Search for Dark Matter in Cosmic Rays with the AMS-02 space spectrometer

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Abstract.

    The cosmic rays spectrometer AMS-02 will be placed on the ISS Space Station in April 2011 and should take data for at least 10 years. After a short review of the impressive observational data collected in the last few years by satellites and underground experiments in the quest for Dark Matter (DM), we describe the AMS-02 space spectrometer with its powerful particle identification capabilities. The performances of the experimental apparatus and the perspectives opened by this new powerful observational instrument for the DM search will be briefly reviewed. In particular the extension at the TeV scale of the positron and electron spectra with high statistical significance well beyond the PAMELA results will hopefully clarify the quest for Dark Matter evidence in cosmic rays. Finally the present status of the AMS-02 payload for the Shuttle transportation and installation on the International Space Station , and the implementation of the Control Center for data collection and analysis is reviewed.

1 Introduction

The astrophysical growing observational evidence for Dark Matter (DM) gives a solid base to the Cosmological Standard Model. The particles and interactions Standard Model, however, has no answer on DM nature. Experimental evidence of DM from underground experiments is under scrutiny while recent results from space experiments have no clear interpretation.

    The last NASA Shuttle Mission STS-134, scheduled in 2011, will bring and install on the International Space Station (ISS) the Cosmic Ray Spectrometer AMS-02, a powerful upgrade of AMS-01 which was flown for 10 days in June 1998.

    The ISS scientific program has been extended up to at least 2020, so that the AMS-02 spectrometer will be a permanent Cosmic Ray observatory looking for DM, AntiMatter, primary Cosmic Ray Nuclei and gamma rays.

2 Review of recent results of DM searches

The claim for a WIMP Cold DM particle interaction signal comes from the DAMA/LIBRA experiment at Gran Sasso [1]. After 7 years of observations they find an annual modulation effect of the inelastic DM scattering in the scintillator, in the 2 – 6 keV energy range of amplitude 0.0114 ± 0.0016 counts/day/kg/keV . The DAMA/LIBRA result, a model independent piece of evidence, has not yet been confirmed by other experiments of the same kind, like CDMS, whose 2 candidate events (with an expected background of 0.9 ± 0.2) have been up to now interpreted as zero signal [2]. In conclusion, concerning the inelastic WIMP collisions in matter we must wait for a confirmation or final rejection of the DAMA effect.

Interesting data have shown up recently from satellite experiments detecting cosmic rays, like PAMELA, or gamma rays, like FERMI. Both experiments can detect the annihilation products of Dark Matter candidate particles, like cold or hot relics in Supersymmetric theories. PAMELA data confirm with high statistics and extend to above 100 GeV the earlier findings of a spectacular rise in the positron fraction from 0.05 around 10 GeV to 0.15 at 100 GeV [3]. FERMI and HESS [4] observe the same rise in the $e^+ + e^-$ cumulative spectra with respect to the expected power law E^{-3} decrease.

Finally experimental evidence has been claimed [5], analysing the FERMI gamma ray spectra from a small region of our galaxy center, for a component not seen in the emission spectrum of point gamma sources. The mean energy of the anomalous gamma rays is of the order of few GeV. A possible interpretation put forward is the annihilation, in the galaxy nucleus where the DM density should be much higher than in the galaxy arms, of about 8 GeV/c^2 mass DM particles in tau leptons. However the FERMI collaboration has analysed the gamma ray spectra in terms of possible gamma peaks and no evidence of spectral lines has been seen in the present data [6].

To conclude this short review, thanks to its large acceptance and unprecedented particle identification capability AMS-02 will be able to answer to the present day questions both on positron-electron spectrum anomalies and the gamma observations from the galactic centre. In our hopes in 10 years of observations on board of the ISS AMS-02 will contribute to cosmic ray physics like the Hubble telescope is contributing to observational astrophysics.

3 The AMS-02 Cosmic Rays spectrometer on the ISS

The success of the AMS-01 10 days mission in 1998 [7], gave a strong boost to the approval of the AMS-02 design. The permanent magnet was replaced by a 5 times stronger magnetic field generated by an array of superconducting coils working in a liquid He bath around 1.8 K to keep the He superfluid with an high thermal conductivity.

The AMS-02 project was financed and started in year 2001, the most challenging project being the superconducting magnet(SM), which should have survived the Shuttle flight and the severe thermal conditions in space. Despite technical and financial difficulties the SM was finally completed in September 2009 and tested extensively. The design was for a 3 years continuous operation with 2500 l of liquid He. The final test performed in the ESA space simulator chamber at ESTEC, Holland, showed that the operational time of the SM was around 28 months.

3.1 *The spectrometer magnet*

A superconducting magnet was ideal for a three year stay on ISS, from 2005 to 2008, as originally planned for AMS. After the 2003 Shuttle accident the AMS program was slowing down while the ISS operation was scheduled to end in 2010. Last year the ISS scientific program has been strengthened and its lifetime has been extended to 2020 (2028). The Shuttle flights, however will go to end in 2011, thus eliminating any possibility of returning and refilling the SM.

A superconducting magnet was therefore no longer the ideal choice. Most importantly, the permanent magnet option will have 10(18) years time to collect data, providing much more sensitivity to search for new phenomena. The replacement of the SM with the old AMS-01

permanent magnet (PM) was performed in less than 5 months, thanks to the fact that the SM had been designed with the same aperture and the same tracker planes as those equipping the PM.

Another important challenge for the experiment was to loose not too much analyzing power at high particles momenta with a 5 times lower magnetic field. This was achieved, at least for high rigidities, with a modified set of tracker planes, exploiting a characteristic property of a magnetic spectrometer. In fact the analyzing power of a dipole field, i.e. the momentum resolution ($\Delta p/p$) is the sum of two contributions:

1. Measurement inside the magnet with an effective length L

$$(Z/p)\cdot(\Delta p/p) \quad \propto \quad 1/BL^2$$

2. Measurement of the incident ($\theta 1$) and exit ($\theta 2$) angles which depend on the lever arm L1

$$(Z/p)\cdot(\Delta p/p) \quad \propto \quad 1/BLL1$$

where L1 is the distance first - second, and second last - last planes of the tracker. For both magnets, L ~ 80 cm, but in the permanent magnet B is 5 times smaller. To maintain the same $\Delta p/p$ the lever arm L1 has been increased from ~15 cm (SM) to ~125 cm (PM).

In figure 1 the comparison of the resolution in rigidity for the SM and the PM is shown. The two lines refer to the calculated rigidity resolution, whereas the points show the results obtained in the 400 GeV proton test beam at CERN for the two configurations of the spectrometer. As one can see, above 1 TV the difference in the resolution is of the order of 12% and is decreasing as the rigidity becomes higher. This is of particular importance for the measurements of electron and positron spectra at high momenta.
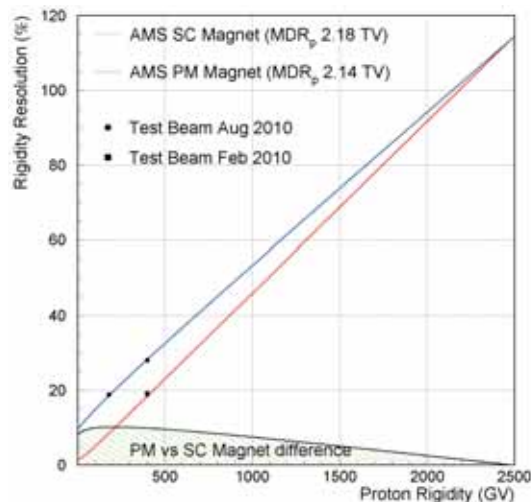

Figure 1 - Comparison of the rigidity % resolution of SM and PM.

3.2 *Particle identification*

The cut-out view of the AMS-02 spectrometer is shown in figure 2, where the different subdetectors are labeled. A cosmic ray particle traversing the spectrometer downward encounters layer 1 of the silicon strip tracker detector (TRACKER), a straw tubes gas transition detector (TRD), the upper two scintillator hodoscope planes of the time of flight detector (UTOF), then inside the cylindrical dipole permanent magnet (PM) the 7 central layers of the TRACKER and, covering the internal magnet surface, the scintillation counters of the cylindrical anticoincidence detector (ACC).
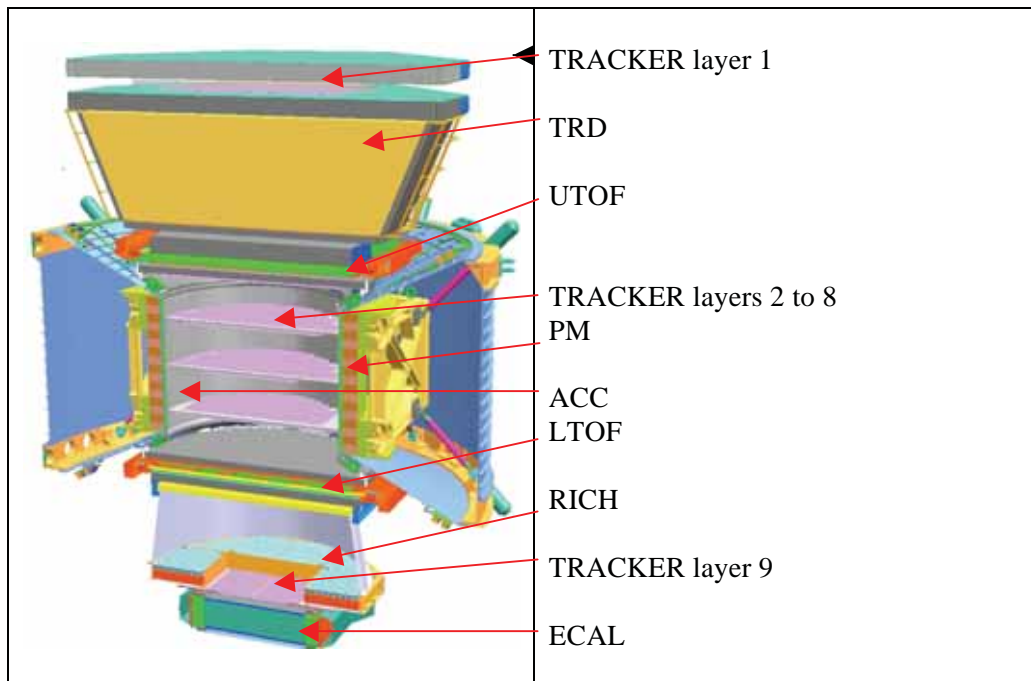
Figure 2 - Cut-out view of the subdetectors for particle identification of AMS-02.

Below the magnet there are the lower two planes (LTOF) of the TOF detector, the ring imaging Cerenkov detector (RICH), the last layer 9 of the TRACKER and the Pb-scintillating fibre electromagnetic calorimeter (ECAL).

3.2.1. TRACKER . The TRACKER detector is made of 9 planes of Silicon crystals arranged in arrays of parallel lecture strips, which in the collector side are orthogonal to the bending plane and on the other side inclined at 45°. Figure 2 shows the actual disposition of the planes. The residuals of a track in the curvature plane of the magnet are of the order of 10 micrometers (see figure 3 below).

3.2.2 TRD . The TRD detector is made of 20 layers of radiator and straw tubes filled with a Xe/Co2 mixture. The TRD is placed at the entrance of the spectrometer and is of great importance in distinguishing positrons from protons up to around 300 GeV and together with the electromagnetic calorimeter it will ensure the separation power between leptons and protons needed for the DM search. The TRD alone at 290 GeV/c beam momentum can detect electrons with a 90% efficiency and reject protons at the level of better than a factor 100 (figure 3).

3.2.3. TOF. The two scintillator [8] hodoscopes UTOF and LTOF, consisting each of two planes of 12 cm wide paddles, respectively in the x and y orthogonal directions, define the spectrometer acceptance for charged particles and provide the fast trigger to start the event data acquisition of all detectors. The scintillator counters, seen at both ends by 2 photomultipliers, can measure on a flight path of 120 cm the particle velocity with a resolution of 4%. The time of flight gives a 10^{10} rejection for upgoing particles excluding to this level the confusion of e.g. an He nucleus going upward with an AntiHelium going down from space. In figure 4 the charge resolution and the time resolution as function of charge are shown.

3.2.4. RICH. Before the calorimeter there is a ring imaging Cerenkov counter consisting of a 2 cm thick Aerogel radiator, a 45 cm expansion space for the ring with a conical mirror and a planar array of PMTs forming a 9 x 9 mm pixel grid. The velocity resolution (figure 3) is of the order of 0.1% , ensuring a good separation of isotopes in the study of the light nuclei.

3.2.5. ECAL . The main detector for an efficient separation of electrons/positrons from protons is the 17 X_0 Pb-scintillator electromagnetic calorimeter made of 9 superlayers of

orthogonal fibres. It allows excellent shower shape reconstruction and has an energy resolution of the order of 4 % (figure 3) . The calorimeter rejection factor for protons is standalone of the order of 10^4 . Together with the TRD the proton rejection amounts to a factor 10^6 .

4 Overall performances of AMS-02

In figure 3, 4 the overall performances of the subdetectors relevant for particle identification, as measured on test beams of protons, selected secondary particle momenta and charge, heavy Ions, are shown.
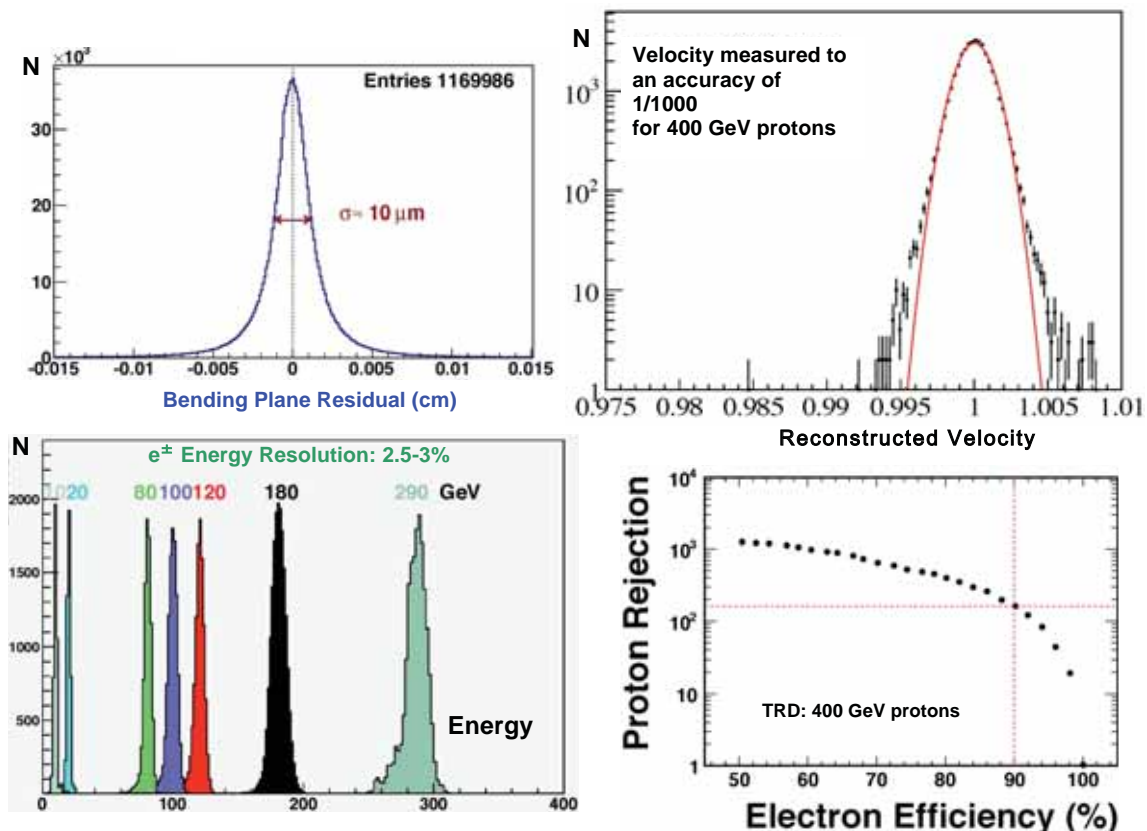

Figure 3 - Test Beam Results with permanent magnet – 8-20 Aug 2010. From left clockwise: The measured residuals of the TRACKER fitted tracks in the curvature plane of the magnet. The measured RICH velocity resolution, about 0,1 %. The measured TRD separation between electrons and protons. The measured ECAL energy spectra of electrons from 10 to 290 GeV.

The performances of the AMS-02 spectrometer are also monitored periodically running a cosmic ray trigger on ground since the first assembly. All detectors are found to behave according to the design characteristics. No degradation of the detectors has been shown from CERN, where it was assembled first, to ESTEC in Holland where underwent the space qualification tests, then at CERN to change from the SM to the PM, and finally to the NASA laboratory KSC in Florida, where is undergoing integration in the Shuttle and the ISS.

Finally we must mention that AMS-02 with the unique features of its electromagnetic calorimeter, a thickness of 17 X_0, and granularity permitting 3D reconstruction of showers, will be also an excellent gamma ray spectrometer. ECAL will measure γ to 1 TeV, with an angular resolution $\sigma(\theta)$ of 2 arc-sec.
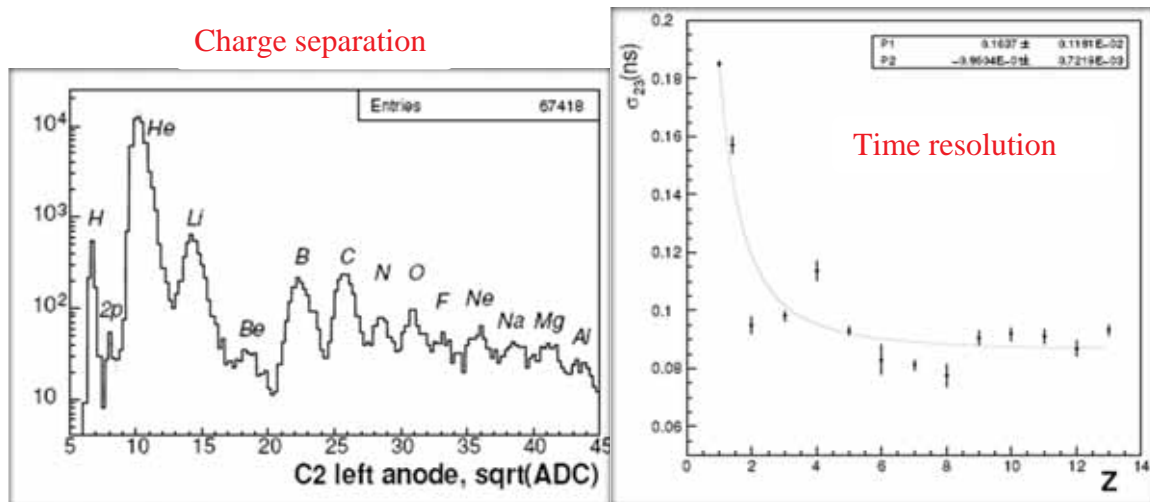
Charge separation

Time resolution

Figure 4 - Measured performances of the TOF detector on an Ions test beam. Left: charge resolution of beam Ions. Right: time of flight resolution as function of Ion charge.

5 AMS-02 and the search for DM

Given the excellent particles identification power and the large acceptance of AMS-02, we expect to improve in few months the present day measurements of electrons, positrons and antiprotons, in the quest for DM signals.
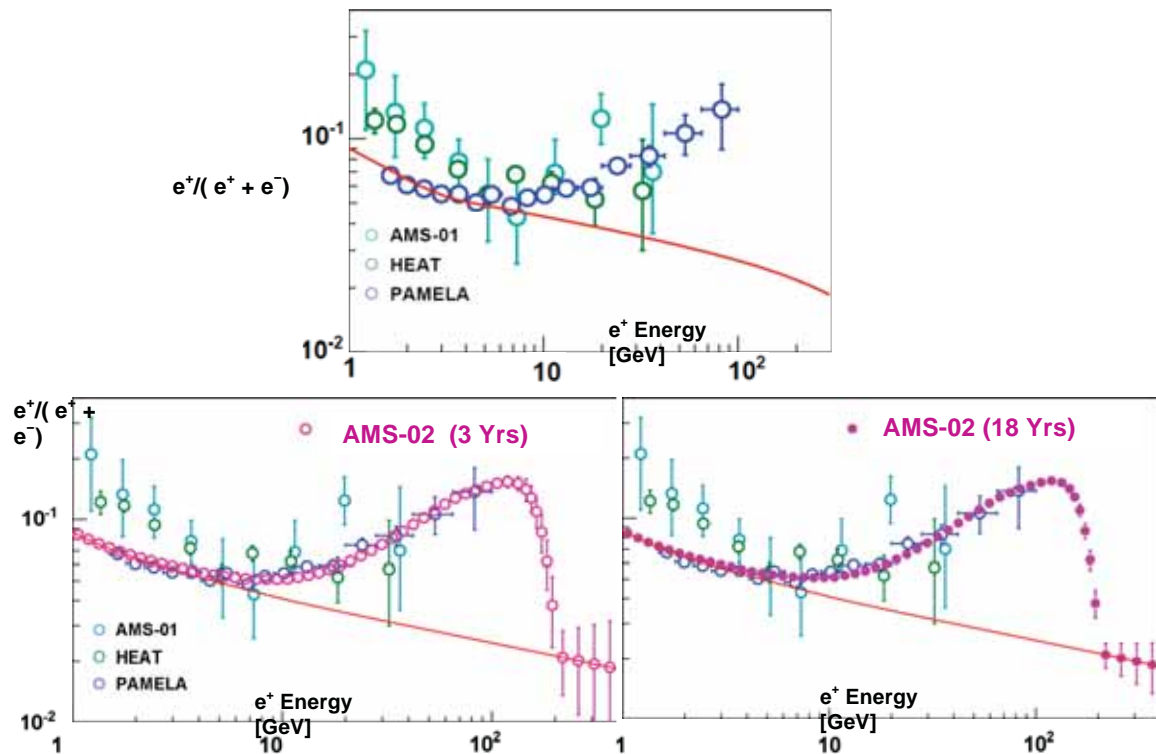

Figure 5 - Potential of AMS-02 in the search for a DM particle compared with PAMELA data.

The excellent rejection at the 10^{-6} level of protons ensures a clean reconstruction of the electron and positron fluxes up to 300 GeV and above. As examples of that figure 5 shows how

the anomalous rise in the e^+ / (e^+ + e^-) ratio would appear in the AMS-02 data, if due to the annihilation of supersymmetric WIMP neutralino DM particles with a mass of 200 GeV.

As another example, Kaluza-Klein Bosons are also DM candidates. In fig. 6 the expected signal in the positron fraction for a TeV Scale Singlet DM candidate is shown. The measured positron fraction rise and fall requires in this case a much longer observation time, to have a statistically significant signal at such high energy.

The lifetime of the ISS in fact could be extended well behind year 2020 and the PM AMS-02 spectrometer has been proved to be capable of taking data for such a long time. The gas system of the TRD straw tubes, for example, has been tested for gas leakages and proven to have a potential lifetime of 30 years.

In any case in less than one year, due to an order of magnitude wider acceptance of AMS-02, the PAMELA results will be recovered and extended to higher energies.
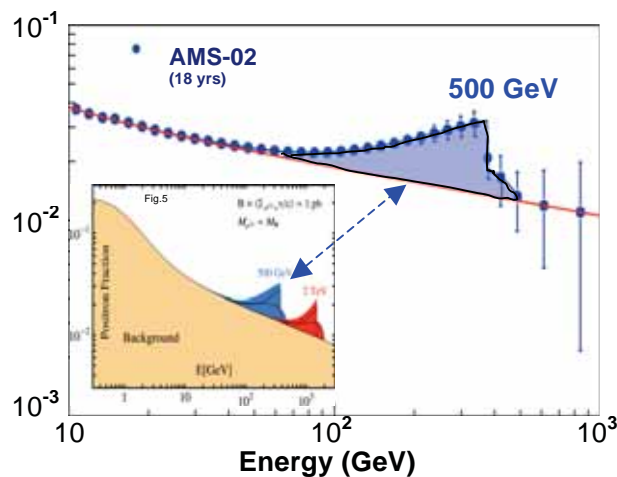

Figura 6 - AMS-02 potential for the search of a 500 GeV/c^2 mass Kaluza-Klein type DM.

6 The preparation of the AMS Payload and science data flow

Figure 7 shows various stages of the AMS-02 spectrometer preparation before launch. The Payload Operations Control Center (POCC), which will monitor the spectrometer and the data taking of AMS-02 before and after the installation on the ISS is still at KSC, Florida, where it is directly connected to the Payload (figure 7d). At the same time a backup POCC has been established at JSC, Houston Tx, to test communications and prepare the final POCC at CERN.

Once installed and completely tested on the ISS in fact, from 15 June 2011, the AMS-02 data, received at ground at the Marshall laboratory in Alabama via the NASA transmission channels, will be transmitted directly via Internet to the CERN POCC. All operations of monitoring, run control and data storage will be then made there. The expected dataflow has already been tested. From JSC to CERN the network bandwidth is 34Mbit/s (AMS requires 10 Mbit/s).

7 Conclusion

In summer 2011 CERN will host the AMS-02 Control Center. An international collaboration of 60 scientific institutes and 500 physicists will have for the next decade the most advanced instrument in space to study CR, from protons to heavy nuclei, from antiparticles to γ rays.

The impact of AMS-02 for astroparticle physics could be comparable to the impact of the Hubble telescope to astronomy. The most exciting objective of AMS is to probe the unknown; to search in nature for phenomena that we have not yet imagined nor had the tools to discover.

The origin and propagation of CR, the AntiMatter mystery, the nature of Dark Matter are the astroparticle physics research themes attached by AMS-02 in the same place, the CERN laboratories, where the LHC experiments try to unveil the cosmological mysteries from the microscopic point of observation, looking beyond the Standard Model.

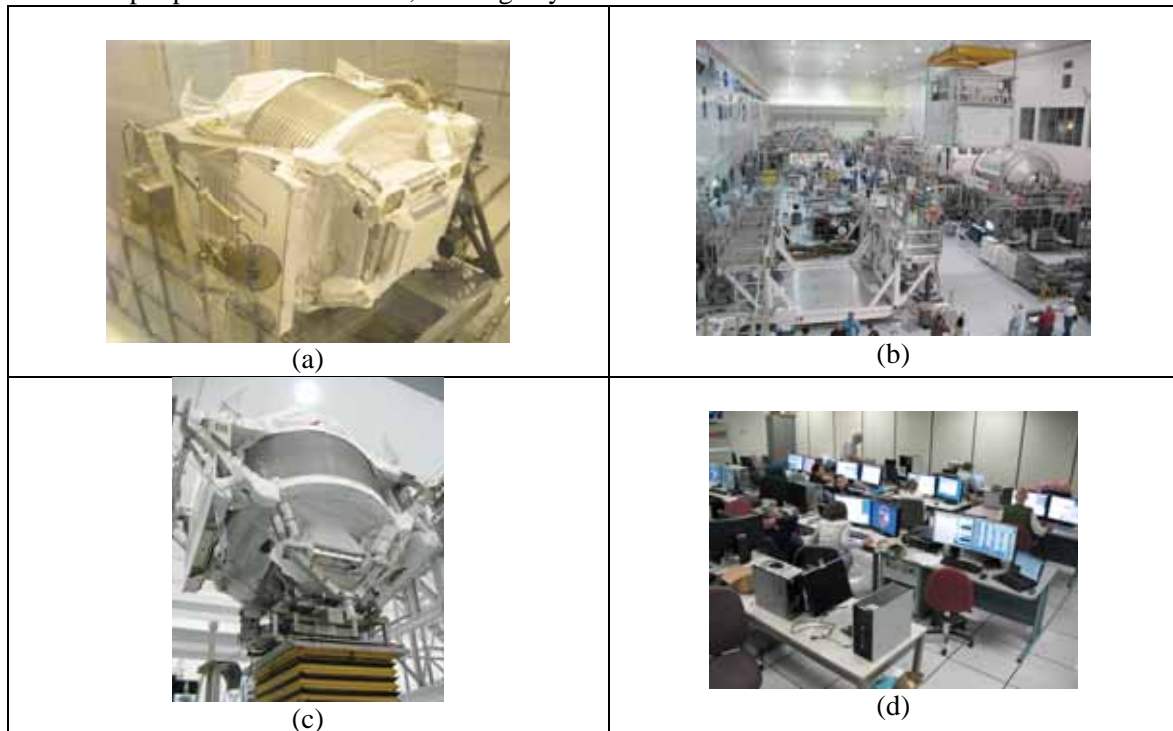(a)   (b)   (c)   (d)

Figure 7 - Preparation of the AMS-02 Payload for the ISS: (a) Calibration of AMS in Test Beam with permanent magnet – 8-20 Aug 2010. (b) AMS being installed in Space Station Processing Facility – 26 Aug 2010. (c) AMS mated with a Payload Attach System simulator - 22 October 2010**.** (d) Since 28 August, AMS has been undergoing tests at the KSC control POCC.

A very exciting decade of experimental results is at our hands and we look forward for discoveries opening new windows in the understanding of our Universe.

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