ITER fusion A&M data needs and future applications

Xavier BONNIN, ITER Science Division

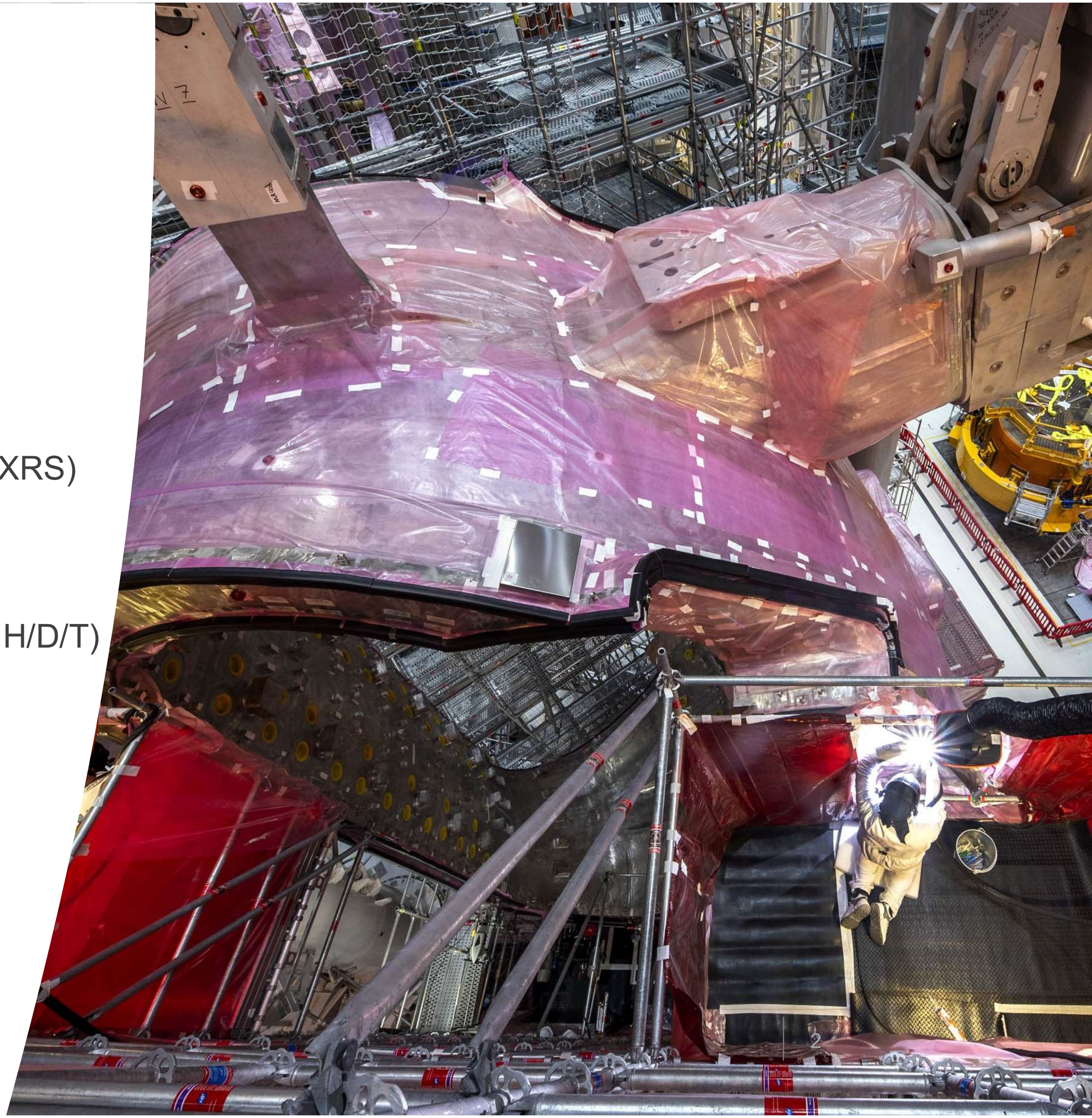
Acknowledgements to Z. Cheng, M. De Bock, A. Loarte, R. Reichle, S.D. Pinches, R.A. Pitts

Decennial IAEA Technical Meeting on Atomic, Molecular and Plasma-Material Interaction Data for Fusion Science and Technology, July 15-19, 2024, Helsinki, Finland
IDM UID: BW9275

china eu india japan korea russia usa

OUTLINE

- Proposed project re-baseline
  - Rationale
  - Sequence of operational campaigns
  - Measurement and modelling requirements
- Spectroscopic ITER diagnostics overview
  - X-Ray Crystal Spectrometer (XRCS)
  - Charge eXchange Resonance Spectroscopy (CXRS)
  - Divertor Impurity Monitor (DIM)
  - VUV spectrometer system
- ITER modelling needs
  - CX rates between Q^0/Q^+ and impurity ions (Q = H/D/T)
  - Isotope-resolved Q_2 molecular data
  - Boron and Argon data
  - Database access
- Summary



Rationale for new project baseline

- Robust achievement of ITER Project goals, in view of past challenges (delays due to the Covid-19 pandemic, technical challenges in completing first-of-a-kind components and in nuclear licensing)
- Realistic and reliable assembly – commissioning - operation
- Achievement of earliest start of the ITER Nuclear Phase (DD operation) and minimization of technical risks
- Stepwise Safety Demonstration
- SRO (Start of Research Operation) and DT-1,2 phases
- Key elements of the new baseline:
  - First Wall: beryllium (Be) → tungsten (W)
  - Optimized heating mix + boronization → ease path to Q = 10 with added W

R.A. Pitts, PSI 2024

ITER revised Operations sequence and associated Research Plan

Install:
- Actively cooled W divertor
- Blanket shield blocks
- Inertial W First Wall panels
- 40 MW ECH
- 10 MW ICH

- Commission PCS and Protection Systems to reduce risks in DT-1
- Hydrogen L-mode to 15 MA/5.3T
- Demonstrate H-mode DD plasmas
- First assessment of boronization, fuel retention/recovery, ICWC

- Final, actively cooled W First Wall
- NBI: 33 MW
- ECH: 40 → 60-67 MW
- ICH: 10 → 20 MW
- Final diagnostics set

Now		~18 months	~26 months		~10 months
Engineering fabrication of systems	Pre-SRO assembly	Integrated Commissioning I	Start of Research Operation (SRO)	Post SRO Assembly	Integrated Commissioning II

DT-1 ~ 9 years, ~3 x 10^{25} neutrons

FPO-1	FPO-2	FPO-3	FPO-4	FPO-5
H, H+T, D	D, DT, 100 MW, ~50 s	D, DT (Q=10) 500 MW, ~50 s	D, DT (Q=10) 500 MW, ≥300 s	D, DT (Q=10) ≥500 s High duty, 250 MW, ≥300 s

→

DT-2, ~3 x 10^{27} neutrons

FPO-x	FPO-(…)	FPO-y
DT (Q=10), high duty ≥ 500 s Q ≥ 5, 1000, 3000 s		

R.A. Pitts, PSI 2024

To achieve its goals, ITER will need to:

- Ensure reliable plasma start-up (boronization?)
- Measure and control the core plasma temperature and density
- Avoid core impurity (W) accumulation
- Control the divertor heat fluxes by maintaining a partially detached state through impurity seeding
- Model the plasma behavior
- Interpret the output from diagnostics
- Limit in-vessel T inventory
- …

For which it will need:

- Line radiation identification and strengths
- Charge transfer rates
- Cooling functions
- Collision rates
  - Charge transfer reactions
  - Molecular break-up
  - Elastic heavy-heavy collisions
- Resolved Q_2 molecular data
- Calculated spectra
- Surface reflection/sputtering coefficients
- Beam-stopping rates
- Nuclear data for α collisions

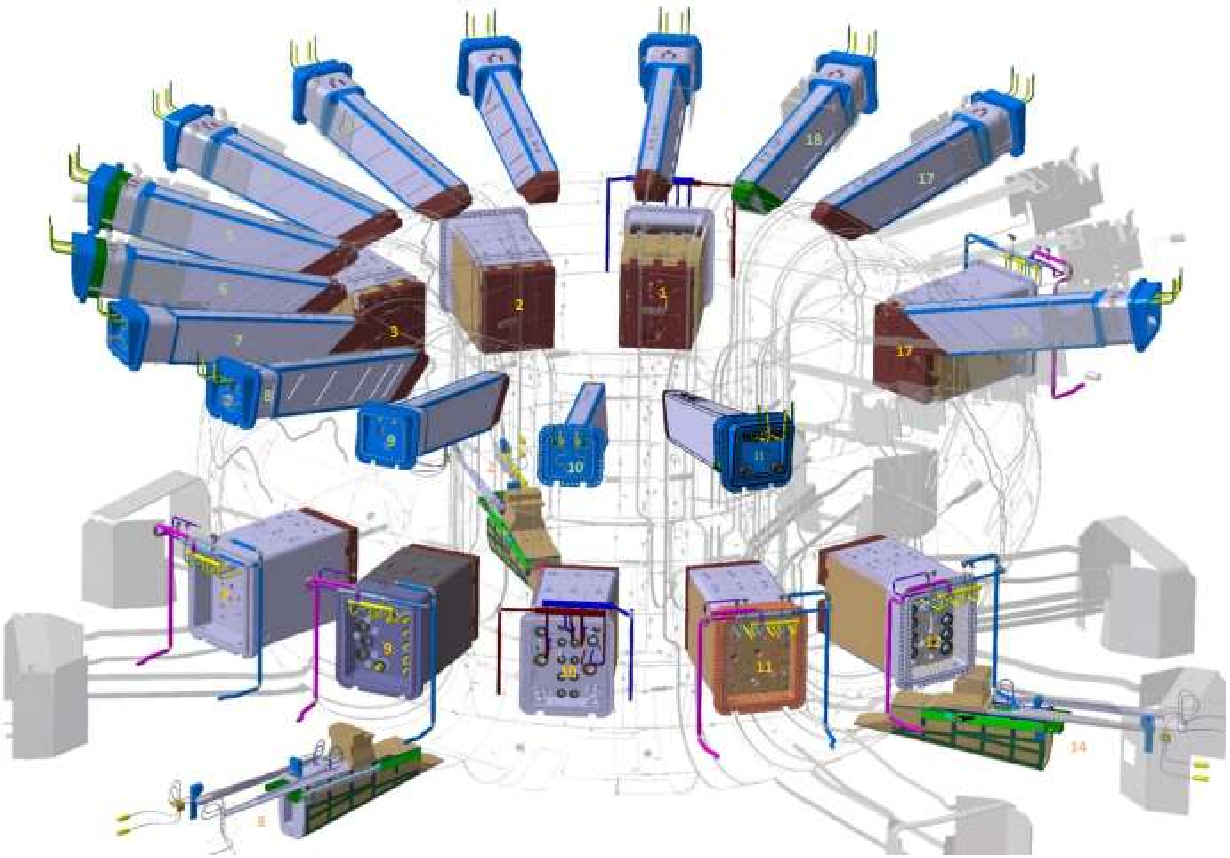
Overall diagnostics situation

ITER has **26 diagnostic ports** which house about **50 diagnostic systems**.

They are procured through **7 different DAs** (CN, EU, IN, JA, KO, RF and US) and by the **ITER Organization**.

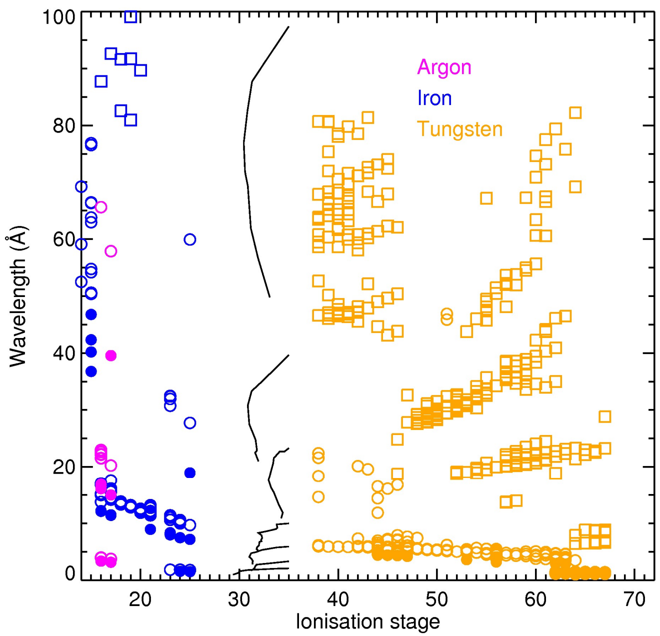
~1/3 are spectroscopic diagnostics:

Visible:	**H-alpha and Visible Spectroscopy** **Divertor Impurity Monitor** **Visible Spectroscopy Reference System**
VUV:	**Vacuum UltraViolet Survey (VUV Survey)** **Vacuum UltraViolet Div (VUV Div)** **Vacuum UltraViolet Edge (VUV Edge)**
X-Ray:	**X-Ray Crystal Spectroscopy Core (XRCS Core)** **X-Ray Crystal Spectroscopy Survey (XRCS Survey)** **X-Ray Crystal Spectroscopy Edge (XRCS Edge)** **Hard X-Ray Monitor**
Charge Exchange:	**Charge Exchange Recombination Spectroscopy Core** **Charge Exchange Recombination Spectroscopy Edge** **Charge Exchange Recombination Spectroscopy Pedestal**



Overview of Diagnostics (port plugs highlighted)

X-ray emission coverage



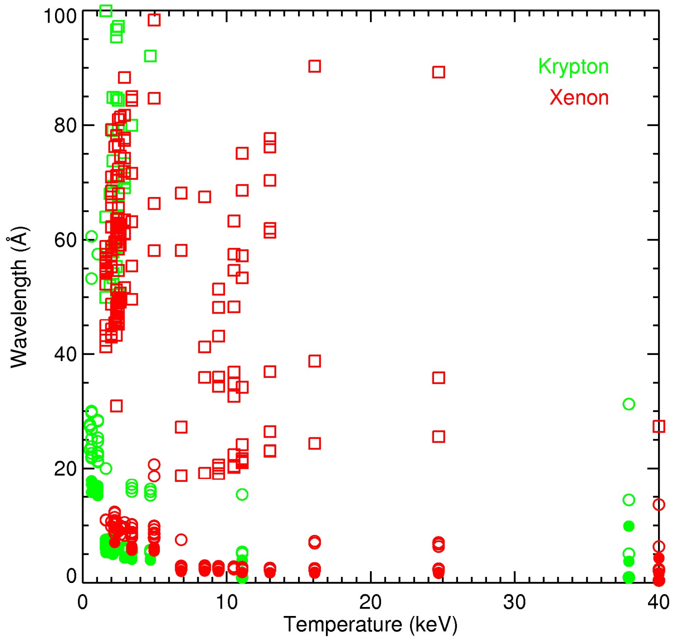
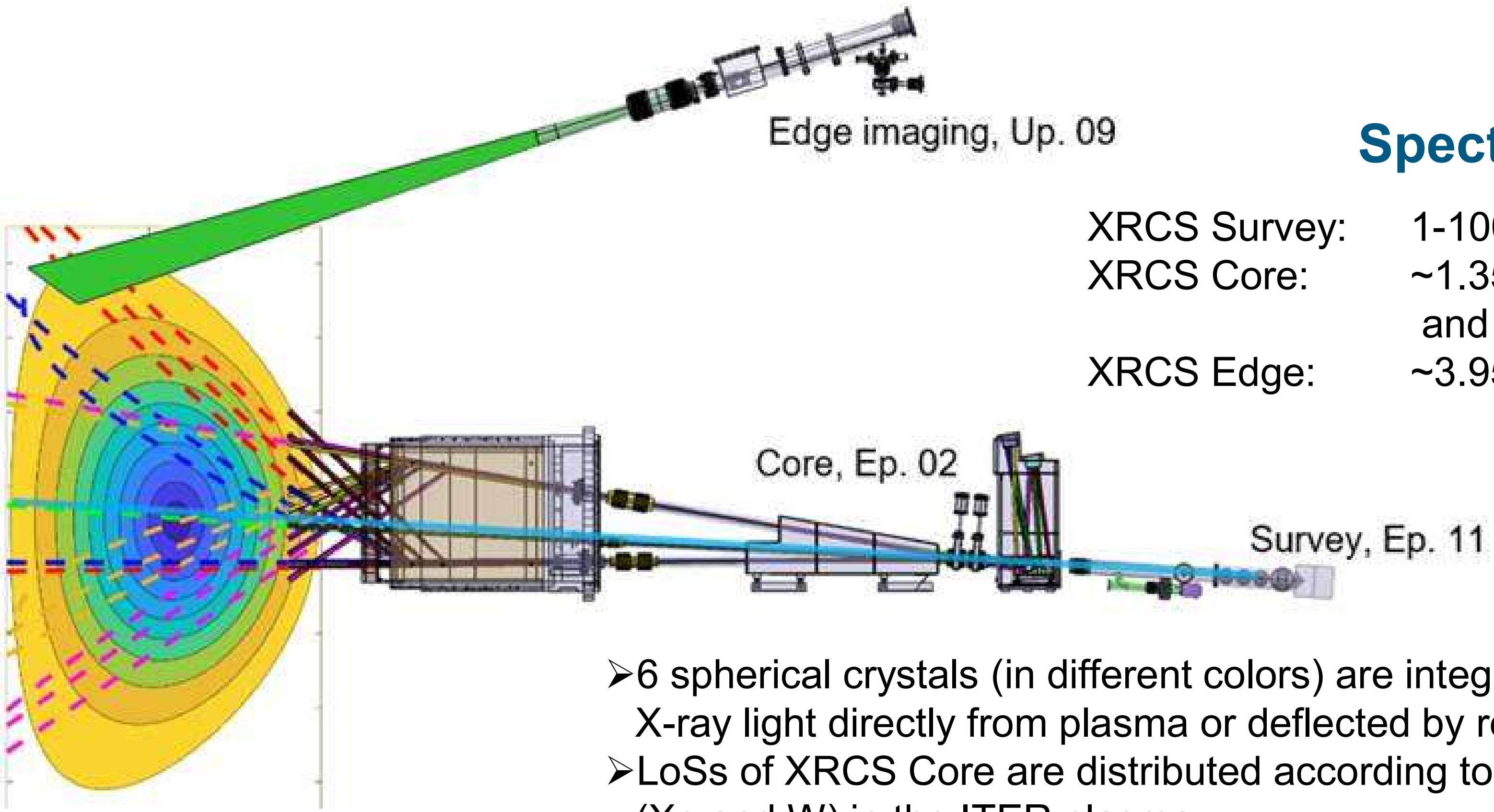


Image credit:
M. O'Mullane (ADAS)

- Strong dipole X-ray lines from intrinsic (Fe and W) and seeded (Ar, Kr and Xe) impurities.
- There are useful lines to probe over a reasonably wide range of temperatures.
- Different crystals can cover ranges over 0.2-10nm region although they have different sensitivities and resolving powers.
- X-ray lines from H-like and He-like B, C, N, O and Ne are also in this spectral region and will be an important measure of the state of the plasma during ramp-up.

ITER XRCS systems

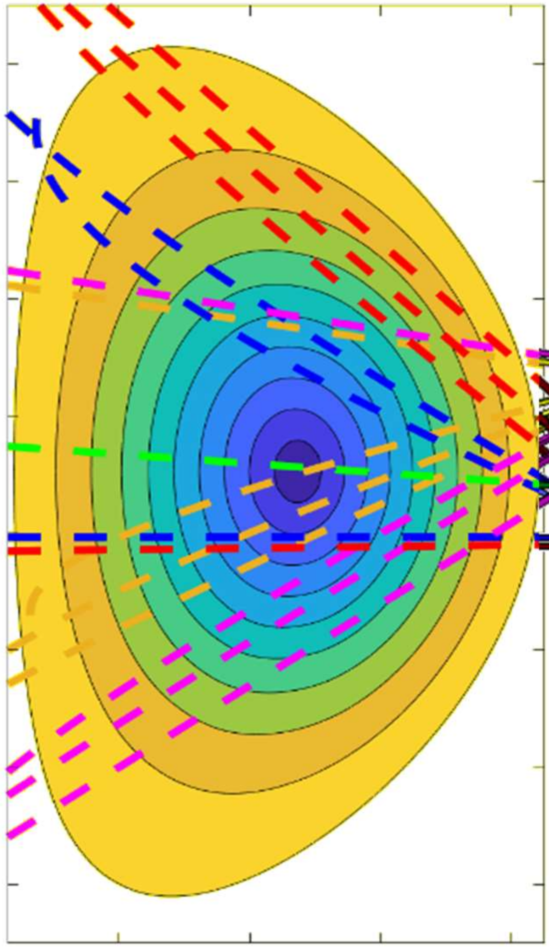


Spectral ranges

XRCS Survey: 1-100 Å
XRCS Core: ~1.354 Å (W^{64+}), 2.1899 Å (Xe^{51+}), and 2.555 Å (Xe^{44+} and Xe^{47+})
XRCS Edge: ~3.95 Å (Ar^{16+}) and ~3.73 Å (Ar^{17+})

- 6 spherical crystals (in different colors) are integrated, with each receiving X-ray light directly from plasma or deflected by reflectors
- LoSs of XRCS Core are distributed according to possible positions for ions (Xe and W) in the ITER plasma
- Bragg reflection on pre-reflector and crystal

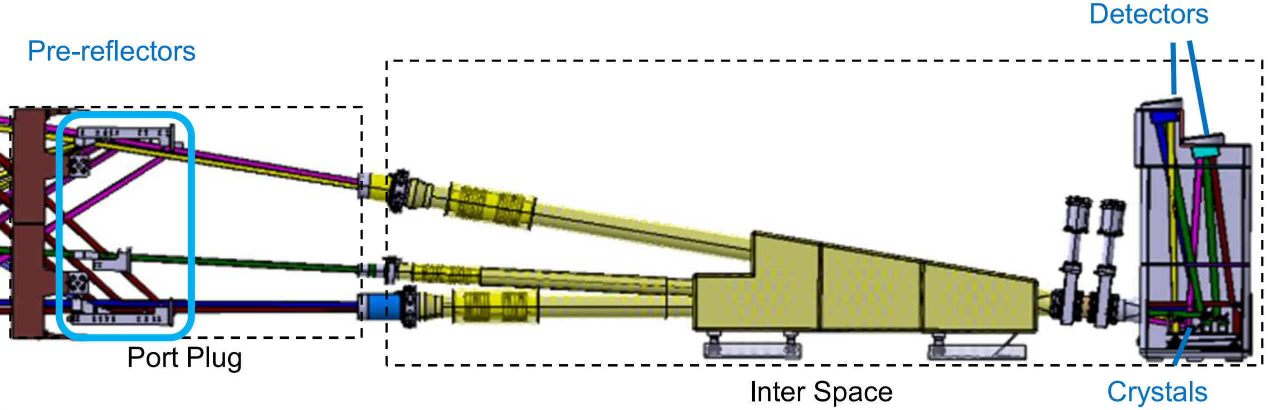
ITER XRCS Core



Red, **Magenta** and **Green-1** sights: Xe^{44+} (2.5525Å) and Xe^{47+} (2.5572Å) from 0 to 0.85a

Blue and **Yellow** sights: Xe^{51+} 2.1899Å for 0 to 0.5a

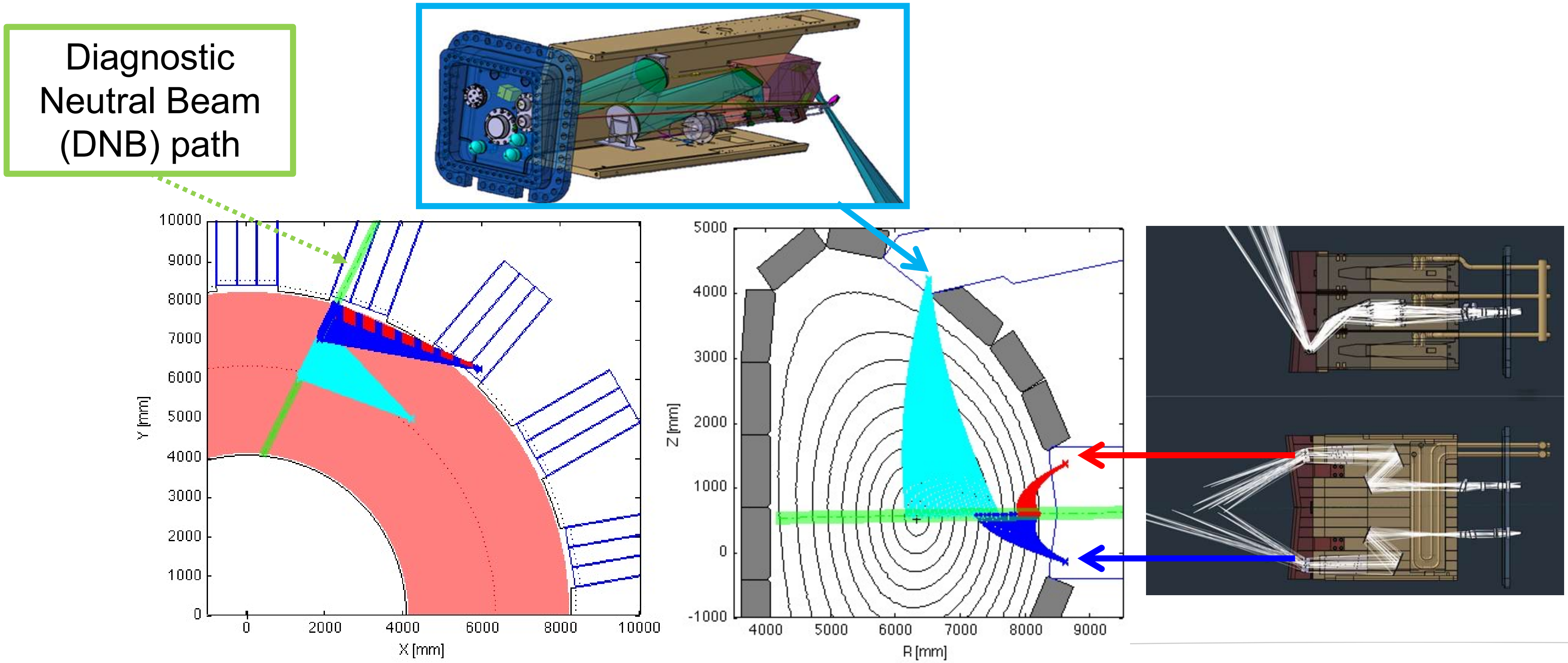
Green-2 sights: W^{64+} (1.354Å) passing through plasma center



The XRCS system was also planned for Gamma ray spectroscopy to measure the alpha energy distribution by means of nuclear α + ^{9}Be reactions: Must now find a replacement for ^{9}Be

The ITER CXRS systems

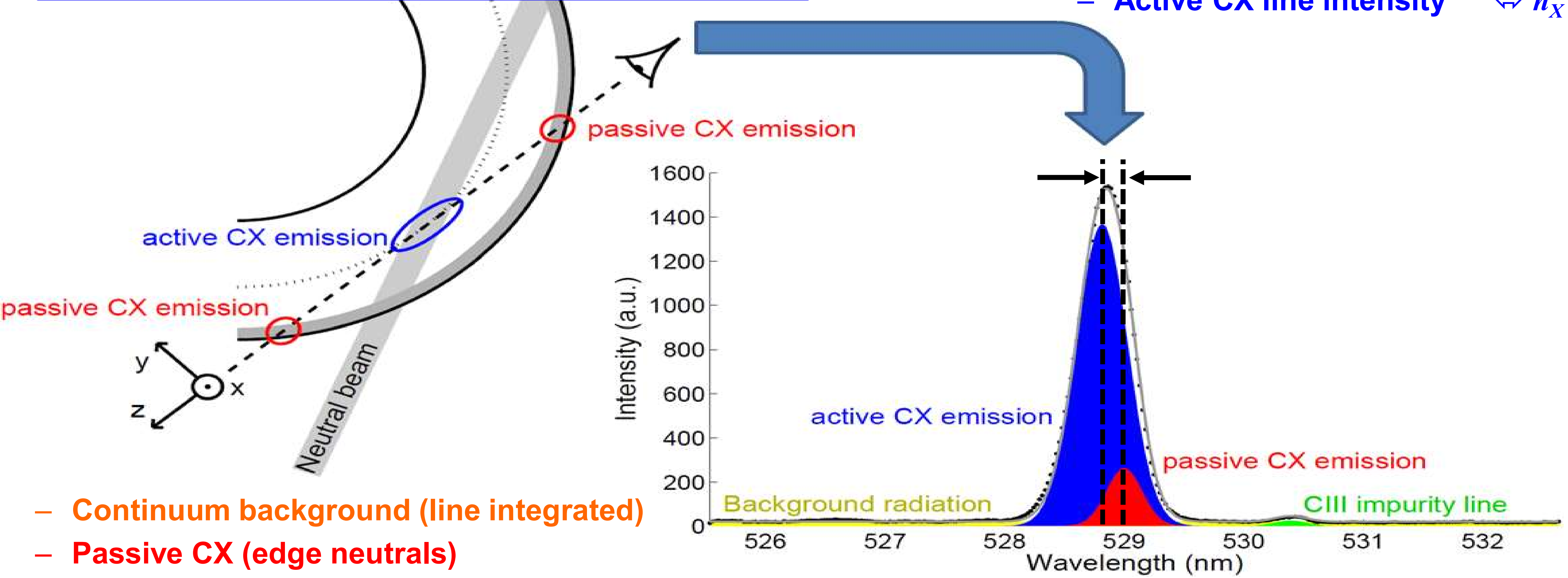
	r/a < 0.6 – 0.7	r/a > 0.5	r/a > 0.85
Name	CXRS-core (55.E1)	CXRS-edge (55.EC)	CXRS-pedestal (55.EF)
Spatial resolution	**a/30**	**a/30 – a/100**	**a/100**



Principle of CXRS plasma emission

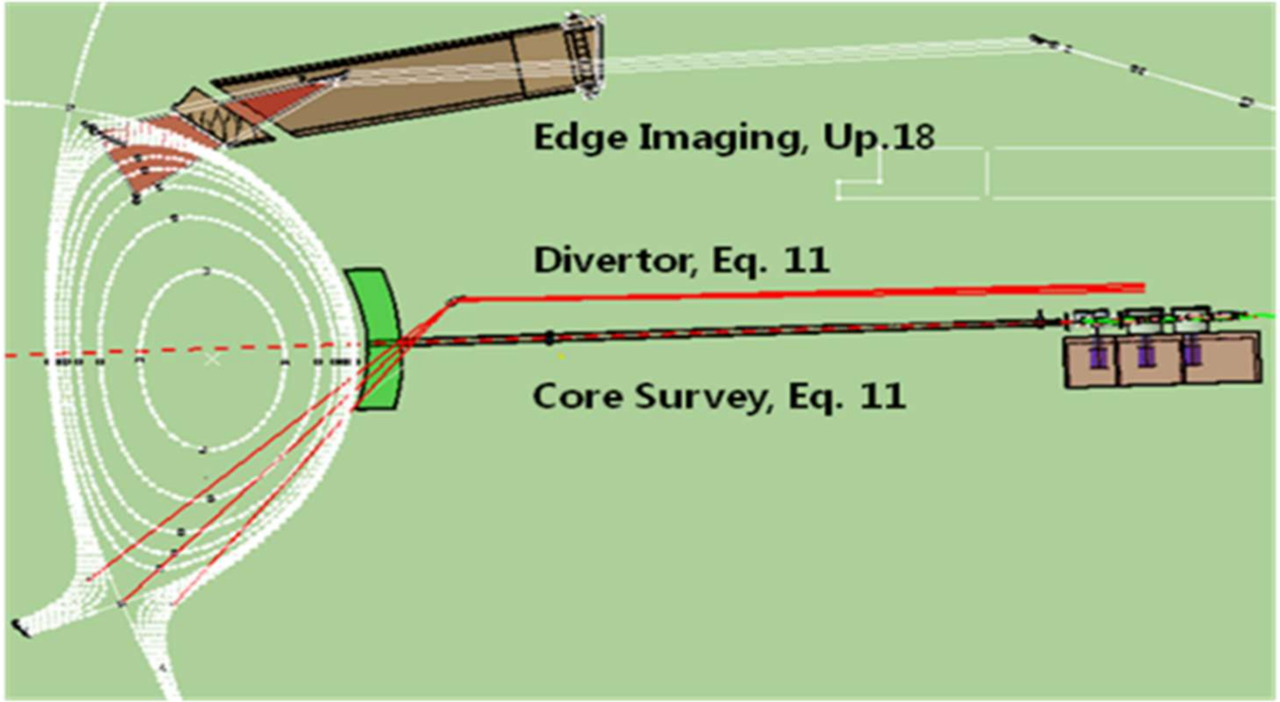
$$H_{DNB} + X^{+Z} \Rightarrow H_{DNB}^{+} + \left(X^{+Z-1}\right)^{*} \Rightarrow H_{DNB}^{+} + X^{+Z-1} + h\nu$$

- 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)
- Reflections

VUV Spectrometers



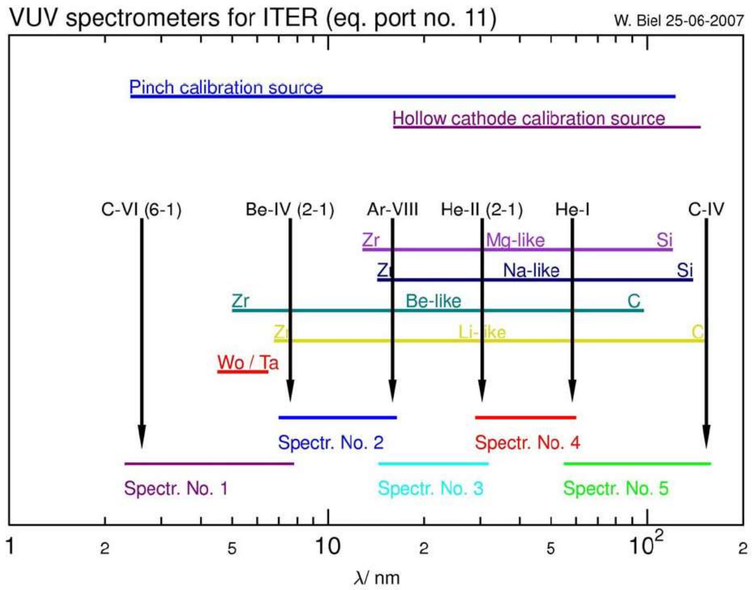


Image credit: KO-DA

- 55.E3 VUV Survey : radial sightline through midplane
  - Wavelength range: 2.4 – 160 nm (W^{46+} 19.6 nm and W^{44+} 132.3 nm)
- 55.EG VUV divertor: inner target up to top of inner baffle (plus x-point and area above the dome)
  - Wavelength range 15 – 32 nm
- 55.EH VUV edges: Top "second X" region
  - Wavelength range: 17 – 32 nm

Divertor Impurity Monitor

Aims to have 6 viewing fans:

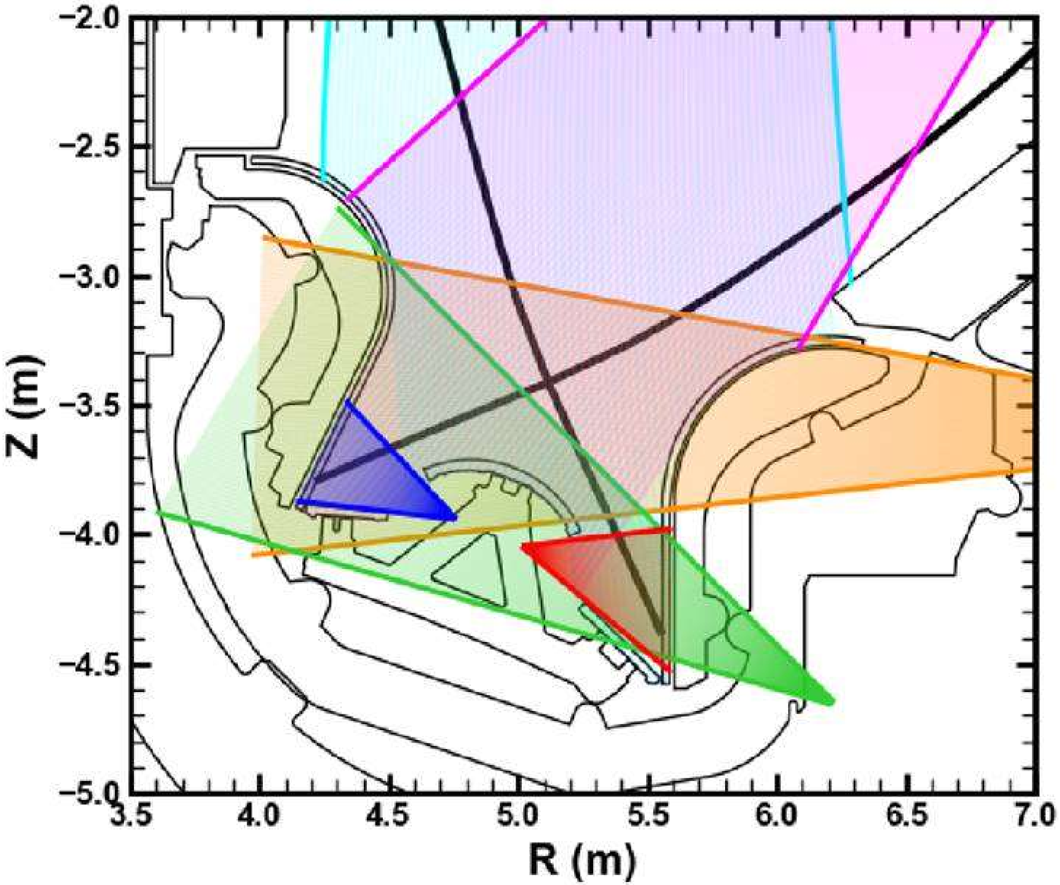
- IVT strike-point
- OVT strike-point

} Essential for divertor detachment control

- Lower divertor region
- X-point region (interesting to explore X-point radiating regimes, but very challenging to implement)
- Two views from upper ports

Detachment control will be done mostly by means of Neon seeding from the bottom of the machine

All chords will be directed to six spectrometer boxes, for which the precise wavelength ranges must be chosen in advance.

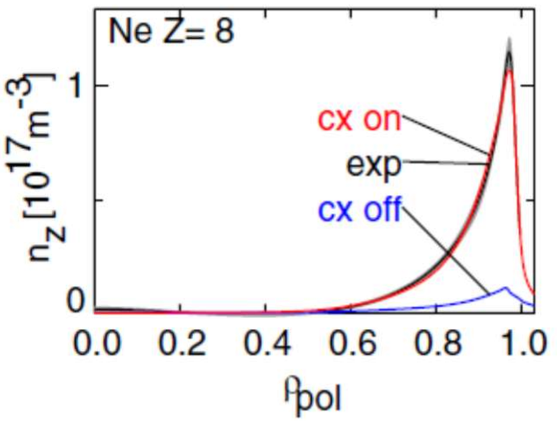


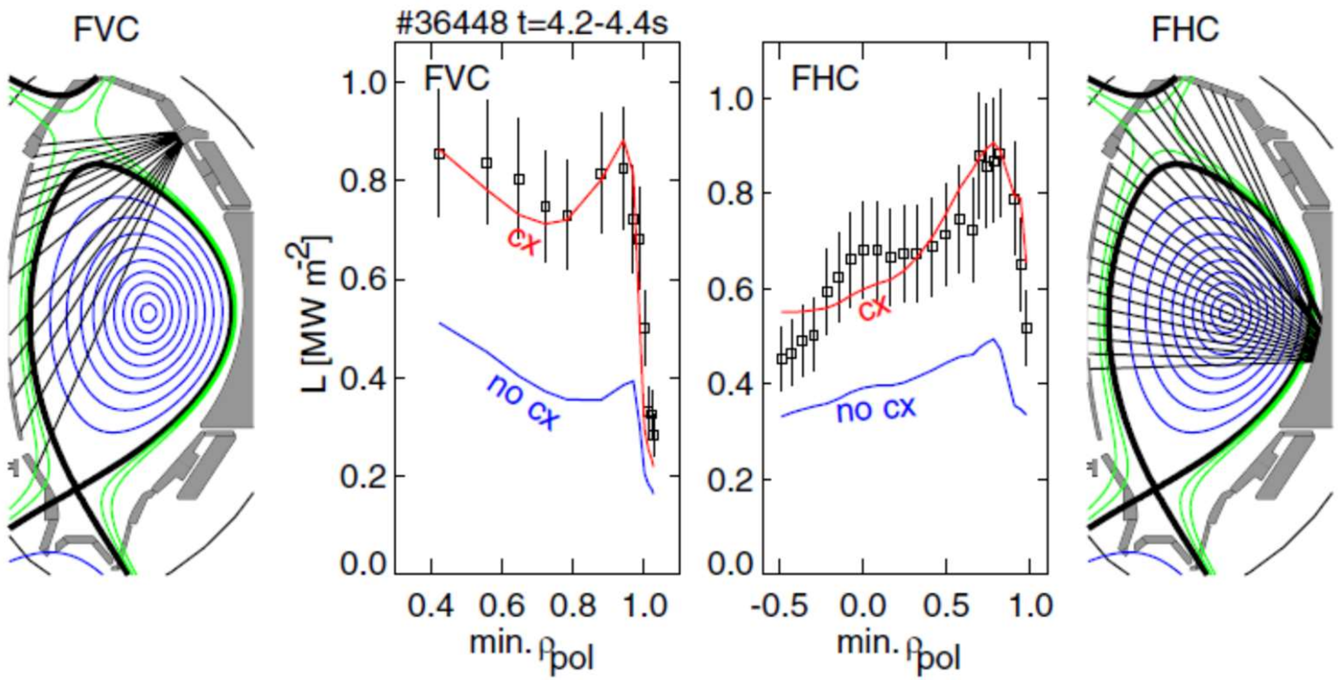
Design wavelength range: 200 – 1000 nm
Dedicated channel for the W^0 400.9 nm line

ITER Modelling needs: Charge exchange rates

- Include $Q^0 + X^{+q} \rightarrow Q^+ + X^{+(q-1)}$ CX rates to better reproduce the impurity ionization balance and match experimental measurements

Largest effect seen on He-like light impurity ions

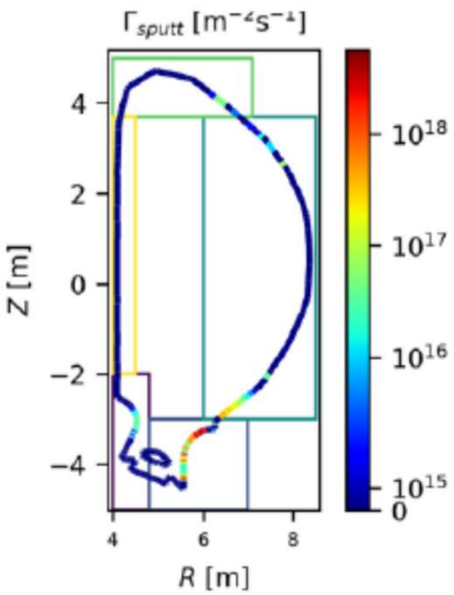


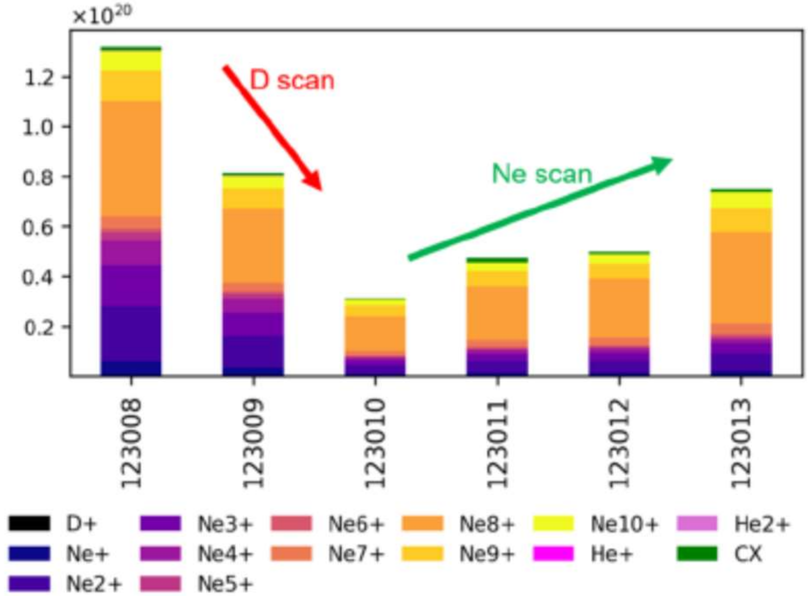


R. Dux, NF 2020

ITER Modelling needs: Charge transfer rates

- $Q^{+} + X^{+q} \rightarrow Q^{0} + X^{+(q+1)}$: an additional channel for the production of high-energy CX neutrals?
- Sputtering thresholds of H/D/T on W: ~300/200/150 eV
- How large will the wall W sputtering source from high-energy CX Q^{0} be and how much plasma contamination can it cause?





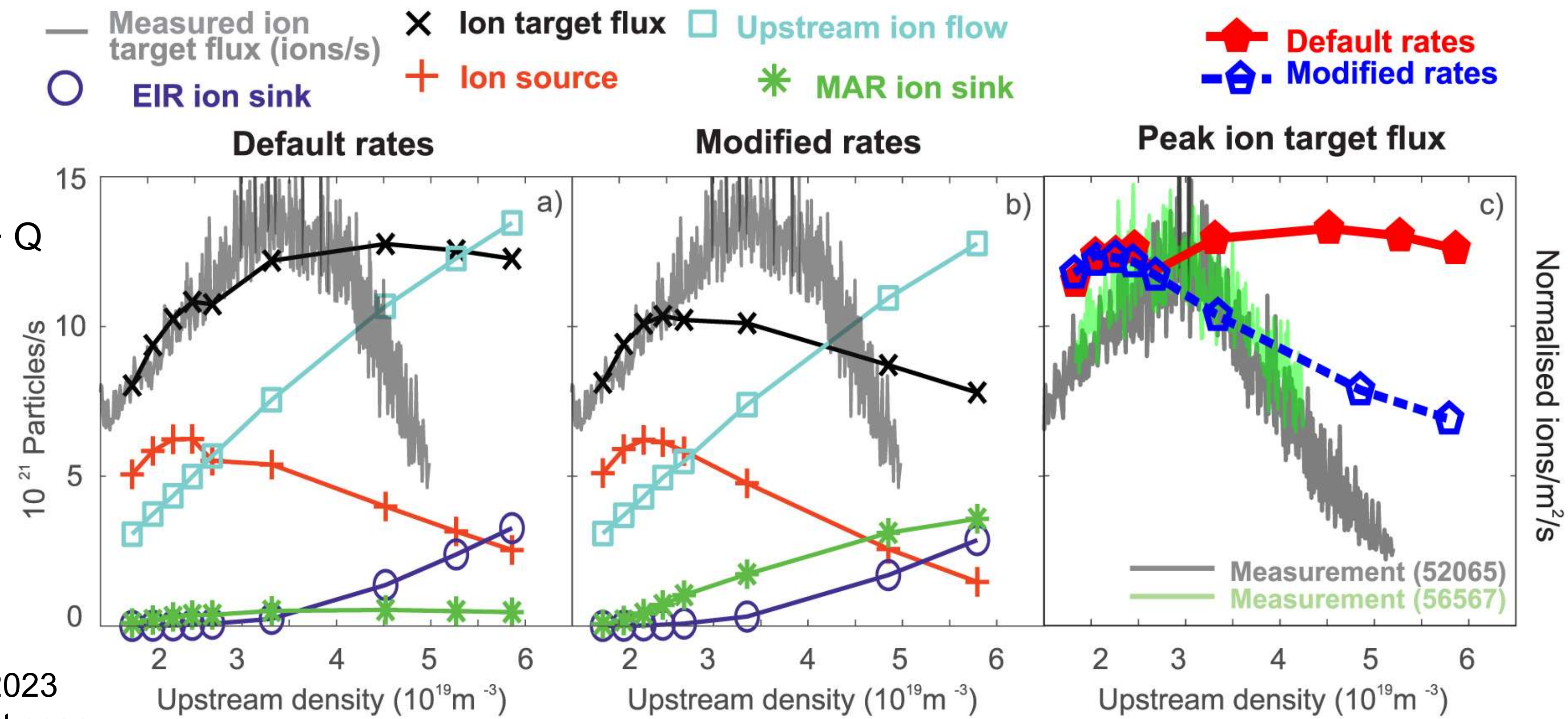
S. Suresh Kumar *et al.*, PSI 2024
SOLEDGE3X full-power
Ne-seeded ITER cases
using standard CX assumptions

ITER Modelling needs: Q_2 molecular rates data

- Isotopologue separated (e.g. CRMs, YACORA)

MAR: $Q_2^+ + e \rightarrow Q + Q$

Scaled H_2 rates
Dedicated D_2 rates

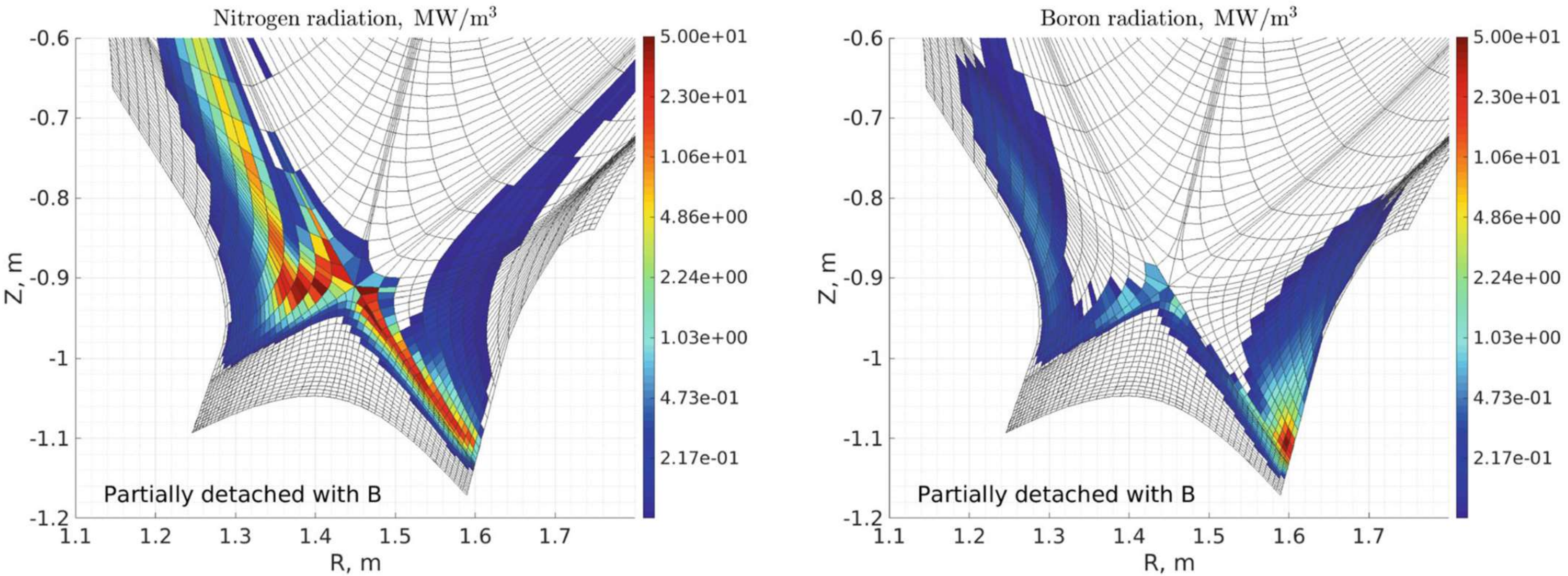


K. Verhaegh *et al.*, NF 2023
TCV density detachment scan

ITER Modelling needs: refined Boron data

For boronization procedure: diborane molecule break-up chain rates

For detachment control: Boron radiation losses and ionization/recombination rates

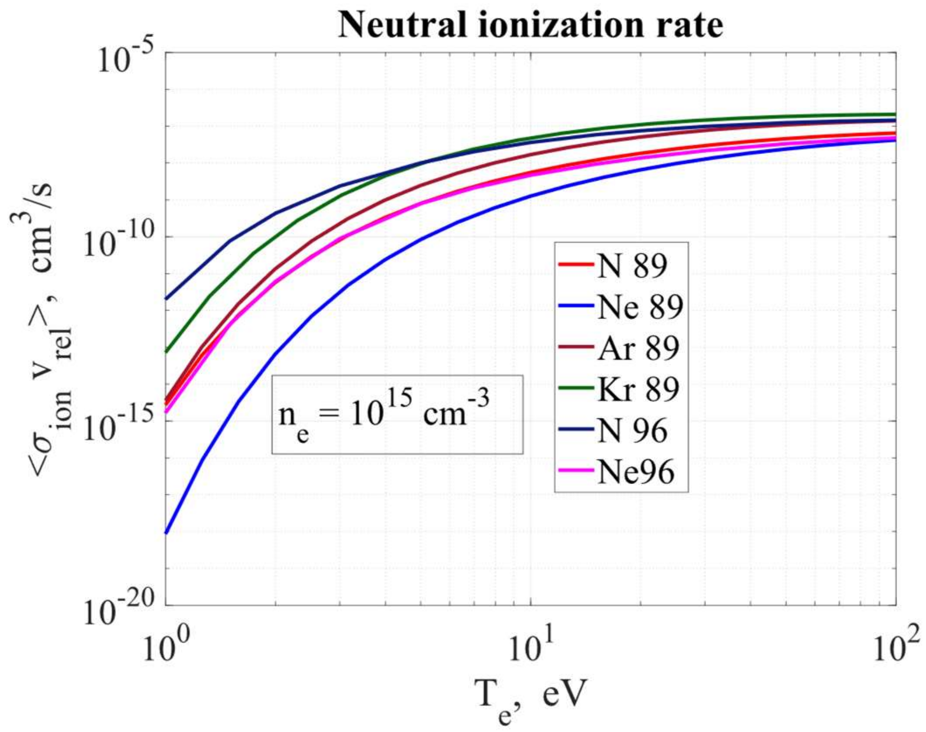


SOLPS-ITER modelling of AUG using custom-made “year 95” ADAS data
B radiation pattern shifted to lower temperatures compared to N

S. Makarov *et al.*, CPP 2023

ITER Modelling needs: Argon data

To properly model plasma detachment in Ar-seeded plasmas, it is necessary to include density dependencies in the ionization and recombination rates, particularly of the first ionization stages, which are not yet available in the ADAS database.



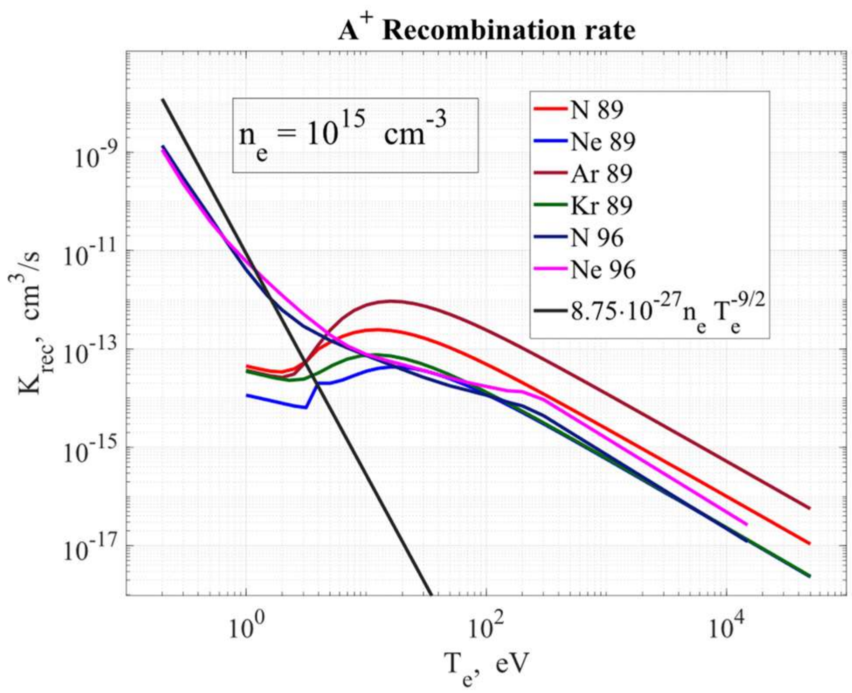


Image credit: I. Senichenkov, SPbSTU

ITER Modelling needs: Database(s) access

ITER simulation and synthetic diagnostics rely on the IMAS platform (Integrated Modelling and Analysis Suite)

Within IMAS, the data needs are met by the AMNS library, which provides:

- Standardized user-facing routine calls to fetch (meta-)data
  - Data should contain pre-digested quantities at the various level of detail depending on needs
    - Cooling rates per species and ionization state
    - Emission rates for specific diagnostic lines of interest
    - Description of radiation spectra
- Server-side routines to pre-compute data tables and/or access remote databases
  - ADAS, AMJUEL/HYDHEL, TRIM
  - Could consider IAEA NDS CollisionDB if peer-to-peer access can be ensured
- Needs to rely on open standardized formats
  - Surface reactions/reflection/sputtering
- Provide extrapolation rules (critical for low-temperature high-density conditions)

Summary

- ITER re-baselining increases the need for quality data: W, Xe, B, Ar, …
- Need to identify wavelength ranges that maximize DIM diagnostic species coverage with good S/N ratios
- Need to ensure good coverage of useful W lines to measure its core concentration
- Dedicated datasets for Q_2 isotopologues are important to model detachment physics
- Charge transfer rates with impurities should be included in calculations
- Open easily accessible databases with standardized formats are desired

Thank you!

iter

china eu india japan korea russia usa