A High-Efficiency and High-Resolution Straw Tube Tracker for the LHCb Experiment

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***Abstract*— The Outer Tracker detector for the LHCb experiment at CERN will provide accurate position information on the charged particles in B-decays. It is crucial to accurately and efficiently detect these particles, in the high-density particle environment of the LHC. For this, the Outer Tracker is being constructed, consisting of ∼55,000 straw tubes, covering in total an area of 360 m^2 of double layers. At present, approximately 90% of the detector has been constructed and fully tested. In addition, a beam test has been performed at DESY, Hamburg, to validate the final read-out electronics, in terms of efficiency, position resolution, noise and cross talk.**

***Index Terms*— LHCb, gas detectors, straw tubes.**

I. Introduction

The LHCb experiment is a single arm spectrometer, designed to study CP violation in B-decays at the Large Hadron Collider (LHC), covering the range $1.8 < \eta < 4.9$ in rapidity.

The tracking system of the LHCb detector is divided in a silicon detector close to the interaction region, a dipole magnet,

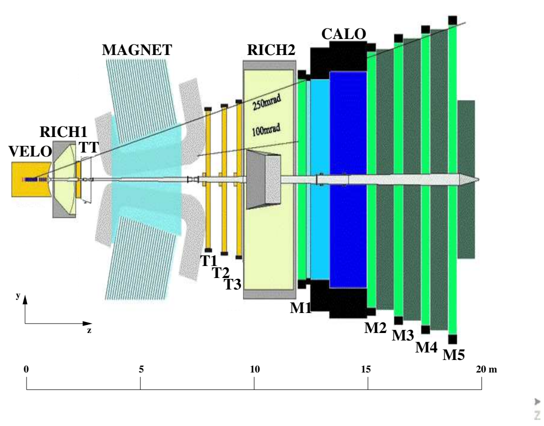

Fig. 1. A schematic picture of the LHCb detector. The T1-T3 stations consist mainly of the Outer Tracker.

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and a tracking system behind the magnet, see Fig. 1. By measuring the deflection of the charged particles by the magnetic field, the momentum of charged particles is determined. The tracking system behind the magnet is divided in two parts: a small silicon detector at high rapidity in the highest particle flux region, and a gaseous straw tube detector, the Outer Tracker (OT), covering most of the LHCb acceptance [1].

This paper describes the design and production of the OT detector, which is foreseen to be completed by the end of 2005 (Section II). Furthermore results on the quality assurance during production will be discussed (Section II). The performance of the OT in terms of efficiency, resolution, cross talk electronic noise has been tested in a beam test, using final read-out electronics (Section IV).

II. Design and Production

The OT detector is divided in three tracker stations, located down-stream of the dipole magnet. One tracker station comprises two vertical layers and two layers with a stereo angle of $\pm 5^o$ (x-u-v-x). A layer consists of 14 long F-modules (500×34 cm^2) and 8 short S-modules above and below the beampipe, see Figs. 2(a)-2(b). In total the OT contains 168 long F-modules and 96 short S-modules.

One F-module consists of two staggered mono-layers of 64 straws (see Fig. 2(c)), split in two in the middle, where they are electrically floating. The wires are read out at the two ends, resulting in a total of 256 channels per module. The anode is 25μm thick gold-plated tungsten wire, whereas the cathode is made of a carbon-doped (XC) kapton straw and aluminum at the outside for electrical shielding. The length of one straw is approximately 2.4 m, the inner diameter of a straw is 4.9 mm, and the straw-to-straw pitch amounts to 5.25 mm. In order to keep the wire in the center of the straw over the full length of the straw, two Noryl wire locators are placed at 80 cm distance. The baseline gas foreseen for the final detector operation is Ar(70%)-CO_2(30%).

At present 90% of the production has been completed, and it is foreseen to complete the full production by December 2005.

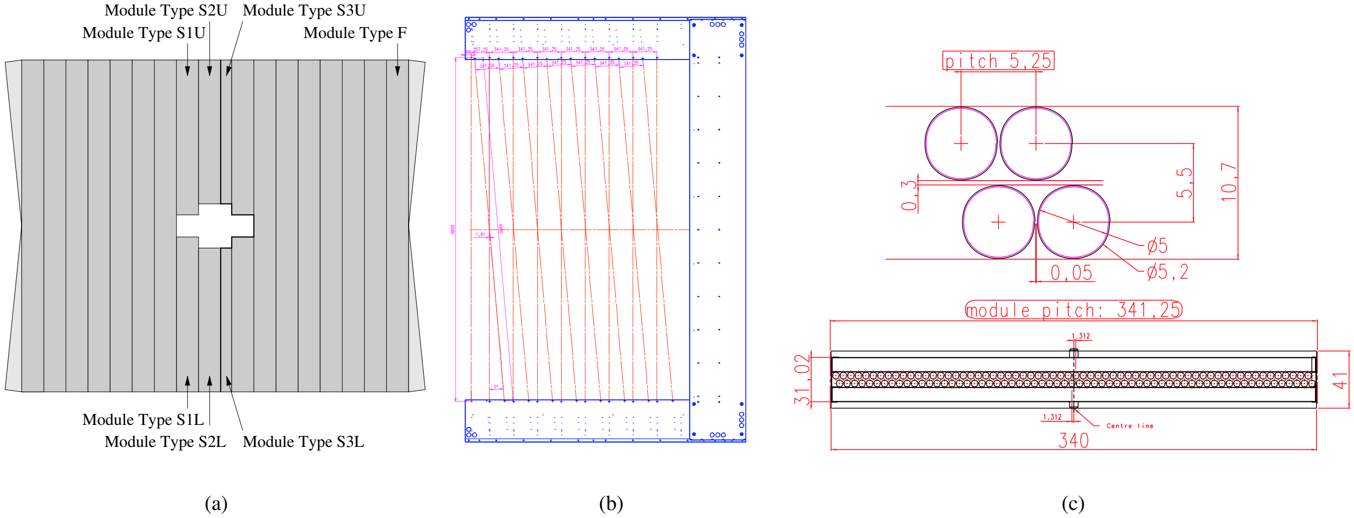

Fig. 2. The design of the Outer Tracker. (a) The front view of an entire tracker station. The full F-modules are located on the left and right of the beampipe, whereas the short S-modules are located above and below the beampipe. Around the beampipe LHCb is equipped with a silicon tracker. (b) The OT modules are mounted in a C-shaped aluminum frame, making a quarter station. Both a vertical and a stereo layer are hang in one frame. (c) One OT module consists of two mono-layers with 64 straws each.

III. Quality Assurance

During module production, stringent quality criteria were applied on the wire tension and HV behaviour of each single wire. After production, the gas-tightness of the entire module was checked, and the module was flushed with counting gas and the detector was put under high voltage for conditioning. Finally, the response to radioactive sources was checked for acceptance.

The wires were mounted with a nominal tension of 75 g, and were individually checked by sending a short pulse to the wire and detecting the oscillation frequency in a magnetic field. Wires that deviated by more than 5 g were replaced. Secondly, the dark current per wire was measured in air, and wires were replaced if the current exceeded 20 nA. Typically two wires per module were replaced. The final result of the wire tension and dark current of a set of 64 wires is shown in Fig. 3. Subsequently the two mono-layers were combined to form a gas-tight module. It is of crucial importance for the OT modules that the counting gas is preserved from contaminating elements. The impurities may enter the modules mostly through leaks. Therefore gas leaks have to be minimized. Both the overpressure decay and the gas leakage rate were measured when an overpressure of 7 mbar was applied inside the module. The module was considered gas-tight if less than 10% of the volume is lost per exchanged volume. This corresponds to a rate of approximately $1.8 \cdot 10^{-3}$ l/s at 7 mb, assuming an overpressure in the final detector operation of 1 mb. Most modules were gas-tight to 10^{-4} l/s, whereas only a few modules exceed the requirement.

Next, the module was flushed with the counting gas Ar(70%)-CO_2(30%) for approximately 12 hours, before the high voltage conditioning was started at 1600 V. Initially

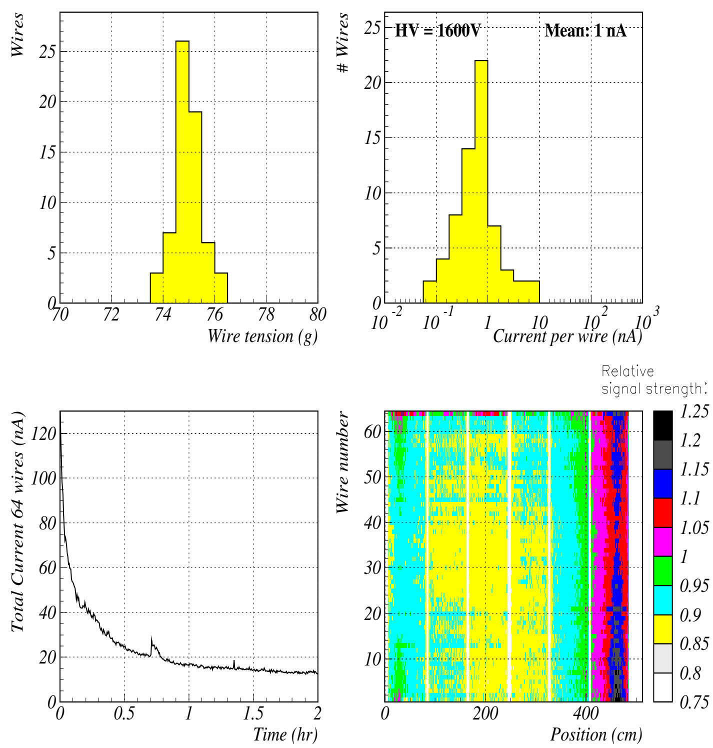

Fig. 3. The various steps in the quality assurance of the OT modules during production are shown. The distributions for the wire tension and dark current in air are shown for a group of 64 channels (top). Only a brief high voltage conditioning is needed to bring down the current of a group of 64 channels (left-bottom). A final validation of the module is done by means of a radioactive source: the response is very uniform, with the exception of a small area at the right of the plot, where the gas enters the module (drying). The plots correspond to a subset of the channels of a single module.

typical dark currents per wire below 1 nA were observed, but occasionally a wire showed a dark current in the order of a few tens of nA. The currents of all wires dropped below 1 nA after a short HV conditioning procedure of 1.5 hours.

Finally, the entire surface in pixels of 0.5 cm^2 for half of the modules of both module mono-layers was scanned with a 20 mCu ^{90}Sr source with the baseline gas mixture Ar(70%)-CO_2(30%), at 1600 V, to determine the uniformity of the response, see Fig. 3. The other half of the modules has been validated by analyzing the pulse height spectrum of ^{55}Fe. Defects of various nature like missing wire locators, poor gas flow, damaged wire surface or deformed straws could be detected. Apart from few initial modules, no module has been rejected. In total less than 0.1% of all channels exhibit a response deviating by more than 25% from the nominal value.

IV. Beam Test Results

In order to validate the combination of detector and frontend electronics, four mass-production S-modules have been tested with a 6 GeV electron beam at the DESY-II facility in Hamburg.

The front-end electronics embodies 8-channel amplifiers ASDBLR version 2002 [2] that amplify, shape and discriminate the charge pulse. If the pulse is above a threshold, the amplifier sends a LVDS differential signal used for the time measurement by the Outer Tracker Time Information System (OTIS) TDC [3]. Four ASDBLR amplifiers are connected to one OTIS TDC. The 32-channel OTIS TDC v1.2 measure the time of the discriminated signal from the amplifier with an accuracy of <1 ns with respect to the clock signal, which in this beam test was asynchronous with the beam. All drift-time data are digitized on board the frontend electronics and shipped out on an optical serial protocol by a radiation hard Gigabit Optical Link (GOL) chip.

The measurement of the detector parameters, such as efficiency and resolution, requires knowledge on the coordinate at which the beam particle traverses the detector plane. In order to have the possibility to independently measure track parameters, a silicon strip telescope was used. It consisted of three pairs (X and Y) of 32x32 mm^2, 0.3 mm thick, single sided silicon

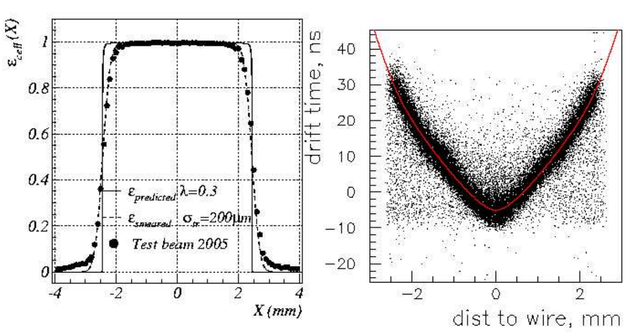

Fig. 4. The efficiency profile inside the straw is given. The efficiency is larger than 99% in the center of the straw, and drops of at the edge of the straw. The relation between the drift-time and distance to the wire is shown on the right. Note the maximum drift-time of approximately 45 ns.

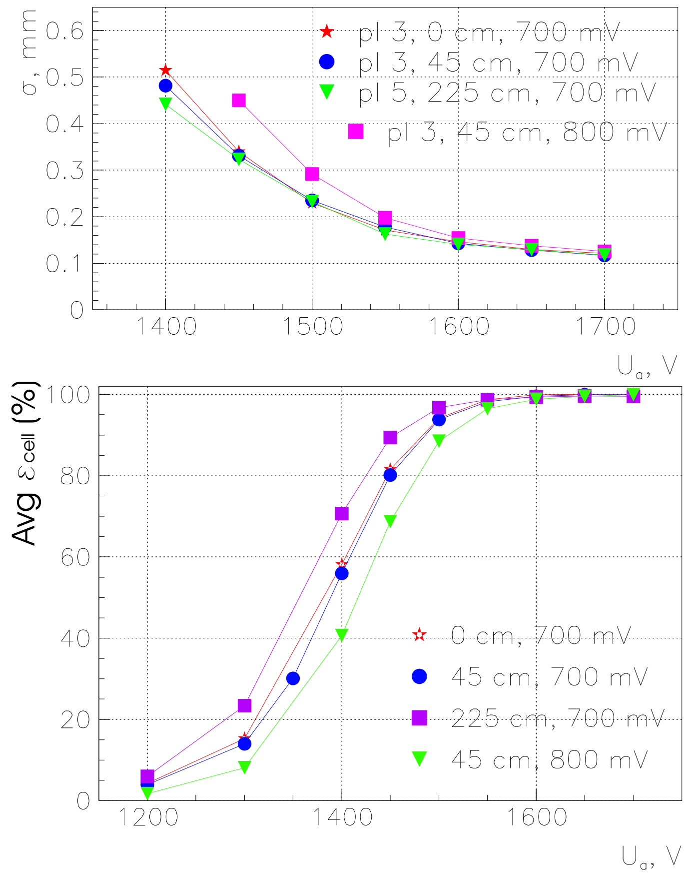

Fig. 5. The detector performance as determined at a beam test. Both the position resolution and the average cell efficiency are shown as a function of the high voltage value. The different curves correspond to different amplifier settings, and different distances of the beam to the amplifier threshold.

strip detectors, with 25 μm strip pitch and 50 μm readout pitch. The detectors were mounted inside light tight boxes with 30 μm thick Al windows.

On the other hand, the total number of OT modules (4 modules, or 8 monolayers) was sufficient to reconstruct tracks using the OT data only. Both studies were systematically compared, yielding identical results. The trigger signal, which served also as time reference, was produced by coincidence of two scintillator counters installed downstream of the OT modules. In runs with the Si-telescope included, additional small scintillation counters with a width of 9 mm and a thickness of 2 mm, mounted on the telescope support, were used in coincidence. The beam illuminated 2–3 straws per OT plane. When only OT modules were used, 5–7 straws were fully illuminated.

The analysis to estimate the performance of the OT detector and its readout electronics, consist of the following basic steps:

1) Attain the predicted distance of closest approach of the particle to the sense wire, obtained either by the silicon telescope or by the OT standalone.
2) Establish the relation between the measured drift time and the predicted distance to the wire, i.e. the rt-relation, see

Fig. 4.

3) Convert each measured drift time into position coordinate.

With the measured position coordinate in hand, the resolution of this measurement can be obtained by comparing it to the predicted position. The hit finding efficiency is attained by verifying whether the OT produced a hit at the predicted position. The efficiency as a function of the distance to the wire is shown in Fig. 4.

The performance of the OT has been measured for values of the high voltage ranging between 1200 and 1700 V, and of the amplifier threshold ranging from 500 till 900 mV, corresponding to 1.5 and 5.5 fC, respectively. The resolution is obtained by a single Gaussian fit to the residual distribution, and the required resolution of 200μm is achieved for high voltage values above 1550 V, see Fig. 5. The efficiency is defined as the average cell efficiency, i.e. the probability to find a hit in the straw where the track points to, or in one of its neighbours. As shown in Fig. 5, efficiencies close to 100% and position resolutions below 150 μm can be attained.

The electronic noise level was found to be low: e.g. at a high voltage of 1550 V and amplifier threshold of 800 mV (corresponding to 4 fC), the noise level is lower than 1 kHz. This translates in an occupancy of less than $7.5 \cdot 10^{-4}$, given the high LHC bunch frequency of 40 MHz.

The crosstalk between neighbouring straws was also quantified and is shown in Fig. 7. The probability to find a coherent hit in the neighbouring straw is lower than 5% for high voltage values below 1600 V and with a amplifier threshold of 800 mV (corresponding to 4 fC).

V. CONCLUSION

The production of the Outer Tracker detector modules for the LHCb experiment is expected to be finished by the end of 2005. The quality of the modules was closely monitored during production, resulting in an excellent performance with less than 0.1% bad channels over the full production.

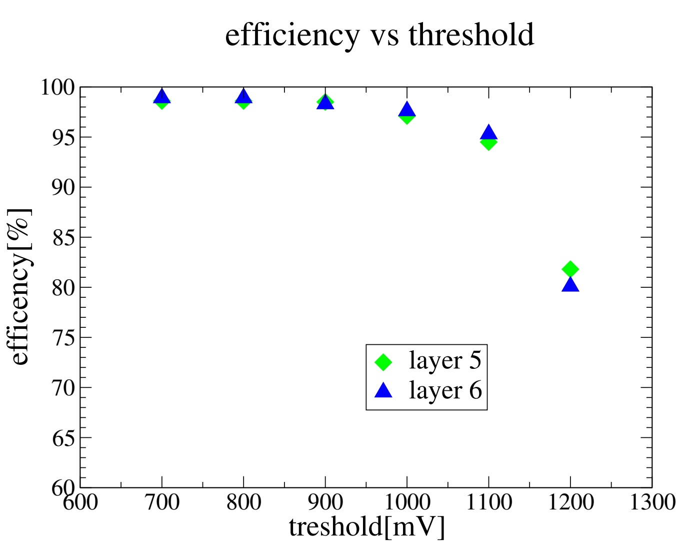

Fig. 6. The efficiency is shown as a function of the amplifier threshold. A threshold of 800 and 100 mV approximately correspond to 4 and 7.5 fC, respectively.

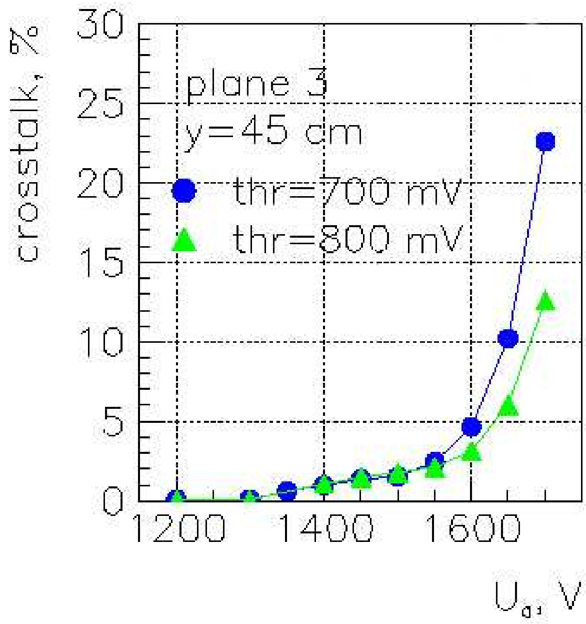

Fig. 7. The cross talk as a function of high voltage is shpwn, for two different values of the amplifier threshold.

Furthermore the performance of the Outer Tracker with final electronics has been determined at a beam test at DESY. A large parameter space between an anode wire voltage of 1500 and 1700 V, and amplifier threshold settings between 3 and 4 fC has been identified, yielding a hit finding efficiency over 98% and a position resolution better than 200μm.

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