The Space-Borne INTEGRAL-SPI Gamma Ray Telescope : Test and Calibration Campaigns

Stéphane Schanne, Bertrand Cordier, Maurice Gros, Michel Mur, Sylvain Crespin, Serge Joly, Jürgen Knödlseder, Pierre Mandrou, Philippe Paul, Jean-Pierre Roques, Gilbert Vedrenne, Yves André, Marie-Anne Clair, Pascale Clauss, Robert Georgii, Giselher Lichti, Andreas von Kienlin, Pierre Dubath

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***Abstract*—The spectrometer SPI aboard the ESA INTEGRAL satellite, which will be launched in 2002, will study the gamma ray sky in the 20 keV to 8 MeV energy band. It achieves the excellent spectral resolution of about 2 keV for photons of 1 MeV thanks to its 19 germanium detectors. A coded mask imaging technique provides an angular resolution of 2°. An active BGO veto shield is used for the definition of the field of view and for background rejection.**

After integration and test at CNES in Toulouse, the flight model of SPI recently underwent a one month pre-launch calibration at the CEA center of Bruyères le Châtel, using an accelerator for homogeneity measurements and high activity radioactive sources for imaging performance measurements.

This paper presents the scientific goals and the different detector components of SPI and reports on the test and calibration campaigns. The methods used to achieve good timing alignment using the Digital Front End Electronics are described and the first detector performance and imaging capabilities are presented.

I. THE INTEGRAL SATELLITE

THE International Gamma Ray Astrophysics Laboratory INTEGRAL [1] was selected in 1993 by the European Space Agency (ESA) as the next gamma astronomy mission in the 15 keV to 10 MeV energy domain, successor to NASA's Compton/GRO and the Russian/French GRANAT/SIGMA missions.

INTEGRAL's scientific goals [2] cover a wide range of astrophysics topics, like the study of :

- Nearby supernovae, if such star explosions should occur during the mission's lifetime.
- Stellar nucleosynthesis, with detection and cartography of short-, medium- and long-lived key nuclides like ^{56}Co, ^{44}Ti, ^{26}Al and ^{60}Fe.
- Structure of our galaxy, including a regular galactic plane scan for the detection of transient sources and for detailed studies of the galactic center.
- Compact Objects, identification of high energy sources, particle acceleration processes and extra-galactic gamma ray astronomy.

The key parameters of INTEGRAL in order to reach these goals are :

- Energy resolution of about 0.2%, and narrow-line sensitivity of about 5 10^{-6} photons $s^{-1}cm^{-2}$ at 1 MeV for a 3σ detection after 10^6 s exposure time, achieved with the Spectrometer aboard INTEGRAL (SPI) [3-6].
- Angular resolution of 12 arcmin, achieved by the Imager aboard INTEGRAL (IBIS) [7].

INTEGRAL will be launched in October 2002 by the Proton launch vehicle of the Russian Space Agency from the launch site in Baïkonur (Kazakhstan). It will have an eccentric orbit with an apogee of 153000 km and a 72 h orbiting period. During its two (up to five) years mission it will be operated as an international observatory with 70% of the observing time allocated to external observers and 30% to the instrument collaborations.

II. THE SPECTROMETER ONBOARD INTEGRAL

The spectrometer SPI is built by an international collaboration of research institutes, with technical leadership by the French Space Agency CNES. It is 238 cm high and has a mass of 1300 kg (see Fig. 1).

The gamma camera is composed of a hexagonal array of 19 high purity germanium detectors covering an area of 500 cm^2 and kept at the temperature of 85 K by a cryogenic system. It

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Stéphane Schanne (corresponding author), chairman of the SPITOG (SPI Test and Operation Group), is with the Commissariat à l'Energie Atomique (CEA), CEA Saclay, DSM/DAPNIA/SEI, F-91191 Gif sur Yvette, France (fax: +33 169083147, e-mail: schanne@hep.saclay.cea.fr). Bertrand Cordier, Maurice Gros and Michel Mur are with the CEA Saclay, DSM/DAPNIA, France. Sylvain Crespin and Serge Joly are with the CEA Bruyères le Châtel, DAM/DPTA, France. Jürgen Knödlseder, Pierre Mandrou, Philippe Paul, Jean-Pierre Roques and Gilbert Vedrenne are with the Centre d'Etudes Spatiales des Rayonnements (CESR) Toulouse, France. Yves André, Marie-Anne Clair and Pascale Clauss are with the Centre National d'Etudes Spatiales (CNES), Toulouse, France. Robert Georgii, Giselher Lichti and Andreas von Kienlin are with the Max-Planck-Institut für extraterrestrische Physik (MPE), Garching, Germany. Pierre Dubath is with the Integral Science Data Center (ISDC), Versoix, Switzerland.

The SPI experiment is an international collaboration of the following research institutes: CESR Toulouse, France ; MPE Garching, Germany ; CEA Saclay, France ; University of Valencia, Spain ; GSFC Greenbelt, USA ; IFC/CNR Milano, Italy ; SSL Berkeley, USA ; CASS La Jolla, USA ; University of Louvain, Belgium ; University of Birmingham, UK ; CBK Warsaw, Poland. The SPI project is managed by CNES Toulouse, France. The SPI calibration site is located at CEA Bruyères le Châtel, France.

provides an energy resolution of about 2 keV for photons of 1 MeV and thus a sensitivity 10 times better than previous experiments. During flight, due to cosmic ray interactions in the germanium crystals, the resolution (thus the sensitivity) can be degraded. In order to repair the crystal structure, it is foreseen to heat the crystals up to 100° C for 24 hours and thus "anneal" the crystal defects.

A mask of tungsten blocks is placed 171 cm above the detection plane. The mask image projected onto the detection plane permits the reconstruction of the sky image with a ~2° resolution. The fully coded field of view of SPI covers 16°. In order to achieve a good imaging performance, the spectrometer takes subsequent images of the same field of view under a slightly different pointing angle. The spacecraft is therefore reoriented every 30 min using inertial wheels, according to a well defined "dithering" pattern.

For efficient background rejection the detector is surrounded by a massive anti-coincidence system (ACS) made of 91 BGO scintillation detector crystals viewed by photo-multipliers, and a 5 mm thick plastic scintillator (PSAC) placed below the mask.

A Pulse Shape Discriminator (PSD) provides online classification of the photons impinging on the germanium detectors. Above 300 keV the photon interaction is dominated by Compton scattering, identified as double pulse events. This allows rejection of single-pulse events coming mainly from background radioactive decays in the detector itself.

The Digital Front End Electronics (DFEE) provides event timing with 100 µs accuracy, event building and classification, event rejection using the anti-coincidence veto signal, and event counting and dead-time monitoring in order to determine absolute incident photon intensities.

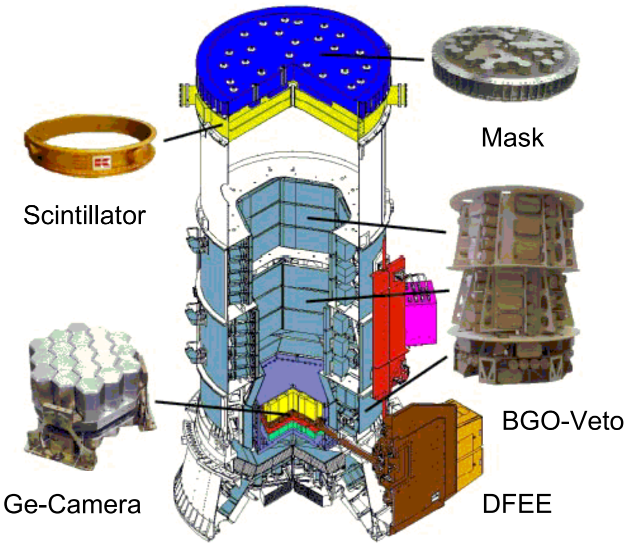

Fig. 1. View of the elements composing the Spectrometer (SPI) aboard the gamma-ray astrophysics satellite INTEGRAL.

The SPI flight model was fully integrated and tested between September 2000 and March 2001 at CNES in Toulouse (France). The scientific performance tests showed that the instrument meets its design goals. The precise timing alignment within 50 ns of the 19 detector channels with respect to the Pulse Shape Discriminator and Anti-Coincidence signals was successfully performed using the built-in test mechanisms of the Digital Front End Electronics. During the thermal vacuum test campaign, the instrument was operated under close to space conditions. During April 2001, the SPI flight model was calibrated on ground before its delivery to ESA.

III. THE SPI DATA ACQUISITION SYSTEM

Each of the 19 Ge-detector crystals is subject to an electric potential of 4000 V between the outer side of the crystal and the central anode (equivalent to a reverse-biased diode). An impinging photon extracts from the valence band of the semiconductor one or more electrons, which migrate in the electric field, inducing an electrical current in the anode. This analogue signal is amplified and filtered by the Analogue Front End Electronics (AFEE) and sent to the PSD for pulse shape analysis (see Fig. 2). Synchronously with the event, a Time Tag signal is sent to the Digital Front End Electronics. In the AFEE the analogue signal is then integrated and converted by an ADC system to a 15-bit numerical value (1 bit for low or high energy gain classification + 14 ADC bits) and sent asynchronously after about 27 µs to the DFEE via a serial transmission protocol.

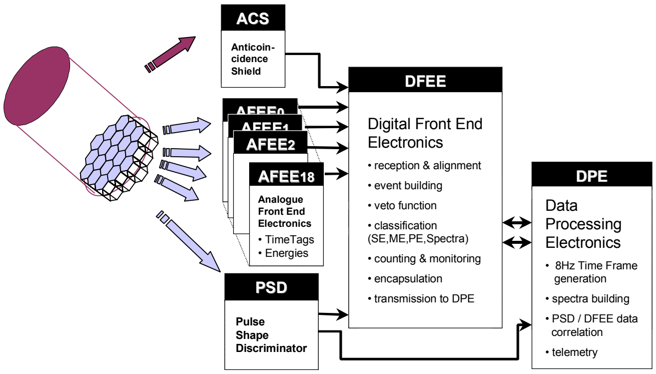

Fig. 2. Architecture of the SPI data acquisition system.

The front stage of the DFEE (see Fig. 3) receives the ACS veto signal, the 19 Time Tags sent by the AFEE and a Time Tag sent by the PSD for every analyzed event. Each signal is delayed internally by a time value configurable in steps of 50 ns. The veto signal length is compared with a configurable threshold value. A signal above threshold is generated when a high energy event saturates the ACS. In order to guarantee the veto function while the ACS is blind, this veto signal is extended in time by an appropriate configurable value. Below the threshold, the veto signal length is also extended by a smaller configurable value, as a compromise between good veto efficiency and low ACS dead-time.

The output signals of the DFEE front stage are used by the association machine of the DFEE, in order to perform the event building. A Time Tag is considered as a Single Detector Event (SE) if no other Time Tag is following within the duration of a configurable “association time window”. The event is a Multiple Detector Event (ME) if a subsequent Time Tag arrives before the closure of the “association time window”, launched by a previous Time Tag. A SE with one PSD-Time Tag arriving during the “association time window” is considered as a Single Detector Event with PSD information (PE). The absolute time of an event classified as SE, ME or PE is measured by the DFEE in units of 102.4 µs with respect to an onboard 8 Hz clock. Within a ME the time between subsequent Time Tags is measured in units of 50 ns. For a PE in a special timing mode the time between the AFEE Time Tag and the PSD Time Tag is measured with a precision of 50 ns. All events are stored into an internal FIFO, in order to wait for the arrival of the numerical values of the energies determined by the AFEE, after which they are extracted from the FIFO and written to output tables together with their energy values. Those tables are handled in a dead-time free double buffer mode and sent on the basis of a time frame defined by the onboard 8 Hz clock to the Digital Processing Unit (DPE). The DPE assembles the PE information with the result of the PSD analysis and sends the resulting stream to the satellite telemetry down-link system.

The high speed data processing of the DFEE is entirely handled by a digital ASIC [8-9] designed at CEA Saclay and built by TEMIC/Atmel in a radiation tolerant CMOS technology required by the space environment (maximal integrated dose 30 krad).

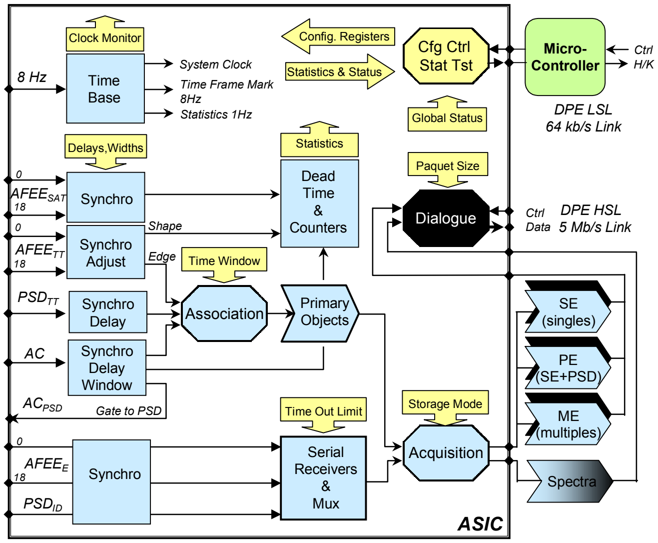

Fig. 3 : Block diagram of the digital DFEE-ASIC.

IV. SYSTEM TIMING PERFORMANCE TESTS OF SPI

After complete assembly of the SPI flight model, system level tests were performed at CNES in Toulouse during December 2000 and January 2001, where all flight model components worked together for the first time. A series of tests procedures were performed as previously defined using the SPI engineering model. Since each of the active subsystems (camera, ACS, PSAC, DFEE, PSD) had been previously tested on their standalone test-benches, the aim of the system performance tests was to check the interoperability of the components.

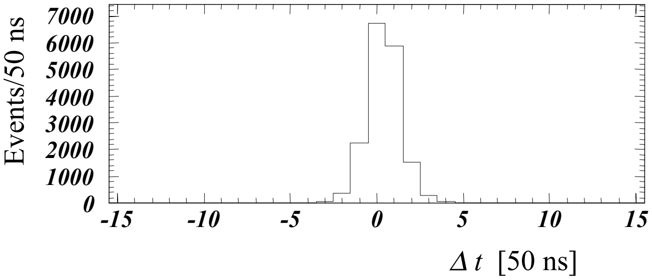

Fig. 4 : Timing alignment of detector n°14 and n°15 in units of 50 ns.

One major test was the check of the timing alignment at the level of the DFEE association machine, where the event building is performed. The delays of the DFEE input stage must be adjusted such that Time Tags issued by two detectors, but corresponding to a same physical event, arrive simultaneously at the association machine input. Such an event can be a photon of energy E impinging on detector i, interacting with an electron by Compton scattering (thus issuing a Time Tag i and an energy measurement E_i) with the re-emission of a secondary photon of energy E_j which will be absorbed completely in an other detector j (producing a Time Tag j). Such an event is classified as a ME (double event) with time difference Δt_{ij} (measured at the association machine in units of 50 ns) and energy information E_i and E_j. The physical scattering is much faster than the electronics time resolution, however, each electronic chain i and j has its own systematic and random delay. The systematic delays have to be compensated by the adjustable delays in the DFEE front stage, such that both Time Tags i and j are in time at the DFEE association machine (zero mean value for Δt_{ij}). The “association time window” has to be adjusted in order to cover the random delay excursions (width of the Δt_{ij} distribution). The measurement was performed with a ^{22}Na source. The timing alignment of the detectors was verified to be within 50 ns, selecting events for which E_i+E_j are in the 1275 keV photo-peak of the source (Fig. 4). The measured jitter in the alignment allows us to set the “association time window” to 350 ns. The PSD Time Tag alignment was checked with respect to the AFEE Time Tags using PE with timing information Δt. This mode was foreseen at the time of design and was implemented in the DFEE ASIC.

In order to perform the alignment of the ACS gate with the AFEE Time Tags inside the DFEE, the DFEE was configured such that the veto function was switched off and the ACS signal was routed internally on the PSD Time Tag path. Thus every front edge of a veto signal is considered by the DFEE as if a PSD Time Tag occurred instead. In this way the association machine groups an AFEE Time Tag together with an ACS front edge, resulting in a PE event, with their time difference Δt measured by the DFEE. The timing alignment is performed with events from environmental radioactivity triggering both a Ge-detector and the ACS (Fig. 5). This can be checked again in space. We conclude that for an efficient veto function and a minimal veto dead-time, the length of the ACS veto gate must be 750 ns. This is done by setting the appropriate ACS veto extension in the DFEE configuration.

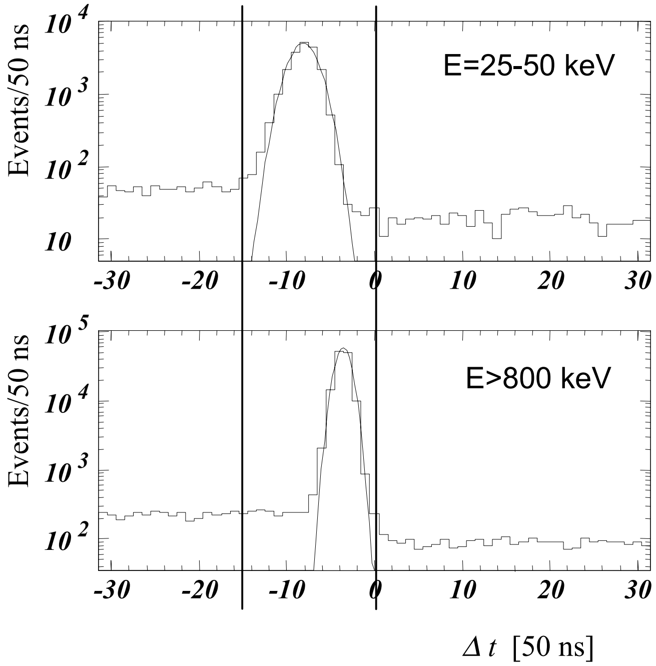

Fig. 5 : Timing difference between arrival of detector Time Tags and the front edge of the ACS gate in units of 50 ns. All ACS gates arrive before the detector Time Tags (peak at $\Delta t<0$). Time Tags from low energy photons arrive later than those from higher energy photons. Accidental hits in the ACS produce a flat Δt distribution with a higher level for $\Delta t<0$. In order to ensure an efficient ACS rejection the ACS veto gate width is set to 750 ns (time window within the vertical bars).

V. GROUND CALIBRATION OF SPI

The SPI ground calibration campaign took place during the month of April 2001 at the CEA center of Bruyères le Châtel (France) [10]. Preparations for the SPI calibration began in 1996. The CEA site of Bruyères le Châtel was selected since it offered the possibility to manipulate high activity radioactive sources as well as the use and modification of its accelerator complex. A clean room experimental hall with an airlock annex was built in order to accommodate the spatial equipment close to the accelerator. The infrastructure was ready for the calibration activity at the end of 1999.

The SPI arrived in Bruyères le Châtel on March 28, 2001. The calibration lasted for 21 days (including 108 h of accelerator measurements) and was operated continuously, with a turnaround of three shifts per day. 38 scientists from seven laboratories[1] contributed to the scientific shifts. The CNES participated in the SPI calibration with 14 people during installation and dismantling, additionally two CNES operators were permanently on call inside the CEA Bruyères le Châtel center. A representative of CEA Bruyères le Châtel was also permanently present. Data were transmitted in near real time to the Integral Science Data Centre (ISDC) in Vesoix (Switzerland).

The aim of this measurement campaign was to determine for the whole energy range of 20 keV to 8 MeV the detector efficiencies, the homogeneity of the detection plane, and the pre-launch imaging performance. Therefore a series of measurements was taken with sources at different angles of incidence and at distances of 8 m for the energy and efficiency calibration and 125 m for the imaging calibration.

For calibration SPI was installed with its optical axis in the horizontal position on a motorized mechanical ground support permitting a precise 360° rotation around the vertical axis and two positions around the optical axis of SPI, such that the sources could be seen by SPI at different angles (Fig. 6). In this way the whole field of view could be monitored and the spacecraft dithering simulated.

Fig. 6 : The spectrometer SPI is installed on its mechanical ground support in the clean room at the accelerator complex of Bruyères le Châtel, looking towards the high intensity sources.

The efficiency and homogeneity measurements in the energy domain below 2 MeV were performed using 11 different radioactive sources (each with an activity of about 8 MBq) producing photons in the range from 60 keV (^{241}Am source) to 1836 keV (^{88}Y source). In subsequent acquisition periods those sources were placed on the optical axis of SPI at a distance of 8 m. In order to illuminate all detectors uniformly the spectrometer's tungsten block mask was removed.

For efficiency and homogeneity measurements above 2 MeV the 4 MV-van de Graaf accelerator of the Bruyères le Châtel center was used in order to produce a high intensity proton beam (250 µA proton current) impinging on a water cooled ^{13}C target. A nuclear reaction in this target produces an excited state of ^{14}N, which decays and generates a set of photons of well known energies. During a first 36 h data acquisition period, protons of 1742 keV were used to generate photons of up to 9172 keV, resulting in narrow lines used for a precise energy calibration. In a second 36 h period, the proton beam energy was set to 550 keV and a different set of photons of up to 8062 keV was generated, with broader

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[1] CEA Saclay, CESR Toulouse, CNES Toulouse, MPE Garching, GSFC Greenbelt, ISNSM Orsay, University of Louvain.

lines but higher statistics, used for efficiency measurements. For these measurements the SPI had its mask removed and its optical axis formed an angle of 0° (and 8° in a second run) with respect to the target, placed at a distance of 8 m behind a plastic window, separating the accelerator hall from the experimental clean room.

Fig. 7: An artificial gamma ray "star" shines at the Bruyères le Châtel site on April 18, 2001. The ^{24}Na high activity radioactive source is ready for operation 125 m away from the SPI germanium spectrometer.

The measurements of the imaging performance were performed with the mask present, using high-activity radioactive sources placed at 125 m from the SPI on a dedicated alignment platform, situated on the Bruyères le Châtel site, outside the experimental clean room, which remained confined by a plastic window. At a distance of 125 m a source appears point-like for the SPI telescope with its angular resolution of 2° (FWHM). The photon beam was defined by dedicated source collimators, such that the cone diameter was about 4 m at SPI level. To verify the source alignment a monitoring tool, made of a NaI detector, mounted on an motorized X vs. Y arm, was placed in front of the SPI in order to obtain the horizontal and vertical beam profile at this position.

For an acceptable counting rate at the detector, a high source activity is needed. With the following 4 different high activity sources a large energy domain was covered: ^{241}Am (activity 3 Ci, photopeak energy 60 keV), ^{137}Cs (0.5 Ci, 661 keV), ^{60}Co (0.25 Ci, 1172 keV, 1332 keV) and ^{24}Na (0.08 Ci, 1370 keV, 2753 keV). The ^{24}Na source, with its short life time of about 15 hours was produced for this purpose in a nuclear reactor of CEA Saclay (France) for direct usage at the Bruyères le Châtel calibration site. Each source was shielded from the environment using a massive container (e.g. 550 kg of lead for the ^{24}Na source). The photon beam of each source was defined by a collimator equipped with a mechanical beam shutter. For security reasons the source operation (e.g. transportation, opening of the collimator) was performed by a dedicated team from CEA Saclay under supervision of the radio-protection team of Bruyères le Châtel, and the source zone was guarded. Additionally all the measurements using high activity sources were performed at night, when fewer people were present at the CEA Bruyères le Châtel center.

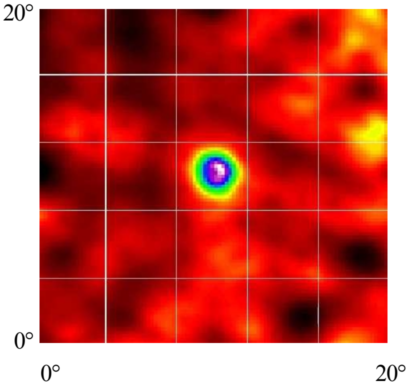

Fig. 8 : The first reconstructed image of the 2.7 MeV line for the high activity ^{24}Na source shows that an angular resolution of 2° is obtained with the mask imaging technique of SPI.

Interleaved with the imaging performance measurements (during daytime) low intensity 8 m-sources were used to illuminate the spectrometer in its flight configuration with the mask present. In dedicated acquisition periods the optical axis of SPI was oriented with respect to each source at different angles (varying between 0° and 360°). Incidence angles outside the field of view of the telescope are important for ACS leakage studies.

During the SPI on-ground calibration a total of 413 data acquisition periods in different configurations were recorded and are currently being analyzed. Fig. 7 shows as an example the installation of the high activity ^{24}Na radioactive source at 125 m from SPI on April 18, 2001, and Fig. 8 shows the corresponding reconstructed image of the 2.7 MeV line. It is the highest energy image so far obtained by a mask projection technique.

The SPI on-ground calibration ended 5 days before schedule on April 29, 2001, due to a power outage affecting the whole center of Bruyères le Châtel. The cryogenic system had been switched off resulting in a risk of detector pollution. Due to the tight delivery schedule, the decision was taken to perform a short (three days) out-gassing, but after this some residual pollution was still observed. Since no time was left to perform a complete out-gassing, the calibration was stopped at this point on May 2nd. The SPI was dismounted and shipped to Alenia in Turin (Italy), where a complete out-gassing was performed (five days at 70° C), after which the full detector resolution was recovered. The loss in measurements for the calibration program is insignificant. Only two off-axis periods of accelerator measurements for shield-transparency studies as well as half of the long exposures for continuum studies are missing.

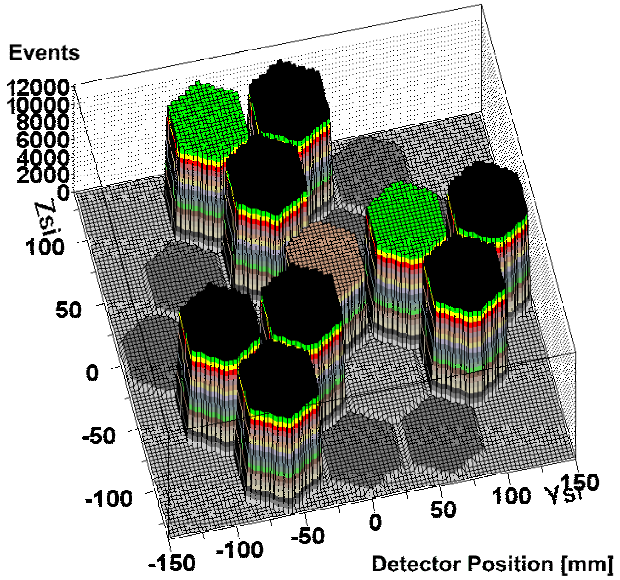

Fig. 9 : The pattern of the germanium detector counts produced by a ^{60}Co source at long distance and aligned on the optical axis of the spectrometer (1332 keV peak) reflects the pattern of the mask.

Quick-look analysis programs used during the runs for efficiency calibration confirmed the expected detector performance (Fig. 9 and Fig. 10). The understanding of multiple-detector interactions and of the impact of the anti-coincidence system have to be refined. First offline image de-convolution confirms the expected 2° angular resolution from the imaging runs. Full offline analysis of all measurements is in progress at the SPI collaboration institutes. One of the goals is to verify the response simulation based on the mass-model before the launch of the spacecraft.

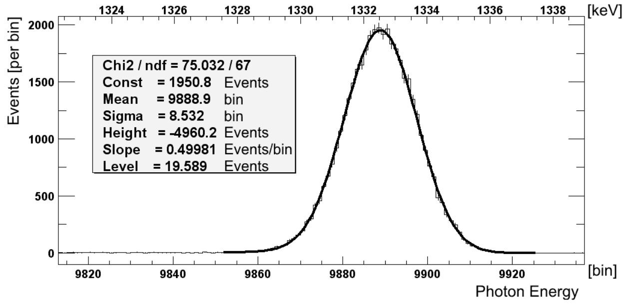

Fig. 10 : SPI Germanium detector energy spectrum for a short distance ^{60}Co source (upper scale: keV, lower scale: ADC bin). A resolution of 2.6 keV (FWHM) is obtained for 1332 keV photons, as expected. During this measurement session the pre-amplifiers where not at nominal but at room temperature. A thermal-vacuum test with cold pre-amplifiers has been performed previously and shows even better results.

A complementary calibration period, aiming at a determination of spacecraft effects and a cross-calibration between SPI and IBIS is planned at INTEGRAL level, during the end-to-end tests of the spacecraft at ESA in Noordwijk (The Netherlands) in February 2002.

VI. ACKNOWLEDGMENT

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