Innovative Tokamak First Wall and Divertor Material Concepts

“What surface materials should be considered for CTF/FDF and DEMO?”

by
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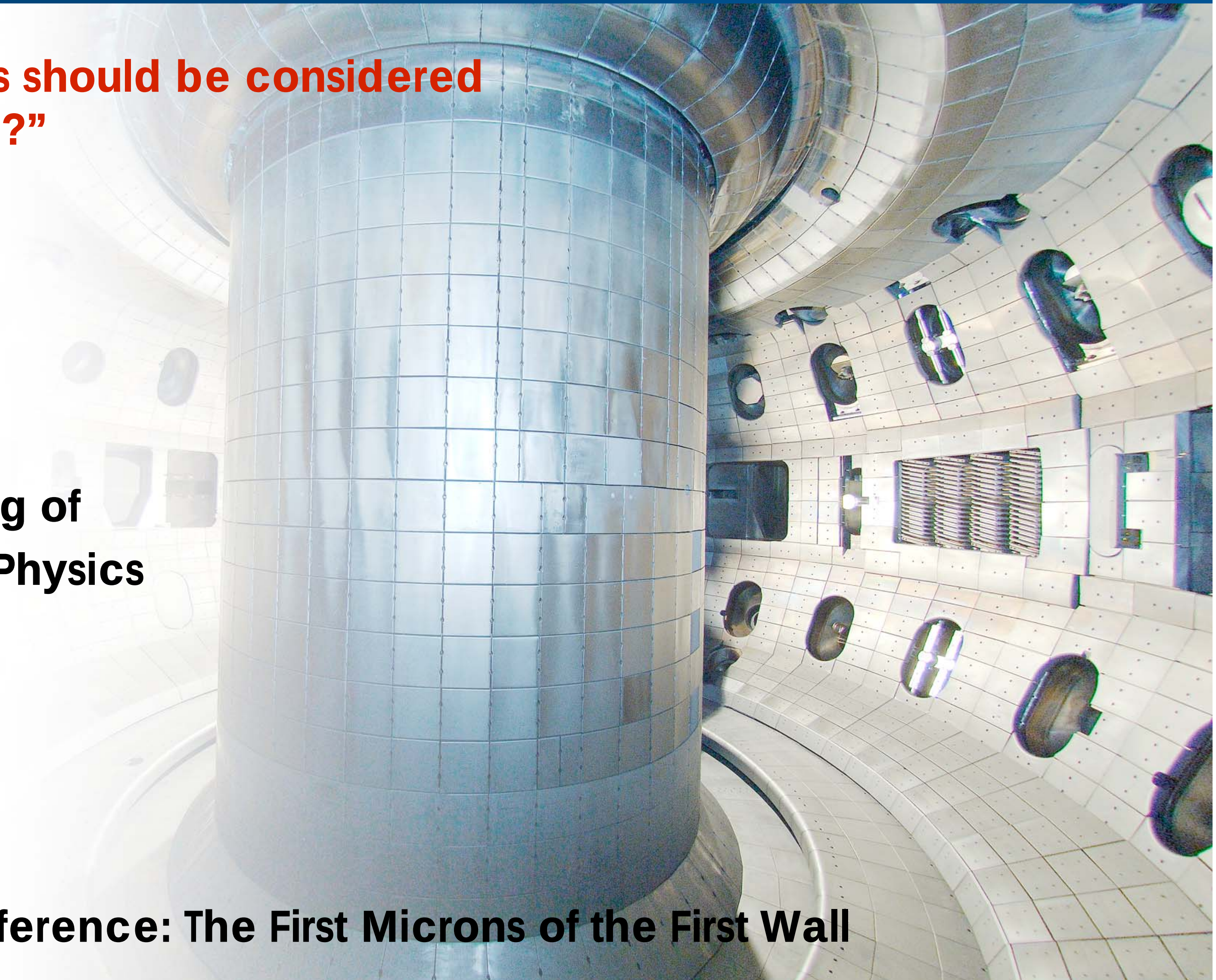


Mini-conference: The First Microns of the First Wall

Can Conventional PFC Materials be Extended to DEMO?

Some known properties:

- **Carbon**…high physical & chemical erosion rates, radiation damage, high tritium inventory

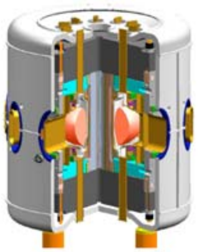
- **Mo**… lower physical erosion rate, melting, radiation surface damage and possible high trapped tritium inventory

- **W**… lowest physical erosion rate, melting, radiation surface damage and possible high trapped tritium inventory

- **Be**…moderate physical erosion rate, melting, radiation damage …0-3% swelling at ~10 dpa 3%-10% swelling at ~30-100 dpa

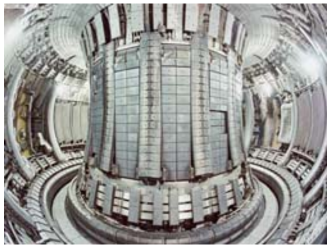
(ITER fluence < 3 dpa)

DIII-D: C

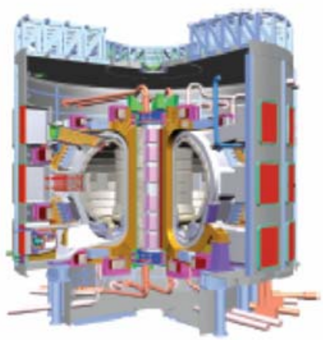


C-Mod: Mo

AUG: W



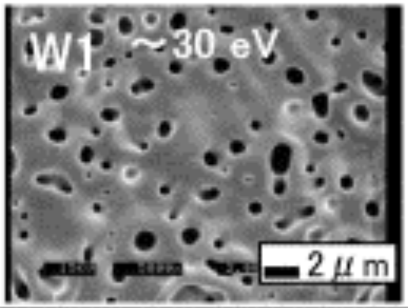
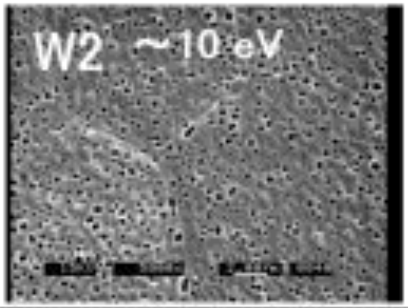
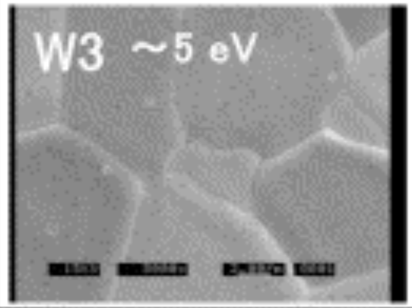
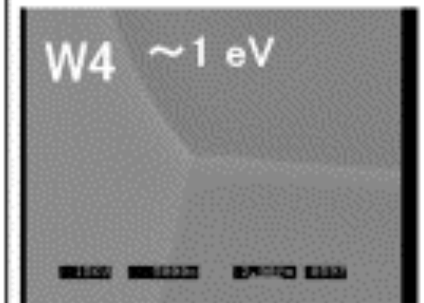
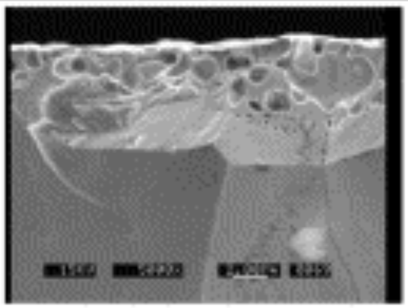
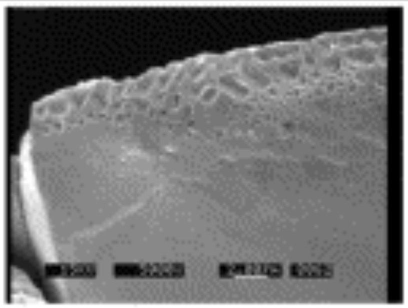
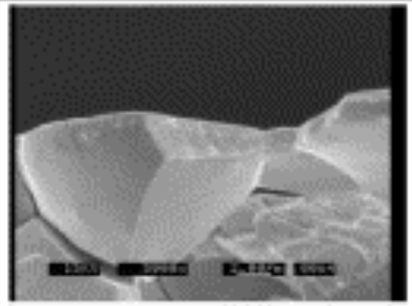
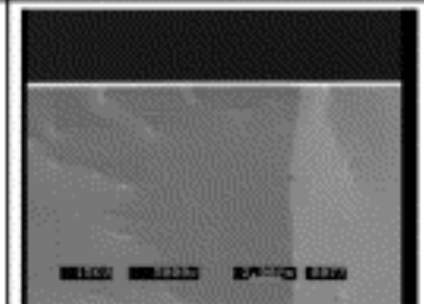
JET: Be & W (C)



ITER: C, Be & W

Are Mo and W the most suitable surface materials for DEMO?

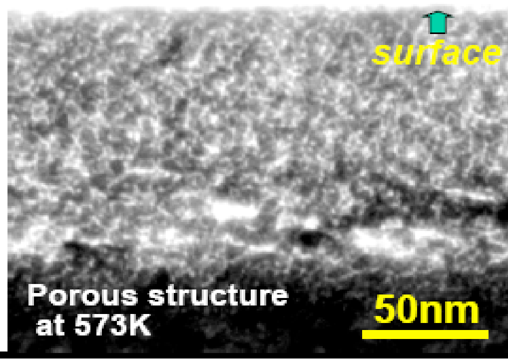
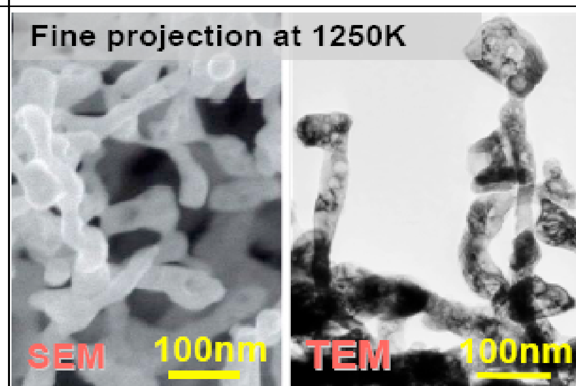
Bubbles and Holes Formation on W Surface @ > 10 eV
Low Energy He Irradiation in Plasma Simulator NAGDIS-H

Fluence Ion flux Time Temperature	2.6×10^{27} /m^2 3.7×10^{23} /m^{2}s 7200 s 2100 K	0.9×10^{27} /m^2 1.2×10^{23} /m^{2}s 7200 s 2600 K	0.8×10^{27} /m^2 1.1×10^{23} /m^{2}s 7200 s 2200 K	0.8×10^{27} /m^2 1.1×10^{23} /m^{2}s 7200 s 2950 K
Surface				
Cross section				

Nishijima, D. / Ye, M.Y. / Ohno, N. / Takamura, S. ,
Journal of Nuclear Materials, 329, p.1029-1033, Aug 2004

Formation of Blistering @ keV and Fine Hairs at 10-100 eV From He Ions on Mo and W Mirrors

Studies on He Irr. Effects on Optical Reflec.

	1st Wall Relevant Conditions	Divertor Relevant Conditions
Research G.	Yoshida Lab. (Kyushu U.)	Takamura Lab. (Nagoya Univ.)
Material	Mo	W
Irr. Temps.	R.Temp.~873K	1250K~3000K
Ion Energy	1.2keV, 8keV, 14keV	10eV~100eV
Ion Fluence	$\leq 3\text{x}10^{22}He^{+}/m^{2}$	$\leq 4\text{x}10^{27}He^{+}/m^{2}$
Mechanism of Blackening	•Blistering •Porous structure by nm-size He bubbles	•Fine projections (a few 10nmϕ) at 1250K •Projections (a few 100nmϕ) and pin holes (~1μmϕ) above 1500K
Micro-structure	Cross sectional view  	

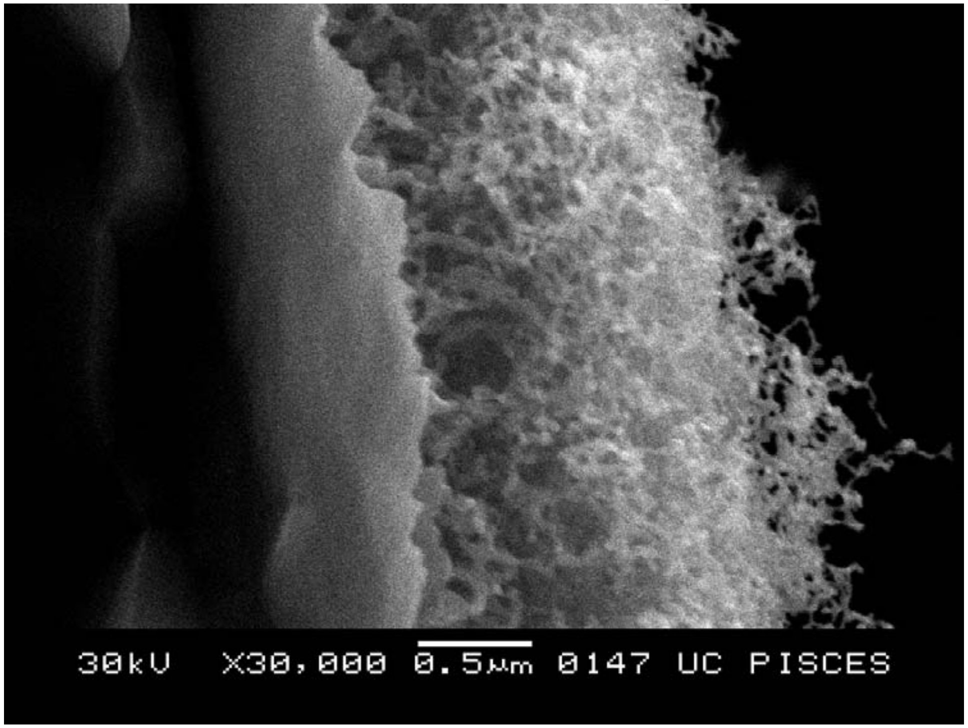
⇨ A few hundred ITER 400 s discharges

Courtesy of Prof. N. Yoshida, Kyushu U.,
IEA 12th ITPA Meeting on Diagnostics, PPPL, March 2007

Similar Morphology Change on W Surface Has Been Confirmed in PISCES-B Pure He Plasma

PISCES-B: pure He plasma

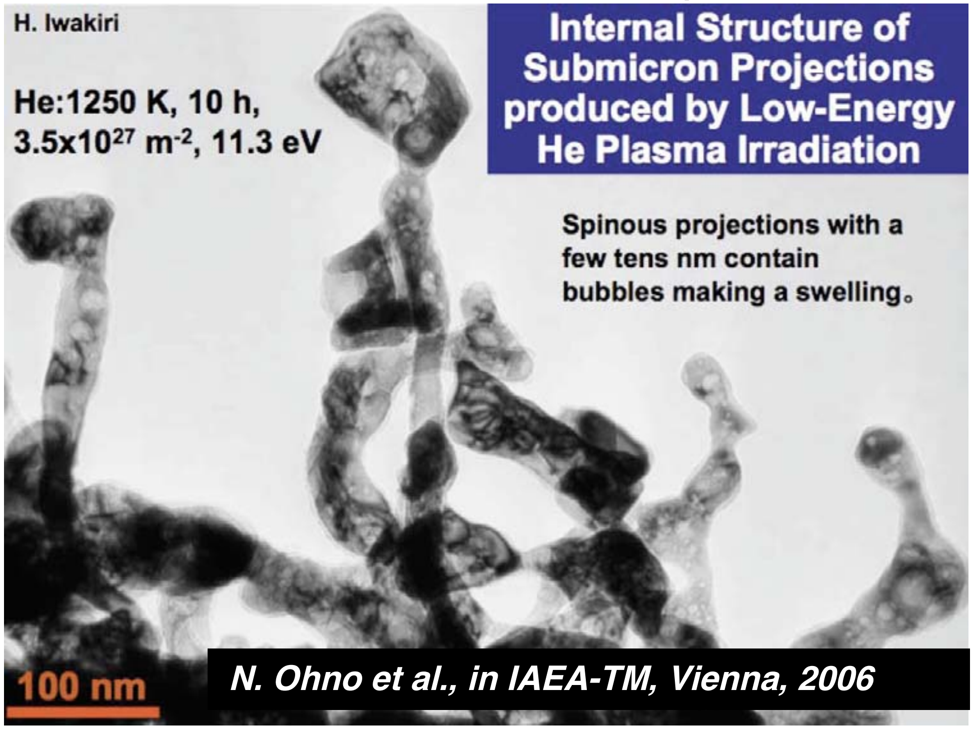
T_s = 1200 K, Dt = 4290 s,
Fluence = 2×10^{26} He^+/m^2, E_i = 25 eV



Scanning electron microscope (SEM)

NAGDIS-II: pure He plasma

T_s = 1250 K, Dt = 36,000 s,
Fluence = 3.5×10^{27} He^+/m^2, E_i = 11 eV



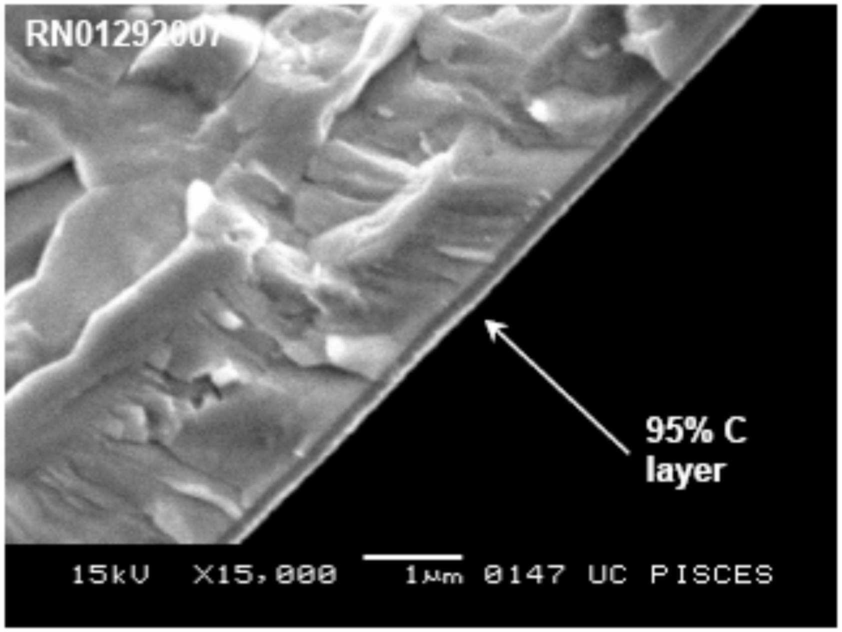
Transmission electron microscope (TEM) in Kyushu Univ.

Courtesy of Dr. M.J. Baldwin, UCSD, PFC Meeting, ANL, June 4-7, 2007

C Plasma Impurities Can Inhibit Morphology Change with D_2-He with C Discharges

E_i = 15 eV, T_s = 1100 K, Fluence = 10^{25} He^+/m^2,
n_{He+}/n_e ~ 10 %, n_{C+}/n_e < 0.1 % Δt = 3600 s

D_2-He with C



Similar results were obtained with Be and could be projected for B

At E_i=15 eV, C deposited on W has not been sputtered away

Goals for the Selection of Chamber Surface Materials From Present Machines to DEMO - 1 of 2

Experimental machines like: DIII-D, C-Mod, JT-60, JET, AUG, TEXTOR ...etc

- Withstand ELMs and Disruptions
- Minimize oxygen and impurities contamination, establish low Z_{eff}
- Ease of wall conditioning
- Minimum fuel dilution from the edge
- Minimum core and edge radiation
- Safe and low cost

(Approach: C, W, Mo wall with different means of boronization or siliconization)

Superconducting coil devices like LHD, KSTAR and EAST...long discharges

- All of the above plus
- Wall conditioning with RF assisted coating

(Approach: C, W, Mo wall with boronization and Si-doped carbon tiles)

Goals for the Selection of Chamber Surface Materials From Present Machines to DEMO – 2 of 2

ITER…D-T discharges, more severe ELMs and disruptions, n fluence up to 0.3 MW.yr/m^2

- All of the above plus
- Control of tritium inventory

(Approach: C, W divertor, Be wall, all C and metal-wall machine proposed)

CTF and FDF… between ITER and DEMO

DEMO… more severe ELMs and disruptions, steady state operation, high neutron fluence of up to 15 MW.yr/m^2 and high He^+ fluence for 3-5 years at neutron wall loading of ~3 MW/m^2, also needs heat removal

- Most of the above plus
- Steady state operation
- Protect metallic substrate from charged particle damage, e.g. He blistering and nano-hair formation
- Minimum impacts to FW/divertor heat transfer and tritium breeding

(Approach: Unknown…will we need real-time surface material recovery?)

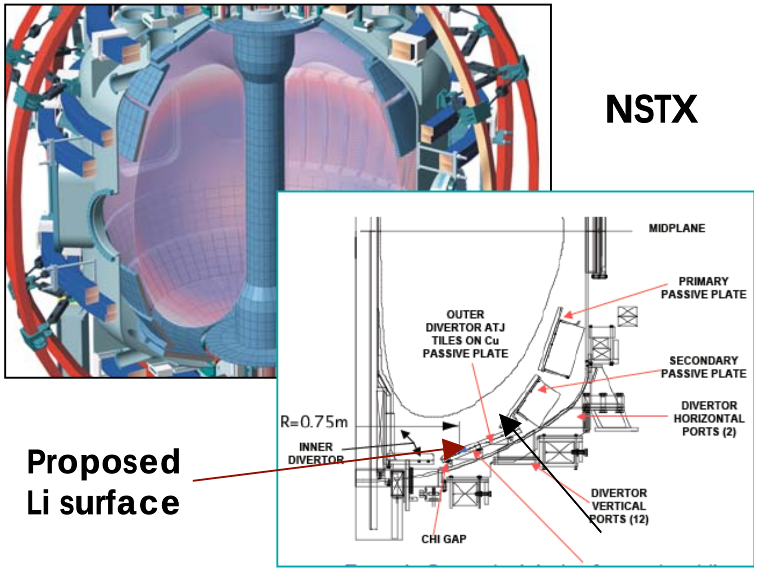
Innovative Liquid Surface PFC Material Concepts

- **Capillary Porous system (Mo or SS mesh infiltrated with Li) limiter demonstrated in T-3M, T-11M**
- **Li-surface wall and divertor, LTX and NSTX**

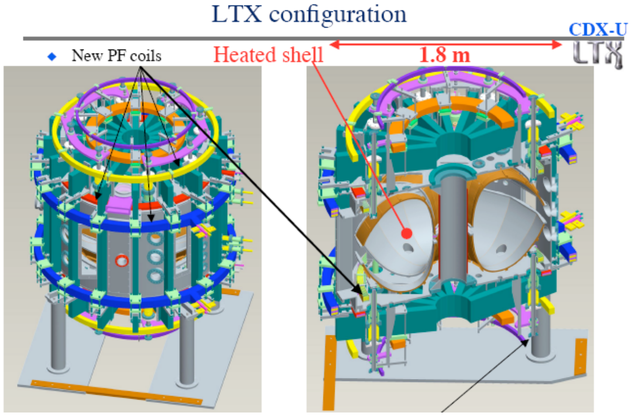
FTU limiter:
withstand~60 discharges with heat flux up to 5 MW/m2 and withstood disruptions

A. Vertkov et al., "Technological aspects of liquid lithium limiter experiment on FTU tokamak", Fusion Engineering and Design (2007) to be published

NSTX



Proposed Li surface



LTX

Pros: Renewable surface, radiation tolerance and can withstand heat flux and transients
Cons: Handling of Li and extraction of tritium, difficult to design for tokamak chamber surface coverage, and high efficiency power conversion

All High Performance MFE Machines Have Been Boronized or Siliconized

All high performance MFE machines have been boronized or siliconized:

- DIII-D, C-Mod, JET, JT-60U, AUG, NSTX, TEXTOR, JFT-2M, LHD, HT-7…etc
- Basic physics interaction between B and plasma not fully understood

(Recent results from DIII-D demonstrated many discharges can be run without boronization…P. West of DIII-D)

Tokamaks with metal walls require routine BZN for high performance

- C-MOD with Mo walls (Lipshultz, PSI 2006)
  AUG with mostly W walls (Neu et al, PSI 2006)
- Both cases routine boronizations are required to reduce high Z contamination and associated high radiated power in attempts to produce high performance discharges.

Different boron compounds (B_2H_6, $B(CD_3)_3$, $B_{10}D_{14}$, $C_2B_{10}H_{12}$) have been used with success

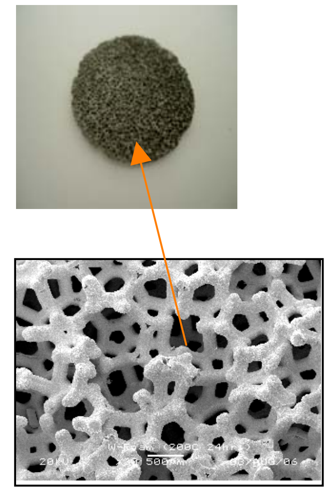
Concerns in the Use of Boronization for DEMO:

- Erosion rate of B is quite high, what to do in steady state operation?
- Can we achieve acceptable real time boronization?
- Can re-deposition rate be maintained equal to the eroded rate ?
- Thin B-layer (~100 nm) will not be able to take disruptions and ELMs in tokamaks
- Difficult to maintain B thick layer thickness >200-300 nm due to thermal miss-match
- B is a good neutron absorber: will it reduce tritium breeding and suffer radiation damage?
- B has poor thermal conductivity, how to make it applicable for high heat flux components?
- Can it be a protective layer for the metallic substrate from charge-exchange neutrals and He^+?
- What about the trapping of tritium?

"Boron infiltrated W-mesh"

The concept

- Infiltrate B into a W-mesh such that all the W surfaces are covered with B and protected from the plasma
- B coating could protect W due to low mean free path of charged particles (~10s of nm ?)
- The plasma would only see B, thereby retaining needed plasma performance
- Exposed W would have a low erosion rate
- Design example: the W-mesh can be about 2 mm thick and 50% dense, its function is to provide the source of B and the high kth of W is to provide the thermal conducting path
- It should trap enough B to withstand ELMs and a few disruptions (vaporized B layer < 100 μm/disruption ?)
- Should be able to control tritium inventory at temperature ~400-500° C
- For steady-state operation real time boronization will be needed



W-mesh

Dr. T. Noda et al.,"Boronization in future devices – protecting layer against tritium and energetic neutrals," J. of Nuclear Materials 266-269 (1999) 234-239

A Boron Tungsten-mesh Concept…2 of 2

"Boron infiltrated W-mesh"

Issues:

- **Uniform coating and deposition rate for steady state operation**
- **Similar tritium concerns as for carbon**
- **Radiation damage on W from neutrons, but may be less of a concern than from He^+**
- **B will become another consumable for DEMO with impacts to vacuum and tritium separation systems**

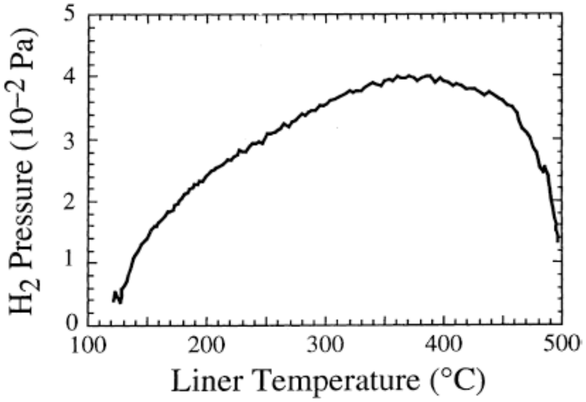
Need to demonstrate:

- **Production of B infiltrated W-mesh sample**
- **Tolerance to ELMs and disruptions**
- **Real time boronization at acceptable rate even at high erosion rate locations**
- **Trapping and release of tritium in a tokamak**
- **Physical and thermal attachment to a FS substrate**
- **High heat flux removal**
- **Robustness of the BW-mesh**

Boron Film Works as a Hydrogen-Isotope Free Wall at 400–500°C

Basic chemistry: For T>300° C, B_2H_6 rapidly decomposes into boron and hydrogen

- **It was confirmed by experiment that most hydrogen isotope atoms are re-emitted from a boron film at T 300-400°C. (For carbon film, corresponding temperature would be as high as 1000°C)**



H_2 pressure versus B-film temperature, all implanted hydrogen atoms are released ~300˚-400˚C (Noda 99)

*** B- film becomes a protective layer, hydrogen isotopes do not penetrate into the substrate of stainless steel in this temp. range. The glow discharge hydrogen implanted depth was ~10 nm in a B-film thickness of 110 nm**

We have to study impacts in a tokamak environment

Real Time Boronization Has Been Applied to Many Machines

- **Many MFE machines have tried real time boronization:**
  DIII-D, NSTX, TEXTOR, Tore Super, JT-60U, C-Mod, JFT-2M, HT-7, LHD (Rm T) “not a complete list”

- **Different B-gaseous compounds have been tried**

- **General results: reduced oxygen, He influx and impurities improved confinement**

But pulse machines will not need real time boronization

Radiation Damage to B Can Be Controlled by Isotopic Tailoring

Natural Boron, i.e. 20% B-10

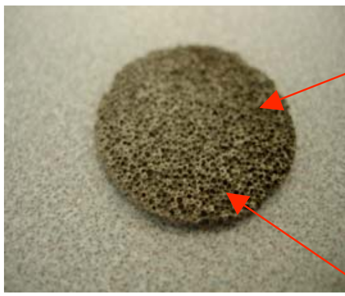
	ITER	FDF	Power Reactor
Fluence	0.38 MW.yr/m^2	3.8 MW.yr/m^2	19 MW.yr/m^2
B depletion	9.84%	19.97%	20.24%
Li	9.84%	19.79%	19.48%
Be	0.0037%	0.024%	0.109%
C	0.00008%	0.0008%	0.0042%
He		2.0056*10^5 appm	2.0873*10^5 appm
H		1.26*10^3 appm	9.253*10^3 appm

100% B-11

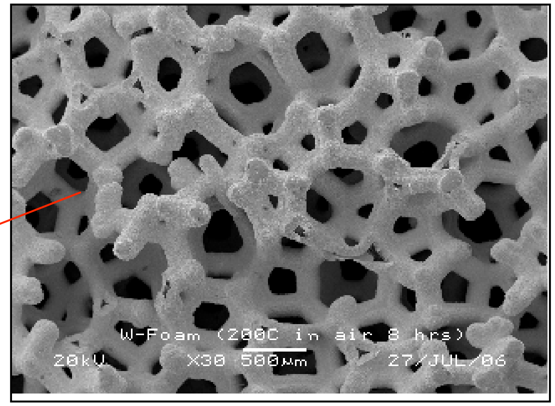
	Power Reactor
Fluence	19 MW.yr/m^2
B depletion	0.43%
Li	0.08%
Be	0.13%
C	0.005%
He	6171 appm
H	2110 appm

Courtesy of : Prof. Mohamed Sawan and Ms. Rachel Slaybaugh of UW

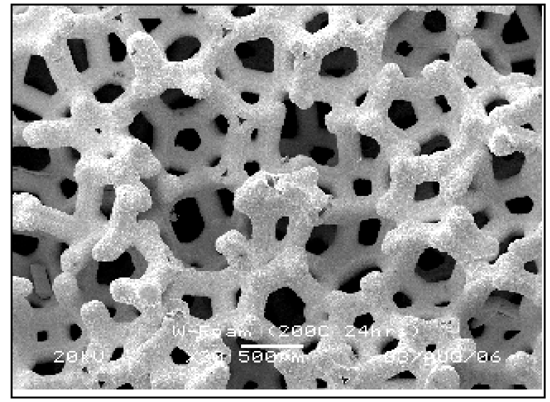
W-Form Structure: Tubular Form Containing C



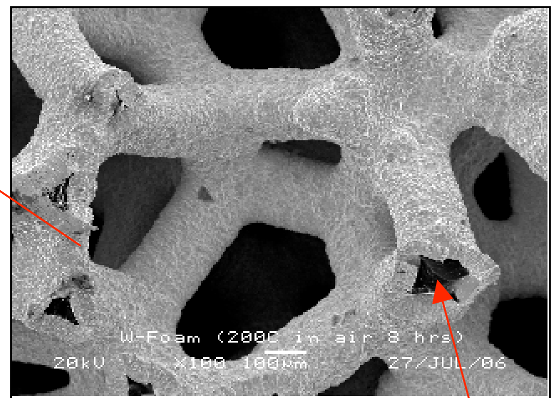
W-foam



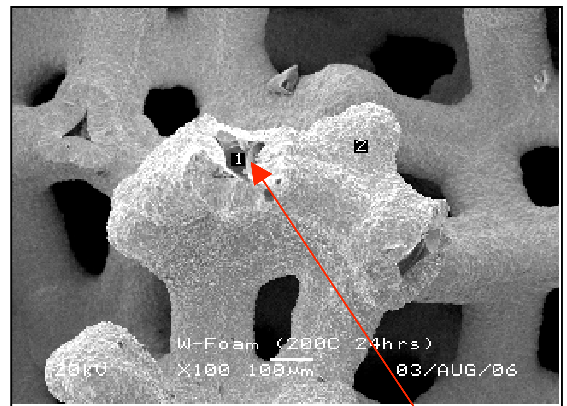
—— 500 µm



—— 500 µm



—— 100 µm

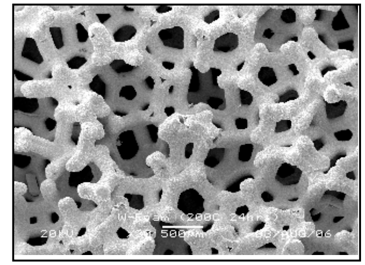


—— 100 µm

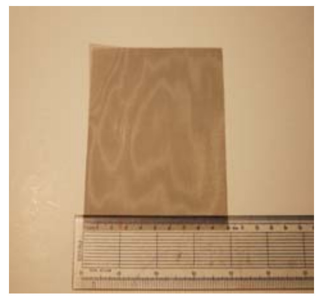
EDX analysis 95.14 wt%C, 4.42 wt% O, 0.45 wt% W 91.32 wt%C, 8.03 wt% O, 0.65 wt% W

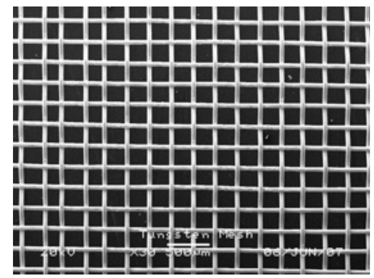
W-Mesh Options and B Infiltration

W-Foam



W-wire sheet

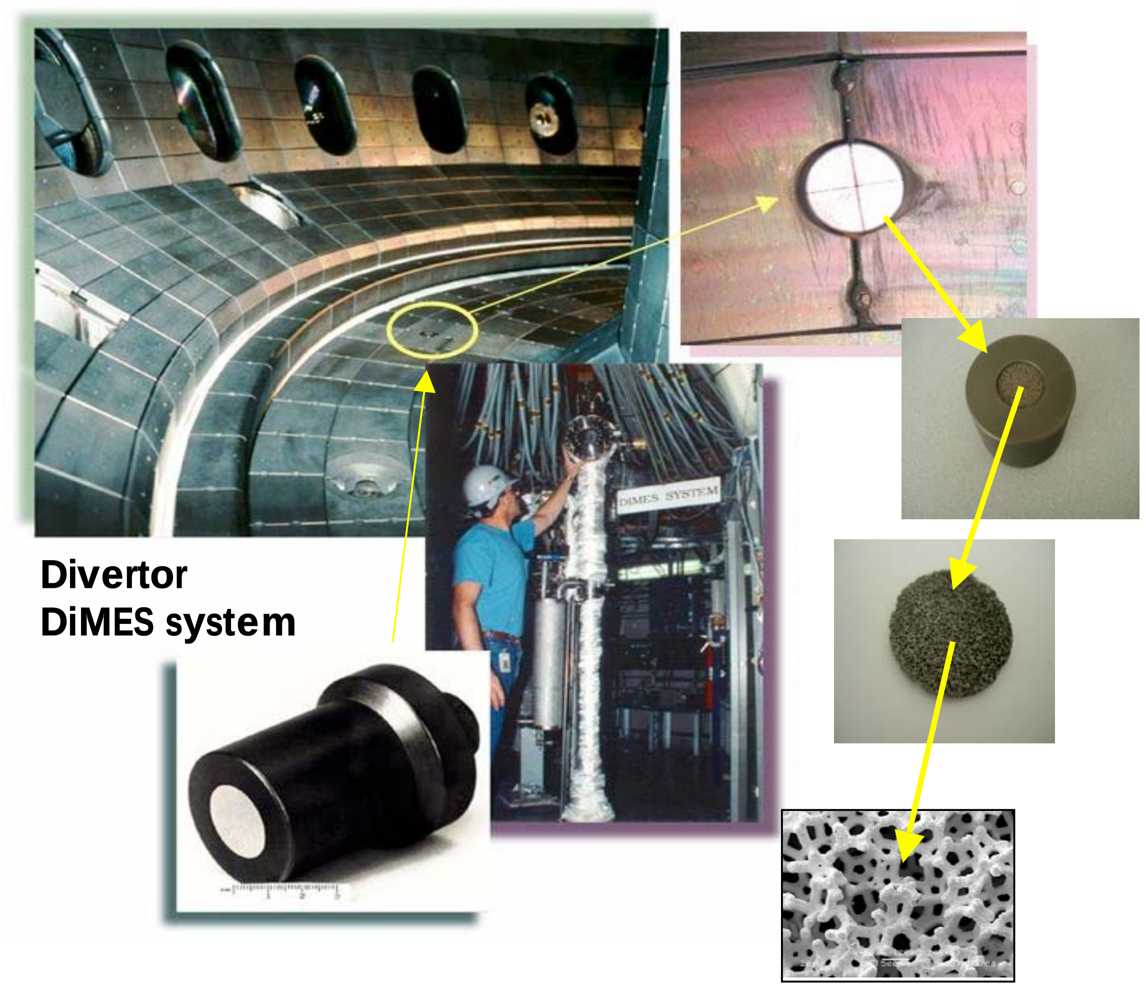


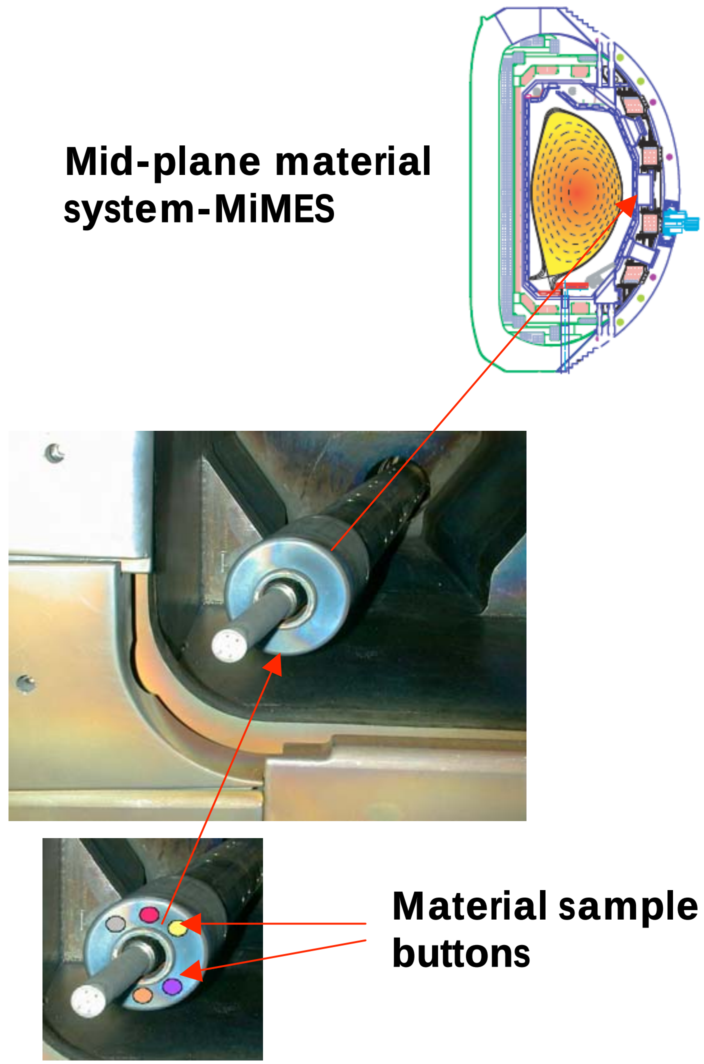


Other W-mesh forms?

B-infiltration: We are trying infiltration by magnetron sputtering (UCSD) and will consider other methods like by CVD and PVD…options open

Boron Tungsten-Mesh Concept Can be Tested with the DiMES and MiMES Systems in DIII-D





B W-mesh Concept Can Be Demonstrated by Operating Tokamaks

- Detailed migration and accountability of boron
- real time boronization: demonstration of deposition rate and necessary surface uniformity
- Accountability of tritium (D) absorption, release and distribution
- Protection of W-mesh
- Testing of BW-Mesh (e.g. DiMES and MiMES in DIII-D)

  including transient tolerance of BW-mesh, ELMs and disruptions
- Other?

Note: Real time boronization approach could also be applied to ITER

Recommendation

When considering CTF/FDF and DEMO it is prudent to consider Boron as a backup plasma facing material to W and Mo