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Thermo-stress analysis of actively cooled diagnostic windows for quasi-continuous operation of the W7-X stellarator

O.V. Ogorodnikova [a,*], R. König [b], A. Pospieszczyk [a], B. Schweer [a], J. Linke [a]

[a] Forschungszentrum Jülich GmbH, EURATOM-Association, D-52425 Jülich, Germany
[b] Max-Planck-Institut für Plasmaphysik, Greifswald, EURATOM-Association, D-17491 Greifswald, Germany

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Abstract

Finite element method calculations have been performed in order to develop and demonstrate the design of actively cooled windows for the W7-X stellarator which are adequate for diagnostics in the UV, VIS and IR spectral regions at quasi-stationary thermal loads of 50 kW m^{-2}, mainly originating from short-wavelength radiation. The results have shown that sapphire which is suitable for the spectral range from 150 nm to 4.5 μm is the only material for large window diameters (about 13 cm) which could cope with the expected maximum power loads for W7-X of 50 kW m^{-2} for more than 20 min. Other materials like fused silica, MgF_2, ZnSe and ZnS can only be used for smaller diameter windows (<5 cm) or lower thermal loads. CaF_2 and BaF_2 are unacceptable as W7-X window materials because of strong in-plane distortions during long pulses. The investigations show in which operating regimes the different materials are suitable with regard to pulse duration and power load for windows of different diameters and thicknesses.

1. Introduction

In fusion devices like tokamaks or stellarators, the development of materials which are exposed to thermal loads is necessary not only for the first wall and the divertor but also for vacuum windows to get diagnostic access to the plasma in the UV, visible and IR spectral regions.

Depending on the type of fusion experiment and the window location, the value and the duration of the heat flux on the windows span a wide range. For example, the plasma pulse duration is less than 10 s in TEXTOR [1] while it is 1000 s in Tore Supra [2,3]. A heating power of 10 MW [4] in W7-X for pulse durations of up to 30 min will be available. A large fraction of this power will be lost as energetic particles and directed towards specially designed divertor target plates which can handle power loads of up to 10 MW m^{-2}. Only a fraction of the power will be lost in the form of radiation and an even smaller part as energetic neutral particles (following charge exchange reactions) leading to an expected quasi-continuous power load of about 50

* Corresponding author. Tel.: +49 2461 61 4683; fax: +49 2461 61 3699.
E-mail address: o.ogorodnikova@fz-juelich.de (O.V. Ogorodnikova).

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$kW\,m^{-2}$ on large parts of the main vessel components and therefore also on the diagnostic windows [5,6]. Such heat loads on plasma-facing components of spectroscopic observation systems are the subject of major design challenges. The radiation emitted by the plasma is absorbed directly at the surface of any plasma-facing material due to its predominantly short wavelength (less than 6 nm) [7].

Every material has an upper limit for the operating temperature above which it cannot be used. The temperature limit is defined by its loss of strength or optical transmission resulting from physical or chemical changes. A material might be usable at a certain power load for short pulse durations but not usable for a longer period at the same load. In general, to prevent disturbances of any measurements, the window temperature should usually be less than 600 °C, while considerably lower temperatures are required for IR measurements. In addition, the windows should be able to survive at extremely high thermal stresses without any damage. Consequently, to protect the diagnostic system from heat and particle loads the window materials should comply with the following common criteria: (i) They should not intensively radiate (temperature limit less than 600 °C). (ii) Their temperature should remain sufficiently low to prevent decomposition. (iii) They should not show any cracks.

The material choices are strongly driven by the optical properties of the materials in different wavelength ranges (e.g., the transmittance). For spectroscopic measurements, the optical material for the visible and near infrared range should have a transmissivity of >90%. Materials which satisfy this condition are shown in Table 1. Suitable window materials are quartz, fused silica, sapphire, MgF_2, BaF_2 and CaF_2 and CVD-diamond while for far infrared measurements ZnSe and ZnS are required.

Although the main aim of this paper is to study ceramic materials for their suitability as windows for W7-X, the general dependence of the material behaviour on the power load and time has been studied in addition. This means that the calculations presented here for the selected optical materials can also be used for other high heat-flux applications to estimate suitable window design parameters.

2. Calculations

2.1. Material parameters

A transient 3D finite element model is used for the prediction of the temperature and stress distributions in different window materials. The thermal model considers a heat transfer mechanism from the high-temperature region to the low-temperature region. The boundary conditions include surface cooling by thermal radiation and convective heat transfer from the hot side of material to flowing cooling water. In the present paper, the commercial code ANSYS was used for heat transport, thermo-hydraulic and thermo-stress calculations. Candidate window materials were quartz, fused silica, sapphire, ZnSe, ZnS, MgF_2, BaF_2 and CaF_2. CVD-diamond is not considered here because of its extremely high cost although it has the best thermal properties. The input parameters for the ANSYS code are the temperature dependent thermal conductivity, the specific heat capacity and the coefficient of linear thermal expansion.

Preference has to be given to materials offering a low linear thermal expansion coefficient, high thermal conductivity and high strength. The material should keep its optical properties unchanged and work without

Table 1
Window material properties [8–10]

Material	Transmission range (μm)	Thermal conductivity at room temperature ($W\,m^{-1}\,K^{-1}$)	Melting temperature (°C)	Stress limit at room temperature (MPa)
Fused SiO_2	0.16–3	1.4 [8]	1715	38.25
Quartz	0.2–3	6.2 [8]	1700	50
CaF_2	0.14–12	8.1 [8]	1418	37
BaF_2	0.15–15	11.7 [9]	1280	26.2
MgF_2 (Irtran 1[a])	0.11–7.5	14.9 [9]	1255	50
MgF_2^{sc} (single crystal)	0.11–7.5	21 [9]	1255	50
ZnSe	0.5–22	18.2 [8,10]	1550	55
ZnS (Irtran 2[a])	0.5–13	15.49 [9]	1827	97.1
ZnS (CVD[b])	0.5–13	17 [9,10]	1827	102.7
Sapphire Al_2O_3	0.17–5.5	46.06 [8]	2050	350–690
Diamond (CVD[b])	0.12–10	1900 [8]	–	1100–2500

[a] Hot pressed polycrystalline windows were formerly sold by the Eastman Kodak Company under the following trade names: Irtran 1 (MgF_2) and Irtran 2 (ZnS).
[b] CVD: chemical vapour deposition.

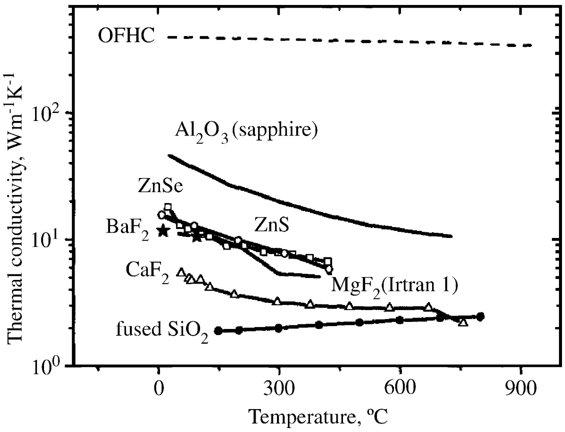

Fig. 1. Thermal conductivity of window materials [8–10]. The data for oxygen free copper (OFHC) are also shown for comparison.

damage in the UV, visible and IR range during long pulses of thermal load. However, no materials exist which comply with all these criteria. Therefore, a system performance compromise has to be made which allows for the optical and thermo-mechanical limitations of available materials.

The temperature dependence of the thermal conductivity of selected materials is shown in Fig. 1. Among the selected materials, sapphire has the highest thermal conductivity [8]. It needs to be noted that the properties of sapphire depend on the cut of the crystal, its form and its surface quality. For magnesium fluoride and sapphire crystals, thermal conductivity values are given in directions parallel to and at right angles to the optical axis. Single-crystal MgF_2 has a high thermal conductivity of 21 W m^{-1} K^{-1} [9]. However, data about the temperature dependence of the thermal conductivity of single-crystal MgF_2 are not available in the literature. For polycrystalline MgF_2 (Irtran 1) the thermal conductivity decreases with temperature. The thermal conductivity of fused silica improves with temperature, while for other materials it decreases with temperature. A comparison of the thermal conductivity of fused silica and single-crystal quartz is shown in Fig. 2. Like other optical materials the thermal conductivity of quartz decreases with temperature. It needs to be noted that the thermal conductivity of quartz depends on the crystal orientation (λ_{xx} is the thermal conductivity parallel to the c axis and λ_{yy} is the thermal conductivity perpendicular to the c axis).

The temperature dependence of the specific heat capacity c_p for the selected window materials is shown in Fig. 3. The specific heat capacities of ZnSe and ZnS are excellent. The specific heat capacity of BaF_2 is close to that of ZnS. Fused silica has a high specific heat coefficient, followed by sapphire and CaF_2. MgF_2 has an even higher heat capacity.

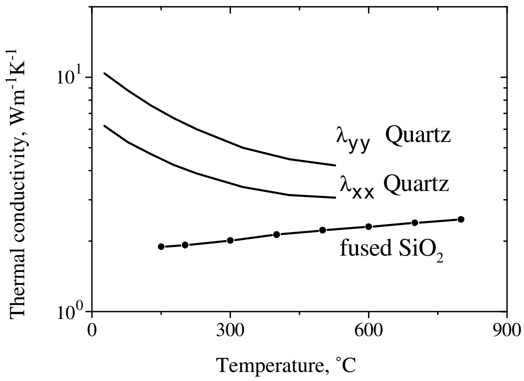

Fig. 2. Comparison of the thermal conductivity of single-crystal quartz and fused silica [8].

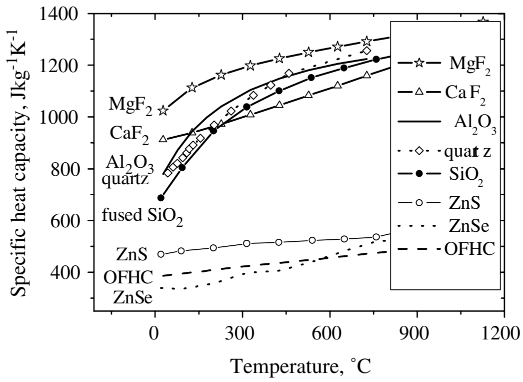

Fig. 3. Specific heat capacity of window materials [8]. The data for oxygen free copper (OFHC) are also shown for comparison.

Most window materials of interest have a thermal expansion coefficient in the range of 5–20 × 10^{-6} K^{-1} at room temperature. From the materials investigated, only fused silica has an exceptionally small thermal expansion coefficient (Fig. 4). Sapphire is followed by fused silica, then ZnSe together with ZnS and, finally, MgF_2. Both CaF_2 and BaF_2 have the highest thermal expansion coefficient, particularly at elevated temperatures, and it increases drastically with increasing temperature.

Due to expected intense heat loads during quasi-continuous operation in W7-X, all windows need to be actively water-cooled. In the present design, the cooling water is flowing along copper tubes attached to the edge of the window plate. There is also a possibility to cool 10 mm of the window loading surface (Fig. 5). The cooling conditions were the following: temperature of cooling water 20 °C, water velocity 10 m s^{-1}, surface roughness 3 μm. FEM calculations show that an increase of the wetted surface near the edge as well as an increase of the water flow velocity from 10 to 15 m s^{-1} has virtually no influence on the radial temperature distribution across

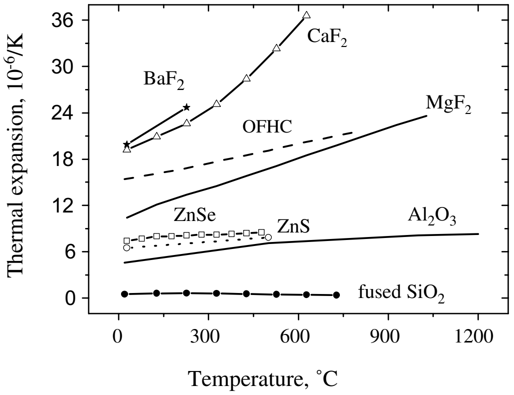

Fig. 4. Coefficient of thermal expansion of window materials [8–10]. The data for oxygen free copper (OFHC) are also shown for comparison.

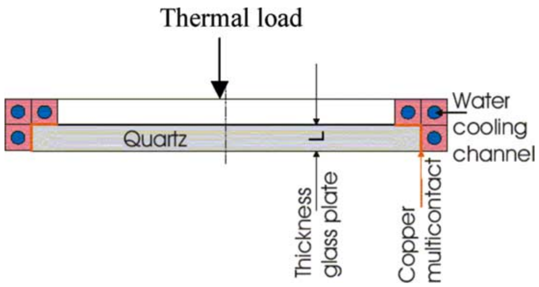

Fig. 5. An example of window design used in ANSYS calculations.

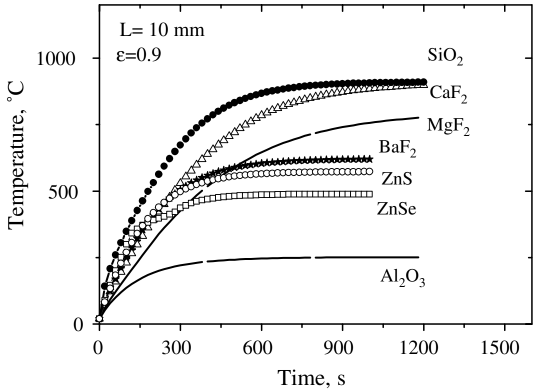

Fig. 6. Time dependence of the maximum temperature of the window materials for a power load of 50 kW m^{-2}. Design parameters are: diameter $D = 170$ mm, thickness $L = 10$ mm. An emissivity of $\varepsilon = 0.9$ is assumed for all materials, except sapphire ($\varepsilon = 0.2$).

large windows. A window with a diameter of $D =$ 170 mm and a thickness of $L = 10$ mm as main reference case has been studied in detail. Instead of the direct contact of the water with the window material a set of three cooling tubes of 1 mm inner diameter has been used for the modelling. The material assumed for the cooling water tubes was oxygen free copper (OFHC). OFHC copper is a compliant material with low yield stress and high thermal conductivity which reduces thermal gradient and stresses in a ceramic window. Its thermo-mechanical data are shown in Figs. 1–4 in comparison with the optical materials.

For comparison, a design of the water cooled window consisting of a Helicoflex seal on either side of the window surfaces and with the window substrate sticking out into the coolant is also considered. In this case, hygroscopic materials such as fluorides (CaF_2, MgF_2 and BaF_2) cannot be used.

2.2. Thermal analysis

The time evolution of the peak temperature for windows of different optical materials is shown in Fig. 6. After 5–15 min the temperature reaches a steady state.

Due to the higher thermal conductivity of sapphire, the energy diffuses more rapidly towards the cooled edge of the window than in the case of the other materials. Thus, Al_2O_3 reaches thermal equilibrium faster than any of the other materials. In the investigated case, Al_2O_3 reaches a steady-state temperature already after about 5 min while it takes about 10–15 min for SiO_2. The maximum temperature in the centre of the loading surface of a sapphire window is $T = 268$ °C which from the design point of view is an acceptable value.

Using the thermal conductivity for Irtran 1 from [9], a MgF_2 window would be more suitable than one made from fused silica since the expected maximum temperature that might be reached in a quasi-continuous W7-X discharge would be lower. A single-crystal MgF_2 window looks even more attractive for high heat flux applications because of its high thermal conductivity. However, the poor database in particular for the temperature dependence of physical parameters for single-crystal MgF_2 makes the prediction of the MgF_2 behaviour at high power load impossible. A large BaF_2 window reaches a maximum temperature about 640 °C. Moreover, barium fluoride cleaves easily and it is highly susceptible to thermal load. Another reason not to use BaF_2 is its cost. Unlike CaF_2, BaF_2 is not found in the native state and all material must be synthesised chemically making BaF_2 relatively expensive to produce.

ZnSe and ZnS windows have lower equilibrium temperatures than the other optical materials, except sapphire. Both ZnSe and ZnS are attractive choices for IR protective windows. It should be mentioned that although ZnSe and ZnS are certainly better than silica for the temperature requirements for a diagnostic window, they cannot be applied for the measurements in a major part of the visible range because of their optical properties (see transmission range in Table 1).

Because the temperature and stress evaluation for quartz and fused silica demonstrated that both materials behave very similarly, only one material, fused SiO_2, is considered below.

The emissivity of quartz ranges from 0.7 to 0.92 depending on the surface state (roughness, contamination, etc.). The emissivity of CaF_2, MgF_2, BaF_2 and ZnSe and ZnS was assumed to be $\varepsilon = 0.9$. It should be mentioned that the results of the calculations do not significantly differ for emissivities between 0.7 and 0.9.

Fig. 7 shows the dependence of the equilibrium temperature of a window on its thickness. For the sapphire window the temperature reduces considerably with increasing thickness as $\simeq L^{-1.4}$. In the cases of SiO_2, CaF_2 and MgF_2 ($\varepsilon = 0.9$), the temperature becomes nearly independent of the thickness for the large diameter. However, for the small diameter window the heat reaches the cooling edge faster and the cooling is more effective in the reduction of the window temperature. In this case, the reduction of the sample thickness influences the window temperature by increase of the maximum temperature even for low thermal conductivity materials such as quartz and fluorides. FEM calculations show that the temperature decreases with the thickness approximately as $\simeq L^{-0.5}$ for small diameter samples of quartz and fluorides.

In the case of a large quartz window, the temperature falls from the plasma-facing surface to the rear side of the window by about 10% while for sapphire this temperature gradient is very small (Fig. 7). The steady-state temperature distribution of quartz is strongly influenced by its radiation emission and saturates at 50 kW m^{-2} close to 900 °C, while the radiation effect is still negligible for sapphire due to its low temperature. Since the emission of light from the window itself can exceed the signal being observed, the temperature of a window should be less than 600 °C. In the case of IR monitoring of the temperature of in-vessel components of course even much lower temperatures need to be reached. Under the given constraints quartz windows may only be used up to fairly small diameters of $D < 50$ mm, as the peak temperature dependence on window diameter in Fig. 8 shows. Sapphire, on the other hand, seems to be a suitable material even for the largest windows presently envisaged for W7-X with a diameter of $D \simeq$ 150 mm, e.g., for the CXRS diagnostic. The maximum temperature can technically still be safely handled.

It seems that even for the largest windows the usage of expensive CVD diamond windows can be avoided. In order to find out whether a sapphire window can survive the highest expected heat loads in W7-X without any cracks or other damages the stress distribution in the different window materials has also been investigated (Section 2.3).

The calculations so far have been performed for a maximum power load of 50 kW m^{-2}. For lower power densities the use of other optical materials is also possible (Fig. 9). As one can see from Fig. 9, sapphire is the best material for both high and low heat loads. However, for power densities less than 20 kW m^{-2} fused silica and fluorides like BaF_2, CaF_2 and MgF_2 can also be candidates for window materials from the temperature limit point of view. ZnSe and ZnS are also good candidates for large IR protective windows for power loads less than 20 kW m^{-2}. However, even for a sapphire window its diameter should be reduced or the thickness significantly increased for power loads higher than 100 kW m^{-2} in order to satisfy the temperature limit of $T < 600$ °C.

For extremely high power loads like 400 kW m^{-2} which might occur future in fusion devices such as

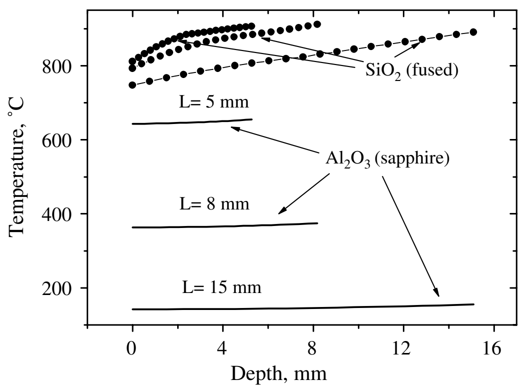

Fig. 7. Temperature distribution within the window materials at steady state for 50 kW m^{-2}. Design parameters are: diameter $D = 170$ mm, thickness, L, varied.

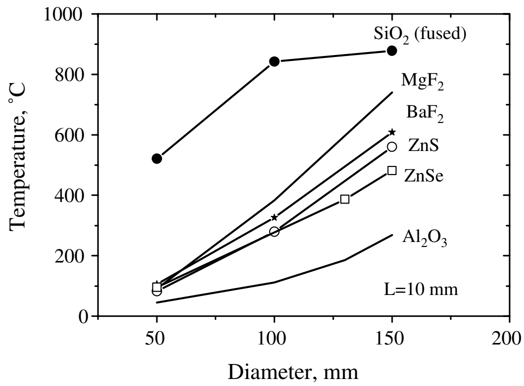

Fig. 8. Loading diameter dependence of the maximum temperature of window materials at steady state for a power load of 50 kW m^{-2}. Design parameters are: diameter varied, thickness $L = 10$ mm.

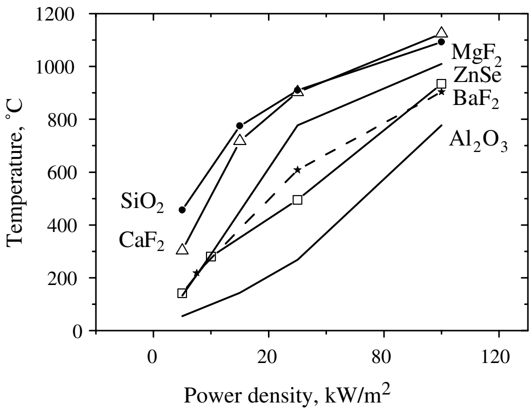

Fig. 9. Maximum temperature of the window materials as a function of power density for 20 min pulse duration. Design parameters are: diameter $D = 170$ mm, thickness $L = 10$ mm.

ITER, smaller windows have to be used. Calculations of the peak temperature depending on the window parameters, thickness L and diameter D, for a surface heat load of 400 kW m^{-2} are shown in Fig. 10. A sapphire window of $D = 50$ mm and $L = 10$ mm would still be suitable. However, these estimations do not take into account any volumetric heat sources such as neutrons and gamma radiation. To predict the behaviour of protective windows in next step fusion reactors, such as ITER and DEMO, the knowledge of the degradation of thermomechanical properties of optical materials due to neutron irradiation is necessary. The expected high heat loads and neutron fluxes, however, will not allow to use any windows adjacent to the plasma. The first elements can only be cooled metal mirrors.

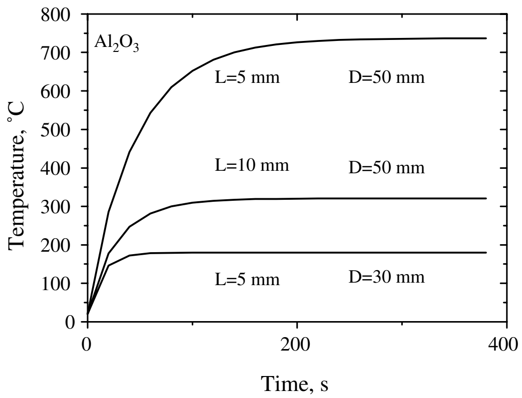

Fig. 10. Temporal evolution of the maximum temperature of a sapphire window at a power load of 400 kW m^{-2} which is expected for ITER. Design parameters are: diameter varied, thickness varied. Assumptions: (i) 400 kW m^{-2} power load is absorbed on the window surface (X-ray radiation) and (ii) volumetric loads such as neutrons and gamma radiation have not been taken into account.

2.3. Stress analysis

The protective transparent window must be able to survive high thermal stresses in order to prevent catastrophic failure. To avoid plastic deformation of the window, which could cause remarkable optical distortion, the strength should be at least less than the 'flexural apparent elastic limit'. The failure stress according to the Weibull statistic, i.e., stress where the probability of material failure is close to unity, or simply the 'stress limit' is given in Table 1. However, the materials' strength is only known as approximate value. It varies with the quality of surface defects, fabrication method, material purity, grain size or microstructure, type of the test and size of the sample. This means that in practice only a fraction (often 50–99%) of the intrinsic material strength is achieved in an industrially manufactured window unless surface defects can be eliminated. The presence of small cracks can significantly change the apparent failure strength. The strength is temperature dependent [11,12]. The rupture modulus for most optical materials of interest is reported in the literature only at room temperature. There are very few data available at elevated temperature. However, when one is designing systems which are supposed to operate reliably at elevated temperatures, one needs to make sensible judgments with respect to a possible temperature dependence of the strength.

The temperature distribution in the numerical calculations, is calculated as a function of time and then these results are used in the structural finite element (FE) model to determine the corresponding thermal distortions. The magnitude and direction of the distortion vectors are strongly dependent on the absorbed power, the total loading time and the thermal and mechanical boundary conditions. All calculations have been done for a design with the window sticking out directly into the cooling water, except for fluoride materials, for which a design with water flowing through Cu tubes is used (see Fig. 5). The calculations have been done for damped windows.

The 3D thermal analysis has shown that the thermal stresses were predominantly due to radial temperature variations. The magnitude of the temperature gradient depends on the thickness and the conductivity of the material. The calculations revealed that the edge of the window is in tension and that the centre is in compression. The highest thermally induced stresses are compressive. However, for ceramics, the compressive strengths are much higher than the tensile strengths. In most cases, the fracture initiation of the window will be due to tensile stress in the periphery of the window, namely, along the interface of window and cooling water.

For largest expected heat loads in W7-X, the maximum principal stresses within optical materials as a

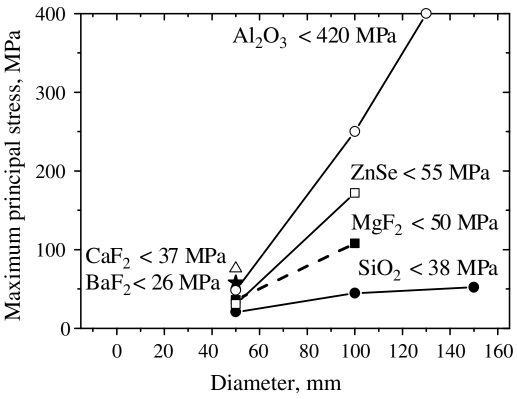

Fig. 11. Maximum principal stress for actively cooled window materials caused by a heat flux of 50 kW m^{-2} at steady state as a function of diameter. Design parameters are: diameter varied, thickness $L = 10$ mm. The values in the figure indicate the stress at which the probability of material failure is close to unity.

function of window diameter and thickness are shown in Figs. 11 and 12, respectively. The values on the figure indicate the failure stress according to the Weibull statistic. The simplest brittle fracture criterion states that fracture is initiated when the highest tensile principal stress in the material reaches a stress limit. A comparison with the stress limits shown in Table 1 indicates that small size windows made of ZnSe, ZnS and SiO_2 are not seriously affected by thermo-stresses. The fairly high thermal expansion coefficients of CaF_2 and BaF_2, however, cause in-plane distortions which are 6 times higher than for SiO_2. The thermo-mechanical characteristics of calcium and barium fluorides make these materials poor candidates for windows on W7-X. The thermo-stresses within MgF_2 are also close to the stress limit. Sapphire has very promising characteristics which make it a suitable candidate even for window diameters up to $D = 140$ mm. The failure probability for sapphire is close to unity at relatively high strength such as >350 MPa. The thermo-stress within sapphire caused by a heat load of 50 kW m^{-2} during more than 20 min does not exceed the rupture modulus for those windows (Fig. 11). However, due to the very local character of the peak window tensile stresses, such a prediction should be used very carefully. When average stresses are acceptable, these particular local stresses should not result in any damages of the window because these stresses remain very localised [3]. For example, although the maximum principal stress of 172 MPa is exceed the stress limit for ZnSe windows with a diameter of 100 mm, ZnSe windows may survive at 50 kW m^{-2} because the maximum principal stress is very localised at the interface between window and the cooling water and therefore, may not result in a crack in the bulk of the window. Such a prediction needs an experimental verification to find a right failure criterion. Another problem in the calculation of the failure load of the window is the stress evaluation in the bonding joint area. Due to unknowing properties of the bonding joint between the ceramic window and the Cu tube or between the ceramic and a Helicoflex seal, a prediction of the development of the cracks at the edge is too complicated. In the present calculations, the bonding joint has not been simulated. To verify the failure criteria, appropriate qualification tests of window materials are necessary.

Fig. 13 shows the thermally induced maximum principal stress within the optical materials as a function of the central temperature. The stress increases with temperature for most materials. One exception is fused silica

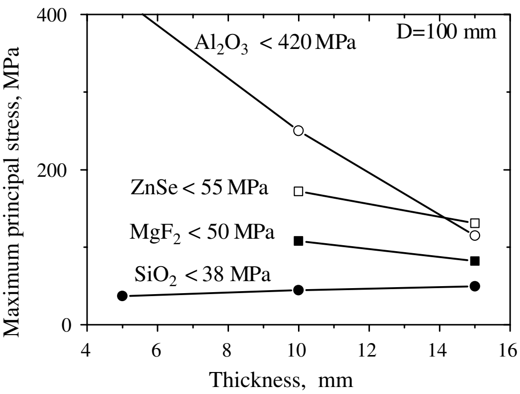

Fig. 12. Maximum principal stress for actively cooled window materials caused by a heat flux of 50 kW m^{-2} at steady state as a function of thickness. Design parameters are: diameter $D = 100$ mm, thickness varied. The values on the figure indicate the stress at which the probability of material failure is close to unity.

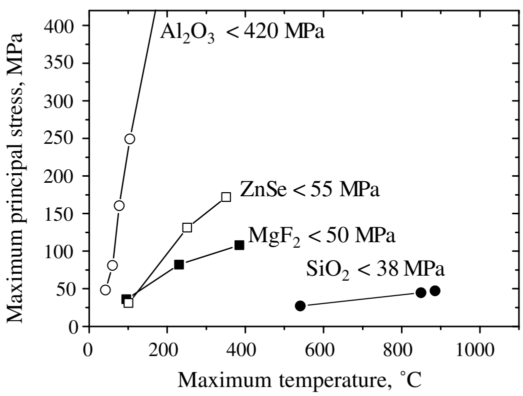

Fig. 13. Maximum principal tensile stress for actively cooled window materials under thermal loads as a function of maximum temperature. The values in the figure indicate the stress at which the probability of material failure is close to unity.

Table 2
Recommended diameters, D, of actively cooled window materials

Material	Transparency	Thermal load		
		100 kW m^{-2}	50 kW m^{-2}	20 kW m^{-2}
Sapphire	UV, visible, IR	$D < 50$ mm	$D < 140$ mm	very large
Fused silica	UV, visible, IR	–	$D < 50$ mm	$D < 100$ mm
MgF_2 (Irtran 1)	UV, visible, IR	–	–	$D < 50$ mm
ZnSe	IR	–	$D < 50$ mm	$D < 150$ mm
ZnS	IR	–	$D < 50$ mm	$D < 150$ mm

which maintains similar stresses over a wide range of temperatures due to strong radiation cooling. However, the temperature of fused silica windows gets quite high for long pulse durations in W7-X. The typical failure strength for a commercial sapphire window is 420 MPa. If a failure strength of 420 MPa is assumed for sapphire, a temperature difference of approximately 200 °C at the water/sapphire interface could result in thermal stress failure. Thus, for an actively cooled sapphire window ideally the central window temperature should be held less than 200 °C to maintain a sufficiently low stress level; for MgF_2 and ZnSe the temperature limit is less than 100 °C. Although MgF_2 has a higher thermal expansion coefficient, the peak tensile stress of MgF_2 is lower than the one of ZnSe. The reason for this is that the cooling design based on Cu tubes was used for fluorides which generally results in less edge stresses (in suggestion of ideal joint) than the design with the window sticking out directly into the cooling water. Table 2 shows the diameter limitation of different actively cooled diagnostic windows under different steady-state thermal loads. It is worth mentioning again that the results of the stress calculations should be used carefully because of uncertainties in the failure criteria, apparent value of the stress limit and discrepancies between an ideal and a real joint type. Moreover, an accurate prediction of the stresses and strains would require modelling of the 'cyclic' stress–strain behaviour with accumulation of plastic strains in addition to the effort of material failure on the thermal load.

3. Conclusions

Present calculations indicate that edge water cooled large quartz, CaF_2, BaF_2 and MgF_2 windows are not suitable as diagnostic window materials at the maximum incident-radiated power of 50 kW m^{-2} for pulse durations of >1000 s. The absorption of a large fraction of the radiated power in a window material for long pulse durations, together with a low thermal conductivity of the window, leads to unacceptably high temperatures and thermal stresses. Among the optical materials studied here only sapphire has thermal conductivities which are large enough to allow for sufficient active cooling during high heat flux loading. Therefore, sapphire is the most promising candidate for fairly large windows. Other investigated optical materials require more complex cooling systems if used as a large window for W7-X. Consequently,

(1) the results indicate that at the expected power levels the usage of extremely expensive CVD diamond windows, which are being used as entrance windows for the ECRH heating system, can be avoided even for large windows with a diameter of $D \approx 130$ mm;
(2) sapphire windows will be suitable for most visible and infrared optical systems which will be installed on W7-X;
(3) large windows made of quartz, MgF_2, CaF_2, BaF_2 and ZnSe and ZnS will often reach unacceptably high surface temperatures. Small diameter windows of 50 mm made from ZnSe or ZnS can probably be applied for far infrared measurements. Polycrystalline MgF_2 windows can be used for diameters up to $D < 100$ mm for powers less than 20 kW m^{-2} or for short plasma exposure. The use of CaF_2 and BaF_2 windows under high thermal heat load conditions is not recommended because of unacceptably high stress levels.

3.1. Further research and development

In order to develop and demonstrate a window designed to operate with visible and IR sensors for long discharge durations and thermal loads of 50 kW m^{-2} from short-wavelength radiation, finite element calculations have been performed. Nevertheless, appropriate qualification tests are needed and are under progress in a heat flux test facility [13] to verify the accuracy of the model calculations and to evaluate the parameters which influence the failure probability. The ability to predict the behaviour of the different window materials from the model calculations might be limited because of lack of data concerning the apparent values of the stress limit at room temperature and stress–strain curves for elevated temperatures for all materials and because of large uncertainties with respect to (i) failure criteria, (ii) joint imperfections, (iii) the contamination of the window materials by continuous implantation of impurities and (iv) characteristic material data for neutron-irradiated materials.

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