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New leakage current, noise and depletion voltage expectations for Run IIb

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Abstract

This note gives an update on leakage current, noise and depletion voltage estimates for Run IIb.

1 Introduction

A general overview of radiation damage in silicon detector can be found in DØ note [1]. The leakage current of silicon detectors increases with irradiation dose due to the creation of additional gap states which will lead to more electron-hole pair generation and thus to an increase in bulk or generation current. This generation current is by far the dominating part of the entire leakage current after the silicon has been irradiated. The increase in leakage current can be parameterized as

$$I = I_0 + \alpha \cdot \Phi \cdot A \cdot d \qquad (1)$$

where I_0 is the bias current before irradiation, α is a damage coefficient usually defined at $T = 20°$C and dependent on particle type, Φ is the particle fluence given in particles per cm^2, A the detector area and d the thickness of the detector. The exact value of α depends on particle type and energy and varies between 2 and $3 \cdot 10^{-17} A/cm$ once the silicon is completely annealed. The leakage current rises linearly with fluence and does depend neither on silicon detector properties nor on special process characteristics during the silicon detector manufacturing. The leakage current in silicon detectors due to generation of electron-holes pairs is strongly temperature dependent and the ratio of currents at two temperatures T_1, T_2 is given by

$$\frac{I_2(T_2)}{I_1(T_1)} = \left(\frac{T_2}{T_1}\right)^2 \exp\left(-\frac{E_g}{2k_b}\frac{(T_1 - T_2)}{T_1 \cdot T_2}\right) \qquad (2)$$

with k_b being the Boltzmann constant ($k_b = 8.6 \cdot 10^{-5} eV/K$) and E_g the gap energy in silicon ($E_g = 1.2eV$).

The change in the effective impurity or doping concentration $N_{eff} = 2\epsilon\epsilon_0/(ed^2) \cdot V_{depl}$ measured as a function of the particle fluence for n-type starting material shows a decrease until the donor concentration equals the acceptor concentration or until the depletion voltage V_{depl} is almost zero, indicating *intrinsic* material. Towards higher fluences the effective concentration starts to increase again and shows a linear rise of acceptor like defects. This phenomena of changing from n-type to p-type like material has been confirmed by many experimental groups and usually the detector is said to have undergone a "type inversion" from n-type to p-type. The change of the effective doping concentration can be parameterized as

$$N_{eff}(\Phi) = N_{D,0} \cdot \exp(-c_D\Phi) - b \cdot \Phi \tag{3}$$

where the first term describes a donor removal from the starting donor concentration $N_{D,0}$ and b indicates the rate of the radiation induced acceptor state increase. Hence donor removal happens exponentially whereas acceptor states are created linearly with fluence. Type inversion for standard resistivity n-type material with $\rho \approx 5k\Omega cm$ typically occurs at a fluence of about $1 - 2 \cdot 10^{13} cm^{-2}$.

2 Fluence estimation for RunII

Several fluence predictions for Run II have been given by Frautschi et al. [3], Matthews et al. [4] and Ellison et al. [5]. The most solid expectations are based on leakage current measurements performed on the CDF SVX and SVX' silicon detectors as a function of sensor radius from the beam and delivered luminosity during Run Ia+b. The derived charged particle fluence quantities vary among the various authors between $1.5 \cdot 10^{13} MIPs/cm^2/fb^{-1}$ and $1.9 \cdot 10^{13} MIPs/cm^2/fb^{-1}$ for the new SVX II layer 0 detectors, which are located at a radial distance of r=2.416 cm and r=2.438 cm from the beam axis. All the mentioned CDF expectations have in common that the radial scaling of the fluence occurs with $r^{-1.68}$, a fact which has been verified by independent doses measurements in the CDF detector.

In a DØ specific Monte Carlo study done by Ellison et al., the authors concluded with a charged particle fluence estimation of $1.7 \cdot 10^{13} MIPs/cm^2/fb^{-1}$ if normalized to the CDF SVX II layer 0, so well in between the given range of the CDF extrapolations. However, Ellison et al., are using a r^{-2} scaling of the charged particle fluences, which would be justified if the charged particle fluence is solely coming from physics processes and no beam losses are expected.

To normalize the observed CDF leakage current measurements to a standard neutron or proton fluence, assumptions about the radiation damage constant α of equation (1) have to be made. Matthews [4] has given an equivalent 1 MeV neutron fluence per fb^{-1} of $2.19 \pm 0.63 \cdot 10^{13} \cdot (r[cm])^{-1.68} [cm^{-2}/fb^{-1}]$. In his fluence determination he assumed a frequently used α value for 1 MeV neutrons in order to convert the observed current increase to an effective 1 MeV neutron fluence. In his paper he took an α-value of $2.86 \pm 0.18 \cdot 10^{-17} A/cm$, which is still today a good value for neutrons [6], if most of the annealing of the leakage currents have happened. Since the CDF strip measurements are not done in a fully annealed state, he applied a factor of 1.1 to α according to common annealing parameterizations [7] in order to take the present annealing of the detector currents into account. Matthews propagated the uncertainties on silicon temperature, leakage current measurements and α-value into a final fluence uncertainty of $\pm 30\%$.

In a recent reevaluation of the fluence predictions for Run II, S. Worm [8] has used a 40% higher number of α[1], therefore reducing the effective 1 MeV neutron fluence by the same amount. After consultation with M. Moll, I believe, that this value for α is in my point of view too high and does not reflect the annealing of the currents properly. I will therefore stick to the previous fluence estimation by Matthews.

The number of secondary particles produced in the Be-beam pipes of the CDF and DZERO experiment should be rather similar. The only difference may occur in the number of curling particles which are caused by different magnetic fields strength of 1.5T compared to 2T for CDF and DZERO respectively and are traversing the silicon layers more than once. In the MC study by Ellison et al., an estimation for the contribution of the looping particles to the total charged particle fluence was done. They found that 50% of the total fluence will come from looper particles in the DZERO magnetic field. Frautschi, who has done similar studies for CDF assumed a 30% contribution only.

The strategy of the predictions for the leakage current rise and depletion voltage changes for Run II presented in this note will be as follows: For the leakage current estimations we are using the measured strip current numbers by CDF in Run I and scale to the appropriate DZERO geometries and Temperatures. This approach is essentially independent on the α value, but assumes the same fluences of charged particles in the CDF and DZERO experiment. In order to estimate the upper uncertainties for the leakage currents, we varied the temperature at which the CDF strip leakage current measurements took place according to their given uncertainties. Furthermore, we increased the CDF strip currents and hence the fluence by another 20%, in order to take a possible difference of the numbers of looper between DZERO and CDF into account.

For the depletion voltage predictions, the 1 MeV neutron fluence number as given by Matthews are taken and under the assumption of the so-called nonionizing energy loss (NIEL) hypothesis, we calculate the depletion voltage changes according to the latest parameters of the Hamburg model [9], which gives up to date the best phenomenological description of the change in effective doping concentration in silicon during hadron irradiation. To obtain an upper error bound on the depletion voltage after irradiation, a safety factor of 1.5 in agreement with CDF is added and the 1 MeV equivalent neutron

[1] S. Worm's value of α was 4 and he has applied the same 1.1 correction factor for the partial annealing, ending up with an effective α of 4.4.

Table 1: Geometrical Parameters of the DZERO RunIIb detector

Layer	min radius (cm)	max active lenght (cm)	pitch (μm)	strip volume (mm^3)
L0-A	1.78	7.67	25	0.614
L1-A	3.48	7.67	29	0.712
L2-A	5.32	19.66	30	1.887
L3-A	8.62	19.66	30	1.887
L4-A	11.69	19.66	30	1.887
L5-A	14.7	19.66	30	1.887

fluence is varied accordingly. Note that the fluence uncertainty, which was originally suggested by Matthews in his analysis is already 30%.

3 Parameters of the DZERO RunIIb detector

The following table contains the design parameters of the DZERO RunIIb silicon detector, which are necessary to perform the leakage current and depletion voltage changes. The thickness of the silicon sensors is taken to be 320 μm.

4 Leakage current extrapolations for RunII

Strip leakage current measurements have been performed in the CDF SVX and SVX' silicon detectors as a function of sensor radius from the beam and delivered luminosity during Run Ia+b. From the measured values in the innermost layer at $r = 3cm$ and $T = 24 \pm 2°C$, CDF could derive [2] an average increase in the strip currents of $I_{SVX} = 0.8\, nA/strip/pb^{-1}$ and $I_{SVX'} = 0.63\ nA/strip/pb^{-1}$. The radial dependence of the leakage currents or the fluence was found from these measurements to scale with $r^{-1.7}$. To obtain a leakage current prediction for Run II the measured $I_{avg} = (I_{SVX} + I_{SVX'})/2$ can be scaled from CDF's strip geometry in RunI (pitch 60μm, length 25.5cm) to any new DØ configuration as given in table 1. The average temperature of $T = 24°C$ for SVX and SVX' needs also to be taken into account. The radial scaling to the other layers mentioned in table 1 is done by using a $r^{-1.7}$ behavior.

The table 2 gives the strip leakage currents in nA and per fb^{-1} for the various layers of the DZERO RunIIb detectors as a function of four different Temperatures.

In table 3 the total currents in μA per fb^{-1} are shown based on the module geometry of table 1. The maximum length for layer 2-5 modules is assumed and the upper limit on the strip currents is taken. This total module or ladder current is important to understand if

Table 2: Expected strip leakage currents in nA/fb^{-1}

Layer	T=-10C	T=-5C	T=0C	T=+5C
L0-A	$9.0^{+4.8}$	$15.3^{+8.3}$	$25.5^{+14.3}$	42^{+22}
L1-A	$3.3^{+2.8}$	$5.7^{+3.0}$	$9.5^{+5.1}$	$15.4^{+8.5}$
L2-A	$4.3^{+2.3}$	$7.2^{+4.5}$	$12.1^{+6.2}$	$19.8^{+10.7}$
L3-A	$1.9^{+1.0}$	$3.2^{+1.7}$	$5.3^{+2.9}$	$8.7^{+4.7}$
L4-A	$1.2^{0.5}$	$1.9^{+1.3}$	$3.2^{1.7}$	$5.2^{+2.8}$
L5-A	$0.8^{+0.3}$	$1.3^{+0.7}$	$2.1^{+1.2}$	$3.5^{+1.9}$

Table 3: Expected module leakage currents in $\mu A/fb^{-1}$

Layer	number of strips	T=-10C	T=-5C	T=0C	T=+5C
L0-A	511	7.2	12.1	20.2	33.0
L1-A	767	4.0	6.7	11.2	18.4
L2-A	1277	8.5	14.5	24.1	39.5
L3-A	1277	3.7	6.4	10.6	17.4
L4-A	1277	2.2	3.8	6.3	10.4
L5-A	1277	1.5	2.6	4.3	7.0

there is a current limitation by the HV power supplies, if two modules are ganged together. The ganging for LV and HV purposes is different among the layers. The expected currents drawn from the power supplies after a luminosity period of 15 fb^{-1} is finally given in table 4. Here, every row in table 4 contains the leakage current entries after 15 fb^{-1} in μA at diffferent temperatures for the variuos ganging types, in order to understand if the power supplies will run into current limit after the run period is over. For such considerations, it is conservative to apply an addional safety factor of 2 to the currents listed in the table.

The shot noise in ENC which is caused by the strip leakage currents is obtained in the following way [10]: $ENC_{shot} = \sqrt{12 \cdot I[nA] \cdot \tau}$, where τ is the shaping time of the amplifier in ns. The table 5 shows the expected noise in ENC after 15 fb^{-1} for the DZERO RunIIb detector. A further extrapolation to 20 fb^{-1} for the ENC noise caused by the leakage current is done for layer 0-2 in table 6.

The uncertainties in the measured CDF strip currents were 10%. In addition, there is a temperature uncertainty of $\pm 2°C$. By changing the operation temperature of SVX and SVX' from $T = 24°C$ to $T = 22°C$ our estimation produces 15-20% higher leakage current results. The tables however, include a more conservative upper error estimate. In

Table 4: Expected total leakage currents for ganged modules after a period of 15 fb^{-1} in μA

ganging type	T=-10C	T=-5C	T=0C	T=+5C
L0-79	107	181	303	496
L1-79-79	119	202	337	553
L2-200-100	191	325	542	889
L2-100-100	128	217	362	592
L3-200-100	84	143	239	391
L3-100-100	56	95	159	261
L4-200-200	67	114	190	311
L4-100-100	33	57	95	155
L5-200-200	45	77	128	210
L5-100-100	23	39	64	105

Table 5: Expected strip noise in ENC after 15 fb^{-1}

Layer	T=-10C	T=-5C	T=0C	T=+5C
L0-A	462^{+92}	603^{+145}	780^{+186}	996^{+241}
L1-A	282^{+68}	367^{+89}	474^{+114}	606^{+147}
L2-A	318^{+78}	415^{+100}	535^{+130}	685^{+166}
L3-A	211^{+52}	275^{+66}	355^{+86}	455^{+109}
L4-A	163^{+39}	212^{+52}	274^{+67}	351^{+85}
L5-A	134^{+29}	175^{+42}	226^{+54}	289^{+70}

Table 6: Expected strip noise in ENC for layers 0-2 after 20 fb^{-1}

Layer	T=-10C	T=-5C	T=0C	T=5C
L0-A	535^{+130}	697^{+169}	900^{+220}	1152^{+279}
L1-A	326^{+81}	424^{+103}	548^{+133}	702^{+169}
L2-A	370^{+89}	482^{+117}	622^{+151}	797^{+198}

addition to the temperature uncertainty of the leakage current measurements, the value itself was increased by 20%, taking into account the possibility of the different charged particle fluences between DZERO and CDF since the number of curling particles traversing the silicon detectors changes with the magnetic fields. The combined resulting error from these error sources is given in the tables. This approach should be conservative enough to estimate the expected leakage currents and hence the shot noise levels for Run2b in a safe way.

In order to determine an upper tolerable limit of the ENC noise, we have to make assumptions about the expected noise coming from the front end electronics due to the load capacitance. The silicon sensors designed for RunIIb are expected to have a capacitance of 1.3-1.5 pF/cm, dominated by the interstrip capacitance. The detectors in layer 2-5 represent with a maximum active length of 19.66 cm a total capacitive load of up to $\sim 30\ pF$. The noise figure of the SVX4 chip is taken to be $450 + 43 \cdot C_{load}[pF]$, as requested in the design specifications, hence giving a noise as high as $\sim 1700\ e$ for two-sensor modules in layers 2-5. If we want to limit the performance loss in the S/N due to shot noise contribution to 10% only, a maximum of not more than 700 e added in quadrature should be allowed. This would mean that Layer 2 should operate at a temperature of 0°C or lower in order to avoid a 10% performance degradation after 15 fb^{-1}.

Layer 0 and 1 are shorter sensors and represent therefore less capacitance load. The 10% S/N performance loss due to shot noise after 15 fb^{-1} can be maintained if the layer is kept at a temperature of $T = -5$°C or lower. If an operation at $T = -10$°C is even achieved, the S/N loss would be mitigated to only 5% after 15 fb^{-1}. The innermost layer is a special one, since it has an up to $\sim 430\ mm$ long analog cables to route the signals to the hybrids. These cables will be designed to have a maximum capacitance of not more than $\sim$ 20 pF [11], so that the total capacitance load of the silicon ladder including the analog cable can be kept around 30 pF. Due to this large load capacitance and the serial resistance of the cable, which can not be neglected at all, the noise in the front end will keep the S/N close to 10:1 and any further degradation by additional shot noise should be carefully avoided. The strategy would be therefore to keep the detectors as cold as possible, i.e. at an operating temperature of -10°C.

It is important to remark here, that the predictive power of this approach has some limitations: It can be only applied for detectors which are slightly above depletion voltage and are far away from the junction breakdown. However, the large radiation damage in RunIIb will force us to run in a mode in which the detectors are significantly overbiased to compensate any charge collection deficiencies. The biasing above depletion voltage will eventually increase the leakage currents even more since the detector may be operated close or even at junction breakdown. Therefore, for a realistic current estimation, an additional safety factor in the leakage currents of 1.5 translating into a 22% increase in ENCnoise should be most likely be applied.

Table 7: The Tevatron Run IIb operation scenario

year	max. lumi. pb-1/wk	shutdown (months)	lumi. fb-1/year	total lumi. fb-1
2005	61	4	1.81	1.81
2006	81	1	3.38	5.19
2007	81	1	3.85	9.04
2008	81	1	3.85	12.89

5 Depletion voltage

As previously mentioned, the depletion voltage predictions we are presenting are based on the 1 MeV neutron equivalent fluence assumptions for Run II by Matthews et al. In addition we are applying a safety factor of 1.5 to that fluence. The latest parameters for the stable damage constants, the beneficial annealing and the reverse annealing constants have been used [6] in the Hamburg-model along with the following assumptions for the Tevatron running scenario of Run IIb, which are presented in the table 7.

It is assumed that the slicon detector is kept cold entirely during the luminosity runs and during the shutdown periods. The resulting depletion voltage for different operating and temperatures for layer 0 and layer 1 are shown in Figure 1. We present three calculations for layer 0 at temperatures of -10°C, 0°C and +10°C and with a starting depletion voltage of 150V as well as one scenario for layer 0 with starting depletion voltage of 50V only. Furthermore, we give a depletion voltage prediction for layer 1 in figure 1.

The depletion voltage of layer 0 will reach values of 300V for the given Run IIb scenarios long as the temperature does not exceed 0°C. Layer 1 is expected to deplete around 100V at the end of the running period. Note, that these values represent only the value of the depletion voltage itself and do not guarantee a full charge collection efficiency in the silicon. A safety margin of at least a factor of 1.5 in the bias voltage should be applied in order to have enough flexibility in overbiasing the detectors and to compensate potential ballistic charge losses after irradiation. Therefore, we have specified the breakdown of the layer 0 sensors to be above 700V to provide for such a safety margin.

As it is demonstrated in figure 1, temperature effects of reverse annealing tend to saturate below 0°C, since the depletion voltage values for T=0°C and T=-10°C do not differ much. However, reverse annealing increases rapidly if the operation temperature reaches +10C. At such high temperatures the reverse annealing makes a significant contribution and cannot be neglected anymore.

There is some variation in the radiation damage constants and reverse annealing parameters used in the Hamburg model for different silicon wafer materials. However, theses uncertainties are absorbed in the fluence safety factor of 1.5, which we have included

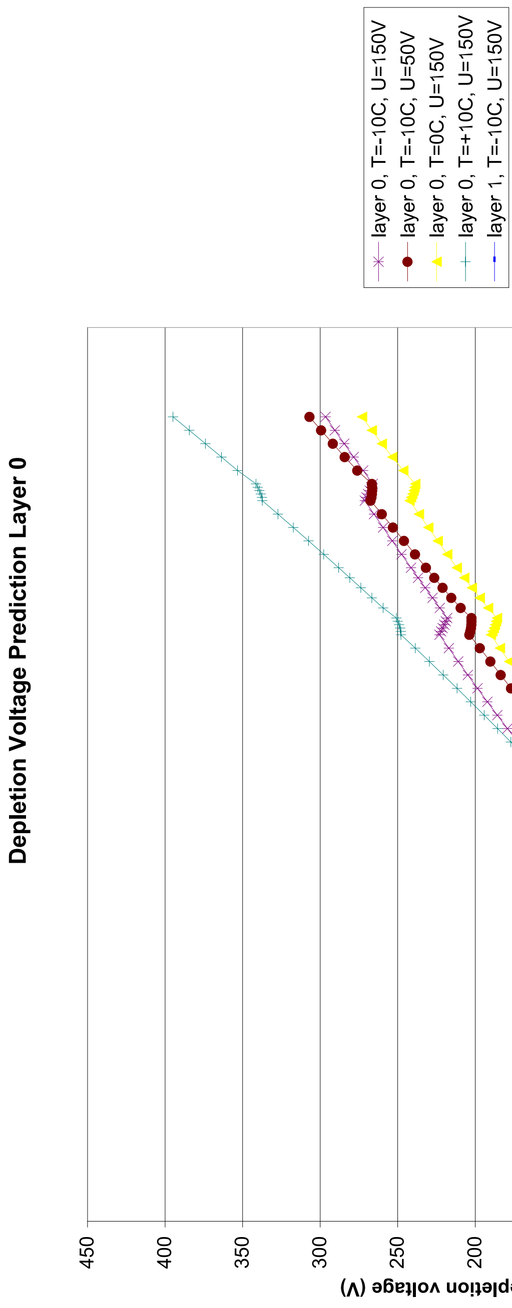

Figure 1: Depletion Voltage as function of time over the course of 5 years corresponding a cumulated luminosity of 15 fb^{-1}

in the depletion voltage calculations.

In figure 2, we expand the Run IIb scenario now over a total of 7 years and calculate the anticipated depletion voltage after having accumulated a total luminosity of 20 fb^{-1}. The depletion voltages are shown for layer 0 only. Now, the layer 0 sensors are expected to deplete at around 450V and since we are specifying the sensor breakdown to be at least 700V, we would still have enough margin in the biasing to accommodate a longer Tevatron running of up to 20 fb^{-1}. In addition, figure 2 contains two other layer 0 depletion voltage graphs for this expanded running scenario: Four warming-up periods each lasting 4 weeks at room temperature are included, in order to see the reverse annealing effects. One calculation was done at T=-10°C and the other one at T=0°C. The depletion voltage change is now more dramatic, if such maintenance periods at room temperature become necessary. The reverse annealing will dominate after irradiation, if the detectors are being warmed up and will shift the depletion voltages to much higher levels of around 700V. It is therefore quite important to avoid any warm-up after the detector has been irradiated.

Another interesting observation can be made by comparing figure 1 and figure 2. It seems in figure 1 that layer 0 depletes at slightly less voltages if the layer is kept at T=0°C than at T=-10°C, but only if no real warming up periods are included in the running scenario. This is in fact the result of the short beneficial annealing periods, which are detectable only during the accelerator shutdown. The beneficial annealing has a time constant of roughly one year (50days) if the detectors are at T=-10C (0C), meaning that the drop of the depletion voltage during accelerator shutdown periods occurs faster at higher temperatures. If the detector is warmed up, the reverse annealing will overwhelm any beneficial annealing effects and dominates the depletion voltage change in the maintenance periods, since the time constant of the beneficial annealing at room temperature is only in the order of 2 days. By including warming up periods in the running scenario, a complex interplay between reverse and beneficial annealing takes place. Based on the Hamburg model calculations, it seems to be more advantageous and safer to have the silicon detectors maintained at T=-10°C during the running rather than at T=0°C, as the graphs of figure 2 shows. Therefore, we should point out that for the operation of the silicon detectors in layer 0 and layer 1, a temperature of -10°C is much more safer against reverse annealing than keeping them at 0°C, especially if warming up periods - either through accidents or done by purpose - are included in the depletion voltage scenarios and calculations.

6 Conclusion

For the operation temperature of the silicon detectors in the various layers we would suggest to keep the silicon sensors generally at temperatures at or below 0°C. Layer 3-5 can be kept at 0°C over the entire Run IIb, since leakage current noise will not be the dominant noise source. In layer 2 we will most likely encounter a 10% S/N performance degradation if

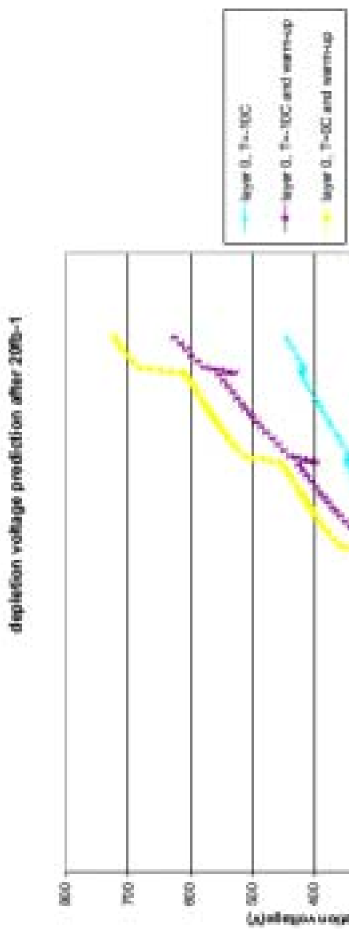

Figure 2: Expected depletion Voltage as function of time over the course of 7 years corresponding now to a cumulated luminosity of 20 fb^{-1}

the detectors are kept at 0°C. This can be reduced to 5% only, if layer 2 sensors will be operated at T=-5°C at the end of the running. Furthermore, the split mechanical design of layer 0 and 1 on the one side and layer 2-5 on the other side, will allow an independent cooling passage for the two innermost layers. We would suggest to design the cooling of the inner layers such, that they are able to operate at temperatures as low as -10°C. This low temperature operation limits the shot noise contribution and helps in suppressing the reverse annealing effect if potential warming up periods are happening. There should still be sufficient margin if we can cool layer 0 to T=-10°C, in order to survive even an extended Run IIb of 20 fb^{-1}.

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