Development of candidate high heat flux components for steady state operation of the EAST devices

Presented by J.L.Chen[1]

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Outline

- Motivation
- Development of carbon based plasma facing components

---- GBST1308 with thick SiC gradient coatings as PFM;

---- Mechanical jioning by bolts to copper alloy heat sink (Convenient, cheap and reliable);

---- Simulation with electron high heat flux experiments and FEM analysis;

---- HT-7 limiter plasma irradiation with long pulse experiments;

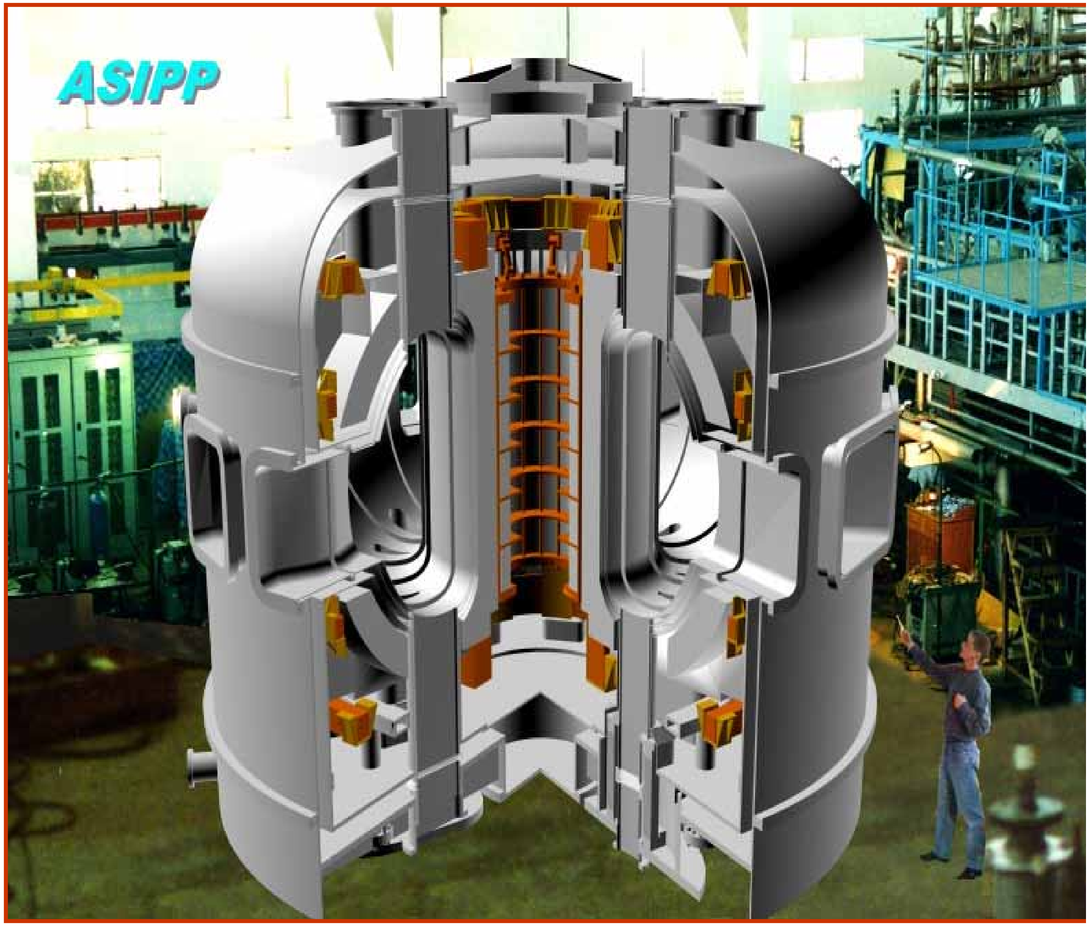
- Development *of* tungsten based plasma facing components

---- Vacuum plasma spray or CVD tungsten coatings directly on copper alloy heat sink

---- Blast compound or Braze with W/Cu functionally gradient compliant layer

- Discussion and Conclusions

EAST superconducting tokamak and main parameters



Main Parameters

Toroidal Field, B_o	3.5 T
Plasma Current, I_P	1 MA
Major Radius, R_o	1.7 m
Minor Radius, a	0.4 m
Aspect Ratio, R/a	4.25
Elongation, K_x	1.6 - 2
Triangularity, d_x	0.6 - 0.8

Heating and Current Driving

$P_{LHCD} + P_{ICRH} + P_{ECRH} = 7\sim8MW$ (1st)

$P_{LHCD} + P_{ICRH} + P_{ECRH} + NBI = 20MW$ (2ed.)

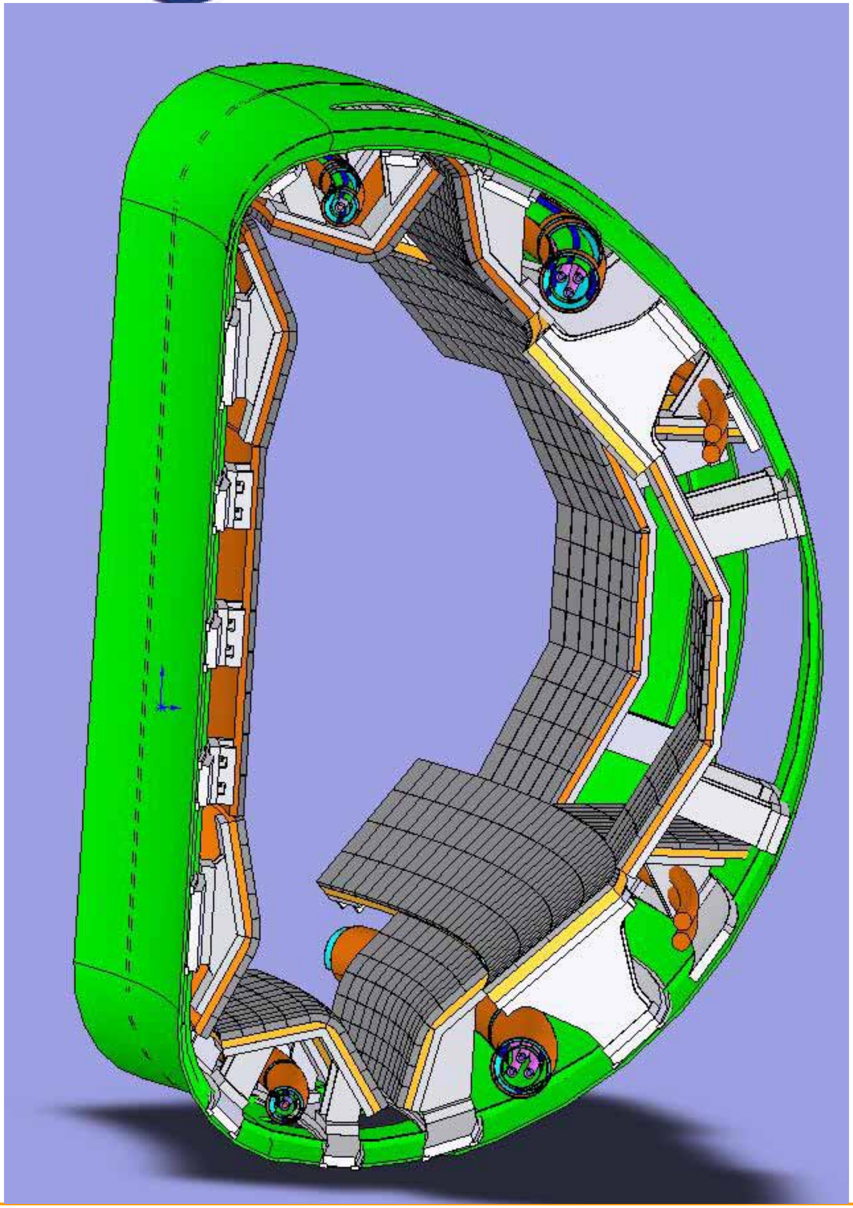
Pulse length 60-1000s

Configuration

Double-null divertor,

Single null diver

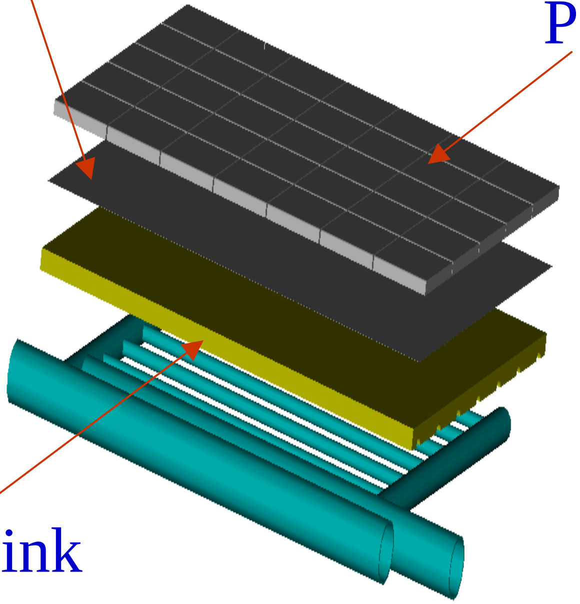
Pump limiter



Motivation

Two phases:

- Carbon based plasma facing components;
- Tungsten clad on copper alloy heat sink.



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Carbon as plasma-facing material?

Main advantages of carbon as PFM:

✓ low Z: Compatibility with plasma;

✓ High thermal shock resistance;

✓ No melting under transient power loads (ELMs and disruptions)

But...

✗ large **chemical erosion**

⇨ component lifetime limitation

⇨ co-deposition (with T ⇨ high inventories)

✗ Brittle materials (especially difficult for materials integration as PFC)

⇨ **Graphite performance can be improved by doping some elements**

Main properties of GBST1308

- A name of GBST1308 (1%B_4C, 2.5%Si, 7.5%Ti) with **high thermal conductivity up to 180 W/m.K (RT)**, has been successfully developed and chosen as the PFM for limiter and normal first wall;
- The erosion experiment indicates that CS yield of the mixed carbon materials **at 50eV and 1KeV D^+ bombardment was decreased by a factor of 35% and 5**, respectively, in comparison with that of pure graphite;
- The bending strength of GBST1308 is higher than **46 MPa**;
- Good thermal shock resistance, which can withstand **8MW/m^2 high heat loads for 100s and 3ms ~2MJ/m^2,** no obvious crackle phenomena occurs;
- Good vacuum engineering properties with low outgassing rate favorable for reducing recycling and density control; **the total outgassing rate is 5×10^{-13}Torr.L /s.cm^2 at RT**, which nearly one order low than of IG-430U, an isotropic fine grain graphite;

Thick SiC gradient coatings on GBST1308

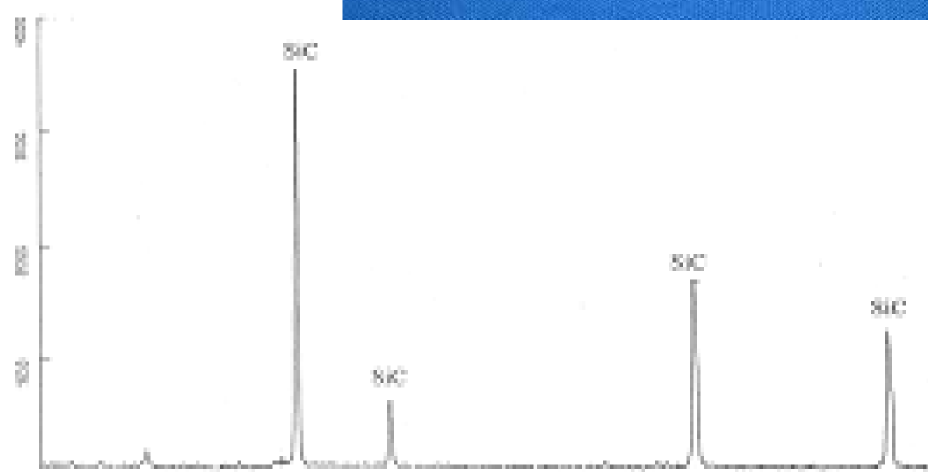
Chemical vapor reaction (**CVR**) combined with chemical vapor infiltration (**CVI**) in a high temperature-furnace,

$$Si(gas) + C(solid) \rightarrow SiC(solid)$$

- Temperature: in the rage of 1600～1800^{0}C
- Si Vapor infiltrate the open pores and react with grap
- Time: 3-4 hours
- Thickness: 100~200μm

Crystalline structure

A mixture of β-SiC and Si phases



Mock-up of PFC and the experimental conditions

Structure and materials

PFM：Doped graphite (GBST1308)

Heat sink: Chromium copper alloy

Joining ：Mechanical joints by bolts

Compliant layer: Super carbon sheet (0.2μm, 0.38 μm)

Heating conditions

Steady state heat flux:

1MW/m^2、3MW/m^2、5MW/m^2

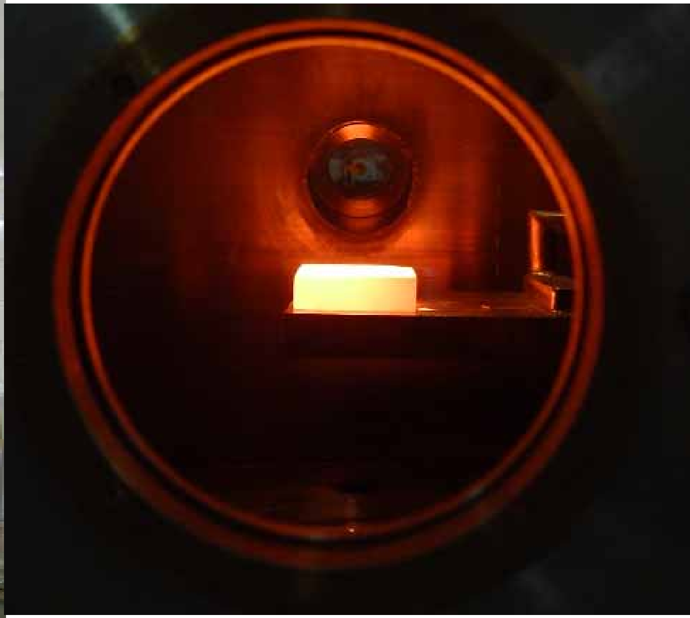
Cooling conditions

Inlet water temperature: 25^0C

Inlet pressure: 1MPa

Rectangle pipe：32*14mm^2

Water flow rate：6m^3/h、 4.5m^3/h 、3m^3/h

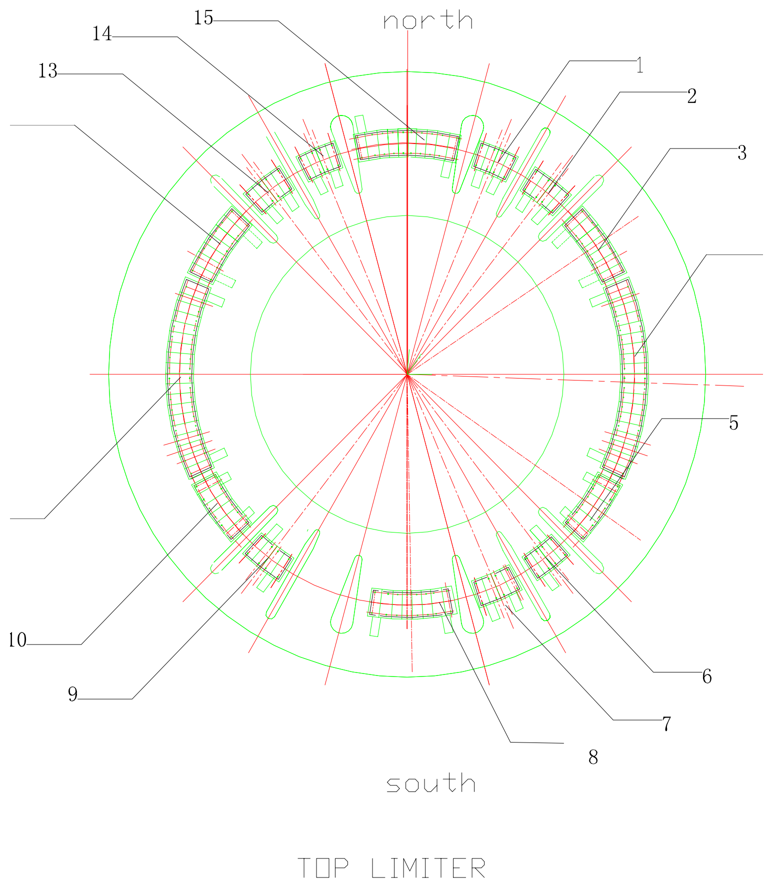


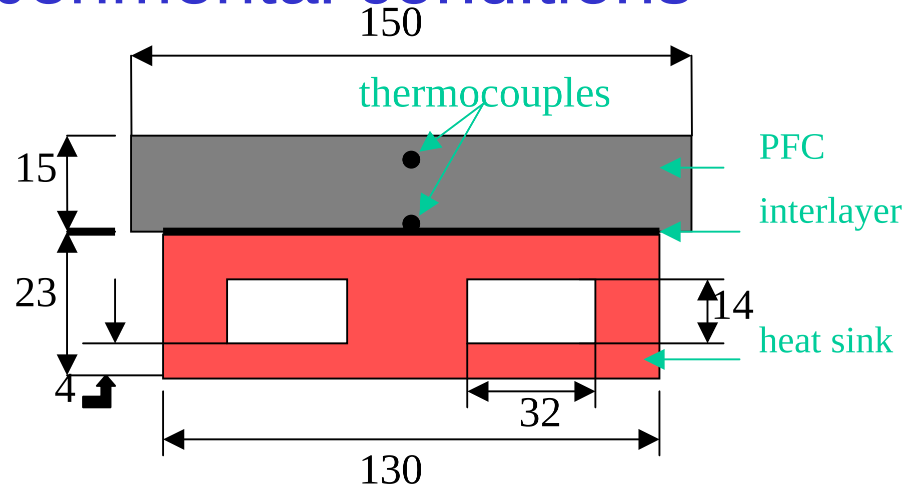
Maximum Power: 20KW, Beam current:10mA～1A, Scaning rate:200Hz

Electron energy: 20KeV, Scanning area: 1～10cm^2 ,

Cooling condition: 1MPa, 1.7m/s and 15^{0}C respectively

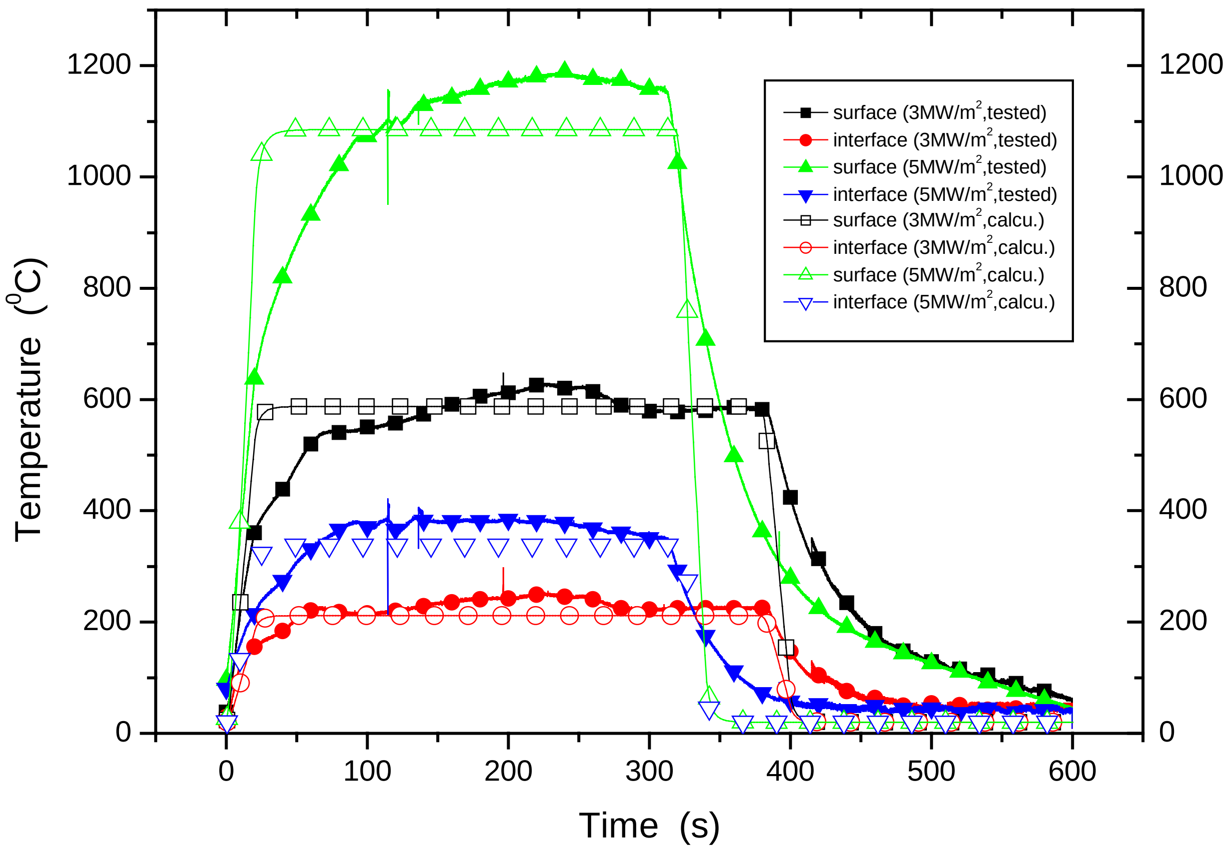
Mock-up and the experimental conditions



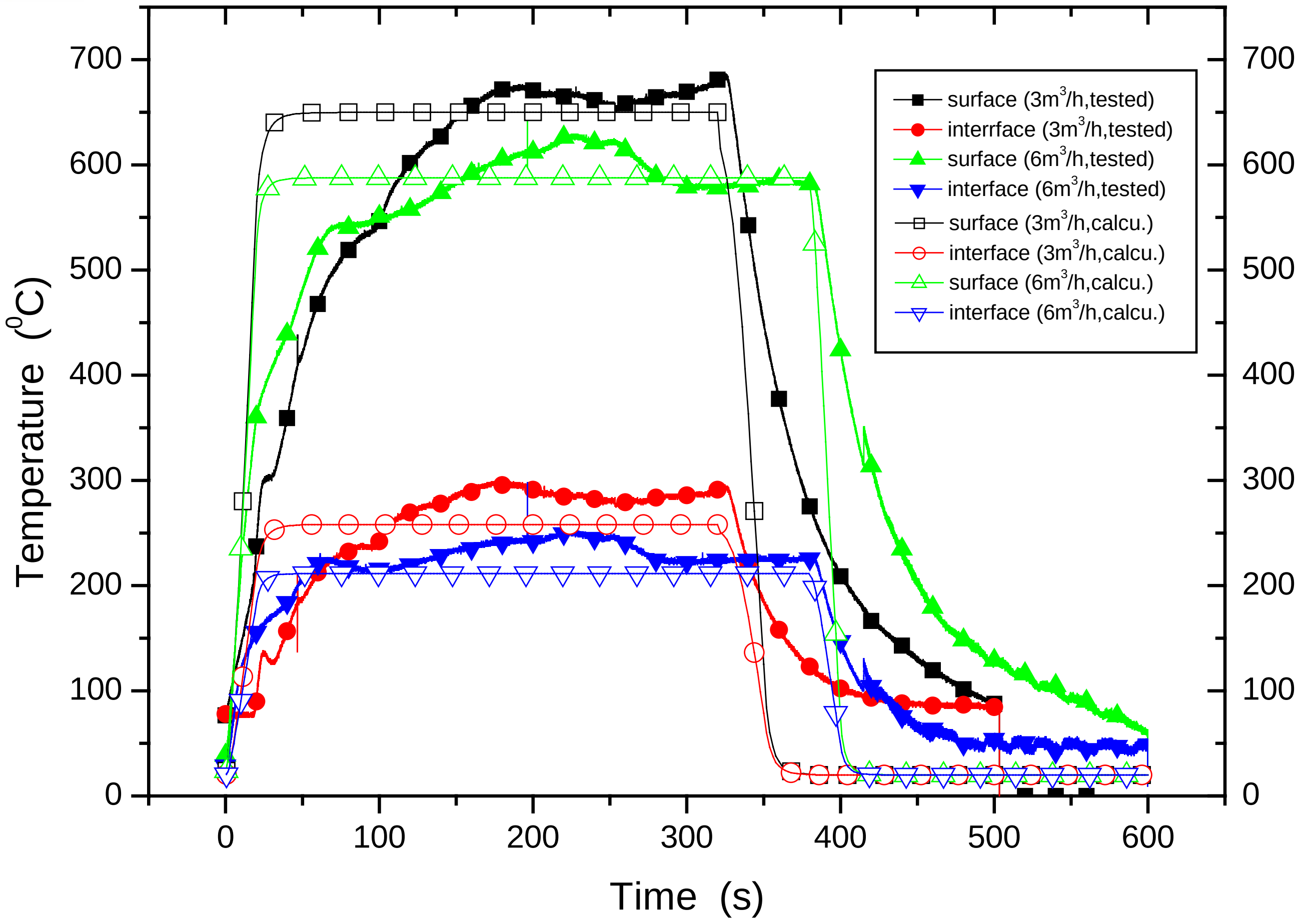


Cross-section view of the mock-up

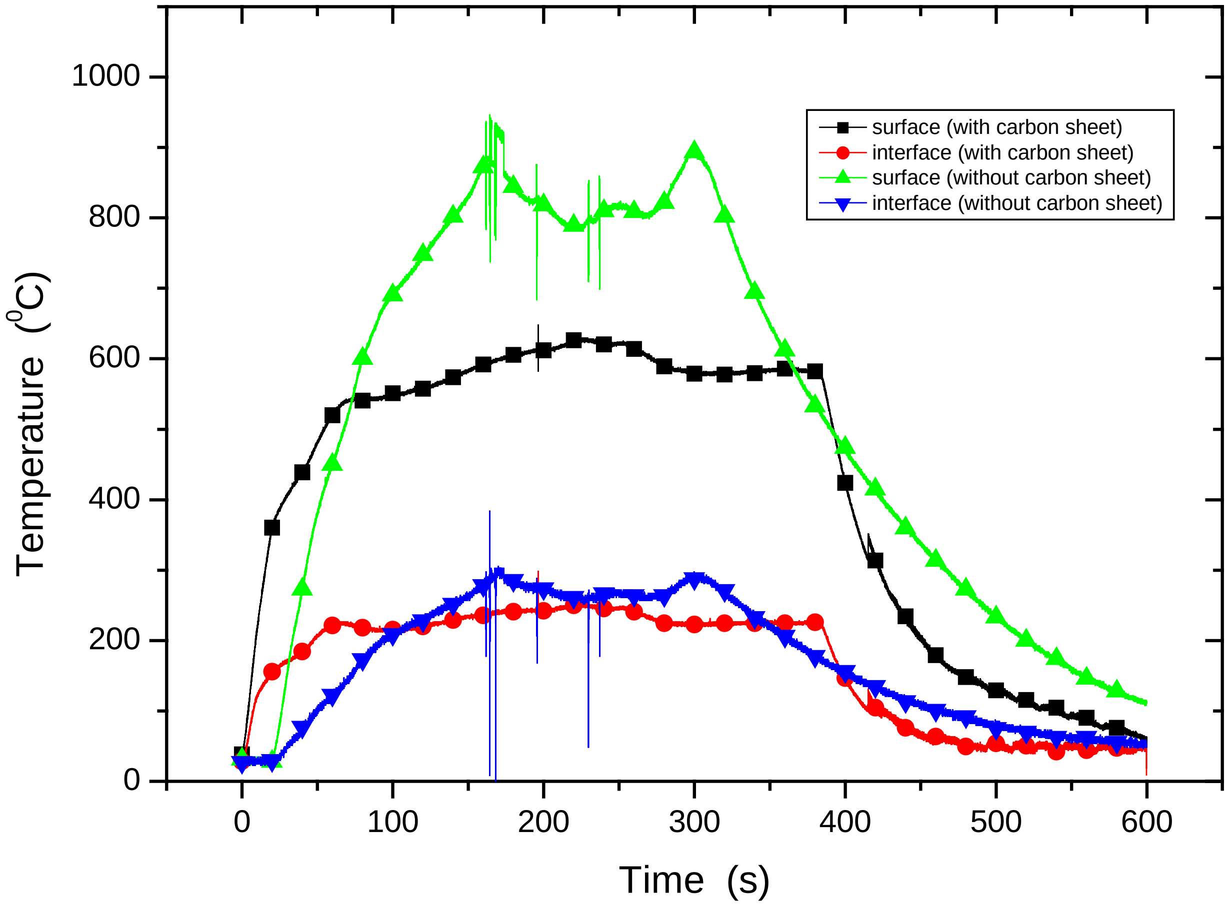
High Heat load test and simulation results



Temperature dependence of heat flux under 6m^3/h water flow rate. The solid legends demonstrate the tested results and the hollow legends demonstrate the calculated results by ANSYS. The interface denotes the below surface of the graphite tile.

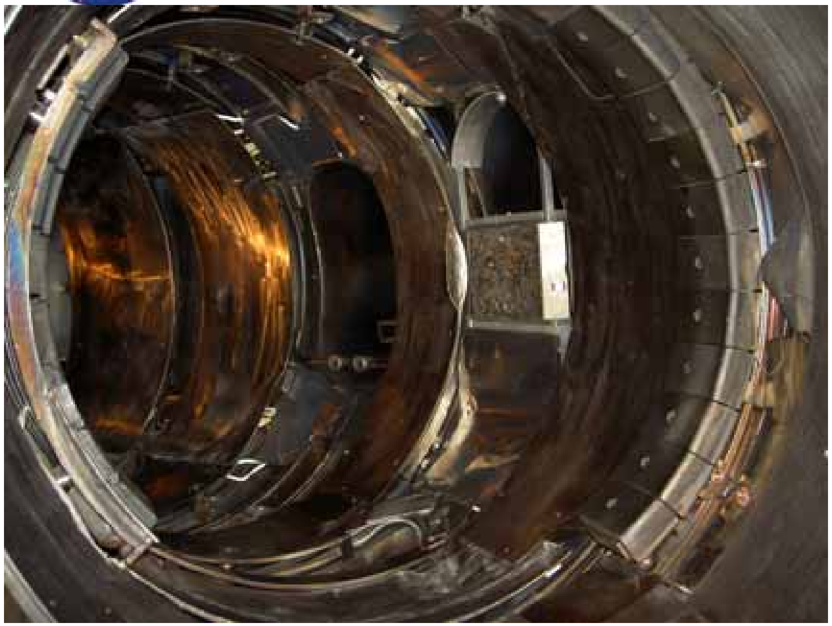


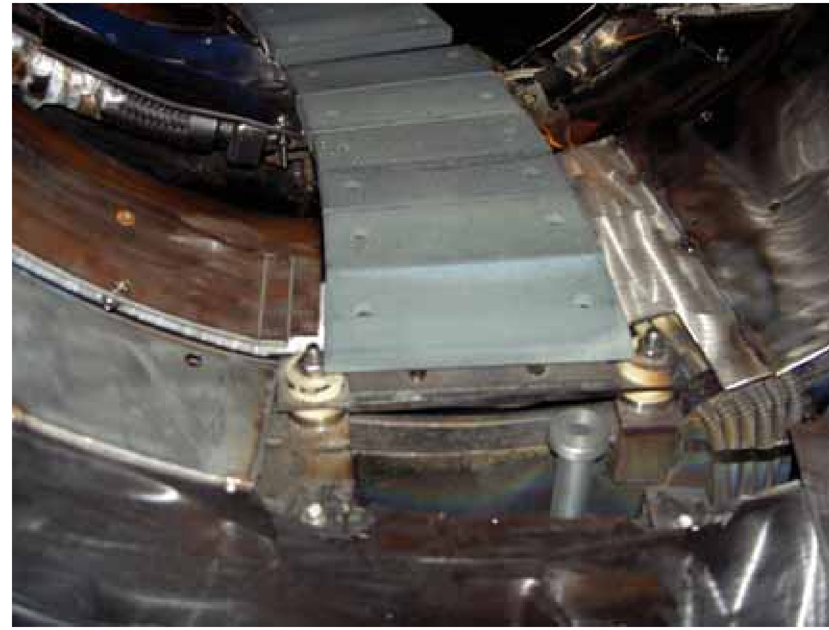
Temperature dependence of water flow rate under 3MW/m^2 heat flux. The solid legends demonstrate the tested results and the hollow legends demonstrate the calculated results. The interface denotes the below part of the graphite tile.



Comparison of the temperature between with and without soft carbon sheet as an interlayer. The conditions were 3MW/m^2 heat flux and 6m^3/h water flow.

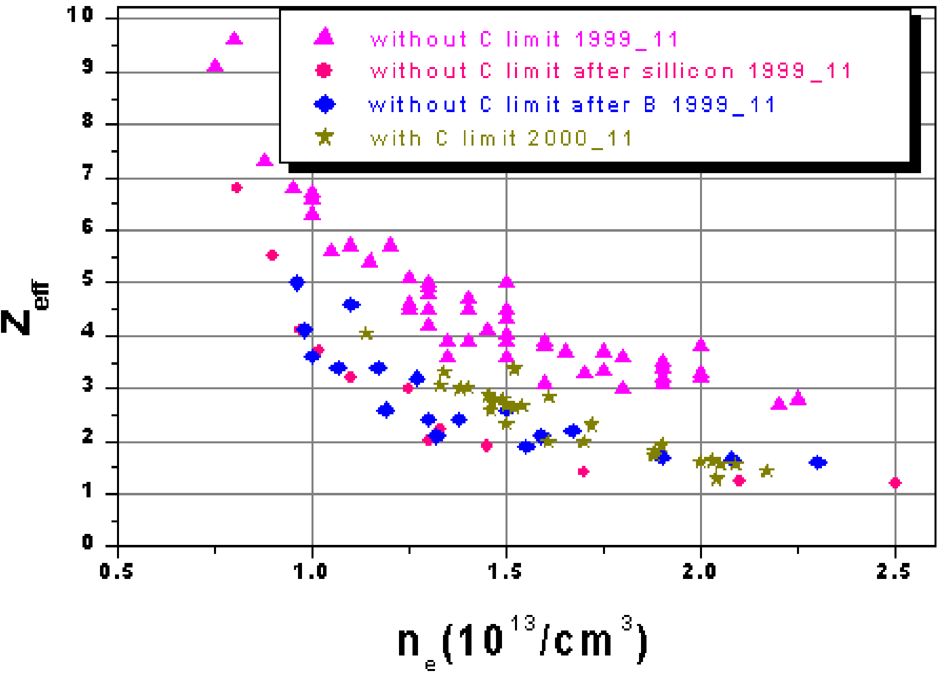
ASIPP



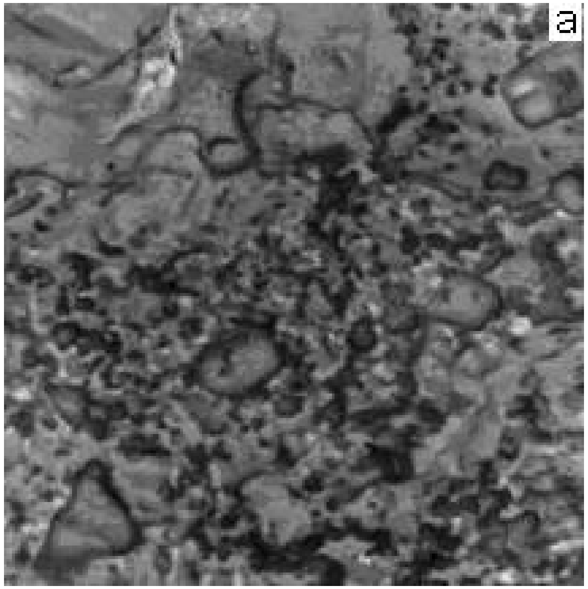


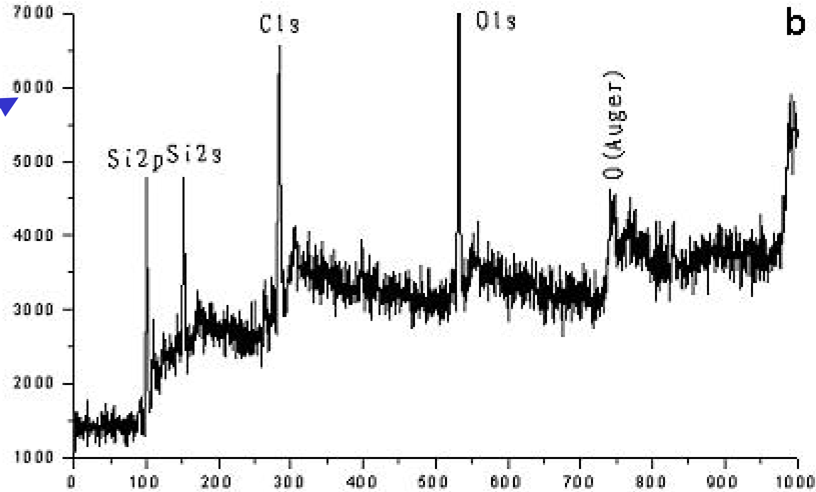
ASIPP

HT-7 limiter plasma irradiation



Limiter materials effect on Z_{eff}

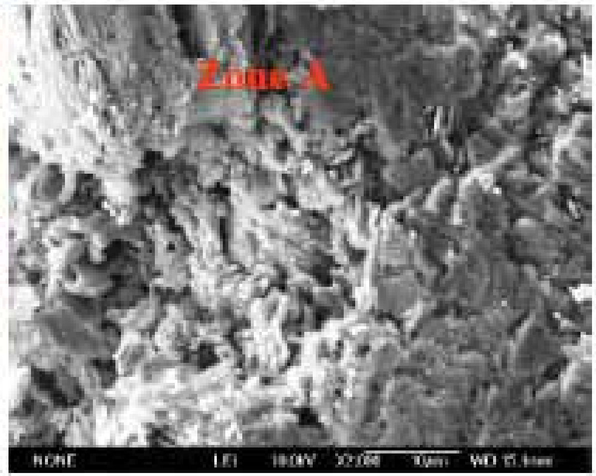


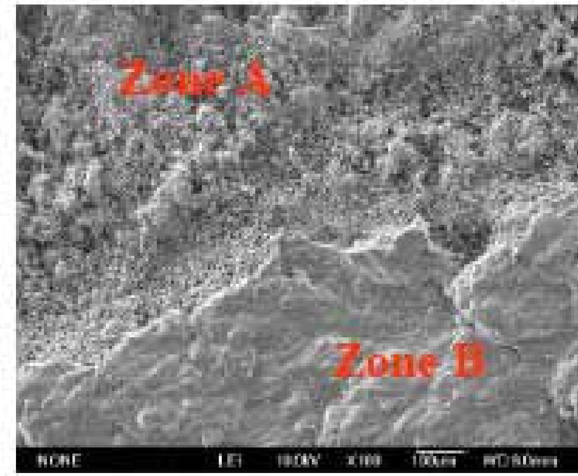


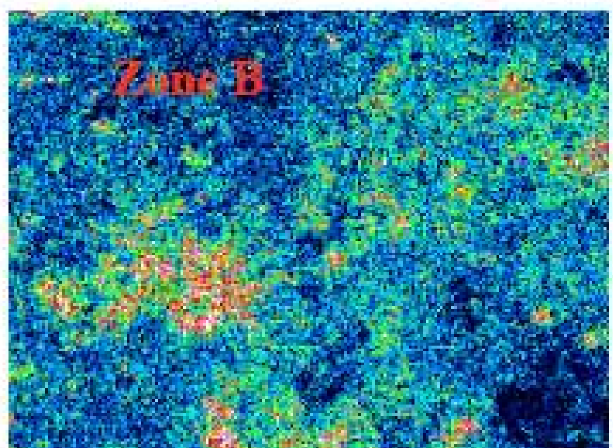
SEM surface photograph of GBST1308 sample coated with SiC after exposure to HT-7 limiter plasma (a, x500), and XBS results (b) of the surface of SiC coated GBST1308 after two experimental campaigns under the HT-7 limiter plasma irradiation

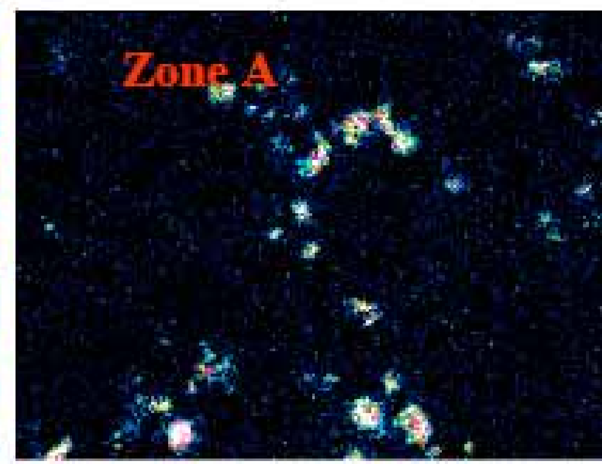
Erosions of leading tiles at both side of ICRF antenna

Zone A: heavily eroded area; Zone B: metal shine area; Zone C: lightly eroded area; Zone D: No apparent erosions and with a few dust

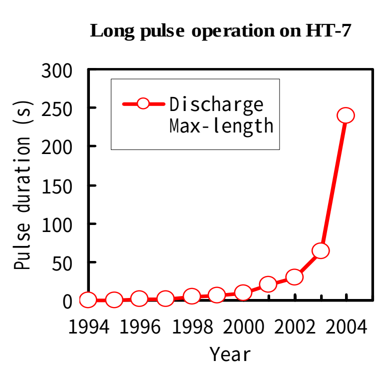






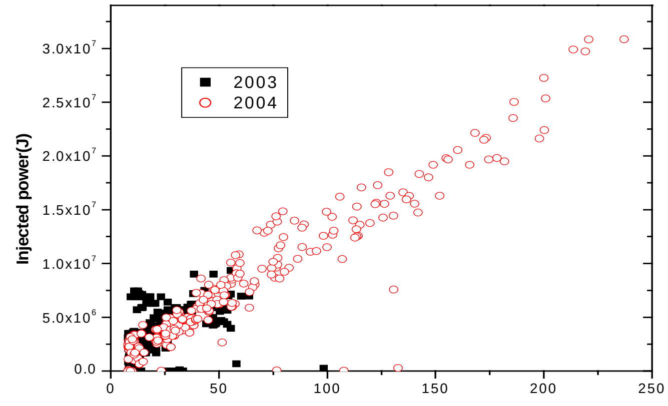


Main limiter experimental results of 2004

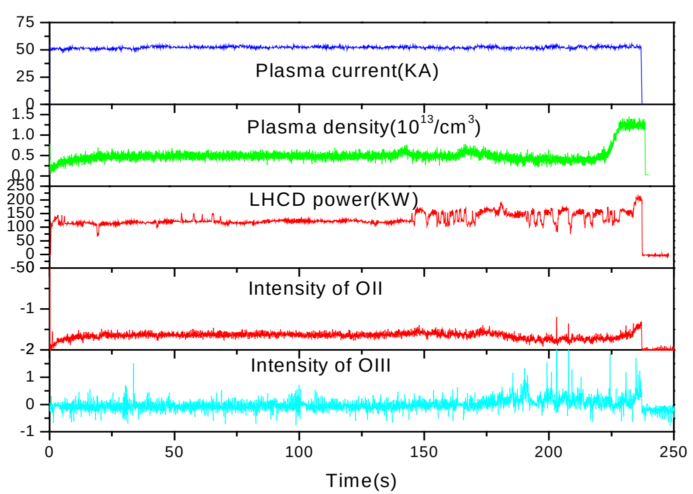


1994:First plasma
1996:Development of plasma control and diagnostics system
1998:Feedback control for plasma current, displacement and density
1999:RF wall condition
2000:Upgrade data acquisition & diagnostics
2001:Ferritic steel to reduce ripple loss; New LHCD antenna system
2002:Water cooling poloidal and belt graphite limiters
2003:Water cooling toroidal double-ring graphite limiters

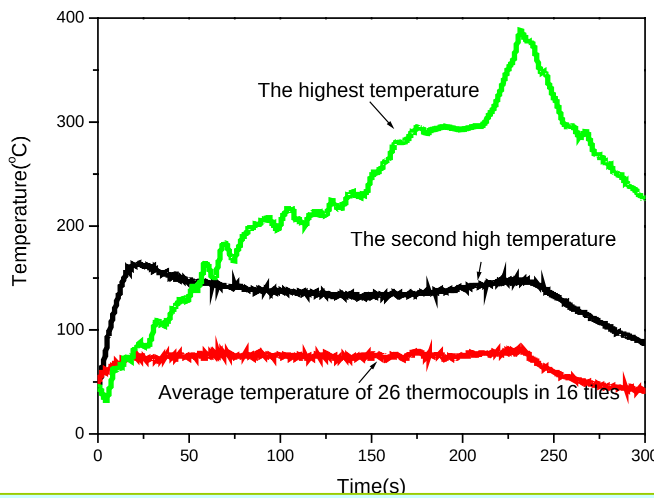
Long plasma operation on HT-7 in the past ten years



Plasma duration and LHW injected energy in 2003 and 2004 campaigns of HT-7



Main parameters of the long plasma (237s)



The temperatures detected by thermocouples (inserted at 3mm to limiter surface)

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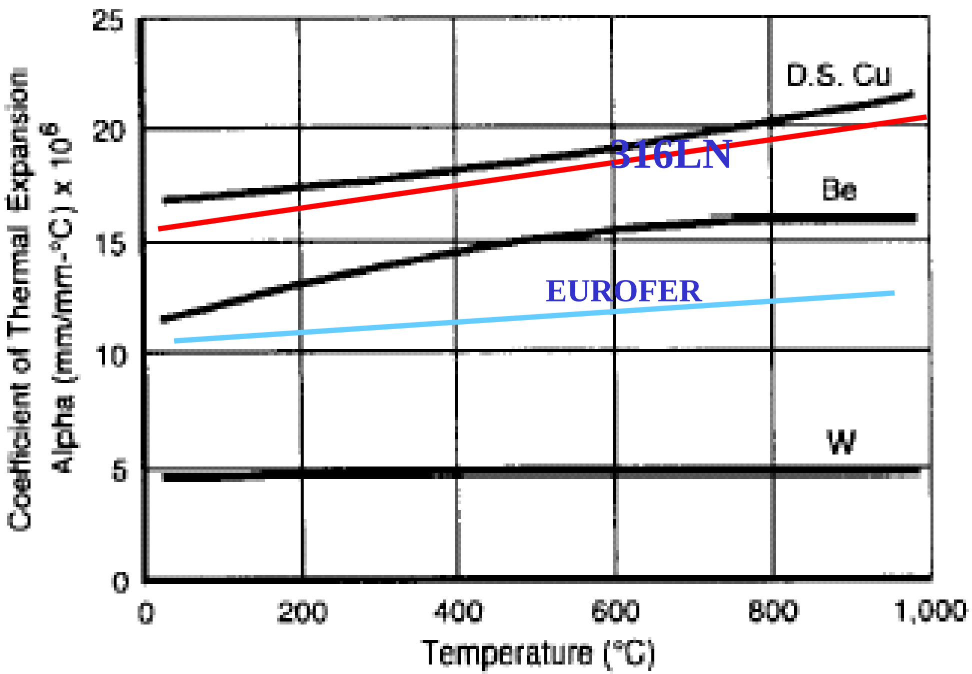
Difficulty for W based PFC

How to fabricate PFM with excellent properties (Ductility, DBTT).

How to join with heat sink

(such as copper alloy).



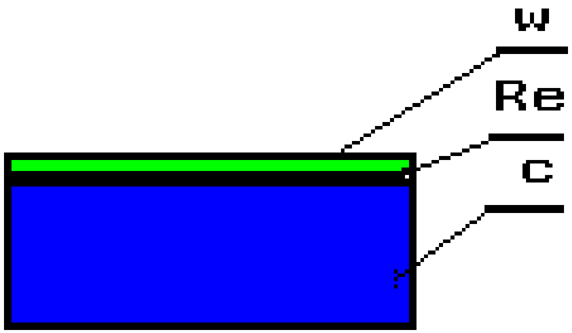
Tungsten has low CTE

(coefficient of thermal expansion)

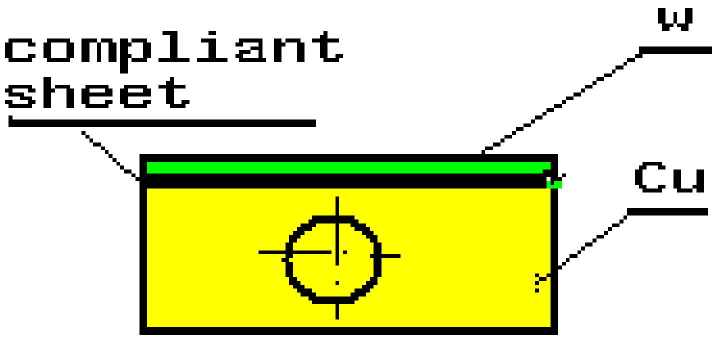
J.W. Davis, J. N. Mater. 233-237(1996) 604-608

Main properties of W and Cu

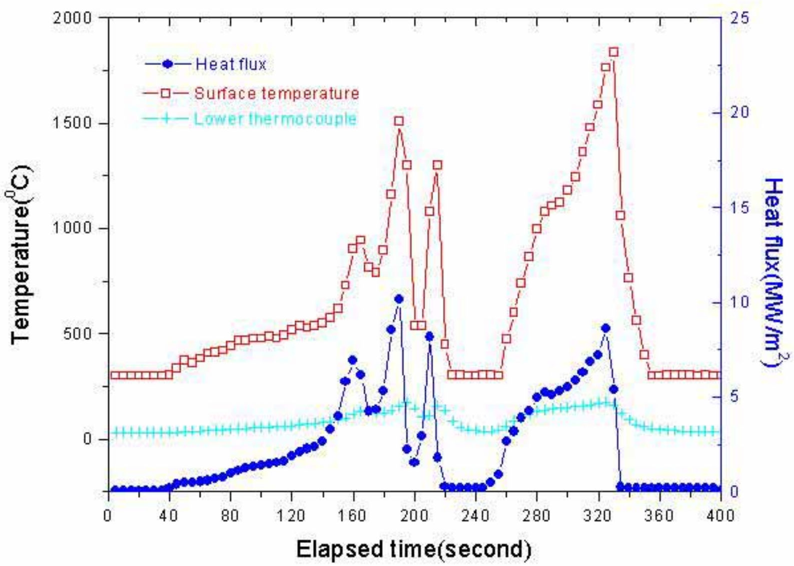
Materials	Density (g/cm^3)	Melting point (℃)	Thermal conductivity (W/mk)	Thermal expansion Coefficient (10^{-6}/℃)
W	19.3	3410	170	4.5
Cu	8.9	1083	393	17

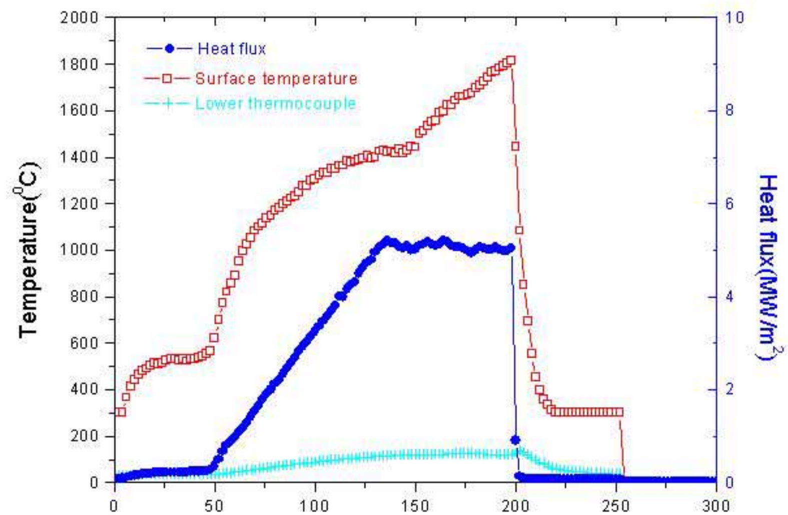


CVD-W coating on graphite（Re as a interlayer)



Tungsten and Cu blast compound


Heat flux
Surface temperature
Lower thermocouple
Temperature(°C)
Heat flux(MW/m²)
Elapsed time(second)


Heat flux
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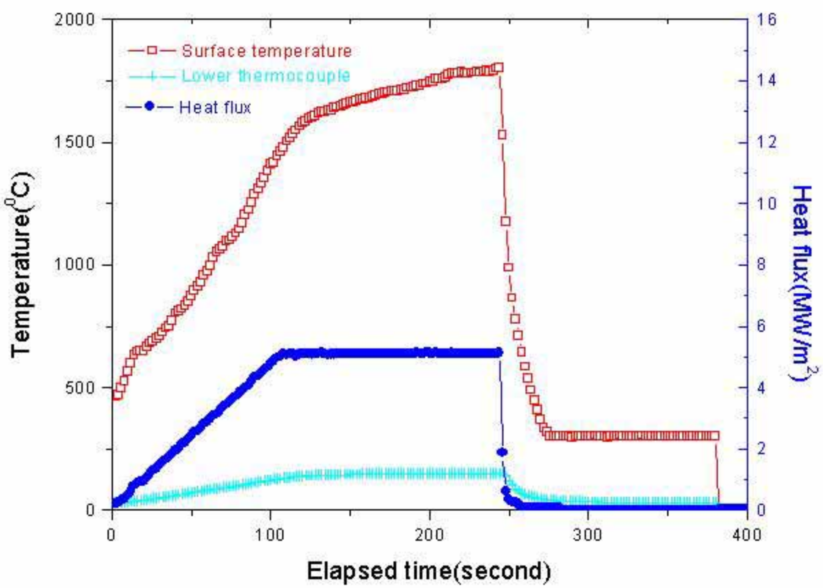
Surface temperature
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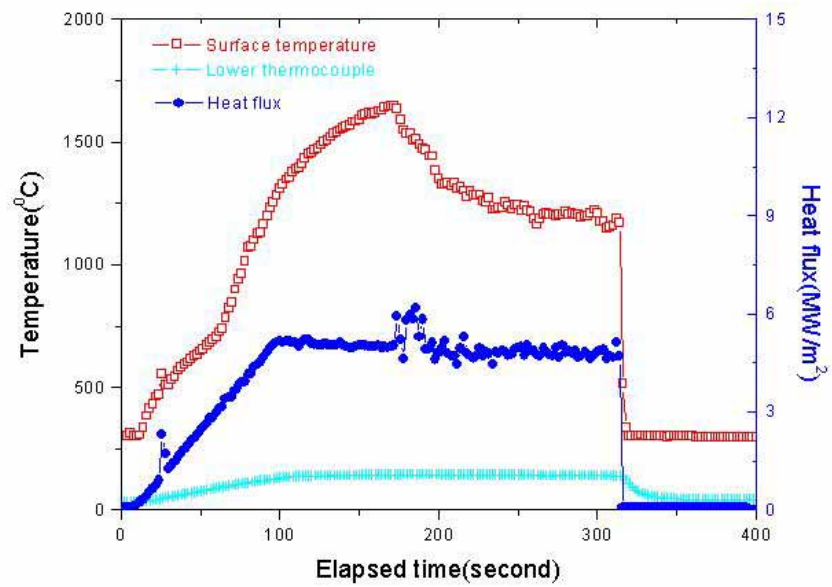
Elapsed time(second)


Surface temperature
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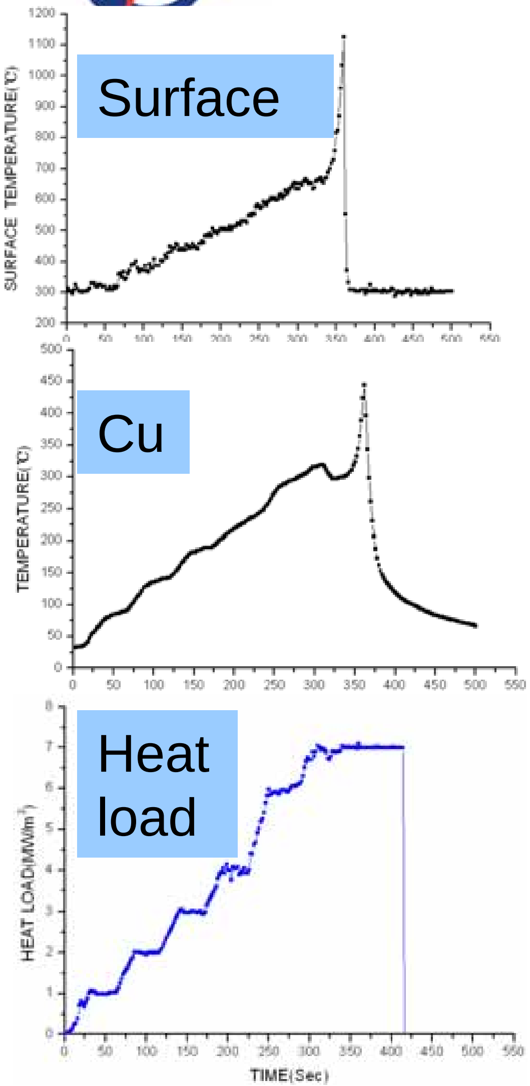
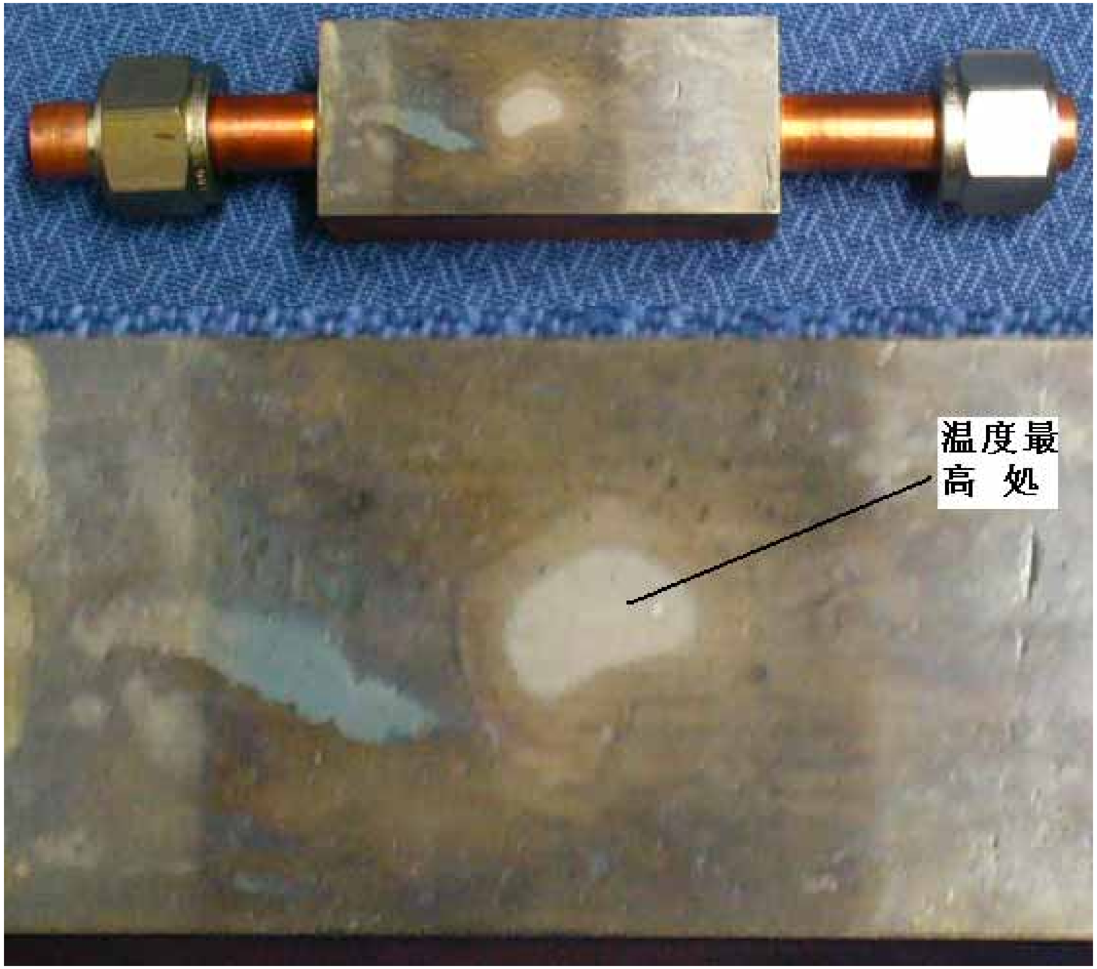




$T_S 561^0C$，铜的温度416^0C

The temperature at the center of the surface (bright point) rised rapidly, then test stoped

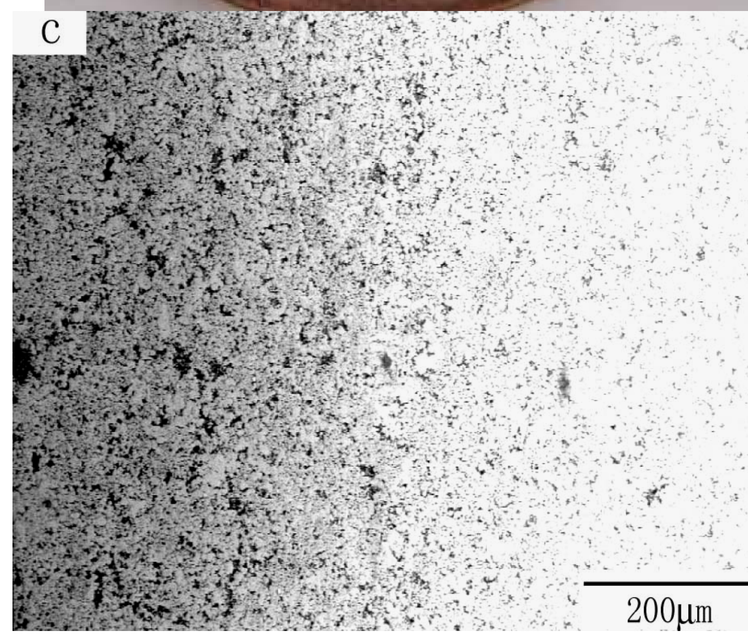
Infiltration-then joining method

This process includes three steps:

Making a porous graded W skeleton

Infiltration with liquid Cu in Vacuum, at 1300°C, 1h

By using W powder with different particle size (3, 7, 15 μm for each layer). and pore additive, heating at about 1200 °C.



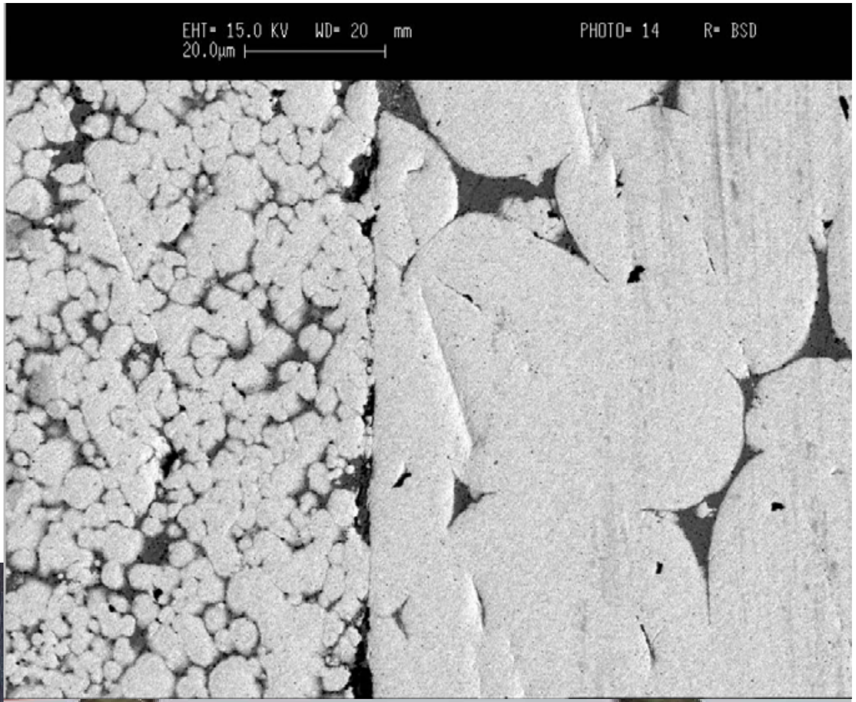
SEM micrographs
W/Cu transition layer

Joining W plate on the

W-rich surface of the specimen,

By blast compound or

Welding 900°C, 30Mpa, 1h



Conclusions

After evaluation and integration into PFC in HT-7 limiter plasma irradiation experiments, the main conclusions can be primarily drawn as following:

1. By optimization, A triply doped graphite of GBST1308 with thick SiC gradient coatings can be used as PFM in the first phase of the EAST device;
2. A pile of doped graphite used as PFC under steady state high heat flux and HT-7 limiter plasma exposure have been carefully investigated. the longest discharge duration has been more than 237s, edge recycling, plasma density and impurity can be easily handled;
3. By properly design, mechanical joining PFC, can also effectively realize heat removal not more than 1-2MW/m^2. These results have demonstrated that new carbon based plasma facing components will be an attractive choice to make them competitive with other candidate materials for the first wall of fusion device.
4. For heat flux more than 1-2MW/m^2, this mechanically joined carbon based PFC can not meet the requirements of steady state operation; 1-2 mm thick tungsten coating is now under consideration, but carefully material design, manufacture and evaluation should be further investigated.

谢谢大家！

Thanks for your attention!