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ScienceDirect
Journal of Nuclear Materials 363–365 (2007) 1334–1339
journal of nuclear materials
www.elsevier.com/locate/jnucmat

Limiter material experiments towards long pulse operation in the HT-7 superconducting tokamak ☆

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Abstract

Selection and testing of candidate materials for plasma facing components (PFC) in next-step fusion devices is an important and strongly addressed point in the research programme of HT-7 device. A kind of B, Si and Ti doped graphite with thick SiC gradient coatings has been chosen as the main limiter material for the HT-7 device. From only a 0.3 m^2 of poloidal limiter to a total covered area of 2.5 m^2 new belt limiter plus up and down toroidal limiters with actively water-cooled, the change in the HT-7 device was very successful, the plasma performance has been significantly improved and the longest discharge duration has been more than 306 s. These results have demonstrated that new carbon armored PFC can also be used in the first phase of the EAST device, and might be an attractive choice for the first wall of steady state fusion devices.

PACS: 52.40.Hf; 52.55.Fa; 65.60.+a; 81.05.Uw

Keywords: Doped graphite; Plasma facing components; Plasma performance; Long pulse operation; HT-7

1. Introduction

Carbon based materials (CBM), such as fine grain graphite and carbon fiber composite (CFC), are widely used for divertor, limiter and first wall materials in existing fusion devices. Many machines have expanded CBM coverage to nearly include all of the vacuum vessel wall, and CFC is also selected as the armored material of ITER divertor target near the strike-points, because of its high thermal shock resistance and tolerance to off-normal events (ELMs, disruptions) without melting, thereby avoiding surface irregularities. However, the increase in discharge duration from seconds in present tokamak devices to many minutes in a next generation devices, together with the increase in plasma energy, give rise to important plasma surface interactions that will critically influence the performance, operation and safety.

For carbon materials, erosion due to low energy ion impact is high and the chemical reactivity with hydrogen atoms further enhances the erosion [1]. The erosion limits the lifetime of the components,

☆ The work is supported by NSFC under the project of 10475080 and the Foundation of 2006YZJJ-1.
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doi:10.1016/j.jnucmat.2007.01.244

dilutes the plasma with impurity and leads to high tritium inventories in deposited layers on less exposed areas of the vessel wall [2]. Therefore, the search for low erosion CBM, together with the methods to apply some thick gradient distributed low-Z carbide coatings (SiC, B_4C) on doped graphite [3], will be the main characteristic of our research activities aimed at developing the PFC of steady state operation fusion devices [4–7].

HT-7 is a superconducting tokamak with limiter configuration, designed to operate at experimental conditions of high power and steady state duration discharge, which impose severe criteria for PFM [3]. It seems that doped graphite with optimized composition and microstructure can be one possible path to be used as PFM with reduced chemical erosion, optimized thermal–mechanical properties, and with reduced hydrogen retention. Research works carried out in ASIPP, mainly focused on evaluating the performance and behavior of the candidate materials under the long pulse plasma irradiation.

2. Limiter materials

2.1. Overall performance evaluation of GBST1308

By optimizing the proportion of doped elements and the preparation technique, one kind of doped graphite named GBST1308 (1% B_4C, 2.5% Si, 7.5% Ti) has been developed. The overall performance evaluation can be found in Refs. [3,7]. The thermal conductivity of GBST1308 is up to 150–180 W/m K at room temperature (RT), and very stable with the temperature rise, even at 773 K which only decreases 15% compared with the value at RT, on the other hand that of pure fine grain graphite has a decrease more than 40% [8]. The experiment also indicates that the chemical sputtering (CS) yield of GBST1308 at 50 eV and 1 keV D^+ bombardment was decreased by a factor of 30% and 5%, respectively, in comparison with that of pure fine grain graphite [3,9]; and good vacuum engineering properties with a low degassing rate (the total degassing rate is 3×10^{-12} Torr l/s cm^2 at RT, which nearly approach as the level of IG-430U isotropic fine grain graphite used in JT-60U and LHD, Japan) and is favorable for reducing recycling and for density control in fusion experiments [10]. Its mechanical strength is also higher, $\sigma_b \geqslant 40$ MPa (bending strength). Furthermore the thermal and mechanical properties are much more stable in the case of the bulk temperature is below 1373 K [8].

2.2. Thick SiC gradient coating

The main disadvantages of a pure carbon material are its strong chemical erosion and high temperature sublimation ($T > 1273$ K). As for the surface characteristics of the graphite, however, it is necessary to reduce the impurity generation due to its high sputtering yield, the density build-up due to its large retention of hydrogen isotopes, and so on. Especially, the limited oxygen gettering capability of graphite allows considerable contamination of the core plasma by oxygen influx. Many efforts have been made to improve the surface characteristics of graphite by use of boron or silicon contained materials which have a strong affinity for elemental oxygen.

The SiC coating used for the limiter tile surface can endure the high heat flux without large erosion or damage, and exhibit superior surface characteristics for a sufficiently long lifetime. A thick SiC coated graphite is a good siliconized material because it does not have a negative effect on the good thermal characteristics of the graphite. However, exfoliation of the coating should be avoided. A new SiC coating technique, CVR combined with CVI, has been developed in application to the HT-7 limiter plate, which provides gradient SiC coating by the infiltration of reaction gas through open pores [3]. This process yields sufficient resistance against exfoliation. The optical microstructure of thick SiC gradient coatings on carbon tiles are shown in Fig. 1, showing homogeneous microstructure almost without porosity or unreacted carbon.

3. HT-7 limiter plasma irradiation experiments

Selection and testing of materials for PFC in next-step fusion devices is an important and strongly addressed point in the research programme carried out in the HT-7 device. The aims of testing candidate materials are (a) to evaluate their impact on the plasma performance, (b) to recognize the material erosion and damage, (c) to determine the fuel retention and (d) to investigate the applicability of materials integration into PFC to steady state operation.

For the limiter configuration of HT-7 device, the last closed flux surface was defined by the main up

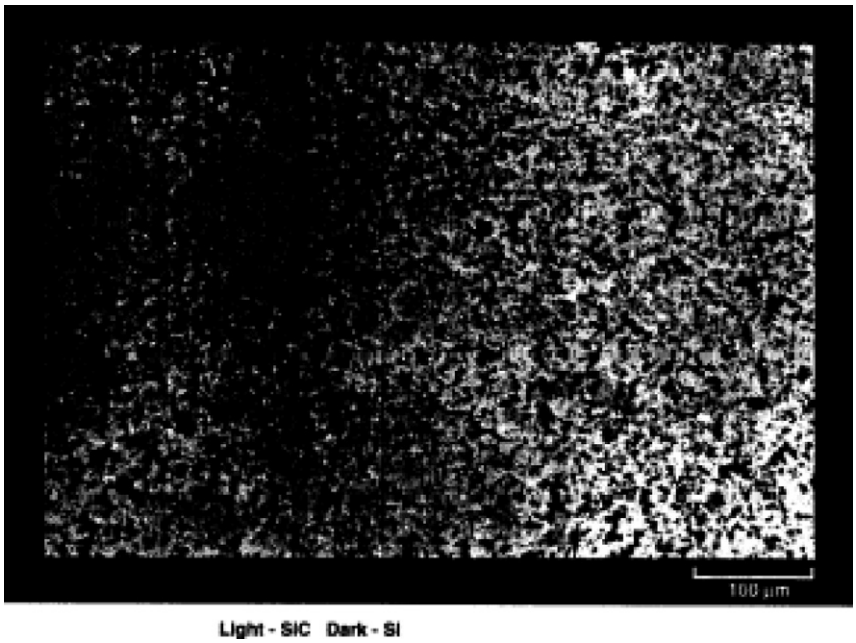

Fig. 1. The optical microstructure of thick SiC gradient coatings on carbon tiles.

and down toroidal limiter and a new belt limiter in high field side, which receive the highest heat loads and largest flux of energetic particle bombardment from the plasma and thus imposes severe requirements on the main limiter materials. In the past, due to energetic particle bombardment and overheating problems, the plasma discharge was usually terminated by very strong hard X-ray radiation, hot spot and high-Z impurities problems.

In the last campaign of year 2000, a smaller and discrete molybdenum limiter was switched to a larger and fully circular carbon limiter with actively water-cooled. GBST1308 doped graphite was chosen as the main limiter material for the HT-7 device. The main limiter was designed as a complete circular ring in the poloidal direction with a minor radius $r = 27$ cm as shown in Fig. 2, which is smaller than the previous molybdenum limiter ($r = 28.5$ cm). To protect the first wall and control impurities, widen the SOL and provide a good protection for the stainless steel liner from energetic ions bombardment. The total surface area of the main limiter is about 0.3 m^2, when auxiliary heating power was applied in the HT-7 device (400 kW-LHCD, 200 kW-RF, 400 kW-OH), the average steady state heat flux on the new carbon limiter is as high as 2–3 MW/m^2.

The change of the new carbon limiter in the HT-7 device was identified to be very successful, the hard X-ray and high-Z impurity central radiation problem have been alleviated, and plasma performance has been significantly improved [10]. The Hugill stable operation window has been enlarged, and higher efficiency of LHCD (Low hybrid current driven) has also been obtained. The edge recycling, plasma density and impurities became easily handling. The recycling coefficient can be easily controlled by proper arrangement of different RF conditioning techniques [11].

From the first campaign of year 2004, a new belt carbon limiter plus up and down toroidal limiter coated with SiC with total area of 2.5 m^2 with actively water cooled have been installed in HT-7 device as shown in Fig. 3. GBST1308 as the PFM and the minor radius is still 27 cm. It has been found from laboratory experiments and in-pile tests in the HT-7 device that the thick SiC gradient coating on graphite exhibits superior surface characteristics and satisfactory thermal shock resistance. Contrary to carbon based materials, SiC has much lower chemical and sputtering, is capable of oxygen gettering and lower hydrogen recycling. This is very important for impurity control during long pulse discharges, which can be certified by Z_{eff}. After installation a new carbon limiter, the value of Z_{eff} is similar to the case of boronization, only slightly higher than siliconization, which can be seen clearly in Fig. 4 [11]. XPS analysis shows that the surface of

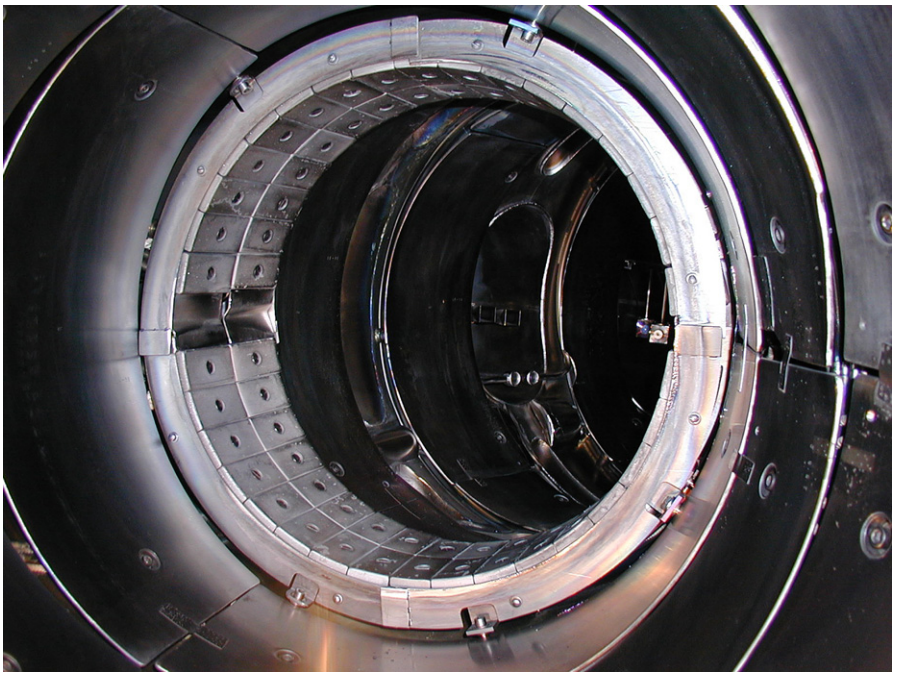

Fig. 2. A fully circular poloidal limiter installed in HT-7 device.

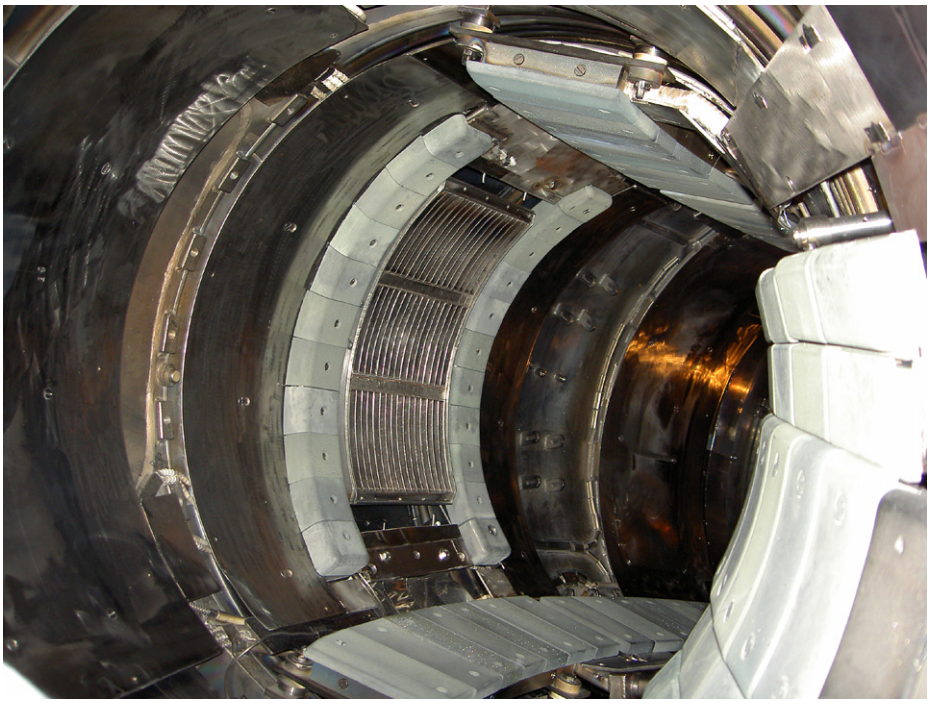

Fig. 3. A belt limiter on the high field side plus up and down toroidal limiter in HT-7 device.

the carbon tile absorbs a large amount of oxygen and forms a stable SiO_2 [12].

A high performance discharge has been obtained, for example shot number 52324 (Fig. 5), with the

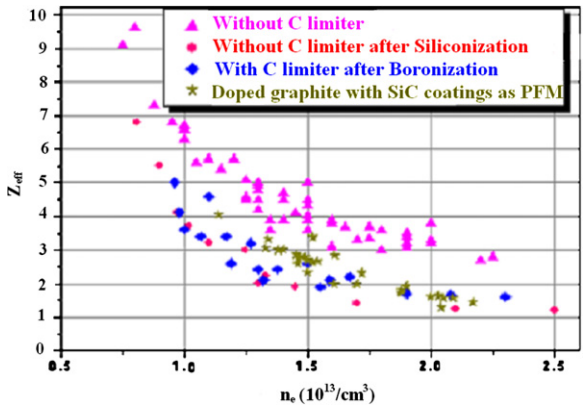

Fig. 4. The effect of limiter materials on Z_{eff}.

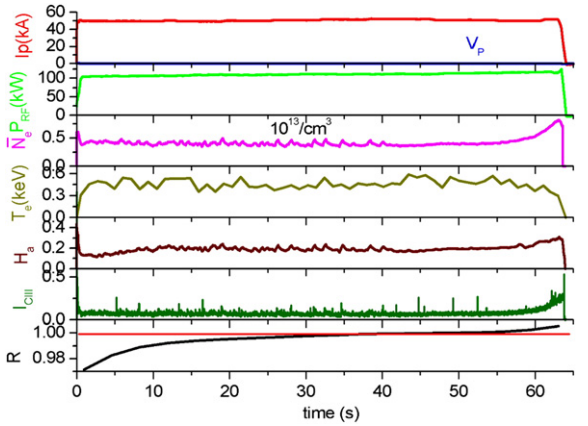

Fig. 6. With low density and low LHW power, recycling and impurities can be well controlled by wall conditioning.

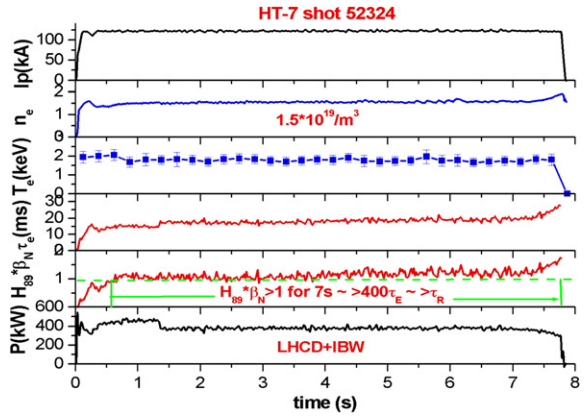

Fig. 5. A typical high performance discharge with LHCD + IBW.

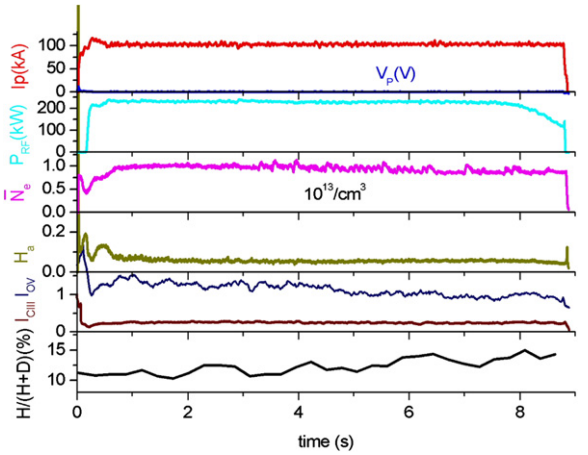

Fig. 7. Impurity and H/(H + D) behavior during a high density and high LHW power discharges.

combination of LHCD and IBW auxiliary heating, the normalized value of energy confine time $H_{89} * \beta_N$ is larger than 400 τ_E. In Fig. 6, R means the global recycling coefficient. In a low density plasma (line averaged density 10^{13} cm^{-3}) with low LHW power (100 kW), density was under controllable up to 50 s. In the later time, recycling dominated the particle balance. The main contribution of hydrogen and impurities was from the surfaces of the limiter and first wall due to an increase of the surface temperature (out-gassing), which was obtained with a boronized wall. Fig. 7 shows the hydrogen to deuterium ratio increasing slowly in a higher density plasma with higher LHW power (250 kW). The slow increase of the recycling of hydrogen only came from the surfaces of the limiter and the first wall. There was no increase of the impurity influxes as indicated by CIII and OV emis-

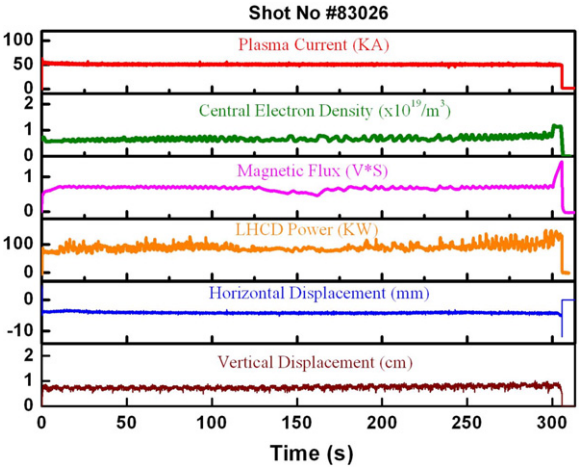

Fig. 8. The longest discharge of more than 306 s.

sion till the end of discharge. This shot was obtained after several hundred shots after boronization. So the hydrogen contained in the coated film was removed shot by shot. But the film was still effective to suppress the impurity. The H/(H + D) ratio kept a low level during the discharge.

Long duration discharges were performed using a double control: plasma current and position was controlled by the ohmic poloidal system, and central line averaged electron density was controlled by feedback control of deuterium gas injection using a pulsed piezo-electric valve. The longest discharge, shot 83026 in Fig. 8, is more than 306 s, which has demonstrates well the new PFC, power and particle injection and exhaust capabilities, diagnostics and feedback control loops, etc.

4. Conclusions

A series of multi-element doped graphite materials has been developed. After overall performance evaluations and integration into PFC in HT-7 limiter plasma irradiation experiments, the main conclusions can be primarily drawn as following.

By optimization, a triply doped graphite of GBST1308 with thick SiC gradient coating was successfully used in HT-7, which can also be used as PFM in the first phase of the EAST device. By properly design, mechanical joining PFC, can handle a heat load of 1–2 MW/m^2 and pulse length of few hundred seconds. All these results have demonstrated that new carbon based PFC will be an attractive choice to make them competitive with other candidate materials for the first wall of fusion device. Erosion and co-deposition behavior of doped graphite with SiC coating still need to be further recognized.

Acknowledgements

This work has been supported partially by the JSPS-CAS Core-University Program in the field of 'Plasma and Nuclear Fusion', and many helpful discussions with Professor N. Noda and Professor T. Hino of Japan.

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