The detectors were built all over the world and assembled at CERN, near Geneva, Switzerland.
AMS Detector is built with the same precision and detection capabilities as the large LHC detectors.
AMS: A TeV precision, multipurpose particle physics spectrometer in space.

Particles and nuclei are identified by their charge ($Z$) and energy ($E \sim P$).

Z, $P$ are measured independently from Tracker, RICH, TOF and ECAL.
The Magnet

The detailed 3D field map (120k locations) was measured in May 2010

In 12 years the field has remained the same to <1%
Transition Radiation Detector: TRD

Identify $e^+$, reject $p$

Leak rate: CO2 $\approx 5 \, \mu g/s$

Storage: 5 kg, >20 years lifetime
Time of Flight (TOF)

Provides trigger for charged particles

Trigger time is synchronized to UTC time to 1µs

Measures the time of relativistic protons to 160 picoseconds

\[ \Delta t/t = 160\text{ps} \]

UTOF

LTOF

4 scintillator planes

TOF Time

\[ Z = \sqrt{\text{ampl}} \]
Veto System rejects random cosmic rays

Measured veto(ACC) efficiency better than 0.99999
MDR\textsubscript{P} = 2.14 TV
MDR\textsubscript{He} = 3.75 TV
10,880 photosensors

Intensity $\propto Z^2$

$\Theta \propto V$

Radiator detectors

Reflector

Particle

NaF Aerogel

Radiator

Intensity $\propto Z^2$

$\Theta \propto V$

Single Event Displays

RICH test beam $E=158$ GeV/n
Calorimeter (ECAL)

A precision, $17 \times X_0$, TeV, 3-dimensional measurement of the directions and energies of light rays and electrons.

\[
\sigma(E) = \frac{10.6 \pm 0.1}{\sqrt{E}} (1.25 \pm 0.03)\% 
\]

Test Beam Results

50,000 fibers, $\phi = 1$ mm distributed uniformly inside 1,200 lb of lead.
AMS electronics on ISS

650 processors,
300,000 channels.
up to 400% redundancy
A ten year effort by 75 engineers

Reduce data volume
7 Gbit/s to 10 Mbit/s
Tracker Readout Computers

196,608 Pulse Heights, 216 Low Voltages,

192 Tracker Data Reduction (TDR)

16 Readout Computers (JINF-T)

1. Collect data from TDR
2. Format, send to next level
3. Control Low Voltages
4. Combine Busy signals
5. Distribute Trigger
6. Distribute command to TDR

• Analog to digital conversion
  coordinate resolution of 10 um
• Data reduction:
  Pedestal subtraction
  Noise suppression
  Cluster finding
• Format, send to next level

• Collect data from TDR
• Format, send to next level
• Control Low Voltages
• Combine Busy signals
• Distribute Trigger
• Distribute command to TDR
AMS Electronics

The AMS group performed extensive radiation tests to select components that tolerate the radiation of space.
2009: AFTER 9000 hrs of TVT...THE END OF SUB-SYSTEM TESTS
AMS in the ESA Electromagnetic Interference (EMI) Chamber, March 2010, ESTEC, Noordwijk, Netherlands
AMS in the ESA TVT Chamber, April 2010, ESTEC

Duration 330 hours

P < \(10^{-6}\) mbar

Ambient temperature from -90°C to +40°C
Tests at CERN
AMS in accelerator test beams Feb 4-8 and Aug 8-20, 2010

AMS in accelerator test beams Feb 4-8 and Aug 8-20, 2010
Velocity measured to an accuracy of 1/1000 for 400 GeV protons

Bending Plane Residual (cm)

$\sigma \approx 10 \mu m$

Energy Resolution: 2.5-3%

$e^\pm$ Energy Resolution: 2.5-3%

TRD: 400 GeV protons

Measured combined rejection power at 400 GeV: $e^+/p = 10^{-6}$
May 16, 2011, 08:56 AM

Total weight: 2008 t
AMS weight: 7.5 t

STS-134
Endeavour
AMS installed on the ISS at 5:15 CDT May 19, 2011

AMS taking data since 9:35 CDT May 19, 2011
First Data from AMS and detector performance

The detectors function exactly as designed and, in 18 months, we have collected over 24 billion events.

Every year, we will collect $16 \times 10^9$ events and in 10-20 years we will collect $160-320 \times 10^9$ events.

This will provide unprecedented sensitivity to search for new physics.
AMS Operations

AMS Payload Operations Control and Science Operations Centers (POCC, SOC) at CERN

AMS Computers at MSFC, AL

AMS TDRS Satellites

Ku-Band
High Rate (down): Events <10Mbit/s

S-Band
Low Rate (up & down):
Commanding: 1 Kbit/s
Monitoring: 30 Kbit/s

Flight Operations

Astronaut at ISS AMS Laptop

Ground Operations

AMS Operations at CERN

White Sands Ground Terminal, NM
AMS Payload Operation and Control Center for ISS

1. Management
2. Shift Leader
3. Commander
4. DAQ+Trigger +RunControl
5. Data Handling
6. Tracker+Laser Align.+Cooling
7. TRD+TRD Gas
8. TOF+ACC
9. RICH
10. ECAL
11. Thermal
12. NASA Liaison
13. Consultants
14. On call

Science Operation Center

AMS Payload Operation and Control Center (POIC)
MSFC

365 days/year
3 shifts/day

The Wall

POIC, MSFC
store all AMS data

~12 persons on shift for AMS
POCC at CERN in control of AMS since 19 June 2011
Thermal Control is the most challenging task in the operation of AMS

The thermal environment on ISS is constantly changing due to:

- Solar Beta Angle ($\beta$)
- Position of the ISS Radiators and Solar Arrays
- ISS Attitude

Over 1,100 temperature sensors and 298 heaters are monitored around the clock in the AMS POCC to assure components stay within thermal limits and avoid permanent damage.
Thermal variables:
• ISS Radiator positions
• Starboard Solar Array position
• ISS attitude changes (primarily for visiting vehicles)

Visiting Vehicles (Soyuz or Progress)

STBD Main Radiator moved from -8° to +25°

3 Sep
3 Sep

TRD Pump temperature

STBD Main Radiator parked at -8°

4 Sep, 2011
AMS Flight Electronics for Thermal Control

- **TRD**
  - 24 Heaters
  - 8 Pressure Sensors
  - 482 Temperature Sensors

- **Silicon Tracker**
  - 4 Pressure Sensors
  - 32 Heaters
  - 142 Temperature Sensors

- **ECAL**
  - 80 Temperature Sensors

- **TOF & ACC**
  - 64 Temperature Sensors

- **Magnet**
  - 68 Temperature Sensors

- **RICH**
  - 96 Temperature Sensors

**ECAL Temperature**

- Starboard
- Ram
- Wake
- Port

Graph displaying ECAL temperature over time.
Orbital parameters of AMS DAQ

Particle rates vary from 200 to 2000 Hz per orbit

On average:
DAQ efficiency 85%
DAQ rate ~700Hz
To date AMS collected over 24 billion events

18 month of AMS operations
AMS Physics Potential

- **Searches for primordial antimatter:**
  - Anti-nuclei: $\text{He}$, ...

- **Dark Matter searches:**
  - $\text{e}^+$, $\text{e}^\pm$, $\text{p}$, ...
  - simultaneous observation of several signal channels.

- **Searches for new forms of matter:**
  - strangelets, ...

- **Measuring CR spectra** – refining propagation models;

- **Understanding of local sources:**
  - SNR, Pulsars, PBH, ...

- **Study effects of solar modulation on CR spectra over 11 year solar cycle**

- ...
Physics of AMS: Nuclear Abundances Measurements

For energies from 100 MeV to 1 TeV with 1% accuracy over the 11-year solar cycle.

These spectra will provide experimental data that go into calculating the background in the Search for Dark Matter, i.e., $p + C \rightarrow e^+$, ...
Multiple Independent Measurements of the Charge ($|Z|$)
Time of Flight System

Measures Velocity and Charge of particles

TOF 1 and 2

TOF 3 and 4

Z=2
\(\sigma_\beta = 2\%\)
\(\sigma_{\text{Time}} = 80\text{ps}\)

Z=6
\(\sigma_\beta = 1.2\%\)
\(\sigma_{\text{Time}} = 48\text{ps}\)

ISS Data
$Z_{TRK\_L1} = 26.4$

$Z_{TRD} = 23.9$

$Z_{TOF\_UP} = 27.1$

$Z_{TRK\_IN} = 26.9$

$Z_{TOF\_LOW} = 26.8$

$Z_{RICH} = 26.8$

$Z_{TRK\_L9} = 26.1$
Data from ISS

Nuclei in the TeV range

- $Z = 7$ (N), $P = 2.088$ TeV/c
- $Z = 10$ (Ne), $P = 0.576$ TeV/c
- $Z = 13$ (Al), $P = 9.148$ TeV/c
- $Z = 14$ (Si), $P = 0.951$ TeV/c
- $Z = 15$ (P), $P = 1.497$ TeV/c
- $Z = 16$ (S), $P = 1.645$ TeV/c
- $Z = 19$ (K), $P = 1.686$ TeV/c
- $Z = 20$ (Ca), $P = 2.382$ TeV/c
- $Z = 21$ (Sc), $P = 0.390$ TeV/c
- $Z = 22$ (Ti), $P = 1.288$ TeV/c
- $Z = 23$ (V), $P = 0.812$ TeV/c
- $Z = 26$ (Fe), $P = 0.795$ TeV/c
Data from AMS on ISS: He rate

$\Theta_M < 0.2$

$0.4 < \Theta_M < 0.6$

$0.6 < \Theta_M < 0.8$

$1.0 < \Theta_M$
He Rates

- $^4\text{He}$ OverCutoff $\beta<0.85$: $3.65\pm0.09$
- $^3\text{He}$ UnderCutoff $\beta<0.85$: $2.86\pm0.04$
AMS data: He rate and Solar Flare

Polar region

Equatorial region

Solar Flare, 24/1/2012

Quiet period
Search for the origin of Dark Matter:
Collisions of Dark Matter will produce additional e+.
These characteristics of additional e+ can be measured very accurately by AMS.

The Origin of Dark Matter

~ 90% of Matter in the Universe is not visible and is called Dark Matter.

The physics of AMS include:
Proton rejection at 90% e$^+$ efficiency

• ISS data

TRD performance on ISS

Proton rejection at 90% e$^+$ efficiency vs. Rigidity (GV)
ECAL performance on ISS

Proton rejection at 90% e+ efficiency

Particle Momentum (GeV/c)
AMS data on high energy $e^\pm$:

**1.03 TeV electron**

**AMS Event Display**

Run/Event 1315754945 / 173049  GMT Time 2011-254.15:31:15

**Tracker and Magnet:**
- Measure momentum

**ECAL:**
- Identifies electron and measures its energy

**TRD:**
- Identifies electron

**RICH:**
- Charge of electron
120 GeV photon

Unique Features: 17 $X_0$, 3D ECAL, measure $\gamma$ to 1 TeV, time resolution of 1μsec

120 GeV photon, direction reconstructed with 3D shower sampling
Electron $E=1.1$ GeV
Run/Event 1315150703/ 667540

Positron $E=1.1$ GeV
Run/Event 1316182344/ 919896

Front view

Side view
Electron $E=10.1$ GeV  
Run/Event 1314950197/ 296945

Positron $E=9.5$ GeV  
Run/Event 1316692684/ 283617
Electron $E=99$ GeV  
Run/Event 1318944028/ 505503

Positron $E=100$ GeV  
Run/Event 1334274023/ 338433

yz view  
$xz$ view  
yz view  
$xz$ view
Electron $E=982$ GeV
Run/Event 1329775818/ 60709

Positron $E=636$ GeV
Run/Event 133119-743/ 56950

Electron $E=982$ GeV
Positron $E=636$ GeV
AMS
1600 e+ events (65-100 GeV)

<table>
<thead>
<tr>
<th>Energy (GeV)</th>
<th>e^+ / (e^+ + e^-)</th>
<th>Error size</th>
</tr>
</thead>
</table>

FERMI: M. Ackermann et al., PRL 108 (2012)
The Big Bang origin of the Universe requires matter and antimatter to be equally abundant at the very beginning.
Experimental work on Antimatter in the Universe

**Direct search**

- **New CP**
  - BELLE
  - BaBar
    
  $\sin 2\beta = 0.672 \pm 0.023$ (consistent with SM)
  - FNAL KTeV
    
  $\text{Re}(\varepsilon' / \varepsilon) = (19.2 \pm 2.1) \times 10^{-4}$
  - CERN NA-48
  - CDF, D0

- **Proton decay**
  - Super K
    
  $T_p > 6.6 \times 10^{33}$ years

**Search for Baryogenesis**

- LHC-b, ATLAS, CMS

No explanation found for the absence of antimatter (no reason why antimatter should not exist)

Increase in sensitivity: $x 10^3 - 10^6$

Increase in energy to $\sim$TeV
Physics Example of AMS: “Strangelets”


Jack Sandweiss, Yale

All the material on Earth is made out of u and d quarks

Diamond (Z/A ~ 0.5)

Is there material in the universe made up of u, d, & s quarks?

Strangelet (Z/A < 0.1)

This can be answered definitively by AMS.
Physics Example of AMS

B/C ratio up to TeV

Precise measurement of the energy spectra of B/C provides information on Cosmic Ray Interactions and Propagation

Interactions with the Interstellar Medium:
\[ C + (p, \text{He}) \rightarrow B + \ldots \]
Rigidity $\sim 3$ GV

**Boron**
Rigidity = 3.7 GV
Run/Event 1333501084/ 42231

- $Z_{TRK_L1} = 5.3$
- $Z_{TRD} = 5.1$
- $Z_{TOF_UP} = 5.1$
- $Z_{TRK_L2-L8} = 4.9$
- $Z_{TOF_LOW} = 4.9$
- $Z_{RICH} = 5.1$
- $Z_{TRK_L9} = 5.0$

**Carbon**
Rigidity = 3.3 GV
Run/Event 1327519853/ 487070

- $Z_{TRK_L1} = 6.4$
- $Z_{TRD} = 5.9$
- $Z_{TOF_UP} = 6.1$
- $Z_{TRK_L2-L8} = 6.1$
- $Z_{TOF_LOW} = 6.1$
- $Z_{RICH} = 5.9$
- $Z_{TRK_L9} = 6.5$

Rigidity = 3.3 GV
Boron
Rigidity = 3.7 GV
Carbon

Run/Event 1333501084/ 42231
Run/Event 1327519853/ 487070

Front view
Side view
Front view
Side view

Z_{TRK_L9} = 5.0
Z_{TRK_L9} = 6.5
**Rigidity ~ 20 GV**

**Boron**  
Rigidity=24 GV  
Run/Event 1326201809/ 798775

- $Z_{TRK\_L1}=4.7$  
- $Z_{TRD}=4.9$  
- $Z_{TOF\_UP}=5.1$  
- $Z_{TRK\_L2-L8}=4.9$  
- $Z_{TOF\_LOW}=5.0$  
- $Z_{RICH}=4.8$

**Carbon**  
Rigidity=24 GV  
Run/Event 1329490720/ 473181

- $Z_{TRK\_L1}=6.0$  
- $Z_{TRD}=5.9$  
- $Z_{TOF\_UP}=6.0$  
- $Z_{TRK\_L2-L8}=5.9$  
- $Z_{TOF\_LOW}=6.0$  
- $Z_{RICH}=6.2$
Rigidity ~ 200 GV

**Boron**
Rigidity=187 GV

Run/Event 1329086299/ 747549

- $Z_{TRK_L1}=4.9$
- $Z_{TRD}=4.5$
- $Z_{TOF_UP}=5.0$
- $Z_{TRK_L2-L8}=4.9$
- $Z_{TOF_LOW}=5.1$
- $Z_{RICH}=5.2$

**Carbon**
Rigidity=215 GV

Run/Event 132643580/ 132197

- $Z_{TRK_L1}=6.1$
- $Z_{TRD}=5.9$
- $Z_{TOF_UP}=5.9$
- $Z_{TRK_L2-L8}=5.8$
- $Z_{TOF_LOW}=5.8$
- $Z_{RICH}=6.1$

Rigidity

- Boron: 187 GV
- Carbon: 215 GV

Run/Event

- Boron: 1329086299/ 747549
- Carbon: 132643580/ 132197
Boron
Rigidity=680 GV
Run/Event 1319990213/ 235892

Carbon
Rigidity=666 GV
Run/Event 1327184805/ 266043

Z_{TRK_L1}=5.2
Z_{TRD}=5.2
Z_{TOF_UP}=5.5
Z_{TOF_LOW}=5.4
Z_{RICH}=4.8
Z_{TRK_L9}=5.1
Z_{TRK_L2-L8}=5.0

Z_{TRK_L1}=5.8
Z_{TRD}=6.0
Z_{TOF_UP}=6.1
Z_{TOF_LOW}=6.5
Z_{RICH}=6.1
Z_{TRK_L9}=6.1
Carbon Fragmentation to Boron in Upper TOF
Rigidity 10.6 GV
Detector calibrations are completed for the 1st year 10+ years onboard ISS – great physics potential
The most exciting objective – to probe the unknown