Diagnostic systems in DEMO: engineering design issues

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Contents

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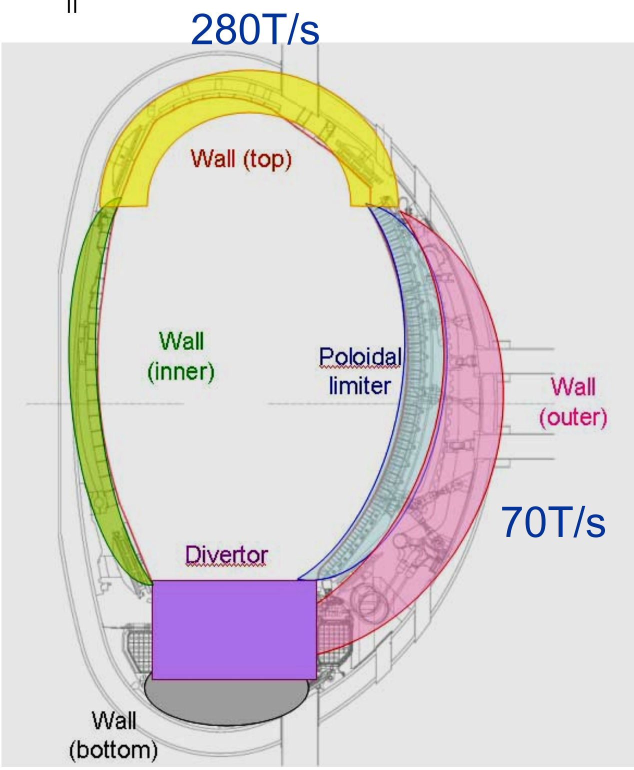
Non-nuclear requirements

- UHV and plasma purity compatibility
- physical compatibility (other systems & their maintenance schemes)
- lines of sight restrictions
- clearances & tolerances
- vibration, acceleration (seismic and "rare" disruption induced)
- magnetic field and its rate of change
- dust, debris & condensate immunity
- environmental temperature
- neutral particle (etc) erosion
- avoidance of halogens (*re* T plant)
- earthing policy, EMI, EMC
- insulating breaks
- system isolations for maintenance etc
- RAMI (difficult for high complexity systems)

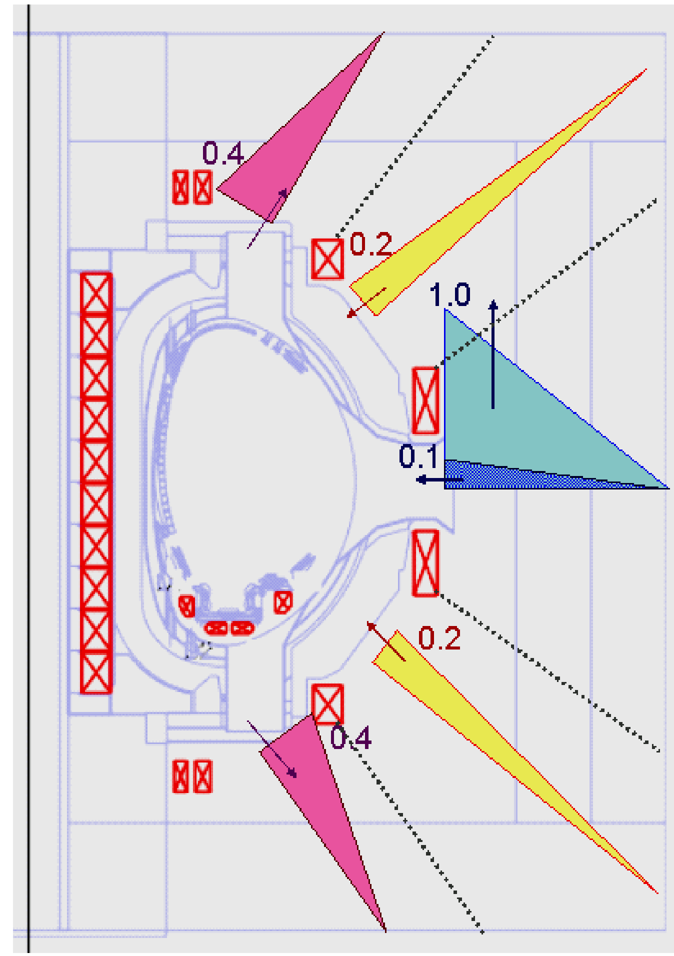
… and doubtless many more!

In JET, regions inside and outside the torus are mapped in zones where peak B, dB/dt, disruption acceleration (up to 4g) etc are defined, for component stress analysis:

$dB_{||}/dt$ in-vessel



B ex-vessel



But in ITER, as doubtless it will be in DEMO, it is necessary to analyse the EM and acceleration environment of each sub-assembly uniquely.

Nuclear requirements

- Regulatory approval
    - * tritium and dust containment
    - * machine control integrity
    - * machine protection reliability
    - * possible human safety issues
- Nuclear damage
    - * displacements per atom (changing crystal structure)
    - * transmutation (function, calibration, LAM)
    - * hydrogen and helium production
        - swelling (hence tolerances)
        - reweldability
- Nuclear signal interference
    - * RI EMF, RI Conductivity, RI Luminescence, RI Thermal EMF
- Nuclear heating
- RAMI
    - * maintenance requirements
    - * Remote Handling – and to achieve the desired overall machine availability, RH must be very much faster than JET and ITER
    - * diagnostic system life (& rationale) if not maintainable
- Failure recovery
- Shielding, labyrinths
- Human access controls – bioshield location

ITER DOORS* on Diagnostics (1)

- ITER has 3 classes for diagnostics: primary, back-up & supplementary, covering 52 identified systems in a number of different types of site for these diagnostics
- Then there are 4 categories: protection, control, advanced control, & physics studies.
- SIC (Safety Important Class) for T containment – double walls etc. as JET, diff pumped and monitored
- Temperatures of 200 and up to 350 (400)°C
- Accelerations, B, B-dot and rad fields have to be elucidated case by case
- Seismic loads – unlike other machines to date, very formal
- No more than 5 replacements of Upper & Equatorial port-plugs – all “unplanned”, and no more than 3 for divertor cassette changes – all heavily planned
- Direct coupled (eg VUV) systems should all be on one sector
- Can put diagnostics in RH ports but only if impact on RH deployment is small
- Port-plug exterior fixings must be bolted not welded
- ...maintenance detritiation... ...RH systems...
- Cabling etc. is cooled by conduction into the vessel

*Dynamic Object-Oriented Requirements System

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*Dynamic Object-Oriented Requirements System

ITER DOORS* on Diagnostics (2)

- Off-normal events include 2bar steam pressurisation of the vessel.
- Accommodate differential movements
- Fire standards for cables, no halogenated insulation in T areas
- Earthing, EMC etc. – much like JET and other present-day machines
- Active cooling against nuclear heating etc.
- Diag port plugs have to maintain shielding of main shield; ditto wall penetrations
- UHV materials now have to avoid high vapour pressure of transmutation products
- Co, Nb restrictions - LAM
- Special mirror requirements
- Special decommissioning requirements – LAM
- No window etc can be >0.02m^2
- Must tolerate control failure of RH systems (meaning impacts)
- Behind bioshield, there must be <10microSv/hr 24hrs after shutdown
- The current DOORS does not clearly accommodate the scenario for some flux loops– early death
- RAMI includes specific requirements, which could be compared with JET's (low) and DEMO's (high)

JET – ITER – DEMO compared

As onerous as the JET design criteria are often viewed, those of ITER and one day DEMO have to be far more so...

Comparison of radiological impacts of JET-ITER-DEMO First Wall (approximate!)

	Site T Inventory, g	Average $MWyr/m^2$	Peak n/m^2 >0.1MeV*	dpa	He appm	Operating Gy/sec	Shut-down Gy/hr
JET 1997	20	10^{-7}	$1x10^{19}$	10^{-6}	10^{-5}	n: 40 γ: 100	0.01
ITER all life	4000	0.3	$4x10^{25}$	2	20	n: 200 γ: 500	500
DEMO 3 FPY	6000?	6	$8x10^{26}$	50	500	n: 300 γ: 500	10,000

*About 5x the neutron fluence due to virgin 14MeV neutrons alone

NB Fission reactor neutron spectra are much softer than fusion neutron spectra and as a result generate about 1/10 of the He appm per dpa.

In epoxy, polyimide, glass, carbon & alumina, there is ~$(0.1\text{-}1.0)x10^{-15}$ $Gy/(n/m^2)$

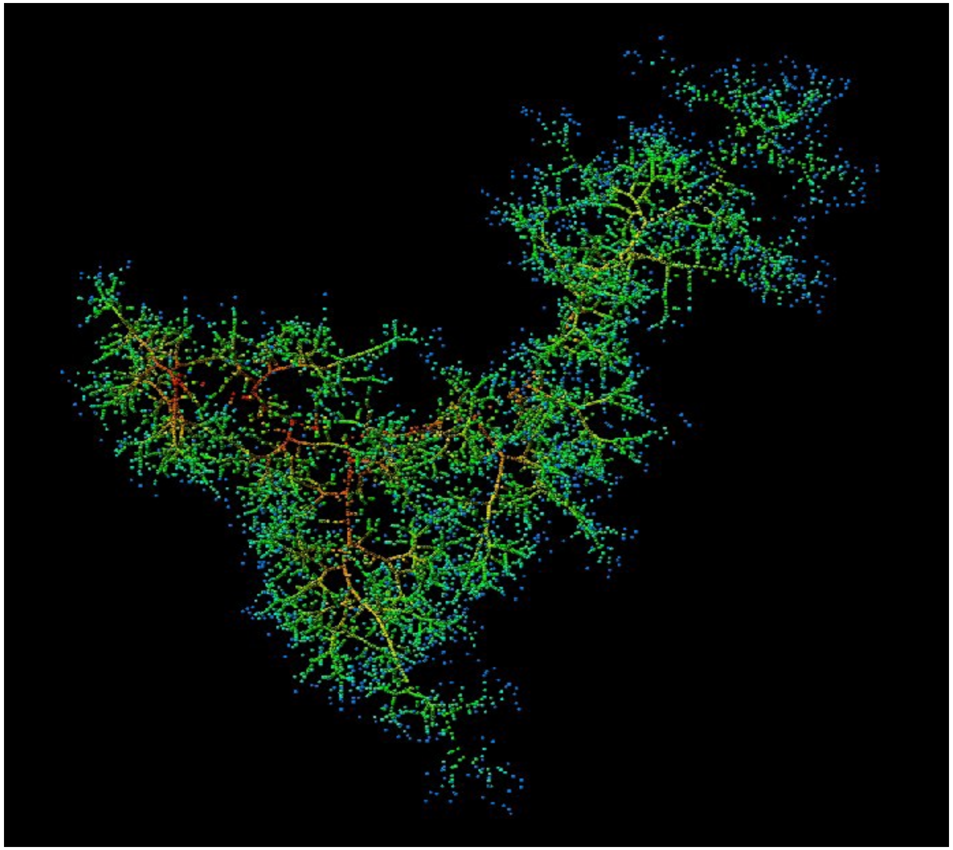
DEMO Structural Materials issues

Example of Fe lattice damage caused by one “cascade” induced by a 150keV Fe ion recoiling from a single neutron impact.

Size of simulation cell: 475 Å;

6.75 million atoms

Nearly all the displacements are Frenkel Pairs (vacancy + interstitial atom) which recombine rapidly (faster with higher temperature), but still hundreds remain, together with more complex crystal defects.



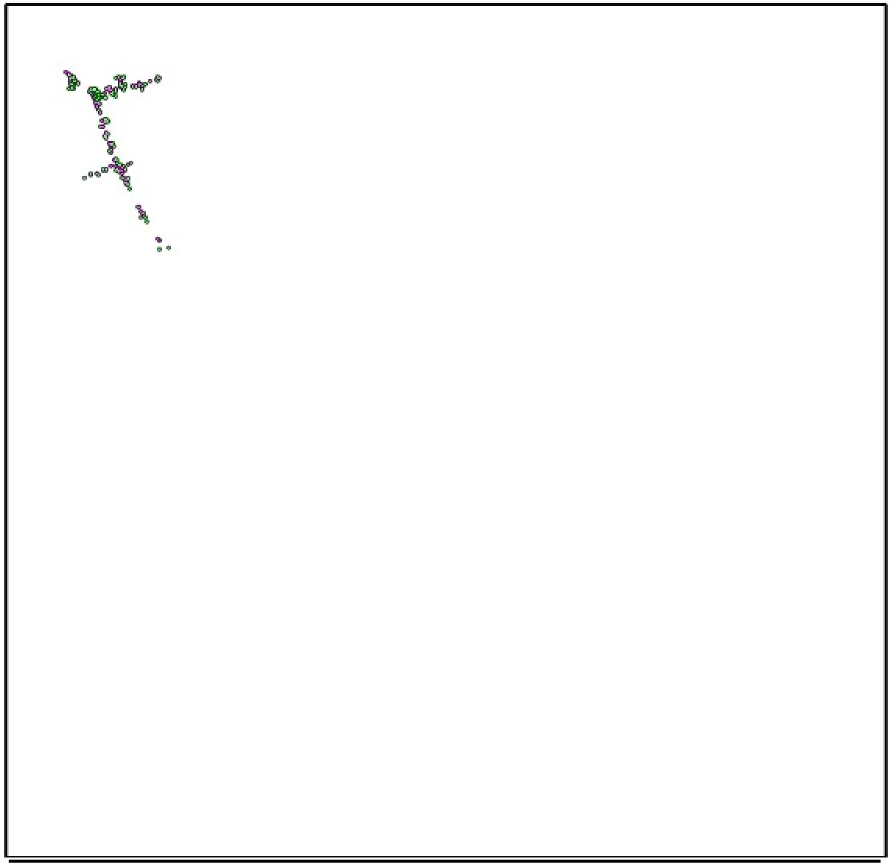
K. Nordlund, TEKES – University of Helsinki: December 2012

DEMO Structural Materials issues

Example of Fe lattice damage caused by a 500keV Fe ion recoiling from a single neutron impact. Initial temperature 300K.

Duration of video ~20ps.

Nearly all the displacements are Frenkel Pairs (vacancy + interstitial atom) which recombine rapidly (faster with higher temperature), but still hundreds remain, together with more complex crystal defects.

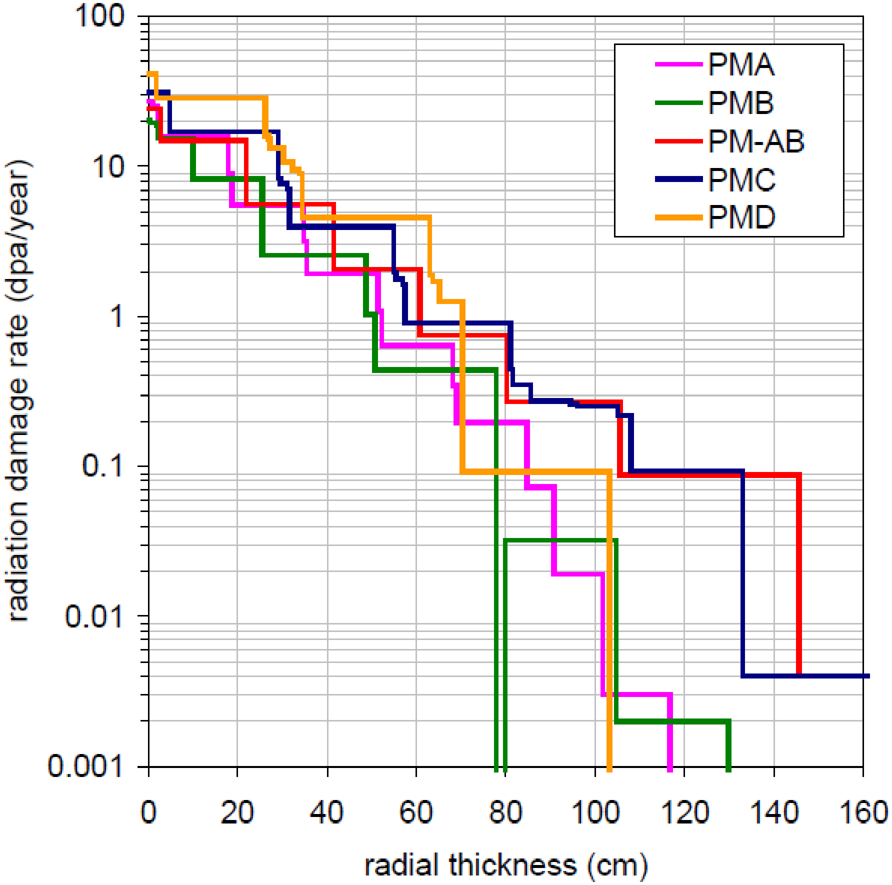


The nature of high-energy radiation damage in iron, E Zarkadoula et al, Journal of Physics: Condensed Matter, Volume 25, Number 12

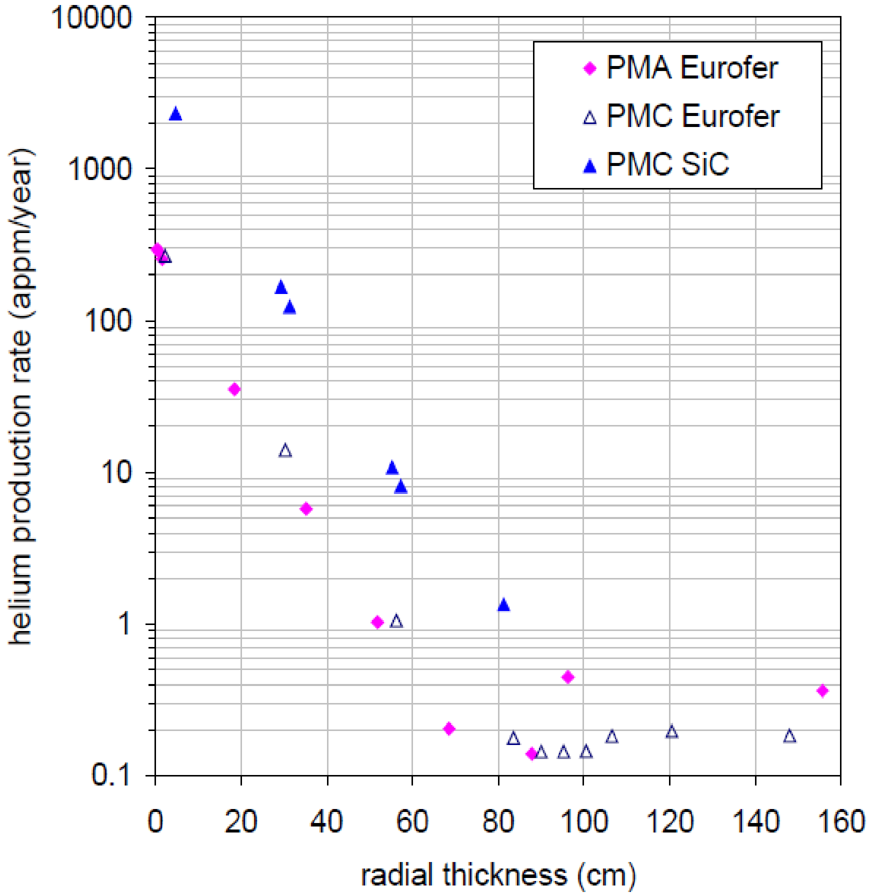
Damage profile through the breeding blanket

The neutron damage in DEMO of course reduces strongly through the thickness of the blanket and shield modules – away from any gaps

dpa/year for the PPCS designs



He appm/year for PPCS-A and -C options

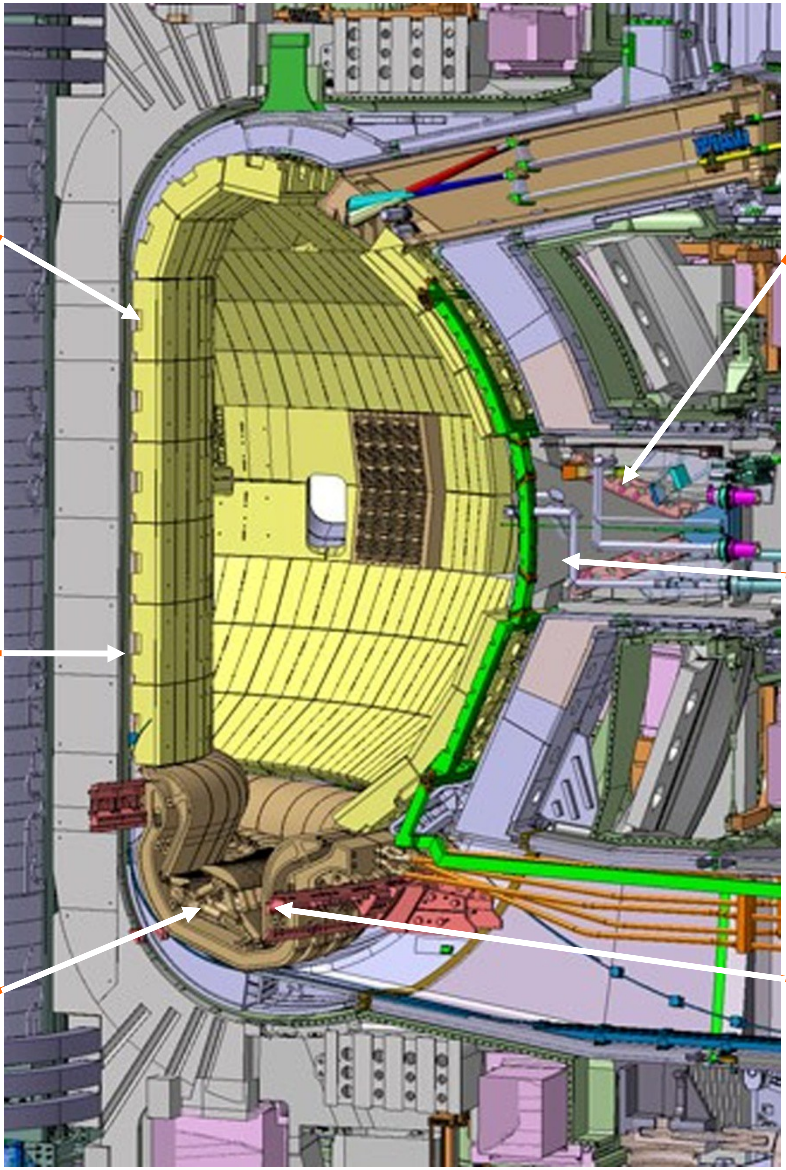


Radiation effects on fusion diagnostics

Magnetic coils
- Radiation Induced Conductivity (RIC)
- Radiation Induced Electric Degradation (RIED)
- Radiation Induced Electromotive Force (RIEMF)
- Any integrators must be ultra-low drift

Bolometers
- RIC
- Nuclear Heating
- Sputtering
- Contact degradation
- Differential swelling and distortion

Pressure gauges
- RIC
- RIED
- Filament aging



Neutron cameras
- Noise due to γ-ray, proton, α
- Radiation damage on solid state detectors

Optical diagnostics

Mirror
- Deposition, erosion
- Swelling, distortion

Window
- Permanent and transient absorption
- Radioluminescence
- Swelling, distortion

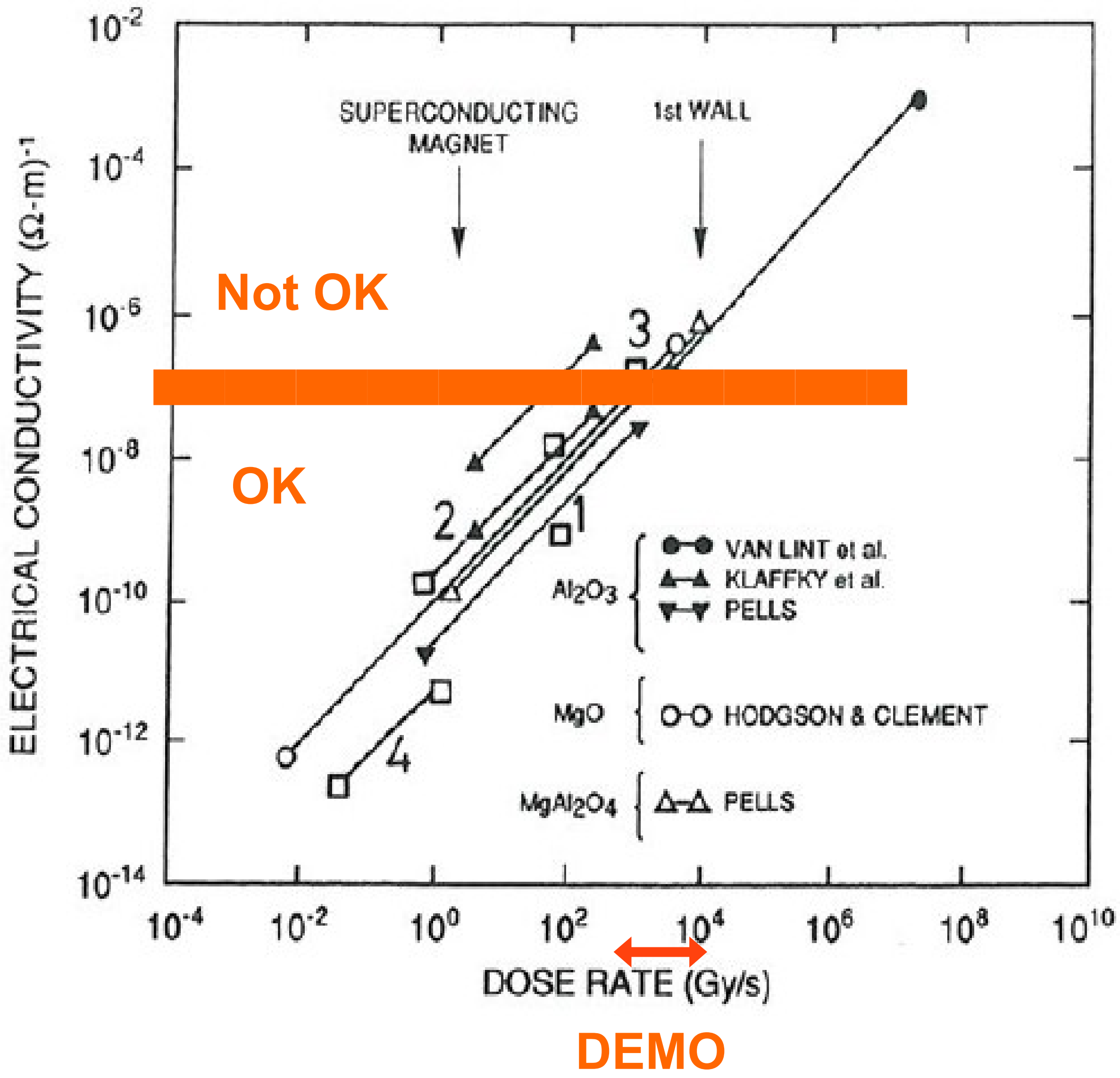
Impurity monitoring

Mirror and windows
- same as above

Fibers
- Permanent and transient absorption
- Radioluminescence

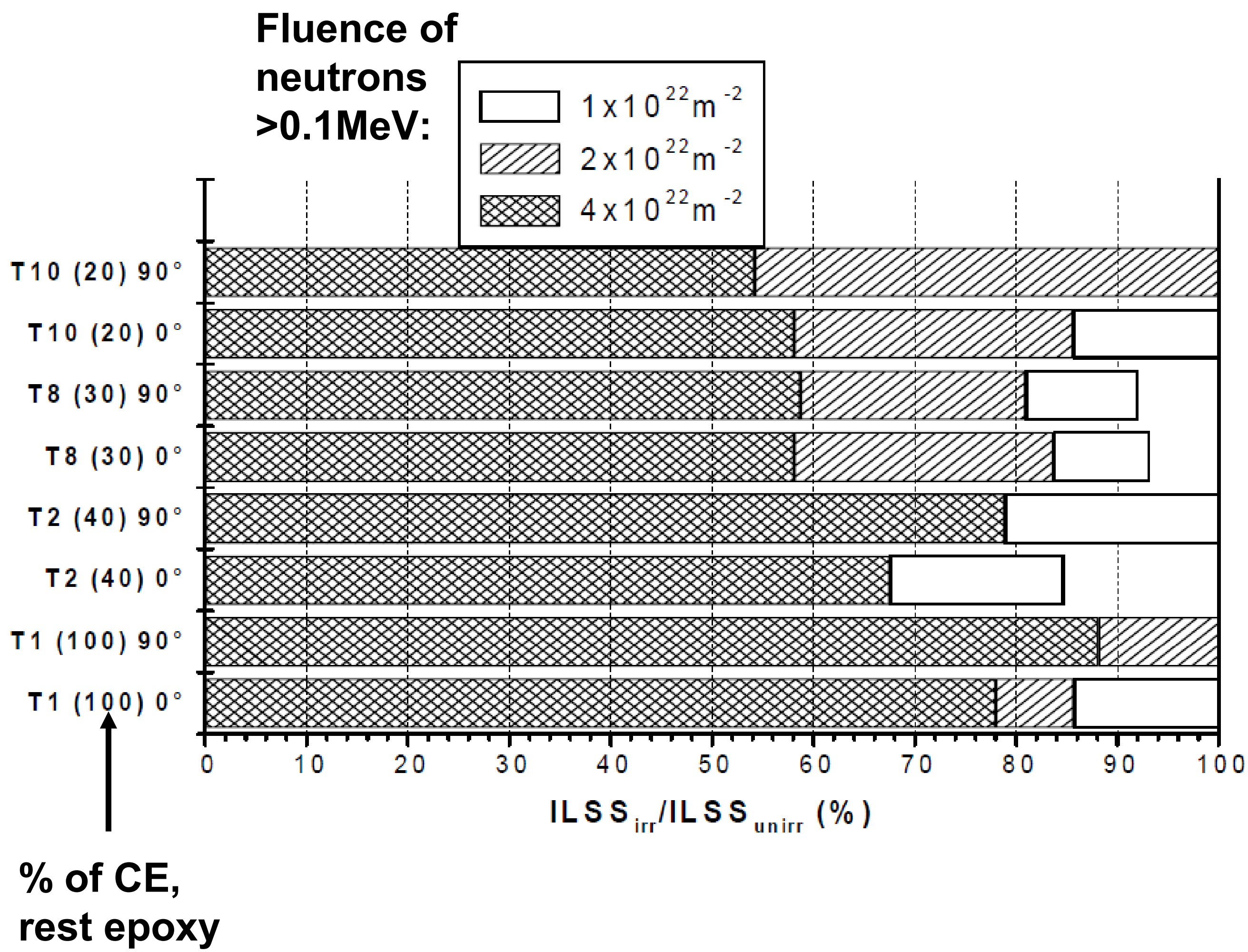
Radiation induced conductivity

Insulators conduct too well if radiation >1000Gy/sec



Radiation induced loss of interlaminar shear strength

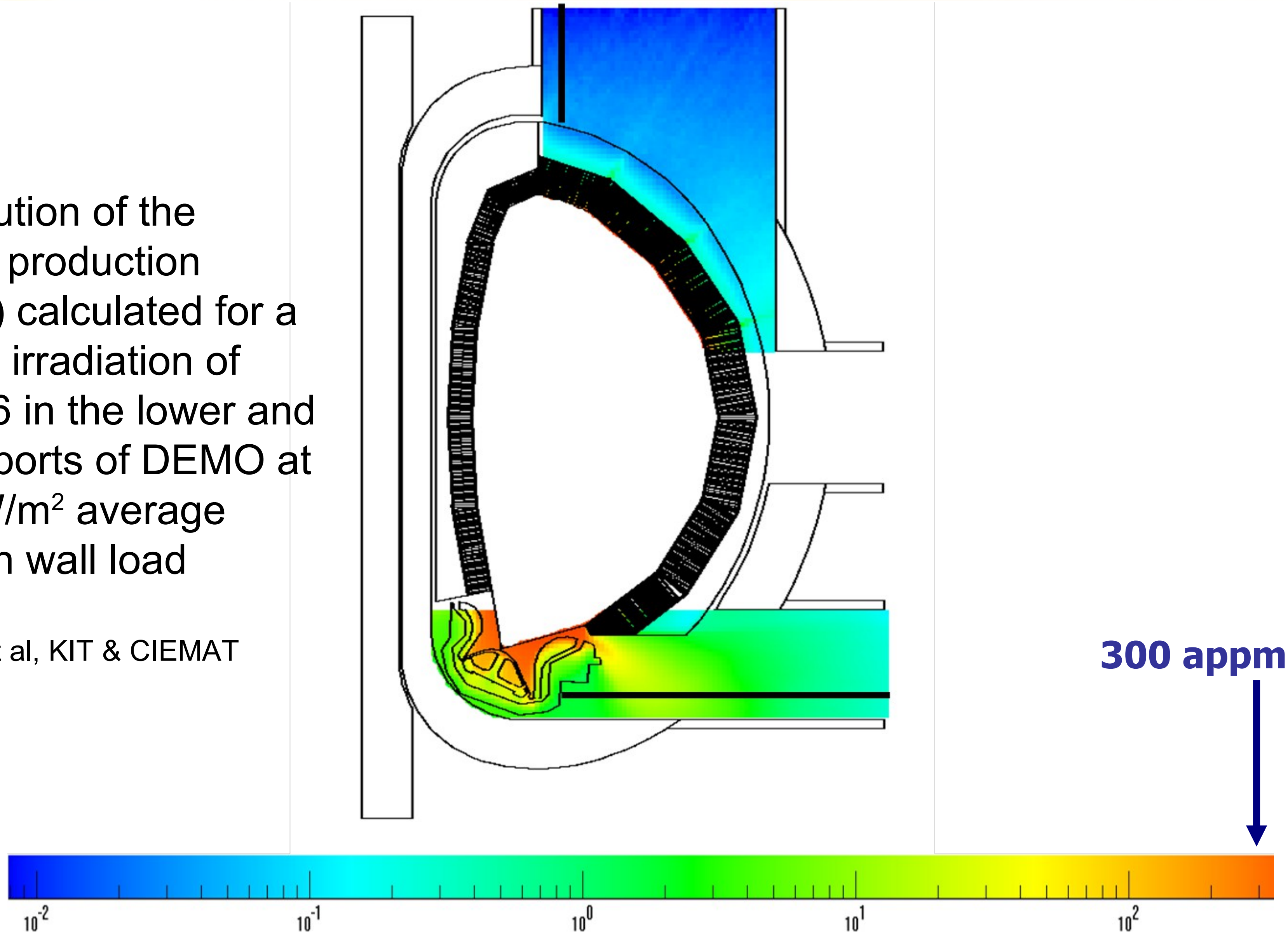
At doses ~100MGy, or ~10^{23} n/m^2, the mechanical strength of epoxy is severely degraded, although cyanate ester is less so.



He production in steel: ~10 appm / dpa

Distribution of the helium production (appm) calculated for a 5 year irradiation of SS-316 in the lower and upper ports of DEMO at 1.2MW/m² average neutron wall load

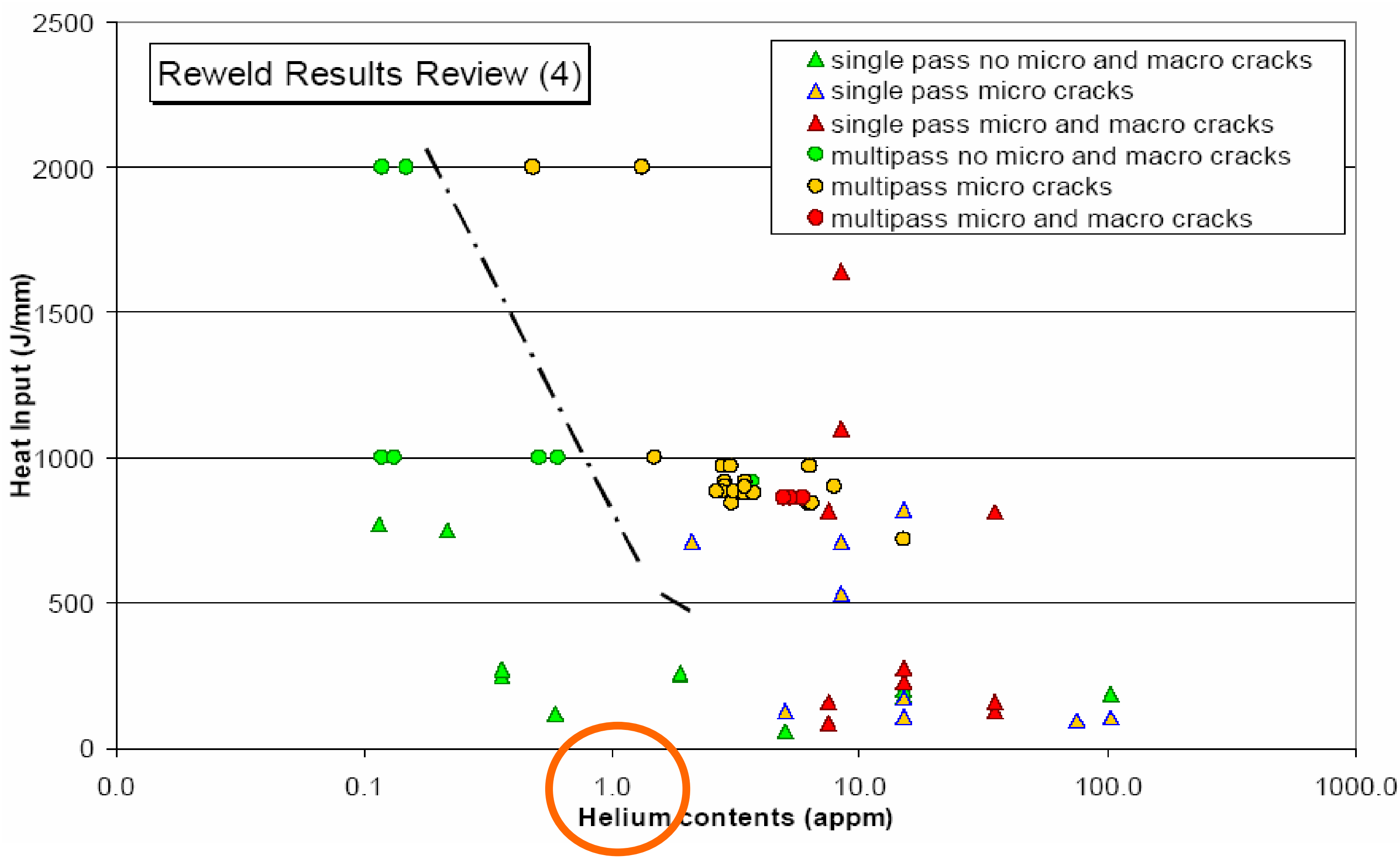
Fischer et al, KIT & CIEMAT



He production in steel: rewelding limit

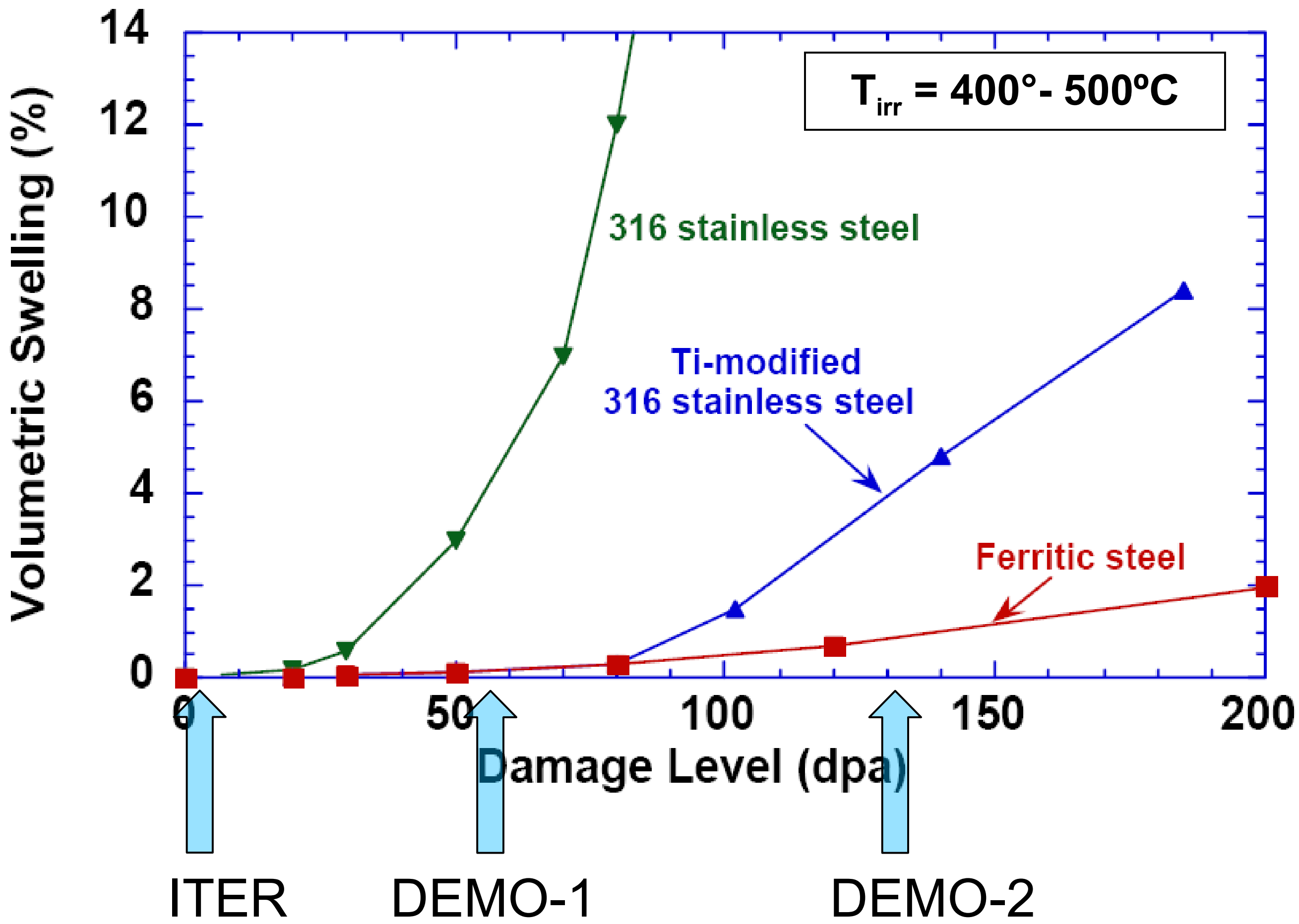
Reweldability of Stainless steel 316L(N)-IG

K. Asano, J. van derLaan, MAR, 2001v



He production in steel: swelling

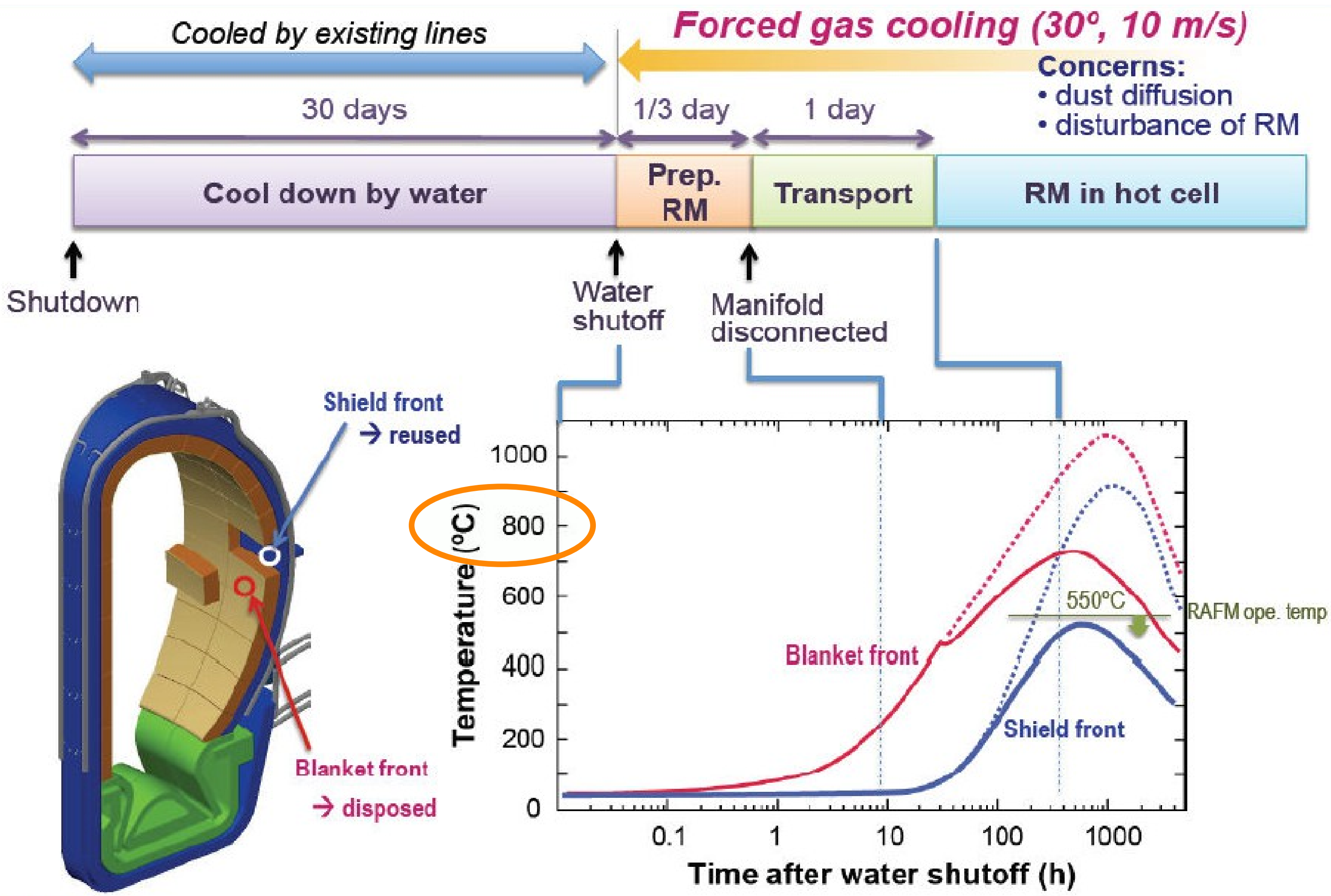
Swelling is not a problem for JET or ITER but will drive material selection in DEMO



Eurofer μ_R~50
F82H μ_R~15

Nuclear heating is severe – instantaneous and delayed

Decay heat is a significant problem in DEMO, e.g. for blanket maintenance



ITER solutions to nuclear plasma diagnostic problems

- **Radiation risk on lenses and electronics – even mirrors**
  Optical doglegs, no lenses in portplugs or use of rad-hard material, cameras behind bioshield and extra shield if needed, mirrors behind thick shields
- **Nuclear heating of front-end components**
  Water cooled first mirrors
- **Radiation – ALARA for servicing operations**
  Removal of portplug, Interspace rack and port-cell rack via rail systems
- **Disruption loads on endoscopes**
  Vertical sectioning of Diagnostic first wall, no rigid tube connections from closure plate into Diagnostic shield module
- **Risk to lose first mirrors due to inaccessibility and long service intervals**
  Single crystal Mo mirrors for erosion resistance, Small pupil designs, Shutters, sputtering of deposits on first mirrors by discharges or laser or gas curtain
- **Coping with thermally expanding and disruption moved vessel and fixed platforms**
  Use of optical hinges
- **Integration challenge**
  Cohabitation with other systems, standardization, neutronics

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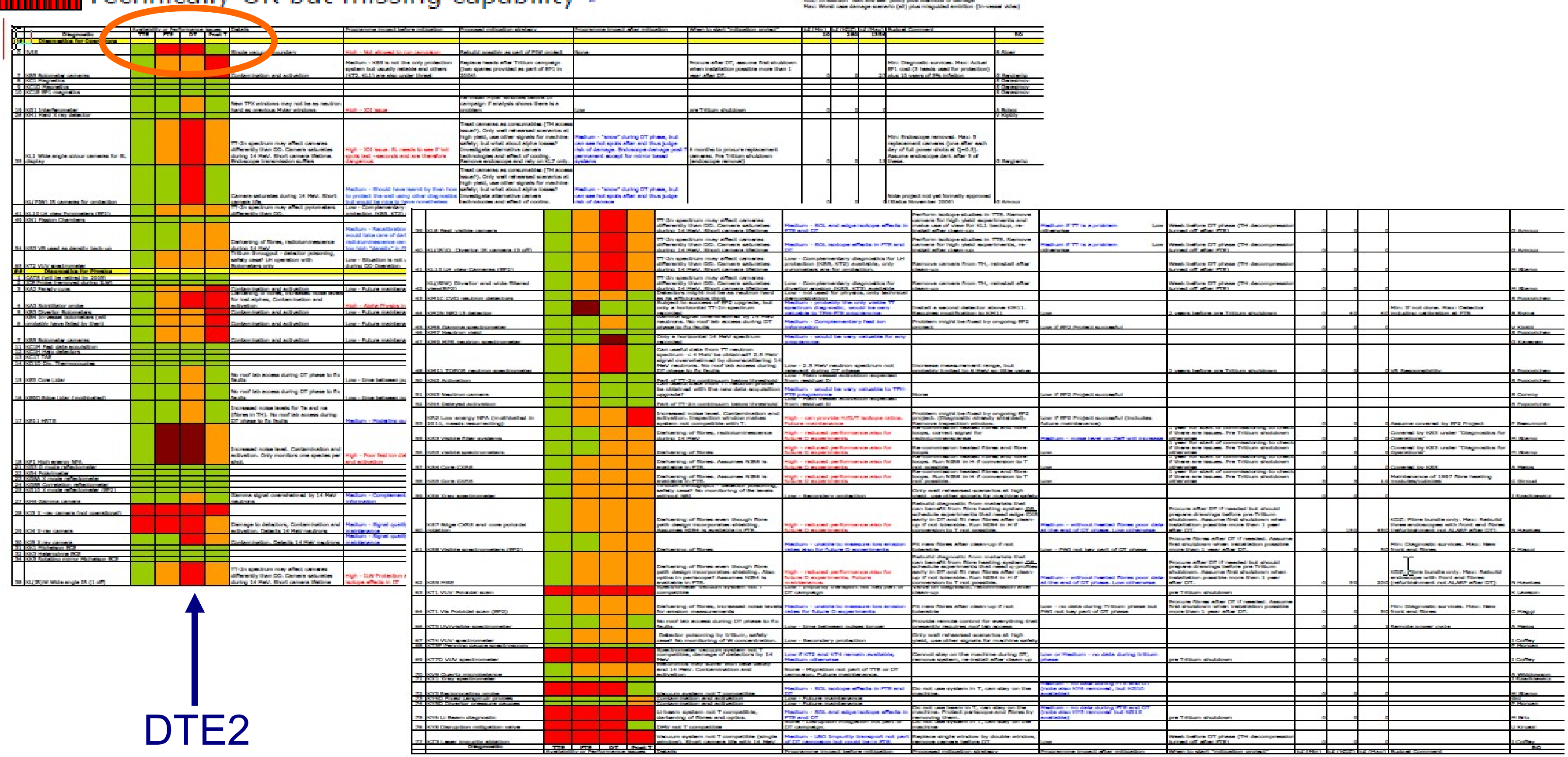
Compatibility of diagnostics with DT operations

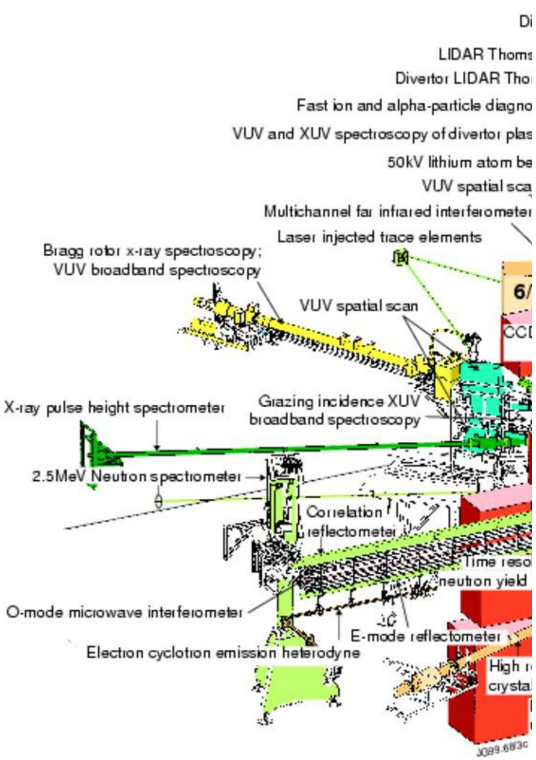
Even in JET, getting diagnostics ready for the next DT experiment is non-trivial; this is a table of the status in 2011:

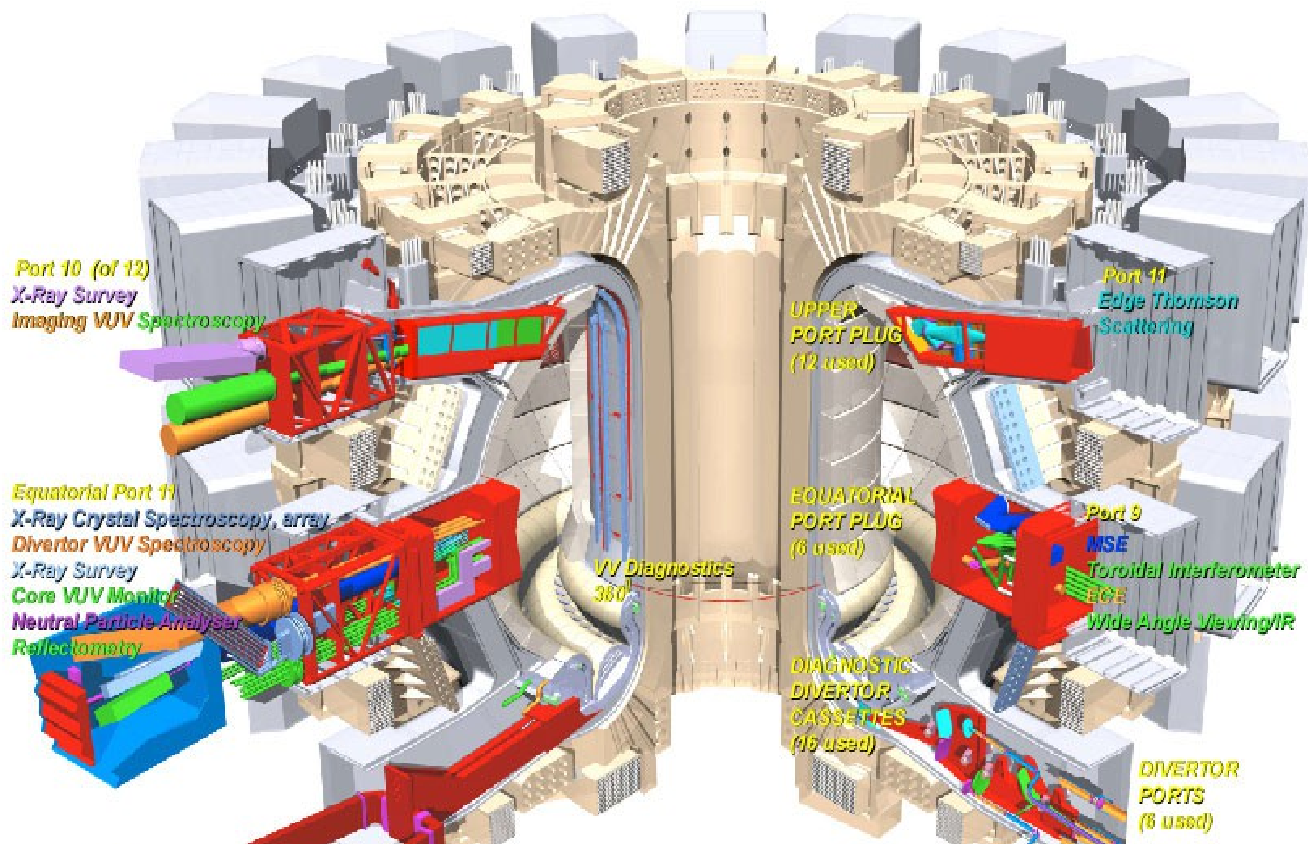
- Definitely OK
- Further engineering analysis required
- Definitely not OK
- Technically OK but missing capability



How sophisticated can DEMO diagnostics be?

Like other *research* machines, JET and ITER are crowded with plasma diagnostics...

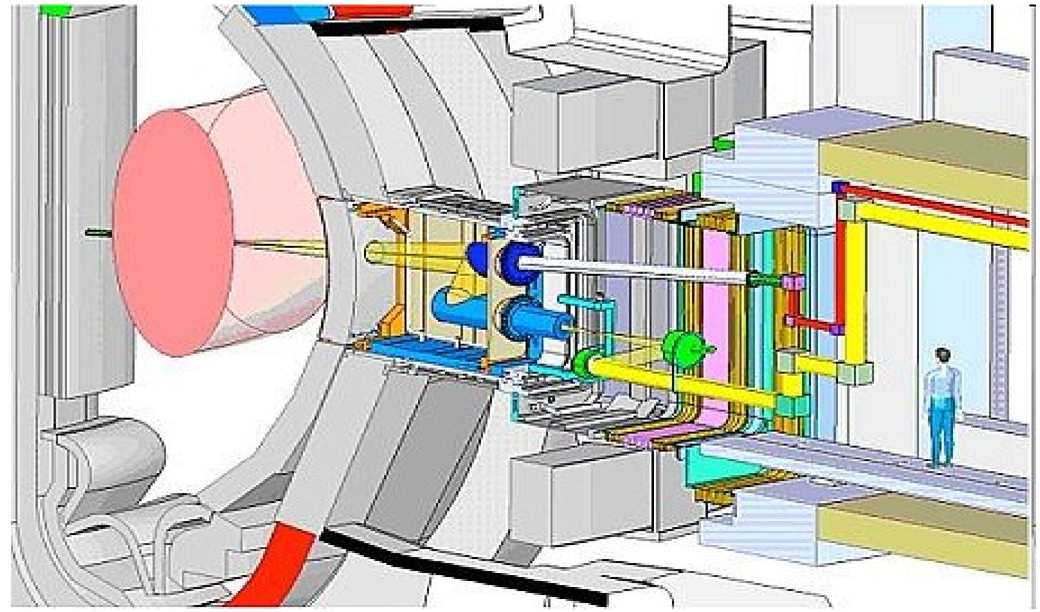




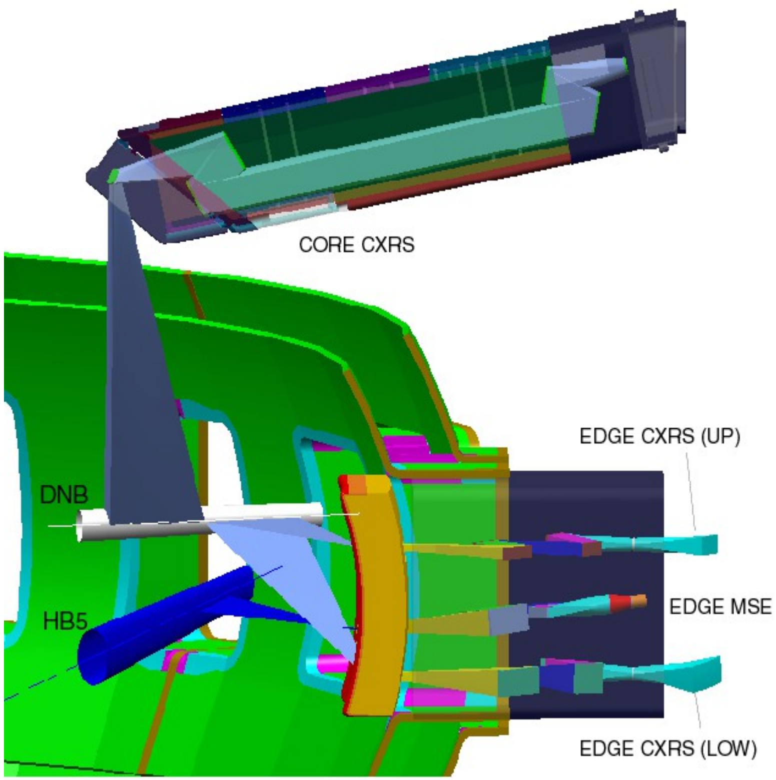
These require a large total port area

Some examples of diagnostics for ITER

It is difficult to see how port space allocations like this can be made in DEMO



Core LIDAR Thomson scattering system (Courtesy M. Walsh)

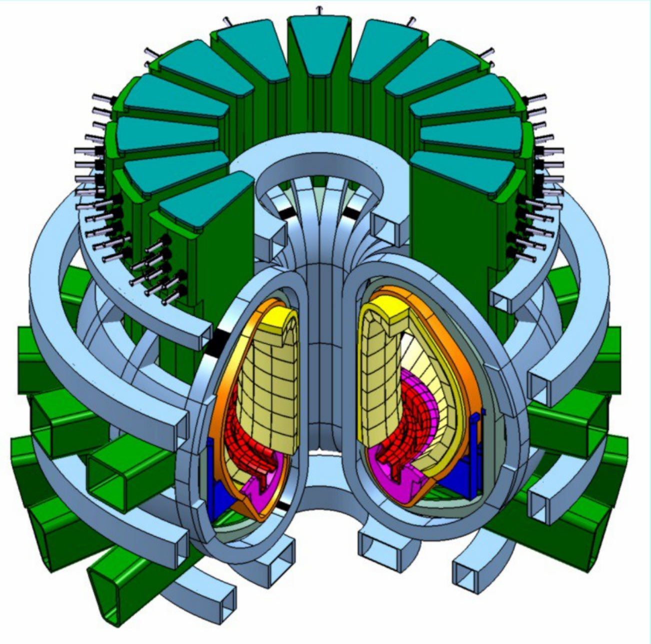


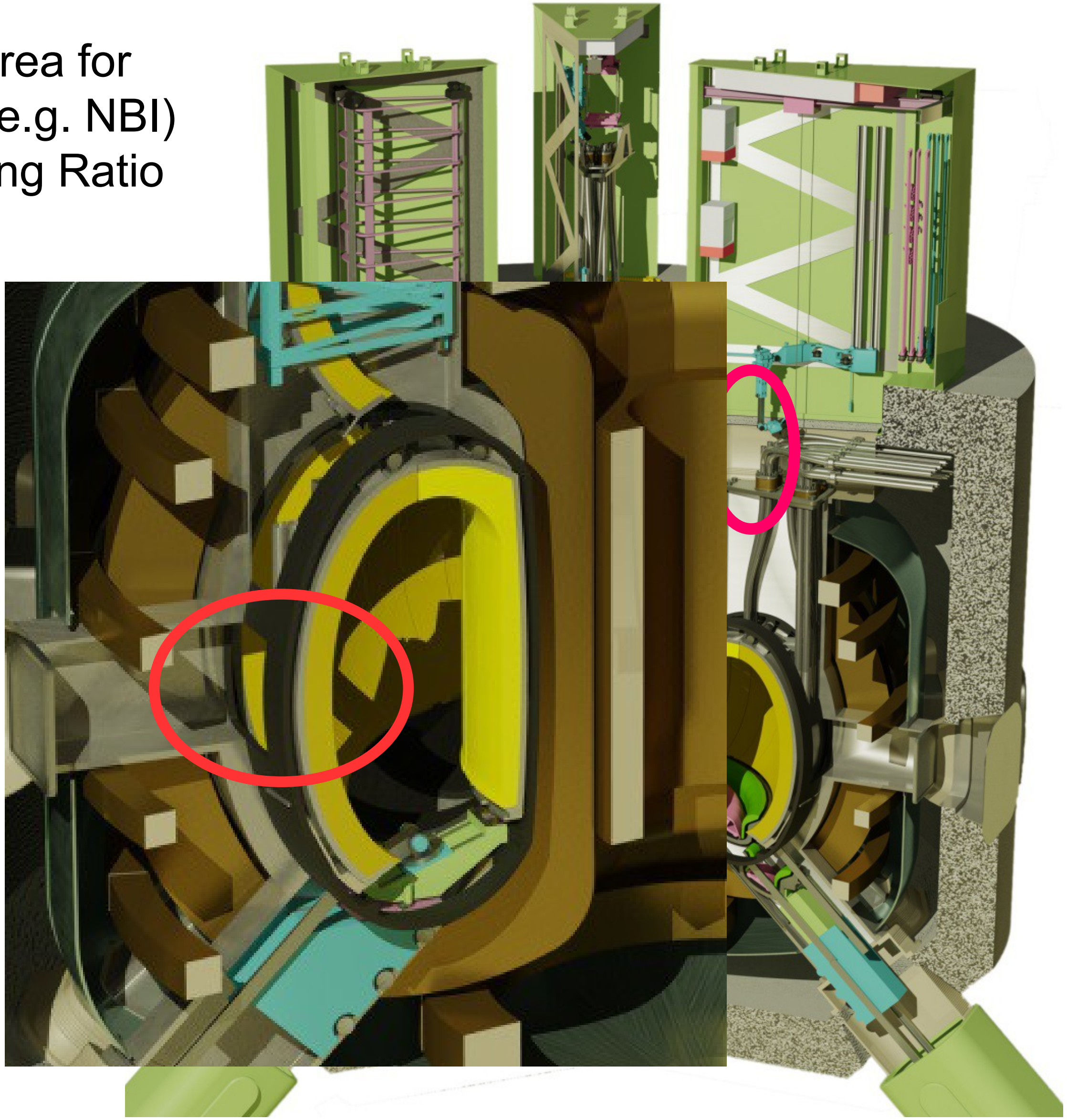
Charge Exchange Recombination Spectroscopy (Courtesy M. von Hellermann)

Space for DEMO diagnostics will be very limited

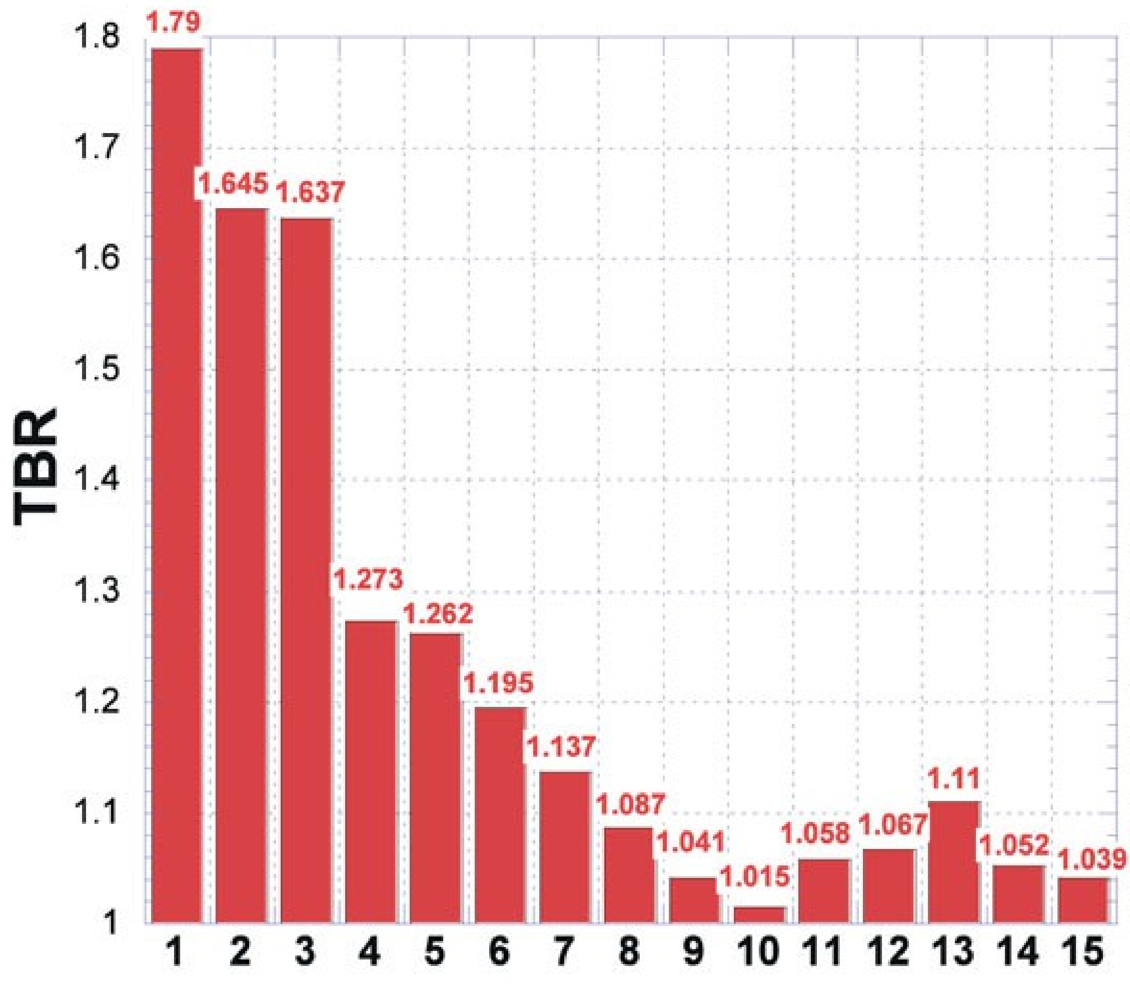
But in DEMO, even the port area for the plasma heating systems (e.g. NBI) matters for the Tritium Breeding Ratio

Ports like those shown here will mostly be blinded by breeding blanket modules





Reduction in TBR with added realism



90% Enriched Li

1. 1-D infinite Cylinder: 100% LiPb breeder surrounded with FS shield
2. $Li_{17}Pb_{83}$ surrounding plasma in toroidal geometry
3. $Li_{15.7}Pb_{84.3}$ surrounding plasma
4. $Li_{15.7}Pb_{84.3}$ confined to 80 cm OB blanket and 45 cm IB blanket. Outer FS shield, and W-based divertor added
5. 2 cm assembly gap between blanket modules
6. Materials assigned to 3.8 cm thick IB and OB FW
7. Materials assigned to side, bottom/top, and back walls of blankets
8. IB and OB cooling channels added
9. SiC FCI added
10. W Stabilizing shell added
11. Extended IB Blanket
12. Extended OB Blanket
13. Extended IB and OB Blankets

70% Enriched Li

14. 70% enriched Li-6 with extended IB and OB blankets
15. Penetrations added (assuming ~1.6% reduction in OB breeding.

Bar chart showing the reduction of TBR from 1.8 to 1.04 upon including the internals of the DCLL blanket and its surrounding components.

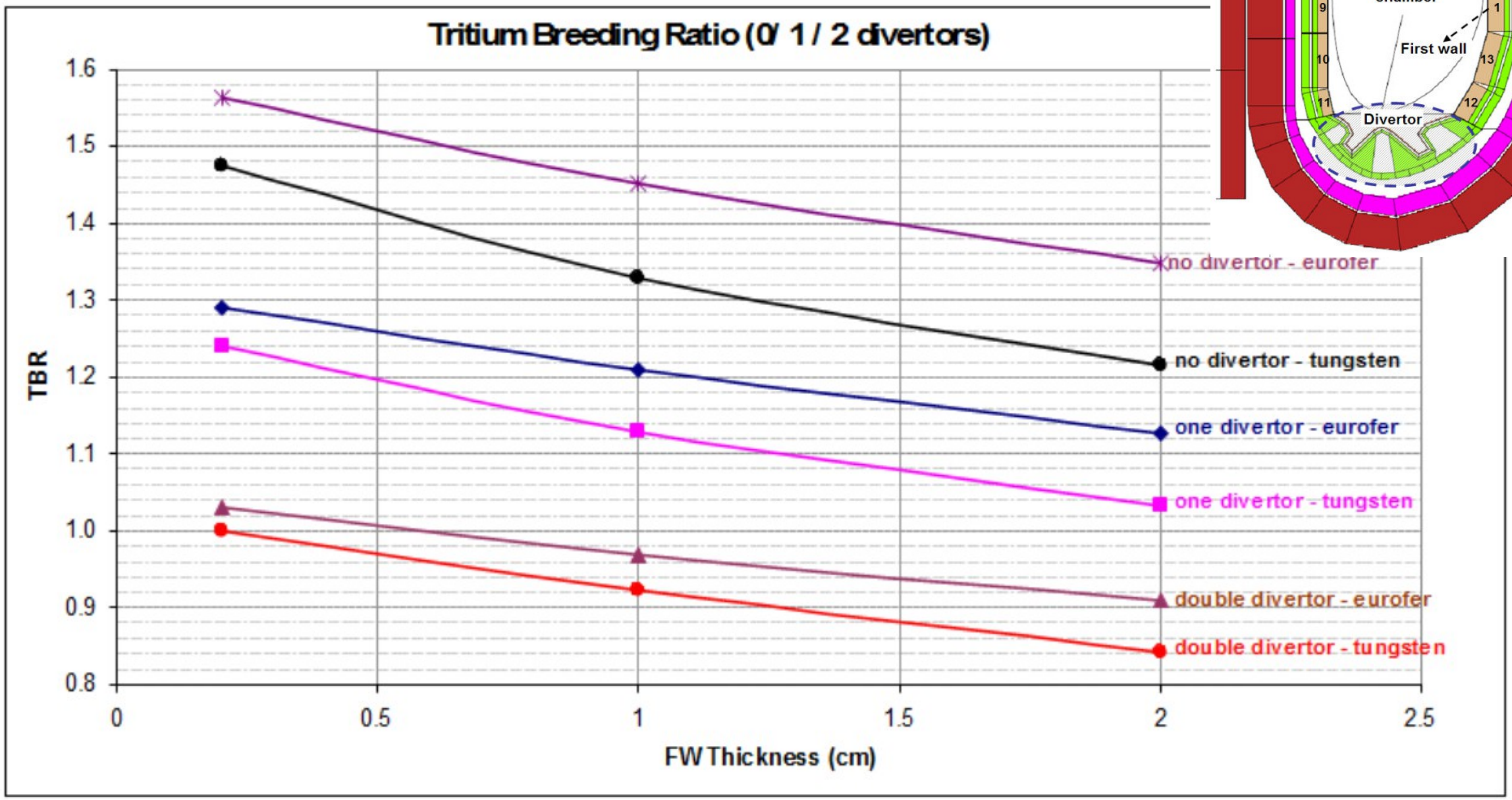
L. A. EL-GUEBALY, et al., FUSION SCIENCE AND TECHNOLOGY, VOL. 61, 2012.

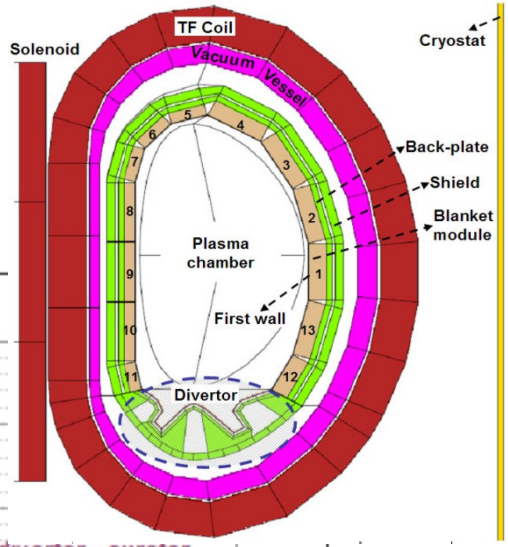
TBR: effects of divertor option and first wall cladding

3D model (First wall materials: Eurofer, Tungsten)

FW thickness: 0.2cm, 1cm, 2cm

No / single / double divertor(s)



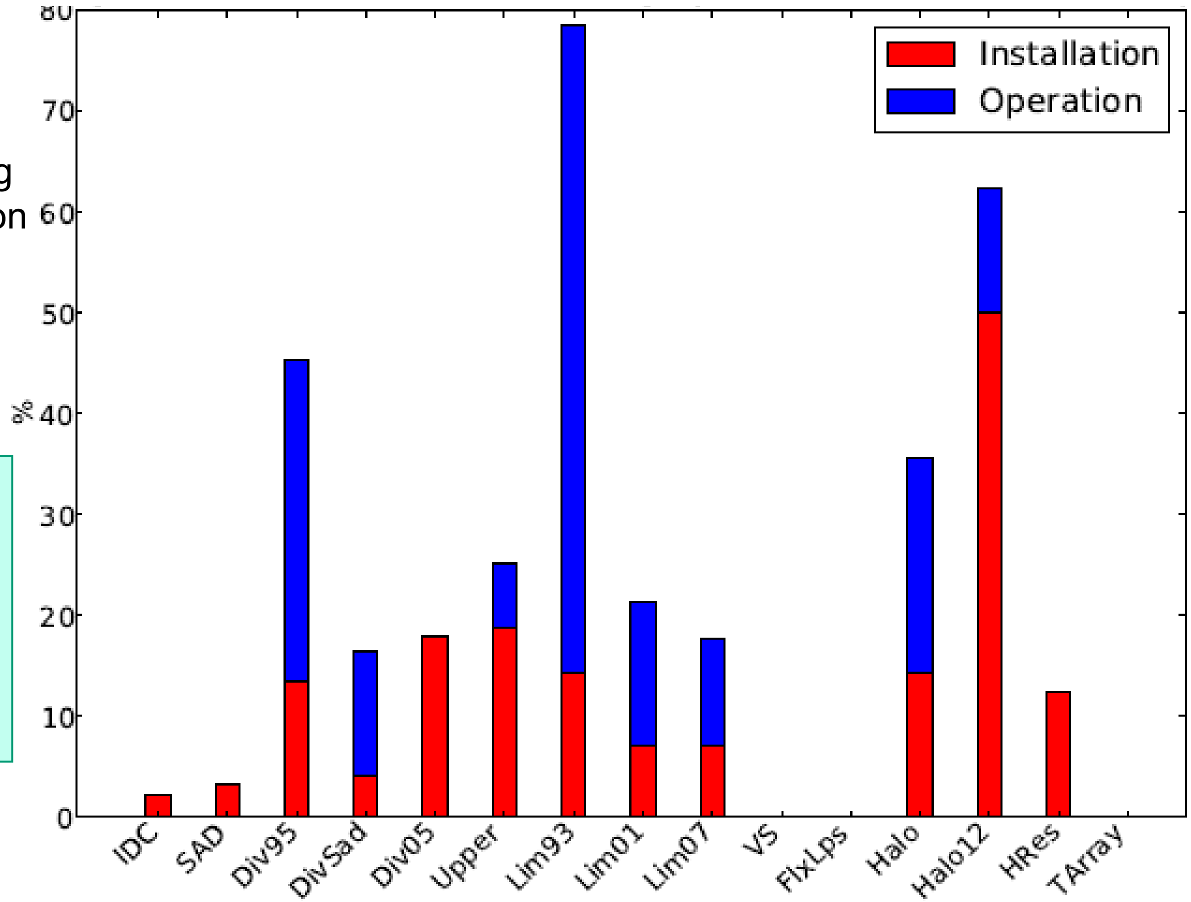


S. Zheng, personal communication, CCFE Physics & Technology talk, 5th July 2013

RAMI issues - JET magnetic diagnostic failures

- 18 types, 482 sensors (coils and loops) considered, 1995-2013
- 6 types have never failed (mainly outside the vessel and with only one connector)
- Highest percentage failures were in the divertor and limiters, especially halo current sensors
- Plasma operational life of those that failed in operation was 12-65 hours, or 2k-10k pulses
- NB A significant percentage of failures was in installation (e.g. at RH connectors)

Percentage of JET magnetic pick-up coils and loops broken during installation and operation

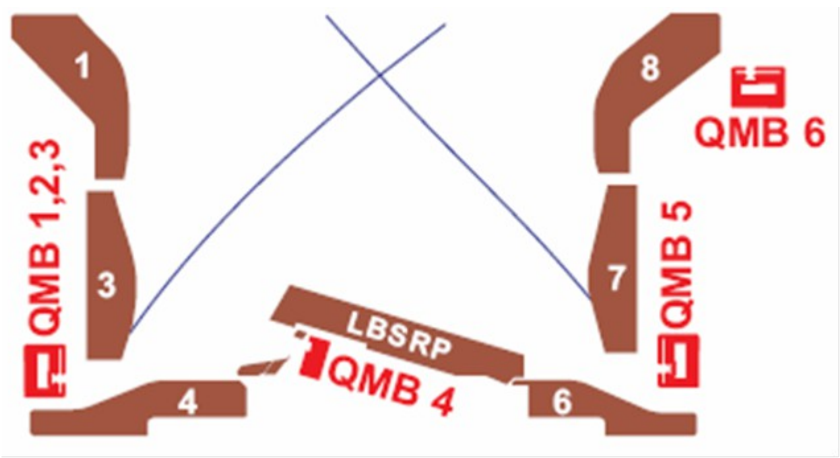


JET anticipates magnetic diagnostic failures in considering machine protection strategies:

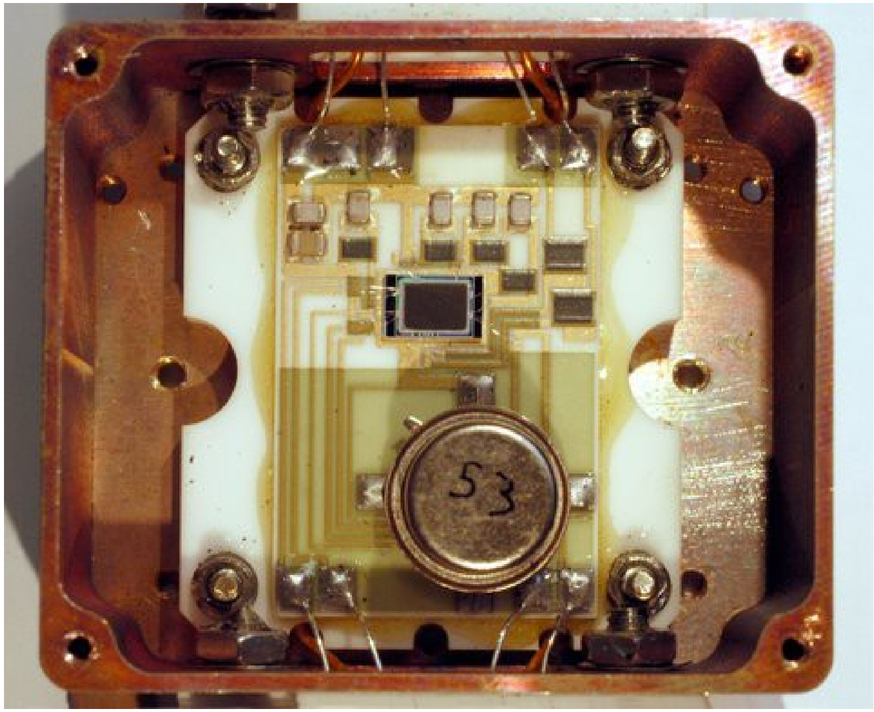
ITER is having to do so for inaccessible flux loops etc.

RAMI issues - JET Quartz MicroBalance failures

- JET Quartz Micro-Balances
- *These are electronic cards that sit in the shadow of divertor tiles, with a small window exposing one surface of a quartz crystal – defining the resonance of a tuned circuit - to plasma deposition. A second device provides temperature compensation and both are compared to a reference oscillator in an ASIC.*
- *Thus they are complex electronics in the full radiation field, subject to the temperature excursions behind the radiatively cooled tiles – and importantly, disruption induced voltages.*



Schematic showing location of QMBs in the divertor



RAMI issues - JET Quartz MicroBalance failures

	2005-2007	2008-2009	2011-2012
QMB1	70606 – Shutter failed Disruption 68.4s Crystals work to end 2009		80263 Depo and temp failed: fast stop, runaways
QMB2	Did not work. Problem with divertor carrier wiring	75674 Thick deposit calibration not valid. Shutter slightly open. Crystals worked to end.	80253 Depo and temp failed during testing off shutters 2 & 3
QMB3	66273 Depo failed, temp also affected 69100 Temp failed	Left in vessel but not working	80263 Depo and temp failed: fast stop, runaways
QMB4	65697 Depo failed – overheating suspected 67547-Temp failed: fast stop	Intermittent. Broken connections at QMB suspected.	80153 – Temp failed 80160 Depo failed – soft stop. Poor isolation an issue. Pick up from shutters.
QMB5	67547 Depo and temp failed – fast stop	76720 Depo fails as shutter activated. Also ELMs. Depo frq→Temp frq Temp work to end.	80160 Temp failed – Soft stop 80248 Depo failed – shutter testing
QMB6	73760 Depo and temp failed	Cracked crystal on removal in 2009 (not observed in 2007)	No installation

ASIC failed

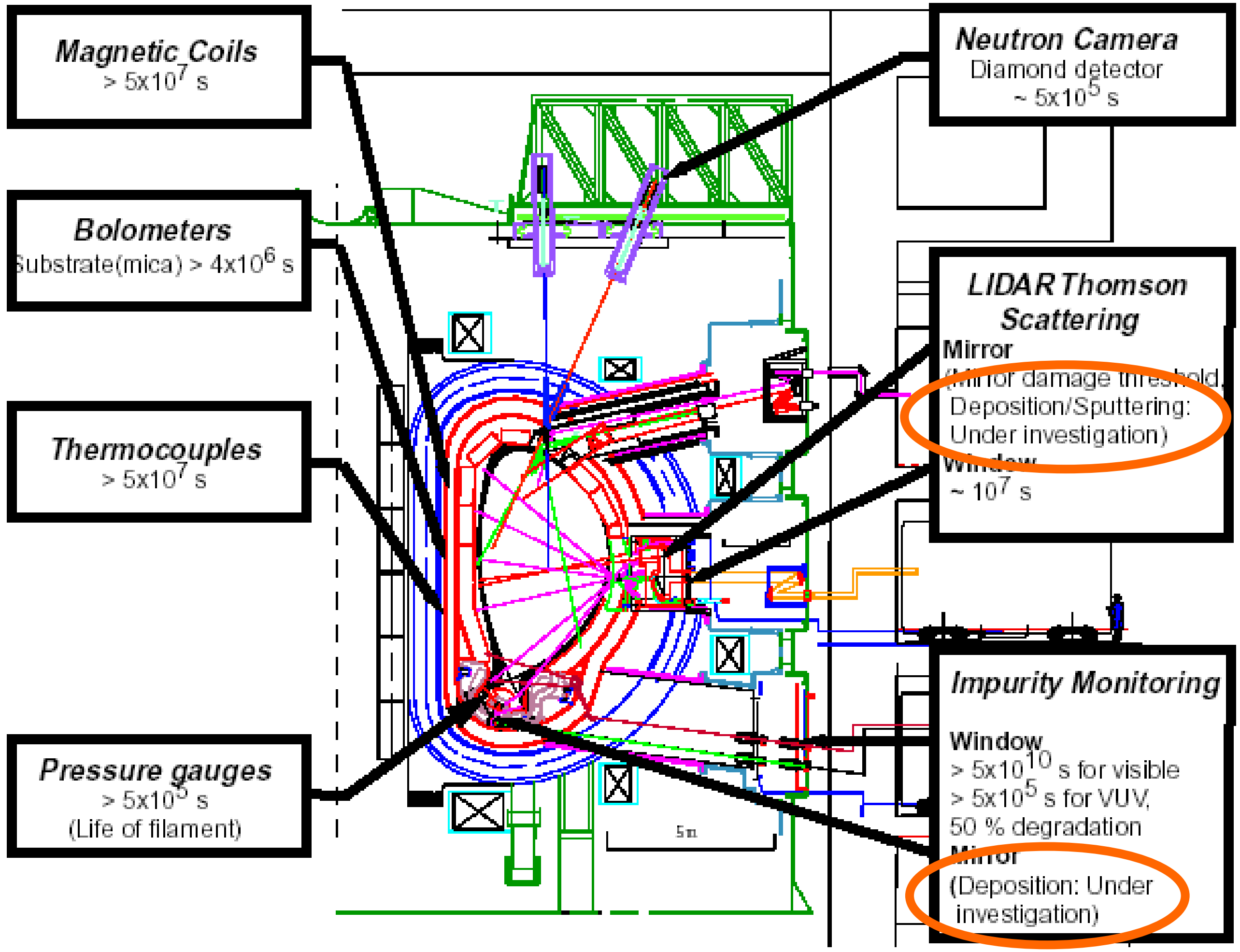
Examples of diagnostic lifetimes in ITER

Extract from G. ***Vayakis, The ITER radiation environment for diagnostics,*** ***55 RI 38 04-05-06 W 0.1***

- Life-time of some key diagnostics components at neutron power density of 0.5 MW / m^2 i.e. neutron power of 450 MW

- The fluence of 0.3 MWa / m2
- = 2 x10^7 s burn at 450 MW

- The life-time is mainly limited by radiation effects, except where shown with ()



Promising diagnostic options

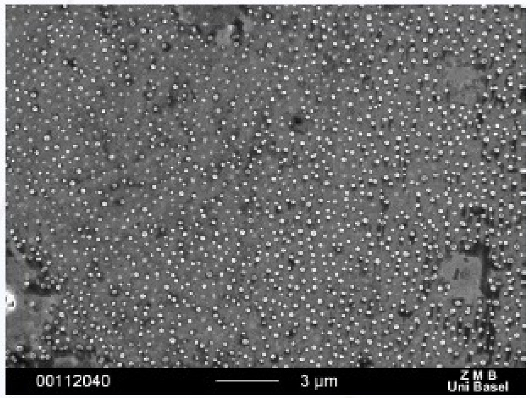
- ***But all is not lost!***
- Some diagnostics are largely immune to the problems created by the erosion / deposition and nuclear effects, such as:
  - microwave diagnostics, which use small waveguides and can incorporate complex labyrinths, while the wavelength is long enough to tolerate minor mirror imperfections
  - and diagnostics using penetrating radiation:
    - Neutron diagnostics, for ion temperature and tomography
    - Gamma ray diagnostics, e.g. using n,γ reactions for impurity tomography
- Some are likely to be possible given sufficient development, e.g.:
  - SXR diagnostics – if rad hard detectors can be developed e.g. photocathodes
- Some might be enabled by in-situ cleaning techniques of mirrors and (remote) windows
  - Work on mirrors is encouraging, e.g. erosion does not degrade specular reflection – although if cm of erosion occur, focal length etc will surely alter
- And there are emerging technologies e.g.:
  - diffractive mirrors and gratings, tolerant of some erosion or deposition
- And very low duty cycle exposures of delicate diagnostics behind (non-electrical) shutters
- And gas-blowing to slow and repulse erosion and deposition particles

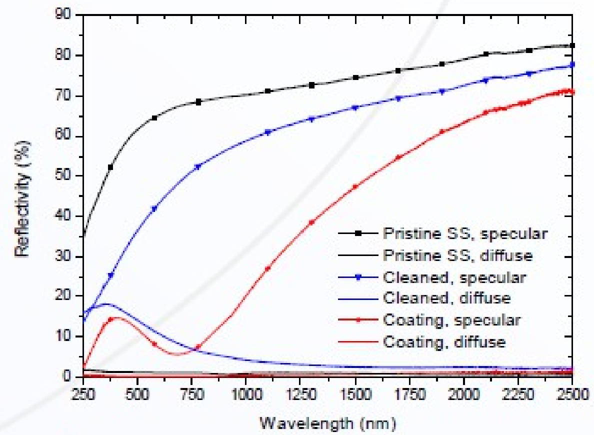
RAMI issues – Can 1st mirrors be effectively cleaned?

- Cleaning tests in vacuum have been performed on three samples coated with different mixtures of aluminium, tungsten and carbon, at 532 and 230 nm.
- It was found that the initial recovery of the reflectivity obtained at 532 nm could be further improved by additional exposure at 230 nm.

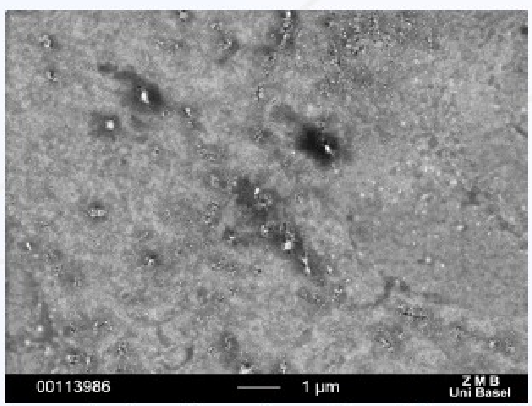
Sample 1: 532 nm only

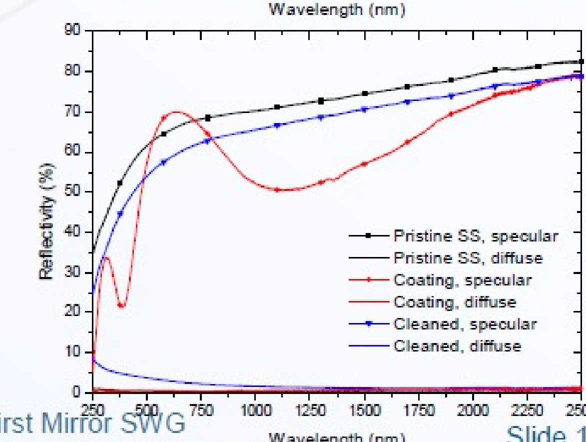
Tungsten dust remains on the surface → higher diffuse reflectivity





Sample 2: 532 followed by 230 nm

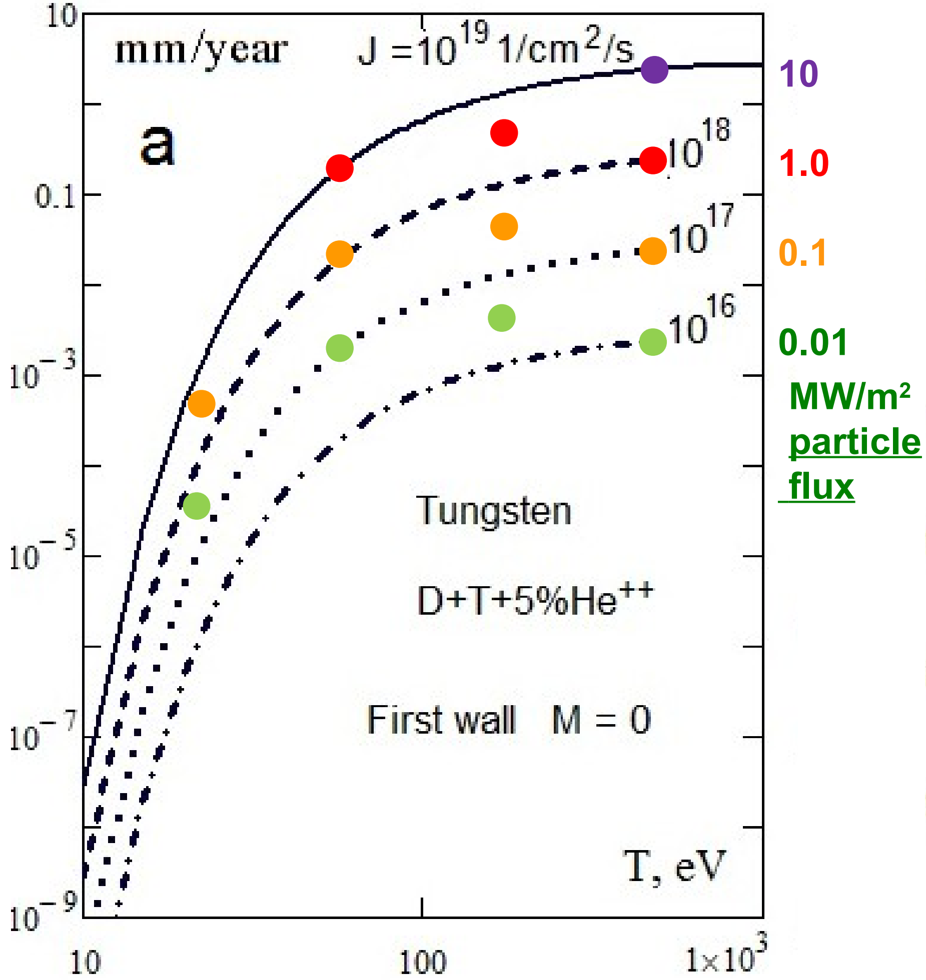




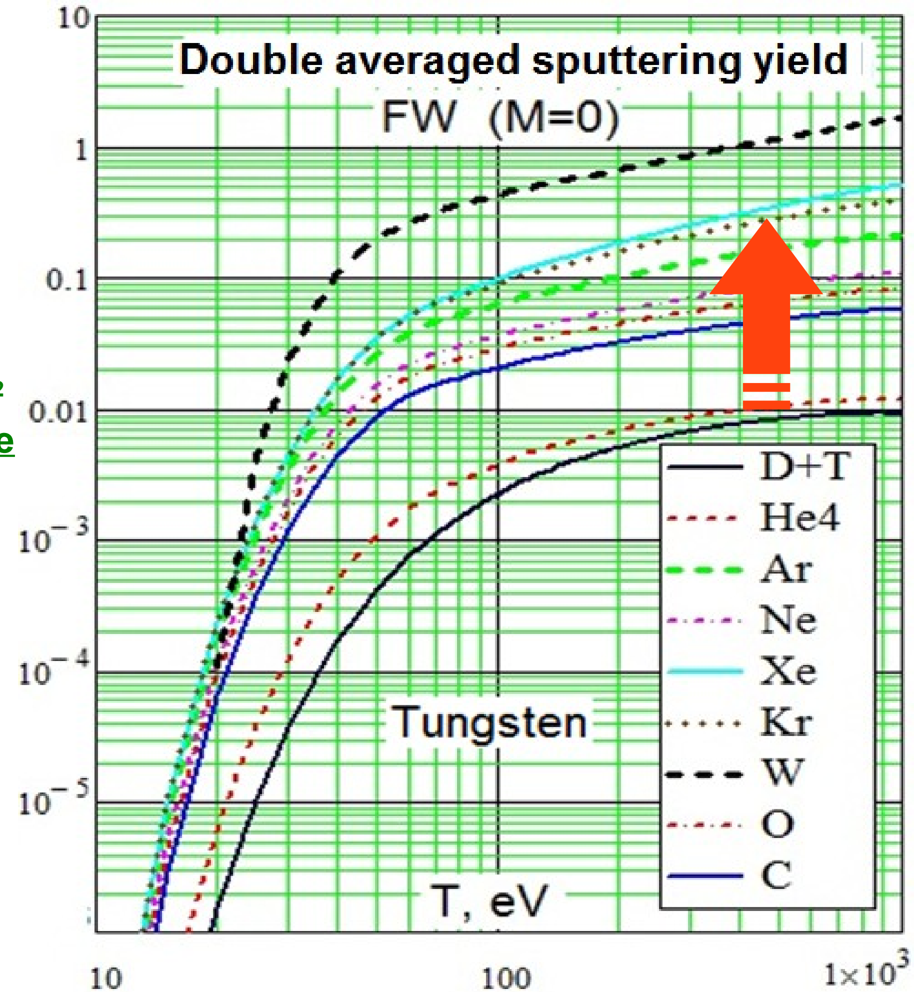
Andrey Litnovsky and contributors, Report of the First Mirror SWG
22nd Meeting of the ITPA TG on Diagnostics, Moscow, Russia, May 14-17, 2012

RAMI issues – If a 1st mirror was like the First Wall

Then up to ~1mm/year would be eroded with just D,T & He:

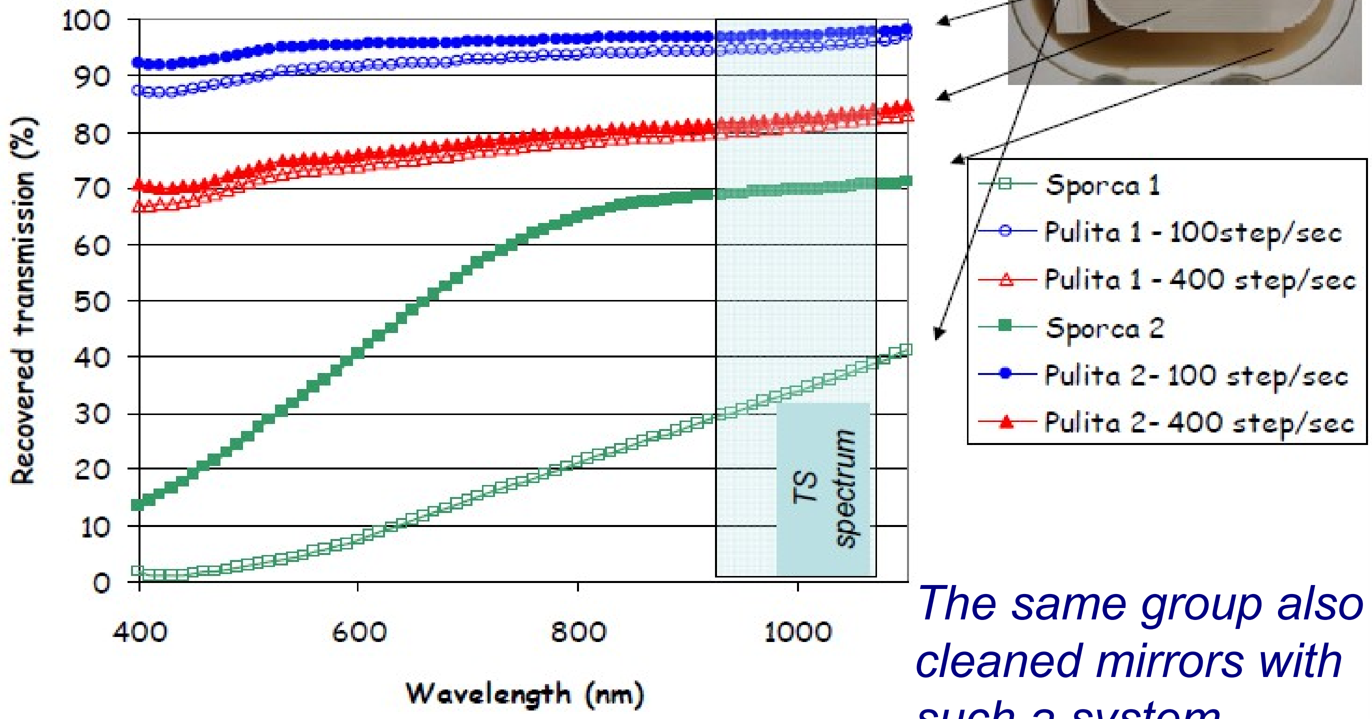


But really there will be impurities as well:



RAMI issues – Can DEMO windows etc be cleaned?

A very effective system for the windows of RFX:



The same group also cleaned mirrors with such a system.

However the brown coating in RFX was mainly B and C – DEMO would be W etc, but hopefully only loose dust as far back as likely windows should be.

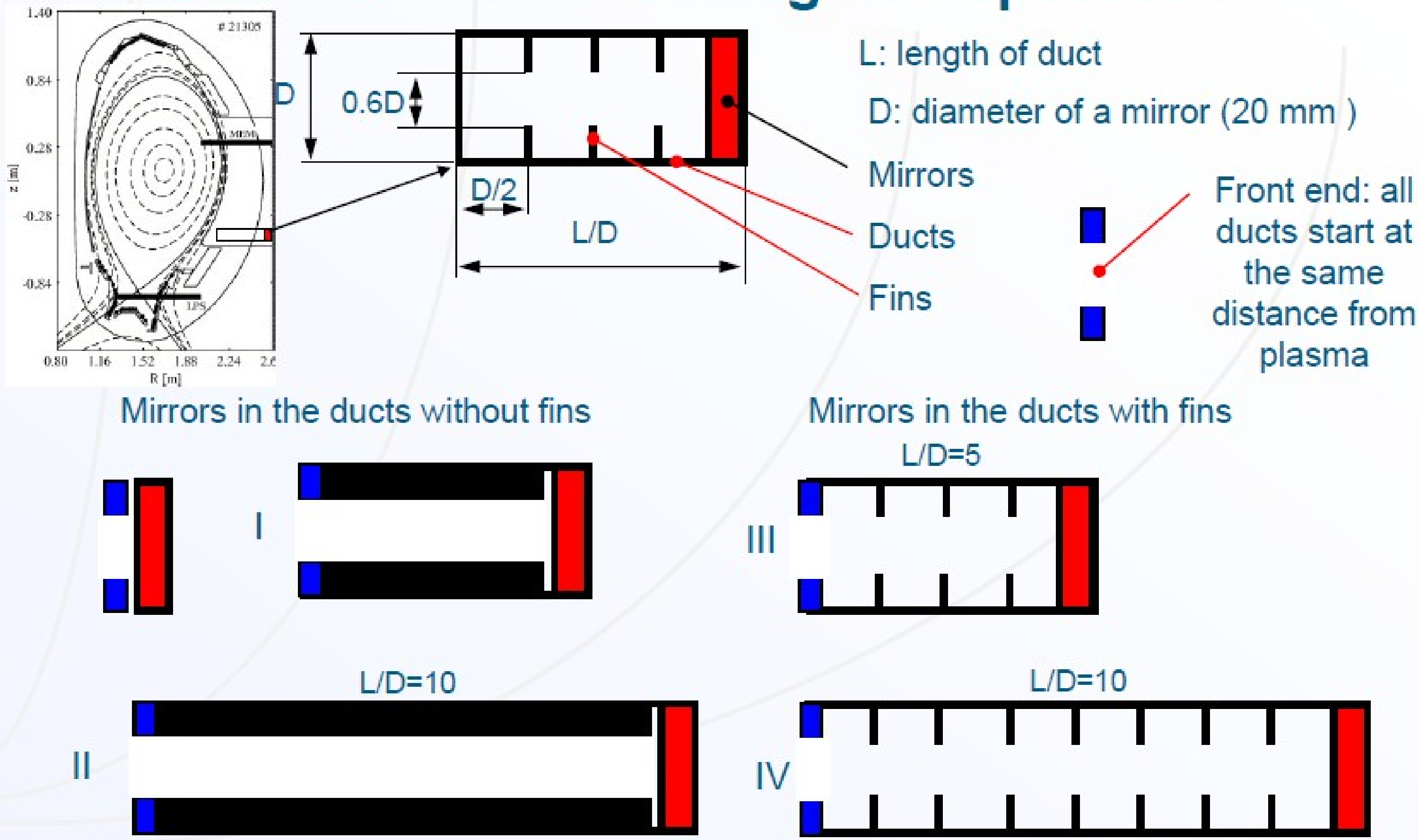
Any windows and fibres will darken due to neutron damage, although this can be relieved by (continuous) annealing at >250°C.

Promising diagnostic options

Mirror station: a concept

JÜLICH FORSCHUNGSZENTRUM

Ducts with fins to mitigate deposition



❖ **All ducts have same apertures**

Andrey Litnovsky and contributors, Report of the First Mirror SWG
22nd Meeting of the ITPA TG on Diagnostics, Moscow, Russia, May 14-17, 2012

Slide 16 of 28

Concept of Hybrid system

Baffled duct and mitigation by gas blowing

Kotov's calculation ; duct with baffles
ITER_D_AHMDZX

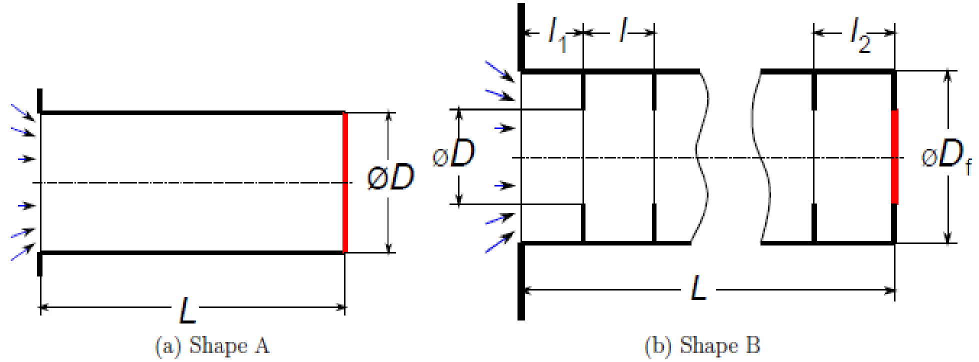


Figure 4: Generic shapes of the diagnostic ducts which were investigated

Mukhin et al. ; Blow-out techniques by a gas counter flow, *Nucl. Fusion* **49** (2009) 085032

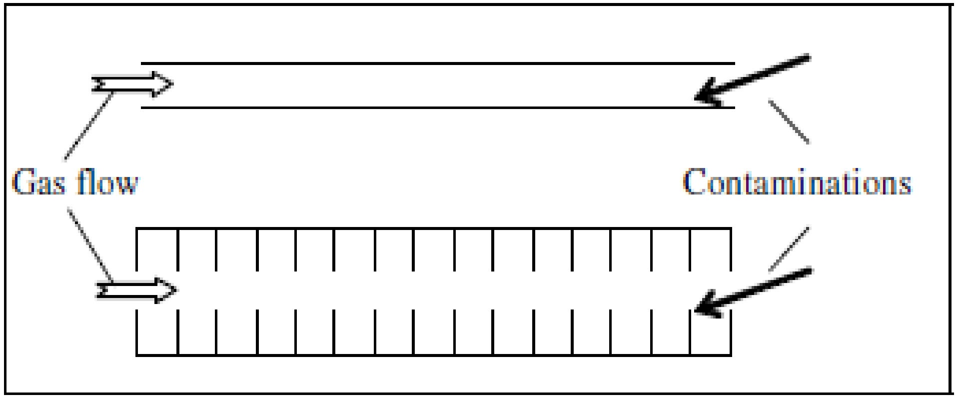
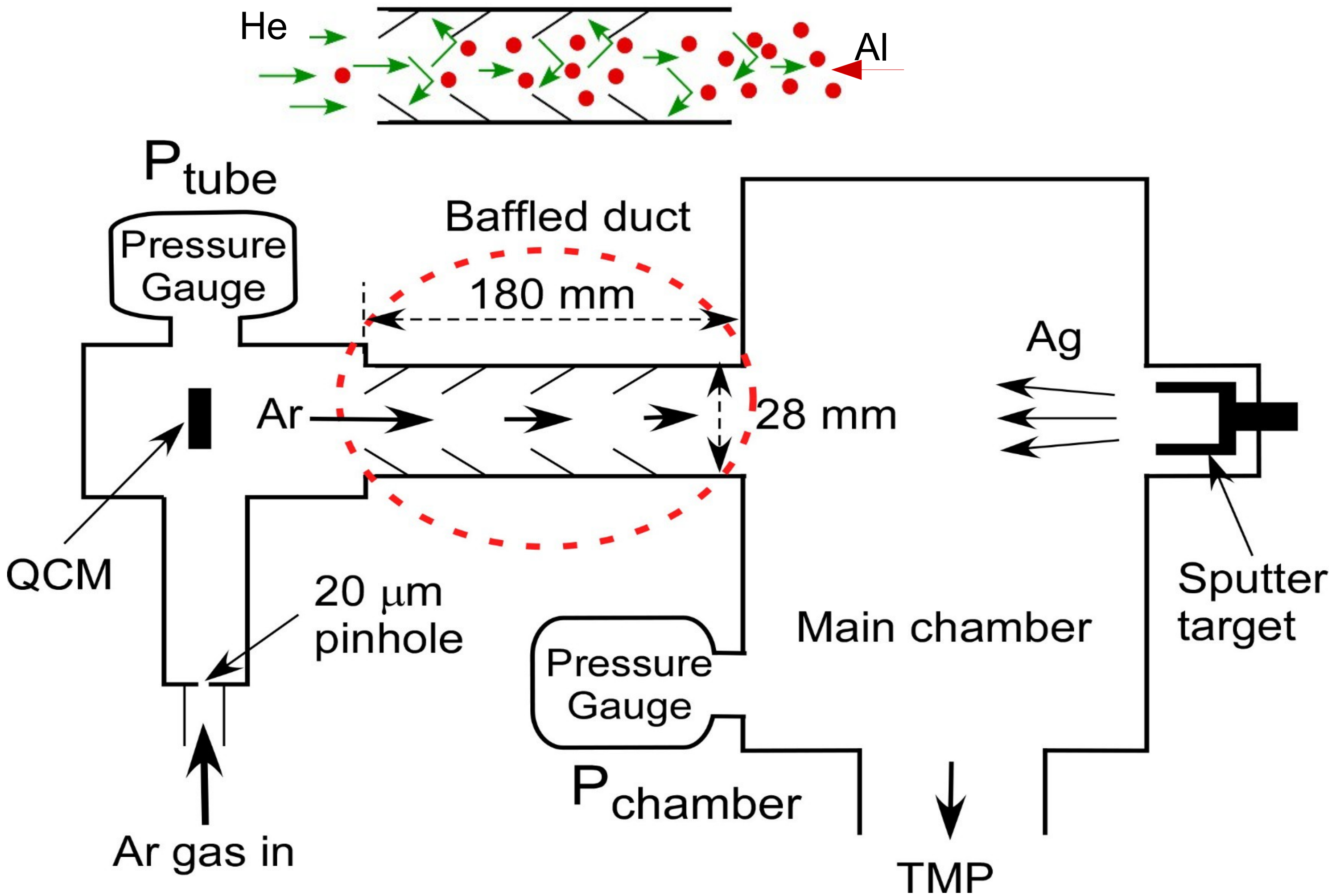


Figure 6. Example of the two duct geometries. The lower one with a much higher internal surface area is more efficient in trapping the contamination.

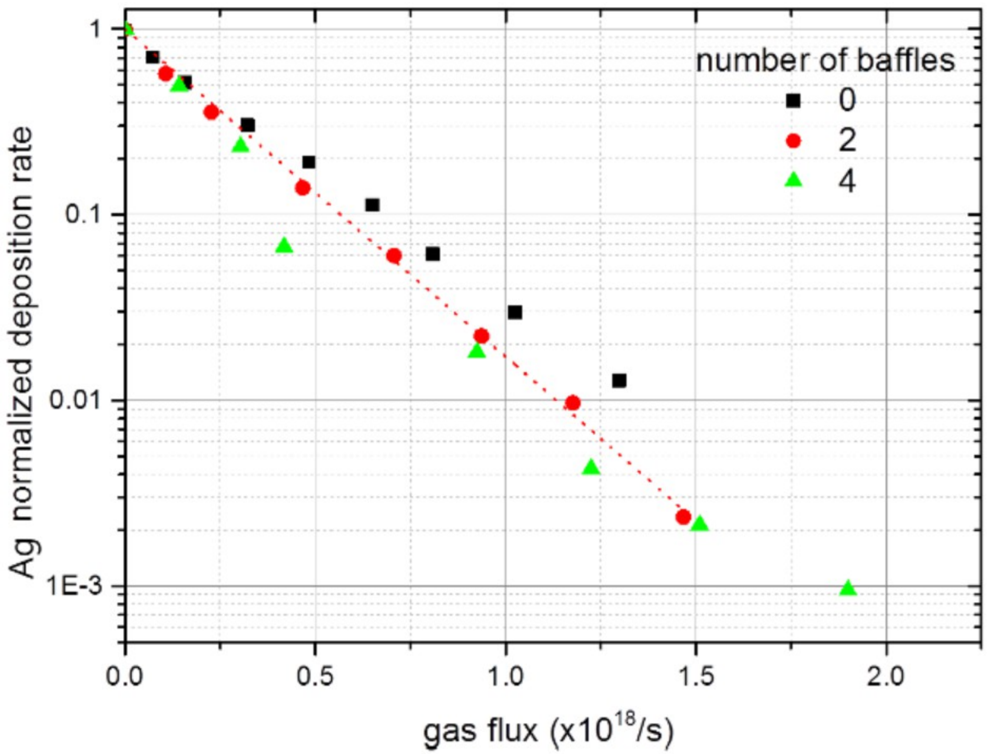
And it greatly improves the pressure ratio...

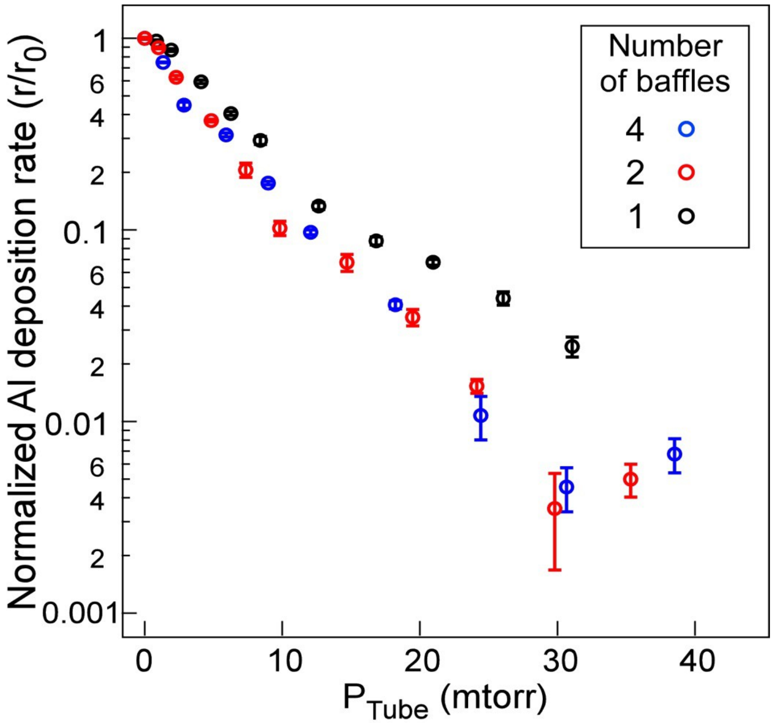
Schematic of gas blowing system



B. S. Kim [1], S. G. Oh [1], C. R. Seon[2], H. G. Lee[2], J. S. Park[3], J. H. Hong[3], W. Choe[3]
[1] Ajou University [2] ITER Korea, National Fusion Research Institute [3] KAIST

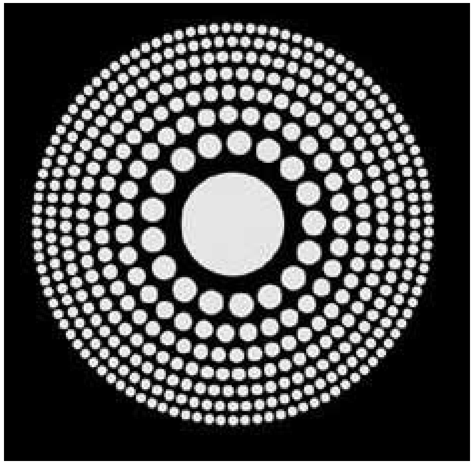
Dependence of contaminant flux on gas flux





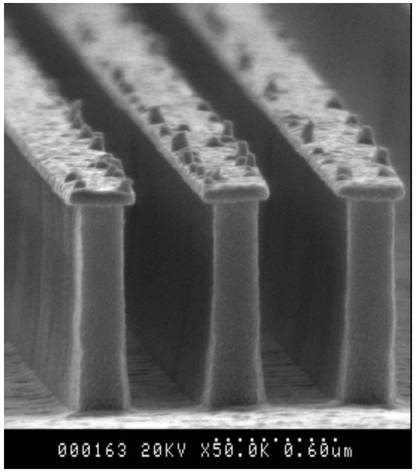
The same effect of He to Al with 10 x 10^{18} He/s as Ar to Ag with 1 x 10^{18} Ar/s

Promising diagnostic options



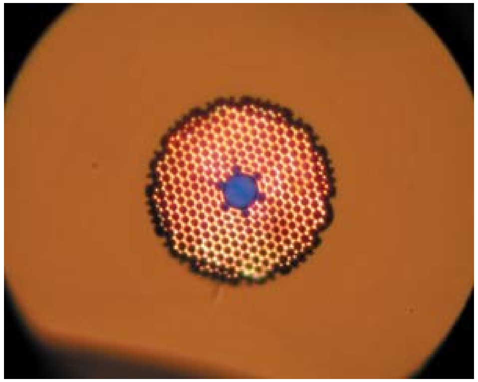
Photon sieve lens

(Courtesy Mitre)



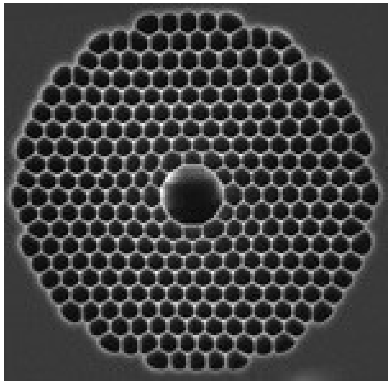
Freestanding metallic transmission gratings

(Courtesy CNRS-LPN)



Hollow or holey fibre

(Courtesy Optics.org)



Photonic crystal hollow fibres

(Courtesy Crystal Fibre)

Conclusions

- JET is not subject to nuclear licensing but it is a step towards ITER, including tritium recycling plant and a range of radwaste and neutron radiation effects, both real-time and accumulated.
- Like many fusion research devices, JET often does not exhibit the complete system reliability for plasma operations that a nuclear regulator will insist upon, although its human safety and machine protection systems function in depth with good reliability.
- DEMO will have all the same non-nuclear requirements on its diagnostic engineering as any presently operating tokamak of considerable size and complexity.
- It will also have a number of nuclear requirements and constraints, currently little recognised by the wider fusion community, but of course standard thinking for those in ITER.
- ITER will demonstrate many aspects of radiation hardening for diagnostic systems on the torus, but has a very much lower neutron fluence than DEMO
- JET and ITER are research machine requiring many sophisticated plasma diagnostics...
- Even without the problems of radiation damage, port space in DEMO must be heavily constrained to maintain adequate tritium breeding ratio
- Also in DEMO, the design of plasma diagnostic systems is “extremely challenging”, and may necessitate a learning period transition from well-equipped to sparsely equipped as unmaintainable systems fail early in the life of the machine.

This work was funded by the RCUK Energy Programme under grant EP/I501045 and the European Communities under the contract of Association between EURATOM and CCFE. The views and opinions expressed herein do not necessarily reflect those of the European Commission

Summary

- Controlled fusion has many challenges – but the battle is worth the effort!

And this is why!

Here's the River Thames near Culham, and a typical record of its flow rate over a year:

That 4t/sec contains ~4x10^{25} D atoms/sec, which could be fusion reacted to make helium and hydrogen and a neutron, releasing ~7MeV for each D atom, thus ~45TW, **about twice the whole world's current total energy usage!**
(A D-D reactor is, however, "a bit challenging...", so we'll begin with D-T.)

Additional acknowledgements & References

- Vayakis - The ITER radiation environment for diagnostics, N 55 RI 38 04-05-06 W 0.1
  - SRD-55 (Diagnostics) from DOORS (ITER_D_28B39L v3.1)
- Lobel *re JET component stress analysis guidelines and DTE2 diagnostics preparations*
- Zastrow *re JET diagnostics failures*
- Maas *re JET DTE*
- Igitkhanov *re tungsten sputtering*
- Donné *re reactor diagnostics*
- Widdowson *re JET QMB failures*
- Fischer et al *re radiation fields and helium production in DEMO*
- Gerasimov *re JET magnetic diagnostic failures*
- Zheng *re tritium breeding ratio*
- Sublet *re dpa & He appm ratios*
- Young *re Radiation-Induced Conductivity*
- Tobita – IAEA DEMO Programme Workshop, UCLA, October 2012
- Alfier *et al* - Rev. Sci. Instrum. 81, 123509 (2010); doi: 10.1063/1.3511557
- Asano *re rewelding*,
- Stork *re swelling*
- Gerasimov *et al re JET magnetics failures*
- Prokopec *et al* – Mechanical behaviour of cyanate ester/epoxy blends after reactor irradiation to high neutron fluences
- Pampin & Karditsas – Fusion power plant performance analysis using the Hercules code.
- Shikama & Pells – Journal of Nuclear Materials 212-215 (1994) 80-89

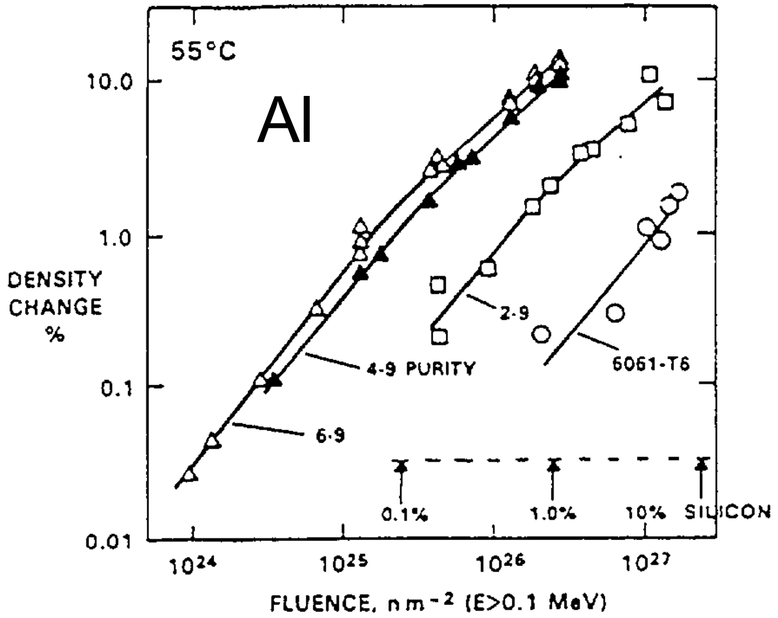
END

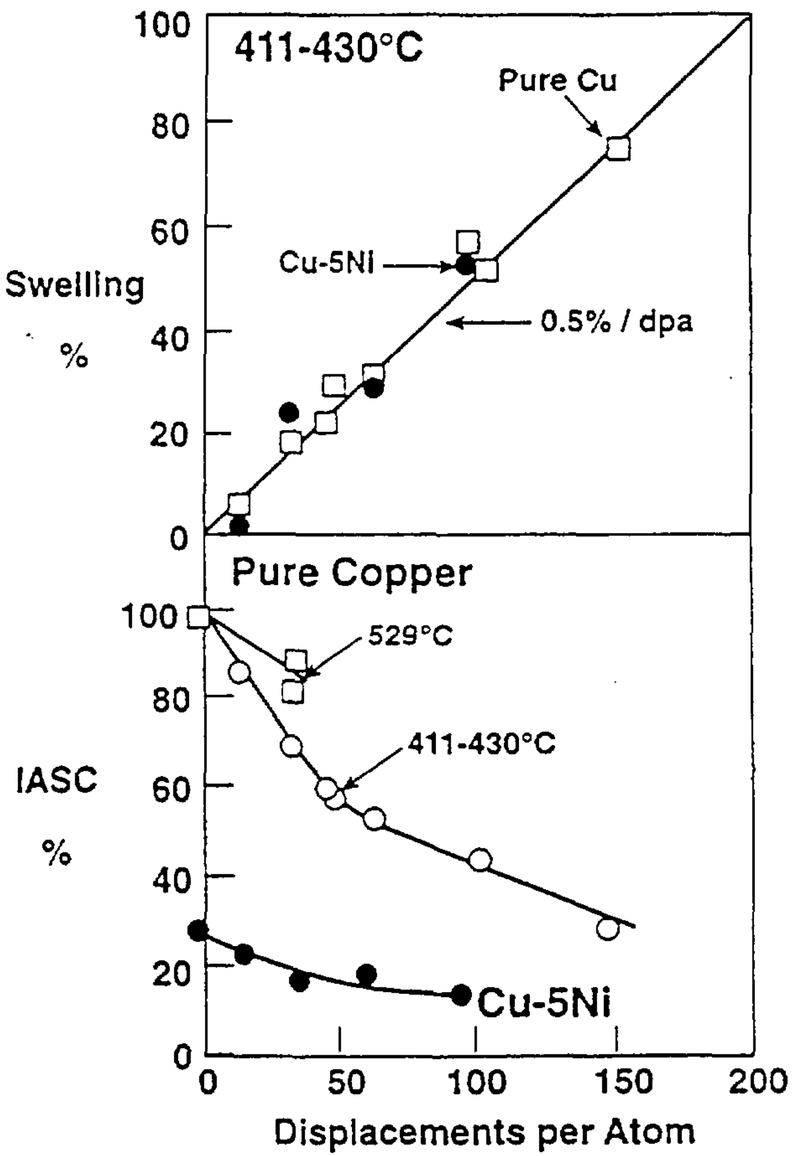
From A. Costley et al, ITER Diagnostics R&D, Fusion Engineering and Design (2001

Typical Numbers

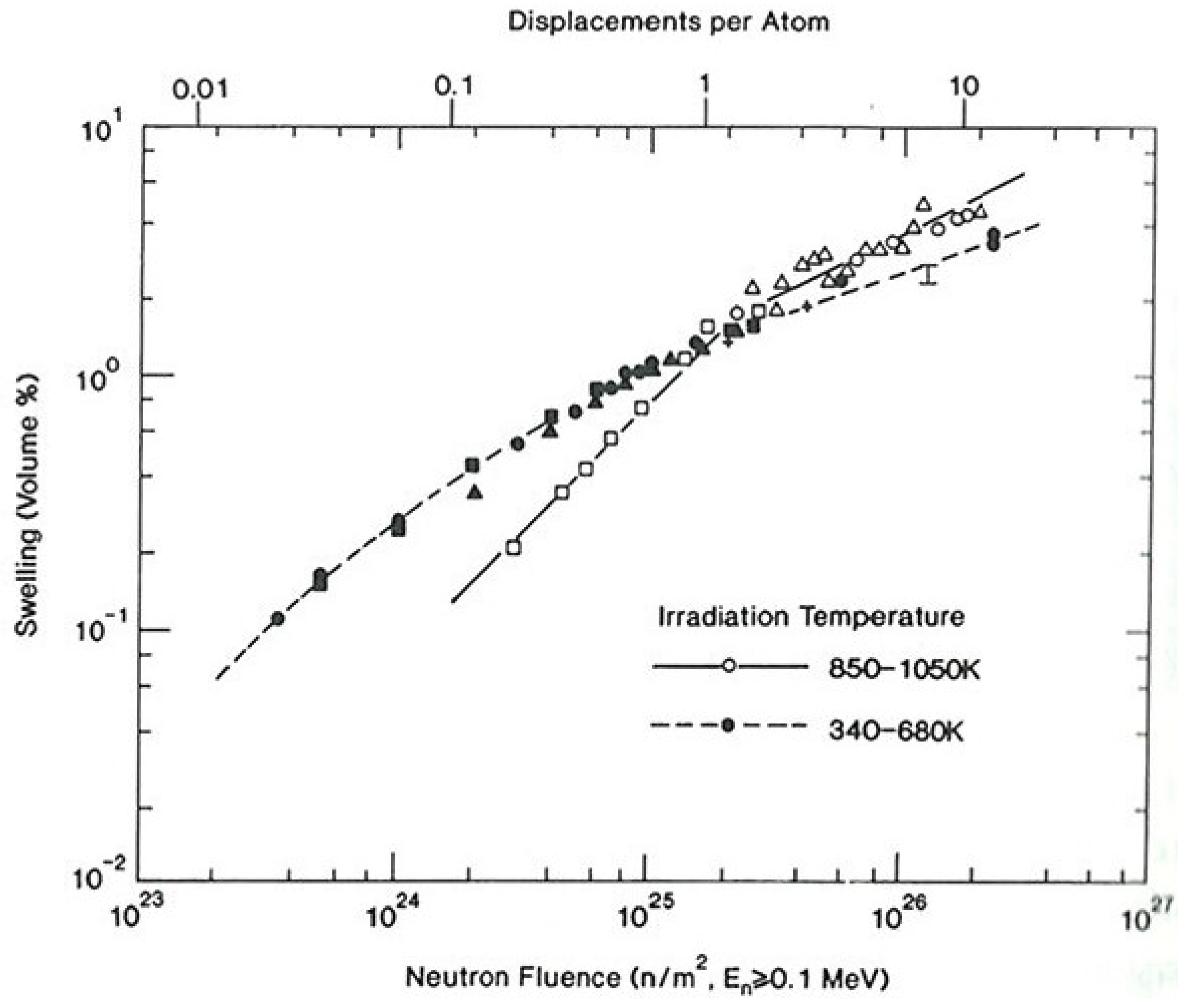
Location *Typical diag. component*	Neutrons > 0.1 MeV n/m^{2}s	Neutrons 14 MeV n/m^{2}s	Dose Rate Gy/s	Fluence > 0.1 MeV n/m^2	Particle flux atoms /m^{2}s	Plasma radiation (peak) kW/m^2
First Wall [1]	$3x10^{18}$	$8x10^{17}$	$2x10^{3}$	$3x10^{25}$	~ $5x10^{19}$	500
Near Blanket Gap (on VacuumVessel) *Mag. coils* *Bolometers* *Retroreflectors*	0.2 - $1x10^{17}$	0.8 - $4x10^{16}$	20 - 100	0.4 - 2.0 $x10^{24}$	~ 10^{18}	10
Vacuum Vessel (Behind Blanket) *Mag. loops*	$2x10^{16}$	$3x10^{14}$	² 20	$2x10^{23}$	~ 0	~ 0
Diagnostic block *First mirrors*	$1x10^{16}$	$9x10^{15}$	20	$1x10^{23}$	~ 10^{17}	~ 1.5
Labyrinth Second mirrors,Windows	$2x10^{13}$	$3x10^{13}$	10^{-2}	$2x10^{20}$	~ 0	~ 0
Vacuum Vessel (Inboard TFC side) *Mag. loops*	$1x10^{14}$	$1x10^{12}$	0.1	~ 10^{21}	~ 0	~ 0
Divertor Cassette *First mirrors*	$1x10^{18}$	$3x10^{17}$	$1x10^{-3}$	~ 10^{25}	10^{17} Ğ 10^{19}	1 - 100
Divertor Port *Second mirrors*	10^{13}~10^{15}	10^{12}~10^{14}	10^{-2} - 1	10^{19}~ 10^{21}	TBD	TBD

G. Vayakis, The ITER radiation environment for diagnostics, N 55 RI 38 04-05-06 W 0.1





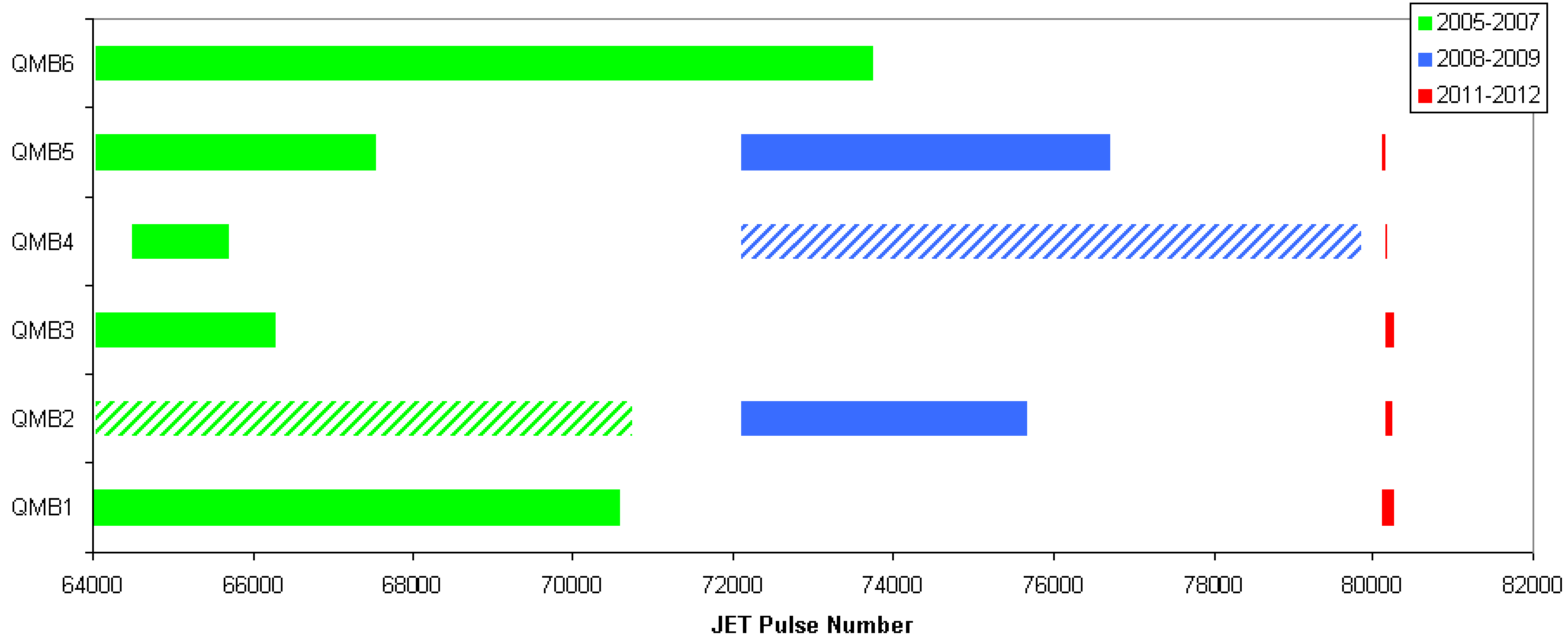
Both Al and Cu have about 8dpa at 10^{26} n/m^2



Swelling of alumina [Shakima & Pells]

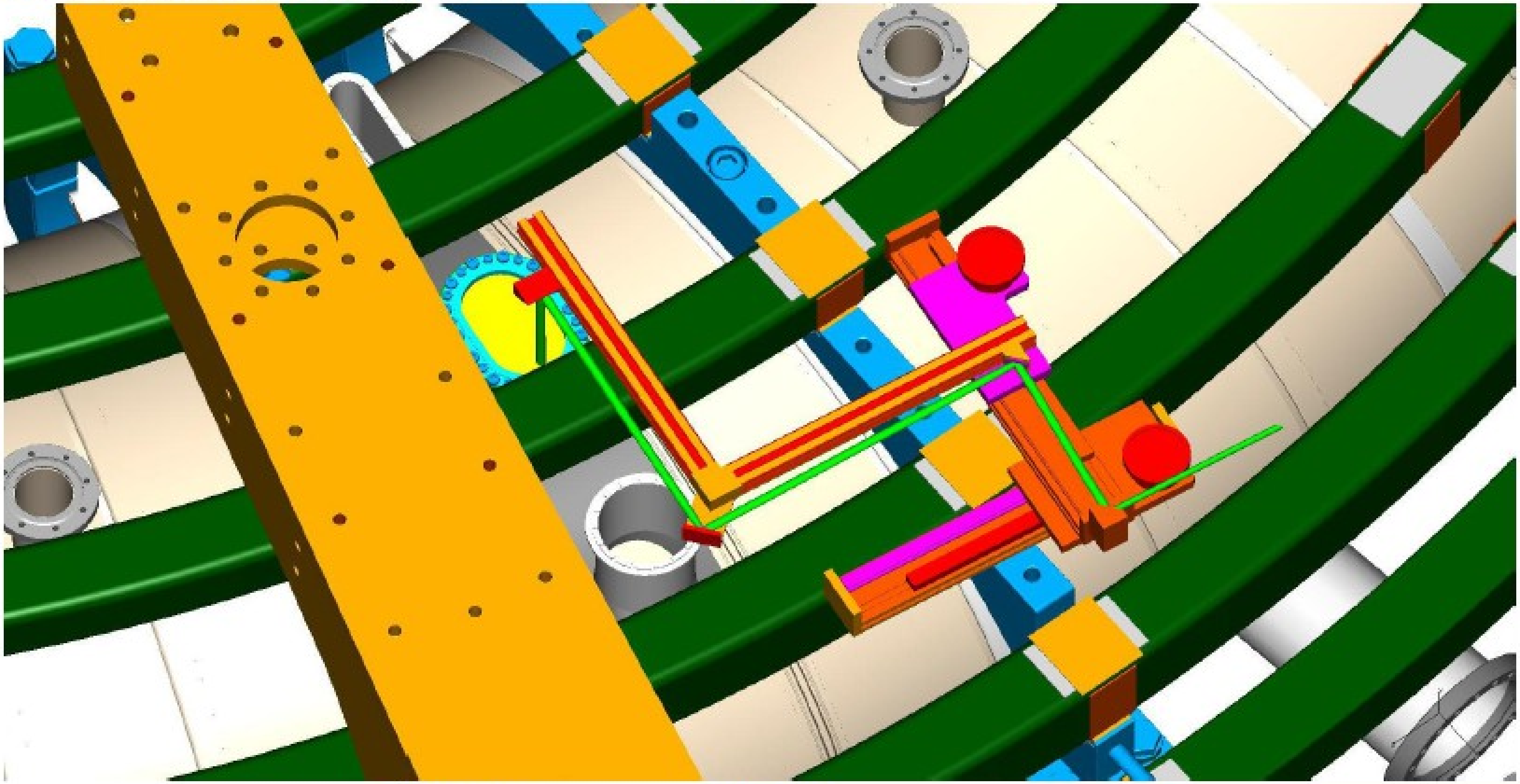
Journal of Nuclear Materials 212–215 (1994) 80–89

Summary of QMB Lifetimes



RAMI issues – Can DEMO windows etc be cleaned?

Window cleaning *in situ* – demonstrated in RFX



Elegant – but the x-y motors and the system's own mirrors may need to be retractable.

Diagnostic systems in DEMO: engineering design issues

T N Todd
Culham Centre for Fusion Energy, Oxfordshire

Contents

The UK fusion research programme is funded jointly by the Engineering and Physical Sciences Research Council and by the European Communities under the contract of Association between EURATOM and UKAEA.

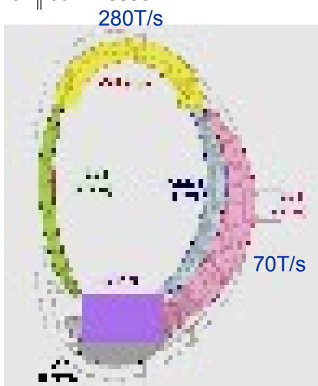
Non-nuclear requirements

- UHV and plasma purity compatibility
- physical compatibility (other systems & their maintenance schemes)
- lines of sight restrictions
- clearances & tolerances
- vibration, acceleration (seismic and "rare" disruption induced)
- magnetic field and its rate of change
- dust, debris & condensate immunity
- environmental temperature
- neutral particle (etc) erosion
- avoidance of halogens (*re* T plant)
- earthing policy, EMI, EMC
- insulating breaks
- system isolations for maintenance etc
- RAMI (difficult for high complexity systems)

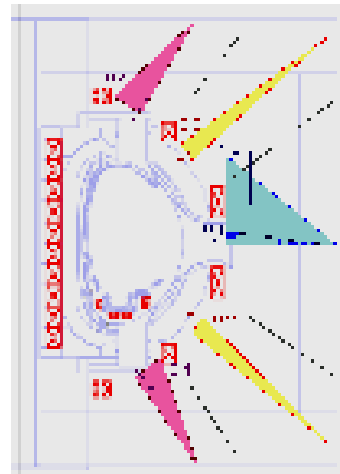
… and doubtless many more!

In JET, regions inside and outside the torus are mapped in zones where peak B, dB/dt, disruption acceleration (up to 4g) etc are defined, for component stress analysis:

$dB_{||}/dt$ in-vessel



B ex-vessel



But in ITER, as doubtless it will be in DEMO, it is necessary to analyse the EM and acceleration environment of each sub-assembly uniquely.

Nuclear requirements

- Regulatory approval
  * tritium and dust containment
  * machine control integrity
  * machine protection reliability
  * possible human safety issues
- Nuclear damage
  * displacements per atom (changing crystal structure)
  * transmutation (function, calibration, LAM)
  * hydrogen and helium production
    - swelling (hence tolerances)
    - reweldability
- Nuclear signal interference
  * RI EMF, RI Conductivity, RI Luminescence, RI Thermal EMF
- Nuclear heating
- RAMI
  * maintenance requirements
  * Remote Handling – and to achieve the desired overall machine availability, RH must be very much faster than JET and ITER
  * diagnostic system life (& rationale) if not maintainable
- Failure recovery
- Shielding, labyrinths
- Human access controls – bioshield location

ITER DOORS* on Diagnostics (1)

- ITER has 3 classes for diagnostics: primary, back-up & supplementary, covering 52 identified systems in a number of different types of site for these diagnostics
- Then there are 4 categories: protection, control, advanced control, & physics studies.
- SIC (Safety Important Class) for T containment – double walls etc. as JET, diff pumped and monitored
- Temperatures of 200 and up to 350 (400)°C
- Accelerations, B, B-dot and rad fields have to be elucidated case by case
- Seismic loads – unlike other machines to date, very formal
- No more than 5 replacements of Upper & Equatorial port-plugs – all "unplanned", and no more than 3 for divertor cassette changes – all heavily planned
- Direct coupled (eg VUV) systems should all be on one sector
- Can put diagnostics in RH ports but only if impact on RH deployment is small
- Port-plug exterior fixings must be bolted not welded
- ...maintenance detritiation... ...RH systems...
- Cabling etc. is cooled by conduction into the vessel

Dynamic Object-Oriented Requirements System

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*Dynamic Object-Oriented Requirements System

ITER DOORS* on Diagnostics (2)

- Off-normal events include 2bar steam pressurisation of the vessel.
- Accommodate differential movements
- Fire standards for cables, no halogenated insulation in T areas
- Earthing, EMC etc. – much like JET and other present-day machines
- Active cooling against nuclear heating etc.
- Diag port plugs have to maintain shielding of main shield; ditto wall penetrations
- UHV materials now have to avoid high vapour pressure of transmutation products
- Co, Nb restrictions - LAM
- Special mirror requirements
- Special decommissioning requirements – LAM
- No window etc can be >$0.02m^2$
- Must tolerate control failure of RH systems (meaning impacts)
- Behind bioshield, there must be <10microSv/hr 24hrs after shutdown
- The current DOORS does not clearly accommodate the scenario for some flux loops– early death
- RAMI includes specific requirements, which could be compared with JET's (low) and DEMO's (high)

JET – ITER – DEMO compared

As onerous as the JET design criteria are often viewed,
those of ITER and one day DEMO have to be far more so...

Comparison of radiological impacts of JET-ITER-DEMO First Wall (approximate!)

	Site T Inventory, g	Average MWyr/m^2	Peak n/m^2 >0.1MeV*	dpa	He appm	Operating Gy/sec	Shut-down Gy/hr
JET 1997	20	10^{-7}	1×10^{19}	10^{-6}	10^{-5}	n: 40 γ: 100	0.01
ITER all life	4000	0.3	4×10^{25}	2	20	n: 200 γ: 500	500
DEMO 3 FPY	6000?	6	8×10^{26}	50	500	n: 300 γ: 500	10,000

*About 5x the neutron fluence due to virgin 14MeV neutrons alone

NB Fission reactor neutron spectra are much softer than fusion neutron spectra and as a result generate about 1/10 of the He appm per dpa.

In epoxy, polyimide, glass, carbon & alumina, there is ~(0.1-1.0)x10^{-15} Gy/(n/m^2)

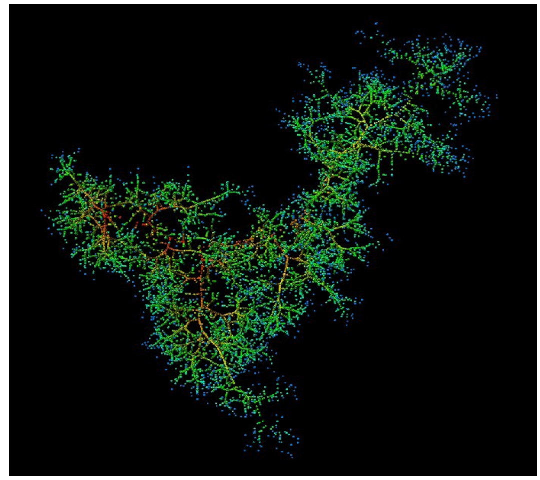
DEMO Structural Materials issues

CCFE CULHAM CENTRE FOR FUSION ENERGY

Example of Fe lattice damage caused by one “cascade” induced by a 150keV Fe ion recoiling from a single neutron impact.

Size of simulation cell: 475 Å;
6.75 million atoms

Nearly all the displacements are Frenkel Pairs (vacancy + interstitial atom) which recombine rapidly (faster with higher temperature), but still hundreds remain, together with more complex crystal defects.



K. Nordlund, TEKES –
University of Helsinki December 2012

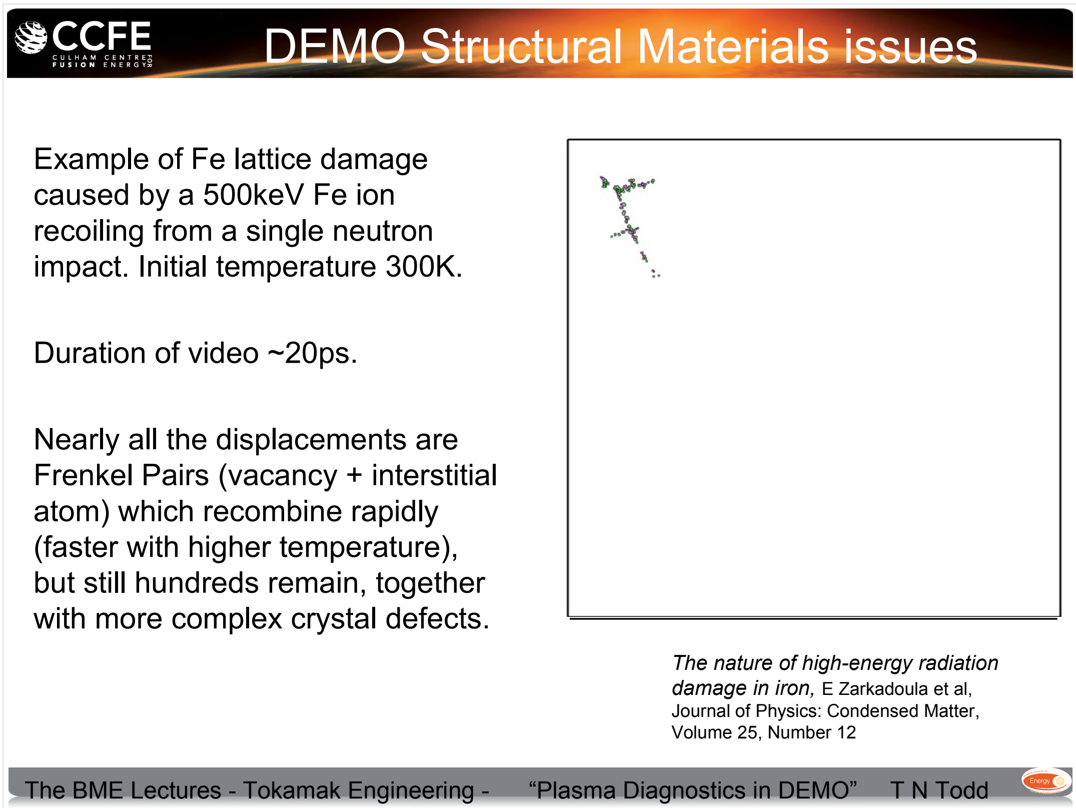
The BME Lectures - Tokamak Engineering - “Plasma Diagnostics in DEMO” T N Todd

In this graphic, the colours of the dots represent time (in the order of picoseconds), illustrating from red to blue the progress of the branching cascade.

The research field that addresses this type of analysis is called Molecular Dynamics. It requires a detailed 3D electric potential distribution around each ion in the lattice under study, and this potential distribution is very challenging to compute. As a result (at least as experts informed me in 2013), attention has focused on single-element regular crystals subjected to a single incident fast ion (and the cascade of displaced lattice ions that this fast ion creates by Coulomb collisions). The necessary potentials for binary, trinary and more complex alloys (such as typical steels) have not yet (in 2013) been calculated, especially noting the wide range of different crystal positions (and crystal phases) the different atoms can occupy.

In addition, the various lattice defects that the ion displacements create also perturb the electric potentials, to some extent lessening the apparent precision of the displacement cascade analysis. Even so, the MD analyses are very revealing in the nano-dynamics of the basic interactions of the recoil ions from fast neutron impacts (or accelerated ion beams incident on a target) and the specific types of lattice defects thus predicted have been validated by experiment.

Note that as the cascade progresses, the energy of the original incident ion becomes shared amongst very many displaced lattice ions, so there is a “Bragg Peak” of local energy deposition on each major branch of the cascade, resulting in very transient liquefaction of a few dozen (?) atoms in each such region.



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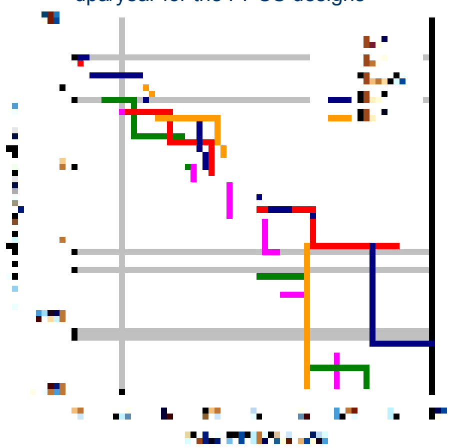
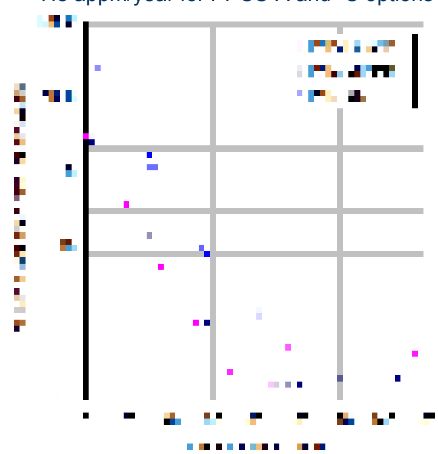
Damage profile through the breeding blanket

The neutron damage in DEMO of course reduces strongly through the thickness of the blanket and shield modules – away from any gaps

dpa/year for the PPCS designs



He appm/year for PPCS-A and -C options



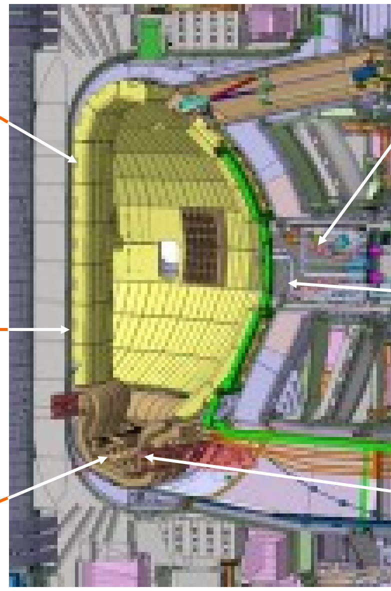
CCFE CULHAM CENTRE FUSION ENERGY

Radiation effects on fusion diagnostics

Magnetic coils
- Radiation Induced Conductivity (RIC)
- Radiation Induced Electric Degradation (RIED)
- Radiation Induced Electromotive Force (RIEMF)
- Any integrators must be ultra-low drift

Bolometers
- RIC
- Nuclear Heating
- Sputtering
- Contact degradation
- Differential swelling and distortion

Pressure gauges
- RIC
- RIED
- Filament aging



Neutron cameras
- Noise due to γ-ray, proton, α
- Radiation damage on solid state detectors

Optical diagnostics
Mirror
- Deposition, erosion
- Swelling, distortion

Window
- Permanent and transient absorption
- Radioluminescence
- Swelling, distortion

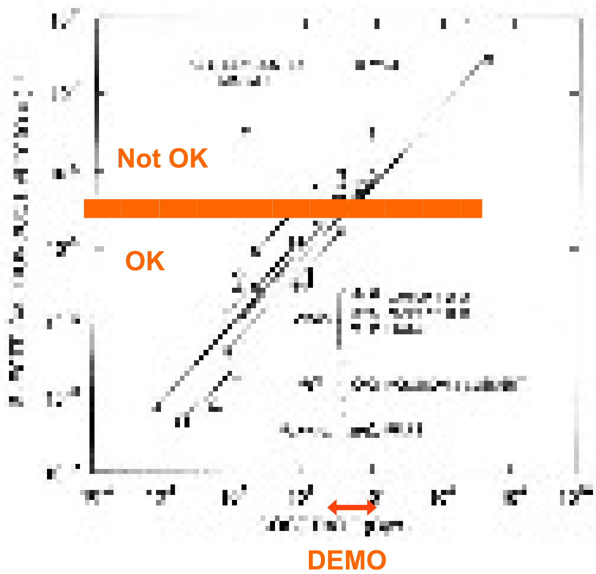
Impurity monitoring
Mirror and windows
- same as above

Fibers
- Permanent and transient absorption
- Radioluminescence

CCFE

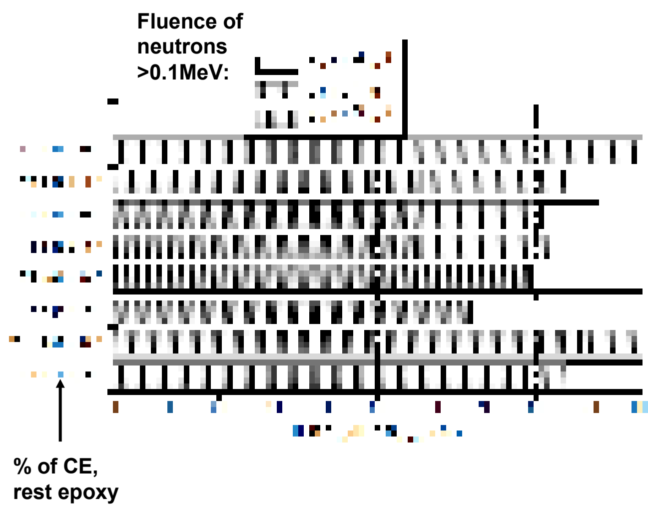
Radiation induced conductivity

Insulators conduct too well if radiation >1000Gy/sec



Radiation induced loss of interlaminar shear strength

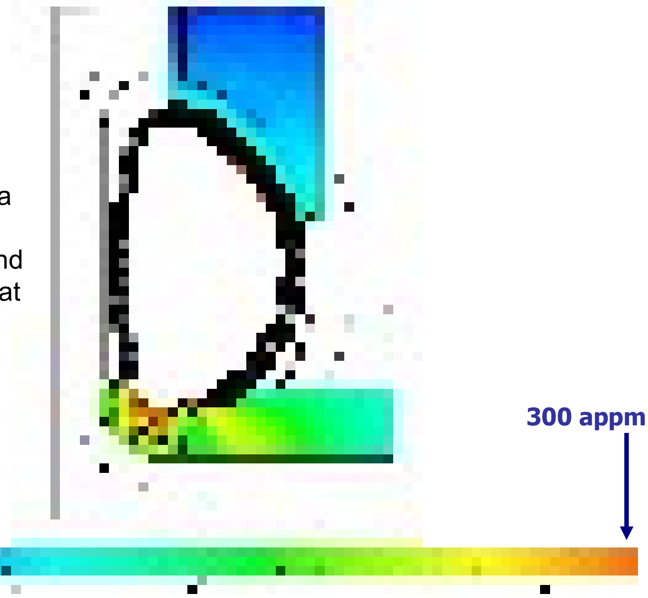
At doses ~100MGy, or ~10^{23} n/m^2, the mechanical strength of epoxy is severely degraded, although cyanate ester is less so.



He production in steel: ~10 appm / dpa

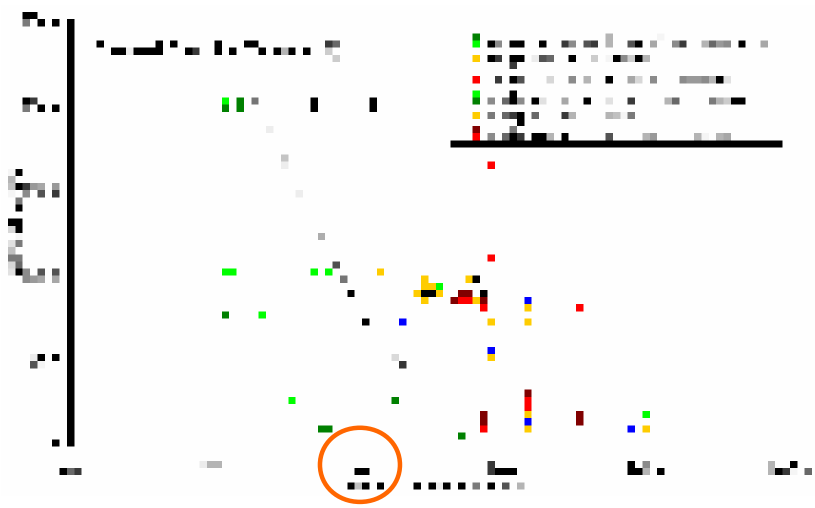
Distribution of the helium production (appm) calculated for a 5 year irradiation of SS-316 in the lower and upper ports of DEMO at 1.2MW/m² average neutron wall load

Fischer et al, KIT & CIEMAT



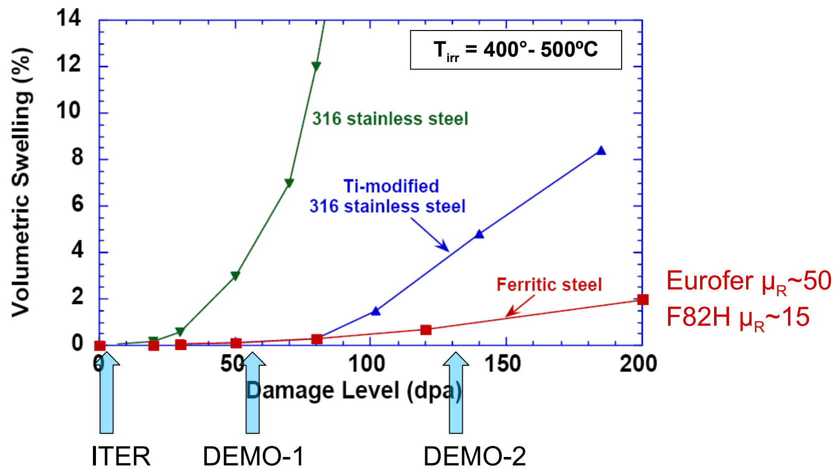
Reweldability of Stainless steel 316L(N)-IG

K. Asano, J. van derLaan, MAR, 2001v



He production in steel: swelling

Swelling is not a problem for JET or ITER
but will drive material selection in DEMO



Nuclear heating is severe – instantaneous and delayed

Decay heat is a significant problem in DEMO, e.g. for blanket maintenance

ITER solutions to nuclear plasma diagnostic problems

CCFE
CULHAM CENTRE FOR FUSION ENERGY

ITER solutions to nuclear plasma diagnostic problems

[illegible]

Compatibility of diagnostics with DT operations

Even in JET, getting diagnostics ready for the next DT experiment is non-trivial; this is a table of the status in 2011:

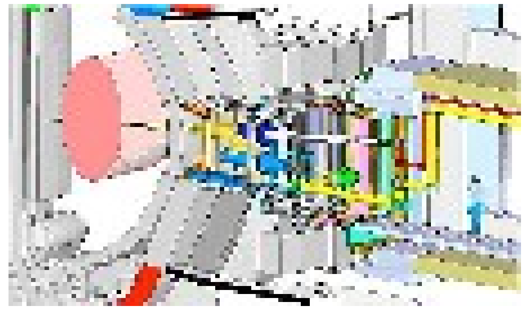
How sophisticated can DEMO diagnostics be?

Like other *research* machines, JET and ITER are crowded with plasma diagnostics...

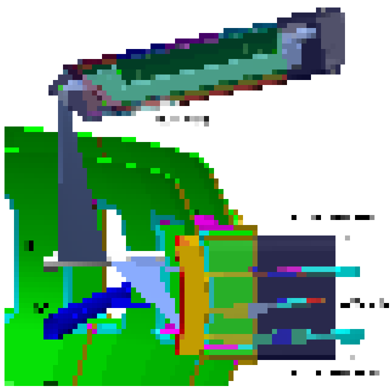
These require a large total port area

Some examples of diagnostics for ITER

It is difficult to see how port space allocations like this can be made in DEMO



Core LIDAR Thomson scattering system (Courtesy M. Walsh)



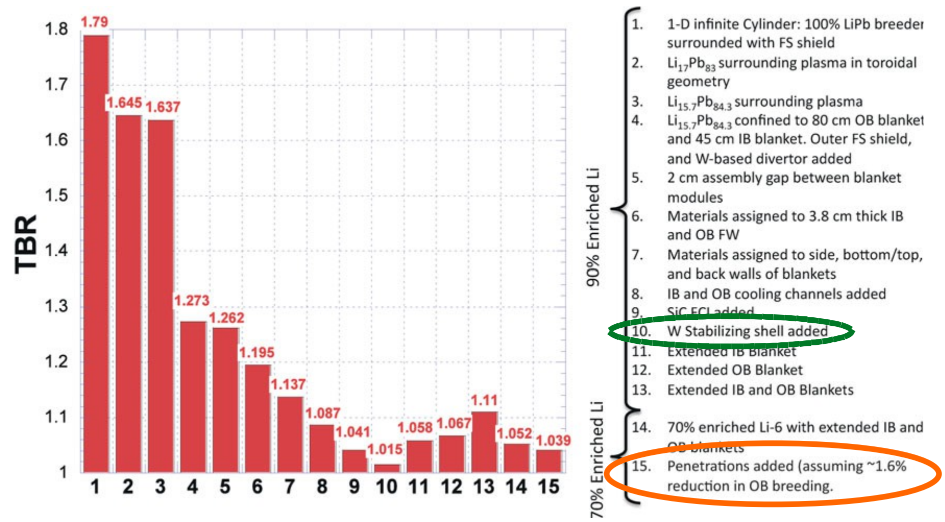
Charge Exchange Recombination Spectroscopy (Courtesy M. von Hellermann)

Space for DEMO diagnostics will be very limited

But in DEMO, even the port area for the plasma heating systems (e.g. NBI) matters for the Tritium Breeding Ratio

Ports like those shown here will mostly be blinded by breeding blanket modules

Reduction in TBR with added realism



Bar chart showing the reduction of TBR from 1.8 to 1.04 upon including the internals of the DCLL blanket and its surrounding components.

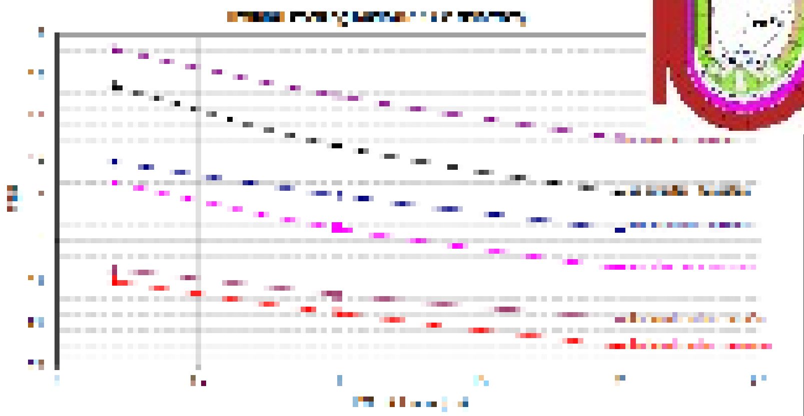
L. A. EL-GUEBALY, et al., FUSION SCIENCE AND TECHNOLOGY, VOL. 61, 2012.

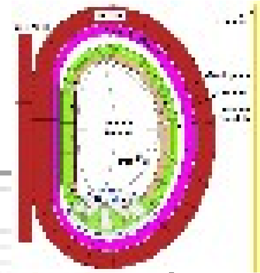
TBR: effects of divertor option and first wall cladding

3D model (First wall materials: Eurofer, Tungsten)

FW thickness: 0.2cm, 1cm, 2cm

No / single / double divertor(s)



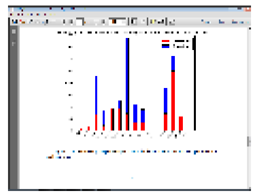


S. Zheng, personal communication, CCFE Physics & Technology talk, 5th July 2013

RAMI issues - JET magnetic diagnostic failures

- 18 types, 482 sensors (coils and loops) considered, 1995-2013
- 6 types have never failed (mainly outside the vessel and with only one connector)
- Highest percentage failures were in the divertor and limiters, especially halo current sensors
- Plasma operational life of those that failed in operation was 12-65 hours, or 2k-10k pulses
- NB A significant percentage of failures was in installation (e.g. at RH connectors)

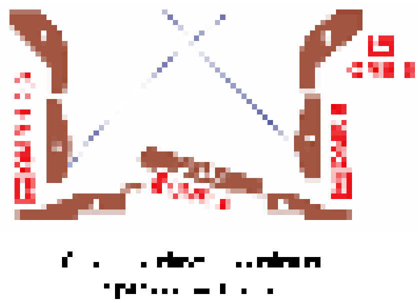
Percentage of JET magnetic pick-up coils and loops broken during installation and operation

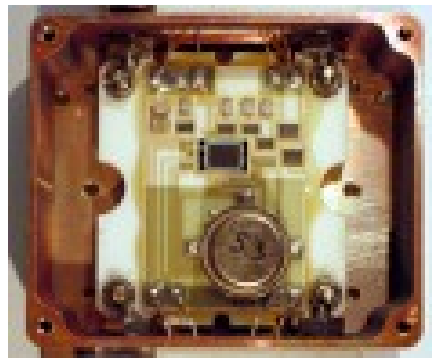


JET anticipates magnetic diagnostic failures in considering machine protection strategies:
ITER is having to do so for inaccessible flux loops etc.

RAMI issues - JET Quartz MicroBalance failures

- JET Quartz Micro-Balances
- *These are electronic cards that sit in the shadow of divertor tiles, with a small window exposing one surface of a quartz crystal – defining the resonance of a tuned circuit - to plasma deposition. A second device provides temperature compensation and both are compared to a reference oscillator in an ASIC.*
- *Thus they are complex electronics in the full radiation field, subject to the temperature excursions behind the radiatively cooled tiles – and importantly, disruption induced voltages.*





RAMI issues - JET Quartz MicroBalance failures

	2005-2007	2008-2009	2011-2012
QMB1	70606 – Shutter failed Disruption 68.4s Crystals work to end 2009		80263 Depo and temp failed: fast stop, runaways
QMB2	Did not work. Problem with divertor carrier wiring	75674 Thick deposit calibration not valid. Shutter slightly open. Crystals worked to end.	80253 Depo and temp failed during testing off shutters 2 & 3
QMB3	66273 Depo failed, temp also affected 69100 Temp failed	Left in vessel but not working	80263 Depo and temp failed: fast stop, runaways
QMB4	65697 Depo failed – overheating suspected 67547-Temp failed: fast stop	Intermittent. Broken connections at QMB suspected.	80153 – Temp failed 80160 Depo failed – soft stop. Poor isolation an issue. Pick up from shutters.
QMB5	67547 Depo and temp failed – fast stop	76720 Depo fails as shutter activated. Also ELMs. Depo frq→Temp frq Temp work to end.	80160 Temp failed – Soft stop 80248 Depo failed – shutter testing
QMB6	73760 Depo and temp failed	Cracked crystal on removal in 2009 (not observed in 2007)	No installation

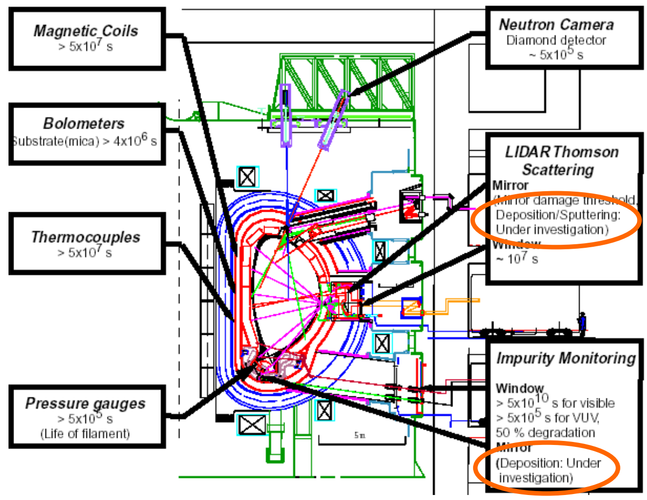
ASIC failed

RAMI issues – ITER diagnostic lifetimes

Examples of diagnostic lifetimes in ITER

Extract from G. ***Vayakis, The ITER radiation environment for diagnostics,*** ***55 RI 38 04-05-06 W 0.1***

- Life-time of some key diagnostics components at neutron power density of 0.5 MW / m² i.e. neutron power of 450 MW
- The fluence of 0.3 MWa / m2
- = 2 x10⁷ s burn at 450 MW
- The life-time is mainly limited by radiation effects, except where shown with ()



Promising diagnostic options

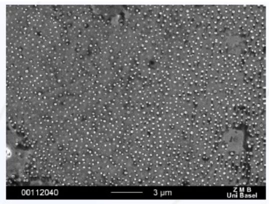
- ***But all is not lost!***
- Some diagnostics are largely immune to the problems created by the erosion / deposition and nuclear effects, such as:
  - microwave diagnostics, which use small waveguides and can incorporate complex labyrinths, while the wavelength is long enough to tolerate minor mirror imperfections
  - and diagnostics using penetrating radiation:
    - Neutron diagnostics, for ion temperature and tomography
    - Gamma ray diagnostics, e.g. using n,γ reactions for impurity tomography
- Some are likely to be possible given sufficient development, e.g.:
  - SXR diagnostics – if rad hard detectors can be developed e.g. photocathodes
- Some might be enabled by in-situ cleaning techniques of mirrors and (remote) windows
  - Work on mirrors is encouraging, e.g. erosion does not degrade specular reflection – although if cm of erosion occur, focal length etc will surely alter
- And there are emerging technologies e.g.:
  - diffractive mirrors and gratings, tolerant of some erosion or deposition
- And very low duty cycle exposures of delicate diagnostics behind (non-electrical) shutters
- And gas-blowing to slow and repulse erosion and deposition particles

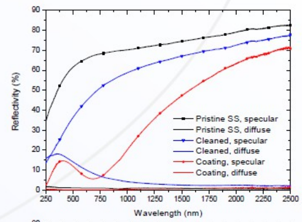
RAMI issues – Can 1st mirrors be effectively cleaned?

- Cleaning tests in vacuum have been performed on three samples coated with different mixtures of aluminium, tungsten and carbon, at 532 and 230 nm.
- It was found that the initial recovery of the reflectivity obtained at 532 nm could be further improved by additional exposure at 230 nm.

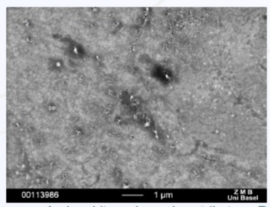
Sample 1: 532 nm only

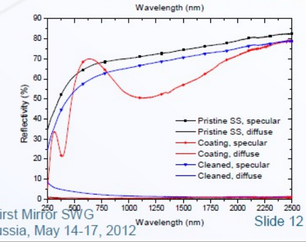
Tungsten dust remains on the surface → higher diffuse reflectivity





Sample 2: 532 followed by 230 nm

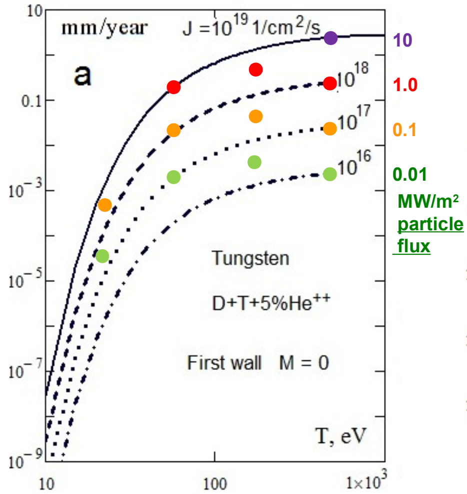




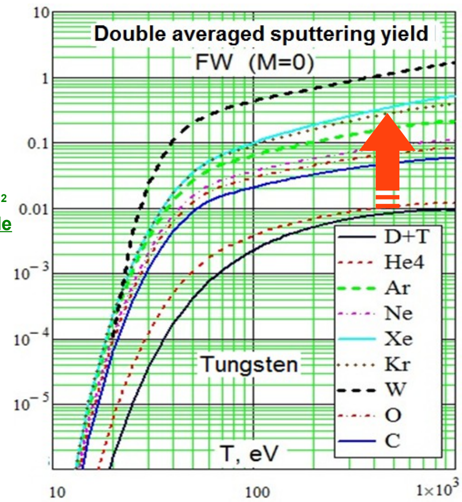
Andrey Litnovsky and contributors, Report of the First Mirror SWG
22nd Meeting of the ITPA TG on Diagnostics, Moscow, Russia, May 14-17, 2012

RAMI issues – If a 1st mirror was like the First Wall

Then up to ~1mm/year would be eroded with just D,T & He:

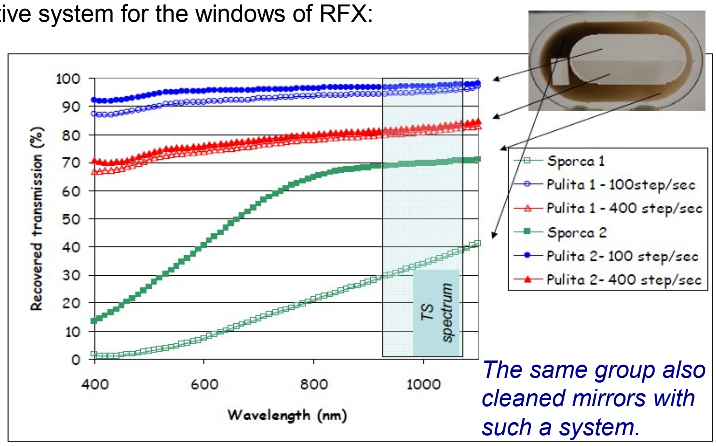


But really there will be impurities as well:



RAMI issues – Can DEMO windows etc be cleaned?

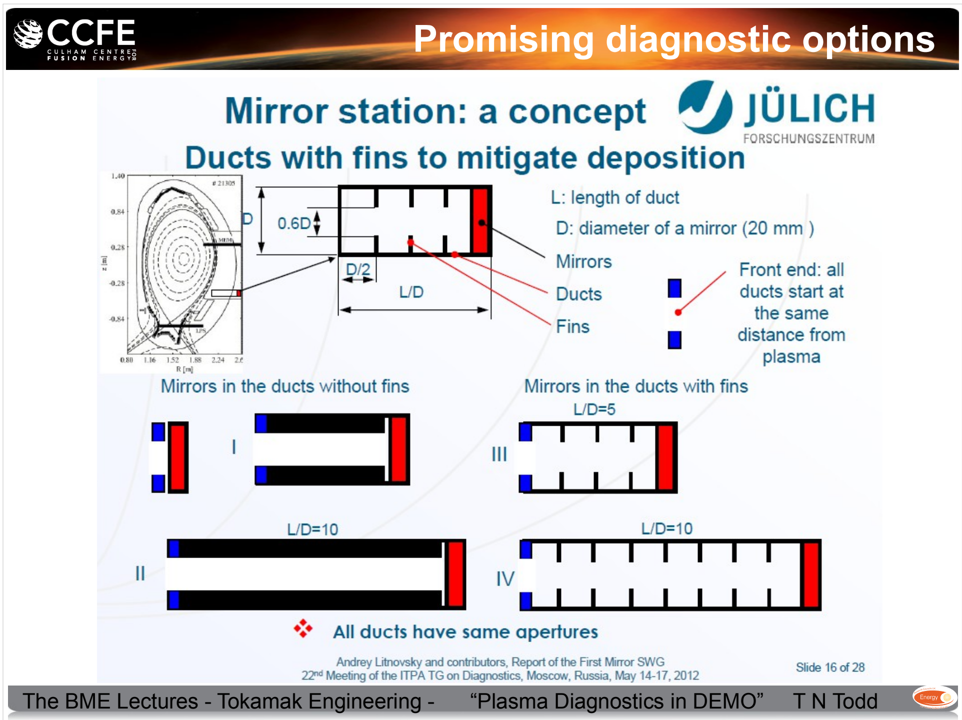
A very effective system for the windows of RFX:



The same group also cleaned mirrors with such a system.

However the brown coating in RFX was mainly B and C – DEMO would be W etc, but hopefully only loose dust as far back as likely windows should be.

Any windows and fibres will darken due to neutron damage, although this can be relieved by (continuous) annealing at >250°C.



Promising diagnostic options
Mirror station: a concept
JÜLICH
FORSCHUNGSZENTRUM
Ducts with fins to mitigate deposition
D
0.6D
D/2
L/D
L: length of duct
D: diameter of a mirror (20 mm)
Mirrors
Ducts
Fins
Front end: all ducts start at the same distance from plasma
Mirrors in the ducts without fins
Mirrors in the ducts with fins
L/D=5
I
III
L/D=10
L/D=10
II
IV
All ducts have same apertures
Andrey Litnovsky and contributors, Report of the First Mirror SWG
22nd Meeting of the ITPA TG on Diagnostics, Moscow, Russia, May 14-17, 2012
Slide 16 of 28
The BME Lectures - Tokamak Engineering - “Plasma Diagnostics in DEMO” T N Todd

Concept of Hybrid system

Baffled duct and mitigation by gas blowing

Kotov's calculation ; duct with baffles
ITER_D_AHMDZX

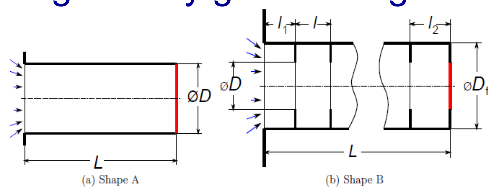


Figure 4: Generic shapes of the diagnostic ducts which were investigated

Mukhin et al. ; Blow-out techniques by a gas counter flow, *Nucl. Fusion* **49** (2009) 085032

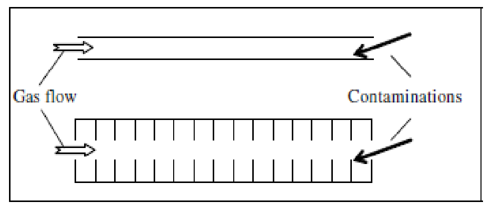
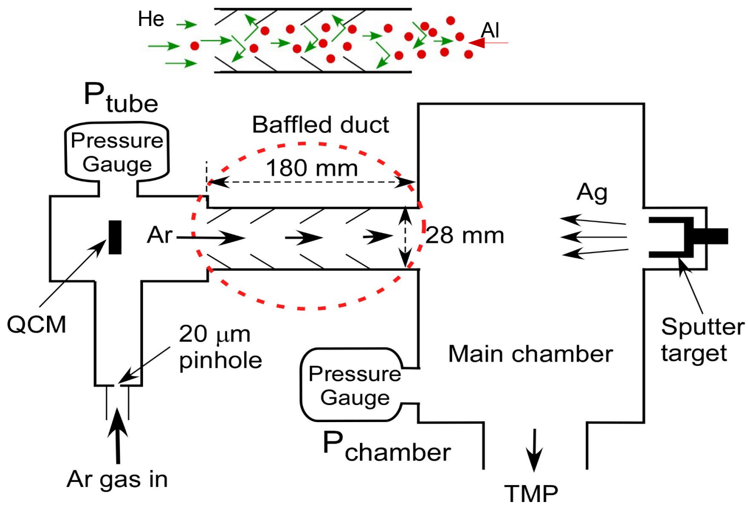


Figure 6. Example of the two duct geometries. The lower one with a much higher internal surface area is more efficient in trapping the contamination.

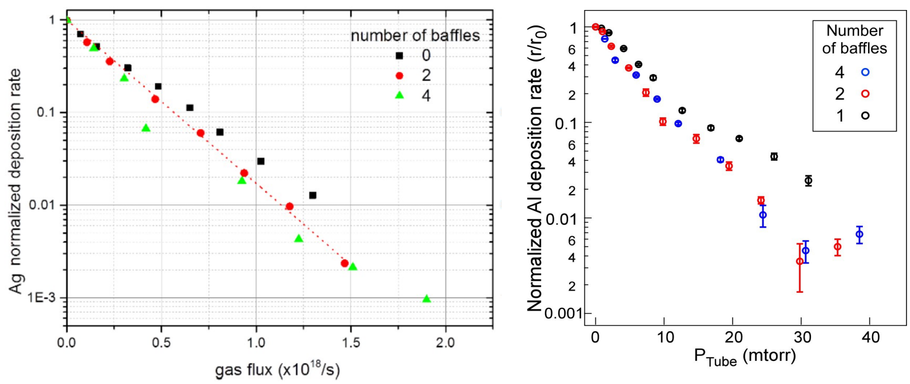
And it greatly improves the pressure ratio...

Schematic of gas blowing system



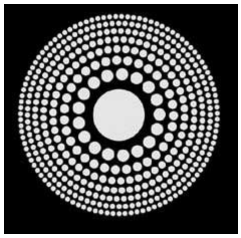
B. S. Kim [1], S. G. Oh [1], C. R. Seon[2], H. G. Lee[2], J. S. Park[3], J. H. Hong[3], W. Choe[3]
[1] Ajou University [2] ITER Korea, National Fusion Research Institute [3] KAIST

Dependence of contaminant flux on gas flux

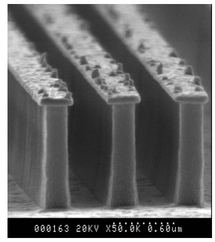


The same effect of He to Al with 10 x 10^{18} He/s as Ar to Ag with 1 x 10^{18} Ar/s

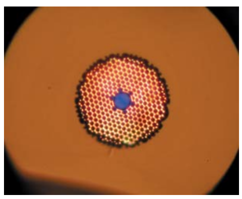
Promising diagnostic options



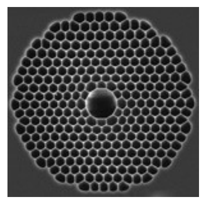
Photon sieve lens
(Courtesy Mitre)



Freestanding metallic transmission gratings
(Courtesy CNRS-LPN)



Hollow or holey fibre
(Courtesy Optics.org)



Photonic crystal hollow fibres
(Courtesy Crystal Fibre)

Conclusions

- JET is not subject to nuclear licensing but it is a step towards ITER, including tritium recycling plant and a range of radwaste and neutron radiation effects, both real-time and accumulated.
- Like many fusion research devices, JET often does not exhibit the complete system reliability for plasma operations that a nuclear regulator will insist upon, although its human safety and machine protection systems function in depth with good reliability.
- DEMO will have all the same non-nuclear requirements on its diagnostic engineering as any presently operating tokamak of considerable size and complexity.
- It will also have a number of nuclear requirements and constraints, currently little recognised by the wider fusion community, but of course standard thinking for those in ITER.
- ITER will demonstrate many aspects of radiation hardening for diagnostic systems on the torus, but has a very much lower neutron fluence than DEMO
- JET and ITER are research machine requiring many sophisticated plasma diagnostics...
- Even without the problems of radiation damage, port space in DEMO must be heavily constrained to maintain adequate tritium breeding ratio
- Also in DEMO, the design of plasma diagnostic systems is “extremely challenging”, and may necessitate a learning period transition from well-equipped to sparsely equipped as unmaintainable systems fail early in the life of the machine.

This work was funded by the RCUK Energy Programme under grant EP/I501045 and the European Communities under the contract of Association between EURATOM and CCFE. The views and opinions expressed herein do not necessarily reflect those of the European Commission

Summary

- Controlled fusion has many challenges – but the battle is worth the effort!

And this is why!

Here's the River Thames near Culham, and a typical record of its flow rate over a year:

That 4t/sec contains ~4x10^{25} D atoms/sec, which could be fusion reacted to make helium and hydrogen and a neutron, releasing ~7MeV for each D atom, thus ~45TW, **about twice the whole world's current total energy usage!** (A D-D reactor is, however, "a bit challenging...", so we'll begin with D-T.)

Additional acknowledgements & References

- Vayakis - The ITER radiation environment for diagnostics, N 55 RI 38 04-05-06 W 0.1
  - SRD-55 (Diagnostics) from DOORS (ITER_D_28B39L v3.1)
- Lobel *re JET component stress analysis guidelines and DTE2 diagnostics preparations*
- Zastrow *re JET diagnostics failures*
- Maas *re JET DTE*
- Igitkhanov *re tungsten sputtering*
- Donné *re reactor diagnostics*
- Widdowson *re JET QMB failures*
- Fischer et al *re radiation fields and helium production in DEMO*
- Gerasimov *re JET magnetic diagnostic failures*
- Zheng *re tritium breeding ratio*
- Sublet *re dpa & He appm ratios*
- Young *re Radiation-Induced Conductivity*
- Tobita – IAEA DEMO Programme Workshop, UCLA, October 2012
- Alfier *et al* - Rev. Sci. Instrum. 81, 123509 (2010); doi: 10.1063/1.3511557
- Asano *re rewelding*,
- Stork *re swelling*
- Gerasimov *et al re JET magnetics failures*
- Prokopec *et al* – Mechanical behaviour of cyanate ester/epoxy blends after reactor irradiation to high neutron fluences
- Pampin & Karditsas – Fusion power plant performance analysis using the Hercules code.
- Shikama & Pells – Journal of Nuclear Materials 212-215 (1994) 80-89

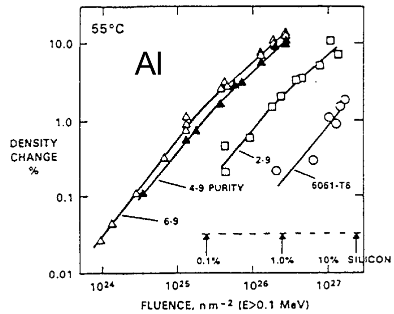
END

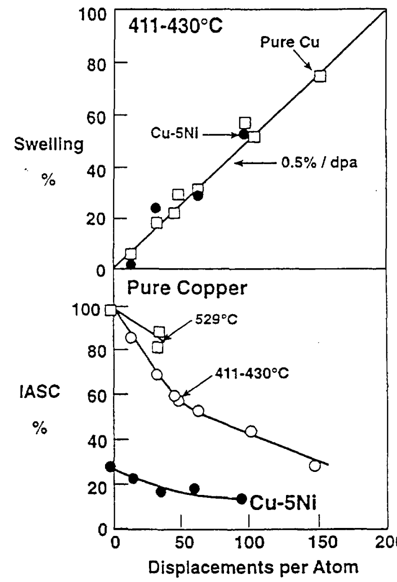
Typical Numbers

From A. Costley et al, ITER Diagnostics R&D, Fusion Engineering and Design (2001

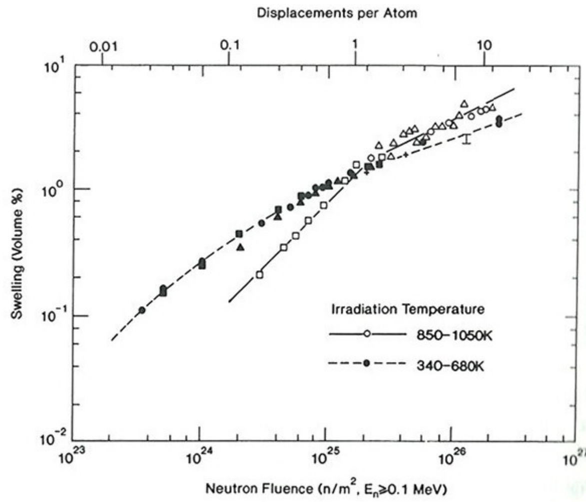
Location *Typical diag. component*	Neutrons > 0.1 MeV n/m^2s	Neutrons 14 MeV n/m^2s	Dose Rate Gy/s	Fluence > 0.1 MeV n/m^2	Part icle flux atoms $/m^2s$	Plasma radiation (peak) kW/m^2
First Wall [1]	$3x10^{18}$	$8x10^{17}$	$2x10^{3}$	$3x10^{25}$	$\sim 5x10^{19}$	500
Near Blanket Gap (on VacuumVessel) *Mag. coils* *Bolometers* *Retroreflectors*	0.2 - $1x10^{17}$	0.8 - $4x10^{16}$	20 - 100	0.4 - 2.0 $x10^{24}$	$\sim 10^{18}$	10
Vacuum Vessel (Behind Blanket) *Mag. loops*	$2x10^{16}$	$3x10^{14}$	^{2} 20	$2x10^{23}$	~ 0	~ 0
Diagnostic block *First mirrors*	$1x10^{16}$	$9x10^{15}$	20	$1x10^{23}$	$\sim 10^{17}$	~ 1.5
Labyrinth Second mirrors,Windows	$2x10^{13}$	$3x10^{13}$	10^{-2}	$2x10^{20}$	~ 0	~ 0
Vacuum Vessel (Inboard TFC side) *Mag. loops*	$1x10^{14}$	$1x10^{12}$	0.1	$\sim 10^{21}$	~ 0	~ 0
Divertor Cassette *First mirrors*	$1x10^{18}$	$3x10^{17}$	$1x10^{-3}$	$\sim 10^{25}$	10^{17} Ğ 10^{19}	1 - 100
Divertor Port *Second mirrors*	$10^{13}\sim10^{15}$	$10^{12}\sim10^{14}$	10^{-2} - 1	$10^{19}\sim 10^{21}$	TBD	TBD

G. Vayakis, The ITER radiation environment for diagnostics, N 55 RI 38 04-05-06 W 0.1





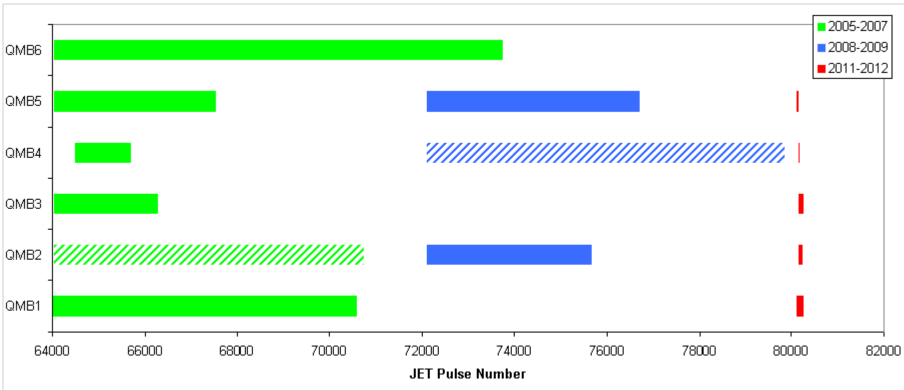
Both Al and Cu have about 8dpa at 10^{26} n/m^2



Swelling of alumina [Shakima & Pells]

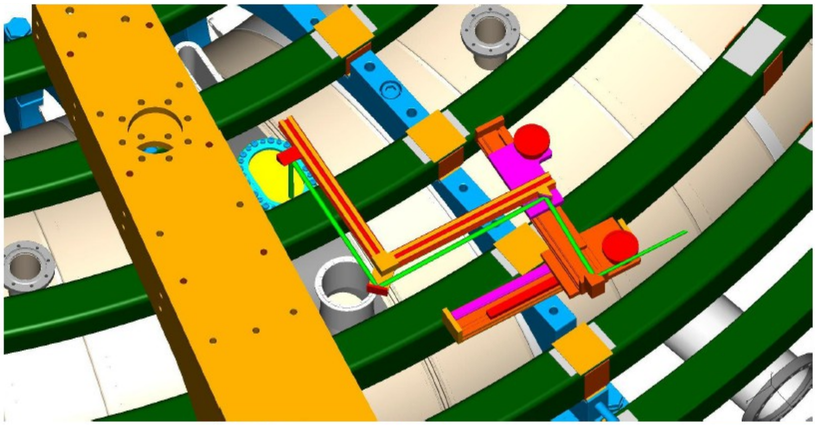
Journal of Nuclear Materials 212–215 (1994) 80–89

Summary of QMB Lifetimes



RAMI issues – Can DEMO windows etc be cleaned?

Window cleaning *in situ* – demonstrated in RFX



Elegant – but the x-y motors and the system's own mirrors may need to be retractable.