Atomic Physics in ITER
The Foundation for the Next Step to Fusion Power

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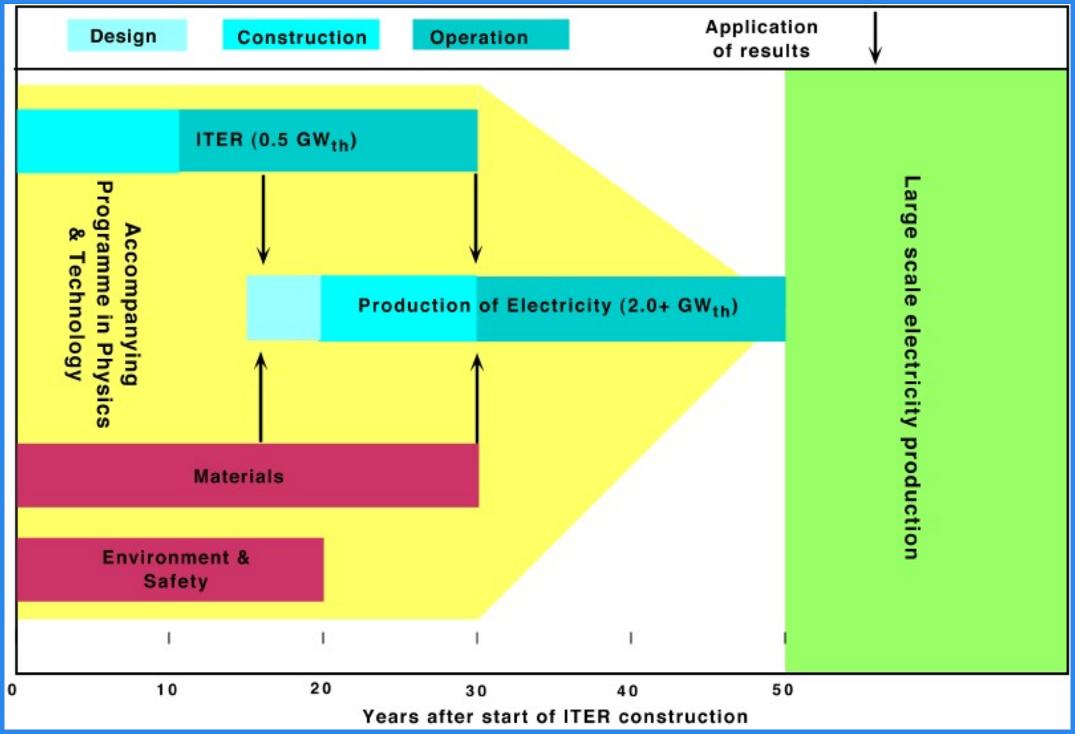
ITER
http://www.iter.org

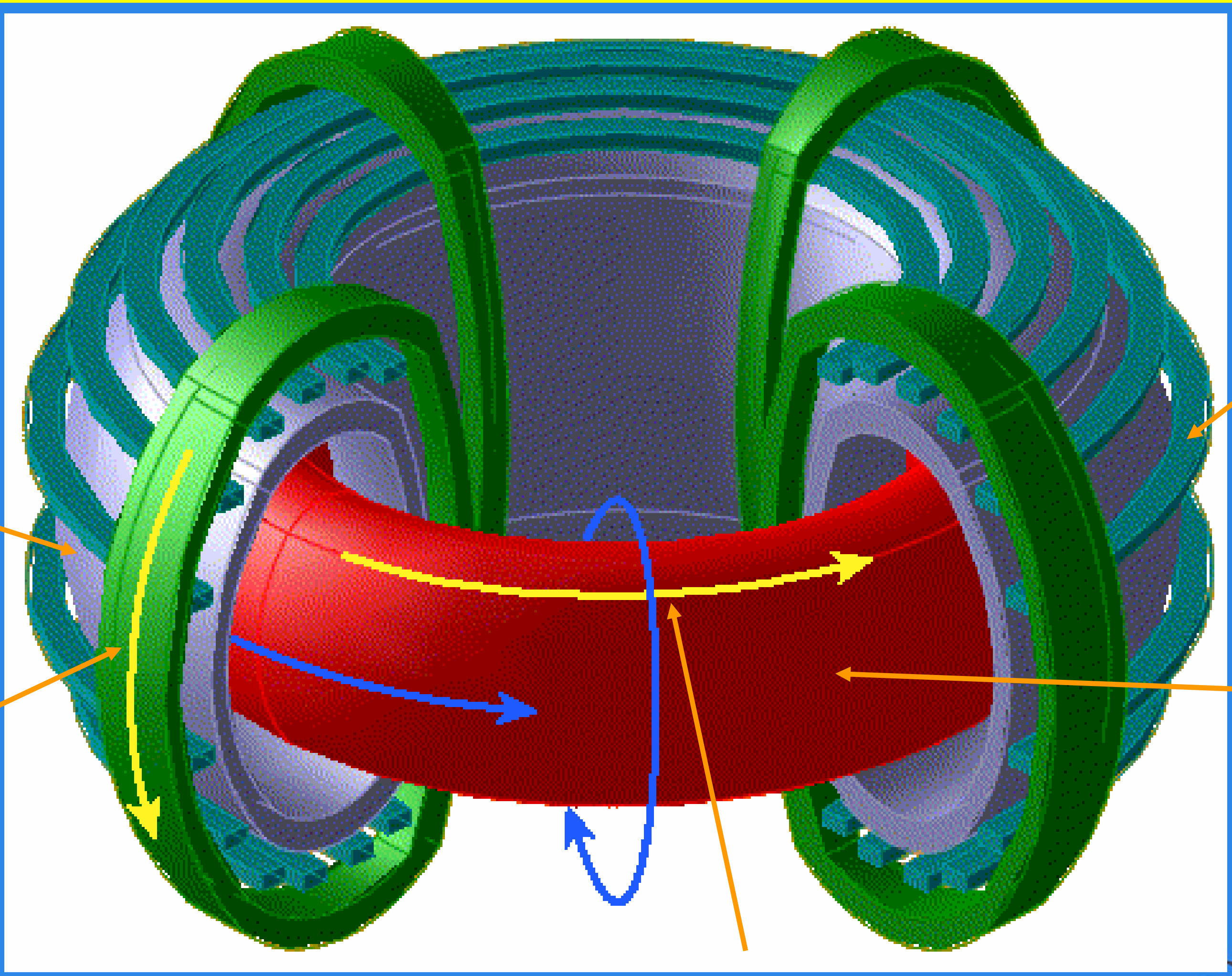
ITER Will Demonstrate Scientific & Technological Feasibility of Fusion Power

- Produce & control burning fusion plasma for extended periods of time [ITB 2002, IPB 1999].
- Test reactor relevant technologies:
  - Superconducting magnets,
  - High heat & neutron flux components,
  - Remote maintenance.
- ITER will not generate net electricity,
  - But, will test power reactor blanket modules,
  - And tritium breeding concepts.
  - ITER will also need to "recycle" tritium on site.



[Smith 2004, IFRC 2005, Socolow 2006]

The Most Successful Magnetic Confinement Configuration is the Tokamak



Stabilizing and shaping magnetic fields are generated by currents in other coils

vacuum vessel

plasma

Current driven through coils distributed around torus creates primary magnetic field

An external transformer induces a current in plasma around torus that creates a smaller magnetic field

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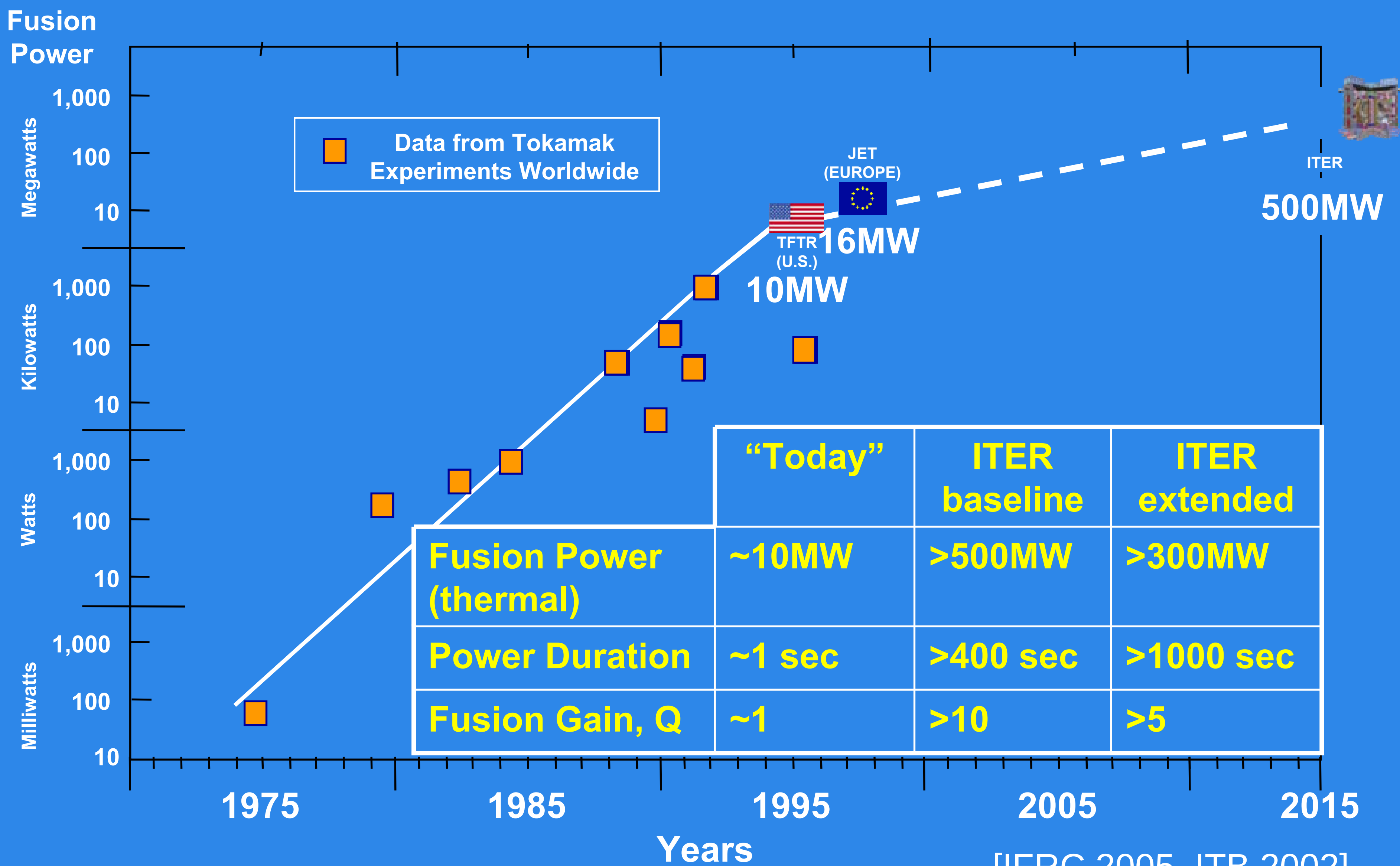
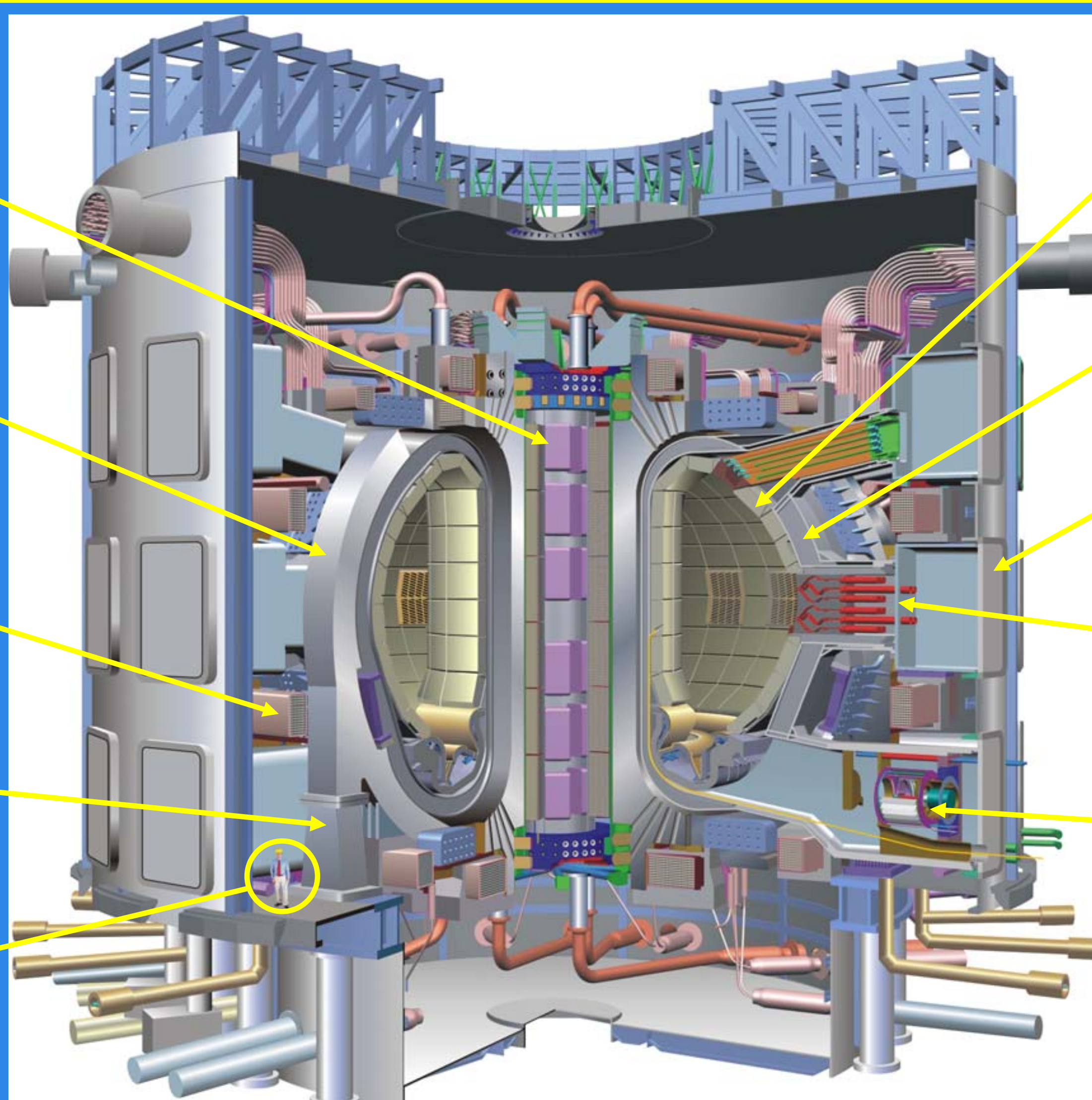
ITER's Fusion Performance in Context



	"Today"	ITER baseline	ITER extended
Fusion Power (thermal)	~10MW	>500MW	>300MW
Power Duration	~1 sec	>400 sec	>1000 sec
Fusion Gain, Q	~1	>10	>5

[IFRC 2005, ITB 2002]

ITER: $R = 6.2$ m, $a = 2.0$ m, $V_p = 850$ m^3
$I_p = 15$ MA, $B_T = 5.3$ T, $W_{mag} = 41$ GJ



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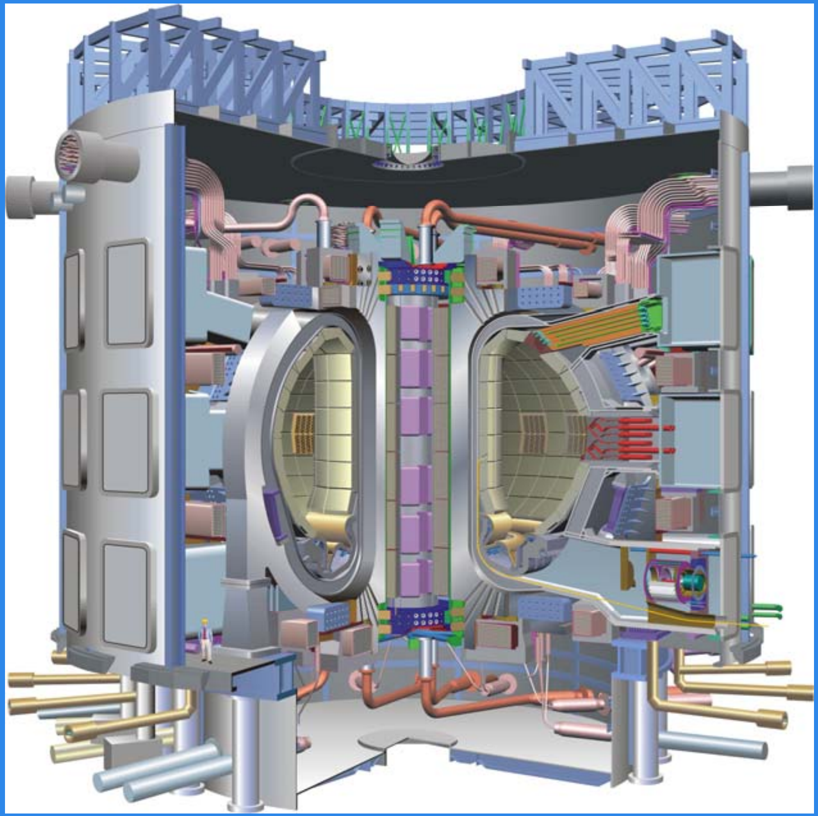
In May 2006, the ITER International Agreement was Initialed

- The partner governments:
  - Have judged sufficient scientific and technological readiness and benefits,
  - Are committing 110% of the ITER value for construction,
  - Have agreed on the hardware responsibilities of each party,
  - Have developed organizational and legal arrangements for the ITER Legal Entity.
- International agreement was initialed in May; signing is planned for November 21.
- Transitional activities are underway.



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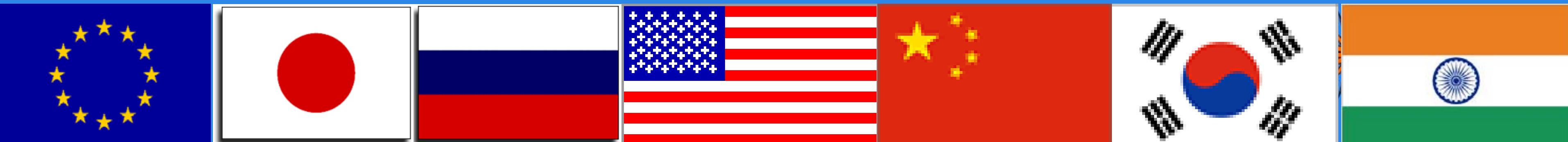

Outline

1. Introduction / ITER Experiment
2. Boundary of Tokamak Plasmas
3. Atomic Physics in the Edge & Divertor Plasmas
   A. Recycling
   B. Radiating Mantle
4. Atomic Physics in Core Diagnostics
   A. CX Recombination Spectroscopy
   B. Motional Stark Effect
   C. X-ray Crystal Spectroscopy

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FORS, VLT, ESO


NASA, ESA and J. Hester (Arizona State University)

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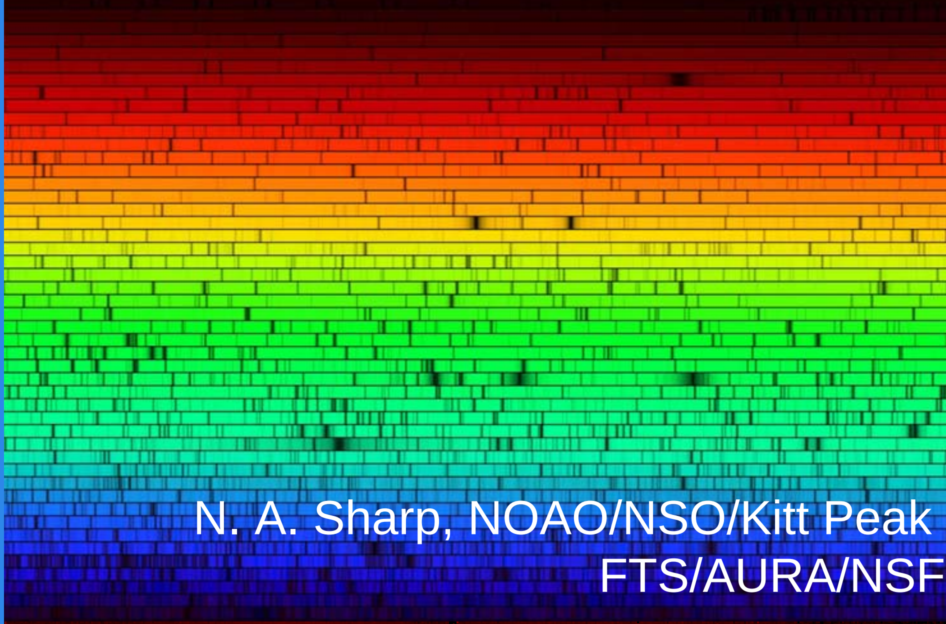
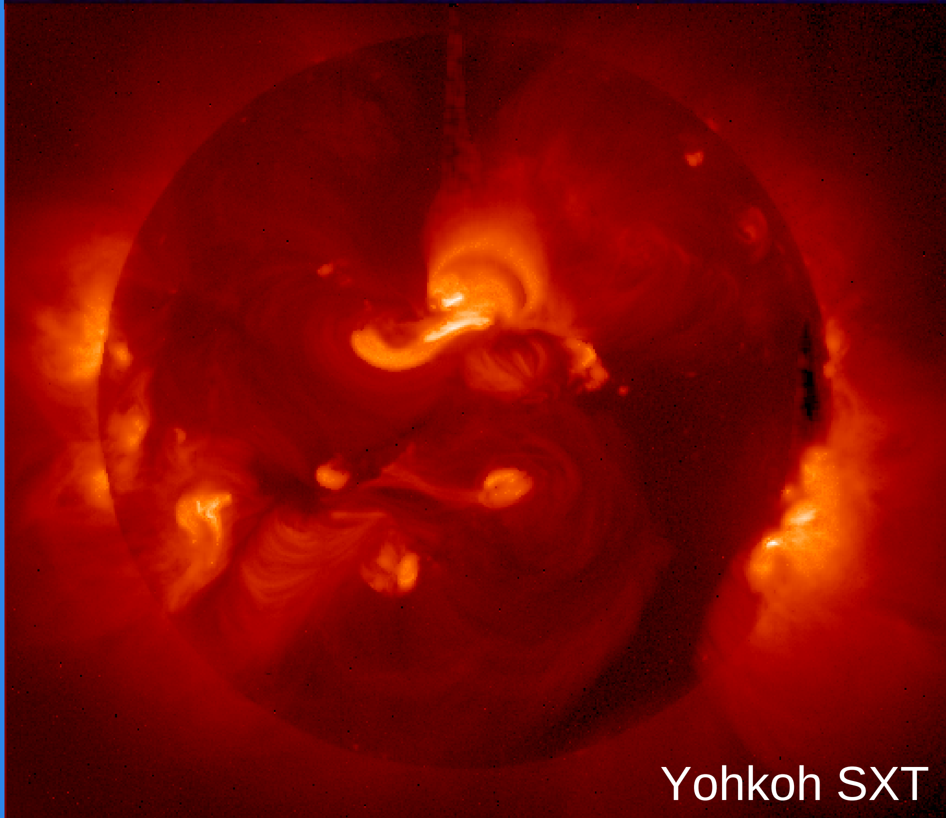
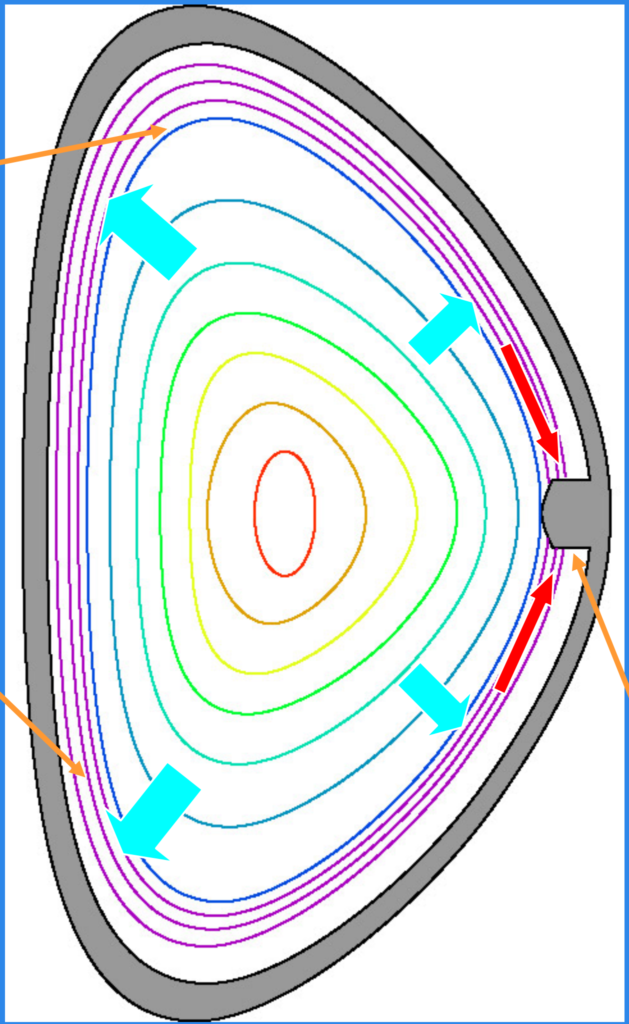


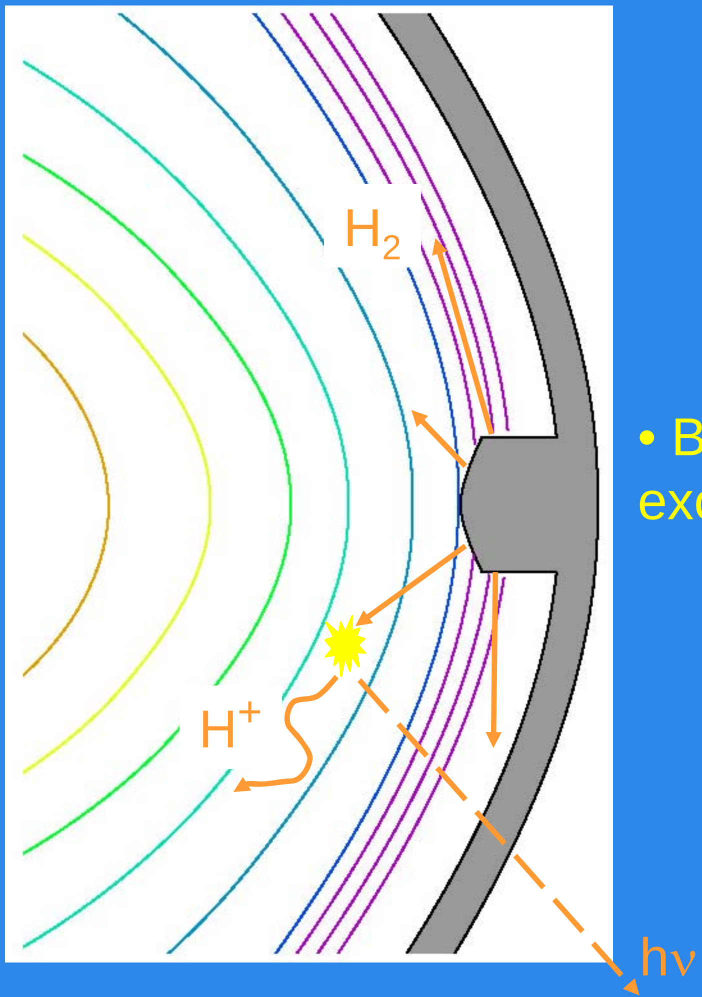


Simplest Plasma-Material Interaction Configuration Is the Limiter



- Limiter location defines last-closed flux surface,
    - Intercepts open field lines / flux surfaces ⇒ scrape-off layer (SOL).
- General reference: [Stangeby 2000],
    - See also: [Reiter 2005].

Limiter Acts as a Sink for Plasma Particles and Power



- Not for mass, however:
  - Electrons & ions recombine at surface,
  - In steady-state, resulting neutral atoms & molecules recycle back into plasma.
  - Neutrals travel freely across field lines,
  - & be ionized near or far from limiter
  - ⇒ plasma can refuel itself.
- Before being ionized, H atoms can be excited by electron impact,
  - Radiatively decay & emit photons,
  - ⇒ Markers of ionization.
  - E.g., n = 3 → 2 transition (Balmer-alpha or H_α) at ~6560 Å dominates visible emissions & is often used for diagnostics.

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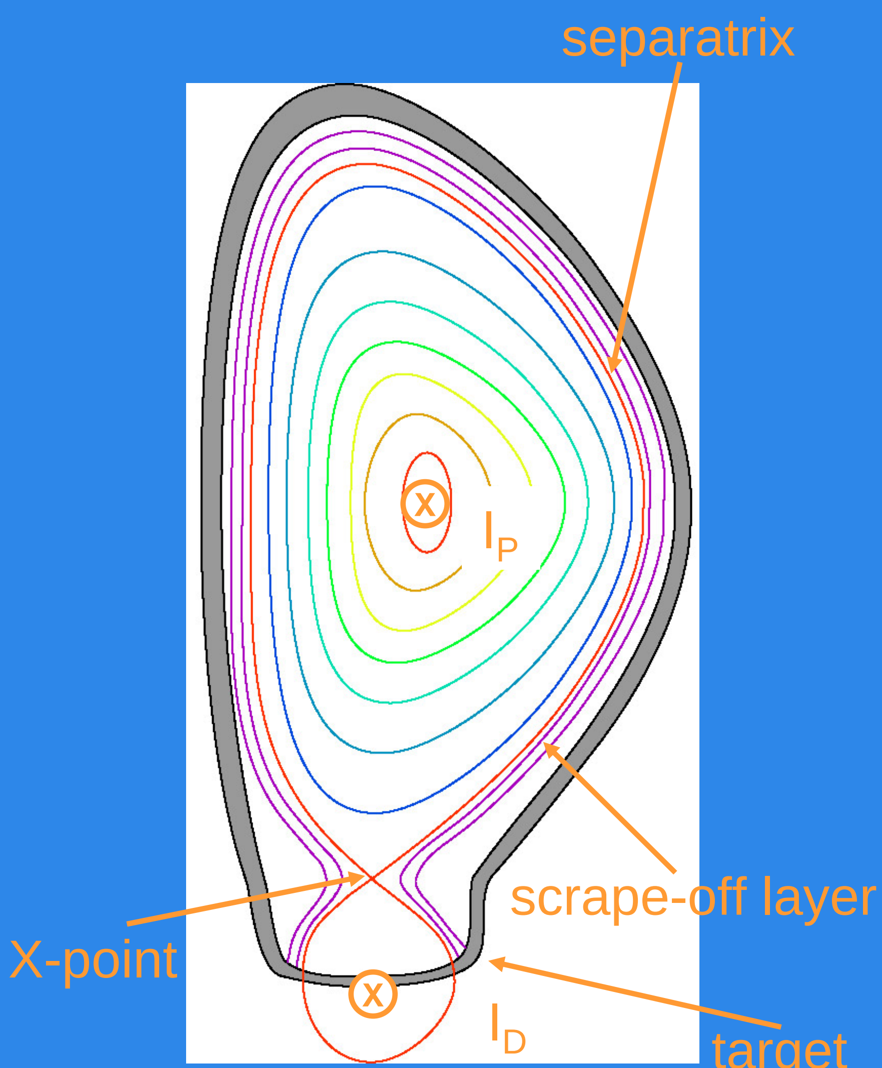
Tokamak Divertor Configuration Moves the Plasma Material Interaction Away From Core



- Divertor created by adding coil I_D with current in same direction as I_P.
- In between, get B_{pol}=0.
  - This is the X-point.
  - Corresponding surface is separatrix; becomes the LCFS.
  - Separates SOL from core plasma.
- SOL field lines strike material surface at the divertor targets.
- Divertors concentrate particles & power.
  - Facilitates pumping,
  - But complicates power handling!

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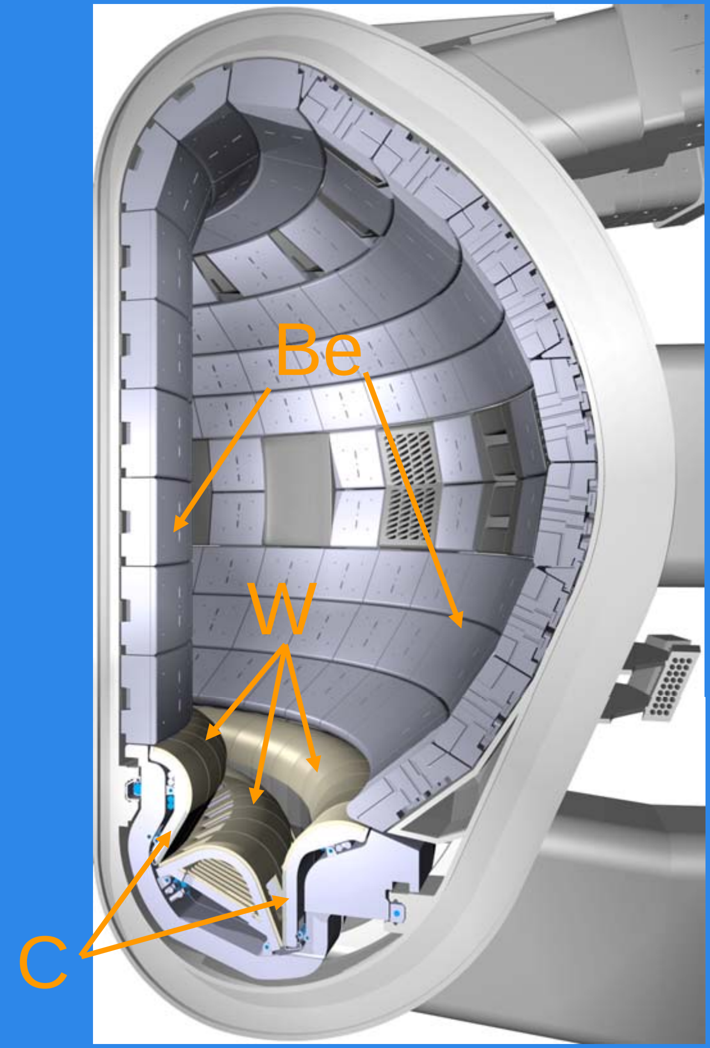
ITER Will Use a Mix of Plasma Facing Materials



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- Main chamber: Be.
- Divertor surfaces mostly W,
  - Except for target strike points, C.
- Existing tokamak database dominated by all carbon machines,
  - More aggressive research with ITER relevant materials under way.
- Divertor plasma parameters:
  - $n_e = 10^{20} – 10^{21}$ m^{-3},
  - $T_e = 0.1 – 100$ eV,
  - $n_D = 10^{19} – 10^{20}$ m^{-3},
  - $P_{D2} = 0.1 – 10$ Pa (plenum).

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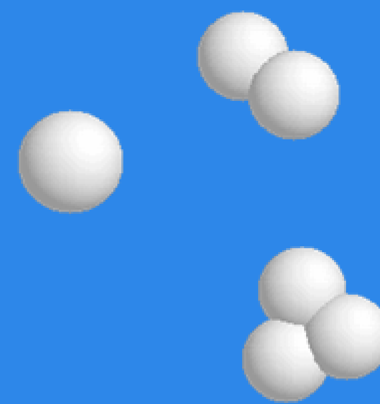
Atomic Physics Processes Mediate Exchange of Mass, Momentum, & Energy Between Plasma & Neutrals

- H CR ionization & recombination,
  - H & H^+ not in equilibrium! [Reiter 1993]
- Elastic scattering of H, H_2 on H^+,
  - Fully quantal $d\sigma/d\Omega$ [Krstic 1998, Stotler 2001],
  - Momentum transfer to H_2 crucial.
- H_2, H_2^+ dissociation, ionization,
  - Basic processes: [Janev 1987].
- Vibrational excitation $\Rightarrow$ ion conversion, H_3^+, H^-, …
  - Became relevant with higher n_e, lower T_e divertors,
  - Need combined atomic & molecular CR model [Fantz 2001].
  - Assessment: more data needed [Janev 2003].
- Neutral – neutral collisions (viscosity),
  - Significant in highest density experiments (& ITER [Kukushkin 2005]).
- Lyman-α radiation trapping by H,
  - Need self-consistent simulation of plasma, gas, and radiation [Reiter 2002],
  - With detailed line profiles [Adams 2004].
- For an example: see [Reiter 2005].



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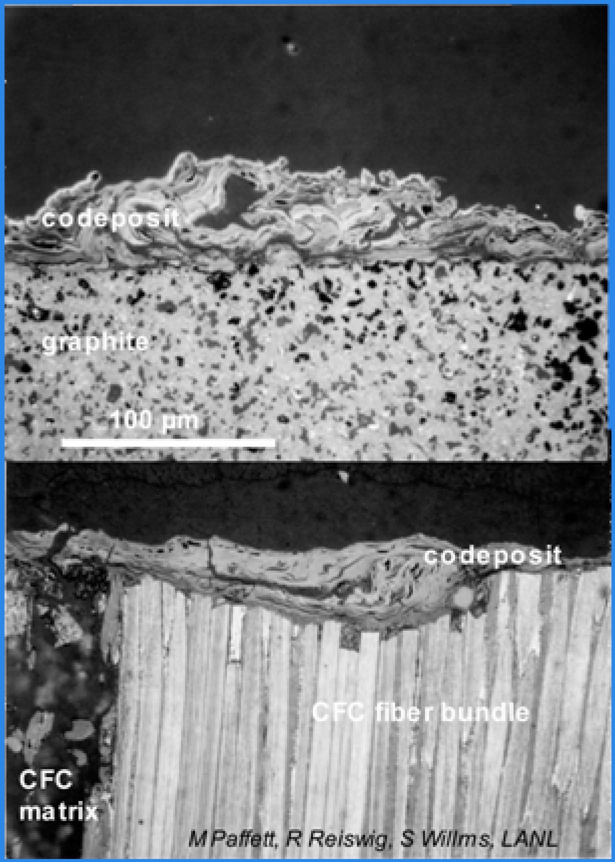
Will Need to Understand Hydrocarbon Behavior

- Safety concerns limit amount of in-vessel tritium in ITER [Federici 2001],
  - Trapped in redeposited hydrocarbons,
  - Extrapolation of existing data ⇒ serious problem.
- Mechanisms of hydrocarbon creation, transport, & deposition not completely understood.
- Starting point: data for dissociation & ionization of hydrocarbons improving,
  - CH_y, C_2H_y, C_3H_y [Janev 2002, Janev 2004],
  - See also HYDKIN reaction analysis tool: http://www.eirene.de/eigen/index.html
- Resulting system very complicated!
  - ~500 processes!
  - Need to reduce to a simpler model for use in simulations.
  - May not be possible in general [Reiter 2006].
- Tritium removal techniques also being pursued.



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Can Estimate Heat Flux Striking Material Surfaces in ITER

- **ITER objective: Q = 5 → 10,**
  - Q = 10, P_{fus} = 500 MW ⇒ P_α = 100 MW, P_{in} = 50 MW, $P_\alpha + P_{in}$ = 150 MW.
- **How to exhaust 150 MW from plasma to surrounding materials?**
  - Plasma will carry it along field lines,
  - Area of divertor target receiving plasma flux determined by plasma through competition between parallel (classical) and perpendicular (turbulent) transport,
    - Latter not well understood ⇒ just have models for ITER.
  - Extrapolate empirical models: ≥ 2 m^2 [Herrmann 2003],
  - ⇒ 75 MW/m^2 heat flux.

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Use Impurity Atoms to Radiate Power Over Larger Area

- Would like to radiate ~75% of the power [Kukushkin 2005].
- Where radiation takes place matters:
  - Too far into core ⇒ occurs at expense of fusion reactions,
  - Too close to divertor targets ⇒ power still concentrated,
  - Ideal: radiating mantle just inside last closed flux surface,
  - Even there, too much radiation spoils core confinement.
  - Modeling shows radiation in edge, SOL, and divertor reducing heat load to 10 MW/m^2 [Kukushkin 2002].
- "Recycling" extrinsic impurities prevent in-vessel accumulation of deposits in steady-state,
  - E.g., noble gases: Ne, Ar, Kr, Xe; also N_2.
  - Using gases makes controlled introduction easier.
- Atomic physics data used for modeling impurity radiation appear in good shape,
  - But, in most present day devices, C is dominant impurity.

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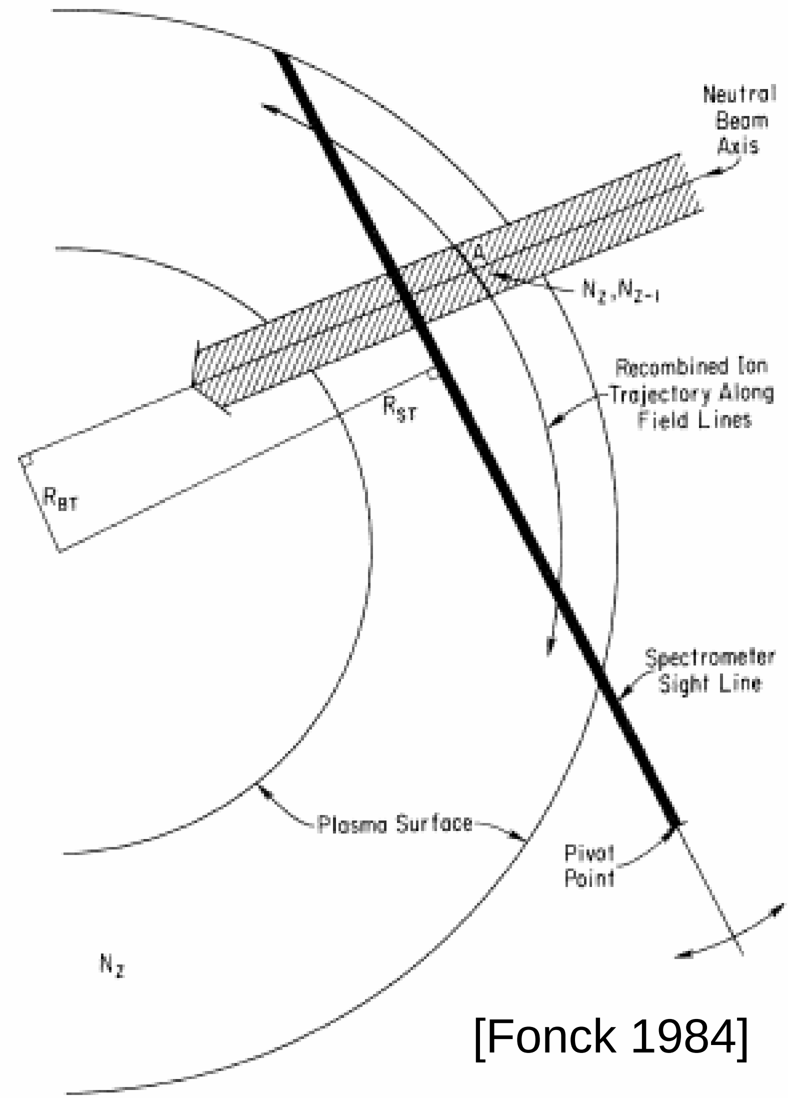
Charge Exchange Recombination Spectroscopy ⇒ n_i, T_i, v_i

- Spectroscopy of optical transitions from CX of injected neutral beam with fully stripped impurity ions in core [Isler 1994],
  - $H + A^{+q} \rightarrow H^{+} + [A^{+(q-1)}]^{*}$
- Use fully stripped ions:
  - That's what's in the core!
  - Resulting ion is H-like.
- Beam energy must be high enough to penetrate to core,
  - Use heating beam
  - Or dedicated diagnostic beam.
- Ideally, use data for CX into (n,l) states of $A^{+(q-1)}$,
  - Cross sections primarily calculated.
  - But, plasma can mix nearly degenerate states.
  - Also need rates for cascade towards ground state & corresponding emission.



[Fonck 1984]

Interpreting Resulting Spectrum Requires Accounting for Many Complicating Effects

- Contributions by "halo" H atoms [Isler 1994],
  - Thermal H^+ that has CX'd with beam,
  - Can in turn CX with impurity ions.
- "Plume" ions are [$A^{+(q-1)}$] ions created by CX on another flux surface [Fonck 1984],
  - Can drift into sight line and be excited by electrons,
  - ⇒ Contribute at different temperature.
- Beams have significant ½ & 1/3 energy components from H_2^+ & H_3^+ in source,
  - Need CX cross sections at lower energies to take these into account.
- Beam atoms can be in excited states [Isler 1994],
  - Small fractions, but much larger cross sections!
- Gyro-orbit dependence [Bell 2000],
  - Combine with $\sigma(E)$ & finite lifetimes to complicate velocity measurements,
  - ⇒ Need kinetic treatment of ions rather than fluid.
  - Multiple views help sort out these effects.

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CXRS Issues for ITER

- ITER active beam spectroscopy: [Malaquias 2004, von Hellermann 2004].
- Should have multiple views to sort out gyro-orbit effects.
- Need (n,l) resolved cross sections,
  - And at energies low enough to account for ½ & 1/3 beam energy contributions.
  - Heating beam: 500 keV/amu, DNB: 100 keV/amu.
- Take plume emission into account for He measurements,
  - Essential to track flow of ash.
- C & Be coatings will degrade first mirrors over time,
  - $\Rightarrow$ Will need some method of tracking reflectivity & polarization over time.
  - Or in situ cleaning.

Motional Stark Effect → Spatially Resolved Measurements of Magnetic Field Orientation

- Tokamak magnetic field consists of poloidal & toroidal components,
  - Poloidal field due to plasma currents ⇒ determined self-consistently within plasma & cannot be computed a priori.
  - ⇒ Important measurement to aid in equilibrium reconstruction and in testing theories of plasma equilibrium, stability, and transport.
- MSE diagnostic also relies on heating or diagnostic beam,
  - Consider Balmer-α emissions due to excitation of beam atoms by background plasma.
  - Stark effect associated with $E = V_{beam} \times B$,
  - ⇒ wavelength splitting of several angstroms & polarization of emitted radiation [Levinton 1989].
- Initial applications on PBX-M & TFTR measured direction of polarization ⇒ local B_p/B_T [Levinton 1993].
- As with CXRS, single beam with multiple sight lines ⇒ profile of $B_p/B_T(r)$.

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MSE Issues for ITER

- Mirror coatings may prevent accurate polarimetry $\Rightarrow$ considering alternatives.
  - Namely, precision spectrometry.
  - Line shifts much less sensitive to changes in reflectivity,
  - Investigating prospects for getting enough data from them to measure field line pitch.
- Developing CR model including (n,l) sublevels,
  - Need correspondingly detailed cross sections,
  - Do these exist?
- Another approach based on measurement of ratio of π and σ line components has been proposed [von Hellermann 2004, Malaquias 2004],
  - Will require isotropic reflection throughout optical system.

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Independent Measurements of Plasma Parameters Always Desired!

- E.g., X-ray spectroscopy can also give T_i and flow velocity,
  - Looks at emission lines from higher Z impurities than CXRS: Kr, Ar, W, etc.
  - Considering He-like & H-like Kr, Ar, Fe for ITER [Barnsley 2004],
    - Spectra for these are in good shape.
    - Amount added limited by increment in P_{rad}.
    - Free-free & free-bound continuum emission is important source of noise in ITER!
- W may be more problematic,
  - Used for divertor target plates ⇒ intrinsic impurity.
  - Need reliable energy levels, emission rates,…
  - Models can be tested on existing experiments: ASDEX-U (now), JET (coming soon).

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Summary

- ITER is an ambitious project,
- In the process of designing & preparing to build it, we're testing existing models and developing new ones more aggressively than ever before.
- This is especially true for the edge & divertor plasmas,
  – It's here that our knowledge of atomic physics is crucial to the project's success,
  – In dealing with plasma-wall interactions, taming problems like tritium retention, and spreading out exhaust power.
- Much work also remains to be done on the atomic physics aspects of ITER's core diagnostics,
  – We will need to be confident in interpreting their signals to gauge ITER's performance.

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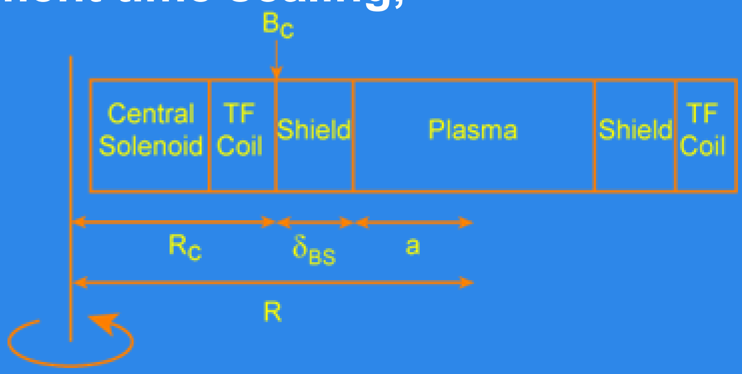
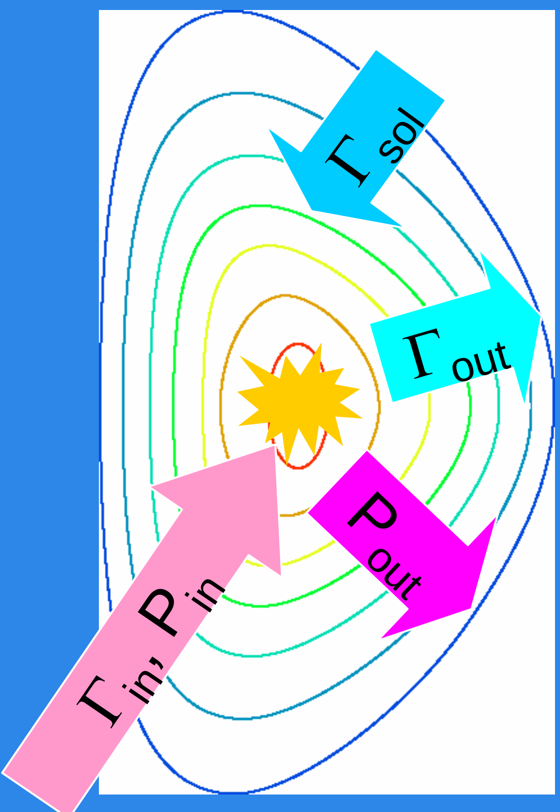
Supplementary Slides

What Is Holding Up Fusion Progress?

- Alternatively: Why is ITER So Big?
- Years of tokamak confinement experience + fusion cross section $\Rightarrow P_\alpha / (P_\alpha + P_{in}) \propto [\, I_p (R/a) H / 46]^3$,
  - H: multiplier on empirical energy confinement time scaling,
  - Assumes $T_i \cong 10$ keV.
- Tokamak radial build $\Rightarrow R = R_c + \delta_{BS} + a$,
  - R_c = radius at TF coil,
  - δ_{BS} = Blanket / shield thickness = 1.3 m.
- Ampere's Law $\Rightarrow R = R_c B_c / B_T$,
  - B_c = 12 T for Nb_3Sn.
- Macroscopic stability $\Rightarrow$ Safety factor $q = 5 a^2 B_T f / R I_p \cong 3$,
  - Shape factor $f \cong 2.3$.
- Conventional tokamak $\Rightarrow R / a = 3$,
  - With $I_p (R/a) = 46 \Rightarrow a = 2.0$ m, R = 6.4 m,
    - But, no margin for fuel dilution, less than expected confinement, …
  - ITER EDA: $I_p (R/a) = 60 \Rightarrow a = 2.6$ m, R = 7.8 m.



In Steady State, Have Power & Particle Flows To Material Boundaries



- In a reactor, 80% of fusion power leaves as neutrons,
  - Captured in blanket.
- Other 20% flows out of plasma & strikes material boundaries.
- Particle flows replace fuel ions & remove He ash.
- In non-DT experiment, $P_{out} = P_{in}$,
- Particle flows determined by competition between sources (core & edge) and diffusion.
- General reference: [Stangeby 2000]

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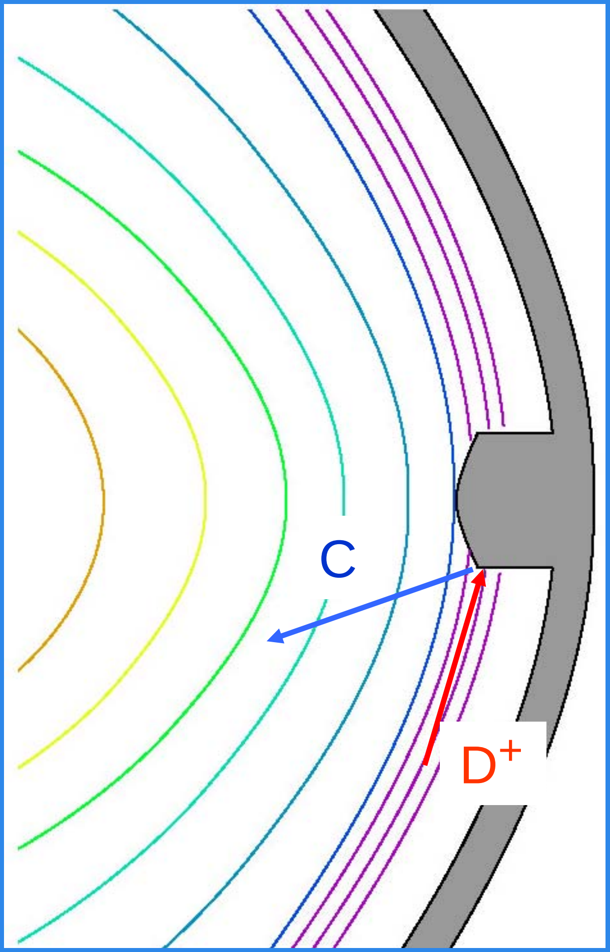
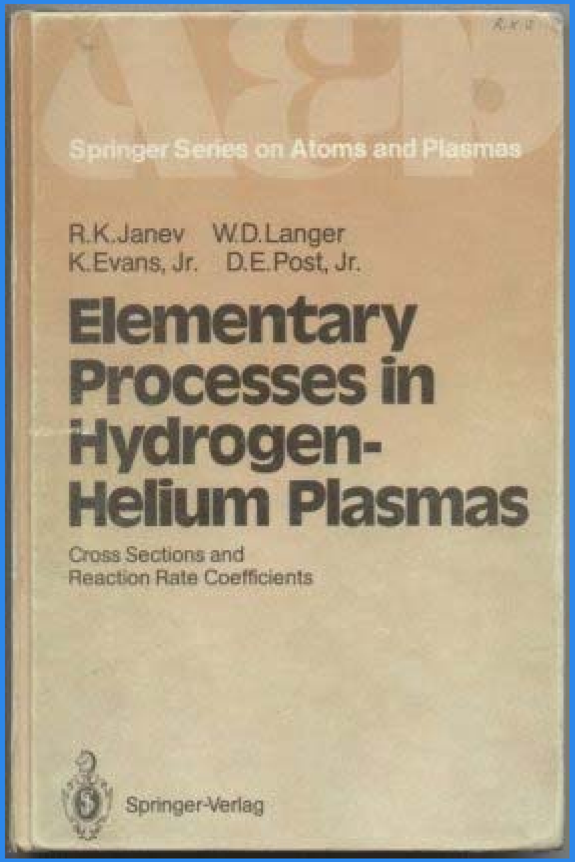
High T_e Near a Material Can Lead to Impurity Sputtering



- Particles striking a material at high enough energy can knock off substrate atoms ⇒ physical sputtering.
- Becomes a significant particle source for *E* ~ few 100 eV – 1 keV,
  - ⇒ Is a concern for T_e > 100 eV.
- Can lead to self-sputtering,
  - Efficient due to similar projectile & substrate mass,
  - And due to $Z > 1$.
- Sputtered impurities can harm core,
  - Efficient radiators ⇒ P_{rad},
  - Dilute hydrogen fuel.

Fundamental Set of Atomic Physics Processes & Rates Essentially Unchanged for ~20 Years

1. **Dissociation, ionization, etc. of H_2, H_2^+**
   - From [Janev 1987]
   - Maxwellian averaged reaction rates as function of T_e,
   - Simple dissociation energies & energy losses.
2. **Collisional radiative model for electron impact ionization and recombination of H,**
   - But, H & H^+ not in equilibrium!
   - See [Reiter 1993] & references therein.



$$\frac{Dn_0}{Dt} = -n_0 n_e S_{\text{eff}} + n_i n_e R_{\text{eff}}$$

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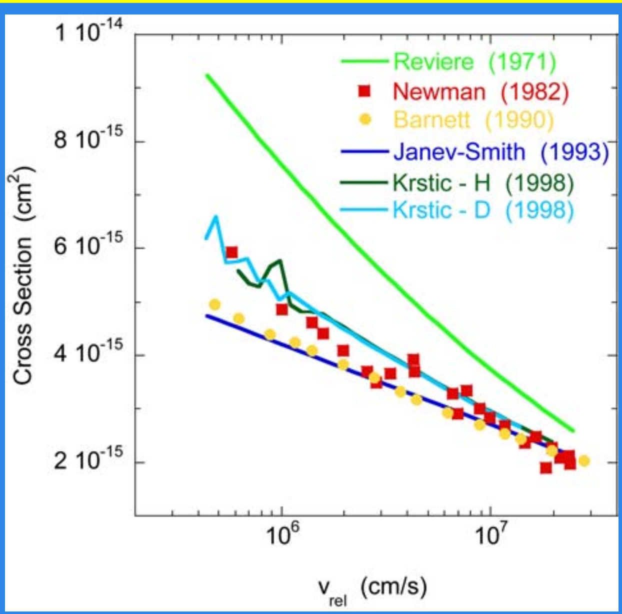
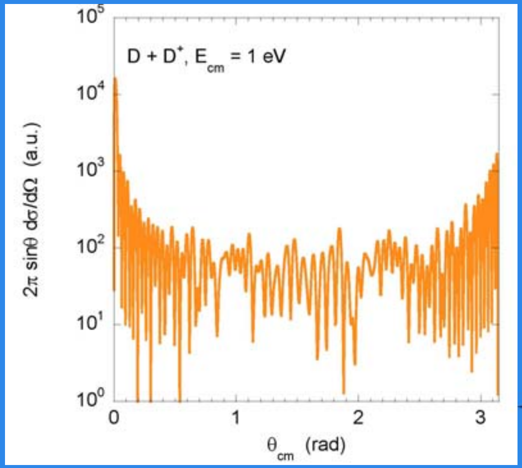
Treatment of Elastic Scattering Recently Improved

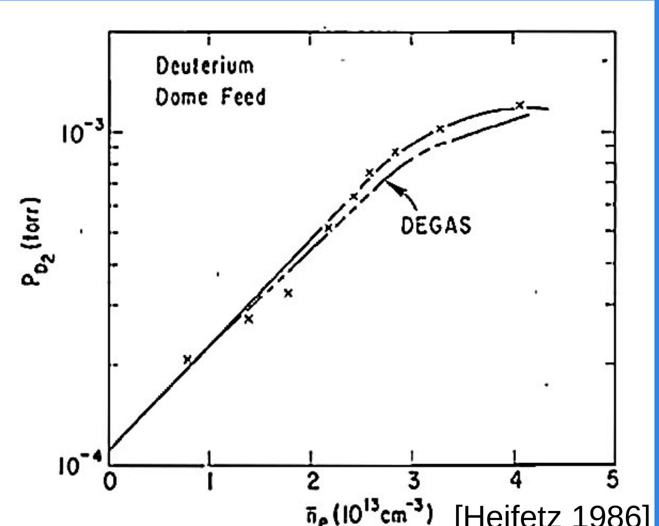
- $H + H^+ \rightarrow H^+ + H$,
  - Originally handled purely as charge exchange,
  - Improved dramatically with **dσ/dΩ calculations by Krstic & Schultz** of total elastic scattering cross section [Krstic 1998].
- $H_2 + H^+ \rightarrow H_2 + H^+$,
  - Elastic scattering important mechanism for momentum and energy transfer to $H_2 \Rightarrow$ longer mfp.
  - Computed by Krstic & Schultz.



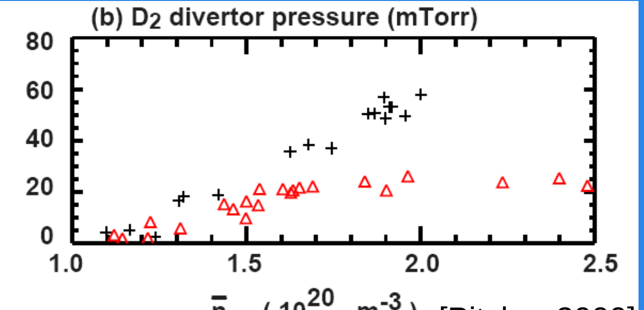


More Recent Modeling Has Dealt with Higher Densities and Lower Temperatures in Divertor

- **Viscosity of neutral gas becomes important,**
  - I.e., neutral – neutral elastic scattering of D, D_2, (and He),
  - D_2 – D_2 mfp = 8 cm / P_{D2} (mTorr)
    - ⇒ High density experiments well into “transition” regime, mfp << d.
  - For ITER, P_{D2} ~ few mTorr, d ~ 10 cm.
- **Good theoretical cross sections exist [Krstic 1998],**
  - But, handling nonlinearity requires approximate BGK description [Kukushkin 2005],
    - Rates based on empirical viscosities & diffusivities.
  - Large effect on simulated neutral pressures,
    - Again due mostly to heating of D_2 by D [Kukushkin2005].



[Heifetz 1986]



[Pitcher 2000]

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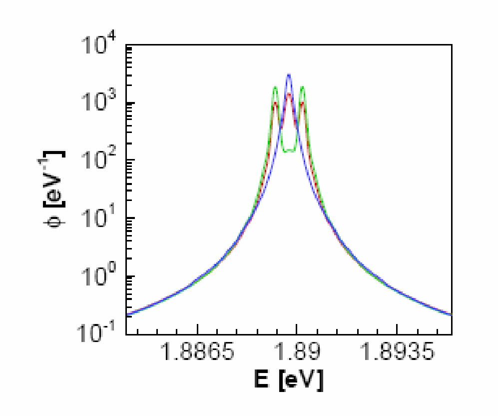
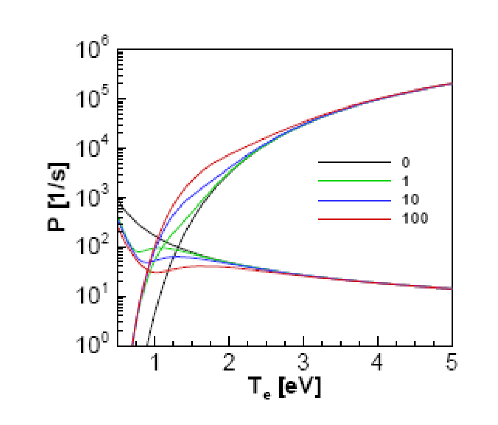
Trapping of Lyman Series Radiation

- **Mean free path for Ly-α ~ 0.2 cm / $n_D(10^{20}\ m^{-3})$ [Post 1995],**
  - **$\Rightarrow$ << local dimensions in some present machines & in ITER.**
- **Modeling is extremely complex since it couples plasma $\leftrightarrow$ neutrals $\leftrightarrow$ radiation field,**
  - **Even more nonlinear,**
  - **Line shape effects important.**
- **Photon transport modeled in EIRENE with same Monte Carlo tools used for atoms & molecules,**
  - **And incorporates photo-excitation into H CR model [Reiter 2002],**
  - **Stand-alone code examining line shape effects [Reiter 2006].**
  - **Self-consistent B2-EIRENE model of ITER shows factor of two increase in plasma density, somewhat lower plasma temperature [Reiter 2006].**
- **Alternative approach: incorporate simple plasma transport model into NLTE code CRETIN [Adams 2004],**
  - **Used to benchmark modified CR rates [Scott 2004] $S_{eff}(n_e, T_e, L)$, $R_{eff}(n_e, T_e, L)$ for use in existing plasma & neutral transport codes.**





[Adams 2003]

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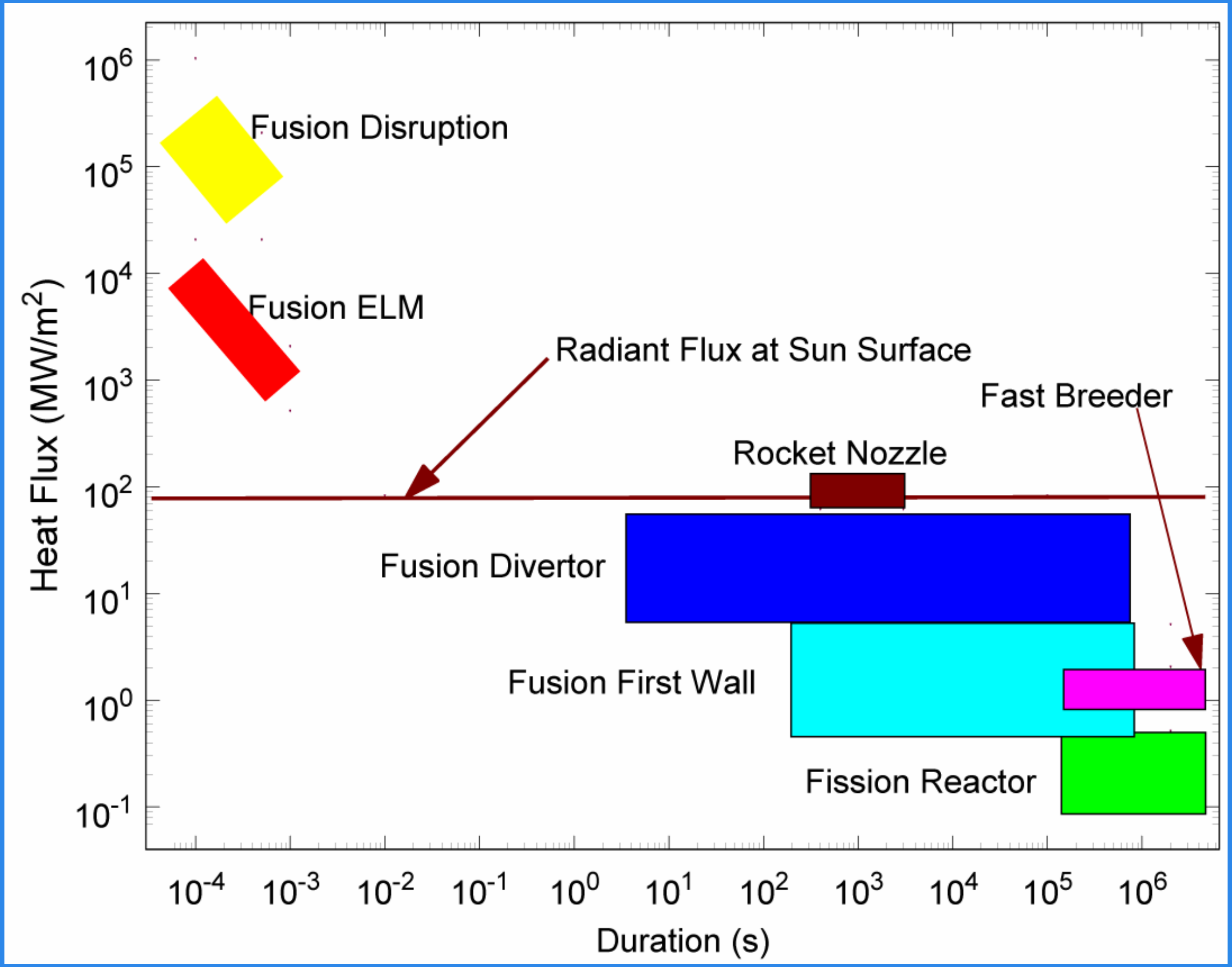
More Complex H_2, H_2^+ Behavior

- Lower temperatures ⇒ H_2 lifetime extended ⇒ undergo additional processes,
  - Including vibrational excitation & de-excitation,
  - ⇒ ion conversion: $H_2(v) + H^+ \rightarrow H_2^+ + H$,
  - Also brings in other species: H_3^+, H^-.
- Initial predictions were for “Molecule Assisted Recombination” [Krasheninnikov 1997],
  - But, ASDEX-U modeling [Fantz 2001], showed instead “Molecule Assisted Dissociation”!
  - Explicitly modeled transport of vibrationally excited molecules!
- Attempts to fold effects into effective “collisional radiative” rates for H_2, H_2^+: [Sawada 1995, Greenland 2001, Pigarov 2002].
- [Janev 2003] reviews & assesses current data,
  - More data still needed:
    - State-selective processes involving vibrationally excited states,
    - Impact of rotational excitation on plasma kinetics,
    - Isotope specific data.
  - Sawada has more complete model on the way.
  - Still need to be integrated into comprehensive, simplified model for simulations.

Is 60 MW/m² a Problem?



[M. A. Ulrickson, Sandia National Labs]