Atomic and molecular data at ITER
- status and prospects

IAEA, Vienna, 19-21 December 2016

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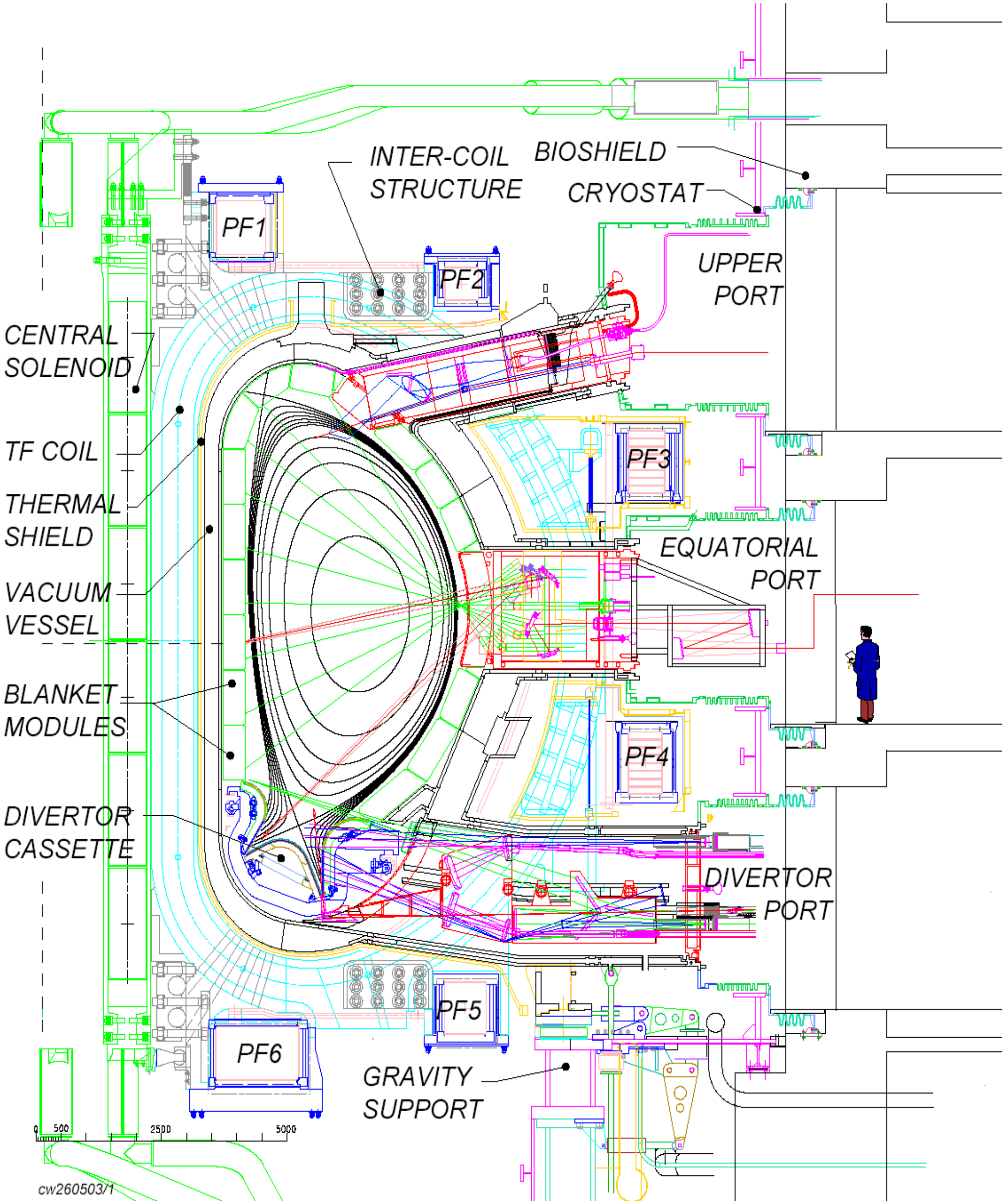
- Overview of ITER status
- A&M data for plasma-material interactions
-Plasma emission modelling for diagnostics

ITER (www.iter.org)



- Superconducting Tokamak
- Single-null divertor
- Elongated, triangular plasma
- Additional heating from RF, ECH, and negative-ion neutral-beams

R (m)	**6.2**
a (m)	**2**
V_P (m^3)	**850**
I_P (MA)	**15(17)**
B_t (T)	**5.3**
δ,κ	**1.85, 0.5**
P_{aux} (MW)	**40-90**
P_α (MW)	**80+**
Q (P_{fus}/P_{in})	**10**
Pfus(MW)	**500**

china eu india japan korea russia usa

Worksite progress

400 kV switchyard

Preparatory works
Magnet Conversion Power

Contractors area

ITER IO Headquarters

Tokamak Complex
Construction underway

Transformers

Assembly Hall
Being equipped

Preparatory works
Control building

Construction underway
Chauffage RF

PF Coil winding facility

Being equipped
Bâtiment servitudes

Construction underway
Cooling water system

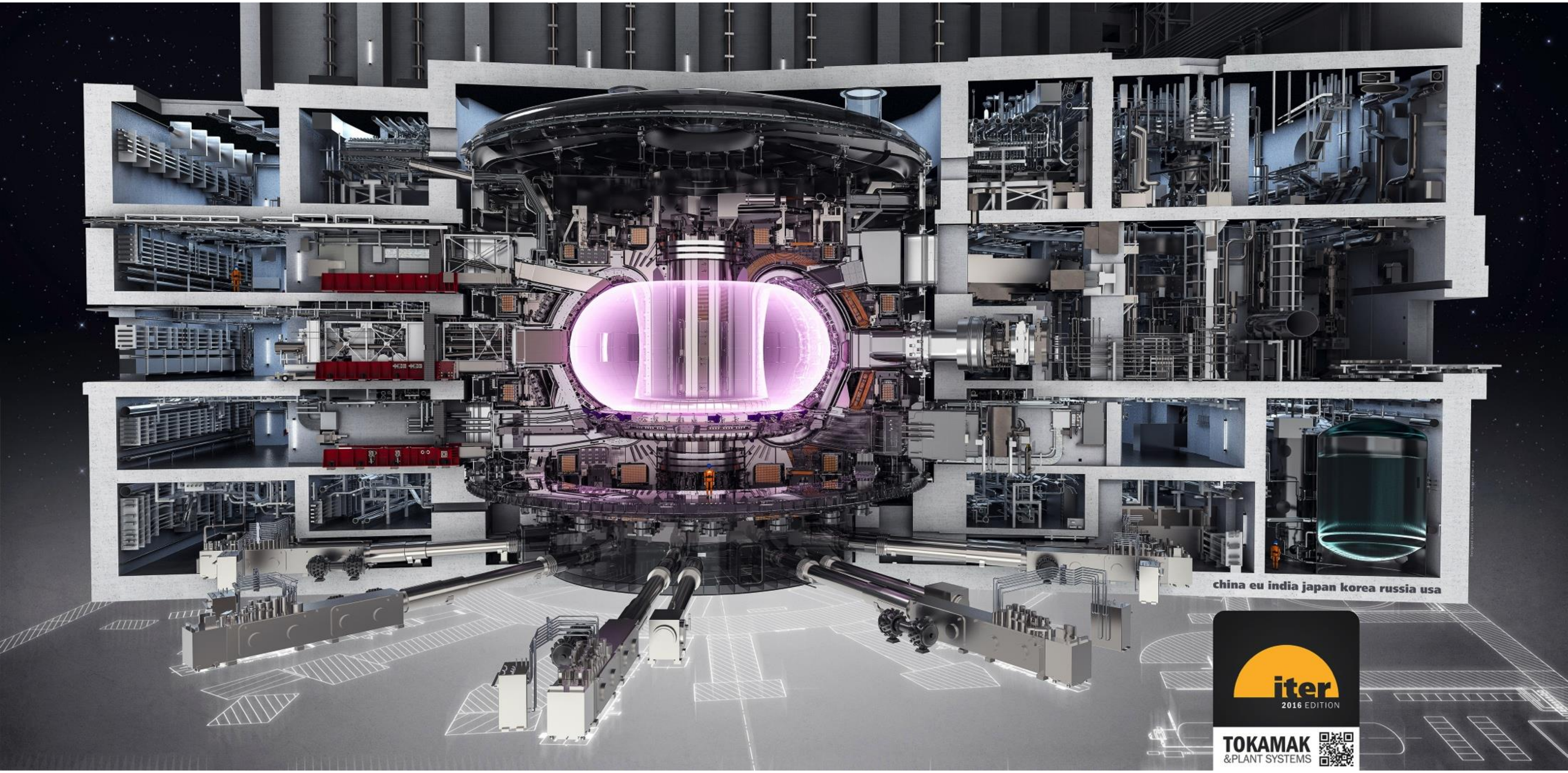
Cryostat workshop

Construction underway
Cryoplant

Construction underway
Cleaning facility

(October 2016)

Tokamak Building



A cutaway of the Tokamak Building, which is the major element of the Tokamak Complex (which also includes the Diagnostics Buildlng and the Tritium Building)

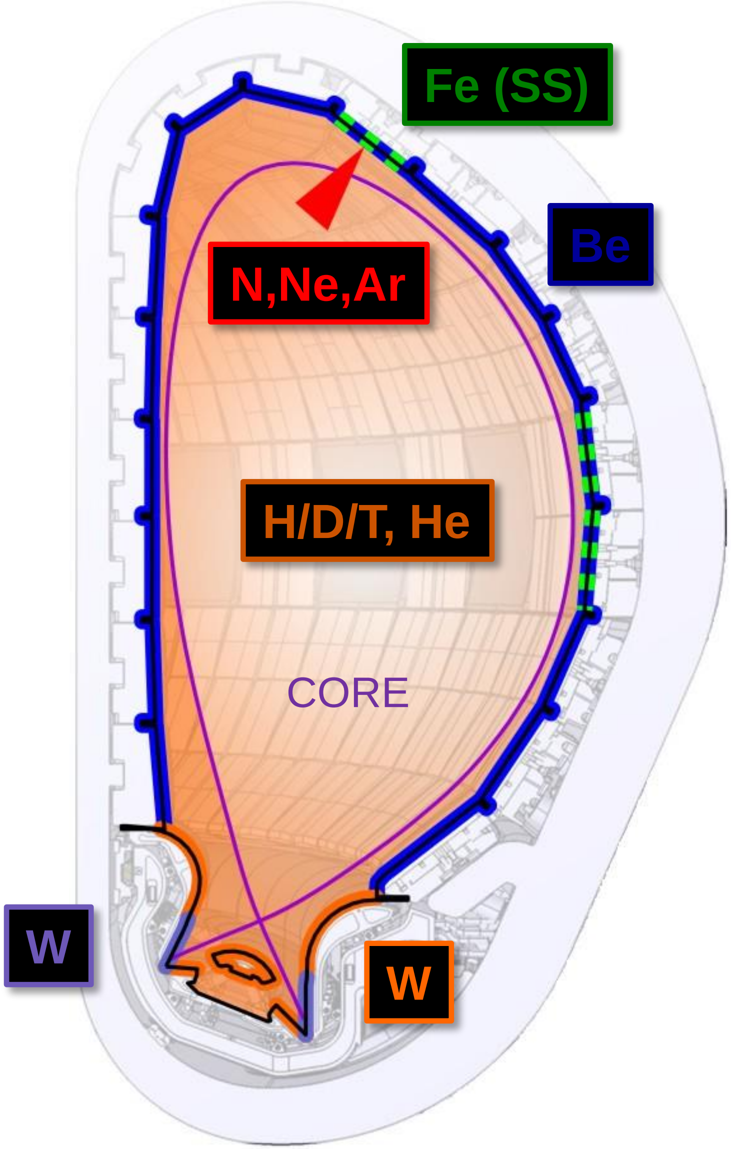
PF Coil winding facility

Too large to be transported by road, four of ITER’s six ring-shaped magnets (the poloidal field coils, 8 to 24 m in diameter) will be assembled by the EU in this 12,000 m² facility. Fabrication of a dummy for PF Coil # 5 (17 m. in diameter) is ongoing.

ITER Operation Stages

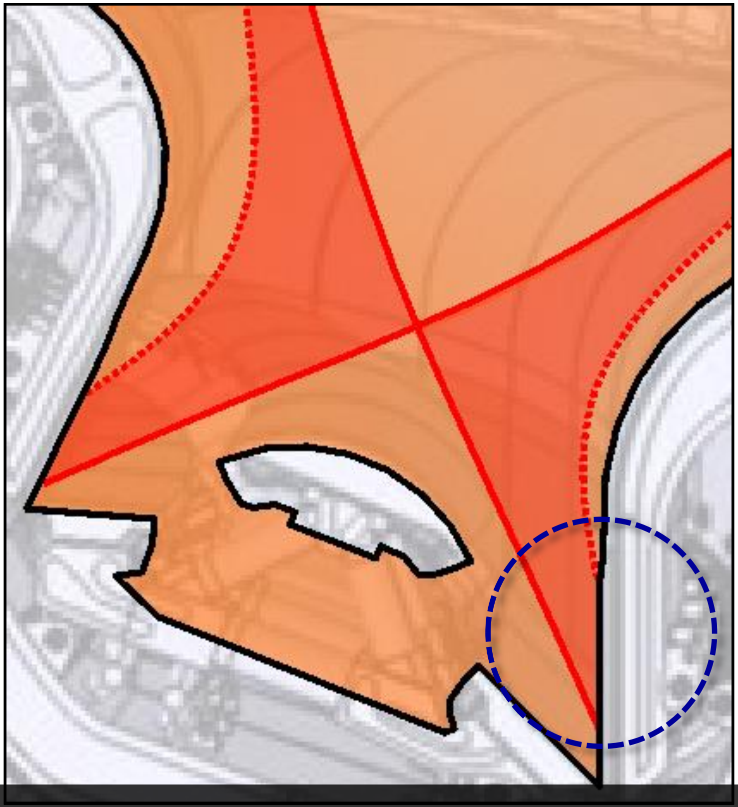
	Operation Stages	Target Performance
1	**First Plasma** (followed by Engineering Operation)	• Nominally 100 kA / 100 ms • Up to 1 MA / 3 sec during Engineering Operation (option) (8 MW ECRH)
2	**Pre-Fusion Power Operation 1** (non-active H/He)	• Up to 7.5 MA operation (20 MW ECRH)
3	**Pre-Fusion Power Operation 2** (non-active H/He)	• Up to 7.5 MA H-mode operation and 15 MA L-mode operation (73 MW H&CD)
4	**Fusion Power Operation** (nuclear D/DT)	• 15 MA DT-operation

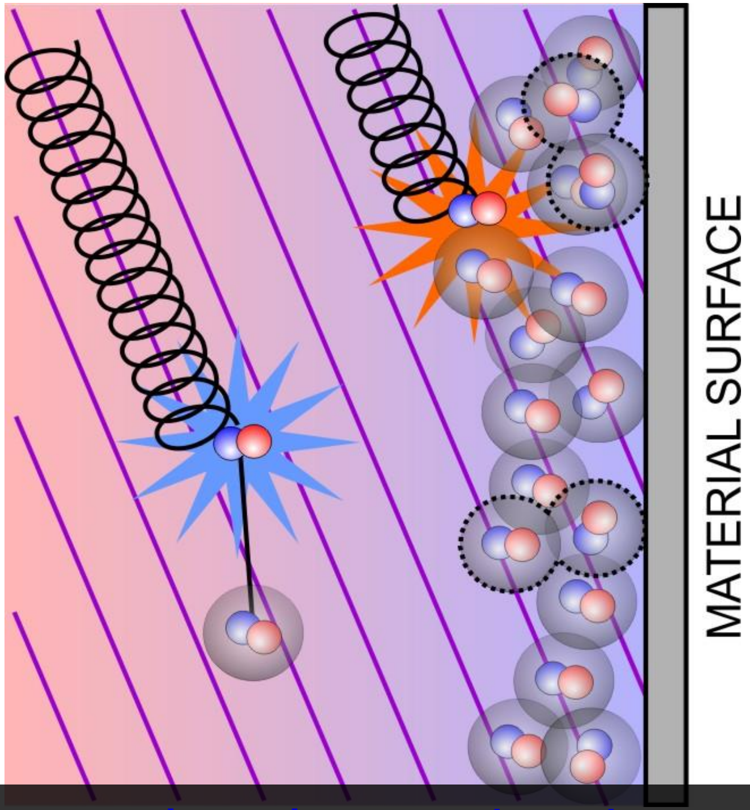
The main elements relevant to the ITER plasma



Plasma “detachment” in the divertor: “gas target”

- Need to radiate ~75% of the plasma energy entering the boundary in order to reduce the divertor heat loads: N, Ne, and/or Ar injected to increase radiation

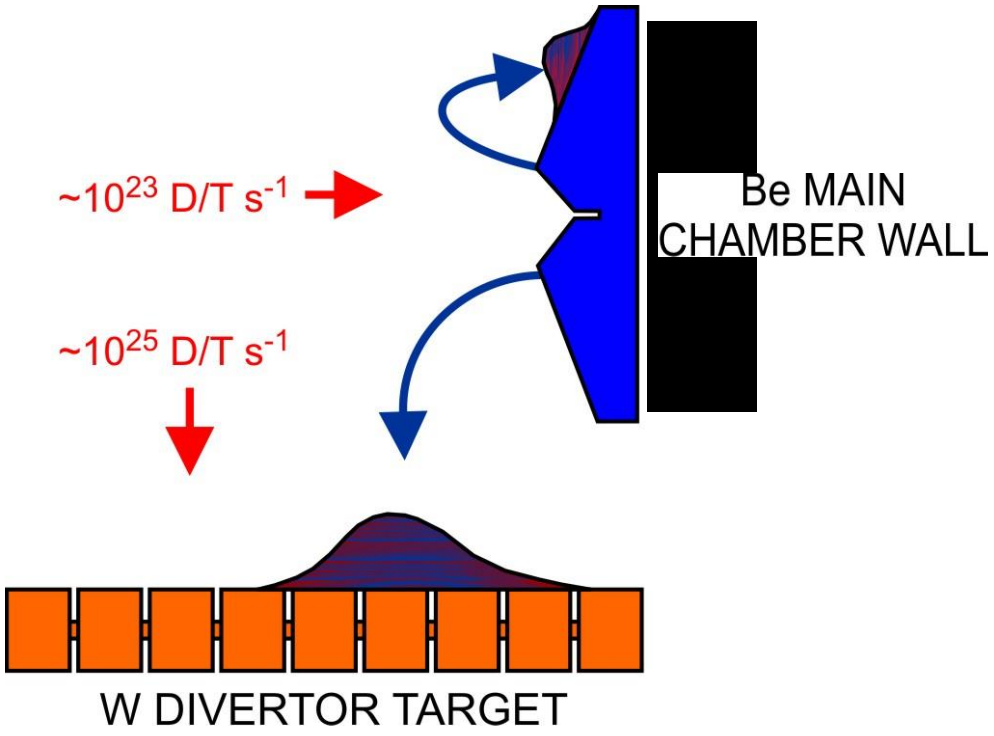




- Low temperature plasma (< 5 eV) → complex plasma chemistry
  - high neutral particle densities, molecular effects, strong radiation

Material migration places new demands on PMI data

- High wall fluence results in extensive material erosion and re-deposition



- Surface morphology and composition: material mixing, alloying, surface layers → effect on sputtering rates, ion / neutral particle reflection coefficients, dust / flake production, etc.
- Retention of tritium fuel in the wall – big issue!

Boundary plasma transport codes need A/M/PMI data

- Applications:
  - Engineering design support: plasma-facing components and diagnostics
  - Operational scenario planning, i.e. plasma pulse design
  - Interpretation of experimental data, i.e. transport model validation

- Types of codes:
  - Fluid or fluid/kinetic (SOLPS, SONIC, EIRENE, etc.) → Rate coefficients
  - Fully kinetic codes (BIT-1, BIT-N, etc.) → Differential cross-sections

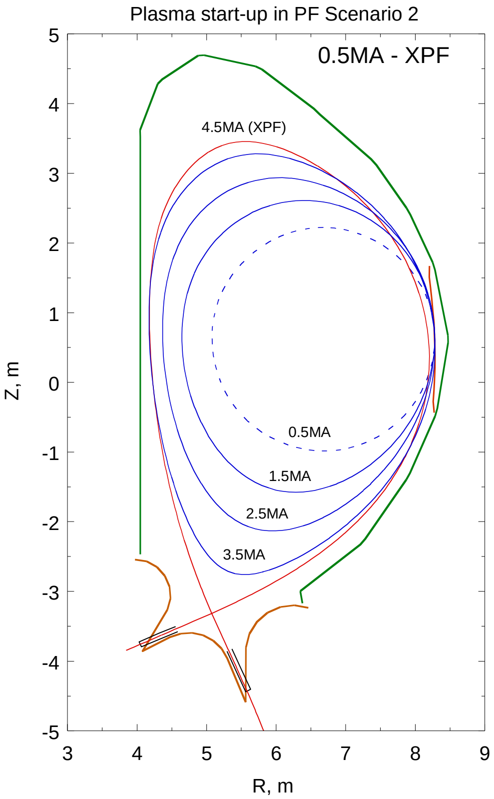
- Full range of P/M/PMI data is of interest: excitation, recombination, charge-exchange, electron cooling, momentum transfer, vibrational excitation, molecular break-up, sputtering, reflection, implantation, fuel retention, etc.

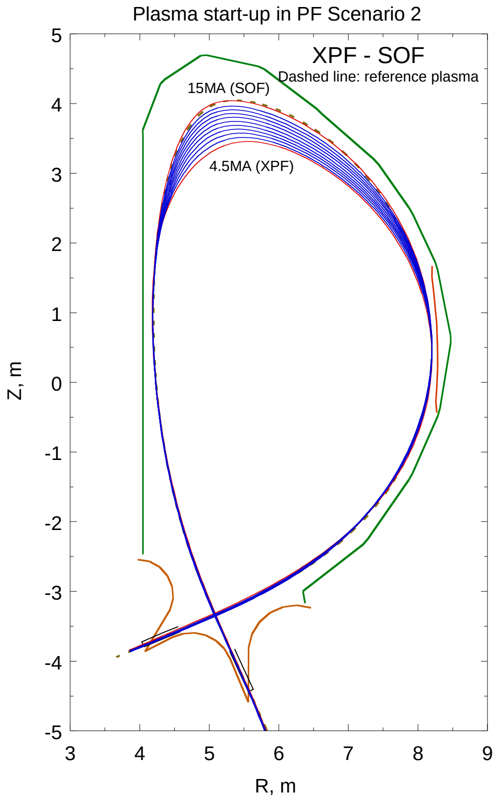
- Typically, the codes are generalized and can handle an arbitrary number of processes, including meta-stables, vibrational excitation of molecules (explicit), and complex molecule reaction chains (hydrocarbons)

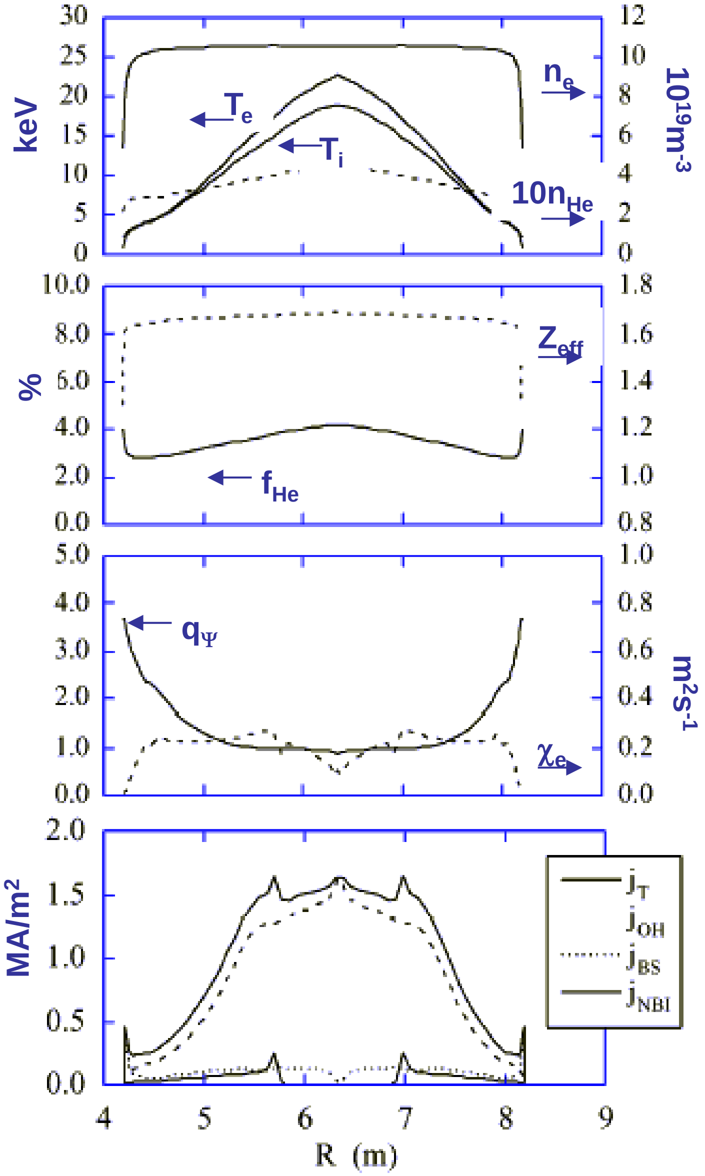
Project Requirement on Diagnostics is for **Measurements**

A Q=10 scenario with (ELMy H-mode):

I_p=15MA, P_{aux}=40MW, $H_{98(y,2)}$=1

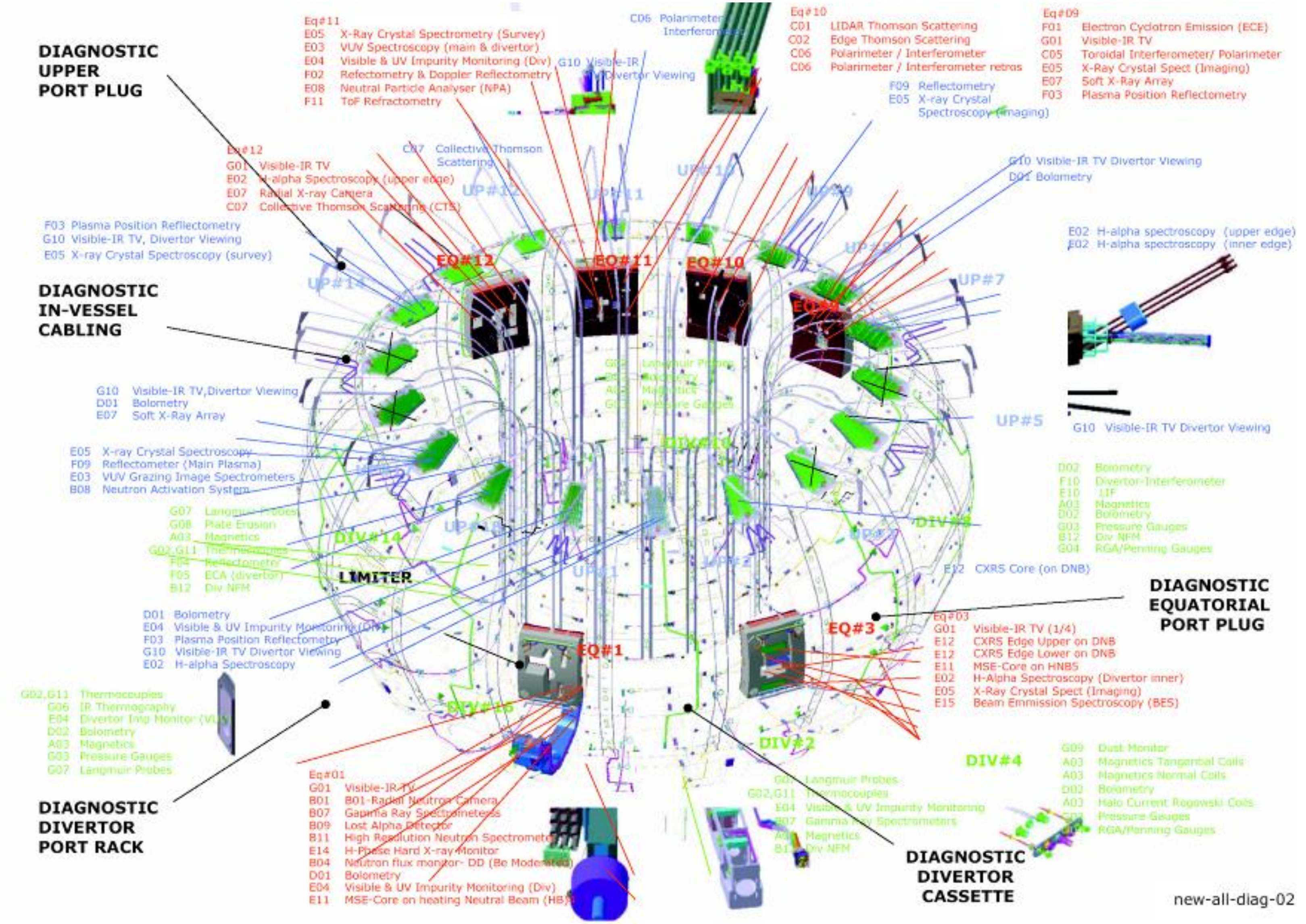




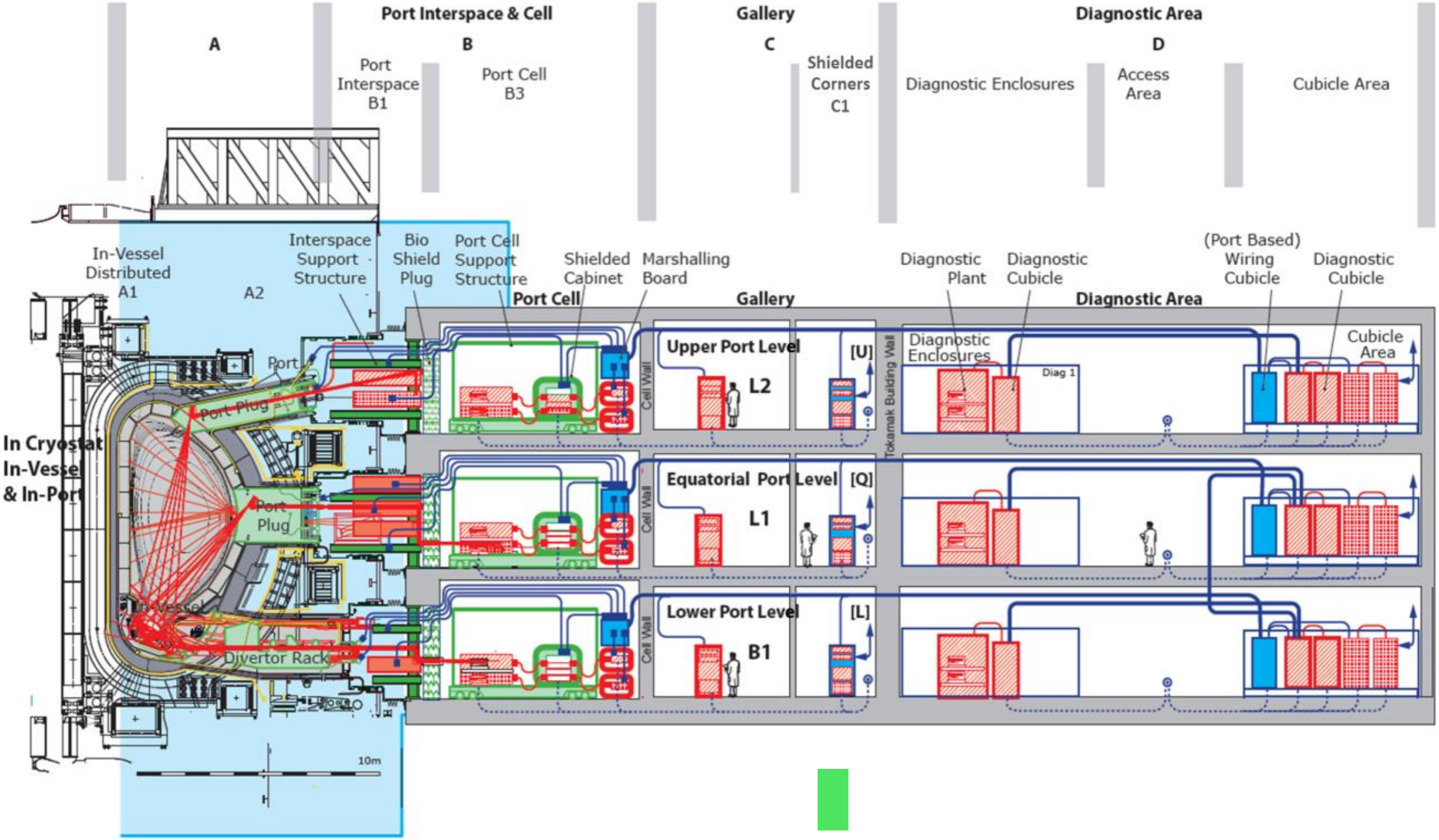


Current Ramp-up Phase

Diagnostics are highly integrated



High priority in Dec 2016 – Cabling specifications



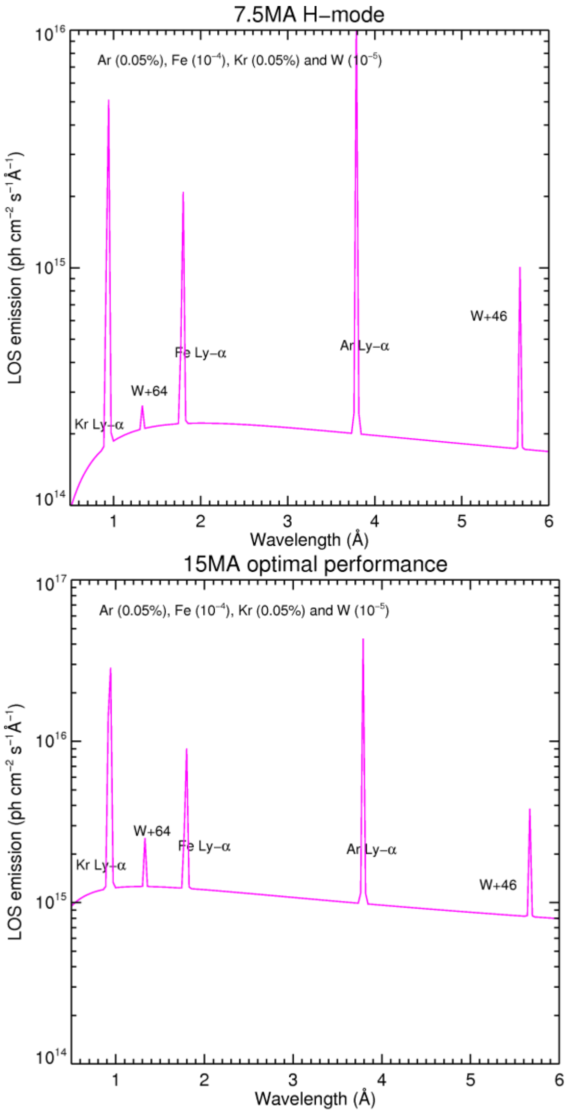
PBS	**System**	**Range**	**Function**	PA	**Status**
55E4	Divertor imp monitor	200 – 1000 nm	Impurity species and influx, divertor He density, ionisation front position, T_i.	Yes	PDR prep
55E2	Ha system	Visible region	ELMs, L/H mode indicator, n_T/n_D and n_H/n_D at edge and in divertor.	Yes	PDR prep
55E3	VUV spectr. – main	2.3 – 160 nm	Impurity species identification.	Yes	PDR held
55EG	VUV spectr. – divertor	15 – 40 nm	Divertor impurity influxes, particularly Tungsten	Yes	PDR held
55EH	VUV spectr. – edge	15 - 40 nm	Edge impurity profiles	Yes	PDR held
55ED	X-ray spectr. – survey	0.1 – 10 nm	Impurity species identification	Yes	PDR prep
55EI	X-ray spectr. – edge	0.4 – 0.6 nm	Impurity species identification, plasma rotation, T_i.	Yes	PDR prep
55E5	X-ray spectr.-core	0.1 – 0.5 nm		Yes	PDR prep
55E7	Radial x-ray camera	1 – 200 keV	MHD, Impurity influxes, Te	Yes	PDR held
55E	Hard X-ray Monitor	100keV – 20MeV	Runaway electron detection	**IO**	**PDR Dec 2016**
55EB	MSE	Visible region	q (r), internal magnetic structure	Yes	PDR prep
55E1	Core CXRS	Visible region	T_i (r), He ash density, impurity density profile, plasma rotation, alphas.	No	CDR held
55EC	Edge CXRS	Visible region		Yes	PDR prep
55EF	Pedestal CXRS	Visible region	View optimized for edge pedestal	No	CDR
55E8	NPA	0.01- 4 MeV	n_T/n_D and n_H/n_D at edge and core. Fast alphas.	Yes	PDR closed
55EA	LIF	Visible	Divertor neutrals	No	Pre- CDR held

Plasma emission modelling

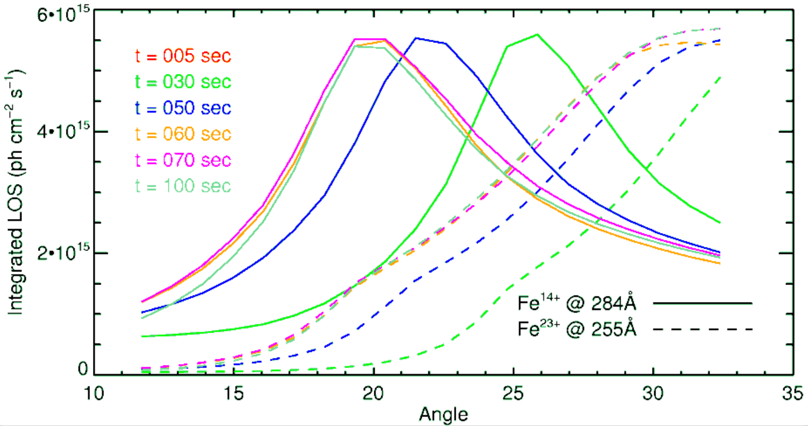
- Impurity emission modelling is essential input to designs – sets requirements for instrument:
  - Sensitivity
  - Spectral range and resolution
  - Field of view and spatial resolution
- Atomic data from ADAS – Atomic Data and Analysis Structure (open.adas.ac.uk).
- Plasma emission modelling with SANCO impurity transport code
- Continuously refined and expanded
  - Wide range of plasma scenarios
  - Wide range of impurities
  - Impurity radiated power – line and continuum
  - Input to all spectroscopy designs
  - Input to Bolometry design

Emission modelling for passive spectroscopy, SXR and bolometry

- Variety of plasma scenarios modelled – pre-fusion and high performance phases.
- Whole plasma lifetime simulations.
- Mixture of intrinsic and introduced impurities.
- Sensitivity analysis to transport.
- Energy-resolved radiated power predictions to high energies, up to HXR region.
- Core and edge (divertor+SOL) contribution to total radiation assessed.
- New fundamental atomic data calculations for diagnostic lines and DR processes.



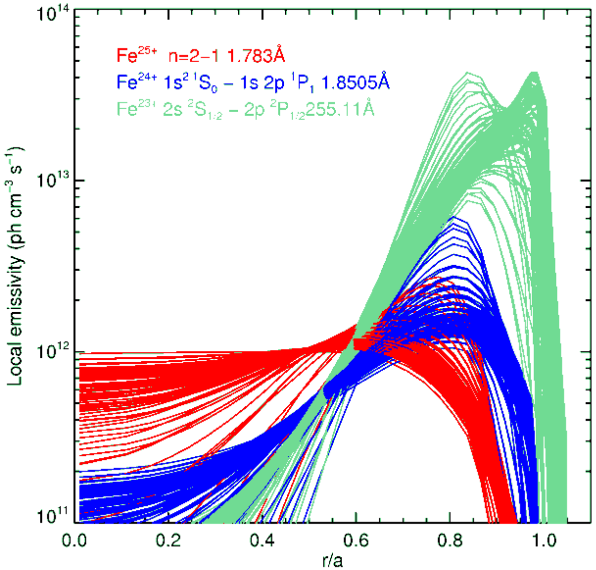
X-ray line of sight integrated spectra for different scenarios



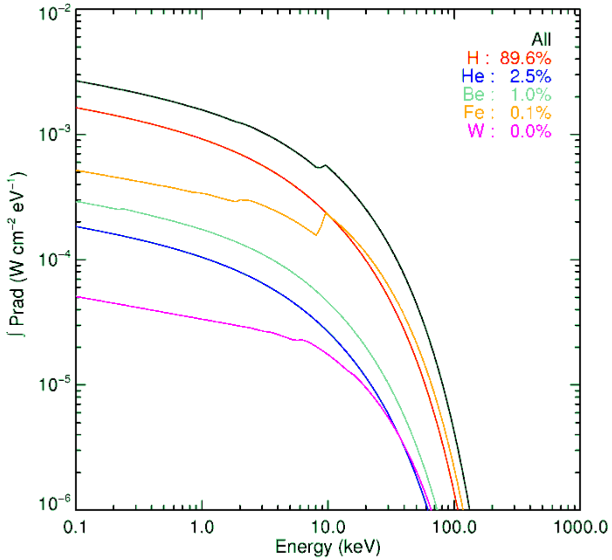
VUV upper port view of evolving Fe LOS emission

Emission modelling for passive spectroscopy, SXR and bolometry

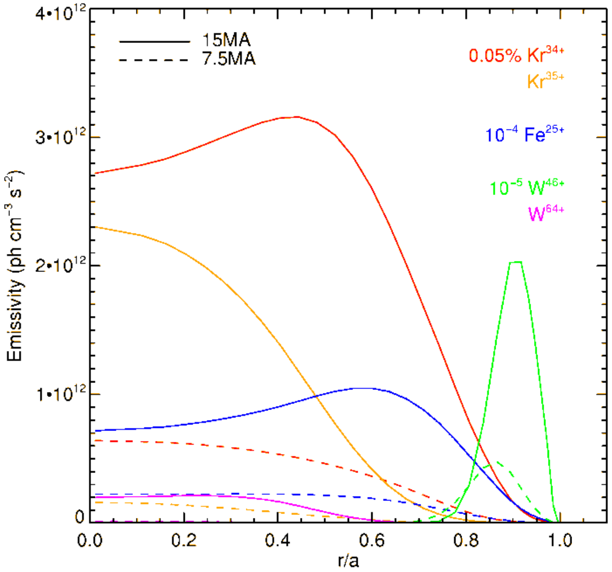
Sensitivity of X-ray lines to transport



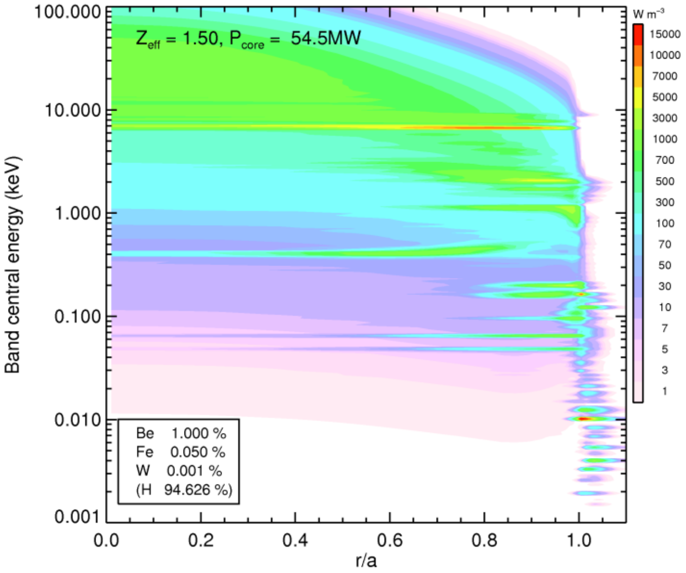
Line of sight SXR emission



Intrinsic vs introduced impurities in different scenarios

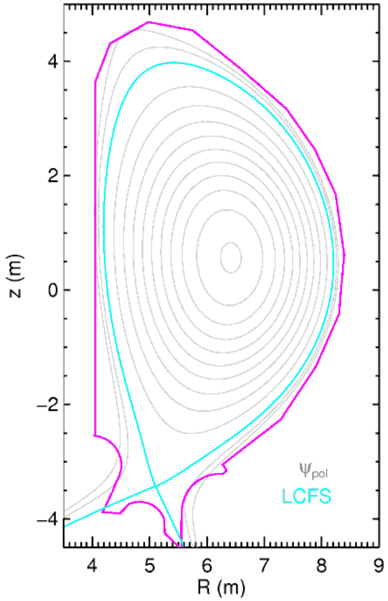


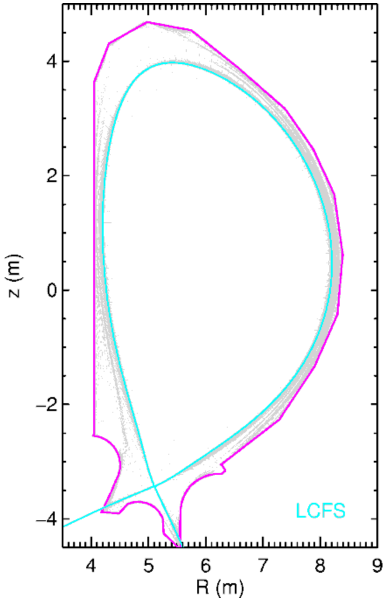
Total radiated power

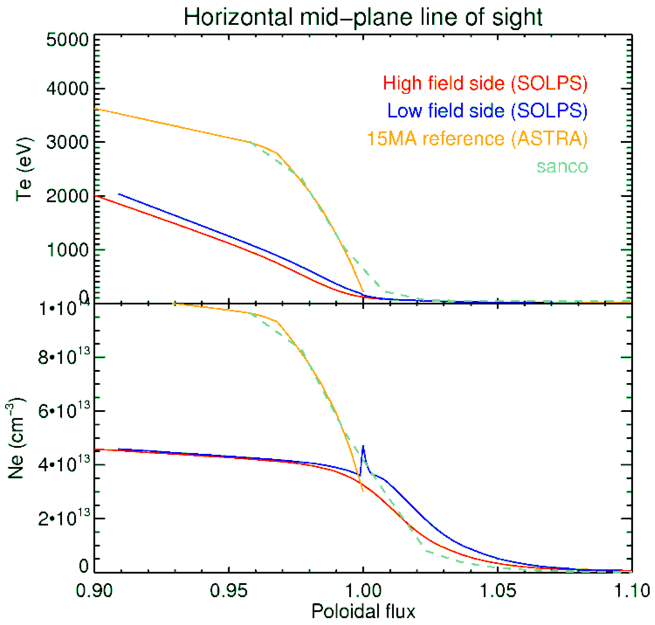


Emission modelling for passive spectroscopy, SXR and bolometry

- Total radiated power (MW) for core and divertor/edge regions
- Simulation domains are similar but not completely self-consistent

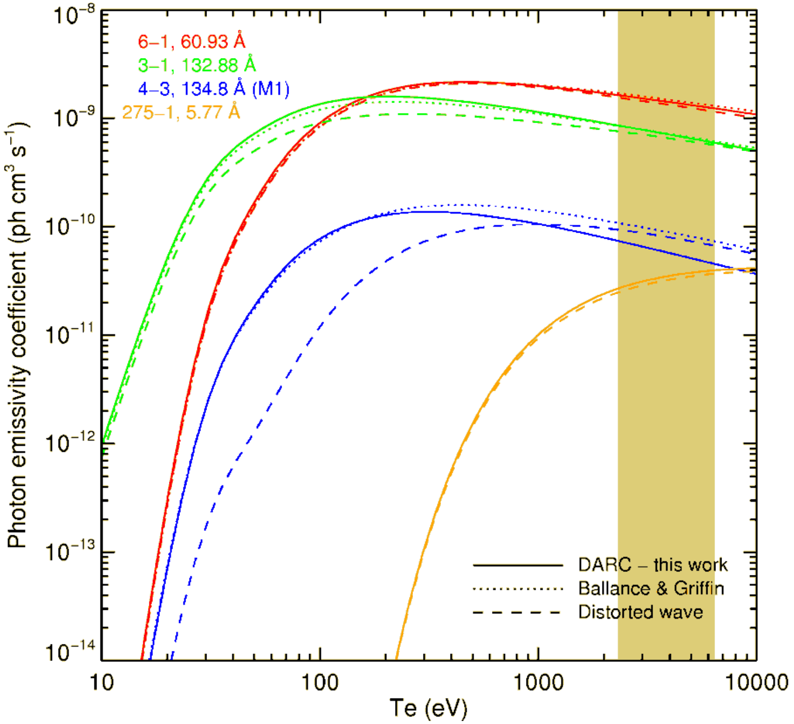


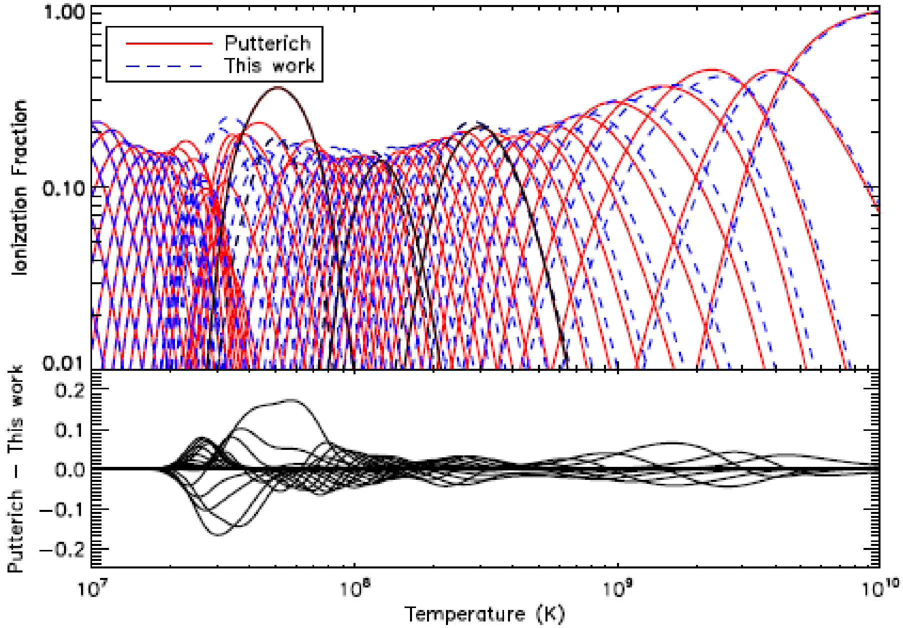




		SANCO		SOLPS	
Elem.	conc.	core	SOL	outside LCFS	inside LCFS
H	100.0	15.70	1.75	6.76	0.159
He	2.0	1.15	0.26	0.31	0.013
Be	2.0	8.57	2.07	3.64	0.144
Ne	0.1	2.68	0.08	0.68	0.25
Ar	0.1	18.73	3.31	2.16	1.58
W	0.001	8.58	0.0078	0.49	0.95

Emission modelling for passive spectroscopy, SXR and bolometry

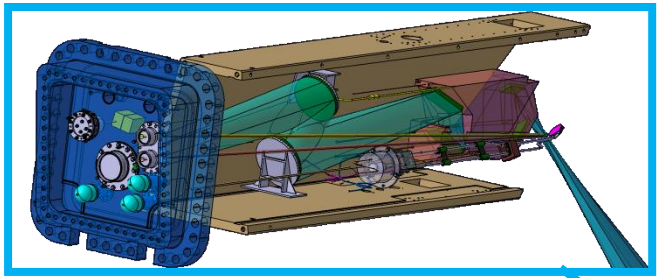


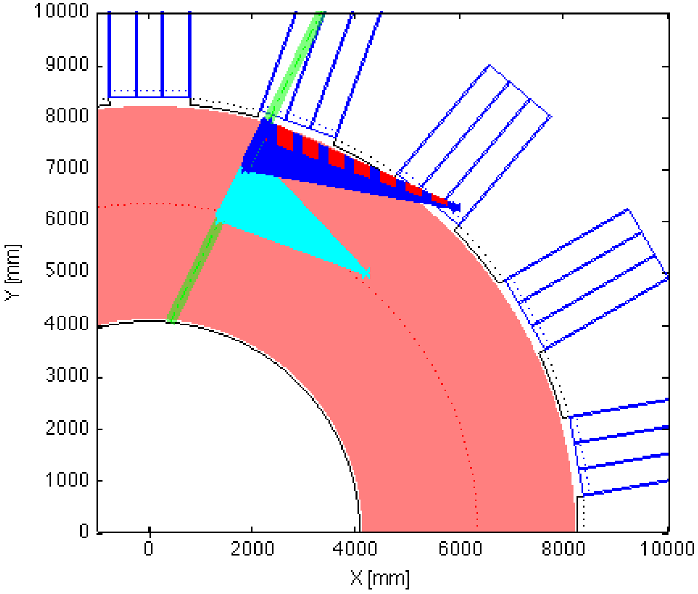


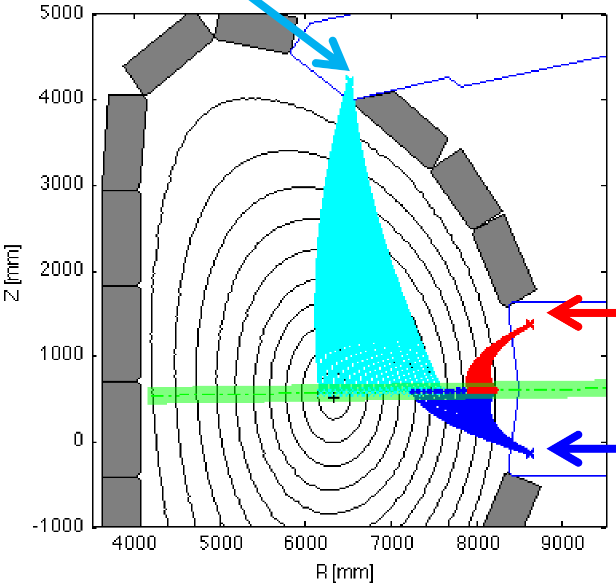
- Emission modelling for ITER instrument design highlighted missing fundamental data.
- W44+ data calculated as result of survey X-ray instrument scoping (5.77A line identified as an important radator).
  - Bluteau et al, J Phys. B, 48 (2015) 195701
- Influence of new dielectronic recombination data on tungsten ionisation balance.
  - Preval et al, Phys. Rev. A, 93 (2016) 042703 + article in press
- All data produced for ITER diagnostic evaluation will be included in ADAS and OPEN-ADAS.

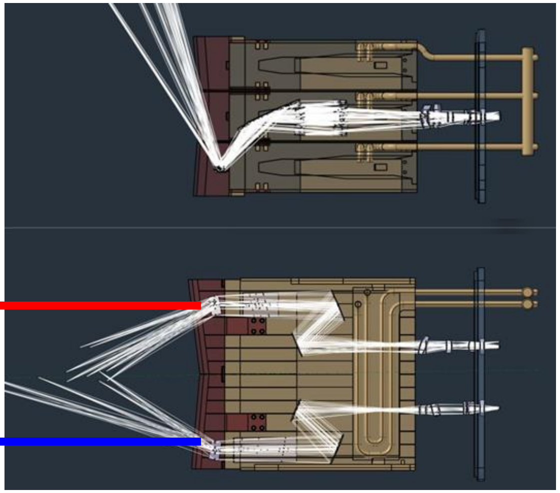
CXRS systems on ITER

	r/a < 0.6 – 0.7	r/a > 0.5	r/a > 0.85
Name	**CXRS-core**	**CXRS-edge**	**CXRS-pedestal**
Spatial resolution	**a/30**	**a/30 – a/100**	**a/100**









CXRS: Requests on atomic data modelling

- Accuracy CXRS measurements relies on:
  - Photon statistics
  - Absolute calibration
  - Atomic data cross sections

$$I_Z = \frac{C_Z n_Z < \sigma v >_Z}{4\pi} \int_{\mathbf{l.o.s}} ds\, n_B$$

$$I_{BES} = \frac{C_{BES} n_e < \sigma v >_{BES}}{4\pi} \int_{\mathbf{l.o.s}} ds\, n_B$$

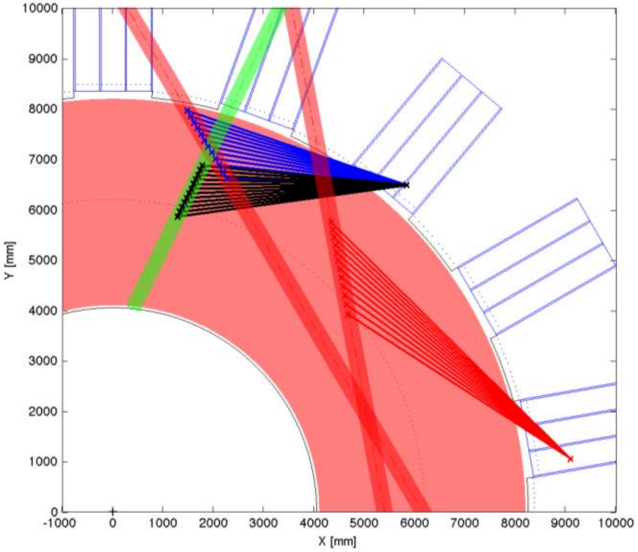
- Photon statistics optimized by design
- Absolute calibration simplified to relative calibration by ratio CXRS and Beam Emission Spectroscopy (BES)

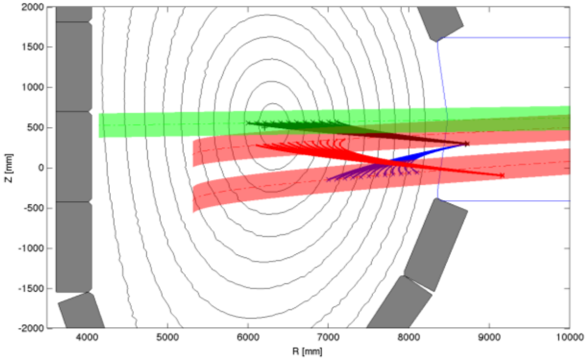
$$\frac{n_Z}{n_e} = \frac{C_{BES}}{C_Z} \frac{< \sigma v >_{BES}}{< \sigma v >_Z} \frac{I_Z}{I_{BES}}$$

- **Errorbars on atomic data cross sections requested**

MSE systems on ITER

- MSE views:
  - EPP3: off-axis, edge view on HNB2
    ⬄ ‘always’ edge q and high signal
    AND on-axis, core view on DNB
    ⬄ ‘always’ core q, but low signal
  - EPP1: on-axis, core view on HNB1
    ⬄ core q, high signal, but only available when HNB1 is on-axis





MSE: Requests on atomic data modelling

- MSE-LP polarization measurement is affected by Paschen-Back effect

  Check of following requested:
  - Coupling Stark-Effect and Paschen-Back effect
  - Result on polarization state (Stokes vector)

- MSE-LR intensity ratio measurement is affected by the population distribution on the upper Stark levels

  (Check of) modelling upper level population as function of density, field …. including accuracy requested

Summary

- Current need for edge modelling is improved recombination data for Ne

- The atomic data we need for most of the elements in ITER is known 'well enough' to design diagnostics and develop operating scenarios.

- ITER gave an impetuous to work on tungsten. Not all atomic data for this element are available at a quality/precision required yet but should be available well before ITER's first plasma.

- Beam-aided measurements rely on accuracy of atomic data

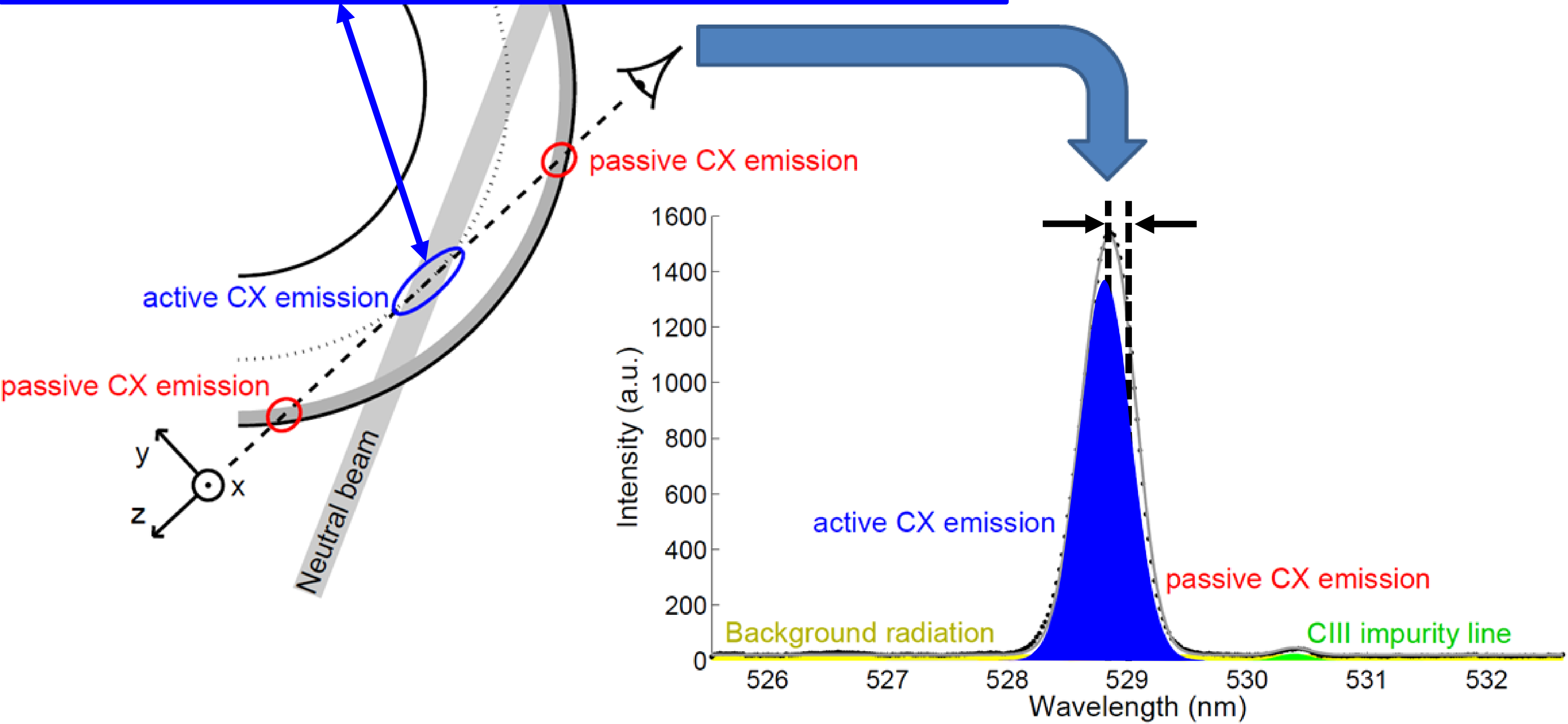
- Key long-term needs ~30 years
  - Expansion of data and improved accuracy
  - Management/curation of existing data
  - Continuity of expertise

The ITER construction site - December 2016

Back-up slides

CXRS: The principle

$$\boldsymbol{H_{DNB} + X^{+Z} \Rightarrow H^{+}_{DNB} + \left(X^{+Z-1}\right)^{*} \Rightarrow H^{+}_{DNB} + X^{+Z-1} + h\nu}$$



- **Active CX line width** ⇔ T_i
- **Active CX line shift** ⇔ v
- **Active CX line intensity** ⇔ n_X

- **Continuum background (line integrated)**
- **Passive CX (edge neutrals)**
- **Edge lines (electron impact excitation)**

MSE: The principle

- Beam emission Stark split due to “motional” Lorentz electric field. Information about B in:
  - Polarization of the emission lines ⬄ MSE-LP
  - Line shift of the emission lines ⬄ MSE-LS
  - Line intensity ration of the emission lines ⬄ MSE-LR

➔ Constraints in equilibrium reconstruction that give the current/q-profile