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Upgrading the ATLAS Barrel tracker for the super-LHC

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On behalf of ATLAS ID collaboration

Abstract

It has been proposed to increase the luminosity of the Large Hadron Collider at CERN by an order of magnitude, with the upgraded machine dubbed Super-LHC. The ATLAS experiment will require a new tracker for this high luminosity operation due to radiation damage and event density. In order to cope with the order of magnitude increase in pile-up backgrounds at the higher luminosity, an all silicon tracker is being designed. The new strip detector will use significantly shorter strips than the current silicon tracker in order to minimize the occupancy. As the increased luminosity will mean a corresponding increase in radiation dose, a new generation of extremely radiation hard silicon detectors is required. An R&D programme is under way to develop silicon sensors with sufficient radiation hardness. New front-end electronics and readout systems are being designed to cope with the higher data rates. This paper discusses the challenges facing the sensors and the cooling and mechanical support. A possible tracker layout is also described.

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Introduction

The large hadron collider (LHC) started operation in 2008 and will be the world's most powerful particle physics accelerator when commissioned. The accelerator will have an initial luminosity of up to 10^{33} $cm^{-2}s^{-1}$, which will be increased to the peak luminosity of 10^{34} $cm^{-2}s^{-1}$ within 3 to 5 years. The luminosity of the LHC could be increased to 2 x 10^{34} $cm^{-2}s^{-1}$, after a first phase of machine upgrades, assuming the number of protons per bunch can be increased. For an increase in luminosity beyond this a significant upgrade to the machine will be required, known as the super-LHC (sLHC). This will deliver a factor of 10 increase in luminosity to 10^{35} $cm^{-2}s^{-1}$. The time scale for such a significant accelerator upgrade is driven by two major factors. The first is the fact that the LHC magnets will be damaged by radiation. Most significantly the quadrupole magnets at the interaction points (IR-Q magnets) will end their lives around an integrated luminosity of 700 fb^{-1}, corresponding to a date between 2014 and 2016 depending on the LHC's integrated luminosity. The second driver is the rate of accumulation of statistics in the physics analysis channels. After 5 years of operation, with only a nominal LHC luminosity, ALTAS will require a further 6 years of operation to halve the statistical error on its physics measurements. More ambitious LHC luminosity plans imply even longer operation times, of up to 8 years after 5 years of operation, to halve the statistical error. A significant luminosity upgrade to the sLHC is therefore proposed for the middle of the next decade. The increase in integrated luminosity extends the LHC discovery reach and makes additional and more precise measurements possible.

Such an increase of luminosity has two major impacts on the ATLAS experiment, namely: an increase of pileup events per beam crossing from 20 to 200, and an increase of total fluence of particles corresponding to the integrated luminosity increase. The detectors however must maintain their performance despite the increases of pileup events and particle fluence. To enable this a new phase of R&D has started within the ATLAS collaboration. This paper reports on the work being undertaken within the tracker community to replace the inner detector of the ATLAS experiment.

The ATLAS tracker upgrade

Due to the factor ten increase in pileup events the transition radiation tracker (TRT) will cease to work and will be replaced by a silicon microstrip system, resulting in a full silicon inner detector. To keep the occupancy below the 1% level, required for pattern recognition and momentum resolution of the traversing particles, the pixel system will be extended to a higher radius (27 cm is proposed compared to the present 15 cm), and the pixel size will be reduced from 50 x 400 μm to 50 x 250 μm. The present suggestion is to fill the remaining tracker volume with 5 silicon microstrips layers at radii of: 38 cm, 49 cm , 60 cm, 75 cm and 95 cm. For comparison, the present semiconductor tracker (SCT)[1] barrel consists of only 4 layers extending from a radius of 30 cm to 51 cm. The inner three layers are required, by occupancy considerations, to have short 24 mm long strips with a pitch of approximately 70 μm, these are known as the short strip layers. The outer two barrel layers, the long strip layers, will have strip detectors 96 mm long with a pitch of 80 μm. This design is expected to keep the occupancy below 1.6% at the innermost radius, which is considered adequate. The present proposal has a barrel of 200 cm in length for the short strips and for the long outer strips a barrel of 380 cm in length. The tracker will be completed with a set of disks arranged normal to the beam axis.

The pixels will cover an area of 5 m^2 and have 300 million channels, the short strips will cover 60 m^2 with 28 million readout channels, and the long strip detectors will cover 100 m^2 and have 15 million channels. This can be compared to 80 million channels and an area of 1.8 m^2 for the pixel detector and 6.3 million channels and an area of 61 m^2 for the SCT. This demonstrates the increase in engineering complexity that the sLHC tracker upgrade poses.

An all silicon tracker means that the neutron moderating effect of the TRT is not present. Therefore an additional 5 cm of polymer moderator installed at the outer radius of the tracker is required to reduce the back splashed neutron flux. The increase in particle flux, due to the increase in luminosity, will increase the radiation environment inside the tracker by roughly the same factor as the increase in luminosity. The inner pixel layer, at a radius of 5 cm, will have to survive a radiation fluence of 10^{16} 1 MeV n_{equ} cm^{-2} for the expected integrated sLHC luminosity of 2500 fb^{-1}, compared with 3 x 10^{15} 1 MeV n_{equ} cm^{-2} for the present pixel detector. The short microstrips are required to withstand 9 x 10^{14} 1 MeV n_{equ} cm^{-2} which consist of approximately 50% neutrons and 50% charge hadrons, while the outer layers will be exposed to up to 4 x 10^{14} 1 MeV n_{equ} cm^{-2} consisting of mostly neutrons. The outer layer's silicon detectors will therefore be similar in length and be exposed to a similar radiation fluence as the present SCT detectors. The increased radiation survival requirement for the short strip detectors has initiated a research and development programme on silicon microstrip detectors for ATLAS.

Silicon microstrip detector development

The present SCT detectors are fabricated from high resistivity n- float zone silicon with p+ implants defining the strips and a uniform n+ implant for the back side contact. Therefore the depletion region extends from the strips and holes created by ionization drift towards them. During irradiation defects are created in the silicon that turn the n- silicon into pseudo p- silicon. This has the effect of moving the maximum electric field to the back side n+ contact. As a consequence, to obtain full charge collection and minimize charge spreading over many strips, the detector has to be operated over depleted. With increasing radiation the effective doping density increases along with the full depletion voltage. At sLHC short strip fluencies it is no longer possible to fully deplete a 300 μm silicon strip detector. Therefore detectors with n+ implants defining the strips are required. To minimize fabrication and handling complexity p- bulk material is desired (forming n-on-p detectors) as this only requires a uniform back side implant, unlike n- bulk detectors with n+ strips which have backside guard rings. Electrons are collected on n+ strips which has a further benefit as electrons have an improved lifetime over holes as a function of radiation fluence.

Previous results[2], obtained within RD50, show that after a fluence of 10^{15} 1 MeV n_{equ} cm^{-2} a charge signal from a minimum ionizing particle of 8000 electrons is collected from a 300 um thick strip detector operated at 500 V. This implies an amplifier noise of 700 electrons and a discriminator threshold of 4500 electrons is necessary for the required signal to noise value of 10 which allows 100% detection efficiency. Stable operation of a large system of binary electronics with such a low discriminator threshold will be an engineering challenge. The signal could be further increased if a bias voltage above 500 V was possible, however at present this is excluded due to existing infrastructure.

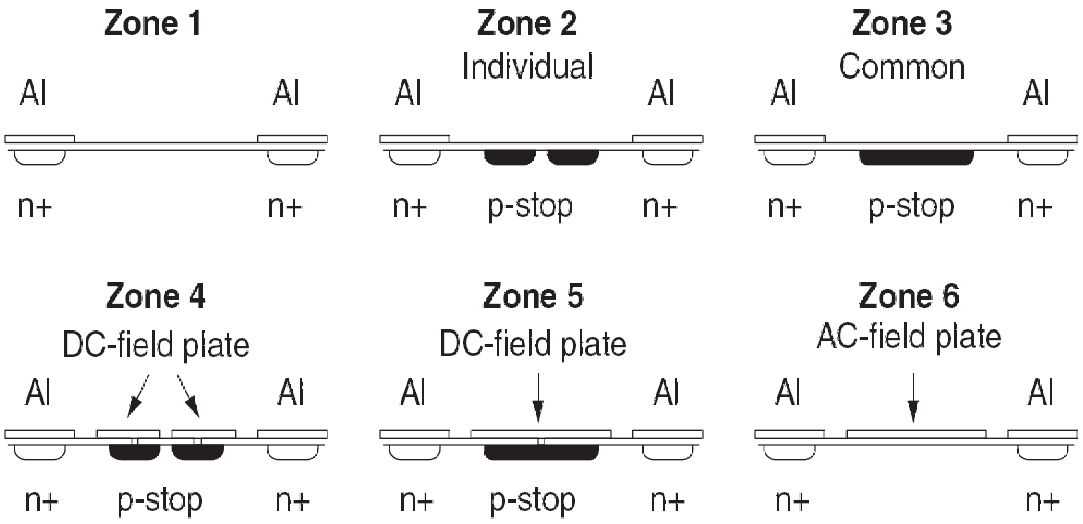

Fig 1: The 6 different miniature strip detector designs being investigated for the ATLAS silicon tracker upgrade

These measurements were made on sensors fabricated at small scale establishments. The upgrade, as with the SCT, will require a mass producer of detectors. To this end work is on going in ATLAS to develop an n-on-p strip detector process suitable to be operated up to 800 V at Hamamatsu, Japan. The present research programme includes 6 different miniature strip detector designs, which differ in their p-stop isolation between the strip implants[3], shown in Fig 1. With these sensors strip isolation, high voltage performance, punch-through protection and charge collection as a function of irradiation fluence will be investigated. These devices were fabricated with and without an additional p-spray doping. A full irradiation program has begun and the first results will be available soon. As well as the miniature devices large area detector have been fabricated which have 4 rows of 2.38 cm long strips with 1280 channels per row. These devices will enable yield and module design issues to be addressed.

Silicon strip barrel super-module design

The ATLAS tracker upgrade will have to be designed and built in a shorter time and with less money and people than the original SCT. This compressed time scale leads to a requirement for engineering designs that build on the present SCT and wherever possible simplify the engineering. To enable a faster barrel assembly with a higher possibility of module re-work the individual modules of the SCT will be replaced by small modules mounted onto a super-support structure that can be tested and assembled onto the barrel support cylinders as complete units. These will be installed from the end of the cylinder therefore enabling multiple barrel cylinders to be assembled before module installation begins. The super-support structure must hold the detector elements in a well defined and understood fashion, while supplying the services of cooling, power and communication. Recently the ATLAS collaboration reviewed the competing designs and proposed that the stave concept[4], based on the CDF upgrade stave, be pursed exclusively.

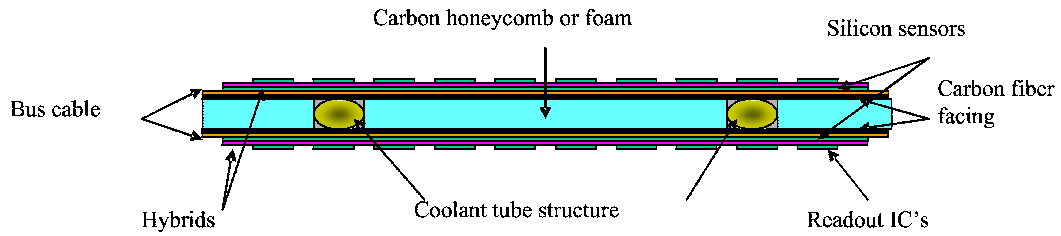

Fig 2: The Cross-section of the proposed barrel silicon strip stave

The stave, illustrated in Fig 2, consists of a carbon honeycomb structure with embedded cooling pipes. The honeycomb has a carbon fibre facing on each side for mechanical strength. On each side a bus cable is glued directly to this facing. On top of this the sensor is glued, and then the hybrids are glued directly on to the sensors. This gives the best possible thermal path between the heat sources (hybrid and sensor) and the cooling pipe while minimizing the material budget of the stave. The mechanics are significantly simplified over the present SCT barrel module which should enable a faster build. However, the radiation hardness of such a glued structure with n-on-p detectors is still under investigation. The stave consists of single sided detectors with the stereo sensors separated by a small gap in radius which is a function of cooling pipe diameter.

Summary

A possible layout for the proposed ATLAS tracker upgrade for the sLHC has described. The challenges facing the design of the silicon sensors of the tracker upgrade and the cooling and mechanical support of these has been reported.

Acknowledgements

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References

[1] A. Ahmad et al., Nucl. Instr. And Meth. A 578 (2007) 98.
[2] P.P. Allport et al. IEEE Trans. Nucl. Sci. 52 (5 III) (2005) 1903.
[3] Y. Unno, Nucl. Instr. And Meth. A 569 (2006), 41.
[4] J. Kierstad et al., Nucl. Instr. And Meth. A 579 (2007) 801.