Radiation hardness of the ZEUS MVD frontend chip
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Chapter 6

Radiation hardness of the Helix 3.0

Reflected synchrotron radiation, off-momentum particles and particles created by interactions between the beams and the residual gas may interact with the beampipe causing sprays of particles in the MVD. The damage caused by this radiation can increase the leakage current in the sensors and degrade the performance of the chip. However, the Helix is a programmable chip allowing partial compensation of the radiation damage by changing the operation point.

In this chapter the mechanisms behind radiation damage in the Helix will be discussed and measurements will be presented showing the effects of the radiation damage. For these measurements hybrids connected to single modules were irradiated and the combined performance was tested with beam particles and the internal testpulse. From these measurements radiation damage compensation strategies were derived.

6.1 Radiation damage effects

The radiation damage in the ZEUS detector has two components, damage due to non-ionising energy loss (NIEL) and ionising energy loss. The principal mechanism of damage due to NIEL is the displacement of atoms from their place in the lattice. Here only the ionising energy loss is studied.

During irradiation of the chip, electron-hole (e-h) pairs are generated throughout the chip. Although mostly fast recombination makes this process harmless, e-h pairs generated in the SiO$_2$ are dangerous. When an e-h pair is produced the electrons will drift towards the gate, but the mobility of the holes in the oxide is very low. Therefore, the holes will move very slowly towards the $Si - SiO_2$ interface of the MOS structure and may get trapped in the $SiO_2$. This leads to charging up of the oxide. Some holes may reach the $Si - SiO_2$-interface where they capture electrons and form interface traps. The electric field component perpendicular to the direction of the cur-
Figure 6.1: Schematical view of an NMOS transistor under irradiation.

rent accelerates the electrons towards the $Si - SiO_2$ interface where they scatter or are captured by traps. The traps will release the trapped electrons with large time constants. This leads to reduced carrier mobility in the channel[31] and to an increase in the 1/f or flicker noise[32, 33].

The threshold voltage, $V_T$, can be expressed as[34]

$$V_T = 2\phi_b + \frac{2\sqrt{qN_A\varepsilon_s\phi_b}}{C_{ox}} + \phi_{ms} - \frac{Q'_{ox}}{C_{ox}} - \frac{Q'_{it}}{C_{ox}}$$  \hspace{1cm} (6.1)

where $\phi_b$ is the silicon bulk potential, $q$ the elementary charge, $N_A$ the acceptor density, $\varepsilon_s$ the dielectric constant of the substrate, $C_{ox}$ the oxide capacitance, $\phi_{ms}$ the metal-to-silicon work function i.e. the difference in Fermi potential between the substrate and the gate, $Q'_{ox}$ the effective oxide charge and $Q'_{it}$ the interface charge. The trapped holes in the oxide yield an increase in $Q'_{ox}$ and therefore a decrease in $V_T$. The holes reaching the interface capture electrons yielding an increase in $-Q'_{it}$ and therefore an increase in $V_T$. For NMOS transistors the hole trapping in the bulk will initially dominate the $V_T$ behaviour. However, at a certain accumulated dose, the bulk will be saturated by trapped holes and the interface traps will dominate the $V_T$ behaviour. In figure 6.2 the threshold voltage is plotted as a function of the accumulated dose as measured for a test-structure produced in the 0.8$\mu$m technology used for the Helix chip[29].

For transistors used as resistors, the resistance value is given by equation (5.9)

$$R = \frac{L}{\mu_n C_{ox} W (V_{gs} - V_T - V_{ds})}$$

Hence, the resistance value will be different because of the altered values of $V_{gs}$ and $\mu$. Due to the hole trapping in the oxide, the resistance value initially decreases for the same
value of $V_g$, i.e. the same decimal register value in DAC-counts. The reduction of the electron mobility in the channel yields larger values of the resistance for the same value of $V_g$ and an increase of the noise. It was found (see section 6.3.4) that the shift of $V_T$ is the most important. Therefore, the values of $V_{fp}$, $V_{fs}$ and $V_{offset}$ will have to be decreased after irradiation to recover the same resistance value.

When the transistor is used as a current source, like for the registers $I_{pre}$, $I_{sha}$, $I_{pipe}$ and $I_{driver}$, the current is given by equation (5.6)

$$i_d = \frac{\mu_n C_{ox} W}{2L} (V_{gs} - V_T)^2$$

and the transconductance by equation (5.8)

$$g_m = \frac{\mu_n C_{ox} W}{L} (V_{gs} - V_T)$$

The radiation induced threshold voltage shift yields larger currents and larger and faster output signals.

Due to the irradiation electron-hole pairs are generated throughout the whole chip. Charge may be trapped in insulating layers, changing their properties. Parasitic NMOS structures might be turned on which can lead to conductive paths. This could play a role in the preamplifiers feedback resistor, since that is the largest resistance present in the chip.
The biasing circuit

All analog values of the settings are derived from an internal biasing circuit. A reference current is generated using an external power supply and an external resistor. Internally, a second current is generated using $V_{dd}$ and $V_{ss}$ using two internal resistors. Using a differential amplifier and an array of PMOS transistors in a current mirror configuration, the internally generated current is made equal to the external reference current. Any radiation damage to the PMOS transistors is equal on both sides of the mirror. Thus, despite radiation damage the value of the reference current remains constant. All settings are derived from this reference current and have a constant behaviour irrespective of any radiation damage[29].

6.2 Irradiation program

For the irradiation test the single modules mentioned in chapter 5 were used. The hybrids have been irradiated using a $^{60}$Co-source at the “Nederlands Meetinstituut”\(^1\). The hybrids were irradiated in sets of two. In table 6.1 an overview of the accumulated doses per hybrid is given. Each hybrid was measured before irradiation and at 3 of the 5 different accumulated doses. The uncertainties in the accumulated doses are given by the “Nederlands Meetinstituut”.

<table>
<thead>
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<th>Acc. dose (krad)</th>
<th>Dose rate (krad/hour)</th>
<th>o187</th>
<th>o668</th>
<th>o445</th>
<th>o681</th>
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<td></td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>11 ± 2</td>
<td>0.7</td>
<td>-</td>
<td>-</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>48 ± 10</td>
<td>0.7</td>
<td>x</td>
<td>x</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>103 ± 30</td>
<td>3.6</td>
<td>-</td>
<td>-</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>200 ± 50</td>
<td>3.6</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>502 ± 146</td>
<td>3.6</td>
<td>x</td>
<td>x</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 6.1: Overview of the accumulated doses.

6.2.1 Experimental setup

Measurements were performed in the testbeam as well as with the internal testpulse. Performing measurements in the testbeam has the advantage that the input charge is always the same and that the most important parameter for a position sensitive detector, the

\(^1\)Dutch institute for standards and calibrations.
spatial resolution, can be measured directly. The usage of the internal testpulse circuit has the advantage of a very high measurement frequency, allowing scans over the whole Helix parameter space. The experimental setup and the analysis for the internal testpulse measurements are described in section 5.2.

### 6.2.2 Testbeam measurements

The setup used for the measurements in the testbeam was described in section 4.1. The setup was slightly modified to run with a 10 MHz clock, see appendix B. The analysis was described in chapter 4. The asymmetric crosstalk for the Helix 3.0 was found to be 3.73±0.02 % before irradiation and decreases to 3.3±0.1 % after 500 krad. In the analysis the appropriate value for each dose was used. To measure the signal-to-noise ratio, the clusters of variable size were reconstructed using a $5\sigma_{\text{strip}}$ cut on all strips. The position reconstruction was done with the $\eta$-algorithm. Data collected before irradiation were taken with the beam spot near the bond pad region, while the data taken with irradiated modules were taken far away from the bond pad region. As described in section 4.8, this leads to different resolutions and signal-to-noise ratios. In the remainder of the chapter all results obtained before irradiation will be depicted by open symbols.

### 6.3 Results

#### 6.3.1 Signal to noise

Due to the irradiation the effective values of the parameters will change. Therefore, the value of the signal (S) and the noise (N) will be different while the programmed values of the parameters are not changed. In figure 6.3 the S/N-ratio averaged over all chips is displayed as a function of the accumulated dose. The S/N-ratio shows an exponential decrease from 21.6±0.3 before irradiation to 12.0±0.5 after an accumulated dose of 500 krad using the default values of the Helix settings.

#### 6.3.2 Position resolution

The worsening of the S/N-ratio will lead to worse position resolution. This is shown in figure 6.4, where the resolution is plotted as a function of the accumulated dose and as a function of the N/S-ratio. The resolution worsens from 9.4±0.1 \(\mu\text{m}\) after an accumulated...
dose of 10 krad to 12.2±0.4 μm after 500 krad. As discussed in section 4.6.3 the relation between the resolution and the S/N-ratio is given by

\[ \sigma = \alpha \frac{N}{S} + \beta \]  

(6.2)

As can be seen in figure 6.4(b), the data agrees well with the model. This fit will be used to translate the improvement in the S/N-ratio obtained with the internal testpulse circuit into improvements in the spatial resolution.

### 6.3.3 Comparison of internal testpulse and testbeam data

Because the event rate in the testbeam is of the order of a few Hz, it takes too long to make large scans over the parameter space of the Helix. Therefore, these scans are made using the internal testpulse of the Helix. Here the event rate can be of the order of 100 Hz. Since the internal testpulse was never designed to be a precise calibration tool and since the circuit itself might also get damaged by the irradiation the question arises whether the testpulse yields the same results as the measurements in the testbeam.

To compare the results obtained with the internal testpulse and with the testbeam, the S/N-ratios were compared. In figure 6.5 the ratio measured in the testbeam is plotted versus the ratio measured using the internal testpulse for all irradiated chips. There is a clear correlation between both ratios. Assuming that the measured S/N-ratio depends linearly on the true S/N-ratio of the Helix chip only, there should be a linear relationship

![Figure 6.3: S/N-ratio versus the accumulated dose.](image)
between the S/N-ratio measured in the testbeam and the S/N-ratio measured using the internal testpulse.

To estimate the size of the error introduced by the internal testpulse circuit, figure 6.5 was analyzed in more detail. Addition of a relative error of 15% to the S/N measured with the internal testpulse, results in a $\chi^2/ndf$ of 1 for a straight line fit, justifying the comparison between the testbeam measurement and the internal testpulse measurements.

**Signal decay in the pipeline**

The signal decay in the pipeline was measured as a function of the accumulated dose. No clear dependence was found of the decay time constant on the accumulated dose. Even with the smallest value obtained for $\tau_{\text{leak}}$ the amplitude of the signal after storing it for the maximum latency decreases by less than 1.2%. The leakage in the pipeline can therefore be neglected in the MVD.

### 6.3.4 Performance study of irradiated Helix

To study the effect of irradiation on the performance, the measurements discussed in section 5.3 have been repeated after each irradiation. Here the results will be discussed
as a function of the accumulated dose; they are averaged over all working chips that were exposed to the accumulated dose.

**Frontend parameters**

$V_{fp}$ sets $V_{gs}$ of the transistor used for the feedback resistor of the preamp. The radiation yields a decrease in $V_T$ of the transistor, resulting in a lower value of $R_{fb}$ at the same decimal register value of $V_{fp}$. This leads to smaller peak signals. In figure 6.6(a) the peak signal is plotted versus $V_{fp}$ for different accumulated doses. The expected decrease of the peak signal for increasing accumulated dose at constant $V_{fp}$ is observed. Furthermore, after the first irradiation a threshold is visible. The threshold could be reproduced in a SPICE simulation by adding a radiation induced leakage current at the input of the preamplifier.

The value of $R_{fb}$ only enters the peak time of the preamp in the logarithmic term, see equation (5.16). Therefore, the decrease in $R_{fb}$ will not influence the peaktime of the shaper. In figure 6.6(c) the peak time and in figure 6.6(e) the S/N-ratio is plotted versus $V_{fp}$ for different accumulated doses.

$I_{pre}$ sets the bias current of the preamp by setting $V_{gs}$ of the transistor controlling the bias current and thus the $g_m$. Increasing $I_{pre}$ increases the peak signal and decreases the peaking time. Radiation damage induces a decrease of $V_T$ leading to larger $g_m$ at the same value of $I_{pre}$ and thus to increasing peak signal and decreasing peaktime for increasing accumulated dose. In figure 6.6(b) the peak signal, in figure 6.6(d) the peaktime and

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Figure 6.5: $S/N$-ratio obtained in the testbeam versus the $S/N$-ratio measured with the internal testpulse circuit.
in figure 6.6(f) the S/N-ratio is plotted versus $I_{prc}$ showing the increase of the peak signal with $I_{prc}$. Due to the radiation damage $g_m$ should increase for the same value of $I_{prc}$. Because all parameters are shifted due to the radiation damage the absolute signal heights cannot be compared directly. But one does see that the ratio $\frac{S_{prc=250}}{S_{prc=80}}$ increases with the dose as expected.

$V_{fs}$ controls the value of the shaper feedback resistor. Increasing $V_{fs}$ decreases the value of $R_{fb}$ yielding a decreasing peaktime and peak signal. Radiation damage will result in a decrease of $V_T$ and therefore in a decrease of the peak signal and peaktime at constant $V_{fs}$. In figure 6.7(a) the peak signal and in figure 6.7(c) the peaktime is plotted versus $V_{fs}$ for different accumulated doses. The expected decrease of the peak signal and peaktime with increasing $V_{fs}$ as well as increasing accumulated dose are observed. The S/N-ratio is plotted in figure 6.7(e). If the value of $V_{fs}$ becomes too low the transistor does not behave as a resistor anymore. The shape does not return to zero within the measured time range making the obtained fit results meaningless.

$I_{sha}$ determines the $g_m$ of the shaper. Increasing $I_{sha}$ corresponds with increasing $g_m$. Therefore, the peak signal and the peaktime are expected to decrease with increasing $I_{sha}$. Radiation damage will increase $g_m$ at constant $I_{sha}$ yielding smaller peaktimes and peak signals at the same value if $I_{sha}$. In figure 6.7(f) the S/N-ratio is plotted versus $I_{sha}$ and in figure 6.7(d) the peaktime is plotted versus $I_{sha}$. The expected behaviour of the signal and the peaktime are observed.

**Other parameters**

The signal height and the peaktime are mainly determined in the preamplifier and the shaper. The remaining settings will mainly influence the S/N-ratio by adding additional noise or clipping the signal. Therefore, only the results for the S/N-ratio of these settings will be presented here.

In figure 6.8(a) the S/N-ratio is plotted as a function of $I_{buf}$ for different accumulated doses. No decrease in the S/N-ratio is expected nor observed except for the overall S/N-ratio decrease generated in the frontend. This is because the buffer amplifier is realized as a source follower. $I_{buf}$ sets the resistance value of the load resistor. Radiation damage suffered by the “resistor” is the same as the damage done to the input transistor. A decrease in the S/N-ratio at one accumulated dose as a function of $I_{buf}$ would indicate a too low $g_m$ of the amplifier. Even after 500 krad there is no dependence of the S/N-ratio on $I_{buf}$.

\(^2\)For all other parameters the decimal values are kept at the same default values, but this now corresponds to different voltages and currents.
Figure 6.6: Signal, peaktime and S/N-ratio versus $V_{fp}$ (a), (c) and (e) and versus $I_{pre}$ (b), (d) and (f).
Figure 6.7: Signal, peaktime and S/N-ratio versus $V_{fs}$ (a), (c) and (e) and versus $I_{sha}$ (b), (d) and (f). The shaded area represents the region where the behaviour of the chip becomes unpredictable.
In figure 6.8(b) the S/N-ratio is plotted as a function of $I_{\text{pipe}}$. $I_{\text{pipe}}$ sets the bias current of the pipeline readout amplifier. The transistor is in strong inversion. Besides the frontend generated decrease in the S/N-ratio also a shift in the end of the operational plateau of $I_{\text{pipe}}$ is observed. This is due to the decrease of $V_T$. Because of the decrease of $V_T$ more current is flowing at the same value of $I_{\text{pipe}}$, see equation (5.5). When the current becomes too large, the output of the pipeline amplifier reaches the limit of the input of the multiplexer.

$I_{s_f}$ controls the drive strength of the first stage of the multiplexer. The transistor is part of a simple source follower in the multiplexer. Also here any damage to the “resistor” is cancelled by the input transistor. A decreasing S/N-ratio at a constant accumulated dose would indicate that the buffer would become too slow. There are no indications in the
data that the buffer becomes too slow, not even after 500 krad, see figure 6.8(c).

$I_{\text{driver}}$ controls the output driver current. The current buffer is implemented as a differential transistor stage. Both sides of the differential transistor use the same current set by $I_{\text{driver}}$. Therefore, changes in the current are cancelled and only the decrease generated in the frontend in the S/N-ratio is observed, see figure 6.8(d).

![Graph](image)

Figure 6.9: S/N-ratio versus $V_d$ (a), $V_{\text{dcl}}$ (b) and $V_{\text{offset}}$ (c) for different accumulated irradiation doses.

In figure 6.9(a) the S/N-ratio is plotted versus $V_d$ for different accumulated doses. $V_d$ determines the offset of the signal from the frontend. As long as $V_d$ remains within the region such that the output signal of the pipeline still fits within the input range of the multiplexer, no effects on the S/N-ratio are expected at constant accumulated dose. Since
$V_d$ is just a level and the bias circuit is radiation hard, no effects on the S/N-ratio are expected due to irradiation. Only the decrease in the S/N-ratio originating from the frontend is observed.

The current flowing through the input transistor of the pipeline readout amplifier is determined by $V_{gs}$. The input signal coming from the buffer is $V_g$ and $V_{del}$ sets the $V_s$ of the input transistor. Since also $V_{del}$ is just a level like $V_d$, no decrease in the S/N-ratio is expected nor observed except for the frontend generated decrease, see figure 6.9(b).

$V_{offset}$ controls the offset of the output current buffer. The output current buffer is implemented by placing PMOSFETs at both sides of a differential transistor stage. On one side the $V_g$ is set by the signal from the multiplexer, on the other side the $V_g$ is set by $V_{offset}$. Since this is PMOS the radiation damage will decrease the already negative $V_T$ instead of decreasing the absolute value of $V_T$. Therefore, the radiation damage will result in a shift of the lower side of the operational plateau to higher values (exactly the opposite of $I_{pipe}$). This is also observed, see figure 6.9(c).

Radiation damage induced readout problems

In the MVD each module has 8 chips that are read serially. After the last bit a token is passed to the next chip in the chain. Upon reception this chip starts sending its data. During the readout of a chip, the output level of the AnalogDummy remains approximately around -300 mV. Since the reading of the data starts immediately after the previous chip has finished, the voltage level remains constant around -300 mV during the readout of all chips. The data acquisition procedure is illustrated in figure 6.10. In the first design of the data acquisition electronics for the MVD a DataValid signal for the ADCs, the DataStrobe, was derived from the dummy using a single threshold value. However, after irradiation the output driver reacts too slowly which results in a spike in AnalogOut and AnalogDummy, see figure 6.11. This spoils the information of the first channel of a chip. Furthermore, the spike in AnalogDummy may get so large that a spike occurs in the DataStrobe. This spike may get so large by itself that the ADC fails to convert the signal of the first channel of a chip. Hence, the reconstructed position of the traversing particle may get shifted by 1 strip per preceding chip in the daisy chain. These effects have been observed after an accumulated dose of 200 krad.

The spikes can be minimised by shifting the output level of AnalogDummy down by increasing $V_{del}$, increasing $V_d$ or lowering $V_{offset}$. This is similar to changing the threshold voltage of the DataStrobe. A different method would be to increase $I_{driver}$. After increasing $I_{driver}$ the spikes are gone. This indicates that the problem is mainly caused by the output driver becoming too slow.

As mentioned before these spikes spoil the pulseheight information of the channel bonded to the first channel of the chip. For the detectors in the wheels this could have been handled by leaving the first channels of each chip disconnected since there are only 480 readout strips on the wheel sensors while there are 512 input channels on the chips.
Figure 6.10: Before irradiation there is no interruption in the AnalogDummy. Hence, the DataStrobe remains continuously high during the data readout. After irradiation, the output drivers become too slow and a spike occurs in the DataStrobe leading to an interruption of the sampling clock of the ADC, while the AnalogOut is being readout out. Thus the first channel of chip $i + 1$ is not converted.

The problem for the DataStrobe is solved by only using the falling edge in the AnalogDummy. After a falling edge a DataStrobe signal is generated that lasts long enough to readout all chips in the daisy chain. During the DataStrobe no new triggers are accepted.

**Power consumption**

During all steps in the measurement program the power consumption is monitored. Although there is a spread in the initial power consumption on the various hybrids, no significant change is observed.

Also during the settings scans the power consumption was monitored. For most parameters, the power consumption remains constant as a function of the accumulated dose. However, the consumption is still dependent on the value of the parameters. For some settings an accumulated dose dependence is observed. In figure 6.12 the currents measured on the +2 and -2 V lines are plotted versus $I_{pipe}$. For the accumulated doses where data of hybrid 817 and hybrid 445 is available, the values are averaged. Since the currents measured on the two hybrids differs significantly, the curves are normalised to the current value at the lowest setting before irradiation.

When plotting the power consumption for $V_{fp}$, see figure 6.13(a), the same threshold behaviour as in figure 6.6(a) is observed. This demonstrates that the chip does not
Figure 6.11: Detail of the output signals of two consecutive Helix 3.0 (a). The top signal is AnalogOut around the trailer while the lower signal is AnalogDummy. At the interface between the output of two chips a spike is observed in both the AnalogOut and the AnalogDummy. In (b) the lower signal is the resulting AnalogOut-AnalogDummy and the top signal the accompanying DataStrobe.

Figure 6.12: Normalised current measured on the +2 V line (a) and on the -2 V line (b) versus the value of $I_{\text{pipe}}$ at different accumulated doses.

operate properly for too low values of $V_{fp}$. 
Figure 6.13: Normalised current measured on the +2 V line (a) and on the -2 V line (b) versus the value of $V_p$ at different accumulated doses.

6.4 Optimising the operation point

The S/N-ratio is mainly determined in the frontend. To optimise the S/N-ratio, it is most effective to tune the pulse in the shaper and the amplitude of its input. A longer shaping time leads to a larger peak height and a better S/N-ratio. The most important parameters to optimise the S/N-ratio are $I_{pre}$ and $V_{fs}$.

$I_{pre}$ determines the amplitude and risetime of the input signal to the shaper. To achieve a large signal and a small risetime, $I_{pre}$ should be operated at as large a value as possible. As shown in figure 5.11(a) the power consumption is directly proportional to the value of $I_{pre}$. When operating all chips in the MVD at the maximum value of $I_{pre}$, in total approximately 720 W of heat is dissipated. Since the cooling system is designed with a maximum cooling power of 1.2 kW[16], there is no problem to run with $I_{pre}$ set at 255.

A longer shaping time yields a larger signal and more noise is averaged out. Hence, longer shaping results in a better S/N-ratio. Longer shaping is achieved by a larger feedback resistance, thus smaller $V_{gs}$. Therefore, the register $V_{fs}$ should be operated at a value just above the threshold voltage of the feedback transistor of the shaper. The limiting factor for the shaping time is the occupancy. When the pulse is not back to zero at the arrival of the next event, pulses can start to overlap. However, the interesting physics event rate is very low, 800 Hz after the first level trigger compared with the 10.4 MHz bunch crossing frequency. On top of that the background track rate is low. The typical number of tracks in an event before the upgrade is only $\sim$12. Therefore, it should be possible to run with the minimum value of $V_{fs}$, which will correspond to a peaktim of approximately 70 ns.
6.4. Optimising the operation point

Figure 6.14: S/N-ratio as a function of the accumulated dose as measured in the testbeam using the default Helix settings (a). Also shown are the S/N-ratios that can be achieved by increasing $I_{\text{pre}}$ to 255, by decreasing $V_{fs}$ to 135 and by setting both $I_{\text{pre}}$ at 255 and $V_{fs}$ at 135. The effect of the improvement of the S/N-ratio on the resolution is shown in (b) where the intrinsic resolution is plotted versus the accumulated dose.
The maximum improvement measured using the internal testpulse circuit can be used to predict the testbeam performance. The result is displayed in figure 6.14(a) where the S/N-ratio measured in the testbeam using the default values of the registers is plotted as a function of the accumulated dose. Also shown are the S/N-ratios that will be achieved by optimising the value of $I_{\text{pre}}$, by optimising the value of $V_{f_s}$ and by optimising both values under the assumption that improvements of the S/N-ratios are independent. Adjusting $I_{\text{pre}}$ and $V_{f_s}$ the S/N-ratio increases from $21.6\pm0.3$ to $28.7\pm0.6$ before irradiation and from $12.0\pm0.5$ to $15.3\pm0.7$ after 500 krad.

The improvement in the S/N-ratio translates into an improvement in the resolution. Using the fit result from section 6.3.2 the achievable resolutions can be calculated. The results are displayed in figure 6.14(b). The results show that the S/N-ratio can be increased significantly, reducing the resolution. Even after an accumulated dose of 500 krad a resolution of $10.6\pm0.5$ $\mu$m can still be achieved.

### 6.4.1 Extrapolation to full modules

The irradiation test was performed using single modules. In the MVD the chips are connected to two silicon sensors. This affects the results. The main difference is the increase of the input capacitance. As discussed in section 5.1.2 this leads to a slower risetime in the preamplifier and hence to a lower output signal of the Helix. The equivalent noise charge$^3$ (ENC) of the Helix can be expressed as

$$ENC = \alpha + \beta C_i$$  \hfill (6.3)

For the Helix 2.2 $\alpha$ and $\beta$ were measured to be $\alpha=462$ electrons and $\beta=35.4$ electrons/pF$[29]$. The increase of the input capacitance, which is about a factor of two, yields an increase in the noise of the order of $60\%$.

Thus, for a full module the S/N-ratio decreases and the peaktime will be a bit longer, but the optimisation of the S/N-ratio by increasing $I_{\text{pre}}$ and decreasing $V_{f_s}$ can be performed in the same way.

### 6.5 Summary & Discussion

The Helix chips in the MVD will be exposed to radiation due to reflected synchrotron radiation and off-momentum particles hitting the beampipe. When the chips are exposed to radiation, electron-hole pairs are created throughout the chip, which results in

$^3$The ENC is the amount of charge, expressed in electrons, applied at the input of the chip that will give the same output signal height as the noise.
Radiation induced effect | Running strategy
---|---
Preamp output becomes faster and larger | Operate $I_{pre}$ at maximum; keep $V_{fp}$ just above $V_T$
Shaper output becomes faster and smaller | Operate $V_{fs}$ just above $V_T$; keep $I_{sha} \approx 20$
S/N plateau shift in pipeline readout amplifier | Operate $I_{pipe}$ between 10 and 30
S/N plateau shift in current buffer | Operate $V_{offset}$ between 80 and 120

Table 6.2: Overview of the effect of the radiation damage and the running strategy.

The chips were irradiated with a $^{60}$Co-source at the “Nederlands Meetinstituut”. The effects of the irradiation on the performance of the chip were studied in a testbeam setup and using the internal testpulse of the chip. The effects of irradiation on the performance of the chips are well understood. In table 6.2 the main effects of the radiation are summarized together with a running strategy. The operation plateaus for the remaining registers are summarized in table 6.3. The S/N-ratio drops from 21.6±0.3 before irradiation to 12.0±0.5 after an accumulated dose of 500 krad. The spatial resolution deteriorates from 9.4±0.1 $\mu$m to 12.2±0.4 $\mu$m. From the internal testpulse measurement it follows that the S/N-ratio can be increased by increasing the value of $I_{pre}$ and decreasing the value of $V_{fs}$. The measurements show that the S/N-ratio can be increased from 21.6±0.3 to 28.7±0.6 before irradiation and from 12.0±0.5 to 15.3±0.7 after 500 krad. This improves the predicted spatial resolution from 9.4±0.1 $\mu$m to 8.4±0.3 $\mu$m before irradiation and from 12.2±0.4 $\mu$m to 10.6±0.5 $\mu$m after 500 krad.

Since the radiation damage in the MVD will not be homogeneous, the peaktimes in the

<table>
<thead>
<tr>
<th>Register</th>
<th>Operation region</th>
</tr>
</thead>
<tbody>
<tr>
<td>$I_{buf}$</td>
<td>$&gt; 40$</td>
</tr>
<tr>
<td>$I_{sf}$</td>
<td>$&gt; 25$</td>
</tr>
<tr>
<td>$I_{driver}$</td>
<td>$35 \leq I_{driver} \leq 65$</td>
</tr>
<tr>
<td>$V_d$</td>
<td>$50 \leq V_d \leq 100$</td>
</tr>
<tr>
<td>$V_{dcl}$</td>
<td>$180 \leq V_{dcl} \leq 240$</td>
</tr>
</tbody>
</table>

Table 6.3: Overview of the operation regions of the registers that are not affected by the irradiation.
MVD will not be uniform after irradiation. This causes timing problems for the trigger, since the pulse in the shaper has to be sampled at the peak to get the best S/N-ratio. The results presented allow the change of the settings such that the peak time will be the same throughout the whole MVD.