Track Momentum Discrimination Using Cluster Width in Silicon Strip Sensors for SLHC

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Abstract

The cluster width of a particle crossing a silicon strip (mini strip) detector can be exploited to measure its transverse momentum when the strips are parallel to the B field. This suggests the discrimination of the clusters widths to filter the majority of low momentum particles.

Once performed directly on the detectors, such discrimination can be used both for low level trigger (L1) and for data reduction. This approach is discussed in the context of a first level trigger based on the Tracker for SLHC.

The quality of the measurements and their discrimination capability are discussed with respect to the geometry of the sensors and to the detectors layout. Electronics issues and constraints are also reviewed.

I. INTRODUCTION

At Super LHC, the increase of the luminosity to 10^{35} cm^{-2} s^{-1} implies 200 proton-proton interactions per bunch crossing, ten times more than those of LHC at the same frequency (40 MHz). As it is not excluded that the frequency is lowered to 20 MHz [1] we expect that the number of interactions per bunch crossing can be doubled. All this will imply the production of an enormous quantity of charged particles that will heavily engage detectors and read out system. But the large part of particles is due to background events, the so-called minimum bias events [2], while the events of interest are much more rare. Hence the necessity of new strategies for the first level trigger which, based on more exclusive signatures, limit the trigger rates and the amount of data transfers [3].

A challenging and promising improvement is to exploit the silicon tracker vertexing / tracking capability in the global L1 trigger decision. For this end ideas on next generation silicon trackers have being developed in CMS [4], [5], [6]. The present work sets itself in this research activity and can be integrated within another project [6].

The method here outlined is based on the use of silicon strip detectors of depletion thickness ≥200 μm and on the possibility of rough measurements of transverse momenta (p_T) of particles directly on the detector. The pitches are chosen from few tens up to one hundred microns and the detectors are placed in the barrel part of a tracker in presence of a strong magnetic field. As the rare events of interest have particles with p_T above several GeV/c and only ≈ 5% of the minimum bias particles have p_T > 2 GeV/c, we propose a real time discrimination of medium/high transverse momenta in order to transmit quickly their data outside the detector. The transmitted data are processed together with data coming from other detectors to search for correlations and signatures useful to the definition of the L1 trigger. The data of the large part of low p_T particles, if not to be rejected according to different requirements, are stored on the detector and wait for the L1 trigger acquisition command. This item is not discussed in this work that is focused instead on the p_T measurement and on the discrimination within a single strip detector. For what concerns the fast processing we limit ourselves to indicate as attractive tools the Associative Memories Devices that, successfully deployed in the CDF experiment [7], are discussed in reference [6].

The aim of the method is to bring outside the detector much of the real time processing so as to limit the complexity of the detectors, the power budget requirements and the high rate data links. The advantage of the external processing is to have as the only constraint the calculation speed. The detector complexity concerns the front end, the discrimination electronics and hence the number of strips. To emphasize the basic requirements of the discrimination method on a full-scale application we sketch a system of four barrel layers as possible part of the next CMS tracker. Three layers could be enough to recognize a high p_T particle but their efficiency could not be sufficient. Also the position of the layers can be changed. We have chosen a distance range so to have wide arcs of circumference as much as possible outside the high radiation critical region and to limit the strip specific capacitance without the use of thick sensors. We have not taken into account the Z coordinate resolution issue which, we estimate, could imply the doubling of the strip number on a couple of layers at least.

The present method of discrimination is applied to the barrel part of a tracker. With a suitable extension of the strip sensor concept it can be used with thinner sensors as well as in the end caps of the tracker, but this is not discussed here.

II. THE PRINCIPLE OF THE DISCRIMINATION

The barrel is the central part of the tracker around the Interaction Point of the proton beams. In the barrel the sensors are arranged in concentric cylindrical layers of finite length, which are coaxial with the beams axis (Z). The magnetic B field and Z axis are parallel. The helices radii of the minimum ionizing particles coming from the IP depend on the transverse momentum p_T, the steps depend both on p_T and the pseudorapidity η.

On the R-Φ plane, orthogonal to Z axis (Fig.1), the projections of the intersections (tracks) of minimum ionizing particles with a sensor layer have widths (TW) that depend on their p_T. TW depends also on R, the distance of the layer from the beam axis, and on ΔR, the thickness of the sensors.

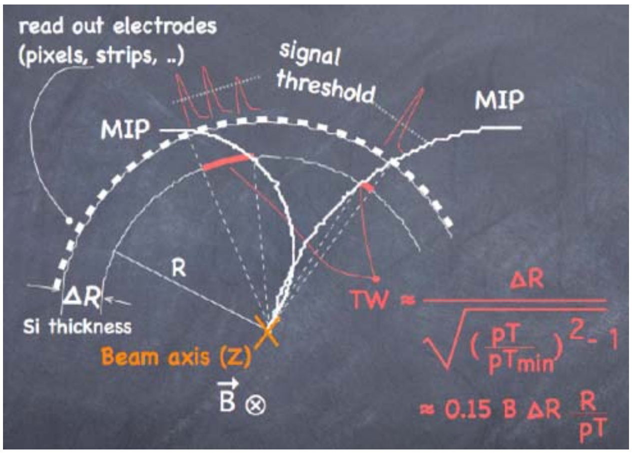

Figure 1: Ideal tracker barrel: R-Φ sector of a layer. The two MIPs have different Track Widths (TWs) depending on their p_T. Only MIPs with $p_T \geq p_{Tmin}$ reach the layer. The number of contiguous strips with signals exceeding "signal threshold" gives the measure of TW.

Assuming ΔR = 300 µm and B = 4 T (CMS), the track width values (TW0, Tab.1) are of the order of the strip pitches for p_T less than 2 GeV/c and layers above 30 ÷ 50 cm from the beams. This suggests choosing a suitable value for the sensor pitch so as to measure TWs in pitch units (cluster size) and to reject the largest clusters in order to select the few medium/high p_T particles among the large amount of low p_T minimum bias. The optimal pitch value depends on the radius of the layer and on the thickness of the sensors, but we will show that it is not a critical parameter.

Table 1: Track Widths (TW0/µm) of particles in a 4 T magnetic field and of different p_T passing through cylindrical layers of 300µm thickness at different radii (R).

pT /GeV/c \ R/cm	10	30	50	70	90
1	18	54	94	138	191
2	9	27	46	75	84
3	6	18	30	42	55
5	4	11	18	25	33
7	3	8	13	18	23
10	2	5	9	13	16

Actually Si sensors are flat and barrel layers are cylindrical assemblies of Si tiles which can be tilted around Z by an angle (α) either to partially compensate for the B drift or for a residual misalignment of the mechanics (Fig. 2). This makes the behaviour of TW more complex than in the ideal case. If we restrict ourselves to particles hitting the sensor near its centre (|X/R|<<1), TW can be approximated with a linear function of the X coordinate (Fig.3) with the slope sign depending on the charge sign and the intercept corresponding to the value of the ideal case of Figure 1. Also in this approximate condition p_T measurements become difficult to do but a rough separation between low p_T (< 2 ÷ 3 GeV/c) and the few higher p_T is still possible. This is just what we need to reduce considerably the amount of data to transmit outside the detector in real time.

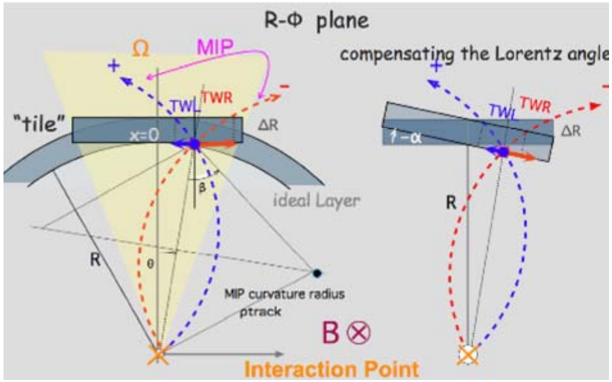

Figure 2: Real sensor of the barrel: TWs depend on the impact point (X), on the charge sign of the particles, on the tilting angle α of the sensor.

TW is not a pure geometric quantity. At a higher order it depends on the particle-sensor bulk interaction and on the electrical characteristics of the sensor. So effects as such diffusion, delta rays, strip coupling and noise can affect the actual value of TW. Also misalignments between B and strips can affect the track width. These contributions will be shortly recalled in the discussion to highlight their possible size.

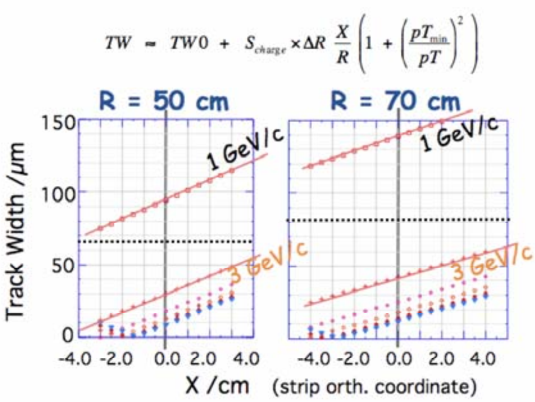

Figure 3: Track Width as function of the impact coordinate X ($\alpha = 0$) for particles of the same charge ($s_{charge} = +1$) passing through 300µm thick sensors at two different distances from Z. The wide separation between 3 GeV/c and 1 GeV/c allows discriminating between low and high p_Ts.

III. VALIDATION OF THE PRINCIPLE: SIMULATION

To verify the feasibility of the discrimination of medium/high p_T among all other low p_T, minimum bias particles have been simulated according to their p_T, η spectra at LHC/SLHC [8]. The particles are bent by a B = 4 T field and can reach Si flat sensors placed at distance R, in the pseudorapidity interval |η| < 1.5 corresponding to the 25 ÷ 155 degree angular range with respect to the beam direction (Z). Due to the radial symmetry of the particle production the simulation takes into account only one single string of sensors along Z. The magnetic field B, the beam axis Z and the strips are assumed to be parallel. Sensors are completely depleted.

The measurements of the track widths (TW) are performed comparing the signals of the strips with a constant threshold (Fig.1). The number of contiguous strips exceeding the threshold (Cluster) gives the TW measure. This algorithm is a simplified version of the one used for the cluster finding in strip sensors where the search is done using two thresholds at least, one for the "seed" strip, one for the next ones.

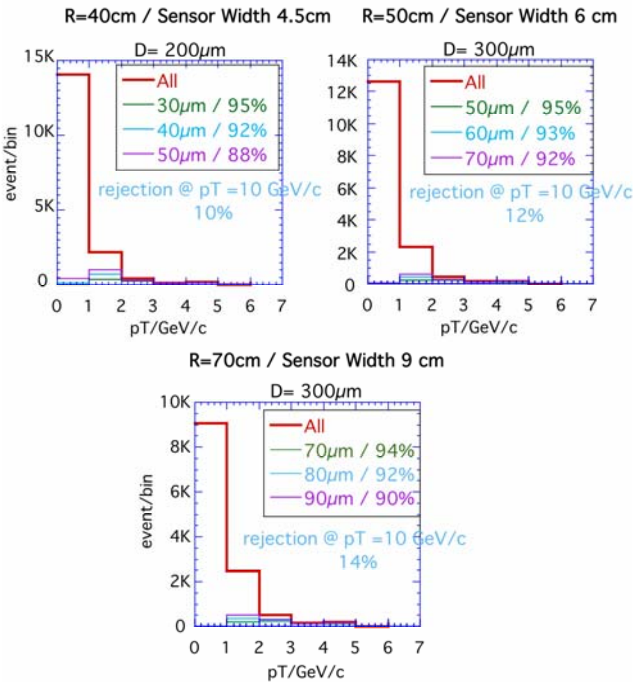

Figure 4: p_T spectra (thick red lines) of a minimum bias particles sample, in a 4 T magnetic field, through sensors of thickness D at different R distances. Thin lines show the spectra of "one-strip cluster" particles (4 σ_{noise} threshold) for different pitches and different total low p_T rejections. The rejections of p_T = 10 GeV/c particles refer to 40 µm, 60 µm and 80 µm pitches starting from R = 40 cm

The value of the threshold depends mostly on the noise of the signals but effects such as charge diffusion and strip capacity coupling can impose adjustments.

The simulation includes energy straggling and gaussian noise (S/N ≈ 20). It does not include diffusion, delta-ray production and strip coupling. The threshold has been fixed at 4 σ_{noise}.

The p_T spectra of a minimum bias particle sample when passing through sensors at different distances from the beam are shown in Fig. 4. It is clear the filter effect of the magnetic field. Selecting particles with TW = 1 strip ("one-strip cluster") we see that the spectra are heavily suppressed at p_T < 1 GeV/c and more or less suppressed at p_T < 2 GeV/c. This is what we expected in order to discriminate the few medium/high p_T particles among the large amount of minimum bias. The total rejection is good, of the order of 90% or better for particles mostly with p_T < 2 GeV/c, and it shows a good stability with respect to the pitch values which have been choosen in the range correspondent to p_T = 1 GeV/c and p_T = 2 GeV/c (Tab.1). Also the thickness of the sensors does not show drawbacks as well as their tilting of few degree (not shown here) is not critical.

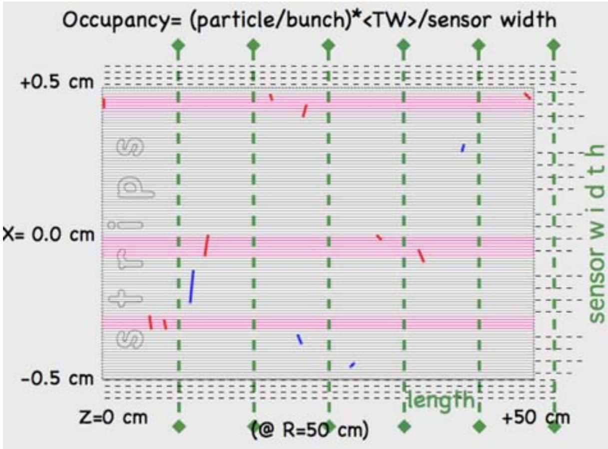

Figure 5: Occupancy formula and map of simultaneous tracks in a portion of the sensor string (-0.5cm < X < +0.5 cm, 0 cm < Z < 50 cm). The vertical broken lines mark the length of the sensors (strips) in the string and limit the shadow superimpositions.

The discrimination between low and medium/high p_T is not sharp, and it has a small tail at higher p_T according the (TW/pitch) ratio of the particle. This behaviour affects the efficiency of the search for medium/high p_T particles as indicated in Fig.4 in the case of p_T = 10 GeV/c. The effect is intrinsic to the "one-strip cluster size" selection and charge diffusion, capacitive coupling and misalignments can enhance it even if partially compensated by the choice both of the pitch and of the threshold. One way to cancel the effect is the use of smaller pitches and the selection of "two-strips" and "one-strip" clusters which implies an increase of the detector complexity (sensor + electronics). But we do not exclude other simple cluster recognition algorithms which, a bit more sophisticate than the simple width measurement, limit the increase of the sensor complexity while attenuating the inefficiency tail of the discrimination. However pros and cons of any choice must be evaluated in the light of a detector system.

Table 2: Statistics of the minimum bias tracks of the sensors strings of Figure 4 with the SLHC frequency of 20 MHz.

R/cm	<TW> /µm	Std Dev /µm	Occup./ΔZ /%/cm
40	173	419	0.32
50	300	702	0.30
70	380	1351	0.15

For what concerns the sensor geometry, while the width has the soft constraint of $|X/R| << 1$ as complied in Fig. 4, the length (strip length) must be chosen so as to keep the strip occupancy low and to limit shadow effects and hence inefficiency (Fig.5). The occupancy depends on the number of particles simultaneously impinging on the detector and on their track widths. It does not depend on the width of the sensor and on the number of its strips while it depends linearly on the length. At SLHC, assuming [2] the mean value of 36000 charged particles per bunch (20 MHz) and a magnetic field of 4 T, an occupancy < 2% requires strip lengths of ≈ 5 cm, at medium R distances, and ≈10 cm at higher distances (Table. 2).

IV. POSSIBLE BARREL LAYOUT (CMS)

Four layers of strip sensors are equipped to discriminate medium/high p_T as before described (Fig.6). The sensors, fully depleted, are 300 µm thick in the three external layers and 200 µm thick in the innermost one. The detectors reject $p_T \leq 2$ GeV/c particles and send the data (position) of the few "one-strip cluster" particles out of the detector for a quick, flexible and efficient search for the p_T measurement and correlations with other sub-detectors. The layers are equispaced and placed in the CMS barrel region from R = 40 cm to R = 90 cm (Tab. 3). Their length ranges up to 2 m, depending on the R distance, and their angular acceptance (η) is within the range ±1.5. The links for the real time data transmission are organized in Φ (Z) sectors each corresponding to a base independent processor unit outside in the barrack to speed up calculations. □□□ number of sectors expected may range between 50 and 100.

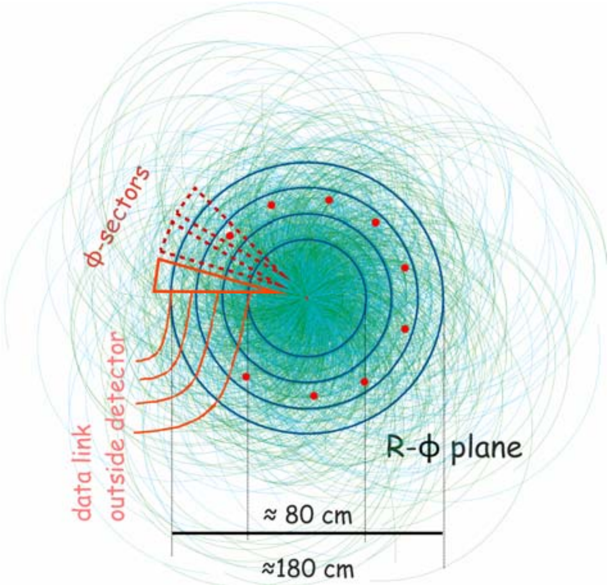

Figure 6: Sketch of the four barrel layers section superimposed to the charge particles produced during one bunch crossing at SLHC (20 MHz) in a 4 T magnetic field (CMS). The data transmission of each sector is addressed to its processor unit in the barrack.

According to our simulation the mean number of "one-strip clusters" per bunch crossing detected by the four layers is ≈ 1200 (Table 3). The number of hits decreases with increase of the distance R both for the η acceptance variation and the filtering action of the magnetic field. Since the rejection of the discrimination is ≥90% and the mean cluster width calculated is ≥5 strips, the total mean number of hits expected on the detectors is much higher, about 85000 hits. This gives an idea of how powerful the selection is.

The total real time transmission rate needed to send outside the 1200 hits is given by the formula "one-strip clusters" x 32 bit x bunch cross frequency which, at 20 MHz as SLHC frequency, gives ≤ 800 Gbps. This estimate is invariant with the SLHC frequency because it depends only on the beam luminosity. 32 bit/hit is a safe number of bits to encode the digital information of the hit, time stamp included. The number of optical links necessary and their distribution will depend on the characteristics of the link, on the geometry of the layer, on the sectors we want to use. Without entering into details we can get an idea of the order of magnitude with a simple exercise. Using the GBT chip transmitter [9] as a 2.5 Gbps unity and assuming a prudent factor 2 margin, the numbers quoted in Table 3 give a total of ≈ 600 GBTs which should mean few hundred watts of power to add to the overall power requirements (stored data transmission included). We find this first order evaluation very encouraging both for the power and the number of links.

Table 3: Main features of the four layers, minimum bias particle statistics (SLHC at 20 MHz, 4 T magnetic field) and data rate required for 1 strip cluster transmission. In the "strips" column the smaller factor is the number of sensors along Z (string).

R/cm	pitch/ µm	Total length/ m	strips	no. hits/ bunch (unsel.)	1 strip cluster/ bunch	Data/ layer/ Gbps
40	40	2x0.85	≈ 65K x 35	≈35K	≈550	350
57	60	2x1.0	≈ 60K x 40	≈25K	≈250	160
73	90	2x1.0	≈ 50K x 20	≈15K	≈250	160
90	90	2x1.0	≈65K x 20	≈10K	≈150	95
Total			**7.0 M**	**85K**	**1200**	**765**

But attention must be paid to the effective transmission bandwidth required. Our simulation analyses only strips involved by signal charges and ignores the noise of all the other strips the contribution of which can be critical for the transmission bandwidth, especially for the effects of non Gaussian tails and noisy strips. So the control both of the signal threshold and the comparator is crucial. This is sketched in Fig. 7 where the comparator is controlled by the enable input. Another crucial issue is the pedestal subtraction, the properties of which have a strong influence on the discrimination process.

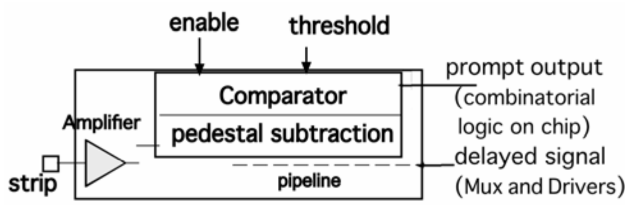

Figure 7: Block diagram of the channel electronics (strip). The amplifier output is connected both to the comparator/pedestal for the prompt output and to the pipeline for the delayed one.

Both the comparator and the pedestal circuitry receive the output of the amplifier. The result of the comparison is fed into the combinatorial circuitry on the detector (not shown in the figure) that recognizes the "one-strip cluster" and allows the position of the hit to be sent outside to contribute to the generation of the first level trigger. It is easy to think that a same combinatorial circuitry could support either the "one-strip" selection or the "two-strips" selection. With different cluster recognition algorithms we expect variations of the combinatorial circuitry and perhaps of the basic block of Figure 7.

V. CONCLUSION

The measurement of the track widths in pitch units in the presence of a strong magnetic field provides a simple and very selective criterion to recognize few high p_T particles from the huge amount of minimum bias low p_T ones. This allows to transmit outside in real time the track data useful for first level trigger with a modest requirement of the power budget and a small number of fibres. At medium/high distances from the interaction point the requirements on the geometry of the sensors are simple, the depletion thickness appears to be not a critical parameter going from 200 µm to 300 µm. As generally expected big efforts are required on the electronics (front-end, control, transmission..) which however concerns simple one-side detectors.

In the proposed tracker application (barrel), the large amount of channels imposes a good control of the signal threshold to limit the strip noise contribution and the bandwidth requirements. This can be seen as the price to pay to the simplicity of the detector structure and of the selection method. The same comment holds for the tail of selection inefficiency at the medium/high p_T which may be worsened by some cluster smearing effects. We have neglected them thinking to limit their contribution by choosing pitch and signal threshold. If such compromise is not acceptable, extension of the selection criterion to “two-strips cluster” seems to overcome the problem but the complexity and the power consumption are at least doubled as well.

The overall result obtained is good and we feel encouraged to refine the discrimination method in more details and to study possible evolutions of the algorithm without leaving the simplicity of the approach.

VI. REFERENCES

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