Atomic collision processes in plasmas of ASDEX Upgrade, JET and ITER

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Outlook

- Status of fusion research applying magnetic confined plasmas in tokamak devices
- Choice of first wall material ⟹ determines atomic data needs
- Plasma edge modelling
- Active plasma spectroscopy using atomic beams
- Summary

Magnetic confinement fusion

It is necessary to confine effectively enough a sufficiently dense and hot D, T plasma to produce

$$D + T \Rightarrow {}^{4}He + n + 17.59\ MeV$$

$10^{20}\ m^{-3}$

Density (n)

=> Reaction rate

5 s

Confinement time (τ_E)

=> Self-sustainment

10 keV

Temperature (T)

=> Reaction rate

Lawson criteria:

Specifies the conditions that must be met for fusion to produce a net energy output

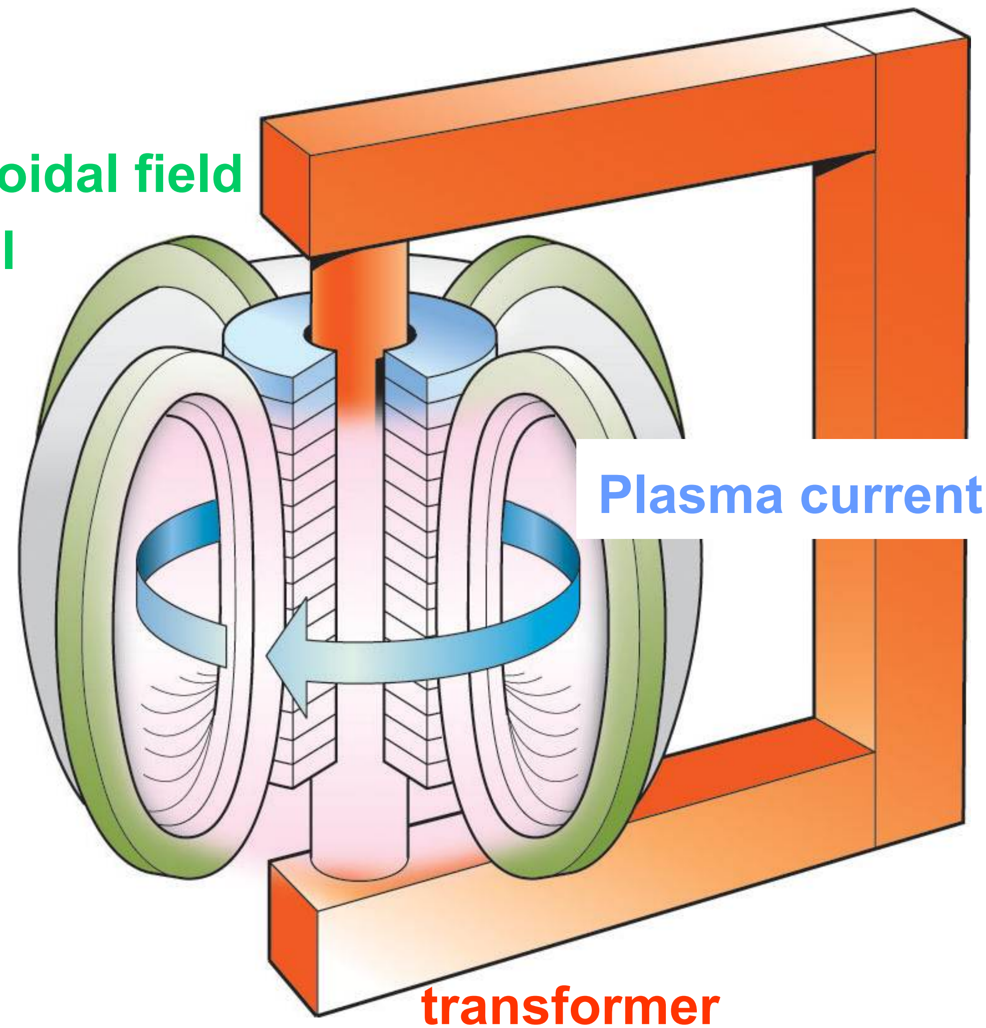
$$n\,T\,\tau_E > 5\times10^{21}\ (keV\ m^{-3}\ s)$$

Fusion in magnetic confined hot plasmas

ASDEX Upgrade, JET and ITER are tokamaks of similar geometry and different size.

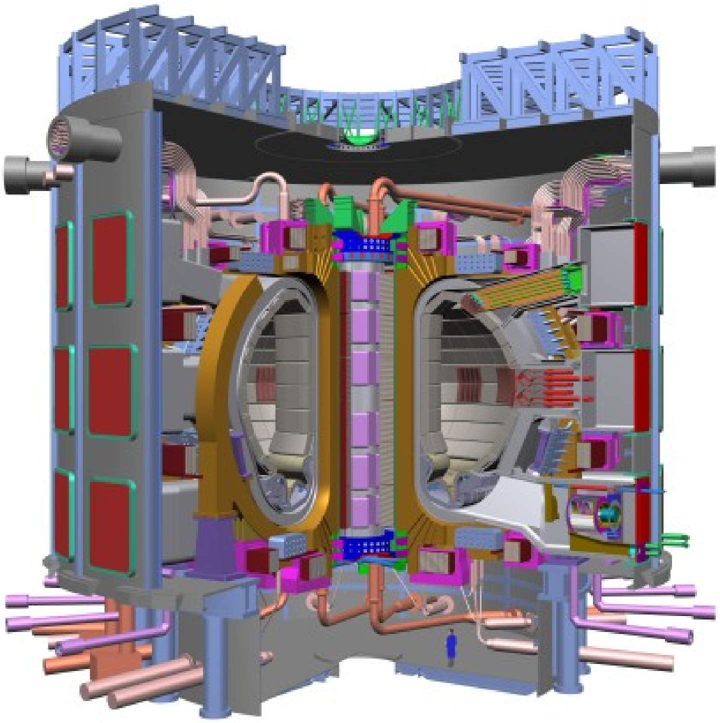
Necessary density n_e and temperature T_i reached in present day Tokamaks, energy confinement time needs bigger device ⇨ **ITER**

Tokamak - the most advanced magnetic confinement concept

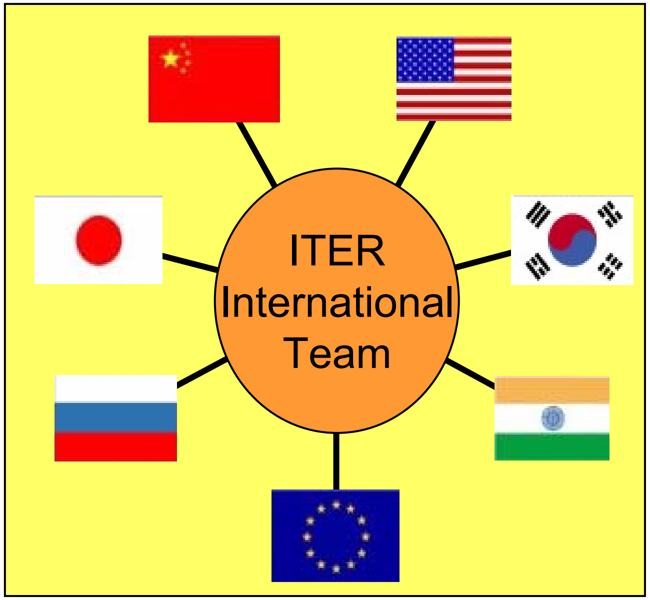


What is ITER?

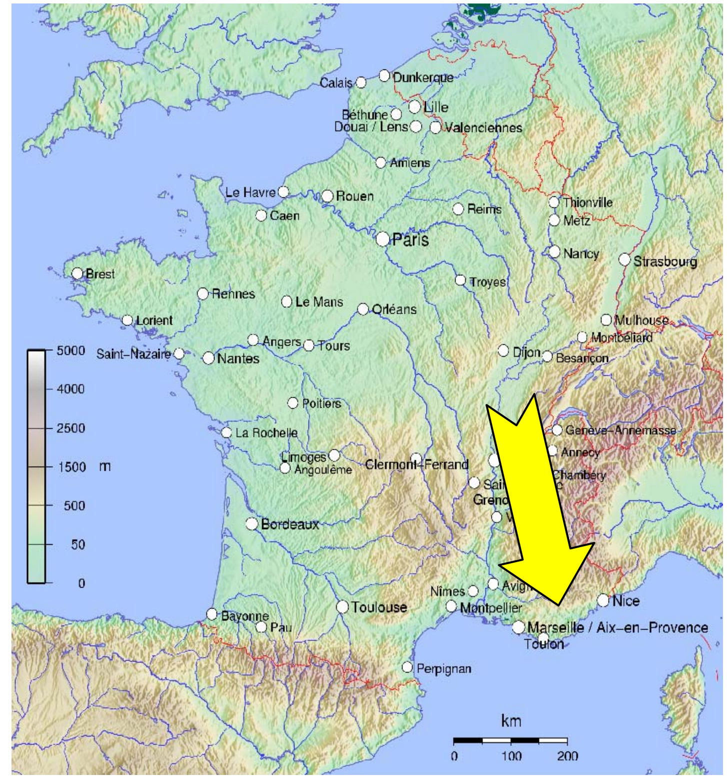
- ITER ("the way" in Latin) is the essential next step in the development of fusion following the tokamak line.
- Objective - to demonstrate the scientific and technological feasibility of fusion power.
- The world's biggest fusion energy research project.
- An international collaboration.



ITER - A Joint Project of EU, Japan, USA, Russia, South Korea, China, India



„**Fusion for Energy**“ body
hosted in Barcelona, Spain
organises
EU contributions to ITER
from
EU Fusion Labs
&
Industry



ITER site: Cadarache, France

Investment ~ 5 Billion €
24. Mai 2006 Signature of ITER Implementing Agreement
Design Review: 2007, ongoing
Construction: 2008 – 2016

ITER objectives

A burning plasma is dominated and maintained by its own internal heat source characterized by the

- power amplification factor: **Q**

  Q = power generated by fusion reactions / heating power injected in the plasma

- fraction of plasma self-heating by fusion born α-particles: $\mathbf{f_{\alpha}}$

ITER objectives:

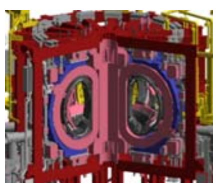
• Q ≥ 10 with P_{fus} = 500 MW for > 400s, for the first time access to plasmas with adequate self heating (f_{α} > 2/3)

• explore the domain of “advanced” (continuous) tokamak operation with Q ≥ 5 (f_{α} > 1/2)

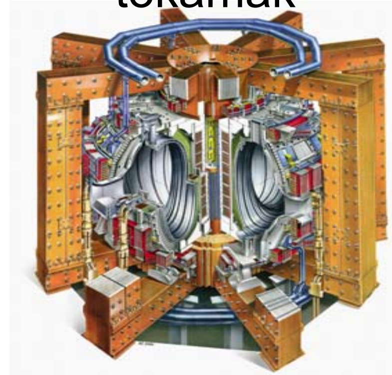
• integrate essential technologies in reactor-relevant conditions

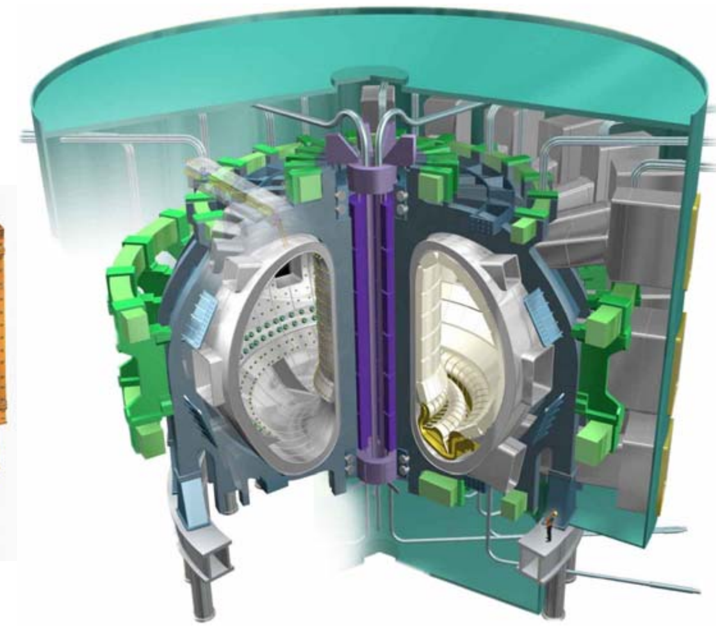
Comparison ASDEX Upgrade, JET, ITER

The ITER design is based on results of JET and other Tokamaks like ASDEX Upgrade



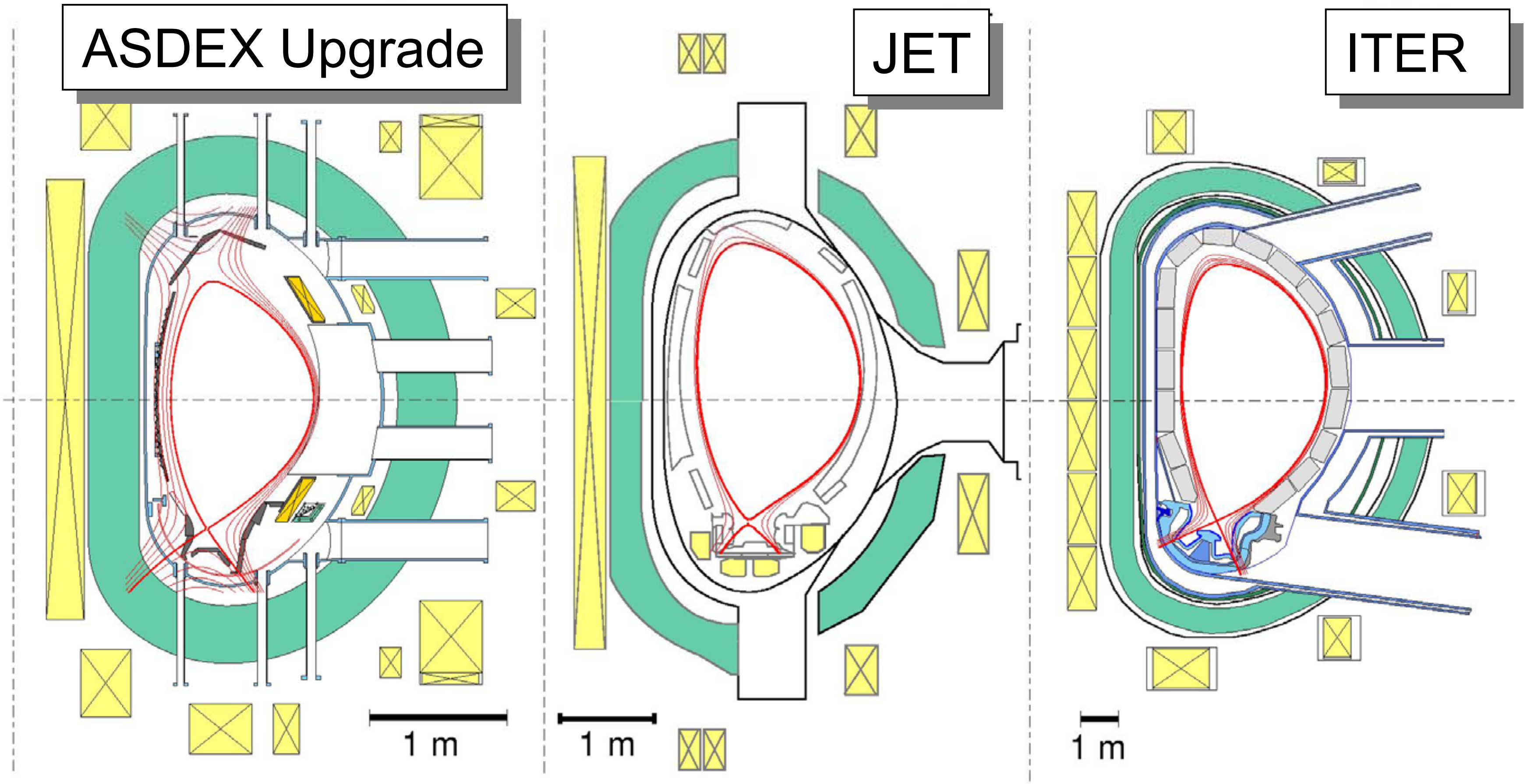
Largest existing tokamak





	ASDEX Upgrade	*JET*	*ITER*
Diameter (torus)	*3.3 meters*	*6 meters*	*12 meters*
Plasma Volume	*14 m^3*	*80 m^3*	*800 m^3*
Fusion power	*~ 5 kW_{th}*	*~ 16 MW_{th}*	*~ 500 MW_{th}*

ASDEX Upgrade and JET form a step ladder to ITER



Geometry similar to ITER, linear dimensions scale 1:2:4

- ASDEX Upgrade and JET play an essential role in the design and operation of ITER.
- Both play also a growing role in the preparation of the DEMO concept.

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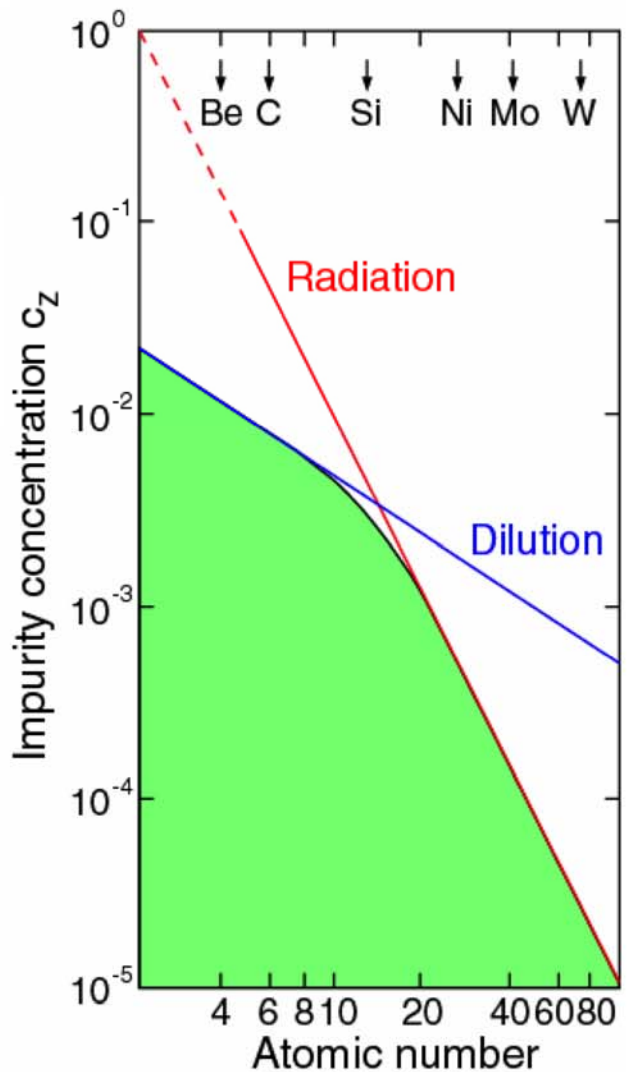
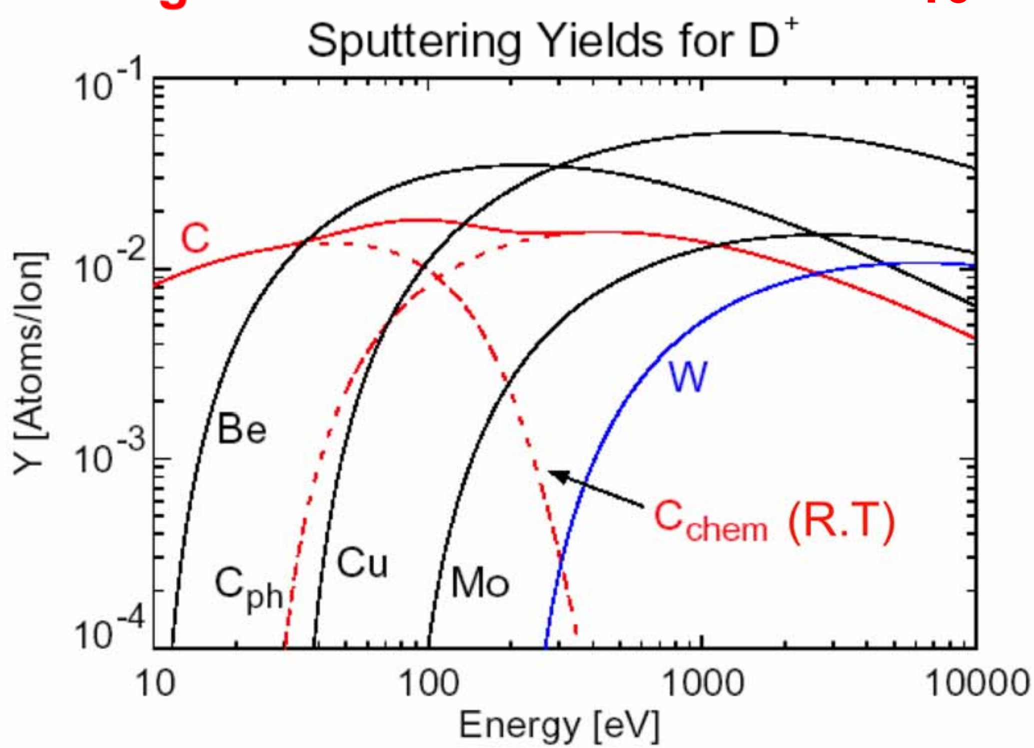
Comparison of first wall materials, Be, C, W

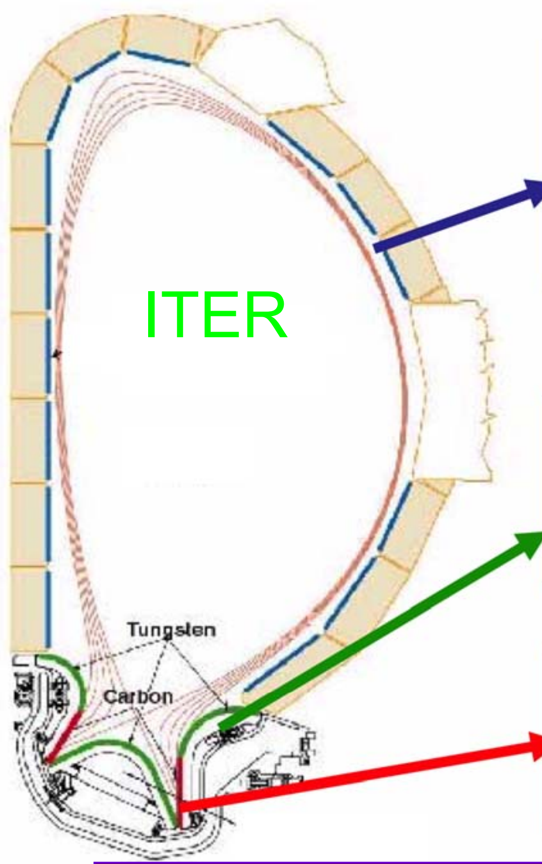


Tungsten: **Low erosion**
High threshold
Low tolerable concentration $< 2 \cdot 10^{-5}$

Carbon: Higher but moderate erosion yield
High tolerable concentration $\approx 10^{-2}$



ITER's material mix - still an issue



Be main wall (700m²)
- Low Z
- Oxygen getter
- *Lower T retention (?)*

Tungsten baffles (100m²)
- Low erosion
- Small T retention

Graphite CFC (50 m²)
- No melting
- Best heat shock resistance

Why?

Plasma performance

Rationale for ITER material choice is

to guarantee access to a broad range of plasma scenarios

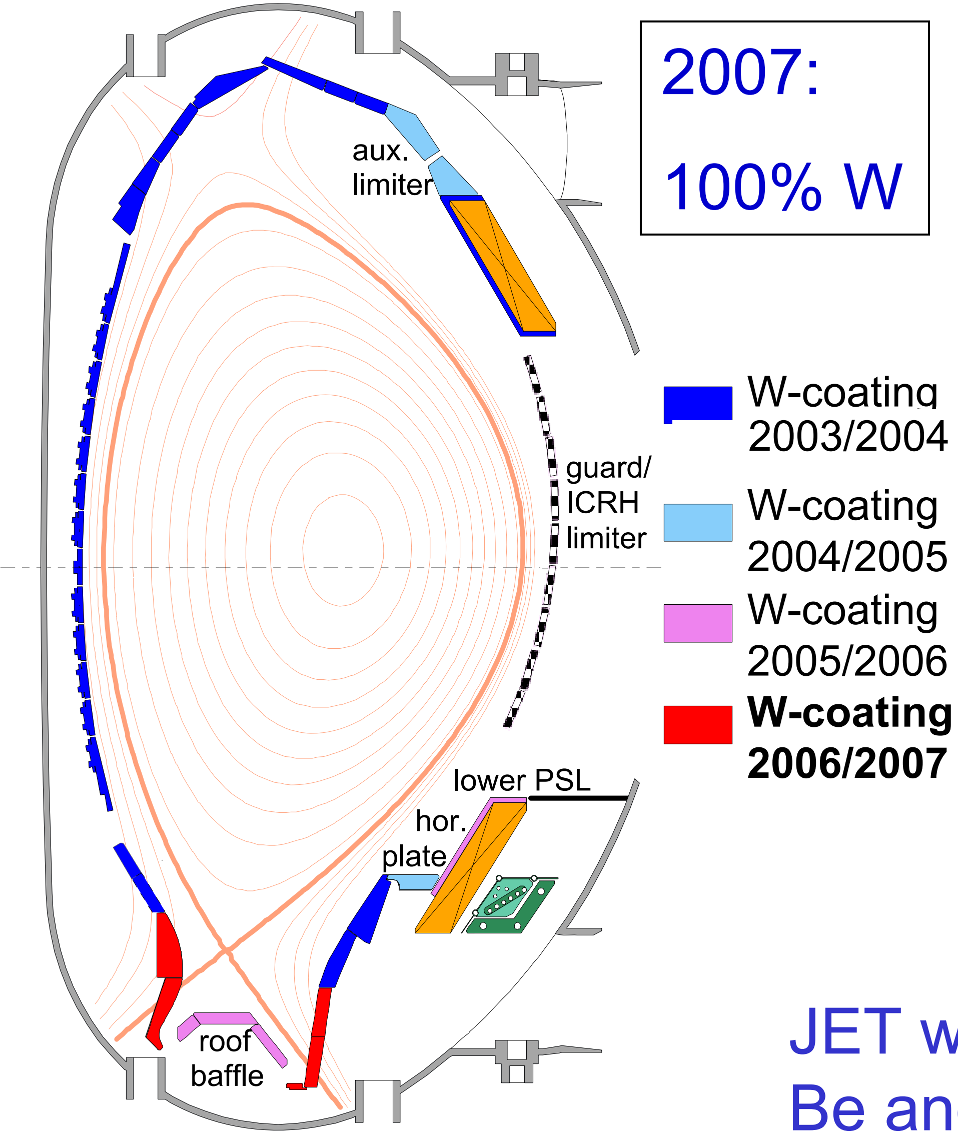
Erosion & lifetime

Future REACTOR (DEMO):

Power Plant Conceptual Study (PPCS) - Lifetime considerations dominate material selection

At the moment tungsten is the only candidate as first wall material for a reactor

ASDEX Upgrade 2007 - a full tungsten inner wall



Stepwise increase of tungsten covered area of the inner wall from 2003 - 2006 by coating of graphite tiles with tungsten.

Investigation of the compatibility of ITER relevant plasma scenarios with large tungsten surfaces.

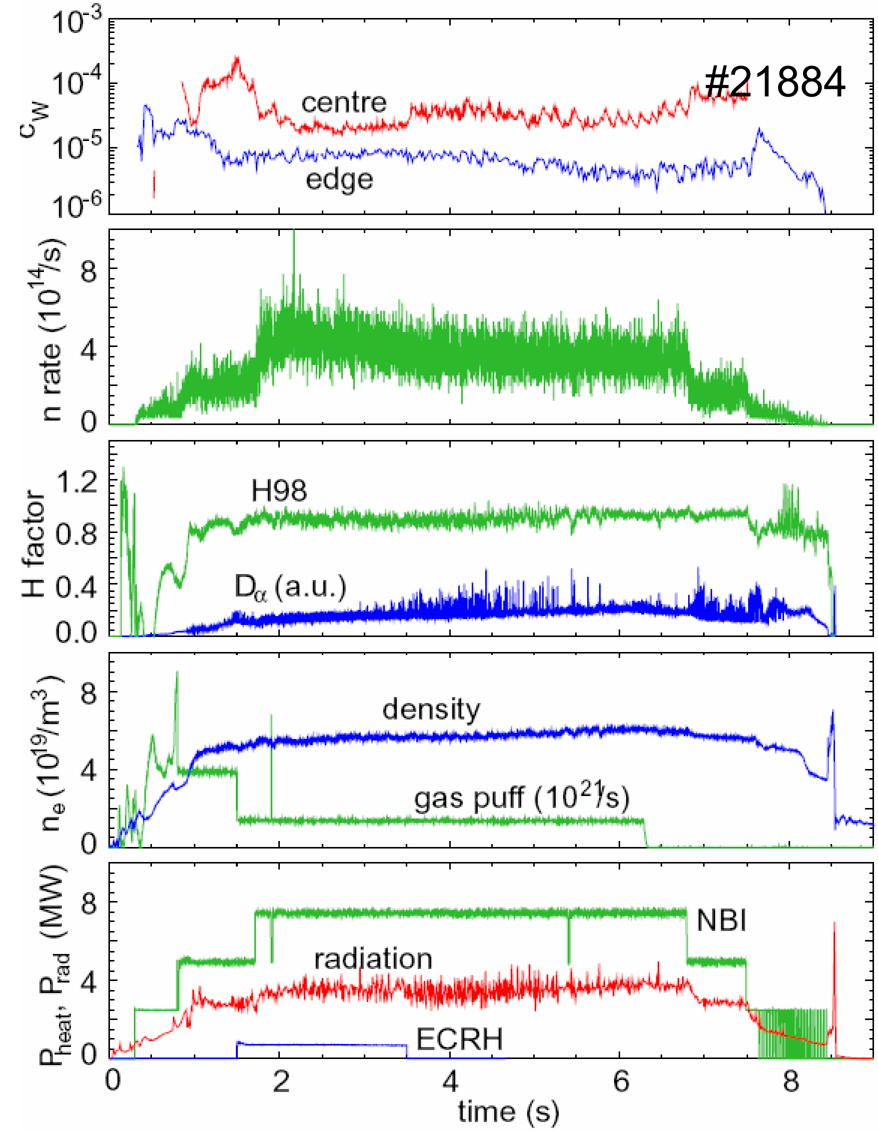
JET will change to a combination of Be and W in the next major shutdown in 2009

ASDEX Upgrade (AUG) the pioneer in using W

Wide-angle view into the AUG vessel - all tiles covered with tungsten

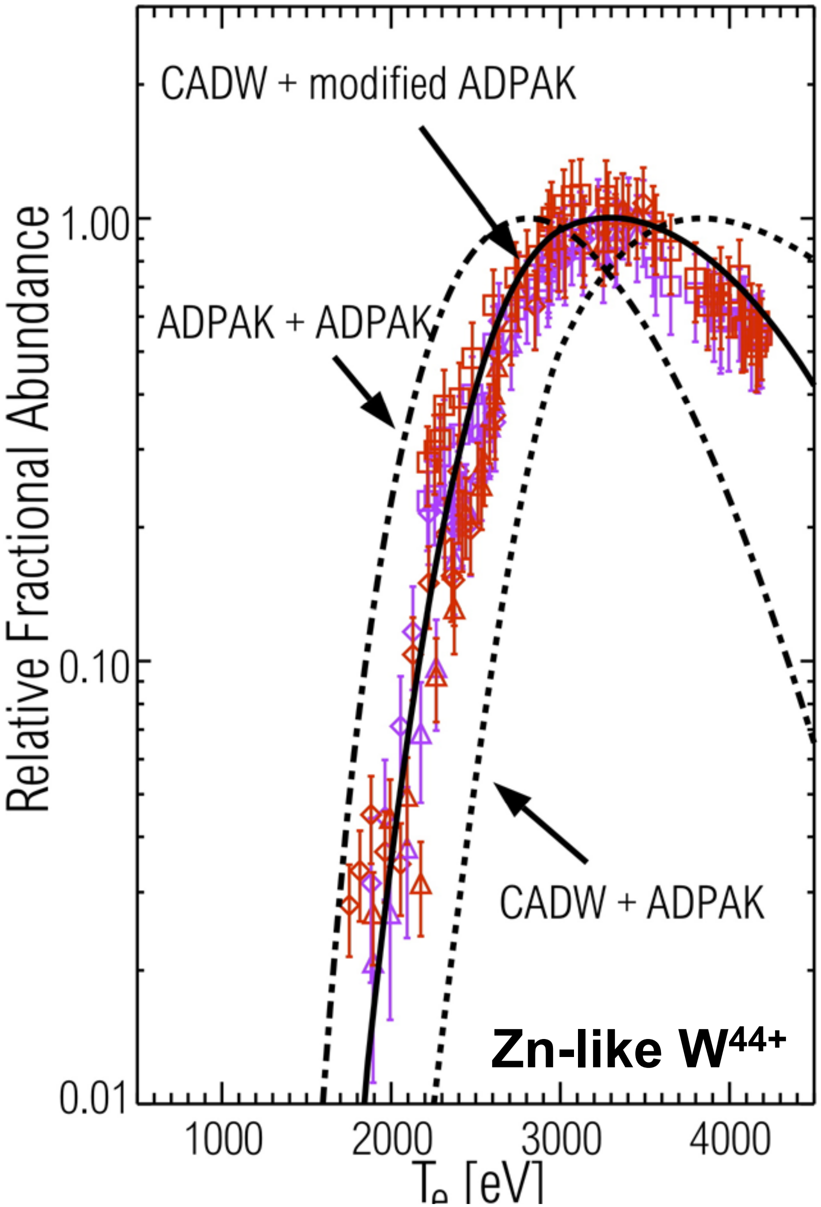
ASDEX Upgrade (AUG) operation with full W inner wall

- good confinement with W wall quickly reached
- tolerable W concentration
- tailoring of discharge necessary to avoid central W accumulation - much operational experience gained
- radiation typically > 50% at intermediate density
- quasi-stationary for more than 4 seconds (equivalent to 60 t_E or 1.5 t_{CR})



High performance achieved with tungsten wall at AUG

Spectroscopy: relative fractional abundance of W^{44+}



Benchmark of atomic data with measurements (symbols)

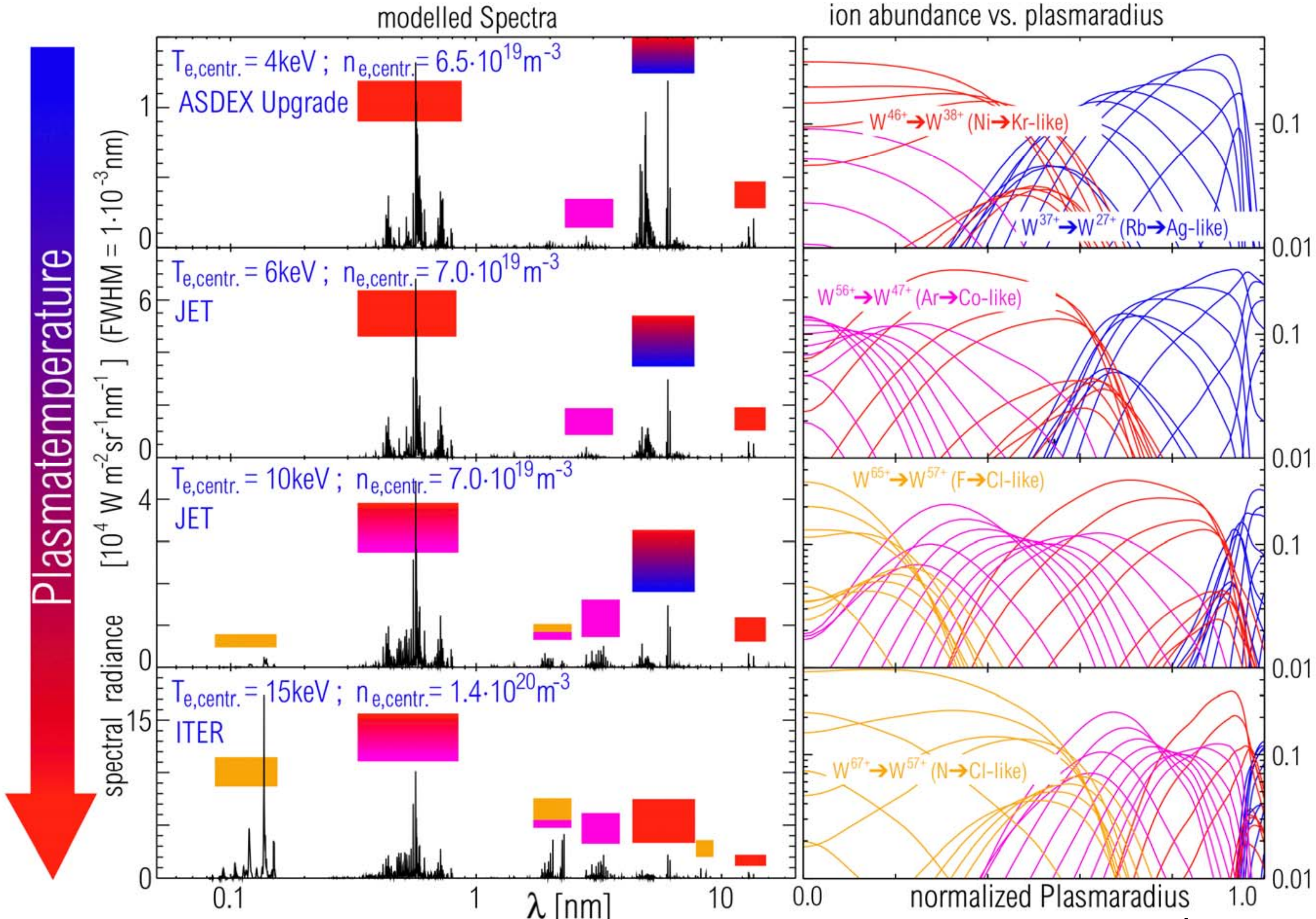
Calculation w. Cowan code of:
- Atomic / Ionic structure
- Transition probabilities
- e^- impact excitation(CADW Configuration Averaged DW)

Collisional-radiative modelling (using ADAS routines & ADPAK recombination data, AIM)

In general, good agreement for Ion states W^{40+} to W^{46+}

Th. Pütterich

Modelled W spectra & ionization states



Th. Pütterich

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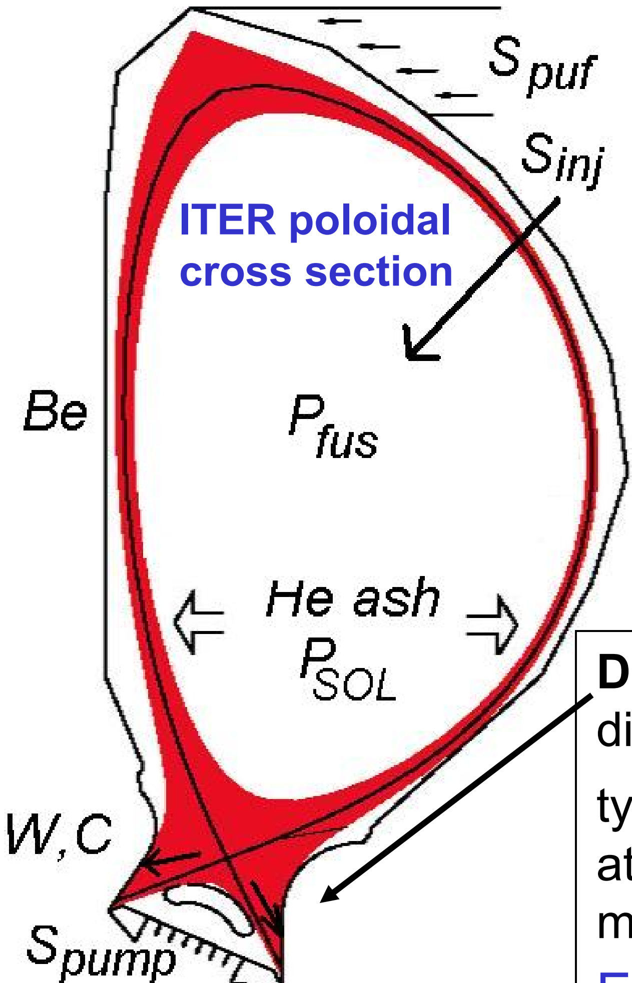
Edge / Divertor Modelling



ITER parameter

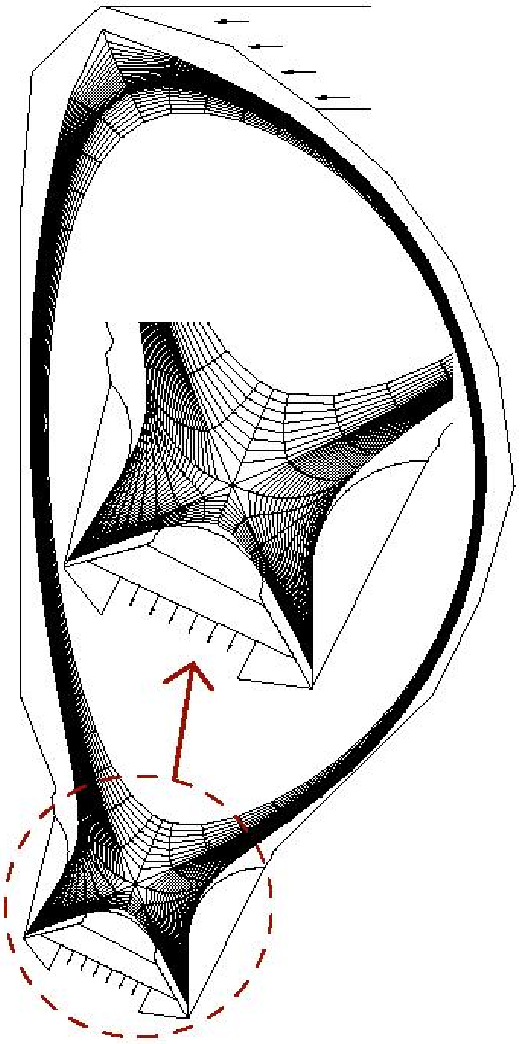
- $P_{fus} \approx$ 540-600 MW
  $\Rightarrow$ He flux
  $\Rightarrow P_{SOL} \approx$ 86-120 MW
- $c_{He} \leq 6\%$
- $q_{pk} \leq 10$ MW/m^2

Divertor: impurity control, power and particle exhaust are dislocated from the main chamber

typical $T_e \sim 1 - 100$ eV; e^-, H^+, H, H_2
atomic impurities: He,Be,B,C,O,Cu,W; q=0 - 3, 4
molecular impurities: C_xH_y, CO, CO, CO_2, OH, H_2O, BeH

Extremely large variety of collision processes due to low plasma temperatures, presence of neutrals, molecular species and low charge state impurities.

Design of the ITER divertor is guided by B2-EIRENE simulations



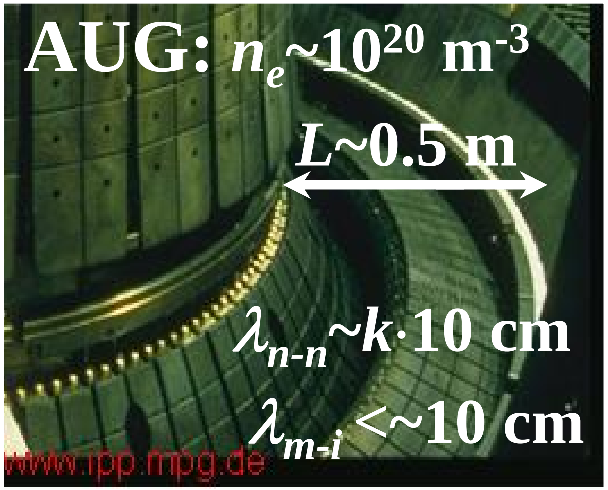
Divertor

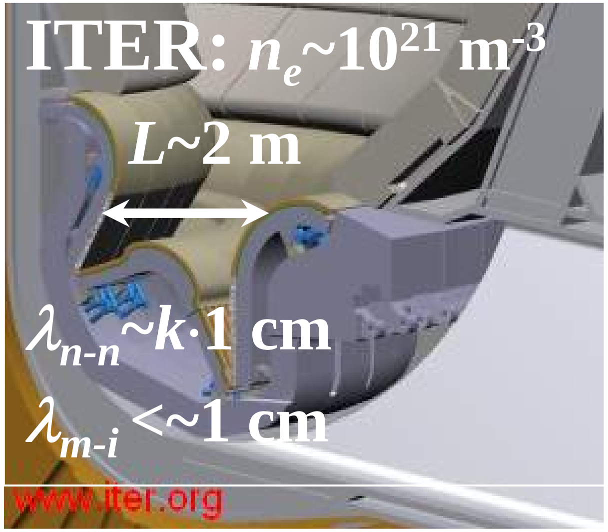
B2: 2D, time-dependent set of Braginskii equations. Finite-volume scheme on quasi-orthogonal grid, multi-fluid.

EIRENE. Monte-Carlo neutral transport. Calculates sources for B2, based on 3D kinetic gas transport, **plasma surface interaction and atomic and molecular plasma chemistry**

Numerical book-keeping for all known processes.

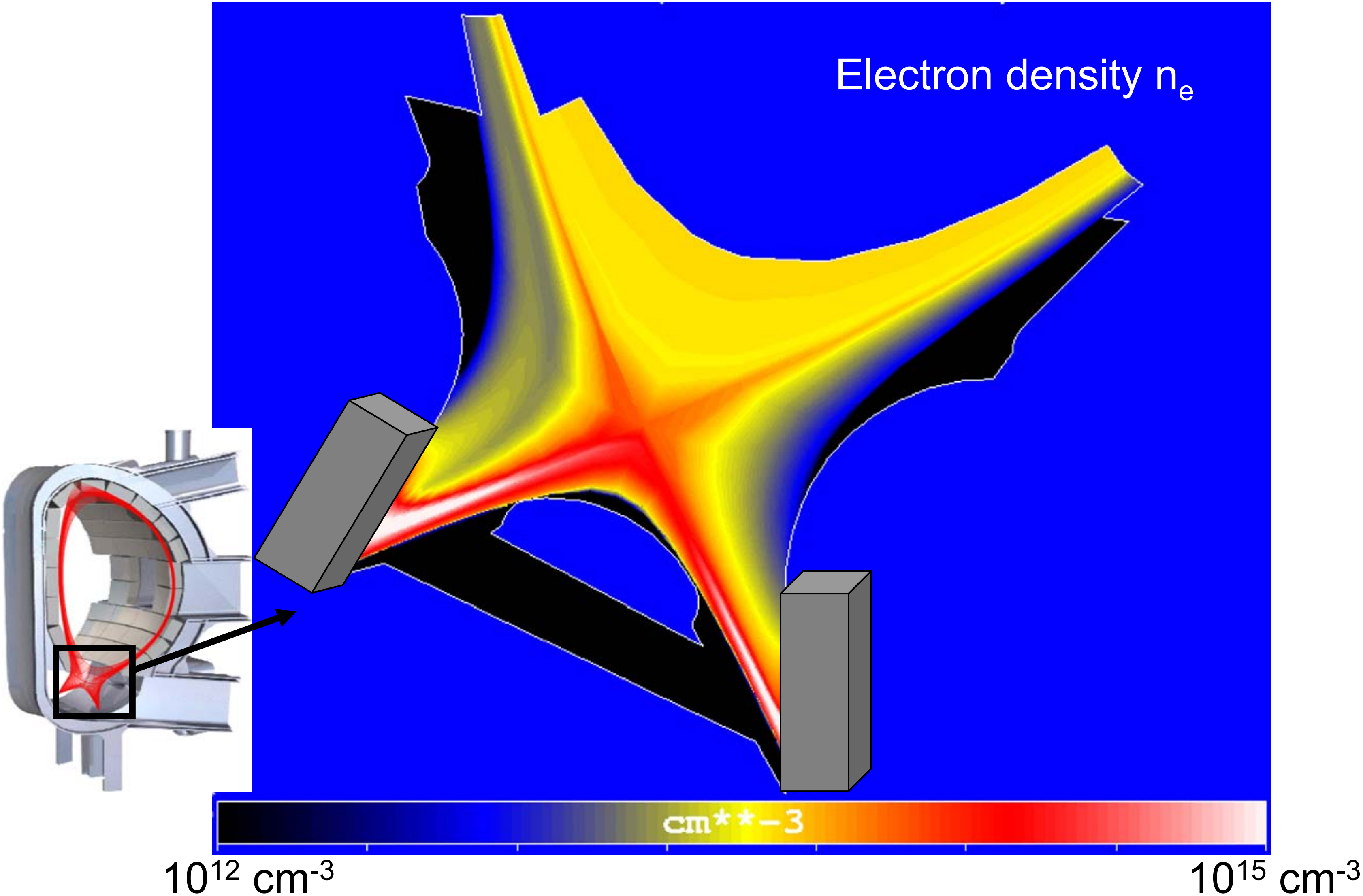
Comparison AUG - ITER divertor





- The ITER divertor will have much larger $L\cdot n$ then all existing tokamaks.
- It is necessary to take into account effects which have been safely ignored in divertor modeling for most present-day devices
- One such effect is *neutral-neutral collisions (viscous effects in gas)*
- Large regions of dense, low temperature plasma requires more accurate simulation of the *molecular reaction kinetics*, including *molecule-ion collisions*

B2-Eirene simulation, detached divertor, n_e



Simulations deliver as well, T_e, n_{atom}, n_{molec}

D. Reiter, FZ-J

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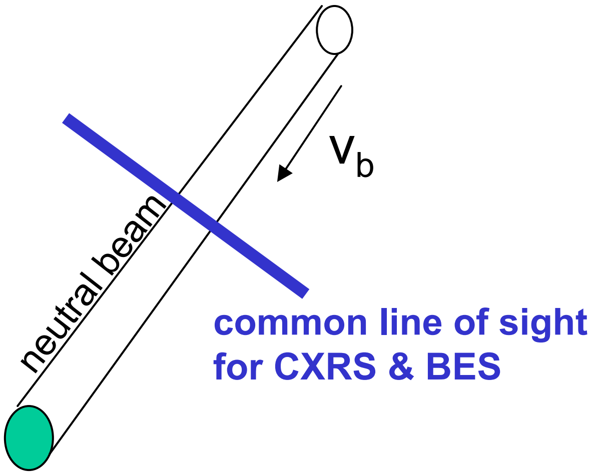
CXRS & BES plans for ITER (i)

CXRS: Charge Exchange Recombination Spectroscopy

BES: Beam Emission Spectroscopy

- dedicated hydrogen diagnostic beam (DNB): 100-200 keV/amu, 2.2MW, modulated to improve S/N ratio
- Combination of CXRS and BES to get absolute impurity densities n_z (e.g. He ash) by just relative measurements.



$$I_{CXRS} = \frac{1}{4\pi} \cdot n_z \cdot \sigma_{CX}(E) \cdot v_b \cdot \int n_b ds$$

$$I_{BES} = \frac{1}{4\pi} \cdot n_e \cdot \sigma_{BES}(E) \cdot v_b \cdot \int n_b ds$$

$$\Longrightarrow \quad n_z = n_e \cdot \frac{I_{CXRS}}{I_{BES}} \cdot \frac{\sigma_{BES}}{\sigma_{CXRS}}$$

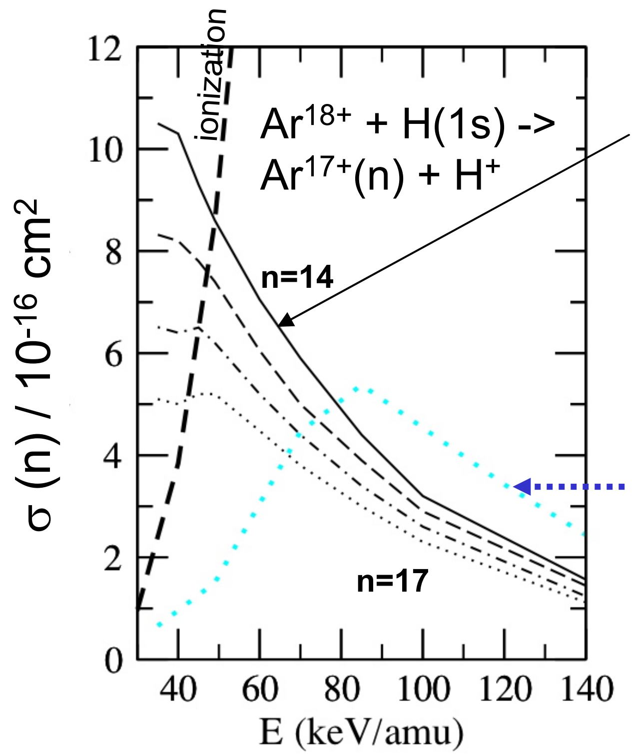
Review of BES atomic data set needed, including excited states;
Accurate beam composition and attenuation in plasma needed.

CXRS & BES plans for ITER (ii)

Species	λ_{min} / nm	λ_{max} / nm
D I, **Ar XVI**	432	440
He II, Be IV	460	474
Ar XVIII, Ne X, C VI	519	533

Argon seeding to reduce the power load of the ITER divertor → Accurate Ar densities needed

n -> n'	Ar XVIII
16 - 15	5223 Å



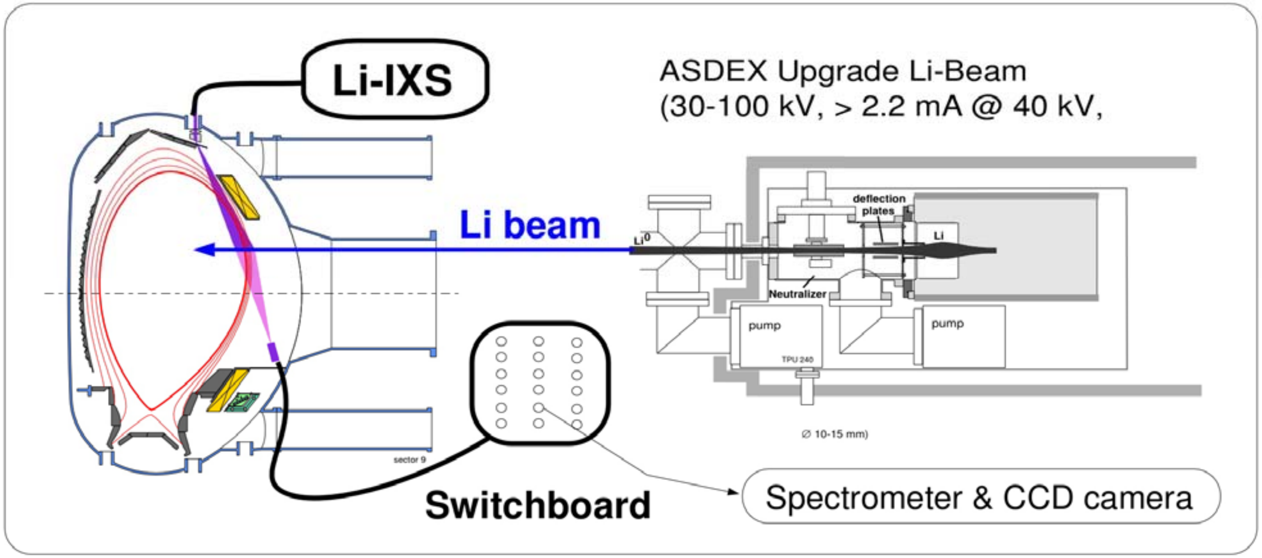
Improved CTMS calculations for n=14-17 using a hydrogenic initial distribution

Standard CTMS for n=14 with micro-canonical initial distribution

Errea et al. J.Phys. B 2006

These CTMS results are the only data source. Benchmarking experiments on AUG have just started.

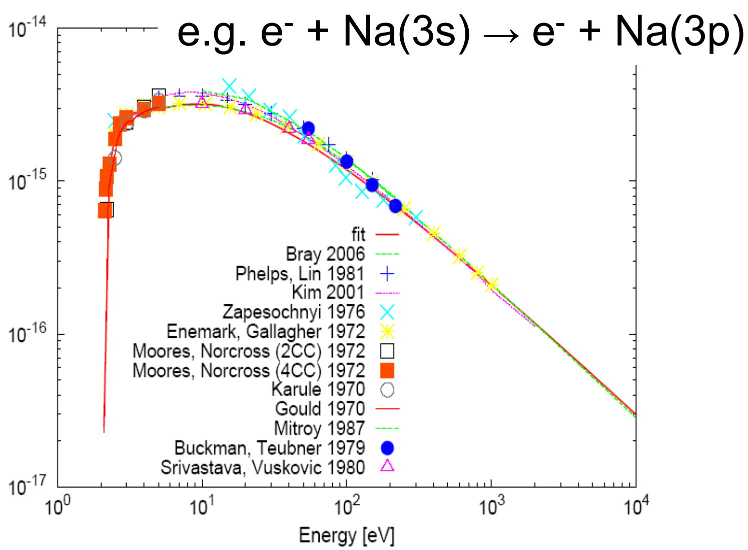
Alkali beams for edge diagnostic



Lithium beam - standard diagnostic for n_e, T_i, c_z since many years at AUG & JET

Sodium beam - A couple of advantages, will be next step

Database for Na almost finished



Beam modeling requires database

(A = Li(nl≤4f), Na(nl≤4f,5s))

- Excitation:

  $e^- + A \rightarrow e^- + A^*$

  $H^+, Z^{q+} + A \rightarrow H^+, Z^{q+} + A^*$

- Ionization:

  $e^- + A \rightarrow 2e^- + A^+$

  $H^+, Z^{q+} + A \rightarrow H^+, Z^{q+} + e^- + A^+$

- Charge transfer:

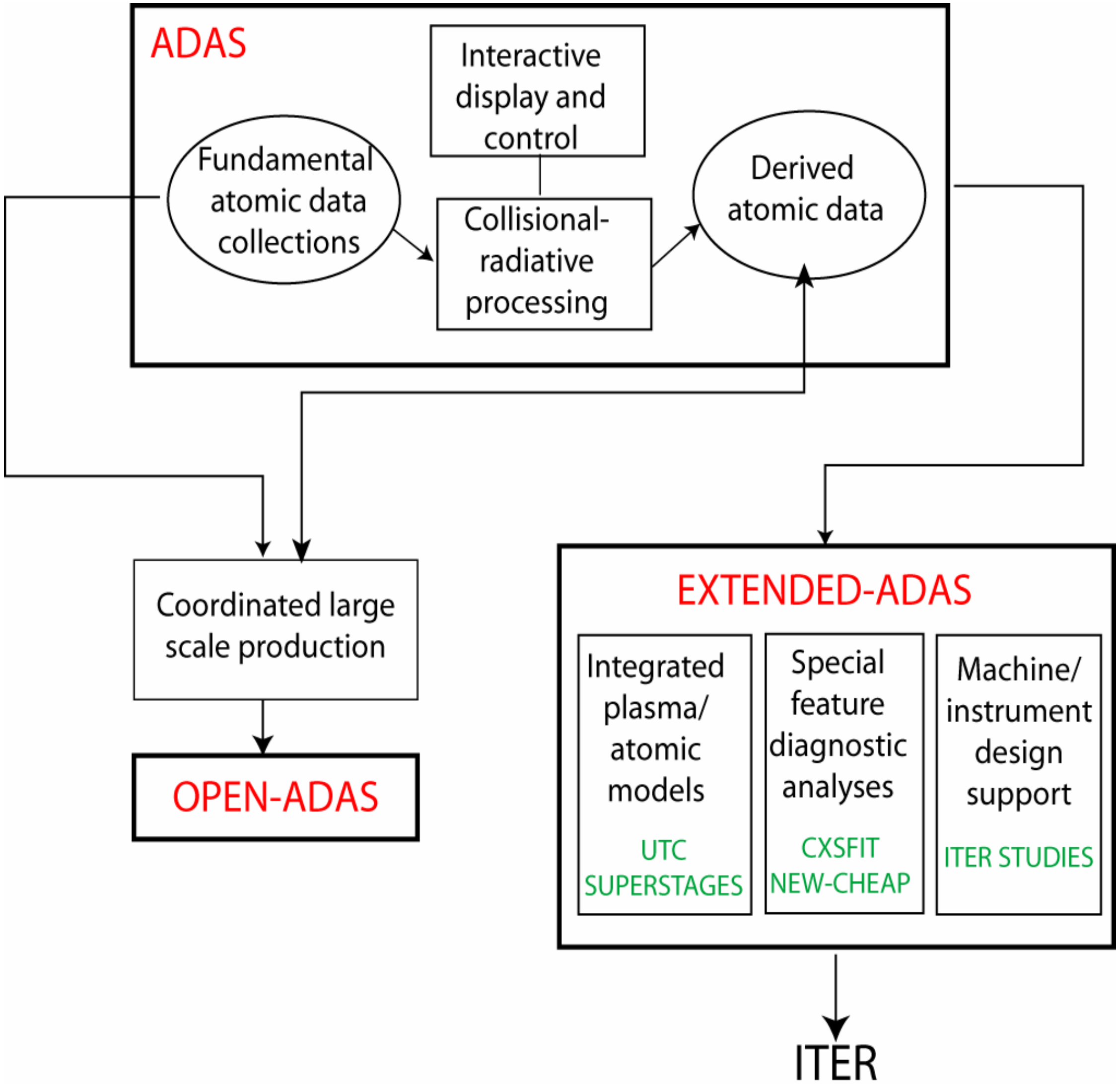
  $H^+, Z^{q+} + A \rightarrow H^0, Z^{(q-1)+} + A^+$

Summary: Requirements for basic atomic data

- Energy levels and wavelengths of high-Z, highly ionised elements, in particular tungsten, for spectroscopic diagnostics in ITER - theoretical and experimental
- Ionisation, recombination and excitation rate coefficients for simulation codes, low- and high-Z elements, including collisional-radiative population codes - theoretical data, possibly benchmarked by individual experiments
- Charge-exchange data, in particular for medium-Z elements for spectroscopic diagnostics (radiative edge cooling, e.g. argon), theoretical data, validated by present fusion plasmas
- Data for molecular reactions in the edge and divertor plasmas, e.g. H_2, D_2, T_2, hydrocarbons, boron - theoretical and experimental

- The Atomic Data and Analysis Structure, ADAS, is a system of computer codes and data for the support of fusion and astrophysics.
- It originated at the JET Joint Undertaking in 1986 and has operated since 1994 through the ADAS Project.
- The Project is self-funded by its members.
- Most large fusion laboratories are members of the ADAS Project.

ADAS schematic



- ADAS is a graphical interactive system which allows immediate calculation and display of derived quantities, such as effective recombination coefficients and photon emissivity coefficients.
- ADAS includes a very large database of fundamental and derived atomic data.
- ADAS includes extensive subroutine libraries. These range from basic atomic calculations such as generation to ionisation equilibria evaluation. They also include a range of routines for accessing the database and delivering data to user codes (plasma modelling).
- ADAS includes a substantial capability for calculation of fundamental atomic data such as energies, transition probabilities, Auger rates and electron impact collision cross sections.

ADAS CXS development map

ITEM	PHYSICS AND APPLICATION ISSUES	STUDIES/SOURCES
Shared CXS analysis (CXSFIT) (NEW-CHEAP)	Machine independent CXS spectral region spectral fitting, local machine characteristics and spectrocopy interfaces. CXS spectral line interpretative analysis for concentrations plasma parameters, reverse and forward modelling, predictive with error propagation and analysis	TEXTOR (MGvH) ASDEX-U (LDH) JET (K-DZ, ADW)
CXS for argon (state selective xsects)	Discrepancy between CTMC models. - origin in classical microfield representation. Improved-CTMC production for Ar^{+18}, Ar^{+16}. CCMO/CCCAO extension to overlap energy for Ar^{+18} Experimental verification in CXS spectroscopy	UAM Madrid (CI, LM) UAM Madrid (AR, LM) Hahn-Meitner(WF ,CDL)
Multiple receiver element charge states	Potential simultaneous observation of Ar^{+18}, Ar^{+17}, Ar^{+16}, Ar^{+17} predicted but unexplored. Shell localisation core temperature dependent. Localised simultaneous CXS - transport (UTC/SANCO)	ASDEX-U (CFM, CI, HPS, MGvH,ADW) JET (CG, MGvH, MOM, ADW)
Heavy element CXS analysis	Higher n-shell visible CXS adds n-shell mixing on top of main l-shell mixing/cascade mechanism. Bundle-n projection extension for theoretical CXS emissivities. Universal CXS emission prediction - multi-line feature.	Strathclyde (HPS) EFDA-JET (HPS) MAST(AF) UAM Madrid (CI,LM)

■ Lead theoretical university group representing extended cooperation

ADAS availability and dissemination

- ADAS is a provision for the laboratories which are its sponsors. All persons and visitors at these sites have access to ADAS. There is central provision at EFDA-JET accessible from all Associated Laboratories of the European fusion programme.
- There is access through data centres at Oak Ridge National Data Centre, USA and the National Institute for Fusion Science, Japan.
- Of the ~2.5 Gbyte of ADAS data, ~1.5 Gbyte is public domain, ~150 Mbyte of key adf11 and adf15 data are supplied freely with transport models from IPP-Garching since 1998.
- Under the joint sponsorship of the IAEA Atomic and Molecular Data Unit, Vienna and the ADAS Project, an initiative is underway to give access to selected ADAS data and facilities via the IAEA website – called OPEN-ADAS.
- A new tagging, index and search system is being developed for the principal ADAS data formats to enable identification of appropriate data for applications and to provide guidance on the use of the data. The tagging of ADAS data is being expanded to support this.
- Sets of procedures for download, along with the data themselves are being provided in a number of languages for reading ADAS data into a user's own code.

Comparison of material properties C vs. W

C based first wall materials:

✓ Low cooling factors at core electron temperatures

✓ Good power handling capabilities (Sublimation, thermal conduction)

✗ Strong T co-deposition ➡ Radiation inventory

✗ High erosion yields (Chemical) ➡ Component lifetime

ITER

• DEMO

Knockout criteria

W as first wall material:

✓ Low sputter yields (Threshold energy (D) = 178 eV)

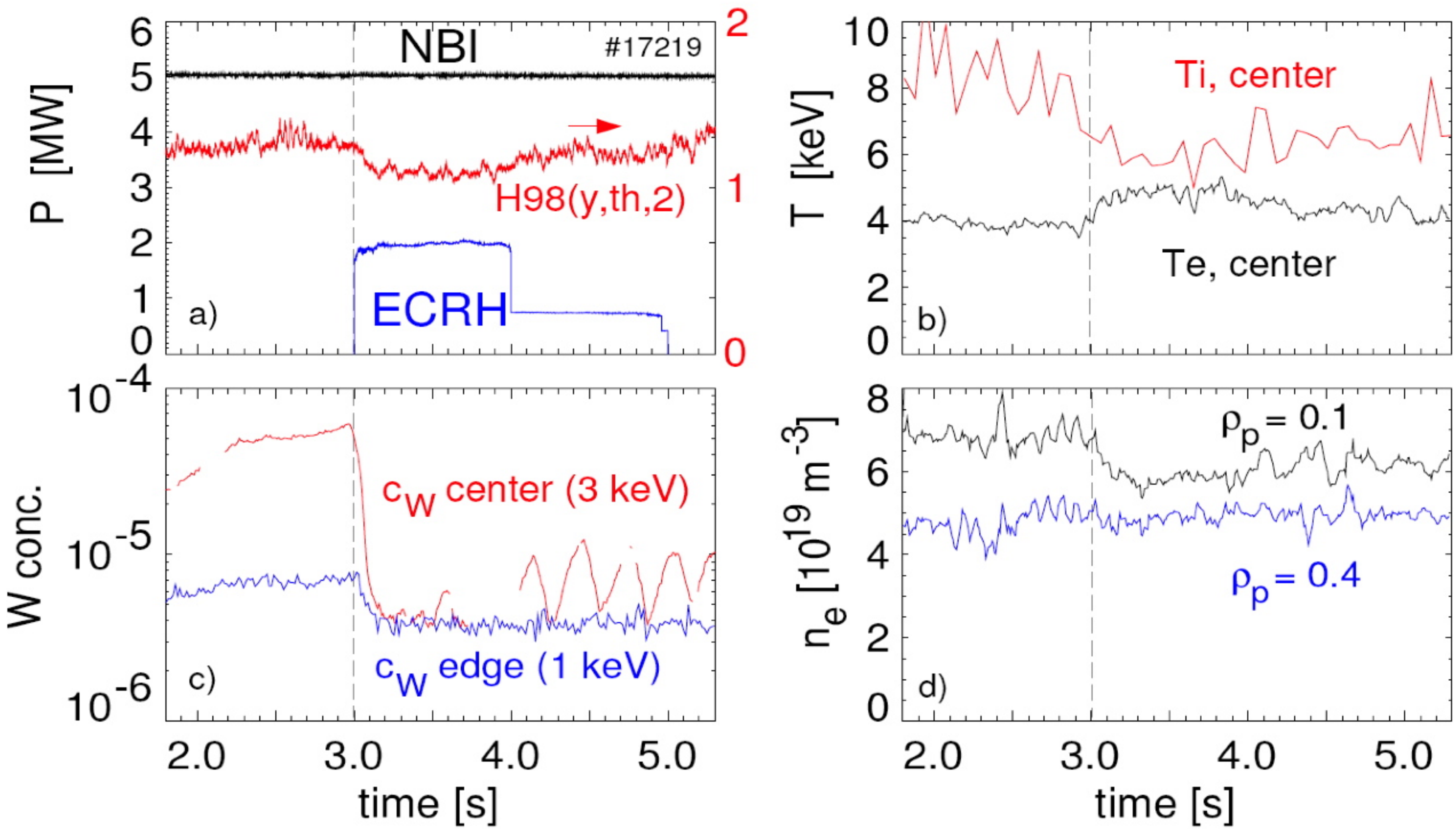
✓ Low T co-deposition

✗ High cooling factors at core electron temperatures

✗ Poor power handling capabilities (melting, low thermal conduction)

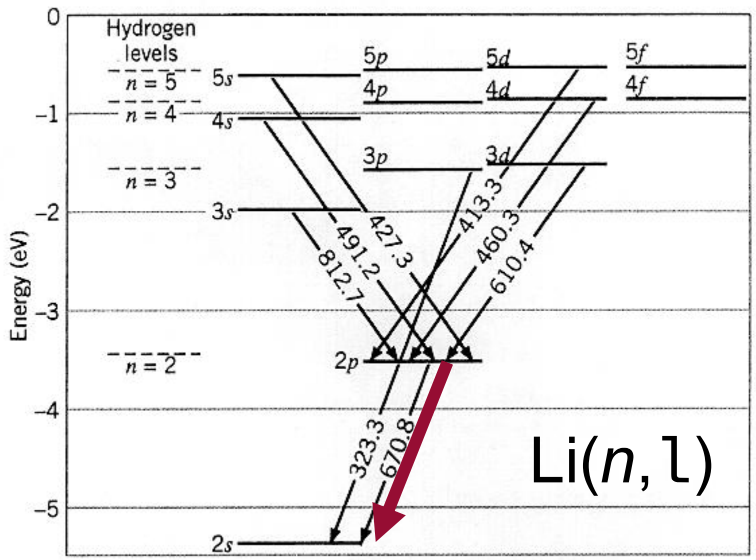
✗ Requires seeded impurities (Ar, Ne) to radiate power from SOL

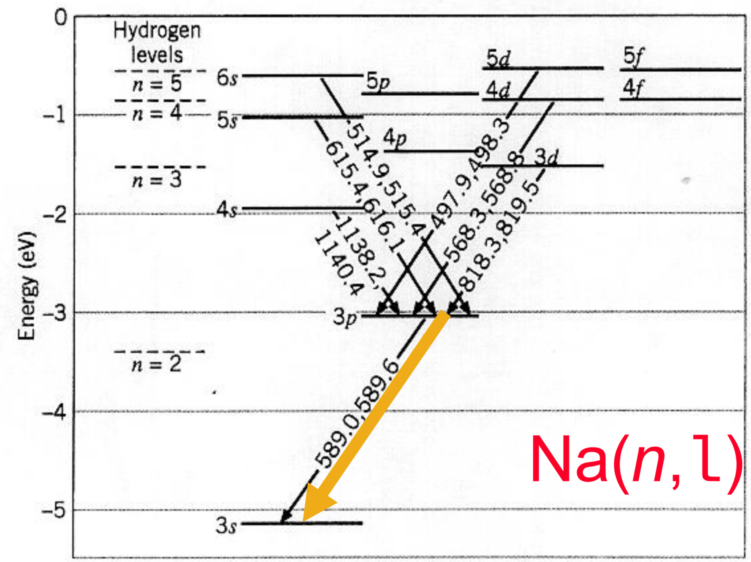
Central heating important to avoid impurity peaking



Reduction of peaking by increased anomalous transport in the centre with moderate effect of the global confinement. ECRH better than ICRH (W sputtering at antenna -> additional source)

Li compared to Na





(b)

$$I_{Li} = 5.4eV \qquad I_{Na} = 5.1eV$$

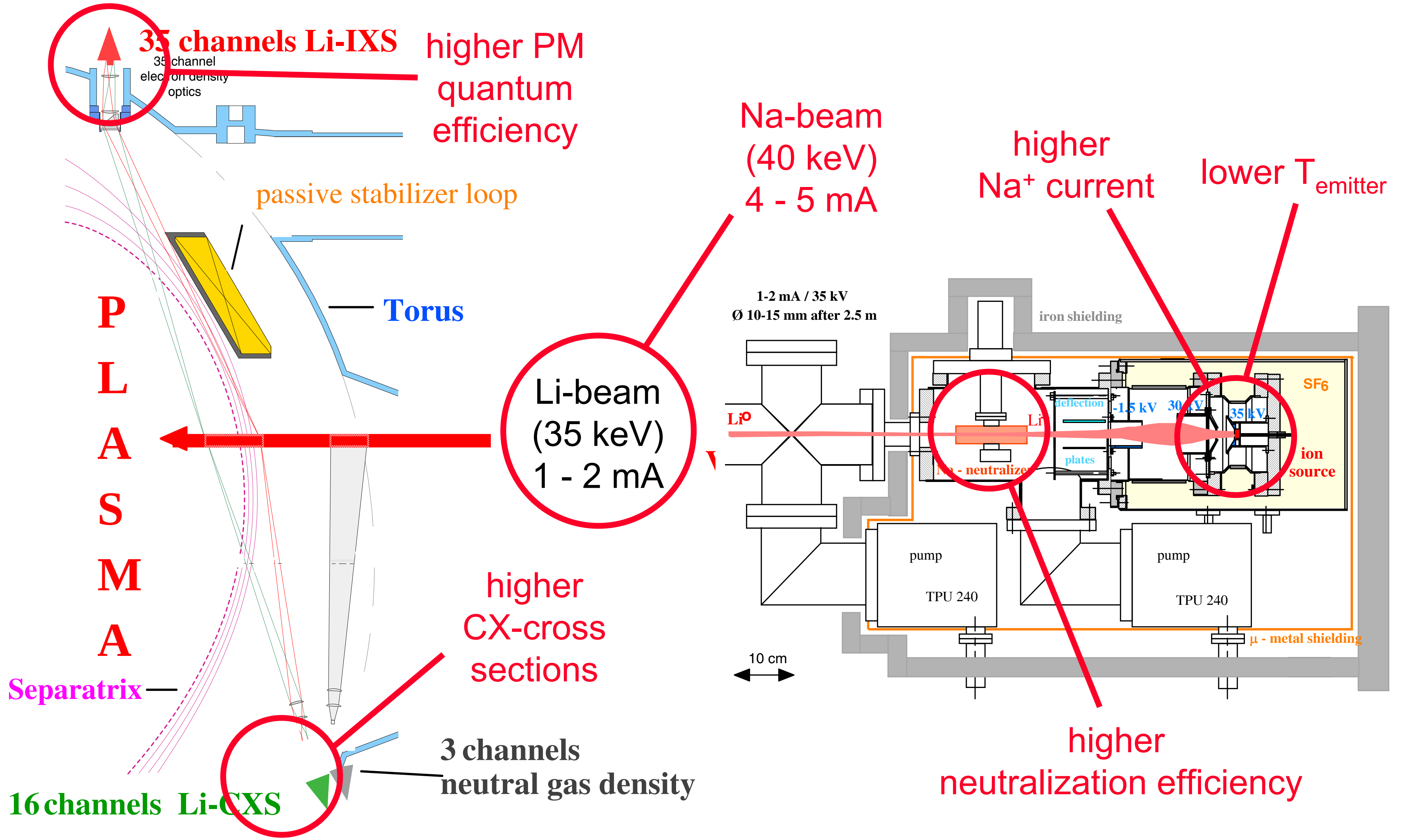
$$\lambda_{Li(2p-2s)} = 670.8nm \qquad \lambda_{Na(3p-3s)} = 589.0nm / 589.6nm$$

$$\boxed{\tau_{Li(2p)} = 27\ ns \qquad \tau_{Na(3p)} = 16\ ns}$$

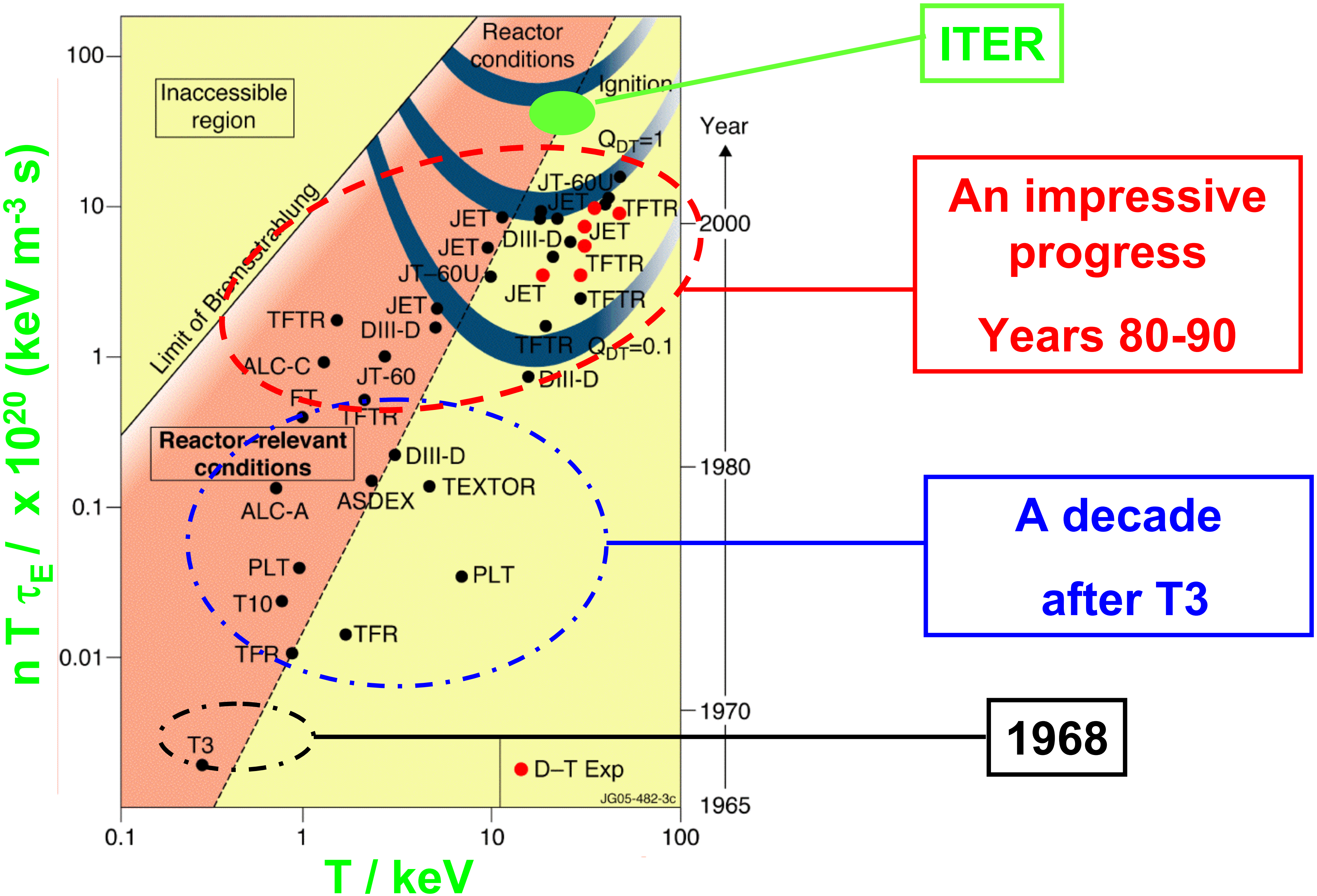
$$m_{Li} = 7amu \qquad m_{Na} = 23amu$$

Shorter Na(3p) lifetime compensates probably higher mass

Advantages of Na beams as compared to Li



Tokamak : a rapid development



JET key tool in the preparation of ITER

The Joint European Torus, is the largest existing Tokamak