

Diagnostic systems in DEMO: engineering design issues

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Contents

- Non-nuclear engineering requirements
- Nuclear requirements
- Radiation in JET ITER DEMO compared
- Radiation-induced problems (examples)
 - conductivity
 - loss of strength in resins
 - helium production
 - reweldability
 - swelling
 - decay heat
- Port space constraints (TBR)
- Diagnostics mortality
- First windows and mirrors (cleaning and erosion)
- All is not lost!
- Conclusions

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.



The BME Lectures - Tokamak Engineering -

"Plasma Diagnostics in DEMO" T N Todd



- 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!







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. **B** ex-vessel







- 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 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, <u>advanced control, & physics studies.</u>
- 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



- 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 >0.02m²
- 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)





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 (<u>approximate!</u>)

	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 V: 100	0.01
ITER all life	4000	0.3	4x10 ²⁵	2	20	n: 200 V: 500	500
DEMO 3 FPY	6000?	6	8x10 ²⁶	50	500	n: 300 V: 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 $\sim (0.1-1.0) \times 10^{-15} \text{ Gy}/(n/m^2)$



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

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

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

The BME Lectures - Tokamak Engineering -"Plasma Diagnostics in DEMO"

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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

Energy 🥚

At doses ~100MGy, or ~ 10^{23} n/m², 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

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

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:

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"Plasma Diagnostics in DEMO"

T N Todd

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

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

CORE CXRS EDGE CXRS (UP) DNB EDGE MSE EDGE CXRS (LOW)

Core LIDAR Thomson scattering system (Courtesy M. Walsh)

Charge Exchange Recombination Spectroscopy (Courtesy M. von Hellermann)

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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

TF Coil

Solenoid

Cryostat

Back-plate

Blanket

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

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

RAMI issues - JET magnetic diagnostic failur

- 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)

EFJET R

- 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

C T RAMI issues - JET Quartz MicroBalance failures

	2005-2007	2008-2009	2014-2012
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 / 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 ()

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- 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

- 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 \rightarrow higher diffuse reflectivity

Sample 2: 532 followed by 230 nm

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

But really there will be impurities as well:

T N Todd

A very effective system for the windows of RFX:

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.

CCFE

Promising diagnostic options

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...




B. S. Kim¹, S. G. Oh¹, C. R. Seon², H. G. Lee², J. S. Park³, J. H. Hong³, W. Choe³ ¹Ajou University ² ITER Korea, National Fusion Research Institute ³ KAIST



The same effect of He to AI with 10 x 10¹⁸ He/s as Ar to Ag with 1 x 10¹⁸ Ar/s



Promising diagnostic options



Photon sieve lens (Courtesy Mitre)



Freestanding metallic transmission gratings (Courtesy CNRS-LPN)





Photonic crystal hollow fibres (Courtesy Crystal Fibre)

Hollow or holey fibre (Courtesy Optics.org)

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- 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 <u>non-nuclear</u> 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





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

Summary





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 ~4x10²⁵ 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.)



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- Sublet *re dpa* & *He appm ratios*
- Young re Radiation-Induced Conductivity
- Tobita IAEA DEMO Programme Workshop, UCLA, October 2012
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- 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



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END





Typical Numbers

Location	Neutrons		Dose Rate	Fluence	Part	Plasma
Typical diag. component	> 0.1 MeV n/m ² s	14 MeV n/m ² s	Gy/s	> 0.1 MeV n/m ²	icle flux atoms /m ² s	radiation (peak) kW/m ²
First Wall ¹	3x10 ¹⁸	8x10 ¹⁷	2x10 ³	3x10 ²⁵	$\sim 5 { m x} 10^{19}$	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	$3 x 10^{14}$	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	$\sim 10^{21}$	~ 0	~ 0
Divertor Cassette First mirrors	1x10 ¹⁸	3x10 ¹⁷	1x10 ⁻³	$\sim 10^{25}$	10 ¹⁷ Ğ10 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

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"Plasma Diagnostics in DEMO"

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Both AI and Cu have about 8dpa at 10²⁶ n/m²









Summary of QMB Lifetimes







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

<u>Contents</u>

- · Non-nuclear engineering requirements
- Nuclear requirements
- Radiation in JET ITER DEMO compared
- Radiation-induced problems (examples)
 - conductivity
 - loss of strength in resins
 - helium production
 - reweldability
 - swelling
 - decay heat
- Port space constraints (TBR)
- · Diagnostics mortality
- First windows and mirrors (cleaning and erosion)
- All is not lost!
- Conclusions

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.

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Secces 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
The BME Lectures - Tokamak Engineering - "Plasma Diagnostics in DEMO" T N Todd

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, <u>advanced control, & physics studies.</u>
- 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 ٠
- 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 >0.02m²
- Must tolerate control failure of RH systems (meaning impacts)
- ٠ 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
- ٠ RAMI includes specific requirements, which could be compared with JET's (low) and DEMO's (high)

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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...

(Compar	ison of radiolo	gical impac	ts of JET-IT	ER-DE	EMO Fir	st Wall (<u>ap</u>	oroximate!)
		Site T Inventory, g	Average MWyr/m ²	Peak n/m ² >0.1MeV*	dpa	He appm	Operating Gy/sec	Shut-down Gy/hr
JH 19	ET 997	20	10-7	1x10 ¹⁹	10-6	10-5	n: 40 V: 100	0.01
I] al	ER 1 life	4000	0.3	4x10 ²⁵	2	20	n: 200 Y: 500	500
D 3	EMO FPY	6000?	6	8x10 ²⁶	50	500	n: 300 V: 500	10,000
	ł	About 5x the ne	eutron fluenc	e due to virgin	14Me	V neutror	ns alone	
	1	NB Fission reac spectra and as a	tor neutron s a result gene	pectra are mu rate about 1/1	ch soft 0 of the	er than fu e He app	usion neutron m per dpa.	
I	n epoxy	, polyimide, g	lass, carboi	n & alumina,	there	is ~(0.1	-1.0)x10⁻¹⁵ C	Gy/(n/m²)
The	BME Le	ectures - Tokam	ak Engineeri	ing - "Plasr	na Diad	anostics i	n DEMO"	T N Todd 🛛 🥯

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),



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.

SCCFE DEMO Structu	ral Materials issues	
		1
Example of Fe lattice damage caused by a 500keV Fe ion recoiling from a single neutron impact. Initial temperature 300K.	denser.	
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

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Bamage 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





















EFPA 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:
Further engineering analysis required Definitely not OK Technically OK but missing capability
DTE2 The BME Lectures - Tokamak Engineering - "Plasma Diagnostics in DEMO" T N Todd




Space for DEMO diagnostics will be very limited







EFPET 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.
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EFJEARAMI issues - JET Quartz MicroBalance failures

	2005-2007	2008-2009	2014-2012
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 esting
QMB6	73760 Depo and temp failed	Cracked crystal on removal in 2009 (not observed in 2007)	Noinstallation



Secces

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

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



Seccre RAMI issues – Can DEMO windows etc be cleaned?











CCFE Conclusions JET is not subject to nuclear licensing but it is a step towards ITER, including tritium recycling 0 plant and a range of radwaste and neutron radiation effects, both real-time and accumulated. 0 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. 0 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 0 the wider fusion community, but of course standard thinking for those in ITER. 0 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... 0 Even without the problems of radiation damage, port space in DEMO must be heavily constrained 0 to maintain adequate tritium breeding ratio 0 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 "Plasma Diagnostics in DEMO" The BME Lectures - Tokamak Engineering -T N Todd





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Typical Numbers									
Location	Neu	Neutrons		Fluence	Part	Plasma			
Typical dia componen	$8 \cdot \frac{> 0.1}{MeV}$	14 MeV n/m ² s	Gy/s	> 0.1 MeV n/m ²	icle flux atoms /m ² s	radiation (peak) kW/m ²			
First Wall	1 3x10 ¹⁸	8x10 ¹⁷	2x10 ³	3x10 ²⁵	$\sim 5 \times 10^{19}$	500			
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Vacuum Vessel (Inboard TFC si Mag. loops	de) 1x10 ¹⁴	1x10 ¹²	0.1	$\sim 10^{21}$	~ 0	~ 0			
Divertor Cassett	e 1x10 ¹⁸	3x10 ¹⁷	1x10 ⁻³	$\sim 10^{25}$	$10^{17} { m \check{G}} 10^{19}$	1 - 100			
First mirrors Divertor Port	10 ¹³ ~10 ¹⁵	1012~1014	10 ⁻² - 1	$10^{19} \sim 10^{21}$	TBD	TBD			







