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Test with high-energy and high-intensity proton beam on ATLAS silicon detectors towards HL-LHC

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Summary. — The ATLAS silicon tracker was designed to sustain a high level of dose integrated over several years of LHC operations. The radiation tolerance should nevertheless guarantee the survival of the detector in the case of accidental beam loss. In 2006, an experiment performed on an ATLAS Pixel module established that they are able to sustain beam losses in the order of 1.5×10^{10} protons/cm^2 with a minimal or no performance degradation. Recently, a new experiment was performed with a higher-intensity and -energy proton beam on two IBL Pixel modules and one ITk strip in the HiRadMat area at CERN. Preliminary results are presented along with perspectives of 2018 test beams.

1. – Introduction

The aim of the experiment is to provide an estimate of the damage threshold of the ATLAS [1] inner detector sensors and electronics under fast extracted and intense proton beam irradiation.

The Pixel Detector [2] is the innermost component of the ATLAS silicon tracker detector and it is therefore located very close to the interaction region. The initial Pixel Detector (before the addition of the Insertable B-Layer) has been designed to face

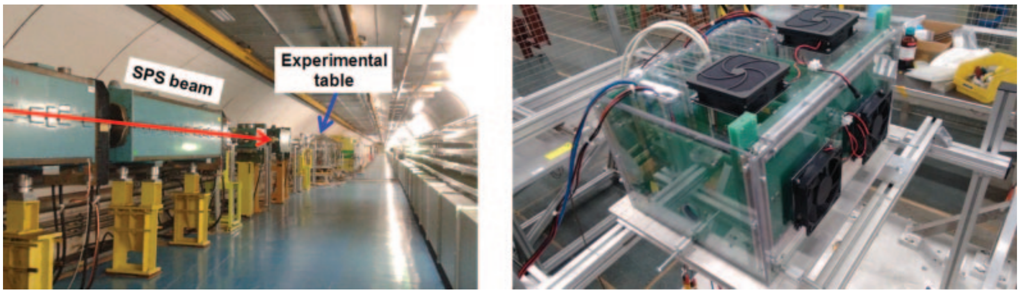

Fig. 1. – HiRadMat experimental area (TNC tunnel) and the test-box.

a Total Ionizing Dose (TID) of 50 MRad (expected at 300 fb^{-1}), a NIEL([1]) of 1×10^{15} 1 MeV n_{eq} cm^{-2}. The Insertable B-Layer (IBL) [3] is the current innermost pixel layer, it was added between the beam pipe and the Pixel Detector during the first long shutdown (2013–2014). In the IBL, two different silicon sensor technologies have been used: planar n-in-n and 3D with passing through columns. The IBL has been built to sustain high radiation levels, up to a NIEL of 5×10^{15} 1 MeV n_{eq} cm^{-2} and a dose of 250 Mrad. In 2023–2025, a third long shutdown will be necessary to upgrade the accelerator to the ultimate operation mode: the High Luminosity LHC (HL-LHC). A new Inner Tracker (ITk) is currently in development [4] for HL-LHC: new tests are required to probe the ITk Pixel and Strip sensors and electronics with high-intensity and -energy beams.

2. – HiRadMat facility and operations

High-Radiation to Materials (HiRadMat) [5] is a test beam facility at CERN, designed to provide high-intensity pulsed beams to an irradiation area where material samples can be tested. The facility uses the high-energy 440 GeV/c^2 proton beam extracted from the CERN Super Proton Synchrotron (SPS). Each pulse is made of 1 to 288 bunches, with 25 ns separation or higher. Two parallel tunnels host the beam line with the experimental tables (TNC tunnel, fig. 1) and the read-out system (TT61 tunnel).

The HiRadMat facility has been used to irradiate ATLAS silicon sensors in July 2017, a second test is going to be performed in May 2018. Two beam configurations were tested in 2017:

- 2 mm radius (global effects): 1, 4, 12, 24, 36, 72, 144, 288 bunches (5×10^{10} p);
- 0.5 mm radius (local effects): 1, 12, 72, 288 bunches (1×10^{11} p).

3. – Setup and devices

The experimental table held the ATLAS test-box (epoxy fiber glass, makrolon and aluminum) which was equipped with a cooling system (four fans $12\times12\,\mathrm{cm}^2$, fig. 1). The three tested modules are loaded on fiber glass frames within the test-box, perpendicular with the beam.

([1]) NIEL: Non-Ioninizing Energy Loss, where 1 MeV n_{eq} is the number of particles with a non-ionizing energy loss of a 1 MeV neutron.

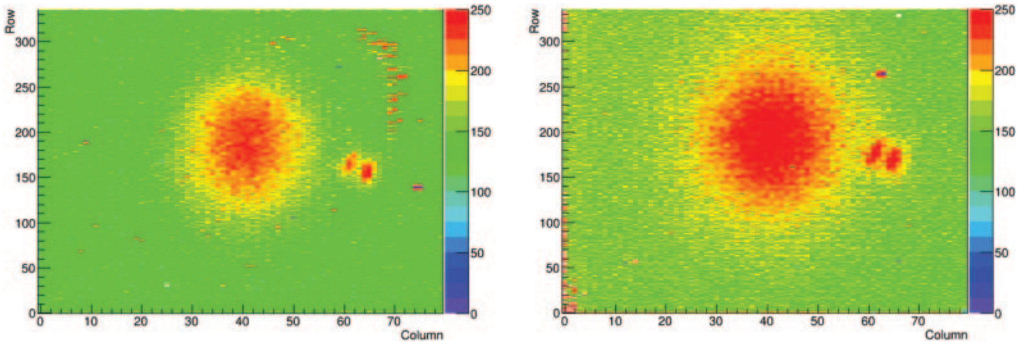

Fig. 2. – Noise maps obtained with threshold scan of IBL module 1 (left) and module 2 (right).

Two IBL modules with 3D silicon sensors [6] have been tested in 2017, at least a factor 5 more radiation-hard than the Pixel modules used in the 2006 experiment [7]. The new FE-I4 chip was designed to cope with higher radiation levels (250 Mrad). It has a total size of $20.2 \times 18.8\,\text{mm}^2$ (5 times larger than the FE-I3 used in Pixel modules) with 26880 pixel cells organized in a matrix of 80 columns ($50\,\mu$m pitch) by 336 rows ($250\,\mu$m pitch). The ITk Strip module [8] tested in 2017 consists of two $1 \times 1\,\text{cm}^2$ silicon strip sensors (ATLAS12) wire-bonded to a readout chip (ABC130). A total of 104 strips ($74.5\,\mu$m pitch in 2 rows) are included with Punch Through Protection (PTP) structures. In 2018, one IBL module with planar silicon sensor and two ITk Strip modules (with and without PTP) will be tested, with similar beam configurations.

During the 2017 operations, the IBL module configuration was lost after each pulse, but the normal detector operation was recovered with a reconfiguration. The last 288 bunches shot with 0.5 mm radius caused a short in FE at pixel level in both IBL modules: from that moment, it was not possible to send the configuration to them. After the beam passage, the material activation was visible in correspondence of the beam impact region on the IBL modules, performing self-triggering scans.

4. – Preliminary results

The noise maps obtained with Threshold scan are shown in fig. 2 for IBL modules 1 (left) and 2 (right): in both IBL modules, the noise increases in correspondence of the beam spot.

In fig. 3 we show the increase of the leakage current with global irradiation (2 mm radius) monitored on the ITk module. The increment of leakage current follows the increase of the beam intensity. No drift of leakage current was visible, even after 288 bunches.

5. – Conclusions

After the last shot (288 bunches narrow beam) the FE-I4 was irremediably damaged for both IBL modules. The problem seems to indicate the presence of a short circuit between ground and analog voltage in the FE-I4 read-out chip in the incident beam region. The lower limit for IBL modules on radiation damage has been evaluated at $\sim 10^{13}$ MIPs/cm^2 for the 288 bunches wide beam. The ITk Strip modules are able to drain

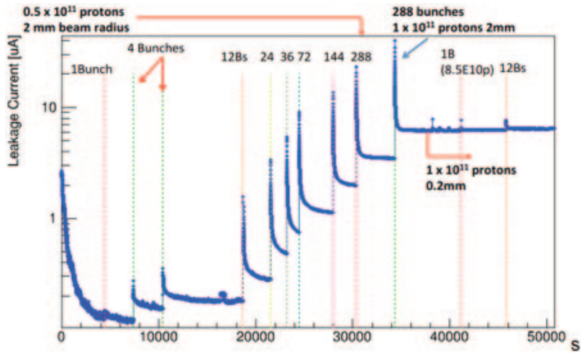

Fig. 3. – ITk strip module leakage current.

the charge density generated in the bulk without evident radiation damages. New tests are planned for 2018 on different modules with an improved control on the temperature of the box (below 40 °C) and with full readout monitoring of the ITk Strip sensor.

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