UNIVERSITÀ DEGLI STUDI DI MILANO

FACOLTÀ DI SCIENZE MATEMATICHE,
FISICHE E NATURALI
DOTTORATO DI RICERCA IN FISICA, ASTROFISICA E
FISICA APPLICATA. CICLO XVIII

A new micro-strip tracker for the
new generation of experiments at
hadron colliders

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Anno Accademico 2004-2005

*Io stimo piú il trovare un vero, benché di cosa
leggiera, che'l disputar lungamente delle massime
questioni senza conseguir verità nissuna.*

Galileo Galilei, *Opere*. Ristampa dell'Edizione
Nazionale, Firenze 1968, Vol. IV, p. 738.

*To Debora, Francesco, Giulia,
Alessandro and to the baby who
is coming to life.*

Acknowledgements

I wish to acknowledge Luigi Moroni, together with Daniele Pedrini, Dario Menasce and Silvano Sala, for giving me the opportunity to accomplish my Ph.D studies in their group (even after having flood the basement of their house); I really believe this Ph.D. was one of the best chance I have ever had. I want to thank in particular Luigi for having taught me so much and having accurately read and correct this thesis; he was a very careful tutor. I thank Dario since he was, together with Stefano Magni, my mentor in the software development. I also thank Silvano, with whom was very pleasant to work at Fermilab and, besides, for having taught me the backhand at tennis.

The persons more close to me while I was at Fermilab were Teresa and Pasquale D'Angelo. I really want to thank Pasquale, together with Silvano and Gianluca Alimonti, for helping me to perform some of the most interesting measurements reported in this thesis, and Teresa who was so friendly and helped me to feel at home even being so far from Italy.

I thank Sandra Malvezzi for every single chat we had, she always gave me the right suggestions and I believe she will always do.

I also thank Gabriele Chiodini who came with Pasquale, Silvano and me at IUCF and helped us to irradiate the Silicon micro-strip sensors; but even more I thank Gabriele for having brought me to visit some of the most interesting places of Indiana . . .

With Laura, Marco and Massimo I shared the three years of the Ph.D. We had lots of interesting discussions and I hope to work with them in the future.

I thank Francesca who worked with me during the last year of my Ph.D.

She was always so willing to learn; without her some of the extraordinary measurements presented in this thesis wouldn't be possible.

The last but, for sure, not the least I want to thank Lorenzo and Claudia. With them I spent the most agreeable moments at Fermilab; indeed they prepare the best barbeque I have ever eaten. In particular I thank Lorenzo for being extremely helpful at work and to be a very good friend.

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Introduction

This thesis concerns the development and characterization of a prototype Silicon micro-strip detector that can be used in the forward (high rapidity) region of a hadron collider. These detectors must operate in a high radiation environment without any important degradation of their performance. The innovative feature of these detectors is the readout electronics, which, being completely data-driven, allows for the direct use of the detector information at the lowest level of the trigger. All the particle hits on the detector can be readout in real-time without any external trigger and any particular limitation due to dead-time. In this way, all the detector information is available to elaborate a very selective trigger decision based on a fast reconstruction of tracks and vertex topology. These detectors, together with the new approach to the trigger, have been developed in the context of the BTeV R&D program; our aim was to define the features and the design parameters of an optimal experiment for heavy flavour physics at hadron colliders.

Application of these detectors goes well beyond the BTeV project and, in particular, involves the future upgrades of experiments at hadron colliders, such as Atlas, CMS and LHCb. These experiments, indeed, are already considering for their future high-intensity runs a new trigger strategy *a la* BTeV. Their aim is to select directly at trigger level events containing B -hadrons, which, on several cases, come from the decay of Higgs bosons, Z^0 's or $W^\pm$'s; the track information can also help on improving the performance of the electron and muon selection at the trigger level. For this reason, they are going to develop new detectors with practically the same characteristics as those of BTeV. To this extent, the work accomplished in this thesis could serve as guide-line for those upgrades.

I contributed to all the phases of this development, from the initial design to the final assembly of the prototypes and their tests. This included studies of the behaviour of the micro-strip sensors when exposed to the highly non-uniform irradiation expected in the forward region of a collider experiment. I also developed a method for their full characterization. The method allows for a complete bidimensional mapping, point to point, of the sensor characteristics over its entire active area. Information is gathered through the Q-V characteristic, measured scanning the sensor with an infra-red laser source. I built the setup that I used to perform the measurements on the Silicon micro-strip sensors, which I previously irradiated non-uniformly up to a peak fluence of $\sim 10^{14}$ 1 MeV equivalent neutrons per cm^2 . I developed an analytical model to fit the Q-V characteristics and extract the local full-depletion voltage and the local carriers trapping-time. With this method one can even obtain the profile of the absorbed dose. The description of the method is the subject of chapter 3.

I contributed to the definition of the design requirements for the readout chip of the detector and I certified, with simulations, the readout efficiency capabilities of the digital section at different luminosities. These measurements are reported in chapter 4.

Subsequently I prepared a test-stand at Fermilab and Milan by which I performed a complete characterization of the chip prototypes. The measurements I performed on the first version of the chip helped the electronics engineers to tune the design parameters for the second and last version. The characterization procedure was based on the measurement of the analog section linearity, the test of all the digital section functionalities, and the determination of the global performance of the chip in terms of gain, noise and threshold dispersion. These measurements are reported in chapter 4.

After having fully characterized the sensors and the chip, separately, and having understood their behaviour and performance, I assembled them into the Silicon micro-strip detector prototype which I characterized and calibrated with an Am^{241} γ -source. These measurements are reported in chapter 4.

The scientific community has already demonstrated interest for this detector design. Indeed, the collaborations of CBM (Compressed Baryonic

Matter experiment, at GSI) and PHENIX (Pioneering High Energy Nuclear Interaction eXperiment, at BNL) are considering the possibility of using it for their Silicon tracker. Both of them are experiments of heavy-ion physics that need a performant trigger based on tracking and vertexing, that could efficiently detect particular processes in a high-multiplicity environment. The detector I studied provides exactly those capabilities.

In chapter 1 I describe the BTeV experiment stressing its innovative features and presenting its extraordinary sensitivities. In chapter 2, as introduction to my study on radiation hardness, I report the most up to date knowledge on radiation induced damages in Silicon detectors. Concluding remarks on my work are summarized in the last chapter.

Challenges to the new generation of experiments

The increasing average number of charged tracks generated at each bunch crossing and the decreasing collision time, see Tab. 1, results in unprecedented data rates, see Tab. 2, and track multiplicities. At the same time the granularity of tracking detectors in HEP experiments has improved, as can be gauged by the very large number of channels which constitute the majority of the total number of channels of a HEP experiment, see Tab. 2.

Accelerator	Type	Luminosity [$10^{30} \text{ cm}^{-2} \text{ s}^{-1}$]	Collision time [ns]	# charged tracks
LEP	$e \rightarrow \leftarrow \bar{e}$	65	2200	~ 20
Tevatron	$p \rightarrow \leftarrow \bar{p}$	200	396	~ 600
LHC	$p \rightarrow \leftarrow p$	10000	25	~ 800

Table 1: *Luminosity, collision time and average number of charged tracks per each bunch crossing at the Large Electron Positron Collider (LEP), Tevatron and Large Hadron Collider (LHC) [1, 2, 3, 4].*

In the new generation of experiments at hadron colliders, highly sophisticated selection criteria, before storing data on archive, are required. Here the tracking system plays a crucial role. Tracking detectors, besides han-

dling an ever increasing number of tracks per unit time, are exposed to very high radiation levels.

Experiment	Accelerator	# channels	Data rate	
			Input	Output
Aleph, Opal L3, Delphi	LEP	$\sim 250\text{--}500$ K	~ 45 KHz	~ 15 Hz
CDF, D0	Tevatron	~ 1 M	~ 7 MHz	~ 50 Hz
BTeV	Tevatron	~ 23 M	~ 2.5 MHz	~ 2.5 KHz
Atlas, CMS	LHC	~ 100 M	~ 500 MHz	~ 100 Hz

Table 2: *Date-rate and number of channels per experiment.*

Information provided by the tracking detectors is usually used just in the off-line analysis programs, since, up to few years ago, it was practically impossible to perform track reconstruction and vertex finding in real-time at trigger level. Currently, with the improvement of the Application Specific Integrated Circuit (ASIC) technology, Field Programmable Gate Array (FPGA) and increased speed of networks it is possible to fully exploit this information at trigger level. The main physics motivations to use tracker information at the lowest level of the trigger are:

1. **identify special decay topology:** some particles produced during collisions, specifically D -hadrons and B -hadrons, have life-times of the order of picoseconds. In particular B -hadrons selection at trigger level is very important to tag the presence of several much heavier particles such as Higgs bosons, Z^0 's and $W^\pm$'s. Therefore a trigger based on impact parameter detection is a powerful tool for event selection
2. **improve calorimetric and muon measurements:** the reconstructed tracks matched with electromagnetic-calorimeter clusters can improve electron identification, as well as stubs in the muon system can ameliorate muon identification and momentum resolution

The R&D program carried out by the BTeV collaboration has addressed and resolved the crucial issues highlighted above.

Chapter 1

The BTeV experiment

The BTeV experiment was designed to challenge the Standard Model (SM) explanation of CP violation, mixing and rare decays of beauty and charm quark states (see appendix A) and find out what lies beyond the SM. In doing so, the BTeV results would also shed light on phenomena associated with the early universe such as why the universe is made up of matter and not antimatter. The interest on flavour physics and CP violation arises from:

- the observed baryon asymmetry of the Universe requires CP violation beyond the SM
- almost all extensions of the SM contain new sources of CP and flavour violation
- flavour physics and CP violation may help to distinguish between different models

Therefore the BTeV aim is not only to measure the CKM elements, but to over constrain the SM by many “redundant” measurements in order allow for detailed cross-checks.

The b sector is particularly interesting for the following reasons:

- all the three angles of the unitarity triangle involving the beauty quark are of the same magnitude, this leads to large CP violating effects
- some of the hadronic physics is understood model-independently ($m_b \gg \Lambda_{QCD}$)

- top quark loops are neither GIM nor CKM suppressed (large mixing, rare decays)

1.1 Physics motivation

BTeV is designed to run at the Tevatron in order to exploit the huge potentials on B production offered by hadron colliders. In the next sections will be described the physics motivation for the BTeV technical design.

1.1.1 B production at Tevatron

The Tevatron running at luminosity of $2 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$, produces 4×10^{11} b -hadrons per year of operation. Differently from b -factories that run at the $b - \bar{b}$ resonance $\Upsilon(4S)$, at Tevatron all B species, B_u , B_d , B_c , B_s and b -baryons are produced at the same time. The total cross-section is 75 mb, while the $b - \bar{b}$ production cross-section is 1/500 of the total cross-section [5, 6, 7], to be compared with 1 nb at b -factories. In Tab. 1.1 are summarized the Tevatron main characteristics.

Tevatron characteristics	Values
Luminosity	2×10^{32}
Interactions per second	15×10^6
$B - \bar{B}$ each 10^7 s	3×10^{11}
B events per background event	1/500 (only 1/500000 are “interesting” B decays)
Bunch spacing	396 ns
Luminous region length	$Z = 30 \text{ cm}$ (r.m.s.)
Luminous region radius	$\sigma_x \simeq \sigma_y \simeq 30 \text{ } \mu\text{m}$
Interactions per beam crossing	$< 6 >$

Table 1.1: *Tevatron main characteristics.*

The number of interactions per second results in a data volume that is too large to be stored on archives for analysis. The trigger must select from this huge rate the approximately 1000 events per second that contain B -

Figure 1.1: *Event containing a B -meson, that eventually decays into two particles, showing the significantly detached secondary vertex from the primary vertex.*

hadrons and enter the spectrometer. A very sophisticated trigger is needed to reject the huge number of typical interactions which involve only light quarks. To form a trigger, we must exploit properties of events with B -hadrons that differentiate them from the much larger number of ordinary, or “minimum bias,” events. Figure 1.1 illustrates the key characteristic that distinguishes B events. The B ’s produced in the interaction travel a

Figure 1.2: $\beta\gamma$ of the B ’s versus η .

short distance, between zero and many millimeters from the point of the interaction (with a most probable decay length of 3 mm) and then decay

into two or more (typically 5) particles. The presence of these “detached vertices” or “secondary vertices” is the signature of a B event. However, this requires the trigger to reconstruct tracks and assemble them into vertices to find those with evidence of detached vertices. This task must be done in quasi-real time so that a decision can be made on average every 396 ns. This represents a formidable challenge that has not been achieved yet in particle physics.

Figure 1.3: *The production angle (in degrees) for the hadron containing the b -quark plotted versus the production angle for the hadron containing the $\bar{b}$ -quark in the same event, from the Pythia Monte Carlo generator. Zero degrees represents the direction of the incident proton and 180° the incident antiproton.*

BTeV is designed to cover the forward region of the $p - \bar{p}$ interaction from 10 mrad to 300 mrad ($1.9 < \eta < 4.5$). There are several advantages to operate in this region and they come from the peculiar features of the B production at hadron colliders:

- the B -hadrons are much faster than in the central region around $\eta = 0$.

This means that their decay products are much less deviated from their trajectories by multiple Coulomb scattering and, therefore, can be reconstructed with better precision

- there is a strong angular correlation between the b and $\bar{b}$ directions, which greatly facilitates the flavour-tagging since both the produced B -hadrons are likely to fall within the spectrometer acceptance

Figure 1.2 shows the behaviour of $\beta\gamma$ of the B -hadrons as a function of η obtained by the Pythia Monte Carlo generator at $\sqrt{s} = 2$ TeV. It can be clearly seen that, near $\eta = 0$, $\beta\gamma$ is at a minimum value around 1, while, at higher $|\eta|$, $\beta\gamma$ can easily reach values around 6. The pseudo-rapidity η is defined as:

$$\eta = -\ln(\tan(\theta/2)) \quad (1.1)$$

θ is the angle of the particle with respect to the beam direction. In Fig. 1.3 the production angle of the hadron containing the b -quark is plotted versus that of the hadron containing the $\bar{b}$ -quark. There is a very strong correlation peak near the proton and the antiproton direction. Both these features can be easily understood recalling that the dominant mechanism for b -quark production at this energy is gluon-gluon fusion, *i.e.* a two-body process. Whenever the two gluons have strongly unbalanced Feynman- x , the center of mass of the produced $b-\bar{b}$ pair is boosted along the direction of the higher momentum gluon.

1.1.2 Detector requirements

The spectrum of detector requirements following from a choice of a general menu of physics measurements related to CP violation in B decays, see appendix A, are reported in Tab. 1.2. The considerations on vertex separation, K and π separation, photon detection and lepton identification, summarized in this table, leads to the following BTeV design requirements [8]:

pixel detector: based on several pixel planes placed normally to the beam direction along the interaction region, it is used to trigger on detached heavy quark decay vertices at the first trigger level. Fine-segmented

Physics quantities	Decay modes	Detector properties				
		V	K/ π	γ	τ	L
$\sin(2\alpha)$	$B^o \rightarrow \rho\pi \rightarrow \pi^+\pi^-\pi^o$	✓	✓	✓		
$\cos(2\alpha)$	$B^o \rightarrow \rho\pi \rightarrow \pi^+\pi^-\pi^o$	✓	✓	✓		
$\text{sign}(\sin(2\alpha))$	$B^o \rightarrow \rho\pi$ & $B^o \rightarrow \pi^+\pi^-$	✓	✓	✓		
$\sin(\gamma)$	$B_s \rightarrow D_s^\pm K^\mp$	✓	✓		✓	
$\sin(\gamma)$	$B^- \rightarrow \bar{D}^0 K^-$	✓	✓			
$\sin(\gamma)$	$B^o \rightarrow \pi^+\pi^-$ & $B_s \rightarrow K^+K^-$	✓	✓		✓	
$\sin(2\chi)$	$B_s \rightarrow J/\psi\eta', J/\psi\eta$	✓	✓	✓	✓	✓
$\sin(2\beta)$	$B^o \rightarrow J/\psi K_S$					✓
$\cos(2\beta)$	$B^o \rightarrow J/\psi K^o, K^o \rightarrow \pi\ell\nu$	✓	✓			✓
$\cos(2\beta)$	$B^o \rightarrow J/\psi K^{*o}$ & $B_s \rightarrow J/\psi\phi$					✓
x_s	$B_s \rightarrow D_s^+\pi^-$	✓	✓		✓	
$\Delta\Gamma$ for B_s	$B_s \rightarrow J/\psi\eta', D_s^+\pi^-, K^+K^-$	✓	✓	✓		✓

Table 1.2: *Some crucial measurements and the relative detector requirements. V: vertex separation; K/ π : K and π separation; γ : photon detection; τ : superb decay time resolution; L: lepton identification.*

pixel detectors are crucial since they provide precise and unambiguous three-dimensional space points for track reconstruction

dipole magnet: centered at the interaction region, it places a magnetic field of 1.6 T on the pixel detector thus allowing the use of momentum determination in the trigger

Silicon micro-strips & straws tubes: for precision tracking. This system, when coupled with pixels, provides excellent momentum and mass resolution out to 300 mrad

Ring Imaging CHerenkov detector (RICH): for excellent charged particle identification. The RICH provides hadron identification from 3–70 GeV and lepton identification from 3–20 GeV, out to the full aperture of 300 mrad

ElectroMagnetic calorimeter (EM-cal): for reconstructing final states

with single photons, π^0 's, η 's or η' 's and identifying electrons. It's made with a high quality PbWO_4 crystals with excellent energy resolution, position resolution and segmentation

muon detector: for muon identification. It consists of a dedicated detector with steel toroids instrumented with proportional tubes. This system has the ability to both identify single muons above momenta of $\sim 10 \text{ GeV}/c$ and supply a di-muon trigger

detached vertex trigger at Level 1: using the pixel detector, detects characteristic B decays topology. It makes BTeV efficient for most final states, including purely hadronic modes. The trigger eliminates from its calculations tracks of very low momentum particles. These particles can badly scatter and their tracks can appear to be erroneously detached from the primary vertex, resulting in “fake” triggers

Figure 1.4: *Layout of the BTeV spectrometer.*

Figure 1.4 shows the layout of the BTeV spectrometer. I will start describing BTeV from its most innovative and challenging part, the detached vertex

trigger.

1.2 Detached vertex trigger

The challenge for the BTeV trigger and data acquisition system is to reconstruct particle tracks and interaction vertices for every interaction that occurs in the detector, and to select preferably interactions with B decays. The trigger performs this task using 3 stages, see Fig. 1.5, referred to as Levels 1, 2 and 3:

L1: looks at every interaction, and rejects at least 98% of background based on full track and vertex reconstruction using a Silicon pixel detector

L2: uses L1 results and performs more refined analyses for data selection

L3: performs a complete analysis using all of the data available for an interaction

Figure 1.5: *BTeV three-level trigger architecture. A data-compression algorithm is used before storing data on archive, giving the reduction factor 3.125 in Level 2/3.*

The total effect of the trigger is to reject $> 99.8\%$ of background and keep $> 50\%$ of B events that are actually used for physics analysis. The Data Acquisition System (DAQ) [10] saves all of the detector data in memory for as long as is necessary for Level 1 to analyze each interaction (0.5 ms

on average for L1) and moves data to L2/3 processing units and archival storage for selected interactions.

The trigger system is **data-driven** since it actually deals with “beam crossings,” treating each crossing as a separate computing problem and trying to determine whether any of the interactions are B events. Since the crossings have a variable number of interactions and the individual interactions have varying complexity, the time it takes to compute for an individual crossing is highly variable. In order to keep all processing elements busy, BTeV’s trigger and DAQ have no fixed latency at any level. Decisions are taken in variable amounts of time and transmitted as soon as they are known, like an asynchronous system¹, without any requirement of time ordering. This in turn requires massive amounts of buffering throughout the system. To limit the amount of that needs to be buffered, the front end electronics needs to **sparsify** the data by transferring only channels above a certain threshold.

The Level 1 trigger consists of:

pixel trigger: reconstructs tracks and vertices for every bunch-crossing. It is able to carry out track and vertex reconstruction at the bunch-crossing rate because of the very high-quality, low-noise, three-dimension tracking information provided by the pixel detector

muon trigger: looks for tracks in the muon detector consistent with muons originating in the interaction region. The main jobs of this system is to identify di-muons events, in our quest to collect a large sample of B decays containing J/ψ ’s, and to help calibrate the Level 1 pixel trigger

In the next sections I will describe the detectors that constitute the BTeV spectrometer. I will start by its core, the pixel detector.

¹Current modern collider experiments (CDF, CMS, etc ...) operate with a pipelined, synchronous Level 1 trigger system: all trigger data move in lockstep with the beam crossing clock through the trigger decision chain, therefore no time markers are required for the data. The synchronicity must be maintained throughout the entire trigger system with hundreds of boards.

1.3 Pixel detector

The key features of the pixel detector are excellent spatial resolution, ease of tracking pattern recognition, radiation hardness, material thinness and readout of data fast enough for use in the Level 1 BTeV trigger system. In particular, pixel detectors have very few noise hits, this, together with remarkable radiation hardness properties, enables the detector elements to be placed very close to the beam (in the same vacuum $\sim 10^{-8}$ torr, outside several wires used for RF shielding) minimizing track extrapolation errors.

Figure 1.6: *Pixel detector elements and dimensions.*

The pixel sensors are made of Silicon doped $n + /n/p+$ type, with pixel dimensions of $50 \times 400 \mu\text{m}^2$ and $250 \mu\text{m}$ thick; they are organized in 22 columns and 128 rows. Each sensor is bump-bonded to the Fermilab PIXel readout chip (FPIX), made with $0.25 \mu\text{m}$ CMOS technology. FPIX performs a **data-driven sparsified** readout and provides the following information:

- channel up threshold (row-column coordinate)
- 8 bit BCO counter (the time stamp)
- 3 bit analog information

Properties	Values
Total station radiation length (incl. RF shielding)	3%
Total pixels	$\sim 2.3 \times 10^7$
Readout	analog (3 bits, <i>i.e.</i> 8 thresholds)
Trigger	data-driven (signals are used in Level 1)
Rate requirements	time between beam crossings: 396 ns, 132 ns BCO also fully supported
Noise requirement	desired: $< 10^{-6}$ per channel/crossing required: $< 10^{-5}$ per channel/crossing
Resolution	better than $9 \mu\text{m}$
Angular resolution	better than 0.1 mrad
Radiation tolerance	$> 6 \times 10^{14}$ particles per cm^2 (10 years of BTeV operation)
Power per pixel	$\sim 60 \mu\text{W}$
Occupancy	$\sim 10^{-4}$ (at 396 ns BCO)
Vertex separation resolution	$138 \mu\text{m}$ (from simulations)
Proper time resolution	46 fs (from simulations)

Table 1.3: *Pixel detector properties.*

The pixels detector is composed of thirty stations; each station is divided in two half L-shaped stations and each half station has two views, one measuring X with high precision and Y with lower precision and the second measuring Y with high precision and X with lower precision (see Fig. 1.6). In order to reduce the noise and increase the sensors life-time the pixel detector has to operate at -5°C . During beam refill the half stations of the detector are moved away to $\sim \pm 2 \text{ cm}$ from the beam, using a system of actuators and motion sensors. When the beam is stable the detectors are moved close to the beam for data taking, with a reproducibility $< 50 \mu\text{m}$. Other important properties of the pixel detector are reported in Tab. 1.3.

1.4 Forward tracker

The BTeV forward tracking system is based on seven stations of straw and Silicon strip planes, which cover an acceptance of ~ 300 mrad in the forward region. Three stations are placed in the dipole magnet, three stations in the field-free region just upstream of the RICH and one station just downstream of the RICH. The major functions of the forward tracking system are to provide high precision momentum measurements for tracks found in the pixel system, to reconstruct and measure all parameters for tracks which do not pass through the vertex detector (such as K_S and Λ^0 daughter tracks) and to project tracks into the RICH counters, EM-cal and muon detectors.

1.4.1 Silicon strip detector

Silicon strip planes are placed in the innermost region, around the beam pipe, where the particle fluence is very high, and cover the acceptance from

Figure 1.7: *Sketch of a forward Silicon tracker plane. The two pairs of sensors on each ladder are readout separately by the front-end electronic chips placed at the two ends of the same ladder. There is some overlap between adjacent ladders to ensure good efficiency over the entire plane.*

the beam pipe to the inner edge of the forward straw system, which starts at 13 cm. The design consists of stations with three planes of $320 \mu\text{m}$ thick single-sided silicon strip detectors with $100 \mu\text{m}$ pitch (providing a $\sigma = 100 \mu\text{m}/\sqrt{12} = 29 \mu\text{m}$ resolution, adequate for the physics goals). The

Figure 1.8: *Sketch of the mechanical support of a forward Silicon tracker half-plane. A cooling duct runs through the structure and reaches the regions where the readout electronics is located and the heat load is concentrated.*

Silicon sensors, having an area of $\sim 7.9 \times 7.9 \text{ cm}^2$, are arranged in ladders of 2 daisy-chained sensors each, in such a way that four adjacent ladders form a plane, as illustrated in Fig. 1.7.

The ladders are mounted on a low-mass carbon fiber support (see Fig. 1.8) that can be stacked and properly rotated to provide three views in each station: X , U and V . The two stereo views, U and V , are at $\pm 11.3^\circ$ around the Y bend coordinate. Each plane contains 6144 readout channels; the entire system of seven stations has 129024 channels in total.

The Silicon sensors are the standard p/n type and are produced with the same technology developed by the CMS collaboration for their IB2 detectors. A description of these sensors and their radiation hardness performance are the subject of chapter 3.

The sensors are readout by the Fermilab Silicon micro-Strip Readout chip (FSSR), made with $0.25 \mu\text{m}$ CMOS technology. FSSR performs a **data-driven sparsified** readout and provides the same information as the pixel readout chip since it has the same digital back-end section. A description of the FSSR chip and its performance are the subject of chapter 4. The front-end electronics is distributed along the two opposite edges of each plane and is cooled to $\sim -5^\circ \text{C}$ by a fluid circulating in a duct embedded in the

Properties	Values
Total station radiation length	0.4%
Total channels	$\sim 1.3 \times 10^5$
Readout	analog (3 bits, <i>i.e.</i> 8 thresholds)
Trigger	data-driven (signals are used in Level 2/3)
Rate requirements	time between beam crossings: 396 ns, 132 ns BCO also fully supported
Noise requirements	$< 10^{-3}$ per channel/crossing
Radiation tolerance	$> 1.6 \times 10^{14}$ particles per cm^2 (10 years of BTeV operation)
Power per channel	~ 4 mW
Occupancy	$\sim 2.4\%$ (at 396 ns BCO)

Table 1.4: *Forward Silicon tracker detector properties.*

support structure around the periphery of the plane (see Fig. 1.8). Other important properties of the forward Silicon tracker detector are reported in Tab. 1.4.

1.4.2 Straw detector

The outer region of the forward tracker is instrumented using straw tube drift chambers. Straws have been chosen because they can be used to make large chambers with small cell size and because they can be built to surround the beam pipe without requiring a massive frame near the beam. The basic element in the construction of a detector station is the “module” consisting of 48 straws of 4 mm diameter, arranged in 3 rows. The gas used is Argon-CO₂ with a drift time, in the 4 mm straw section, of ~ 50 ns. In order to keep the straws at a constant humidity, dry nitrogen is flown at room temperature in the volume surrounding the straws. Other important properties of the straw detector are reported in Tab. 1.5.

Properties	Value
Total station radiation length	0.9%
Total channels	$\sim 5.3 \times 10^4$
Trigger	data-driven (signals are used in Level 2/3)
Resolution	better than 100 μm
Occupancy	$\sim 0.2\%$ (at 396 ns BCO)

Table 1.5: *Forward straw tracker detector properties.*

1.5 RICH

Charged particle identification is an absolute requirement for an experiment designed to study the decays of b and c quarks. The forward geometry is well suited for a Ring Imaging CHerenkov detector (RICH), that provides powerful particle identification capabilities over a broad range of momentum. Even with the excellent mass resolution of BTeV, there are kinematic regions where signals from one final state could overlap those of another final state. For example, $B_s \rightarrow D_s K^-$ signal must be distinguished from $B_s \rightarrow D_s \pi^-$ background in order to measure the CKM phase γ (see appendix A). These ambiguities can be eliminated almost entirely by an effective particle identifier. The RICH detector consists of two independent systems, whose signals are used in Level 2/3 trigger:

gas radiator: has a 3 m long $\text{C}_4\text{F}_8\text{O}$ gas volume. Charged particles radiate Cherenkov light in this medium. The light is focused with a segmented mirror onto an array of photo-detectors sensitive to light between 280–600 nm. The photo-detectors are Multi-Anode Photo-Multiplier tubes (MAPMT)

liquid radiator: used mainly for separating kaons and protons below 10 GeV/c, consists of a liquid C_5F_{12} radiator, approximately 1 cm thick, placed in front of the gas volume. Cherenkov photons generated in this medium exit the sides of the gas tank and are detected in an array of Photo-Multiplier Tubes (PMT)

Figure 1.9: *Sketch of the main RICH components.*

The momentum range over which excellent hadron identification is required is between 3 and 70 GeV/c. The low momentum hadron identification optimizes flavour tagging, whereas the high momentum range enables to separate π 's and K 's from two body B -meson decays. Besides providing excellent hadron identification, the RICH detector is also an integral part of the lepton identification system in the solid angle between 200 and 300 mrad. It is the only detector element available to distinguish e , μ and hadron species within that solid angle, as the muon detector and the electromagnetic calorimeter have smaller solid angle coverage.

The separation of charged hadrons into different species is accomplished in the data analysis by characterizing each charged track with a set of probabilities for being an electron, muon, pion, kaon or proton. From a knowledge of the distribution of Cherenkov angular resolutions per track such probabilities can be derived. For example, the difference in emission angle of Cherenkov photons from pions and kaons at 70 GeV/c is 0.44 mrad, so achieving a resolution per track of 0.11 mrad would give a separation of 4σ .

Figure 1.10: *Cherenkov angle for various particle species as a function of particle momentum for the gas C_4F_8O ($n=1.00138$) and the liquid C_5F_{12} ($n=1.24$) radiators.*

Separation improves dramatically as momentum decreases. Furthermore, the average Cherenkov resolution per track can be understood in terms of the average Cherenkov resolution per photon and the number of photons. A separation of at least 4σ for π , K and p in the momentum range of 3–70 GeV/c is required. Other important properties of the RICH detector are reported in Tab. 1.6.

Radiator type	Angle resolution	Cherenkov ring thickness (r.m.s.)	Photons per track
Gas	0.12 mrad	< 0.85 mrad	> 50
Liquid	1.9 mrad	< 6.5 mrad	> 12

Table 1.6: *RICH detector properties.*

1.6 EM-cal

A thorough investigation of B decays requires not only the ability to track and identify charged particles, but also the ability to reconstruct photons. To address many of the B -physics issues, one needs to disentangle various isospin components of the decays. This inevitably involves decay modes containing π^0 's. Detection of neutral pions is critical, for example, in extracting the α angle of the unitary triangle using $B \rightarrow \rho\pi \rightarrow \pi^+\pi^-\pi^0$ or $B \rightarrow \rho^+\rho^- \rightarrow \pi^+\pi^-\pi^0\pi^0$. It is also crucial to detect $\eta(\prime)$'s and isolated photons. The decay mode $B_s \rightarrow J/\psi\eta(\prime)$ used for the determination of the angle χ involves either $\eta \rightarrow \gamma\gamma$, $\eta' \rightarrow \pi^+\pi^-\eta$ or $\eta' \rightarrow \rho\gamma$. Other important decays involving direct photons are $B \rightarrow \gamma K^*(\rho \text{ or } \omega)$ (see appendix A).

Figure 1.11: *Measurements of the EM-cal resolution. On the left: energy resolution vs. beam energy. On the right: position resolution vs. beam energy.*

Total absorption shower counters made of scintillating crystals have superb energy and spatial resolutions. The crystals act as both the shower development media and scintillation light emitter. Since the entire calorimeter is used to measure the energies of photons, the resolution can be excellent. Lead tungstate (PbWO_4) crystals are distinguished by their high density (8.3 g/cm^3), short radiation length (0.89 cm), small Moliere radius (2.2 cm) and short relaxation time (15 ns for the major component) as well as their

high tolerance to radiation. The light output, of 10 photoelectrons per MeV into 2 inch Photo-Multiplier Tube (PMT) with a standard bi-alkali photocathode, is modest compared to many other scintillation crystals, but adequate. For experiments operating in a very high particle density environment, it is very important that signals from two particles do not overlap in space and time very often. The smaller the Moliere radius, the more compact are the showers created by photons and the less frequently two of them do overlap in space. The shorter the scintillation signal, the less likely that two of them overlap in time. The dense nature of the PbWO_4 crystals makes it possible to construct a compact calorimeter. The shorter calorimeter gives hadron showers less room to spread out when their parent hadrons interact in the calorimeter, making them less likely to overlap with photon signals.

Properties	Values
PWO crystal radiation length	0.89 cm
Interaction lengths	22.4 cm
Trigger	signals are used in Level 2/3
Refractive index	2.3
Maximum of emission	440 nm
Radiation tolerance	after 10 Mrad energy and position resolution should not deteriorate by more than a factor of 2
Working temperature	15–20° C
Temperature stability	0.1° C, since the light output depends strongly on the temperature: 2.3%/° C

Table 1.7: *EM-cal detector properties.*

The EM-cal consists of ~ 10000 crystals, each having a $28 \times 28 \text{ mm}^2$ cross-section in the back and 220 mm length. They are slightly tapered in shape so that they can be arranged in a projective geometry where all the crystals are pointing to a place near the interaction point. The projective geometry secures better resolutions, in particular, position resolution, especially in the

outermost area of the calorimeter. In order to avoid lining up gaps between crystals with potential paths of photons, the convergence point is displaced from the interaction point by 10 cm both in the horizontal and vertical directions.

The first plot of Fig. 1.11 shows the measured energy resolution for a 5×5 array of crystals, superimposed with the fit function:

$$\sigma_E/E = \sqrt{a^2 + \frac{b^2}{E} + \frac{c^2}{E^2}} = a \oplus b/\sqrt{E} \oplus c/E \quad (1.2)$$

a: arises from calibration errors, shower longitudinal leakage and non-uniformity of the light collection efficiency along the length of the crystals (expected 0.35%)

b: arises from photon statistics variations and the transverse leakage of shower outside the array (expected 1.68%)

c: arises from the momentum measurement errors due to multiple scattering of the electrons in the beam line upstream the prototype

The second plot of Fig. 1.11 shows the measured position resolution with superimposed the fit function:

$$\sigma_x = \sqrt{a^2 + \frac{b^2}{E}} = a \oplus b/\sqrt{E} \quad (1.3)$$

Other important properties of the EM-cal detector are reported in Tab. 1.7.

1.7 Muon detector

The muon detector has two primary functions:

muon identification: many of the experiment's physics goals rely on efficient muon identification with excellent background rejection. Muon identification is important for rare decay searches, CP violation studies which require tagging, studies of beauty mixing, semileptonic decays and searches for charm mixing

J/ψ and prompt muon trigger: besides selecting interesting physics (including J/ψ final states of B decays, direct J/ψ production and rare

decays), this trigger performs an important service role by selecting a large enough sample of b events on which the more aggressive and technically challenging vertex trigger can be debugged and evaluated

Figure 1.12: *Perspective view of the muon detector. (A): smooth faceplate located on each side of each toroid. (B): coils which wrap around both toroids. (C): main steel for the first toroid. (D): shielding wall located in front of the last muon station. The locations of the three muon detector stations are labeled μ_1 , μ_2 and μ_3 .*

The muon detector design combines a toroidal magnet with fine-grained tracking elements. This design permits a “stand-alone” trigger: *i.e.* a di-muon trigger based solely on information from the muon detector. In addition, improved background rejection is possible by comparing this measurement with momentum and tracking information from the rest of the spectrometer.

Two toroids, approximately 1 m long with 1.5 T field, provide the bending power and filtering of non-muons. There are three stations of detectors, one between the two toroids and two behind the toroids (farther from the interaction point in z), as shown in Fig. 1.12. The momentum of tracks can be measured using the two, well shielded, downstream stations and the nominal beam constraint. The station between the two toroids provides an important confirming hit for the rejection of fake tracks.

Figure 1.13: *On the left: beams-eye view of one muon station (eight overlapping octants arranged in two layers). On the right: arrangement of planks to form each of the four views in an octant (r view is repeated).*

The basic element in the construction of a detector station is a “plank” of stainless steel proportional tubes. There are 32 tubes in each plank, arranged in two rows of 16, offset by half a tube diameter. In order to avoid ghost tracks in the system, the minimum requirement is that all hits from one beam crossing be collected before the next beam crossing. The same gas as used for the straw detectors, a mixture of Argon- CO_2 , meets this goal. To minimize occupancy at small radii, twelve planks of increasing length are arranged into pie shaped octants. To minimize pattern recognition confusion, three arrangement of planks (r , u , or v) are used. The r views are radial. The u and v views are rotated $\pm 22.5^\circ$ with respect to the radial views and measure the azimuthal angle, ϕ . A schematic of this arrangement is shown in Fig. 1.13. In order to provide redundancy in the most important view in terms of pattern recognition for the trigger and momentum measurement, the r view is repeated. Other important properties of the muon detector are reported in Tab. 1.8.

In the next sections I will present the extraordinary sensitivities and flavour tagging performance of BTeV. I will first start by showing the background rejection capabilities and efficiencies of the Level 1 trigger algorithm.

Properties	Values
Total channels	36864
Spatial resolution	1.4 mm
Momentum resolution	better than $\sigma_p/p = \sqrt{0.25^2 + (0.01p)^2}$
Min. bias rejection	500
Di-muon efficiency	80%
Trigger	signals are used in Level 1

Table 1.8: *Muon detector properties.*

1.8 The Level 1 trigger algorithm

The Level 1 trigger algorithm has two major stages:

1. segment finding
2. track and vertex finding

1.8.1 Segment finding

In order to speed the track finding, pixel hits from three neighbouring stations are used to find the beginning and ending segments of tracks. These three station segments are called “triplets.” An “inner triplet” is associated with a track as it enters the pixel detector from the interaction region and represents the start of the track. Since nearly all tracks traversing the pixel detector and entering the forward spectrometer have a hit in the first centimeter of the pixel detector, only that limited region is used to “seed” or initiate searches for triplets. This greatly reduces the number of calculations that have to be performed. Similarly, an “outer triplet” is associated with a track as it leaves the pixel detector, either through the side or the front or rear faces. An “outer triplet” represents the end of the track in the pixel detector. Again, nearly all outer triplets start very close to the detector boundary so only a limited region is used to seed the search for “outer triplets.” The segment finding algorithm works as follows:

1. starting with a seed hit in the “inner region” of plane $N - 1$, one

projects a cone onto plane N that corresponds to a range of legitimate and interesting tracks that would fall within the pixel detector acceptance

2. for each hit, “ I_N ,” within this range, one projects from this hit and the seed back to the Z position of plane $N - 2$. If the projection falls within pixel plane $N - 2$, then the seed is not the first point on an inner segment with hit I_N . One advances to the next hit in plane N
3. if the projection falls inside the beam hole in the pixels at station $N - 2$ instead, then one projects the seed and hit I_N into pixel plane $N + 1$; if a confirming hit “ J ” is found, this seed, I_N , and J_{N+1} are an “inner segment”

The opportunities for parallelism are evident. Outer segment finding is done in the same way and in parallel. In the bend view, both inner and outer segments are found (research for strait tracks over three stations in the bend view guarantees a momentum cut of $p > 3$ GeV/c). These are eventually matched and the difference in directions between an inner segment and its outer matching segment gives a measurement of the momentum. In the non-bend view, segment finding is done in parallel with the bend view, but only inner segments are searched for since they provide enough information to measure the track horizontal position and angle to extrapolate it back to the interaction vertex.

1.8.2 Track and vertex finding

The next stage involves delivering all the segments associated with a single beam crossing to one CPU in the track/vertex finding processor farm. The processor then does segment matching to form tracks and applies an algorithm to find “primary interaction vertices.” Vertex finding constitutes projecting found tracks back into the interaction region and clustering them. Since tracks from B decays tend to have somewhat higher transverse momentum relative to the beam direction than tracks from the main interaction vertex, a requirement is placed on the tracks used in the clustering that they be below a certain transverse momentum. Typically several interaction ver-

tices are found in each crossing, but they are usually quite well separated due to the length of the Tevatron luminous region. Each track not falling into these clusters and whose transverse momentum is above some value (typically 300 MeV/c) is extrapolated back to the nearest interaction vertex and its impact parameter b , relative that vertex and its associated uncertainty σ_b , are calculated. The quantity b/σ_b is used to evaluate detachment. The primary Level 1 trigger requires two tracks detached with respect to the same primary vertex to meet the criteria for a “Level 1 accept.”

Cuts	Values
Momentum p	> 3 GeV/c (implicit in the reconstruction)
Transverse momentum p_t	< 1.2 GeV/c (for track making the primaries) > 0.5 GeV/c (for candidate heavy flavour daughter tracks)
Impact parameter b	< 2 mm
b/σ_b	> 2.8
Primary multiplicity	> 3 tracks
Detached tracks	≥ 2

Table 1.9: *Level 1 trigger cuts.*

1.8.3 Level 1 trigger performance

Figure 1.14 shows an example of simulated Level 1 trigger background rejection and efficiency, respectively. To avoid bandwidth saturation less than 1% of crossings should pass the trigger; this is attained with the condition to have 2 detached tracks with $b/\sigma_b > 2.8$. With these criteria, the trigger efficiencies are large. For example, the process² $B_s \rightarrow D_s^+ K^-$ has an 80% acceptance (efficiency here means the fraction of the off-line reconstructable events that pass the trigger).

In Tab. 1.9 are reported the Level 1 trigger cuts used to compute the

² $D_s^+ \rightarrow \phi\pi^+, K^{*0}K^+$.

Figure 1.14: *Level 1 trigger background rejection and efficiency. On the left: trigger response for minimum bias events for a crossing time of 132 ns and an average of 2 interactions per bunch crossing. On the right: trigger efficiency for $B_s \rightarrow D_s^+ K^-$ events with a crossing time of 132 ns and an average of 2 interactions per bunch crossing.*

efficiencies reported in Tab. 1.10, for a crossing time of 132 ns and an average of 2 interactions per bunch crossing.

Processes	Efficiencies
Minimum bias	1%
$B_s \rightarrow D_s^+ K^-$	80%
$B^0 \rightarrow J/\psi K_S$	65%
$B^0 \rightarrow \phi K_S$	74%
$B^0 \rightarrow 2\text{-body modes}$ ($\pi^+ \pi^-$, $K^+ \pi^-$, $K^+ K^-$)	80%

Table 1.10: *Level 1 trigger efficiencies for (first entry) crossings containing only minimum bias events and (remaining entries) crossings also containing B decays.*

1.9 Sensitivities

The sensitivities to CP violating angles and related quantities are summarized in Tab. 1.11. In the simulations a luminosity of $2 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$ and 10^7 seconds of running time (corresponding to one year) have been considered. All of the measurements listed here to determine χ , α , β , γ and x_s , except for the determination of γ using $B \rightarrow K\pi$ modes, are completely free of hadronic uncertainties or errors due to theoretical models. Ultimately, at the level of errors below 1° for α , β and γ (and a much lower number for χ), the effects of other diagrams or higher order terms in the Wolfenstein approximation need to be considered.

Reaction	$\mathcal{B} \times 10^{-6}$	# event	S/B	Parameter	Error
$B_s \rightarrow D_s^+ K^-$	300	7500	7	$\gamma - 2\chi$	8°
$B_s \rightarrow D_s^+ \pi^-$	3000	59000	3	x_s	75
$B^0 \rightarrow J/\psi K_S$	445	168000	10	$\sin(2\beta)$	0.017
$B^0 \rightarrow J/\psi K^0$					
$K^0 \rightarrow \pi^\pm l^\mp \mu$	7	250	2.3	$\cos(2\beta)$	~ 0.5
$B^0 \rightarrow \pi^+ \pi^-$	4.5	14600	3	Asymmetry	0.03
$B_s \rightarrow K^+ K^-$	17	18900	6.6	Asymmetry	0.02
$B^- \rightarrow$ $\overline{D}^0(K^+ \pi^-) K^-$	0.17	170	1		
$\overline{D}^0(K^+ K^-) K^-$	1.1	1000	> 10	γ	13°
$B^- \rightarrow K_S \pi^-$	12.1	4600	1		$< 4^\circ +$
$B^- \rightarrow K^+ \pi^-$	18.8	62100	20	γ	theory
$B^- \rightarrow \rho^+ \pi^-$	28	5400	4.1		
$B^- \rightarrow \rho^0 \pi^0$	5	780	0.3	α	$\sim 4^\circ$
$B^- \rightarrow J/\psi \eta$	330	2800	15		
$B^- \rightarrow J/\psi \eta'$	670	9800	30	$\sin(2\chi)$	0.024

Table 1.11: *Yearly sensitivities to CP violating angles and related quantities. Reactions between lines are used together.*

Some comments on these measurements:

- $\sin(2\beta)$ is obtained originally by fitting the time distribution, which results in a 20% improvement in the error relative to that of the time-integrated symmetry measurement
- to determine α we use the method originally proposed by Snyder and Quinn $B^0 \rightarrow \rho\pi \rightarrow \pi^+\pi^-\pi^0$ [11]; ~ 500 effective flavour tagged $\rho^\pm\pi^\mp$ events and ~ 75 $\rho^0\pi^0$ per year are expected
- although the $B \rightarrow K\pi$ modes provide the smallest experimental error in determining γ , there are model dependent errors associated with this method. On the other hand, two other methods, which use $B_s \rightarrow D_s^\pm K^\mp$ and $B^- \rightarrow \bar{D}^0 K^-$, provide model independent results and can be averaged. The interplay of the three methods can be used to resolve ambiguities
- the measurement of $\sin(2\chi)$ can take few years, if it is in the SM range. Including $B_s \rightarrow J/\psi\phi$ can reduce the time
- the asymmetry in $B^0 \rightarrow \pi^+\pi^-$ may be useful to gain insight into the value of α with theoretical input or combined with $B_s \rightarrow K^+K^-$ and theory to obtain γ
- the sign of $\cos(2\beta)$ can be determined in few years without any theoretical assumptions using $B^0 \rightarrow J/\psi K^0$, with $K^0 \rightarrow \pi^\pm l^\mp \nu$, allowing the removal of two of the ambiguities in β . This reconstruction can also be used for CPT tests

As a result to these studies it's evident that BTeV would have had outstanding performance in carry on its flavour physics and CP violation program.

1.9.1 Experiment comparison

A comparison of BTeV, LHCb, BABAR and BELLE in 2005, and e^+e^- machines with a luminosity of 10^{35} and $10^{36} \text{ cm}^{-2} \text{ s}^{-1}$, is given in Tab. 1.12 for several states of importance to the study of CP violation in B decays.

This study indeed demonstrates that it takes a $10^{36} \text{ cm}^{-2} \text{ s}^{-1} e^+e^-$ collider operating at $\Upsilon(4S)$ to match the performance of BTeV on B^0 and

Parameter	BTeV 10^7 s	LHCb 10^7 s	BABAR BELLE (2005)	e^+e^- 10^{35} 10^7 s	e^+e^- 10^{36} 10^7 s	e^+e^- at 10^{36} vs hadron
$\sin(2\beta)$	0.017	0.02	0.037	0.026	0.008	Equal
$\sin(2\alpha)$	0.05	0.05	0.14	0.1	0.032	Equal
$\gamma[B_s(D_sK)]$	$\sim 11.5^\circ$					Hadron
$\gamma[B(DK)]$	$\sim 13.2^\circ$		$\sim 20^\circ$		12°	Equal
$\sin(2\chi)$	0.024	0.04				Hadron
$\mathcal{B}(B \rightarrow \pi^0\pi^0)$			$\sim 20\%$	14%	6%	e^+e^-
V_{ub}			2.3% (sys)	$\sim 1\%$ (sys)	$\sim 1\%$	e^+e^-

Table 1.12: *Comparison of the CP reach of several experiments. The last column is a prediction of which kind of facility would make the dominant contribution to each physics measurement [12].*

$B^\pm$ mesons, while for B_s or other b -flavoured hadrons, BTeV would have given the dominant contribution to the measurements.

1.10 Flavour tagging

Flavour tagging, determination of the flavour of the signal B -hadron at the time of its production, is an essential component of the study of mixing and CP violation in B decays. We define the tagging “power” ϵD^2 (ϵ is the efficiency and D is the dilution) as:

$$\epsilon = \frac{N_R + N_W}{Total}, \quad D = \frac{N_R - N_W}{N_R + N_W} \quad (1.4)$$

N_R and N_W are the number of correct and incorrect tags, respectively and *Total* refers to the sample of fully reconstructed neutral B -mesons in the mode of interest. The determination of the flavour tagging ϵD^2 takes advantage of the precision tracking provided by the pixel detector and excellent particle identification afforded by the RICH.

There are three quasi-independent flavour tagging methods:

Sample	Independent tag $\epsilon D^2(\%)$	Overlaps removed $\epsilon D^2(\%)$
Away-side kaon tag	5.8	5.8
Away-side muon tag	1.3	1.3
Same-side kaon tag	5.7	4.5
Jet charge tag	4.5	0.4
Sum	-	12.1
Electrons + Likelihood fit	-	0.9
BTeV expected	-	13

Table 1.13: *Results on ϵD^2 for four algorithms for B_s decays.*

same-side tagging: (kaon for B_s and pion for B^0) utilizes the correlation which emerge between a neutral B -meson, and the charge nearby tracks produced in the fragmentation chain. Since these tracks are produced in the fragmentation of the b -quark (not the decay), same-side candidates emerge from the primary interaction vertex. When a B_s ($\bar{b}s$) forms, an extra $\bar{s}$ is available to form a K -meson. About half of the time it will produce a K^+ (the other half being a K^0 , which is not useful) which is 100% correlated with the flavour of the B_s at production. For B^0 mesons the same analysis holds, except the particle tag is a charged pion. This tagging method is not affected by the mixing of the tagging b

away-side tagging: exploits the fact that, in strong interactions, b -quarks are produced in pairs and therefore the second (away-side) b -quark in the event must have opposite flavour. Generally this is done by examining the charge of kaons or leptons from the away-side b -hadron decay or the charge of its associated jet. Since these particles come from the decay of the away-side b -hadron, away-side flavour tag algorithms usually exclude tracks which point back to the primary vertex. Because we examine the decay products, this method of flavour tagging is affected by mixing of the away-side b

jet charge tagging: reconstructs the location and decay products of the $b \rightarrow cW^-$ vertex. The particles associated with the W^- decay have a charge which is 100% correlated with the flavour of the parent b -hadron

Sample	Independent tag $\epsilon D^2(\%)$	Overlaps removed $\epsilon D^2(\%)$
Away-side kaon tag	6.0	6.0
Away-side muon tag	1.2	0.8
Jet charge tag	4.8	1.4
Same-side pion tag	1.8	1.0
Sum	-	9.2
Electrons + Likelihood fit	-	0.8
BTeV expected	-	10

Table 1.14: *Results on ϵD^2 for four algorithms for B^0 decays.*

In the simulations a simple approach to combine the tagging algorithms have been used. The algorithms are ranked in order of decreasing dilution and the algorithm highest on the list determines the flavour tag for a given event. If an event is not tagged by the first algorithm, the second is checked and so on. In this way the flavour determination comes from a single tag algorithm, the one with the highest dilution. The final results for ϵD^2 for B_s are shown in Tab. 1.13 and for B^0 in Tab. 1.14. The second column shows the results when the taggers are treated independently and the third column shows the results when overlaps are removed. It is expected to achieve a very remarkable tagging powers, ϵD^2 , of 13% for B_s decays and 10% for B^0 decays³.

³The away side electron tags are not explicitly treated and we might expect to get another 0.7% in ϵD^2 .

Chapter 2

Theory of radiation damage in Silicon sensors

In these years many studies have been carried out in order to get a better understanding of the radiation induced damages in semiconductors [13, 14]; even though the Research and development on Silicon for future Experiments (ROSE) collaboration has been established, the underlying physics processes are still not yet entirely understood. In this chapter I will present the most reliable model for the description of this phenomenon.

2.1 Radiation induced crystal damages

The radiation damage process, affecting sensors exposed to high fluences of incident particles, proceeds through the following steps:

1. the radiation displaces a Silicon atom from its lattice location (primary knock-on atom recoil)
2. the primary knock-on atom generates a cluster defect at the end of its recoil, where the atom loose its last amount of energy and the elastic scattering cross-section increases by several order of magnitude

Radiation generates basically three different kinds of defects in semiconductor crystals:

point defects: they are isolated defects as shown in Fig. 2.1. In order to create this kind of defect the energy provided to the recoil atom must be higher than 25 eV, otherwise it degrades to phonon excitations. They can be of three types:

vacancy: empty lattice site

interstitial: additional atom between regular lattice sites

Frenkel: complex of an interstitial next to a vacancy

complexes of defects: they are formed by reactions of vacancies and interstitials with Silicon dopant impurities, like Phosphorous for *n*-type Silicon, and non-dopant impurities, typically Oxygen and Carbon

clusters of defects: local high concentration of point defects that are expected to behave somewhat differently from uniformly distributed point defects. Such defect clusters are capable of producing local charge concentrations and thus, depending on the type, of attracting or repelling charge carriers from the surrounding region. In order to create cluster defects the energy provided to the recoil atom must be between 2 KeV and 12 KeV. Above 12 KeV several clusters will be produced

Figure 2.1: *Point defects in a simple lattice.*

Defects are not necessary immobile objects in the crystal. Point defects will typically anneal either by an interstitial filling a vacancy or by diffusing out to the surface. Depending on temperature, they may also diffuse and on their way form defect complexes with other defects or impurities. Similarly, defect complexes and clusters may break up at elevated temperatures and diffuse until they form different complexes. They may, however, also interact with another defect and form a new type of defect complex that becomes immobile at room temperature.

The probability for creating a primary knock-on atom, as well as its energy distribution, depends on the type and energy of the radiation. Indeed, charged particles, such as protons, scatter by electrostatic interaction with the (partially screened) nucleus, while neutral particles, such as neutrons, scatter by strong interaction with the nucleus only. The kinematics and, in particular, the energy transferred to the Silicon atom are strongly dependent on the mass of the impinging radiation. In order to better appreciate the radiation damage on Silicon, I report in Fig. 2.2 the results of a simulation of the defects induced by protons and neutrons at different energies.

Figure 2.2: *Distribution of vacancies produced by 10 MeV protons (left), 24 GeV protons (middle) and 1 MeV neutrons (right). The plots are projections over 1 μm of depth and correspond to a fluence of 10^{14} cm^{-2} (figure from [15]).*

Consequence to radiation induced defects is a change in the macroscopic properties of the Silicon. Defect complexes may change the doping concentration and, after enough dose, *n*-type Silicon becomes *p*-type. The following

defect complexes are those considered in literature to be the main cause of change in Silicon doping concentration:

donor removal complexes: examples of reactions for n -type Silicon, that lead to these kind of complexes, are $V + P_s \rightarrow VP$ and $C_i + P_s \rightarrow C_i P_s$. Where C_i (P_i) stands for Carbon (Phosphorus) atom interstitial and C_s (P_s) stands for Carbon (Phosphorus) atom substitutional (at a regular lattice site), whereas V stands for Vacancy. Since these are stable complexes with new electrical properties, the Phosphorous atom no longer influences on the effective doping concentration

acceptor-like complexes: an example of a reaction that leads to these kind of complexes is $V + O \rightarrow VO + V \rightarrow V_2O$, where O stands for Oxygen. This is a stable complex that behaves as an acceptor state

It is worth noting that to limit the formation of these complexes oxygenated Silicon can be used. Since V and C_i do also react with Oxygen, in presence of a high Oxygen concentration, the Phosphorus removal is thus suppressed. Moreover, since the formation of V_2O is in competition with the reaction $V + O \rightarrow VO$, the acceptor-like complexes creation is also suppressed [16].

Other macroscopic consequences to radiation induced defects are the increase of leakage current, since they create energy states close to the middle of the band gap, which are very effective in creation of thermal electron-hole pairs, and the reduction of the carriers trapping-time. The changes, in the macroscopic properties of the Silicon, on the sensor detecting performance will be discussed in the next section.

Although the primary interaction of radiation with Silicon is strongly dependent on the type and energy of the radiation, this dependence is to a large extent smoothed out by the secondary interaction of primary knock-on atoms. It is therefore customary to scale measurements of radiation damage from one type of radiation and energy to another. As the interaction of radiation with low energy electrons produces ionization but no crystal defects, the quantity used for scaling is the Non-Ionizing Energy Loss (NIEL) [17]. The NIEL scaling can be reduced to the definition of the 1 MeV equivalent neutron fluence ($\Phi_{eq.n.}^{1MeV}$) which produces the same damage as an arbitrary

beam with a certain spectral distribution and fluence Φ :

$$\Phi_{eq.n.}^{1MeV} = k\Phi \quad (2.1)$$

k is called the hardness factor.

2.2 Macroscopic effects after irradiation

Four main macroscopic effects are seen in sensors as a consequence of energetic hadron irradiation. The first effect is the change in the doping concentration with severe consequences for the operating voltage needed for total depletion. In this case we can define an effective doping concentration, N_{eff} , using the following relation:

$$V_d \approx \frac{q_0}{2\epsilon_0\epsilon_r} |N_{eff}| d^2 \quad (2.2)$$

q_0 is the electron charge, $\epsilon_0\epsilon_r$ is the dielectric constant of Silicon and d is the bulk thickness. The sign of the effective doping concentration term, N_{eff} , depends on donor removal and generation of acceptor-like defects: $N_{eff} = N_d - N_a$, with N_d being the donor concentration and N_a that of acceptors. Figure 2.3 shows the dependence of N_{eff} on the accumulated 1 MeV equivalent neutron fluence for standard and oxygen enriched Float Zone (FZ) [18] Silicon irradiated with neutrons, protons and pions. The minima of the curves correspond to the fluence at which the bulk effective doping concentration becomes nearly intrinsic and, for this reason, it is called “type inversion.” The second effect is the deterioration of charge collection efficiency due to charge-carriers trapping, causing a reduction of particle detection efficiency. These first two effects are the most severe, as the operation voltage cannot be increased to very high values because of the break-down, and trapping could drastically limit the collected charge. It is worth noting that a large operating voltage, together with a large reverse current, leads also to an increase of dissipated power, which may affect the cooling system and, if not uniformly distributed, can induce thermal run-away effects.

The third effect is the fluence-proportional increase in the leakage current, I , caused by creation of generation-recombination centers. The in-

Figure 2.3: *Dependence of the bulk effective doping concentration (N_{eff}) on the accumulated 1 MeV equivalent neutron fluence for standard and oxygen enriched FZ Silicon irradiated with neutrons, 23 GeV protons and 192 MeV pions (figure from [14]).*

crease of the reverse current due to bulk damage, exhibits a simple dependence on particle fluence as shown in Fig. 2.4. Its measurement, at full-depletion voltage, is proportional to the active volume, V , of the bulk and to the equivalent fluence, $\Phi_{eq.n.}^{1MeV}$, to which the sensor was exposed:

$$I = \alpha \Phi_{eq.n.}^{1MeV} V \quad (2.3)$$

This effect has consequences on the signal-to-noise ratio for particle detection. However, this can be largely reduced by operating the sensors at a moderately low temperature, such as $\sim -10^\circ \text{C}$.

The last effect is the increase of the positive charge trapped in the oxide layer on the surface of the sensor. This could increase the electrical field in proximity of the electrodes and eventually cause voltage break-down. This effect can be drastically reduced by a proper design of the electrodes geometry.

Figure 2.4: *Fluence dependence of leakage current for different sensors with different resistivity (figure from [14]).*

2.3 Evolution with time of the effective doping concentration

The effective doping concentration, N_{eff} , changes with time (t) and temperature (T), and could be described by an empirical model called “Hamburg model” [19]. In this model, measured data points (see Fig. 2.5) are described by two exponential terms and a constant term, which does not depend either on time nor on temperature. The two exponentials account for the following two process:

beneficial annealing, $N_A(\Phi_{eq.n.}^{1MeV}, T, t)$: describes the process that leads to a reduction of acceptors, N_a , and to an increase of donors, N_d . This process has a typical time constant of ~ 1.5 hours at 60°C (~ 5 days at room temperature)

reverse annealing, $N_Y(\Phi_{eq.n.}^{1MeV}, T, t)$: describes the process that leads to a reduction of donors, N_d and to an increase of acceptors, N_a . This process has a typical time-scale of ~ 8 days at 60°C (~ 1.5 years at room temperature)

Figure 2.5: *Typical annealing behaviour of the radiation-induced changes in the effective doping concentration at a temperature of 60° C after irradiation up to a fluence of $1.4 \times 10^{13} \text{ cm}^{-2}$ (figure from [14]).*

Figure 2.5 shows the typical time dependence of the effective doping concentration. There is a clear evidence for the three contributions to the evolution in time. From these considerations it follows that, in general, the sensor life-time can benefit from low temperature. However, periodic annealing at higher temperature, short enough to let the beneficial annealing act, can improve the life-time because of the partial restoration of the crystal lattice order.

Chapter 3

Silicon sensors radiation damage characterization

One of main issues in employing Silicon detectors in HEP experiments is to certify through dedicated measurements their radiation tolerance (see chapter 2). This is particularly crucial for detectors used at hadron colliders, where the total fluence after ten years of operation can reach values well in excess of 10^{14} 1 MeV equivalent neutrons per cm^2 . The picture is even more complicated in presence of highly non-uniform irradiation since the performance of the sensors can dramatically vary over the active area. In these cases a local characterization of the sensors is required.

For these reasons I developed a method for their full characterization. The method allows for a complete bidimensional mapping, point to point, of the sensor characteristics over its entire active area. Information is gathered through the Q-V characteristic, measured scanning the sensor with an infra-red laser source. I performed the measurements on the Silicon micro-strip sensors that I previously irradiated non-uniformly up to a peak fluence of $\sim 10^{14}$ 200 MeV protons per cm^2 . I developed an analytical model to fit the Q-V characteristics and extract the local full-depletion voltage and the local carriers trapping-time.

As expected, I observed a continuous evolution of the bulk behaviour moving along a single strip toward the highest irradiated region, a smooth transition from the original *p*-type to the inverted type behaviour. From

the measurement of the carriers trapping-time I was able to reconstruct the absorbed dose profile and compare it with the actual one.

3.1 The Silicon micro-strip sensor and readout electronics

The Silicon micro-strip sensors, used to carry out the radiation tolerance studies, are the same as those used for the second layer of the Inner Barrel (IB2) for the CMS experiment [20] developed by Hamamatsu.

Figure 3.1: *Sketch of the Silicon micro-strip sensor.*

The sensors are made in standard FZ [18] Silicon p/n type, $320\ \mu\text{m}$ thick, with crystal orientation $\langle 1\ 0\ 0 \rangle$ and resistivity $\sim 2.5\ \text{K}\Omega\ \text{cm}^{-1}$ (*i.e.* $\sim 150\ \text{V}$ full-depletion voltage). They have 512 strips, 116 mm long and with a $120\ \mu\text{m}$ pitch. The active area is $\sim 61 \times 116\ \text{mm}^2$. The total inter-strip capacitance, as seen by the readout electronics, is $\sim 1.3\ \text{pF}\ \text{cm}^{-1}$ at depletion voltage. Each strip has a $p+$ implant width of $30\ \mu\text{m}$, AC-coupled to an Aluminum metallization with an overhang of $5\ \mu\text{m}$ on both implant sides, see Fig. 3.1. The overhang of the strip metallization is necessary in order to prevent the break-down due to accumulation of electric field in proximity of the $p+$ implant after irradiation. The sensors main characteristics are summarized in Tab. 3.1 and the mask design, together with details on their

dimensions, is presented in Fig. 3.3. A cross-section of the sensor showing its

Sensor characteristics	Values
Sensors type	p/n
Active area dimensions	$\sim 61 \times 116 \text{ mm}^2$
Strips	512
Pitch	$120 \text{ } \mu\text{m}$
Bulk thickness	$320 \text{ } \mu\text{m}$
Full depletion voltage	$\sim 150 \text{ V}$
Break-down voltage	$> 500 \text{ V}$
Coupling to readout electronics	AC

Table 3.1: *Main characteristics of the Silicon micro-strip sensors.*

biasing circuit, the guard-ring and the AC (DC) pad connection is reported in Fig. 3.2. The high voltage is provided through a bias-ring to which each strip is connected by a polysilicon resistor of $\sim 1.5 \text{ M}\Omega$, while the ground is provided through the Aluminum back plane of the sensor.

Figure 3.2: *CMS IB2 Silicon micro-strip sensors cross-section in proximity of the edge of the strip. Shown are the bias circuit, the guard-ring and the AC (DC) pad connection.*

The readout chip employed is the TAA1 produced by Ideas [21]. TAA1 chips are made with $0.8 \text{ } \mu\text{m}$ CMOS technology and have a low power consumption of just 0.29 mW per channel. Each chip has 128 channels and from each channel the analog signal can be readout. The main characteristics of the TAA1 chips are the $3 \text{ } \mu\text{s}$ shaping time, that guarantees a very low

readout noise of $\sim 150 \text{ e}^-$ per channel, and the possibility to readout either positive or negative input signals. The VA-DAQ data acquisition system, comprised of a LabVIEW readout software and a board to interface the PC to the TAA1 chips, is as well provided by Ideas [22]. One of the main features of the VA-DAQ board is to digitize, in two's complement with a 14 bit ADC, the analog signal coming from the TAA1 chips; moreover it provides an internal pulser used to characterize each single channel of the chips.

Figure 3.3: Layout of the CMS IB2 Silicon micro-strip sensors.

3.2 Sensor irradiation and measurements

Spectrometers like BTeV, instrumented in the very high η region ($1.9 < \eta < 4.5$), present a typical non-uniform irradiation that scales as $\sim 1/r^2$, where r is the transverse distance from the beam line. The non-uniform irradiation causes a non-uniform effective doping profile in Silicon sensors (see chapter 2), with the consequence of having regions with different full-depletion voltages. The Silicon sensors performance can thus dramatically vary over the active area. Figure 3.4 shows a simulation of the radiation environment, of the BTeV experiment, for the first micro-strip station; the

Figure 3.4: *Radiation dose as a function of the position in the first station of the forward Silicon tracker. The horizontal magnetic field concentrates more particles above and below the central beam hole than on either side.*

radiation dose peak expected is $\sim 1.6 \times 10^{13}$ particles per cm^2 per year, corresponding to $\sim 0.8 \times 10^{13}$ 1 MeV equivalent neutrons per cm^2 per year. Since we are dealing with highly energetic particles, the fluence has been rescaled according to Eq. (2.1) using a hardness factor $k = 0.5$ [17]. Given the previous considerations, I decided to irradiate our micro-strip sensors non-uniformly. The irradiation was performed at Indiana University Cyclotron Facility (IUCF) [23], with a proton beam of 200 MeV energy. The beam was approximately centered on the edge of the sensors opposite to the readout

Figure 3.5: *IUCF irradiation geometry. Shown are the proton beam Gaussian shape and the approximated position of the beam peak which was centered on the edge of the sensor, opposite to the readout electronics.*

electronics, as shown in Fig. 3.5. The beam shape was measured with the wire scanner technique and the data, together with a Gaussian fit, are presented in Fig. 3.6. I irradiated two sensors: Mod1 up to a peak fluence of

Figure 3.6: *IUCF proton beam shape measured with the wire scanner technique. Gaussian fit $\sigma \simeq 19$ mm.*

$\sim 0.8 \times 10^{14}$ 1 MeV equivalent neutrons per cm^2 , corresponding to 10 years of BTeV operation; and Mod2 up to a peak fluence of $\sim 3.5 \times 10^{13}$ 1 MeV equivalent neutrons per cm^2 , corresponding about to the dose at the type inversion (see Fig. 2.3). Since low energetic protons, like those of IUCF, cause the same damage as neutrons of 1 MeV energy, I used a hardness

factor $k = 1$ [17] for fluence rescaling.

Figure 3.7: *I-V characteristics for Mod1 (on the left) & Mod2 (on the right) measured during irradiation at room temperature. In the inset, in the upper right corner, is shown the I-V characteristic before irradiation.*

Figure 3.7 shows the I-V characteristics measured at different fluences during irradiation at room temperature. It's worth noting that the break-

Figure 3.8: *Mod1&Mod2 leakage current measured biasing the sensors at 400 V as a function of the peak fluence. The straight line is the expected empirical curve taken from literature. The measurements were performed at room temperature.*

down voltage still remains higher than 500 V. After irradiation the sensors were always kept at a temperature lower than -12° C without applying any

annealing cycle. Figure 3.8 reports the leakage current, measured biasing the sensors at 400 V, as a function of the peak fluence. Since the irradiation was non-uniform, I calculated the total absorbed dose by integrating the two-dimensional Gaussian shape of the radiation beam, $\Phi_{eq.n.}^{1MeV}(x, y)$, over the sensor surface. Thus, Eq. (2.3) should be modified as follow:

$$I = \alpha \int \Phi_{eq.n.}^{1MeV}(x, y) dV = \alpha d \int \Phi_{eq.n.}^{1MeV}(x, y) dx dy \quad (3.1)$$

d is the sensor bulk thickness and $\alpha = 4.56 \times 10^{-7} \text{ A cm}^{-1}$ was taken from literature [24]. The expected behaviour of the leakage current with the fluence is confirmed by my measurements.

Figure 3.9: *Histogram of the noise for Mod1 (on the left) & Mod2 (on the right), measured at different conditions: (1) pure readout electronics noise, sensor disconnected; (2) measured noise on strips before the irradiation; and (3) after the irradiation.*

Figure 3.9 shows the noise value measured on several channels of Mod1 and Mod2 for three different conditions:

1. pure readout electronics noise, sensor disconnected
2. noise measured on strips **before** irradiation
3. noise measured on strips **after** irradiation

I observed an appreciable increase of the noise due to the irradiation, which, for the highest irradiated sensor, goes up from $\sim 985 \text{ e}^-$ to $\sim 1200 \text{ e}^-$.

3.3 Laser setup and measurements

The characterization method that I developed is based on **local** measurement of the Q-V characteristic. I used an infra-red laser source [25], whose main characteristics are reported in Tab. 3.2, to locally generate electron-hole pairs uniformly all along the bulk thickness of the sensor.

Laser characteristics	Values
Wavelength	1064 nm
Spectral band width	0.1 nm
Pulse duration	1 ns
Beam power (at the tip of the optical fiber)	5 mW
Absorption length in Silicon	~1.1 mm at 25° C [26]

Table 3.2: *Laser main characteristics.*

In order to perform a bidimensional scan of the sensor with the laser source, I placed the detector on an $X - Y$ moving table, whose step-motors were controlled by a personal computer that guaranteed very precise and reproducible movements. The laser pulses were carried through a monomode fiber to the final focusing lens, which was mounted directly on the Z -axis of the table. The sensor was kept at -12° C by an underlying Aluminum-Copper plate cooled by a Nestlab CB-80 water-glycol refrigeration system. The atmosphere around the detector was filled with Nitrogen to prevent condensation. The whole setup apparatus is sketched in Fig. 3.10, while Fig. 3.11 shows a picture of the actual setup, where the Nitrogen bag and the Aluminum-Copper thermal exchanger are visible. A pulse generator provided the very fast signal to the laser diode current-driver; the same generator provided also a synchronous NIM signal, which was used to trigger the Ideas readout electronics.

The stability of the laser wavelength was guaranteed by a temperature control system operating with Peltier cells. The system constantly monitored the temperature of the laser diode with a thermistor and consequently

Figure 3.10: *Setup apparatus for local measurement of Q - V characteristics on irradiated Silicon micro-strip sensors. It consists of an $X - Y$ moving table controlled by a personal computer. The sensor is kept at -12°C by an underlying Aluminum-Copper plate cooled by a water-glycol refrigeration system. The atmosphere around the detector is filled with Nitrogen to avoid condensation. The moving table is kept in a dark box.*

regulated the current in the Peltier cells that cooled the laser diode. The laser pulse amplitude was monitored through an oscilloscope; indeed an optical beam splitter sent half of the beam to the laser optics and half of the beam to an Opto Electronics [27] photo detector connected to the oscilloscope.

It is worth noting that the temperature stability is crucial for these measurements; precisely, the laser absorption in Silicon, in the infra-red region of the spectrum, critically depends not only on the laser diode temperature but also on the sensor temperature. Figure 3.12 reports two sets of measurements of the collected charge performed on a non-irradiated sensor at different temperatures, 27°C and -13°C . From these measurements the dependence of the collected charge on the temperature can be estimated; in the simplified hypothesis of linear dependence, it turns out to be $\sim 17500 \text{ e}^-$ per degree Celsius, which means a variation of the collected charge of $\sim 2.2\%$

Figure 3.11: *Sensor cooling system. A water-glycol mixture was flowed through ducts placed inside the Aluminum plate, over which the sensor was placed.*

Figure 3.12: *Temperature dependence of the collected charge for a non-irradiated sensor. The collected charge was measured at positions transversal to strips at two different temperatures, 27° C and −13° C. The measurements were performed biasing the sensor at 160 V.*

per degree Celsius at -13° C. Therefore I constantly monitored the temperature with a thermocouple placed on the Aluminum-Copper cooling plate and a thermistor placed close to the sensor. I regulated the Nitrogen flux and the refrigerator pump in order to keep the temperature stable within 1° C.

I illuminated the sensor on the strip side. In this situation, only the

fraction of the laser light impinging on the sensor between adjacent strip metallizations could reach the bulk of the sensor. To reduce to a negligible level the dependence of the quantity of absorbed light on the position of its source, I illuminated a wide region, ~ 20 strips, by placing the sensor out of the focal plane of the lens, as shown in Fig. 3.13. Given the ratio of metallization to pitch, $40\text{ }\mu\text{m}/120\text{ }\mu\text{m}$, only $2/3$ of the laser light penetrates the bulk.

Figure 3.13: *Sketch of the laser spot and the relative position of the sensor with respect to the laser focusing plane.*

For each position of the laser beam on the sensor and for different bias voltages, I sent ~ 1000 laser pulses and I measured the collected charge. The

Figure 3.14: *Gain and pedestal calibrations.*

final value of the total collected charge was obtained by the following data handling procedure:

1. I previously calibrated the system in the same experimental condi-

tions, of temperature and bias voltage, as the laser measurements. I subtracted the pedestal and converted the scale from millivolt to electrons for all the ~ 1000 measurements, channel to channel. A typical calibration, measured at -12°C and 350 V, is shown in Fig. 3.14

2. calculated and subtracted the common-mode for each of the ~ 1000 measurements
3. summed all the ~ 1000 measurements channel to channel, and divided the result by the number of pulses; obtaining one single pulse as shown in Fig. 3.15
4. fitted with a Gaussian the laser peak. This was done in order to smooth the charge collection difference between strips due to dead channels
5. finally the total collected charge was calculated integrating the Gaussian fit

Figure 3.15: *Collected charge per strip after averaging ~ 1000 pulses. On the left: row data. On the right: data after equalization and common-mode subtraction with the Gaussian fit superimposed. This measurement was taken biasing the sensor at 350 V.*

Figure 3.15 shows a typical laser pulse averaged over ~ 1000 pulses, before and after equalization and common-mode subtraction.

An Am^{241} γ -source was used to provide an absolute calibration of the apparatus. Am^{241} emits photons of 59.6 KeV, corresponding to ~ 2.6 fC in

Figure 3.16: *Typical signal from an Am^{241} γ -source. At higher ADC values the 59.6 KeV signal peak is visible above the noise. Both peaks are fit with Gaussians. The spectrum was shifted to the left positioning the pedestal to zero.*

Silicon. A typical spectrum of the γ -source seen by a single strip is shown in Fig. 3.16. Here the spectrum has been shifted so the pedestal peaks at zero. The peak corresponding to 59.6 KeV is clearly visible at higher ADC values; while at lower ADC values is visible the pedestal peak. The position of the signal, as well as that of the pedestal, was measured by Gaussian fit to the 59.6 KeV peak and pedestal peak, in absence of signal, respectively. The noise spectrum is reported in Fig. 3.17. From the signal fit I obtained a value of 367.1 ± 3.3 ADC counts; that corresponds to ~ 134.4 mV. Therefore the gain was ~ 52 mV fC $^{-1}$, whereas the internal calibration gave ~ 57 mV fC $^{-1}$.

Figure 3.17: *Typical pedestal peak spectrum with superimposed the Gaussian fit for the determination of its position.*

Figure 3.18: *Mod1 Q-V characteristics superimposed with fits to the model. On the left: data from the opposite side of the radiation beam peak; $\rho_0 = 3302 \pm 12 \text{ e}^- \mu\text{m}^{-1}$, $\tau = 1000 \text{ ns}$ (fixed parameter), $V_d' = 101.0 \pm 1.4 \text{ V}$, $V_{off} = -0.1 \pm 0.1 \text{ V}$. On the right: data from the radiation beam peak side; $\rho_0 = 3341 \pm 23 \text{ e}^- \mu\text{m}^{-1}$, $\tau = 29.3 \pm 1.4 \text{ ns}$, $V_d' = 25.3 \pm 1.5 \text{ V}$, $V_{off} = 6.0 \pm 0.2 \text{ V}$.*

Figure 3.18 presents two typical sets of measurements superimposed with fits to the model that will be described in the next section. In blue and red are also reported the two contributions, due to electrons and holes respectively, to the total induced signal. These measurements were performed in two particular positions of Mod1 sensor, the first plot refers to measurements taken on the non-irradiated region, the second refers to measurements taken on the highest irradiated region. It is worth noting the change of the shape between the two sets of measurements and also the change of the relative contribution of electrons and holes to the total induced signal. In the next section I will describe the model that I developed to extract physical information from the shape of the Q-V characteristic.

An important conclusion can already be made; these sensors, non uniformly irradiated up to a fluence corresponding to ~ 10 years of BTeV operation, are able to collect more than the 95% of the total charge if biased at 350 V at least. Which makes them well suited to be used in the BTeV experiment.

3.4 Collected charge model

I approximated the sensor as a simple p/n diode with infinite plane electrodes. To the extent of describing the total collected charge by all the strips, the validity of this approximation is only limited by the different electric field configuration near the p -implant. In this region the transport of the carriers is different and, thus, could in principle affect the evaluation of the carriers trapping-time. On the other hand, the extension of this region is negligibly small, and therefore no appreciable biases will be introduced by my model [28]. Interestingly enough, for long carriers trapping-time as for non-irradiated sensors, my model reproduces the data with good accuracy, as shown in Fig. 3.18. This means that the progression of the depleted region with the bias voltage is practically identical even in proximity of the p -implant¹. The main advantage of the present approach is that one can apply the simplest version of the Ramo theorem and obtain an analytical expression for the total collected charge, which is extremely advantageous for these kind of applications. My main goal is to characterize the sensor performances for their application in HEP experiments and certainly not to perform a very precise measurement of the physical parameters involved. All in all, this model provides an approximate description of the local Q-V characteristics, *i.e.* the total collected charge as a function of the applied bias voltage in a particular position of a sensor. It is employed to get an estimate of the sensor main physical parameters and, hence, to analyze the damage induced by irradiation.

I will begin by describing the transport of the carriers during their migration toward the electrodes and then I will introduce the Ramo theorem to calculate the total induced signal.

¹Obviously to claim this I have to assume an uniform generation of charge in the bulk of the sensor. On the other hand, this seems to be the most reasonable assumption, since, otherwise, I should advocate a singular conspiracy of effects. “Pluralitas non est ponenda sine necessitate,” W. Ockham (1280–1347).

3.4.1 Transport

In the case of a p/n diode with infinite plane electrodes the problem one has to deal with becomes monodimensional, the only coordinate surviving being x along the electric field lines. Any charge density $\rho(x)$, either electrons or holes, generated at x in the depleted region, drifts toward the proper electrode along the electric field lines and evolves with the following equation:

$$\rho(x + dx) - \rho(x) = -\frac{dx}{\lambda(x)}\rho(x) \quad (3.2)$$

$\lambda(x)$ is the mean free path for trapping and is given by:

$$\begin{aligned} \lambda(x) &= \tau v(E(x)) \\ \text{with: } \tau &= \frac{1}{\sigma v_{th} N_t} \end{aligned} \quad (3.3)$$

E is the electric field, v the drift velocity, τ the carrier trapping-time, σ the trapping cross-section, v_{th} the thermal velocity and N_t the effective trap concentration. σ , v_{th} , N_t and τ do not vary with the electric field. The drift velocity, on the other hand, depends on the electric field through the relation [29]:

$$v(E) = \frac{\mu_0 E}{1 + (\mu_0/v_s)E} \quad (3.4)$$

where μ_0 is the mobility and v_s is the saturation velocity ($88 \mu\text{m ns}^{-1}$ for holes and $116 \mu\text{m ns}^{-1}$ for electrons). The mobilities I used were rescaled from the quoted values, at 300°K ($507 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$ for holes and $1590 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$ for electrons), according to the well known formulae: $\mu_h \propto T^{-2.2}$ and $\mu_e \propto T^{-2.4}$ [30]. There is no evidence that the mobilities and saturation velocities change with irradiation [31].

The solution of the Poisson equation for a constant charge density is a linear electric field:

$$E(x) = \begin{cases} Ax & \text{if } V_b \leq V_d \\ Ax + B & \text{if } V_b > V_d \end{cases} \quad (3.5)$$

It is possible to express the electric field in terms of the bias voltage V_b , the full-depletion voltage V_d and the bulk width w ($320 \mu\text{m}$). In this case A and B can be written as $A = \frac{2V_d}{w^2}$ and $B = \frac{V_b - V_d}{w}$. This solution is rigorously correct for a constant charge density, but, as stated in section 3.4, there

might be slight changes in case of irradiation. I will discuss in section 3.5 the effect of this approximation.

By integrating Eq. (3.2) from x_1 to x_2 one can obtain the residual charge density at x_2 , for a charge density which was originally generated at x_1 and has migrated subjected to trapping up to x_2 .

$$\rho(x_1, x_2) = \rho(x_1) e^{-\int_{x_1}^{x_2} \frac{dx}{\lambda(x)}} \quad (3.6)$$

Equation (3.6) can be explicitly calculated by using Eq. (3.3) and Eq. (3.4):

$$\rho(x_1, x_2) = \rho(x_1) \left(\frac{E(x_2)}{E(x_1)} \right)^{\frac{-1}{\tau \mu_0 A}} e^{-\frac{x_2 - x_1}{\tau v_s}} \quad (3.7)$$

In order to obtain a final analytical expression of the collected charge, I approximated at first order the last term of Eq. (3.7):

$$\rho(x_1, x_2) = \rho(x_1) \left(\frac{E(x_2)}{E(x_1)} \right)^{\frac{-1}{\tau \mu_0 A}} \left(1 - \frac{x_2 - x_1}{\tau v_s} \right) \quad (3.8)$$

This approximation is justified as long as $(x_2 - x_1) \ll (\tau v_s)$, which is satisfied for $\tau \gg 4$ ns, since the highest value that $x_2 - x_1$ can assume is the bulk thickness, 320 μm , and the lowest saturation velocity is 88 $\mu\text{m ns}^{-1}$ for holes.

3.4.2 Induction

Now I apply the Ramo theorem, *i.e.* a charge Q moving in a potential difference dV , induces on the electrodes a charge dQ_I given by:

$$dQ_I V_b = Q dV \quad (3.9)$$

V_b is the electric potential applied between the electrodes. Putting Eq. (3.9) in an integral form and using the transport equation, Eq. (3.8), one can obtain:

$$Q_I = \frac{1}{V_b} \int_0^X \int_{x'}^X \rho(x, x') E(x) dx dx' \quad (3.10)$$

$X = w \sqrt{\frac{V_b}{V_d}}$ is the depth of the depleted region. Finally, integrating explicitly Eq. (3.10), the following expressions for the signal induced by holes and

electrons can be obtained:

$$\begin{aligned}
Q_{Ih} = & \frac{\rho_0}{V_b A^2 (2 - R_h)} \left[E(X)^3 \frac{2 - R_h}{3(1 + R_h)} + \right. \\
& - \frac{E(X)^3}{(1 + R_h)\tau v_s} \left(\frac{E(X)}{A(2 + R_h)} - X \right) + \\
& \frac{E(X)^{2-R_h} B^{1+R_h}}{1 + R_h} \left(\frac{B}{A(2 + R_h)\tau v_s} - 1 \right) + \frac{B^3}{3} \Big] + \\
& \frac{\rho_0}{V_b A^2 (2 - R_h)\tau v_s} \left[\frac{E(X)^3}{1 + R_h} \left(\frac{E(X)}{4A} - X \right) + \right. \\
& - \frac{E(X)^{2-R_h} B^{1+R_h}}{1 + R_h} \left(\frac{E(X)}{A(3 - R_h)} - X \right) + \frac{B^4}{4A(3 - R_h)} \Big] \quad (3.11)
\end{aligned}$$

$$\begin{aligned}
Q_{Ie} = & \frac{\rho_0}{V_b A^2 (2 + R_e)} \left[\frac{E(X)^3}{3} + \right. \\
& - \frac{E(X)^{1-R_e} B^{2+R_e}}{1 - R_e} \left(1 + \frac{1}{\tau v_s} \left(\frac{E(X)}{A(2 - R_e)} - X \right) \right) + \\
& B^3 \frac{2 + R_e}{3(1 - R_e)} + \frac{B^4}{(1 - R_e)(2 - R_e)\tau v_s} \Big] + \\
& \frac{\rho_0}{V_b A^2 (2 + R_e)\tau v_s} \left[-\frac{E(X)^4}{4A(3 + R_e)} + \frac{E(X)^{1-R_e} B^{3+R_e}}{A(1 - R_e)(3 + R_e)} + \right. \\
& \left. - \frac{B^4}{4A(1 - R_e)} \right] \quad (3.12)
\end{aligned}$$

R_h is defined as $R_h = \frac{-1}{\tau_h \mu_h A}$ for holes and $R_e = \frac{-1}{\tau_e \mu_e A}$ for electrons. It is worth noting that in doing these calculations I had tacitly assumed a constant charge, electron-hole pairs, density, ρ_0 , generated by the laser pulse through the whole depleted region. My data seem to confirm this assumption (see the comments at the end of section 3.6.4 and at the beginning of section 3.4).

So far this model has four free parameters:

- ρ_0 : the initial charge density in the bulk, generated by the laser pulse.
It can be expressed either in $[e^- \mu\text{m}^{-1}]$ or $[h \mu\text{m}^{-1}]$
- τ_e : the electrons trapping-time [ns]
- τ_h : the holes trapping-time [ns]
- V_d : the full-depletion voltage [V]

The number of free parameters can be reduced from four to three using the empirical relation [32]:

$$\frac{1}{\tau_{e,h}} = \gamma_{e,h} \Phi_{eq.n.}^{1MeV} \quad (3.13)$$

which relates the trapping-times of electrons and holes to the radiation fluence. The coefficients $\gamma_{e,h}$ are known from literature and are in units of $\text{ns}^{-1} \times 10^{14} \text{ 1 MeV eq.n.} \times \text{cm}^2$, and do not depend on the sensor type. For instance, at -10° C , $\gamma_e = 0.042 \pm 0.003$ for electrons and $\gamma_h = 0.061 \pm 0.003$ for holes [33]. Thus:

$$\tau_h = \frac{\gamma_e}{\gamma_h} \tau_e \quad (3.14)$$

This model can be easily extended to accommodate effects due to non-linearities of the electric field which are typically observed on irradiated sensors [34, 35, 36, 37]. To this extent I allow for an additional fit parameter,

Figure 3.19: *Positive charge trapped in the oxide layer. It changes the electric field in proximity of the electrode.*

V_{off} . This defines a kind of an effective bias voltage, $V'_b = V_b - V_{off}$, which should replace V_b in my previous equations. In the case of an excess of charge close to the p -implant, which is typically caused by positive charge trapped in the oxide layer (see Fig. 3.19), V_{off} acts as an initial offset voltage, which serves to saturate the charge excess; for V_b values higher than V_{off} , the sensor quickly reaches the canonical asymptotic behaviour in V'_b . This requires that the first measurement points, up to voltages of the order of V_{off} , should be eliminated from the fit. In an analogous way, V_{off} is even capable to allow for huge deviations from linearity of the electric field, as those encountered at very high absorbed doses, which could be explained by trapping of generation currents in acceptor and donor traps [38] (cfr. the next section).

At the end, this model has four free parameters, namely: ρ_0 , τ_e , V'_d and V_{off} .

3.5 Model accuracy

I will discuss the accuracy of the model in the context of the main approximations that have been introduced:

- linear electric field inside the bulk
- first order approximation of a term in the transport equation, Eq. (3.7)

I studied in details the biases, that these assumptions might introduce in the extraction of the main physical parameters, by fitting with my model different sets of Q-V characteristics, which were accurately simulated.

Figure 3.20: *Two-slope linear electric field. First figure: under depletion (20 V). Second figure: at depletion (40 V). Third figure: over depletion (150 V). The excess of positive charge at the electrode side is ten times greater than in the bulk and its extension is 60 μm .*

To study the effect of the positive charge trapped in the oxide layer, I approximated the excess of charge near the electrode with a step function having a depth of 60 μm and magnitude ten times greater than the fixed charge in the bulk. The electric field generated by this charge configuration has two slopes, as shown in Fig. 3.20. In this case, the fit to the simulated Q-V characteristic is shown in Fig. 3.21. The parameters used for the simulation were those typically measured on my two sensors. The deviation of the fit parameters from the actual values are reported in Tab. 3.3. The only sizable deviation, 4%, is on the full-depletion voltage, which results from the sum of $V'_d = 31.9$ V and $V_{off} = 9.7$ V.

Figure 3.21: *Fit to the two-slope linear electric field simulation. The parameter values are: $\rho_0 = 3300 \text{ e}^- \mu\text{m}^{-1}$, $\tau_e = 60 \text{ ns}$, $V_d = 40 \text{ V}$ and the extension of the excess of positive charge at the electrode side is $60 \mu\text{m}$.*

Fit parameters	Actual values	Fit deviations
Initial charge density	$3300 \text{ e}^- \mu\text{m}^{-1}$	$< 0.1\%$
Electron trapping-time	60 ns	1%
Full-depletion voltage	40 V	4%

Table 3.3: *Deviation of the fit parameters from two-slope linear electric field simulation.*

Some recent measurements [35, 36, 37] have shown that, at high fluences, of the order of $(5-10) \times 10^{14} \text{ 1 MeV equivalent neutrons per cm}^2$, the electric field inside the bulk becomes highly non-linear and assumes a quasi-parabolic shape. The charge density configuration, that generates this field, seems to be due to the two generation currents, of holes and electrons, trapped by acceptor and donor traps respectively. I approximated this behaviour with a linear charge density that generates a parabolic electric field, as shown in Fig. 3.22. I tested my model at the limit of its validity, which corresponds to a trapping-time of 5 ns (or equivalently to a radiation fluence of $\sim 5 \times 10^{14} \text{ 1 MeV equivalent neutrons per cm}^2$). Fit to the Q-V characteristic is shown in Fig. 3.23. From the last five points of the simulation the model was able to recover the actual values of the parameters with small deviations, as reported in Tab. 3.4.

Figure 3.22: *Parabolic electric field. First figure: under depletion (100 V). Second figure: at depletion (250 V). Third figure: over depletion (350 V).*

Figure 3.23: *Fit to the parabolic electric field simulation. The parameter values are: $\rho_0 = 3300 \text{ e}^- \mu\text{m}^{-1}$, $\tau_e = 5 \text{ ns}$ and $V_d = 250 \text{ V}$.*

I also estimated the effects introduced by the fact that the $\gamma_{e,h}$ coefficients are not well known. I run the simulation with the coefficient ratio of Eq. (3.14) displaced from its central value by $\pm\sigma$, where σ is the error on the γ_e/γ_h ratio. In both cases, of two-slope linear electric field and parabolic electric field, the deviation of τ_e from its actual value is $< 6\%$, which is of the same order of the γ_e error. The effect on the other fit parameters is negligible but for the full-depletion voltage in the case of parabolic field, for which the deviation is $\sim 6\%$.

From these studies and many other, performed for different field configurations and absorbed doses, I can conservatively estimate the biases on the fit parameters as quoted in Tab. 3.5. I don't report any error on the biases since they have been obtained by fitting the simulation that has infinite statistic.

Fit parameters	Actual values	Fit deviations
Initial charge density	3300 e ⁻ μm ⁻¹	2%
Electron trapping-time	5 ns	4%
Full-depletion voltage	250 V	4%

Table 3.4: *Deviation of the fit parameters from parabolic electric field simulation.*

Fit parameters	Biases
Initial charge density	2%
Electron trapping-time	6%
Full-depletion voltage	6%

Table 3.5: *Biases on returned fit parameters.*

3.6 Results and discussion

With the model just described I characterized the highest irradiated sensor, Mod1. Before showing the results of the fit I will briefly discuss the statistical and systematic errors I applied to the measured points.

3.6.1 Errors treatment

It is easy to demonstrate that in my case the statistical measurement error is negligible with respect to the systematic error due to the relative instability of the employed setup. Indeed, the measured values of the collected charge at different voltages were obtained by averaging over ~ 1000 measurements of the same quantity. The statistical error of a single measurement has three components:

- fluctuations of the generated electron-hole pairs, assumed poissonian, $\sqrt{n_{e,h}}$
- electronic noise of the readout channels, σ_{noise} , and
- measured fluctuation of common-mode, σ_{CM}

Taking into account the fact that each measurement comes from the sum of the charge collected by 80 strips, N_{strips} , the total statistical error becomes: $\sigma_{stat}^2 = n_{e,h} + N_{strips}(\sigma_{noise}^2 + \sigma_{CM}^2)$. The second term of the previous expression, which constitutes the electronic contribution to the error, can be computed assuming conservatively that $\sigma_{CM} \sim \sigma_{noise} = 1200 \text{ e}^-$ and thus obtaining $\sqrt{2 \cdot 80 \cdot 1200^2} \simeq 15175 \text{ e}^-$. The total error will then be practically independent on the collected charge since it varies from $\sim 15180 \text{ e}^-$, for the smallest value of collected charge in my measurement ($\sim 150000 \text{ e}^-$), to $\sim 15210 \text{ e}^-$ for the highest value ($\sim 10^6 \text{ e}^-$). This means that the statistical error obtained averaging 1000 measurements is $\sim 480 \text{ e}^-$, which corresponds to $\sim 0.32\%$ of the signal in the worst case.

This figure of statistical error is negligible compared to the systematic error introduced by my setup, which can be *a priori* estimated around 1% taking into account the laser system stability and temperature fluctuations.

Figure 3.24: *NDF-normalized χ^2 distribution for the 12 fits to the measured Q-V characteristics well away from the irradiated region.*

Actually I cross-checked this guess by estimating the fractional systematic error required to obtain an average χ^2 value equal to the number of degrees of freedom for the fits to the data taken in the non-irradiated region of the sensor, where my model is expected to closely reproduce the measurements. The required systematic error turned out to be $\sim 1.2\%$. This is the value I used for my measurements. The NDF-normalized χ^2 distribution for the 12 fits to the measured Q-V characteristics well away from the irradiated region (the first 12 points on the left of Fig. 3.25) is reported in Fig. 3.24.

3.6.2 Fit results

As one can see from the overall measurement points sketched in Fig. 3.25, I performed a detailed map of the Mod1 sensor active area. The reference point for the coordinate along the strips is the edge of the sensor on the chip-side, in the non-irradiated region, while the strip number corresponds to the strip on which the laser spot was centered. The results of the fits

Figure 3.25: *Sketch of the overall measurement points on Mod1.*

to the measured Q-V characteristics are reported in Figs. 3.26, 3.27, 3.28, 3.29, 3.30, 3.31 and 3.32. The electrons and holes contributions to the total induced signal are also reported in blue and red respectively.

Since the first twelve points, on the left of Fig. 3.25, belong to a non-irradiated region, the carriers trapping-time are high enough to allow that practically all the electron-hole pairs generated in the bulk reach the electrodes. I therefore performed the first twelve fits fixing the electron trapping-time to a value for which the exponential term of Eq. (3.7) could be considered equal to 1, thus I set $\tau_e = 1000$ ns.

I adopted the following criteria or guidelines to fit each Q-V characteristic:

1. I started using all data points in the fit
2. if the NDF-normalized χ^2 value of the fit was greater than 2, I disregarded the first measured point and restart the fit. This was done until I reached a normalized $\chi^2 < 2$. In any case this process must

Figure 3.26: *Fit to measurement points at 10 mm from chip side. Strips 77, 145, 208, 281, 344 and 470 from the upper left to the lower right.*

Figure 3.27: *Fit to measurement points at 40 mm from chip side. Strips 77, 145, 208, 281, 344 and 470 from the upper left to the lower right.*

stop before the knee of the Q-V characteristic, which corresponds to the full-depletion voltage

3. if the fit wasn't able to reach adequate convergence, the role of electrons and holes was exchanged in the model and the fit procedure was restarted from step 1

It could happen, as it did in one case, that convergence can be achieved both for a choice of electrons and holes as well for the reverse choice. In this case,

Figure 3.28: *Fit to measurement points at 60 mm from chip side. Strips 77, 145, 208, 281, 344 and 470 from the upper left to the lower right.*

Figure 3.29: *Fit to measurement points at 80 mm from chip side. Strips 77, 145, 208, 281, 344 and 470 from the upper left to the lower right.*

the final decision was guided by the behaviour of adjacent measurement points, *i.e.* imposing a consistency principle.

I report in Tabs. 3.6 and 3.7 the results of the fits on full-depletion voltage and carriers trapping-time respectively; moreover additional measurement points, performed in the highest irradiated region, are reported in Tab. 3.8. I don't report the same table for the ρ_0 parameter since all values are consistent with 3300 e^- within 2%.

Figure 3.30: *Fit to measurement points at 90 mm from chip side. Strips 77, 145, 208, 281, 344 and 470 from the upper left to the lower right.*

Figure 3.31: *Fit to measurement points at 100 mm from chip side. Strips 77, 145, 208, 281, 344 and 470 from the upper left to the lower right.*

I will now discuss the relative contribution that electrons and holes give to the total induced signal.

3.6.3 Remarks on fits

Holes are the carriers that give the highest contribution to the total induced signal for n -type bulk. This fact is explained reminding that, for non-irradiated sensors, holes drift toward higher electric field magnitude, thus,

Figure 3.32: *Fit to measurement points at 110 mm from chip side. Strips 77, 110, 145, 174, 208, 281, 311, 344 and 470 from the upper left to the lower right.*

the integral of the work done by the electric field on this type of carrier is greater than the work done on electrons. Indeed, in the fits of Figs. 3.26 and 3.27 performed in the non-irradiated region of Mod1, the total induced signal by holes is always higher than the signal induced by electrons.

In case of moderate irradiation, before type inversion, the carriers trapping-time is decreased and both electrons and holes might be trapped before reaching the electrodes. In this situation, due to the higher mobility of electrons with respect to holes, the difference of the two contributions to the total induced signal is reduced. Indeed, we can also foresee a situation in which, even before type inversion, electrons give the highest contribution. The first plot of the second row of Fig. 3.30 shows exactly this behaviour, in which, to fit that data set, I didn't exchange the role of electrons and holes with respect to a non-irradiated sensor.

In case of high irradiation the bulk becomes of p -type and the junction moves to the back-plane side. In this case the carriers going toward the

Full-depletion voltage						
D [mm]	# strip					
	77	145	208	281	344	470
10	98.4±1.6	103.9±1.5	100.9±1.4	107.4±1.5	102.2±1.4	101.0±1.4
40	123.9±1.6	128.0±1.7	120.3±1.6	123.5±1.6	111.7±1.4	131.2±1.6
60	124±2.0	117.0±1.8	140.5±2.9	115.2±3.3	134.7±1.7	150.4±1.2
80	145.8±2.6	106.6±3.9	80.5±3.6	86.8±5.2	102.0±3.7	149.0±2.4
90	102.5±3.9	75.2±3.9	38.0±7.5	15.0±7.1	50.5±2.9	109.2±3.8
100	39.6±3.0	23.0±1.3	22.6±1.4	24.1±1.5	21.0±1.2	58.9±2.7
110	25.5±1.2	21.7±1.5	31.3±1.5	41.7±1.7	30.8±1.4	28.6±4.8

Table 3.6: *Fit results on full-depletion voltage. The data reported are the sum of the effective full-depletion voltage, V_d' , and the V_{off} parameter. The errors reported are the sum in quadrature of the errors returned by the fit on the two parameters. An error of 6%, coming from the bias of the model, should be added as reported in Tab. 3.5. D: distance from chip side.*

Trapping-time						
D [mm]	# strip					
	77	145	208	281	344	470
10	1000	1000	1000	1000	1000	1000
40	1000	1000	1000	1000	1000	1000
60	1058±1282	1962±3157	1237±681	930±579	2768±3404	800±688
80	242±98	162±84	74±10	68±11	70±13	1665±1555
90	84.3±18.4	72.3±14.0	59.8±6.1	67.6±4.3	62.7±7.5	77.1±14.6
100	67.4±6.5	40.1±1.6	38.0±1.6	37.6±1.6	44.2±1.9	70.3±9.0
110	50.8±2.7	35.7±1.5	29.3±1.4	25.5±1.5	29.2±1.3	61.3±5.0

Table 3.7: *Fit results on trapping-time. The errors reported are those returned by the fit. An error of 6%, coming from the bias of the model, should be added as reported in Tab. 3.5. D: distance from chip side.*

higher electric field magnitude are electrons, which are also the carriers with the highest mobility; therefore they will give always the highest contribution to the total induced signal. The plots for which I had to exchange the role of electrons and holes are in Figs. 3.31 and 3.32, for instance: (strip 145, 100 mm), (strip 208, 100 mm), (strip 281, 100 mm), (strip 344, 100 mm),

V_d and τ for strips 77, 110 and 174 at 110 mm			
Parameter	# strip		
	110	174	311
V_d	16.1 ± 1.3	19.8 ± 1.7	31.5 ± 1.7
τ	45.5 ± 2.2	30.3 ± 1.2	26.2 ± 1.3

Table 3.8: *Additional measurement points in the highest irradiated region for strips 110, 174 and 311, at 110 mm with respect to the non-irradiated side. The errors reported are those returned by the fit. An error of 6%, coming from the bias of the model, should be added as reported in Tab. 3.5.*

(strip 77, 110 mm), (strip 110, 110 mm), (strip 145, 110 mm), (strip 174, 110 mm), (strip 208, 110 mm), (strip 281, 110 mm), (strip 311, 110 mm) and (strip 344, 110 mm).

3.6.4 Results on full-depletion voltage and carriers trapping-time

I will now discuss the progression of full-depletion voltage and carriers trapping-time along the strips considering three significant examples of my measurements: laser beam centered on lateral strips (#77, #470) and laser beam centered on a central strip (#281). Figure 3.33 reports the full-

Figure 3.33: *Full-depletion voltage along strips. Strips 77 and 470 are lateral strips, whereas strip 281 is a central strip, which presents a minimum at ~ 90 mm, as expected for intrinsic Silicon.*

depletion voltage along the three strips. All the strips present a big drop in the measured full-depletion voltage in correspondence of the highest irradiated side (from 80 mm on). For the central strip the full-depletion voltage

reaches a minimum at ~ 90 mm, then it starts raising again.

Figure 3.34: *Trapping-time along strips. Strips 77 and 470 are lateral strips, whereas strip 281 is a central strip, which presents the lower trapping-time value, correlated to a higher concentration of crystal damages.*

Figure 3.34 reports the carriers trapping-time along the three strips. All the strips present a decrease of the trapping-time in correspondence of the highest irradiated side. The 110 mm lateral strips present a trapping-time greater than 50 ns, whereas for the central strip, and in correspondence to a region of higher concentration of crystal damages, it drops to ~ 20 ns.

The data presented on the full-depletion voltage and carriers trapping-time are consistent with the picture in which the irradiation beam was centered on the edge of the sensor, opposite to the readout electronics, as expected. Indeed, the decrease of the full-depletion voltage along the central strip 281, or else the decrease of the bulk effective doping concentration that originally was of n -type, is related to an increment of the absorbed fluence. At ~ 90 mm, and in the central region, the effective doping concentration of the bulk becomes intrinsic. Going forward, toward the edge of the sensor, the absorbed dose is even higher and the effective doping concentration of the bulk becomes of p -type, causing the increment of the full-depletion voltage (see Fig. 2.3 for comparison).

The model also correctly estimates the initial amount of electron-hole pairs generated by the laser. The value deduced by the model is: $Q_M = \rho_0 \cdot w = 3300 \cdot 320 \simeq (1.06 \pm 0.02) \times 10^6$ e^- per each laser pulse, which is in very good agreement with the laser power at the tip of the optical fiber. In fact from the laser characteristics (see Tab. 3.2) I calculated the energy impinging on the sensor surface, $\frac{5 \text{ mW} \cdot 1 \text{ ns}}{2 \cdot 1.6 \times 10^{-19} \text{ C}} = 15.6 \times 10^6$ eV, where the factor 2 is introduced by the presence of the beam splitter. This value is

Figure 3.35: *Laser multiple reflections inside the micro-strip Silicon sensor.* E_0 is the impinging laser energy. $(1 - \alpha)E$ is the fraction of energy not absorbed by the Silicon bulk.

dumped by a factor that takes into account the multiple reflections due to strips and back-plane metallization. Let's define $\alpha = 1 - e^{-2w/x_0}$ as the fraction of energy released in crossing two times the Silicon bulk thickness as shown in Fig. 3.35; in the hypothesis of small incident angle θ , the total energy, E_{in} , released inside the bulk is:

$$\begin{aligned} E_{in} &= E_0 \frac{2}{3} \alpha + E_0 \frac{2}{3} (1 - \alpha) \frac{1}{3} \alpha + E_0 \frac{2}{3} (1 - \alpha)^2 \frac{1}{9} \alpha + \dots = \\ &= E_0 \frac{2}{3} \alpha \sum_{n=0}^{\infty} \left(\frac{1 - \alpha}{3} \right)^n = E_0 \frac{2\alpha}{2 + \alpha} \end{aligned} \quad (3.15)$$

The total electron-hole pairs generated inside the sensor by each single laser pulse is $Q_C = E_{in}/3.65$, where 3.65 is the energy needed, in electronvolt, to generate an electron-hole pair in Silicon at -12° C. The calculated Q_C is equal to the measured Q_M if the laser absorption length in Silicon (see the laser characteristics in Tab. 3.2), at -12° C, is $x_0 = 1920 \mu\text{m}$, which is a very reasonable assumption as one can see from I. Abt *et. al.* [26], S.M. Sze [29] and S. Gadomski *et. al.* [39].

3.6.5 From trapping-time to fluence

A very interesting result is related to the reconstructed radiation fluence. From the carriers trapping-time I easily recovered the radiation fluence

through the empirical relation expressed by Eq. (3.13). The sensor fluence-

Figure 3.36: *2D-reconstruction of the fluence profile.*

map was then fitted with a 2D-Gaussian shape giving the radiation beam profile shown in Figs. 3.36 and 3.37. My measurements are in good agreement with the beam properties measured at IUCF (see Fig. 3.6) as reported in Tab. 3.9. This constitutes an important cross-check for the reliability of

Beam properties	IUCF measurement	My measurement
Peak [1 MeV eq.n. per cm ²]	0.8×10^{14}	$(1.01 \pm 0.12) \times 10^{14}$
Width [mm]	$\sigma_x = \sigma_y \simeq 19$	$\sigma_x = 21.9 \pm 3.0$ $\sigma_y = 33.4 \pm 1.5$

Table 3.9: *Radiation beam properties. Comparison between irradiation profile gathered through my model and the beam characteristics measured at IUCF with the wire scanner technique.*

my model. Reconstructed fluence cross-sections, fitted with a 2D-Gaussian at different positions, referred as (A) and (B) in Fig. 3.37, are also reported in Fig. 3.38.

Another good result is that the minimum at 90 mm for the central strip in Fig. 3.33 is in correspondence of a region that received a radiation fluence of $\sim 0.35 \times 10^{14}$ 1 MeV equivalent neutrons per cm², which is about the expected fluence needed to obtain type inversion for this kind of sensors, as one can see from Fig. 2.3.

Figure 3.37: Contour plot of the fluence profile (colour scale is in unit of 10^{14} 1 MeV equivalent neutrons per cm^2). The fit parameters are: $(1.01 \pm 0.12) \times 10^{14}$ 1 MeV equivalent neutrons per cm^2 , mean along strips 120 ± 6 mm, σ along strips 21.9 ± 3.0 mm, mean transversal to strips 33.4 ± 1.5 mm, σ transversal to strips 19.0 ± 0.8 mm. Dashed line: sensor position. (A) and (B) refer to the fluence profile cross-sections reported in Fig. 3.38.

Figure 3.38: Reconstructed fluence profile cross-sections. On the left: cross-section at 80 mm from chip side; cfr. (A) in Fig. 3.37. On the right: cross-section at 110 mm from chip side, corresponding to the highest irradiated region; cfr. (B) in Fig. 3.37.

3.7 Conclusions

With a very simple method based on an analytical model for the Q-V characteristics I was able to extract all the physical information required to characterize a Silicon sensor for use in HEP experiments. The method allows for

a local (point to point) characterization of the sensor, which is particularly important in case of a highly non-uniform irradiation. The analytical model has four free parameters only and it is capable to extract reliable information even in case of highly radiation-damaged sensors. This method has also been proven to provide a very good estimate of the dose locally absorbed by the sensor. Thanks to this method, I can conclude that the sensors I tested are well suited for use in the forward region of hadron collider experiments.

Chapter 4

Micro-strip detector prototype

The trigger system of BTeV is conceived to be asynchronous with the Bunch-CrOssing (BCO); this implies that no trigger signal is available to initiate readout of micro-strip data. Furthermore, in order to be able to readout all the information about an event at each BCO, the amount of data that needs to be buffered must be limited. All hit data must be readout in a zero suppressed format and spurious hit data must be minimized. The readout electronics must therefore perform a **data-driven sparsified** readout, which means that every time a channel is above a settable threshold, a hit data must be sent out. The Fermilab Silicon Strips Readout chip (FSSR) is a custom Integrated Circuit (IC) that has been designed to meet these requirements.

4.1 The readout chip

The IC [40] is made with standard deep-submicron $0.25\ \mu\text{m}$ CMOS technology, which has been proved to have good radiation hardness performance. It uses enclosed geometry transistors [41] to meet the radiation tolerance requirement, which is expected to be $(2-8)\times 10^{13}\ 1\ \text{MeV}$ equivalent neutrons per cm^2 , in 10 years of BTeV operation. FSSR has 128 channels, each connected to a detector strip. The signals from the strips, after amplification

and shaping, are compared to a preset threshold. To achieve the required position resolution, the channels have to provide only a binary information (hit / no hit), generating a logical 1 at the output if a signal exceeding the threshold is detected. An additional 3 bit analog information, provided by a flash-ADC, together with an internal square-wave pulse generator are used for calibration and monitoring purposes.

The dimensions of the readout IC are $\sim 7.5 \times 4.5 \text{ mm}^2$ and its layout is presented in Fig. 4.1. The IC needs two power supply voltages, +2.5 V analog and +2.5 V digital, and two separate grounds for the analog and digital section respectively; the nominal power dissipation per channel is $\sim 4 \text{ mW}$.

Figure 4.1: *Layout of the Fermilab Silicon Strips Readout chip (FSSR).*

For each channel with a signal above threshold the strip number, the analog information and the related BCO number are readout and transmitted. Two versions of FSSR have been made with only slight differences. I will refer to the second version.

4.1.1 The analog section

The analog section of the FSSR core [42] consists of 128 channels, each including (see Fig. 4.2):

charge preamplifier: integrates the input charge generated in the active volume of the sensor, the G_m transconductance is needed to discharge

Figure 4.2: *FSSR analog channel block diagram.*

the feedback capacitance C_F

integrator and shaper: used to ameliorate the signal-noise ratio. Its transfer function is CR-(RC)²-type with a programmable peaking time of: 65 ns, 85 ns, 100 ns and 125 ns

comparator: provides the binary information (hit / no hit) to the digital section

BaseLine Restorer (BLR): included to achieve baseline shift suppression. It can be bypassed by a programmable switch

Figure 4.3: *FSSR programmable inject mask circuit.*

The electronic calibration can be performed either by the internal square-wave pulse generator or by an external pulser, providing voltage steps on the integrated inject capacitance of 40 fF. The injected channels can be selected by a programmable inject mask as shown in Fig. 4.3.

Shaping time [ns]	Feedback capacitance [fF]	Gain [mV fC ⁻¹]
125	150	93
85	150	96
65	150	101
125	100	137
85	100	142
65	100	149

Table 4.1: *FSSR nominal gains expected from simulations.*

The gain of the preamplifier is also programmable by changing the value of its feedback capacitance, as shown in Fig. 4.24. The nominal gain values expected from simulations, as a function of the shaping time and feedback capacitance values, are reported in Tab. 4.1.

Figure 4.4: *Preamplifier selectable feedback capacitances.*

Figure 4.5 shows the block diagram of the flash-ADC; there are eight programmable 8 bit-DACs that generate thresholds common to all the channels. A buffer has been introduced in order to reduce the capacitive load to the shaper due to the 1–7 DACs, thus avoiding unwanted changing of the transfer function of the analog chain. The flash-ADC generates a thermometric code which is then converted to a 3 bit binary code.

It is also possible to monitor the output of all the analog blocks of the 128th channel and consequently check the correctness of the analog section working-point.

Figure 4.5: *FSSR flash-ADC. The analog signal is digitized using three bits. The eight thresholds are common to all the channels.*

4.1.2 Measurements

A special board, shown in Fig. 4.6, was built for testing the FSSR chip without any load. The board allows to have access, through lemo connectors and special pins, to the main analog signals of the chip.

The amplitude of the threshold for the number 0 comparator is available on one pad of the chip. The linearity of the DAC that generates this threshold was measured, the data and the relative linear fit are reported in Fig. 4.7. The DAC of threshold 0 presents a remarkable linear behaviour. The DAC circuits that generates the other thresholds are rigorously identical to the DAC of threshold 0.

The amplitude of the internal pulser is also available on one pad of the chip. Figure 4.8 reports the measured amplitudes for different DAC values.

Figure 4.6: *FSSR single chip test board. The chip is under the black cover and is wire-bonded to pads on the board. The connector of the digital signals is visible on the left side of the board. The other lemo connectors and special pins are used for power supply and diagnostic purposes.*

Figure 4.7: *Linearity of the DAC that generates the threshold for the number 0 comparator.*

As one can observe from the linear fit, also the internal pulser DAC shows a good linear behaviour.

I will now present measurements about the analog section for different settings of the shaping time and preamplifier gain. Figure 4.9 shows the shape of the analog signal measured after the shaper and the baseline restorer. These measurements were performed with a shaping time of 125 ns, low preamplifier gain and injecting 1 fC of charge. It's evident the effect of the BLR to restore the signal to zero.

Figure 4.10 shows the analog signal for the four different shaping times:

Figure 4.8: *Linearity of the DAC that generates the internal pulser amplitude.*

Figure 4.9: *Analog signal after shaper and baseline restorer. Shaping time: 125 ns; injected charge: 1 fC; low preamplifier gain.*

65 ns, 85 ns, 100 ns and 125 ns. The measurements were taken after the baseline restorer, with low preamplifier gain and injecting 1 fC of charge.

In Fig. 4.11 the signals measured after the baseline restorer are compared for the two different preamplifier gain values. These measurements were performed with a shaping time of 125 ns and injecting 1 fC of charge.

I also measured the linearity of the analog channel by correlating the amplitude of the signal peak after the baseline restorer with different injected charges¹. The measurements were performed with a shaping time of 125 ns

¹The most probable quantity of charge generated in 320 μm of Silicon by a minimum

Figure 4.10: *Analog signal at different shaping times. The signal is measured after the baseline restorer. Injected charge: 1 fC; low preamplifier gain.*

Figure 4.11: *Analog signal at different preamplifier gains. The signal is measured after the baseline restorer. Shaping time: 125 ns; injected charge: 1 fC.*

and with low preamplifier gain. The data and the relative linear fit reported in Fig. 4.12 show the remarkable linear behaviour of the analog channel.

4.1.3 The digital section

The architecture of the digital back-end is called pseudo-Pixel. It is based on the BTeV pixel readout chip, FPIX2 [43]. The I/O protocols for the two

ionizing particle is ~ 3.6 fC.

Figure 4.12: *Analog signal at different injected charges. The signal is measured after the baseline restorer. Shaping time: 125 ns; low preamplifier gain. On the left: analog signals. On the right: linear correlation between the injected charge and the peak of the analog signal.*

chips are identical. The 128 channels are subdivided into 16 columns of 8 rows, FSSR will look like an FPIX2 of 16×8 array of channels. The FSSR architecture can be described as including four logic sections, as shown in Fig. 4.13:

- the core consists of 128 analog readout channels, the End-of-column logic (16 blocks, one for each column of front-end channels) and the Core Logic, which controls the data flow from the core to the data output interface
- the data output interface accepts data from the core, serializes the data and transmits them off-chip, using a point-to-point protocol
- the programming interface accepts commands and data from a serial input bus and, in response to a command, provides data on a serial output bus. The user can read back the contents of the main programmable registers
- the programmable registers are used to store input values for DACs that provide currents and voltages required by the core, for instance the threshold levels for the discriminators and the bias currents of the

Figure 4.13: *FSSR chip block diagram. Arrows represent control and data flow.*

analog section. They also have additional functions, such as controlling data output speed and selecting the pattern for charge injection tests

All I/O (except the test signal injection) is differential and is fed by means of Low Voltage Differential Signaling (LVDS) to reduce data corruption. The functioning principle of LVDS signals is illustrated in Fig. 4.14.

Let me now go more in detail about the FSSR Core. FSSR Core is a column-based architecture that uses an indirect addressing scheme to associate pixel hits with a time stamp. It is best understood as consisting of three mutually dependent functional blocks as shown in Fig. 4.15. These three blocks are the **Core Logic**, the **End-of-column Logic** and the **Pixel Cell**:

Core Logic: understands time. At the rising edge of the bunch-crossing clock, it stamps every time slice with an 8 bits BCO number. This number is broadcast to all End-of-column Logic blocks. The Core Logic also contains a very simple state machine that knows if the Core is Talking or Silent. The Core is Silent until the End-of-column Logic blocks indicate that they have data to output. When this happens, at the next rising edge of the readout clock, the Core will switch to

Figure 4.14: *Schematic principle of the Low Voltage Differential Signaling concept. When the signal being driven is TRUE, switches A-T and Ab-T are closed, and switches A-F and Ab-F are open. The voltage on the non-inverting amplifier input is 1.4 V and 4 mA flows through the 100 Ω resistor, making the voltage of the inverting terminal 1 V. When the signal is FALSE, switches A-F and Ab-F are closed, A-T and Ab-T are open and the voltages and direction of the current flow are reversed.*

the Talking state, and output can begin. The Core Logic does not wait for any kind of chip token or validation from the DAQ. While in the Talking state, the Core starts passing a Horizontal Token across the End-of-column Logic blocks to arbitrate rights to the output bus. When the Horizontal Token drops out of the other side of the End-of-column Logic blocks, readout is done. The Core switches back to the Silent state at the next rising edge of the readout clock

End-of-column Logic blocks: also understand time, in that whenever there is a hit, they store the BCO numbers broadcast by the Core Logic. Obviously, they also understand hits, which are driven to them from the Pixel Cells via the HFastOR signal. The End-of-column Logic blocks also understand the existence of the Pixel Cells because they communicate to those pixels through a series of command and tokens. Finally, the End-of-column Logic blocks understand output. When the Core is in the Talking state and when a particular End-of-column Logic block has the Horizontal Token and when that End-of-column

Figure 4.15: *The FSSR core organization showing the three major logical blocks: the Pixel Cell, the End-of-column Logic blocks and the Core Logic.*

Logic block has hit pixels to output, then it outputs those pixels

Pixel Cells: themselves know nothing of time. They only understand hits and commands from their End-of-column Logic block. These commands are Idle (do nothing), Listen (listen for new hits), Reset (reset your contents), and Output (output your contents). There are four sets of such commands coming from the End-of-column Logic block. If a pixel is Empty and it receives a hit, it associates itself with whichever command set is issuing the Listen command. From that point and until the Pixel Cell is reset, it obeys only the commands from the associated command set. Rights to the column output bus are arbitrated by a Column Token issued by the End-of-column Logic block

The End-of-column has two type of state machines: the **Column State Machine**, which operates at the rising edge of the readout clock; four **Command State Machines** that operate on the rising edge of the BCO clock, see Fig. 4.16. In the Empty State, the Command State Machines issue the Idle Command to the Pixel Cells. In the Listen State, they issue the Listen Command. Once a hit is received, several things happen:

1. the BCO number currently being broadcast by the Core Logic is stored in the register associated with the Command State Machine currently in the Listen State

Figure 4.16: *The End-of-column Logic block’s state diagrams.*

- 2. that state machine makes the transition to the Full State where it once again issues the Idle command
- 3. the state machine picked by the Hit Priority Encoder as next to Listen moves to the Listen State

Figure 4.17: *The timing diagram of a single pixel hit in a single column.*

Figure 4.17 reports the timing diagram of the Core operations when a “hit” occurs. The Column State Machine starts in the “Nothing to Say” or Nothing State where it remains until it sees an Output command issued by any of the Command State Machines. At the next rising edge of the readout

clock, the Column State Machine makes the transition to the “Something to Say” or Something State. At this point, the Core logic is alerted to the fact that there is data to output, and the Column Tokens are sent up to the first Pixel Cell that needs to be output. The state machine then waits for the arrival of the Horizontal Token from the Core Logic. When the token arrives, the Column State Machine makes the transition to the Talking state, and it releases the readout clock to the Pixel Cells enabling them to output their data. Simultaneously, the stored BCO number (which associates the hit pixels with the time they were hit) is driven onto the bus. At the next rising edge of the readout clock, the Column State Machine makes the transition to the Silent state. When the entire array has been read out, the Horizontal Token drops out of the last End-of-column Logic Block, and the Core Logic makes its transition from Talking to Silent. This signals to all the Column State Machines that they can make their own transition back to the Nothing State. The elapsed time between the occurrences of an hit and the output of the data is the sum of latency time for BCO clock period completion, plus one BCO clock period, plus three readout clock periods.

FSSR is designed to work at 396 ns BCO (2.5 MHz) as well at 132 ns (7.5 MHz) with a readout clock designed to be 70 MHz. The number of output lines, through which data are sent out, is selectable and can be 1, 2, 4 or 6. This means that each single data word can be readout as a single stream of 24 bits, or two streams of 12 bits and so on. Data are readout on both edges of the readout clock for a maximum data transmission rate of 840 Mbit sec⁻¹. The 24 bits of the data word carry the following information: **bit 0**, word marker = 1; **bits 1–3**, channel pulse-height; **bits 4–11**, BCO number; **bits 12–16**, column number; **bits 17–20**, row number; **bits 21–23**, not used, set to 0. Data sent out from the chip are not time-ordered. The BCO number is used off-line to build events. Since the data output lines are point-to-point connected, no chip ID information is needed. The same lines are used for synchronization and monitoring purposes too.

A bus line, shared by all the chips of the same detector, is used to program the chips. The command word has 13 bits organized as: **bits 0–2**, instruction (write, read, set ,reset or default); **bits 3–7**, register number;

bits 8–12, chip ID.

The other main programmable quantities are the polarization currents of the analog section, used to set the working point of the circuit, and the 128 bits of the kill and inject masks.

4.1.4 Efficiency simulations

Simulations of the digital section in Verilog language have been carried out to check the performance in terms of readout efficiency. The input to the Verilog program is a file generated by the simulation framework of BTeV. The file is a list of channels that have been hit by a particle. In the simulation

Figure 4.18: *Readout efficiency of the FSSR digital section. The simulation was run at 396 ns of BCO and 70 MHz of readout clock with 6, 12 and 18 average interactions per BCO. The four cases correspond to 1, 2, 4 and 6 digital output lines.*

I considered only the chip with the highest occupancy corresponding to the innermost detector of the first station. The chip analog section is considered just as a delay in the signal processing chain. I set the FSSR readout clock of the simulation at its nominal value of 70 MHz and the BCO period to 396 ns. The readout efficiency is calculated for three different average number of interactions per BCO: 6, 12, and 18, and for different number of output lines. As one can see from Fig. 4.18, using 6 output lines the readout efficiency goes from 99.6% to 95.6% for 12 and 18 average number of interactions per BCO respectively. It is worth noting that the number of interactions per

BCO for BTeV is 6 at 2 TeV and a luminosity of $2 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$.

This performance ensures that the detector system operates with adequate readout efficiency in all the Tevatron-like accelerator environments. In particular for BTeV a readout efficiency $> 95\%$ was required.

4.2 Hybrid module performance

In this section I will present the results on gain, noise and threshold dispersion of FSSR chips assembled on a “hybrid” module. A hybrid module is a circuit board that has been designed to interface FSSR chips to a Silicon micro-strip sensor. It hosts six FSSR chips with the relative passive components for power supply filtering. The module accommodates also pads for diagnostic purposes and the high voltage filtering network for sensor bias. A picture of a hybrid module is shown in Fig. 4.19.

Figure 4.19: *FSSR hybrid module picture. The hybrid module with the six chips together with the “pig-tail” carrying the connector to the flex circuit, are visible.*

All the measurements, here reported, have been performed with the internal square-wave pulse generator. The threshold curves were measured setting the comparator thresholds at fixed values and changing the pulser amplitude. Each point of a threshold curve represents the percentage of times that the comparator fires for a certain value of injected charge. 255 pulses were sent for each point. The measurement error has been calculated as $\sigma = \sqrt{\epsilon(1-\epsilon)/255}$ with $0 < \epsilon < 1$. The conversion from mV to electrons was performed considering a nominal value for the inject capacitance

of 40 fF.

Figure 4.20: Typical threshold curves with sensor disconnected at different combinations of shaping times and preamplifier gains. From the upper left to the lower right: 125 ns shaping, low gain; 125 ns shaping, high gain; 65 ns shaping, low gain; 65 ns shaping, high gain.

Figure 4.21: Histograms of the noise at different combinations of shaping times and preamplifier gains. From the upper left to the lower right: 125 ns shaping, low gain; 125 ns shaping, high gain; 65 ns shaping, low gain; 65 ns shaping, high gain.

Figure 4.20 shows four typical threshold curves measured at different settings of the shaping time and preamplifier gain for the threshold of the number 0 comparator. The relative fit function, $\text{erf}(x; \mu\sigma)$, is also presented.

The resulting error-function parameters have been histogrammed in order to obtain a figure that can describe the global behaviour of the circuit. The σ -parameter of the error function corresponds to the noise of the channel. Figure 4.21 presents the dispersion of this parameter on a chip for the threshold of the number 0 comparator. For comparison, the Gaussian fits are also given. The four histograms refer to different settings of the shaping time and preamplifier gain.

Figure 4.22: *Dispersion of the thresholds of a single chip at different combinations of shaping times and preamplifier gains. From the upper left to the lower right: 125 ns shaping, low gain; 125 ns shaping, high gain; 65 ns shaping, low gain; 65 ns shaping, high gain.*

Since the thresholds of the comparators are common to all the channels, another important parameter to measure is the threshold dispersion among channels of the same chip. Figure 4.22 reports the histograms of the μ -parameter of the error function with Gaussian fits for the threshold of the number 0 comparator. The four histograms refer to different settings of the shaping time and preamplifier gain.

The same measurements described above have been performed also for all

Figure 4.23: *FSSR* pure electronic noise and threshold dispersion measured at different combinations of shaping times and preamplifier gains: 125 ns shaping, low gain; 125 ns shaping, high gain; 65 ns shaping, low gain; 65 ns shaping, high gain. On the left: noise per threshold. On the right: threshold dispersion per threshold DAC.

the eight DACs that generate the comparator thresholds and the results are summarized in Fig. 4.23. For the higher shaping time the noise is ~ 200 e^- with both preamplifier gains, consistent with what expected, whereas for the lower shaping time the noise rises to ~ 400 – 500 e^- with the low preamplifier gain and to ~ 500 – 600 e^- with the high preamplifier gain. The expected noise for low shaping time should be just tens electrons higher than the noise for high shaping time; the discrepancy I measured must be attributed to the fact that, at 65 ns shaping time, the circuit is much more sensitive to ground connections, that I didn't fully optimize in my setup. From the second plot of Fig. 4.23 it's evident the effect of the gain on the threshold dispersion, since the higher the preamplifier gain, the lower the threshold dispersion. Globally the threshold dispersion is ~ 300 – 500 e^- , as expected.

The global gain was measured by a linear fit to the plot of the threshold set values in mV versus the corresponding charge at the input, averaged over all the chip channels. The results are reported in Fig. 4.24; the four characteristics refer to different settings of the shaping time and preamplifier gain. The measured gains are: 96 mV fC^{-1} , for 125 ns shaping time and low preamplifier gain; ~ 110 mV fC^{-1} , for 65 ns shaping time and low

Figure 4.24: *FSSR global analog section gain measured at different combinations of shaping times and preamplifier gains.*

preamplifier gain; 149 mV fC^{-1} , for 125 ns shaping time and high preamplifier gain; $\sim 151 \text{ mV fC}^{-1}$, for 65 ns shaping time and high preamplifier gain. The measured values are consistent with the nominal values obtained from simulations and presented in Tab. 4.1.

All the measurements presented so far show that the FSSR analog section performance is excellent both in noise and threshold dispersion. In the next section I will present the final measurements on a detector prototype.

4.3 Detector performance

The detector is basically composed of an hybrid module and a Silicon micro-strip sensor. To build the prototypes I used the same sensors as those described in chapter 3 of which I have a deep knowledge. A sketch of the detector is presented in Fig. 4.25, while pictures of the actual setup are reported in Fig. 4.26. The entire detector was placed in an Aluminum Faraday-cage and, in order to avoid overheating of the electronics, I used three Peltier cells placed underneath the hybrid ² to facilitate the heat transfer from the chips to the Aluminum Faraday-cage.

²The support has a window just in correspondence to the hybrid, allowing the direct contact between Peltier cells and the hybrid itself.

Figure 4.25: *FSSR detector sketch. A pitch adapter is needed to adapt the $50\ \mu\text{m}$ FSSR pad pitch to the $120\ \mu\text{m}$ sensor pad pitch.*

Figure 4.26: *FSSR detector pictures. Are evident the blue and red capacitors for high voltage filtering and the Copper sticky tape that brings the high voltage to the back-plane of the sensor. In the second picture are evident the heat-exchanger and the fans used to dissipate the heat subtracted to the chips by three Peltier cells placed underneath the hybrid.*

The detector was characterized with the same methods described in the previous section. Figure 4.27 shows a typical threshold curve of the number 0 comparator, measured at shaping time of 125 ns and low preamplifier gain. The noise is $\sim 4.6\ \text{mV}$, equivalent to $\sim 1150\ e^-$ considering a nominal value for the inject capacitance of 40 fF, corresponding to a signal-noise ratio of ~ 20 for a minimum ionizing particle. The expected total noise,

Figure 4.27: *Typical threshold curves with sensor connected, measured with a shaping time of 125 ns and low preamplifier gain.*

N_T , as a function of the shaping time, τ , can be derived from the following equation [42]:

$$N_T = (C_D + C_{IN}) \sqrt{\frac{A_w}{\tau} + B_{1/f}} = \alpha C_D + \beta \quad (4.1)$$

C_D is the load capacitance while C_{IN} is the capacitance of the preamplifier input, A_w is a coefficient of the white-noise while $B_{1/f}$ is the coefficient of the $1/f$ -noise. The measurements performed with the single chip test board and with different load capacitances are well fitted by Eq. (4.1), giving $\alpha = 24.8 \text{ e}^- \text{ pF}^{-1}$ and $\beta = 200 \text{ e}^-$. Since the nominal capacitance per cm for this type of sensors is $\sim 1.3 \text{ pF cm}^{-1}$, the expected total noise for a pure capacitive load value of $1.3 \cdot 12 = 15.6 \text{ pF}$ is $N_T = 24.8 \cdot 15.6 + 200 \simeq 600 \text{ e}^-$. The discrepancy between this value and the total noise measured with the sensor connected is due to the fact that, since a sensor acts also like an antenna, the non-fully-optimized ground connections and shielding allow for noise pickup.

I performed an absolute calibration with a radioactive source of Am^{241} having an intensity of 1 mCi, whose dominant emission is γ at the energy of 59.6 KeV, corresponding to $\sim 16550 \text{ e}^-$ in Silicon. In order to measure the spectrum one must set the flash-ADC thresholds in a way to define equal-size bins. This was done calibrating each of the eight thresholds of the flash-ADC; the measurements and the linear fits are reported in Fig. 4.28. I set the bin size to 4 mV and the 0 threshold to 43 mV, which, in the hypothesis of

Figure 4.28: *Calibrations of the flash-ADC thresholds. From the upper left to the lower middle: threshold 0 to threshold 7.*

Figure 4.29: *Spectrum of the Am^{241} expressed in mV units. The measurement was performed with a shaping time of 125 ns and low preamplifier gain. I set to ~ 4 mV the bin spacing, starting from ~ 43 mV. On the left: raw data. On the right: after weighting the bin contents.*

40 fF inject capacitance, should cover a range from ~ 10750 e^- to ~ 17750 e^- . Since the threshold value, set in the DAC, must be an integer between 0 and

255 and the slope of the calibrations is $\sim 1 \text{ mV DAC}^{-1}$, the error on the bin spacing is at most $2 \cdot 0.5/4 = 25\%$. Therefore, after measuring the Americium spectrum, I recalibrated the thresholds and I weighted the bin contents of the spectrum with respect to the measured actual bin spacing. The Am^{241} spectra before and after bin weighting are reported in Fig. 4.29.

Figure 4.30: *Noise and internal pulser spectra. The measurements were performed with a shaping time of 125 ns and low preamplifier gain. I set to $\sim 4 \text{ mV}$ the bin spacing, starting from $\sim 43 \text{ mV}$. On the left: spectrum of the noise. On the right: spectrum of the internal pulser whose amplitude was set to the same energy as the Am^{241} γ -emission.*

I measured the noise spectrum for 20 minutes, the same acquisition time as for the Americium. As one can see from Fig. 4.30 on the left, the number of noise hits is negligible. I also compared the Americium peak with the spectrum of the internal pulser whose amplitude was set to the same energy as the Am^{241} γ -emission. In Fig. 4.30 on the right is presented a typical spectrum of the internal pulser. The σ of the Gaussian fit is $\sim 1175 \text{ e}^-$, which is the approximately the noise measured with the threshold curve of Fig. 4.27. The mean values of the Gaussian fit to the Americium spectrum and to the internal pulser spectrum are identical with a precision of one tenth of millivolt. The absolute calibration, performed with the γ -source, is completely consistent with the calibration performed with the internal pulse generator, considering a nominal value for the inject capacitance of 40 fF. Indeed, even if the mismatch between actual and nominal value of integrated capacitances is $\sim 20\%$, the relative deviation among capacitances on the same chip is just $\sim 1\%$. Thus, since the relation between the input, V_{in} , and the

Figure 4.31: *Spectrum of the Am^{241} expressed in KeV units. The measurement was performed with a shaping time of 125 ns and low preamplifier gain.*

output, V_{out} , of the preamplifier is $V_{out} = V_{in} \cdot C_{INJ} / C_F$ (C_{INJ} and C_F being the inject and feedback capacitances respectively) the expected deviation on V_{out} is $\sim 1\%$. Figure 4.31 shows the Am^{241} spectrum expressed in KeV units.

4.4 Conclusions

The measurements performed on the FSSR demonstrate that the chip fulfills the design requirements and certify its the remarkable qualities in terms of noise, $\sim 200 e^-$ without sensor and $\sim 1150 e^-$ with sensor, and threshold dispersion, $\sim 400 e^-$. Silicon micro-strip detectors equipped with FSSR chips are well suited to be employed in all the HEP experiments that require data-driven sparsified readout, allowing the use of tracker information as soon as possible for trigger decision at the lowest level.

Conclusions

The aim of the present thesis was the design, construction and characterization of a new Silicon micro-strip tracker to be employed in the forward region of the new generation of HEP experiments at hadron colliders. Among other important characteristics, these detectors should in particular feature a data-driven readout electronics in such a way that their information could be available as soon as possible for making a trigger decision at the lowest level. Our goals have been successfully reached.

In particular, my measurements on radiation tolerance of the sensors have certified that they can easily resist to doses well in excess of 10^{14} 1 MeV equivalent neutrons per cm^2 , even in presence of highly non-uniform irradiation. To perform these studies I developed a method that allows for a full, point to point, characterization of the sensors using an infrared laser source. With this method one can even derive the radiation dose absorbed by a small portion of the sensor. The two-dimensional dose profile I measured on the prototype is completely consistent with that provided by the irradiation facility personnel. This fact constitutes a strong cross-check for my measurements and guarantees the reliability of my method.

A custom chip was developed to perform a low-noise, data-driven and sparsified readout of the detectors. During the design phase of the chip, I simulated, in Verilog language, the performance of its digital section. At a luminosity of $2 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$ and energy of 2 TeV the readout efficiency is remarkably high, $> 99\%$.

I successfully assembled and tested some detector prototypes. The measured performance fulfills the design requirements. In particular the noise is $\sim 1150 \text{ e}^-$, corresponding to a signal-noise ratio of ~ 20 for a minimum

ionizing particle, and the threshold dispersion is $\sim 400\text{ e}^-$.

The success of this work is also demonstrated by the interest that several people of our community have already expressed for the detectors and their readout electronics. The CBM [44] and PHENIX [45] collaborations are already considering the possibility to use this detector for their Silicon trackers.

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Appendix A

CP violation

A.1 Theoretical account for CP violation

In the Standard Model (SM) of fundamental interactions there are no explicit mass-terms in the Lagrangian; indeed, had the vector bosons explicit mass-terms, the theory wouldn't be gauge-invariant. Particles acquire mass dynamically, interacting with a particular field called the Higgs field. In particular the rest-mass of a particle is the result of its interaction with the Higgs condensate.

The symmetries under which the SM Lagrangian of the electroweak sector is conceived are (Weinberg-Salam-Glashow model): the Lorentz symmetry and the local gauge symmetries $SU(2)_L \otimes U(1)_Y$. The symmetry $U(1)_Y$ corresponds to the invariance to a scalar local phase change of the fields, while the symmetry $SU(2)_L$ deals only with left-handed fields and corresponds to the invariance under a local phase rotation of the doublets $\Psi_i = \begin{pmatrix} \Psi_{ui} \\ \Psi_{di} \end{pmatrix}_L$, the index $i = 1, 2, 3$ is the flavour (or generation) index. When the Higgs field acquires its Vacuum Expectation Value (VEV) by choosing a ground state, the gauge group is Spontaneously Broken (SSB), in such a way that the only symmetry that survives is $U(1)_{EM}$ of electromagnetism ($SU(2)_L \otimes U(1)_Y \xrightarrow{SSB} U(1)_{EM}$); this is done in order to have the corresponding gauge particle (the photon) massless. To realize this aim one has to introduce a set of scalar fields transforming in a convenient way under $SU(2)_L \otimes U(1)_Y$. The simplest choice turns out to be a complex represen-

tation of $SU(2)$ of dimension 2: Higgs doublet. Since the vacuum must be electrically neutral, one of the components of the doublet must also be neutral. One can write the Higgs doublet and its conjugate as:

$$\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} \quad \bar{\Phi} = \begin{pmatrix} \bar{\phi}^0 \\ -\phi^- \end{pmatrix} \quad (\text{A.1})$$

The three generation of quarks, in the Weinberg-Salam-Glashow, are described in Tab. A.1. The Yukawa Lagrangian, describing the interaction

$\begin{pmatrix} u \\ d \end{pmatrix}_L$	$\begin{pmatrix} c \\ s \end{pmatrix}_L$	$\begin{pmatrix} t \\ b \end{pmatrix}_L$
u_R, d_R	c_R, s_R	t_R, b_R

Table A.1: *The three families of quarks.*

between quarks and the Higgs field for the three generation of quarks, is:

$$L_{Yuk}^q = - \sum_{i,j=1}^3 \left[G_{ij}^U \bar{R}_{U_i} (\bar{\Phi}^\dagger L_j) + G_{ij}^D \bar{R}_{D_i} (\Phi^\dagger L_j) \right] + h.c. \quad (\text{A.2})$$

$R_{U_i} = u'_R, c'_R, t'_R$, $R_{D_i} = d'_R, s'_R, b'_R$ and $L_j = \begin{pmatrix} u' \\ d' \end{pmatrix}_L, \begin{pmatrix} c' \\ s' \end{pmatrix}_L, \begin{pmatrix} t' \\ b' \end{pmatrix}_L$. From the vacuum expectation values of Φ and $\bar{\Phi}$ one can obtain the mass terms for the up quarks:

$$\overline{(u', c', t')_R} M^U \begin{pmatrix} u' \\ c' \\ t' \end{pmatrix}_L + h.c. \quad (\text{A.3})$$

and for the down quarks:

$$\overline{(d', s', b')_R} M^D \begin{pmatrix} d' \\ s' \\ b' \end{pmatrix}_L + h.c. \quad (\text{A.4})$$

$M_{ij}^{U(D)} = (v/\sqrt{2})G_{ij}^{U(D)}$ are non-diagonal matrices. The weak eigenstates, q' , are linear superposition of the mass eigenstates, q , given by the unitarity

transformations:

$$\begin{aligned} \begin{pmatrix} u' \\ c' \\ t' \end{pmatrix}_{L,R} &= U_{L,R} \begin{pmatrix} u \\ c \\ t \end{pmatrix}_{L,R} \\ \begin{pmatrix} d' \\ s' \\ b' \end{pmatrix}_{L,R} &= D_{L,R} \begin{pmatrix} d \\ s \\ b \end{pmatrix}_{L,R} \end{aligned} \quad (\text{A.5})$$

$U(D)_{L,R}$ are unitary matrices to preserve the form of the kinetic terms of the quarks. These matrices diagonalize the mass matrices:

$$\begin{aligned} U_R^{-1} M^U U_L &= \begin{pmatrix} m_u & 0 & 0 \\ 0 & m_c & 0 \\ 0 & 0 & m_t \end{pmatrix} \\ D_R^{-1} M^D D_L &= \begin{pmatrix} m_d & 0 & 0 \\ 0 & m_s & 0 \\ 0 & 0 & m_b \end{pmatrix} \end{aligned} \quad (\text{A.6})$$

The V-A charged weak current will be proportional to:

$$\overline{(u', c', t')}_L \gamma_\mu \begin{pmatrix} d' \\ s' \\ b' \end{pmatrix}_L = \overline{(u, c, t)}_L (U_L^\dagger D_L) \gamma_\mu \begin{pmatrix} d \\ s \\ b \end{pmatrix}_L \quad (\text{A.7})$$

with the generation mixing of the mass eigenstates, q , described by:

$$V \equiv U_L^\dagger D_L \quad (\text{A.8})$$

On the other hand the neutral current will be proportional to:

$$\overline{(u', c', t')}_L \gamma_\mu \begin{pmatrix} u' \\ c' \\ t' \end{pmatrix}_L = \overline{(u, c, t)}_L (U_L^\dagger U_L) \gamma_\mu \begin{pmatrix} u \\ c \\ t \end{pmatrix}_L \quad (\text{A.9})$$

We can notice that there is no mixing in the neutral sector since the matrix U_L is unitary: $U_L^\dagger U_L = \mathbf{1}$.

While neutrinos were initially assumed to be massless, recent observations of neutrino mixing have revealed the existence of neutrino mass leading to them having an analogous mixing matrix as the quarks.

The quark mixing, by convention, is restricted to the down quarks:

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix}_L = V \begin{pmatrix} d \\ s \\ b \end{pmatrix}_L \quad (\text{A.10})$$

V is the Cabibbo-Kobayashi-Maskawa (CKM) matrix [46], having one free imaginary phase, being the source of the CP violation, and three free real angles. Indeed, let's take the example of the kaon sector. The two mass eigenstates K_S and K_L are a superposition of the two flavour eigenstates K^o and $\bar{K}^o$: $K_S = K^o + \epsilon \bar{K}^o$ and $K_L = K^o - \epsilon \bar{K}^o$, with ϵ in general a complex parameter. If K_S and K_L were CP eigenstates the following relations would be satisfied only for $\epsilon = 1$: $CP |K_S\rangle = |K_S\rangle$ and $CP |K_L\rangle = -|K_L\rangle$. ϵ depends on the diagonal terms of the Hamiltonian that describes the evolution of the $K^o - \bar{K}^o$ system, and since the Hamiltonian itself directly depends on the CKM matrix, ϵ can't be equal to 1 because of the presence of the CKM phase.

Let's summarize the concepts expressed until now:

- in the weak sector of the SM there is a single source of CP violation coming from the free phase of the CKM matrix
- in the SM, CP violation originates from the flavour structure of the charged current interactions of quarks
- the CP-violating CKM phase could be eliminated through an appropriate unitary transformation of quark fields if any two quarks with the same charge had the same mass, CP violation is therefore closely related to the “flavour problem” of mass hierarchy among the three generations

A.2 The CKM matrix

A.2.1 Introduction

The physical point-like states of nature that have both strong and electroweak interactions, the quarks, are mixtures of base states described by

the CKM matrix:

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix} \quad (\text{A.11})$$

The V_{ij} 's are complex numbers that can be represented by four independent real quantities. These numbers are fundamental constants of nature that need to be determined from experiment, like any other fundamental constant such as α or G . In the Wolfenstein approximation the matrix is written as [47]:

$$V_{CKM} = \begin{pmatrix} 1 - \lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta(1 - \lambda^2/2)) \\ -\lambda & 1 - \lambda^2/2 - i\eta A^2\lambda^4 & A\lambda^2(1 + i\eta\lambda^2) \\ A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1 \end{pmatrix} \quad (\text{A.12})$$

This expression is accurate to order λ^3 in the real part and λ^5 in the imaginary part. It is necessary to express the matrix to this order to have a complete formulation of the physics we wish to pursue. The constants λ and A have been measured using semileptonic s and b decays [48]; $\lambda \sim 0.22$ and $A \sim 0.8$. The η parameter allows for CP violation.

A.2.2 Unitarity triangles

The unitarity of the CKM matrix¹ allows us to construct six relationships. These equations may be thought of as triangles in the complex plane. They are shown in Fig. A.1. In the **bd** triangle, the one usually considered, the angles are all thought to be relatively large. It is described by:

$$V_{ub}V_{ud}^* + V_{cb}V_{cd}^* + V_{tb}V_{td}^* = 0 \quad (\text{A.13})$$

To a good approximation:

$$|V_{ud}^*| \simeq |V_{tb}| \simeq 1 \quad (\text{A.14})$$

which implies:

$$\frac{V_{ub}}{V_{cb}} + \frac{V_{td}^*}{V_{cb}} + V_{cd}^* = 0 \quad (\text{A.15})$$

¹Unitarity implies that any pair of rows or columns are orthogonal.

Figure A.1: The six CKM triangles. The bold labels, i.e **ds**, refer to the rows or columns used in the unitarity relationship.

Since $V_{cd}^* = -\lambda$, we can define a triangle with sides:

$$1 \quad (\text{A.16})$$

$$\left| \frac{V_{td}^*}{A\lambda^3} \right| = \sqrt{(1-\rho)^2 + \eta^2} = \frac{1}{\lambda} \left| \frac{V_{td}^*}{V_{ts}} \right| \quad (\text{A.17})$$

$$\left| \frac{V_{ub}}{A\lambda^3} \right| = \sqrt{\rho^2 + \eta^2} = \frac{1}{\lambda} \left| \frac{V_{ub}}{V_{cb}} \right| \quad (\text{A.18})$$

This CKM triangle is depicted in Fig. A.2. The rescaled unitarity triangle

Figure A.2: Unitarity triangle.

is derived from Eq. (A.13) by:

1. choosing a phase convention such that $(V_{cb}V_{cd}^*)$ is real
2. dividing the lengths of all sides by $|V_{cb}V_{cd}^*|$
3. aligns one side of the triangle with the real axis

4. makes the length of this side 1

The form of the triangle is unchanged. Two vertices of the rescaled unitarity triangle are thus fixed at $(0,0)$ and $(1,0)$. The coordinates of the remaining vertex correspond to the Wolfenstein parameters $(\bar{\rho}, \bar{\eta})$. The rescaled triangle is illustrated in Fig. A.2.

The three angles of the unitarity triangle are denoted by α, β and γ [49], together with the χ' and χ angles of the **ds** and **sb** triangles, have the following expressions.

$$\begin{aligned} \alpha \equiv \arg \left[-\frac{V_{cb}V_{cd}^*}{V_{ub}V_{ud}^*} \right], \quad \beta \equiv \arg \left[-\frac{V_{tb}V_{td}^*}{V_{cb}V_{cd}^*} \right], \quad \gamma \equiv \arg \left[-\frac{V_{ub}V_{ud}^*}{V_{tb}V_{td}^*} \right] \\ \chi \equiv \arg \left[-\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*} \right], \quad \chi' \equiv \arg \left[-\frac{V_{cd}V_{cs}^*}{V_{ud}V_{us}^*} \right] \end{aligned} \quad (\text{A.19})$$

To make predictions for future measurements of CP violating observables, we need to find the allowed ranges for the CKM phases. There are three ways to determine the CKM parameters (see *e.g.* [50]):

direct measurements: related to SM tree level processes. At present, we have direct measurements of $|V_{ud}|$, $|V_{us}|$, $|V_{ub}|$, $|V_{cd}|$, $|V_{cs}|$, $|V_{cb}|$ and $|V_{tb}|$

CKM Unitarity: ($V_{CKM}^\dagger V_{CKM} = \mathbf{1}$) relates the various matrix elements.

At present, these relations are useful to constrain $|V_{td}|$, $|V_{ts}|$, $|V_{tb}|$ and $|V_{cs}|$

indirect measurements: related to SM loop processes. At present, we constrain in this way $|V_{tb}V_{td}|$ (from Δm_B and Δm_{B_s}) and η (from ε_K)

When all recent data are taken into account, the following values of CKM parameters and unitarity triangle angles arise from a global fit [51].

$$\lambda = 0.2262_{-0.0010}^{+0.0010}, \quad A = 0.825_{-0.019}^{+0.011}, \quad (\text{A.20})$$

$$\bar{\rho} = 0.207_{-0.043}^{+0.036}, \quad \bar{\eta} = 0.340_{-0.023}^{+0.023}, \quad (\text{A.21})$$

$$\sin(2\beta) = 0.724_{-0.018}^{+0.018}, \quad \sin(2\alpha) = -0.28_{-0.20}^{+0.24}, \quad \gamma = 58.6_{-5.9}^{+6.8} \quad (\text{A.22})$$

The full information can be described by allowed regions in the $(\bar{\rho}, \bar{\eta})$ as illustrated in Fig. A.3 or the $(\sin(2\alpha), \sin(2\beta))$ planes (see *e.g.* [52]). We

A.3 CP violation in meson decays

In the previous sections have been shown how CP violation arises in the SM. Now the implications of this theory, for the phenomenology of CP violation in meson decays in particular for B -meson decays, will be illustrated. There are three different types of CP violation in meson decays:

mixing: which occurs when the two neutral mass eigenstate admixtures cannot be chosen to be CP-eigenstates

decay (or direct): which occurs in both charged and neutral decays, when the amplitude for a decay and its CP-conjugate process have different magnitudes

interference of decays with and without mixing: which occurs in decays into final states that are common to B^o and $\bar{B}^o$

In each case it is useful to identify a particular CP-violating quantity that is independent of phase conventions and discuss the types of processes that depend on this quantity. This will be done in the next section.

A.3.1 Notations and formalism

To define the three types of CP violation in meson decays and to discuss their theoretical calculation and experimental measurement, I will first introduce some notations and formalism. I will refer specifically to B -meson mixing and decays. The phase convention for the CP transformation law of the neutral B -mesons is defined by:

$$CP|B^o\rangle = w_B|\bar{B}^o\rangle, \quad CP|\bar{B}^o\rangle = w_B^*|B^o\rangle, \quad (|w_B| = 1) \quad (\text{A.23})$$

Physical observables do not depend on the phase factor w_B . The time evolution of any linear combination of the neutral B -meson flavour eigenstates:

$$a|B^o\rangle + b|\bar{B}^o\rangle \quad (\text{A.24})$$

is governed by the Schrödinger equation:

$$i\frac{d}{dt}\begin{pmatrix} a \\ b \end{pmatrix} = H\begin{pmatrix} a \\ b \end{pmatrix} \equiv \left(M - \frac{i}{2}\Gamma\right)\begin{pmatrix} a \\ b \end{pmatrix} \quad (\text{A.25})$$

for which M and Γ are 2×2 Hermitian matrices. CPT invariance guarantees $H_{11} = H_{22}$, that is $M_{11} = M_{22}$ and $\Gamma_{11} = \Gamma_{22}$. The off-diagonal terms in these matrices, M_{12} and Γ_{12} , are particularly important in the discussion of mixing and CP violation. M_{12} is the dispersive part of the transition amplitude from B^o to $\bar{B}^o$, while Γ_{12} is the absorptive part of that amplitude. In the SM these contributions arise from the box diagrams with two W exchanges (see Fig. A.6).

The light B_L and heavy B_H mass eigenstates are given by:

$$|B_{L,H}\rangle = p |B^o\rangle \pm q |\bar{B}^o\rangle \quad (\text{A.26})$$

and their time evolution is given by:

$$\begin{aligned} |B_H(t)\rangle &= e^{-iM_H t} e^{-\Gamma_H t/2} |B_H\rangle \\ |B_L(t)\rangle &= e^{-iM_L t} e^{-\Gamma_L t/2} |B_L\rangle \end{aligned} \quad (\text{A.27})$$

The complex coefficients q and p obey the normalization condition $|q|^2 + |p|^2 = 1$. The mass difference and the width difference between the physical states are defined as follows:

$$\Delta m \equiv M_H - M_L, \quad \Delta \Gamma \equiv \Gamma_H - \Gamma_L \quad (\text{A.28})$$

Solving the eigenvalue equation gives:

$$(\Delta m)^2 - \frac{1}{4}(\Delta \Gamma)^2 = (4|M_{12}|^2 - |\Gamma_{12}|^2), \quad \Delta m \Delta \Gamma = 4\Re(M_{12}\Gamma_{12}^*) \quad (\text{A.29})$$

$$\frac{q}{p} = -\frac{\Delta m - \frac{i}{2}\Delta \Gamma}{2M_{12} - i\Gamma_{12}} = -\frac{2M_{12}^* - i\Gamma_{12}^*}{\Delta m - \frac{i}{2}\Delta \Gamma} \quad (\text{A.30})$$

The time evolution of an initially pure B^o or $\bar{B}^o$ state is:

$$\begin{aligned} |B_{phys}^o(t)\rangle &= f_+(t) |B^o\rangle + \frac{q}{p} f_-(t) |\bar{B}^o\rangle \\ |\bar{B}_{phys}^o(t)\rangle &= f_+(t) |\bar{B}^o\rangle + \frac{p}{q} f_-(t) |B^o\rangle \end{aligned} \quad (\text{A.31})$$

where:

$$f_{\pm}(t) = \frac{1}{2} \left[e^{-i(M_L - \frac{i}{2}\Gamma_L)t} \pm e^{-i(M_H - \frac{i}{2}\Gamma_H)t} \right] \quad (\text{A.32})$$

In the B system, $|\Gamma_{12}| \ll |M_{12}|$ (see discussion below), and then, to leading order in $|\Gamma_{12}/M_{12}|$ Eqs. (A.29) and (A.30) can be written as:

$$\Delta m_B = 2|M_{12}|, \quad \Delta \Gamma_B = 2\Re(M_{12}\Gamma_{12}^*)/|M_{12}| \quad (\text{A.33})$$

$$\frac{q}{p} = -\frac{M_{12}^*}{|M_{12}|} \quad (\text{A.34})$$

To discuss CP violation in mixing, it is useful to write Eq. (A.30) to first order in $|\Gamma_{12}/M_{12}|$:

$$\frac{q}{p} = -\frac{M_{12}^*}{|M_{12}|} \left[1 - \frac{1}{2} \Im \left(\frac{\Gamma_{12}}{M_{12}} \right) \right] \quad (\text{A.35})$$

To discuss CP violation in decay, we need to consider decay amplitudes. The CP transformation law for a final state f is:

$$CP|f\rangle = w_f|\bar{f}\rangle, \quad CP|\bar{f}\rangle = w_f^*|f\rangle, \quad (|w_f| = 1) \quad (\text{A.36})$$

For a final CP eigenstate $f = \bar{f} = f_{CP}$, the phase factor w_f is replaced by $\eta_{f_{CP}} = \pm 1$, the CP eigenvalue of the final state. I define the decay amplitudes A_f and $\bar{A}_{\bar{f}}$ according to:

$$A_f = \langle f|\mathcal{H}_d|B^o\rangle, \quad \bar{A}_{\bar{f}} = \langle \bar{f}|\mathcal{H}_d|\bar{B}^o\rangle \quad (\text{A.37})$$

$\mathcal{H}_d$ is the decay Hamiltonian. CP relates A_f and $\bar{A}_{\bar{f}}$. There are two types of phases that may appear in A_f and $\bar{A}_{\bar{f}}$. Complex parameters in any Lagrangian term that contributes to the amplitude will appear in complex conjugate form in the CP-conjugate amplitude. Thus their phases appear in A_f and $\bar{A}_{\bar{f}}$ with opposite signs. In the SM these phases only occur in the CKM matrix which is part of the electroweak sector of the theory, hence these are often called “weak phases.” The weak phase of any single term is convention dependent. However the difference between the weak phases in two different terms in A_f is convention independent because the phase rotations of the initial and final states are the same for every term. A second type of phase can appear in scattering or decay amplitudes even when the Lagrangian is real. Such phases do not violate CP and they appear in A_f and $\bar{A}_{\bar{f}}$ with the same sign. Their origin is the possible contribution from intermediate on-shell states in the decay process, that is the absorptive part of an amplitude that has contributions from coupled channels. Usually the dominant rescattering is due to strong interactions and hence the designation “strong phases” for the phase shifts so induced. Again only the relative strong phases of different terms in a scattering amplitude have physical content, an overall phase rotation of the entire amplitude has no physical consequences. Thus it is useful to write each contribution to A in three

parts: its magnitude A_i , its weak phase term $e^{i\phi_i}$ and its strong phase term $e^{i\delta_i}$. Then, if several amplitudes contribute to $B \rightarrow f$ we have:

$$\left| \frac{\bar{A}_f}{A_f} \right| = \left| \frac{\sum_i A_i e^{i(\delta_i - \phi_i)}}{\sum_i A_i e^{i(\delta_i + \phi_i)}} \right| \quad (\text{A.38})$$

To discuss CP violation in the interference of decays with and without mixing, we introduce a complex quantity λ_f defined by:

$$\lambda_f = \frac{q}{p} \frac{\bar{A}_f}{A_f} \quad (\text{A.39})$$

We further define the CP transformation law for the quark fields in the Hamiltonian (a careful treatment of CP conventions can be found in [54]):

$$q \rightarrow w_q \bar{q}, \quad \bar{q} \rightarrow w_q^* q, \quad (|w_q| = 1) \quad (\text{A.40})$$

The effective Hamiltonian that is relevant to M_{12} is of the form:

$$H_{eff}^{\Delta b=2} \propto e^{+2i\phi_B} [\bar{d}\gamma^\mu(1 - \gamma_5)b]^2 + e^{-2i\phi_B} [\bar{b}\gamma^\mu(1 - \gamma_5)d]^2 \quad (\text{A.41})$$

$2\phi_B$ is a CP violating (weak) phase. For the B system, where $|\Gamma_{12}| \ll |M_{12}|$, this leads to:

$$q/p = w_B w_b^* w_d e^{-2i\phi_B} \quad (\text{A.42})$$

To understand the phase structure of decay amplitudes, we take as an example the $b \rightarrow q\bar{q}d$ decay ($q = u$ or c). The decay Hamiltonian is of the form:

$$\begin{aligned} H_d \propto & e^{+i\phi_f} [\bar{q}\gamma^\mu(1 - \gamma_5)d] [\bar{b}\gamma_\mu(1 - \gamma_5)q] \\ & + e^{-i\phi_f} [\bar{q}\gamma^\mu(1 - \gamma_5)b] [\bar{d}\gamma_\mu(1 - \gamma_5)q] \end{aligned} \quad (\text{A.43})$$

ϕ_f is the appropriate weak phase. Then:

$$\bar{A}_f/A_f = w_f w_B^* w_b w_d^* e^{-2i\phi_f} \quad (\text{A.44})$$

Eqs. (A.42) and (A.44) together imply that for a final CP eigenstate,

$$\lambda_{f_{CP}} = \eta_{f_{CP}} e^{-2i(\phi_B + \phi_f)} \quad (\text{A.45})$$

A.4 The three types of CP violation in meson decays

A.4.1 CP violation in mixing

$$\left| \frac{q}{p} \right| \neq 1 \quad (\text{A.46})$$

This results from the mass eigenstates being different from the CP eigenstates. In fact if $|q/p| = 1$ this term represents a pure phase and due to the freedom of choosing an arbitrary phase in CP transformation we could define:

$$CP |B^o\rangle = \left| \frac{q}{p} \right| |\bar{B}^o\rangle \quad (\text{A.47})$$

With the convention of Eq. (A.47) B_H and B_L become CP eigenstates. But if Eq. (A.46) holds than there is no legitimate CP transformation, of B^o and $\bar{B}^o$, that will make the mass eigenstates CP eigenstates. This type of CP violation requires also a relative phase between M_{12} and Γ_{12} . In fact it could be demonstrated that B_H and B_L can be CP eigenstates if and only if $\Im(M_{12}\Gamma_{12}^*) = 0$, that is when the relative phase between M_{12} and Γ_{12} vanishes. The way this comes about is because there are two ways in which a B^o can mix into a $\bar{B}^o$: one is the direct way (connected with M_{12} , the dispersive part) and the other is via a common decay mode of the two states (connected to Γ_{12} , the absorptive part), as depicted in Fig. A.4. For the

Figure A.4: *CP violation in mixing.*

neutral B system, this effect could be observed through the asymmetries in

semileptonic decays:

$$a_{SL} = \frac{\Gamma(\bar{B}_{phys}^o(t) \rightarrow \ell^+ \nu X) - \Gamma(B_{phys}^o(t) \rightarrow \ell^- \nu X)}{\Gamma(\bar{B}_{phys}^o(t) \rightarrow \ell^+ \nu X) + \Gamma(B_{phys}^o(t) \rightarrow \ell^- \nu X)} \quad (\text{A.48})$$

In terms of q and p :

$$a_{SL} = \frac{1 - |q/p|^4}{1 + |q/p|^4} \quad (\text{A.49})$$

In the neutral B system, the effect is expected to be small, $\lesssim \mathcal{O}(10^{-2})$. The reason is that one expects that $a_{SL} \lesssim \Delta\Gamma_B/\Delta m_B$. The difference in width is produced by decay channels common to B^o and $\bar{B}^o$. The branching ratios for such channels are at, or below, the level of 10^{-3} . Since various channels contribute with differing signs, one expects that their sum does not exceed the individual level. Hence, we can safely assume that $\Delta\Gamma_B/\Gamma_B = \mathcal{O}(10^{-2})$, where $\Gamma_B = (\Gamma_H + \Gamma_L)/2$. On the other hand, it is experimentally known that $x (= \Delta m_B/\Gamma_B)$ for the B_d meson is $x_d = 0.771 \pm 0.012$ (while for the B_s meson is $x_s > 20.6$ at 95% CL) [55]. To calculate a_{SL} , we use Eqs. (A.49) and (A.35), and get:

$$a_{SL} = \Im\left(\frac{\Gamma_{12}}{M_{12}}\right) \quad (\text{A.50})$$

To predict it in a given model, one needs to calculate M_{12} and Γ_{12} . This involves large hadronic uncertainties, in particular in the hadronization models for Γ_{12} .

A.4.2 CP violation in decay

$$|\bar{A}_f/A_f| \neq 1 \quad (\text{A.51})$$

This appears as a result of interference among various terms in the decay amplitude, and will not occur unless at least two terms have different weak phases and different strong phases.

$$a_{f^\pm} = \frac{\Gamma(B^+ \rightarrow f^+) - \Gamma(B^- \rightarrow f^-)}{\Gamma(B^+ \rightarrow f^+) + \Gamma(B^- \rightarrow f^-)} \quad (\text{A.52})$$

CP asymmetries in charged B decays are purely an effect of CP violation in decay. Equation (A.52) in terms of the decay amplitudes:

$$a_{f^\pm} = \frac{1 - |\bar{A}_{f^-}/A_{f^+}|^2}{1 + |\bar{A}_{f^-}/A_{f^+}|^2} \quad (\text{A.53})$$

To calculate $a_{f\pm}$ we use Eqs. (A.53) and (A.38). For simplicity, we consider decays with contributions from two weak phases and with $A_2 \ll A_1$. We get:

$$a_{f\pm} = -2(A_2/A_1) \sin(\delta_2 - \delta_1) \sin(\phi_2 - \phi_1) \quad (\text{A.54})$$

The magnitude and strong phase of any amplitude involve long distance strong interaction physics and our ability to calculate these from first principles is limited. Thus quantities that depend only on the weak phases are cleaner.

A.4.3 CP violation in the interference between decays with and without mixing

$$|\lambda_{f_{CP}}| = 1, \quad \Im(\lambda_{f_{CP}}) \neq 0 \quad (\text{A.55})$$

Any $\lambda_{f_{CP}} \neq \pm 1$ is a manifestation of CP violation. The special case of Eq. (A.55) isolates the effects of interest since both CP violation in decay, Eq. (A.51), and in mixing, Eq. (A.46), lead to $|\lambda_{f_{CP}}| \neq 1$. For the neutral B system this effect can be observed by comparing decays into final CP eigenstates of a time-evolving neutral B state that begins at time zero as B^o to those of the state that begins as $\bar{B}^o$:

$$a_{f_{CP}} = \frac{\Gamma(\bar{B}_{phys}^o(t) \rightarrow f_{CP}) - \Gamma(B_{phys}^o(t) \rightarrow f_{CP})}{\Gamma(\bar{B}_{phys}^o(t) \rightarrow f_{CP}) + \Gamma(B_{phys}^o(t) \rightarrow f_{CP})} \quad (\text{A.56})$$

This time dependent asymmetry is given by:

$$a_{f_{CP}} = \frac{(1 - |\lambda_{f_{CP}}|^2) \cos(\Delta Mt) - 2\Im(\lambda_{f_{CP}}) \sin(\Delta Mt)}{1 + |\lambda_{f_{CP}}|^2} \quad (\text{A.57})$$

and, for $|\lambda_{f_{CP}}| = 1$, Eq. (A.57) simplifies considerably to:

$$a_{f_{CP}} = -\Im(\lambda_{f_{CP}}) \sin(\Delta m_B t) \quad (\text{A.58})$$

It is expected to be an effect of $\mathcal{O}(1)$ in various B decays. For such cases, the contribution from CP violation in mixing is clearly negligible. For decays that are dominated by a single CP violating phase (for example, $B \rightarrow J/\psi K_S$ and $K_L \rightarrow \pi^0 \nu \bar{\nu}$), so that the contribution from CP violation in decay is also negligible, $a_{f_{CP}}$ is cleanly interpreted in terms of purely electroweak parameters. Explicitly, $\Im(\lambda_{f_{CP}})$ gives the difference between

the phase of the $B - \bar{B}$ mixing amplitude, $2\phi_B$, and twice the phase of the relevant decay amplitude, $2\phi_f$, (see Eq. (A.45)):

$$\Im(\lambda_{f_{CP}}) = -\eta_{f_{CP}} \sin(2(\phi_B + \phi_f)) \quad (\text{A.59})$$

A summary of the main properties of the different types of CP violation in meson decays is given in Tab. A.2.

Type	Exp.	Theory	Calculation	Uncertainties
mixing	a_{SL}	$\frac{1- q/p ^4}{1+ q/p ^4}$	$\Im\left(\frac{\Gamma_{12}}{M_{12}}\right)$	Γ_{12} large
decay	$a_{f\pm}$	$\frac{1- A_{f-}/A_{f+} ^2}{1+ A_{f-}/A_{f+} ^2}$	$-2\frac{A_2}{A_1} \sin(\delta_2 - \delta_1)$ $\sin(\phi_2 - \phi_1)$	δ_i, A_i large
interference	$a_{f_{CP}}$	$-\Im(\lambda_{f_{CP}})$	$\eta_{f_{CP}} \sin(2(\phi_B + \phi_f))$	small

Table A.2: *The three types of CP violation in meson decays.*

A.5 B decays classification

B decay can be classified into four classes. Classes (1) and (2) are expected to have relatively small CP violation in decay and hence are particularly interesting for extracting CKM parameters from interference of decays with and without mixing. In class (3) and (4), CP violation in decay could be significant and might be observable in charged B decays.

1. **decays dominated by a single term** (*e.g.* $b \rightarrow c\bar{c}s$ and $b \rightarrow s\bar{s}s$).

The SM predicts very small CP violation in decay: $\mathcal{O}(\lambda^2)$ for $b \rightarrow s\bar{s}s$. Any observation of large CP asymmetries in charged B decays for these channels would be a clue to physics beyond the SM. The corresponding neutral modes have cleanly predicted relationships between CKM parameters and the measured asymmetry from interference between decays with and without mixing

2. **decays with a small second term** (*e.g.* $b \rightarrow c\bar{c}d$ and $b \rightarrow u\bar{u}d$). The expectation that penguin-only contributions are suppressed compared

to tree contributions suggests that these modes will have small effects of CP violation in decay, of $\mathcal{O}(\lambda^2 - \lambda)$, and an approximate prediction of the relationship between measured asymmetries in neutral decays and CKM phase can be made

3. decays with a suppressed tree contribution (*e.g.* $b \rightarrow u\bar{u}s$).

The tree amplitude is suppressed by small mixing angles, $V_{ub}V_{us}$. The non-tree term may be comparable or even dominate and give large interference effects

4. decays with no tree contribution and a small second term (*e.g.*

$b \rightarrow s\bar{u}d$). Here the interference comes from penguin contributions with different charge 2/3 quarks in the loop and gives CP violation in decay that could be as large as 10%

Classes	Decays
(1)	$B \rightarrow J/\psi K$ $B \rightarrow \phi K$
(2)	$B \rightarrow DD$ $B \rightarrow \pi\pi$
(3)	$B \rightarrow \rho K$ $B \rightarrow \pi K$
(4)	$B \rightarrow KK$

Table A.3: *Classification of some B decays.*

The B decays most relevant to the measurement of the α , β and γ angles of the unitarity triangle are classified in Tab. A.3. The role played by these decays in this context is highlighted in detail in the following sections.

A.6 Techniques for determining β

The angle β of the unitarity triangle is defined by:

$$\beta \equiv \arg \left[-\frac{V_{tb}V_{td}^*}{V_{cb}V_{cd}^*} \right] \quad (\text{A.60})$$

The decay $B^o \rightarrow J/\psi K_S$, belonging to class (1) (see section A.5), is the primary source for measurements of $\sin(2\beta)$. In the common phase convention, CP violation is expected to arise mostly from the mixing, driven by $\Im(q/p)$, while the decay amplitude, $\Im(\bar{A}_{\bar{f}}/A)$, is expected to contribute only a small part. The final state $J/\psi K_S$ is a CP eigenstate and its decay is dominated by only one diagram, shown in Fig. A.5. For this decay mode we have:

Figure A.5: *Decay diagram at the tree level for $B^o \rightarrow J/\psi K_S$.*

$$\begin{aligned} \lambda(B_d \rightarrow J/\psi K_S) &= - \left(\frac{V_{tb}^* V_{td}}{V_{tb} V_{td}^*} \right) \left(\frac{V_{cs}^* V_{cb}}{V_{cs} V_{cb}^*} \right) \left(\frac{V_{cd}^* V_{cs}}{V_{cd} V_{cs}^*} \right) \Rightarrow \\ &\Rightarrow \Im(\lambda_{J/\psi K_S}) = \sin(2\beta) \end{aligned} \quad (\text{A.61})$$

Where the first term comes from $B_d^o - \bar{B}_d^o$ mixing, see Fig. A.6, the second from the ratio $\frac{\bar{A}_{\bar{f}}}{A}$ and the third from the $K^o - \bar{K}^o$ mixing.

Figure A.6: *The two diagrams for B_d mixing. Although u , c and t quark exchange are all shown, the t quark plays a dominant role, mainly due to his mass, since the amplitude of this process grows with the mass of the exchanged fermion.*

In this case we do not get a phase from the decay part because:

$$\frac{\bar{A}_{\bar{f}}}{A} = \frac{(V_{cb} V_{cs}^*)^2}{|V_{cb} V_{cs}|^2} \quad (\text{A.62})$$

is real. The final state is a state of negative CP , *i.e.* $CP|J/\psi K_S\rangle = -|J/\psi K_S\rangle$. This introduces an additional minus sign in the result for $\Im(\lambda)$. Before finishing the discussion of this final state we need to consider in more detail the presence of the K_S in the final state. Since neutral kaons can mix, we pick up another mixing phase. This term creates a phase given by

$$\left(\frac{q}{p}\right)_K = \frac{(V_{cd}^* V_{cs})^2}{|V_{cd} V_{cs}|^2} \quad (\text{A.63})$$

which is zero. It is necessary to include this term, however, since there are other formulations of the CKM matrix than Wolfenstein, which have the phase in a different location, it is important that the physics predictions not depend on the CKM convention.

A.6.1 Results on $\sin(2\beta)$

The first statistically significant measurements of CP violation in the B system were made recently by BABAR and BELLE [56, 57]. This enormous achievement was accomplished using an asymmetric e^+e^- collider tuned to the $\Upsilon(4S)$. The measurements are listed in Tab. A.4, along with other previous indications [58]. The average value of 0.67 ± 0.15 is taken from

Experiment	$\sin(2\beta)$
BABAR	$0.68 \pm 0.30 \pm 0.04$
BELLE	$0.65 \pm 0.04 \pm 0.02$
Average	0.736 ± 0.049
CDF	$0.79^{+0.41}_{-0.44}$
ALEPH	$0.84^{+0.82}_{-1.04} \pm 0.16$
OPAL	$3.2^{+1.8}_{-2.0} \pm 0.5$

Table A.4: *Measurements of $\sin(2\beta)$.*

BABAR and BELLE only. This value is consistent with what is expected from the other known constraints on ρ and η . We have:

$$\bar{\eta} = (1 - \bar{\rho}) \frac{1 \pm \sqrt{1 - \sin^2(2\beta)}}{\sin(2\beta)} \quad (\text{A.64})$$

There is a four fold ambiguity in the translation between $\sin(2\beta)$ and the linear constraints in the $\bar{\rho} - \bar{\eta}$ plane. These occur at β , $\pi/2 - \beta$, $\pi + \beta$ and $3\pi/2 - \beta$. Two of these constraints are shown in Fig. A.3, but from recent measurements one of the two ambiguities can be excluded at 95% CL. The other two can be viewed by extending these to negative $\bar{\eta}$. We think $\bar{\eta} > 0$ based only on measurement of ϵ'_K in the neutral kaon system. This analysis clearly shows that current data are consistent with the SM.

A.6.2 Other modes for measuring $\sin(2\beta)$

New physics can add differently to the phases in different decay modes if it contributes differently to the relative decay amplitudes $\bar{A}_f/A$. Therefore it

Decay mode	Branching ratio
$B^o \rightarrow \phi K^o$	$(8.1^{+3.2}_{-2.6}) \times 10^{-6}$
$B^o \rightarrow D^+ D^-$	$\sim 10^{-3}$
$B^o \rightarrow D^{*+} D^-$	$\sim 10^{-3}$
$B^o \rightarrow \eta' K^o$	$(5.8^{+1.4}_{-1.3}) \times 10^{-5}$
$B^o \rightarrow J/\psi \pi^o$	$(1.94 \pm 0.28) \times 10^{-5}$

Table A.5: *Other modes useful for cross-checking $\sin(2\beta)$.*

is interesting to measure CP violation in redundant modes. For example, the decay $B^o \rightarrow \phi K_S$ should also measure $\sin(2\beta)$. If it is different than that obtained by $B^o \rightarrow J/\psi K_S$, that would be a strong indication of new physics [59]. Other interesting modes to check $\sin(2\beta)$ are listed in Tab. A.5. The branching ratios listed with errors have been measured [56, 60, 61], while those without are theoretical estimates.

A.7 Techniques for determining α

The angle α of the unitarity triangle is defined by:

$$\alpha \equiv \arg \left[-\frac{V_{cb}V_{cd}^*}{V_{ub}V_{ud}^*} \right] \quad (\text{A.65})$$

Measuring α is more difficult than measuring β in several respects. First of all, the decay amplitudes are modulated by V_{ub} rather than V_{cb} , making

the overall rates small. Secondly these decays belong to class (2) or (3) (see section A.5), thus the gluonic penguin rates, see Fig. A.7, are of the same order causing difficulties in extracting the weak phase angle. The penguin

Figure A.7: *Penguin diagram for $B^0 \rightarrow \pi^+ \pi^-$.*

diagrams add a third amplitude to the tree level and mixing amplitudes. It turns out, however, that this complication can be used to remove discrete ambiguities. The decay $B^0 \rightarrow \pi^+ \pi^-$ has often been cited as a way to measure $\sin(2\alpha)$. However, the penguin pollution mentioned above, makes it difficult to extract the angle. Gronau and London [62] have shown that an isospin analysis using the additional decays $B^- \rightarrow \pi^- \pi^0$ and $B^0 \rightarrow \pi^0 \pi^0$ can be used to extract α where a flavour tagged asymmetry measurement is needed in the $\pi^0 \pi^0$ final state. This is extremely difficult and there is generally no decay vertex in the $\pi^0 \pi^0$ final state.

There is however, a theoretically clean method to determine α . The interference between tree and penguin diagrams can be exploited by measuring the time dependent CP violating effects in the decays $B^0 \rightarrow \rho \pi$ as shown by Snyder and Quinn [11]. There are three such neutral decay modes, listed in Tab. A.6, with their respective penguin, denoted by P, and tree amplitudes, denoted by T^{ij} , where i lists charge of the ρ and j the charge of the π . For the $\rho^0 \pi^0$ mode, isospin constraints are used to eliminate T^{00} . The amplitudes for the charged decays are also given. For the $\rho \pi$ final state, the ρ decay amplitude can be parameterized as:

$$f(m, \theta) = \frac{\cos(\theta) \Gamma_\rho}{2(m_\rho - m - i0.5\Gamma_\rho)} \quad (\text{A.66})$$

m_ρ is the ρ mass of 0.77 GeV and Γ_ρ the width of 0.15 GeV. θ is the helicity

Decay mode	Decay amplitudes
$\sqrt{2}A(B^+ \rightarrow \rho^+\pi^0)$	$= S_1 = T^{+0} + 2P_1$
$\sqrt{2}A(B^+ \rightarrow \rho^0\pi^+)$	$= S_2 = T^{0+} - 2P_1$
$A(B^0 \rightarrow \rho^+\pi^-)$	$= S_3 = T^{+-} + P_1 + P_0$
$A(B^0 \rightarrow \rho^-\pi^+)$	$= S_4 = T^{-+} - P_1 + P_0$
$2A(B^0 \rightarrow \rho^0\pi^0)$	$= S_5 = T^{+-} + T^{-+} - T^{+0} - T^{0+} - 2P_0$

Table A.6: $B^0 \rightarrow \rho\pi$ decay modes.

decay angle and the $\cos(\theta)$ dependence arises because the ρ must be fully polarized in this decay which starts with a spin-0 B and ends with a spin-1 ρ and spin-0 π . The full decay amplitudes for $B^0 \rightarrow \rho\pi \rightarrow \pi^+\pi^-\pi^0$ and the corresponding $\bar{B}^0$ decay are given by:

$$\begin{aligned}
A(B^0) &= f^+ S_3 + f^- S_4 + f^0 S_5/2 \\
A(\bar{B}^0) &= f^+ \bar{S}_3 + f^- \bar{S}_4 + f^0 \bar{S}_5/2
\end{aligned} \tag{A.67}$$

where the superscript on the f indicates the charge of the ρ . The sum over the three neutral B decay amplitudes involves only tree amplitudes; the penguins vanish. The angle between this sum for B^0 decays ($\equiv T$) and the sum for $\bar{B}^0$ ($\equiv \bar{T}$) is precisely α . Computing the amplitudes gives a series of terms which have both $\sin(\Delta mt)$ and $\cos(\Delta mt)$ time dependences and coefficients which depend on both $\sin(2\alpha)$ and $\cos(2\alpha)$.

A.8 Techniques for determining γ

The angle γ of the unitarity triangle is defined by:

$$\gamma \equiv \arg \left[-\frac{V_{ub}V_{ud}^*}{V_{tb}V_{td}^*} \right] \tag{A.68}$$

The angle γ could in principle be measured using a CP eigenstate of B_s decay that was dominated by the $b \rightarrow u$ transition. One such decay that has been suggested is $B_s \rightarrow \rho^0 K_S$. However, since it belongs to class (3) (see section A.5), there are the same ‘‘penguin pollution’’ problems as in $B^0 \rightarrow \pi^+\pi^-$, but they are more difficult to resolve in the vector-pseudoscalar final state, the pseudoscalar-pseudoscalar final state here is $\pi^0 K_S$, which

does not have a measurable decay vertex. There are two main methods of measuring γ :

using time-dependent CP violation in B_s decays: this method uses the decays $B_s \rightarrow D_s^\pm K^\mp$ where a time-dependent CP violation can result from the interference between the direct decays and the mixing-induced decays [63, 64, 65]. Figure A.8 shows the two direct decay processes for $\bar{B}_s^0$.

Figure A.8: Two diagrams for $\bar{B}_s^0 \rightarrow D_s^\pm K^\mp$.

Figure A.9: Diagrams for the two interfering processes, (a) $B^- \rightarrow D^0 K^-$ (colour allowed) followed by $D^0 \rightarrow K^+ \pi^-$ (doubly-Cabibbo suppressed) and (b) $B^- \rightarrow \bar{D}^0 K^-$ (colour suppressed) followed by $\bar{D}^0 \rightarrow K^- \pi^+$ (Cabibbo allowed).

using charged B decay rates: this method was proposed by Atwood, Dunietz and Soni [66], who refined a suggestion by Gronau and

Wyler [67]. A large CP asymmetry can result from the interference of the decays $B^- \rightarrow K^- D^0$, $D^0 \rightarrow f$ and $B^- \rightarrow K^- \bar{D}^0$, $\bar{D}^0 \rightarrow f$, where f is a doubly-Cabibbo suppressed decay of the D^0 , for example $f = K^+ \pi^-$, $K \pi \pi$, see Fig. A.9. The overall amplitudes for the two decays are expected to be approximately equal in magnitude, note that $B^- \rightarrow K^- \bar{D}^0$ is colour-suppressed and $B^- \rightarrow K^- D^0$ is colour-allowed. The weak phase difference between them is γ . To observe a CP asymmetry there must also be a non-zero strong phase between the two amplitudes. It is necessary to measure the branching ratio $\mathcal{B}(B^- \rightarrow K^- f)$ for at least 2 different states f in order to determine γ up to discrete ambiguities.

A.9 Summary of crucial measurements for CKM physics

Table. A.7 lists the most important physics quantities and the decay modes that can be used for their measurement. Other modes which also may turn

Physics quantity	Decay mode
$\sin(2\alpha)$	$B^0 \rightarrow \rho \pi \rightarrow \pi^+ \pi^- \pi^0$
$\cos(2\alpha)$	$B^0 \rightarrow \rho \pi \rightarrow \pi^+ \pi^- \pi^0$
$\text{sign}(\sin(2\alpha))$	$B^0 \rightarrow \rho \pi$ & $B^0 \rightarrow \pi^+ \pi^-$
$\sin(\gamma)$	$B_s \rightarrow D_s^\pm K^\mp$
$\sin(\gamma)$	$B^- \rightarrow \bar{D}^0 K^-$
$\sin(\gamma)$	$B^0 \rightarrow \pi^+ \pi^-$ & $B_s \rightarrow K^+ K^-$
$\sin(2\chi)$	$B_s \rightarrow J/\psi \eta'$, $J/\psi \eta$
$\sin(2\beta)$	$B^0 \rightarrow J/\psi K_S$
$\cos(2\beta)$	$B^0 \rightarrow J/\psi K^0$, $K^0 \rightarrow \pi \ell \nu$
$\cos(2\beta)$	$B^0 \rightarrow J/\psi K^{*0}$ & $B_s \rightarrow J/\psi \phi$
x_s	$B_s \rightarrow D_s^+ \pi^-$
$\Delta\Gamma$ for B_s	$B_s \rightarrow J/\psi \eta'$, $D_s^+ \pi^-$, $K^+ K^-$

Table A.7: Required CKM measurements for b 's.

out to be useful include $B^0 \rightarrow D^{*+}\pi^-$ and its charge-conjugate [68], which measures $\sin(-2\beta - \gamma)$ albeit with a small $\sim 1\%$ predicted asymmetry and $B \rightarrow K\pi$ modes which can be used to find γ albeit with theoretical uncertainties. There are three alternative ways to measure γ which serve both to remove ambiguities and perform checks. It will be much more difficult to find other modes to check α , however. One approach is to measure the CP asymmetry in $B^0 \rightarrow \pi^+\pi^-$ and use theoretical models to estimate the effects of penguin pollution. Minimally, a great deal would be learned about the models. It also turns out that the third ambiguity in α can be removed by comparing the CP violating asymmetry in $\pi^+\pi^-$ with that found in $\rho\pi$ and using some mild theoretical assumptions [69]. After the three angles α , β and γ have been measured, we need to check if they add up to 180° . A discrepancy here would be unexpected. To be sure, this check is not complete if ambiguities have not been removed (even if the angles sum to 180° , new physics could hide).

A.10 Rare decays as probes beyond the Standard Model

Rare decays are described by the decay diagrams that feature loops, which makes them sensitive to high mass gauge bosons and fermions; this is particularly important for decays belonging to class (4) (see section A.5). Thus, they are sensitive to new physics. However, it must be kept in mind that any new effect must be consistent with already measured phenomena such as B_d^0 mixing and $b \rightarrow s\gamma$. These processes are often called “penguin” processes [71]. A Feynman loop diagram is shown in Fig. A.10 that describes the transition of a b quark into a charged $-1/3$ s or d quark, which is effectively a neutral current transition. The dominant charged current decays change the b quark into a charged $+2/3$ quark, either c or u . The intermediate quark inside the loop can be any charge $+2/3$ quark. The relative size of the different contributions arises from different quark masses and CKM elements. For $b \rightarrow s$, in terms of the Cabibbo angle ($\lambda=0.22$), we have for $t : c : u = \lambda^2 : \lambda^2 : \lambda^4$. The mass dependence favors the t loop, but the

Figure A.10: *Loop or “Penguin” diagram for a $b \rightarrow s$ or $b \rightarrow d$ transition.*

amplitude for c processes can be quite large $\sim 30\%$. Moreover, as pointed out by Bander, Silverman and Soni [72], interference can occur between t , c and u diagrams and lead to CP violation. In the SM it is not expected to occur when $b \rightarrow s$, due to the lack of a CKM phase difference, but could occur when $b \rightarrow d$. In any case, it is always worth looking for this effect; all that needs to be done, for example, is to compare the number of $K^{*-}\gamma$ events with the number of $K^{*+}\gamma$ events. There are other possibilities for physics beyond the SM to appear. For example, the W^- in the loop can be replaced by some other charged object such as a Higgs; it is also possible for a new object to replace the t .