An Exit Window for the Tesla Test Facility

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1 Overview

The TTF beam (800 MeV, $4 \cdot 10^{13}$ e^- per train with 800 μs length, 10 Hz rep. rate) will be dumped in an aluminum cylinder with a graphite core. The graphite as primary dumping material is necessary because the induced thermal stresses would exceed the possible limits in aluminum. However, graphite can not be incorporated into the ultra-high vacuum system of the linac. Therefore one needs an exit window to separate the dump from the beam-pipe vacuum.

Looking at the beam parameters, especially the high average current and the low duty factor of less than 1 %, it is obvious that such a window is a crucial device. On the other hand in a superconducting linac like the TTF one has to avoid under any circumstances a break of the vacuum system which would be followed by an unavoidable pollution of the cavities. The layout of the window should guarantee a high inherent safety, also with regard to possible operational mistakes.

In this note the suitability of several materials for the window is investigated. Possibilities to cool the window and to lower the temperatures in the beam spot are addressed.

2 Energy Deposition and Instantaneous Heating

As long as we consider a high energy beam penetrating a thin window, which means $d \leq 0.4\ X_{rad}$, a shower is not developed and the energy deposition per unit length is nearly constant. Furthermore the energy deposition depends only weakly on the beam energy. It can be estimated by analytical means as the Bethe-Bloch formula or using the more refined techniques of standard simulation codes. Several results for titanium and 800 MeV electrons are compared in table 1.

The results in table 1 differ by $\pm 15\%$, which may depend partly on the different cutoff-energies used in the individual codes. For the estimations in this note we always use GEANT results.

	EGS4	EGS4	FLUKA	GEANT	MARS	$\left(\frac{dE}{dx}\right)_{min}$	$\left(\frac{dE}{dx}\right)_{E_0}$
E_{cut} [keV]	1	200	10	10	300	-	330
$\left(\frac{dE}{dx}\right)$ $\left[\frac{\text{MeV}}{\text{g/cm}^2}\right]$	1.45	1.55	1.32	1.51	1.73	1.476	1.639

Table 1: Energy deposition values for a 250 μm thick titanium window, obtained from different codes (data from EGS4, Fluka and MARS code provided by N. Mokhov, Fermilab). The energy of secondary particles which fall below a certain cutoff-energy is treated as deposited completely. Therefore the codes underestimate the energy deposition with higher cutoff-energies. $(dE/dx)_{min}$ is the minimum of the Bethe-Bloch formula and the last column gives the result of the Bethe-Bloch formula with correction for polarization effects [3]. In that case the cutoff-energy used in the formula is estimated by $E_{cut} = d \cdot (dE/dx)_{min}$ (following a suggestion by D.Schulte), where d is the window thickness.

During the short passage time $\tau = 800$ μs of a bunch train, the deposited heat is spread transversally by a typical diffusion length of $< d >= \sqrt{\frac{\lambda\tau}{\rho c}} \approx 70\ldots 290$ μm, where the small number corresponds to Ti and the large one to Cu. In any case the diffusion length is small compared to the desired beam size of $\sigma_{x,y} = 1.5$ mm. Therefore we can assume that the passage of a single bunch train leads to an instantaneous heating which is proportional to the particle density distribution of the beam. Neglecting the small temperature dependence[1] of the heat capacity c we end up with a formula for the instantaneous temperature rise in the centre of the beam distribution:

$$\Delta T_{inst} = \left(\frac{dE}{dx}\right) \frac{N_{train}}{2\pi\sigma^2 \rho c} , \tag{1}$$

where N_{train} is the number of particles per train and σ is the rms-width of a round Gaussian beam. Since $(dE/dx)/\rho$ is nearly constant for different materials, the only material-dependent parameter which can be influenced is the heat capacity c. Table 2 gives a comparison of the power deposition calculated by GEANT and the instantaneous temperature rise for different materials.

The instantaneous heating leads to cyclical thermal stresses in the material and reduces the mechanical stability. However, from table 2 it cannot be decided yet which material is best suited because also the average temperature at an equilibrium of power deposition and cooling as well as the stress resistivity of the material at elevated temperatures are important.

[1] The temperature dependence of c should be taken into account in case of the light materials C and Be.

	Be	C	Al	Ti	Fe	Cu	W
$(dE/dm)_{dep/train}$ [J/g]	69.2	79.6	75.9	71.9	72.6	71.3	63.9
ΔT_{inst} [K]	34.5	87.2	82.2	133.3	152.4	180.9	456.0
c (298 K) [J/gK]	1.982	0.711	0.904	0.525	0.448	0.385	0.136

Table 2: Instantaneous heating of several materials. The power deposition is obtained from a GEANT simulation for a 500 μm thick plate. The temperature rise in the beam centre is calculated by a numerical integration of the temperature dependent heat capacity (data taken from [2]), starting from room temperature. The beam size is assumed to be $\sigma_x = \sigma_y = 1.5$ mm.

3 Cooling Mechanisms and Equilibrium Temperature

heat conduction in the window (edge cooling)

In case of edge cooling of the window the thermal conductivity of the material is important. In cylindrical coordinates the equilibrium temperature distribution $T(r)$ obeys the following differential equation:

$$-\lambda\frac{1}{r}\frac{\partial}{\partial r}r\frac{\partial}{\partial r}T(r) = q(r). \tag{2}$$

Assuming a power distribution of

$$q(r) = N_{train}\nu_{mac}\left(\frac{dE}{dx}\right)\frac{2\sigma^2}{\pi(r^2+2\sigma^2)^2}, \tag{3}$$

which is similar to a Gaussian distribution, the temperature distribution can be calculated straight forward. The maximum temperature in the beam spot is:

$$T_{max} = T(r=0) = T_{edge} + \left(\frac{dE}{dx}\right)\frac{N_{train}\nu_{mac}}{4\pi\lambda}\ln\left(1+\frac{b^2}{2\sigma^2}\right) \tag{4}$$

Here ν_{mac} is the train repetition rate. Since beam size σ and plate radius b are contained in the logarithmic term there is only a weak dependence on these parameters. The properties which can be influenced by choice of material are here the thermal conductivity λ and the energy deposition (dE/dx). Results for different materials are given in table 3.

thermal radiation

At very high temperatures cooling by thermal radiation becomes important. The radiated power per area is given by:

	Be	C	Al	Ti	Fe	Cu	W
P_{tot} / 0.5 mm [W]	9.0	12.7	14.5	23.1	40.4	45.2	87.1
ΔT_{eq} [K]	57.0	72.4	68.5	1771	560	131.5	607
λ [W/Kcm]	1.8	2.0	2.4	0.15	0.76	3.9	1.6

Table 3: Total deposited power for a 500 μm plate and equilibrium temperature difference from the window edge to the beam centre for different materials. The beam size is $\sigma_x = \sigma_y = 1.5$ mm. The plate radius is assumed to be equal to the radius of the beam pipe which is 7.5 cm. The values of carbon are valid for pyrolytic graphite.

	λ_g [W/cm K]	ρ_g [g/cm^3]	η [g/cm s]	c_p [J/g K]
He	$1.56 \cdot 10^{-3}$	$1.604 \cdot 10^{-4}$	$1.99 \cdot 10^{-4}$	5.193
N_2	$2.51 \cdot 10^{-4}$	$1.251 \cdot 10^{-3}$	$1.67 \cdot 10^{-4}$	1.0

Table 4: Some properties of He and N_2 gas under normal conditions.

$$h = \varepsilon \sigma_{SB} T^4 \tag{5}$$

where ε is the emissivity of the material (≈ 0.47 for Ti, W) and $\sigma_{SB} = 5.67 \cdot 10^{-8}$ Wm^{-2}K^{-4} the Stefan-Boltzmann constant.

However, the equilibrium temperature for thermal radiation cooling is only for titanium and tungsten below the melting point (see also the simulations for Ti in Fig. 4).

gas cooling

Since the total deposited power in a thin window is rather small ($\approx$ 20 W for a 0.5 mm Ti window) it seems reasonable to cool the window with a forced gas flow on the surface. The achievable heat flux is given by $h = \frac{\lambda_g}{x} N_u$ [1] where λ_g is the thermal conductivity of the cooling gas and x is a typical dimension of the area to be cooled. N_u is the Nusselt number, given by

$$\begin{aligned}
N_u &= 0.664 \cdot Pr^{1/3} Re^{1/2} && \text{(for laminar flow)} \\
N_u &= \frac{0.037 \cdot Pr Re^{0.8}}{1 + 2.443 Re^{-0.1} (Pr^{2/3} - 1)} && \text{(for turbulent flow)} \\
Pr &= c_p \eta / \lambda_g && \text{(Prandtls number)} \\
Re &= x v \rho_g / \eta && \text{(Reynolds number),}
\end{aligned}$$

where v is the gas velocity, ρ_g the gas density and η the dynamic viscosity (see table 4). The switch-over from laminar to turbulent flow occurs at a Reynolds number of $Re \approx 5 \cdot 10^5$.

beam circulation on the window

An additional possibility to relax the situation is to circulate the beam on the window, e.g. with 50 Hz net-frequency. This leads to an increase of the size of the hot area which improves the efficiency of gas cooling and lowers the equilibrium temperature. The circulation can be achieved by a quadrupole or sextupole, if the individual coils are powered with two phase or three phase AC current respectively. The average power distribution in cylindrical coordinates can be calculated by superposition of the Gaussian beam distribution around a circle:

$$\begin{aligned} q(r) &= \frac{q_0}{2\pi}\int_{\varphi=0}^{2\pi}\frac{d\varphi}{2\pi\sigma^2}\,\exp\left(-\frac{(r-r_0\cos(\varphi))^2+r_0^2\sin^2(\varphi)}{2\sigma^2}\right) \\ &= \frac{q_0}{2\pi\sigma^2}\,\exp\left(-\frac{r^2+r_0^2}{2\sigma^2}\right)\mathrm{I}_0\left(\frac{rr_0}{\sigma^2}\right), \end{aligned} \tag{6}$$

where r_0 is the circulating radius. For sufficiently large r_0 the beam spot of a single bunch train is smeared out which leads also to a reduction of the instantaneous temperature by a factor of

$$k = \frac{1}{\pi\nu_0\tau}\int_0^{\pi\nu_0\tau} d\varphi\,\exp\left(-\frac{r^2+r_0^2-2rr_0\cos(\varphi)}{2\sigma^2}\right), \tag{7}$$

where ν_0 is the circulation frequency. The reduction factor as a function of the circulating radius is shown in Fig. 1. Unfortunately a circulation with 50 Hz is to slow for sufficiently smearing out the (relatively) short TESLA bunch train.

heat equation and numerical simulation

The time dependent temperature evolution in the material can be described by the following heat equation which includes the above discussed cooling mechanisms:

$$\begin{aligned} \tfrac{\rho c}{\lambda}\tfrac{\partial}{\partial t}T(r,t) &= \tfrac{\partial^2}{\partial r^2}T(r,t)+\tfrac{1}{r}\tfrac{\partial}{\partial r}T(r,t) && \text{(heat conductivity)} \\ &\quad +\tfrac{1}{\lambda}q(r,t) && \text{(heating term)} \\ &\quad -\tfrac{h}{d\lambda}(T(r,t)-T_0) && \text{(gas cooling)} \\ &\quad -2\varepsilon\sigma T^4(r,t) && \text{(radiation cooling)} \end{aligned} \tag{8}$$

Here d is the thickness of the window.

Though gas- and radiation cooling act only on the surface of the plate, the longitudinal variation of the temperature field is neglected because the plate is thin compared to the beam size. Equation (8) can be solved numerically, an example is shown in Fig. 2.

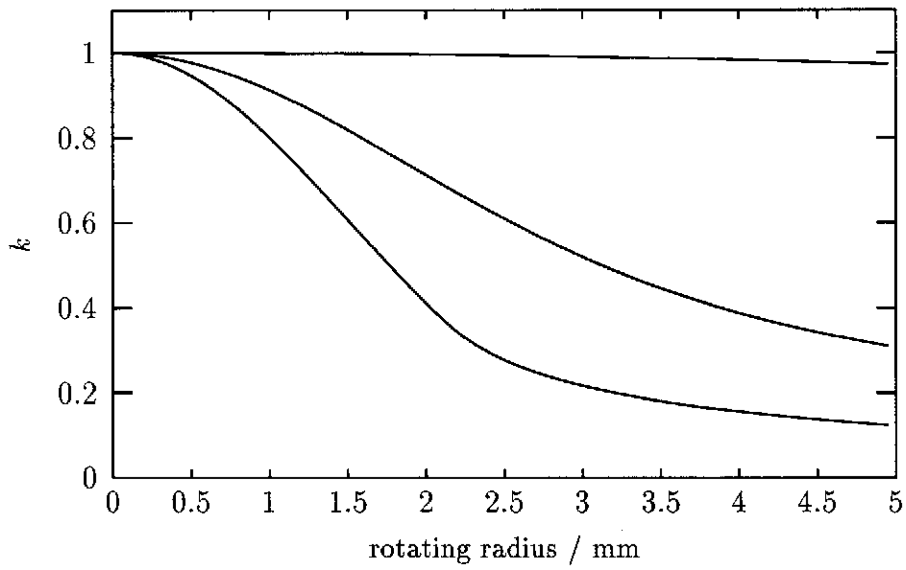

Figure 1: Reduction factor of the maximum instantaneous temperature as a function of the circulating radius. The three curves belong to the rotation frequencies 50 Hz, 500 Hz and 1250 Hz (complete turn during the passage of a bunch train), and the beam size is again $\sigma_{x,y} = 1.5$ mm.

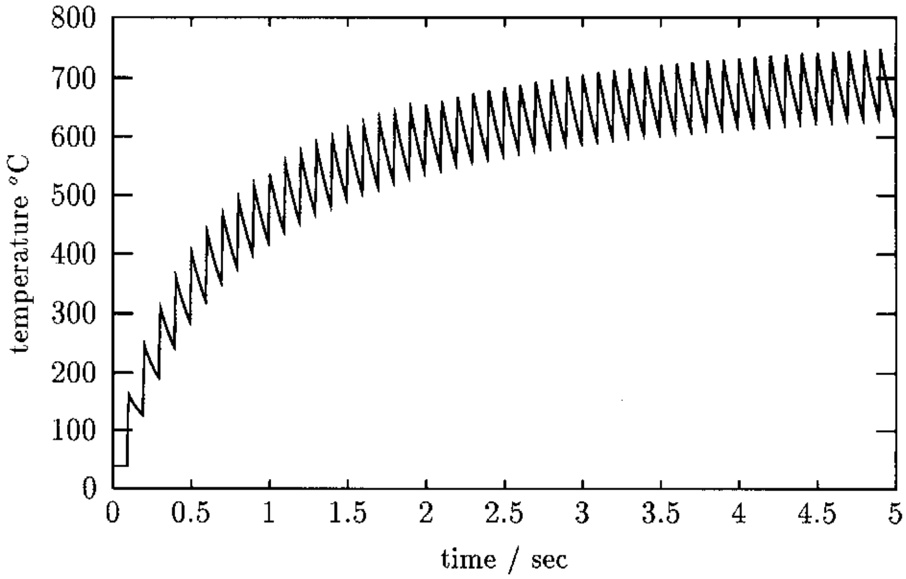

Figure 2: Simulation of a TESLA beam impinging on a Ti15Mo window, $\sigma_x = \sigma_y =$ 1.5 mm, gas cooling rate $h = 40$ mW/cm^{2}K, edge temperature $T_{edge} = 35$ °C. Shown is the temperature evolution in the beam centre.

4 Mechanical Stability and Thermal Stresses

Of course the window must withstand the air pressure. For a circular plate which is fixed at the edge the stress in the midpoint is given by

$$\sigma_{static} = 0.49 \frac{b^2}{d^2}\, p \tag{9}$$

where $p \approx 0.1$ N/mm^2 is the air pressure. The stress at the edge is higher by a factor 1.5 but due to the raised temperature the material will be much more sensitive in the centre. Note the strong (quadratic) dependency on thickness d and radius b.

Another important number is the cyclic thermal stress σ_{cyc} which is caused by the rapid heating of the material during the passage of the bunch train:

$$\sigma_{cyc} \approx \frac{1}{2} \alpha E \Delta T_{inst}, \tag{10}$$

where α is the thermal expansion coefficient and E the Elastic Modulus (formula taken from [5], valid for a radial fixed circular plate).

The window will undergo approximately 10^8 of these heating cycles per year. The decision if a material withstands a certain combination of static and dynamic stresses can be made using a so called Goodman[2] diagram [4] as shown in Fig. 3. On the ordinate one has to plot the endurance limit σ_E of the material at the working (equilibrium) temperature. The endurance limit is the stress maximum that does not produce fatique failure in a specimen subjected to a large number of cycles (typically 10^8). Then the ultimate tensile strength σ_{UTS}, again taken at the working temperature, has to be plotted on the abscissa. The ultimate tensile strength is the maximum stress that a specimen withstands in a single test. A straight line, connecting both points, divides unsafe operating conditions (above the line) from safe ones (below). An individual working point of a material is determined in this plot by the coordinates (σ_m, σ_{cyc}) where $\sigma_m = \sigma_{static} + \frac{1}{2}\sigma_{cyc}$.

5 Selection of Material

The materials in tables 2, 3 can be divided into several groups. First one has the low Z materials C, Be with the advantage of a low (dE/dx) resulting in a low total power loss in the window. The window could be made of graphite but such a window would have a relatively high gas leakage rate and would require differential pumping. Beryllium is in principle an ideal material. In addition to its low (dE/dx) it exhibits a rather high value of the thermal conductivity and also a large heat capacity. However, Be is extremely toxic and therefore difficult

[2] In the German literature the so called *Dauerfestigkeitsschaubild* is known as a similar diagram.

	ρ [g/cm^3]	λ [W/cmK]	α [K^{-1}]	E [N/mm^2]	σ_{UTS} [N/mm^2]	σ_E [N/mm^2]
Ti15Mo at 400 °C	4.95	0.126	$8.6 \cdot 10^{-6}$	$8.8 \cdot 10^4$	850	350
Cu0.6Cr at 20 °C	8.90	3.0	$1.6 \cdot 10^{-5}$	$1.1 \cdot 10^5$	255	175
Be at 250 °C	1.85	1.80	$1.2 \cdot 10^{-5}$	$2.8 \cdot 10^5$	415	205

Table 5: Properties of the alloys Ti15Mo, Cu0.6Cr and Beryllium. The endurance limit is given for $3 \cdot 10^8$ cycles, except the value of Be which is for 10^7 cycles. The data for Be are estimated from [6] and the others from [7].

to handle. Before a decision to use Be is made, other options should be checked carefully.

Then there are materials with a high thermal conductivity as Cu and Al. Even without gas cooling windows made of these materials would reach only moderate equilibrium temperatures (table 3), however, a closer look shows that the induced cyclic stress exceeds acceptable values by far (see the example in Fig. 3). This is caused by moderate stress resistivities, but also by relatively large thermal expansion coefficients.

From the remaining materials titanium exhibits the best mechanical properties. The most important disadvantage is the low thermal conductivity which even for pure titanium is a factor of 25 lower than that of copper. The only way to cool a titanium window is therefore gas cooling of the surface, but also in that case a relatively high thermal conductivity is desirable because it increases the effective size of the hot spot to be cooled. There are several Ti alloys available which exhibit better mechanical properties than pure Ti, but alloys have always a lower thermal conductivity than the pure metal. The Ti15Mo alloy seems to be a good compromise, properties[3] are given in table 5. The Goodman diagram in Fig. 3 shows a comparison of dynamic and static stresses for the Ti alloy and a Cu alloy with a high thermal conductivity. It shows clearly that the copper alloy is far outside possible limits. The Ti alloy could be used with a beam size of $\sigma_{x,y} = 1.5$ mm, but only at a working temperature of ≈ 500 °C. In practice it turns out that such a working temperature is hardly achieved with He gas cooling. Simulations are shown in Figs. 2 and 4. The way out is either to increase the beam spot to $\sigma_{x,y} \approx 3$ mm or to rotate the beam on the window with a similar radius.

[3]Unfortunately at elevated temperatures properties were found only up to 400°C in [7].

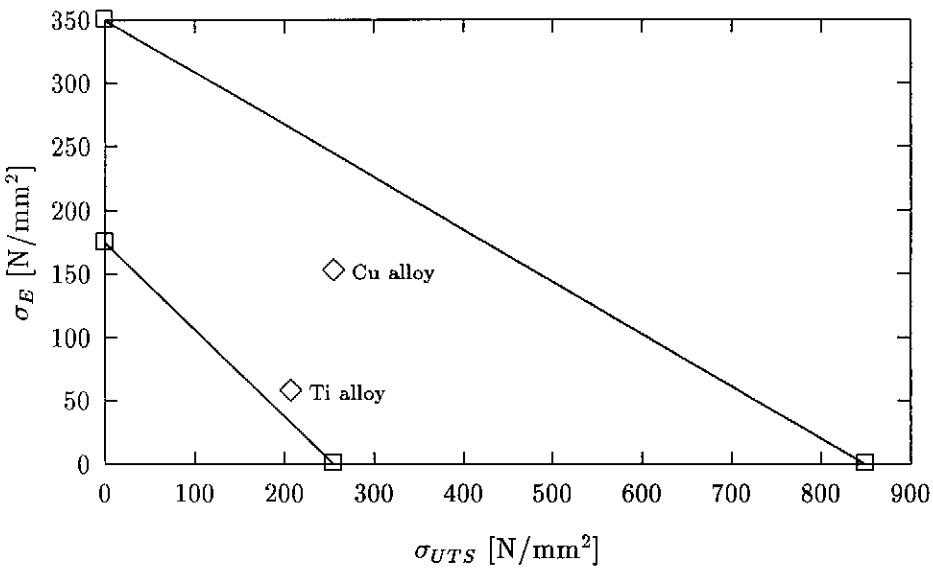

Figure 3: Goodman stress diagram for a Cu0.6Cr and a Ti15Mo window. The upper line and the lower point belong to titanium. The indicated working points correspond to the static stress caused by air pressure on a fixed plate with 60 mm diameter and a thermal cyclic stress caused by a 1.5 mm TESLA beam. The limiting lines are for working temperatures of 400 °C in case of Ti and room temperature in case of Cu.

6 A Possible Design Using Titanium

Once a certain material is selected the layout of the window can be fixed. Using the static stress formula (9) and the allowed stress values at elevated temperatures it turns out that a thin window cannot be extended to the full radius of the beam-pipe which is 75 mm. One has to find a compromise between the window radius which should be as large as possible in view of beam offsets and the window thickness which should be as small as possible to keep the power deposition low. Reasonable values are a thickness of 0.5 mm and a diameter of 60 mm resulting in a static stress of 180 N/mm^2 in the midpoint. We assume He gas cooling with a mass flow of 1 g/s leading to a heat transfer coefficient of $h \approx 40$ mW/cm^{2}K. The gas should be blown with a high velocity on the surface using a narrow nozzle. The gas outlet, however, must be large to avoid an additional static gas pressure on the window. It turns out that for a beam size of 3 mm, achieved either by optical magnification or by rotation, the equilibrium temperature can be kept around 430 °C (see Fig. 4).

A critical point is certainly the possibility that the beam becomes suddenly to small, for example due to an accidental change of the quadrupole settings. This may lead to a rather fast break of the window. One can achieve a higher safety by using a double window. Since it is unlikely that both windows will break at exactly the same time one can monitor the tightness of the windows and switch

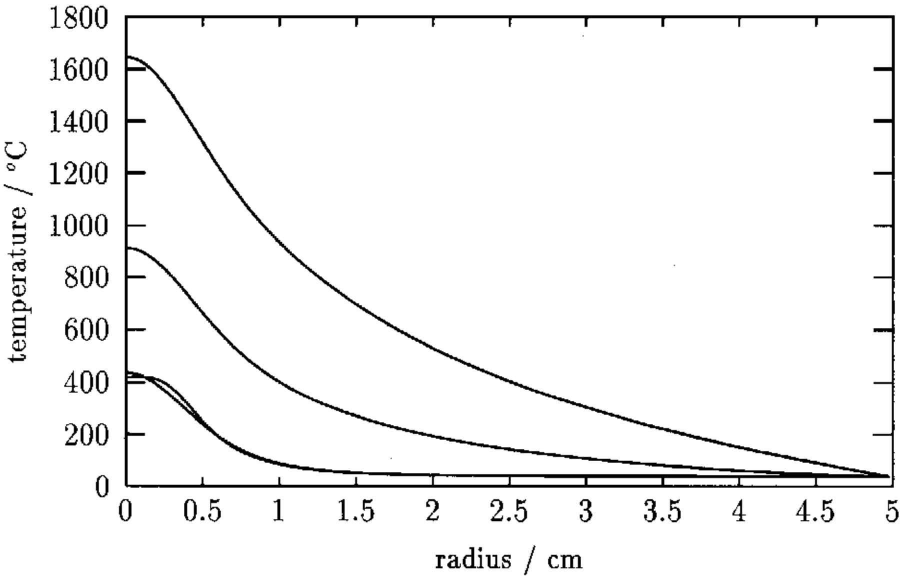

Figure 4: Radial temperature distribution on a Ti15Mo window. For three curves a beam size of $\sigma_{x,y} = 3$ mm was assumed. In the upper curve only edge cooling is applied whereas for the second one thermal radiation is taken into account. In the third case the window is cooled with a He stream of 1 g/s. The achieved heat transfer coefficient is ≈ 40 mW/cm^{2}K. The curve with the dip corresponds to a 1.5 mm σ beam which is circulated with $r_0 = 3$ mm. All curves are taken under equilibrium conditions.

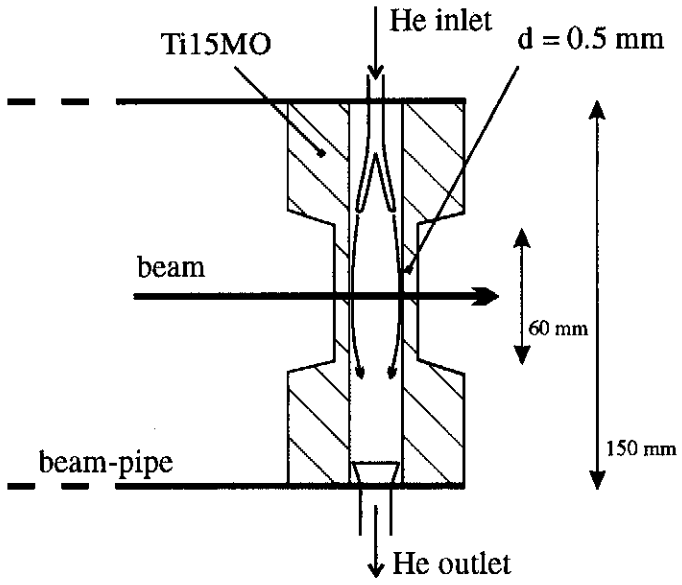

Figure 5: Rough sketch of a possible layout for the double window.

the beam off if one fails. In case of a break of the inner window the beam pipe would be flooded only by a limited amount of clean He gas which is much less dangerous for the cavities than dusty air. A possible layout of such a double window is sketched in Fig. 5.

In case of a magnet/power-supply failure the beam can be switched off by an interlock system within one bunch train cycle. Since some quadrupoles are used to enlarge the beam spot at the window it should be able to accept one bunch train with a reduced spot size in such a case. Assuming a maximum tolerable temperature increment of 900 ^{o}C for this single event, the minimum width of a round beam is $\sigma_{x,y} = 390$ μm. Another question which might be interesting is the maximum possible repetition rate without He-gas cooling. Assuming an equilibrium temperature of 500 ^{o}C and a beam size of $\sigma_{x,y} = 3$ mm, the window is safe with repetition rates lower or equal 3 Hz. If one reduces the number of bunches in a train instead of the rep. rate the situation is less critical since the cyclic stress is reduced which allows a higher working temperature.

7 A Window Using Beryllium

With Be the whole design is much less critical. The thermal conductivity is high enough so that gas cooling is not needed. Be exhibits a relatively large elastic modulus E (table 5), however, due to the low (dE/dx) and the large heat capacity equilibrium temperature and instantaneous heating are moderate and therefore the induced stresses as well. The temperature dependence of the heat capacity is not negligible in case of Be. Taking into account this dependence

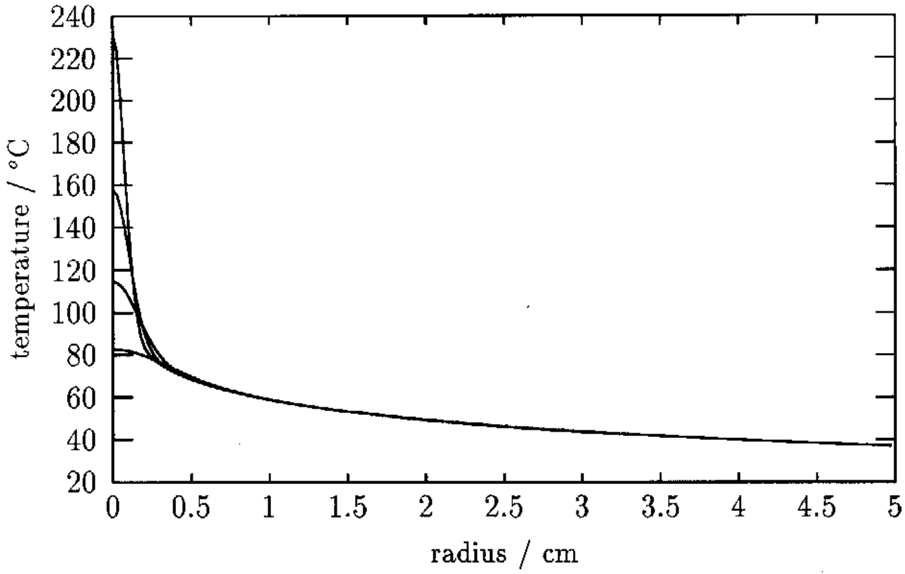

Figure 6: Radial temperature distribution on a beryllium window. The four curves belong to TTF beams with 0.7/1.0/1.5/3.0 mm sigma. All curves are taken under equilibrium conditions, immediately after the passage of a train.

one finds instantaneous temperature jumps of 140/70/32/8.0 °C for TTF beams with $\sigma_{x,y} = 0.7/1.0/1.5/3.0$ mm, where the heating is calculated starting from an equilibrium temperature distribution. In Fig. 6 the simulated radial distributions are shown. The Goodman stress diagram for the 4 beam sizes is depicted in Fig. 7. The position of the limit-line is estimated for a working temperature of 250 °C from data given in [6].

It can be seen that for the nominal beam size of $\sigma_{x,y} = 1.5$ mm the temperatures and stresses are tolerable which makes beam circulation and optical magnification superfluous. These facts lead to a higher inherent safety of the Be window in comparison with the Ti solution.

In a failure situation the Be window can accept a single bunch train with a spot of $\sigma_{x,y} = 260$ μm (compare 390 μm for Ti). The number is based on a maximum temperature jump of 800 °C.

8 Conclusions

Due to the high average current and the low duty factor of the TESLA beam the exit window is a critical device. The large temperature jump during the passage of a bunch train leads to high cyclical thermal stresses in usual materials. There are two possible ways to realize an exit window with the required properties. First one could use a strong material like a Ti alloy which can tolerate the induced thermal stresses thanks to its extremely high stress resistivity.

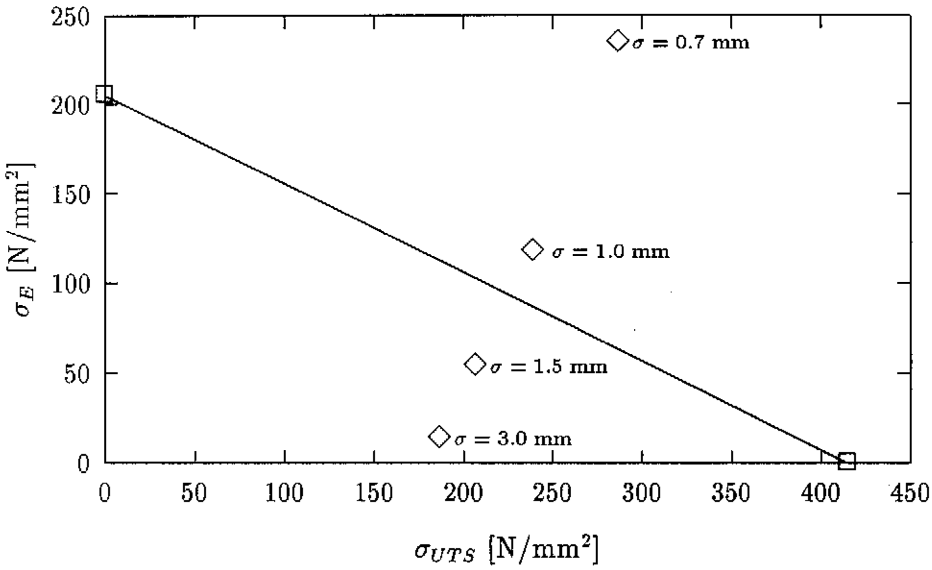

Figure 7: Stress diagram for a 500 μm Be window, radius 3 cm for 4 different beam sizes. The limiting line is estimated for a working temperature of 250 °C.

However, Ti exhibits a low thermal conductivity which leads to untolerable high working (average) temperatures in the beam spot. In order to achieve acceptable temperatures one has to apply gas cooling and the beam spot must be increased by beam circulation or optical magnification. With He as coolant the mass flow should be of the order 1 g/s to achieve working temperatures below 500°C. Of course these things complicate the whole design.

A second possibility is the use of a light material, where Be is the only candidate since C is not tight enough. Due to the outstanding low (dE/dx) of Be and its mechanical properties, tolerable temperatures can be achieved already with edge cooling, even for the nominal small beam spot. The drawback of Be is its toxicity which makes it's handling difficult. However, at Hasylab/DESY several Be windows are in use at synchrotron radiation beam lines [8] and one could take advantage of the experiences gained there. Furthermore premounted Be windows for synchrotron radiation purposes are available from industry in a standardized way.

For a higher safety the window should be doubled. In case of a break of one window the beam can be switched off. In addition a fast closing valve should be installed at a sufficiant distance from the window.

The conclusion from the above considerations is that both designs, the Ti as well as the Be window can fulfill the requirements of TTF, however, the Be window is much simpler and therefore preferable.

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