Wire Scanner using Silicon Telescope: case study (preliminary)

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Abstract

An idea of using a silicon telescope in place scintillators to read the Wire Scanner signal is investigated. The performance of the silicon tracker modules needed in case of measurement of LHC beams is evaluated on the base of two examples: CMS pixel and ATLAS strip modules.

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1 Motivation

One of the main problems of the existing wire scanner systems is a precise control and measurement of the velocity of the wire. Usually this control is provided by resolvers. The signal used to reconstruct beam profile produced by the flux of secondary particles (proportional to the local beam intensity) is collected by simple scintillating detectors placed downstream the Wire Scanner.

In this paper a possibility of measurement of the wire position with use of a silicon telescope to reconstruct the vertex of interaction of the beam with the wire is investigated. The main advantage of this solution is that the problem of measurement of the wire position is handled by precise and fast silicon detectors therefore there is no need of a accurate tracking of the wire position by resolvers. This simplifies the construction of the mechanical part of the system. The same detectors are used to resolve wire position and to collect the beam profile signal.

Silicon telescope, more generally called a particle telescope, is a series of at least 3 silicon detectors pointing in the direction of the area crossed by the wire during the scan. The following parameters of the telescope should be estimated:

1. precision of the determination of the interaction point (in direction of the wire motion),
2. maximum dimension of the observed region,
3. feasibility.

The precision of the determination of the wire position is expected to be less than 10μm. The precision of the vertex location can be larger, but the procedure of reconstructing of the beam profile from many registered tracks provides better precision than reconstruction of a single vertex. The dimension of the observed region should correspond to the beam size and this varies from 1 mm (LHC beam) to more than 1 cm (PS beam). In case of modules discussed here it is of the order of the module physical size which is of the order of a few centimeters - sufficient to cover the largest beam sizes.

The most difficult requirement is to keep telescope occupancy at the level which allows to reconstruct single particles while having the good resolution of the wire position.

2 Silicon detectors

Different kind of silicon detectors have been created for use in particle physics and in industry. For Wire Scanner purpose five parameters are important:

1. pitch (distance between strips) or pixel size,
2. readout type (analog/digital),

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3. readout frequency,
4. radiation hardness,
5. price.

The two main types of Silicon detectors are pixels and stripes. Below two examples are discussed: CMS silicon pixel detector and ATLAS strip detector.

2.1 CMS pixel detector

The pixels detector used by CMS collaboration [1], have pixel size of 100×150 μm. One module sensor is segmented into 66560 pixels (160×416) read out by 16 ROC chips. The physical dimension of the module is 1.6×6.4 cm^2.

The module is read out with LHC clock of 40 MHz, but due to the dead time and the read-out time the maximal counting rate for a single pixel is 100 kHz. The module is capable to register many particles at a time. The readout is analog, therefore the particle position is reconstructed with use of information about signal height in all pixels. This leads to a very good position resolution. CMS pixel end-cap wheels, which are about 50 cm from the interaction region, are able to reconstruct transverse vertex position with accuracy of better than 20μm.

It should be noticed that the pixel module reconstructs the vertex position in two dimensions. Therefore a single wire passage through the beam would allow to reconstruct beam profile in both directions.

The CMS pixels are expected to withstand radiation dose of 1 MGy in two years of operation at high luminosity. The expected dose in the Wire Scanner position is about 1 kGy/year [2]. Therefore the CMS pixel detectors would fit the radiation requirement of LHC Wire Scanner. However it must be stated that in case of CMS the detector is kept in low temperature (-10 °C) in order to protect from thermal annealing which accelerate the irradiation damage.

From the above it can be concluded that Pixel detector fulfills most of the requirements of being use as a detector in a wire scanner system. The occupancy of the detector is estimated in Section 3.1.

2.2 ATLAS strip detector

Strip detector is made of silicon strips which are read-out at the border of the chip. The pitch in case of ATLAS SCT [3] the detector is 112μm and the size of every module containing 728 strips is 6.5×6.5 cm^2. The readout electronics work with 1 MHz clock, what means that it is capable to reconstruct 1 particle every microsecond. If more then one particle is registered in the detector during that time the reconstruction is usually ambiguous, ie. ghost hits are reconstructed. In order to reject this ghost hits ATLAS uses double-layer strip modules with second layer twisted by 40 mrad. This allows for resolution in the direction parallel to the stripes of the

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order of 2 mm, which is enough to reject ghost hits (if there are not too many hist at the same time) but is not useful to detect vertex position with enough accuracy.

The read-out of ATLAS SCT is binary ie. no information about signal level is transmitted. Only the occurrence of the signal above threshold is registered. The advantage of this solution is that the electronics works with nominal speeds and the amount of data transferred is relatively small, while in case of analog readout the electronics work on the limits of electronics frequencies what poses problems with synchronization of the data. The main disadvantage is worse, than in case of analog readout, precision of hit location and poor control of common noise.

Precision of vertex location from a single track in case of strip-based telescope is about 30μm, therefore is worse than in case of analog-readout pixels. The radiation hardness of the detector is similar to previous case with the same requirement of constant cooling to temperature of about -10 °C.

3 Expected particle flux

Geant4 has been used to simulate flux of secondary particles which are produced in the interactions of the beam protons with the wire material. In the following the carbon wire with diameter of 30μm is used.

In Figure 1 the angular distribution of fluence secondary particles is presented. for all particles (upper points), for particles with energies larger than 100 MeV (red points) and for particles with energies larger than 1 GeV (down points). The flux of secondary particles is dominated by slow energy electrons (see [4]).

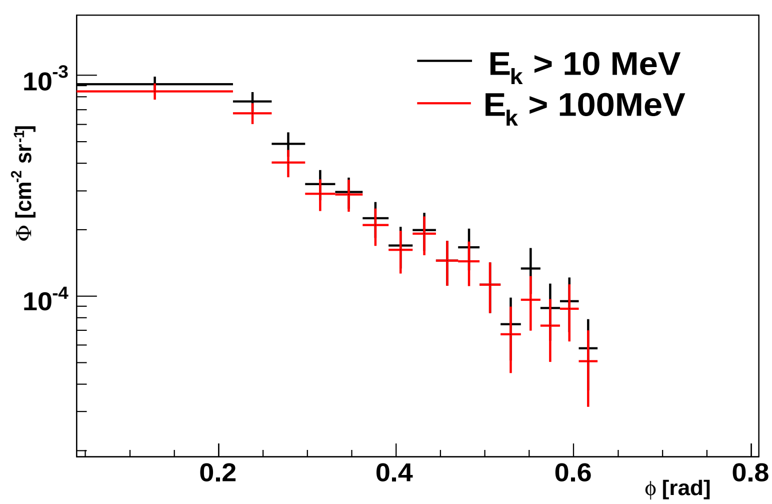

Figure 1: *The angular distribution of the total fluence of secondary particles. It is presented for particles with energies above 10 MeV (black marks) and for particles with energies larger than 100 MeV (red marks).*

In order to calculate the particle rate seen by the first module of silicon telescope, the flux of particles for a given location of the module (phi, r) must be found for the beam maximum which gives the maximum flux. For the wire passing by the beam center the amount of protons passing through in the unit of time is given by Equation 1.

$$\mathrm{R} = \frac{\mathrm{n_b} \cdot \mathrm{n_p}}{\mathrm{t_{LHC}}} \int_{-\mathrm{d}/2}^{\mathrm{d}/2} \exp(-\frac{\mathrm{x}^2}{2\sigma_\mathrm{x}})\mathrm{dx} \tag{1}$$

where: σ_x is the beam width in the direction of scan, $\mathrm{t_{LHC}}$ is the LHC revolution time, $\mathrm{n_b}$ is the number of bunches, $\mathrm{n_p}$ is number of protons in a bunch and d is wire diameter. For the nominal LHC beam this rate reaches maximum of about 10^{16} Hz. Now a two scenarios for CMS pixel and ATLAS strips are analysed.

3.1 Rate in CMS pixel detector

CMS pixels give very good vertex resolution even at distance of about 50 cm (distance to pixel wheels from IP in CMS). Therefore it is assumed that the first pixel module of the silicon telescope is placed 50 cm from the wire, at the distance of 5 cm from the beam axis(outside beam pipe). This localization corresponds to angle between beam axis and direction wire-detector of 0.1 rad (assuming wire position in the beam center). At this angle particles travelling to the detector pass though about 10 times more of beam pipe material (stainless steel) than in case of perpendicular particles. This stops particles in energy range 1-10 MeV and affects direction of particles with higher energies. The effect of the beam pipe on the detector resolution should be estimated. A use of low-Z material for the beam pipe, as in case of experiments, should be considered.

Fluence of particles produced per proton is read from Figure 1 and is about $5 \cdot 10^{-4}\ cm^{-2}sr^{-1}$. The surface of the pixel module is 10 cm^2 and placing it 50 cm from the wire corresponds to solid angle of $4 \cdot 10^{-3}$ sr.

The total rate of particles hitting the first detector of the telescope is:

$$\mathrm{R_{pix}} = 1 \cdot 10^{-5}\mathrm{cm^{-2}sr^{-1}} \times 10^{16}\mathrm{s^{-1}} \times 4 \cdot 10^{-3}\mathrm{sr} \times 10\mathrm{cm^2} = 4 \cdot 10^{11}\mathrm{Hz} \tag{2}$$

Even assuming equal distribution of the incoming flux on all pixels of the module the repetition rate in 6 MHz per pixel and this is 60 times more then maximum single pixel occupancy. As it is not possible to work with maximum occupancy then a factor 100 must be found by moving the telescope at larger distance (but this makes worse the resolution) and more distant from the beam (this has similar effect, as the angle of observation changes). The read-out electronics could be digital what could increase the single-pixel occupancy by almost factor 10. Also smaller size of pixels would help. The most easy to reduce it the wire diameter which might decrease particle fluence by a factor 4. Therefore it can be concluded that the CMS pixel detector, after some modifications, could withstand particle rates produced by the wire scanner.

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3.2 Rate in ATLAS strip detector

Following the same consideration as for CMS pixel detector we find rate in ATLAS strip module. The surface of the module ($6.5 \times 6.5 \text{cm}^2$) is 42cm^2 so it is 4 times larger than in case of Pixel module. Therefore the rate on the first plane of the telescope would be $R_{\text{strip}} = 1.6 \cdot 10^{12}$ Hz.

Assuming again that this rate is uniformly distributed on the module surface and that the flux should allow to perform 2-d reconstruction of the hit (at the level allowing to reject ghosts) it can be found that only about 25 hits can be reconstructed at a time. Therefore a single strip occupancy in case wire passing by maximum of the beam is 64 GHz which is 6400 times more than the maximum readout speed [1]. To overcome this difference an important technological has to be made.

4 Conclusions

The study shows that using advanced silicon detector technology (like CMS pixels) it becomes feasible to use a silicon telescope in the wire scanner devices. The rates achieved assuming nominal LHC beam and existing detectors are still to large to be accommodated by the electronics, but optimizing system for wire scanner use should make this application possible. Further studies concerning geometry of the telescope and accuracy of vertex location have to me made before proceeding with R&D in this direction.

The price of the wire scanner solution based on silicon telescope is not discussed here, but for the moment it is much higher than traditional solution. The technology of silicon strips which became relatively inexpensive in the last years, does not meet the requirements of the wire scanner system and use of more costly pixel technology is necessary.

Nevertheless the constant development of the existing technology leads to lower prices and in a few years a pixel-based wire scanner might became cost-effective method to measure the transverse beam profile. The attention should be kept on emerging technologies like diamond detectors and semiconductors based on GaAs, which offer promising parameters.

[1] The readout speed is not extreme for this kind of electronics, probably an improvement by a factor of a few can be achieved.

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References

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