

Expected irradiation effects on the by-pass diodes for the SIS 300 magnets with single-layer coils and heat-sink dimensioning

1. INTRODUCTION

The new coil design for the SIS300 superconducting magnets, with one layer coils, with higher nominal current (8940A compared to 6800 A) and a lower time constant (4.0 s instead of 4.8 s) because of a lower magnet inductance requires a check if the presently foreseen Copper-heat sinks of 95 mm diameter and 10 mm are still sufficient especially in view of the estimated radiation load.

Furthermore, the irradiation tests at ITEP show that diode 2 has a higher forward voltage at ambient temperature than diode 4, that originally was used as a worst case in radiation resistance estimations. Model calculations and also experience at CERN have shown that the diodes are more affected by higher voltages at ambient temperature than at 77K.

2. ESTIMATIONS OF FORWARD BIAS CHARACTERISTICS AT HIGHER ACCUMULATED NEUTRON FLUENCES

The latest irradiation tests at ITEP were carried out up to a fluence of 1.16 E14 n/cm² for diode 2. Recent estimations at GSI have given an upper fluence limit of about 1.0 10¹⁵ n cm⁻². For this purpose the at ITEP versus dose measured forward characteristics at 300 K and at 77 K were extrapolated for diode 2 in two ways:

- Simple liner extrapolation from the last three measured values up to 1E15 n/cm² as shown in Figure 2.1.
- The following formula, **equation 1**, published at the CEC/ICMC, July 1999, Montreal, was applied as shown in Figure 2.2:

$$U = I (R_{\text{series0}} + K_{R_{\text{series}}} \varnothing t_{\text{irr}}) + \frac{2k_B T}{e} \left(\ln I - \ln (K_{I_{\text{leakage}}} \varnothing t_{\text{irr}}) \right) \quad \text{Eq. 1}$$

With:

$\varnothing * t_{\text{irr}} =$ Accumulated fluence [n/cm²]

$k_b =$ Boltzmann Constant

$R_{\text{series0}} =$ Series resistance of the diode [Ω]

$K_{R_{\text{series}}} =$ radiation damage coefficient for the series resistance [$\Omega/(n/cm^2)$]

$K_{I_{\text{leakage}}} =$ radiation damage coefficient for the leakage current [$A/(n/cm^2)$]

For the extrapolation of the forward bias voltage from 1.18E14 n/cm² to 1.0E15 n/cm² the R_{series0} , $K_{R_{\text{series}}}$, and $K_{I_{\text{leakage}}}$ –values after irradiation at 1.18E14 n/cm² were used. For the linear extrapolation, a higher V_f at ambient temperature and 77 K was obtained, whereas at 77 K the extrapolation method according to Eq. 1 shows a strong saturation of V_f versus neutron fluence and also a lower V_f at ambient temperature.

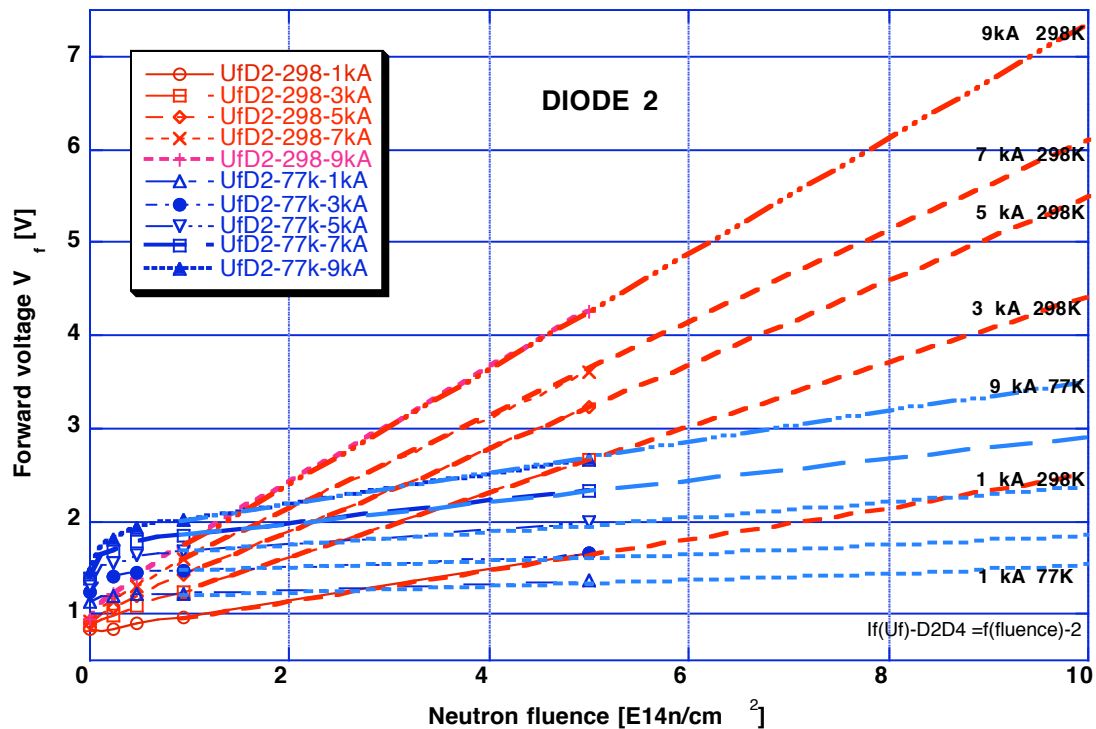


Figure 2.1: Forward bias voltage V_f versus neutron fluence for Diode 2 linearly extrapolated from measurements up to $1E15$ n/cm^2 at 298 K and 77 K for different current levels.

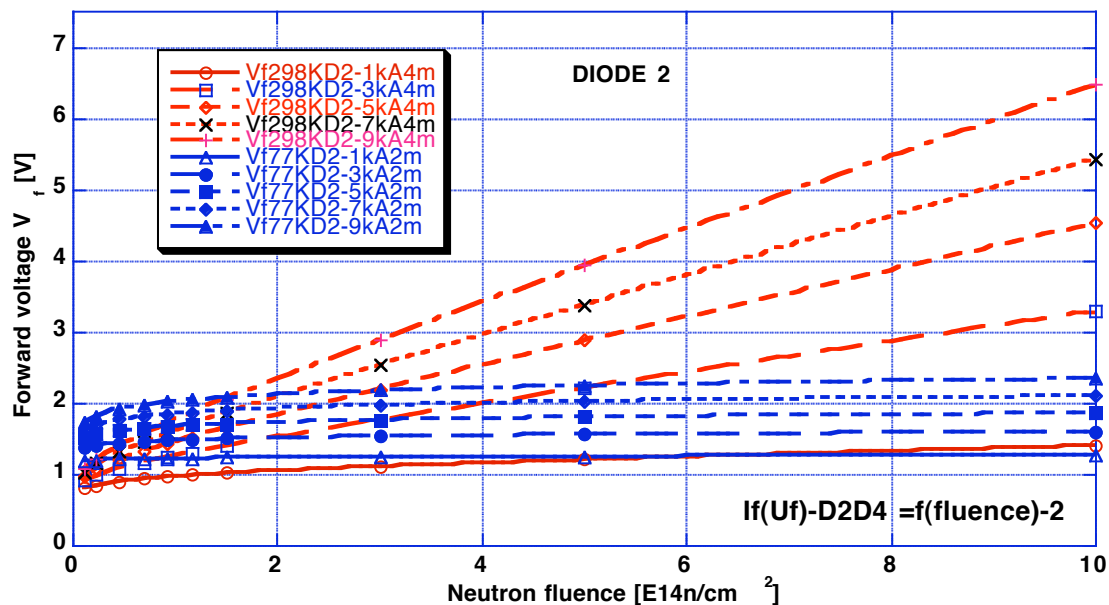


Figure 2.2: Forward bias voltage V_f versus neutron fluence for Diode 2 extrapolated according to Eq. 1 from measurements up to $1E15$ n/cm^2 at 298 K and 77 K for different current levels.

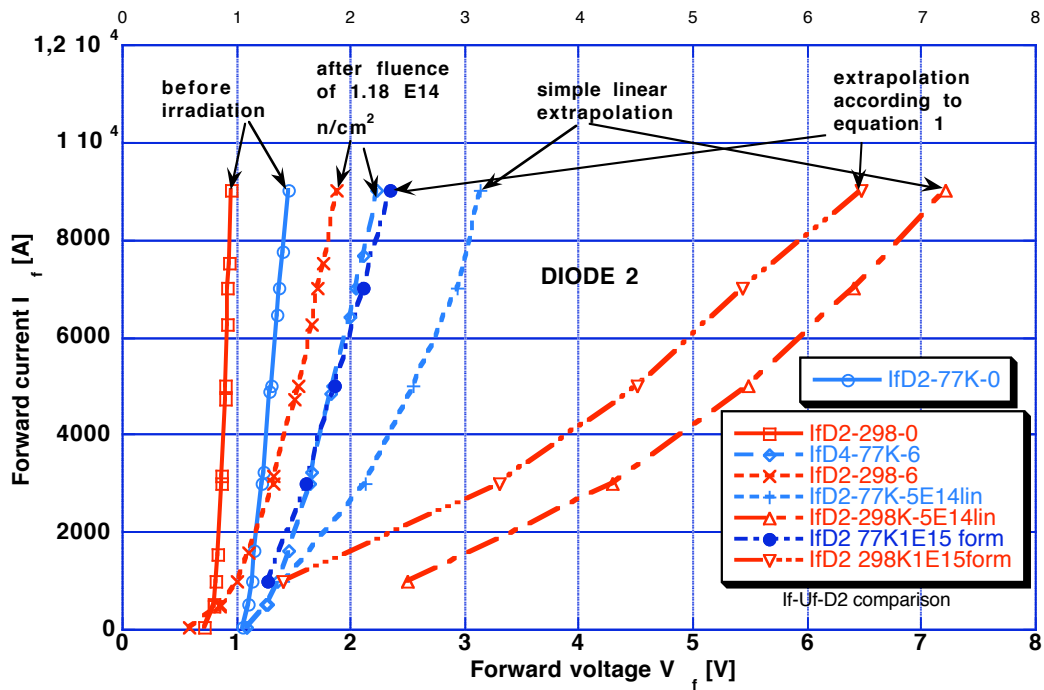
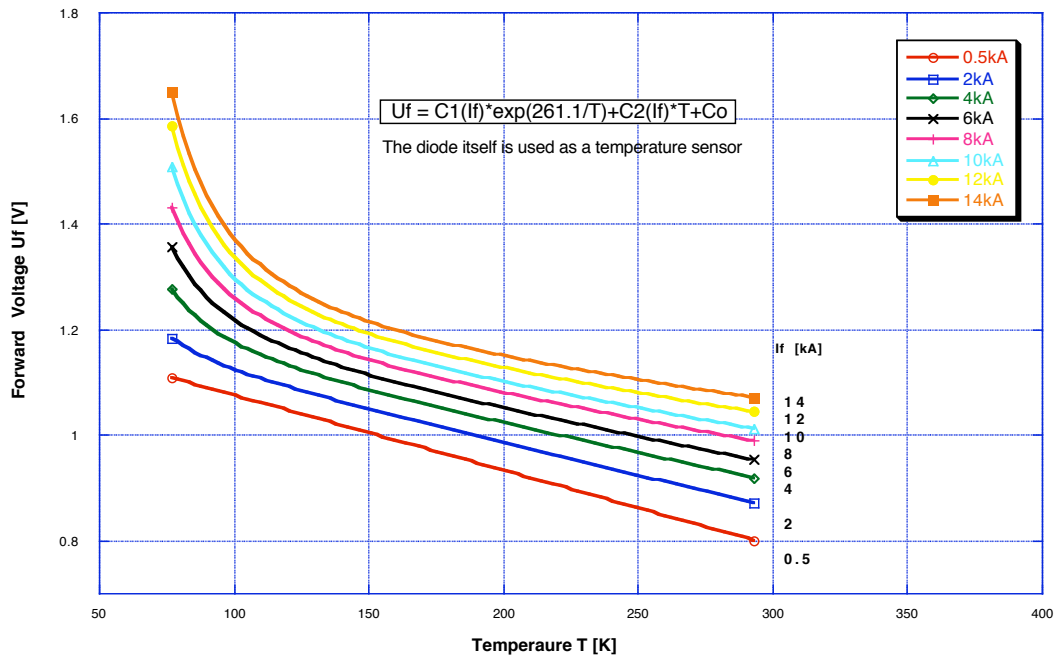


Figure 2.3: Forward characteristics of diode D 2 before and after irradiation and after linear extrapolation and extrapolation according to Eq.1



Forward voltage versus temperature with forward current I_f as parameter derived from I_f - U_f at 77K and 300K for a series diode

Figure 2.4: Forward voltage versus temperature for an LHC-Diode before irradiation.

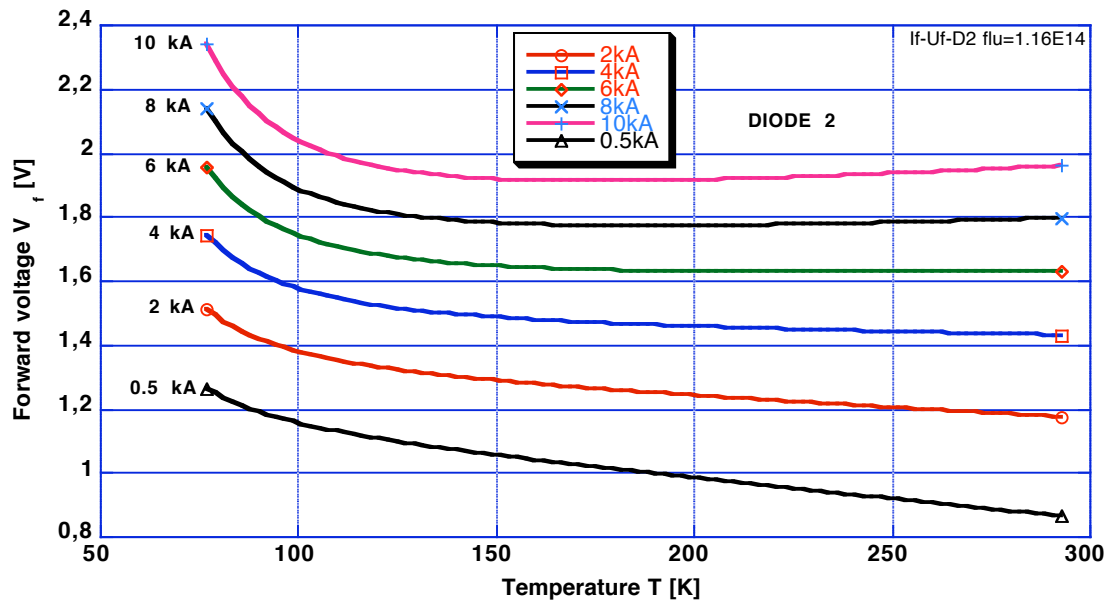


Figure 2.6: Forward voltage V_f versus temperature for diode 2 after $1.18E14 \text{ n/cm}^2$ at different current levels according to the equation in Figure 2.5.

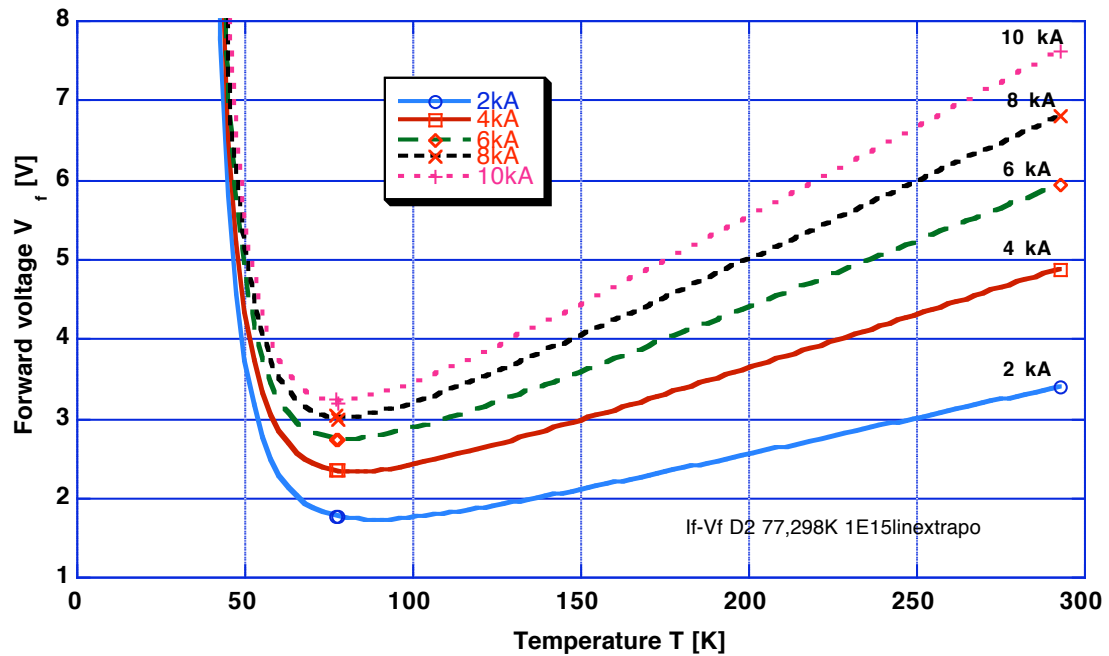


Figure 2.7: Forward voltage V_f versus temperature for diode 2 after linear extrapolation to $1E15 \text{ n/cm}^2$ at different current levels according to the equation in Figure 2.5.

In Figure 2.5 the typical behavior of the forward voltage versus temperature for the pn-junction of a highly doped silicon diode before irradiation is shown. The V_f decreases linearly with temperature above about 120 K. This behavior has changed for an

irradiated diode like D 2 as shown in Figure 2.6. The linear term $C_2(I_f)*T$ is no longer negligible as the forward voltage at higher current levels increases with temperature. The temperature coefficient has become positive.

For a highly irradiated diode after a neutron fluence of $1E15n/cm^2$ the behavior of the forward voltage versus temperature is dominated by the linear term of the equation in Figure 2.5. This linear term represents the highly doped bulk silicon. As shown in Figure 2.7 and Figure 2.8, the diode behaves, above about 100 K, similar to a metallic resistor with a strong positive temperature coefficient that can cause a thermal run away.

At very high irradiation levels that are close to a destruction of the diode wafer the validity of Eq.1 may be out of sense.

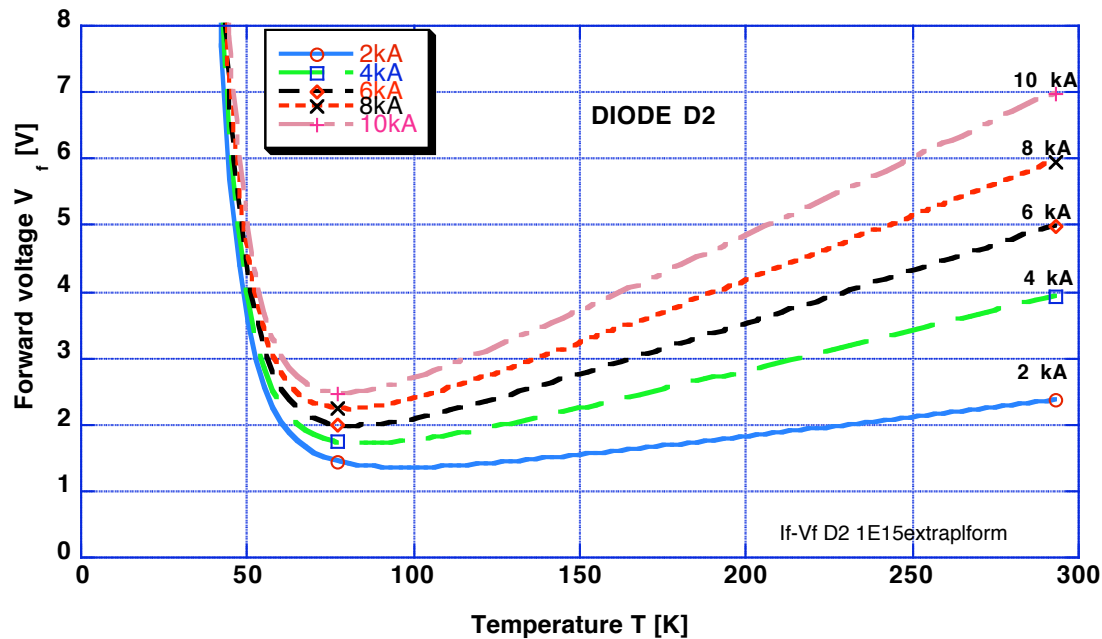


Figure 2.8: Forward voltage V_f versus temperature for diode 2 after extrapolation to $1E15 n/cm^2$ according to equation 1 at different current levels and using the equation in Fig.2.5

3. VERIFICATION OF DIODE HEAT SINK DIMENSIONS

Simulations with a 7-diode stack and an eight-diode stack have shown that the maximum wafer temperature T_{wmax} in a 9-diode stack should be the same as in an 8-diode-stack so that we still can use the eight-diode stack thermo-electrical model.

For each of the two extrapolation methods the maximum wafer temperature has been calculated at the measured fluence of $1.18E14 n/cm^2$, at a fluence of $5E14 n/cm^2$, and at $1E15 n/cm^2$. **Figure 3.1** shows the maximum wafer temperature versus neutron fluence for diode 2 using the two different extrapolation methods and the actual copper heat sink dimensions of 95 mm diameter and 10 mm thickness. The simple linear extrapolation results in a significantly higher maximum wafer temperature and is probably pessimistic as no saturation effects are considered for V_f versus dose. The maximum wafer

temperature using the extrapolation according to Eq. 1 is probably too optimistic as the V_f versus fluence at 77K shows a strong saturation effect that so far could not be approved experimentally.

These extrapolations over nearly one order of magnitude of fluence are rather vague and may not represent reality at all.

By re-dimensioning, i.e. increasing, the heat sink volume the maximum wafer temperature can be reduced to well acceptable limits as shown in Table 3.1 for some combinations of diameter and thickness.

It would be preferable to increase the diameter rather than the copper disc thickness in order to keep the overall length of the diode stack short for mechanical stability.

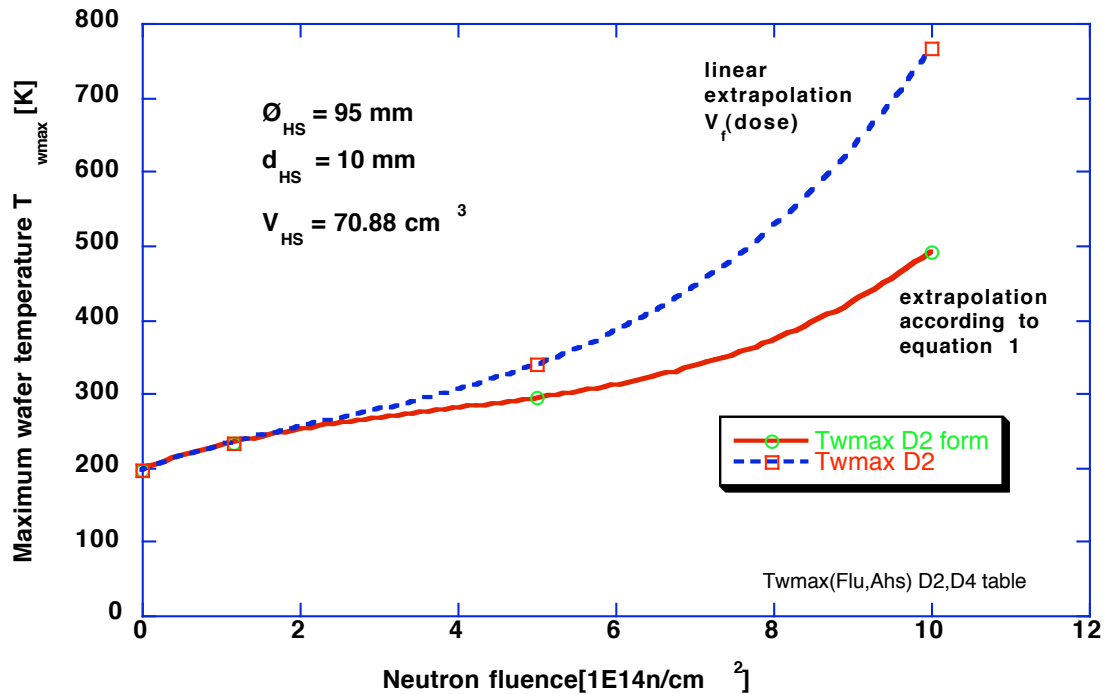


Figure 3.1: Maximum wafer temperature in a stack of eight diodes of type D 2 versus neutron fluence using two different extrapolation methods.

WARNING:

The turn-on voltage V_{to} of highly irradiated diodes at 4.2 K may exceed 50 V or more and this will cause a delay before the diode stack starts to carry current apart from the fact that several hundred volts or even more will occur across the magnet, which could cause insulation problems.

If, due to excessive irradiation, the diode becomes a highly ohmic resistor then the diode chain may not turn on at all.

Non-uniform characteristics of highly irradiated diodes in the stack may also cause a local burn out of one or more diodes within the stack.

Heat sink volume [cm ³]	Heat sink diameter [mm]	Heat sink thickness [mm]	Max. wafer temperature [K] for Diode 2
70.88 actual	95	10	766
113.1	120	10	483
141.4	120	12.5	390
169.65	120	15	332
226.2	120	20	269

Table 3.1: Maximum wafer temperature for a diode stack with 8 diodes with some heat sink volumes and dimensions after irradiation of $1E15 \text{ n/cm}^2$, using the linear extrapolation method.

In Figure 3.2 is plotted the wafer temperature T_w , the heat sink temperature T_{hs} , and the bus bar temperature T_{bb} versus time as well as the forward-current I_f and voltage V_f for a diode in the center of the stack for an extrapolated accumulated fluence (according to Eq.1) of $1E15 \text{ n/cm}^2$ with the actual heat sink of $\varnothing_{hs} = 95 \text{ mm}$, $d_{hs} = 10 \text{ mm}$.

Figure 3.3 shows the corresponding temperature profile across the diode stack at different steps of time.

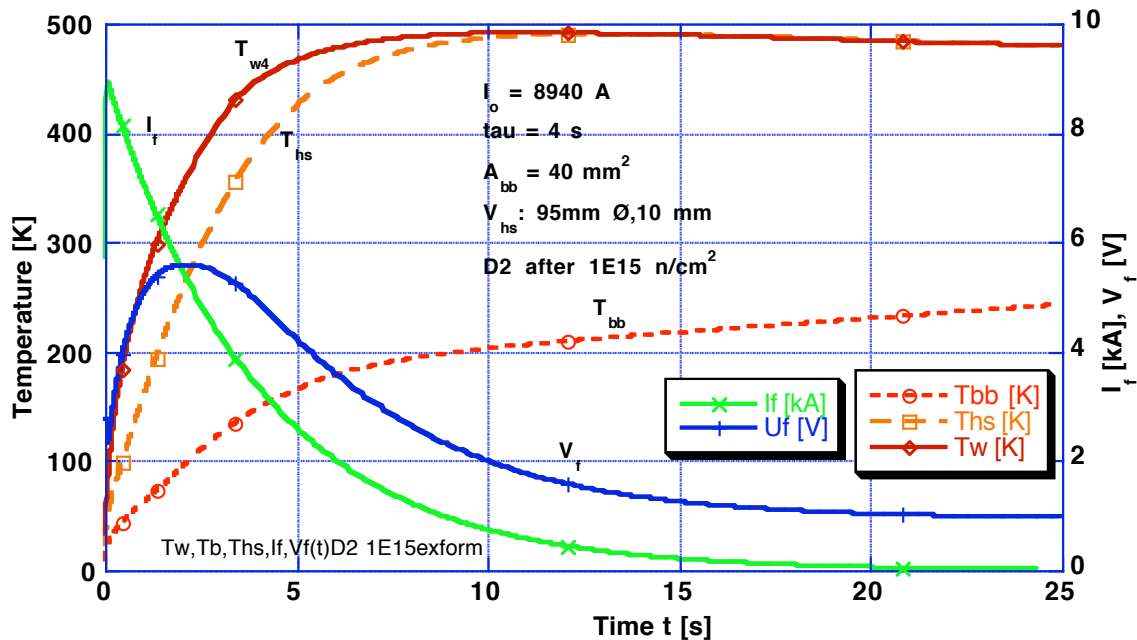


Figure 3.2: Wafer-, heat sink-, and bus bar temperature T_w, T_{hs}, T_{bb} versus time for diode 2 after an accumulated fluence of $1E15 \text{ n/cm}^2$ inside a stack of eight diodes with extrapolation of V_f according to Eq.1.

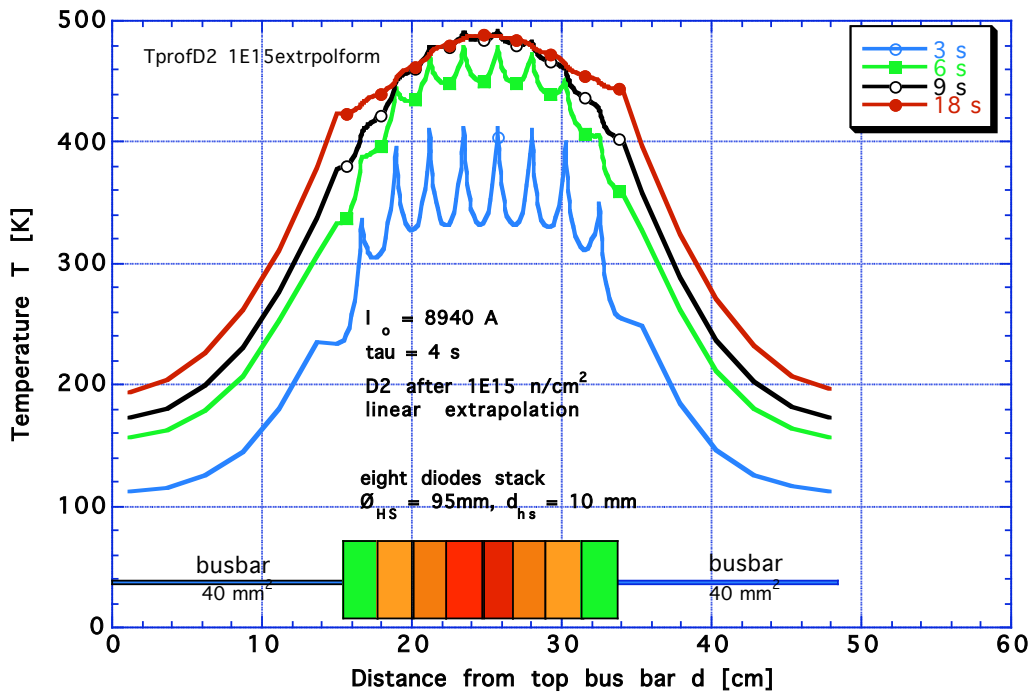


Figure 3.3: Temperature profile at different time steps across a diode stack with 8 diodes of type Diode 2 after an accumulated fluence of $1E15 \text{ n/cm}^2$ with extrapolation of V_f according to Eq.1.

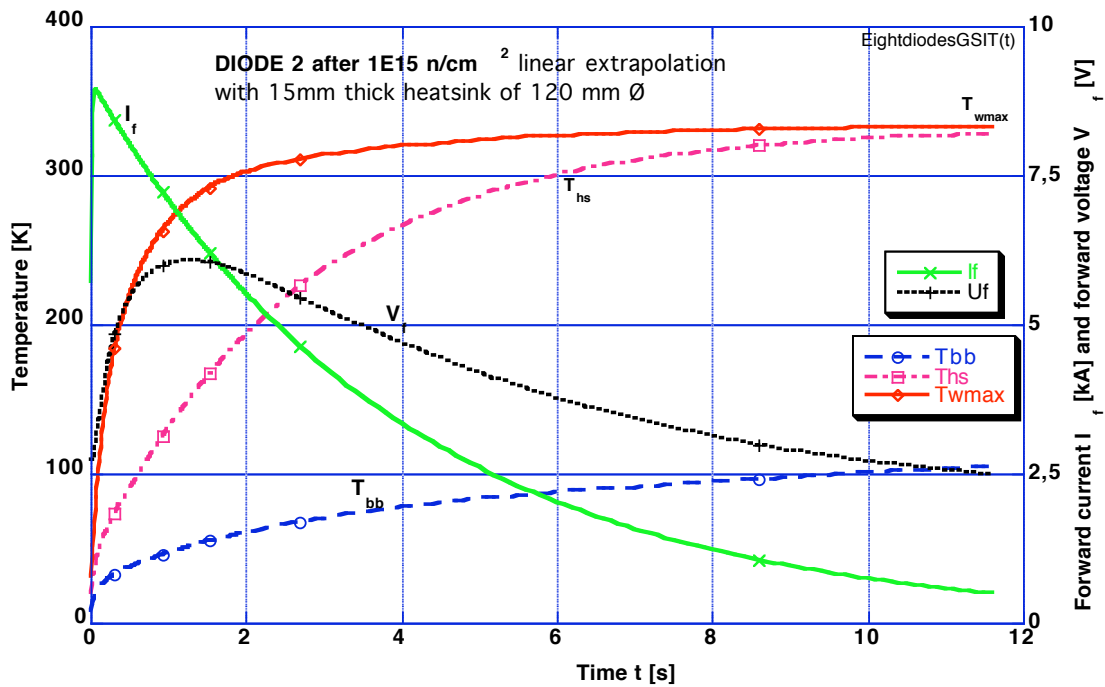


Figure 3.4: Wafer-, heat sink-, and bus bar temperature T_w, T_{hs}, T_{bb} versus time for Diode 2 after an accumulated fluence of $1E15 \text{ n/cm}^2$ inside a stack of eight diodes using linear extrapolation of V_f . and with enlarged copper heat sink of $\varnothing_{hs} = 120 \text{ mm}, d_{hs} = 15 \text{ mm}$.

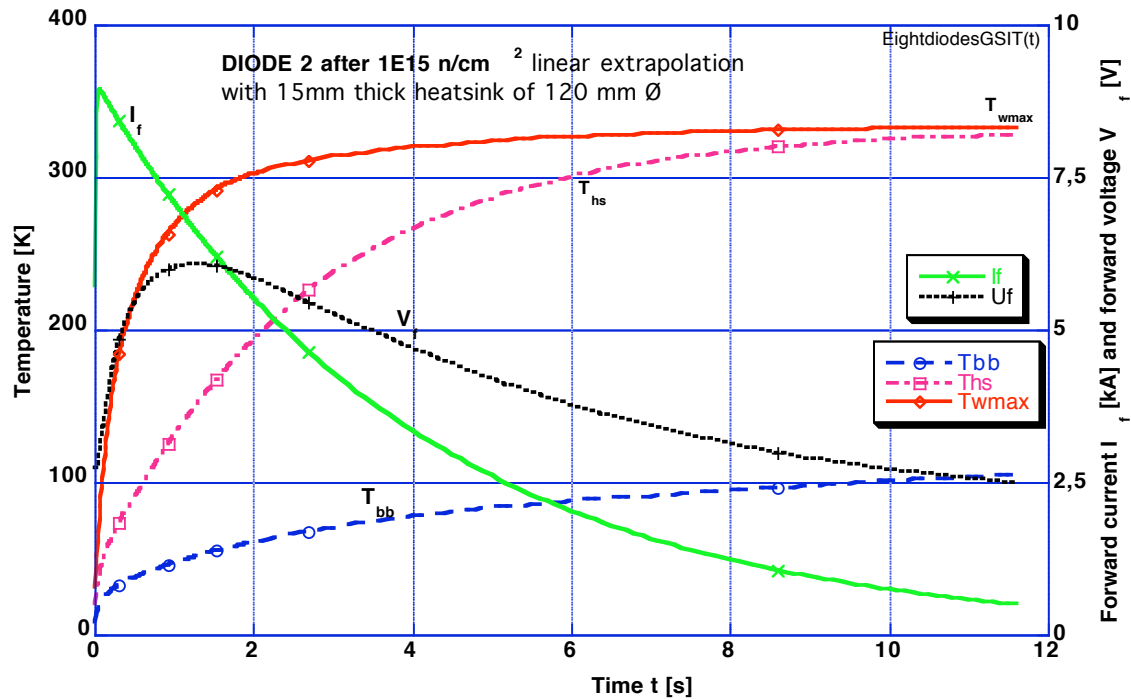


Figure 3.4: Wafer-, heat sink-, and bus bar temperature T_w, T_{hs}, T_{bb} versus time for diode 2 after an accumulated fluence of $1E15 \text{ n/cm}^2$ inside a stack of eight diodes using linear extrapolation of V_f , and with enlarged copper heat sink of $\varnothing_{hs} = 120 \text{ mm}$, $d_{hs} = 15 \text{ mm}$.

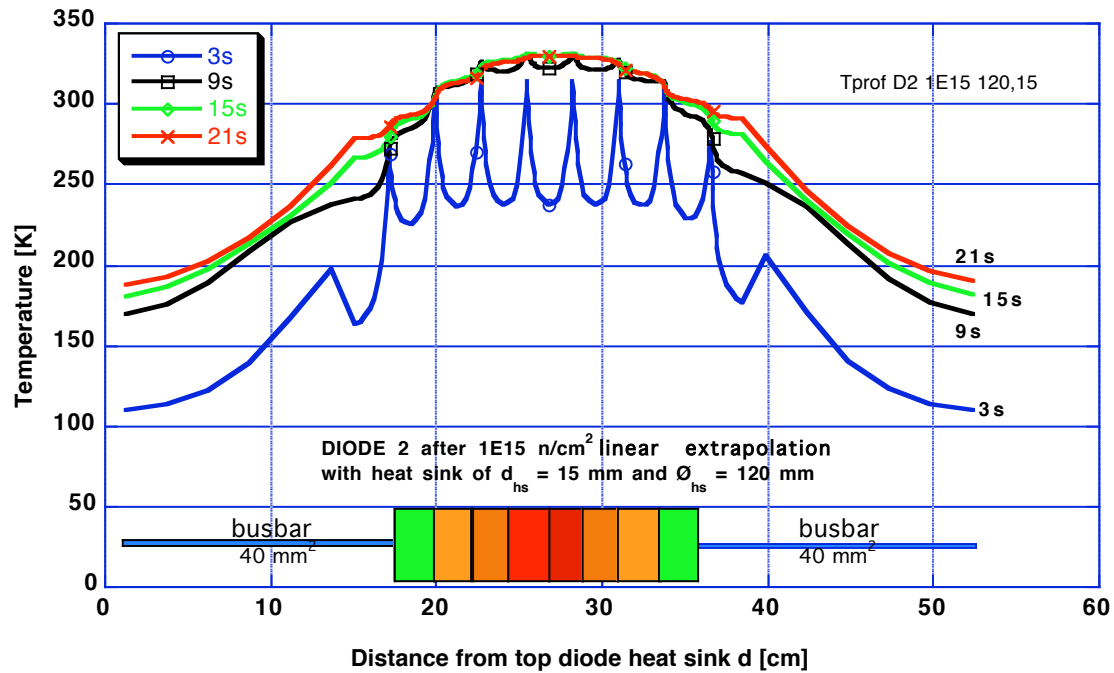


Figure 3.5: Temperature profile at different time steps across a diode stack with 8 diodes of type Diode 2 after an accumulated fluence of $1E15 \text{ n/cm}^2$ using linear extrapolation of V_f versus fluence and with enlarged copper heat sink of $\varnothing_{hs} = 120 \text{ mm}$, $d_{hs} = 15 \text{ mm}$.

With an enlarged Copper heat sink of $\varnothing_{hs} = 120$ mm and 15 mm thickness the maximum wafer temperature can be reduced to well acceptable values even with the linear extrapolation (worst case) of the forward voltage V_f versus accumulated dose up to $1E15$ n/cm².

The wafer-, heat sink-, and bus bar temperatures as well as forward-current and voltage are shown in Figure 3.4. The corresponding temperature profile across a stack of eight diodes is plotted for different time steps in Figure 3.5.

4. CONCLUSIONS

The extrapolation of the forward voltage V_f versus accumulated neutron fluence over almost one order of magnitude is questionable.

The forward voltage versus temperature of highly irradiated diodes shows a strong positive temperature coefficient, that may lead to a thermal run away and a burn out.

The present Copper heat sink dimensions are not sufficient for a diode irradiated up to an accumulated fluence of $1E15$ n/cm² and should be increased to keep the maximum wafer temperature within acceptable limits. Preferable is the increase of heat sink diameter to keep the length of diode stack within mechanically stable limits.

The turn-on voltage V_{to} of highly irradiated diodes at 4.2 K may exceed 50 V or more causing an additional delay apart from high voltages across the magnet.

Due to excessive irradiation, the diode may become a highly ohmic resistor and the diode chain may not turn on at all.

Non-uniform characteristics of highly irradiated diodes may cause a local burn out of one or more diodes within the stack.