USTC SNST 2015 Autumn Semester Lecture Series

Title: Introduction to Research and Development in Tokamak Fusion Energy Science and Technology

Room 1617, 930-1130, **Saturday** November 21, 2015

L4: Frontline: Scrape-Off-Layer (SOL) Divertor Plasma Material Interaction (PMI)

Lecturer: 彭元凯
Class assistant: 徐国梁
Webpage assistant: 王伸吉

Class Dates and Plans for This Special Lecture Series

1. To work around national holidays *and USTC activities?*

Please raise hands to confirm dates!

√	1) 09/12: Philosophy and approach of these lectures
√	2) 09/19: Where fusion plasma meets the material world
√	3) 10/17: Where fusion plasma meets the material world, cont.
√	4) 10/24: H-mode plasma pedestal – behind the "frontline"
√	5) 11/21: Frontline: the interface of SOL and Divertor target
	6) 11/28: 2nd-line: neutron irradiation on the materials
	7) 12/12: 2nd-line: neutron irradiation on the materials, cont.
	8) 12/19: 3rd-line: tritium, tritium, everywhere
	9) 01/09: 3rd-line: tritium, tritium, not here
	10) 01/23: Semester conclusion, discussion, and feedback

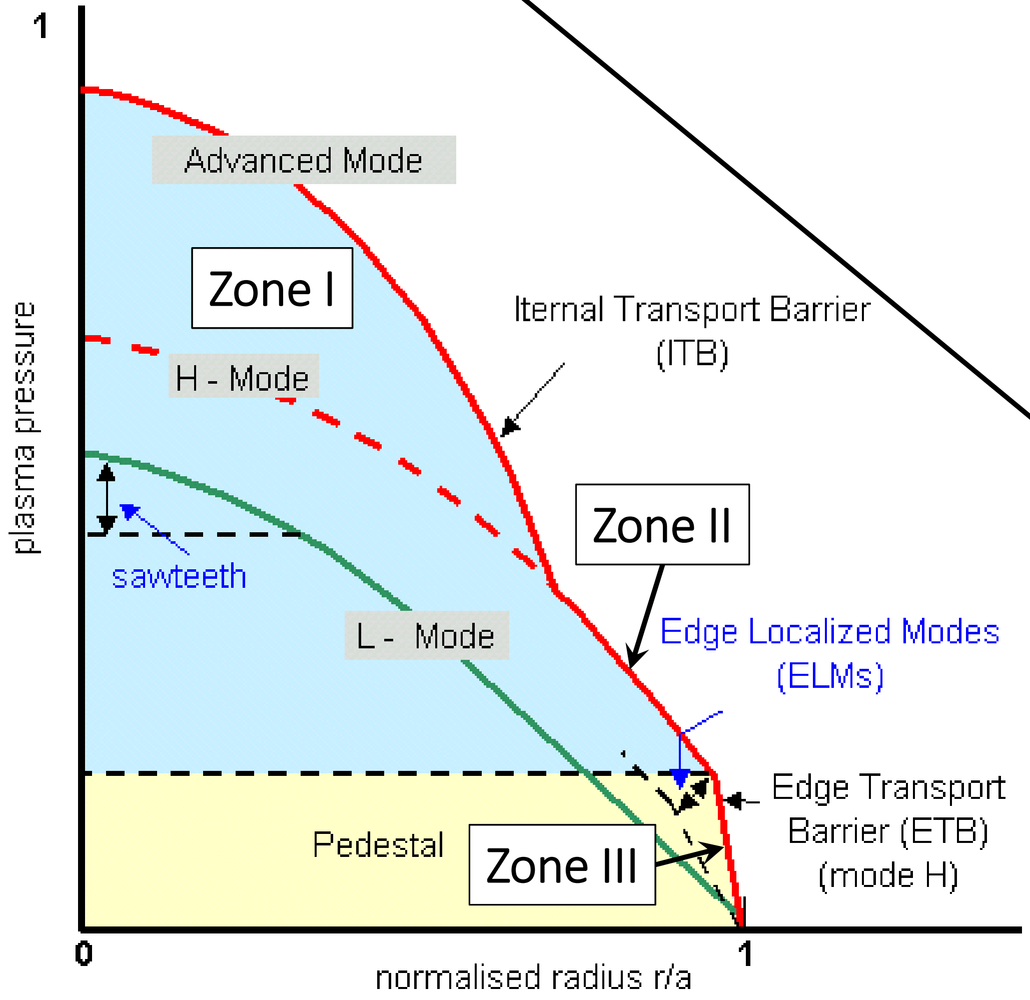
Divertor PMI R&D Has Focused on Weakening the SOL Plasma Fluxes

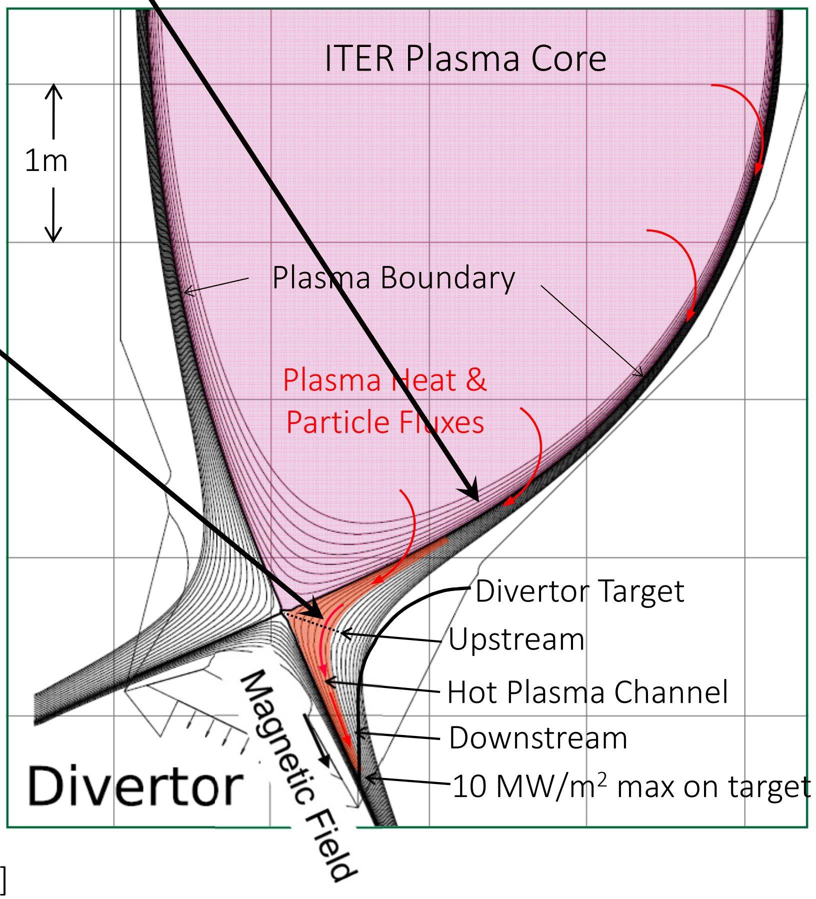
- Tokamak divertor concentrates plasma SOL fluxes on reduced target area
- Pedestal and SOL plasma dynamics spread the fluxes to larger areas, but in strong bursts, which can potentially damage the W divertor in ITER
- Techniques are in R&D to disperse these fluxes, with side effects
  - Inject impurity gas into the divertor plasma to radiate heat
  - Mix up the edge magnetic field to spread the fluxes further
  - Spread out the SOL magnetic field lines
- Further, plasma interactions with W surface cause persistent erosion and alterations in nanoscales
- Philosophy for survival of both SOL and divertor? Make one side so strong that the other can behave freely. Which side to strengthen?

Opportunities abound in R&D to make fusion energy available.

Reminder: fusion H-Mode plasma model contains four zones

- Zone I: Internal transport barrier
- Zone II: normal transport layer
- Zone III: edge transport barrier "pedestal" *(behind the "frontline")*
- The Scrape-Off Layer (SOL) bridges to the PFC (*"frontline"*)





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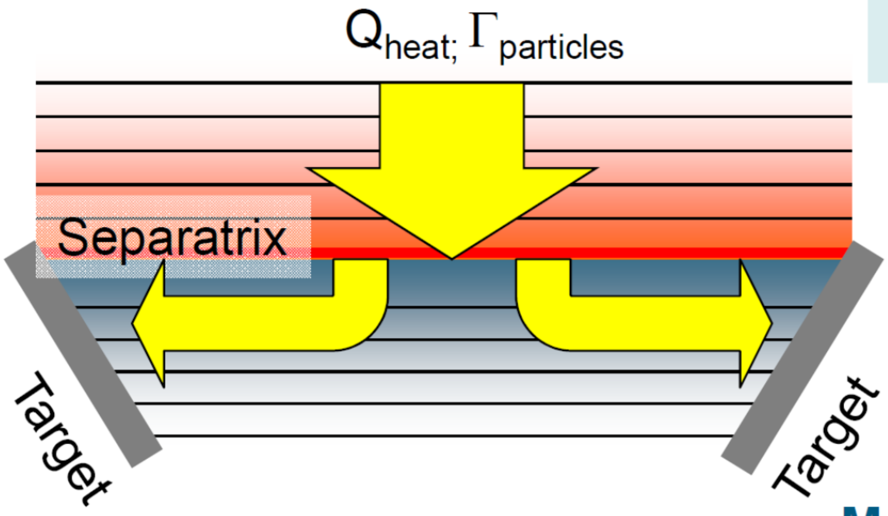
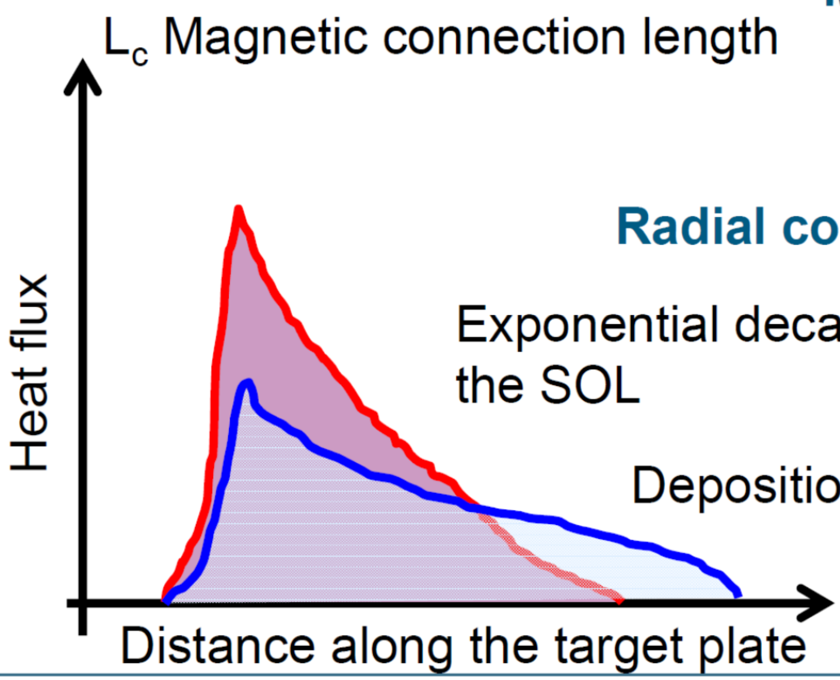
Effects of edge transport and magnetic topology on the PWI



A simplified model for Calculation of Deposition Width

Closed Flux Surfaces region	Radial Transport into SOL $D_\perp$, $\chi_\perp$
Open field line region **SOL**	Parallel Heat $q_\parallel$ and Particle $\Gamma_\parallel$ Fluxes to Target



Mass conservation in open field line region:

$$\frac{\partial}{\partial x} D_\perp \frac{\partial n}{\partial x} = \frac{\partial}{\partial z}(n v_\parallel)$$

Radial constant diffusion, parallel flow with $n/\tau_\parallel$

Exponential decay in the SOL

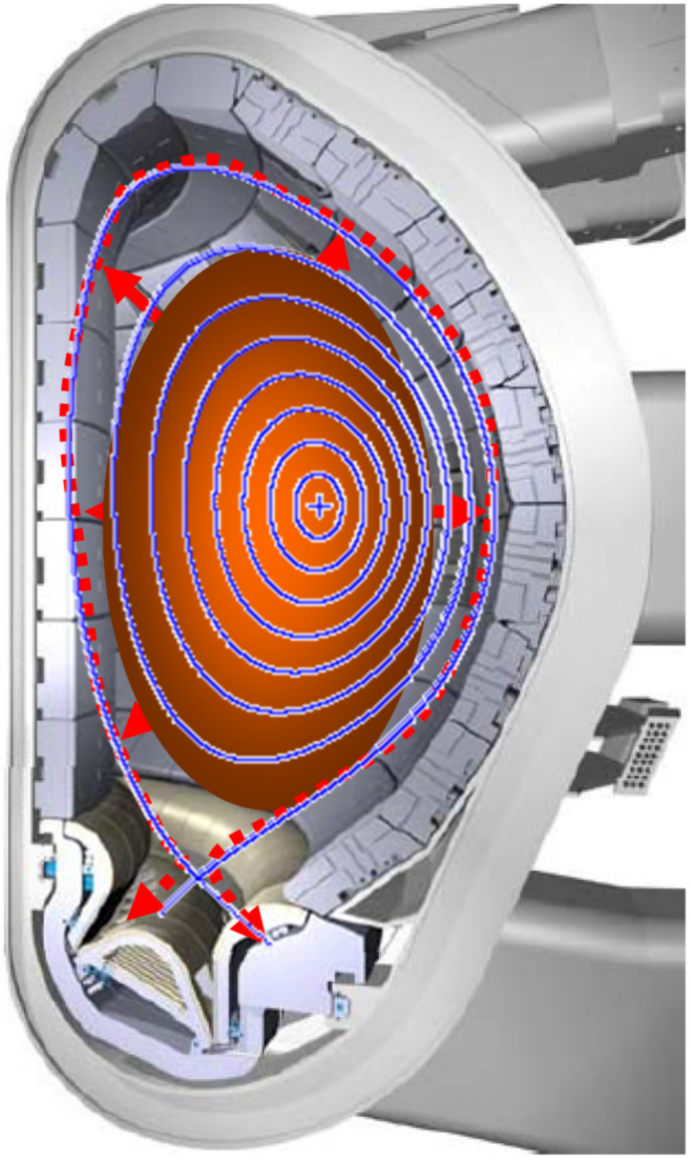
$$n(x) = n(0)\exp(-x/\sqrt{D_\perp \tau_\parallel})$$

Deposition width

$$\lambda = \sqrt{D_\perp \tau_\parallel} \qquad \lambda = \sqrt{\frac{D_\perp\, L}{0.5\, c_s}}$$

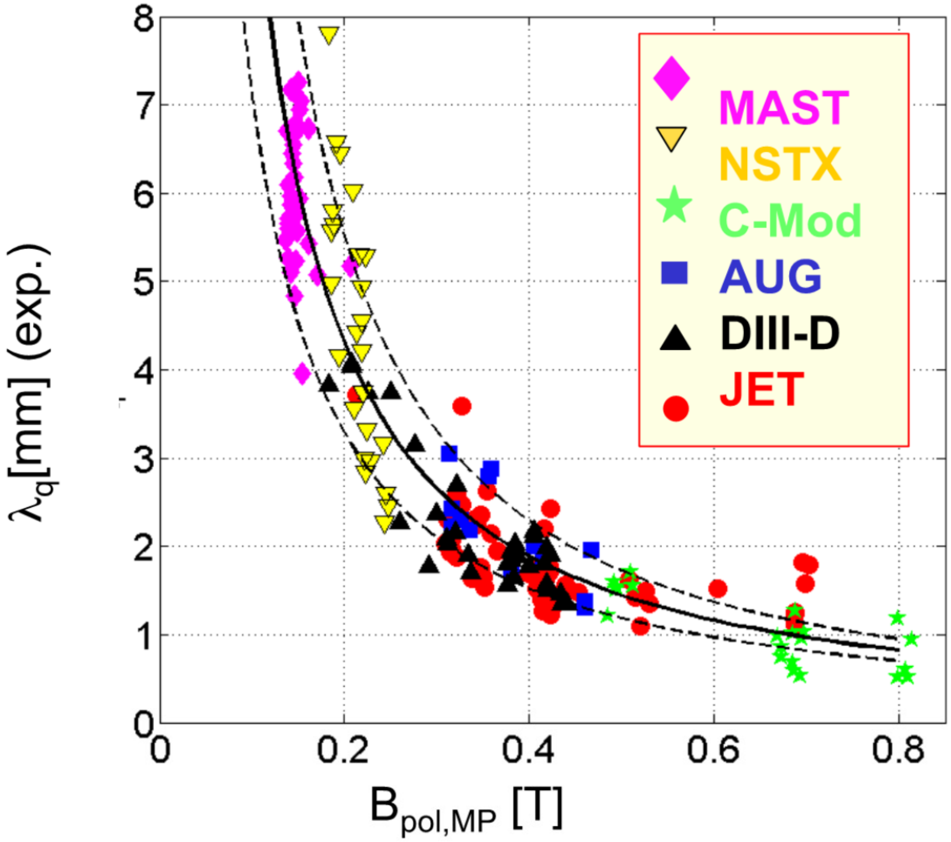
[Yunfeng Liang, Lecture 2015-11-20, ASIPP, Hefei, China]

Divertor SOL concentrates plasma fluxes on target



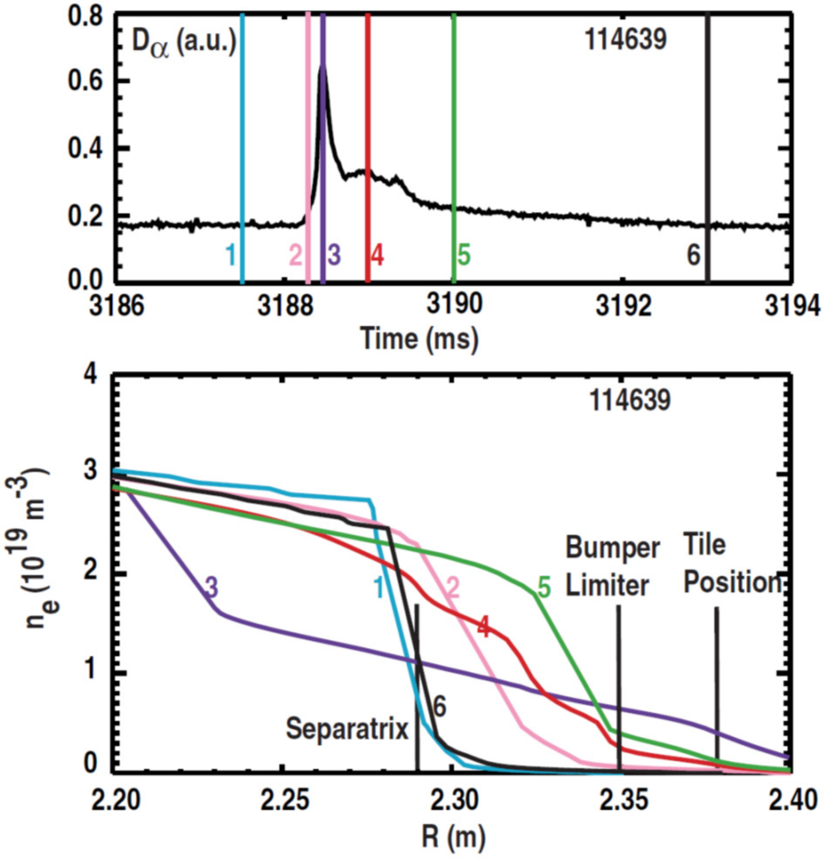
Parallel Heat $q_{||}$ and Particle $\Gamma_{||}$ Fluxes to Target

T. Eich et al. PRL 107 2011



$q_{//,u}$ ~1.8 GW/m^2 (ITER), ~x5 larger in a Demo

Plasma edge instabilities lead to "Edge Localized Modes" (ELMs)

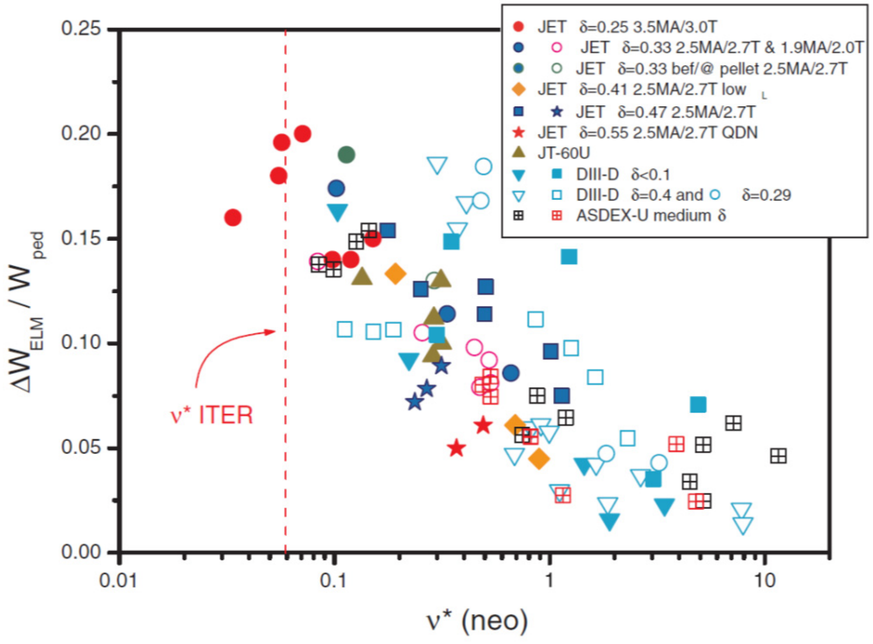


[2004-Zeng-Plasma Phys Control Fusion-v46-pA121]

1) Excellent containment at divertor plasma edge "pedestal," holding up $2 \times 10^{19}/m^3$ in 2 cm at keV temperature!
2) The "dam" weakens; plasma moves out
3) Pedestal plasma spills out in ~ms!
4) "Dam" slowly rebuilds off of outer limiter
5) Continues rebuilding,
6) Recovers excellent containment in 30ms,

This ELM event repeats!

It is projected that 20% of the ITER plasma pedestal energy would be spilled in ~ms, damaging the divertor target.

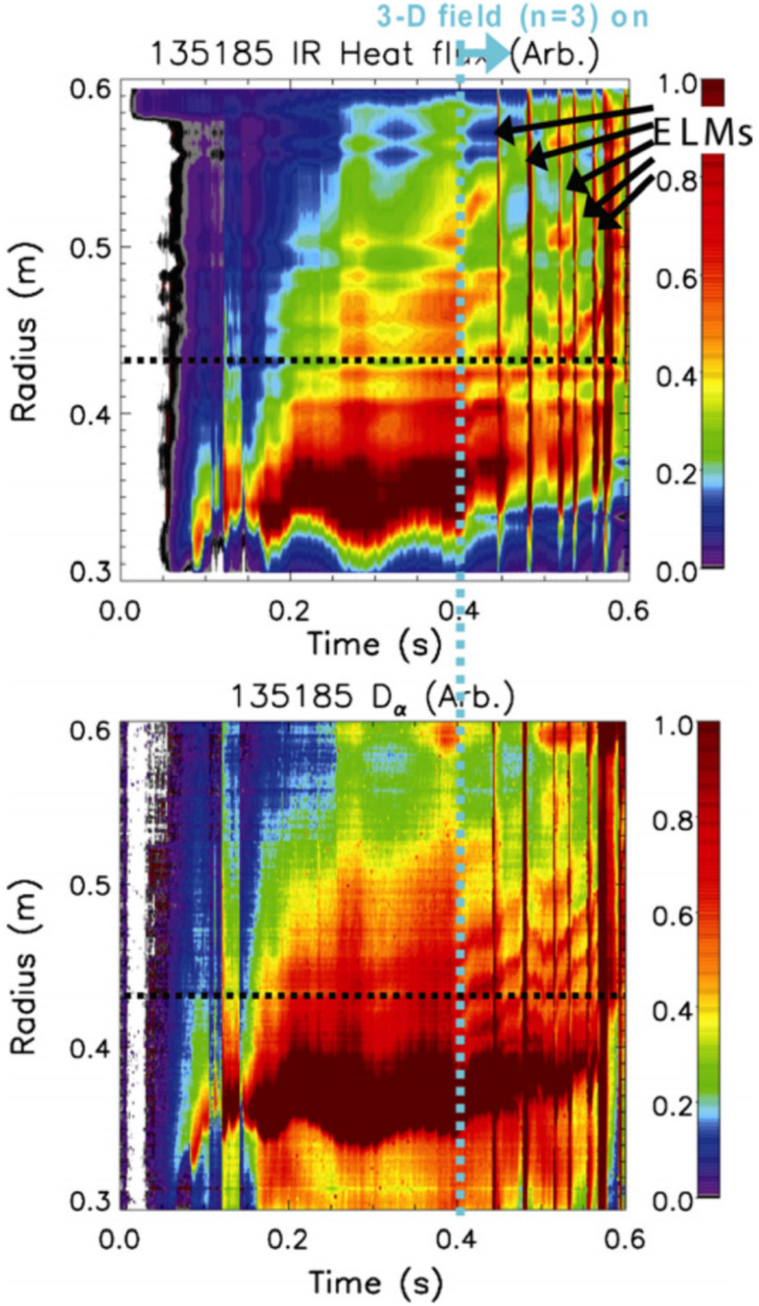


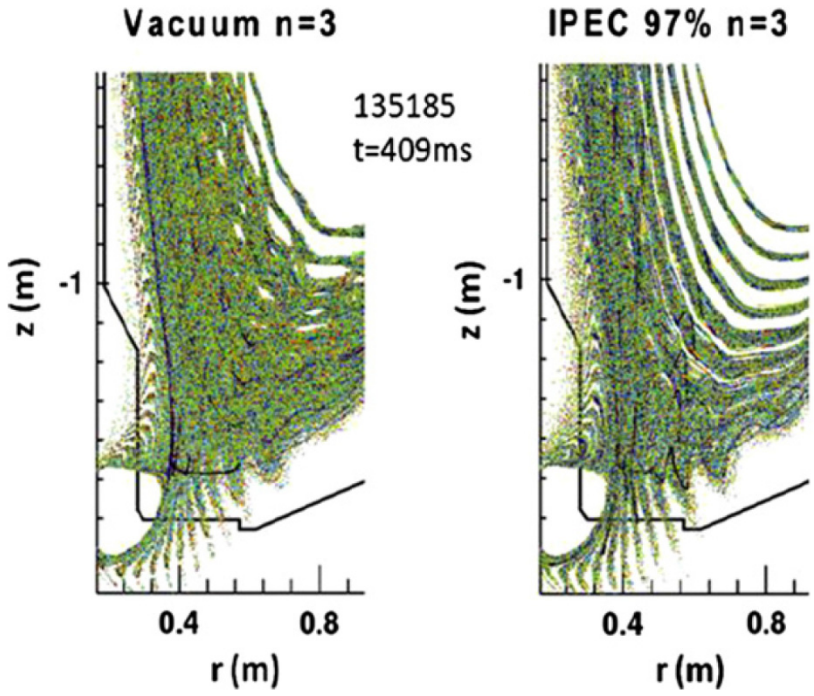
[2003-Loarte-Plasma Phys Control Fusion-v45-p1549]

Plasma spills in multiple stripes in a ELM crash

NSTX example: [2011-Ahn-J Nucl Mat-v415-pS918]]

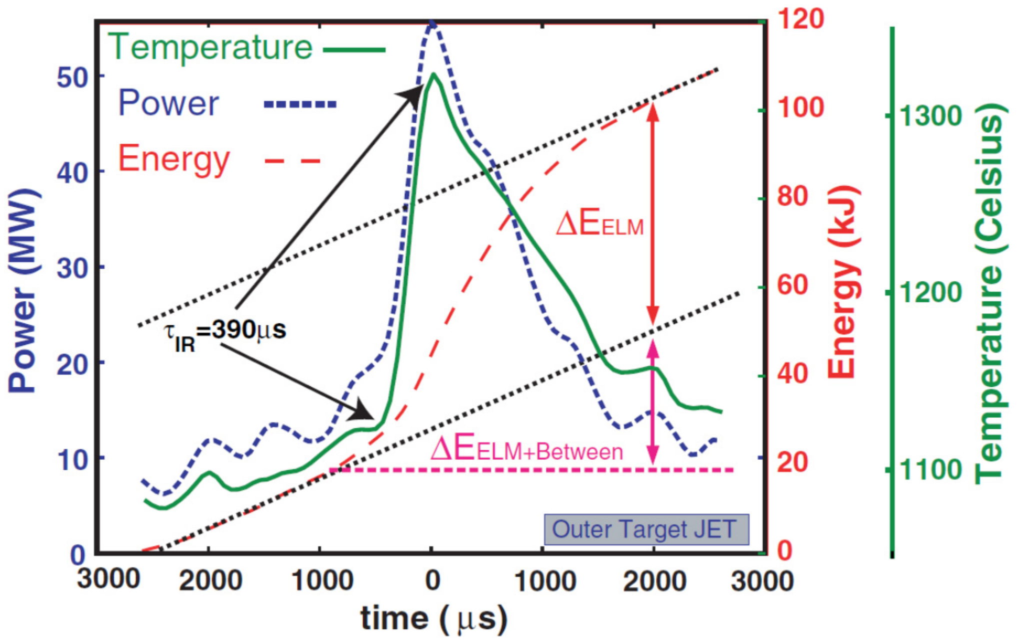
- The instability grows and breaks up the plasma surfaces into stripes that extend to the divertor target
- These can be seen by fast infrared camera as target heating, and D ionization (D_α) radiation near the target





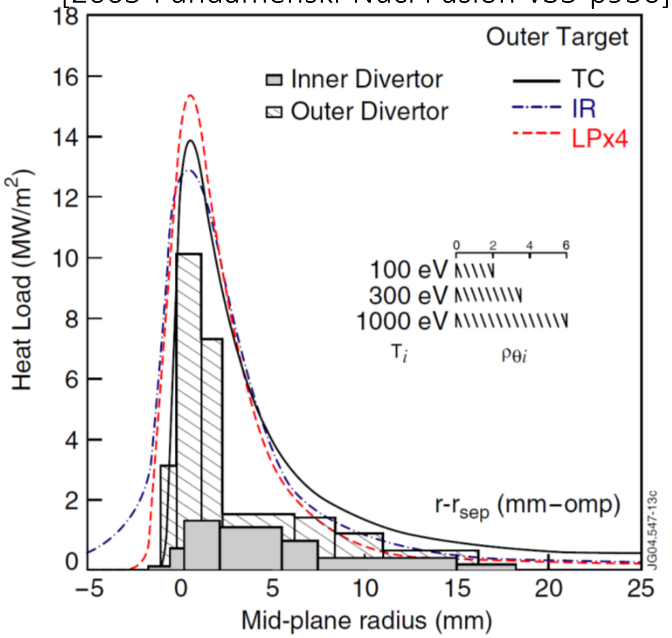
What happens to the divertor target plate in an ELM event?

[2003-Eich-J Nucl Mat-v313-316-p919]

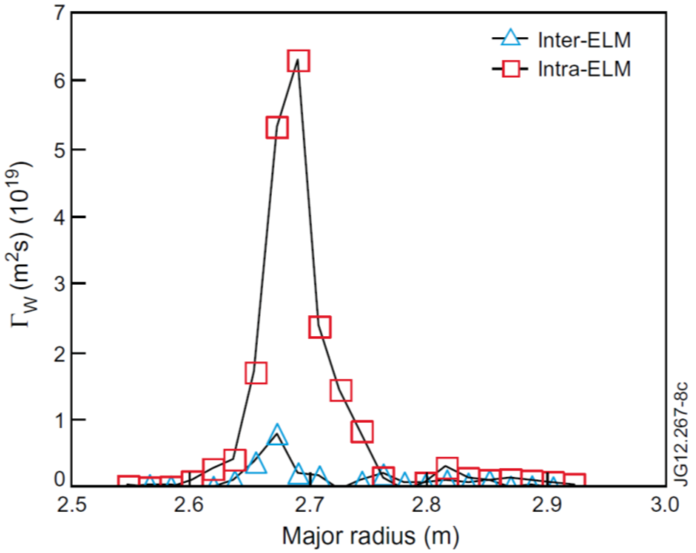


- ELM-induced lost power reaches divertor target in a fraction of ms.
- Surface temperature shoots up by 200°C.
- Deposits 30 kJ heat on divertor.
- Surface heat load over 10 MW/m^2 over narrow footprint.
- Nearly 10 times the W sputtering yield of between ELMs.

[2005-Fundamenski-Nucl Fusion-v35-p950]

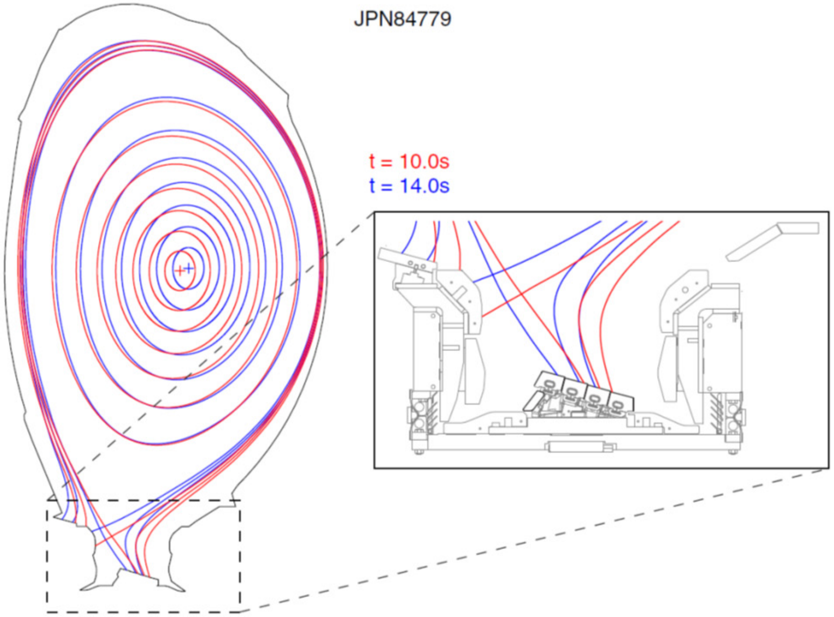


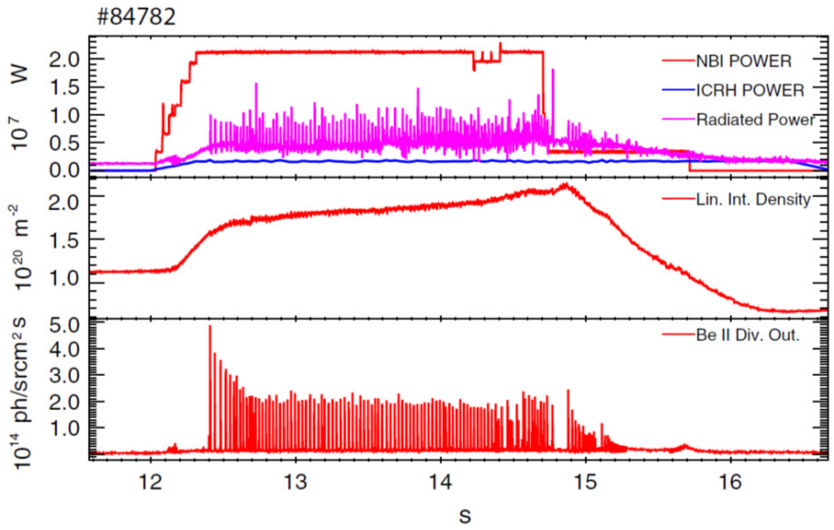
[2013-van Rooij-J. Nucl. Mat.-v438-pS42]

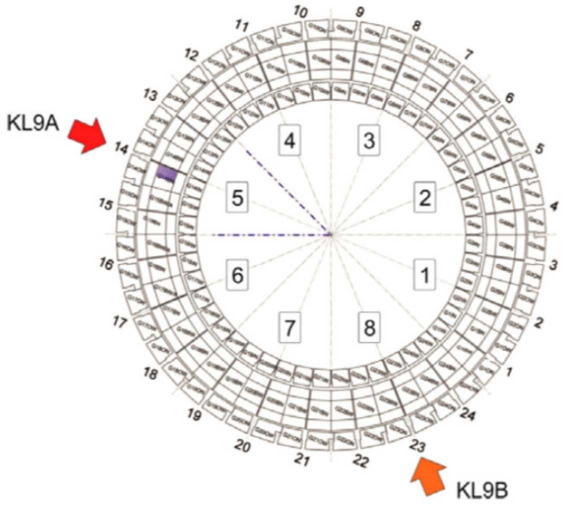


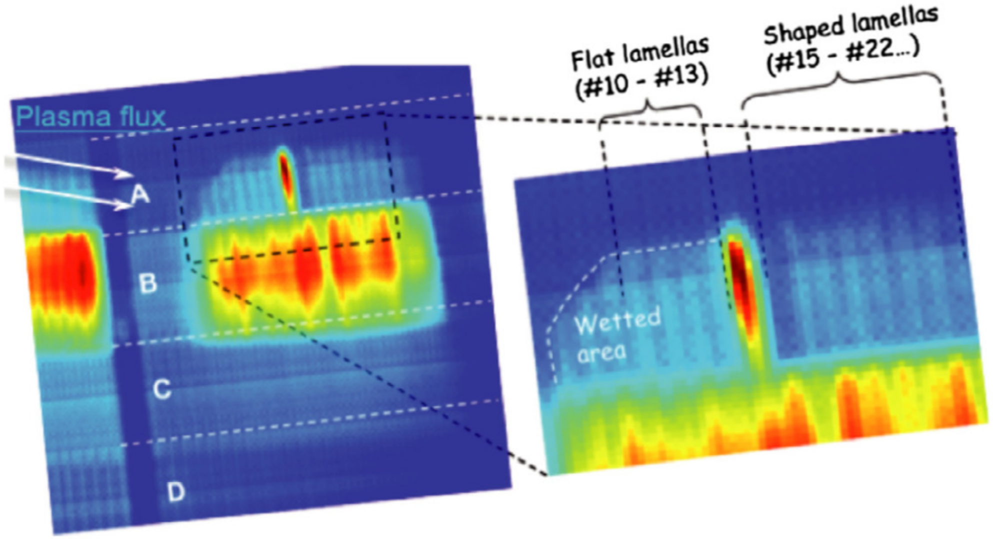
These can lead to damages to the divertor target

- The divertor is subjected to ELMy discharges and received pulses of heat deposition





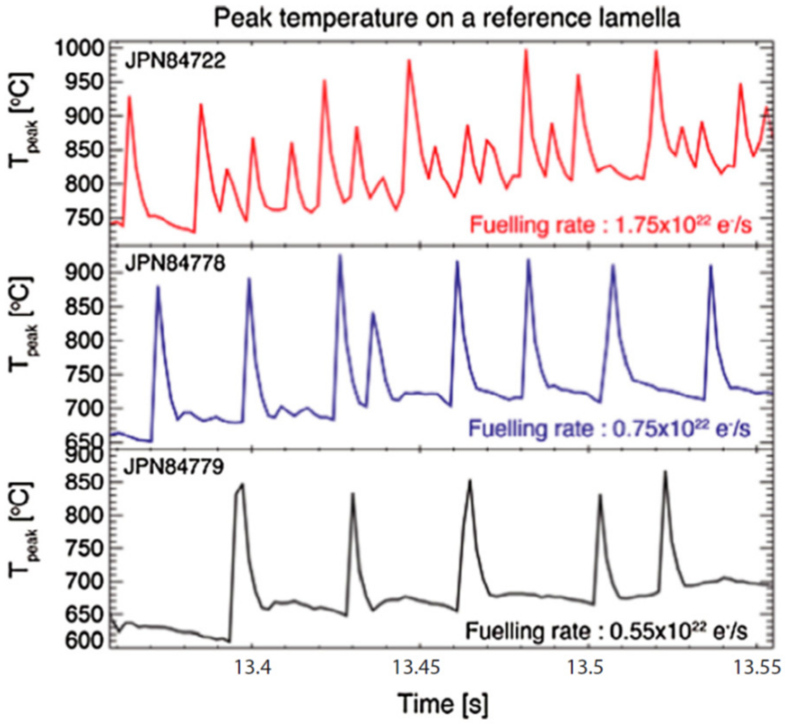


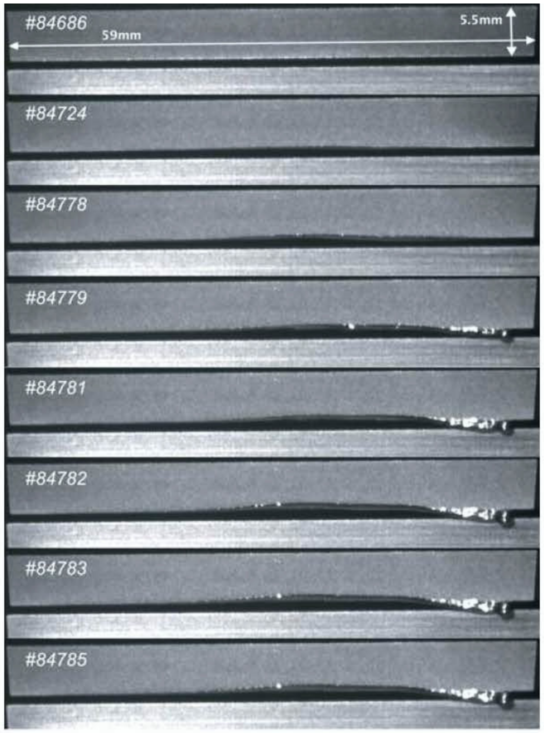


These can lead to damages to the divertor target-II

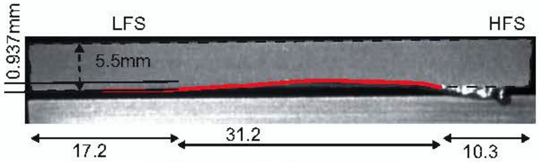
JET example: [2015-Coenen-J Nucl Mat-v463-p78]]

- W temperature rises and progressive damages were monitored
- Damage pattern was compared with ELM temperature rise

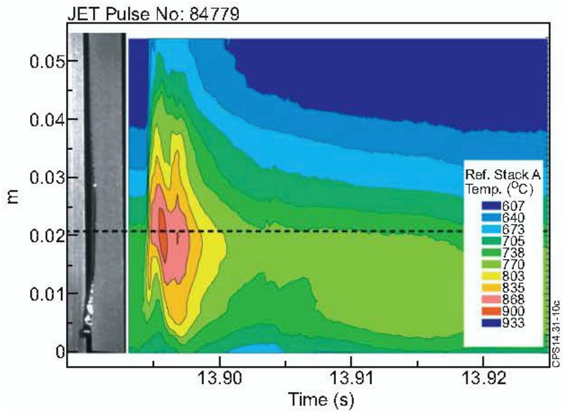




a) Damage evolutions

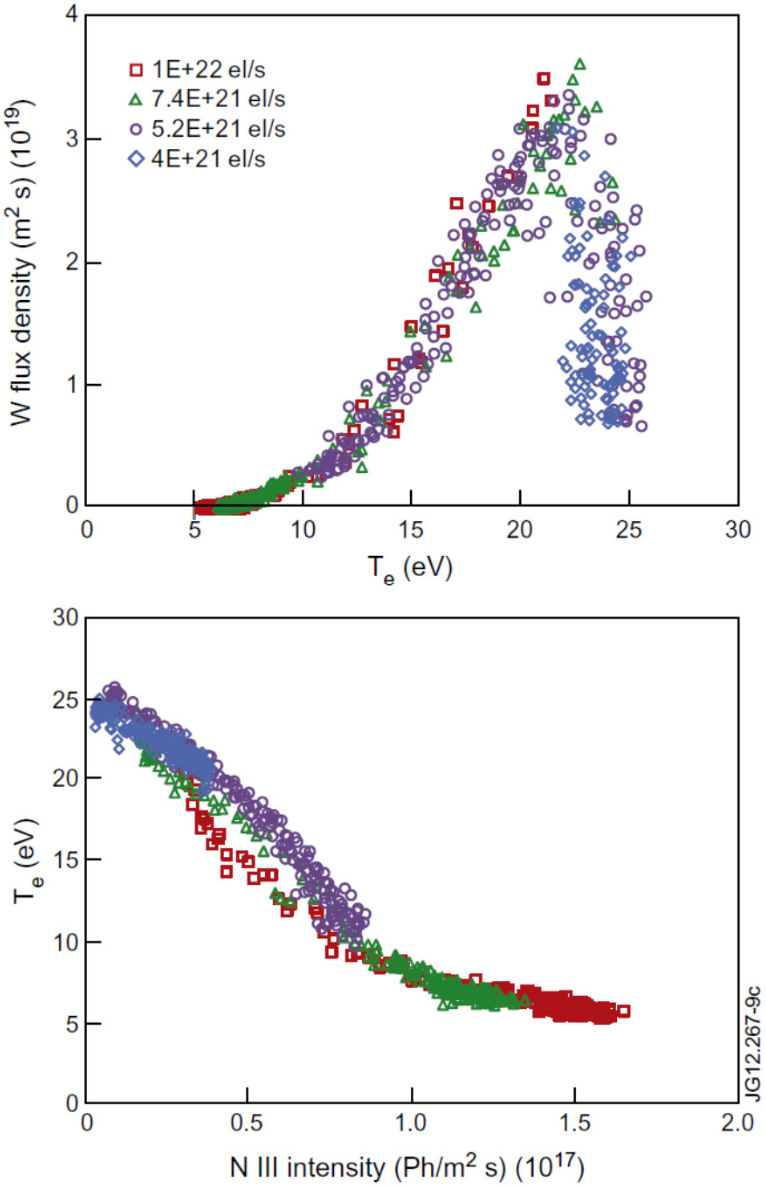


b) Geometrical considerations



Impurity gas injected into the divertor can reduce W erosion

[2013-van Rooij-J Nucl Mat-v438-pS42]



Nitrogen seeding on JET can reduce W sputtering

- Divertor plasma temperature Te drops as N concentration increases.
- At higher Te, tungsten sputtering increase sharply as Te drops from 25eV to 20eV.
- Further lowering Te (increasing N concentration), W sputtering drops to negligible levels for Te < 10eV.
- A slow N impurity rise in plasma core resulted.

EAST Has Modern Divertor Gas Injection System

[Dongsheng Wong, 2012 PhD thesis, ASIPP]

ASIPP

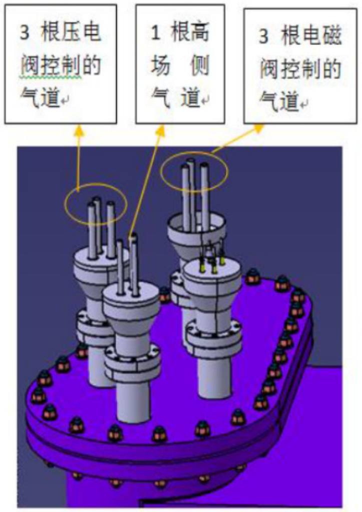


图 8.上 O 窗口法兰图

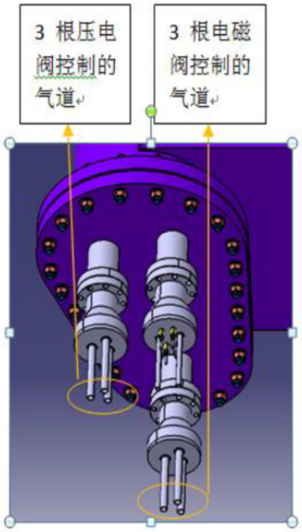


图 9. 下 O 窗口法兰图

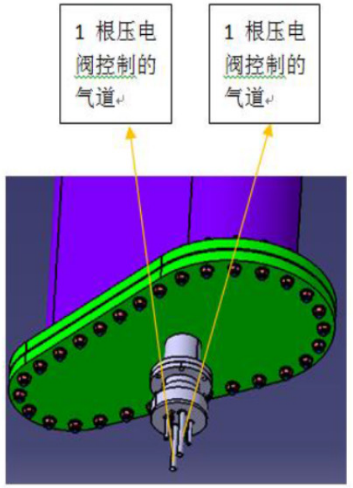
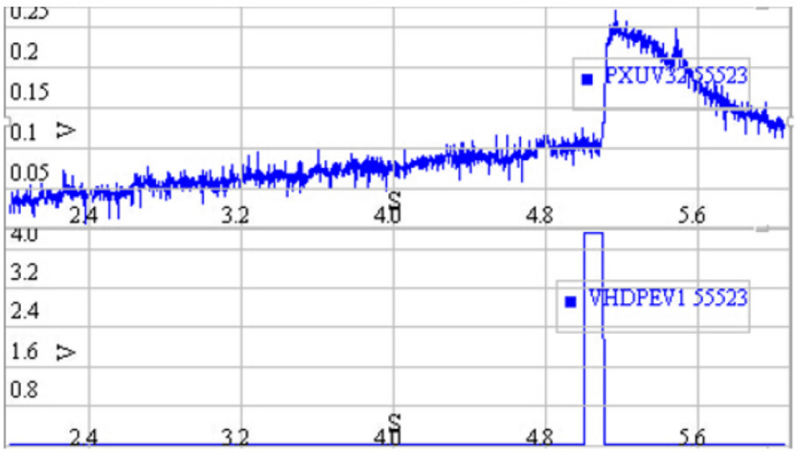
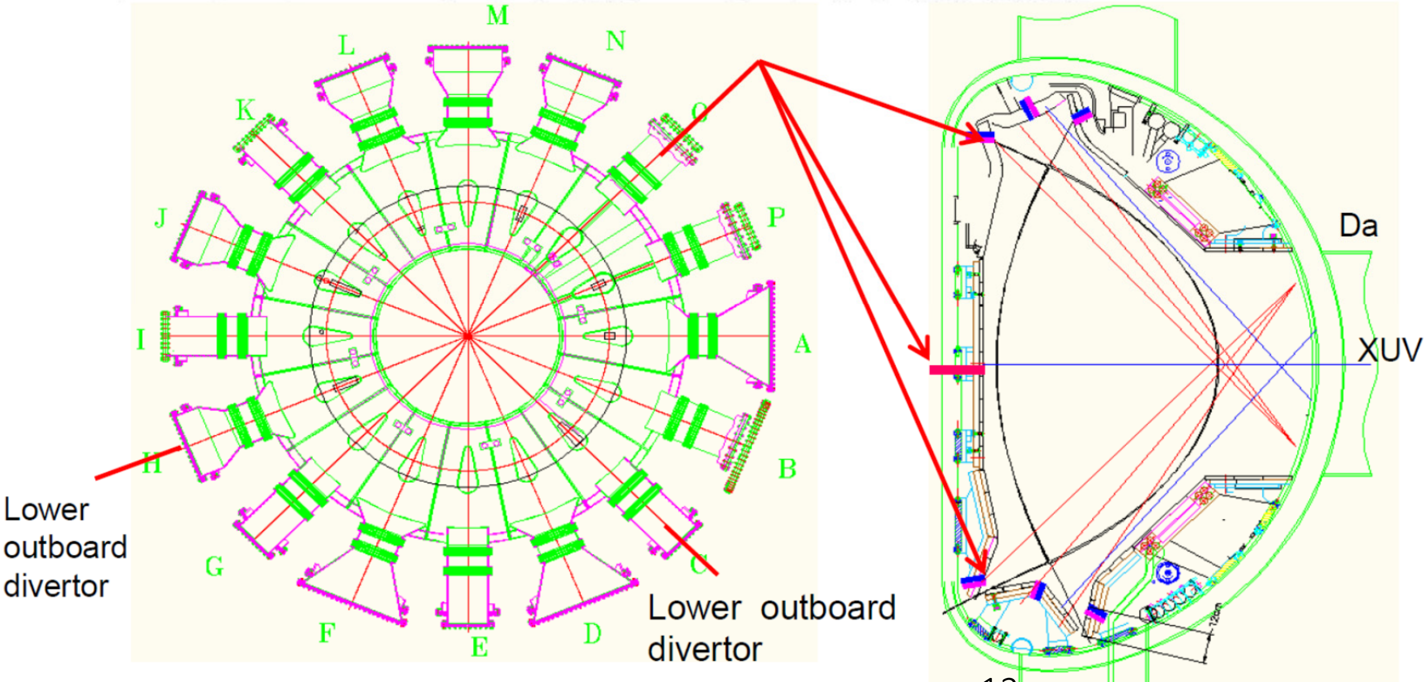


图 10. 下 C 或 H 窗口杂质充气系统法兰图





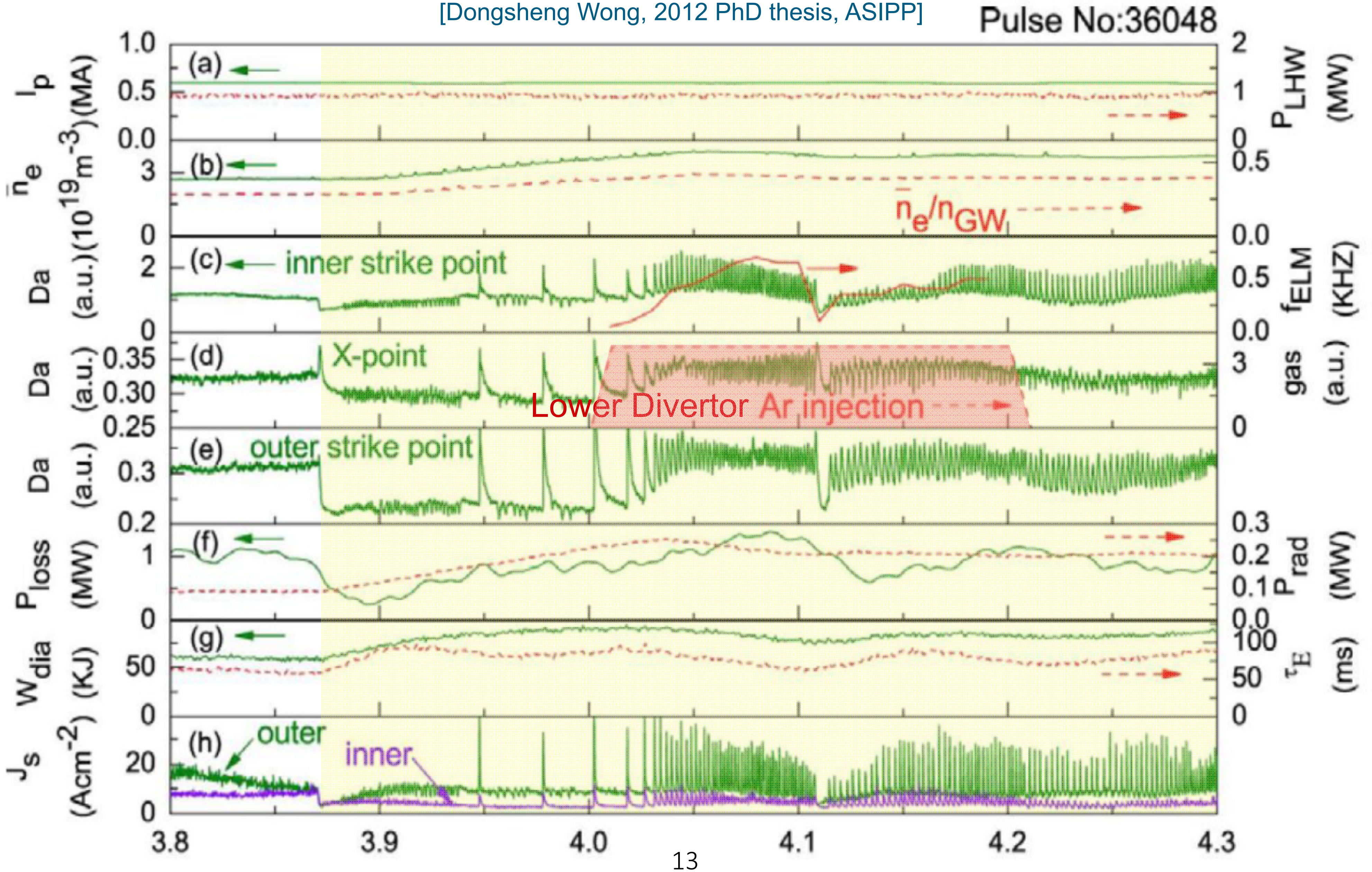
2 sets of 3 injectors for upper (W) and lower (C) divertors.

Delay of ~100ms from fast valve to divertor

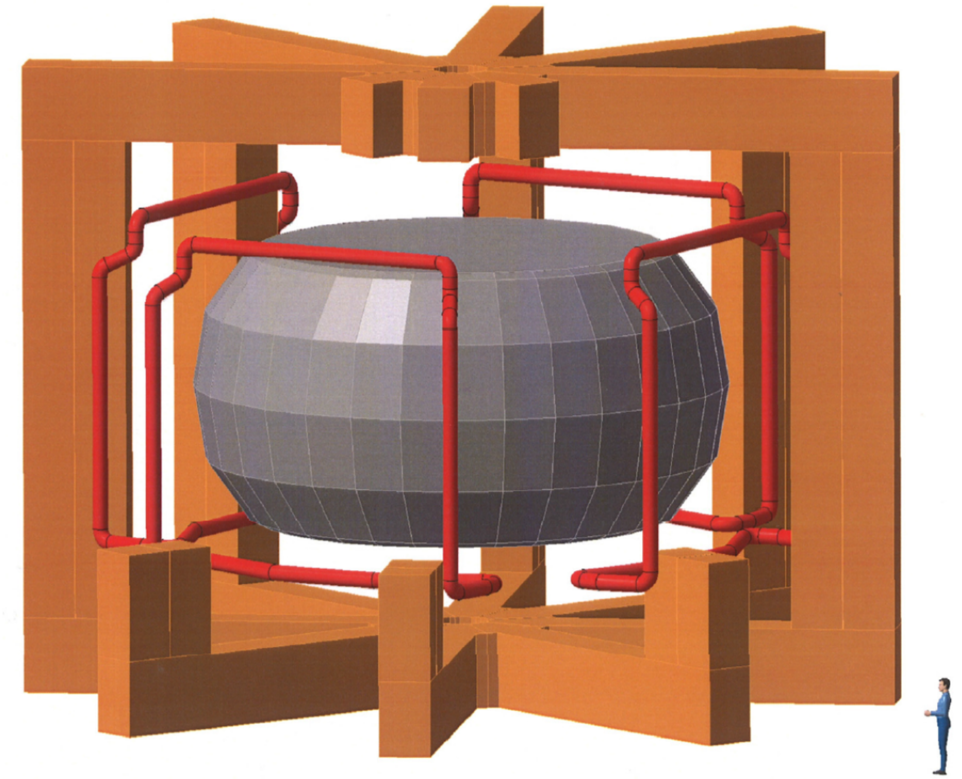
Pure Argon Injection Lowered ELM peaks in 2010

P_{LHW} = 0.9MW, B_T = 1.8T

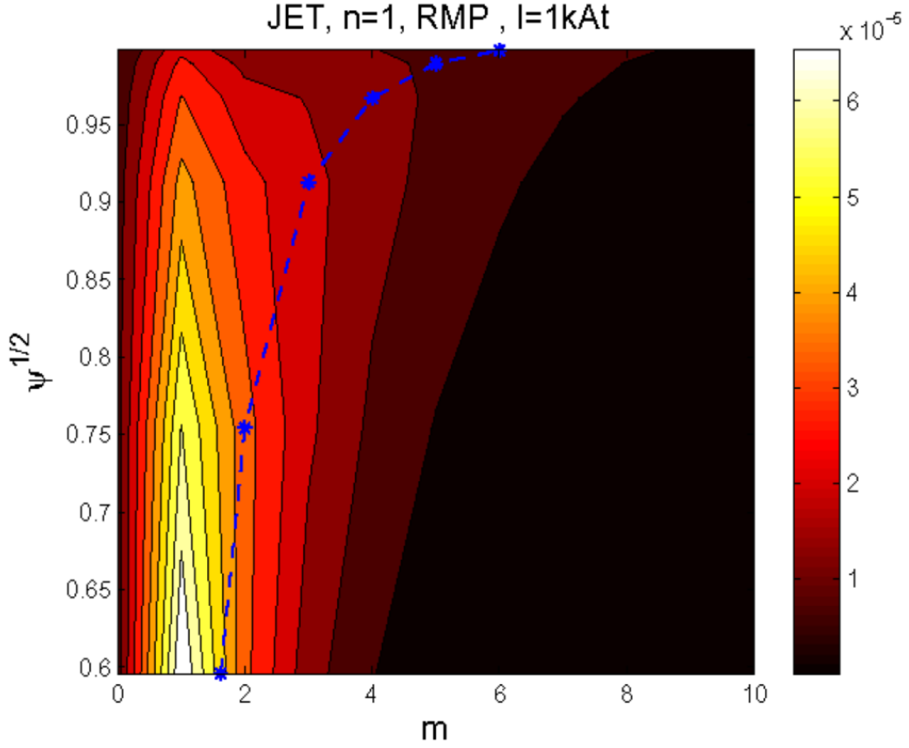
[Dongsheng Wong, 2012 PhD thesis, ASIPP]



Error Field Correction Coils (EFCC) on JET



I_{EFCC} = 1 kAt; B_t= 1.84 T

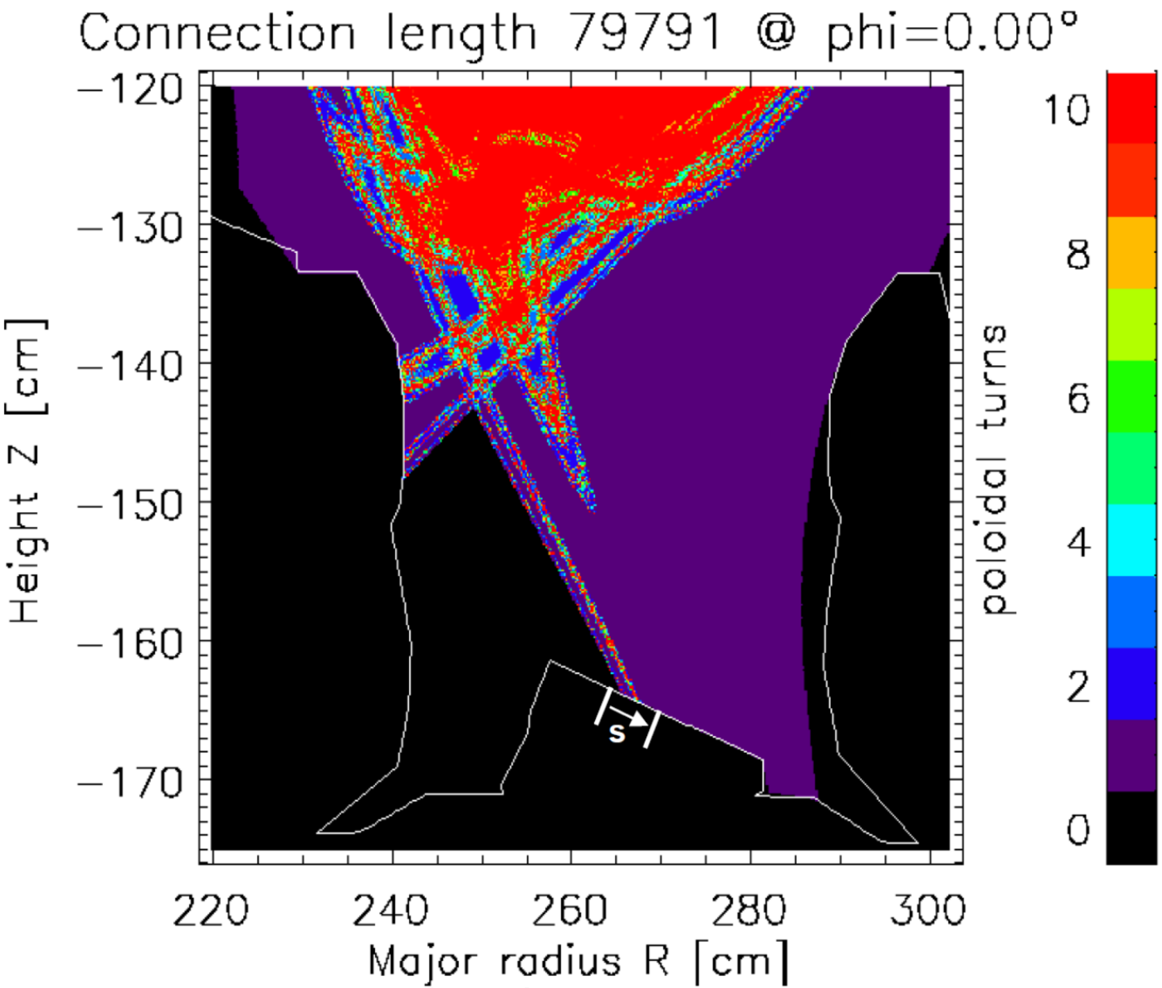


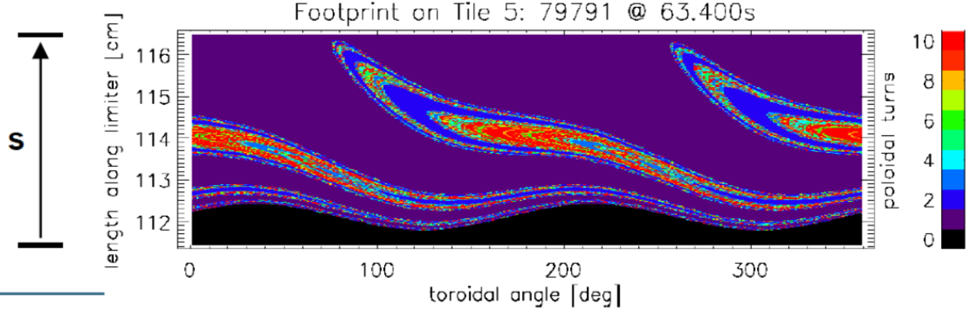
- ➢ Depending on the relative phasing of the currents in individual coils, either *n*=1 or *n*=2 fields can be generated
- ➢ $I_{Coil} \leq$ 3 kA x 16 turns (n = 1 *and* 2)
- ➢ R ~ 6 m; Size ~ 6 m * 6 m
- ➢ B_r at wall ~ 0.25 mT/kAt

Y.Liang et al., PPCF 2007

[Yunfeng Liang, Lecture 2015-11-20, ASIPP, Hefei, China]

Toroidal Evolution of Strike Point



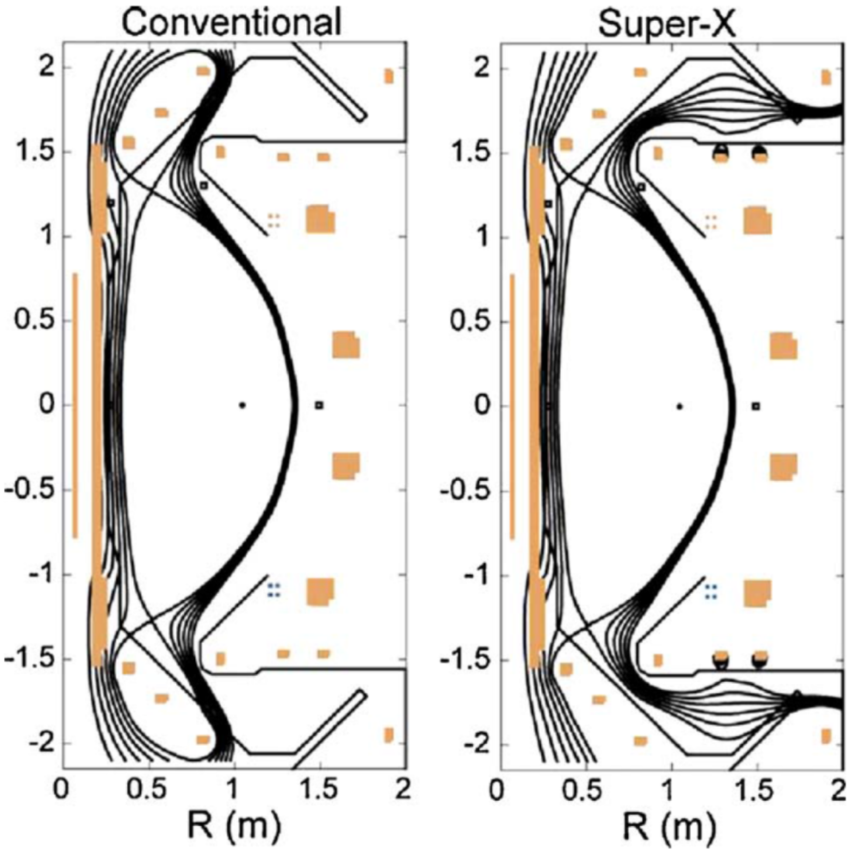


- •Field line tracing in vacuum approximation (superposition of equilibrium and perturbation field)
- •No screening of RMP by poloidal rotation
- •Ergodic field lines form lopes which generate multiple strike points on the divertor
- •Strike point splitting depends on toroidal position
- •Footprint represents n=2 symmetry of perturbation field

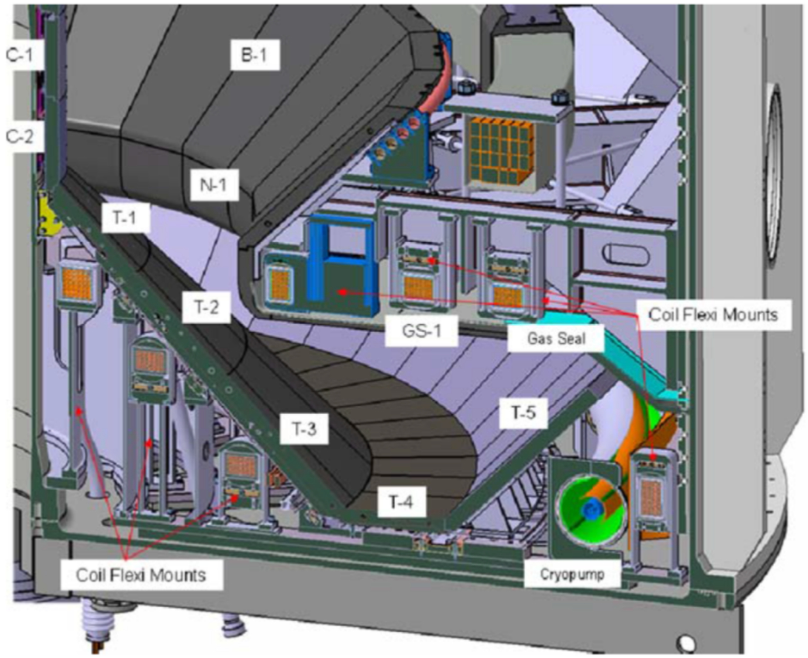
D. Harting, Y.Liang, JET science meeting 2010

A more drastic approach: Super Extended Divertor (SXD)

- SXD extends the plasma divertor channel to large R and increases the field-line connected plasma volume in divertor chamber. (MAST-U)
- Require the use of addition divertor poloidal field coils and a relatively large vacuum vessel.

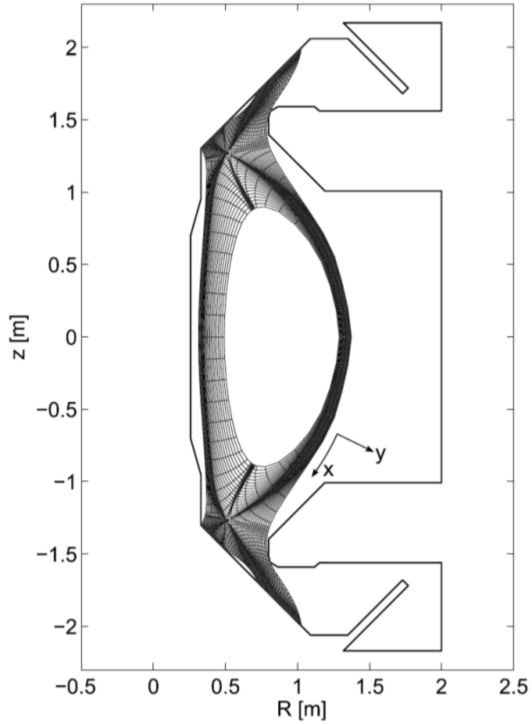


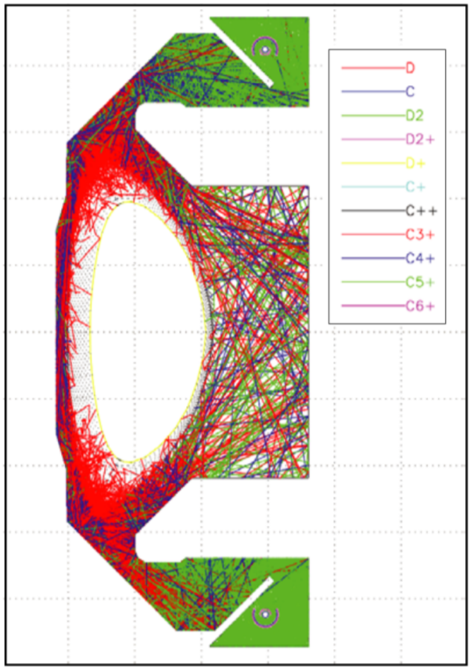
[2011-Katramados-Fusion Eng. Dessign-v86-p1595]



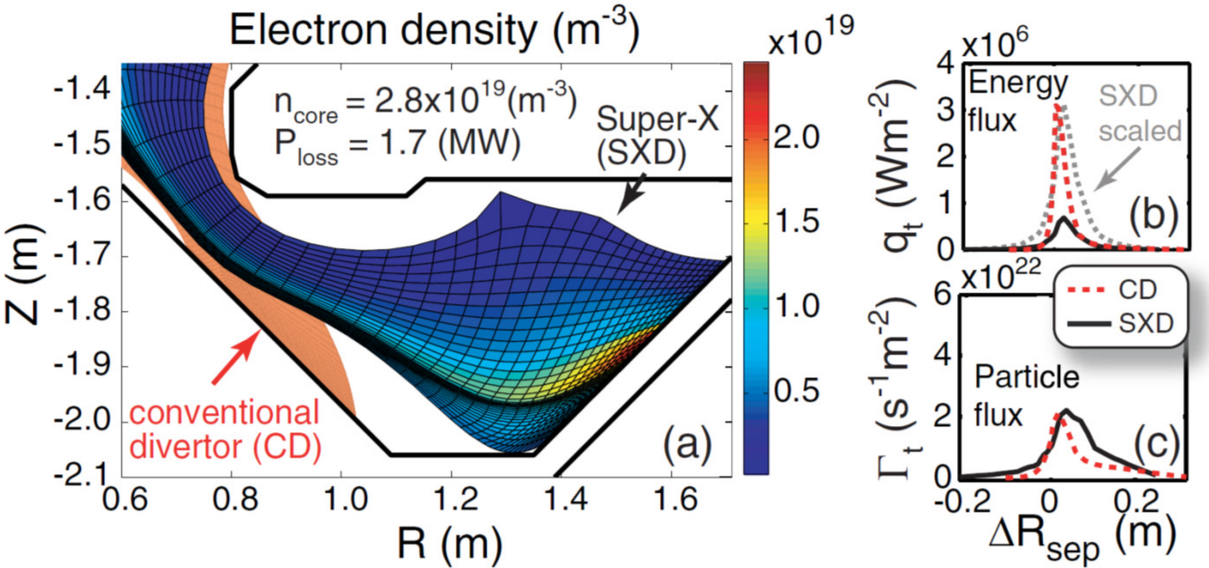
Numerical simulations indicate adequate heat and particle handling

[2014-Havickova-Plasma Phys Control Fusion-v56-p075008]





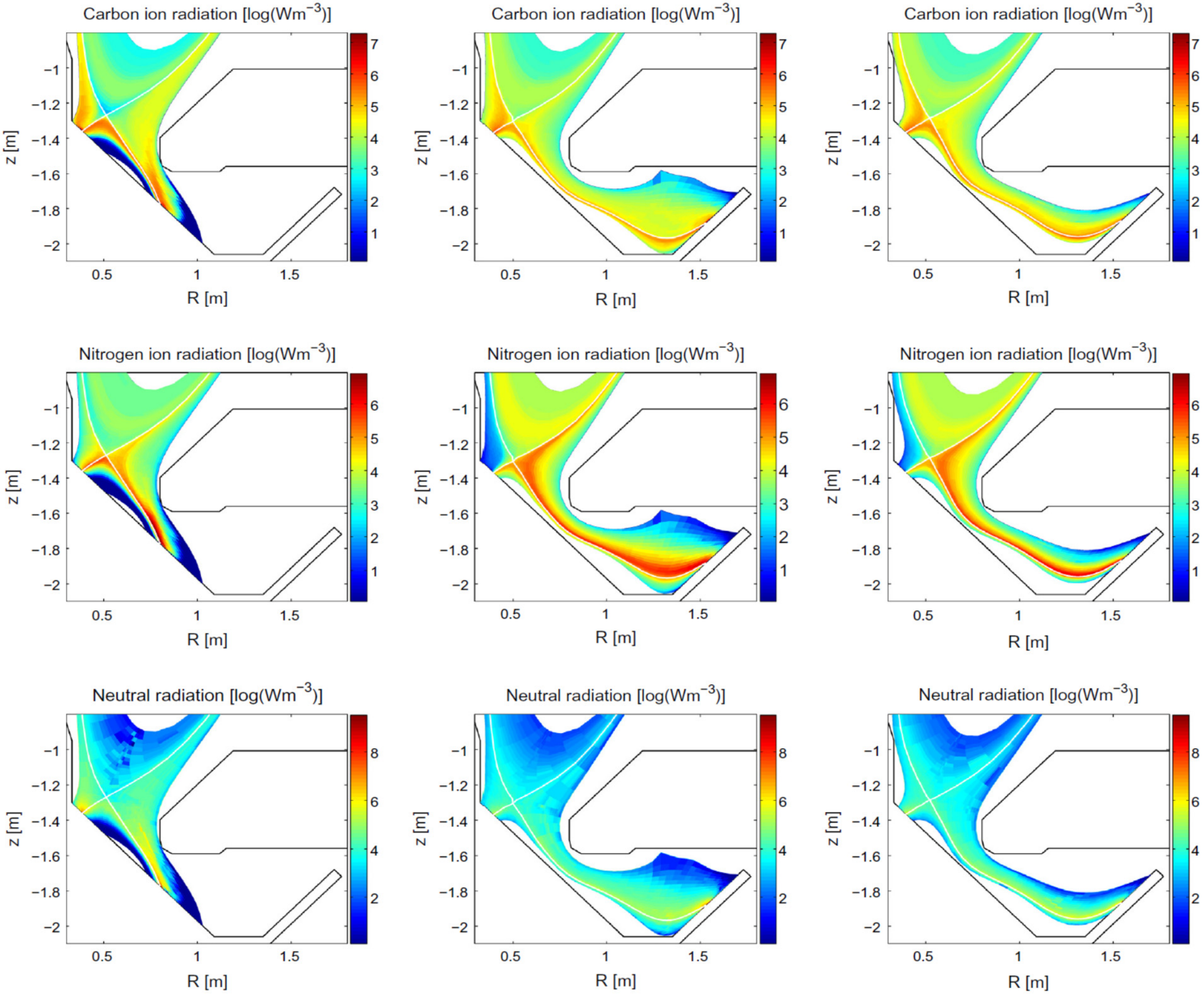
- SOLPS calculates fluid plasma along field lines.
- B2-Eirene simulates Monte-Carlo random trajectories of ions and neutrals.
- Millions of particles simultaneously.
- Obtains stationary conditions while minimizing numerical noise.



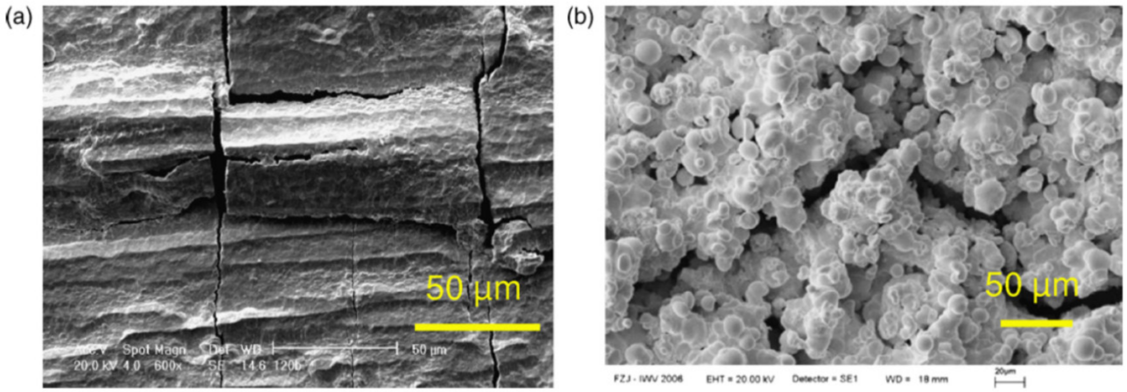
- Under expected core plasma conditions:
- Divertor heat flux reduced 5 times.
- Particle flux remains roughly unchanged.

[2013-Meyer-Nucl Fusion-v53-p104008]

Impurity seeding leads to large radiative cooling of divertor plasma; but how about ingestion by plasma core?



“Strong attraction”: when both sides experience dramatic changes (II: What strongly coupled interactions can do.)



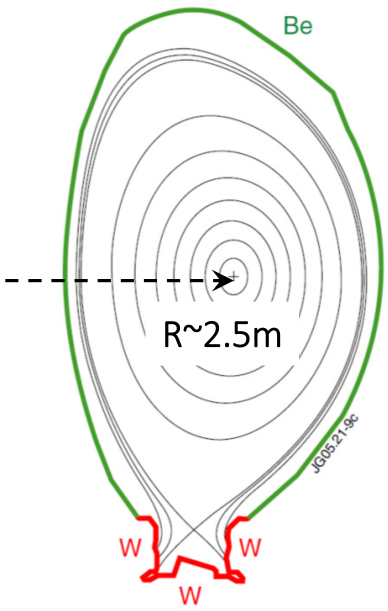
[2007-Hirai-Fus. Engin. Design-v82-p1839]

W coating (200mm thick on CFC) for JET divertor target after heat loading testing:

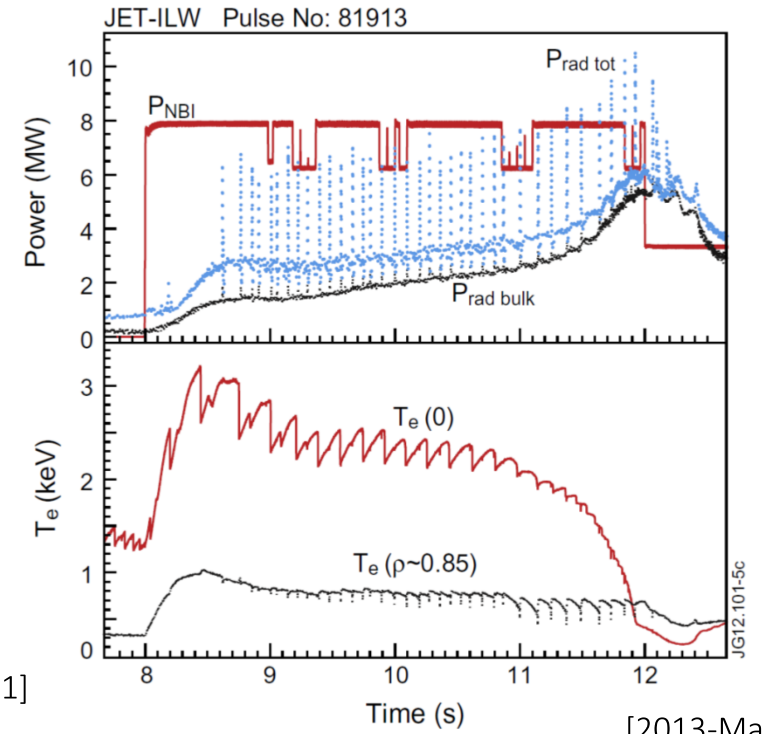
a) Cyclic thermal load ⇒ thermal fatigue cracks.

b) ELM-like pulsed heat load ⇒ grain boundary and surface modified.

JET PFC configuration



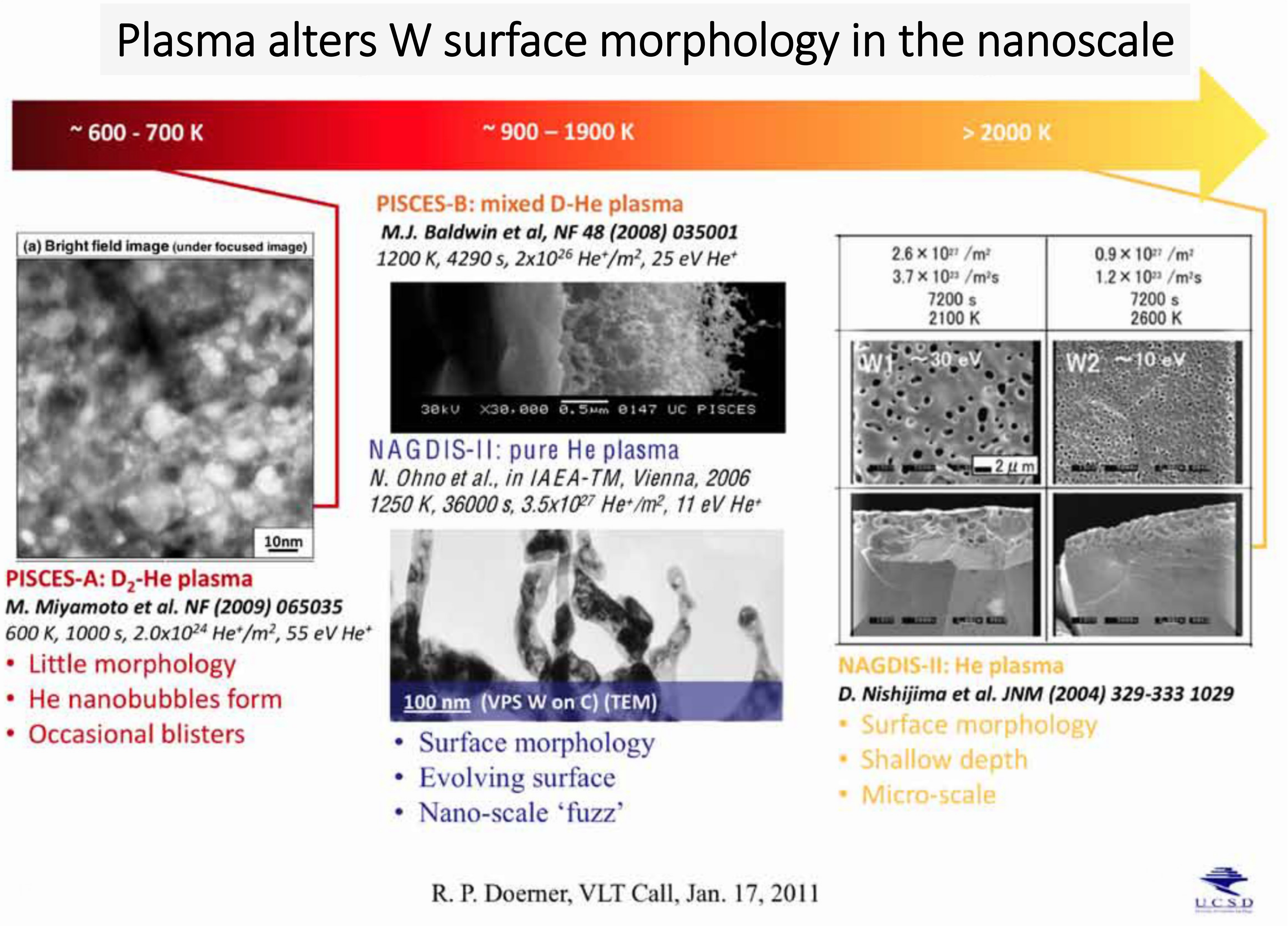
[2007-Pamela-J. Nucl. Mat.-v363-365-p1]



A failed JET plasma pulse operating with W divertor and Be first wall, when large ELMs were present:

- Impurity line radiation increased toward the applied plasma heating power.
- Plasma temperature declined as the plasma starved of net heating.

[2013-Mathews-J. Nucl. Mat.-v438-pS2]



Plasma alters W surface morphology in the nanoscale

PISCES-A: D_2-He plasma

M. Miyamoto et al. NF (2009) 065035

600 K, 1000 s, 2.0x10^{24} He$^+$/m^2, 55 eV He$^+$

- Little morphology
- He nanobubbles form
- Occasional blisters

PISCES-B: mixed D-He plasma

M.J. Baldwin et al, NF 48 (2008) 035001

1200 K, 4290 s, 2x10^{26} He$^+$/m^2, 25 eV He$^+$

NAGDIS-II: pure He plasma

N. Ohno et al., in IAEA-TM, Vienna, 2006

1250 K, 36000 s, 3.5x10^{27} He$^+$/m^2, 11 eV He$^+$

- Surface morphology
- Evolving surface
- Nano-scale ‘fuzz’

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

NAGDIS-II: He plasma

D. Nishijima et al. JNM (2004) 329-333 1029

- Surface morphology
- Shallow depth
- Micro-scale

R. P. Doerner, VLT Call, Jan. 17, 2011

UCSD

Divertor PMI R&D Has Focused on Weakening the SOL Plasma Fluxes

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- Pedestal and SOL plasma dynamics spread the fluxes to larger areas, but in strong bursts, which can potentially damage the W divertor in ITER
- Techniques are in R&D to disperse these fluxes, with side effects
  - Inject impurity gas into the divertor plasma to radiate heat
  - Mix up the edge magnetic field to spread the fluxes further
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- Further, plasma interactions with W surface cause persistent erosion and alterations in nanoscales
- Philosophy for survival of both SOL and divertor? Make one side so strong that the other can behave freely. Which side to strengthen?

Opportunities abound in R&D to make fusion energy available.

2015 / 2016 Major Public Holiday Calendar

Name	Date	Legal Holidays	2015	2016
New Year's Day	Jan. 1	1 day	Jan. 1 - 3 off	**Jan. 1 - 3 off**
Chinese New Year	subject to lunation	3 days	Feb. 19 (Feb. 18 - 24 off)	**Feb. 8 (Feb. 7 - 13 off)**
Qingming	Apr. 4 or 5	1 day	Apr. 5 (Apr. 4 - 6 off)	**Apr. 4 (Apr. 2 - 4 off)**
May Day	May 1	1 day	May 1 - 3 off	**Apr. 30 - May 2 off**
Dragon Boat	5th of 5th lunar month	1 day	Jun. 20 (Jun. 20 - 22 off)	Jun. 9 (Jun. 9 - 11 off)
Victory Day	Sep. 3	1 day	Sep. 3 (70th Anniversary of Victory over Japan)	Sep. 3 (no holiday)
Mid-Autumn Day	Aug. 15 of lunar calendar	1 day	**Sep. 27 (Sep. 26 - 27 off)**	Sep. 15 (Sep. 15 - 17 off)
National Day	Oct. 1	3 days (Oct. 1 - 3)	**Oct. 1 - 7**	Oct. 1 - 7

backup