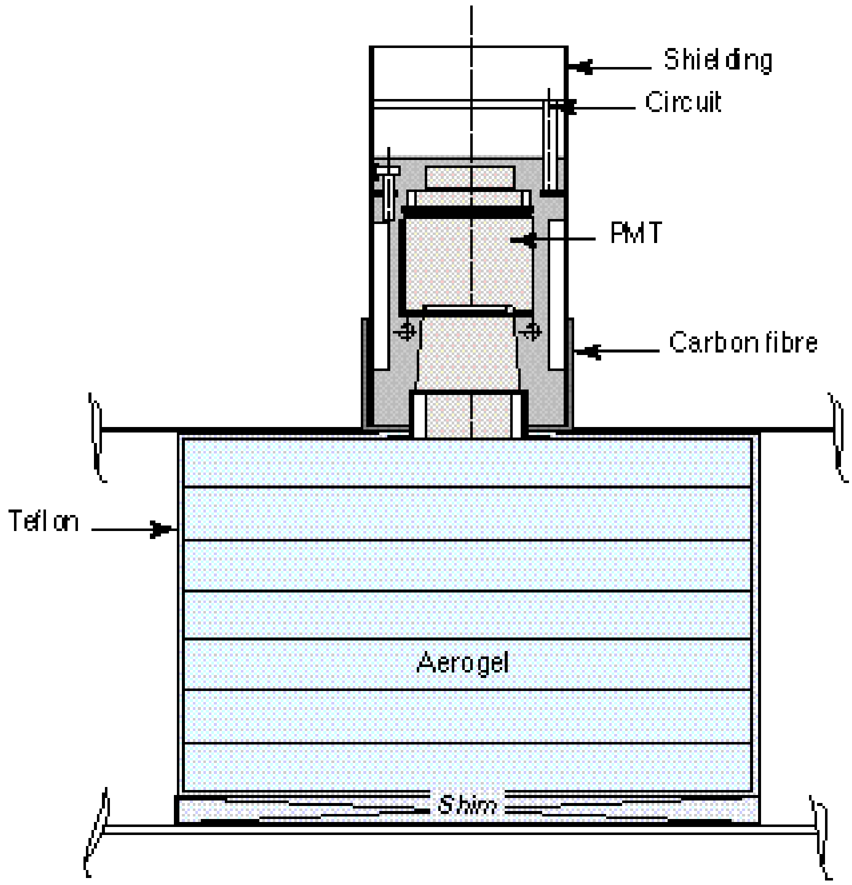


Figure 16 : A cell of the Aerogel Counter.

2. The AMS Silicon Tracker.

Figure 11 shows the location of the AMS-01 Silicon Tracker in the magnet and the specifications of the Tracker.

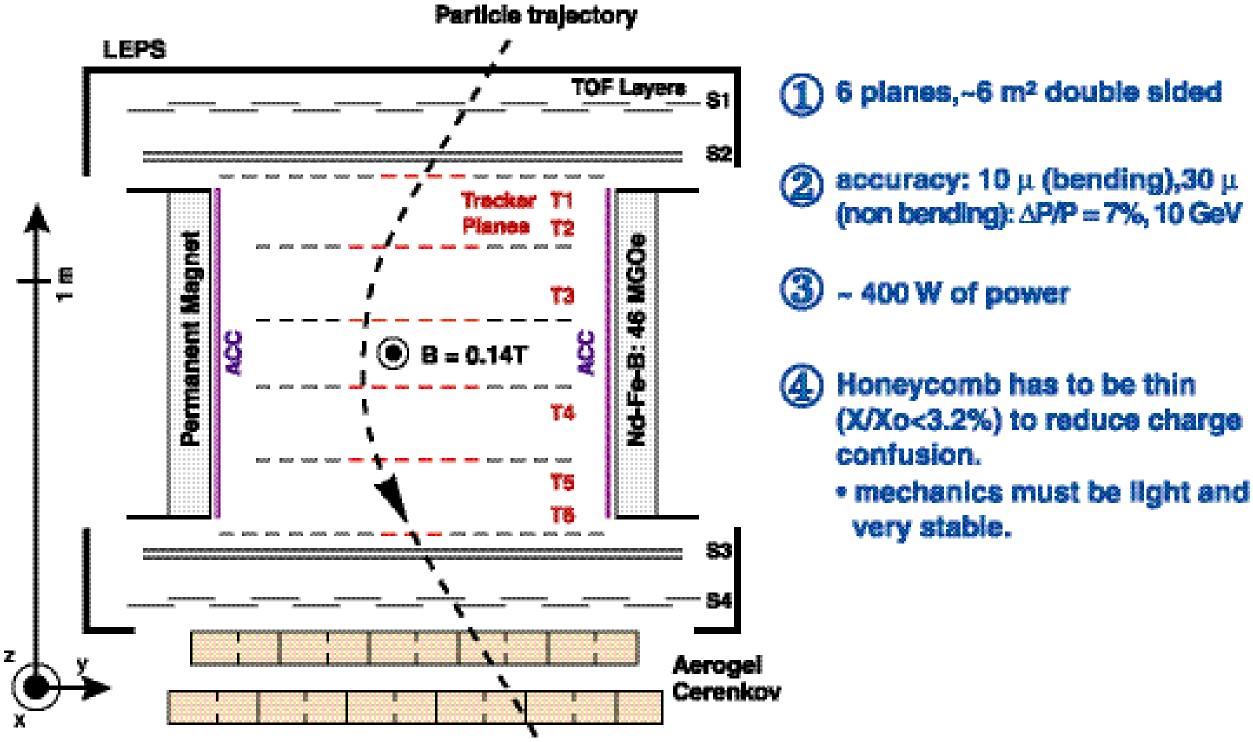
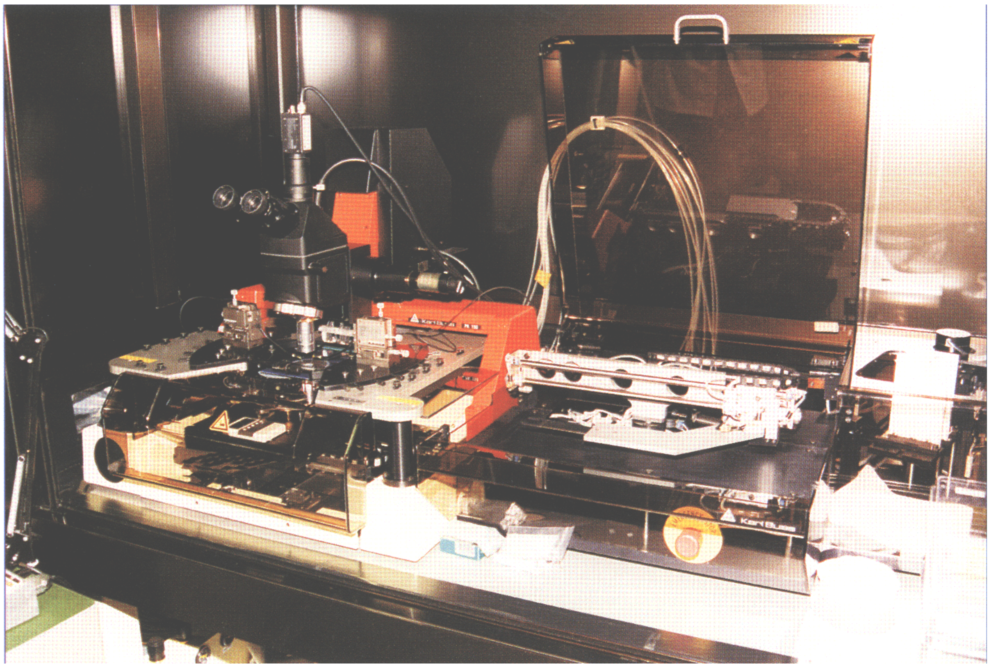


Figure 11 : Location and properties of the Silicon Tracker. Out of the total 6m^2, for this engineering flight 3m^2 were installed, as shown in red.

The design and construction of the Tracker benefited from the construction and operational experience of the Silicon Microvertex Detector (SMD) at the L3 experiment. For the AMS-01 shuttle flight, half the Silicon Tracker was used. To produce a total of 3 m^2 double-sided silicon with a resolution of 10μ in the bending plane and 30μ in the non-bending plane with a total of 70,000 channels, three production facilities were set up : one in Perugia, one at ETH/Zürich and one at the University of Geneva. The photographs below show some of the coordinated international effort from 1995 to 1997.



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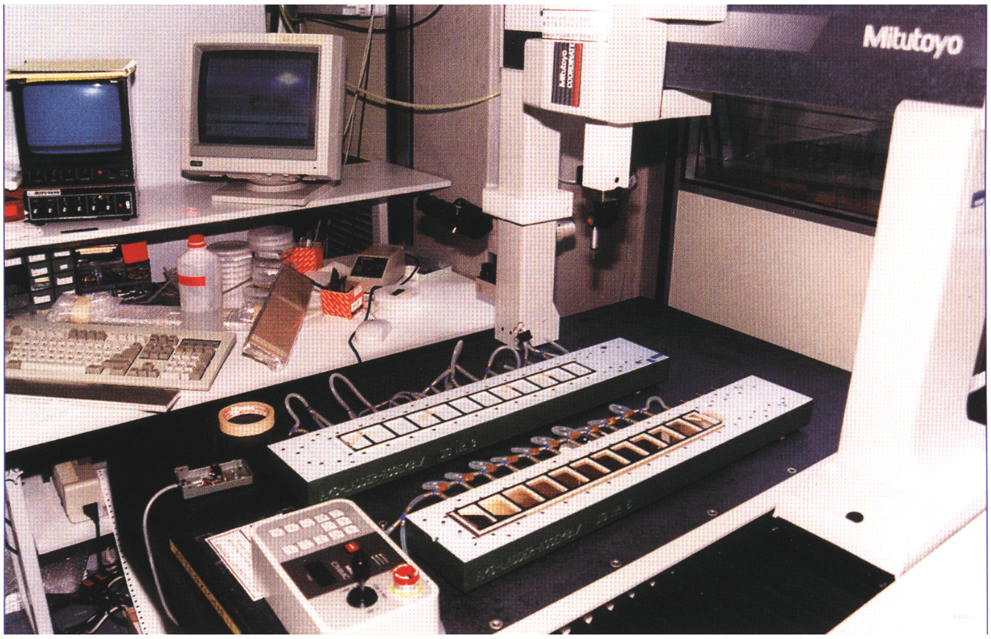

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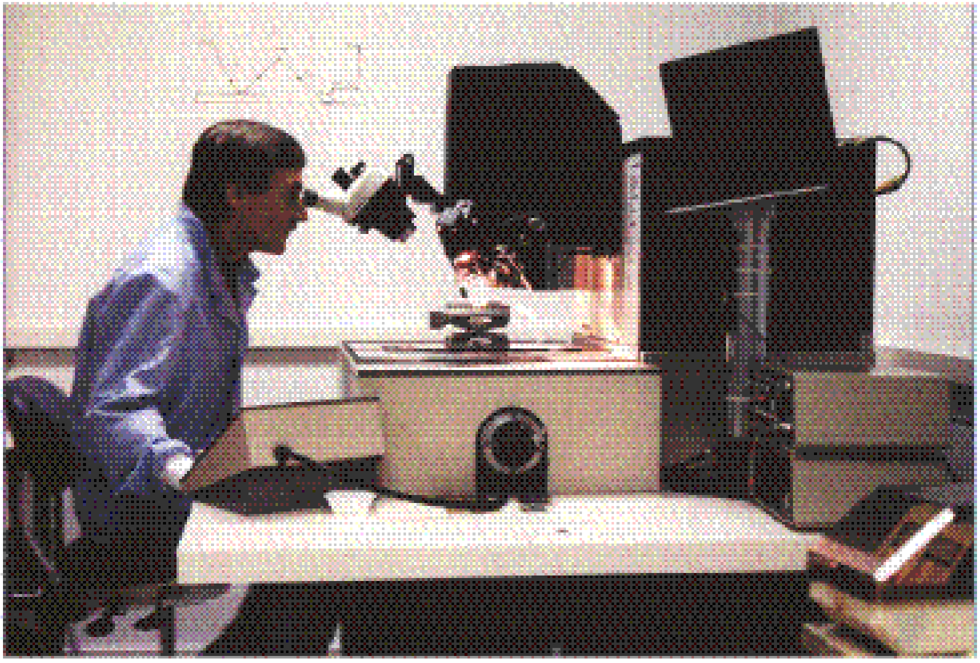

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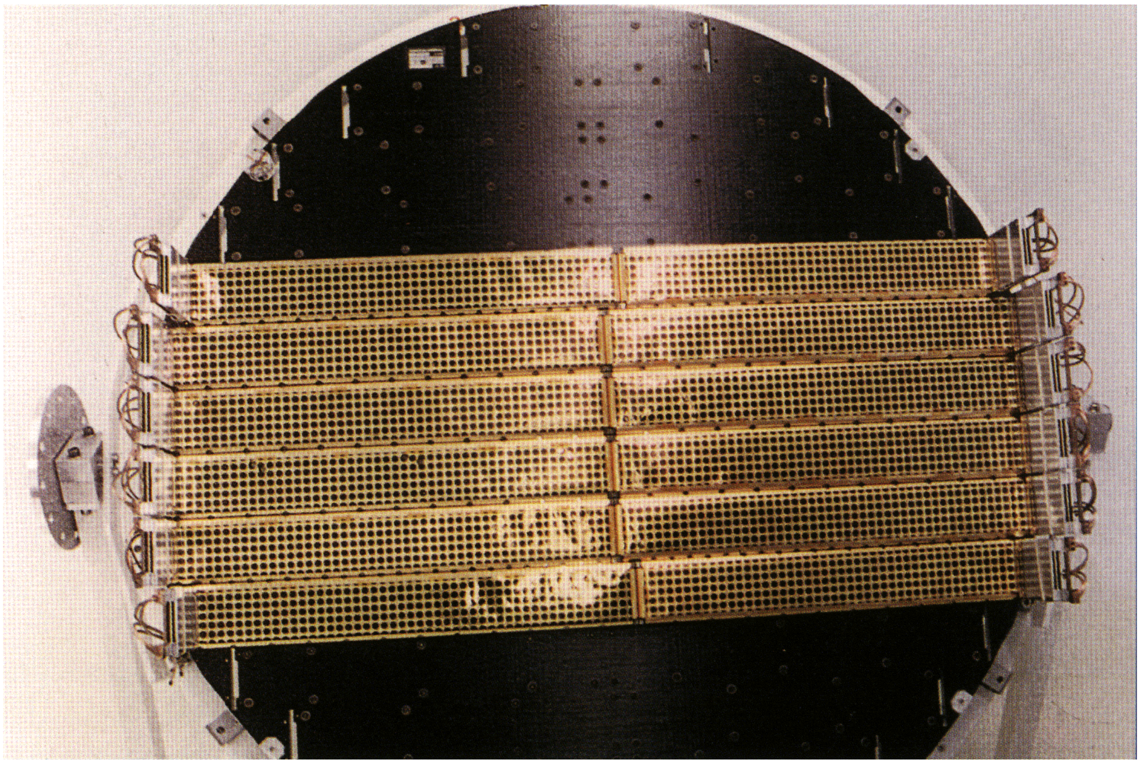

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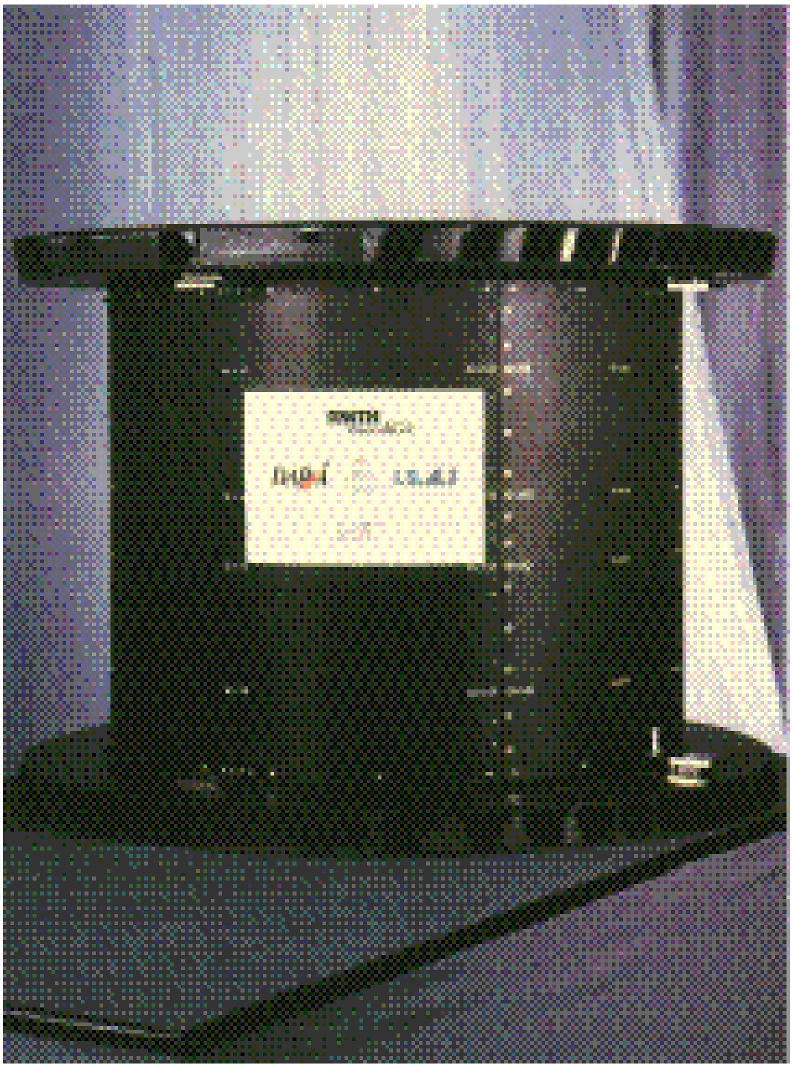

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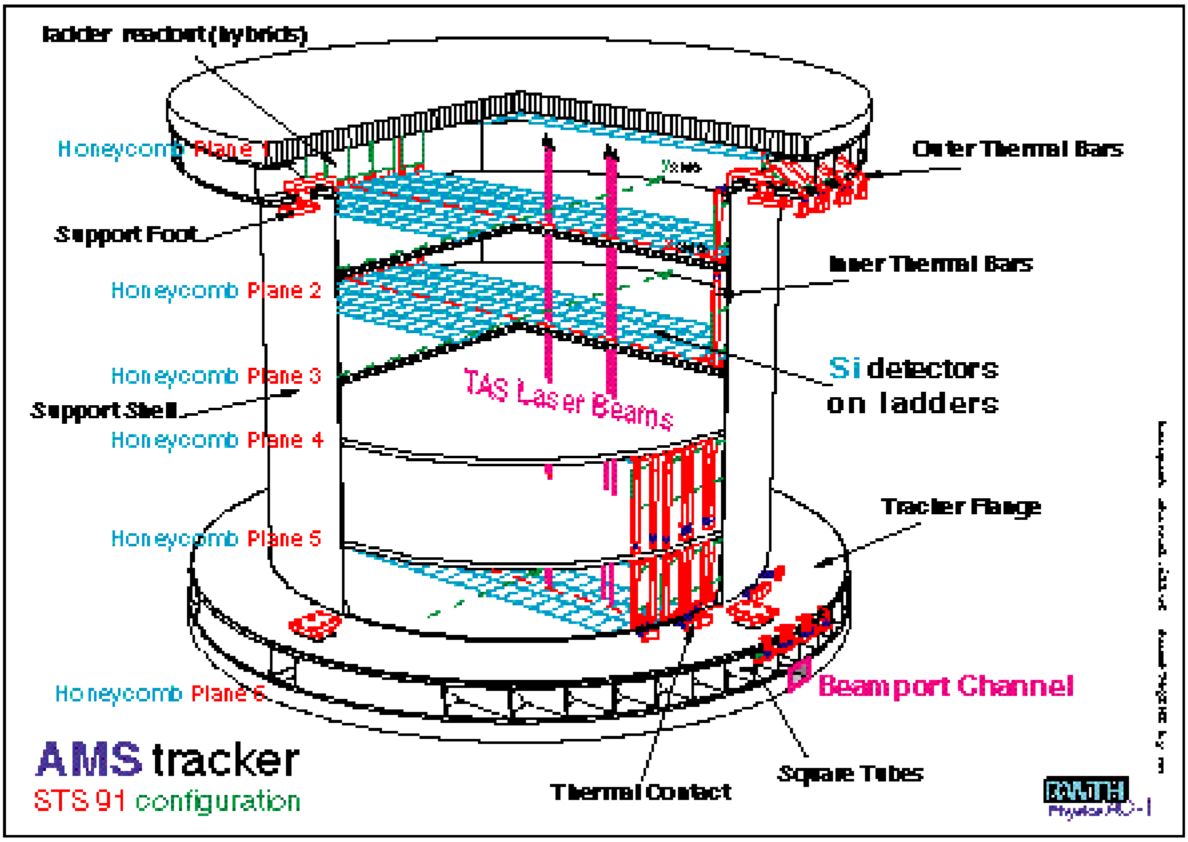

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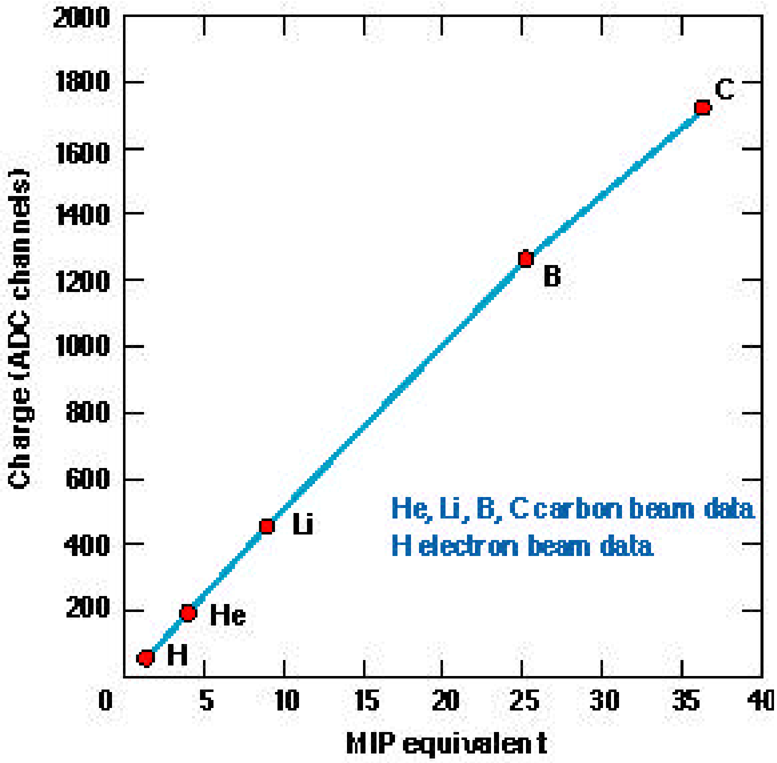

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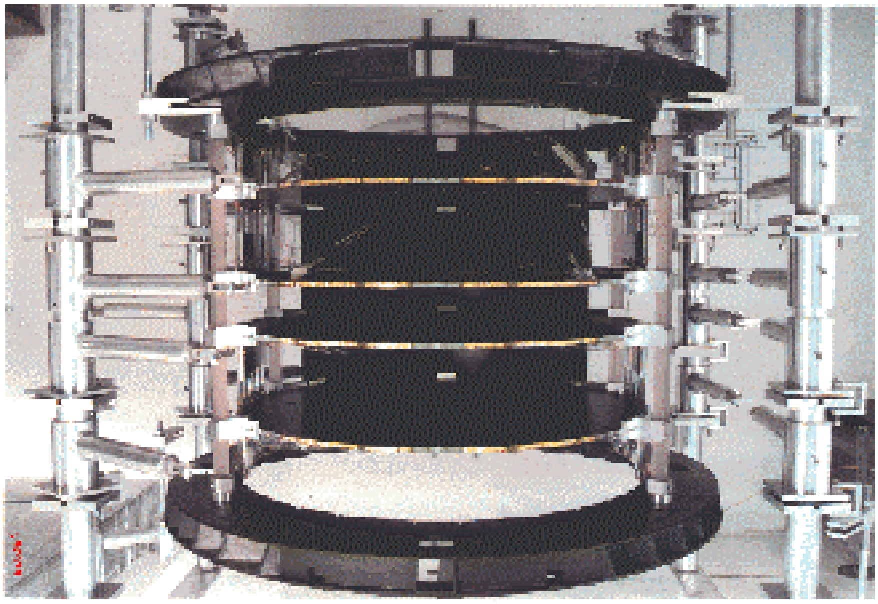

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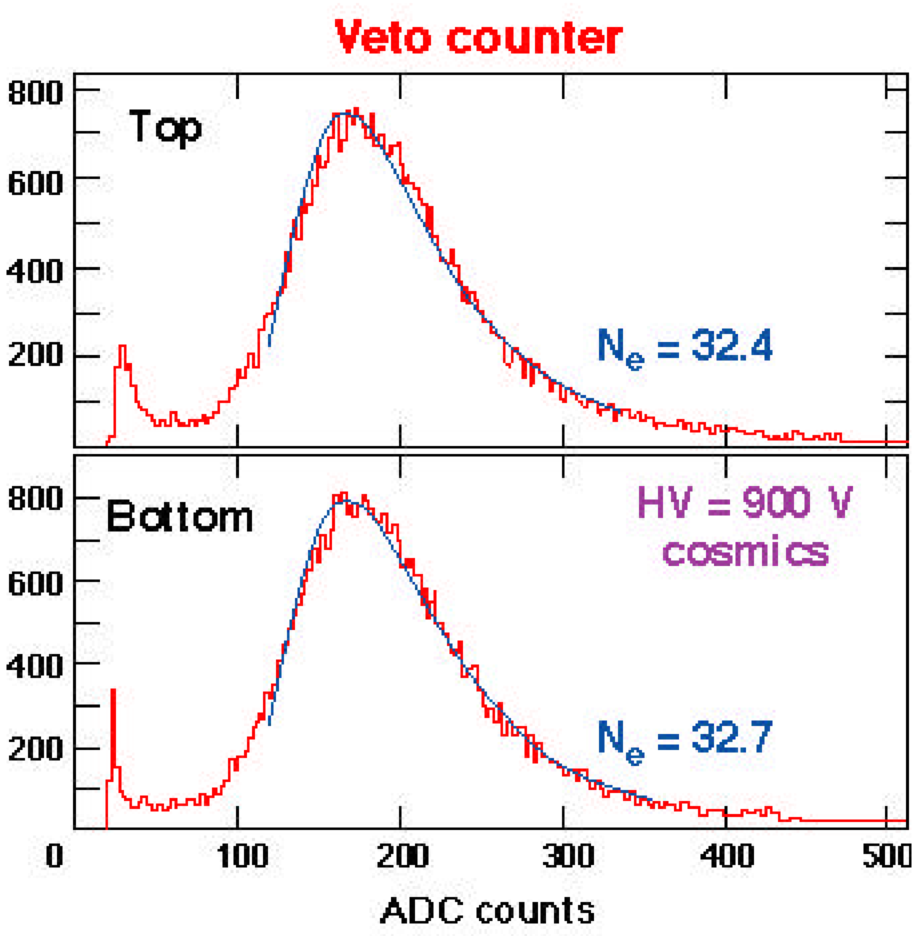

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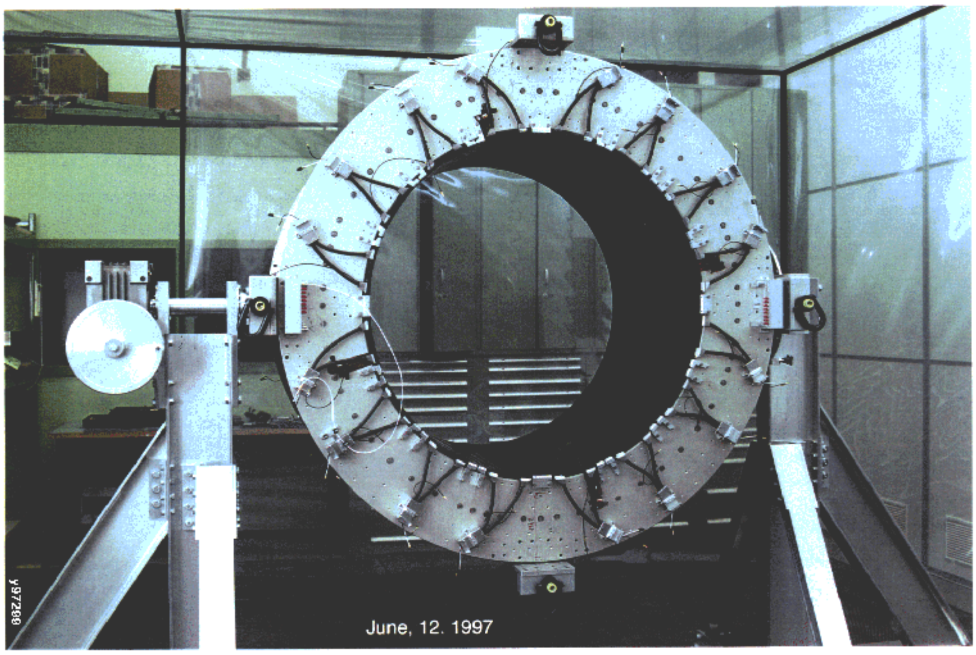

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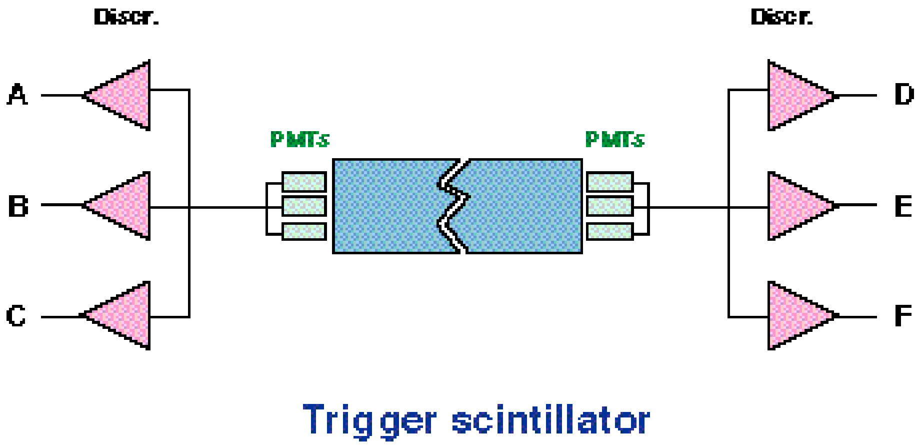

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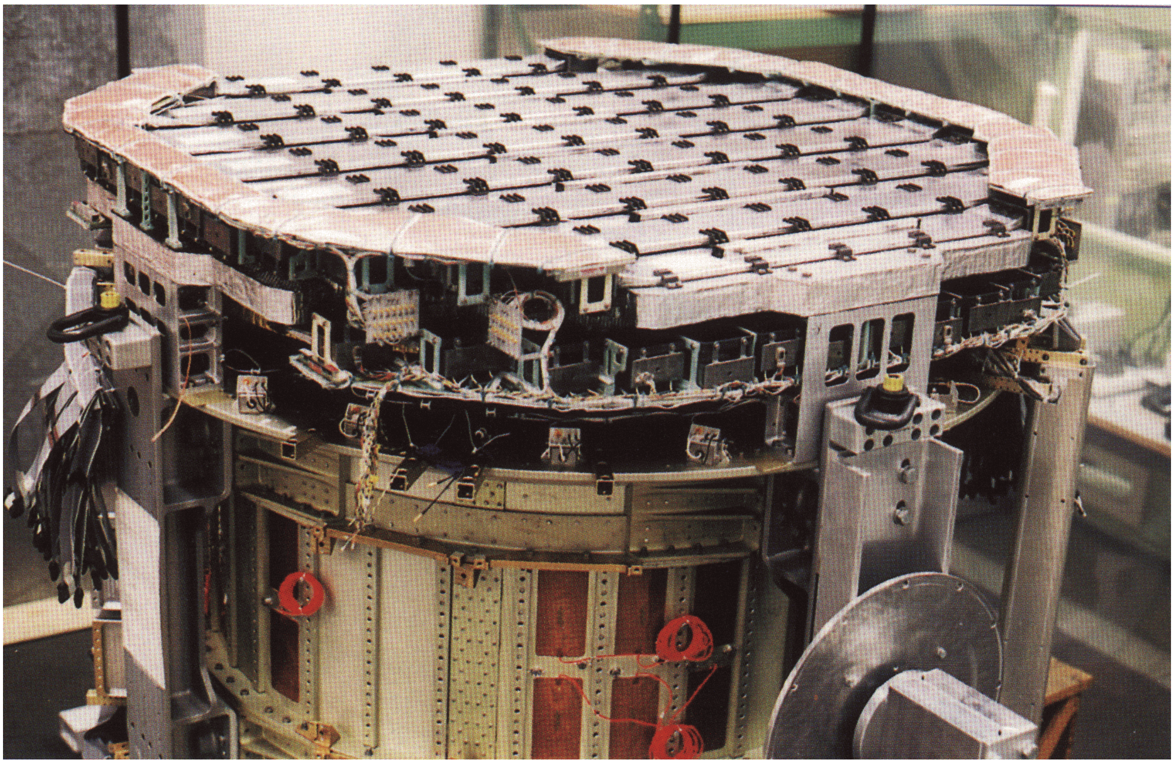

Mounting of Time of Flight on AMS-01 detector during detector integration at ETHZ (end of October 1997).

(iii) Aerogel Cerenkov Counters:

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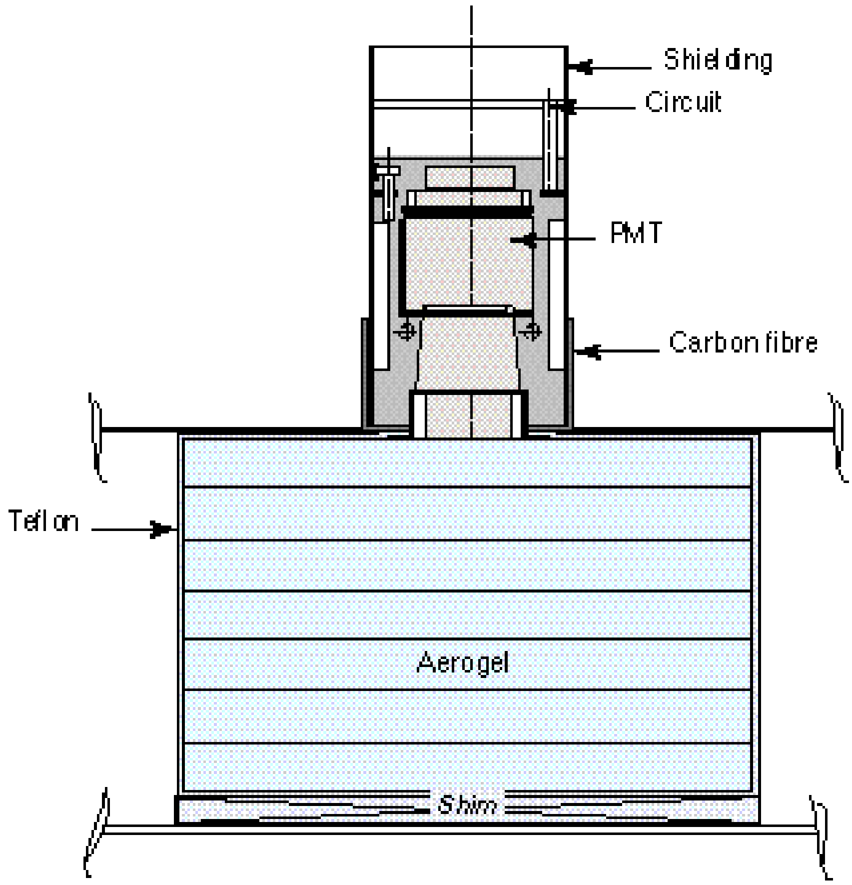


Figure 16 : A cell of the Aerogel Counter.

4. AMS-01 Electronics, Software and Ground Support.

(i) Electronics

AMS is a particle physics detector. Much care and attention are necessary to ensure the particle physics electronics can be applied in space. There are 70,000 channels of tracker signals which provide a coordinate accuracy of 10 μm. There are four layers of Time of Flight hodoscopes providing a time resolution of ~ 100 ps. Both the Silicon Tracker and Time of Flight counters also provide independent dE/dX measurements to identify particle charge. Because of power and weight restrictions, all the electronics were specially designed (by Dr. M. Capell of MIT), manufactured and space qualified by AMS institutions and aerospace industries in Europe and Asia.

Figure 17 shows the principal AMS-01 electronics design which is based on multi-redundancy to safeguard the loss of data in space.

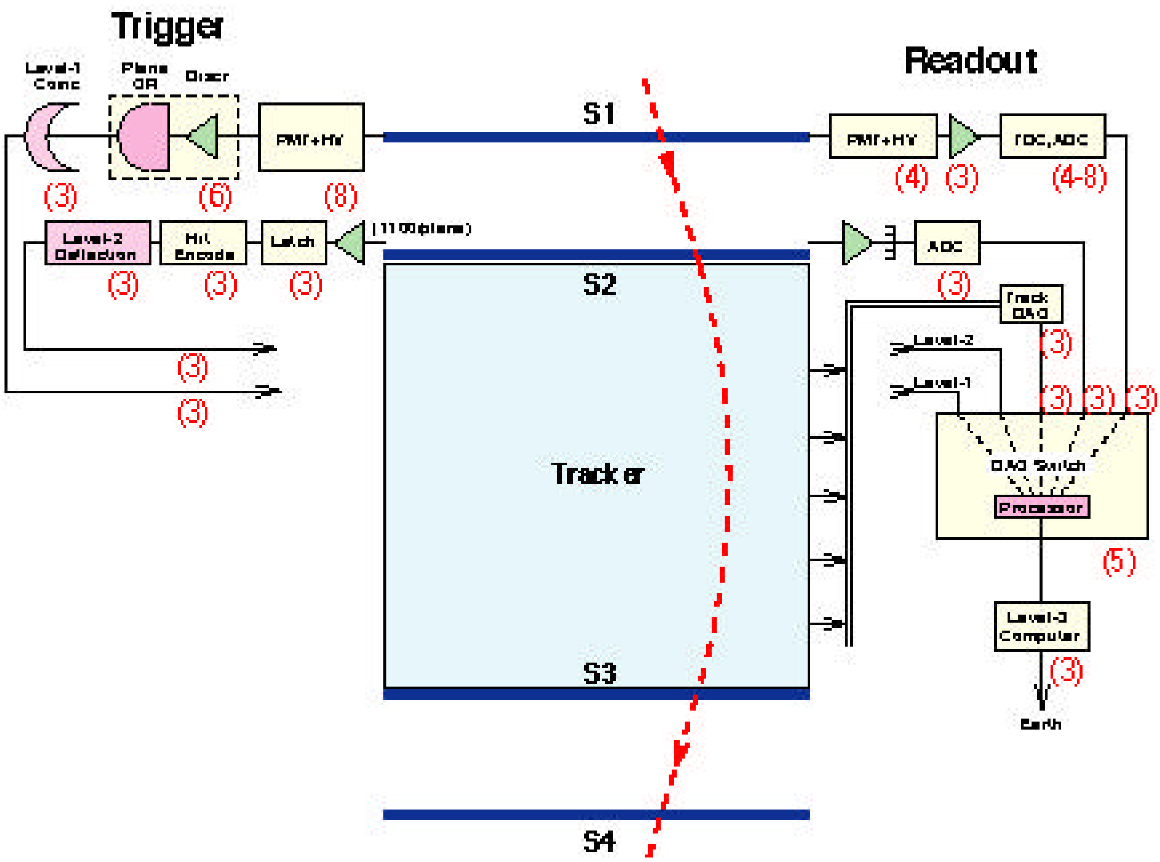


Figure 17 : AMS-01 electronics.
The numbers of redundant elements are given in parenthesis.

Figure 18 shows the detailed design of the AMS-01 electronics

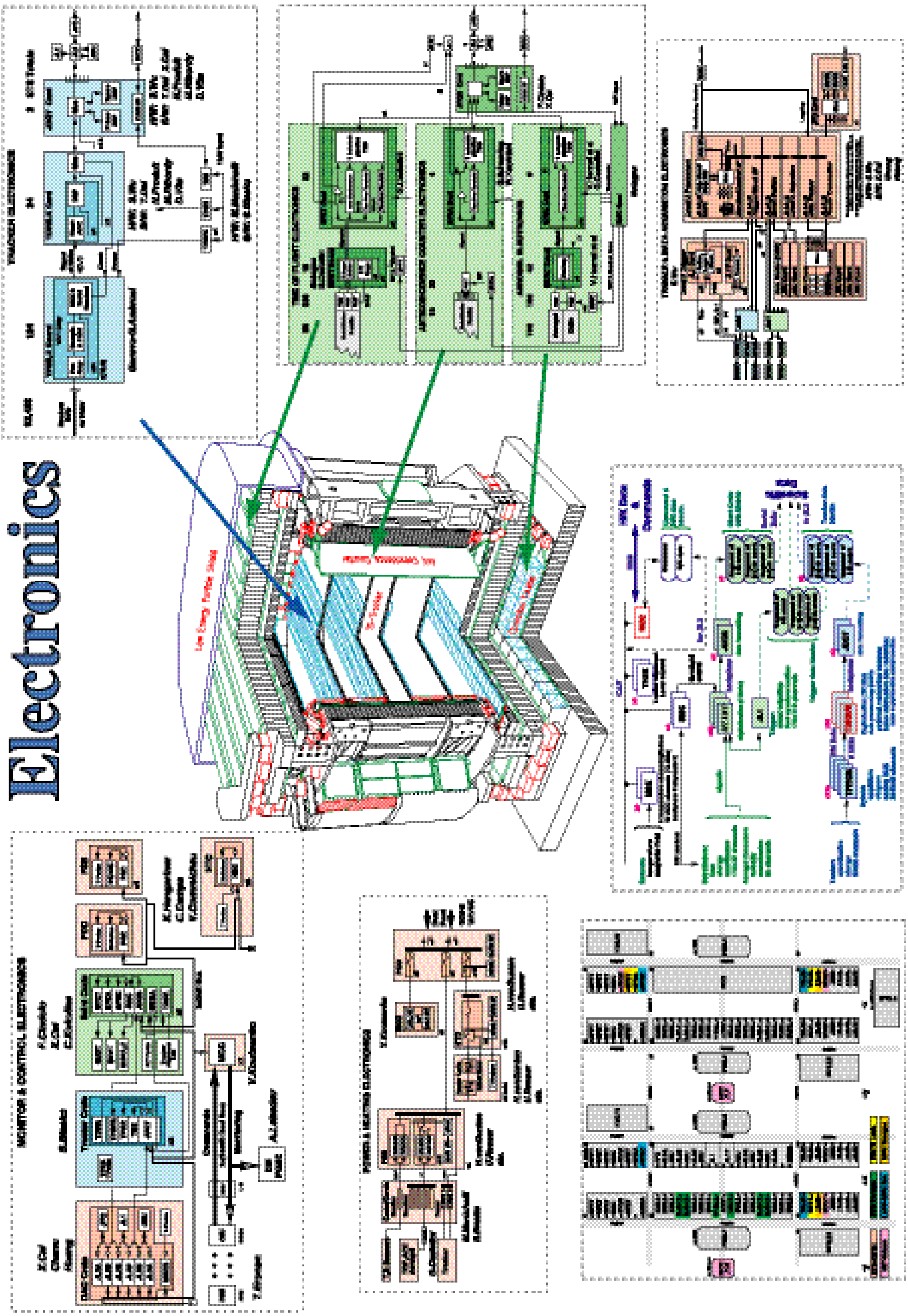


Figure 18 : Detailed Design of AMS electronics.

To space qualify the electronics, the system went through extensive tests which included:

(a) vibration

(b) temperature

(c) thermal vacuum

(d) radiation

(e) electromagnetic interference

The radiation tests were specially carried out at Dubna in August 1997 and these tests were particularly important to ensure there would be no single event latch up in space. Table 6 below shows the beam and energy used in these tests.

Radiation Tests, Dubna, August 1997

Beam	Energy (MeV)
Ne	270
Au	460
Kr	430

Table 6 : Beam Characteristics Used for AMS Radiation Tests at Dubna.

The space qualification tests (vibration, temperature ...) were carried out at the Max Plank Institute for Extraterrestrial Physics in Germany and at the Chung-Shan Institute of Science and Technology in Taiwan; the latter of which also manufactured most of the electronic units.

The electronics were assembled into the detector at ETH/Zürich in December 1997.

(ii) AMS-01 Software Development :

Since the electronics were custom-designed, all the software also had to be specially written. These included

(a) The onboard software :

The onboard software has three major components:

- monitoring and control software which controls the power and heating of the entire system,
- data acquisition software. This system collects and performs initial analysis based on information from Time of Flight, Silicon Tracker, Aerogel Counters and Veto Counters. The control and monitoring of the data acquisition must also integrate the AMS system with NASA avionics.
- crew monitoring software. This is the software which runs on a laptop computer inside the shuttle crew compartment and allows the astronauts to monitor, and as a contingency, to operate the experiment.

(b) Online software :

The online software receives the two data streams, slow rate monitoring telemetry and high rate event data, from the experiment. It also receives the ancillary data directly from NASA which contains the orbiter position, velocity and so on. These data are passed on to monitoring programs. In addition, commands must be input, formatted and sent, via the NASA hardware, to the experiment.

(c) Offline software :

The offline software receives the collected event data and proceeds to analyze it based on the detector settings. The analysis first converts the detector signals into physical quantities for each detector and then these quantities are combined to reconstruct the event. In addition, the detector response to various events is simulated for comparison.

Most of the software program was developed and tested from October 1997 until May 1998.

(iii) AMS-01 Ground Support:

The data from AMS-01 is first transmitted via the orbiter's Ku-Band antenna to the Tracking and Data Relay Satellite (TDRS), to a receiving station on Earth (White Sands) and then to the AMS Ground Station or AMS Payload Operations Control Center (Johnson Space Center in Houston). A backup system was developed by NASA for AMS consisting of the Digital Data Recorder located in the crew compartment and consisting of 33 removable hard drives (9.1 gigabyte each) together with a Payload & General Support Computer (PGSC) to provide over 270 hours of data storage capability.

4) Integration of AMS-01 into the NASA System at Kennedy Space Center.

From October 1997 until 25 January 1998, the detector components from the U.S., European and Asian countries (Germany, Switzerland, France, Italy, Finland, Taiwan and the U.S.) were assembled and tested at ETH-Zürich.

Figure 19 illustrates the assembly of various detectors from Europe, USA and Asia at ETH-Z.

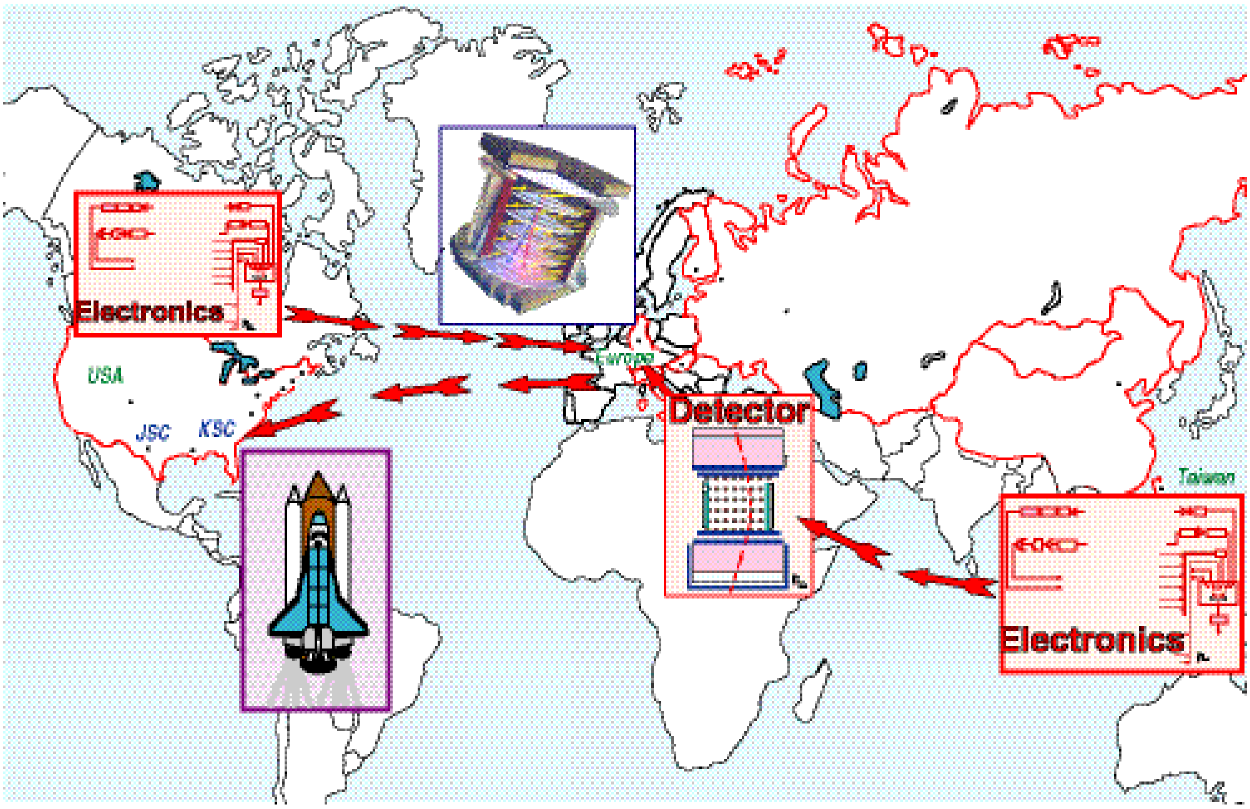


Figure 19 : AMS detector assembly at ETH-Zürich.

AMS-01 has been regularly and intensively reviewed by NASA Safety Board. One of the reports is shown below.

From: "BATES, JAMES R. (JIM) (JSC-SM)" <james.r.bates1@jsc.nasa.gov>
Date: Thu, 9 Oct 97 23:48:07 MET
Subject: AMS Phase II Safety Review went GREAT!!

The AMS set a precedent this week when it became the first payload to begin the meeting as a Flight Safety Phase II review but ended the meeting being approved as a Phase III review. All of the right information plus more was made available to the Payload Safety Review Panel. Questions were answered with facts, not guesses.

So all of the above means that no formal Phase III review will be required.

A big THANK YOU to all who brought this information together, and a special THANX to Tom Tinsler and Ken Bollweg for all their extra effort and 'midnight oil' burning. A special thanks for the AMS Experiment Team overseas for providing us the data as needed.

The AMS Team does good work!

Jim Bates - AMS Mission Manager

Figure 20 summarizes the activities of AMS from the arrival on January 28, 1998, from Zürich to the time of the Shuttle launch on June 2, 1998.

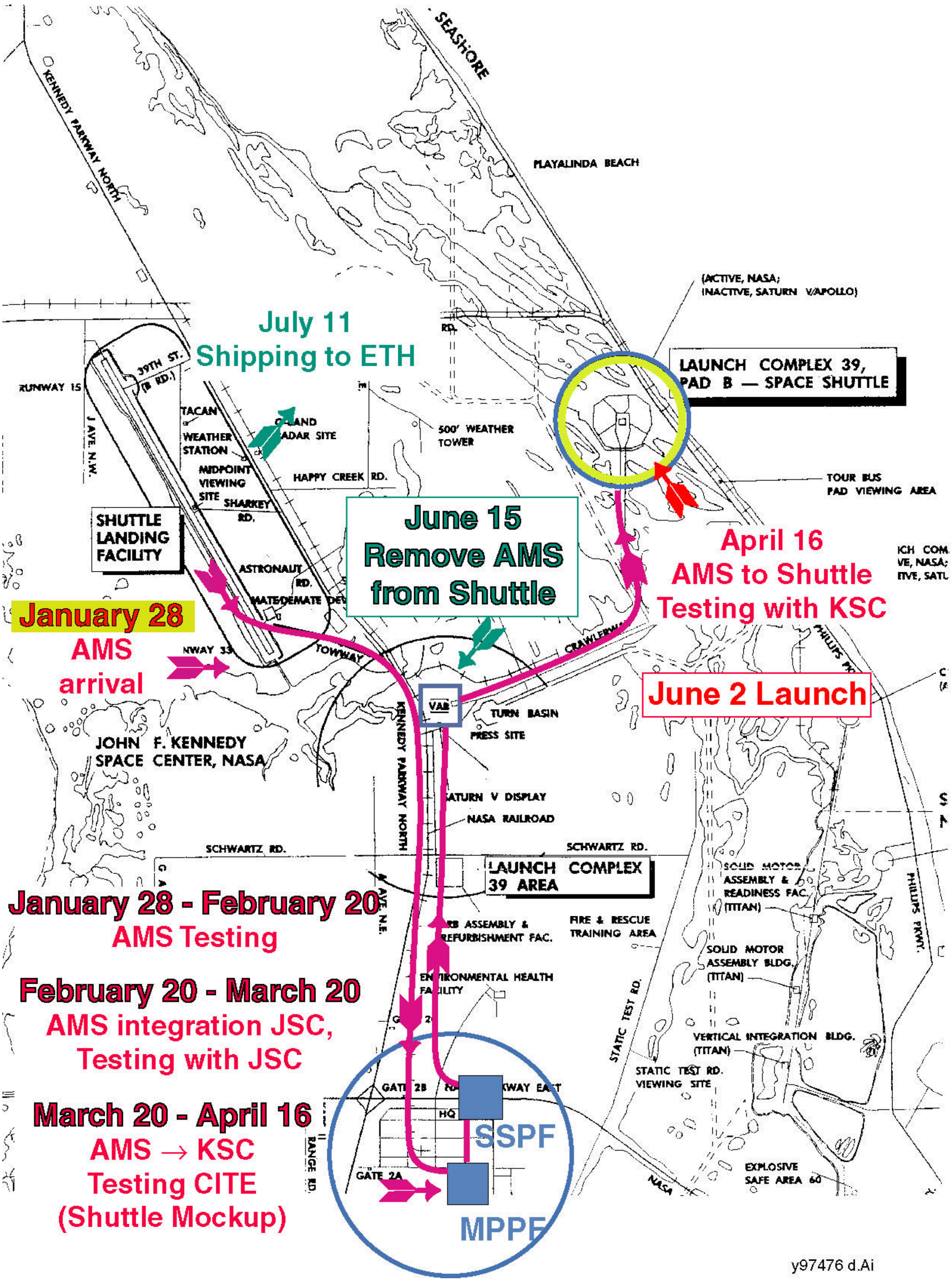


Figure 20 : AMS-01 Activities at NASA Kennedy Space Center

These activities could be divided into four periods:

(i) January 29 - March 20, 1998

AMS-01 performed "stand-alone" tests at the Multi-Payload Processing Facility (MPPF) at Kennedy Space Center. Using cosmic ray muons, we confirmed that the resolution of the detector agreed with our design value.

Preliminary analysis of these events shows that the entire detector did have the desired momentum and time resolution as shown in Figure 21.

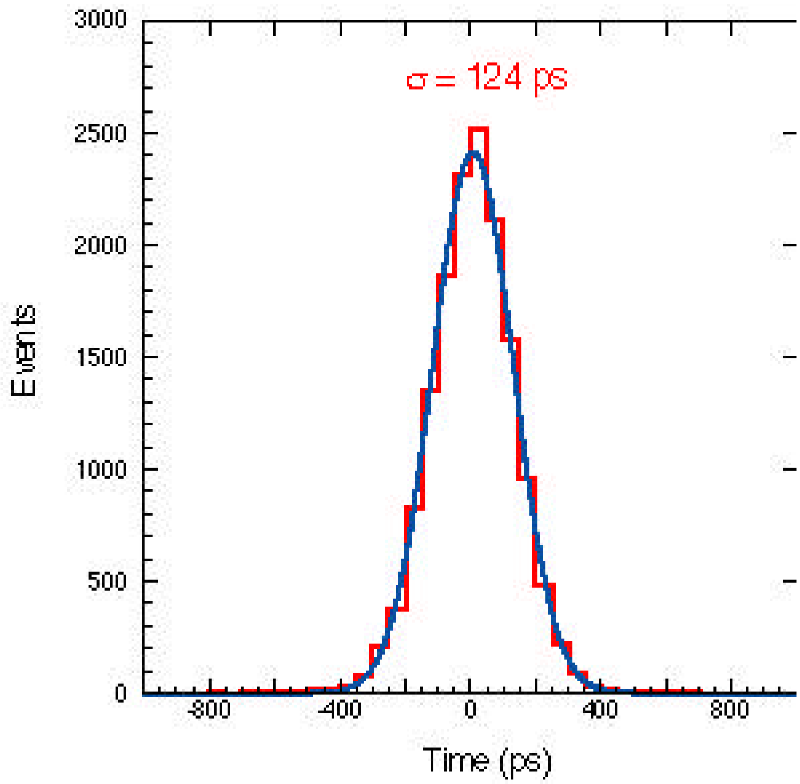


Figure 21 : Preliminary AMS time resolution measured from cosmic muons at Kennedy Space Center.

(ii) March 20 - April 16, 1998

AMS-01 performed integration tests at the Space Station Processing Facility (SSPF) where AMS was installed in the shuttle simulator and the entire data transmission, command and control were tested both from Kennedy Space Center and from Johnson Space Center.

(iii) April 17 - June 2, 1998

AMS was installed in the Orbiter on Launch Pad 39 where we performed final checks of the entire system.

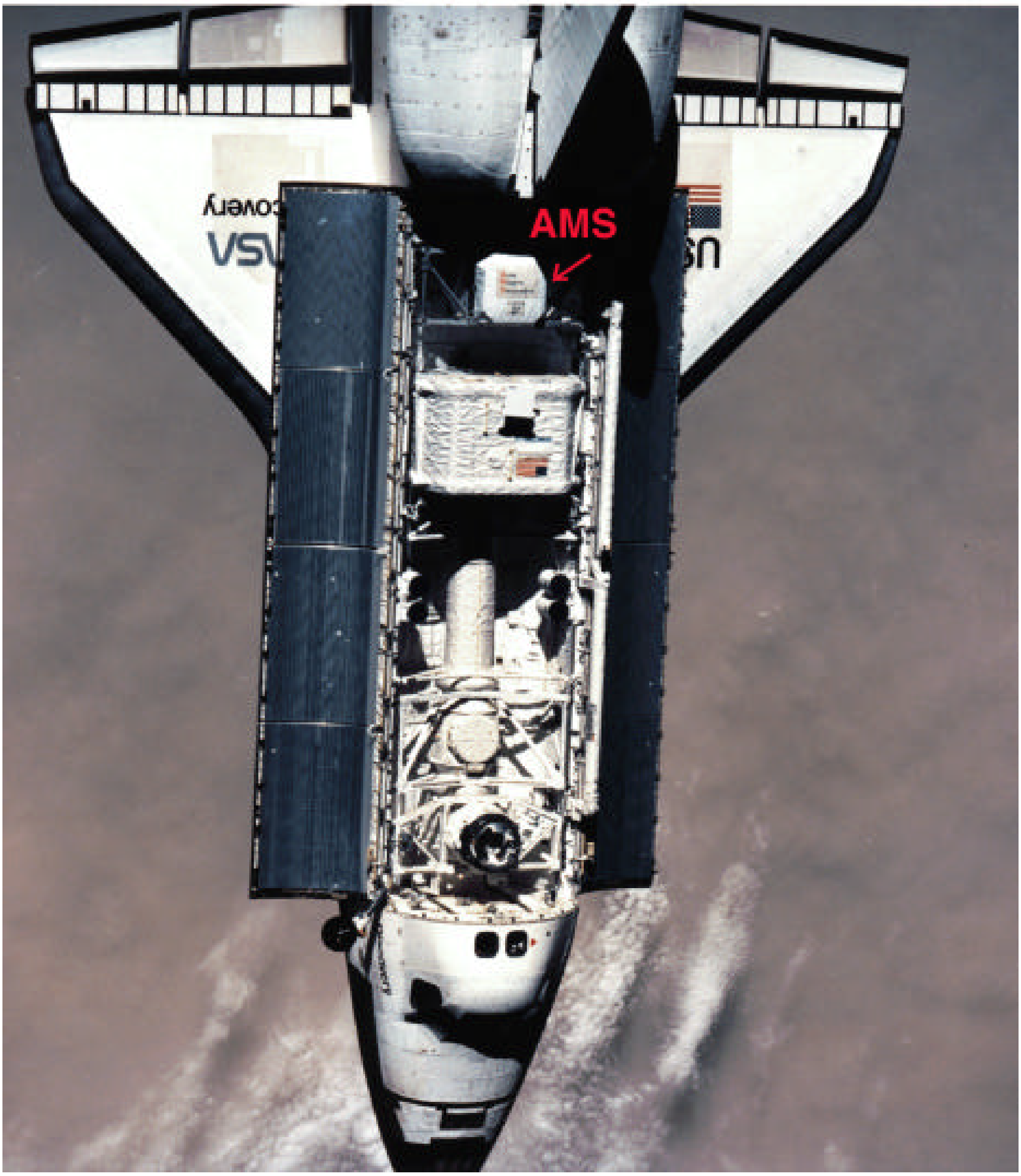
(iv) June 2 - 12, 1998

AMS-01 was launched on the Shuttle Discovery (STS-91 flight). (See photo below). During the ten-day mission of Discovery, AMS was allocated 100 hours of primary time to perform system tests. The rest of the time, Discovery was used for docking and transferring logistic support with MIR. The photographs below show the lift-off of Shuttle Discovery on June 2, 1998, and the docking with MIR (in which AMS-01 is clearly visible in the Shuttle's Cargo bay).

National Aeronautics and
Space Administration

NASA7-726-068

Lyndon B. Johnson Space Center
Houston, Texas 77058



As seen in the message below from Paul Dye, Lead Flight Director for STS-91, NASA/Johnson Space Center, the objectives of the AMS shuttle flight tests were achieved. The data transmitted are presented in the next Chapter.

From: "DYE, PAUL F. (JSC-DA)" <paul.f.dye1@jsc.nasa.gov>
Subject: Thanks and Congratulations
Date: Wed, 17 Jun 1998 12:28:25 -0500
Status:

Dear Sam,

I just wanted to pass on a quick note of congratulations to you and the entire AMS team for successfully completing your first mission in space aboard the Shuttle. From what I have been hearing, it appears that the AMS mission was successful in collecting some science data, as well as in our important goal of checking out the instrument, and how it can best be operated, in preparation for future missions and the extended stay aboard ISS. I felt that you and all of the folks working the mission did an excellent job of reacting to our in-flight failures and adapting to the ever-changing environments of data flow, vehicle attitudes, and thermal profiles.

Thinking back to previous payloads that I have flown, I must say that while I was worried about many of the late aspects of AMS prior to flight, your team did much better overall than many in my experience. By working together throughout the mission, the Flight Control Team and the POCC did an outstanding job of getting the most out of the time we spent on orbit.

I hope that we get a chance to get together and talk in detail sometime about anything that might be unanswered in your mind. I certainly will watch with interest as you evaluate the data obtained during the mission, and wish you all the best in your preparation for ISS. And mostly, I hope that have a chance to work together again. It was interesting, productive, and fun!

All the best,
Paul

Paul F. Dye
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NASA/JSC
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