Le sfide tecnologiche della misura del flusso di raggi cosmici nello spazio: l'esperimento Alpha Magnetic Spectrometer

G. Ambrosi

Legnaro, 22 Aprile 2009

Goal (ambizioso …)

Individuare cosa e' necessario per trasformare uno rivelatore di fisica delle alte energie a terra in uno strumento adatto allo spazio

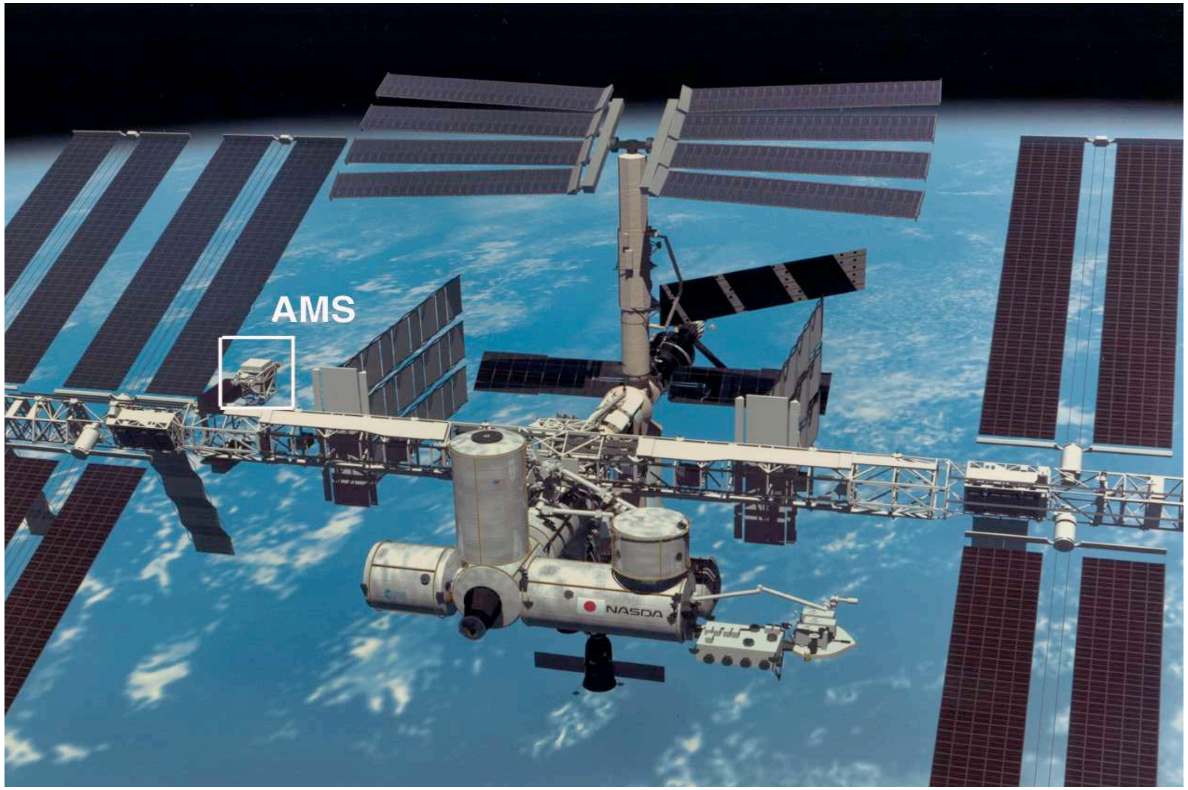
Alcune (molte) delle cose dette possono sembrare (essere) ovvie:
nelle applicazioni spaziali anche le cose ovvie vanno verificate …

Outline

- cosa vogliamo misurare
- lo strumento che ci serve
- il primo volo di AMS
- l’apparato AMS02
- le sfide tecnologiche

AMS on the International Space Station

- Cosmic Antimatter search with 10^{-9} sensitivity
- Indirect Dark Matter search (e^+, $\bar{p}$, γ)
- Relative abundance of nuclei and isotopes in primary cosmic rays
- γ ray astrophysics



The purpose of the AMS experiment is to perform accurate, high statistics, long measurements of charged cosmic rays (0.5 GV - 1 TV) and γ rays (E>1GeV)

Anti-matter search

- No doubt about the existence of Anti-matter since the 30's

Dirac's Nobel speech

"We must regard it rather as an accident that the Earth [...] contains a preponderance of negative electrons and positive protons. It is quite possible that for some stars it is the other way about."

Measure nature's beam

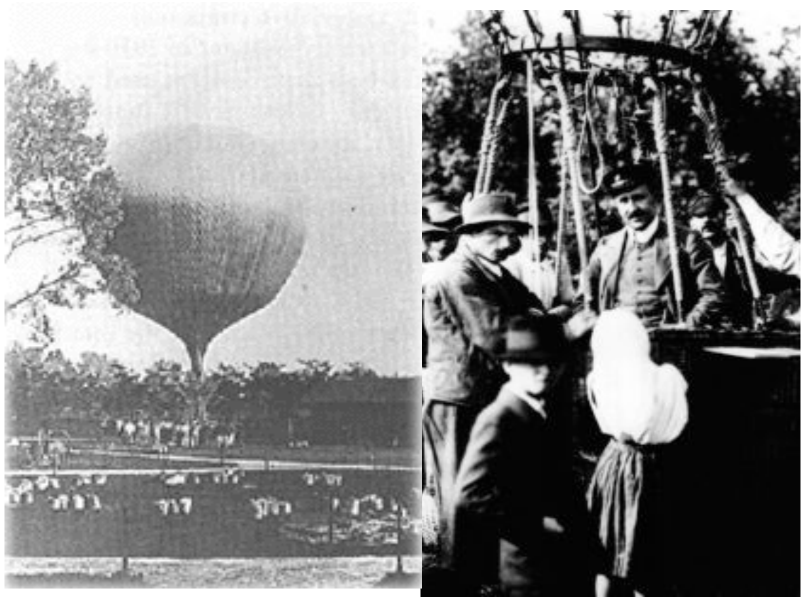
- Cosmic Rays composition:

  ~ 88% proton ~ 9% He nuclei

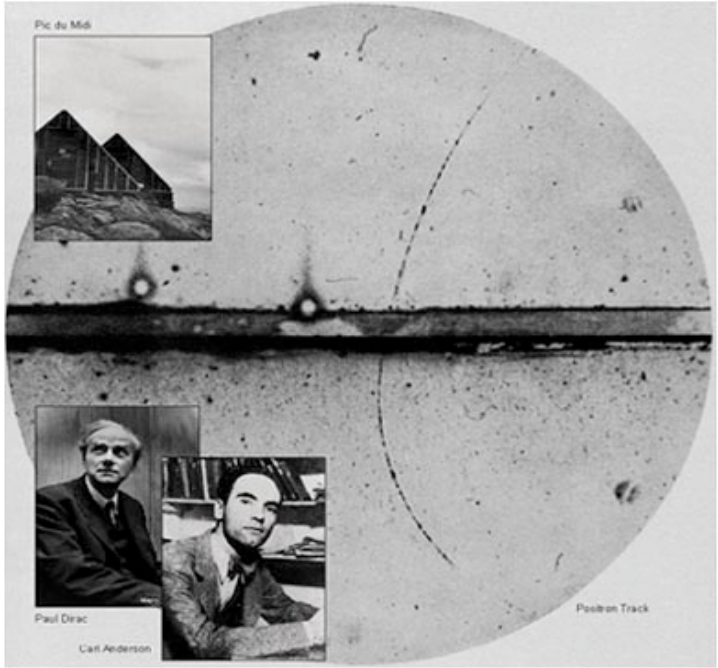
  ~ 1% Z > 2 nuclei ~ 2% electrons
- Best measurements are done outside the atmosphere

  (no bckgd. from secondary particles)
- Precise measurements of composition and spectrum of hadronic and leptonic fluxes is a test for acceleration and propagation models
- Secondary production ($\bar{p}$, e^+) in the ISM is a background for exotic searches ($\bar{p}/p \sim O(10^{-4})$, $e^+/e^- \sim O(10^{-1})$)
- Precise hadron flux is mandatory for atmospheric ν calculation

perchè andiamo nello spazio?



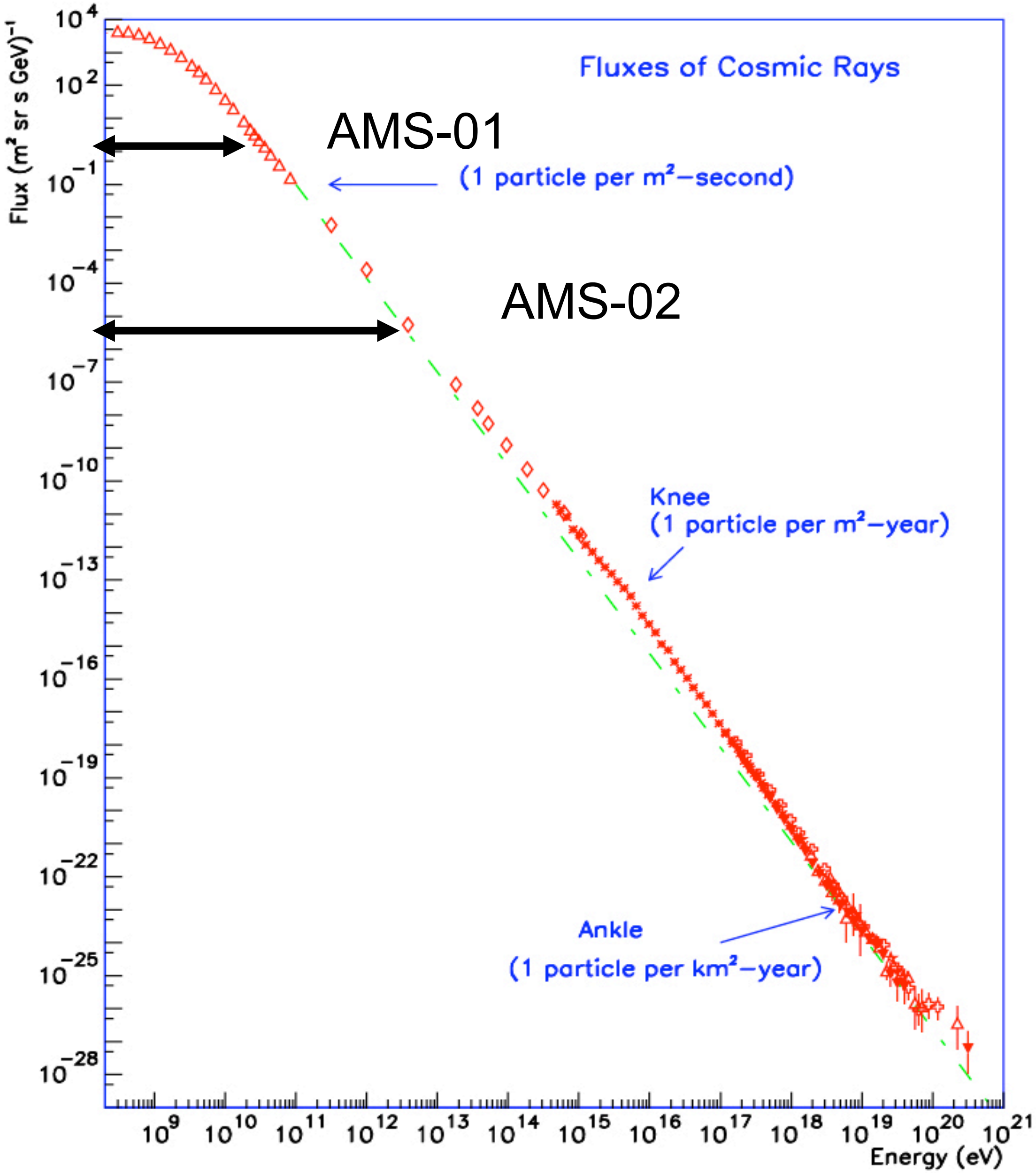
V. Hess ‘scopre’ i raggi cosmici nel 1912



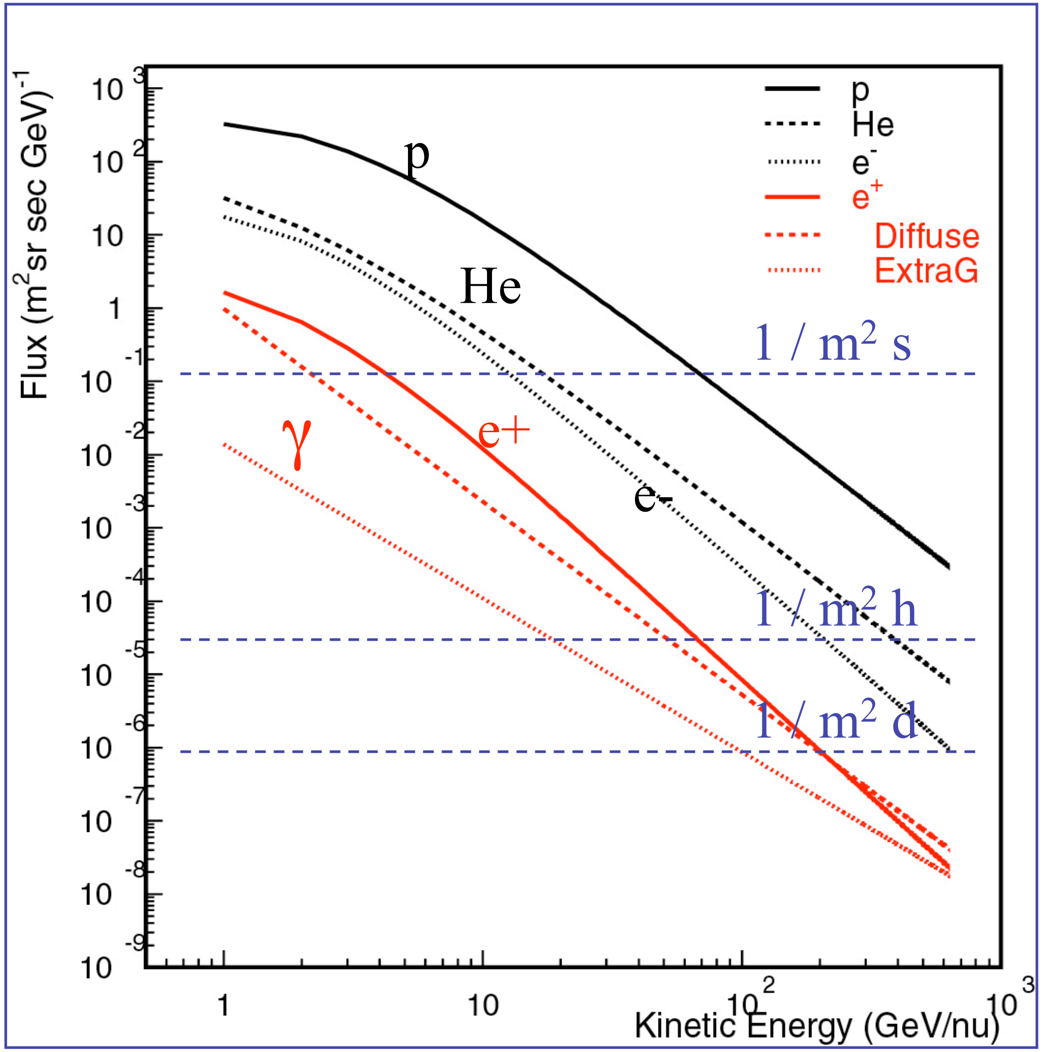
Anderson scopre il positrone nel 1932

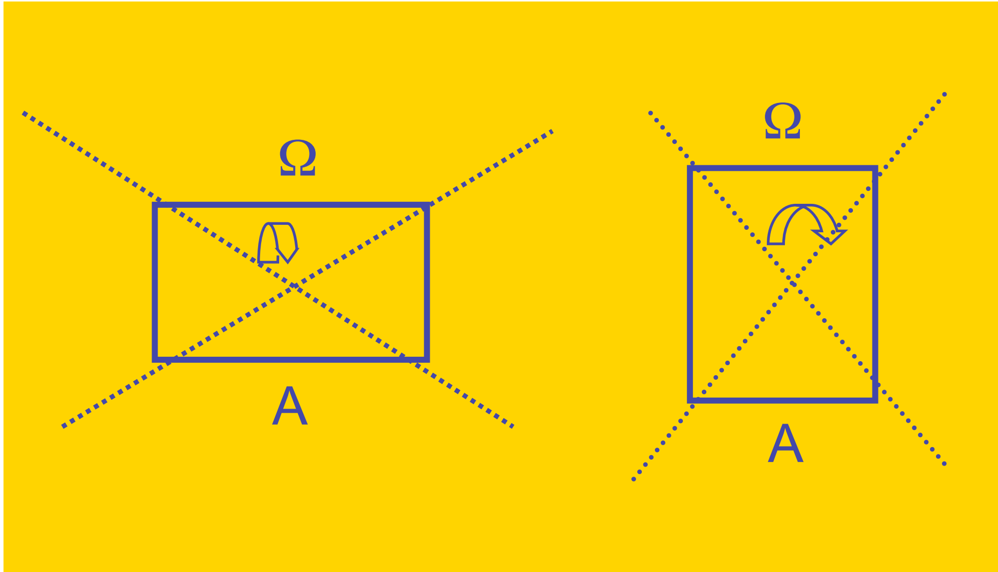
1 atm = 760 mmHg

X_0 del Mercurio = 0.47 cm

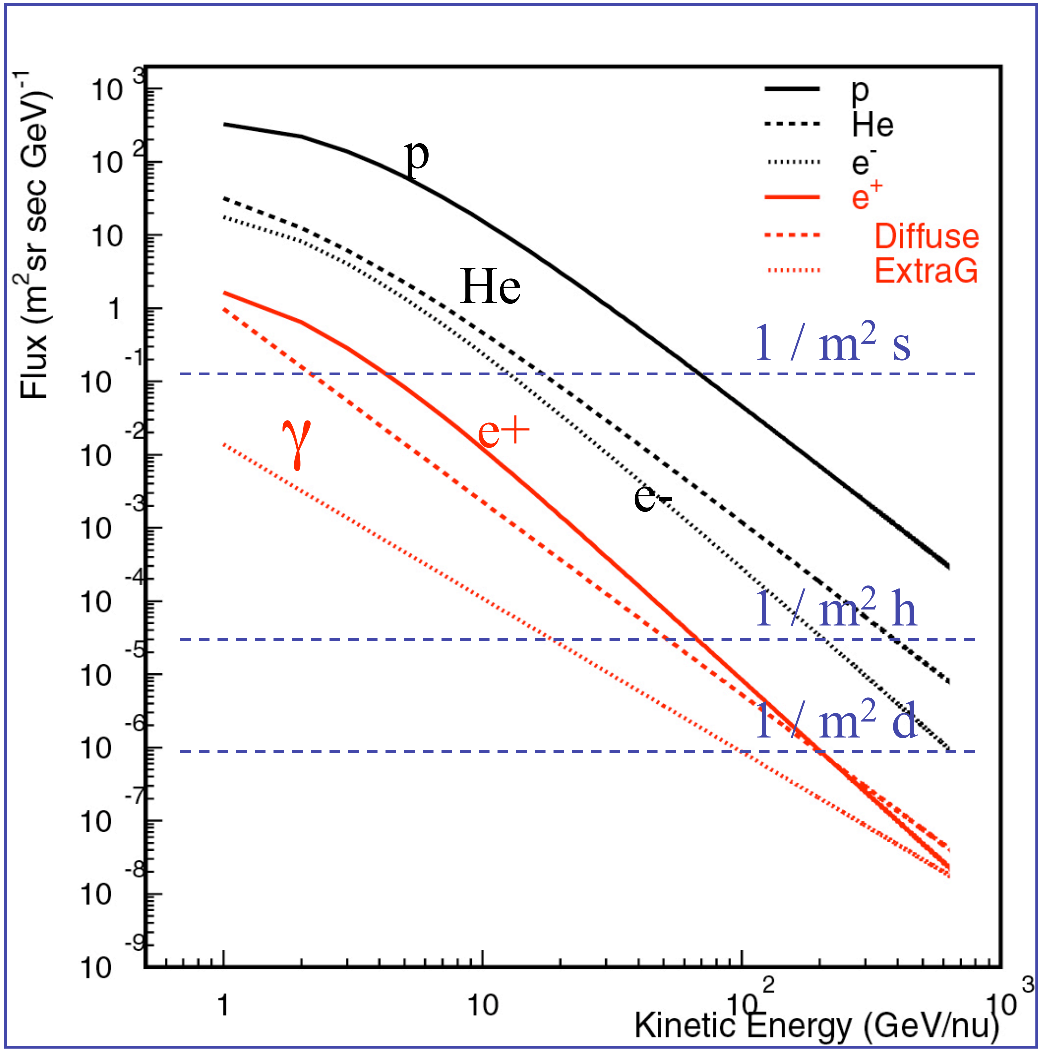

Fluxes of Cosmic Rays
AMS-01
AMS-02
(1 particle per m²−second)
Knee
(1 particle per m²−year)
Ankle
(1 particle per km²−year)
Flux (m² sr s GeV)⁻¹
Energy (eV)

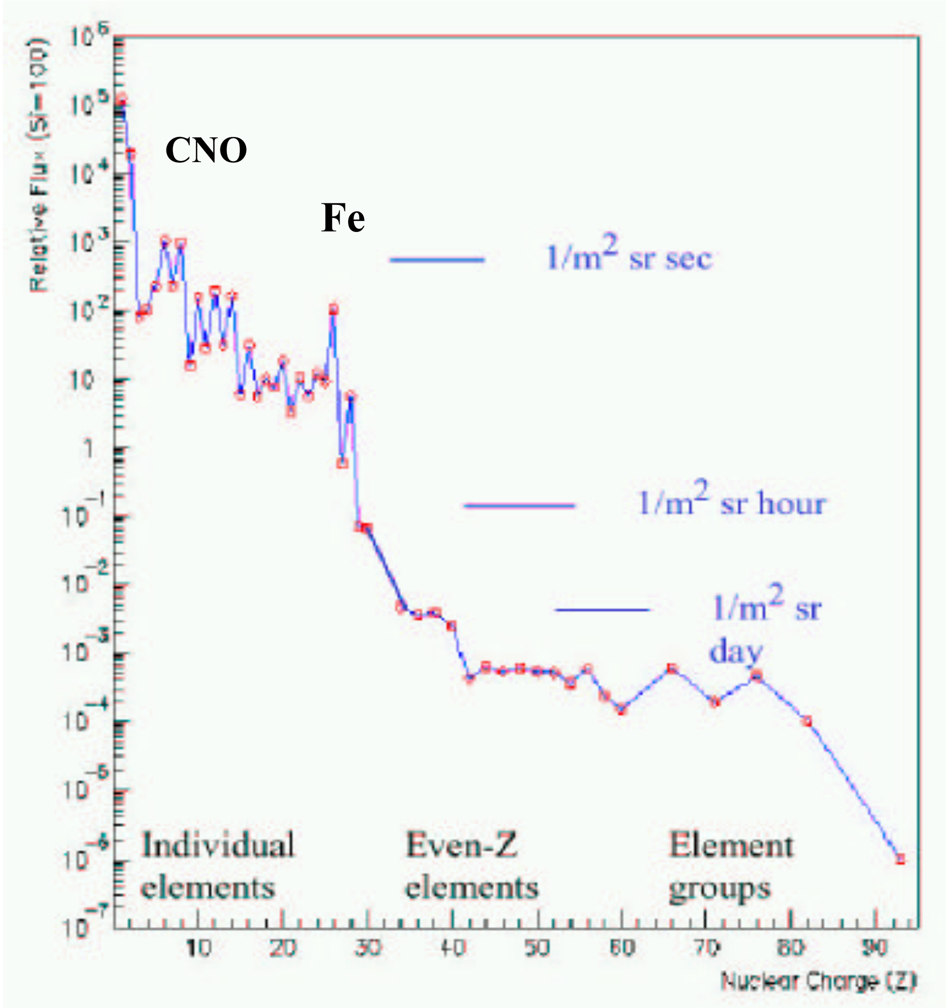
High Energy CR flux and composition





High Energy CR flux and composition

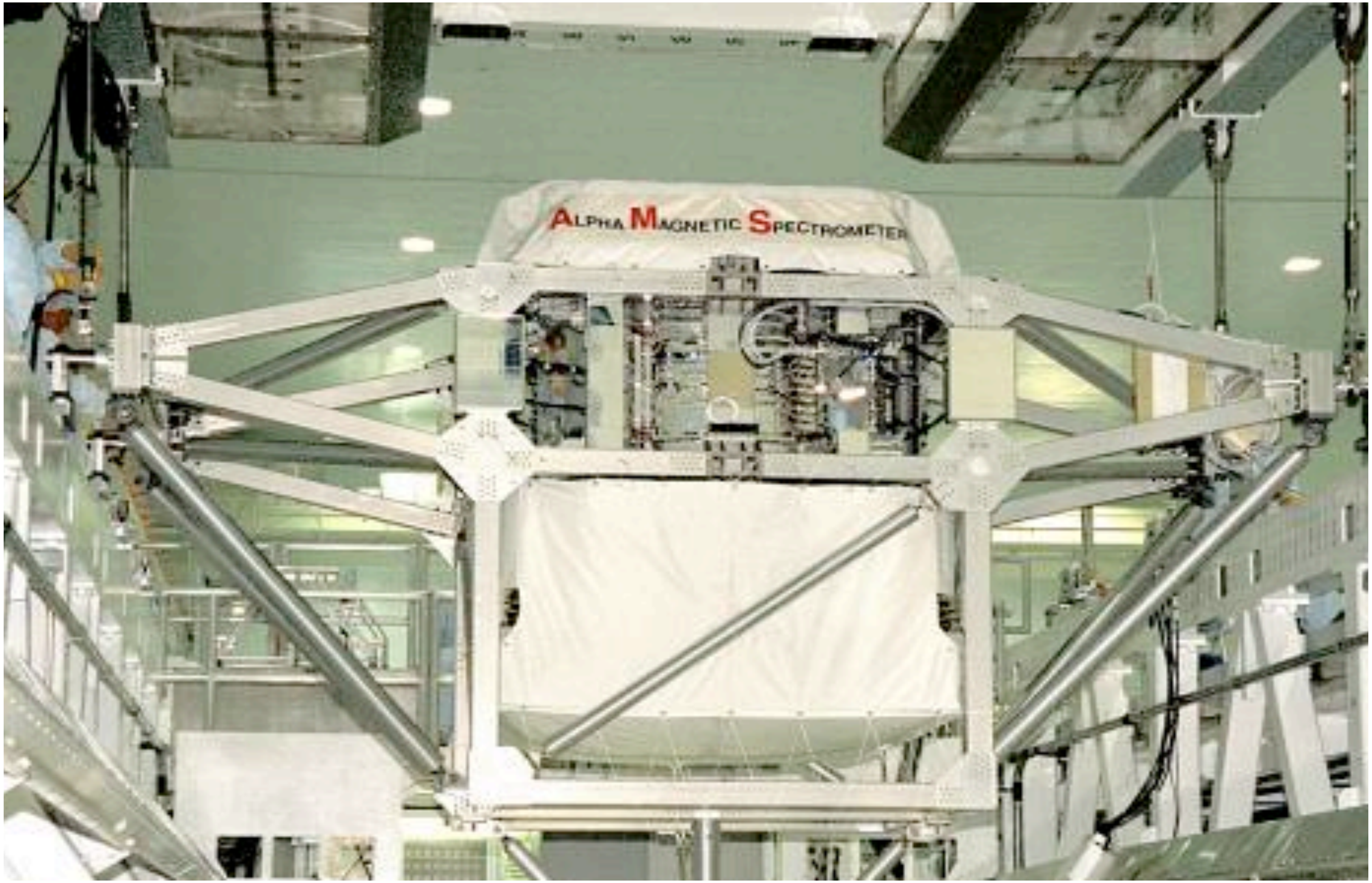




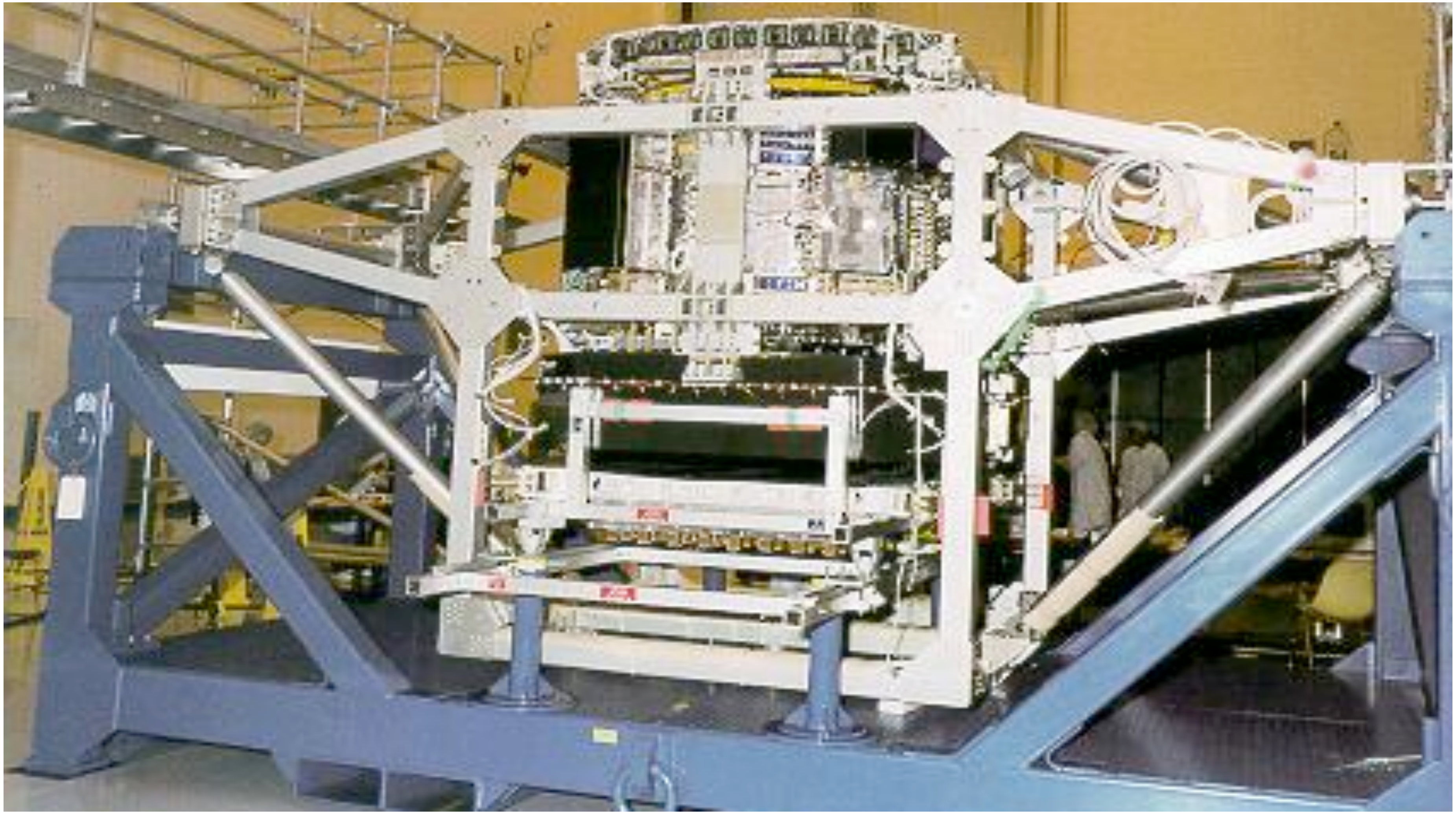
The instrument we need has …

- performance a la ‘particle physics’:
  - high resolution measurements of momentum, velocity, charge and energy
- characteristics to properly work in the space environment:
  - Vibration (6.8 G rms) and acceleration (17 G)
  - Temperature variation (day/night $\Delta T = 100^oC$)
  - Vacuum (10^{-10} Torr)
  - Orbital debris and micrometeorites
  - Radiation (Single Event Effect)
- limitation in weight (15000 lb), power (3KW), bandwidth and maintenance
- Compliant with Electromagnetic Interference and Electromagnetic Compatibility specs

AMS-01 at KSC prima dell'installazione nello shuttle (Maggio 1998)



AMS-01 at KSC before installation on the Shuttle



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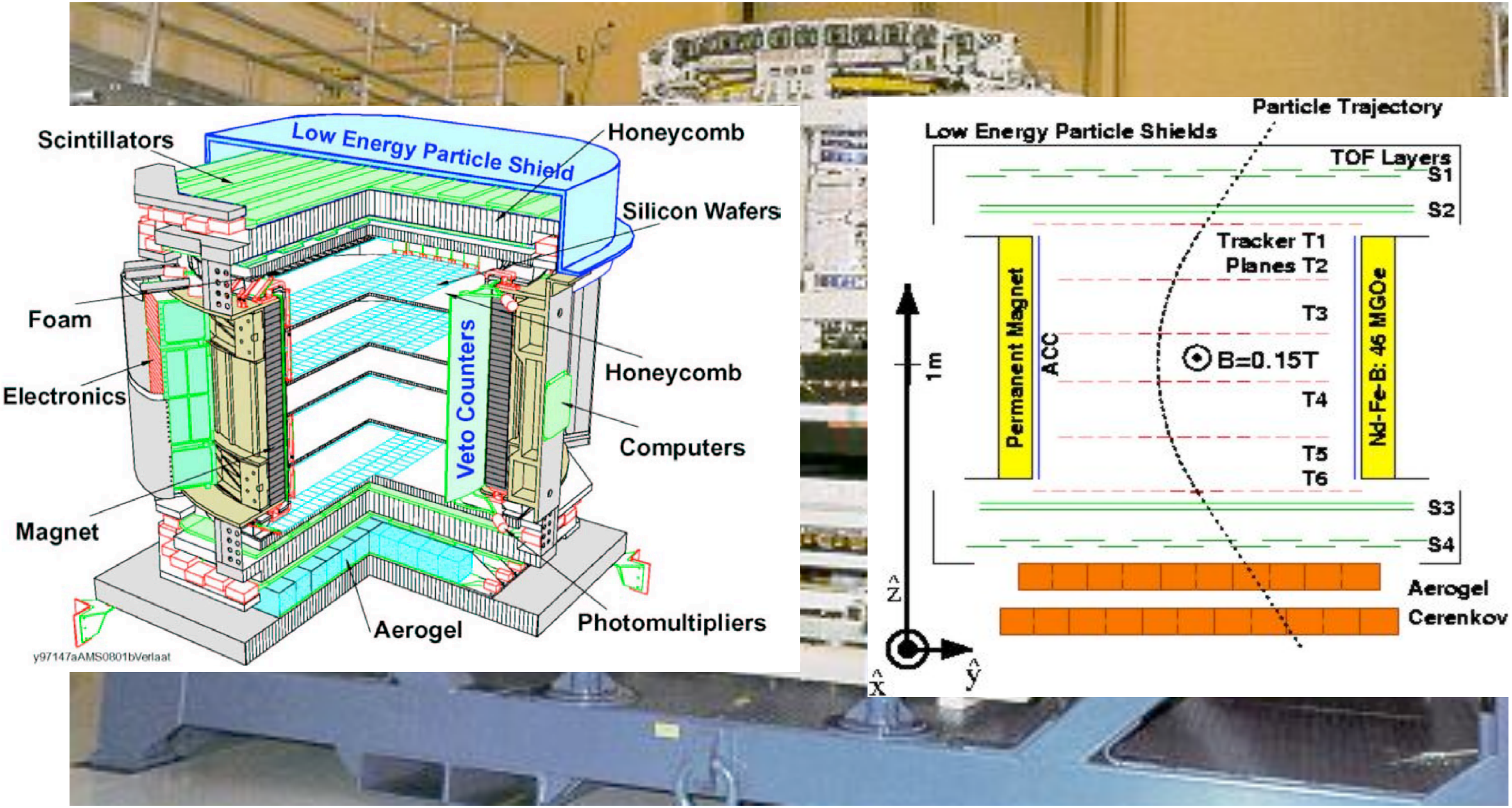
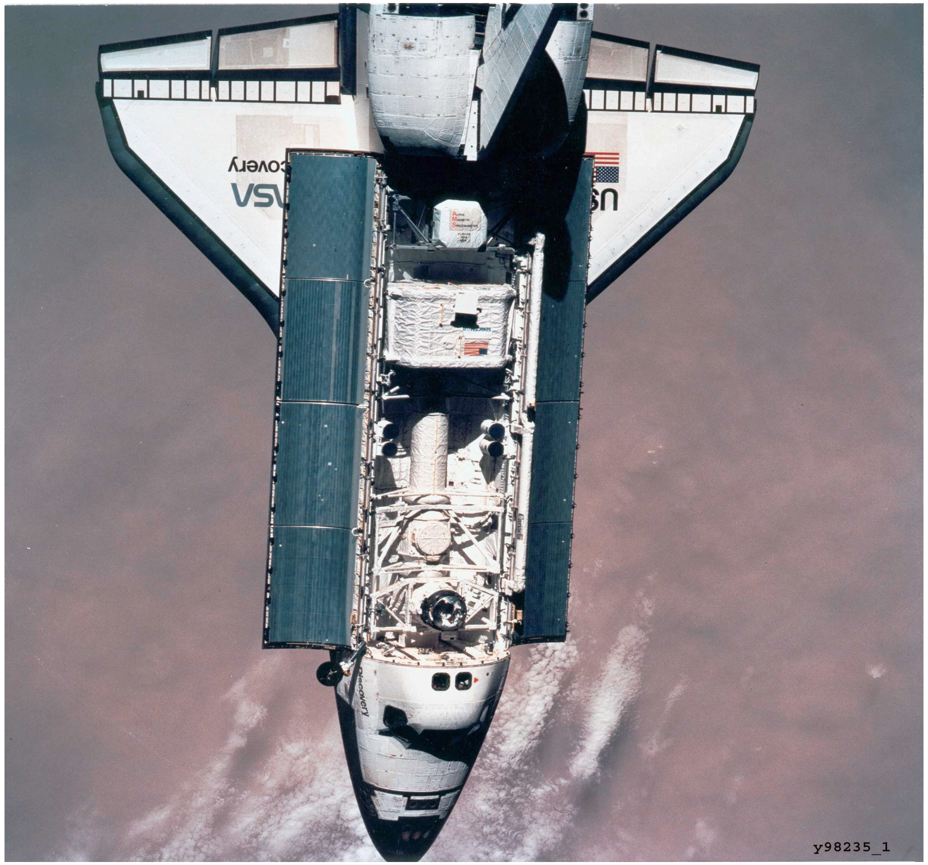


AMS-01 pilot experiment: STS91, June 2nd - 12th 1998

- 10 days of data taking in orbit:
  - 400 Km altitude
  - latitudes +51.7°
  - all longitudes
- 10^8 events recorded
- Physics results
  (Phys. Rep. 366 (2002) 331)
  - precise measurements of primary fluxes
  - detection of secondary fluxes (quasi trapped)
  - antimatter limit at 10^{-6}



AMS-02 Design principles

- High statistics → large acceptance & long exposure time
- Negligible environmental background → space
- Optimize instrumental background → minimum amount of material

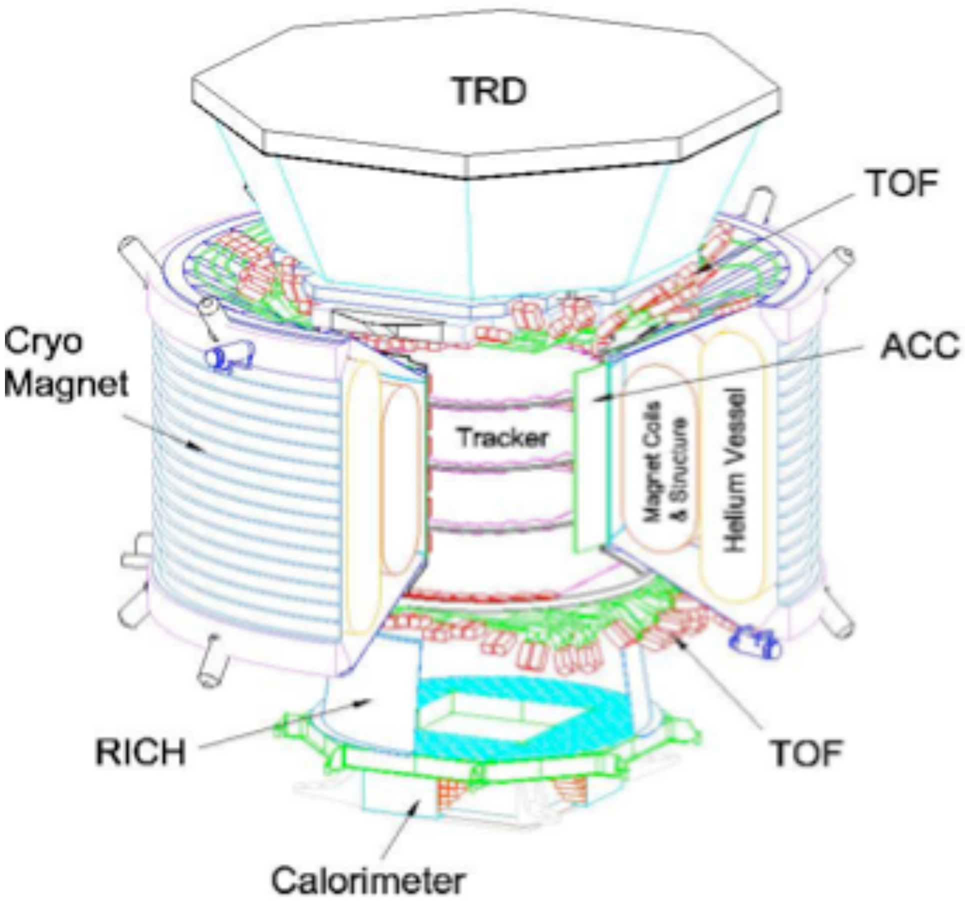
+

- Charge sign and Z measurement
- Particle identification: e/p ~ 10^6
- Mass measurement: ^{9}Be/^{10}Be, D/H, ^{3}He/^{4}He

↓

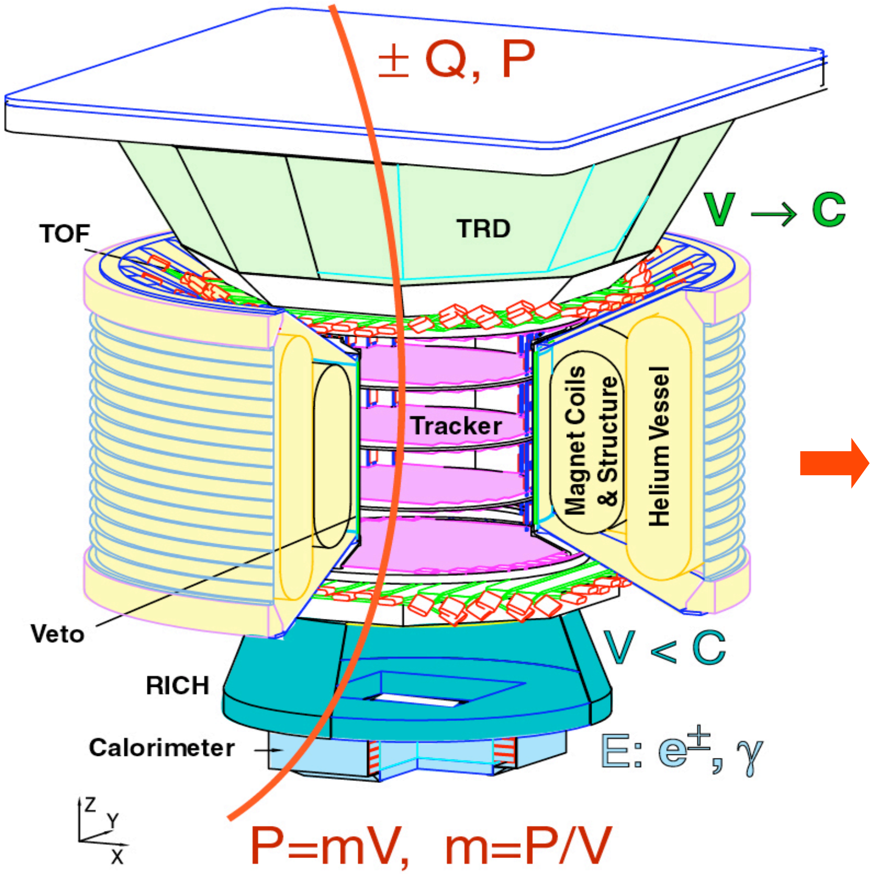
Acceptance ~ 0.5 m^2 sr
Strong B field: B ~ 0.8 T
Tracking: 8 points @ 10μm
Repeated measurements of Z, velocity
Complementary techniques for e/p separation

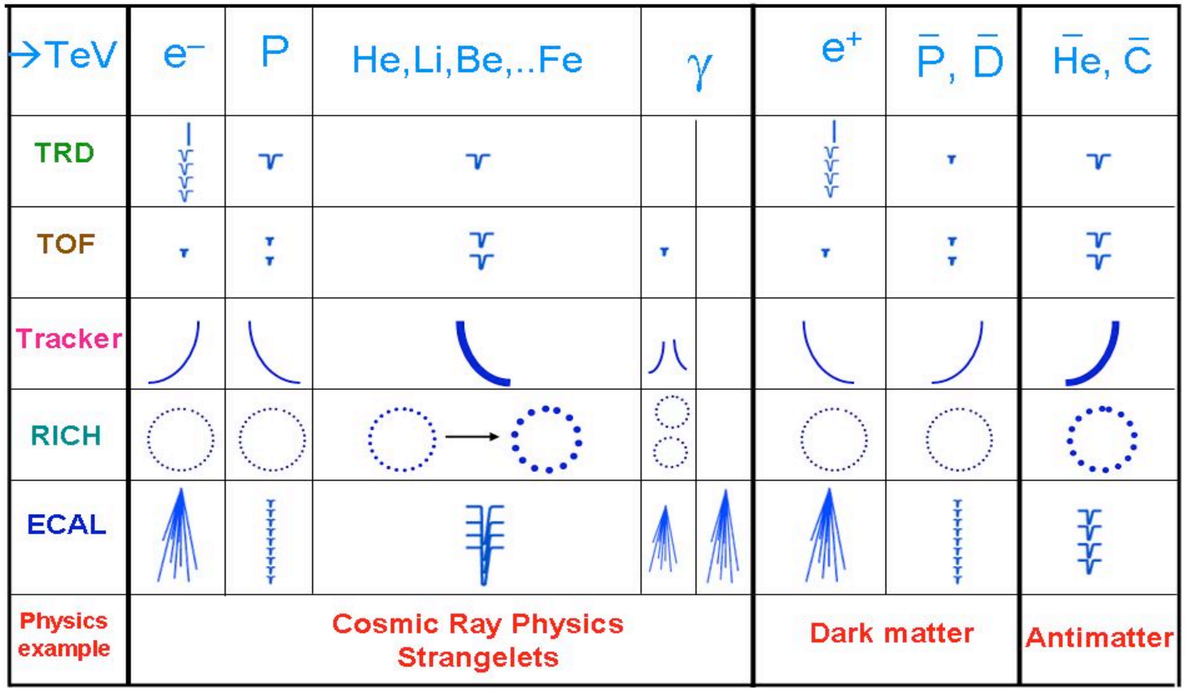
AMS-02 on the ISS



- Improved capability:
  - larger acceptance (~.5 m^2 sr)
  - stronger magnetic field (.8 T)
  - larger tracker (~6.7 m^2)
  - improved momentum resol.
- New detectors
  - Transition Radiation Detector
  - New Cherenkov
  - Electromag. Calorimeter
  - 2 camera Star Tracker
- Orbital parameters
  - ~92 minutes period
  - ~400 Km altitude
  - 51.6^o inclination

The AMS-02 detector





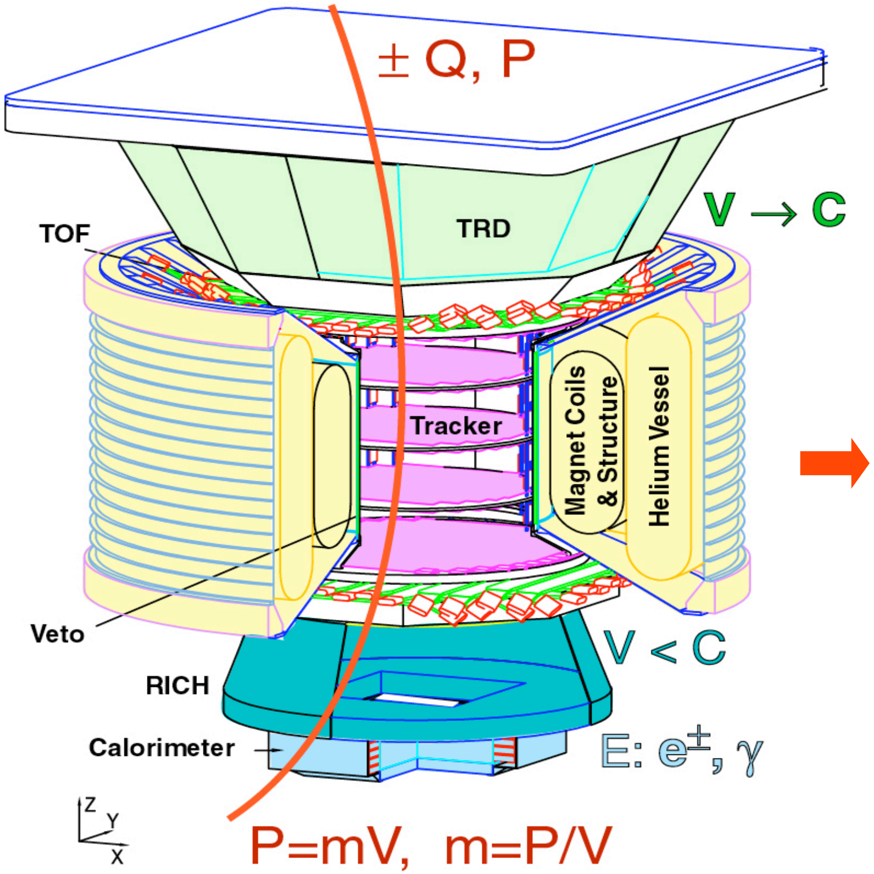
Silicon spectrometer design goals:

dP/P ~ 1% up to 100 GeV

MDR ~ 1 TV

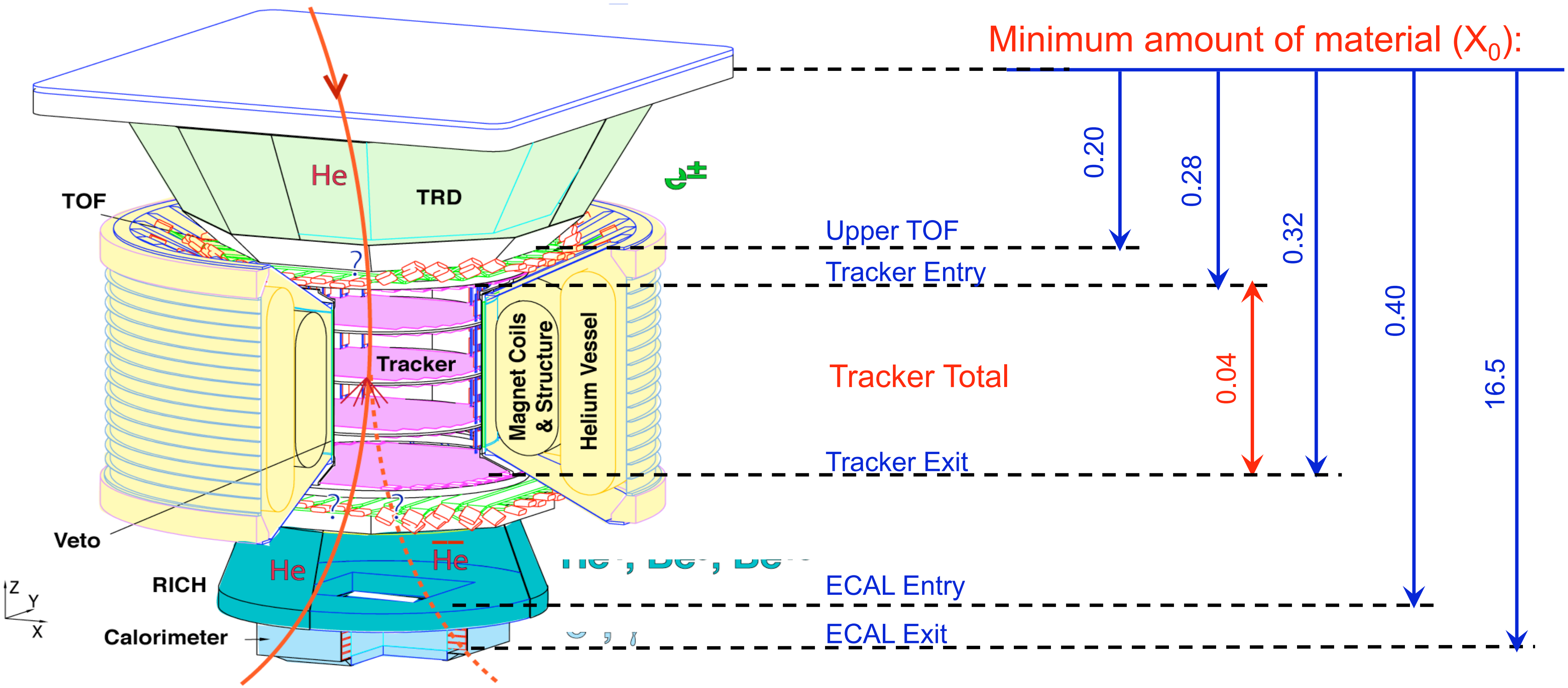
Z measurement up to Iron

The AMS-02 detector



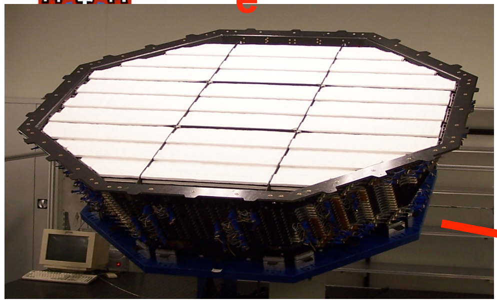
- TRD: e/h separation up tp 300 GeV
- TOF: β, dE/dx, direction
- Tracker: rigidity (p/Ze), Z
- RICH: β, dE/dx
- ECAL: e/h separation, E

transparent detector

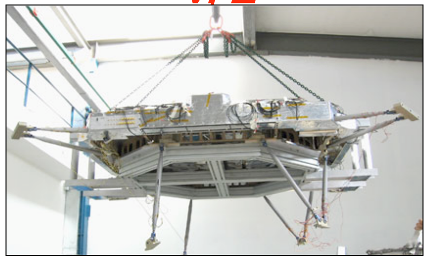


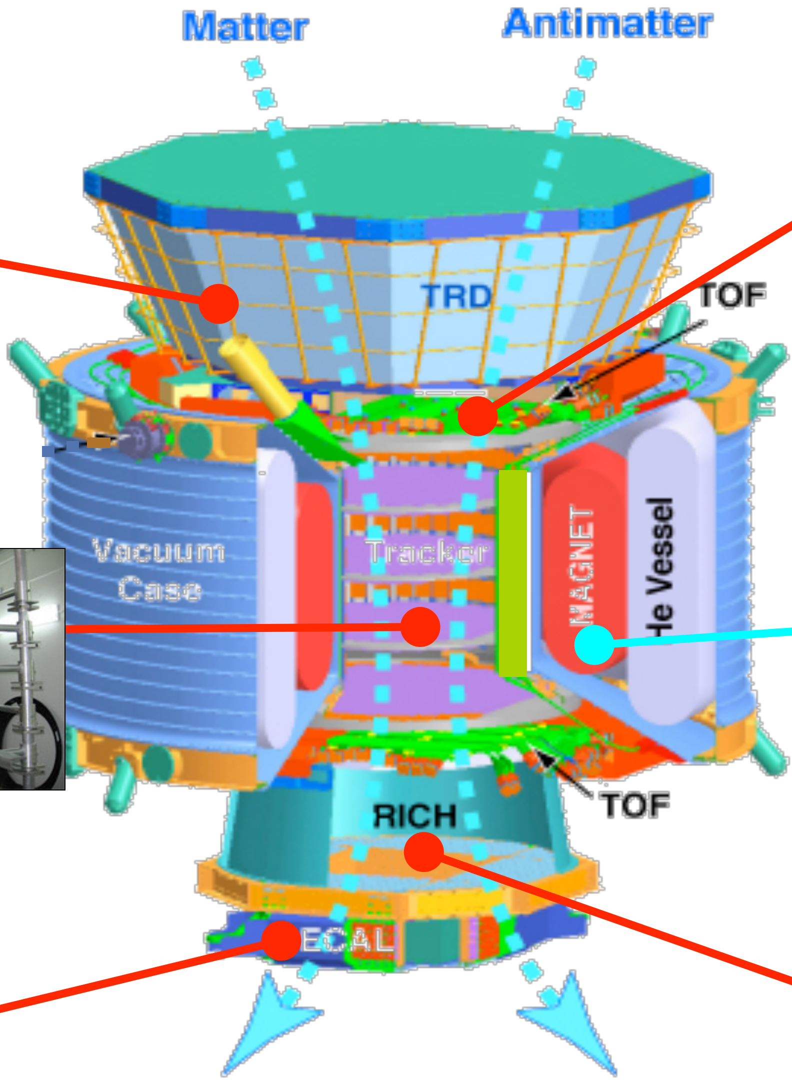
construction complete

TRD
e

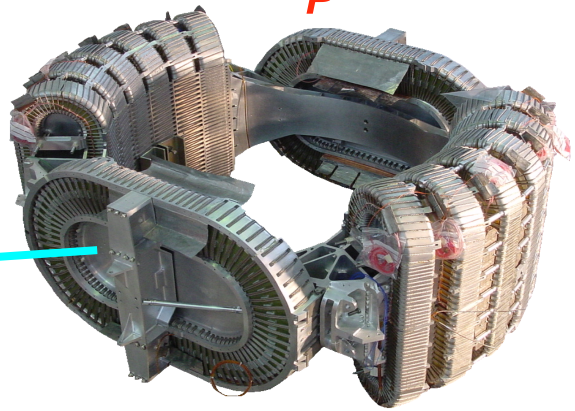


Time of Flight
v, Z





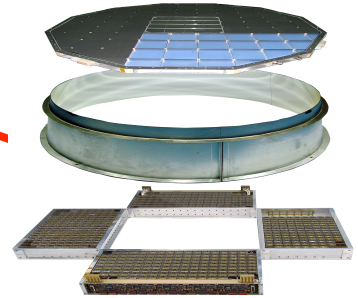
Magnet
P



Silicon Tracker
Z, P

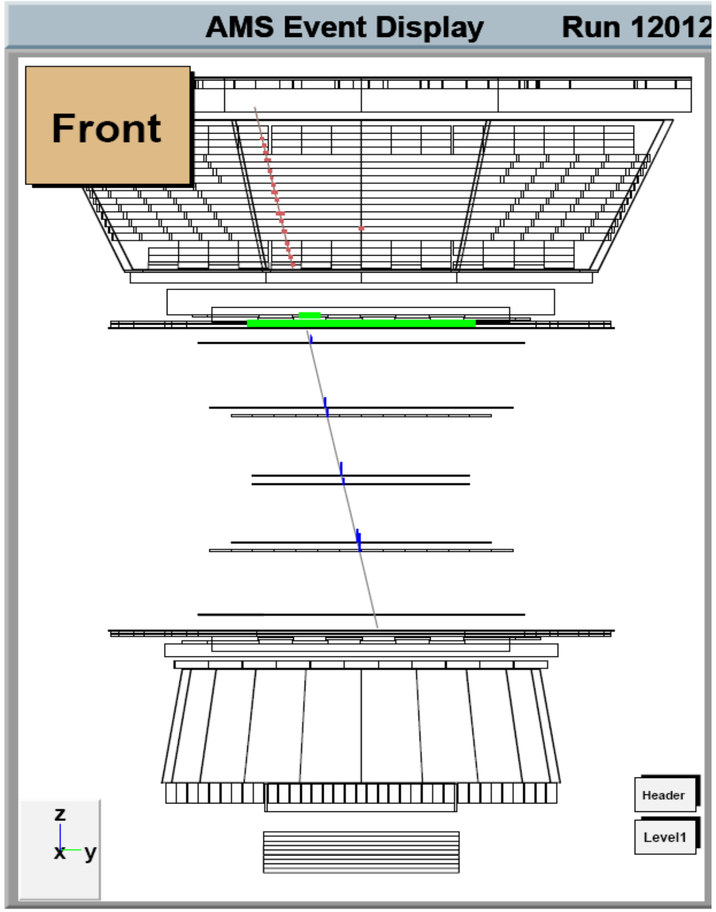
Calorimeter
e, γ

RICH
v, Z



Size: 3m x 3m x 3m
Weight: 7 tons

the full AMS-02 detector!



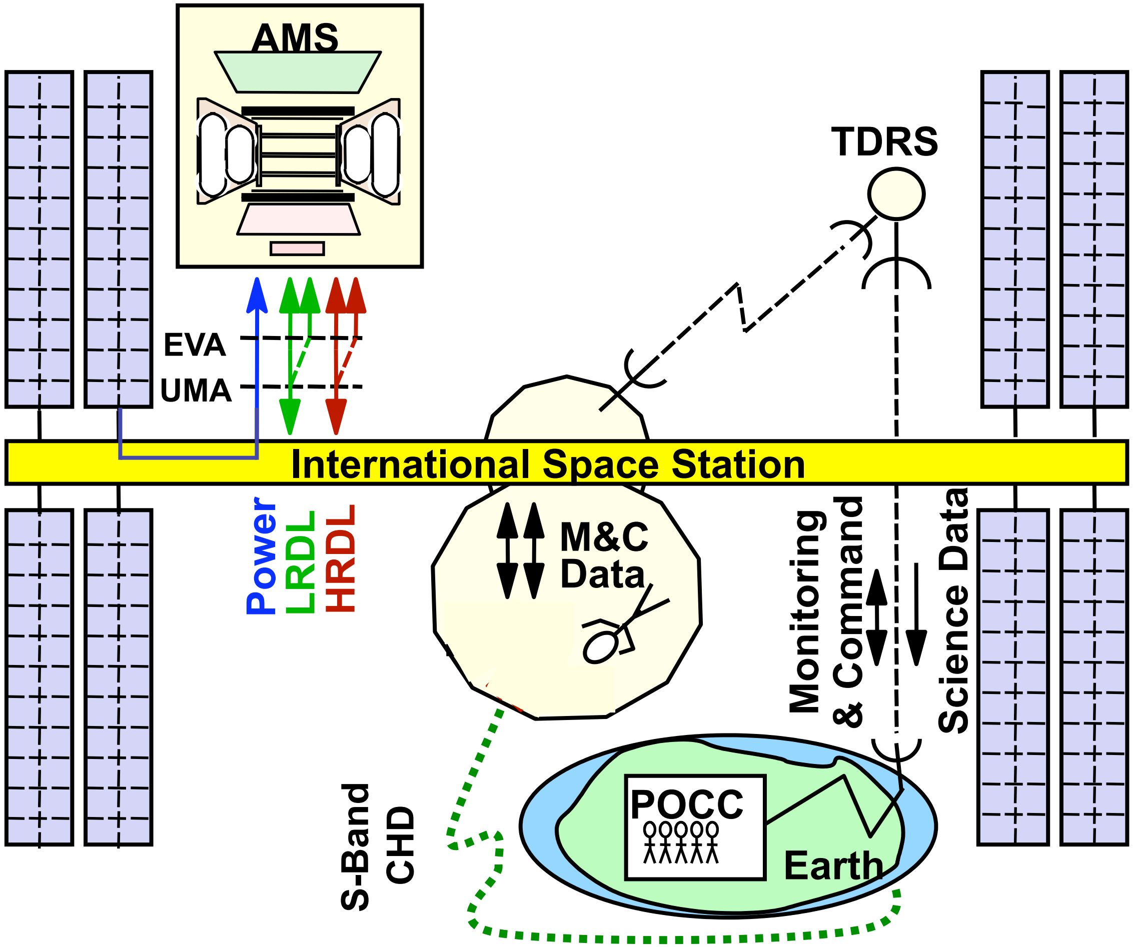
AMS Electrical Interfaces on ISS

Power:
- 109-124VDC
- ~2KW

LRDL
- for Cmd & Mon
- 1553B Bus
- 1 Kbit/s in
- 10 Kbit/s out
- 10 B/sec CHD

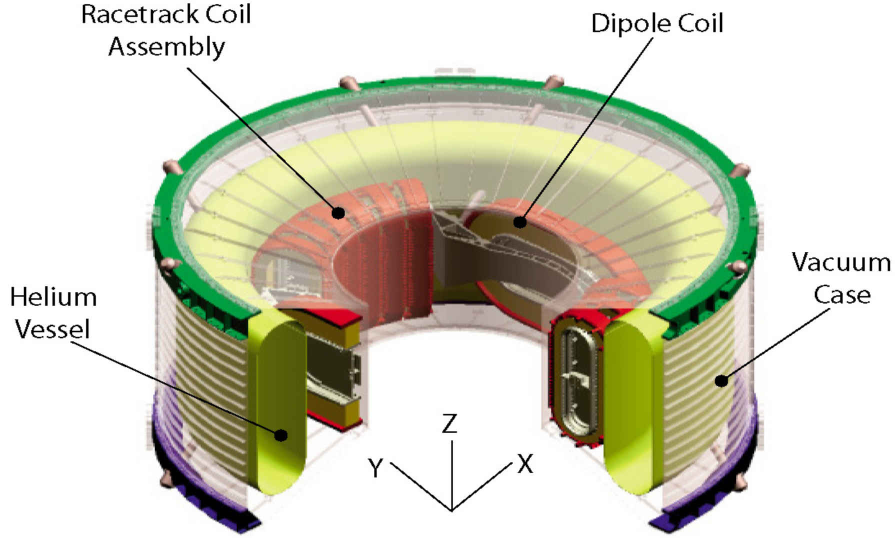
HRDL
- for Event Data
- Taxi F/O
- <2Mbit/s>$_{orbit}$

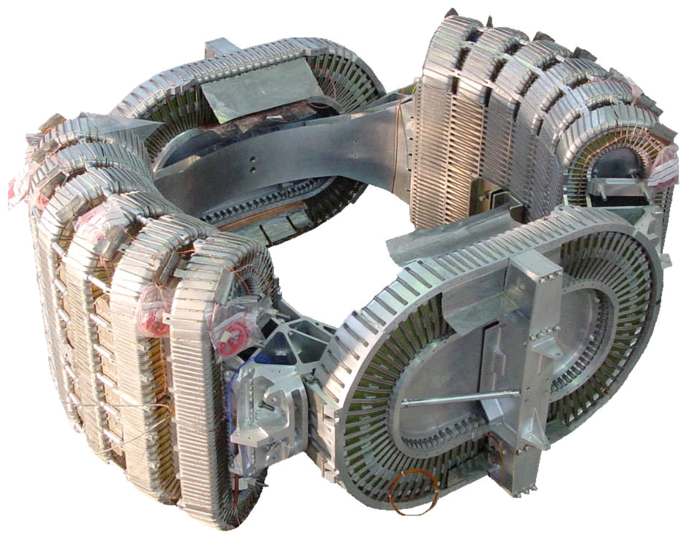
xRDL: Duty cycle ~50-70%



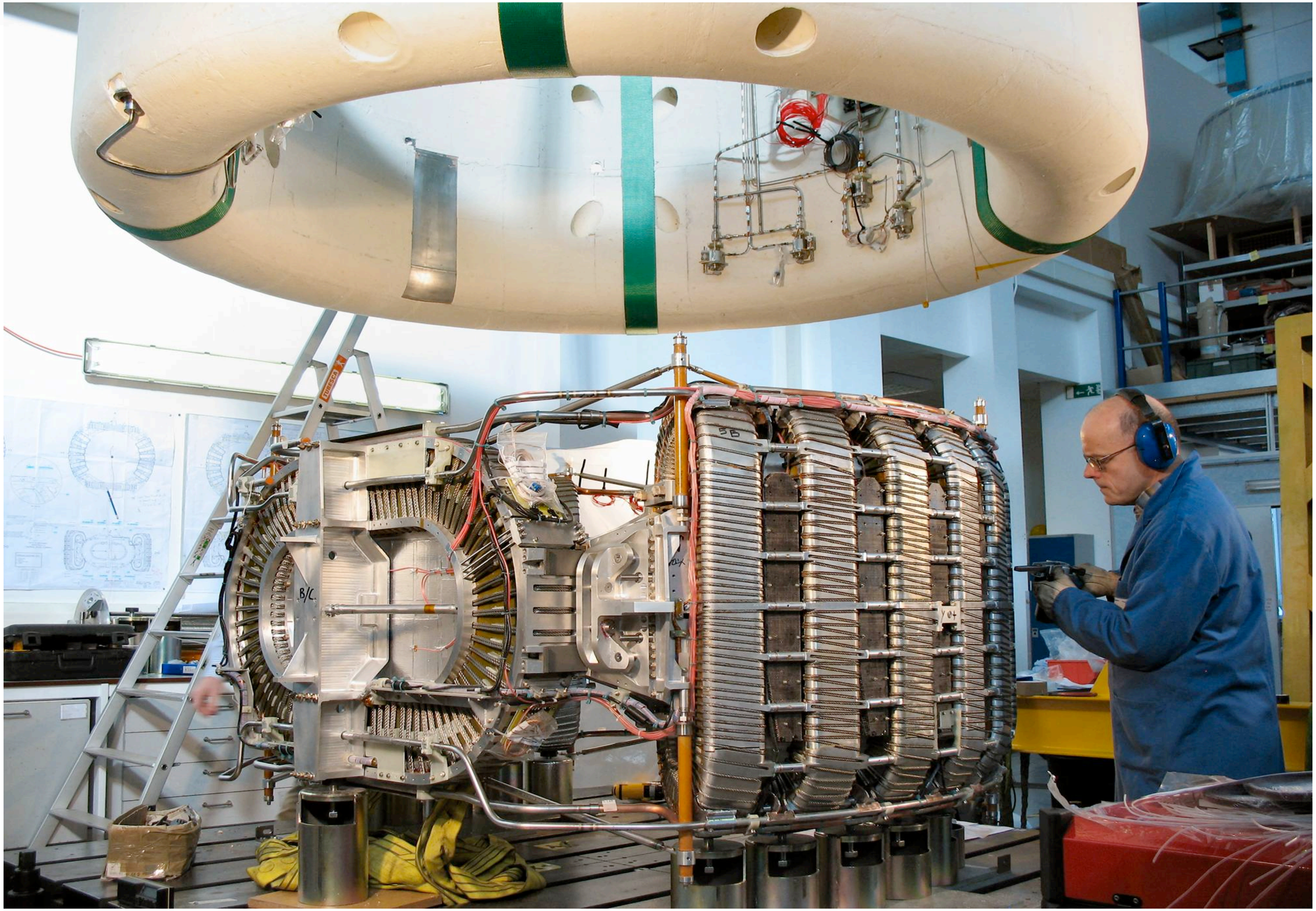
Superconducting magnet

- 2 ‘dipole’ coil, 12 ‘racetrack’ coil (~ no magnetic dipole moment)
- B~0.9 T, 1.1 m inner diameter, 2360 Kg weight
- 55 Km of superconducting wire (NbTi/Cu embedded in pure aluminium)
- Indirect cooling with superfluid helium (1.8 K)
- 2500 liters helium vessel plus cryocuulers for 3 years operation



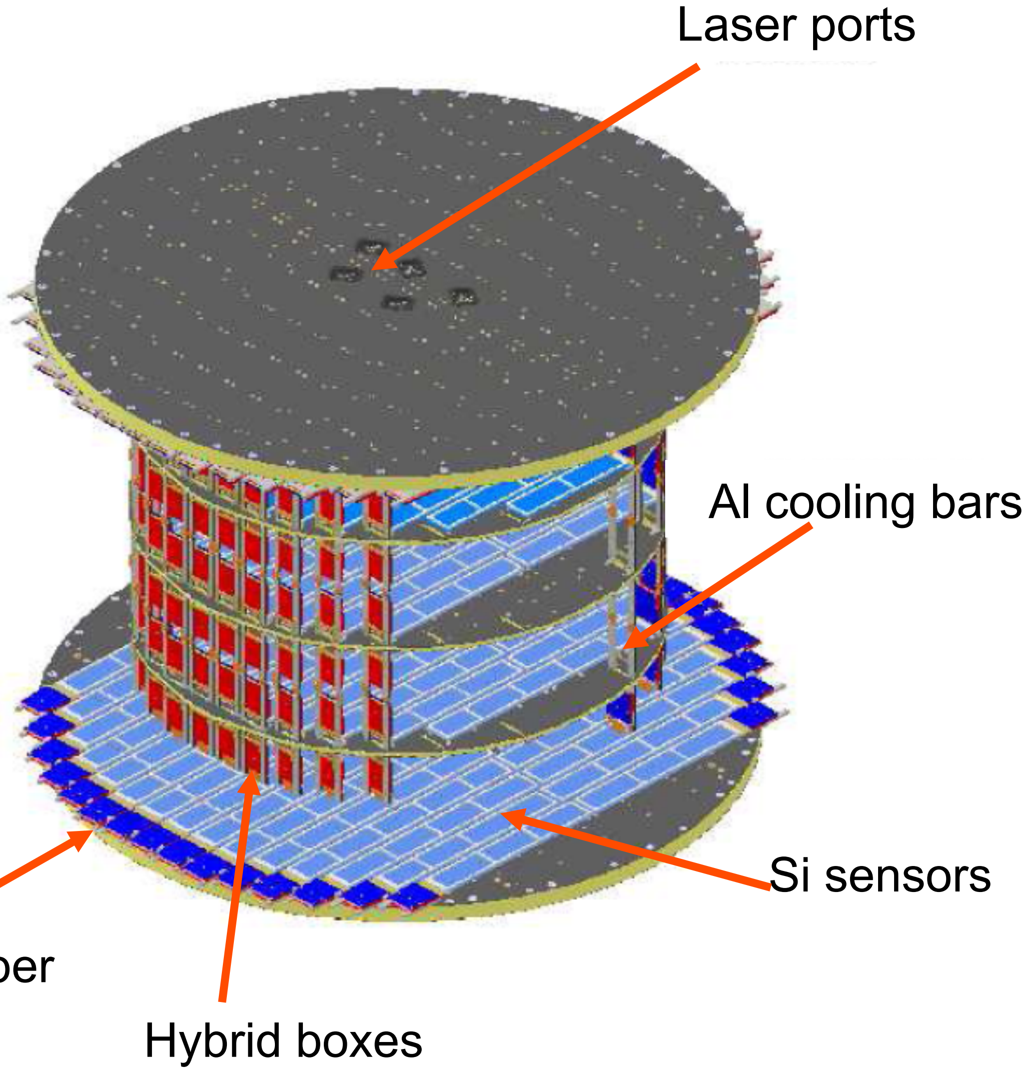


dry magnet



Silicon Tracker

- 8 layers of double sided silicon detectors arranged in 192 ladders
- 5 honeycomb carbon fiber plane
- detector material ~ 0.04 Xo
- total of 200 kchannels for 192 watt dissipated inside the magnet volume
- 10 μm (30 μm) spatial resolution in bending (non bending) plane
- momentum resol 1.5% at 10 GeV
- high dynamic range front end for charge measurement
- wide temperature range (-20/+40 survival, -10/+25 oper.)



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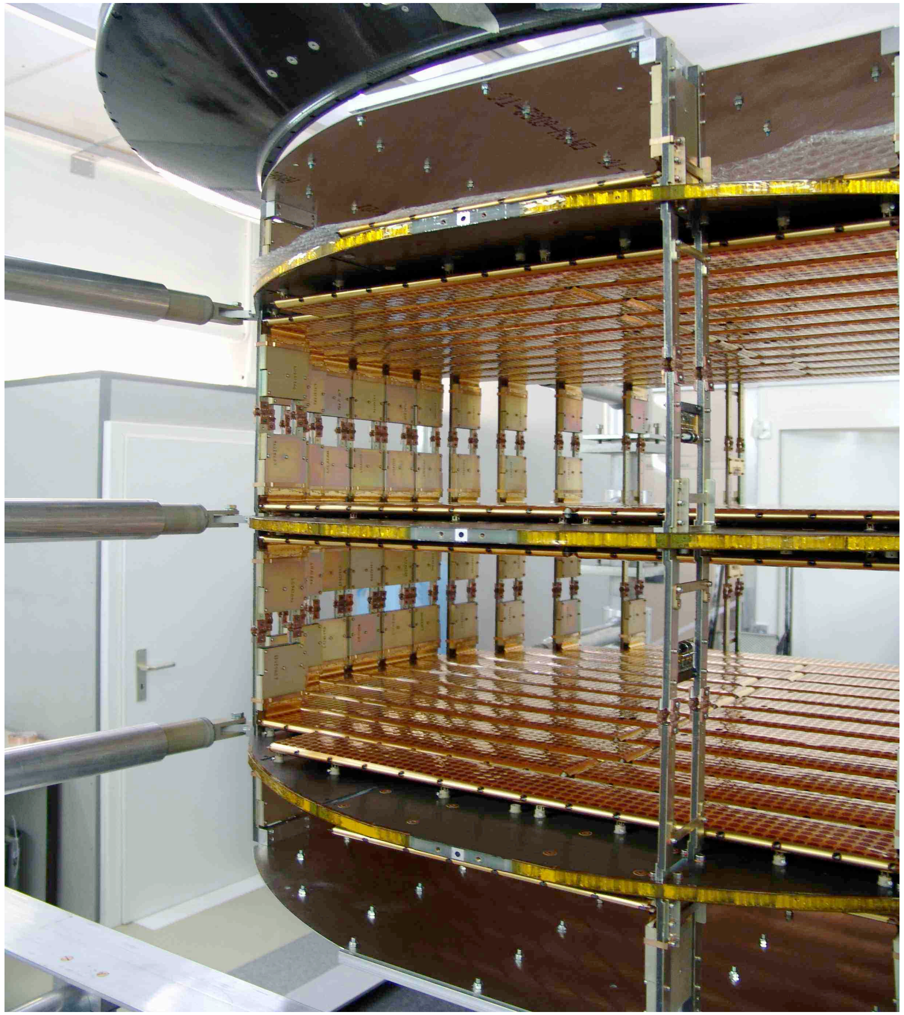
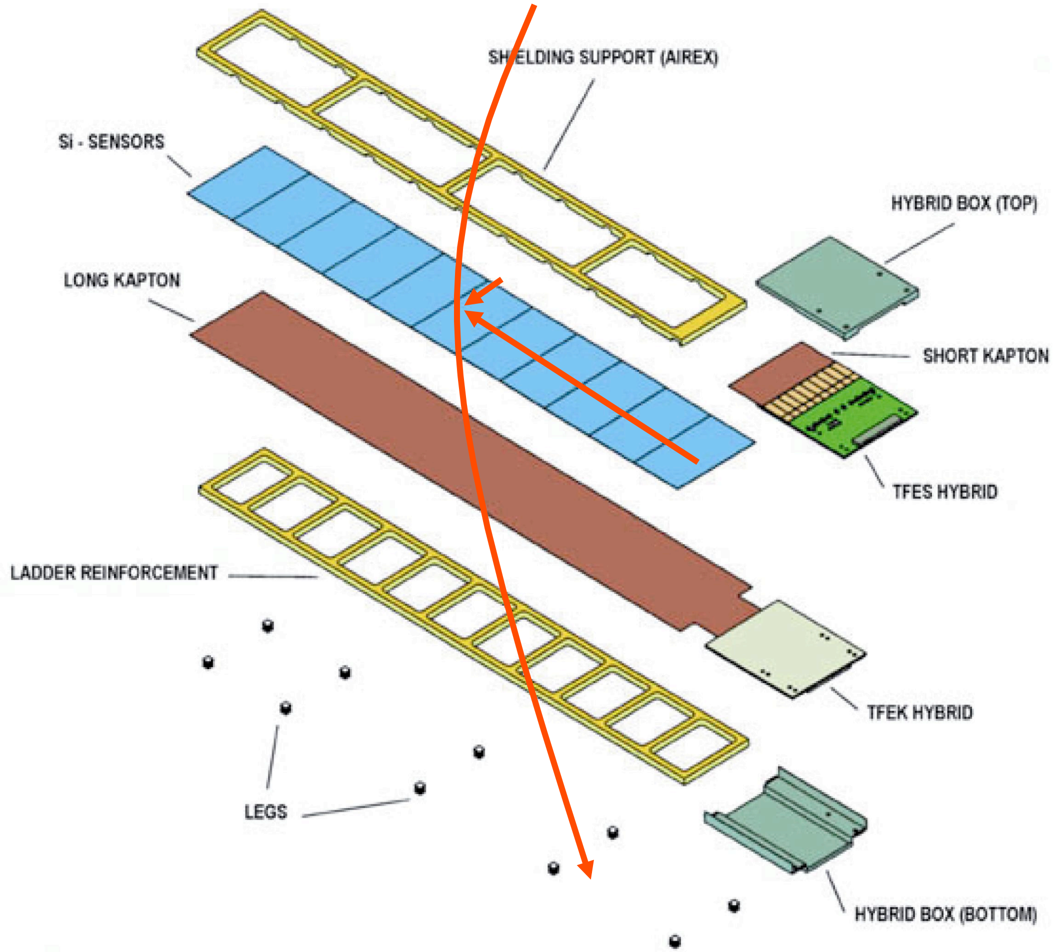


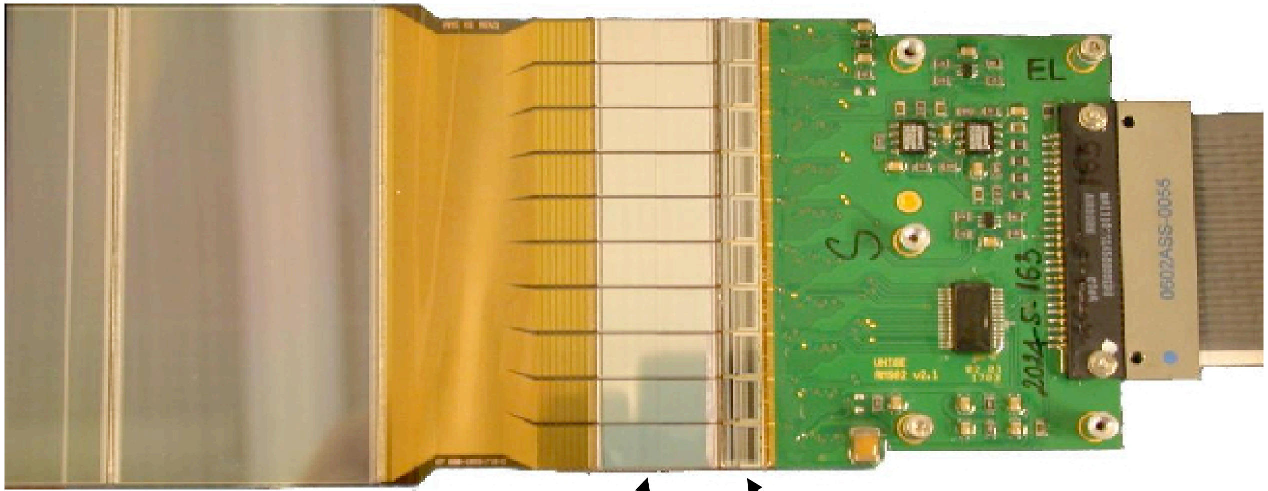
AMS silicon ladders



- 1024 high dynamic range, AC coupled readout channels:
  - 640 on junction (S) side
  - 384 on ohmic (K) side
- Impl/readout pitch:
  - 27.5/110 μm (S side)
  - 104/208 μm (K side)
- 7 – 15 wafers (28 – 60 cm)

192 flight units, 210 assembled in 3 lines:
Perugia (I), Geneva-ETHZ (CH), G&A (Carsoli, I)

Ladder components (p side)



2nd bonding pad row

K6 Upilex

S–hybrid

1st sensor edge

double sided, DC coupled
300 μm thickness
7 - 15 sensors in a ladder
produced at:
- Colybris (CH)
- IRST (IT)

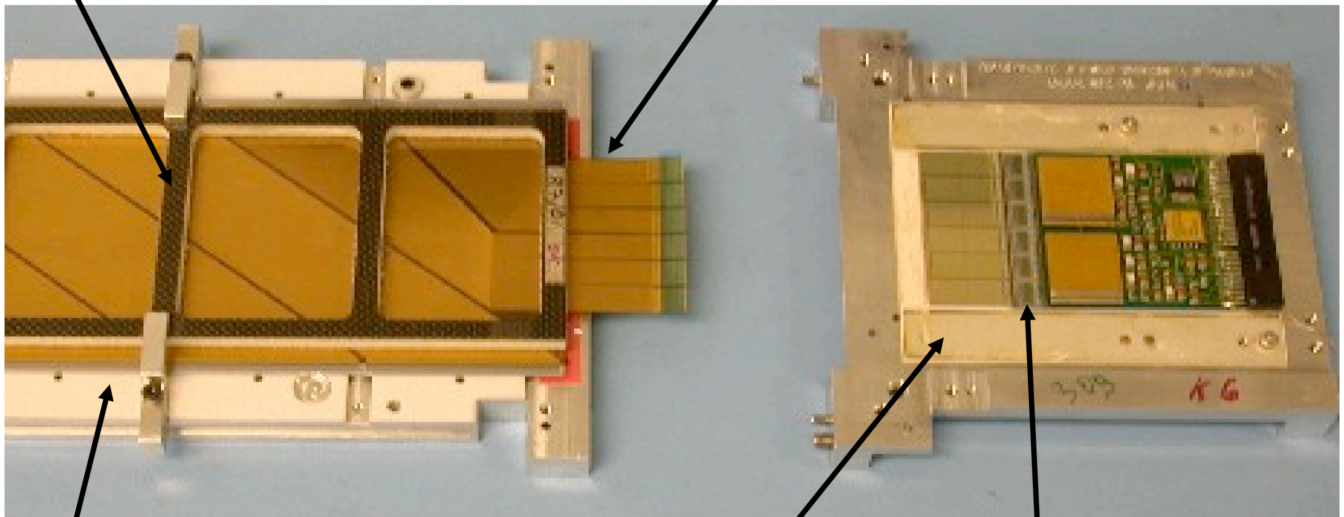
700 pF coupling capa

10 VA_hdr64a (IDEas, NO)
640 channels, 0.7 mW power each
CR-RC shaper and S&H
4 μs shaping time
100 MIP dynamic range

Ladder components (n side)

upilex cable

carbon fiber support

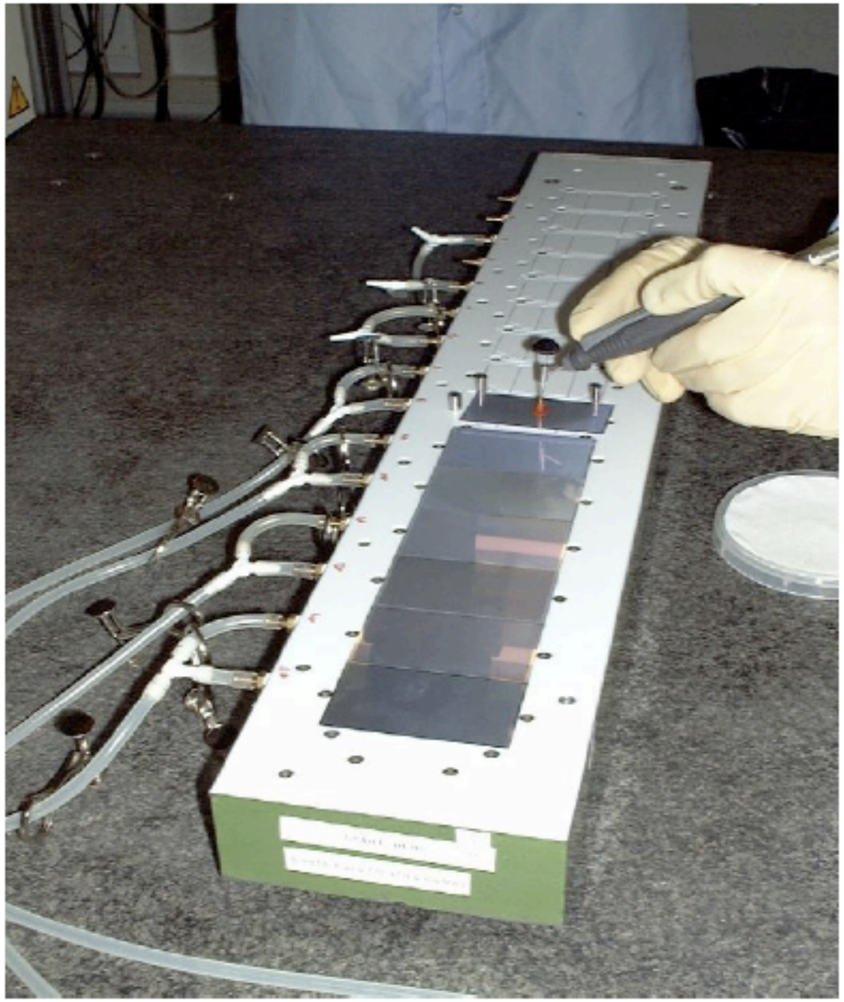


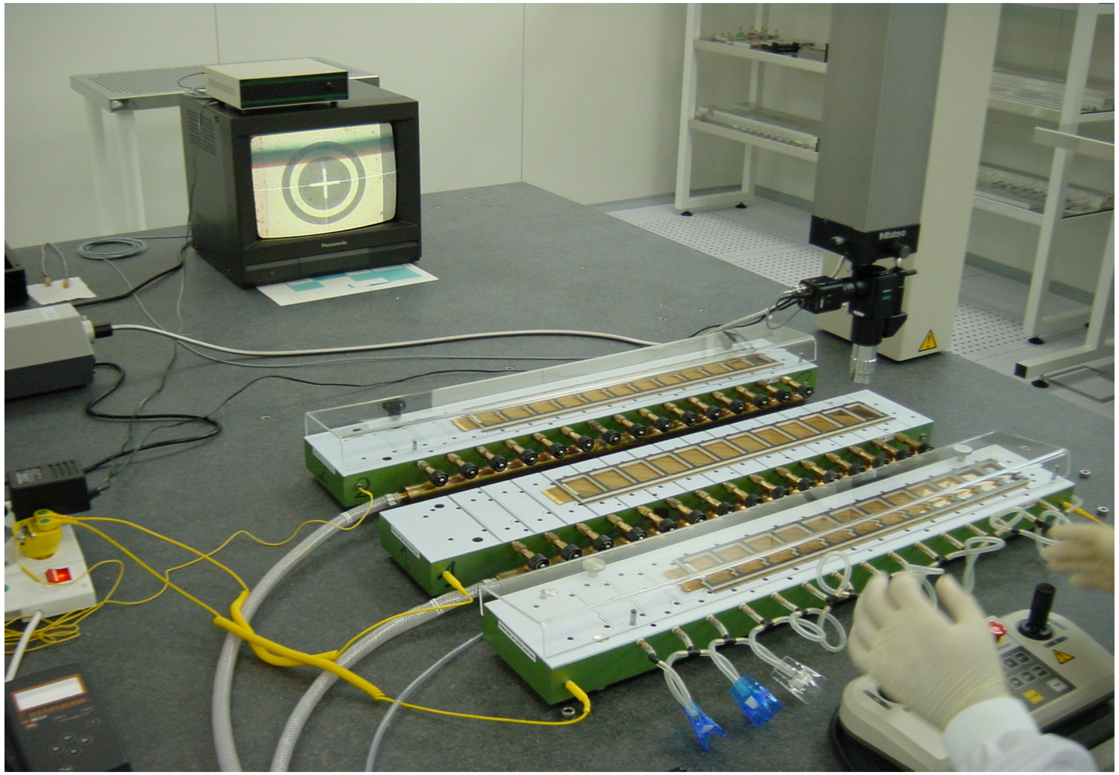
double sided, DC coupled
300 μm thickness
7 - 15 sensors in a ladder
produced at:
- Colybris (CH)
- IRST (IT)

700 pF coupling capa

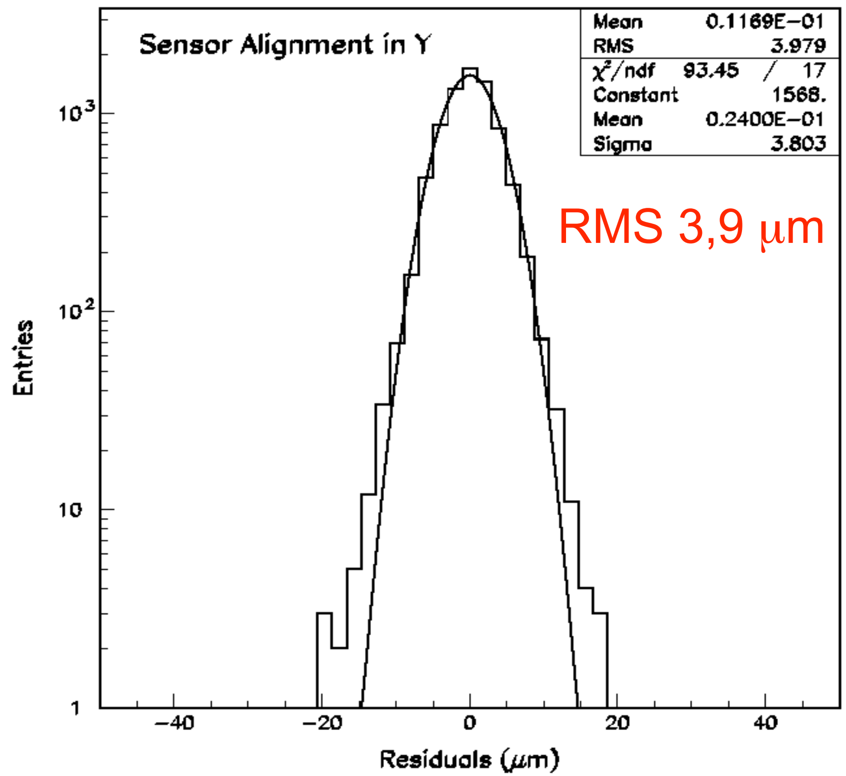
6 VA_hdr64a (IDEas, NO)
384 channels, 0.7 mW power each
CR-RC shaper and S&H
4 μs shaping time
100 MIP dynamic range

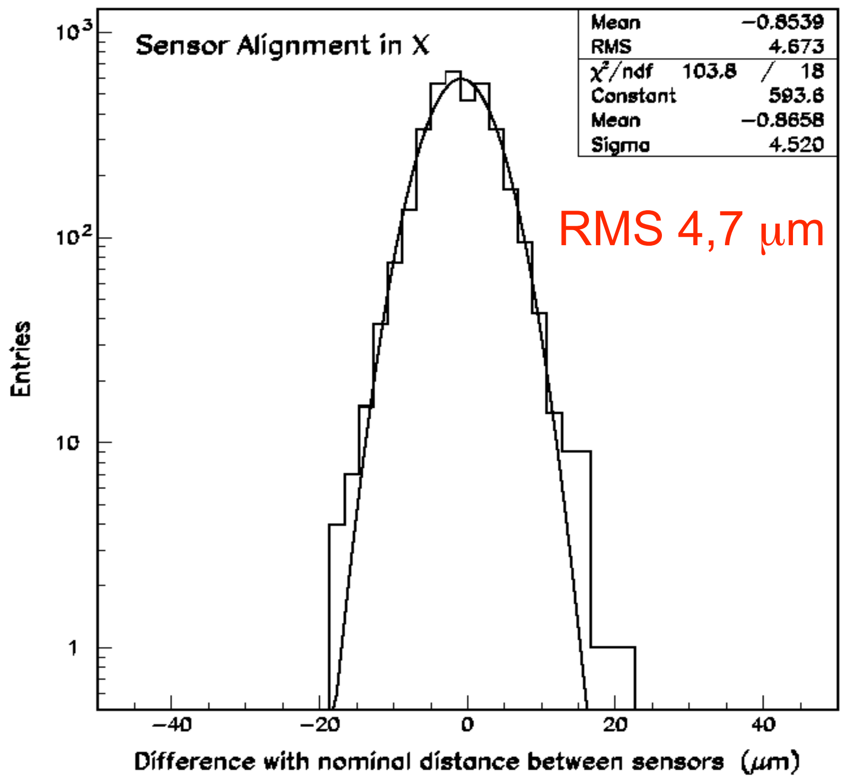
Silicon positioning and metrology



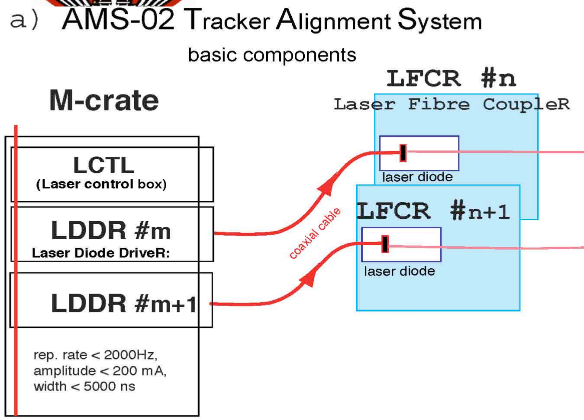


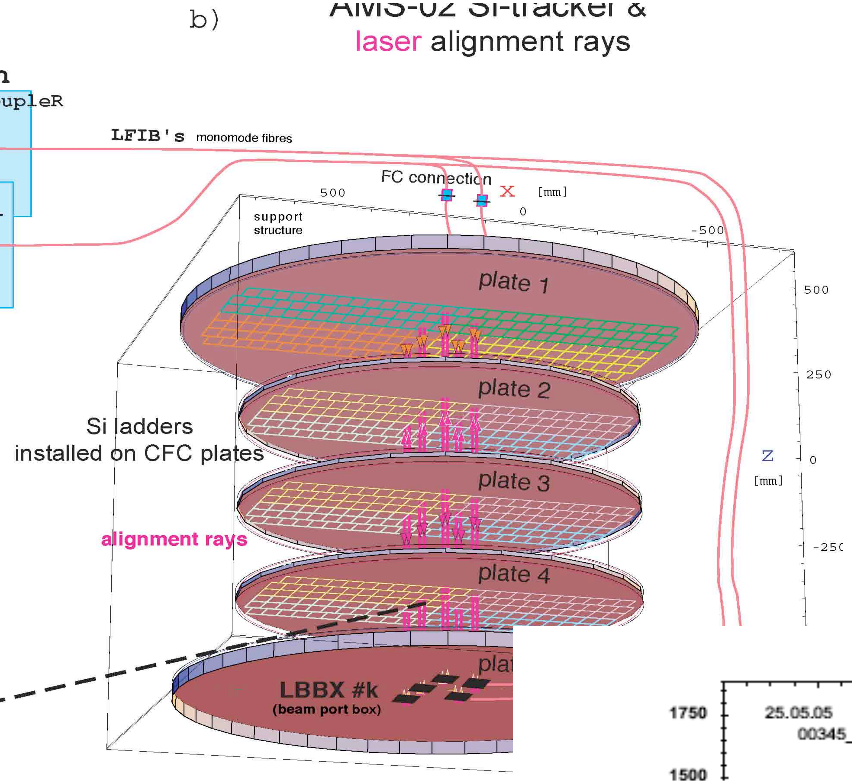
Sensor alignment in ladders

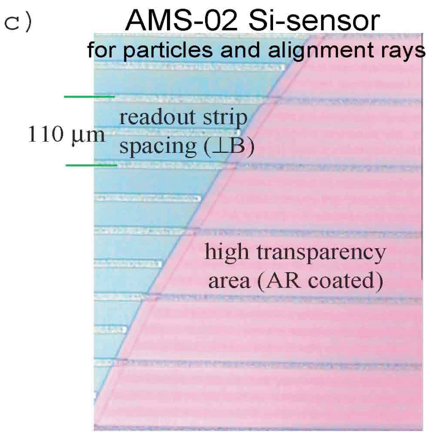




Laser alignment control system

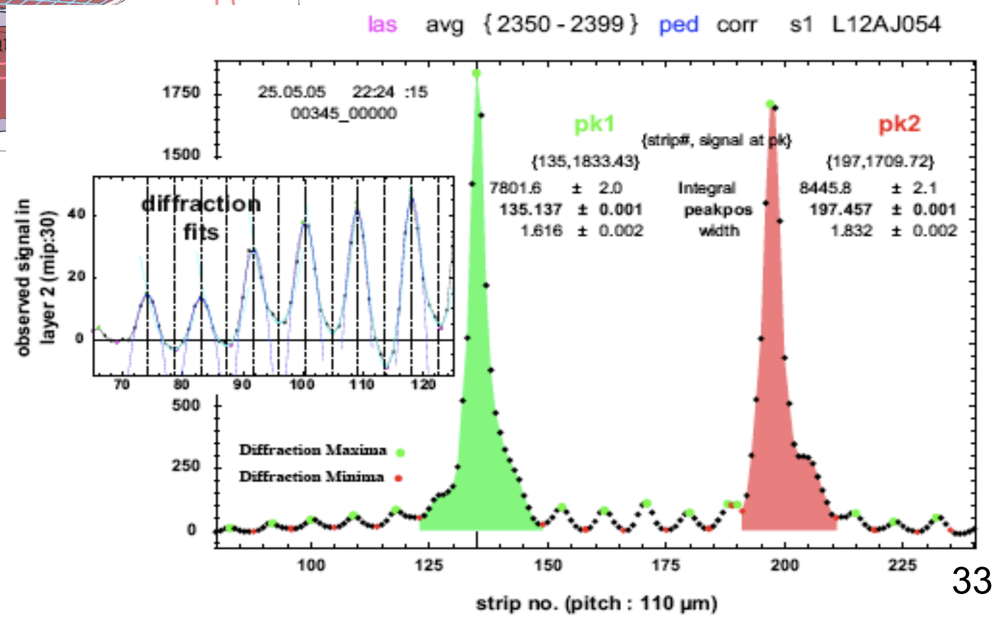






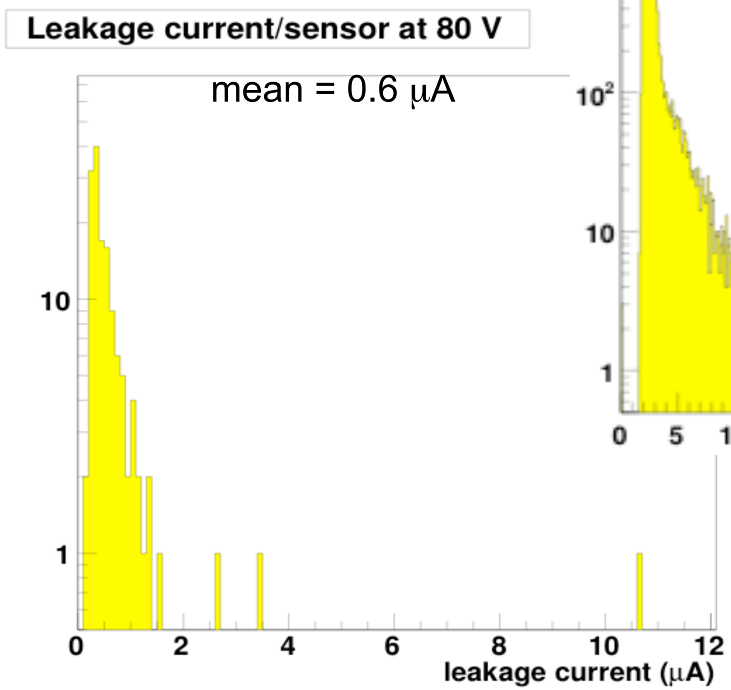
TAS properties

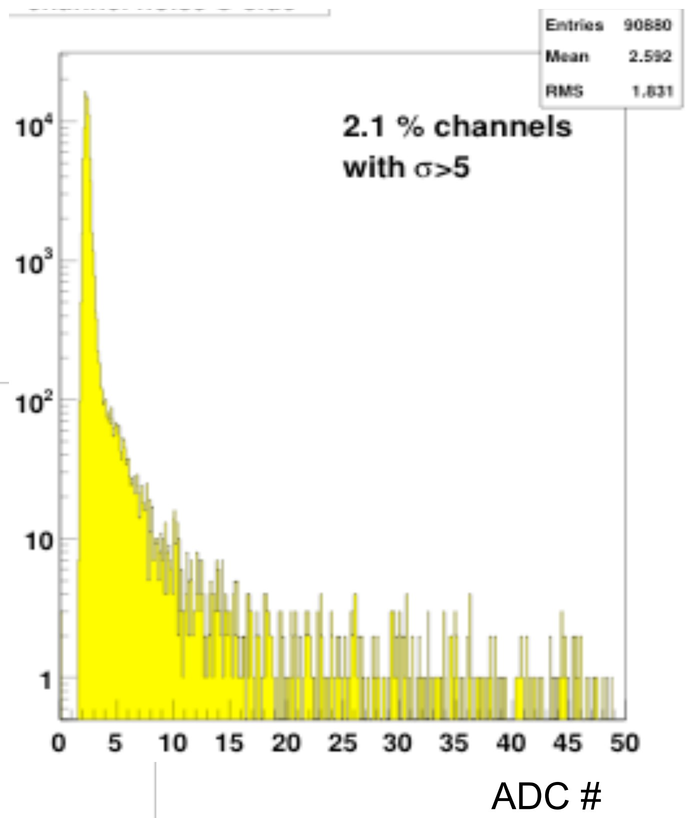
Light weight (3 kg)
Low power (< 0.1 W)
Fast data taking (20s)
Highly accurate (< 5µm)

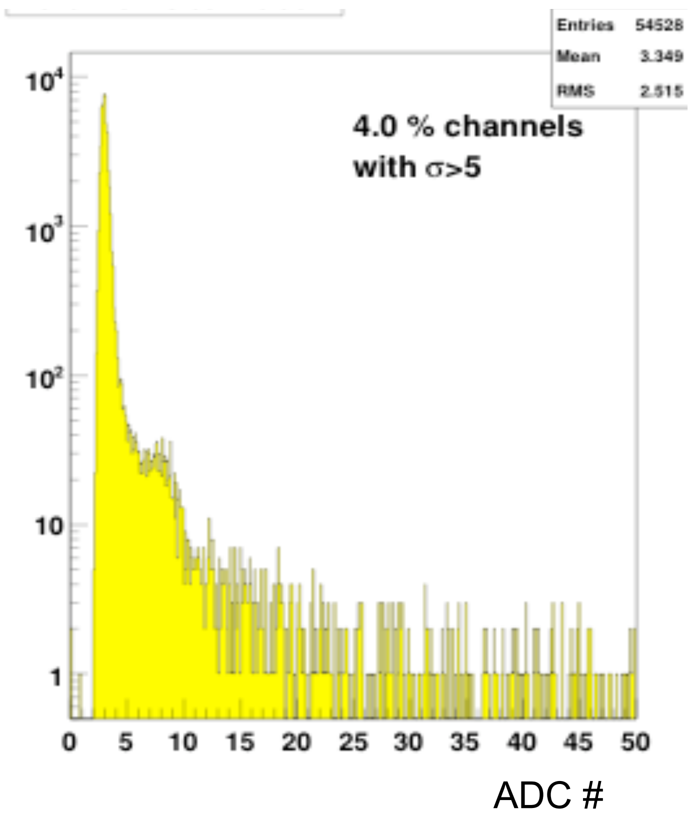


Low power laser diodes (1082nm)
100 nJ pulses

Noise and currents
(after ~ 3 10^6 bonds)



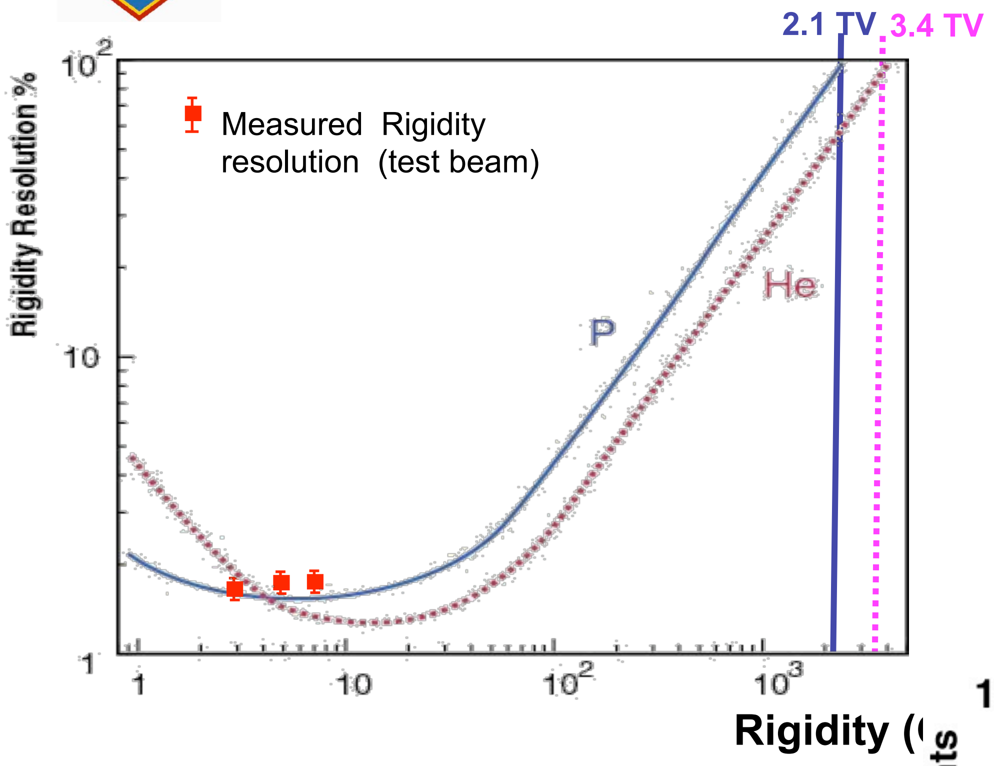


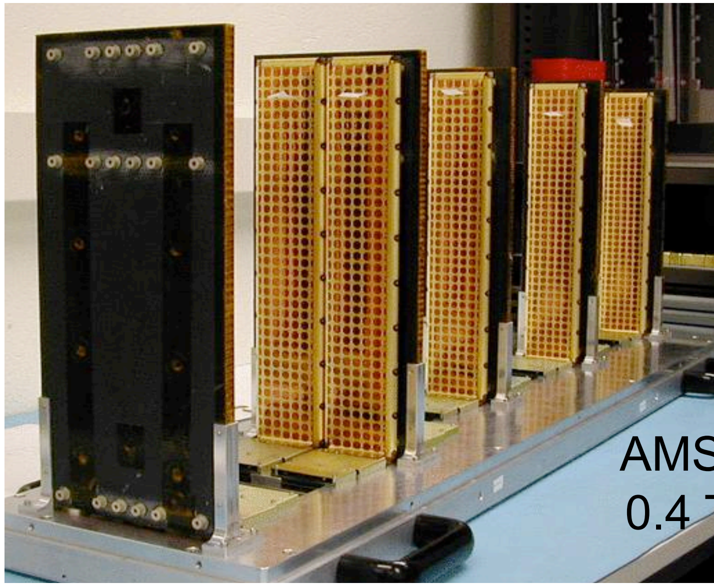


Landau MPV for MIPs ~ 30 ADC#

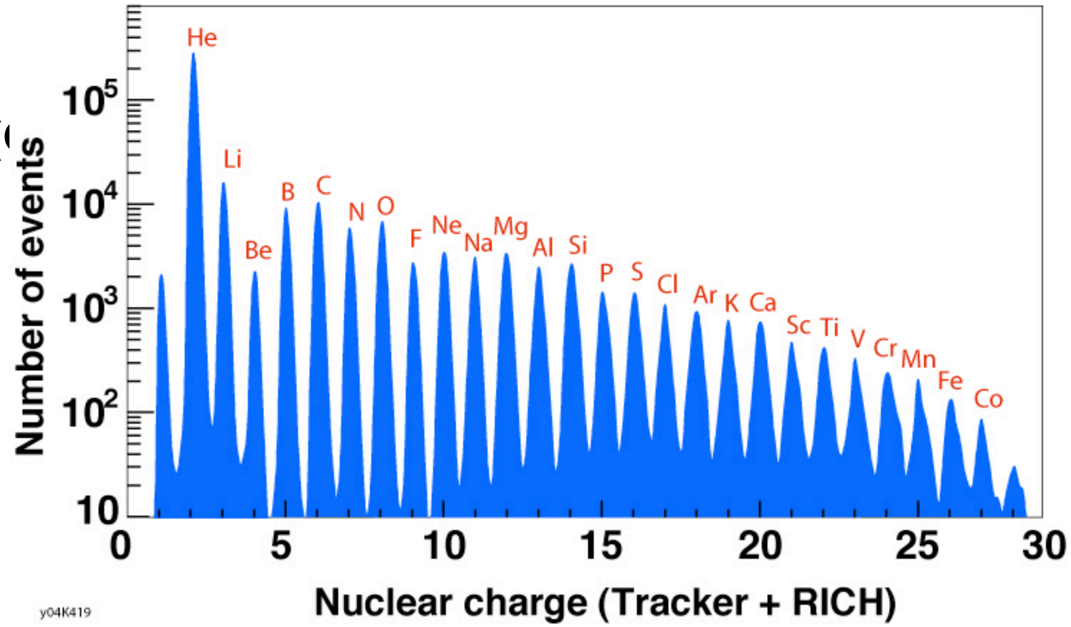
single wafer current was ~ 400 nA

Rigidity res. and charge id.



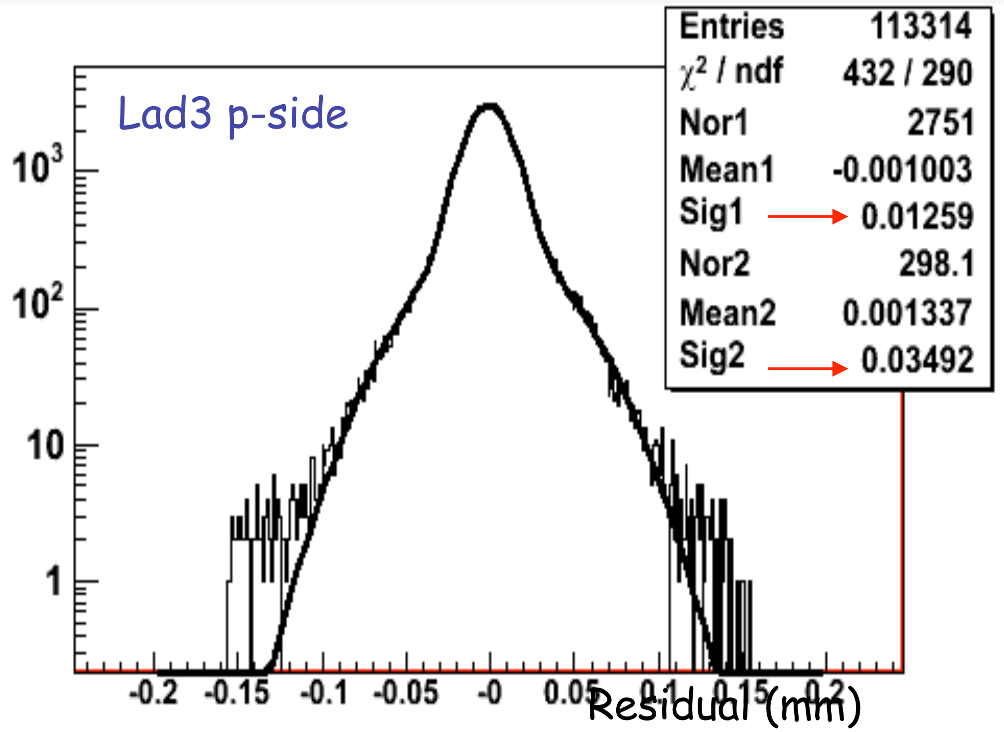


AMS like config.
0.4 T mag. fiels

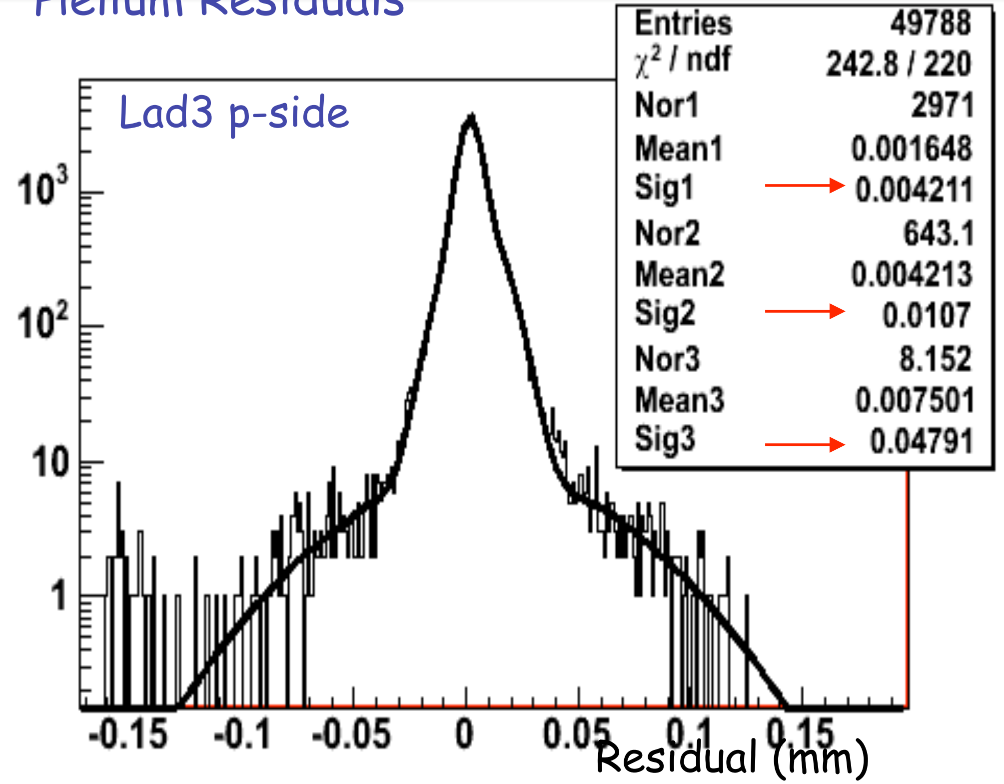


Residual Distributions

Proton Residuals



Helium Residuals



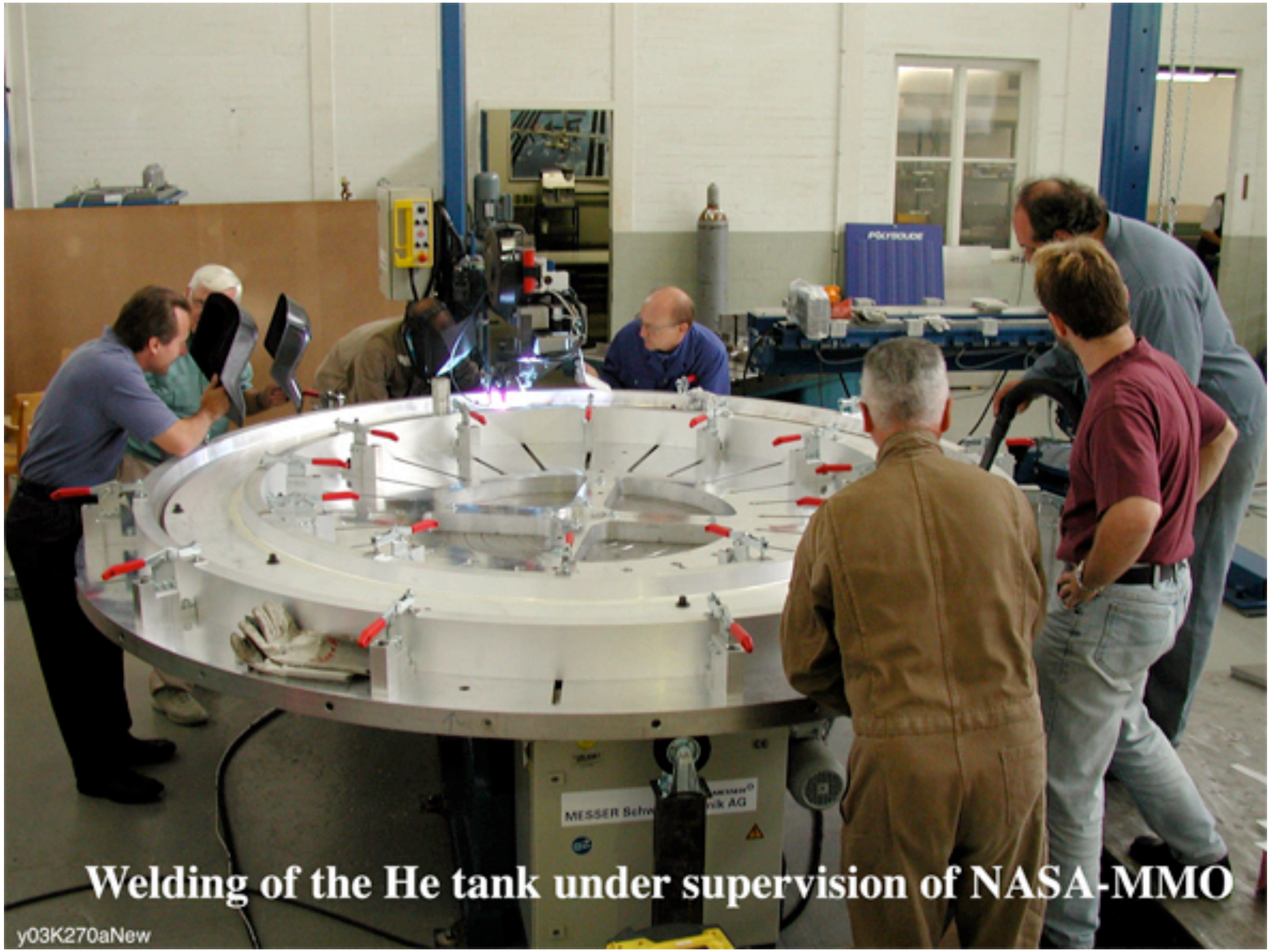
2 gaussian Fit

1st Gaussian 70% of events
2nd Gaussian 30% of events

3 Gaussian Fit

1st Gaussian 63% of events
2nd Gaussian 34% of events
3th Gaussian 3% of events

Space qualification



Quale approccio seguire?

- Spaziale:
  - uso di materiali e componenti già qualificati
  - disegno da parte di personale qualificato
  - costruzione, da parte di personale qualificato, di due apparati (qualifica + volo)
  - procedure e burocrazia

costo

- Particellare:
  - qualifica dei propri materiali e componenti
  - disegno e costruzione in casa
  - procedure e qualifica

Hardware designed for Low Earth Orbit (AMS case)

Static loads	Disegno meccanico	D+E
Vibration	Disegno meccanico, test	D+E
Depressurization	Disegno meccanico	D
0g & Vacum	Disegno termico, materiali, test	D+E
Temperature range	Selezione componenti, test	D+E
Ionizing radiation	Selezione componenti, test	E
Heavy ion (SEE)	Selezione componenti, test, disegno elettronico	E
Atomic O, Solar UV	Materiali	D+E
Space junk	Disegno meccanico	D+E
Elecromag. compa	Shield, grounding, test	D+E

missione

missione

missione

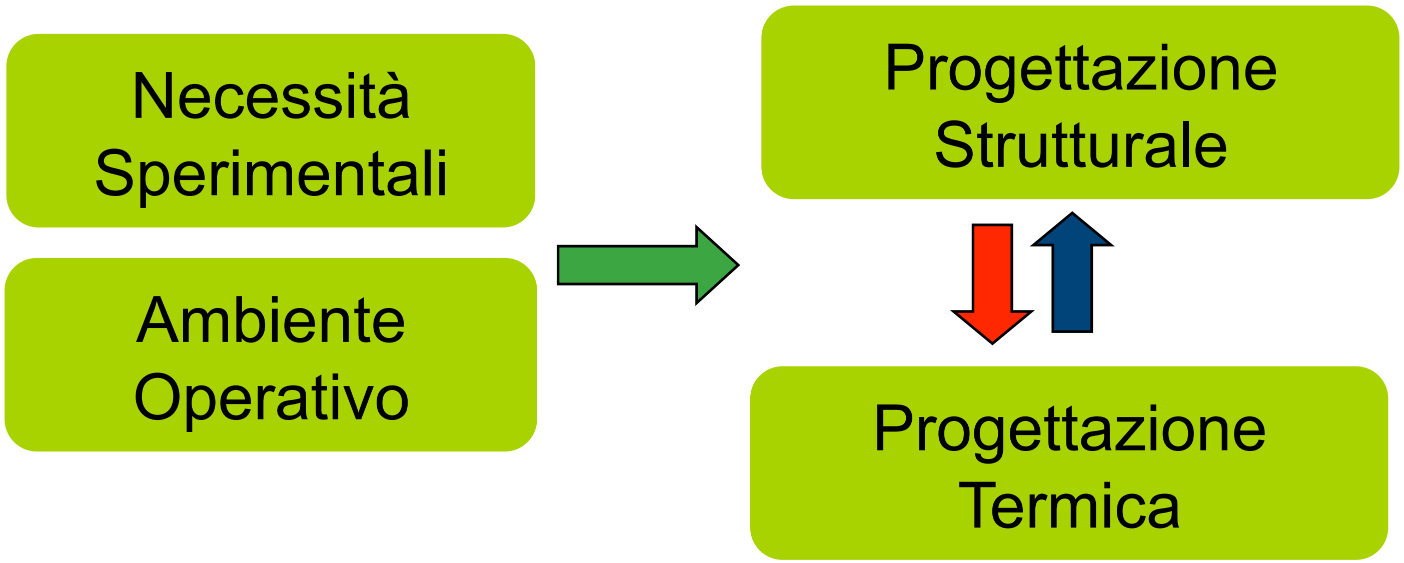
Nessun accesso: ridondanza, affidabilita, test, test, test, test, test

progettazione strumentazione spaziale

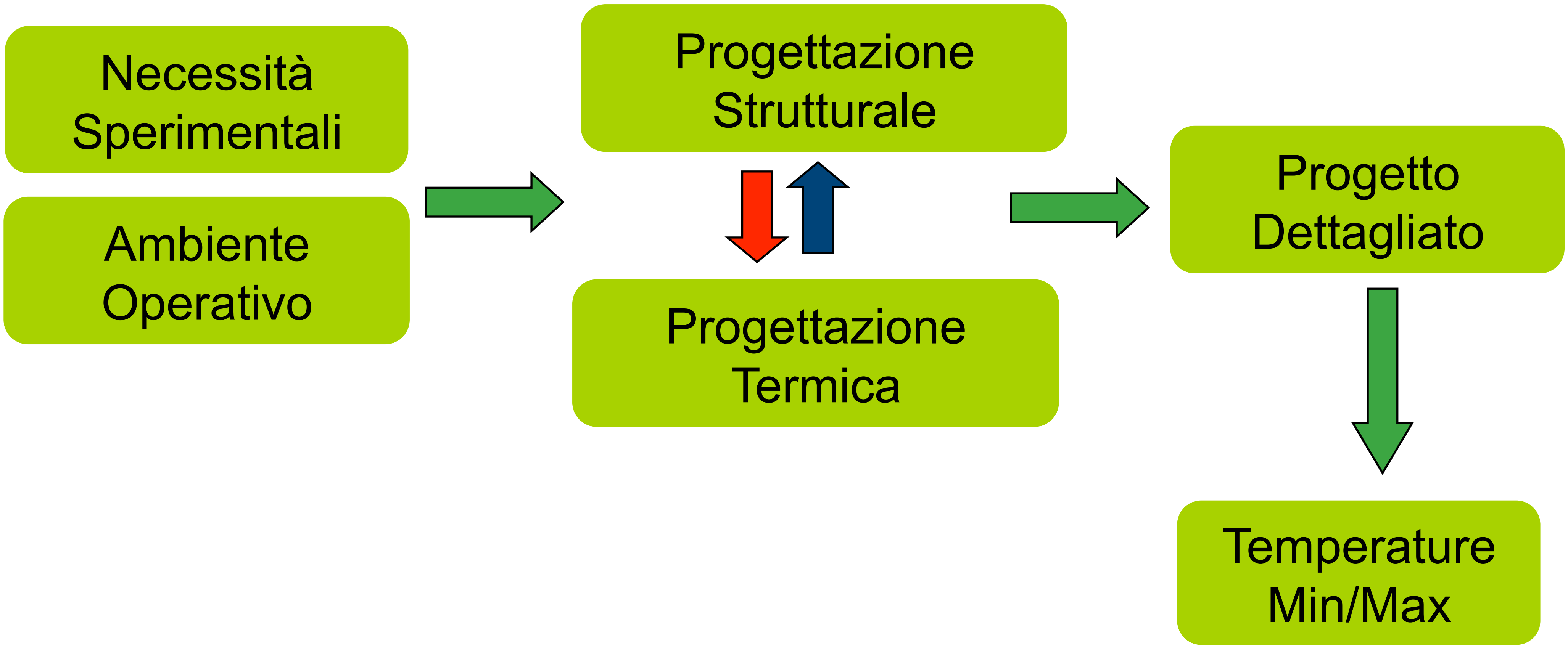
Necessità Sperimentali

Ambiente Operativo

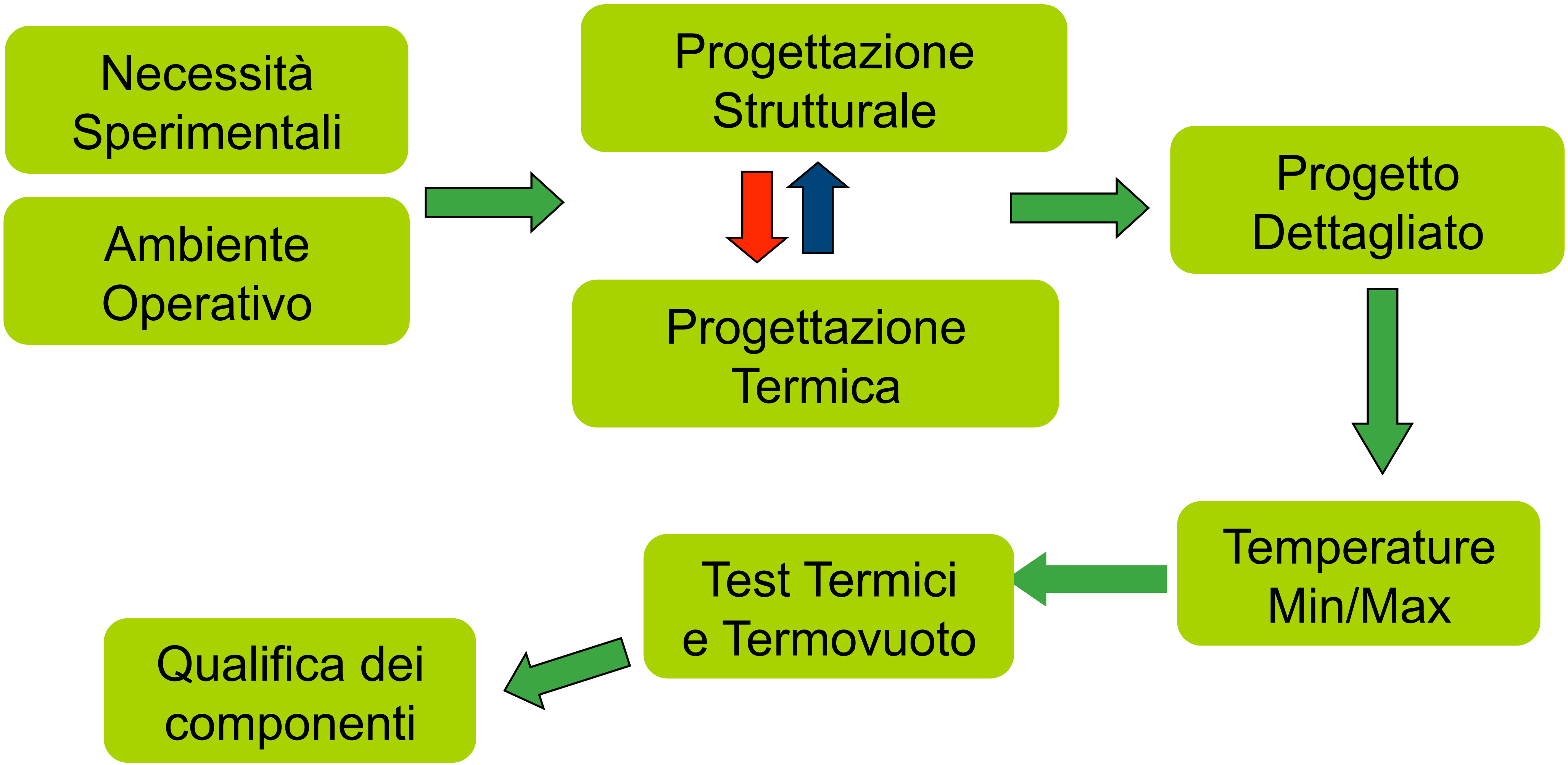
progettazione strumentazione spaziale



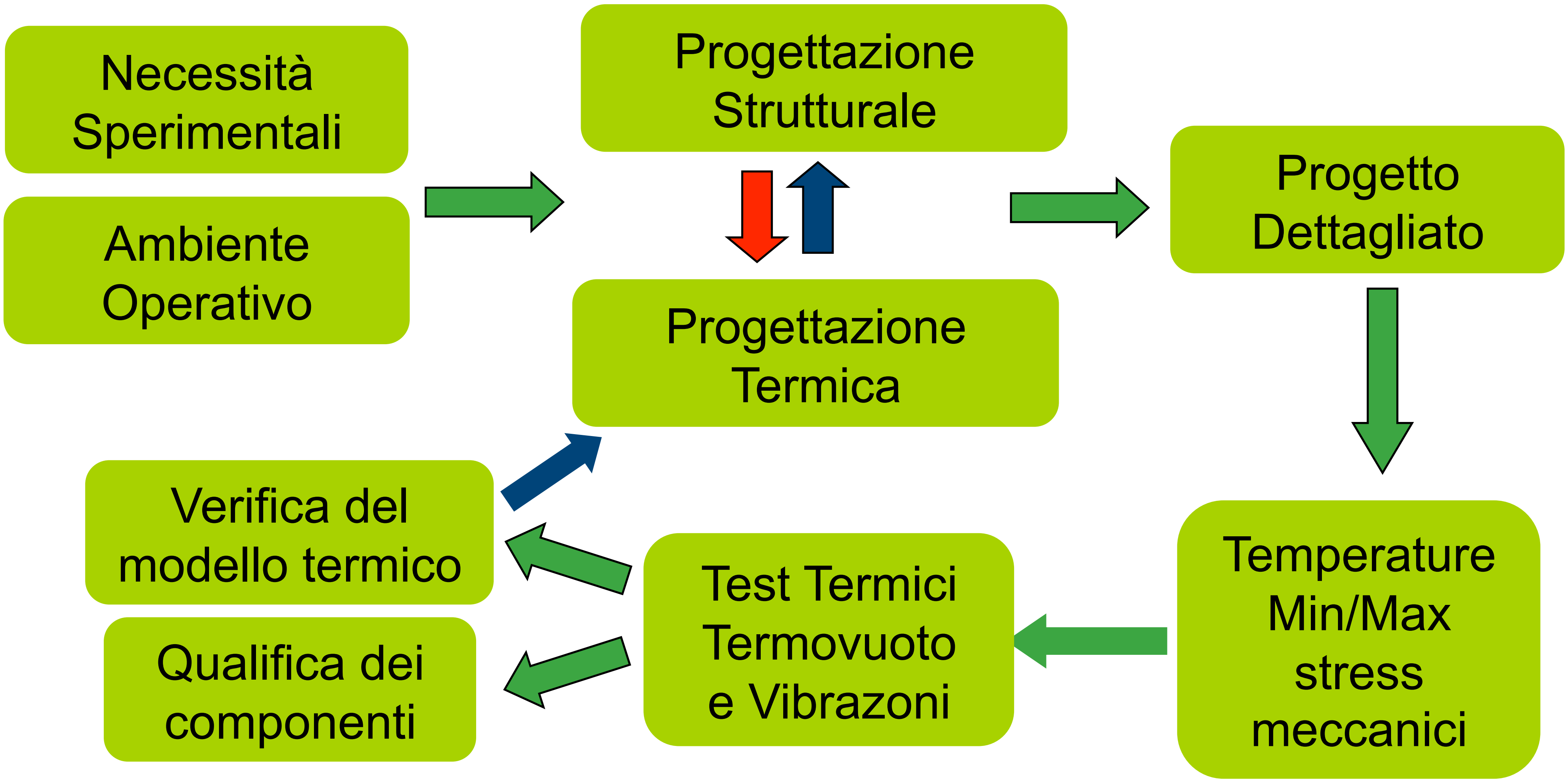
progettazione strumentazione spaziale



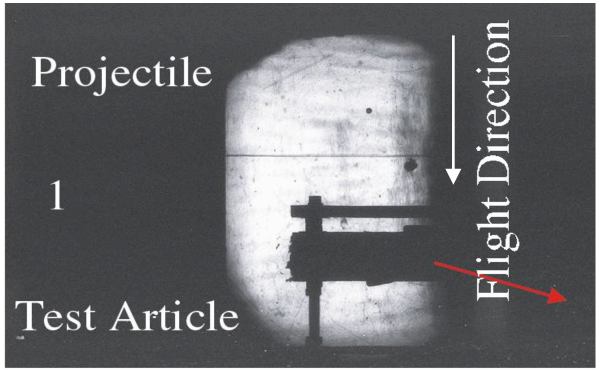
progettazione strumentazione spaziale

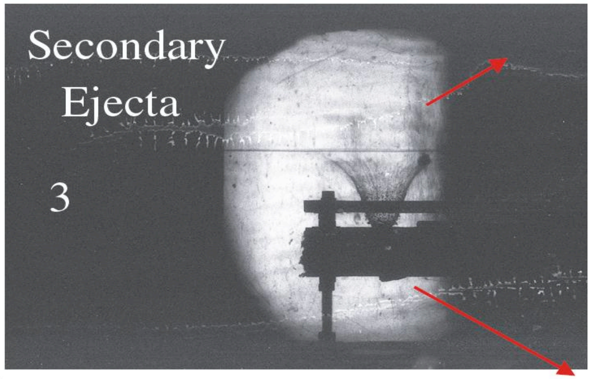


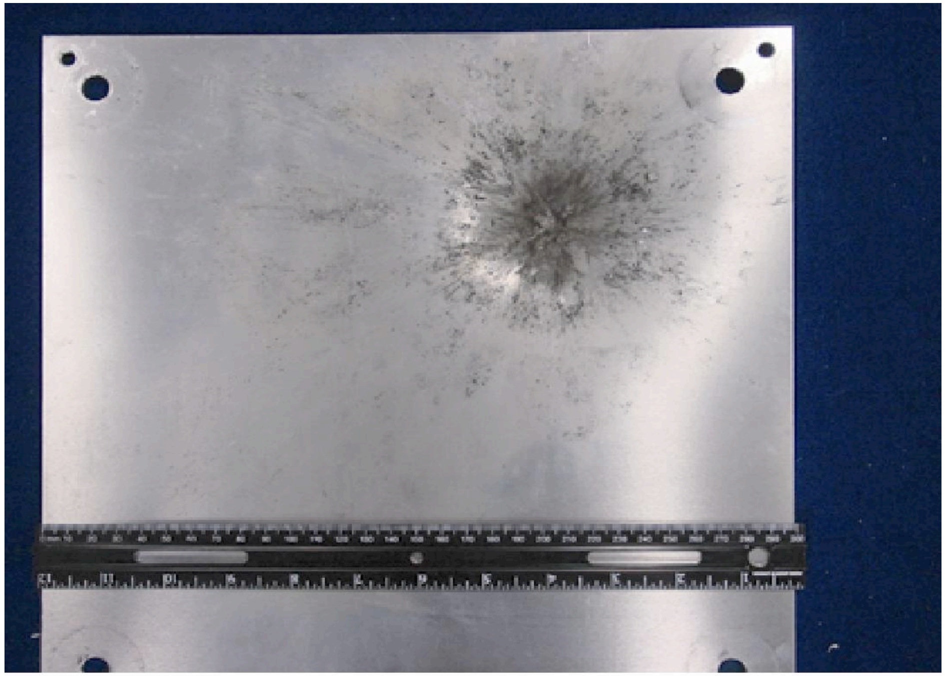
progettazione strumentazione spaziale



Micrometeorites and debris







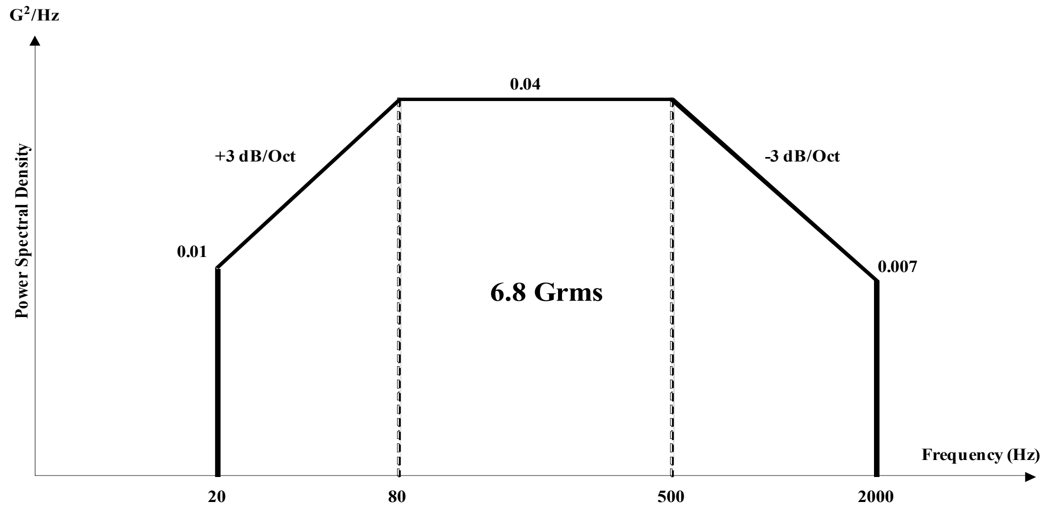
Micro-meteoroid & Orbital Debris Testing

Tipi di Test

- Sollecitazione meccanica**:**
  - Sine sweep per caratterizzazione dinamica di sistemi complessi: al DUT vengono applicate in sequenza vibrazioni sinusoidali monocromatiche effettuando una scansione dell'intervallo [f_{min},f_{max}]Hz: ricerca di eventuali frequenze di risonanza.
  - Random per test di accettazione e fatica: al DUT viene applicata un segnale complesso, con componenti in un determinato spettro di frequenze ed ampiezza definita a priori
- Sollecitazione termica:
  - cicli in camera termica per identificare la 'mortilità infantile'
  - cicli in camera a termovuoto per il test completo del (sotto-)sistema

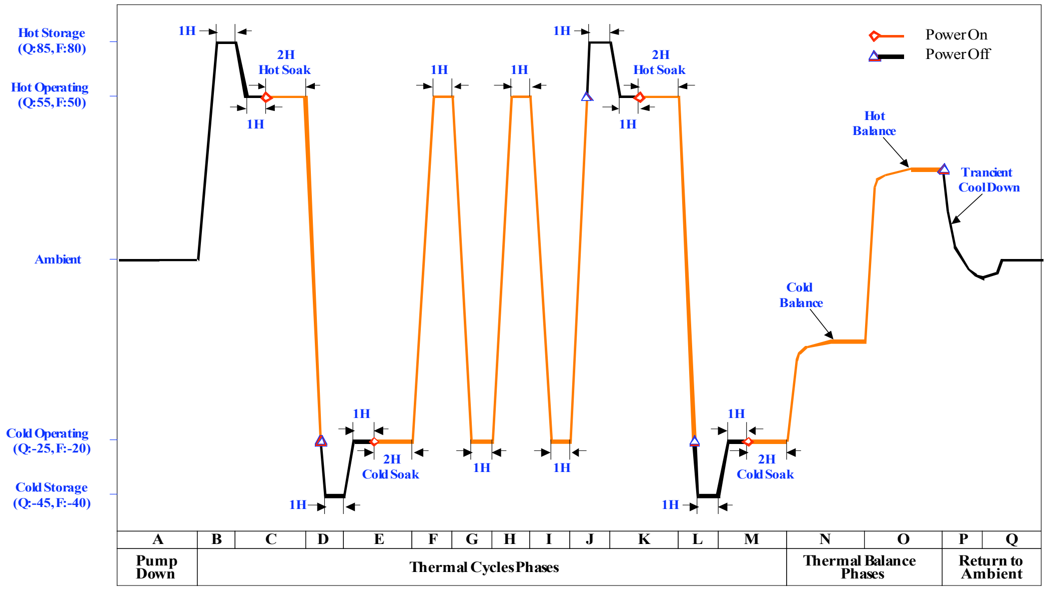
Stress Profile

Vibration
power spectrum



Notes: - 10 minutes for each X, Y and Z direction
- Functional test for each direction without failure

Thermal and
thermo-vacum cycles



il SERMS

per AMS la maggior parte dei test si sono svolti presso il laboratorio SERMS dell'INFN e Università di Perugia:

- Shaker + tavola vibrante
- camere pulite equipaggiate con:
  - camere termiche
  - simulatore spaziale (camera TV)

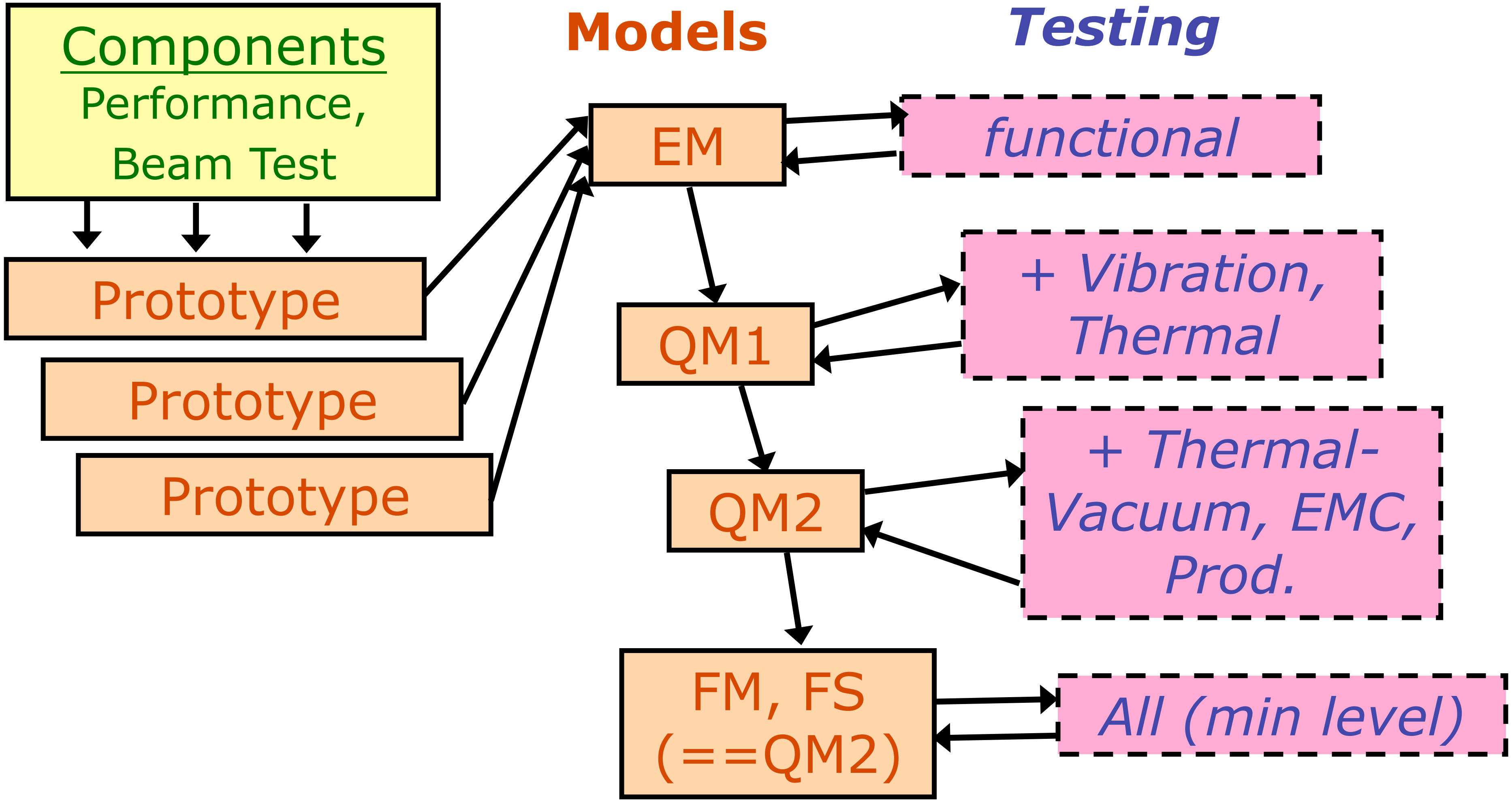
Test procedure

Thermal Stress → Functional check → Mechanical Stress → Functional check

Thermal cycles in Vacuum → Functional check

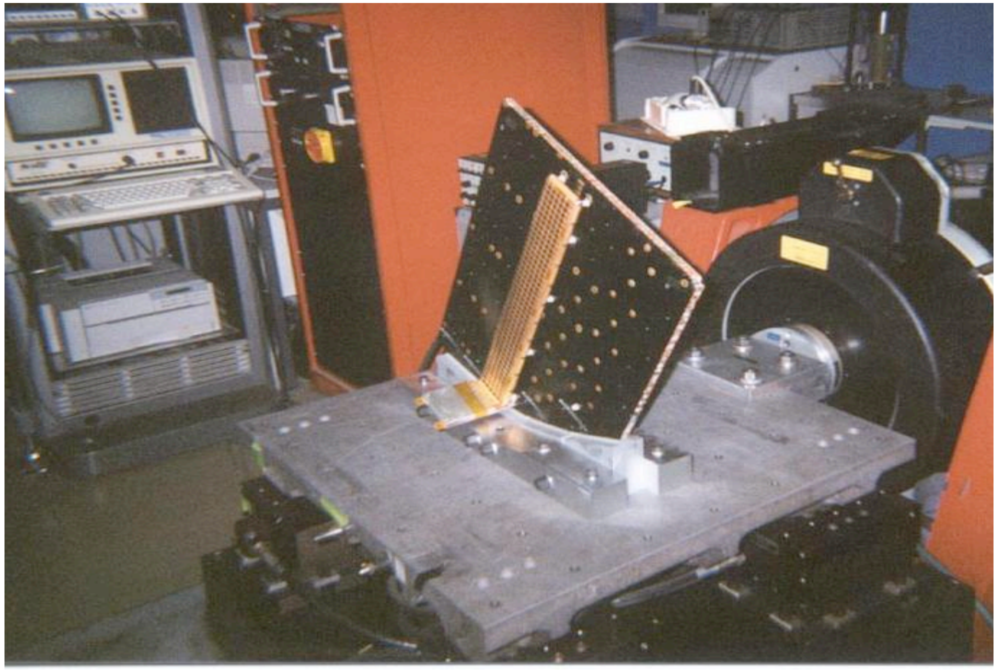
→ EMC

High Energy Physics Electronics and Detectors to Low Earth Orbit



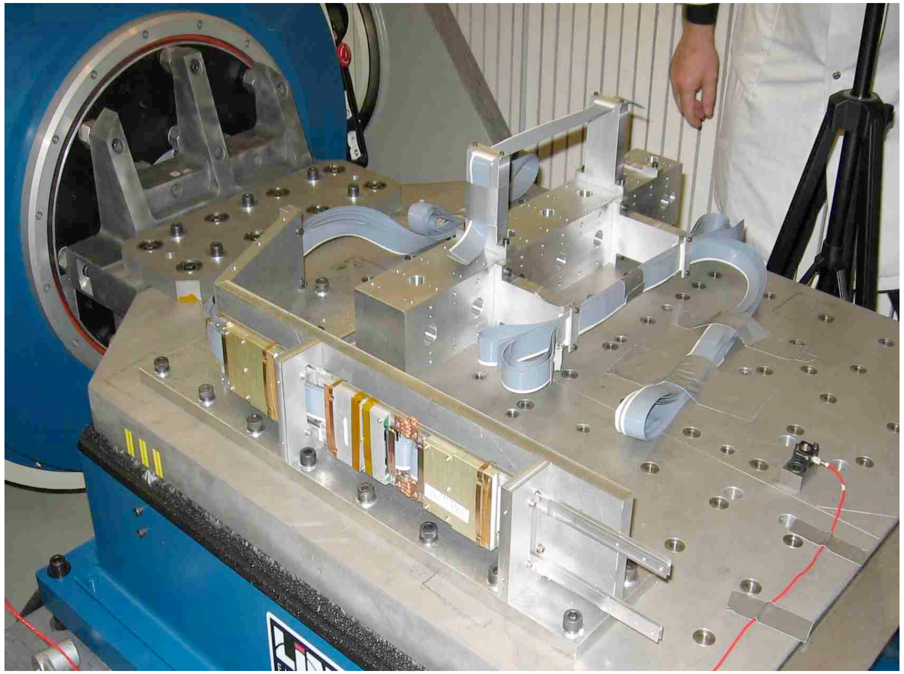
Vibration tests

ladder on plane



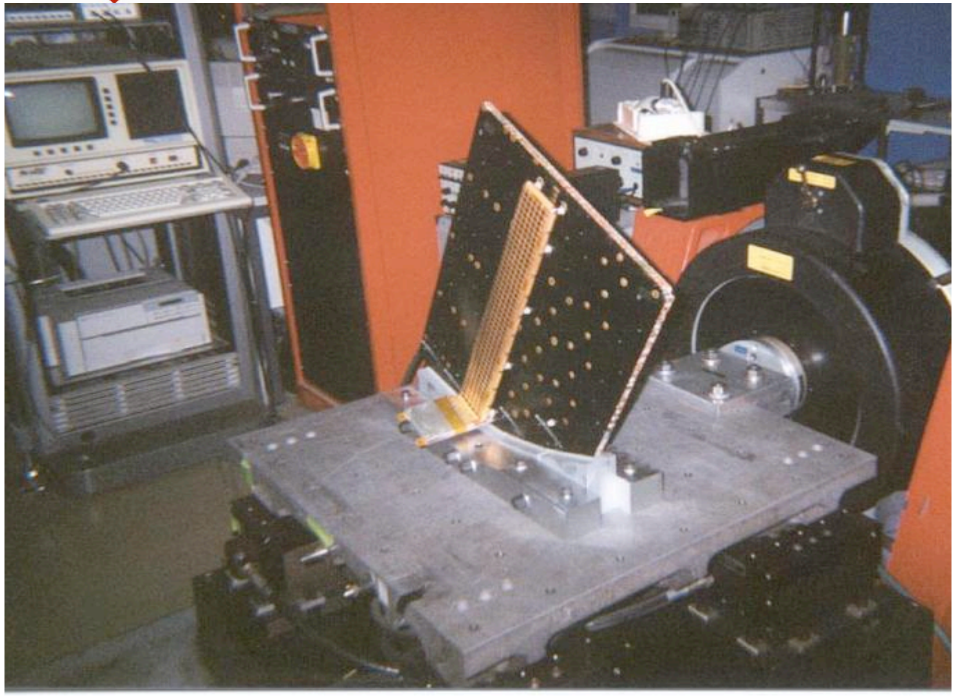
no missing bonds after ladder
and test structure vibration

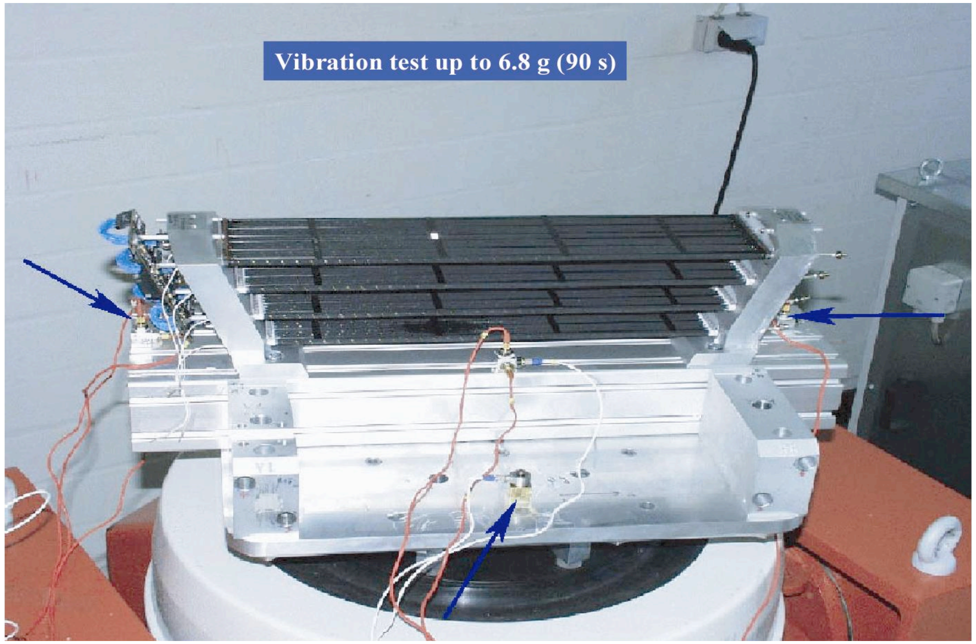
cables and cables support

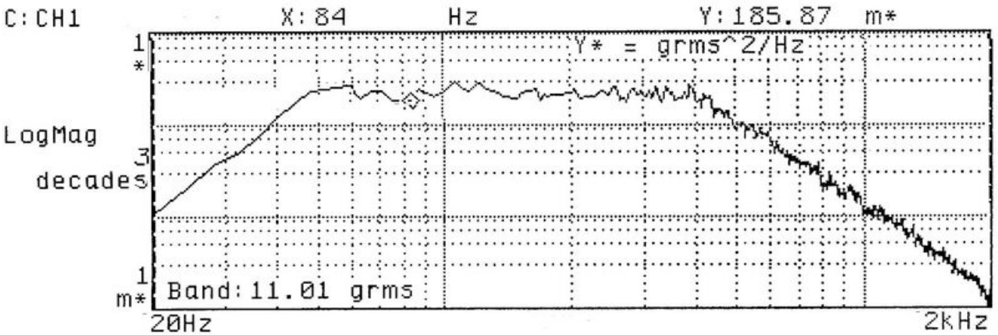


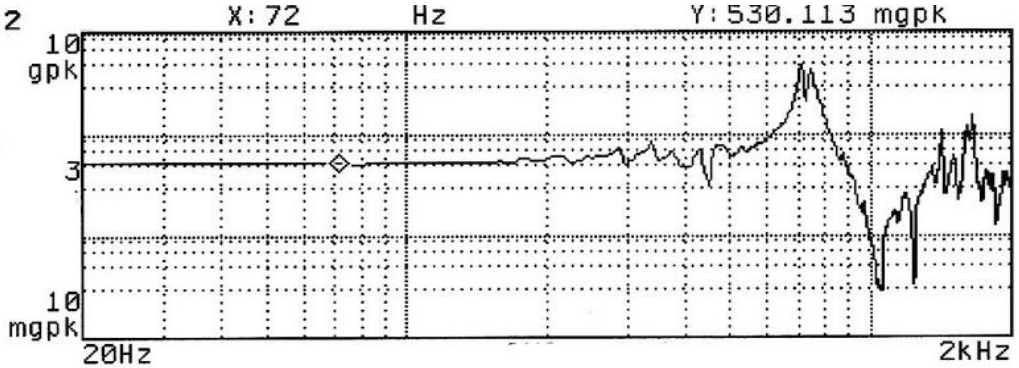
definition of cabled fixation

Test di vibrazione



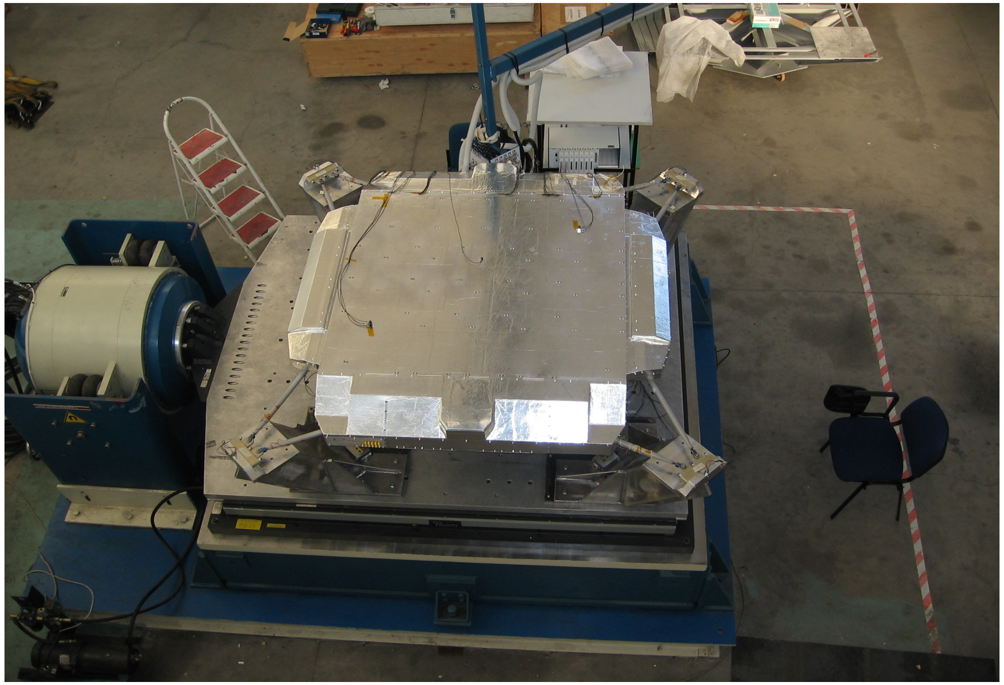


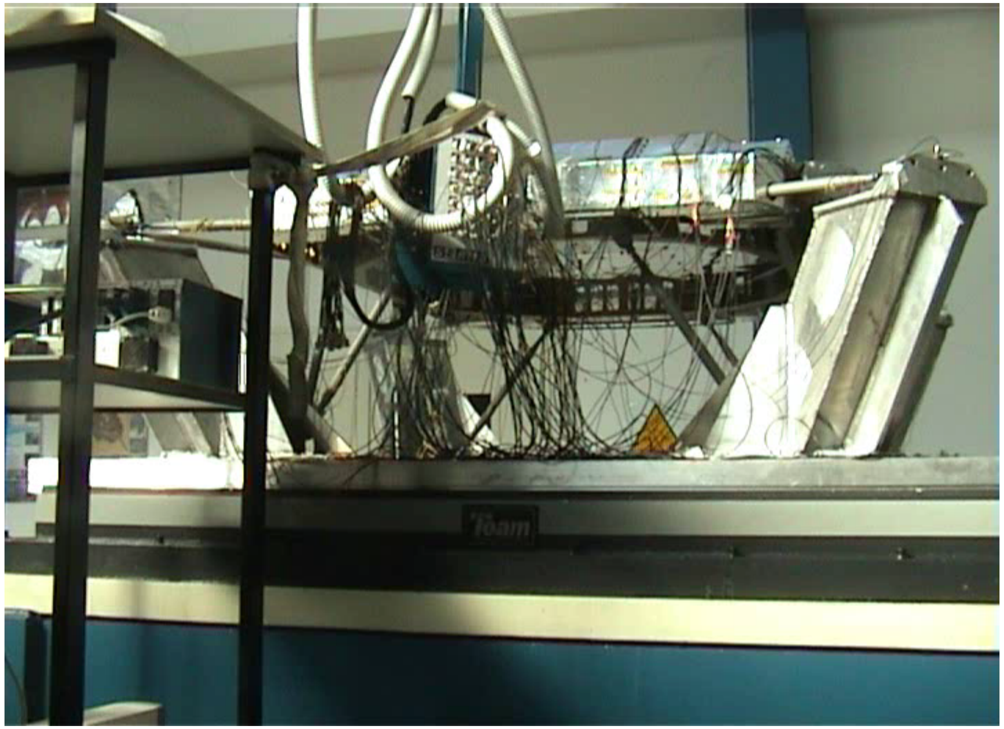




Attenzione alle risonanze …

Test di vibrazione: il TOF





Struttura meccanica di AMS

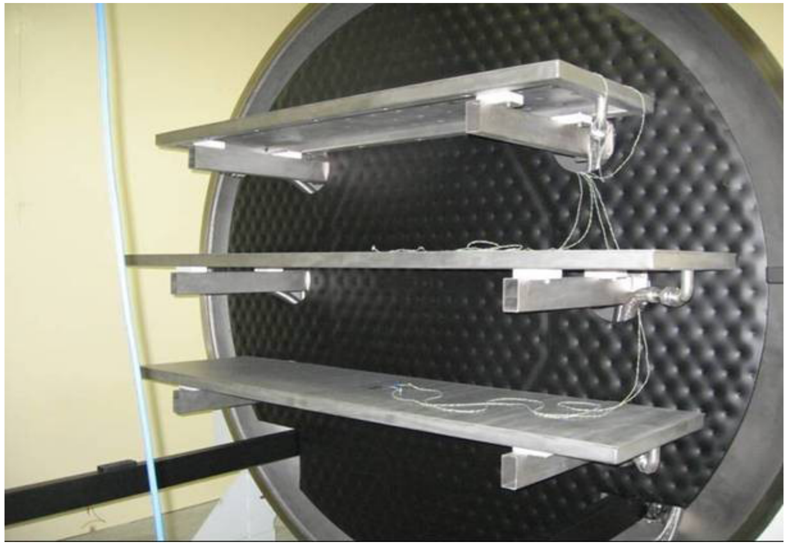
JACOBS SVERDRUP

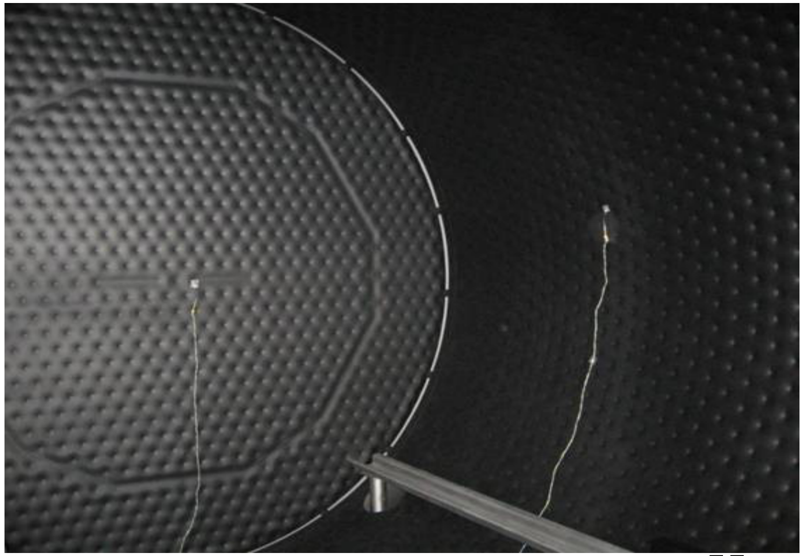
NASA

Istituto Nazionale di Fisica Nucleare

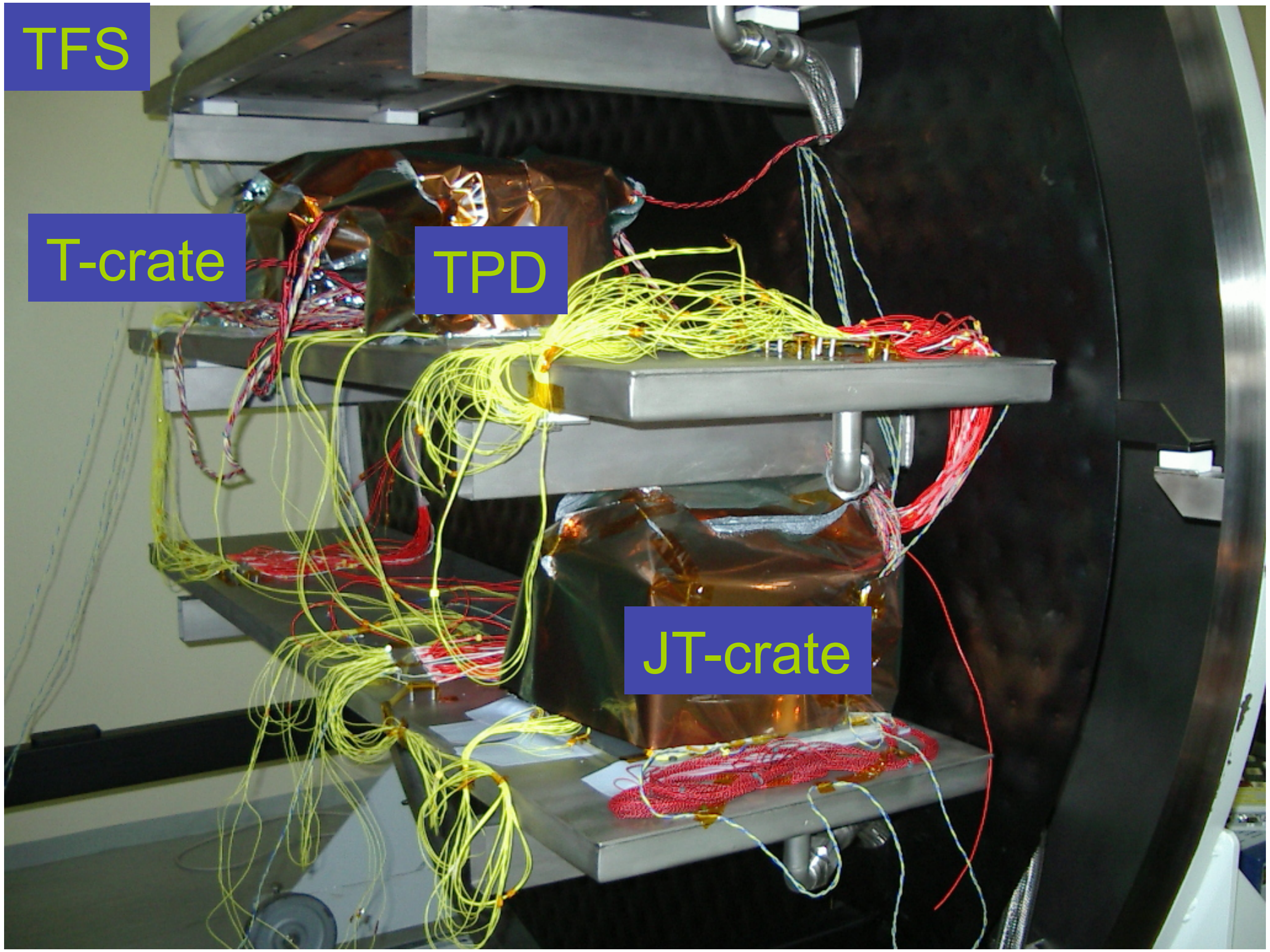
SERMS

TV chamber

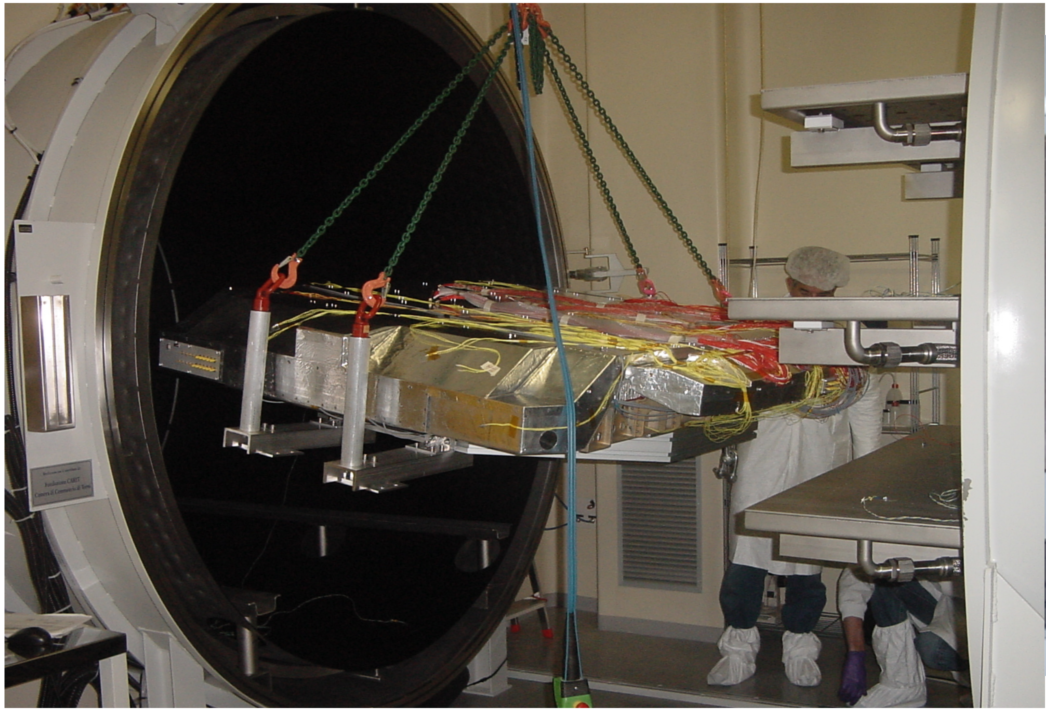




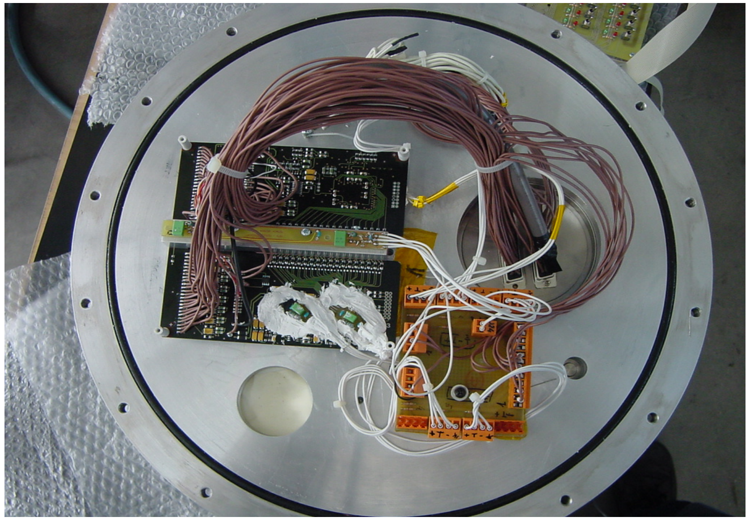
TV test set-up: electronics

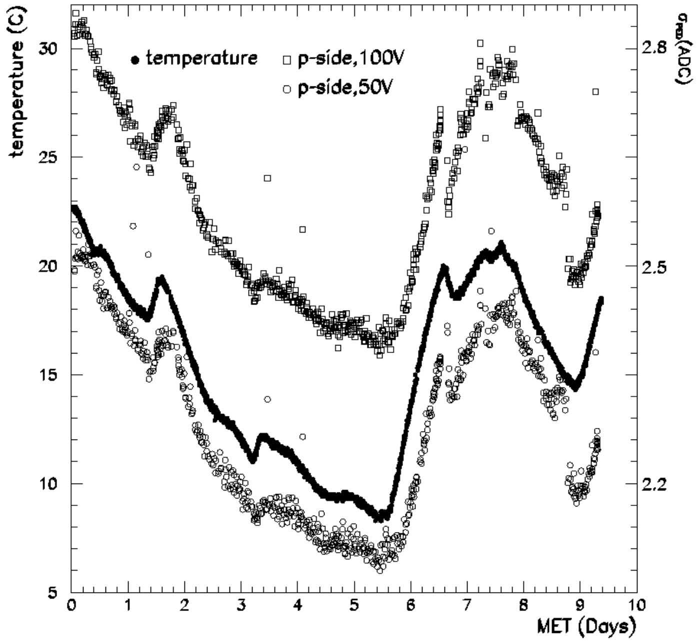


TV test set-up: TOF plane

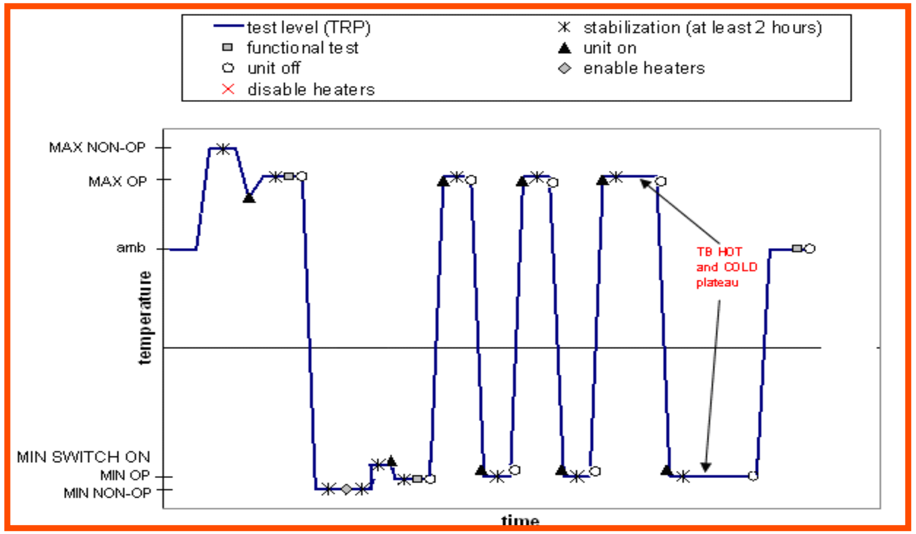


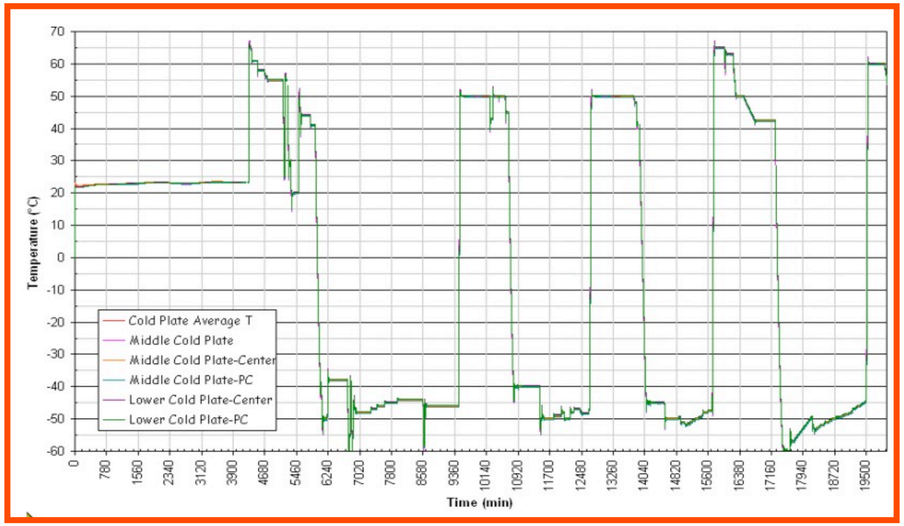
Test di termovuoto

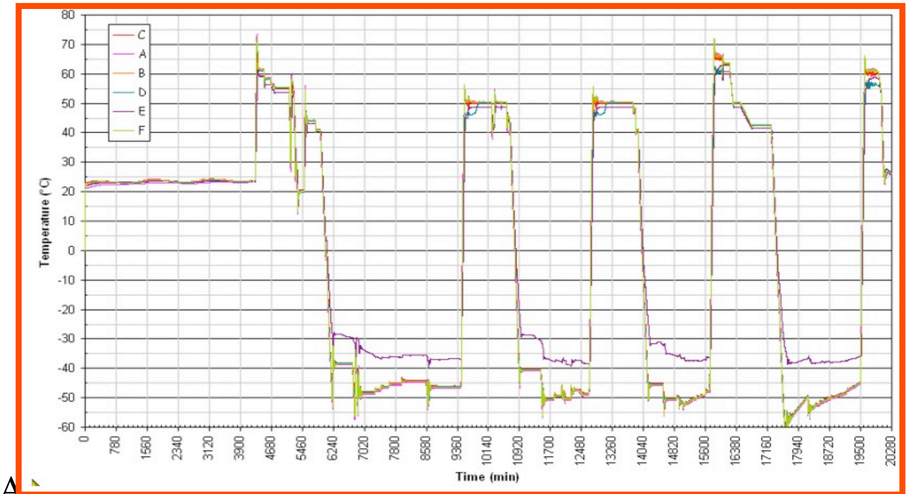


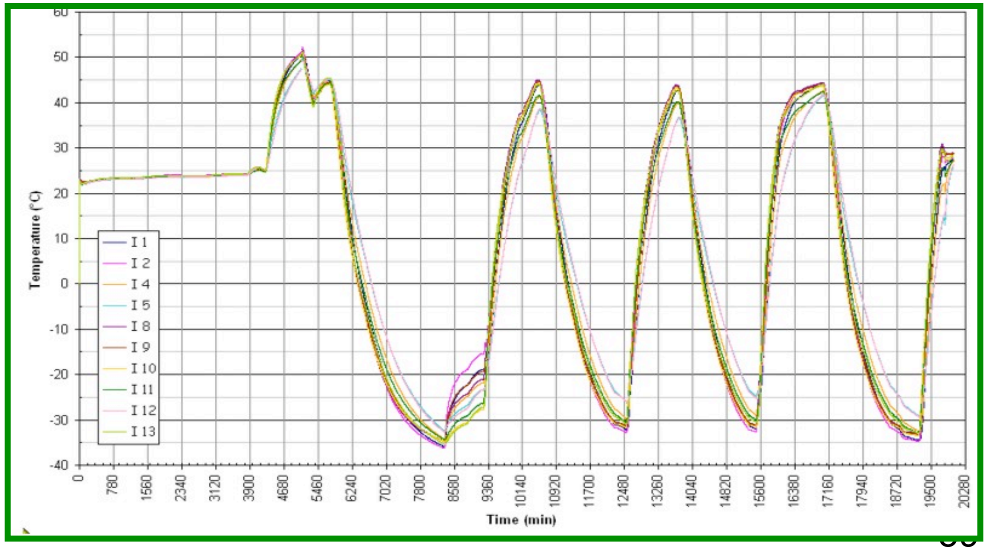


Temperature profiles

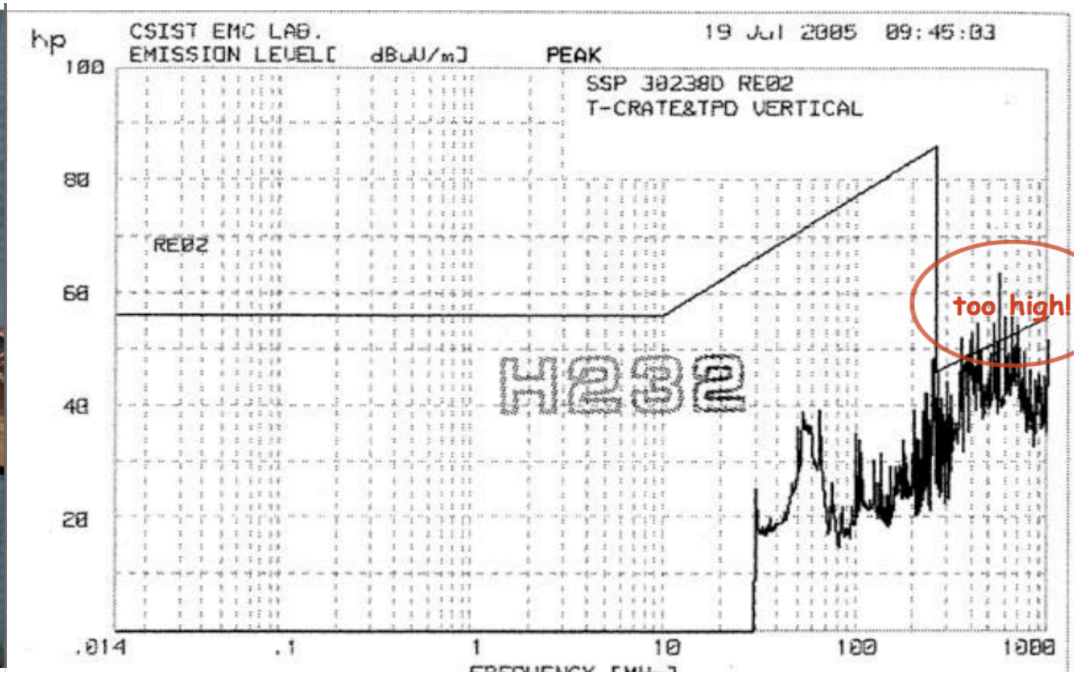






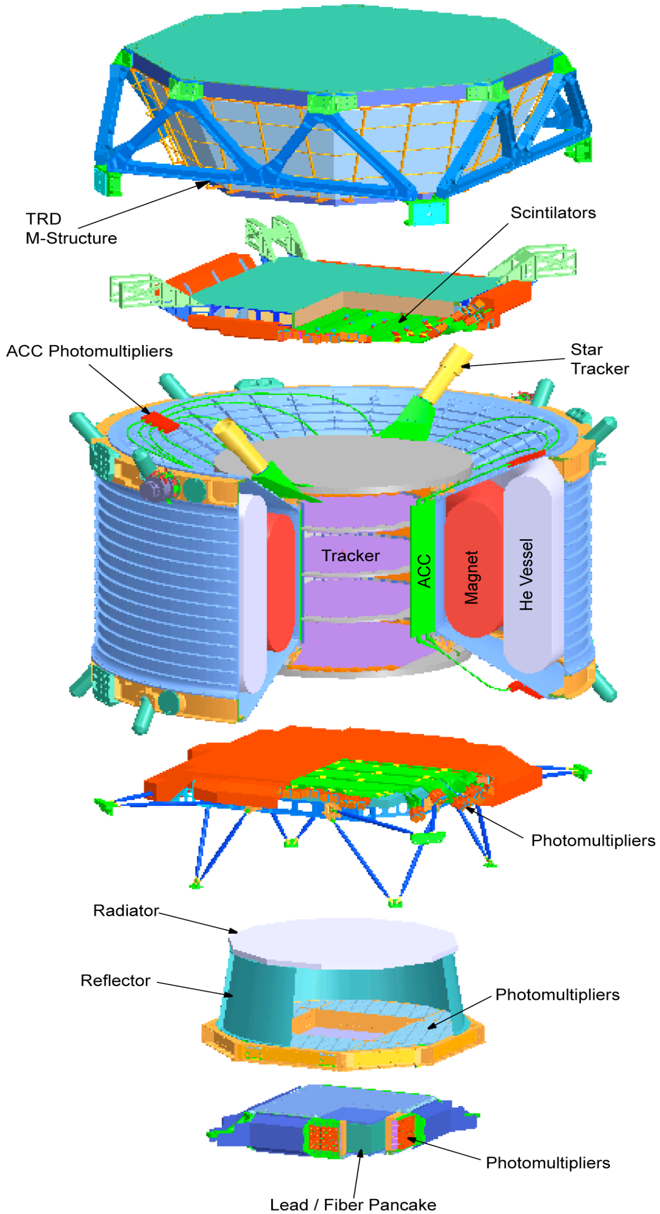


test EMI/EMC
(an example)



Subdetector Requirements: Summary

Subdetector	Req'ments	Channels	Raw Kbits
U: TRD	Gas gain	5,248	84
S: ToF+ACC	100 ps	48*4*8	49
T: Tracker	few fC	196,608	3,146
R: RICH	Single g	680*16*2	348
E: ECAL	1:60,000	324*(4*2+1)	47
Σ Raw Kbits/event			3,674
* Event Rate			≤ 2 Khz
= Total Raw Data Rate			~7 Gbit/sec

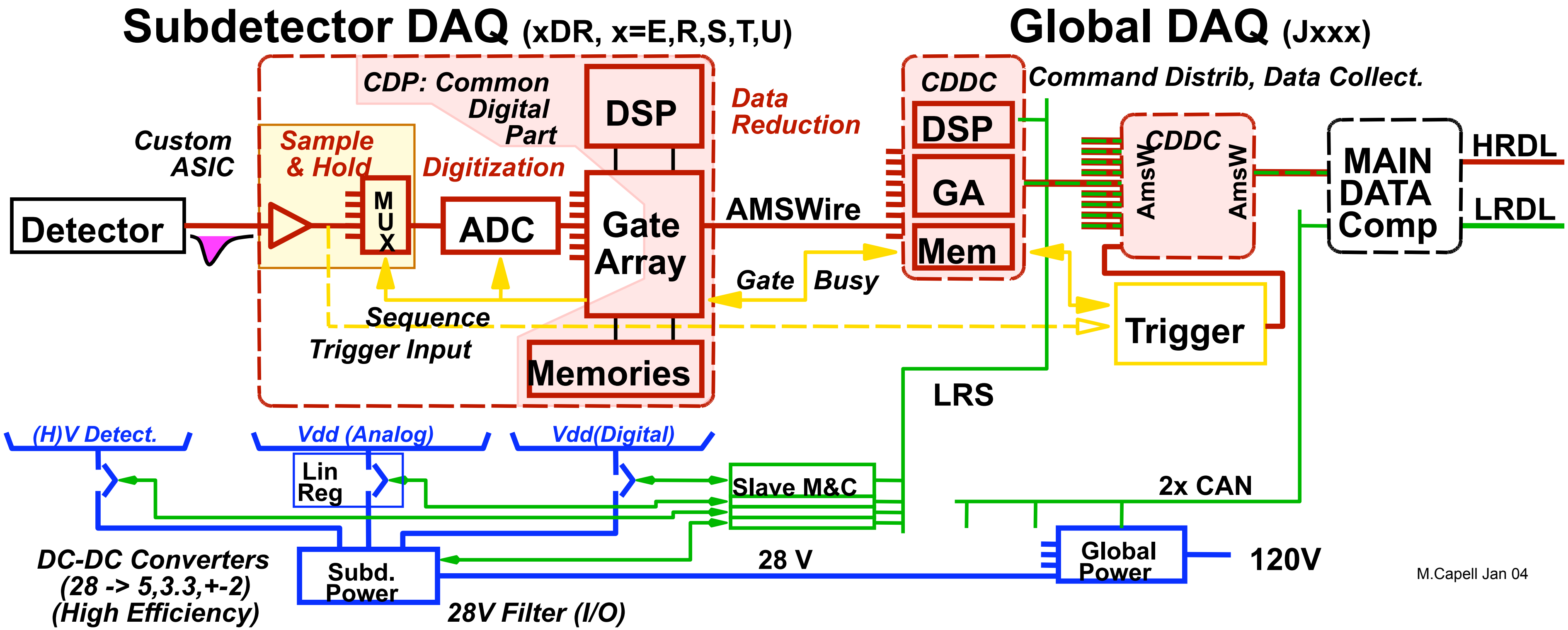


7 Gbit/sec vs 2 Mbit/sec

⇒ Restrict Rate & Size

Specify, design, develop, produce: High Speed, High Capacity,
Low Power, Low Weight, Reliable
Signal & Data Processing
to work in LOW EARTH ORBIT.

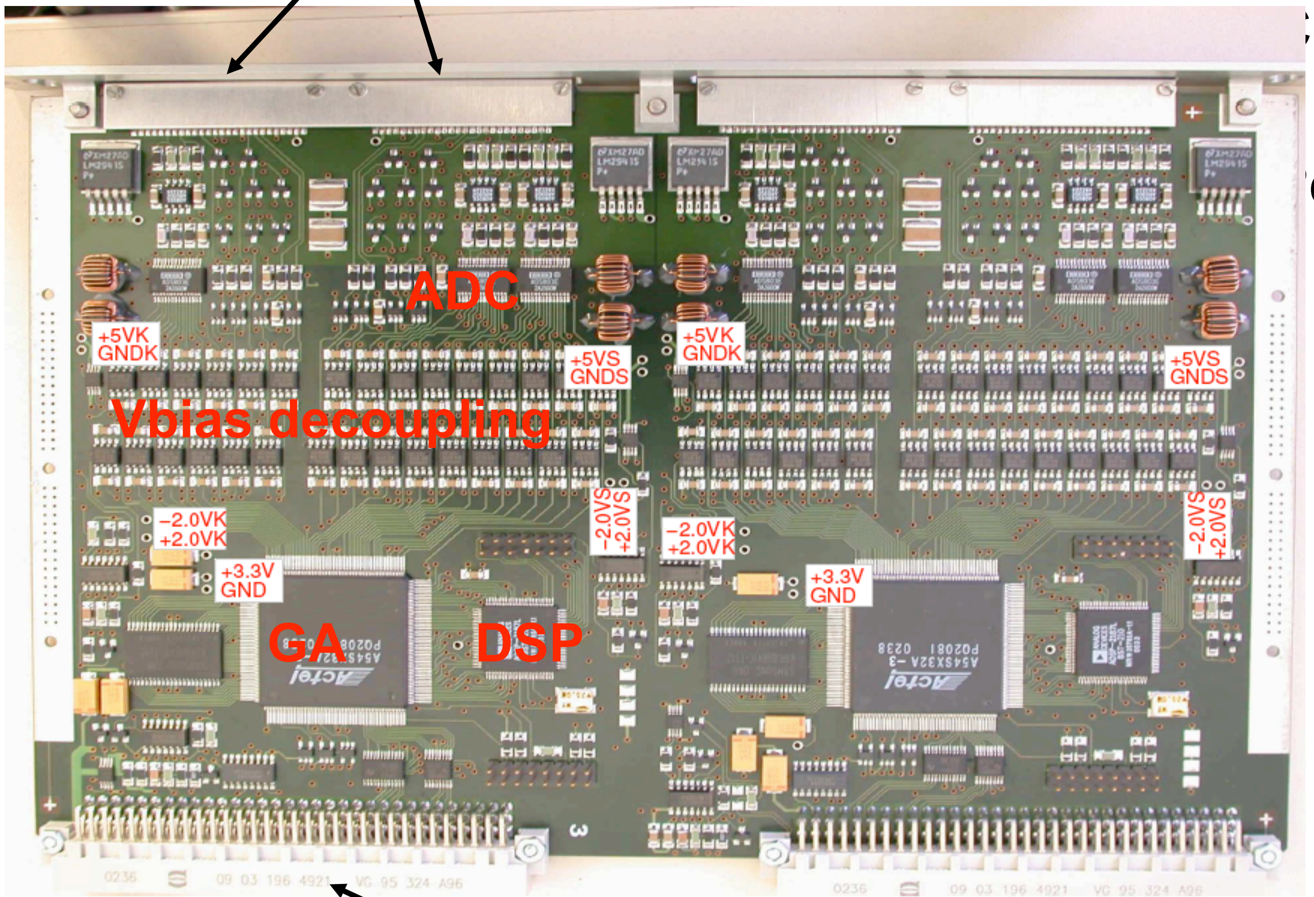
AMS-02 Custom/Common Readout Unit



- Cust/Comm processing unit, software, links.
  - DSP (ADSP-2187L), Gate Array (Actel A54SX-2A), SRAM (Samsung K6R-016V1C), Flash (AMD Am29LV004), LVDS Tx/Rx (TI SN65LVD-39-), etc.
- Cust/Comm monitor & control interfaces.
- Cust/Comm power supplies w/high efficiency.

Data Reduction Board (TDR2)

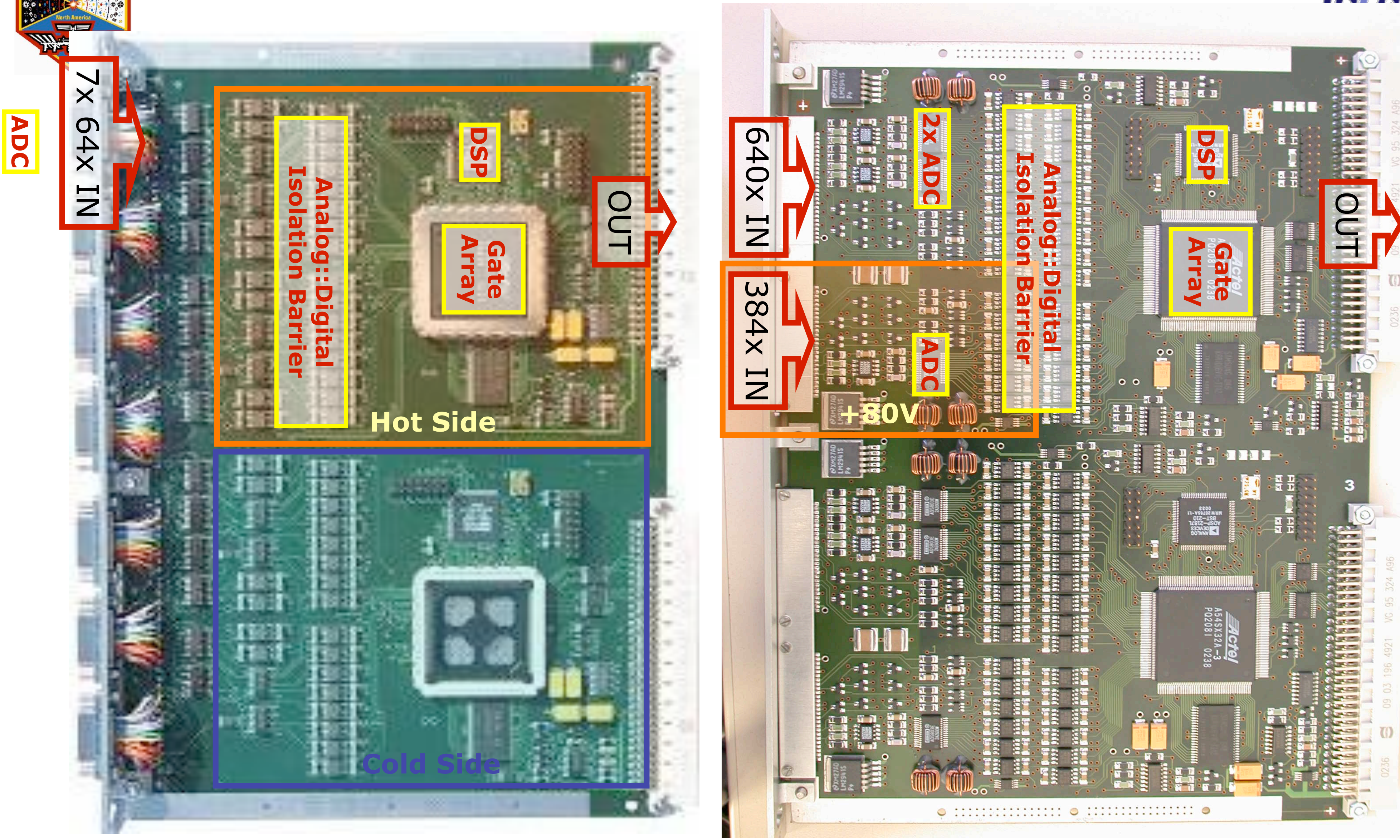
analog signal in



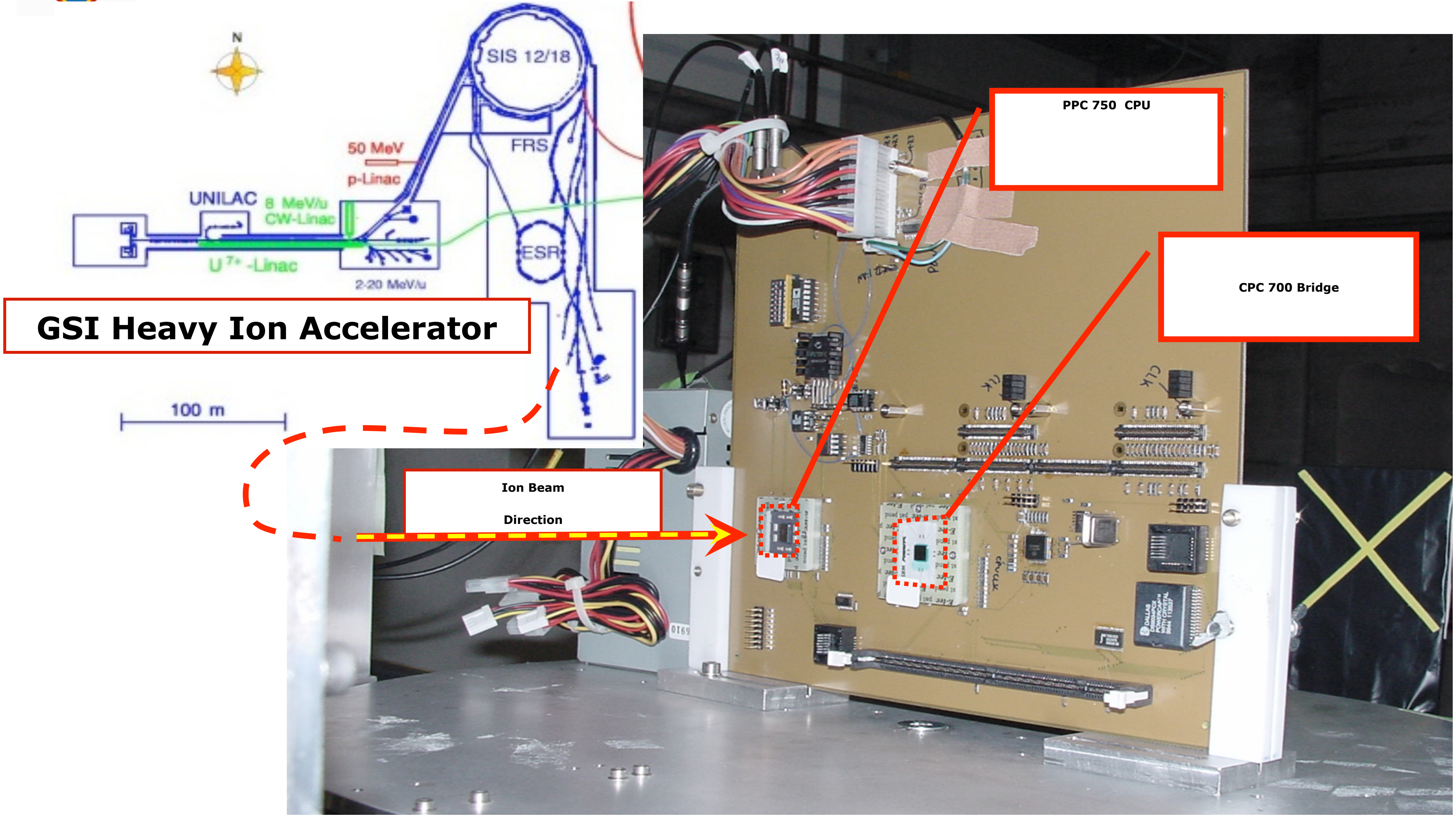
compressed digital out

- Collect analog data and digitize it (100 μs irred. dead time)
- Perform online data compression
  - Remove Pedestals
  - Calculate and Remove Common Noise
  - Search Clusters
- Up to 5 KHz trigger rate in compressed mode

Data Reduction (UDR2, TDR2) Boards



GSI Heavy Ion Beam Test Setup



Radiation 'hard' electronics

The problem are the SEE (Single Event Effect)

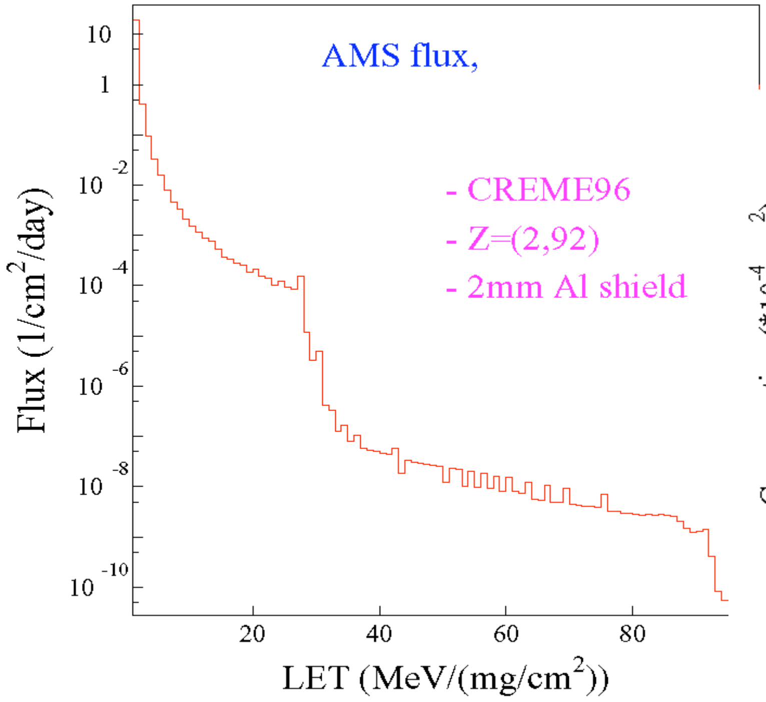


Figure 5: Expected fluxes on ISS in 2003.

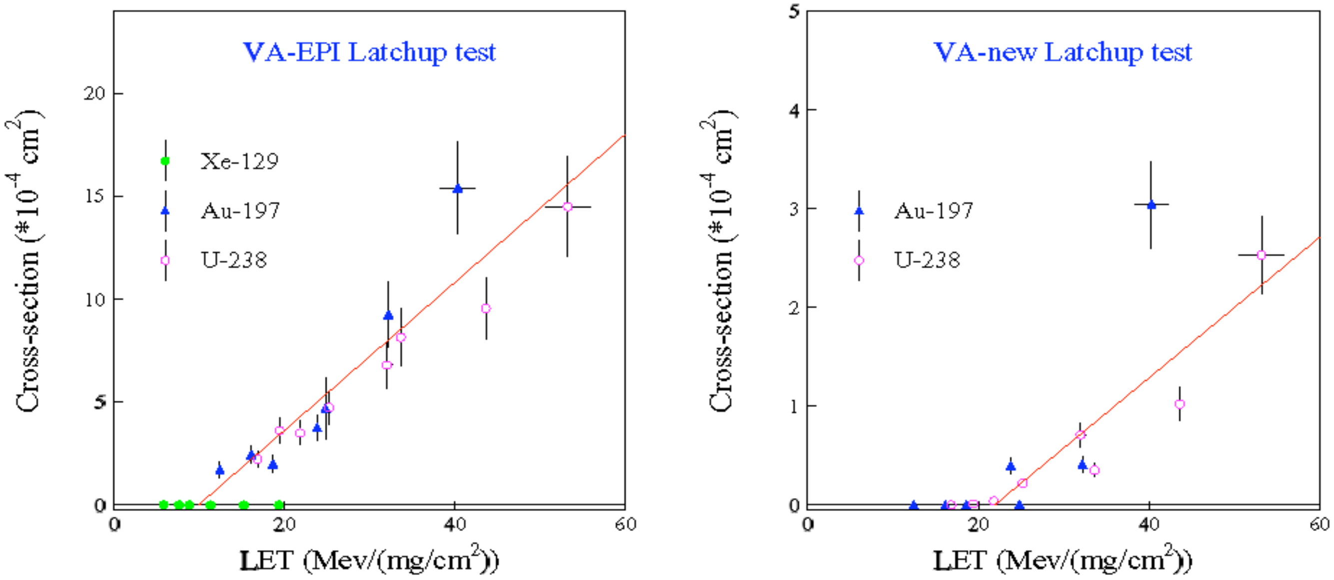
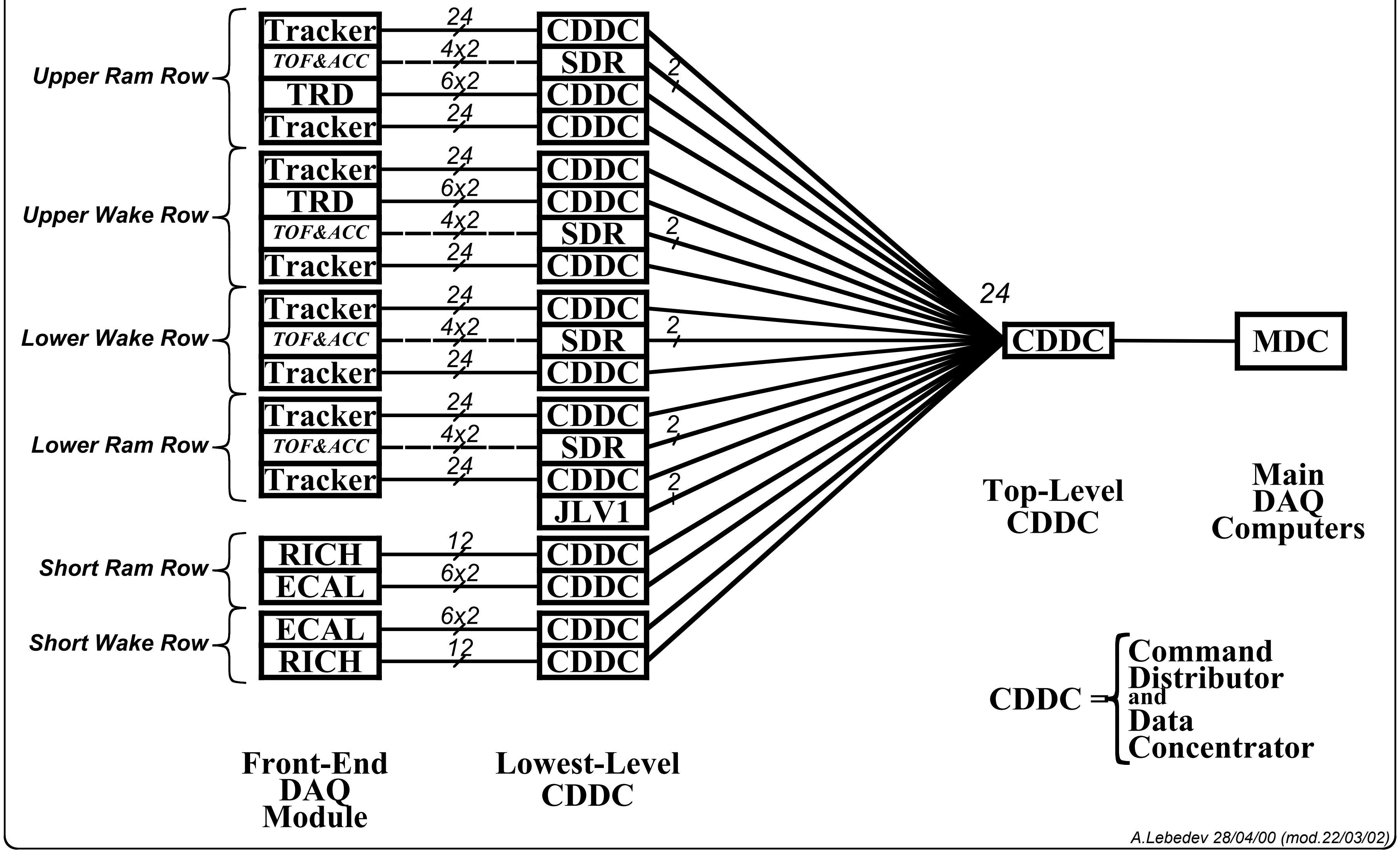


Figure 12: The new VA – SEL rates as measured in GSI

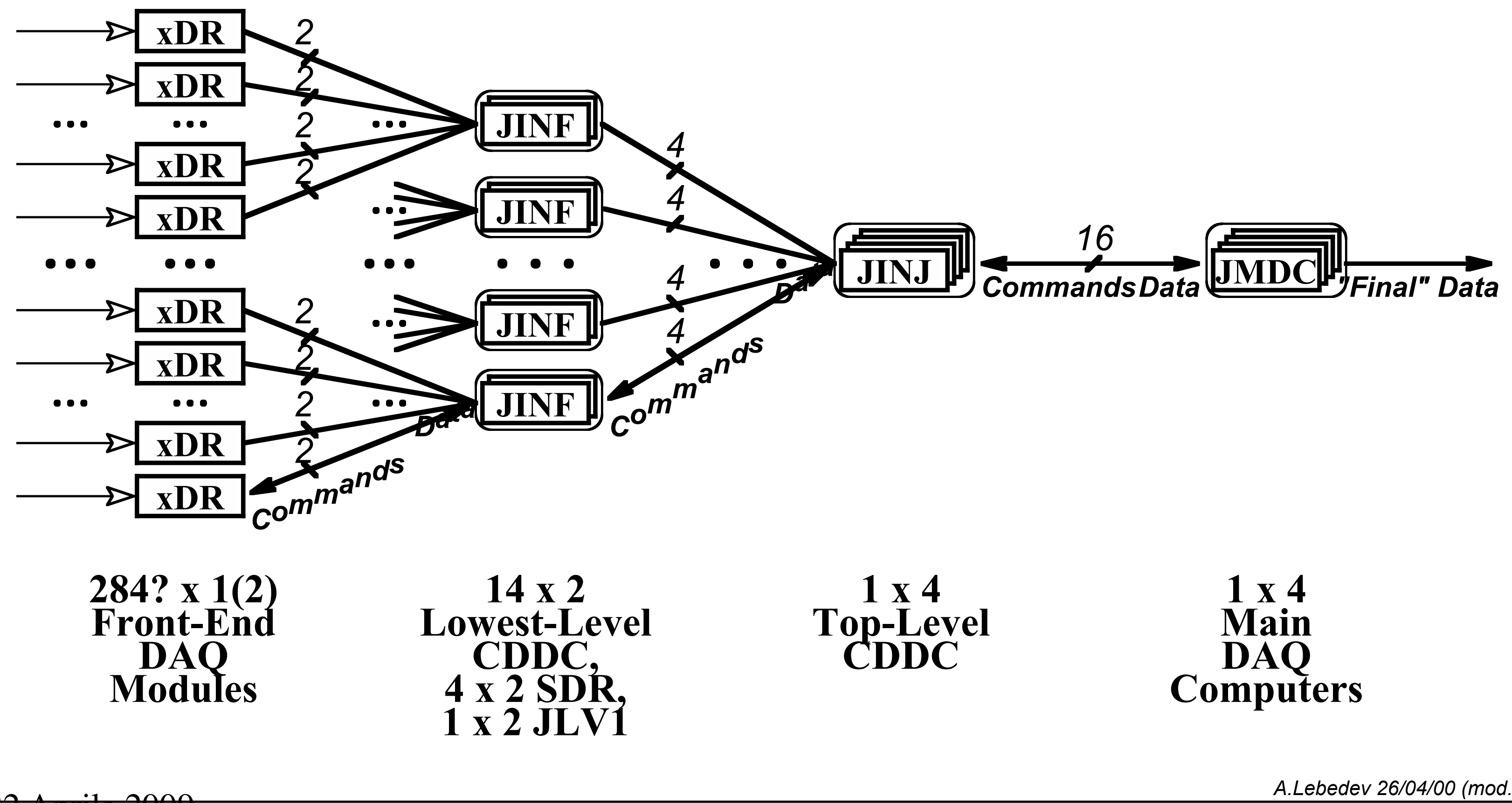
current limit protection is present for all active components

DAQ System Structure (1)

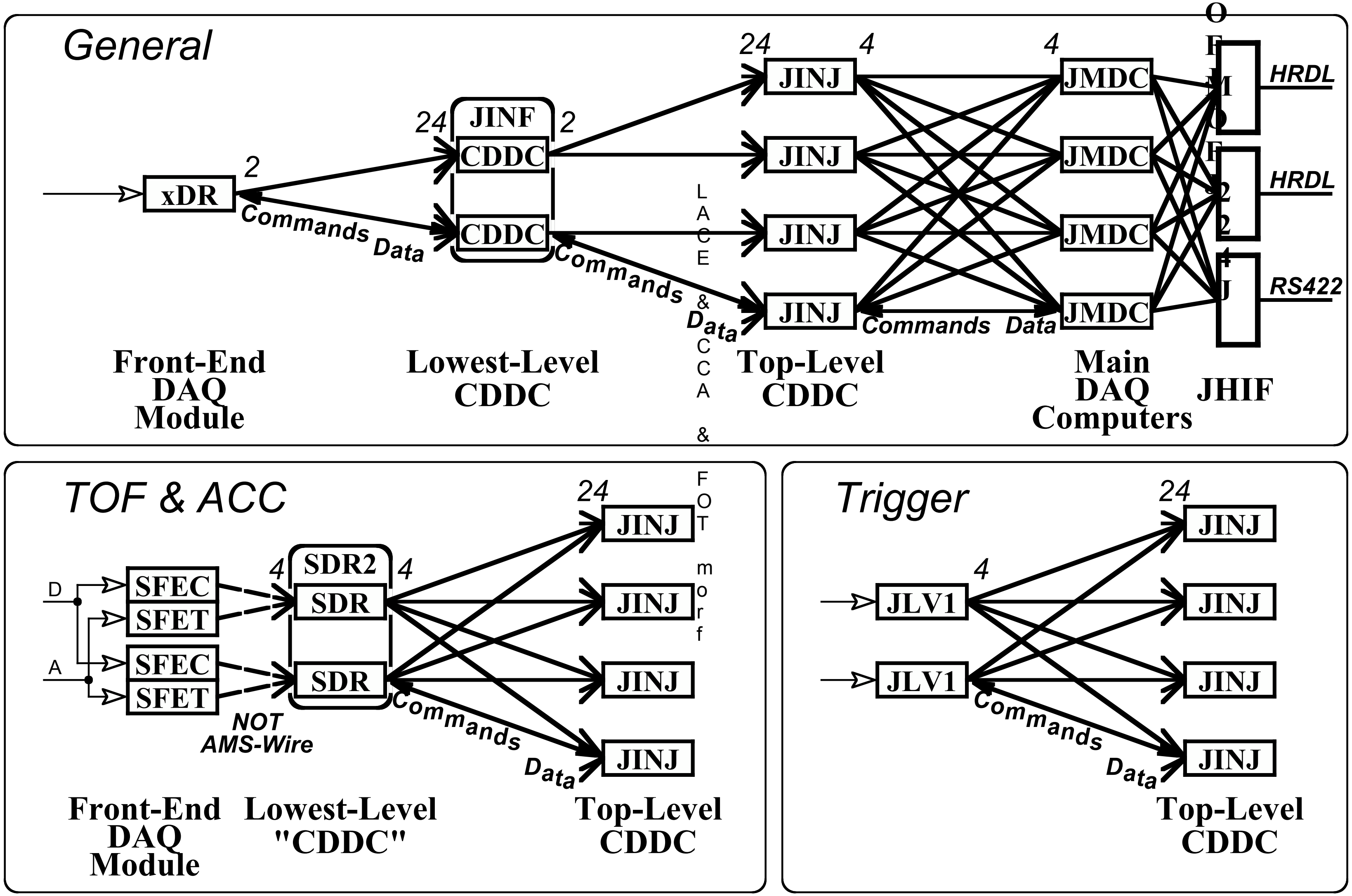


DAQ System Structure (2)

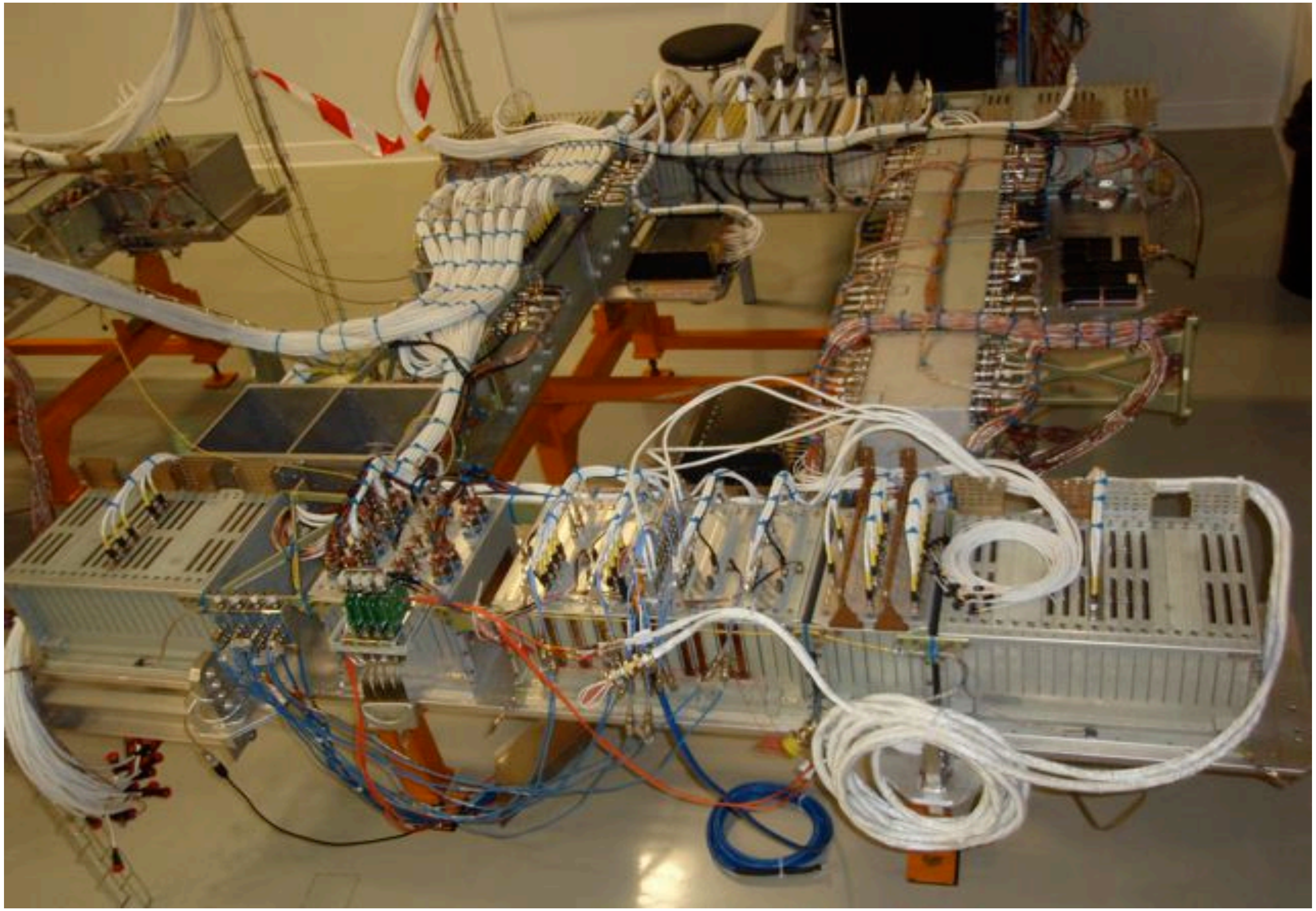
```
Redundancy:
- Front-End DAQ Modules: 1 (2 for TRD, TOF,
- Front-End CDDC:....... 2
- Top-Level CDDC:....... 4
- Main DAQ Computers:... 4
```



DAQ System Structure (3)



A.Lebedev 26/04/00 (mod.19/01/02)

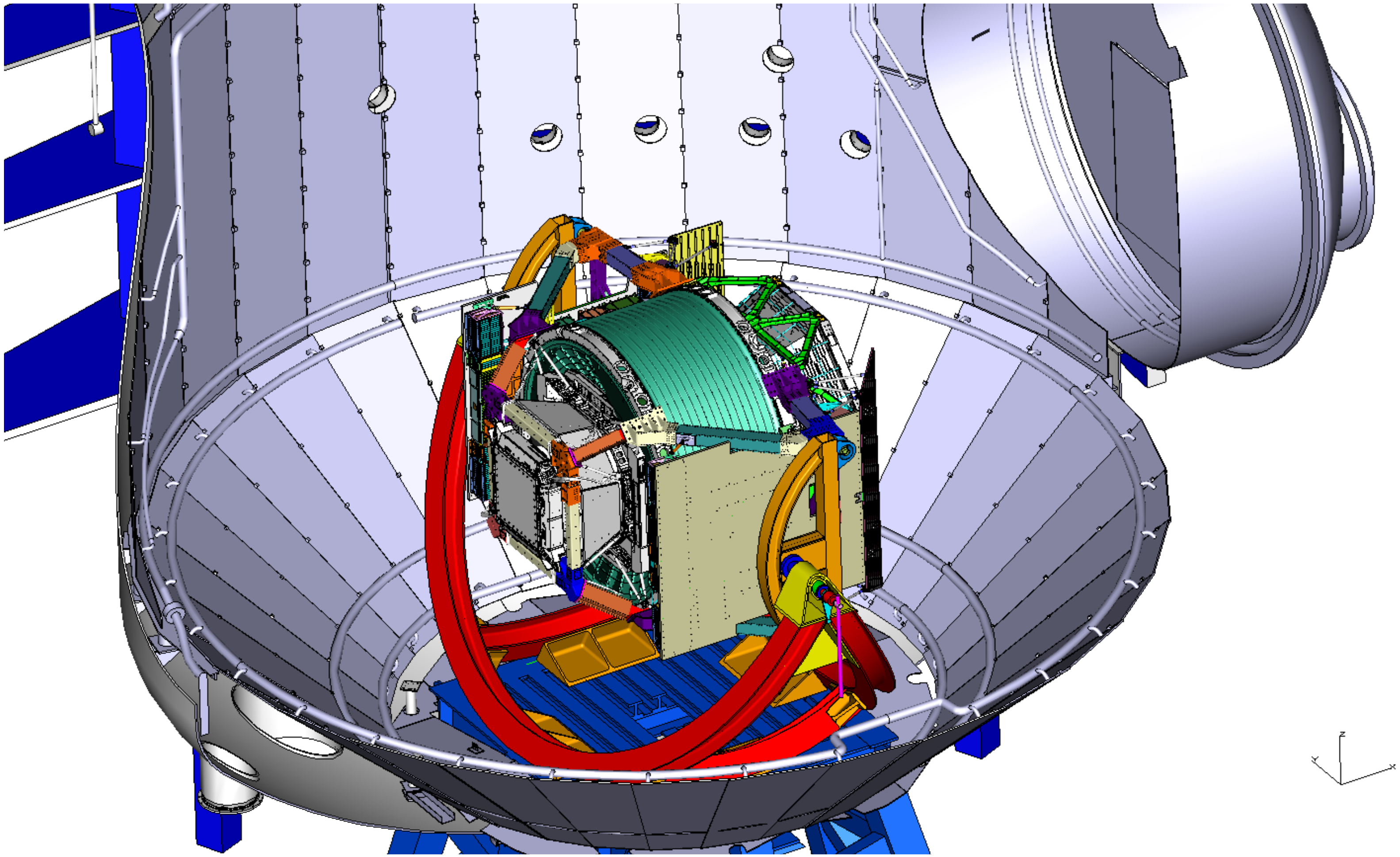


AMS-02 Thermo Vacuum & ThermalBalance Test

LSS - Large Space Simulator

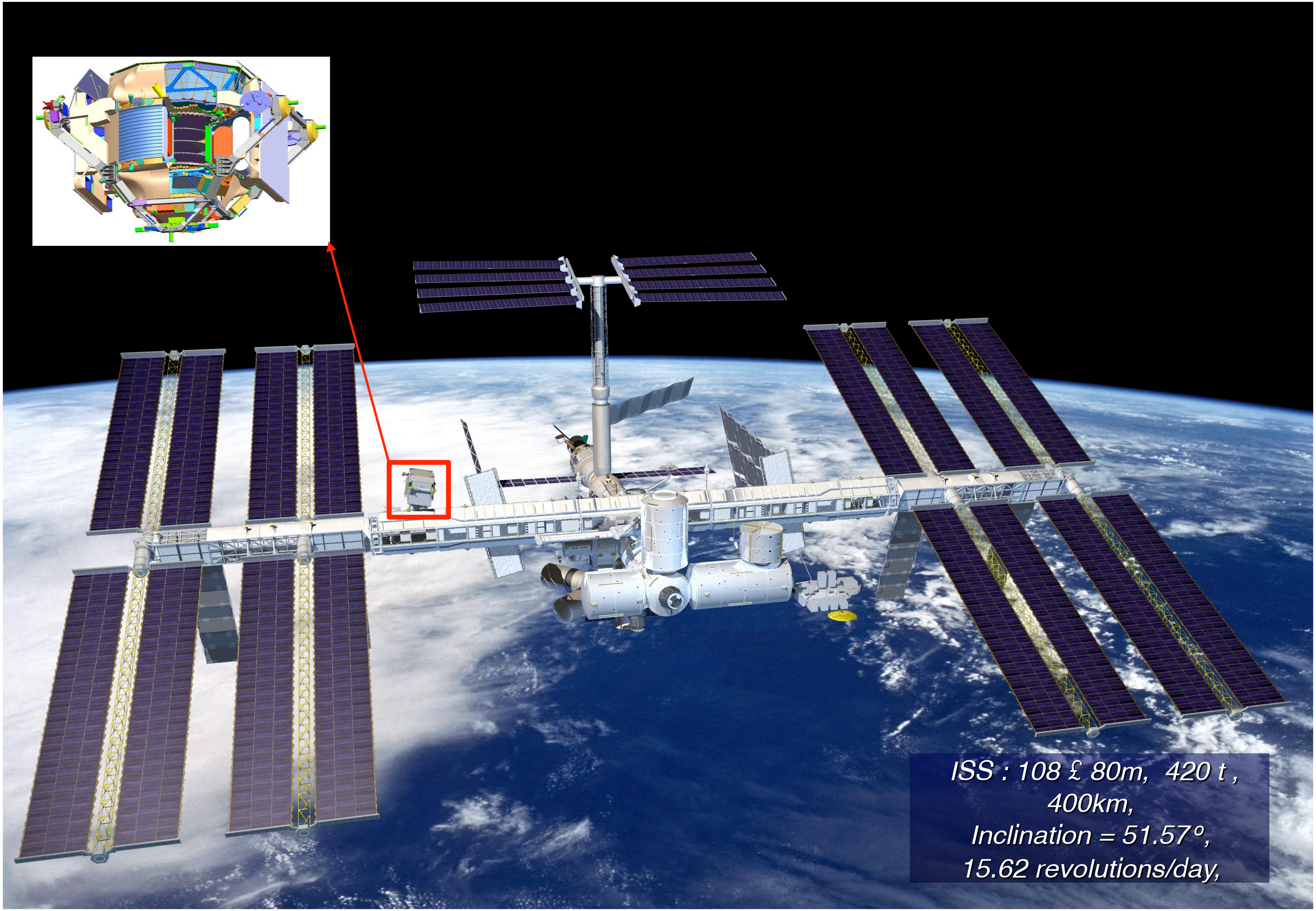
The test will be conducted in the Large Space Simulator (LSS) located at the European Space Research and Technology Center (ESTEC) facility in Netherlands.

TV test of AMS-02



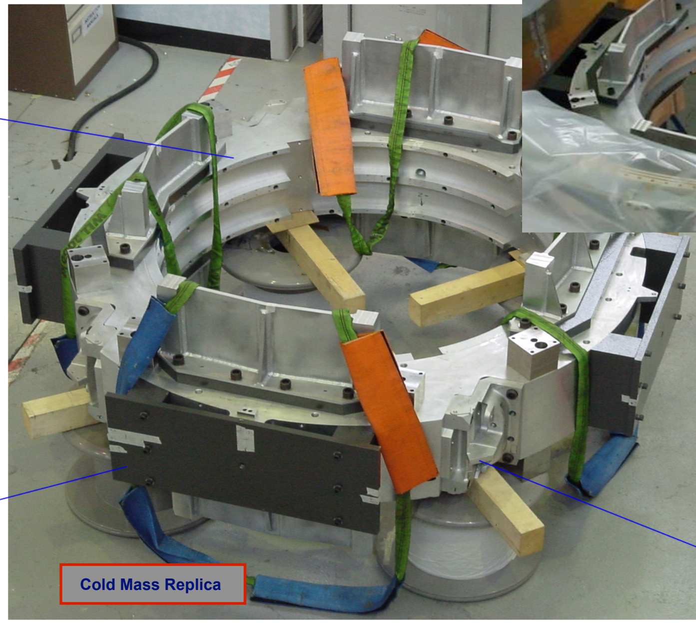
Conclusions

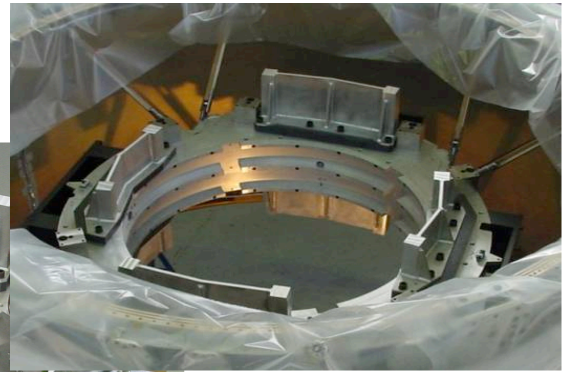
- After the successful test flight on board the Space Shuttle Discovery on June 1998, the AMS capabilities have been extended
- All subdetectors design and performance have been validated with several tests: hep tecnology is usable in space
- All subdetectors are ready since mid 2008
- Final integration is waiting the cooling of the magnet (second half of 2009)
- Full system TV test at the end of 2009
- AMS-02 will be ready for launch and operation on board the ISS in spring 2010

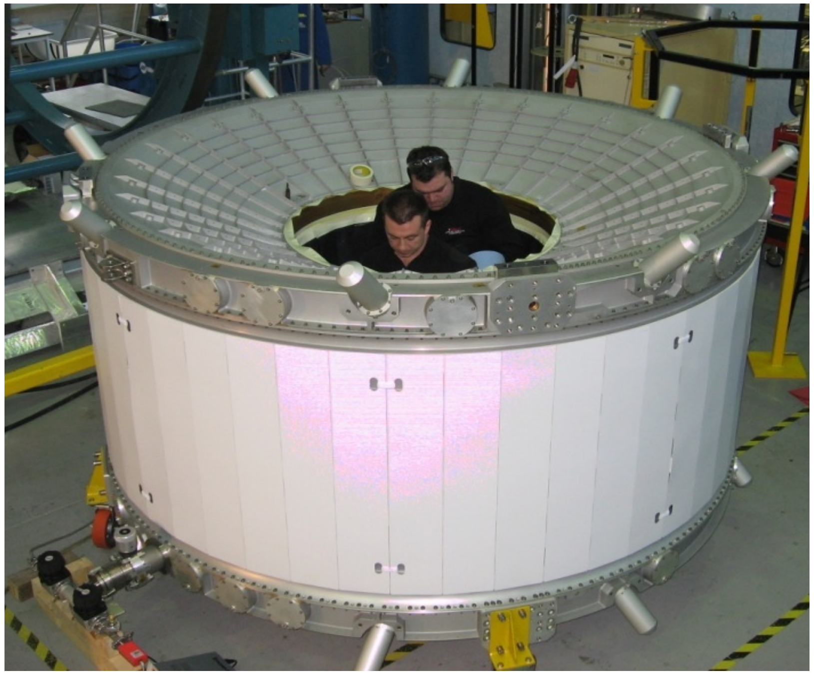

ISS : 108 £ 80m, 420 t ,
400km,
Inclination = 51.57º,
15.62 revolutions/day,

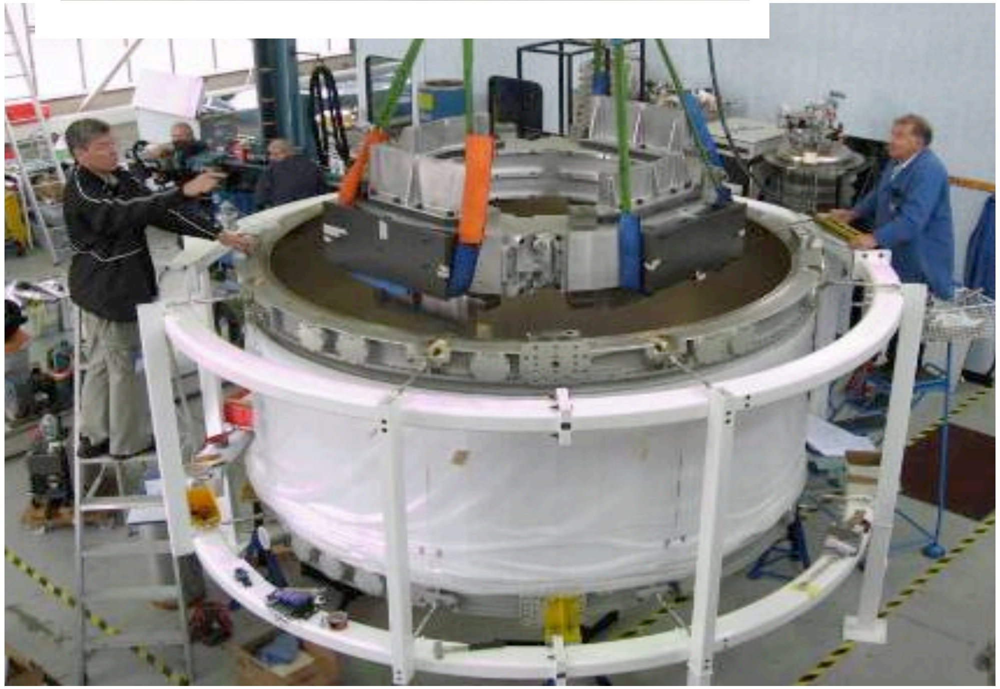
S119E008588

VACUUM CASE EXTENSIVE TESTING :









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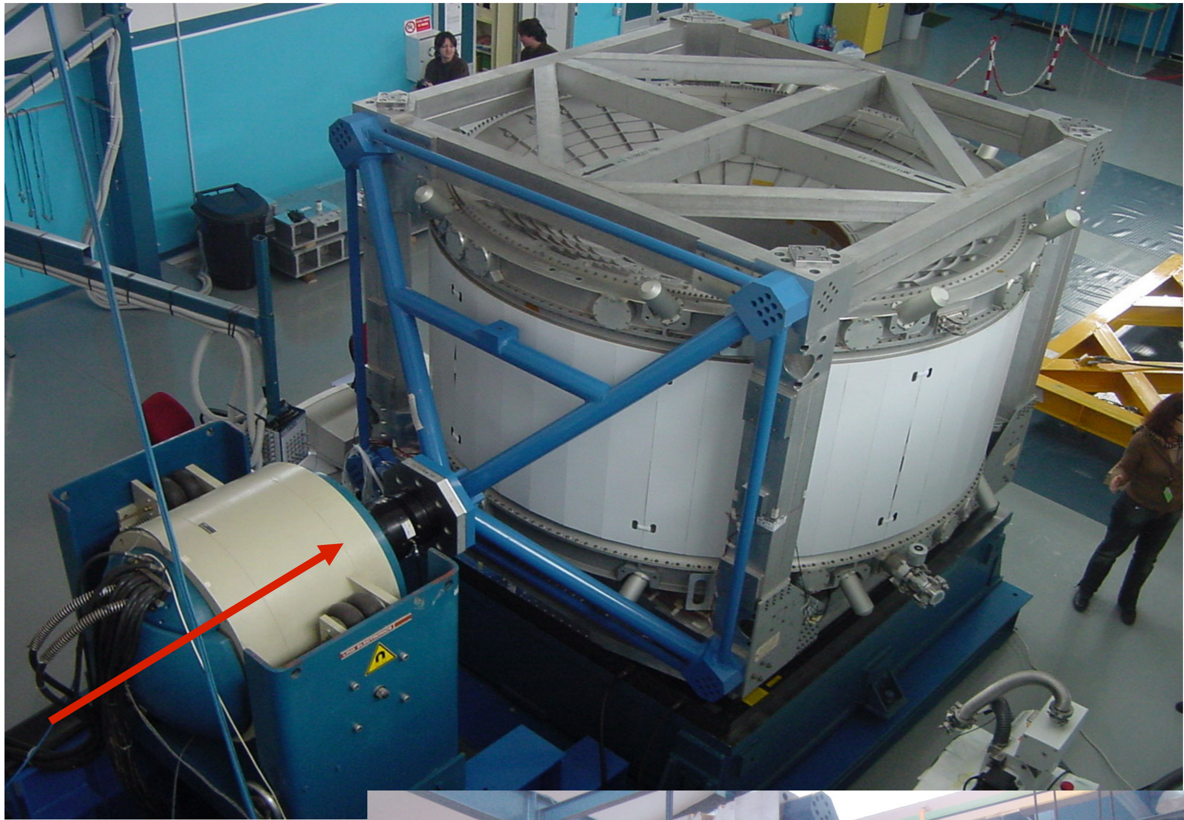
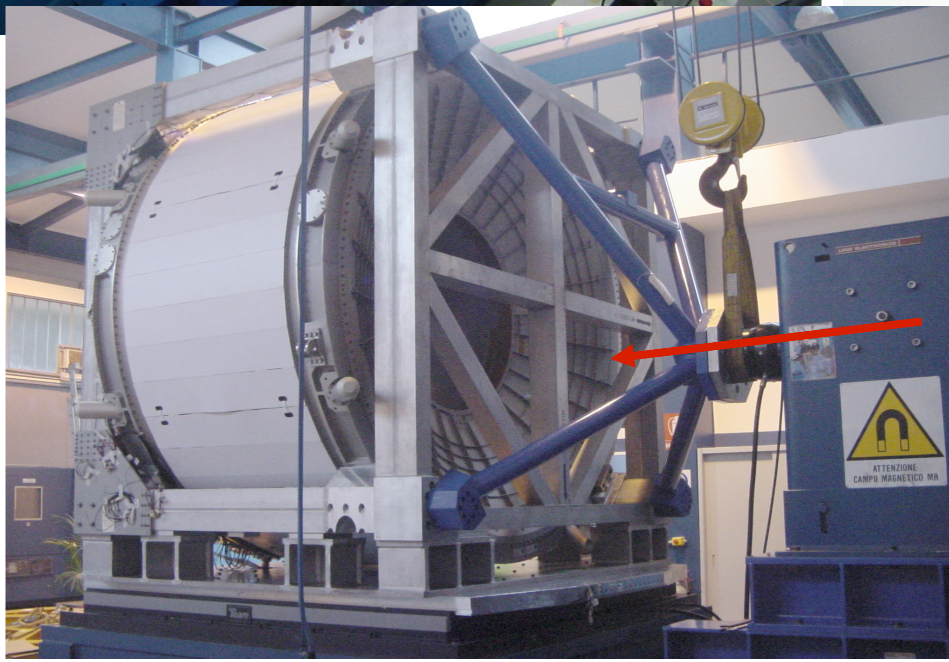
INFN
Istituto Nazionale





SERMS

45 day Thermal-Vacuum test at Noordwijk

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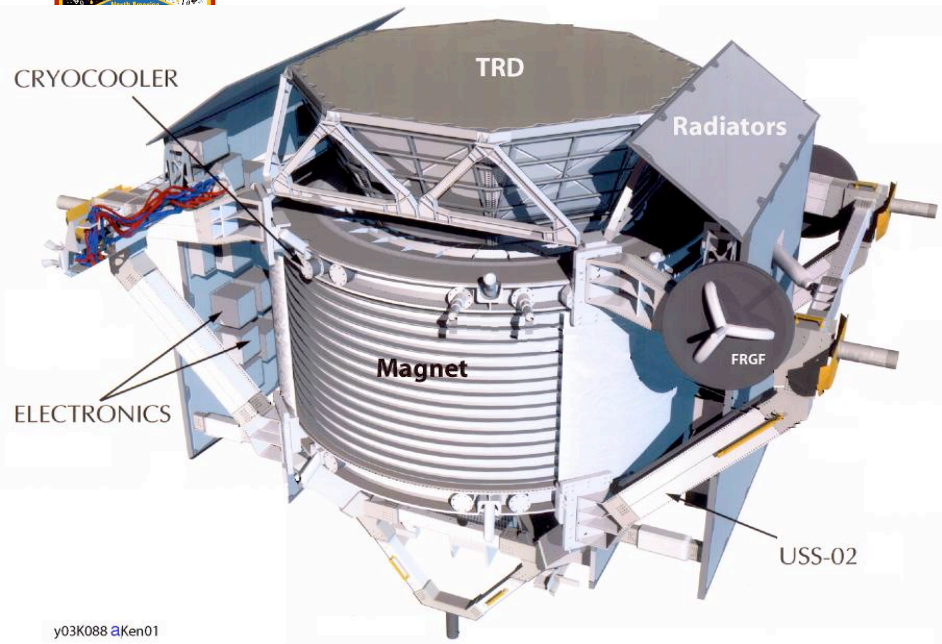

TV TEST WITH FULL DETECTOR