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# Concept of the Beam Exit and Entrance Windows for the TESLA Water based Beam Dumps and its related Beam Lines

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## Introduction and Requirements

In the context of the beam abort systems for the TESLA project, beam windows are required for two purposes. The beam leaves the vacuum system through an exit window at the end of the abort line before it enters the water absorber through a separate entrance window. These windows are heated by about 1 ms long beam pulses (bunch trains), which have a spot size in the order of $\approx 1\ mm^2$ and carry a total number of $N_t$ particles ranging between $4 \cdot 10^{13}$ at the Tesla Test Facility (TTF) and $7.2 \cdot 10^{13}$ for TESLA FEL operation parameters. They repeat at a rate of $\nu$ (5 to 10 Hz), which results in an overall average beam current $I_{ave} = e \cdot N_t \cdot \nu$ in the range of 45µA (TESLA main linac) to 64µA (TTF). Typically the window thickness is chosen to be small compared to its radiation length $X_0$, thus shower development can be neglected. In that case energy deposition in the window is dominated by ionisation losses and therefore independent of the incident particle energy. As shown later, thermal diffusion within the bunch train passage time of 1 ms is negligible.

Each bunch train causes an instantaneous temperature jump $\Delta T_{inst}$ in the window, which, for a given material, only depends on the incident particle density dN/dA, i.e. spot size and $N_t$. After the passage of the bunch train this temperature decays to a certain amount until the next one arrives. Therefore in steady state an equilibrium temperature rise $\Delta T_{eq}$ is reached, around which level the temperature varies with time in a sawtooth-like manner. The equilibrium temperature rise is determined by the average beam current $I_{ave}$, the beam size and the heat transport towards the heat sink.

The described process of heating in combination with the beam parameters as mentioned above leads to strong cyclic thermomechanical stresses in the window, which will mainly determine its lifetime. About $10^9$ cycles will have been accumulated after 10 years of linac operation with $\nu$ = 5 Hz. In addition the windows have to be strong enough to withstand static pressure either caused by atmosphere in case of the exit window or by the 10 bar dump water acting on the entrance window. Leaking of the activated dump water into the vacuum system has to be avoided with a very high probability. Besides the double window concept, which allows failure of one window without severe consequences, the design of a reliable window optimized for long term pulsed beam operation with the given parameters is the key issue.

Different materials and their combinations are discussed in this paper in order to evaluate the potential of being a qualified candidate for the required window. As a result a sandwich like window made from a Ti-membrane embedded between graphite disks is focussed on in more detail.

## Selection of Materials for the Exit and Entrance Windows

Let us consider a classical window made from a homogeneous material, shaped as a cylindrical membrane with radius b and thickness $d \le 0.2 \cdots 0.4 X_0$. The incident beam of a round gaussian type is passing through the windows center. The membrane is cooled by water of temperature $T_{edge}$ flowing around its circumference at $r = b$ (edge cooling). For thin membranes an electromagnetic shower is not developing and energy deposition per unit length, dominated by ionisation loss of the particles, is nearly constant. For this case equation 1 gives the maximum temperature, which develops in the center of the window at the beam axis [1]. It is composed from temperature rise due

$$T_{max} \le T_{edge} + \left(\frac{dE}{dz}\right) \cdot \frac{N_t}{\pi} \cdot \left(\frac{1}{\rho c 2\sigma^2} + \frac{\nu}{4\lambda} \cdot \ln\left(1 + \frac{b^2}{2\sigma^2}\right)\right) \qquad \underline{\textit{Equation 1}}$$

$$\Leftrightarrow \qquad T_{max} \le T_{edge} + \Delta T_{inst} + \Delta T_{eq}$$

where:

| | |
|---|---|
| $T_{edge}$ | temperature of cooling water for edge cooling (≈ 300 K) |
| $\Delta T_{inst}$ | instantaneous temperature jump |
| $\Delta T_{eq}$ | equilibrium temperature rise |
| $dE/dz$ | energy loss in the window per unit length and per one electron |
| $\sigma$ | rms width of the round gaussian beam at the window |
| $N_t$ | number of particles per bunch train |
| $\nu$ | repetition rate of bunch trains |
| $c$ | specific thermal capacity of the window material |
| $\lambda$ | specific thermal conductivity of the window material |
| $\rho$ | mass density of the window material |

to instantaneous and average heating, which are adding to the temperature $T_{edge}$ of the heat sink.

### Effects of pulsed heating

Concentration is now put on the question of mechanical stresses induced by pulsed heating. The thermal and mechanical properties of the materials under consideration are shown in table 1 [2].

During the bunch train passage time $\tau \approx 1\text{ms}$ the temperature distribution propagates transversally by a characteristic thermal diffusion length $L = \sqrt{(\lambda \cdot \tau)/(\rho \cdot c)}$, which is 0.07 mm for titanium and 0.25 mm in the case of copper or graphite. For beam sizes with $\sigma \ge 0.5\text{mm}$ it is justified to neglect thermal diffusion and assume pure instantaneous heating caused by each bunch train according to the incident particle density distribution. The material will experience cyclic mechanical stress as a result of repeating instantaneous thermal expansion.

| | $\rho$ [kg/m$^3$] | c [J/kg/K] | E [GPa] | $\lambda$ [W/m/K] | $\alpha$ [$10^{-6}$/K] | $\sigma_{0.2}$ [MPa] | $\sigma_u$ (# of cycles) [MPa] |
|---|---|---|---|---|---|---|---|
| Be | 1850 | 2050 | 300 | 160 | 12.4 | 370 | 100 ($1 \cdot 10^7$) |
| Be + Al | 2030 | 1760 | 240 | 167 | 13 | 410 | 270 ($2 \cdot 10^7$) |
| Ti alloy | 4600 | 565 | 110 | 10 | 8.5 | 880 | 530 ($1 \cdot 10^7$) |
| Al alloy | 2850 | 922 | 70 | 155 | 23 | 420 | 100 ($2 \cdot 10^7$) |
| Stainless Steel | 7860 | 460 | 210 | 15 | 15-17 | 830 | 80 ($1 \cdot 10^7$) |
| Mg | 1740 | 1050 | 200 | 160 | 25 | 150 | 60 ($2 \cdot 10^8$) |
| Cu | 8960 | 380 | 120 | 400 | 17 | 70 | 28 [1)] |
| Reactor Graphite | 1770 | 960 @300K<br>1400 @600K | 10 | 95 @300K<br>55 @1300K | 7 | | 60 [2)] / 30 [3)] |

[1)] estimation $\sigma_u = 0.4 s_{0.2}$, [2)] compression loading, [3)] tension loading

*Table 1:* Thermal and mechanical properties of materials relevant for beam windows

For each material a reasonable limit of the tolerable temperature jump $\Delta T_{max}$ due to the cyclic mechanical load can be calculated as $\Delta T_{max} = \sigma_u / (2 \alpha E)$, where $\sigma_u$ is the cyclic strength (endurance limit), $\alpha$ is the coefficient of linear thermal expansion and E is the elastic modulus of the material. The endurance limit is the stress value, which does not produce damage or fatigue effects in the material after certain number of mechanical cycles (typically $10^7$ to $10^8$). Although $\sigma_u$ as a function of the number of cycles shows a flat behaviour at $10^7$ to $10^8$, data is not available in the $10^9$ regime, as required for our application. In this respect experiments with a prototype window should be aimed for. Nevertheless it is recommended to operate the window with a safety factor of at least 5 and replace it regularly after $\approx 10^8$ cycles, i.e. every year.

Table 2 lists the tolerable temperature jump $\Delta T_{max}$ and the corresponding limit on the energy density per mass unit $(dQ/dm)_{max}$ . This value must not exceed the maximum energy density caused by instantaneous heating during one bunch train passage. Therefore an upper limit for the maximum allowed incident particle density $(dN/dA)_{max}$ can be calculated from the following equation 2:

$$\left(\frac{dQ}{dm}\right)_{max} = c \cdot \Delta T_{max} \geq c \cdot \Delta T_{inst} = \frac{1}{\rho} \cdot \frac{dE}{dz} \cdot \left(\frac{dN}{dA}\right)_{max} \qquad \underline{\textit{Equation 2}}$$

| | $\Delta T_{max}$ [K] | $(dQ/dm)_{max}$ [J/g] | (dN/dA)max [$10^{12}$ particles/mm$^2$] |
|---|---|---|---|
| Be | 15 | 25 | 0.78 |
| Be + Al | 40 | 70 | 2.2 |
| Ti alloy | 280 | 150 | 4.7 |
| Al alloy | 30 | 27 | 0.84 |
| Stainless Steel | 10-30 | 8-24 | 0.25 – 0.75 |
| Mg | 26 | 26 | 0.81 |
| Cu | 20 | 7.6 | 0.24 |
| Graphite | 430 | 600 | 19 |

*Table 2:* Tolerable limits during one bunch train passage due to cyclic mechanical stress in the window

$\Delta T_{inst}$ is taken from equation 1, except not restricting to a particular beam profile like the round gaussian beam type, where $(dN/dA)_{max} = N_t / (2\pi\sigma^2)$. For a bunch train with $N_t = 7.2 \cdot 10^{13}$ particles, a round gaussian beam requires a rms width of $\sigma \geq 0.8mm$ in the case of graphite (1.6 mm for titanium), in order to keep the cyclic stress of the window below the tolerable limit. It has to be kept in mind, that these numbers are based on $10^7$ to $10^8$ cycles and do not include any safety margin.

**Effects of average heating**

Now the second term in equation 1 describing average temperature rise is considered. A round gaussian beam profile with $\sigma$ = 1 mm and $I_{ave}$ = 64 µA, penetrates through an edge cooled membrane window with radius b = 50 mm. For this case table 3 lists the equilibrium temperature rise $\Delta T_{eq}$, which builts up between the center of the window at $r = 0$ and the heat sink at $r = b$. This figure scales linearly with $I_{ave}$ and has only a

| | Be | Be + Al | Ti | Al | Stainless Steel | Mg | Cu | Graphite |
|---|---|---|---|---|---|---|---|---|
| $\Delta T_{eq}$ [K] | 85 | 85 | 2900 | 120 | 3780 | 80 | 160 | 135 |

*Table 3:* Max. equilibrium temperature rise $\Delta T_{eq}$ in an edge cooled membrane window, window radius b=50mm, beam size $\sigma$=1mm, beam current $I_{ave}$=64µA

weak logarithmic dependence on b/$\sigma$. Therefore $\Delta T_{eq}$ is increased by 20% only, when b/$\sigma$ is doubled.

**Discussion on material selection**

According to table 2 and table 3, graphite shows the best thermomechanical properties, but a window made from it would have bad vacuum abilities. Therefore a metallic membrane is required to fulfill vacuum tightness. Titanium exhibits the best mechanical properties, but the thermal conductivity is a factor 30 to 40 lower than that of copper. In order to use titanium or titanium alloy for such a membrane a more effective cooling over its whole surface area rather than edge cooling at the circumference is necessary. A feasible solution could be a double wall titanium window, where the intermediate volume and thus the inner surface of each wall is cooled by a continuous flow of gas [1]. Even better cooling of the titanium membrane is achieved when it has contact to a heat sink at both sides. The heat sink material should have a low mass density to minimize induced beam loss and needs good thermomechanical properties.

That is why a sandwich like window is favoured, where a thin titanium alloy membrane is embedded by graphite disks from either sides. On the one hand these disks serve as a mechanical reinforcement of the thin window, to give the window its strength against the static pressure. On the other hand heat created in the Ti-membrane will be removed directly from its surface into the graphite instead of travelling radially through the titanium towards the circumferencial water cooling. For its 5 to 10 times better specific thermal conductivity and the bigger cross section, the thermal resistance for heat transport path through the graphite disks is much smaller and therefore reduces the equilibrium temperature level of the Ti-membrane a lot. The following section discusses the thermal and mechanical behaviour of such a composite sandwich-like C-Ti-C window concept in more detail.

## Temperature and Mechanical Stress Distributions in the C-Ti-C Window

Temperature and mechanical stress distributions in a composite graphite-titanium window have been calculated with a finite element method using the program code ANSYS [3]. In a first approach the design of a beam exit window will be investigated. Figure 1 schematically shows the geometry of two variants, which where used as an input for ANSYS calculations. In geometry A the 0.5 mm thick Ti-membrane is embedded between planar graphite disks with a constant thickness of 45 mm each. Therefore its total thickness of 90 mm is not small anymore compared to the radiation length $X_0 \approx 200$ mm of graphite. In geometry B a spherical surface is introduced at one side of each graphite disk. Without significant loss of the mechanical strength the

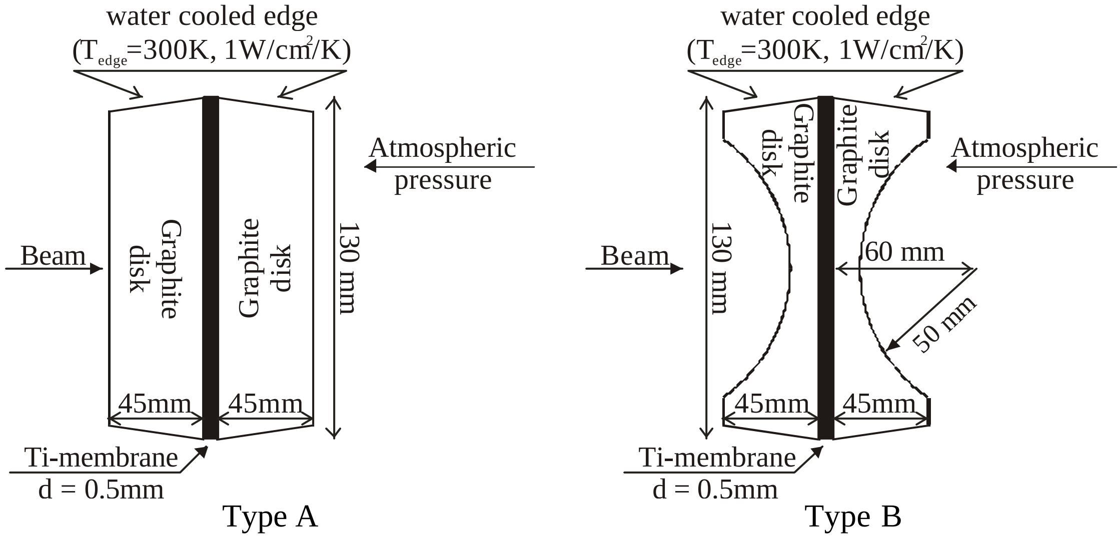



*Figure 1:* Exit window geometries in r-z cross section, as used for ANSYS calculations

graphite thickness is reduced in the area, where the main fraction of the beam penetrates.

The size of the window with a useful diameter of about 100 mm was chosen to fulfill the abort line aperture requirements at TTF II. Presently the TTF I abort line is equipped with a non composite 1 mm thick Cu-alloy membrane window, which is less resistant against small spot sizes. Therefore the composite window scheme should be installed at the future TTF phase II, where in addition operational experience can be derived for such a window. Special interest has to be paid to the thermal contact at the Ti-C boundary. For improvement gold plating of the titanium membrane is foreseen. When pressing the C-Ti-C sandwich together the soft layer of gold is assumed to "flow", thus filling microgaps and improving the thermal contact.

Concentrating on a TTF exit window design, the following ANSYS calculations were performed using TTF parameters, i.e. $N_t = 4 \cdot 10^{13}$ and $\nu = 10\text{Hz}$. A round gaussian beam profile with $\sigma = 1\text{mm}$ is assumed. This beam hits the axis of a window with geometry A or B either with or without a gold plated titanium membrane. Since the actual thermal contact at the Ti-C boundary is unknown, an ideal one was assumed for all cases in the calculations.

**Temperature distribution**

The calculations show that steady state is reached after 1500 beam pulses (bunch trains), i.e. after 150 s of accelerator run. At steady state the maximum temperature in the Ti-membrane at the moments right after a bunch train passage and just before the arrival of the next one are given in table 4 for different situations in terms of graphite geometry and gold coating. The longitudinal temperature distribution along the beam axis in a B-type window right after a bunch train passage is shown in figure 2 (without Au coating) respectively figure 3 (with 20 µm Au coating). The maximum temperature in graphite at the positions, where the beam enters or exits the window does not exceed 450 to 500 K, which is 150° to 200°C. ANSYS plots of the overall r-z temperature distribution in the B-type window are shown in appendix 1.

Longitudinal thermal diffusion within the thickness d = 0.5 mm of the Ti-membrane typically lasts about $T = c\rho d^2 / (2\lambda) \approx 30\mathrm{ms}$. This is much less than the bunch train

| | Maximum temperature [K] | |
|---|---|---|
| Considered case in terms of:<br>• graphite geometry<br>• Au coating | right after passage of bunch train | just before arrival of bunch train |
| Type A without Au coating | 801 | 508 |
| Type B without Au coating | 758 | 453 |
| Type B with 20µm Au coating | 765 | 455 |
| Type B with 40µm Au coating | 862 | 457 |
| Type A without Au coating<br>$\sigma$ = 3mm | 481 | 434 |

*Table 4:* Maximum temperatures in the Ti-membrane,
$N_t = 4 \cdot 10^{13}$, $\nu = 10\mathrm{Hz}$, $\sigma = 1\mathrm{mm}$

repetition period of $1/\nu = 100\mathrm{ms}$. Thus temperatures in titanium and graphite have equalized before arrival of the next bunch train. Off beam axis at $r \geq 3\sigma$ temperature fields are purely determined by the thermal properties of graphite.

**Mechanical stresses**

Following the cyclic thermal load, mechanical stress in the window is as well a superposition of a pulsed and an average contribution. Similar to temperature distributions, mechanical stress reaches its steady state after passage of 1500 bunch trains, which is 150 s of accelerator operation. After that time stresses in the material will regularly cycle between a minimum and a maximum value. These values are given in table 5 for different positions along the beam axis. Positive values give the tension stress, while negative numbers indicate compression of the material.

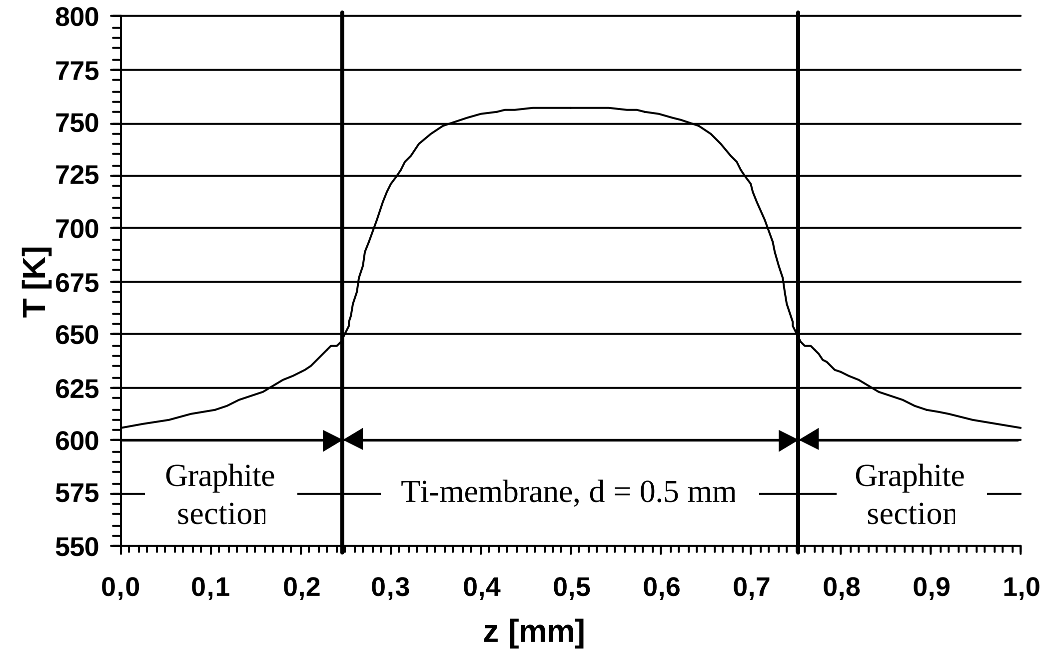



*Figure 2:* Temperature distribution right after bunch train passage along the beam axis in the region of the uncoated Ti-membrane

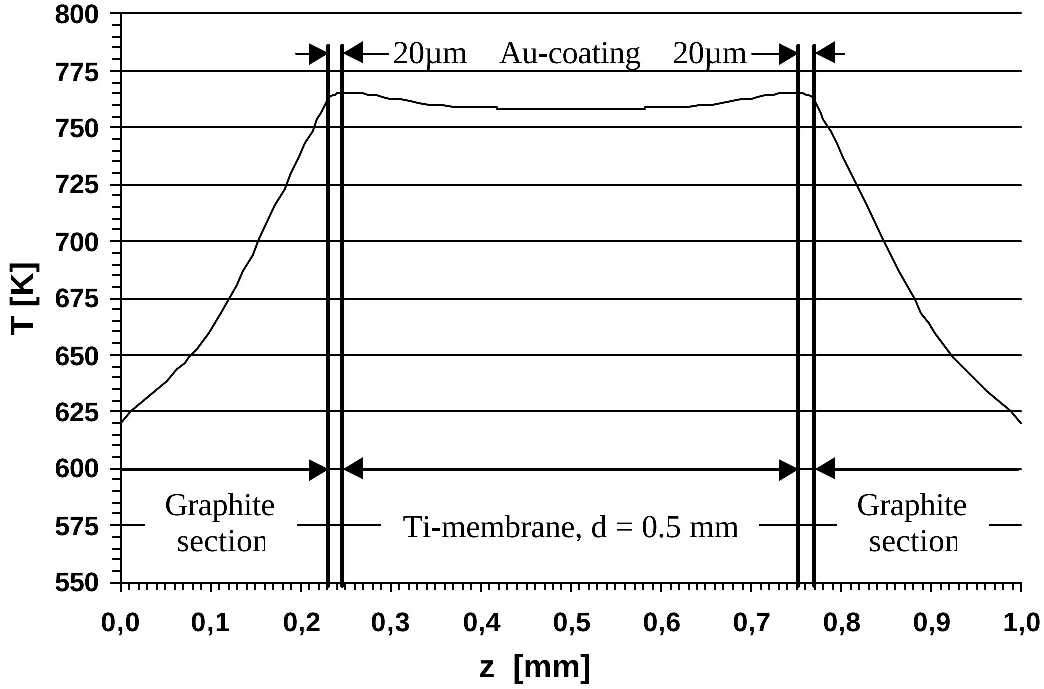



*Figure 3:* Temperature distribution right after bunch train passage along the beam axis in the region of the Ti-membrane coated with 20mm of gold

| Material | Location of interest wrt. stress values | Equivalent stress [MPa] | |
|---|---|---|---|
| | | minimum | maximum |
| Graphite disks | On the beam axis near the Ti-membrane | -17.7 | -6.3 |
| | On the beam axis near position of beam entering or exiting the window | -2.6 | 8.2 |
| Ti-membrane | On the beam axis | 72 | 246 |

*Table 5:* Minimum and maximum mechanical stress values at different location in the window

Maximum compression in the graphite of 17.7 MPa takes place near the Ti-membrane due to its expansion. Tension stress in the graphite is experienced only at the free surface, which is exposed to vacuum or atmosphere. Here tension stress does not exceed 8.2 MPa.

Much higher stress is observed in the Ti-membrane. In the region of maximum load the amplitude of the stress is ±87 MPa, cycling around an average level of 159 MPa.

Nevertheless the calculated equivalent stress in graphite and titanium is far below their endurance limit $\sigma_u$ as listed in table 1. The peripheral parts of the composite window experience static load only. Therefore such a composite window will operate with a certain safety margin at the given TTF parameters.

## Exit and Entrance Window Concept for the Water Dumps at TESLA

The concept of the exit / entrance window assembly for the water beam dump is shown in figure 4. The beam leaves the vacuum system through the exit window and passes an intermediate vacuum volume, before entering the water absorber through a separate entrance window. A failure of either of those windows will be detected due to pressure change in the intermediate volume. Thus safety against dump water leaking

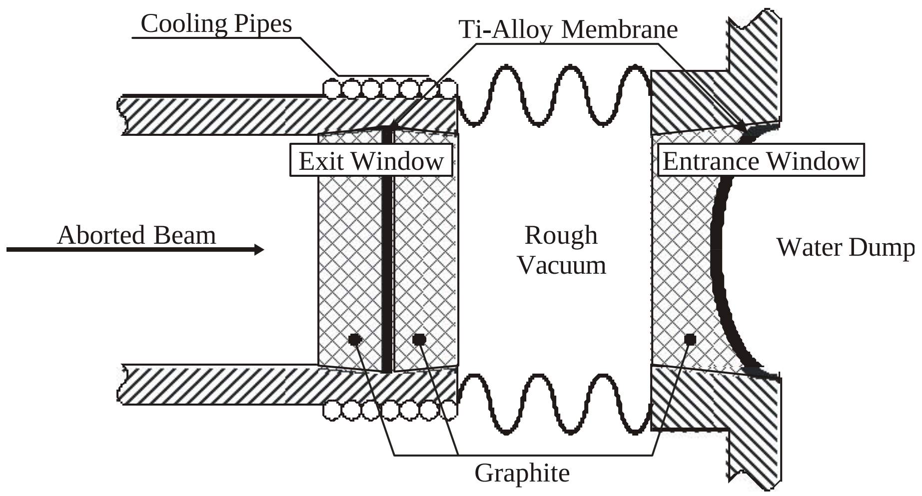



*Figure 4:* Concept of (vacuum) exit and (water dump) entrance window

through the entrance window into the vacuum system or into the environment is achieved.

The entrance window is equipped with a graphite reinforcement and cooling disk on one side only. The other side is directly cooled by dump water. Average heating concerning the entrance window is therefore much more relaxed than for the exit window.

One has to keep in mind, that the size of the window as discussed in the previous section with a diameter of around 100 mm will be not sufficient for the main linac abort system of the TESLA collider. To reduce instantaneous heating of the water absorber, fast circular beam sweeping within the bunch train passage time is applied [4]. Since fast sweep radii in the order of R = 50 mm are necessary, it is obvious, that bigger windows have to be investigated for that application. But of course fast sweeping also reduces instantaneous heating of the window and related cyclic stresses as well. This will surely help the design of a bigger window. The quantitative reduction of instantaneous heating and cyclic stress in the window due to fast beam sweeping is discussed in the next section.

**Effect on windows due to fast beam sweeping**

According to equation 2 instantaneous heating at the window only depends on the incident particle density dN/dA. Assume a round gaussian beam profile with a rms width $\sigma$. If this beam is not sweeped (R=0), the maximum particle density hitting the window normalized by the number of particles is given by equation 3:

$$n_{max}(R=0) = \frac{1}{N_t} \cdot \left(\frac{dN}{dA}\right)_{max} = \frac{1}{2\pi\sigma^2} \qquad \underline{\textit{Equation 3}}$$

If the same beam is sweeped along a circular line with radius R across the window, the normalized particle density $n(R)$ has to be calculated by adding a vector of length R with a random azimuthal direction $0 \le \varphi \le 2\pi$ to each particle position of the gaussian distribution. Therefore its maximum value $n_{max}(R)$ can be written as:

$$\begin{aligned} n_{max}(R) &= \frac{1}{2\pi\sigma^2} \cdot \mathrm{Max}\left\{ \frac{1}{2\pi} \int_{\varphi=0}^{2\pi} \exp\left[-\left(r^2 - 2rR\cos(\varphi) + R^2\right) / \left(2\sigma^2\right)\right] d\varphi \right\} \\ &= \frac{1}{2\pi} \cdot \frac{1}{R\sigma} \cdot f\left(\frac{R}{\sigma}\right) \end{aligned}$$

Where the non dimensional function $f\left(\frac{R}{\sigma}\right)$ is given by:

$$\begin{aligned} f\left(\frac{R}{\sigma}\right) &= \frac{R}{\sigma} \cdot \mathrm{Max}\left\{ \frac{1}{\pi} \int_{\varphi=0}^{\pi} \exp\left[-\left(r^2 - 2rR\cos(\varphi) + R^2\right) / \left(2\sigma^2\right)\right] d\varphi \right\} \\ &= \frac{R}{\sigma} \cdot \mathrm{Max}\left\{ \exp\left[-\left(r^2 + R^2\right) / \left(2\sigma^2\right)\right] \cdot I_0\left(rR/\sigma^2\right) \right\} \end{aligned}$$

where $I_0$ is the zeroth order modified Bessel function

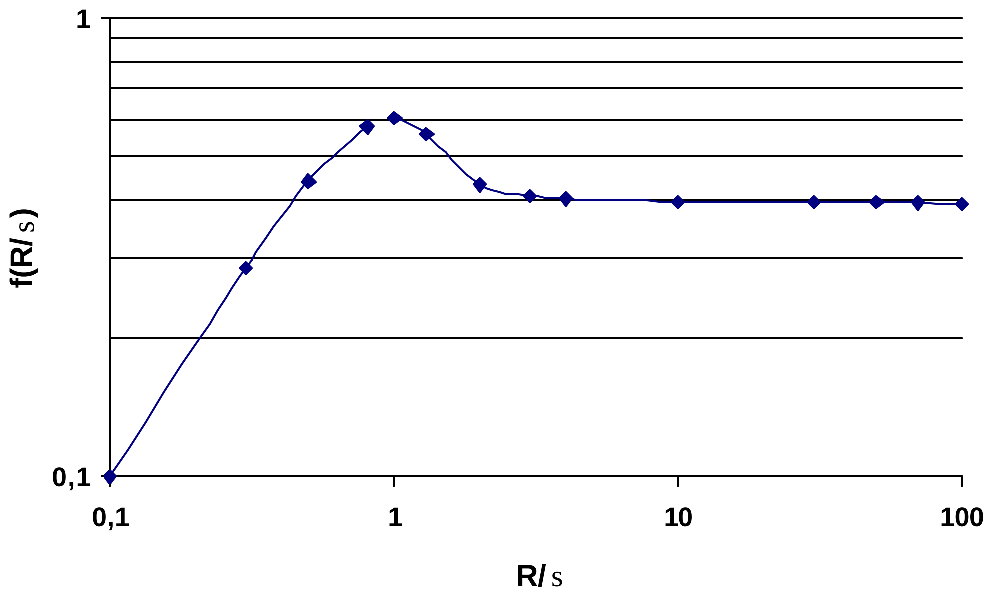



*Figure 5:* Non dimensional function $f(R/\sigma)$ plotted versus $R/\sigma$

This function $f(R/\sigma)$ can be integrated numerically. The result is shown in figure 5. It is obvious, that sweeping has a considerable effect only, if the sweep radius R is large compared to the beam size σ. Thus the following approximations can be made:

$$\text{for } rR/\sigma^2 >> 1: \qquad I_0\left(rR/\sigma^2\right) \approx \frac{\sigma \cdot \exp\left(rR/\sigma^2\right)}{\sqrt{2\pi \cdot rR}}$$

and

$$\text{for } R/\sigma >> 1: \qquad f\left(\frac{R}{\sigma}\right) \approx \frac{1}{\sqrt{2\pi}}$$

Therefore, if $R/\sigma >> 1$, the maximum normalized particle density $n_{max}(R)$ for a round gaussian beam profile, that is sweeped along a circular line with radius R is given by equation 4:

$$n_{max}(R >> \sigma) \approx \frac{1}{2\pi \cdot \sqrt{2\pi} \cdot R \cdot \sigma} \qquad \underline{\textit{Equation 4}}$$

Comparing $n_{max}$ for the sweeped and the unsweeped case, a reduction factor K can defined by equation 5. It describes the reduction of instantaneous heating and mechanical stress, when fast beam sweeping is applied as a function of beam size σ and sweep radius R.

$$K = \frac{n_{max}(R=0)}{n_{max}(R \neq 0)} = \frac{R}{\sigma} \cdot \frac{1}{f(R/\sigma)} \approx \begin{cases} 1 & \text{for } R << \sigma \\ \sqrt{2\pi} \cdot \dfrac{R}{\sigma} & \text{for } R \geq 2\sigma \end{cases} \qquad \underline{\textit{Equation 5}}$$

Equation 5 shows, that circular beam sweeping with a radius of $R = 10\text{mm}$ decreases instantaneous heating and corresponding mechanical stresses, caused by a round gaussian beam with $\sigma = 1\text{mm}$, by a factor of 25!

## Conclusion

It has been shown, that a window design based on a sandwich like C-Ti-C structure allows to avoid extreme stresses in the metallic membrane material. A safe operation of an exit window with a diameter of around 100 mm could be achieved for TTF parameters in combination with rms beam sizes of about 1 mm at the window.

Fast beam sweeping with radius R as required for the beam abort systems of the TESLA main linac significantly reduces instantaneous heating and cyclic mechanical stress in the window. This effect scales as $R/\sigma$ if the sweep radius is large compared to the beam size. As a consequence the design of windows with larger diameter is simplified.

## References


[1] M. Seidel, An Exit Window for the TESLA Test Facility, DESY August 1995, TESLA 95-18

[2] Handbook of the physical value, Atomizdat, Moscow (1991)

[3] ANSYS, User Manual, Awenson Analysis Systems Inc. (1983)

[4] V. Sytchev at al., Concept of the Fast Beam Sweeping for the $e^{\pm}$ Beam Dumps of TESLA, DESY February 2001, TESLA-Report 2001-05

## Appendix 1.: Temperature distributions in the window

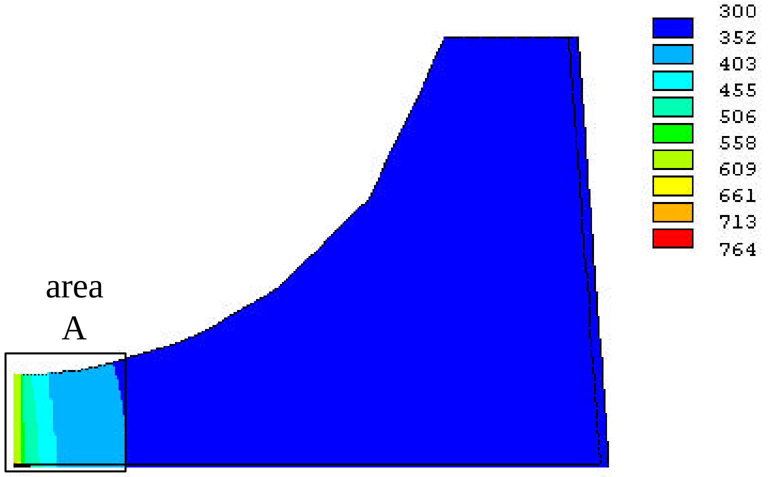



*Figure A1-1:* Temperature [K] distribution right after bunch train passage

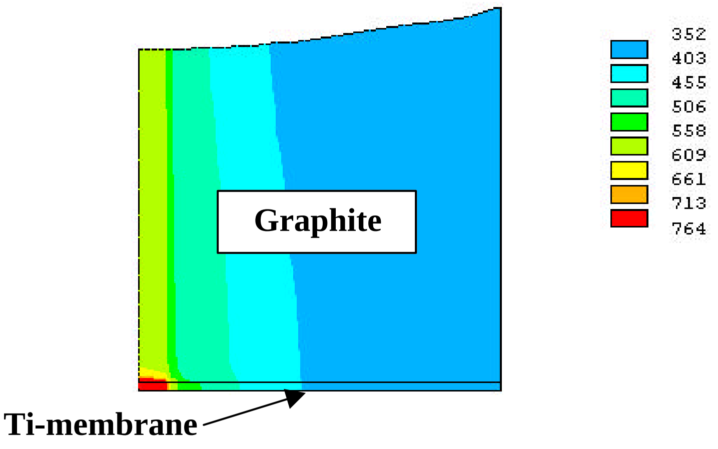



*Figure A1-1a:* Temperature [K] distribution in area A right after bunch train passage

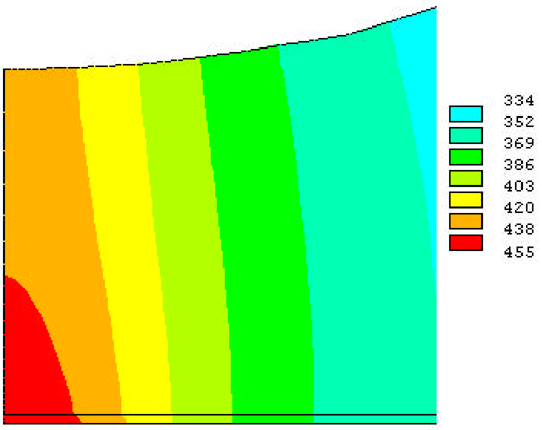
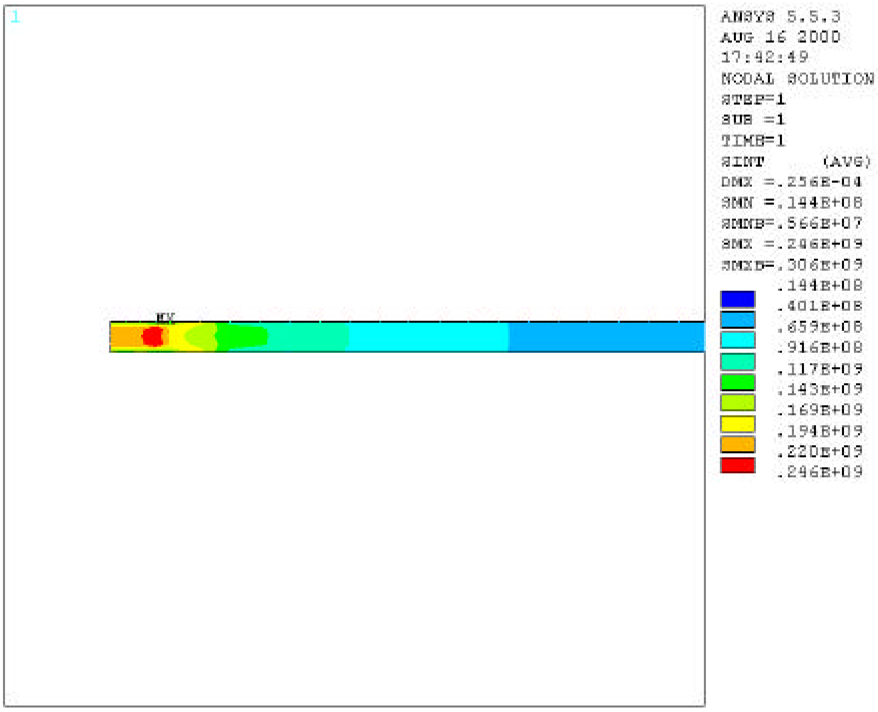
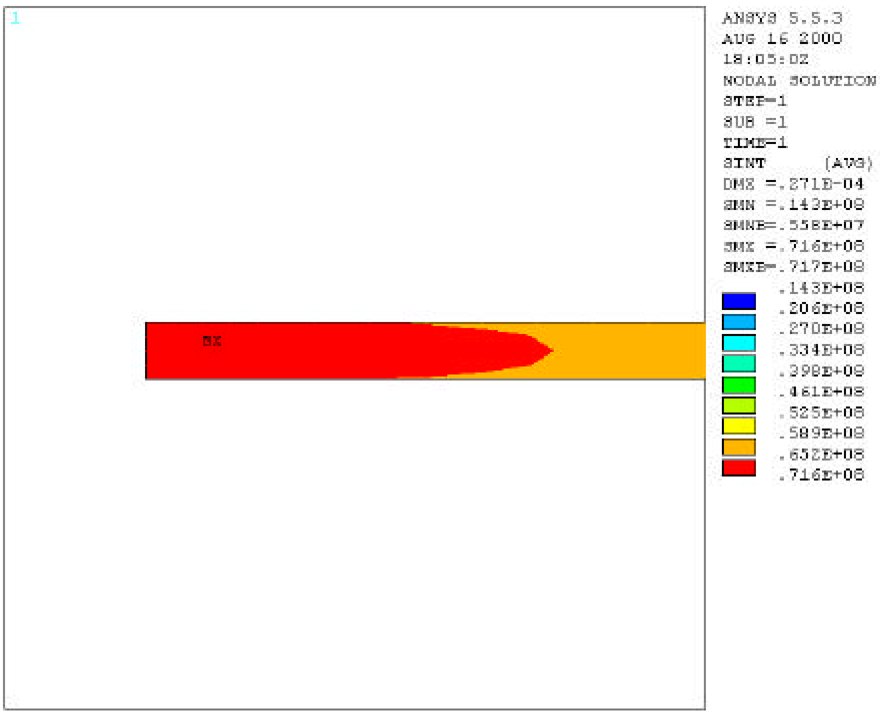



*Figure A1-1b:* Temperature [K] distribution in area A just before bunch train arrival

## <u>Appendix 2.</u>: Mechanical stress distributions in the titanium membrane




*<u>Figure A2-1:</u>* Equivalent stress [Pa] distribution in the Ti-membrane right after the passage of a bunch train.




*<u>Figure A2-2:</u>* Equivalent stress [Pa] distribution in the hot area (r ≤ 10 mm) of the Ti-membrane just before the arrival of a bunch train.