Fusion and Radiation Issues

$D + T \rightarrow {}^4He\ (3.5MeV) + n\ (14.1MeV)$

$T\ (t_{1/2} = 12.3\ yr) \rightarrow {}^3He + e^-\ (5.7\ keV) + \bar{\nu}_e$

In addition to biological shielding, reactor material activation requires

- ✓ **Radiation shielding**
- ✓ **Remote handling**
- ✓ **Earlier recyclable reactor design**

Table 3.2. Effective microscopic cross-sections for reactions producing tritium or precursors[a]

Reaction	$\sigma_{eff}(10^{-28}\ m^2)$
${}^2H(n,\gamma)T$	0.000316
${}^6Li(n,\alpha)T$	693
${}^7Li(n,n\alpha)T$	0.0516
${}^{10}B(n,\alpha)Li$	3060
${}^{10}B(n,2\alpha)T$	1.27

[a]From ref. 37. [Bell, 1973]

Also[b], ${}^3He(n,p){}^3H$ production 5237 barn

[b]From ref. 53 [Fischer, 1977]

- ➢ **Internal tritium doses are hazardous, but**
  - ✓ **Short biological half-life : ~ 10 days**

${}^6Li + n \rightarrow {}^4He\ (2.05MeV) + T\ (2.73MeV)$

${}^7Li + n \rightarrow {}^4He + T + n - 2.47\ MeV$

- ➢ **Tritium cycle is internally closed**
  - ✓ **Total tritium inventory: ~ a few kg**

Radiation Safety and Environmental Issues for Fusion

Considerations for radiation safety and licensing

- Postulated accident scenarios
- Environmental radiation releases during operation
- Occupational radiation exposure
- Radioactive waste

Safety functions

- ➢ Confinement of radioactive material
- ➢ Limitation of exposure to ionizing radiation

- ➢ Tritium cycle is internally closed
  - ✓ Total tritium inventory: ~ a few kg

Table I

Facility	*Location*	*Max Inventory*	*Throughput*	*Status*	*Function*
TSTA	Los Alamos USA [7]	100g	>1kg	Decommissioned	Fuel cycle tests
TFTR	Princeton USA	5g	~100g	Decommissioned	Tokamak
JET	Culham UK	20g	~100g	Operational	Tokamak
TPL	Tokai Japan [8]	60g	–	Operational	Fuel cycle tests
TLK	Karlsruhe Germany [9]	40g	160g	Operational	Fuel cycle tests
ITER		3kg			

Bell
EFDA–JET–CP(02)05/23

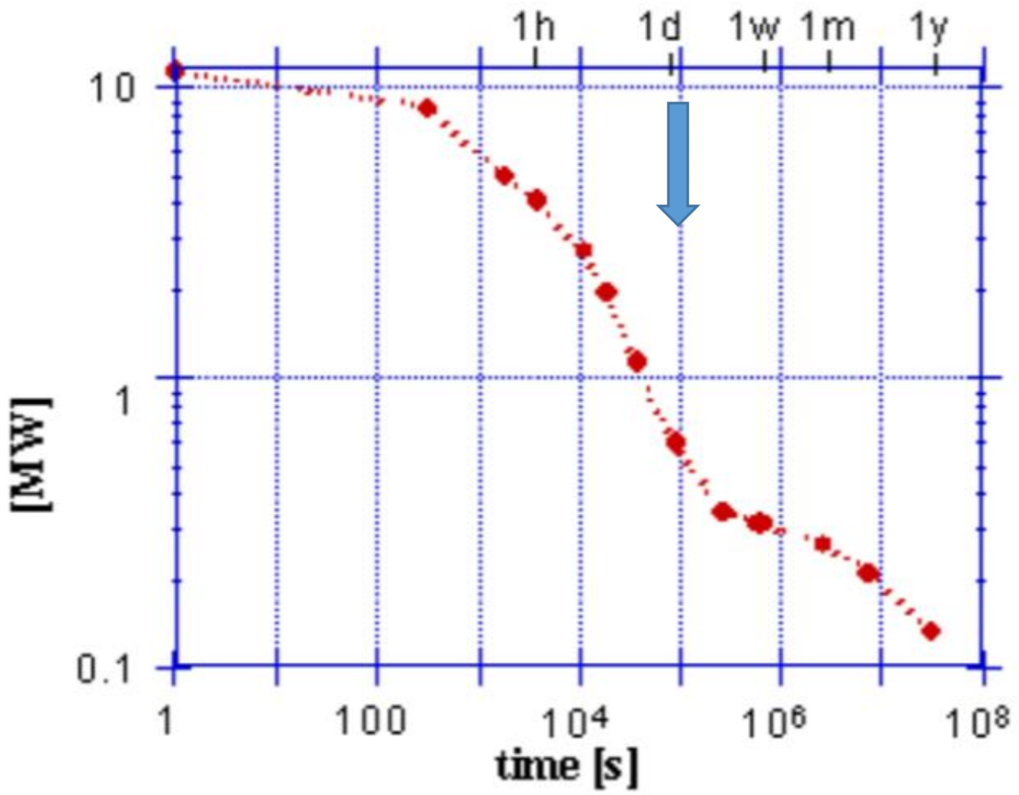
JET: 30g (tritium recycling plant), 20g (torus), 10g (cryo-pumps)
ITER: 450g (VV or fuel cycle sub-systems), 330g (PFC), 120g (cryo-pumps)

Reactor Material Activation : Tungsten

ITER PDD 2001

Decay Heat and Activities

Global Decay Heat In ITER
at End of Life (fluence 0.5 MWa/m²)



Activity of Tungsten and FW/shield Activated Corrosion Products (ACPs)

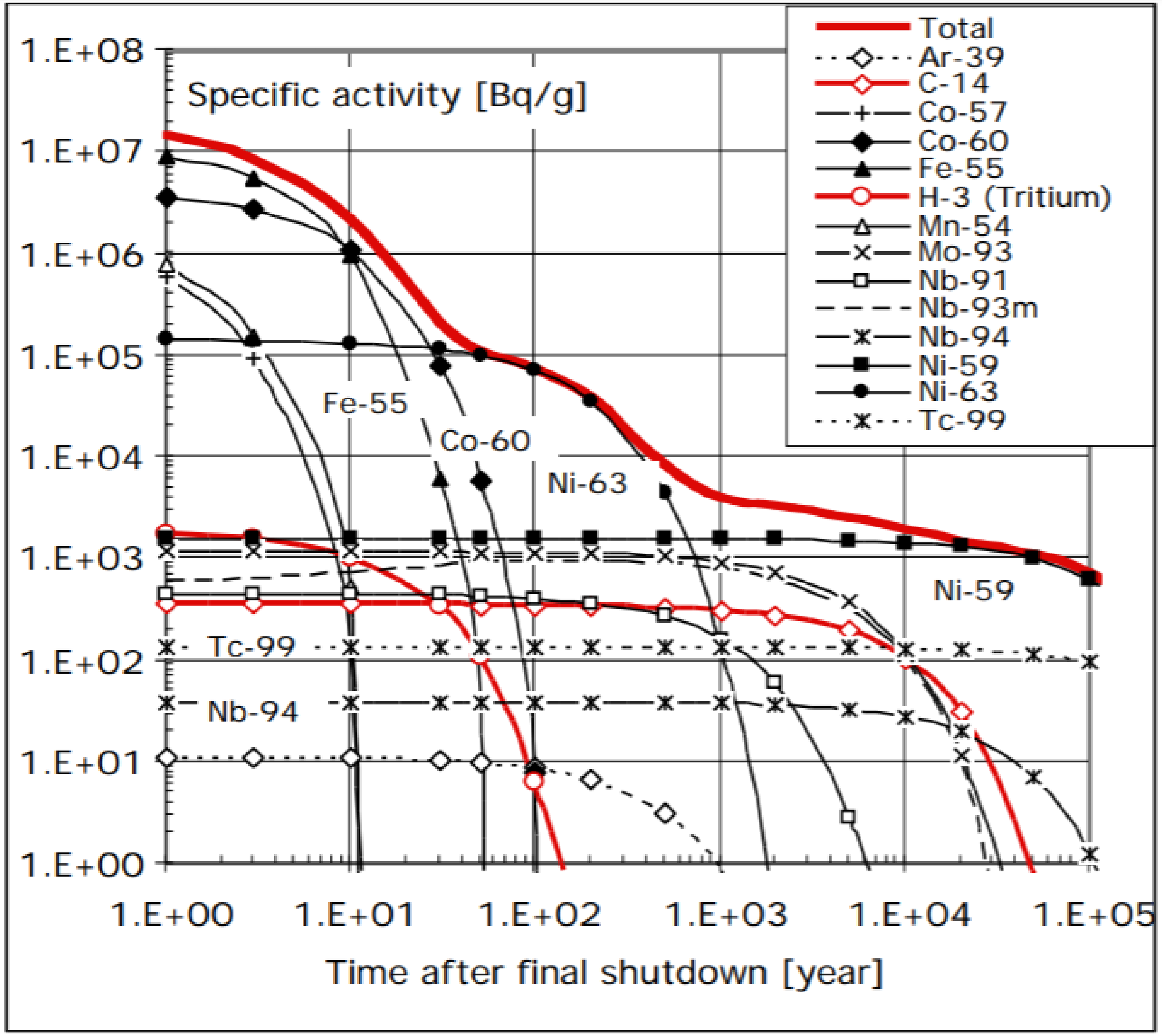
Tungsten activation (plasma surface layer: 25 micro-m)			ACP deposits (steel)			
isotope	half life [y]	activity [Bq/kg]	isotope	half life [y]	deposit activity [Bq/kg-deposit]	Ion and cruds in solution activity [Bq/kg-ion/crud]
W 187	2.72E-03	5.24E+14	Fe-55	2.73E+01	2.07E+12	9.61E+11
W 185	2.06E-01	3.71E+13	Mn-54	8.55E-01	9.86E+10	3.49E+11
W 185m	3.17E-06	3.64E+13	Mn-56	2.94E-04	1.35E+12	1.19E+13
W 181	3.31E-01	1.43E+13	Co-58	1.94E-01	1.06E+11	3.92E+11
Re188	1.94E-03	6.01E+12	Co-60	5.27E+01	1.41E+11	2.39E+11
Re186	1.03E-02	2.20E+12	Cr-51	7.59E-02	1.14E+11	4.54E+08
Re188m	3.54E-05	5.79E+11	Ni-57	4.11E-03	4.52E+10	8.85E+10
W 179	7.13E-05	2.56E+11	Co-57	7.44E-01	2.64E+11	4.96E+11
Ta182	3.14E-01	1.54E+11				
W 179m	1.22E-05	1.02E+11				
Ta186	2.00E-05	6.34E+10				
Ta183	1.39E-02	6.18E+10				
Ta184	9.92E-04	4.34E+10				
Ta182m	3.04E-05	2.88E+10				
Ta179	1.61E+00	2.74E+10				
Re184	1.04E-01	1.99E+10				
Ta180	9.22E-04	1.15E+10				
Hf183	1.22E-04	9.64E+09				

Radiological source terms are (1) tritium, (2) tokamak dust, (3) activated corrosion products (ACPs).

Reactor Material Activation : Structural Materials

Specific Activities of the Transmutation Products in the Structural Steel SS 316 L(N)-IG at the Plasma-side Surface

Key elements: Fe-55, Co-60, Ni-63, Ni-59
Mn-54, Mo-93, Nb-93m, Nb-91, Nb-94



ITER PDD 2001

Reduced Activation Ferritic-Martensitic (RAFM) Steel Development

'Reduced Activation Ferritic-Martensitic' steels are under development:

→ Ta replaces Nb, → V replaces Ti → W or V replaces Mo

→ Cr replaces Mn … up to a point. → Avoid Ni, Cu, N

Program	Steel	C	Si	Mn	Cr	W	V	Ta	N	B	Other
Japan	F82H	0.10	0.2	0.50	8.0	2.0	0.2	0.04	<0.01	0.003	
	JLF-1	0.10	0.08	0.45	9.0	2.0	0.20	0.07	0.05		
	OPTIFER Ia	0.10	0.06	0.50	9.30	1.0	0.25	0.07	0.015	0.006	
Europe	OPTIFER II	0.125	0.04	0.50	9.40		0.25		0.015	0.006	1.1 Ge
	EUROFER	0.11	0.05	0.50	8.5	1.0	0.25	0.08	0.03	0.005	

RAFM steels will be 'cool' enough for simple recycling and re-use after ~ 50-100 years storage (after ~ 5 years service in the reactor first wall).

Advanced Reduced-Activation Alloy (ARAA) : KAERI

Ti-RAFM : KIMM

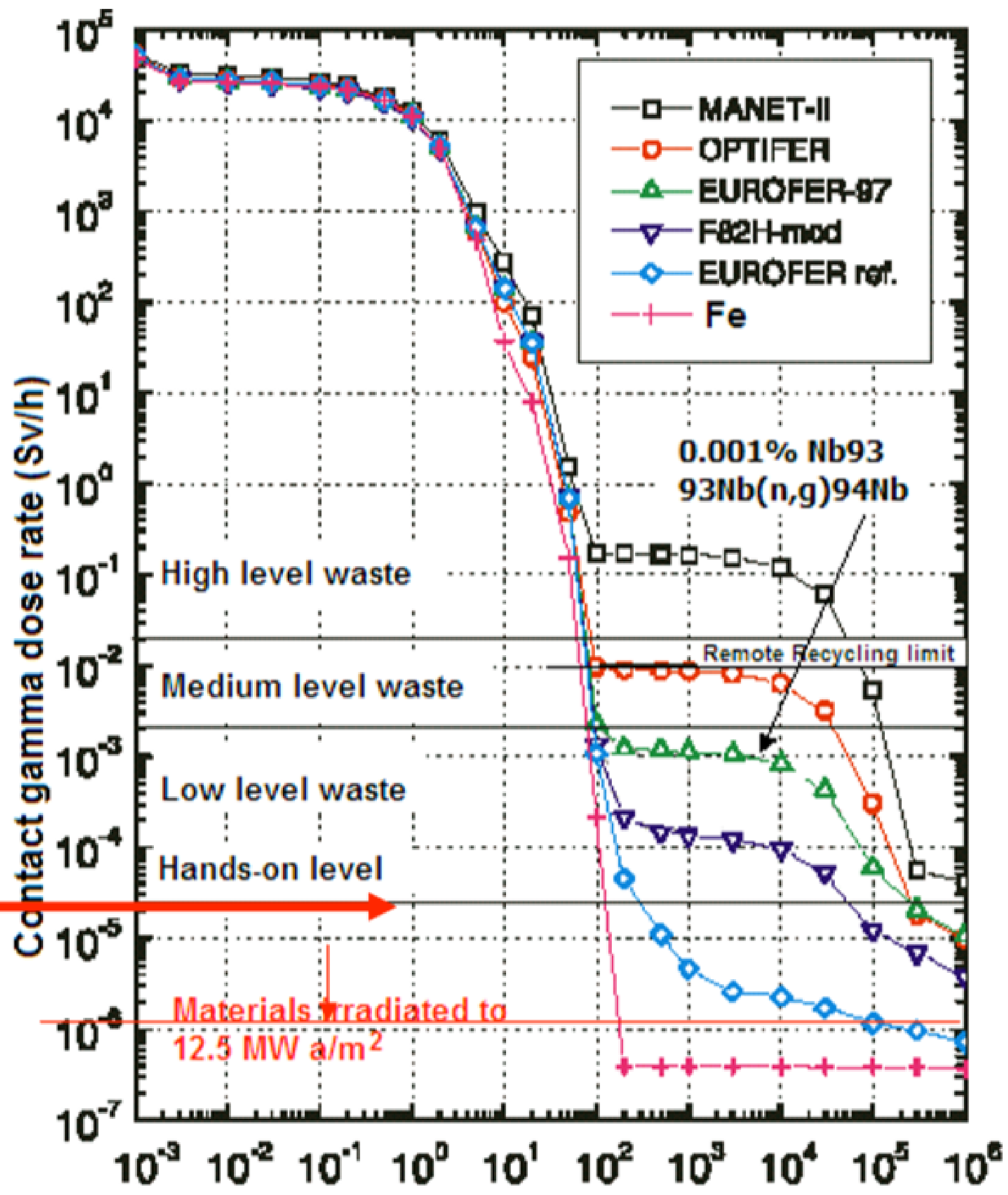
Steels	C	Si	Mn	Cr	W	V	Ta	Ti	N
Ta-RAFM	0.09	0.12	0.54	8.17	1.95	0.21	0.08	-	0.0026
Ti-RAFM	0.08	0.12	0.45	9.09	1.07	0.21	-	0.07	0.0019

RAFM Steel Manufacturability: Effect on Waste

EUROFER Blanket Material
- **replace every 5 years;**
- **P_{fus} = 3 GW;**
- **Neutron Wall Load = 2.3 MW.m^{-2} for 5 years**

For EUROFER to achieve Reference composition Nb impurity needs to be further decreased by two orders of magnitudes to 0.00001% (~0.1 ppm)

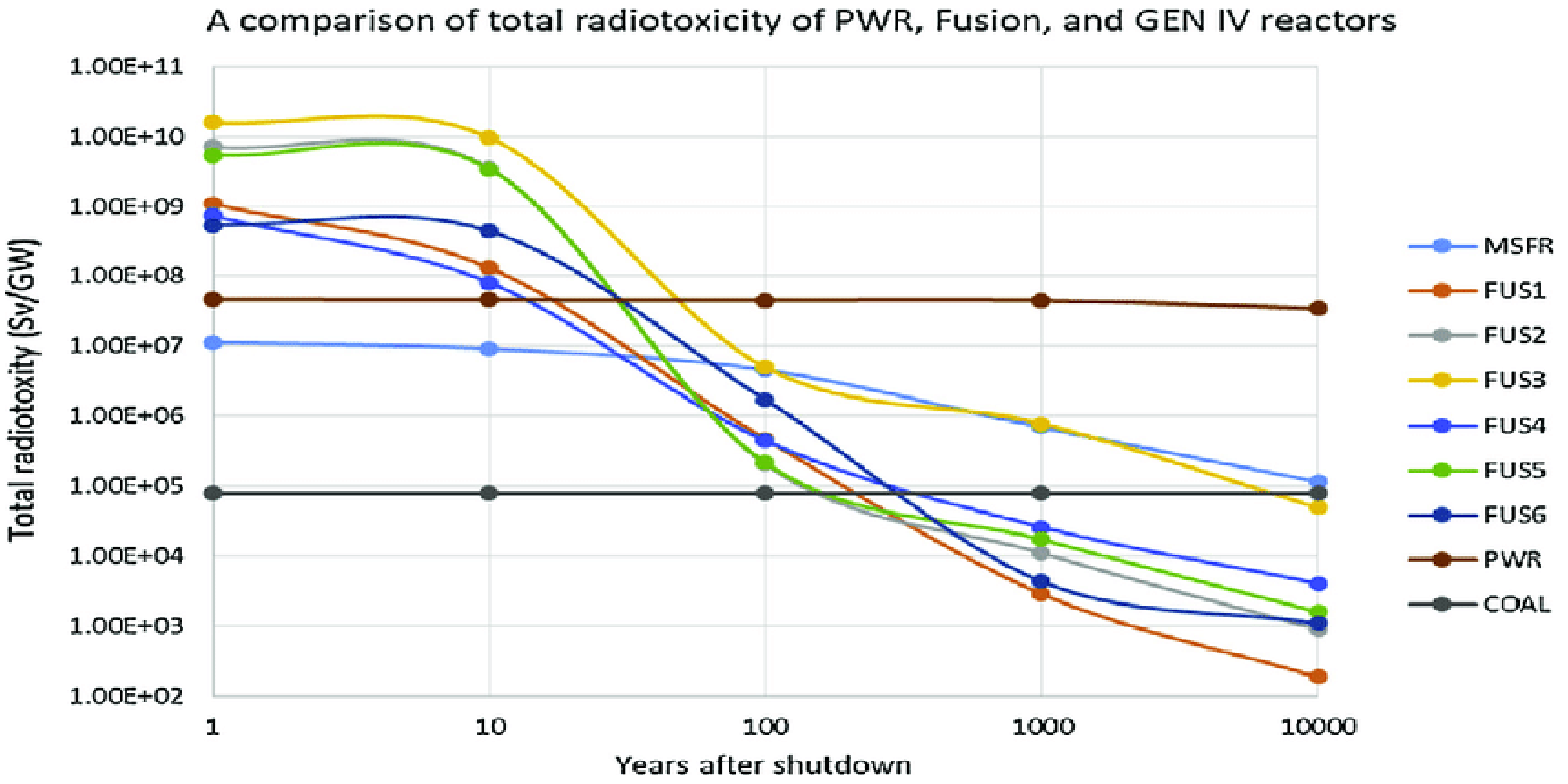
Hands-on recycling level



Ref [9]: P Batistoni et al.

Comparison of Long-lived Radioactive Wastes

A comparison of total radiotoxicity of PWR, Fusion, and GEN-IV reactors. Radioactivity from coal-fired plant ashes are included too. All results are normalized to a 1000 MWe power electricity production.



Fusion Reactor Model
Structure / Breeder
1 V alloy Li2O
2 RAFM Li-Pb
3 RAFM Li4SiO4
4 SiC/SiC Li-Pb
5 RAFM Li-Pb
6 SiC/SiC Li4SiO4

Zucchettia et. al, FED(2018)

Radiation Shielding

- Protect magnet coils
  - superconductor
  - copper stabilizer
  - insulation
- Reduce activation
- Protect people
- Neutrons and gammas attenuation ~ 10^{-7}

Shielding Requirements – ARIES CS
Radiation Limits, 40 full-power years

Fast neutron fluence to coils	$< 10^{19}$	/cm^2
Nuclear heating in Nb_3Sn coils	< 2	mW/cm^3
Dose to coil insulator	$< 10^{11}$	rad
Copper stabilizer displacements per atom	$< 6\times10^{-3}$	dpa

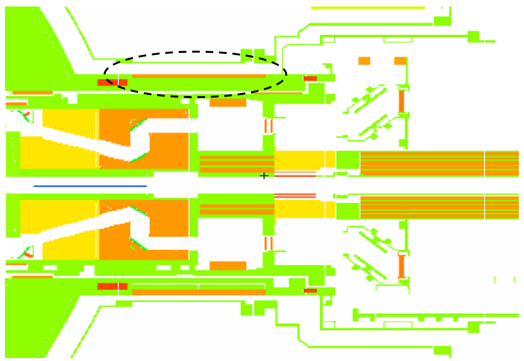
(El-Guebaly FST 2008)

- **WC is used for both neutrons and gammas**
- **ARIES CS: double-wall vacuum vessel**

(RAFM steel structure, borated steel filler, and water)

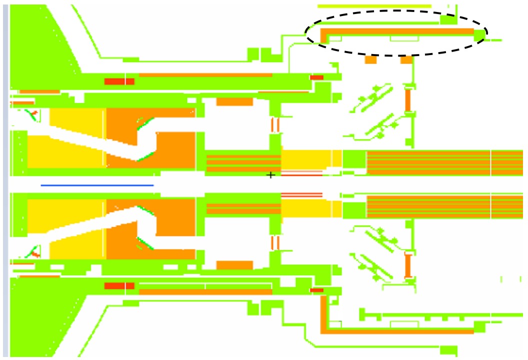
Shutdown Dose Rate (SDDR) in ITER

Case #1



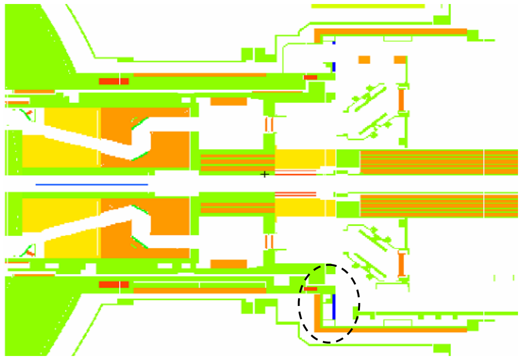
Case #0 + VV belt:
- B_4C
- 6 cm thickness

Case #2



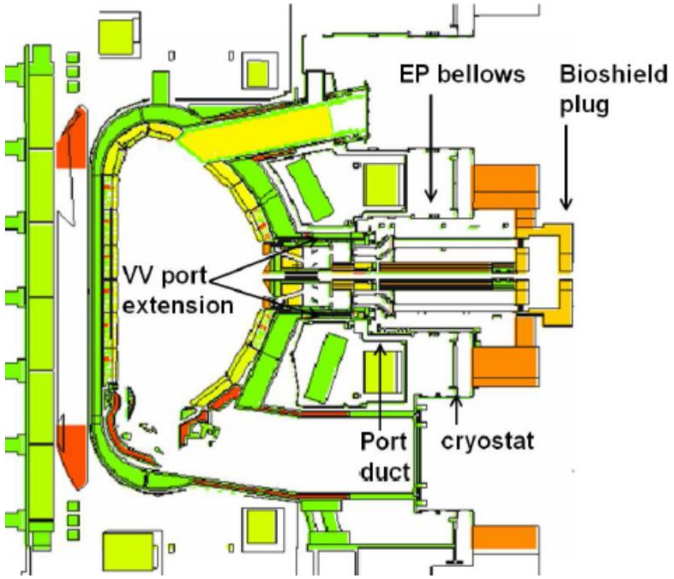
Case #1 + Port Duct out:
- B_4C
- 5 cm thickness

Case #3



Case #2 + Port Duct in:
- Tungsten
- 3 cm thickness

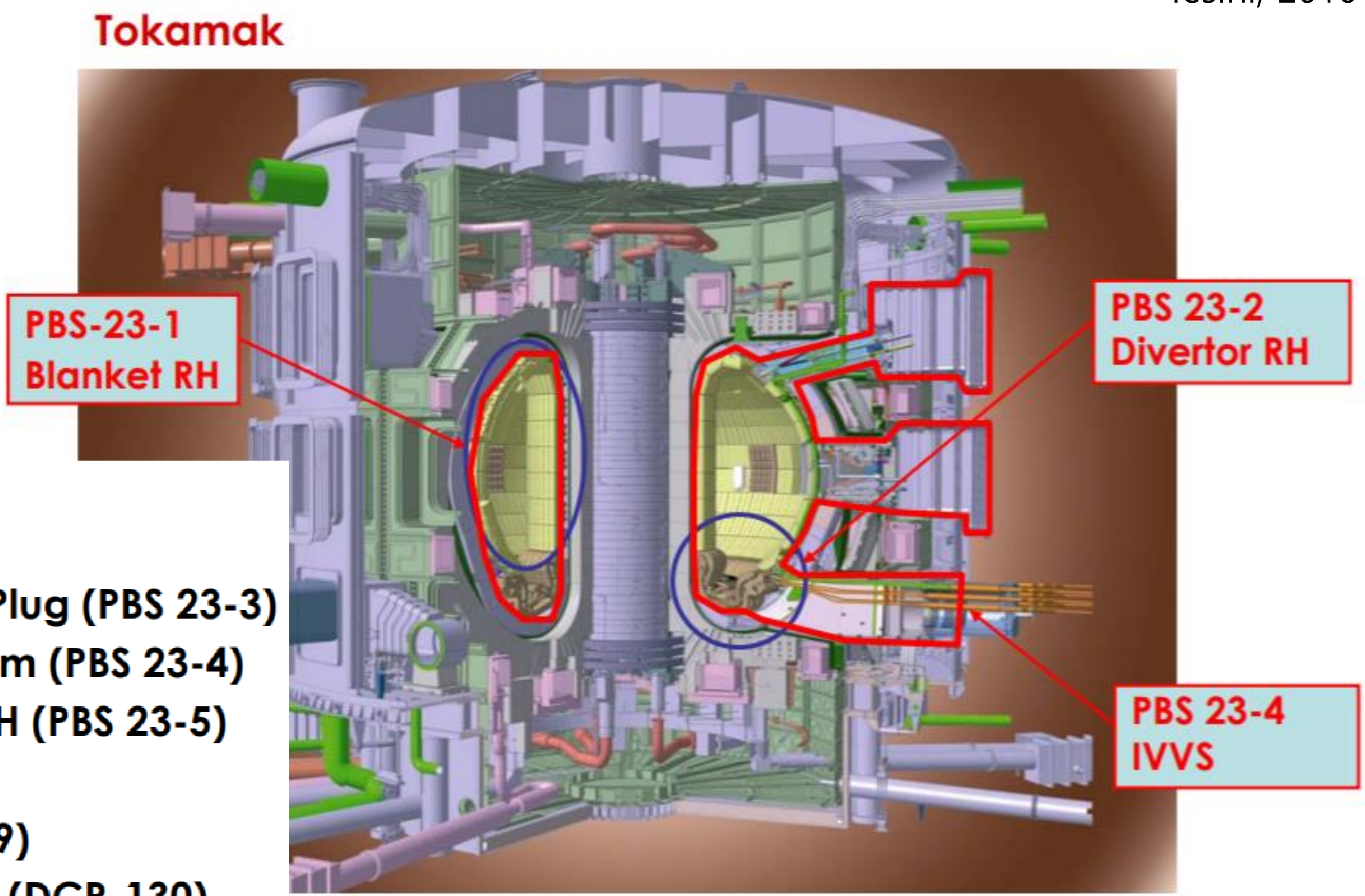
EP#11 MC simulation with ITER C-Lite neutronic model



Right corridor (μSv/h)	Total	EP content	C-lite
Case #0	139_Δ	61_Δ	78_Δ
Case #1 (VV belt)	122_Δ	58_Δ	64_Δ
Case #2 (VV belt + PD out)	78_Δ	50_Δ	28_Δ
Case #3 (VV belt + PD out + PD in)	73_Δ	49_Δ	24_Δ
Left corridor (μSv/h)	**Total**	**EP content**	**C-lite**
Case #0	119_Δ	49_Δ	70_Δ
Case #1 (VV belt)	95_Δ	43_Δ	52_Δ
Case #2 (VV belt + PD out)	59_Δ	38_Δ	21_Δ
Case #3 (VV belt + PD out + PD in)	53_Δ	36_Δ	17_Δ

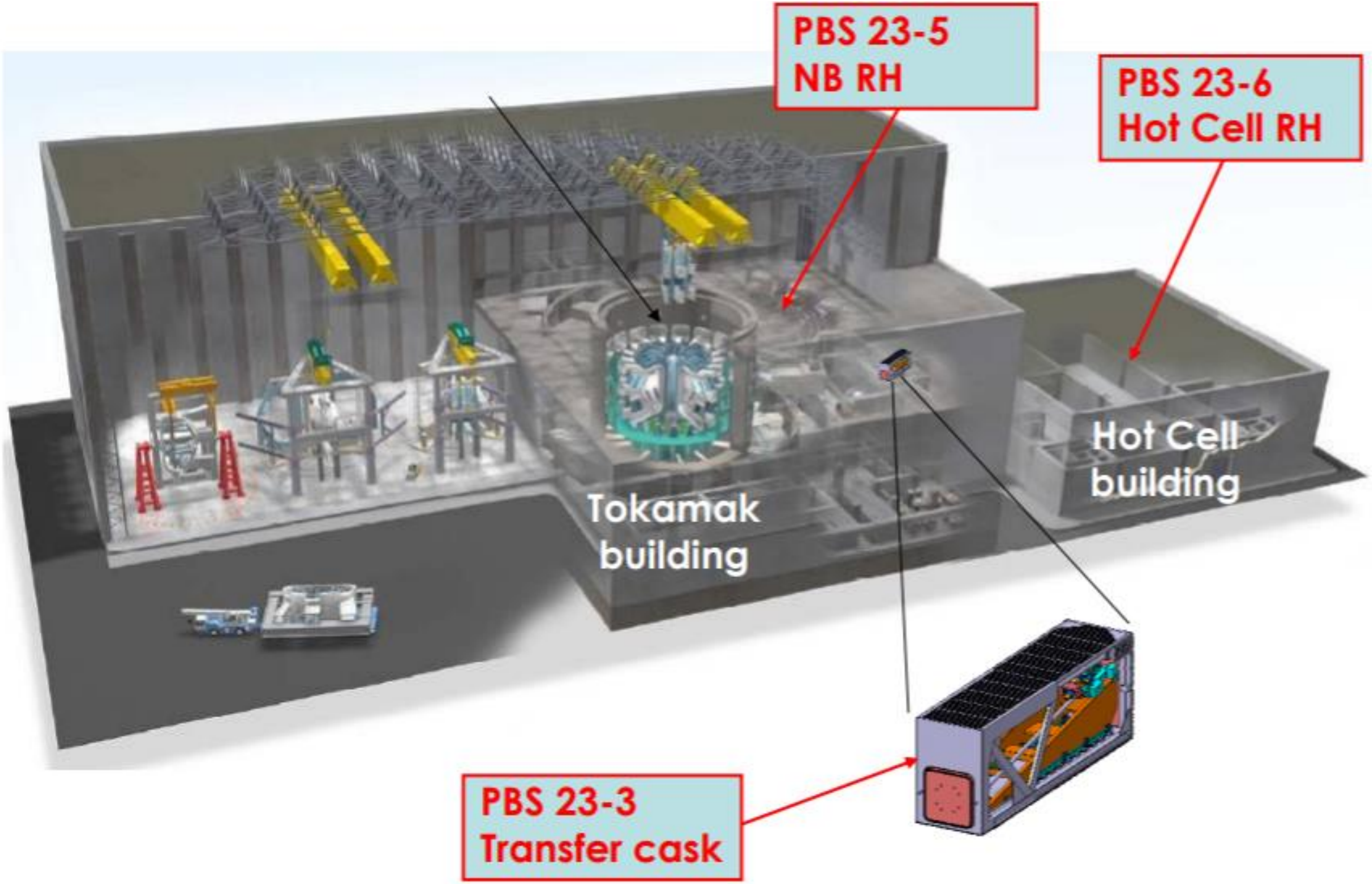
ITER Remote Handling

Tesini, 2010

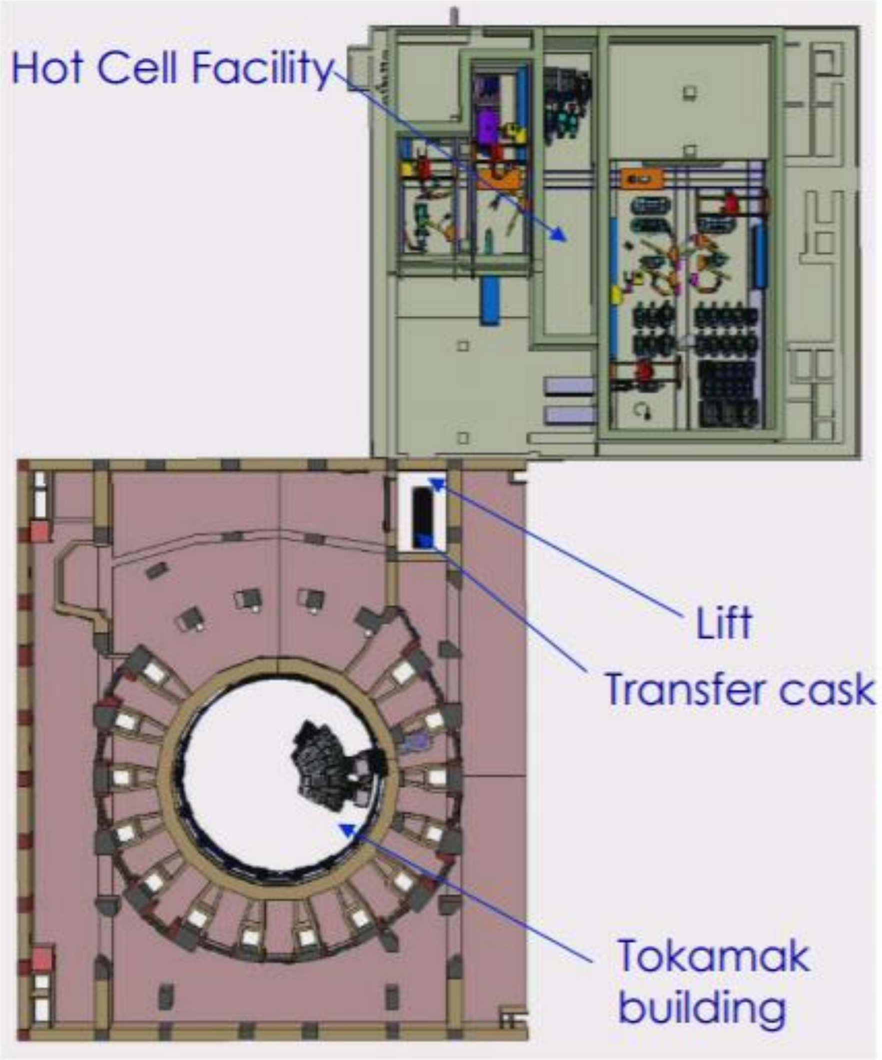


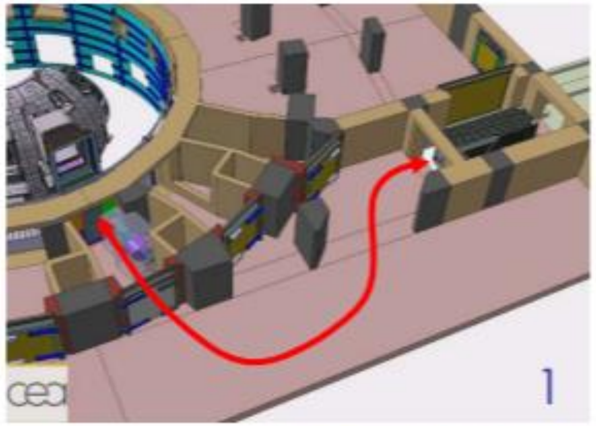
- Blanket RH (PBS 23-1)
- Divertor RH (PBS 23-2)
- Transfer Cask and Port Plug (PBS 23-3)
- In-Vessel Viewing System (PBS 23-4)
- Neutral Beam System RH (PBS 23-5)
- Hot Cell RH (PBS 23-6)
- RH Test Facility (PBS 23-9)
- Multi-Purpose Deployer (DCR-130)

ITER Remote Handling



ITER Remote Handling Processes

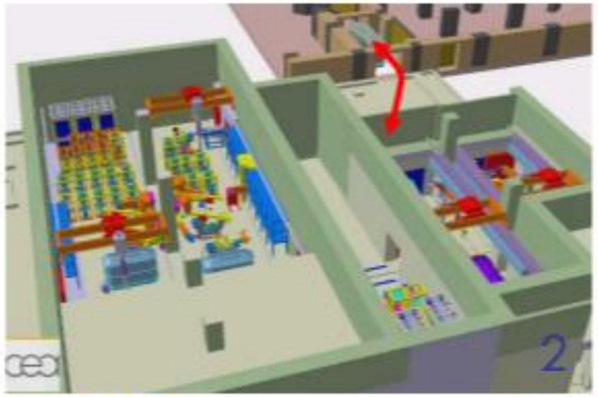




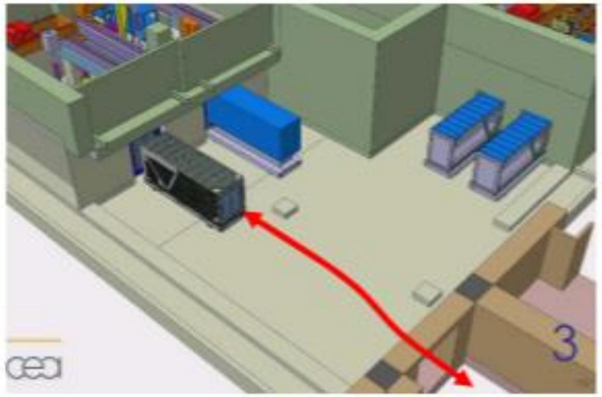
1a) Move TCS from lift to port plug

1b) Install or removal of Tokamak component

1c) Move back to lift



2) Lift up or down



3) Move from lift to HCF port

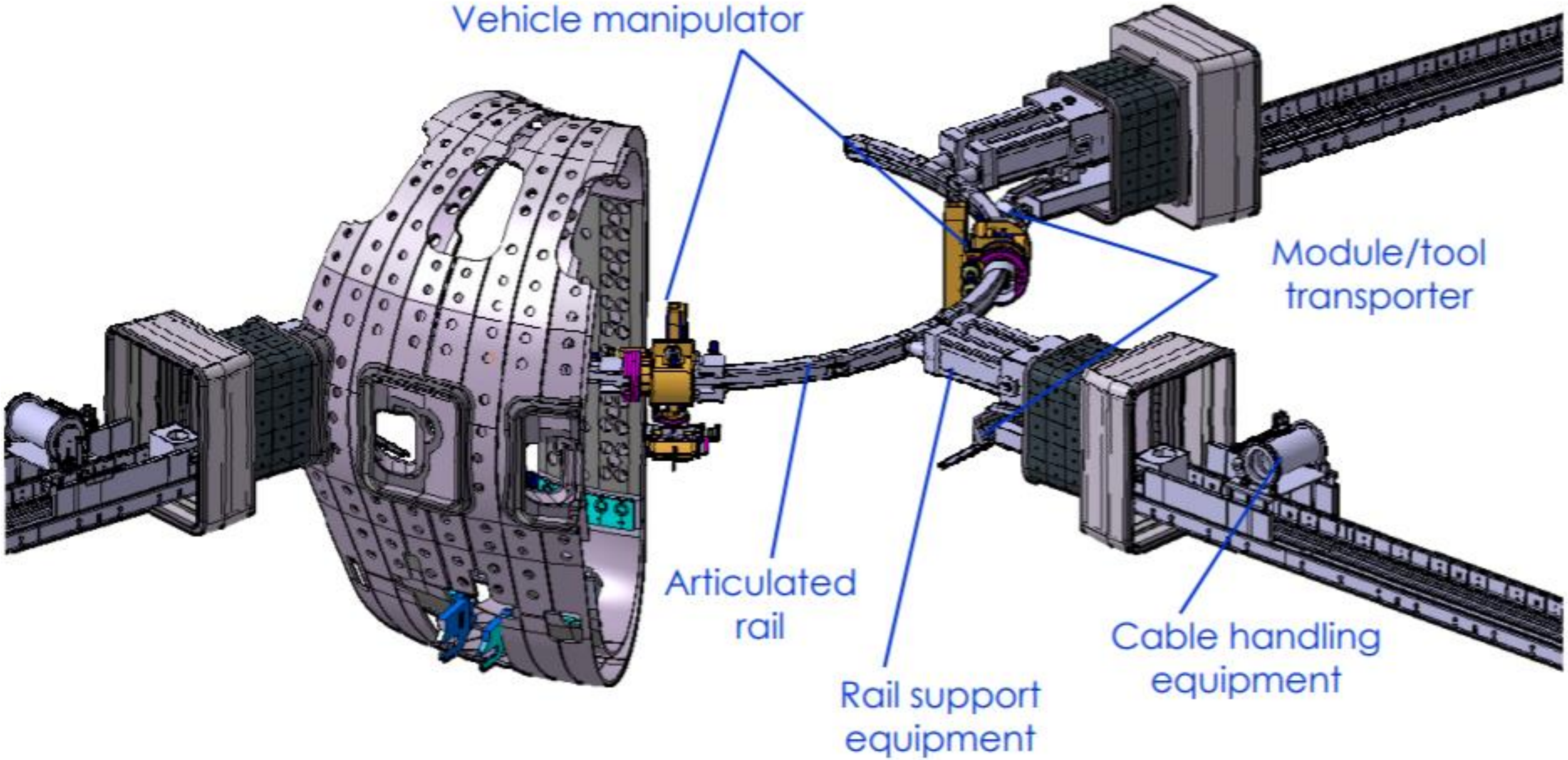
ITER Remote Handling Classifications

Class 1	Those components that require **scheduled remote maintenance** or replacement several times during the life of the machine.
Class 2	Those components that do not require scheduled remote maintenance but are likely to require **unscheduled** and very infrequent remote **maintenance**.
Class 3	Those components not expected to require remote maintenance during the life time of ITER, but **whose failure would prevent ITER operation**.
Unclassified	Those components that do **not require remote maintenance** either because: a) they are in a low or zero contamination / activation area and can be maintained hands-on. or b) their failure would not prevent ITER operation

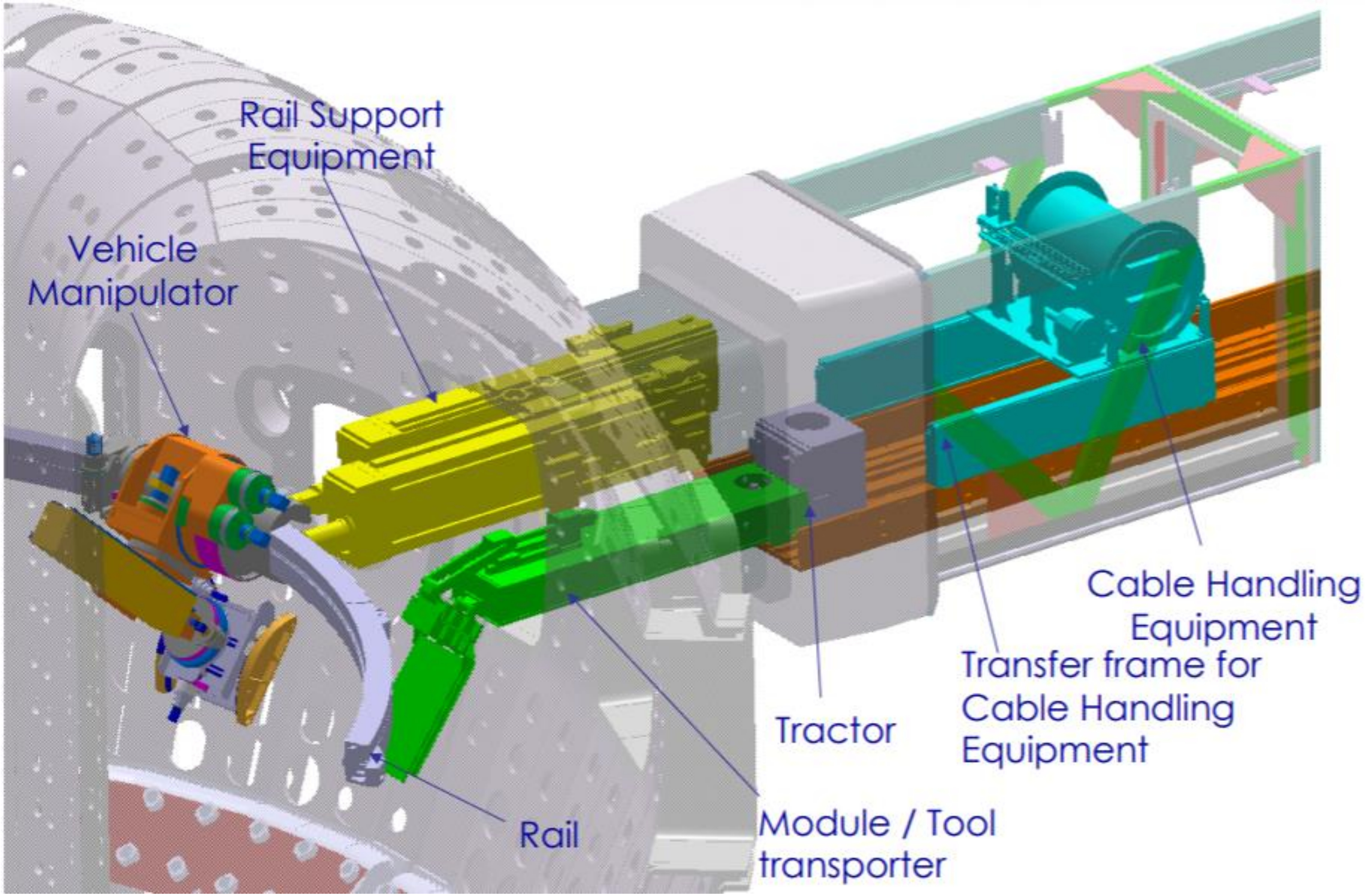
From ITER_D_27ZRW8 - Draft of Project Requirements (2008 Edition)

For more detail classification procedure, see
ITER_D_2FMAJY - ITER Remote Maintenance Management System (IRMMS)

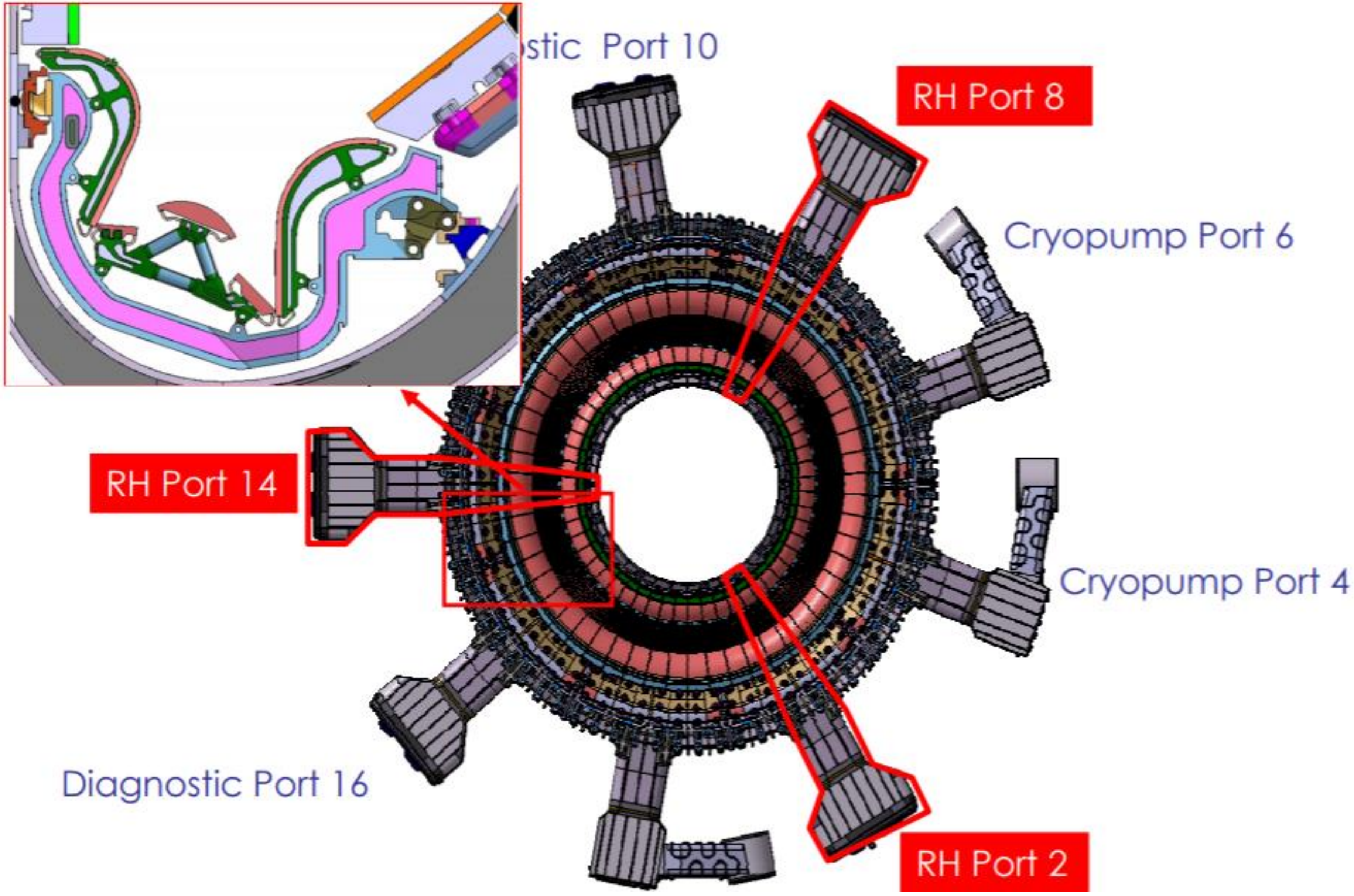
ITER Remote Handling Equipment



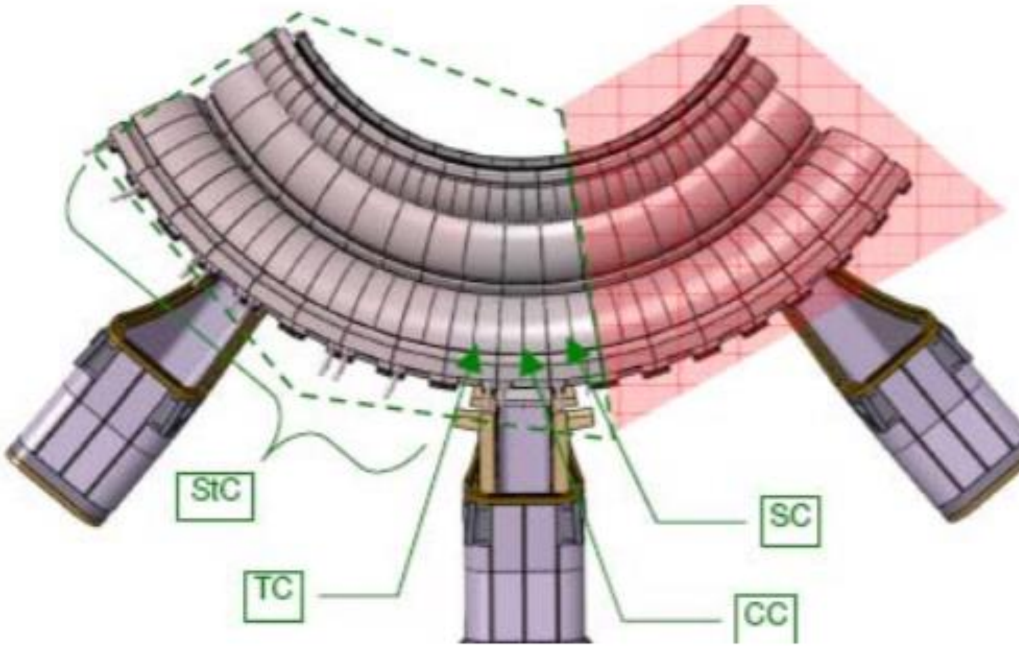
ITER Remote Handling Equipment

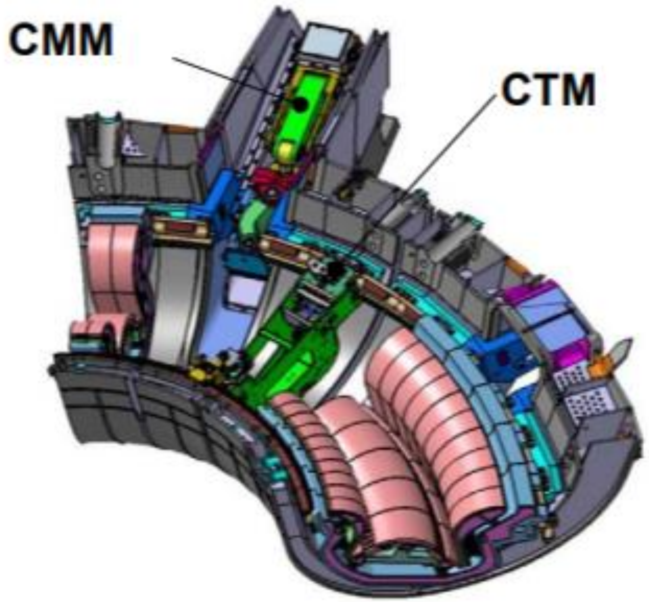


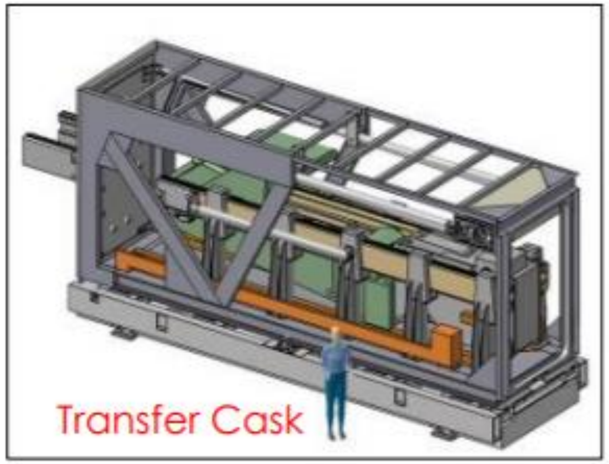
ITER Divertor Remote Handling Equipment

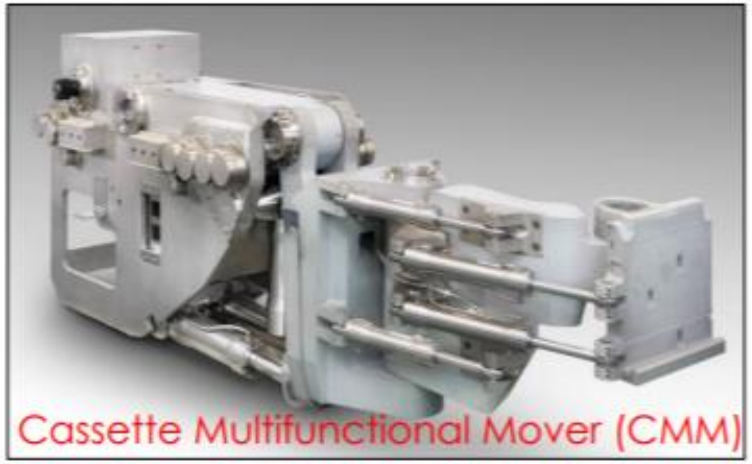


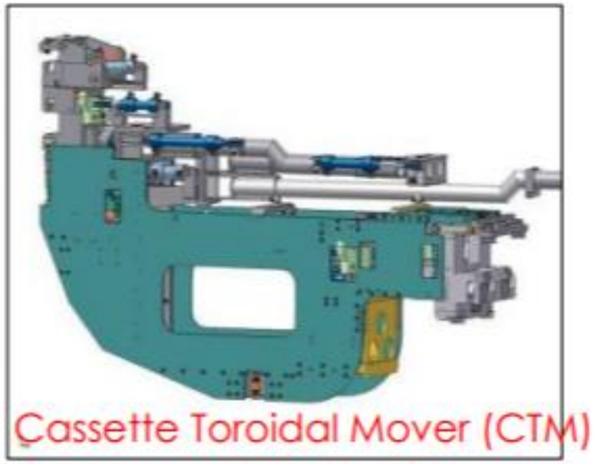
ITER Divertor Remote Handling Equipment



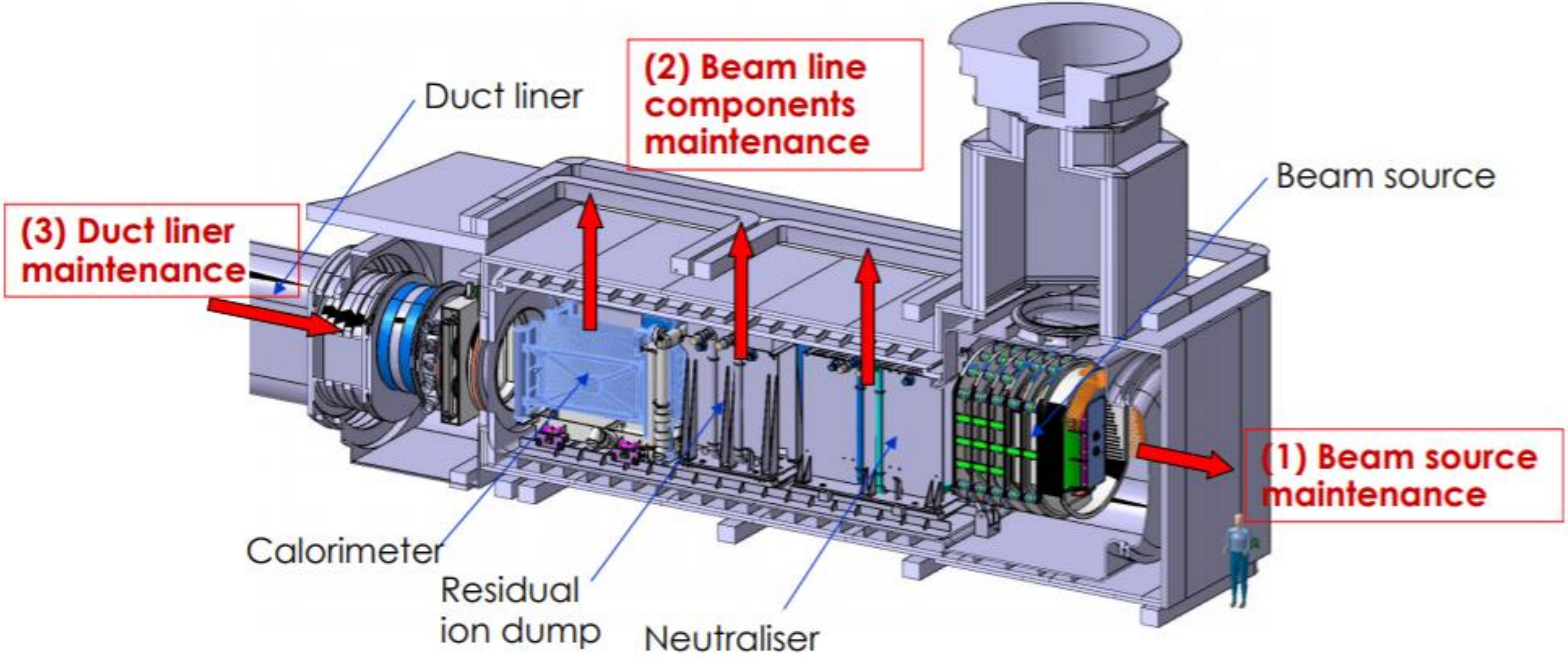








ITER NB Remote Handling System

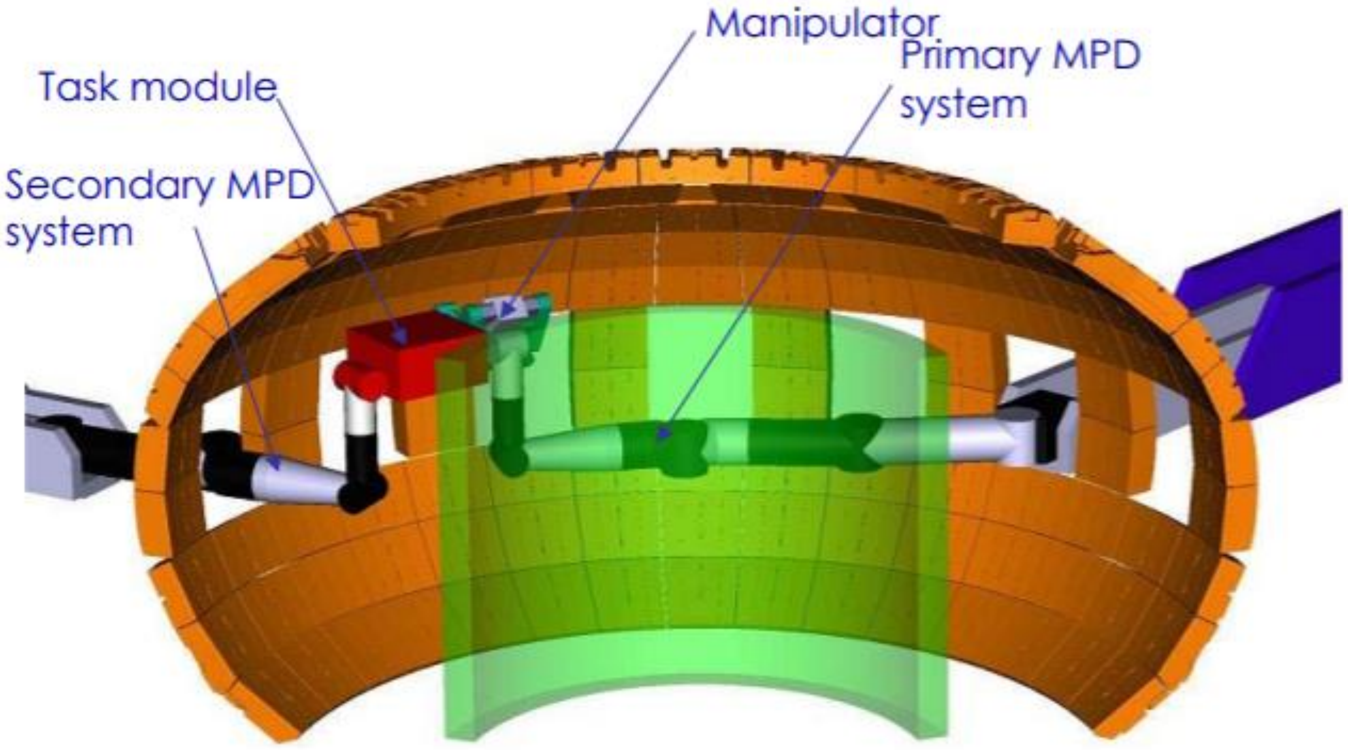


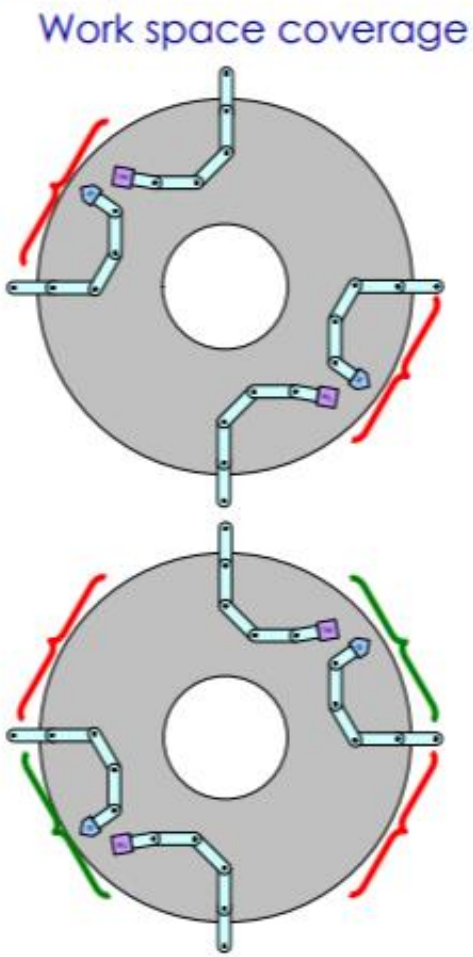
ITER In-Vessel Remote Handling Requirements

	Requirement	Activity	Expected Frequency of Operation	RH class
Mandatory	**Dust accumulation monitoring and removal**	Dust sampling Dust removal	16 months* 16 months*	1 1
	Tritium inventory monitoring	Tritium sampling Tritium removal	16 months* Main system is baking	1 2
	Vacuum vessel inspection	Periodic inspection Periodic requalification	every 40 months every 10 years	1 1
Defined at a certain extent	**Vacuum vessel leak identification**	Leak localisation	Expected few times in ITER operation	1
	In-Vessel diagnostics maintenance	Calibration, alignment, inspection, replacement, cleaning	16 months	TBD
Definition on going	• **VS and ELMs coils** • **Maintenance** • **NB Duct Liner Tile replacement** • **Rescue operation of the other RH systems**	Maintenance Assistance Rescue operation	TBD TBD	TBD TBD

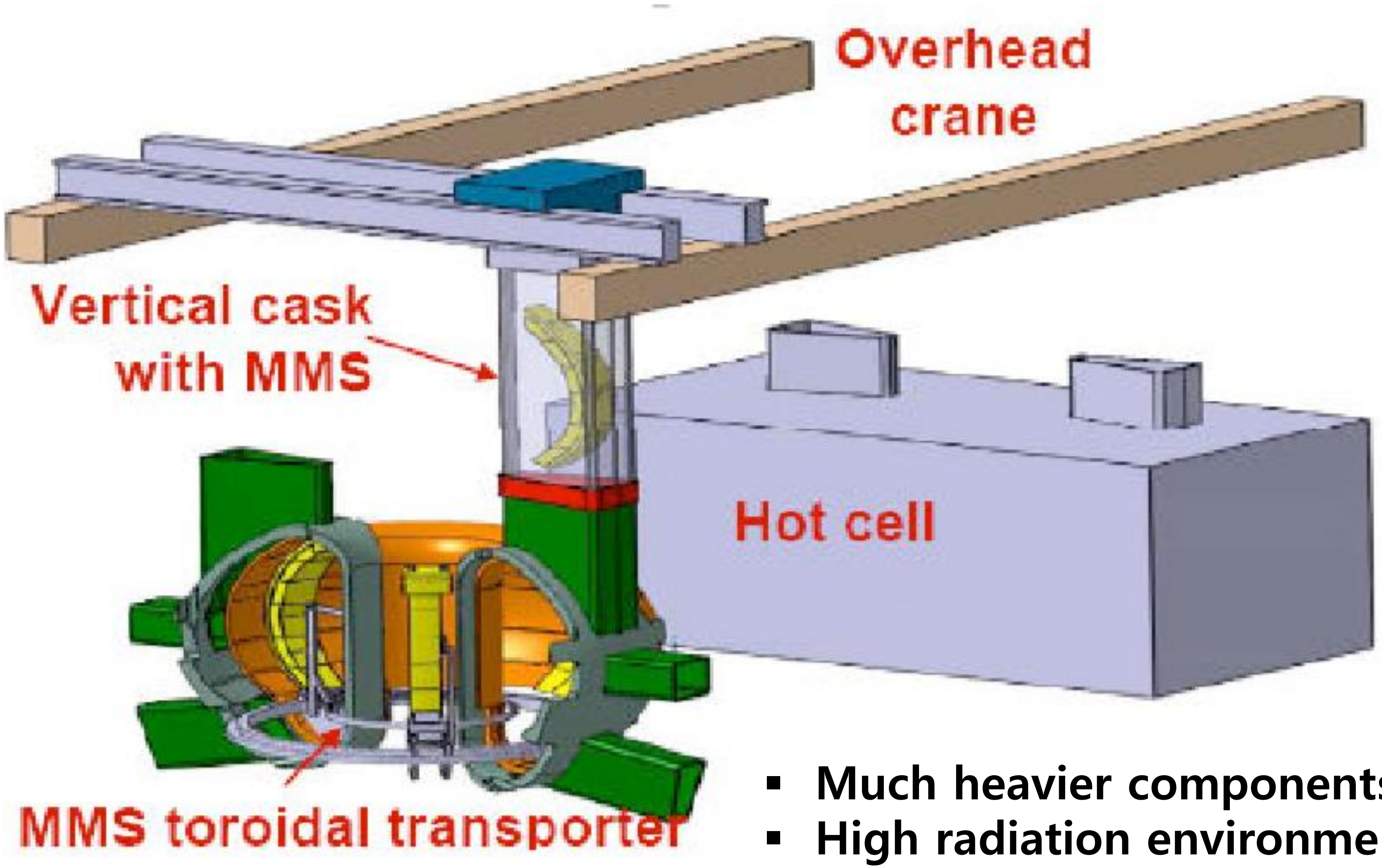
ITER Multi-Purpose Deployer (MPD) Operation Concept

- Operation of the MPD will require a number of tools which must be made available ideally at the manipulator work site for operation time efficiency.
- For this reason a second MPD is deployed with the concept Task Module mounted upon it.





DEMO Remote Handling



- Much heavier components (blanket segments 70-90 tonnes)
- High radiation environment
- Much stricter containment control
- Higher reliability/availability - lower turn-around time