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# Space qualification tests of the PAMELA instrument

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**Abstract**

PAMELA is a satellite-borne experiment which will measure the antiparticle component of cosmic rays over an extended energy range and with unprecedented accuracy. The apparatus consists of a permanent magnetic spectrometer equipped with a double-

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sided silicon microstrip tracking system and surrounded by a scintillator anticoincidence system. A silicon–tungsten imaging calorimeter, complemented by a scintillator shower tail catcher, and a transition radiation detector perform the particle identification task. Fast scintillators are used for Time-of-Flight measurements and to provide the primary trigger. A neutron detector is finally provided to extend the range of particle measurements to the TeV region.

PAMELA will fly on-board of the Resurs-DK1 satellite, which will be put into a semi-polar orbit in 2005 by a Soyuz rocket. We give a brief review of the scientific issues of the mission and report about the status of the experiment few months before the launch.


*Keywords:* Cosmic antimatter; Satellite experiment; Magnetic spectrometer

## 1. The mission PAMELA

Payload for Antimatter Matter Exploration and Light-nuclei Astrophysics (PAMELA) is an experiment for cosmic-ray measurements to be performed on-board of the Russian Resurs-DK1 satellite. This satellite will execute a semipolar, elliptical orbit with an inclination of 70.4° and an altitude varying between 350 and 600 km, for a three-years long mission.

The primary objectives of PAMELA are the precise measurements of the positron flux from 50 MeV up to 270 GeV and of the antiproton flux from 80 MeV up to about 190 GeV. Additional objectives are the search for cosmic antimatter with a sensitivity of the order of $10^{-8}$ in the $\overline{\text{He}}/\text{He}$ ratio and measurements of the energy spectra of protons, electrons and light nuclei ($Z \leqslant 6$) up to an energy of about 700 GeV/nucleon. Finally, as a consequence of the long experiment lifetime and of the orbit features, it will be possible to monitor the long- and short-term modulation of cosmic rays in the heliosphere and to detect particles of solar origin.

The PAMELA spectrometer will be mounted in a dedicated pressurized container (PC) attached to Resurs-DK1. During launch and orbital manoeuvres the PC is secured against the satellite's body. During data-taking it will be swung up to give PAMELA a clear view into space.

An overview of the instrument is given in Fig. 1. PAMELA is built around a 0.4 T permanent magnet spectrometer (tracker) equipped with double-sided silicon detectors which will be used to measure the sign, absolute value of charge and momentum of particles. The tracker is surrounded by a scintillator veto shield (anticounters, AC) which is used to reject particles which do not pass cleanly through the acceptance of the tracker. Above the tracker is a transition radiation detector made of proportional straw tubes and carbon fibre radiators. This allows electron–hadron separation through threshold velocity measurements. Mounted below the tracker is an imaging silicon–tungsten calorimeter that measures the energy of incident electrons and allows topological discrimination between electromagnetic and hadronic showers (or non-interacting particles). A scintillator telescope system provides the primary experimental trigger and Time-of-Flight particle identification. An additional scintillator (Bottom Scintillator, S4) is mounted beneath the calorimeter to trigger the acquisition of the neutron detector that, right at the bottom of the PAMELA detector, provides additional information to separate hadronic from electromagnetic showers up to 10 TeV, thus giving the possibility to extend the electron-flux measurement.

PAMELA has dimensions of approximately $75 \times 75 \times 123\ \text{cm}^3$, an overall mass of 450 kg (plus about 20 kg of Gas Supply system refurbishing the TRD detector) and a power consumption of 355 W. The total geometric factor is $20.5\ \text{cm}^2\ \text{sr}$. Tables 1 and 2 report PAMELA mass and power budget respectively. Detailed descriptions of the characteristics and functionalities of the single PAMELA subdetectors can be found

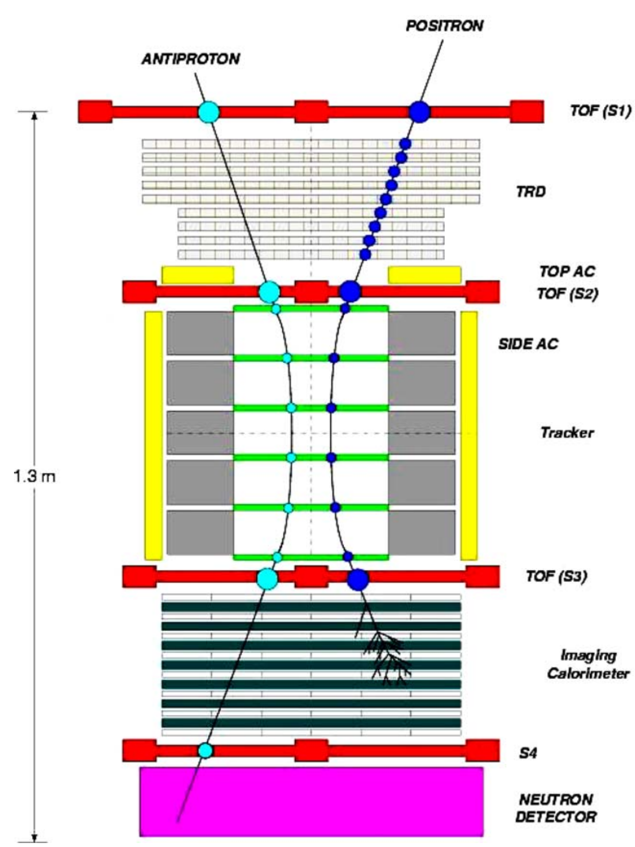


Fig. 1. A schematic view of the PAMELA apparatus.

Table 1
PAMELA mass budget

| Subsystem | Mass (kg) |
|---|---|
| Calorimeter | 104.0 |
| Spectrometer | 126.7 |
| Magnetic screens | 15.0 |
| Anticoincidence | 15.8 |
| Time-of-Flight | 18.0 |
| TRD | 29.3 |
| Bottom scintillator | 8.0 |
| Neutron detector | 30.0 |
| Electronic units | 42.7 |
| Gas supply system | 19.0 |
| General mechanics | 39.8 |
| Thermal system | 21.5 |
| Total mass | 469.8 |

Table 2
PAMELA power budget

| Subsystem | Power (W) |
|---|---|
| Calorimeter | 55 |
| Spectrometer | 63 |
| Anticoincidence | 0 |
| Time-of-Flight | 1 |
| TRD | 10 |
| Bottom scintillator | 1 |
| Neutron detector | 10 |
| CPU | 35 |
| VME crate | 80 |
| DC/DC converters | 65 |
| Power supply system | 35 |
| Total power | 355 |

in Adriani et al. (2003), Boezio et al. (2002), Campana et al. (2003), Pearce et al. (2003), Ambriola et al. (2003) and Galper et al. (2001).

Following the standard procedure for space missions, the instrument PAMELA has been produced in three different models:

Mass-Dimensional and Thermal Model (MDTM), intended for space qualification of mechanical structure and thermal system;
Technological Model (TM), intended for check out of electrical interfaces to Resurs and basic control and data procedures;
Flight Model (FM), which will undergo a minimal number of tests before being sent to space.

## 2. The Mass-Dimensional and Thermal Model of PAMELA

In order to fulfill its scopes, the Mass-Dimensional and Thermal Model reproduces the Flight Model in the following characteristics:

*Geometrical*: global dimensions, total mass, inertial moments, COG, lowest natural frequencies, strength characteristics, spacecraft attachment points and cable connection points;
*Thermal*: external surfaces characteristics (material, coating, degree of roughness, degree of blackness), thermal system, total heat release and its distribution in all subsystems.

All particle detectors in MDTM are simulated by aluminum dummy boxes. Electronics is limited to reproduce the power consumption of every subsystem.

### 2.1. Mechanical qualification tests

The Russian space company TsSKB-Progress (Samara, Russia), manufacturer of the Soyuz launcher and Resurs-DK1, provided the PAMELA collaboration with the spectra of the mechanical loads imposed to the instrument during the different operational phases of the mission (transport, launch phase, orbital operations, unlocking of the PC, flight). In order to ensure that no damage to PAMELA and to the spacecraft occurs in any of these phases, the MDTM had to be exposed to the same mechanical loads as in the real mission, amplified by a "qualification factor" to give a safe margin of operation. Fig. 2 shows the qualification levels for random vibrations for two phases of the rocket launch (PIO-1 and PIO-2).

The vibration tests of the PAMELA MDTM as a stand-alone instrument have been performed in IABG Laboratories (Munich, Germany) in August 2002 (Fig. 3). The success criterion of the test was in the verification that no structural yielding or failure as well as no change in dynamic behavior of MDTM during and after the test occurred.

The PAMELA structure was subjected to vibration loads along the three orthogonal axes according to the qualification levels suggested by TsSKB-Progress.

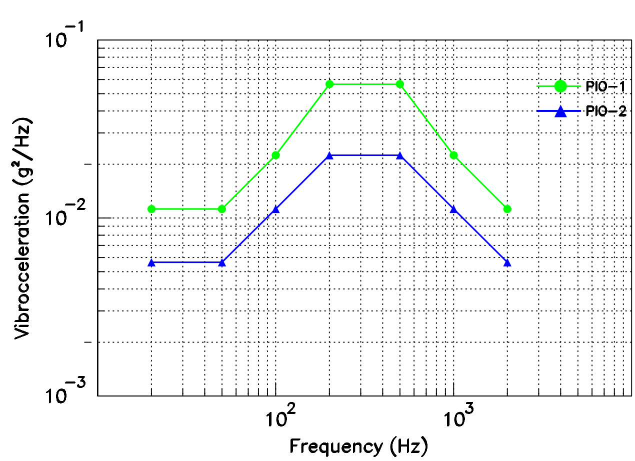


Fig. 2. Qualification random vibration load levels.

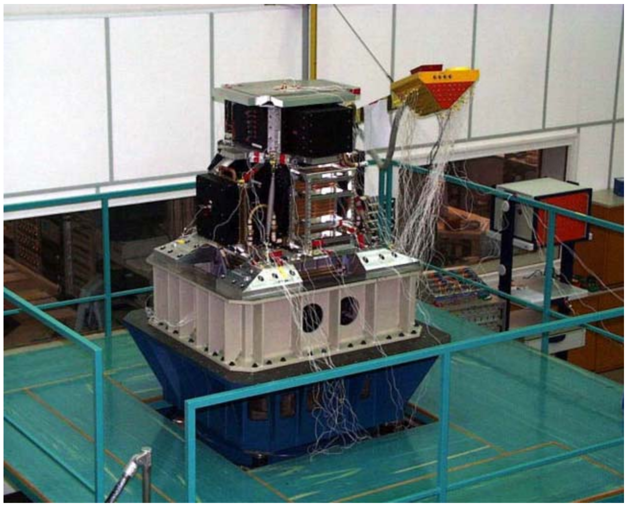

Fig. 3. PAMELA MDTM on the shaker system in IABG (August 2002).

The test was successful and PAMELA Mass-Dimensional and Thermal Model passed the space qualification for random and sine vibration loads.

Since the shaker at IABG did not cover the whole spectrum required, the tests performed in Munich had to be completed to fully qualify the structure PAMELA for all kinds of mechanical loads. Additional transport, vibration and shock tests of the PAMELA MDTM integrated into the PC were performed at the TsSKB-Progress Testing Center in May 2003. In this test, besides checking the vibrational strength of PAMELA and its connections to the PC including the cabling with the Gas Supply system, also transport tests and pyrotechnical shock tests were performed. The first simulate the stress loads imposed to PAMELA during its railway transport at the Baikonur launch site, while the second reproduce the unlocking of the PC in flight from the "parking" to the "data-taking" position. The success criterion of the mechanical test was the same as at IABG.

At the end of the test it was verified that no damage to the structures occurred, and by resonance searches that PAMELA dynamic behaviour did not change. This concluded the test phase aimed to mechanically qualify PAMELA structure for space.

### *2.2. Thermal qualification tests*

Fig. 4 shows the PAMELA thermal system: it consists of a 8.6 m long pipe that joints 4 radiators and 8 flanges. Task of this system is to dissipate the heat produced by the subsystems and transfer it into the spacecraft. Such transfer is performed by means of a heat-transfer fluid pumped by Resurs through PAMELA pipelines.

The spacecraft imposes requirements to the total heat release of PAMELA (maximum 355 W, see Table 2 for

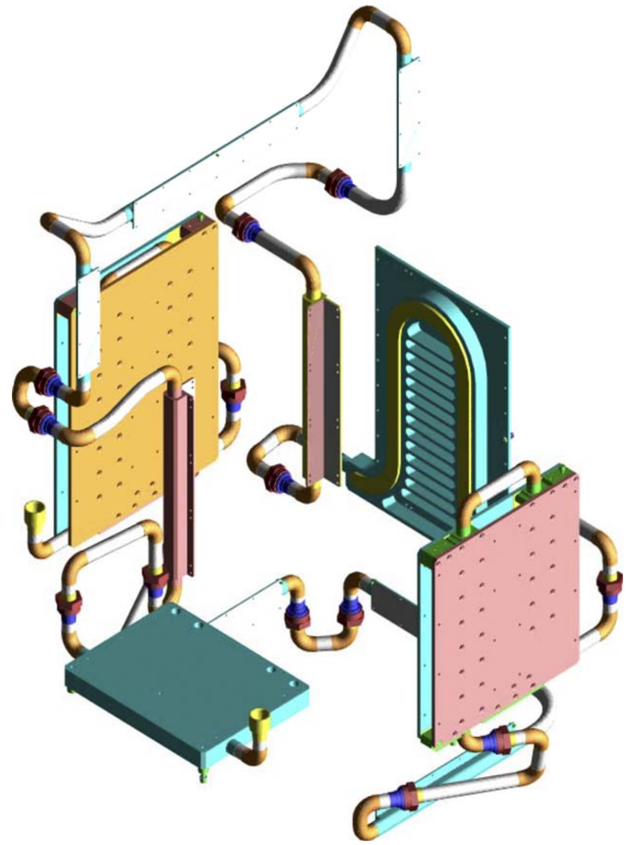

Fig. 4. PAMELA thermal system, made by flanges, radiators and pipes.

the power budget), to the leakiness of its thermal system and to the maximum pressure and temperature of the heat-transfer medium running through the pipelines. These requirements, and those imposed by the PAMELA subdetectors and electronics, determined the final design of the PAMELA thermal system.

The thermal and vacuum tests of PAMELA MDTM were performed in the laboratories of TsSKB-Progress in April 2003. Six thermal modes of operation have been tested, as briefly summarized in Table 3. The relevant parameters during the tests were:

- *PAMELA consumption*, reproduced by a system of resistors mounted inside the MDTM according to Table 2;
- *external heat flows*, corresponding to the orbital radiation flux and simulated by a system of infrared lamps;
- *heat carrier temperature and flow rate*, as pumped from Resurs into PAMELA.

Each mode lasted as long as necessary to reach and maintain a steady state. The last tested mode – simulating a stop of the heat carrier flux into the pipelines due to a malfunctioning – was interrupted after 3 h when PAMELA reached about 60 °C.

Table 3
Testing modes adopted during thermal tests

| | Testing modes | | | | | |
|---|---|---|---|---|---|---|
| | Over heating | Transient mode #1 | Transient mode #2 | Over cooling | Transient mode #3 | Super-overheating |
| PAMELA consumption | 355 W | 355 W | 355 W | 0 W | 355 W | 355 W |
| External heat flows | Maximum | Minimum | Minimum | Minimum | Maximum | Maximum |
| Heat carrier temperature | +30 °C | +30 °C | +8 °C | +8 °C | +30 °C | >30 °C |
| Heat carrier flow rate | 126 ml/s | 126 ml/s | 113 ml/s | 113 ml/s | 98 ml/s | 0 ml/s |
| Duration | 48 h | 24 h | 16 h | 14 h | 19 h | 3 h |

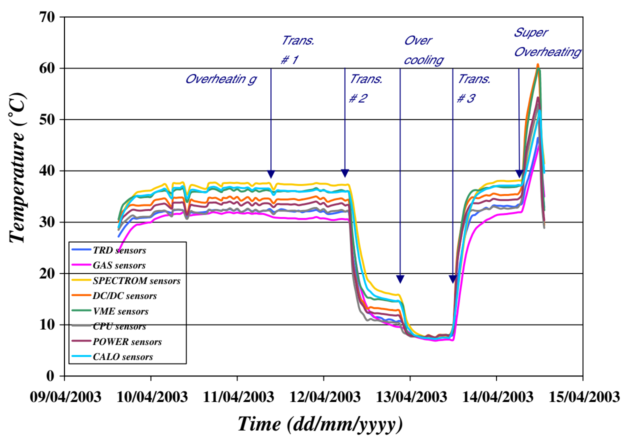


Fig. 5. Results of PAMELA thermal qualification tests.

The qualification test of the PAMELA thermal system was successful: all parameters of the system stayed within the tolerable limits. It was confirmed that the orbiting of Resurs-DK1 has the effect of keeping the temperature of PAMELA oscillating between 38 °C in the hottest systems and 7 °C in the coldest systems, as shown in Fig. 5. The temperature of the instrument depends critically on the heat carrier running inside the pipelines: the last testing mode showed that the autonomy of operation of PAMELA without heat carrier flux is limited to a few hours.

## 3. The Technological Model of PAMELA

PAMELA Technological Model is a 1:1 copy of the Flight Model apart from the particle detectors which are substituted by dummies. Its assembly started in 2003 and was concluded the first months of 2004. The model was then shipped to Samara in April 2004 (see Fig. 6).

Task of this mock-up is to perform all kinds of electrical tests of PAMELA interfaced to Resurs. Schematically, such tests must verify the basic functionality of PAMELA electrical internal structure, the correct execution of Power-On procedures and of procedures initiated by spacecraft telecommands, and the successful transfer of data from PAMELA to the spacecraft memory.

Fig. 6. PAMELA TM during transportation from Rome to Samara (April 2004).

In addition to this, the PAMELA Technological Model will be used for magnetic tests aimed to check that the residual magnetic field of PAMELA – that escaping the screens mounted around the permanent magnet – does not interfere with the Resurs instrumentation.

These complex tests are executed in two steps: a first part was already performed in Rome in December 2003, where the satellite was emulated by a Ground Support Equipment (EGSE). The second and final part started in May 2004 in TsSKB-Progress and is still in progress. By October 2004 PAMELA Technological Model will be integrated into Resurs-DK1 to complete all remaining tests.

## 4. The Flight Model of PAMELA

The Flight Model of PAMELA is currently in its final integration phase in Italy (clean room of the University of Rome Tor Vergata) and will be delivered to TsSKB-Progress between the end of 2004 and the beginning of 2005. The final freezing of the on-board CPU software waits responses from the electro-diagnostic tests in progress with the TM in Samara.

The Flight Model will be shipped to Russia by a dedicated charter flight, housed into a Transport Container especially designed to withstand severe transport conditions, like flight from Rome to Samara and then to Baikonur, and truck and railway transport in Russian territory, with temperature excursion from −40 to + 50 °C and relative air humidity between 10% and 90%.

### *4.1. Beam tests*

From July 2000 until September 2003 PAMELA Flight Model was extensively exposed to beam tests at CERN PS and SPS to study its physics performance. A preliminary integrated flight model set-up consisting of the tracker and anticounting system and calorimeter was exposed to protons (200–300 GeV) and electrons (40–300 GeV) at the CERN SPS in June 2002. The TRD as stand-alone detector was also tested.

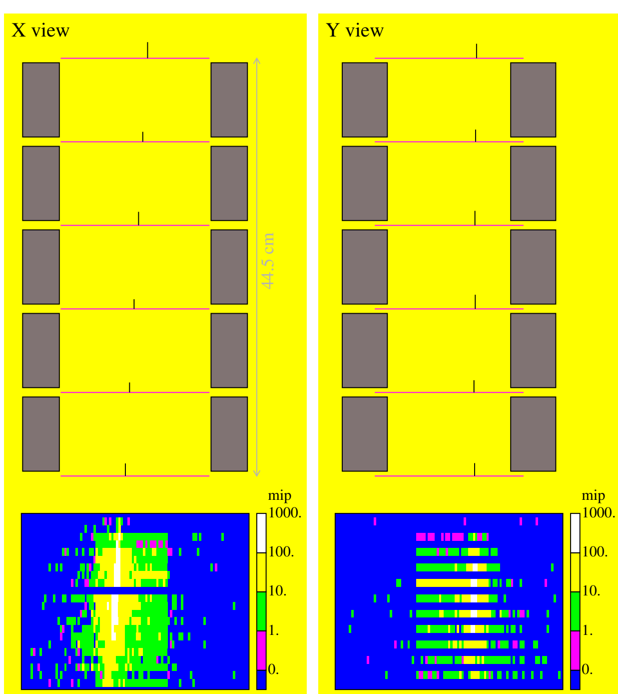


Fig. 7. A showering electron at the September 2003 CERN SPS beam test: tracker (upper part) and calorimeter (lower part).

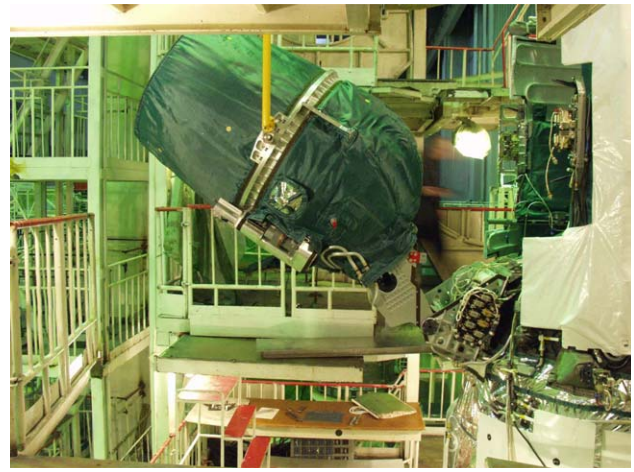

Fig. 8. Tests of PAMELA Pressurized Container orbital operations (May 2002).

Last test with an almost complete Flight Model set-up has been carried out in September 2003 again at SPS. Fig. 7 shows a electron track recorded during this test beam session.

## 5. Satellite and PC tests

In parallel to the activities with PAMELA, important steps in the satellite development were done.

In May 2002 orbital operations tests of the PC took place in Samara. It was verified – in weightless conditions – the movement of the PC from the parking to the data-taking position (see Fig. 8) and results of the tests were positive.

After the mechanical qualification of PAMELA inside the PC, the dynamic verification of the satellite Resurs was performed (July–August 2003). Outcome of this test was also positive.

## 6. Conclusions

The assembly of the instrument PAMELA is very close to its conclusion. The Mass-Dimensional & Thermal Model passed all tests for space qualification. The Technological Model assembly took more than one year and it is now concluded; the model is going to be integrated with the satellite for electro-diagnostic tests in Samara. The Flight Model system integration is under way in Rome. SPS beam tests of an almost complete setup for final calibration and tracker alignment were done in September 2003.

The schedule for the next few months is very tight. After the final integration of the Flight Model, it is planned to expose PAMELA FM to a vibration test at minimal loads at IABG – Munich – for a final check of the structure. Afterwards PAMELA will fly to Samara where the final integration into the satellite, together with the ancillary detectors that will be put onboard – experiments ARINA and EOS – will start. The tests in Samara will last up to 3 months, and then Resurs will reach the Baikonur launch site. The final tests in situ will take between 8 and 12 weeks, ensuring the spacecraft launch before Summer 2005.

## References

Adriani, O., Bonechi, L., Bongi, M., et al. The magnetic spectrometer of the PAMELA satellite experiment. NIM A 511, 72–75, 2003.

Ambriola, M., Bellotti, R., Cafagna, F., et al. PAMELA Space Mission: the Transition Radiation Detector. Proceedings of the 28th ICRC, pp. 2121–2124, 2003.

Boezio, M., Bonvicini, V., Mocchiutti, E., et al. A high granularity imaging calorimeter for cosmic-ray physics. NIM A 487, 407–422, 2002.

Campana, D., Barbarino, G., Boscherini, M., et al. The Time-of-Flight System of the PAMELA Experiment. Proceedings of the 28th ICRC, pp. 2141–2144, 2003.

Galper, A.M., for the PAMELA Collaboration. Measurement of primary protons and electrons on the energy range of $10^{11}$–$10^{13}$ eV in the PAMELA Experiment. Proceedings of the 27th ICRC, pp. 2219–2222, 2001.

Pearce, M., Carlson, P., Lund, J., et al. The Anticounter System of the PAMELA Space Experiment. Proceedings of the 28th ICRC, pp. 2125–2128, 2003.