Development of Si-W Transient Tolerant Plasma Facing Material

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DIII-D NATIONAL FUSION FACILITY

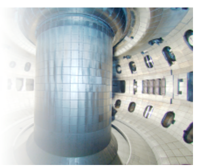
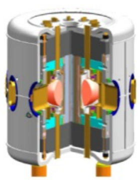
GENERAL ATOMICS

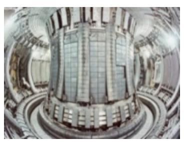
085-12/KHB/rs

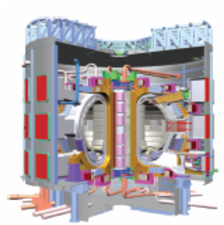
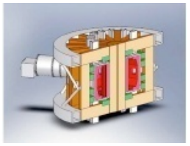
Surface Material is a Key Item for Fusion Development

Surface material is critically important to next generation tokamak devices:

- Plasma performance is affected by transport of impurities
- Surface heat removal, tritium co-deposition and inventory will have impacts on material selection for devices beyond ITER
- Radiation effects from neutrons and edge alphas, material design limits and component lifetimes will have to be taken into consideration




DIII-D	C-Mod	AUG	JET-ILW	EAST	ITER	FNSF	DEMO
C	Mo	W	Be/W	C/W	Be/W/C?	?	?
	Boronizaton	Boronization					

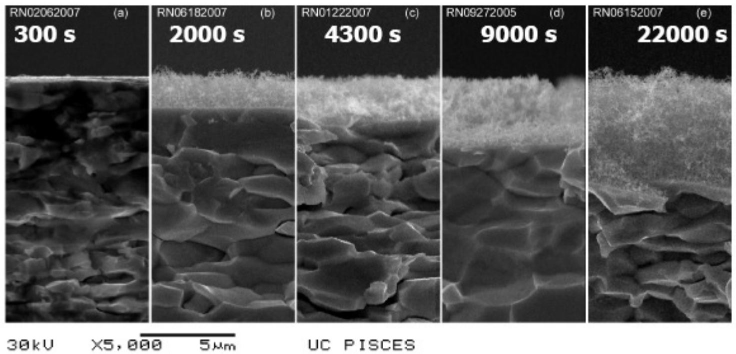
(High neutron and edge alpha fluence)

Surface material options

C and Be will not be suitable for the next generation devices and DEMO due to surface erosion and radiation damage. Presently, W is the preferred choice, but feasibility and performance issues have been identified

Significant Issues Projected for W-surface Operation Independent of Alloy Development

SEM cross-sections of W targets exposed to PISCES-B pure He plasmas.



Consistent He plasma exposures: $T = 1120$ K, $\Gamma_{He+} = 4–6 \times 10^{22}$ m^{-2}s^{-1}, $E_{ion} \sim 60$ eV

PISCES

When exposed to He at high temperature, W surface showed growth of W nano-structure from the bottom; the thickness increases with plasma exposure time

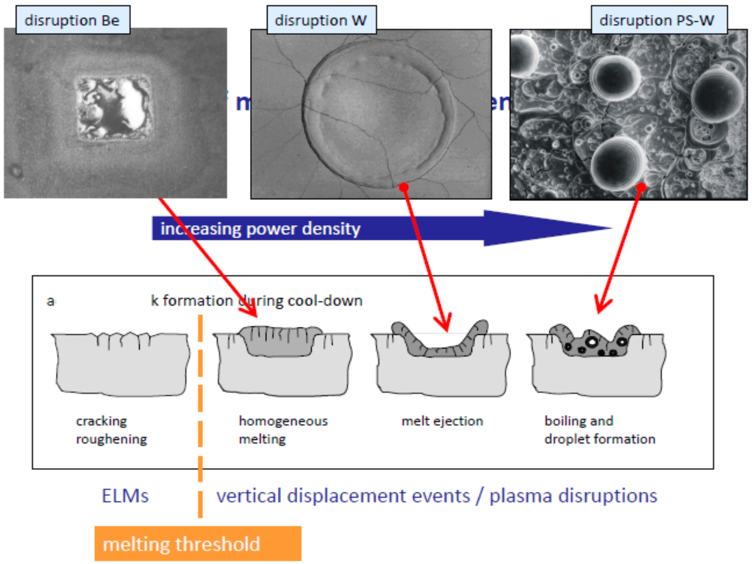
Baldwin and Doerner, Nuclear Fusion 48 (2008) 1-5

Equilibrium thickness of fuzz is expected to form in the erosion zone of a W-divertor, erosion with lower sputter yield than bulk W

Doerner, UCSD, VLT conf. call Jan. 2011

ITER disruption loading:

10-30 MJ/m^2 for 0.1 to 3 ms



Irreversible surface material damage

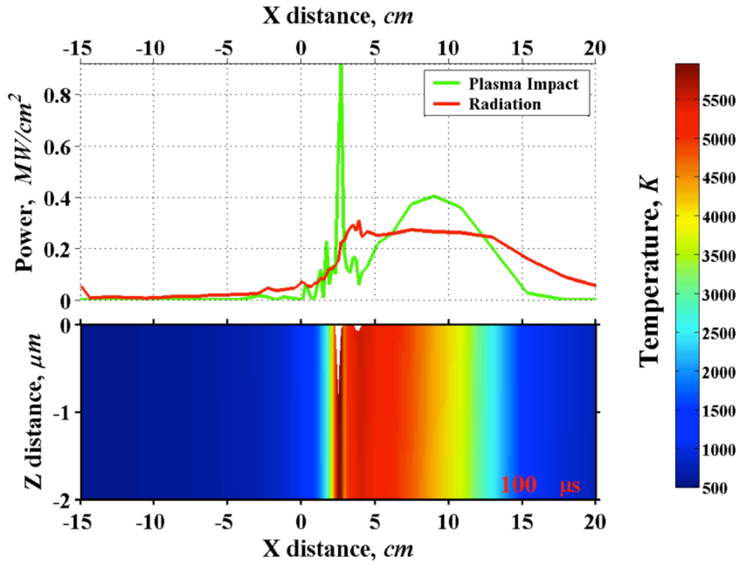
M. Rödig, Int. HHFC workshop, UCSD Dec. 2009

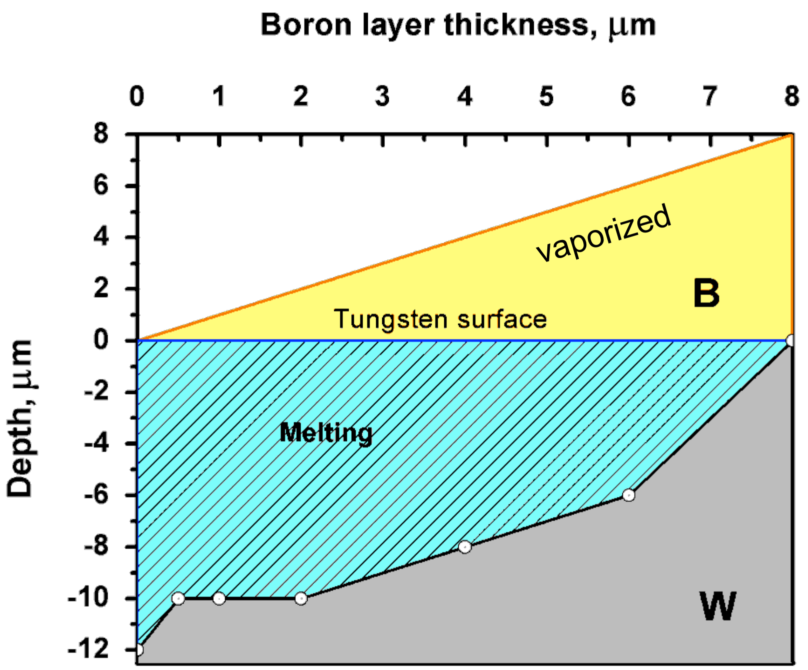
We cannot eliminate un-predicted disruptions even if disruption detection and mitigation working perfectly

Vapor Shield Effect from Boron Could Protect Substrate W Under Disruptions

Disruption condition, ITER parameters:

Energy density	$E = 25\ MJ/m^2$
Impact duration	$t = 0.1$ ms
Magnetic field	$B = 5.0$ T
Incline angle	$\alpha = 5.0$ degree



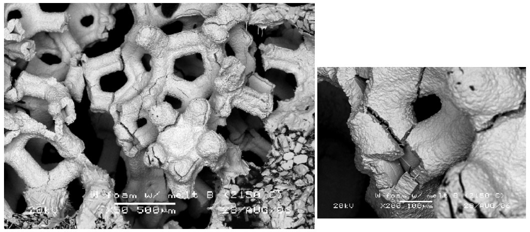


Results from Prof. A. Hassanein

Si W Samples Development History

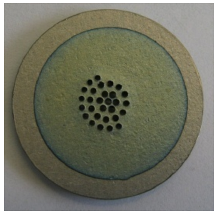
- 2008 started with W-mesh, sample damaged with melting of B @ ~2000°C
- 2009 changed from mesh to plate, and DIII-D boronization confirmed B coating thickness of 0.75 μm < 1 μm
- Switched to Si due to much better match in the coefficient of thermal expansion between Si and W
- W disc was destroyed and broken in pieces when trying to fill with molten Si @ ~1400° C
- 2010: Drilled indentations on W-buttons and the Si was filled in powder form with binder and sintered
- 2010 Si filled W buttons exposed in DIII-D to five plasma discharges
- 2011obtained new W buttons with indentations and slots
- Sample destroyed and broken in pieces during CVD Si fill mishap @ ~ 1400° C
- New CVD filled Si-W buttons exposed to six VDE disruptions & noted the formation of W-silicide eutectic

W-mesh



Damaged W-mesh

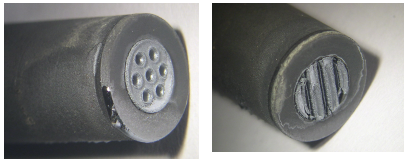
W-disc



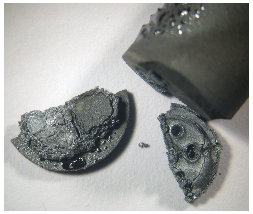
B-coating

W-buttons

W-buttons with Si



W-buttons in CVD fixture



Broken Si-W-buttons

Exposure to Four LSN Discharges and One Disruption, Surface Si Removed but Minimal Impacts Observed

Si filled W-buttons

Loaded DiMES sample
2 Si-W, 3 graphite, 2 W buttons

W-buttons with
1 mm dia. indentation

Shot 142641-142644

Sample exposed
To 4 LSN discharges

Exposed in
DIII-D lower divertor

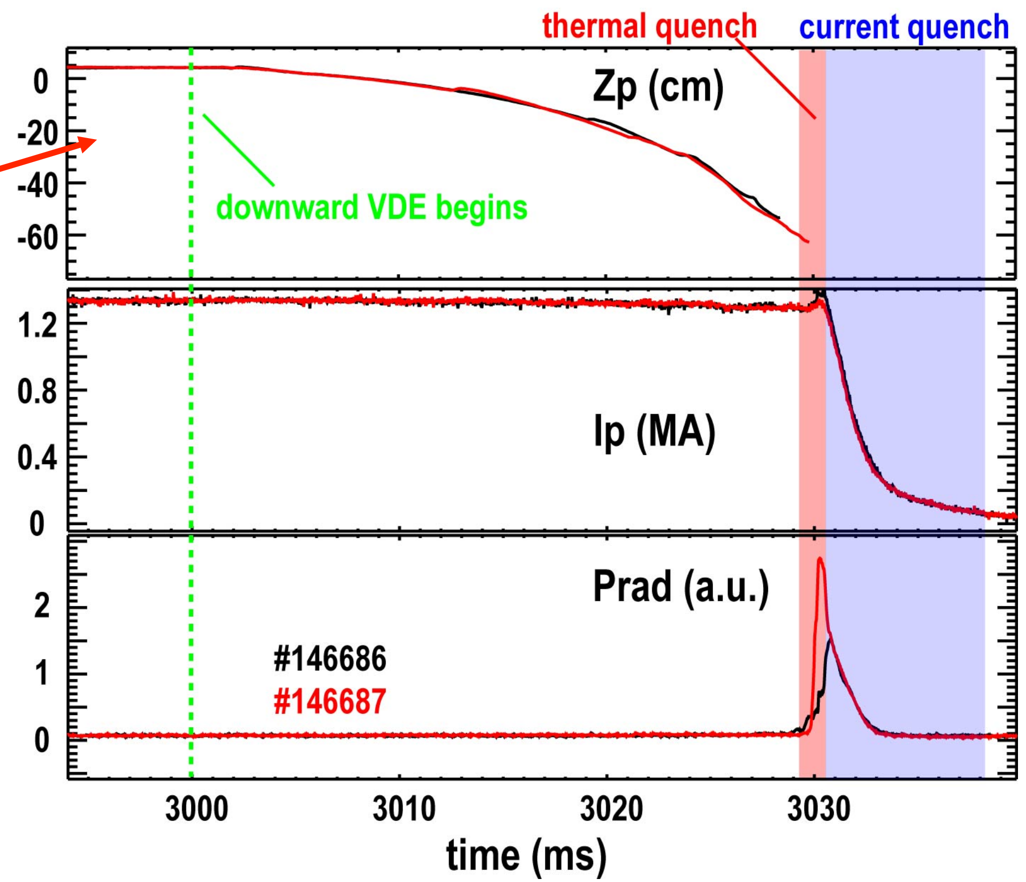
Shot 142706

After one additional disruption
shot without thermal dump on DiMES

Overview of VDE Disruption Experiments

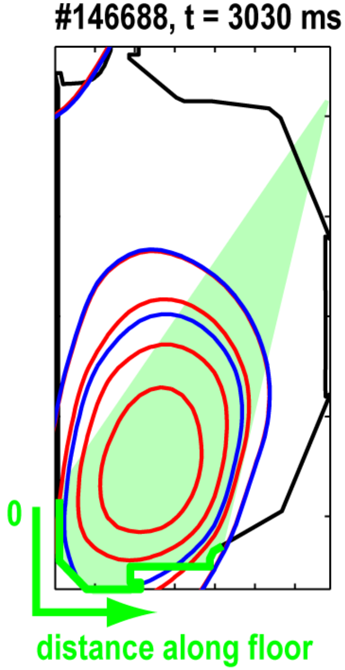
- Create repeatable VDE by turning off feedback and giving plasma slight downward kick with shaping coils
- Achieve reliable exponential growth of vertical position
- Repeat for statistics with 1.5 neutral beam (W_{th} = 0.7 MJ) and 4 neutral beam (W_{th} = 1.1 MJ) H-mode targets
- Repeat 1.5 neutral beam target and mitigate VDE at various times with neon massive gas injection "MGI" (1200 torr-l)

Reliable timing shot of VDEs



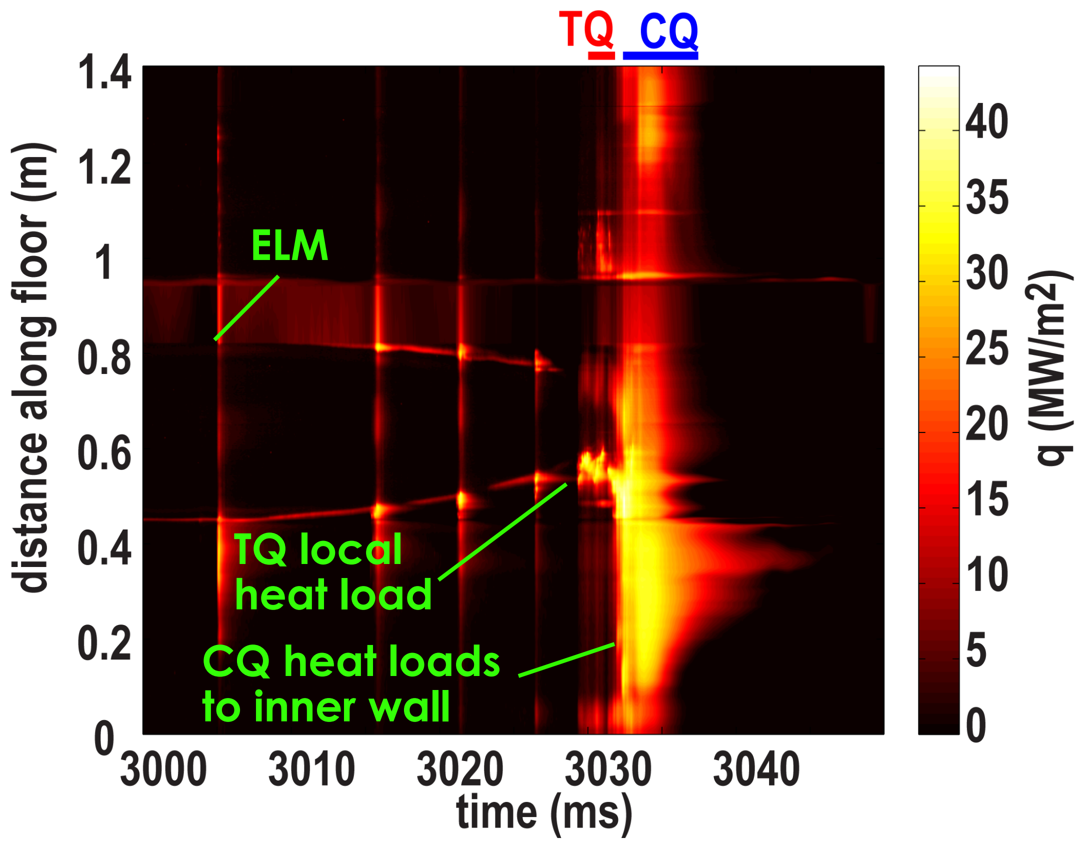
Peak Heat Fluxes in VDE Disruption to Lower Inner Wall at Start of CQ

- IR camera run in line-scan mode to achieve high time resolution.
- Heat fluxes to lower divertor can be estimated from changes in IR brightness.
- Peak heat fluxes typically occur not in thermal quench (TQ), but at start of current quench (CQ).



Viewing geometry of IR camera at R+2, ϕ = 60˚

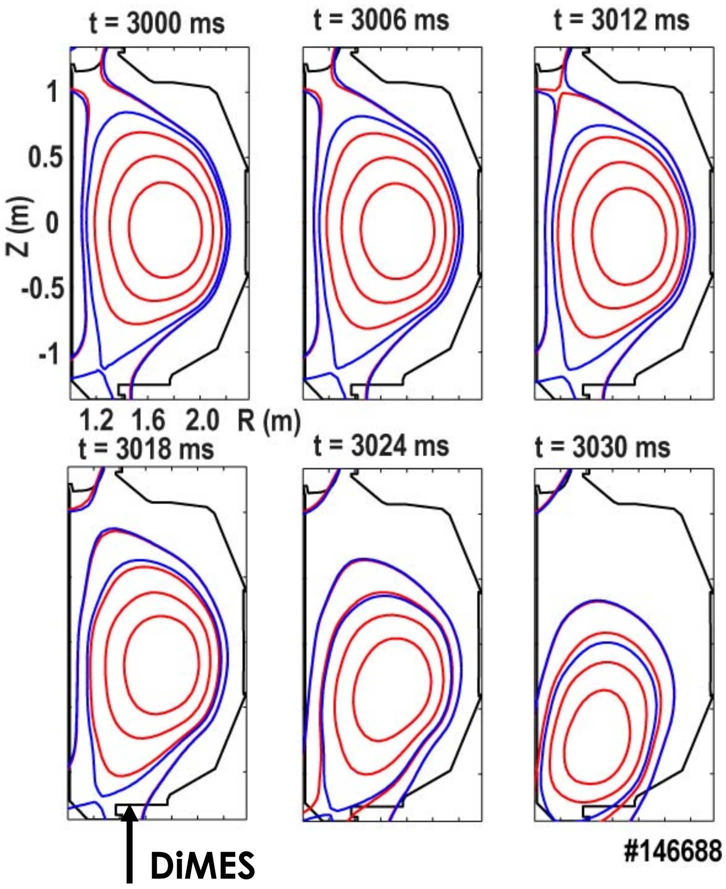
Heat fluxes across lower divertor calculated from IR camera data



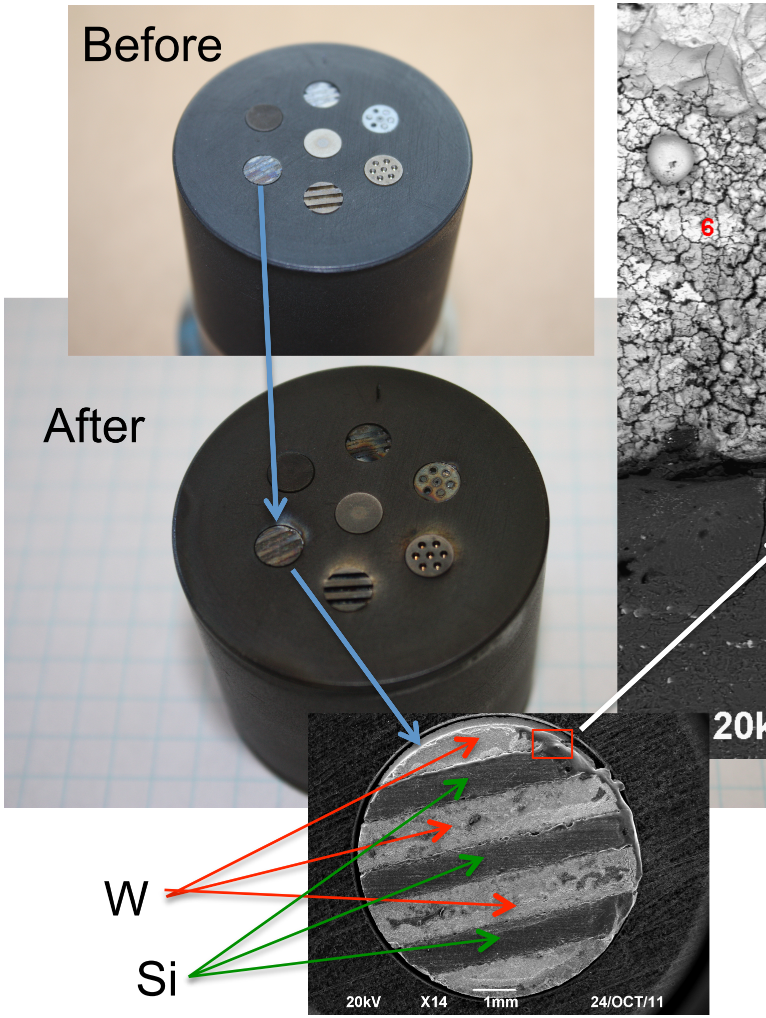
Downward VDE Strikes Inner Wall and Divertor Shelf

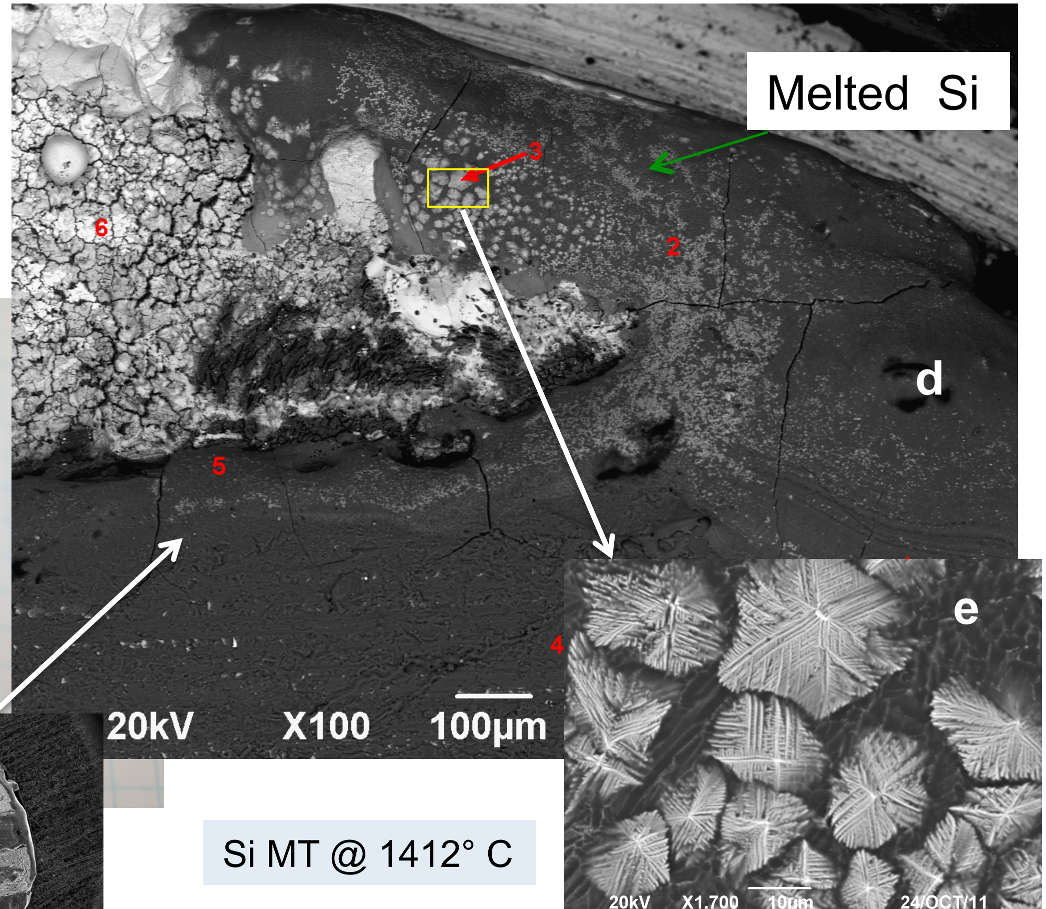
- **Initial target plasma shape is standard "ITER-like" low-triangularity lower single null "LSN"**
- **As plasma drifts down, divertor strike points disappear and plasma limits on inner wall and limits lower divertor shelf**
  - Disruption strike point broadening not well defined for VDE disruption!

JFIT reconstructions of magnetic flux surfaces during unmitigated VDE



Six VDE Exposures Indicating Formation of Si-W Eutectic Mixture





EDX
views area 3

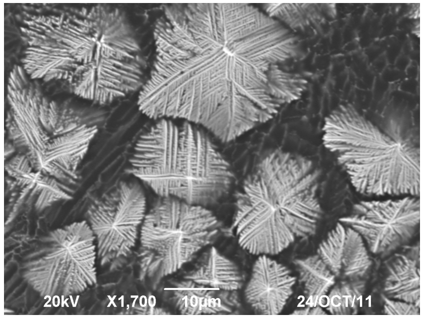
Si MT @ 1412° C

The W button with Si filled slots is damaged
The W button with empty slots is perfectly O.K.

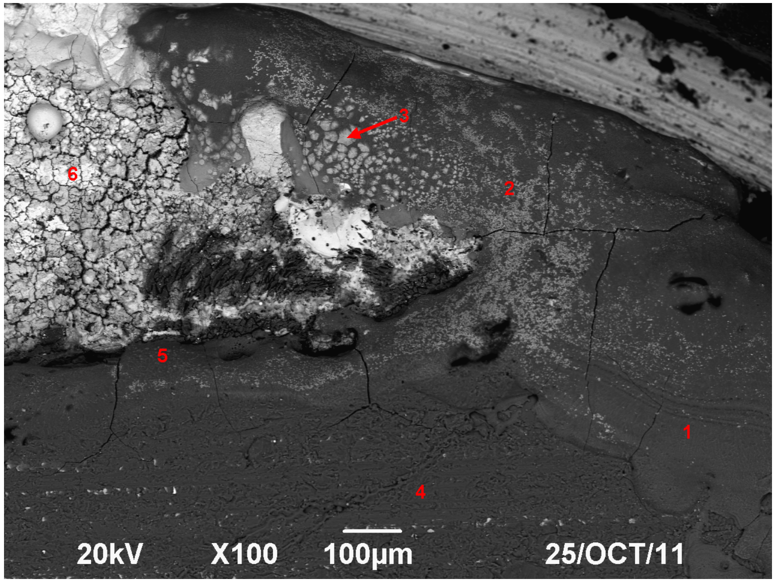
SEM and EDX Analysis at Different Locations Showing Composition of the Si-W Button at Different Areas

Spectrum	C	N	O	Al	Si	W	Total
DiMES area 1	14.24				86.35	0.0	100
DiMES area 2	21.45			0.38	69.56	8.61	100
DiMES area 3	9.57				49.31	41.11	100
DiMES area 4	32.31		13.59	0.58	53.52		100
DiMES area 5	27.10		3.01	1.99	68.00	0.0	100
DiMES area 6	20.57	7.98	19.77	4.99	7.05	39.63	100
DiMES area 7	33.97		7.75			58.28	100
DiMES area 8	46.21		5.43		12.05	36.31	100
Max.	46.21	7.98	19.77	4.99	86.35	58.28	
Min.	9.57	7.98	3.01	0.38	7.05	0.0	

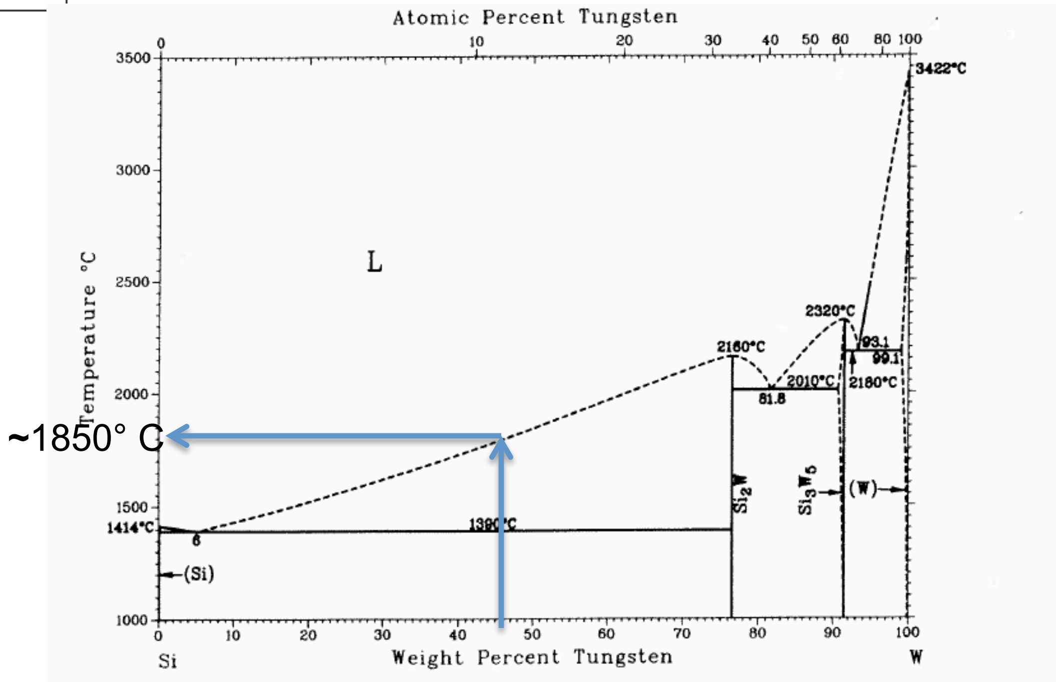
All results in wt%.



SEM views
area 3, W-Si crystal



Melted Si spilled over W



S.V. Nagender Naidu, A.M. Sriramamurthy, and P. Rama Rao, 1989.

Conclusions

- Solid W is the preferred PFM; unfortunately it melts under type-I ELMs and disruption events.
- Sets of Si-W test buttons were fabricated and exposed in the DIII-D lower divertor with the goal of demonstrating the possibility of transient tolerant material design under disruption.
- During fabrication when T~ 1400°C, several samples were destroyed and broken into pieces.
- Si-W buttons with indentations and slots were exposed to six VDE disruptions in DIII-D and showed that part of the W surface was damaged.
- SEM photos showed tungsten-silicide crystalline structure and EDX shows composition of ~49.31 wt% Si and ~41.11 wt% W. This Si-W mixture melts at ~1850°C during a VDE disruption.
- This indicates that the Si-W combination cannot be used as a transient-tolerant surface material, since the surface temperature will be >>1850°C under a disruption event.
- This also implies that for a tokamak, to avoid surface melting, we will need to avoid type-I ELMs and disruptions to avoid melting of any metallic surface
- When Si or B is to be used as the wall conditioning material to mitigate W migration into the plasma core, in order to avoid Si-W and B-W eutectic formation, surface temperature should be lower than the lower eutectic temperature, i.e. 1410°C-100°C = 1310°C and 1970°C-100°C = 1870°C, respectively.