ICANS-XI International Collaboration on Advanced Neutron Sources
KEK, Tsukuba, October 22-26, 1990

Preliminary Thermal and Stress Analysis of the SINQ Window

G. Heidenreich
PAUL SCHERRER INSTITUTE
CH-5232 Villigen-PSI, Switzerland

ABSTRACT

Preliminary results of a finite element analysis for the SINQ proton beam window are presented. Temperatures and stresses are calculated in an axisymmetric model. As a result of these calculations, the H_2O-cooled window (safety window) could be redesigned in such a way that plastic deformation resulting from excessive stress in some areas is avoided.

I. Introduction

A thermal and structural analysis of the proposed design for the proton-beam window for the SINQ Pb-Bi target has been performed using the commercial engineering analysis system ANSYS [1]. A full description of the window design is given elsewhere [2]. In brief, the overall assembly consists of two parts (see Fig 1): an inner window cooled on one side by the flow of the target Pb-Bi and an outer safety window made from two plates with water flowing between. The interspace has a He-flow (which plays no role in the cooling) and the whole assembly is to allow passage of the proton beam from vacuum to the target whilst also supporting the Pb-Bi. The main objects of the present study are the estimation of primary operational limits and safety margins for the window.
The temperatures and stresses depend upon the current density of the proton beam. In normal operation, all the beam passes through the up-stream meson target (Target E) and gives a peak current density of $25\mu A/cm^2$ at the design current of $1500\mu A$. Under certain operating conditions a part of the beam will bypass Target E and result in long-term peak current densities of up to $105\mu A/cm^2$. In the worst case, the full beam misses Target E giving a peak current density of up to $265\mu A/cm^2$: such an extreme fault condition is expected to be rare and to last for only a short time.
In the following analysis a safety factor ≥ 3.5, based upon the yield strength, has been calculated for the PbBi-cooled window and for peak current densities of up to $105\mu A/cm^2$. The H_2O-cooled window (safety window) can, with slight design changes, have a safety factor of ≥ 2.
At the extreme fault condition, where a peak current density of $265\mu A/cm^2$ is expected, the stresses in the PbBi-cooled window exceed the yield strength within a radius $\leq 12mm$ and plastic deformation occurs: this is due to the high peak temperature (about 830^oC).
A brief description of the model details will be given in section 2. In section 3 temperatures and stresses are calculated for a peak current density of $105\mu A/cm^2$. In section 4 the second H_2O-cooled window design changes to avoid excessive stresses are discussed. The window stresses under the extreme fault condition (peak current density of up to $265\mu A/cm^2$) will be discussed in section 5.

II. Model Details

The analysis has been performed with an axisymmetric model: the outlines of the finite element model, which corresponds to the proposed window design, is shown in Fig 1. The material properties of the selected steel X 20CrMoV1 21 (DIN 1.4922) are given below:

Elastic modulus	206 kN/mm^2
Poisson ratio	0.3
Thermal conductivity	0.024 $W/mm/°C$
Thermal expansion	1.12 $10^{-5}/°C$

Yield strength vs. temperature:

20	200	300	400	460	480	500	550	$°C$
490	432	392	353	316	293	265	216	N/mm^2

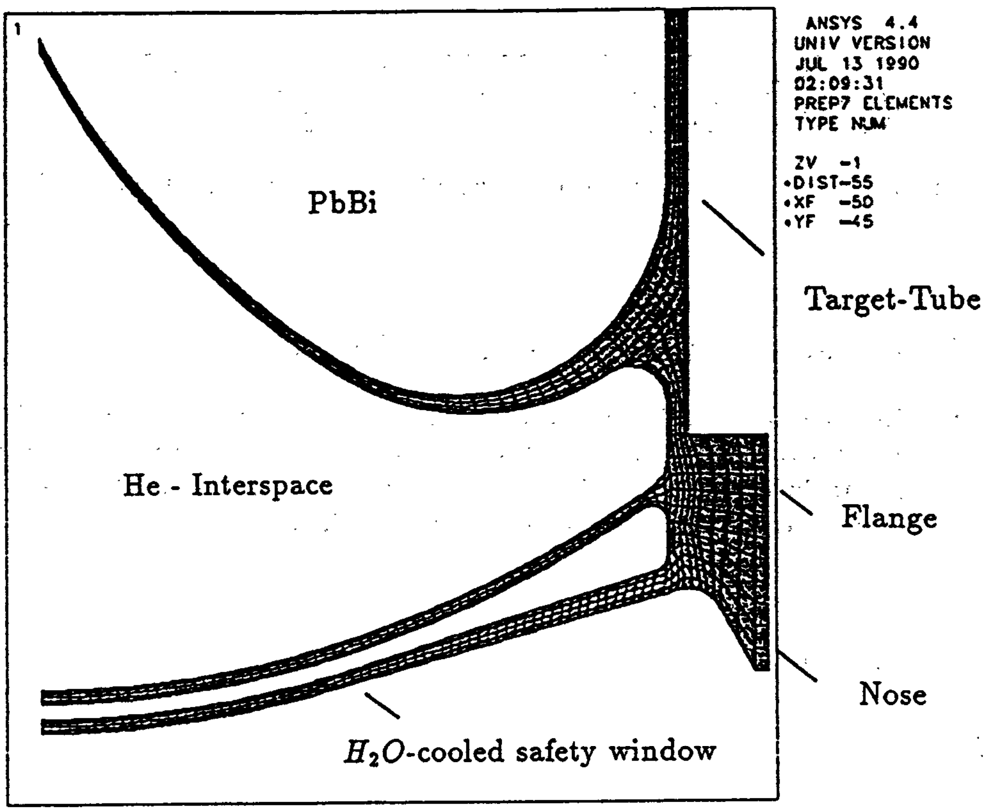

Figure 1: Outlines of the axisymmetric finite element model used in the present analysis.

II.1 Power Deposition

The power density distribution is approximated by a two-component gaussian and calculated as a function of radius r with the following equation:

$$q[W/mm^3] = I_o \; E_o[\frac{\epsilon}{\pi\sigma_1^2}exp(-\frac{r^2}{\sigma_1^2}) + \frac{1-\epsilon}{\pi\sigma_2^2}exp(-\frac{r^2}{\sigma_2^2})] + q_o$$

where

I_o = 1500 μA is the maximum total current,
E_o = 1.69 $W/\mu A/mm$, the energy deposition by ionisation-loss,
σ_1 = 13.4 mm, the S.D. of the fraction by-passing Target E,
σ_2 = 43.6 mm, the S.D. of the 'normal' beam and
q_o = 0.016 W/mm^3.

The above equation takes account of a part, ϵ, of the beam bypassing Target E, which produces a smaller beam spot with a standard deviation of σ_1. The uniform background contribution q_o comes from neutrons, gammas etc. backscattered from the target [3].

II.2 Heat Transfer on the PbBi-cooled Window

The heat transfer coefficients for the PbBi-cooled surface were derived from a thermal-hydraulic calculation [4] and are given in tabular form as a function of radius.

r(mm)	0	1	2	3	4	5	7.5	≥ 10
h(mW/$mm^2/°C$)	0	4.7	6.7	7.5	8.0	8.4	9.1	9.3

A constant bulk temperature ($T_{PbBi} = 226°C$) for the PbBi in the region of the window has been assumed.

II.3 Heat Transfer on the H_2O-cooled Window

The film heat transfer coefficient on the H_2O-cooled surfaces are derived from a modified Dittus-Boelter equation [5] which takes into account the thermal entrance length of the heated region.
For subcooled boiling, the Shah-correlation [6] has been used. Two regimes of subcooled boiling are defined: the low subcooling regime where the following equation holds:-

$$\Psi = \Psi_o$$

and the high subcooling regime

$$\Psi = \Psi_o + \frac{\Delta T_{sub}}{\Delta T_{sat}}$$

Ψ is defined as:

$$\Psi = \frac{q}{\Delta T_{sat} h_l}$$

and Ψ_o is the value of Ψ at zero subcooling and given by:

$$\Psi_o = 230 Bo^{0.5} \quad Bo \geq 0.3\ 10^{-4}$$
$$\Psi_o = 1 + 46 Bo^{0.5} \quad Bo \leq 0.3\ 10^{-4}$$

The transition point between the two regimes has been calculated by the Saha-Zuber correlation [7]:

When $Pe \leq 70000$

$(\Delta T_{sub})tr = 0.0022 q d_h/\lambda_{fl}$

when $Pe \geq 70000$

$(\Delta T_{sub})tr = 154. q d_h/(Pe \lambda_{fl})$

The cooling of the safety window can be supplied either by the main cooling circuit for the target ($T_{bulk} = 128°C$) or by a separate circuit ($T_{bulk} = 40°C$). The predicted heat transfer coefficients, for both bulk temperatures and for different fluid velocities and pressures, are tabulated below. A thermal entrance length of $X_l = 3cm$ has been used to calculate the film heat transfer coefficient: the value of X_l corresponds approximately to the full-width half-maximum of the beam bypassing Target E. A constant bulk temperature is assumed in the flow direction. The critical heat flux has been estimated from the empirical formula given by S.Mirshak [8]:

$$q_{chf} = 151(1 + 0.1197v)(1 + 0.00914\Delta T_{sub})(1 + 0.186p) \quad (W/cm^2)$$

$$5 \leq \Delta T_{sub}(_oC) \leq 75 \quad 1.5 \leq v(m/sec) \leq 14 \quad 1.7 \leq p(bar) \leq 6.2$$

Heat transfer for the H_2O-cooled window ($d_l = 2mm$)

case	T_{bulk}	T_{sat}	p_{H2O}	v_{fluid}	X_l	h_l	q_{chf}
	$°C$	$°C$	bar	m/sec	cm	$W/cm^2/°C$	W/cm^2
a)	40	180	10	2	3	1.4	1220
b)	"	"	"	4	"	2.6	1450
c)	"	"	"	6	"	3.7	1690
d)	128	"	"	2	"	2.0	790
e)	"	"	"	4	"	3.5	940
f)	"	"	"	6	"	4.8	1100
g)	40	160	6.2	2	"	1.4	840
h)	"	"	"	4	"	2.6	1000
i)	"	"	"	6	"	3.7	1170
j)	128	"	"	2	"	2.0	520
k)	"	"	"	4	"	3.5	620
l)	"	"	"	6	"	4.8	720

The wall temperatures T_w for the two windows as a function of the heat flux q are shown in Figs 2 & 3. As can be seen in these figures, case b) or c) should be chosen to avoid subcooled boiling at a current density of $105\mu A/cm^2$: this corresponds to a heat flux of $355W/cm^2$ for the $2mm$ thick window. In the stress analysis, only case b) has been used to calculate the temperature distribution within the H_2O-cooled window.

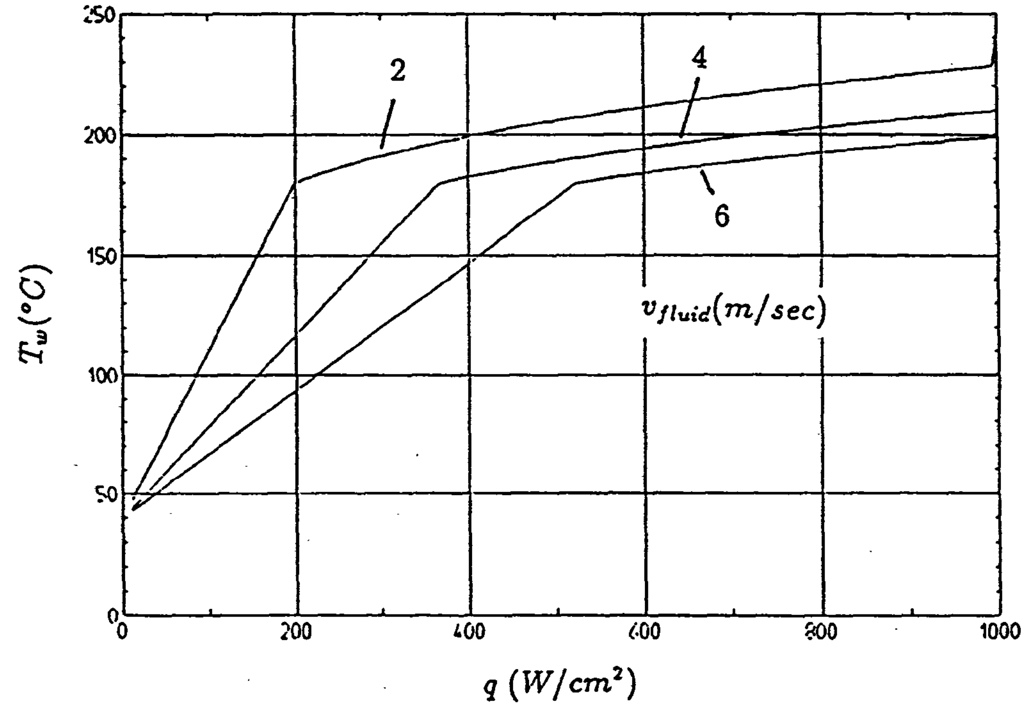

Figure 2: Wall temperature $T_w(°C)$ vs heat flux $q(W/cm^2)$: $T_{bulk} = 40°C, p_{H2O} = 10bar$

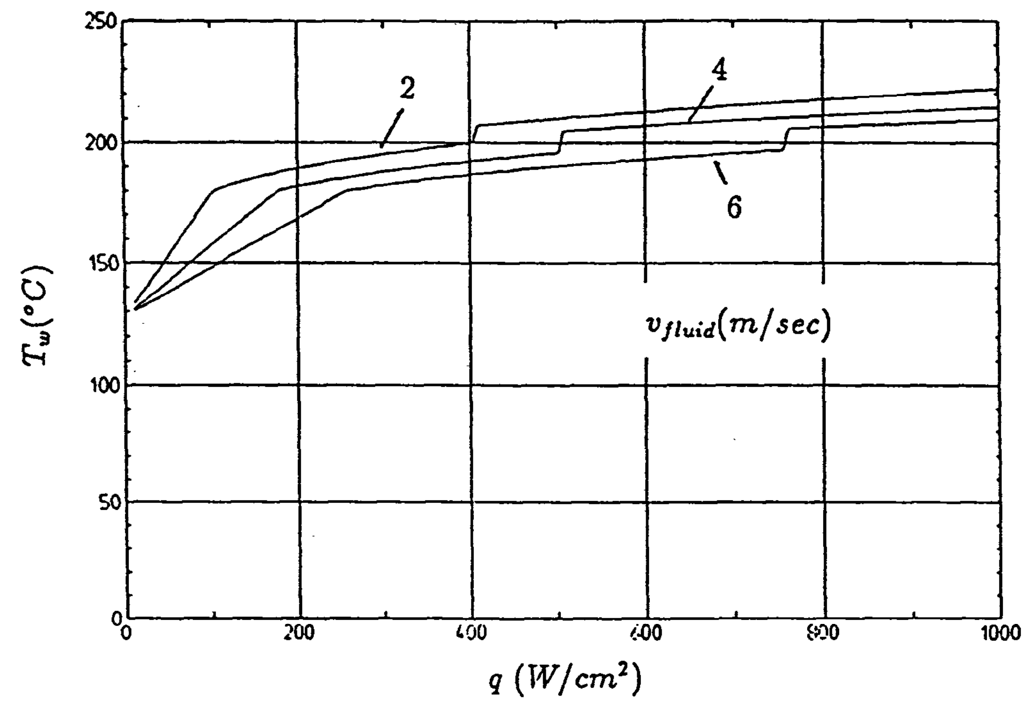

Figure 3: Wall temperature $T_w(°C)$ vs heat flux $q(W/cm^2)$: $T_{bulk} = 128°C, p_{H2O} = 10bar$

III. Thermal and Stress Analysis for a Peak Current Density of $105\mu A/cm^2$

In the following analysis it is assumed, that 33% of the beam bypasses Target E and gives a peak current density of $105\mu A/cm^2$.

III.1 Temperatures and Heat Flow

The above load and boundary conditions have been used to calculate the temperature distribution within the structure. Figs 4 & 5 show the surface temperature of the H_2O-cooled safety window and the PbBi-cooled window respectively as a function of distance along the surface to the center. The calculated heat flow from the structure to the fluids inside ($r \leq 80mm$) and outside the beam region ($r \geq 80mm$) are as follows:

Heat flow to H_2O :

1^{st} Window element ($r \leq 80mm$)	5840 W
2^{nd} Window element ($r \leq 80mm$)	5560 W
Both Window elements ($80 \leq r \leq 90mm$)	3310 W

Heat flow to PbBi:

Window element ($r \leq 80mm$)	6720 W
Window element ($80 \leq r \leq 90mm$)	1530 W
Target-Tube	191 W/cm

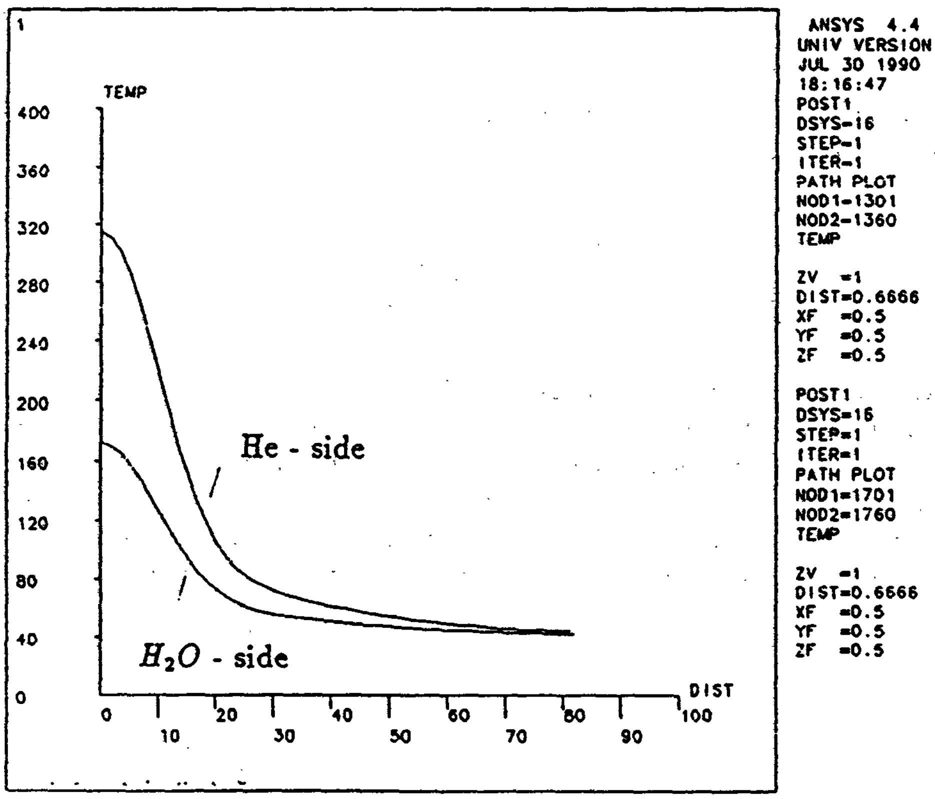

Figure 4: Temperature distribution (^oC) of the H_2O-cooled window plotted as a function of the distance (mm) to its center.

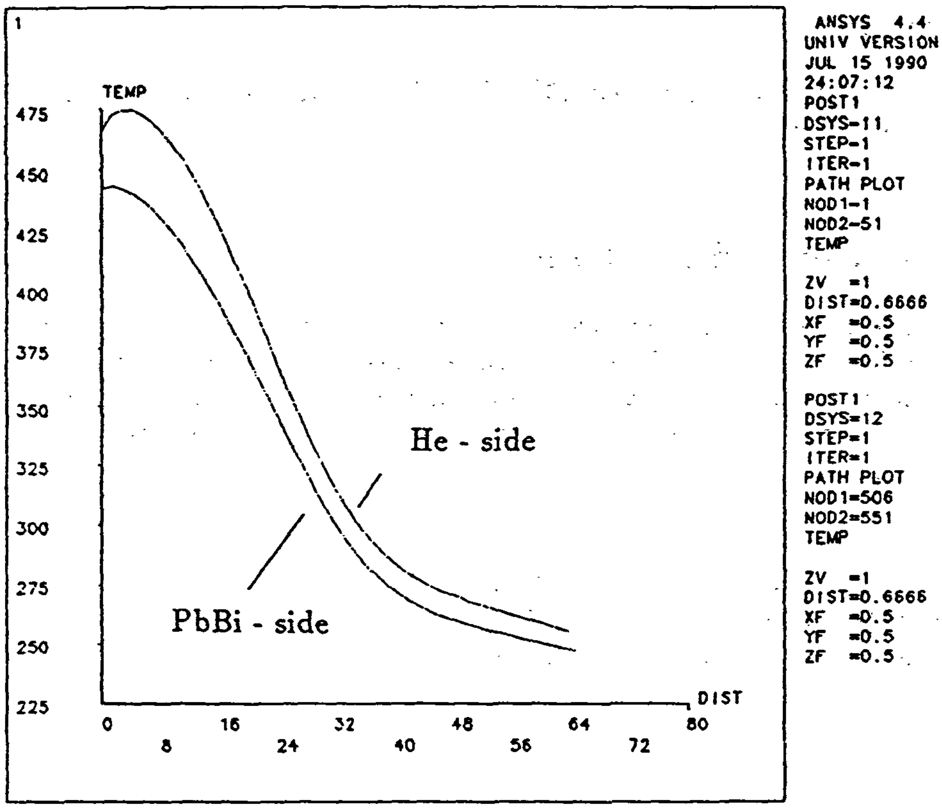

Figure 5: Temperature distribution (^{o}C) of the PbBi-cooled window plotted as a function of the distance (mm) to its center.

III.2 Stresses

A linear structural analysis based upon the calculated temperature distribution has been performed for the following static pressures:

$$\begin{aligned} P_{H2O} &= 10 \text{ bar} \\ P_{He} &= 0\&10 \text{ bar} \\ P_{PbBi} &= 5 \text{ bar} \end{aligned}$$

In the Figs 6 & 7, the calculated component stresses S_y for the two windows are plotted as a function of the distance along the surface to their centers. Here, S_y represents the in-plane component stress in the radial direction. As can be seen in the figures, the main contribution comes from bending stress induced by the thermal load. From the calculated stress distribution the von Mises stress has been used to evaluate a safety factor, based upon the temperature dependent yield strength. The stress maxima and corresponding safety factors are summarized below for the different load cases:

Von Mises Stress (N/mm^2) and safety factor ()
($ppbBi = 5bar$, $pH_2O = 10bar$)

Load	thermal	no	yes	yes
case	$p_{He}(bar)$	0	0	10
1st H_2O-cooled	$r < 50mm$	-	150 (3)	-
window	$r > 50mm$	-	160 (3)	-
2nd H_2O-cooled	$r < 50mm$	40	471 (.81)	432 (.88)
window	$r > 50mm$	145	360 (1.3)	340 (1.4)
PbBi-cooled	$r < 50mm$	40	100 (3.5)	100 (3.5)
window	$r > 50mm$	100	190 (2.0)	170 (2.5)

The safety factor in the center part of the PbBi-cooled window reaches a value ≥ 3.5, while the second H_2O-cooled window shows a safety factor < 1 at its center, where plastic deformation may occur.

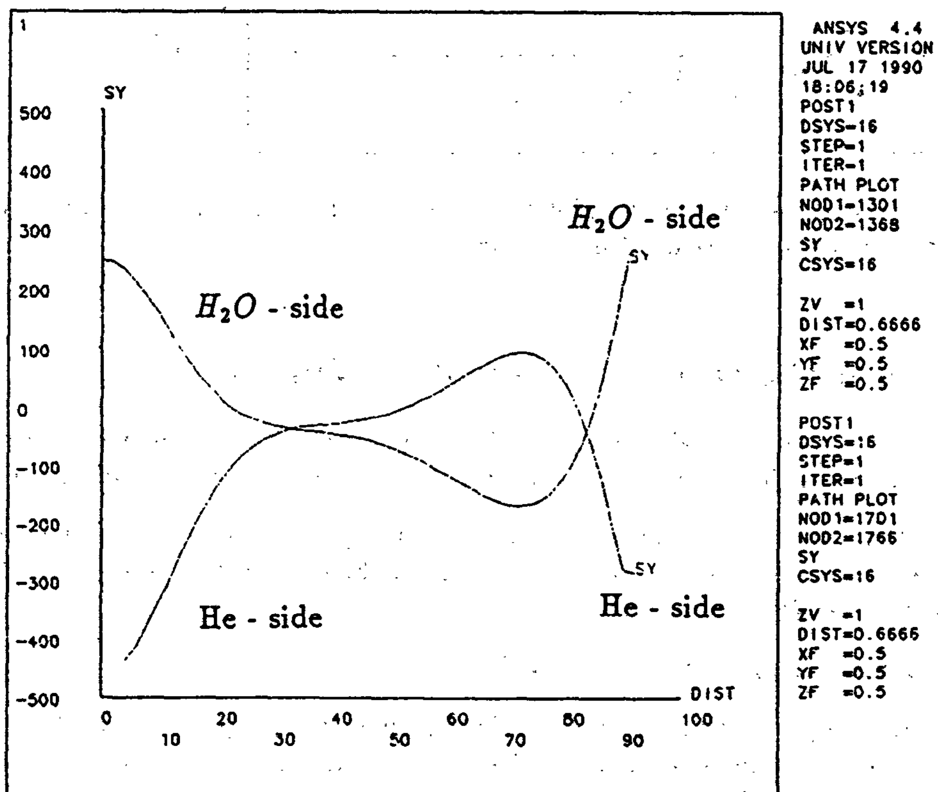

Figure 6: Component stresses $S_y(N/mm^2)$ plotted along the surface of the 2nd H_2O-cooled window as a function of the distance (mm) to its center ($p_{He} = 0bar$).

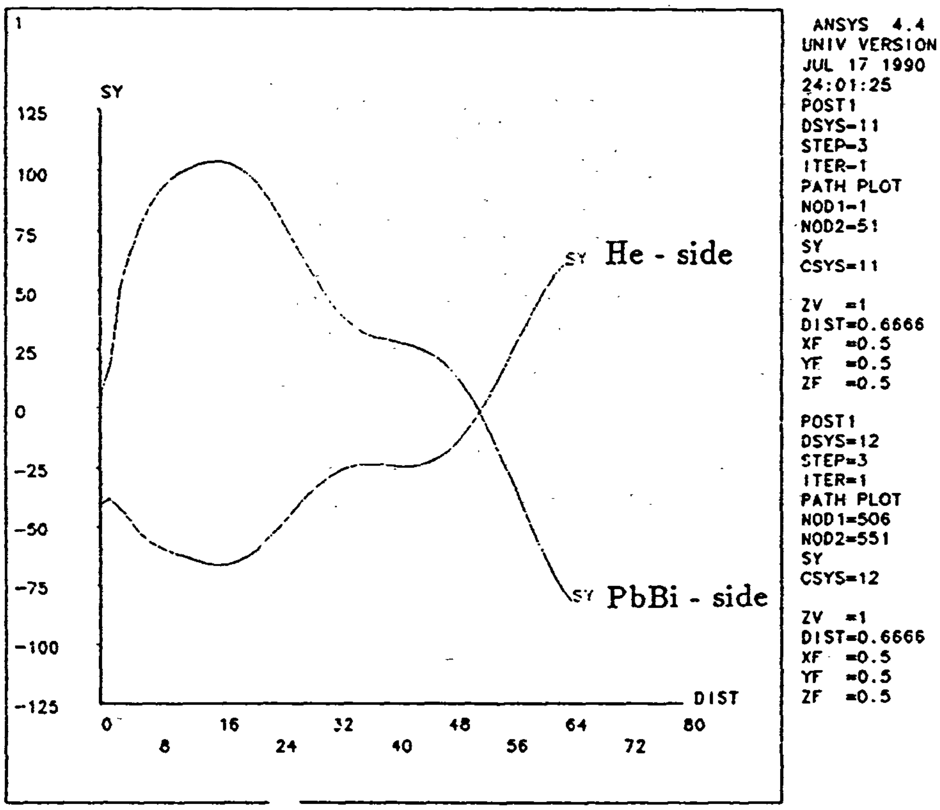

Figure 7: Component stresses $S_y(N/mm^2)$ plotted along the surface of the PbBi-cooled window as a function of the distance (mm) its center $(p_{He} = 0bar)$.

IV. Redesign of the second H_2O-cooled Window

From the present studies the essential influence of the temperature drop at the window center as well as at the flange to the stress level can be seen. Therefore, the following steps have been taken:

- The thickness of the window has been decreased from 2 to 1mm at its center and increased from 2 to 4mm at its edge. This is done by changing the radius of the spherical surface of the He-side from the original 154mm to 141.7mm.

- The nose of the support flange has been removed.

A thermal and stress analysis has been performed for this new geometry. The von Mises peak stress in the window now occurs at the edge and is $264N/mm^2$: at the center, the stress is reduced from $471N/mm^2$ (with the original design) to $220N/mm^2$. The corresponding safety factors, based upon the temperature dependent yield strength, are ≥ 2 throughout the window. The component stresses S_y plotted along the window surfaces are shown in Fig 8 and may be compared with those for the original design in Fig 6.

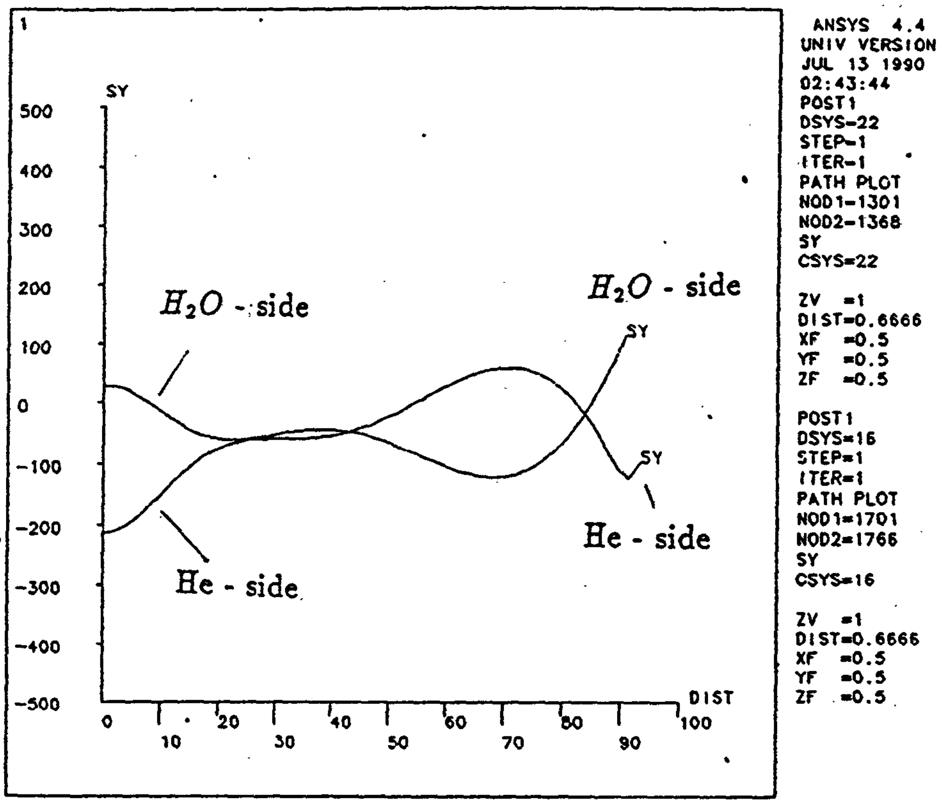

Figure 8: Component stresses $S_y(N/mm^2)$ plotted along the surface of the redesigned $2^{nd} H_2O$-cooled window as a function of the (mm) to its center $(p_{He} = 0bar)$.

V. Thermal and Stress Analysis for a Peak Current Density of $265 \mu A/cm^2$

In the following simulation, the extreme fault condition is assumed, where the full beam bypasses Target E ($\epsilon = 100\%$). The same boundary conditions have been used as in the previous calculations.

V.1 Temperatures

In Fig 9, the temperature response of the PbBi-cooled window at its center has been plotted as function of time. At $t = 0$ the beam has been changed from normal operation (a peak current density of $25 \mu A/cm^2$) to $265 \mu A/cm^2$. The steady-state temperature distribution for each window is shown in the Figs 10 & 12. The surface temperature of the H_2O-cooled window exceeds the saturation temperature of the liquid within a radius $r \leq 12\ mm$ for the first and $r \leq 7\ mm$ for the second window and the high subcooling regime starts. The heat flux from the first window reaches a value of $\sim 900\ W/cm^2$ but is less than the predicted critical heat flux.

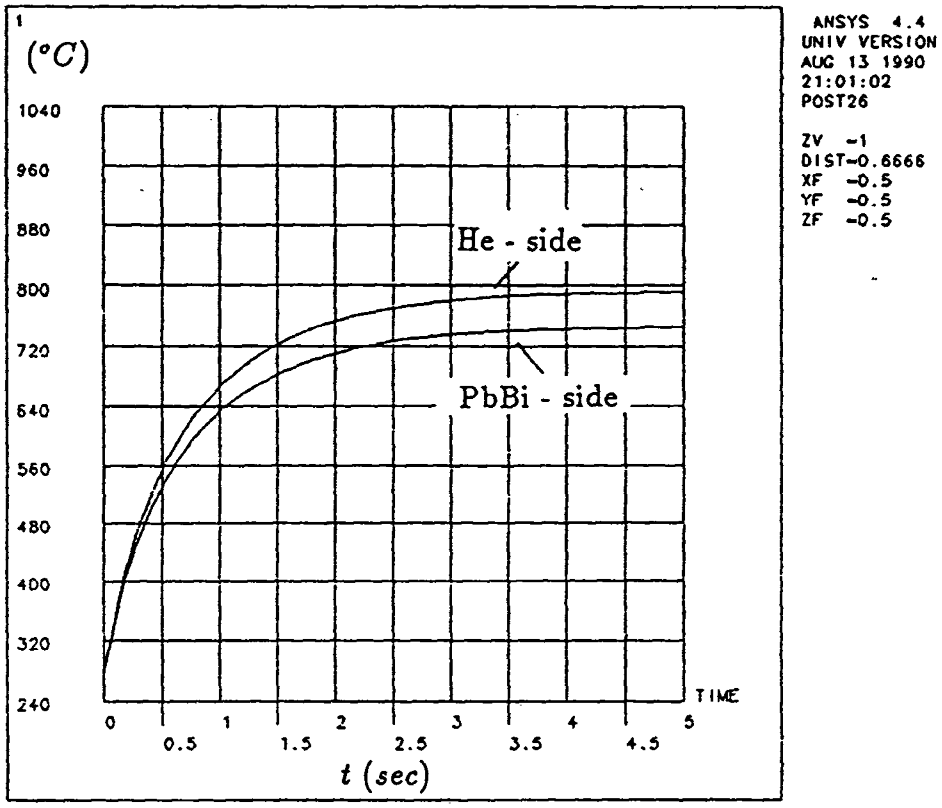

Figure 9: Temperature response ($^{\circ}C$) of the PbBi-cooled window at its center plotted as a function of time t (sec). At $t = 0$ the beam size has been changed from a normal operation at a peak current density of $25\mu A/cm^2$ to a peak density of $265\mu A/cm^2$.

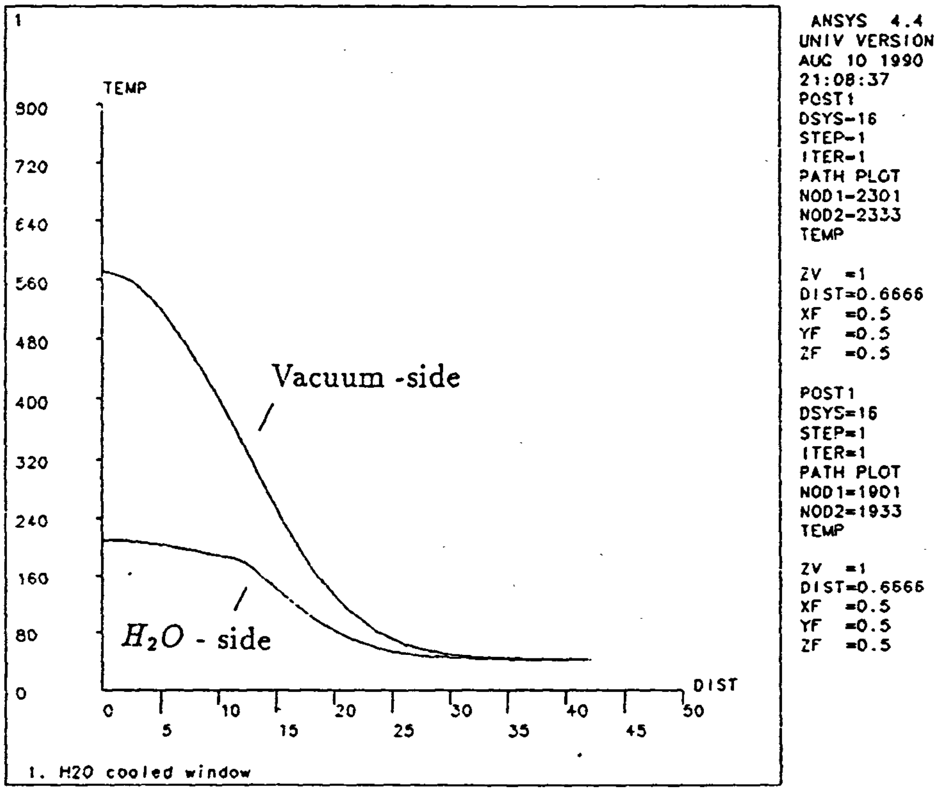

Figure 10: Temperature distribution ($^{\circ}C$) of the first H_2O-cooled window plotted as a function of the distance (mm) to its center ($265\mu A/cm^2$).

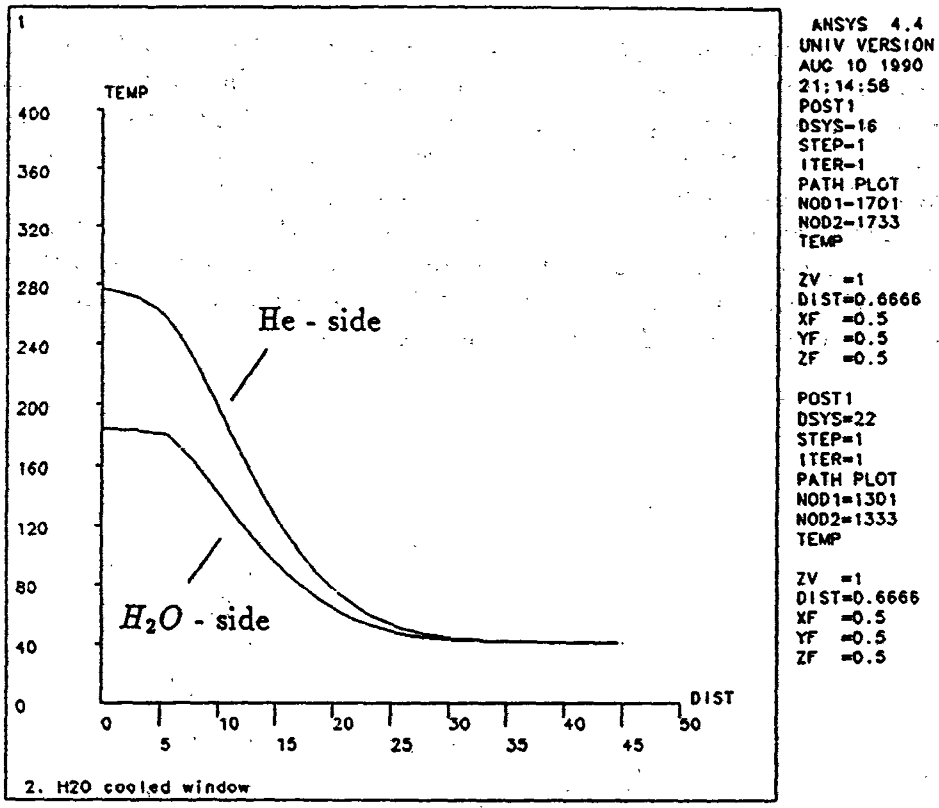

Figure 11: Temperature distribution ($°C$) of the second H_2O-cooled window plotted as a function of the distance (mm) to its center ($265\mu A/cm^2$).

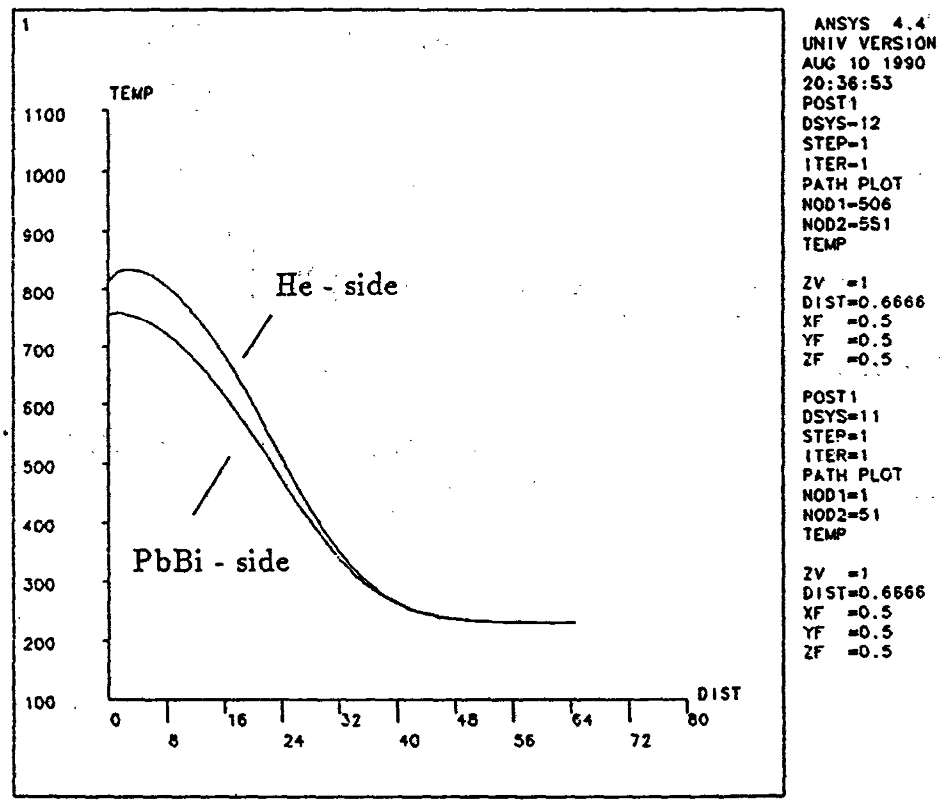

Figure 12: Temperature distribution ($°C$) of the PbBi-cooled window plotted as a function of the distance (mm) to its center ($265\mu A/cm^2$).

V.2 Stresses

In Fig 13, the von Mises stress has been plotted along the surfaces of the first H_2O-cooled window as function of the distance to its center. The stress level is less than the allowable yield strength at the corresponding temperature and at any position of the window. In Fig 14, the component stresses S_y are plotted along the surfaces of the second H_2O-cooled window. At the center, the von Mises stress exceeds slightly the yield strength within a local region. The component stresses S_y along the surfaces of the PbBi-cooled window are shown in Fig 15. Within a path length ≤ 20 mm, corresponding to a radius ≤ 12 mm, plastic deformation occurs and stress relaxation is expected, due to the drop of the yield strength at the high peak temperatures of up to 830°C. The elastic limit is reached at $\sim 550°C$ which is about $0.5sec$ after the current-density increase (see Fig 9).

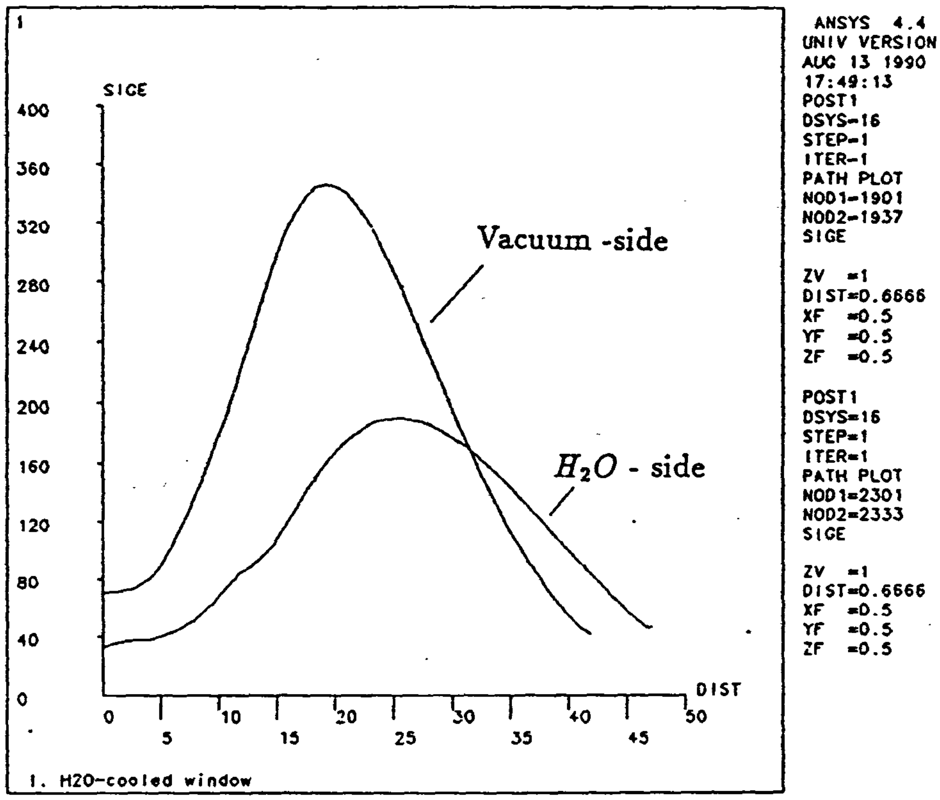

Figure 13: Von Mises stress (N/mm^2) plotted along the surfaces of the the first H_2O-cooled window as a function of the distance (mm) to its center ($265\mu A/cm^2$).

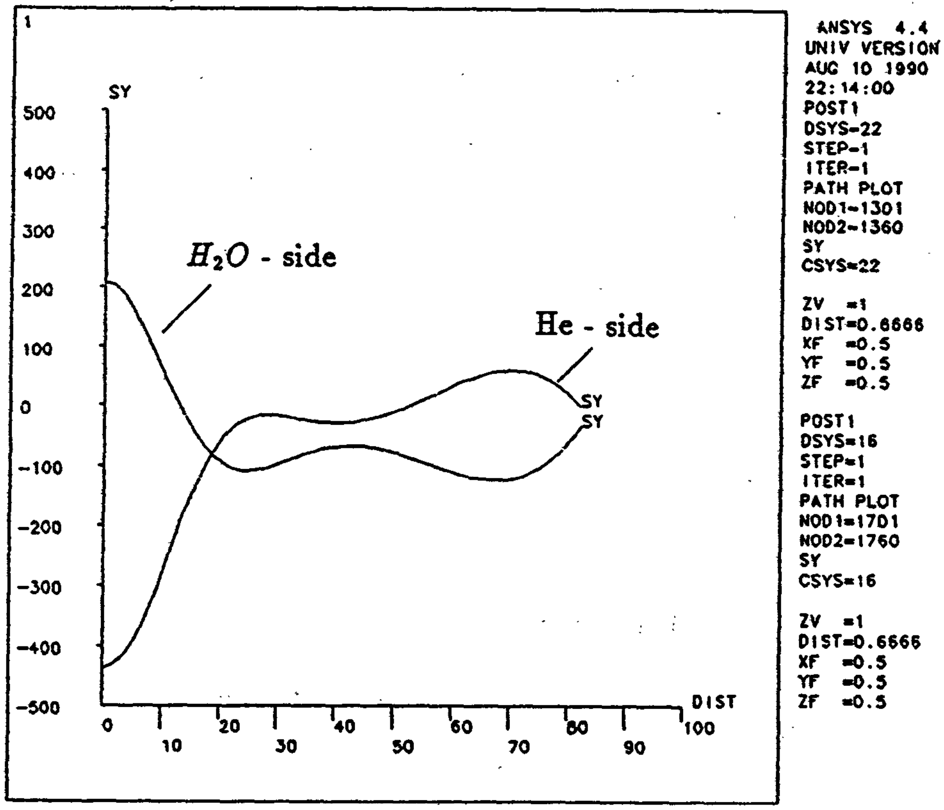

Figure 14: Component stresses $S_y(N/mm^2$ plotted along the surfaces of the second H_2O-cooled window as a function of the distance (mm) to its center ($265\mu A/cm^2$).

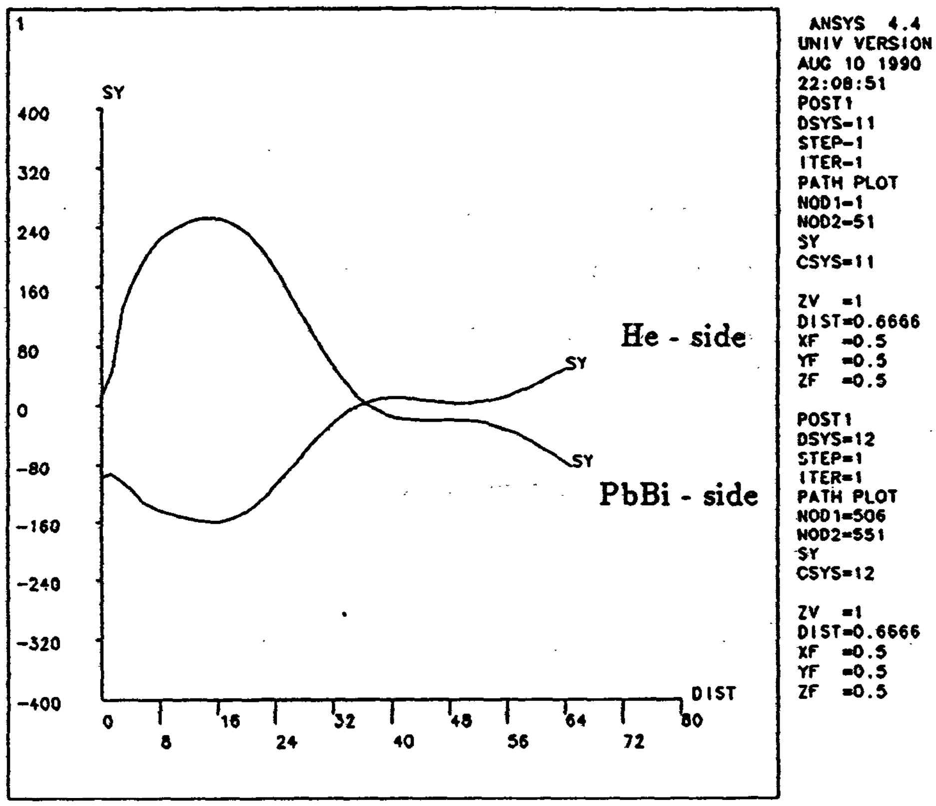

Figure 15: Calculated component stresses ($S_y(N/mm^2)$ plotted along the surfaces of the PbBi-cooled window as a function of the distance (mm) to its center ($265\mu A/cm^2$). Note: in this case, the temperature is higher then $550°C$ and outside the range of yield-strength data.

VI. Conclusions

The present study predicts adequate safety margins for peak current densities of up to $105\mu A/cm^2$ and hence, safe long-term operation may be expected for both windows. For higher current densities, up to $265\mu A/cm^2$, the stresses stay well within the elastic range of the selected steel throughout the H_2O-cooled window. However, the present linear analysis shows that the stresses in the PbBi-cooled window exceed the elastic limit. Further investigations are required to allow prediction of the lifetime and failure mode of this window: these need to include non-linear analysis and load cycling as well as the change of the material properties due to irradiation effects.

VII. Nomenclature

$\Delta T_{sub} =$	$T_{sat} - T_{bulk}$	subcooling
$\Delta T_{sat} =$	$T_w - T_{sat}$	
T_{sat}	saturation temperature of fluid	
T_{bulk}	bulk temperature of fluid	
T_w	wall temperature	
q	heat flux, power density	
q_{chf}	critical heat flux	
h_l	single phase heat transfer coefficient	
Bo	boiling number	
Pe	Peclet number	
X_l	thermal entrance length	
d_l	channel width of fluid	
d_h	hydraulic diameter	
λ_{fl}	thermal conductivity of fluid	

References

[1] ANSYS, Swanson Analysis Systems Inc.,Houston, PA 15342 USA

[2] M. Dubs and J. Ulrich, Design considerations of the target window, ICANS-XI, Japan 1990

[3] F. Atchison, SINQ-project internal report SINQ/816/AF38-002, 1990

[4] B.Sigg et al.,Thermal-hydraulics Investigation for the Liquid Lead-Bismuth Target of the SINQ Spallation Source,ICANS-XI, Japan 1990

[5] VDI-Wärmeatlas 1984, p. Gb3,Gd4

[6] M. Shah, Generalized Prediction of Heat Transfer during Subcooled Boiling in Annuli,Heat Transfer Eng. vol.4 no.1, 1983

[7] P. Saha and N. Zuber, Proc. of the 5th Int. Heat Transfer conf., vol IV, 1974, p. 175

[8] S. Mirshak et al., Heat Flux at Burn-out, du Pont de Namours, Savannah River, DP-355, 1959