PERFORMANCE OF PLASMA-FACING MATERIALS UNDER INTENSE THERMAL LOADS IN TOKAMAKS AND STELLARATORS

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Beside quasi-stationary plasma operation, short transient thermal pulses with deposited energy densities on the order of several tens of MJ/m^2 are a serious concern for next-step devices, in particular, for tokamak devices such as ITER. The most serious of these transient events are plasma disruptions. Here, a considerable fraction of the plasma energy is deposited on a localized surface area in the divertor strike zone region. The timescale of these events is typically on the order of 1 ms. In spite of the fact that a dense cloud of ablation vapor will form above the strike zone, only partial shielding of the divertor armor from incident plasma particles will occur. As a consequence, thermal shock–induced crack formation, vaporization, surface melting, melt layer ejection, and particle emission induced by brittle destruction processes will limit the lifetime of the components. In addition, dust particles (neutron-activated metals or tritium-enriched carbon) are a serious concern from a safety point of view.

Other transient heat loads that occasionally occur in magnetic confinement experiments such as instabilities in the plasma positioning (vertical displacement events) also may cause irreversible damage to plasma-facing components (PFCs), particularly to metals such as beryllium and tungsten. Other serious damage to PFCs is due to intense fluxes of 14-MeV neutrons in D-T burning plasma devices. Integrated neutron fluence of several tens of displacements per atom in future thermonuclear fusion reactors will degrade essential physical properties of the components (e.g., thermal conductivity). Another serious concern is the embrittlement of the heat sink and the plasma-facing materials (PFMs).

To investigate the performance of carbon-based and metallic PFMs under the aforementioned thermal loads, simulation experiments have been performed in highly specialized high-heat-flux test facilities. The neutron-induced degradation of materials and components was investigated on selected test samples that were irradiated in high-flux material test reactors.

KEYWORDS: *plasma-facing components, high-heat-flux testing, carbon-based materials*

I. INTRODUCTION

Plasma facing components (PFCs) in magnetic confinement experiments are subjected to intense thermal loads during plasma operation. The first wall (FW) in present-day and next-step devices will be subjected to power densities of ≤ 1 MW/m^2, comparable to thermal loads in other energy conversion techniques (e.g., stationary turbine blades and fuel rods in fission reactors). Special attention must be paid to high-heat-flux components in the divertor region, both in tokamaks and stellarators. Here, the expected power densities will be at least one order of magnitude above the FW level ($\leq$10 MW/m^2 for Wendelstein 7-X and 5 to 20 MW/m^2 for ITER). These requirements make high demands on the selection of qualified materials and reliable fabrication processes for PFCs (Ref. 1). Further restraints are due to the pulsed operation of tokamak reactors that requires components with a high resistance against thermal fatigue damage. The same problems will apply to the present-day stellarator concepts that will not yet allow uninterrupted plasma operation with long duty cycles.

Irradiation-induced material degradation is another concern. Next-step confinement devices such as ITER

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with an integrated neutron fluence on the order of 1 displacement per atom (dpa) do not pose any unsolvable material problems. However, in commercial fusion reactors with integrated neutron wall loads of 80 to 150 dpa, the fusion community is in need of new, innovative material solutions.[2]

II. THERMAL LOADS IN FUTURE FUSION CONFINEMENT EXPERIMENTS

Design studies for future thermonuclear fusion reactors are, among others, based on the technical feasibilities of PFCs that can guarantee a reasonable lifetime from a safety and economic point of view. This lifetime is limited mainly by thermal loads and by thermally induced mechanical stresses to these components. Here, thermal fatigue during the cyclic plasma operation at power density levels of 5 to ~20 MW/m^2 for the divertor (<1 MW/m^2 for the FW) is a serious concern, in paricular, for discontinuously operating tokamak devices. Transient thermal loads, in particular, tokamak-specific plasma disruptions, can deposit energy densities of several tens of MJ/m^2. These events with pulse durations on the order of 1 ms will damage and erode the divertor, especially in the separatrix strike zone. Further transient events that may deposit a large fraction of the plasma energy on relatively small wall areas (pulse duration typically 100 … 300 ms) are the so-called vertical displacement events (VDEs).

The quasi-continuous plasma operation in large future confinement experiments is associated with another transient heat load event, namely, energy deposition by type-I edge-localized modes (ELMs), which will deposit another nonnegligible amount of energy during each event. The expected power deposition is of the order of 1 GW/m^2 on a submillisecond timescale. Up to now, only limited information is available on the material performance under these events. However, there is a serious concern that high cycle fatigue damage and thermal erosion combined with brittle destruction (BD) might be another lifetime-limiting event.

As mentioned above the loading scenarios for these thermal fatigue and thermal shock loads are strongly design dependent. The most reliable data are now available for the ITER design. For this machine the expected thermal loads and the frequencies of these events are shown schematically in Fig. 1. It should be noted that the continuous flux of fast 14-MeV neutrons will additionally degrade all (plasma-facing and structural) materials. This is the subject of an extensive long-term materials test program.

III. PLASMA-FACING COMPONENTS

To meet the above requirements, reliable PFCs have to be designed. In general the requirements for the plasma-

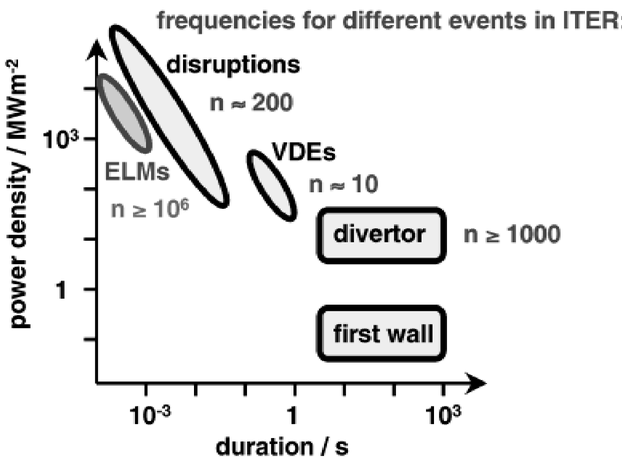


Fig. 1. Plasma-induced thermal loads on PFCs in ITER; n is the expected frequency for these events.

facing material (PFM) and the heat sink cannot be met by a single material (see Fig. 2); hence, qualified joining techniques between the PFM [beryllium, carbon-fiber composites (CFCs), boron carbide, or tungsten] and the heat sink material (e.g., copper alloys) such as brazing, hot isostatic pressing (HIP), or welding have to be developed and tested under fusion-specific thermal loads.[3,4]

IV. DEGRADATION OF MATERIALS AND COMPONENTS

To evaluate the performance of PFCs under realistic operating conditions, a complex material test program has been established that includes modeling by numerical methods, determination of all required material properties in a wide parameter range, and simulation experiments that cover the high-heat-flux performance and the neutron irradiation behavior, including synergistic effects.

IV.A. Thermal Fatigue

The material damage of actively cooled components by a large number of repeated heat pulses is investigated in special electron or ion beam high-heat-flux test facilities. The plasma-facing surface of the component is subjected to fusion-relevant thermal loads. The duration of the heat pulse strongly depends on the design of the mock-up. In any case the heating period should not be terminated before thermal equilibrium has been achieved (typically after 10 to 30 s). The heating cycle is followed by a cooldown period of identical duration. At a given power density level, a predefined number of heat cycles (e.g., $n = 1000 \ldots 3000$) is applied. These tests are repeated at different power densities and with different component histories (e.g., predamaged state or simulation

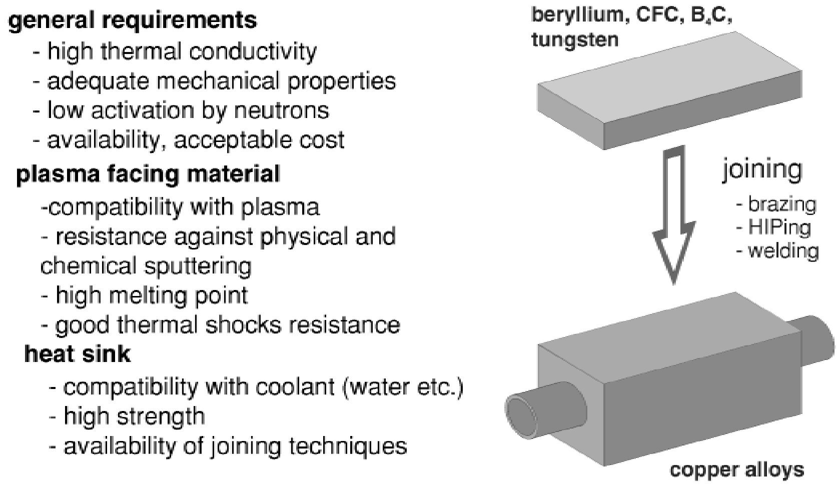


Fig. 2. Major requirements for materials in water-cooled PFCs. Depending on the thermal and neutron loads, today the most promising candidate materials are based on carbon or tungsten (divertor) and beryllium or boron carbide (FW).

of repair processes). The resulting response of the component is investigated by a complex system of in situ diagnostics such as thermocouples, pyrometers, and infrared scanners. Further nondestructive and destructive methods are applied to investigate surface modifications or damage at the interface between the PFM and heat sink.

Today, plasma-facing FW components with beryllium armor show a reliable high-heat-flux performance without any detectable fatigue damage at power densities of ~5 MW/m^2 for ITER-specific cycle numbers (n = 3000). CFC or tungsten-armored divertor components can accommodate the same number of thermal pulses up to power density levels of 18 to 20 MW/m^2.

Internal temperature or stress distributions in PFCs are determined by numerical calculations based on finite element methods; see Fig. 3. This method allows a quantitative evaluation of residual stresses generated during the manufacturing process (e.g., during brazing or

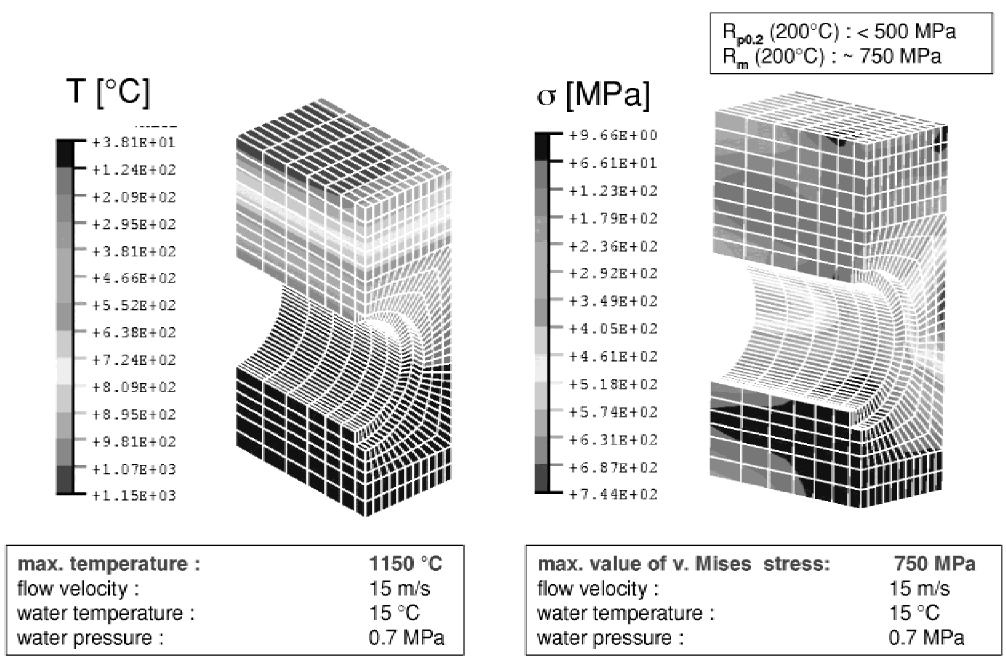


Fig. 3. Three-dimensional finite element analysis of a monolithic W-1%La_2O_3 mock-up at a power density of 11 MW/m^2.

HIP), as well as temperature fields and thermally induced stresses during thermal exposure of the mock-up. The example shown in Fig. 3 shows temperature and van Mises stress distribution in a monolithic, water-cooled component made from the alloy W-1%La_2O_3 at a surface heat load of 11 MW/m^2. Under these loading conditions the maximum stresses in the component approach the rupture strength R_m of this material, and the component will fail. This has been verified experimentally in an electron beam simulation experiment.

IV.B. Thermal Shock

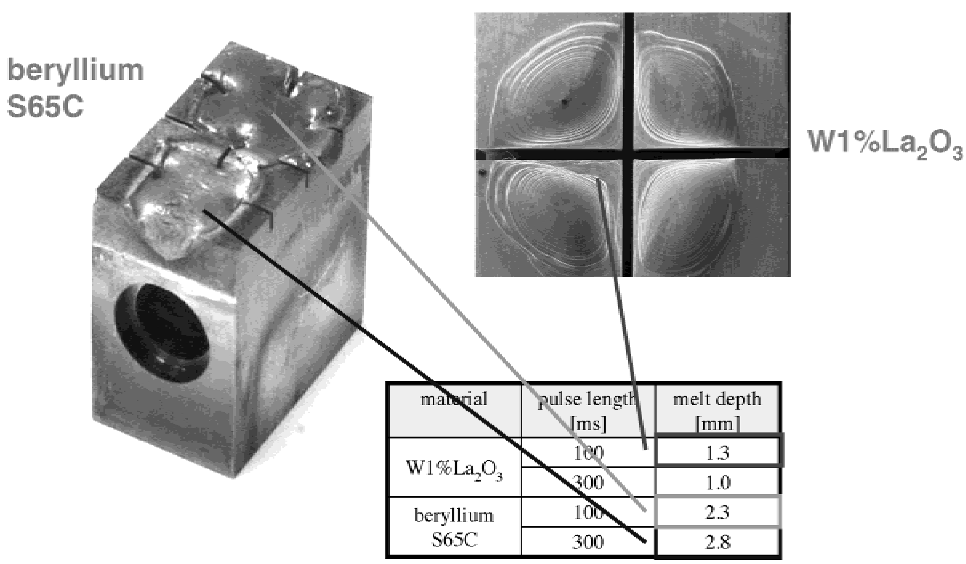
Malfunction of the plasma positioning system may result in extreme short-term thermal loads to PFCs (so-called VDEs). Such an event with deposited energy densities of 60 MJ/m^2 (ITER) will mainly affect the surface of components with metallic PFMs (beryllium or tungsten). The melt layer thickness under these events was determined experimentally in electron beam tests and was found to be on the order of a few millimeters (depending on the pulse duration); see Fig. 4. Mock-ups with undoped CFC armor are more resistant under identical thermal loads since there is no liquid phase; however, some thermal erosion by sublimation has been detected.

Some of the VDE tests have been performed on water-cooled components with active cooling of the heat sink. There is obviously no damage to the interface between the PFM and heat sink. The beryllium mock-up in Fig. 4 was able to resist 1000 thermal fatigue cycles at a power density of 5 MW/m^2 following the VDE testing.

More serious material damage is expected during tokamak-specific plasma disruptions that occur on a millisecond timescale. For ITER the frequency of these events is more than one order of magnitude larger compared to VDEs. The available data about the expected amount of deposited energy density differ significantly; furthermore, part of the incident plasma energy is absorbed by a dense cloud of ablation vapor that forms above the heat-affected surface area. Nevertheless, an absorbed energy density of several MJ/m^2 will be deposited on the PFC surface. Because of the rather short pulse duration ($\Delta t \approx 1$ ms), heat conduction into deeper parts of the PFM does not play any important role, and the major damage is restricted to a thin surface layer with a thickness of several tens of microns.

Depending on the incident energy density and the type of PFM, this surface layer will melt and resolidify immediately when the energy deposition terminates (see Fig. 5). At higher energy densities the thin melt layer will be ejected from the heat-affected area (mainly due to the intense vapor formation at the surface). A further increase of the energy density will result in a boiling process. This mechanism is associated with the formation of bubbles in the melt layer and with the ejection of metallic droplets that finally will contaminate the plasma boundary layer or will be deposited in the form of metallic dust in gaps behind the PFCs. From a safety point of view, this process may generate critical amounts of highly activated tungsten dust that could be mobilized during steam of air ingression accidents.

The short pulse duration of disruption events will generate steep thermal gradients in the surface of the PFM. This will induce severe thermal stresses that may generate cracks with a depth of several hundred microns and beyond. This effect is of special importance if the



material	pulse length [ms]	melt depth [mm]
W1%La_2O_3	100	1.3
	300	1.0
beryllium S65C	100	2.3
	300	2.8

Fig. 4. Electron beam simulation of a single VDE on beryllium and tungsten, with deposited energy density = 60 MJ/m^2 and pulse duration = 100/300 ms.

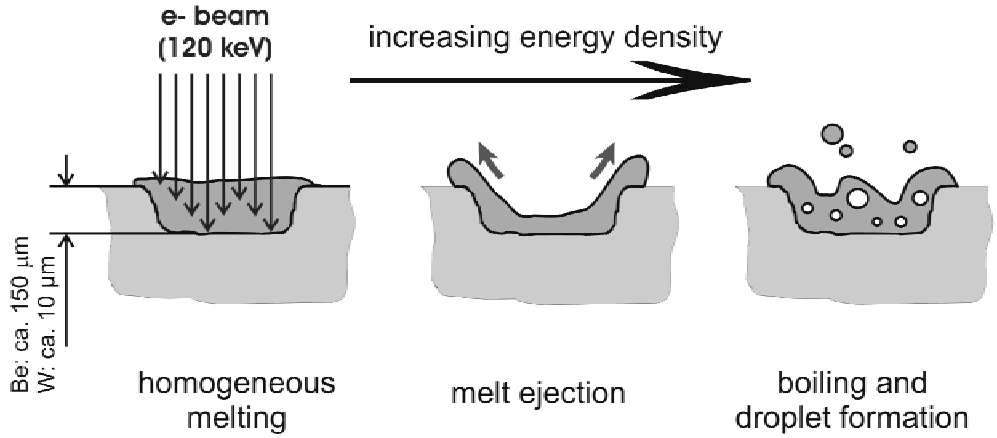


Fig. 5. Electron beam simulation tests with short transient thermal pulses on metallic test samples (schematic).

temperature of the heat-affected material is below ductile brittle transient temperature (DBTT), i.e., at ~400°C for unirradiated tungsten.

Hence, specimens of sintered tungsten that were exposed to intense disruption specific heat pulses (Fig. 6a) show an intense network of cracks in and around the area of direct beam incidence. Identical heat pulses on a sample that was preheated to $T >$ DBTT behave in a ductile manner and do not show any disabling cracks (Fig. 6b). The plasma-sprayed (PS) tungsten sample (Fig. 6c) shows

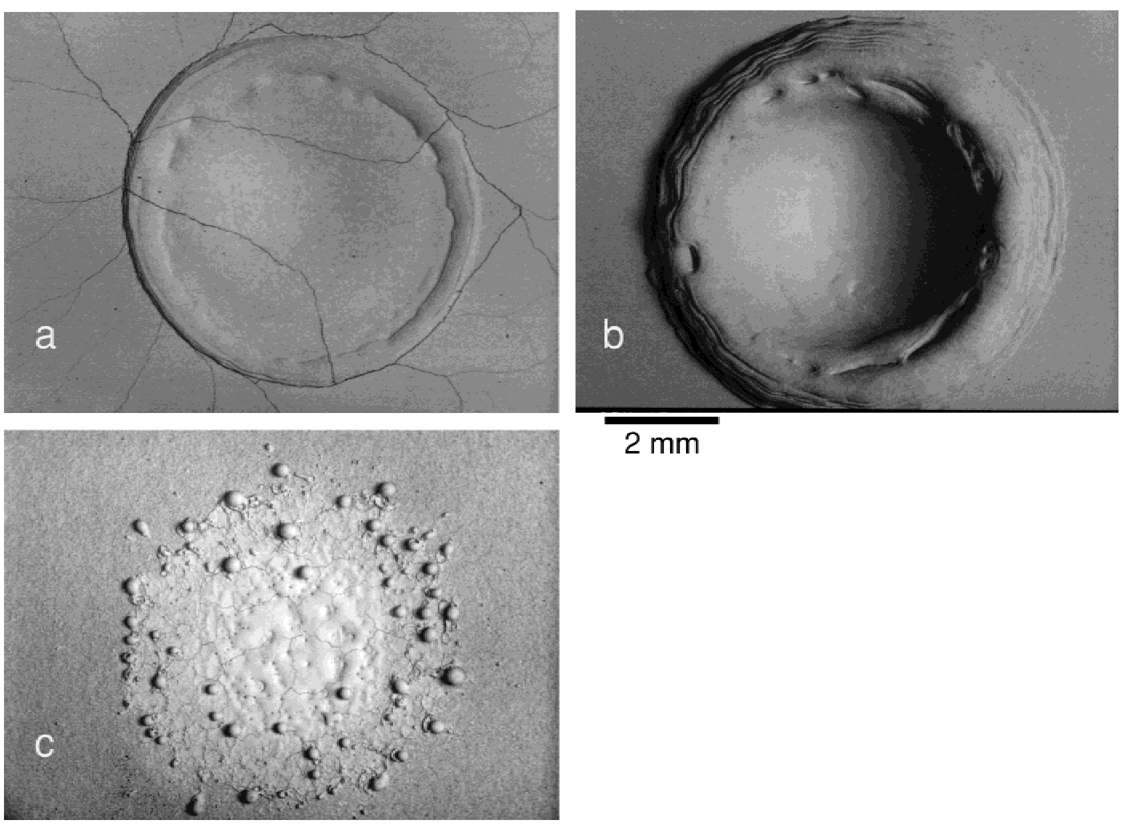


Fig. 6. Electron beam disruption simulation tests; energy density = 2.3 MJ/m^2 and pulse duration Δt = 1.8 ms: (a) sintered tungsten, T_0 = 20°C, n = 10 pulses; (b) sintered tungsten, T_0 = 650 to 700°C, n = 10 pulses; and (c) PS tungsten, T_0 = 20°C, n = 5 pulses.

a clear formation of spherical tungsten particles with a diameter of 100 to 200 μm. Although the applied energy density was identical to the tungsten sample in Fig. 6a, the PS tungsten achieved higher surface temperatures (reduced thermal conductivity compared to sintered tungsten).

Since undoped carbon-based materials (fine-grain graphites or CFCs) do not melt, the formation of dust particles via the aforementioned mechanism does not occur. However, BD (Ref. 5), i.e., generation of thermally induced microcracks in the surface of these materials during intense thermal loads, will result in the formation of carbon dust particles if the critical threshold value of the incident beam power is exceeded. The mechanism of BD is shown schematically in Fig. 7: Below the critical threshold value, no particle emission has been observed; if this value is exceeded, the particle erosion process is initiated. Up to a second threshold value, mainly small- and medium-sized particles are ejected from the surface of the PFM. In fine-grain graphites this process is characterized by the release of the binder phase between the graphitic grains. If the second threshold value is exceeded, large dust particles (grains or grain clusters) are emitted from the surface. Digital images taken from this process show clearly the trajectories of the hot particles that may penetrate deeply into the plasma boundary layer. A major concern of the carbon dust is the codeposition together with tritium in gaps or remote areas behind the divertor structure. In particular, the large-particle emission results in a substantial erosion of the graphite surface. This is clearly demonstrated by weight loss and scanning electron microscopy (SEM) analyses (see Fig. 7).

The threshold values for the onset of BD have been determined for graphites and CFCs both for disruption and VDE specific pulse durations, i.e., for 1 … 5 and for 100 ms. Similar studies for the ELM regime are on the way. For the millisecond electron beam pulses, there is a clear transition with two separate threshold values (no particle emission—small- and medium-sized particles—big particles); see Fig. 8. For longer beam pulses ($\sim$100 ms), only small- and medium-sized particles have been observed. According to Fig. 8 the thermal loads during plasma disruptions and VDEs in ITER are clearly above the threshold values for BD, while the ELMs seem to remain in a "safe operation regime." Nevertheless, BD may also play an important role for ELM-specific loads because of the high frequency of these events and an integrated number of $n > 10^6$ events in ITER.

Obviously, the generation of large particles is restricted to regimes with extreme thermal gradients in the surface layer. Carbon dust particles have been collected

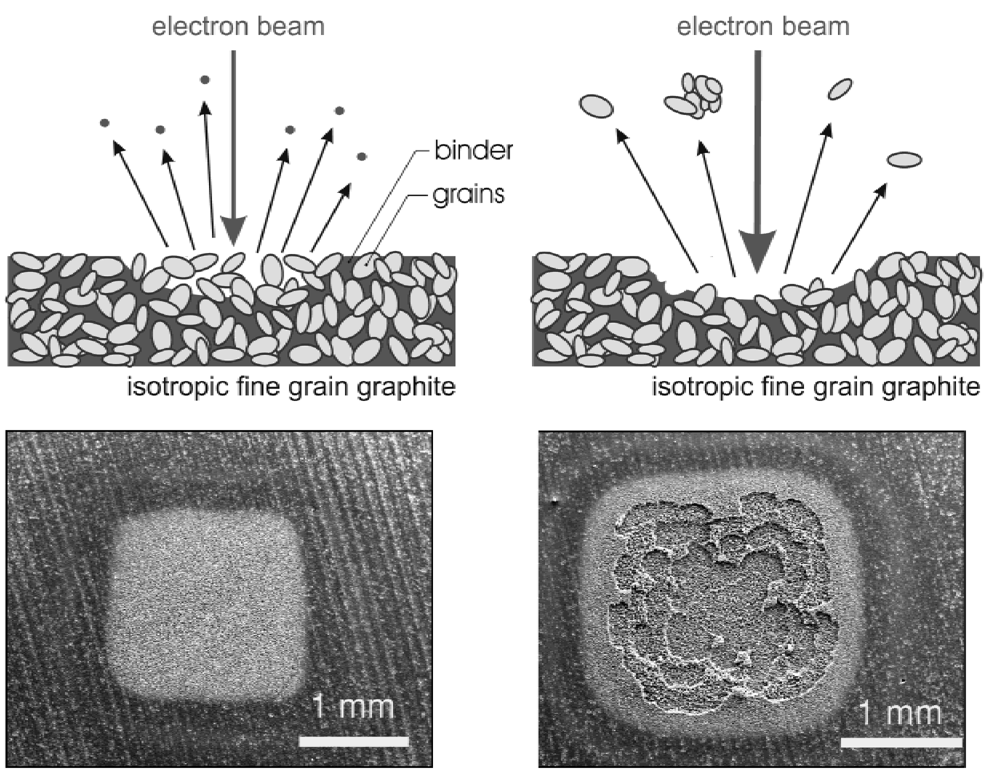


Fig. 7. The BD experiment with short transient electron beam pulses on isotropic fine-grain graphite: top—schematic; bottom—SEM micrographs from the test samples; left side—at lower-power densities, mainly the binder phase is eroded; right side—at higher-power densities, the erosion process is dominated by grains or grain clusters.

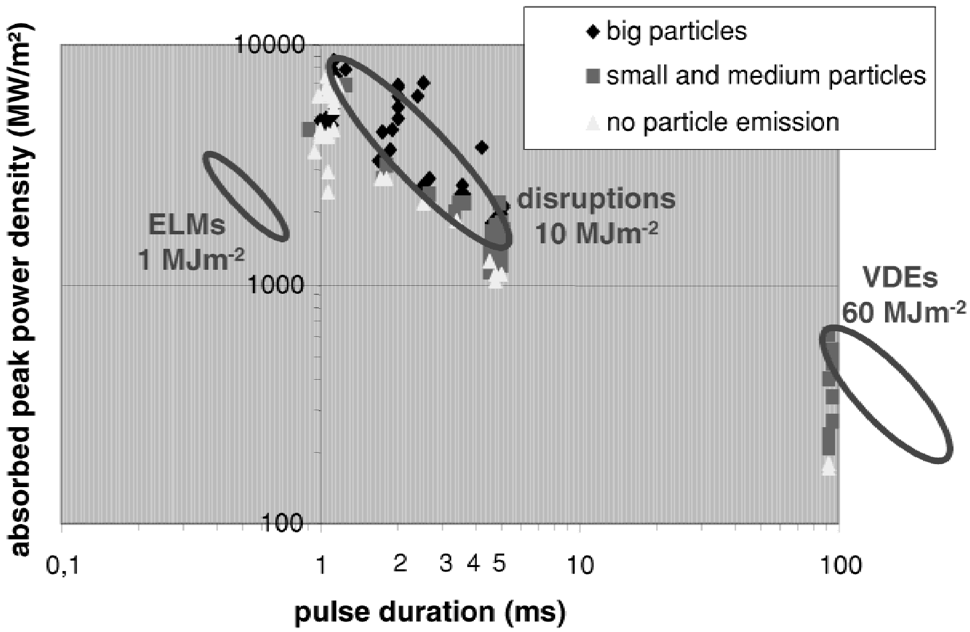


Fig. 8. Threshold values for BD of fine-grain graphite (R6650) and regimes for transient thermal loads in ITER.

and analyzed by different methods. The size of these objects covers a rather wide range from a few nanometers to a maximum of $\sim$100 μm; i.e., their dimensions range from nanotubes to graphitic grains or even grain clusters. Simulation tests with CFCs (Fig. 9) show a rather similar behavior compared to the fine-grain graphites; however, the threshold values are slightly shifted to higher-energy densities. This is due to the improved thermal conductivity of this material. The material erosion strongly depends on the architecture of the CFC and on the type and orientation of the fibers used. Hence, the erosion pattern does not show a homogeneous erosion in the heat-affected area. Fibers oriented parallel to the sample surface are preferentially eroded.

The high thermal conductivity pitch fiber bundles in the CFC material NB31 that are oriented parallel to the incident electron beam (see Fig. 9) remain almost unaffected.

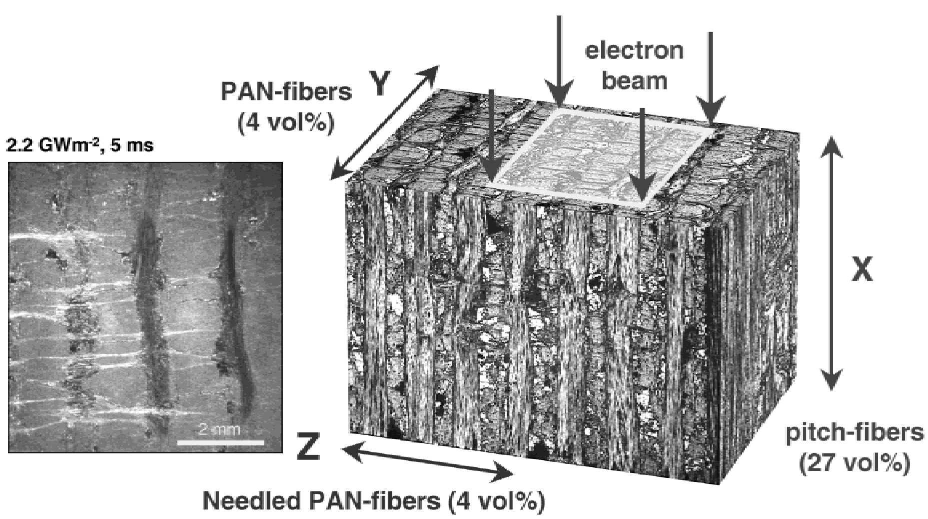


Fig. 9. Inhomogeneous erosion of CFCs (NB31) due to BD: left—micrograph from the eroded test specimen and right—architecture of the three-dimensional weave.

Special diagnostics have been developed to analyze the ablation vapor and dust that are emitted by the BD process. Among these are fast pyrometers, spectrometry, and a photodiode array to determine the speed of the particles[6] (Fig. 10). Using this method a maximum speed of 150 ms^{-1} (Ref. 7) has been determined for carbon dust particles (graphite R6650, $P = 2.4$ GW/m^2, and $\Delta t = 5$ ms).

IV.C. Neutron Irradiation

Plasma-facing components in future thermonuclear fusion reactors will be subjected to intense fluxes of energetic neutrons (up to 14 MeV), which will degrade all materials (PFM, heat sink material, and interface).[8] Degradation can take the form of radiation embrittlement and swelling of metallic systems and reduction of thermal conductivity of ceramic materials, such as graphite. In addition new elements are generated due to transmutation processes that may lead to drastic compositional changes and to severe activation if unqualified or impure materials are used in the manufacturing process. For ITER the integrated neutron dose is still limited and will not exceed values of ~1 dpa for the divertor or the FW. In future commercial reactors, however, the lifetime fluence of structural components will achieve values of up to 150 dpa. Under these conditions frequent replacement of the PFCs is necessary.

To investigate the effect of neutron irradiation on PFM and components, a special electron beam facility (JUDITH) has been installed in a hot cell laboratory. PFCs with beryllium, CFC, and tungsten armor are irradiated in material test reactors to ITER-specific fluences (up to 1 dpa and $T_{irr} = 200 \ldots 700$°C) and then subjected to high-heat-flux simulation experiments in JUDITH (Ref. 9). A typical example of these tests is shown in Fig. 11. The bottom curve (squares) shows the thermal response (T_{surf} versus thermal load) for a CFC armored monoblock component. If surface temperatures of $T \geq 2000$°C are acceptable from a plasma physics point of view, this mock-up can accept thermal loads above 20 MW/m^2 in the unirradiated state. After neutron irradiation ($\Phi = 0.3$ dpa and $T_{irr} = 350$°C), the surface temperature increases significantly. Above $T_{surf} \approx 1000$°C, this effect is slightly decreasing since some of the neutron-induced defects are recovering. Nevertheless, the neutron effect on the heat removal efficiency of CFC armored PFCs is significant. Therefore, the use of carbon-based materials in future commercial reactors is very doubtful.

V. SUMMARY

According to the present state of research and development, today PFCs with tungsten or CFC armor (for the divertor) or with beryllium or boron carbide armor (for the FW) can be reliably manufactured for existing and next-step fusion devices, as long as only moderate neutron fluxes (~1 dpa) have to be considered. These components show an excellent heat removal efficiency up to 20 MW/m^2 for 1000 cycles and beyond.

During off-normal plasma operation (disruptions or VDEs), CFCs and tungsten alloys show excellent thermal shock resistance (if $T >$ DBTT). However, melt layer instabilities or BD may result in nonnegligible material erosion, in the formation of radioactive or tritium-contaminated dust particles, and in contaminations of the plasma boundary layer. The most critical material damage is supposed to occur after neutron irradiation to reactor-relevant doses. Here, embrittlement, swelling, degradation of physical properties, and transmutation processes are of serious concern. These processes will also affect the high-heat-flux performance of the materials and components by synergistic effects. For moderate neutron fluences (≤1 dpa) that are expected in ITER, the existing design solutions appear acceptable.

From the neutron irradiation point of view, future reactors based on the tokamak or on the stellarator design

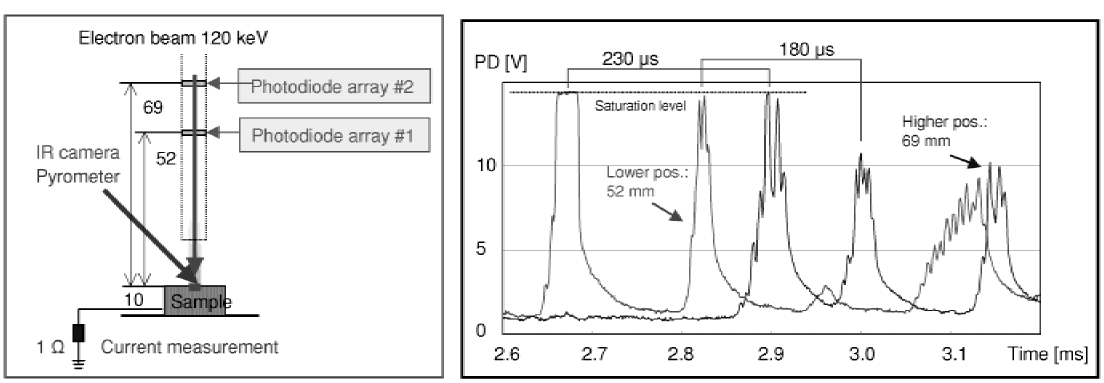


Fig. 10. Photodiode array focused to the particle trajectories 52 and 69 mm above the test sample (left). The particle speed can be determined from the time delay of the photodiode signals (right).

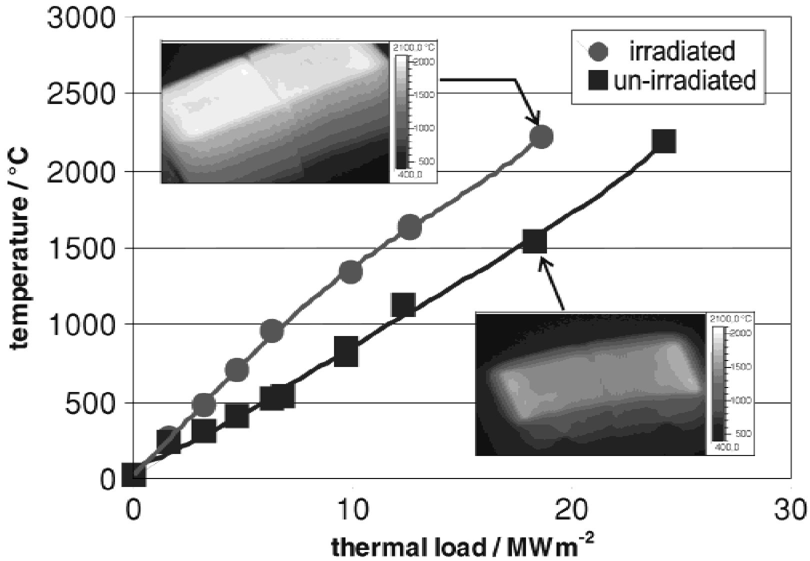


Fig. 11. High-heat-flux performance of unirradiated and neutron-irradiated divertor modules with CFC armor (Dunlop Concept 1); material irradiated to 0.3 dpa at 350°C.

will not have any system-inherent advantages. Since thermal fatigue transient heat load events with severe thermal gradients in the PFM are among the most serious damaging mechanisms for PFCs in future commercial reactors, the stellarator concept per se seems to be superior to noncontinuously operating tokamak systems. Hence, improved design concepts that allow quasi-stationary plasma operation and effective mitigations of plasma disruptions are a prerequisite for an energy-producing commercial fusion reactor.

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