Plasma Materials Interactions

The Dirty Part of Plasma Physics

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Introduction

- The interaction between fusion plasmas and cold materials is complex
- Design of Plasma Facing Components (PFCs) involves science from a diverse set of skills
- Successful PFCs must be robust and forgiving and operate very near the limit of catastrophic failure

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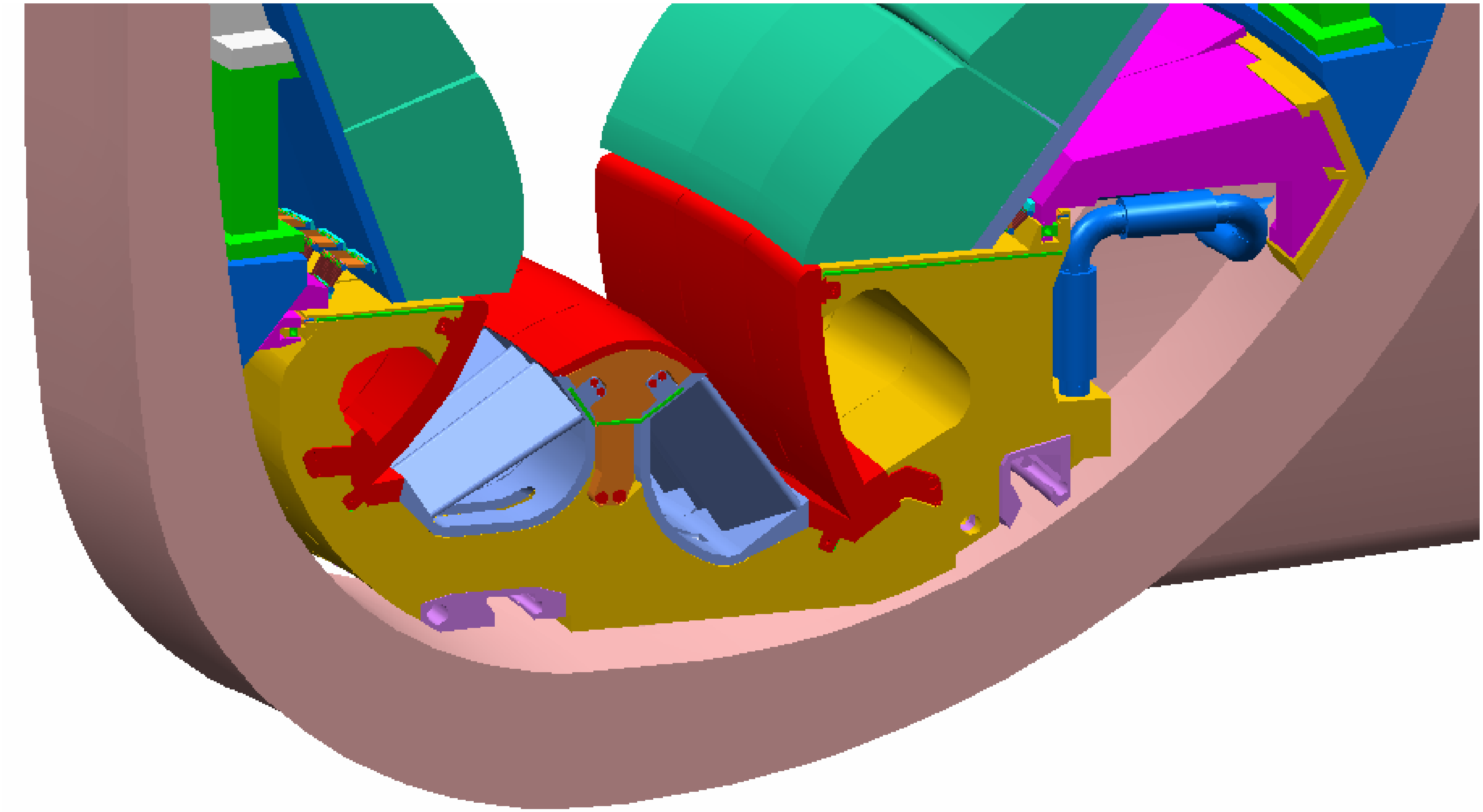
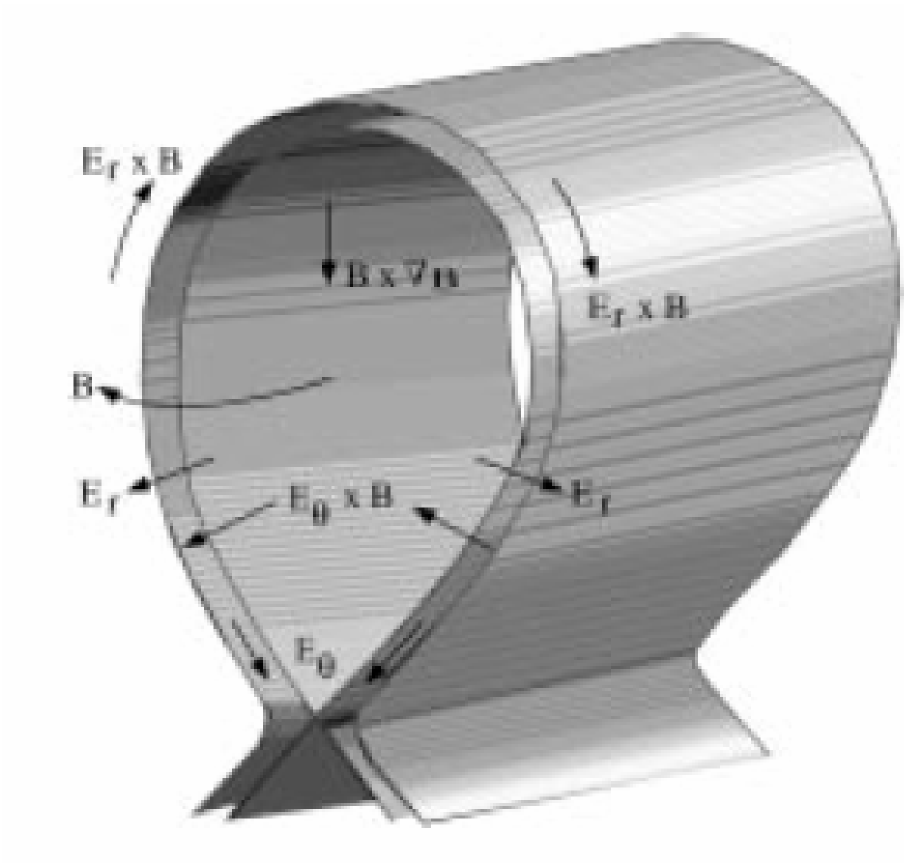
Introduction

- My topics will include:
  - Plasma edge characteristics
  - Plasma materials interactions
  - Materials selection for PFCs
  - Off-Normal events
  - Research opportunities (red titles)

ITER PFCs

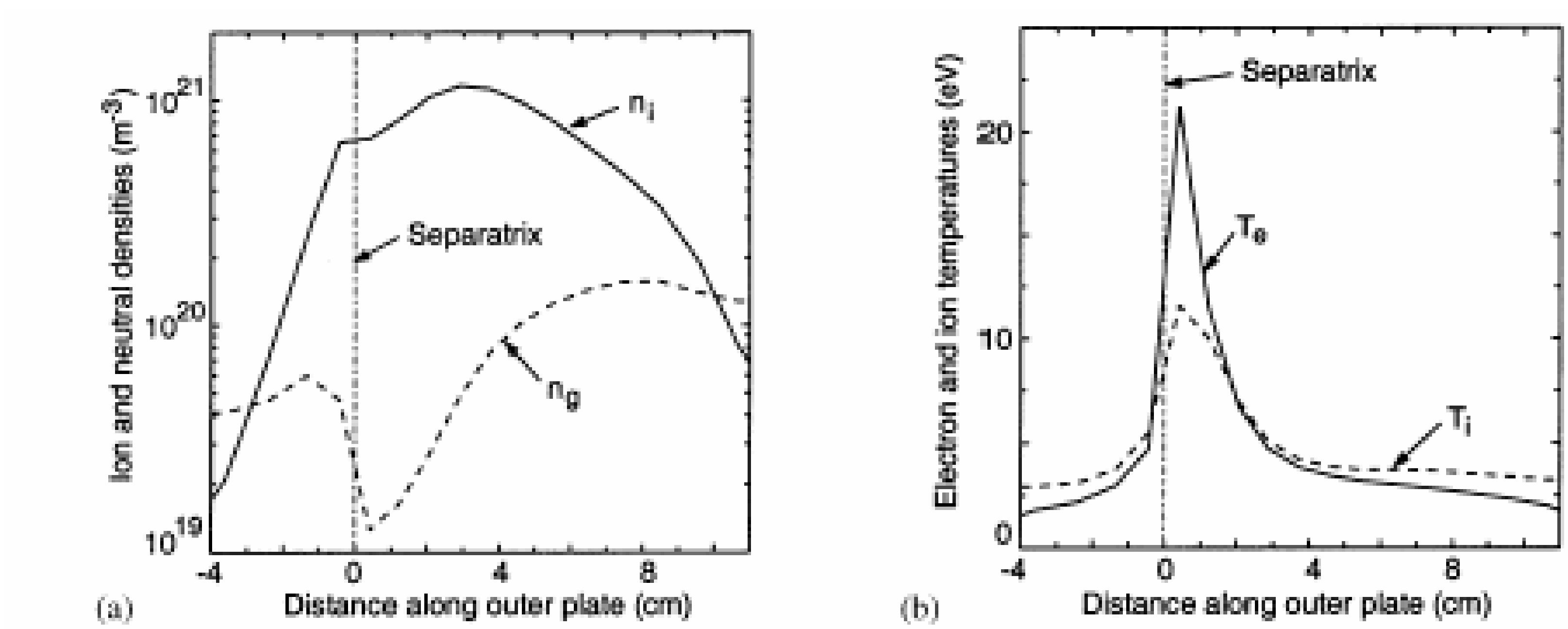


Complex Forces Act in the Scrape-Off Layer



- **Radial Electric fields**
- **Gradients of magnetic fields**
- **Neutral particle influx from the PFCs**
- **Impurity generation at the PFCs**
- **The resulting plasma flows create the plasma conditions in the divertor and at the first wall**

Example of Plasma Parameters at Divertor



Plasma Core to SOL and Divertor Coupling

- **The divertor needs to be at high density and have some impurities to enter the detached regime where heat loads are reduced.**
- **Complete detachment leads to flow stagnation and may not be compatible with He pumping.**
- **But the SOL density needs to be controlled for good core confinement and low wall erosion.**
- **Long pulses and high power also lead to new regimes for plasma wall interactions and erosion.**
- **If SOL pumping is extremely high, flat density profiles and high temperature plasma edge may be realized**

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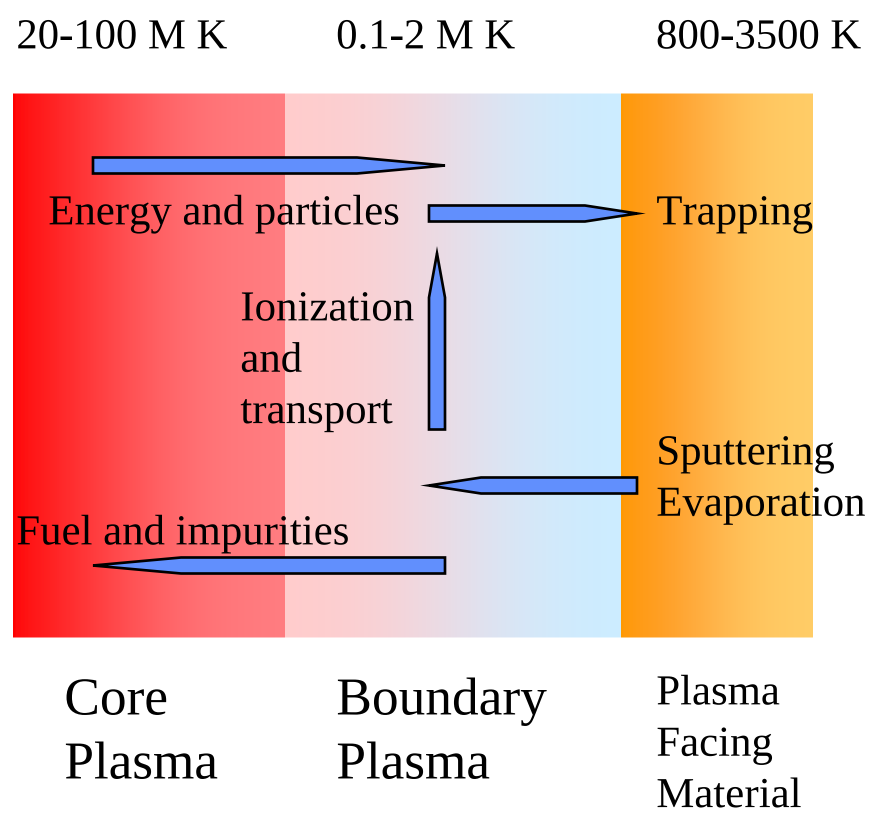
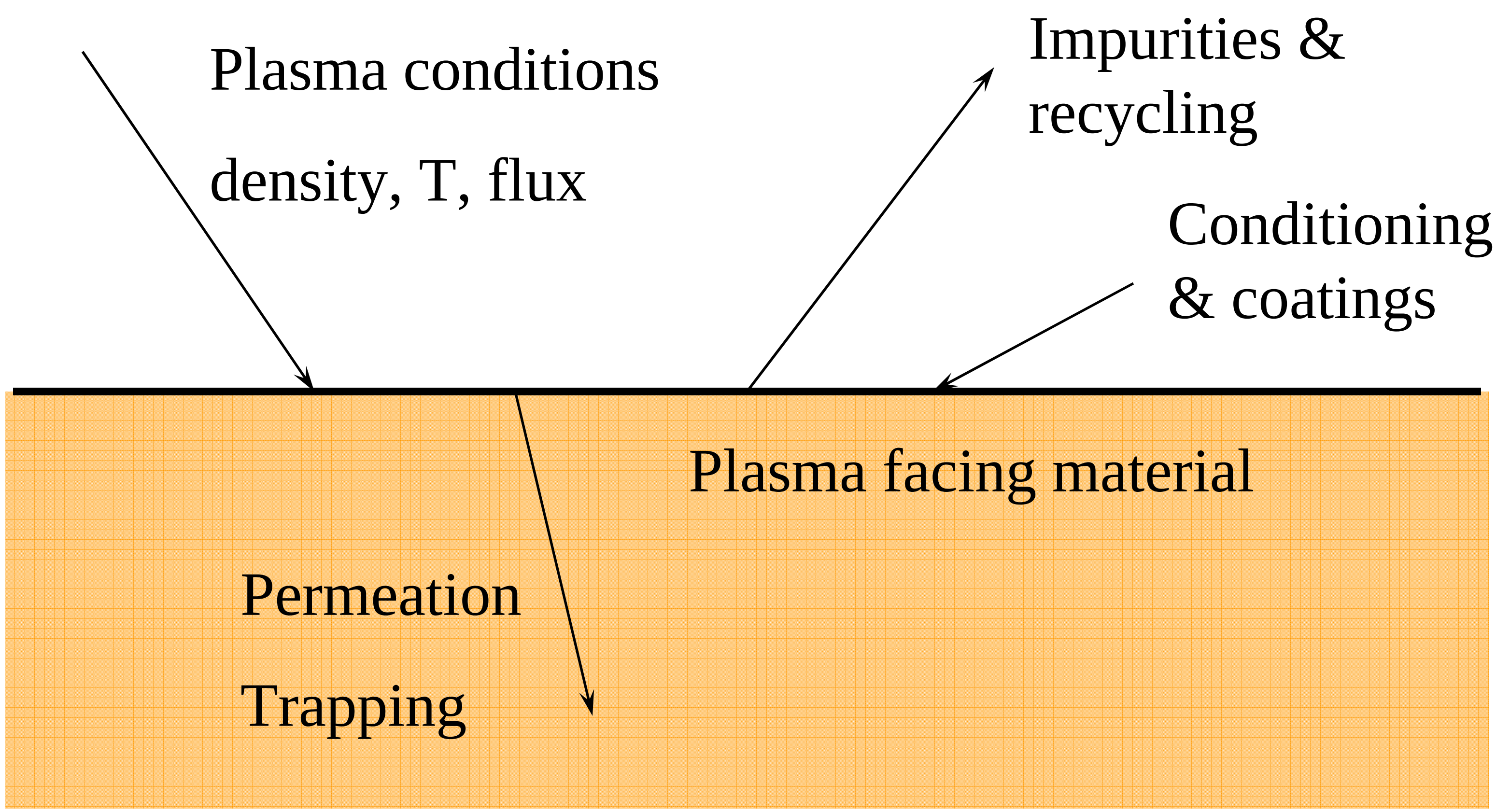
Fusion Plasma Materials Interactions

- The core plasma must be kept clean of impurities and He ash
- The plasma facing component surface sees high density and temperature plasma
- Key issues are hydrogen trapping, erosion, and thermal fatigue
- Spans science specialties from ionized gases to materials science



Plasma Surface Interactions



Science Involved in PFC Design

- Atomic and molecular physics for ionization, dissociation, and photon radiation of plasma and impurity species
- Surface physics for sputtering, chemical erosion, hydrogen trapping and release, surface segregation
- Materials science for nuclear radiation damage, thermal fatigue, stress corrosion, creep, bonding, and hydrogen trapping
- Engineering science for stress management, heat transfer, and component design

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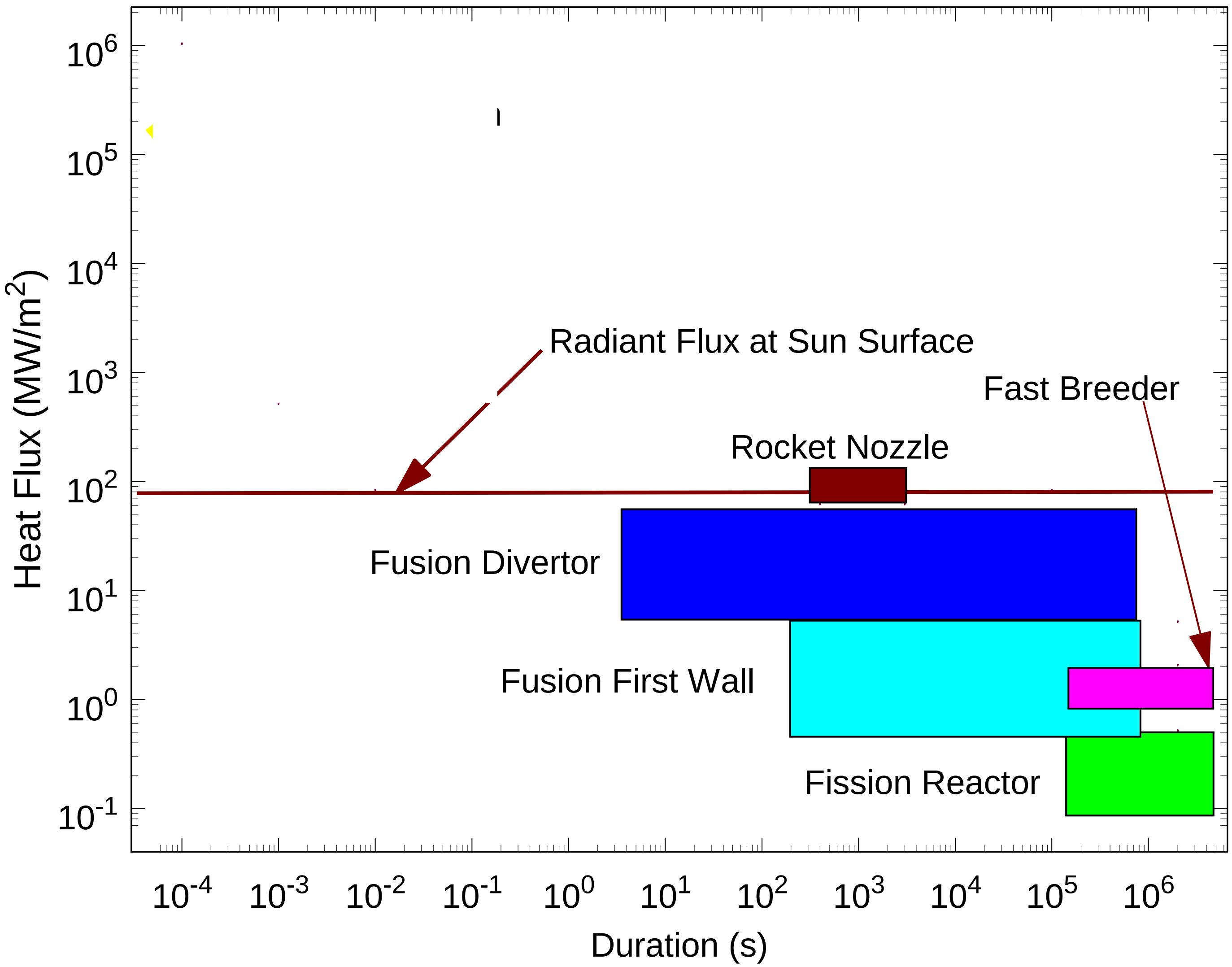
Materials Selection and PFC Design

- Selection limited by capability for absorbing heat and minimization of plasma contamination
- Refractory materials have an advantage
- Plasma interactions can change material properties
- Off-Normal events force compromise in material selection and PFC design

Magnetic Fusion Energy Heat Fluxes



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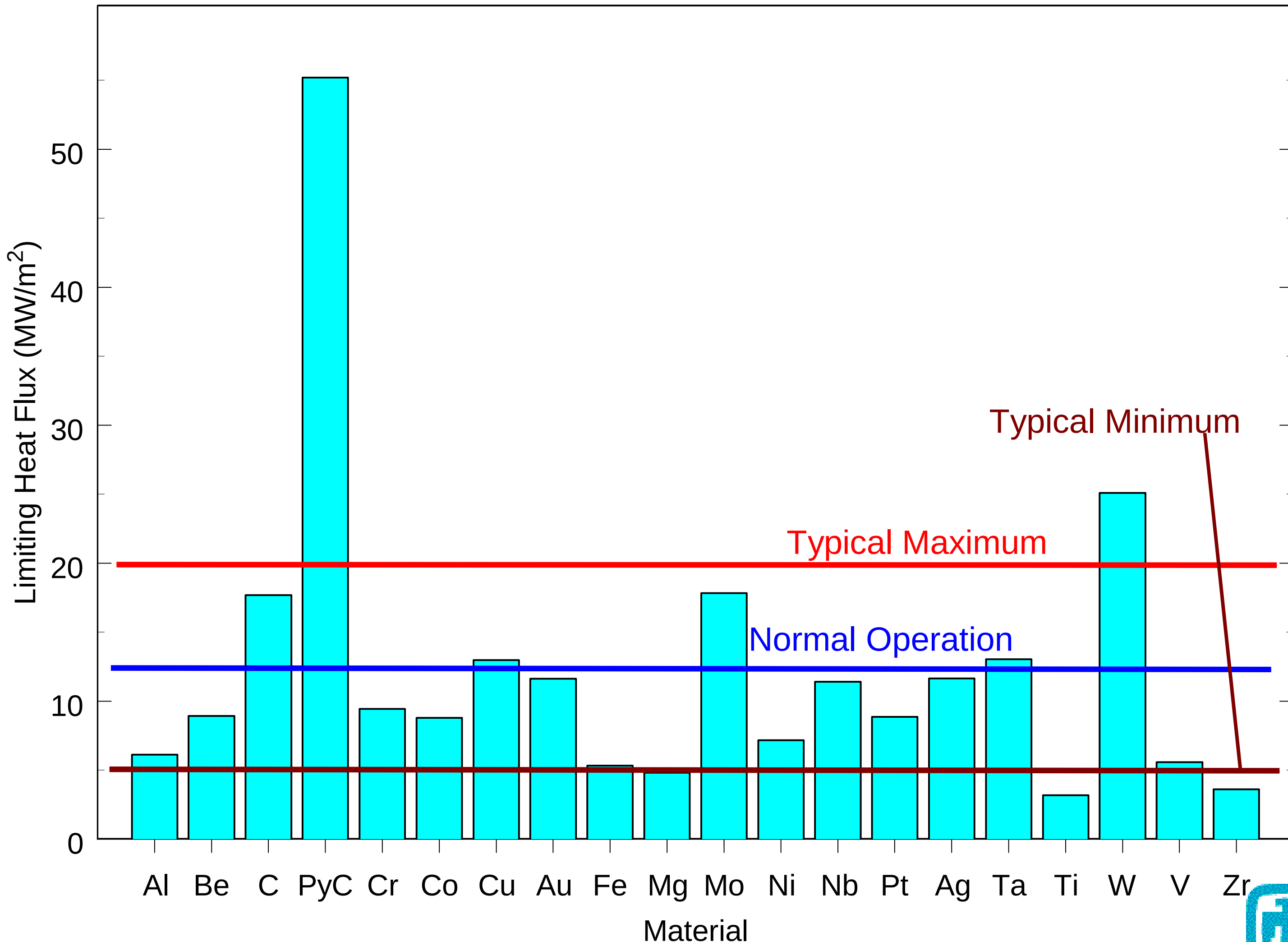
Heat Flux Capability



Materials Choices for PFCs

- Divertor applications
  - Only W and C are acceptable for the highest heat flux (C limited because of T retention and neutron damage)
  - With some radiation in the divertor Mo, Ta, and Nb(?) are candidates (Cu is not acceptable because of erosion)
- For first wall applications
  - Iron alloys (ferritic steel), V (?), Be, and all the divertor materials

Carbon Based Plasma Facing Materials

- Very high temperature operation possible
- Thermal conduction is primarily by phonons (radiation damage lowers performance)
- Chemical reactions with atomic H are a major issue (chemical erosion)
- Control of tritium inventory in C:H layers is a critical issue for ITER
- Hydrogen is very mobile in C

Tungsten Plasma Facing Material

- Second only to carbon in thermal performance
- Tungsten is brittle, it melts, it is not low activation, it cannot be welded
- Can have low or no physical erosion in high recycling divertor
- H isotope retention is very low
- W PFC surfaces must be divided
- Blisters may form due to particle irradiation

Beryllium First Wall PFM

- Very low Z
- Very good oxygen getter
- Good thermal properties
- Low T retention unless thick oxide layers are present
- Low melting point (~1275C) (off-normal events limit lifetime)

Mixed Material Issues

- For example consider the case of a Be first wall and C or W divertor PFC system
  - Be deposition on C by transport through the scrape-off layer will lower the chemical erosion of C (PISCES at UCSD)
  - Be deposition on W can form lower melting point materials (W_2Be, WBe, WBe_{12})
  - The operating T for a high power divertor is several hundred to >2000 C making experiments difficult

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Active Cooling

- To realize the maximum potential for magnetic fusion energy devices must operate either long pulse or steady-state
- Steady-state means the thermal time constant of the PFC is much shorter than the plasma duration
- Water cooling is the method of choice now
- In magnetic fusion reactors the use of Helium gas cooling is the leading candidate
- Only a few devices are exploring this regime now

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Off-Normal Operation

- The two main classes of off-normal events are:
  - Plasma current interruptions (often accompanied by plasma motion)
  - Instabilities in the plasma edge that release short bursts of energy and particle to the PFC (Edge Localized Modes or ELMS)
- Both restrict the maximum acceptable heat flux during normal operation because they require thickening of the plasma facing surface to prevent catastrophic failure of the PFC

Off-Normal Mitigation Progress

- The lifetime of these actively cooled components is governed by disruption and ELM events.
- There has been significant progress on predicting disruptions and mitigating the effect of disruptions.
  - Neural network prediction of disruptions about 50 ms before they occur with a >90% accuracy
  - Massive gas puffing to mitigate halo currents, energy deposition and current decay rates (liquid jets under development)

Off-Normal Mitigation Progress

- Experiments have shown that ELMS can be mitigated by:
  - Double null operation
  - High triangularity operation
  - High edge density
  - Active divertor pumping
  - Coils to perturb the edge
- The full impact on plasma performance remains to be assessed for all options

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Bringing It All Together

- Successful PFC designs have progressed from short pulse devices (fractions of seconds) to tens of seconds of operation (even hours for actively cooled PFCs)
- Plasma contamination due to PFCs is routinely low on well designed devices
- Catastrophic failures are rare and have not occurred on the largest, most advance machines
- Actively cooled devices are rapidly growing in number

Looking Forward

- Helium gas cooled PFCs are being designed for parts of ITER
- Liquid surface PFCs are at the fore-front of PFC research
  - May allow simultaneous heat and particle removal
  - May give access to unique plasma operating regimes (very low particle recycling, flat density profiles, high edge temperatures)
- Control of off-normal events will allow further optimization of PFC designs and greater performance

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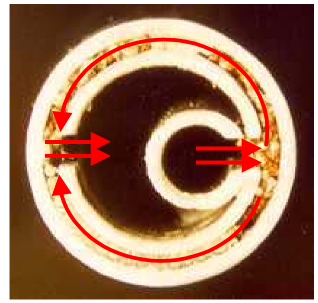
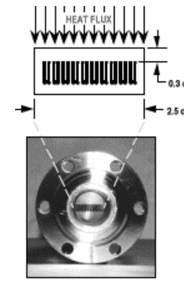
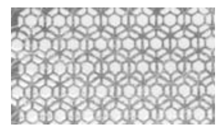
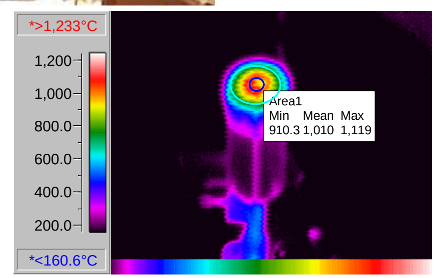
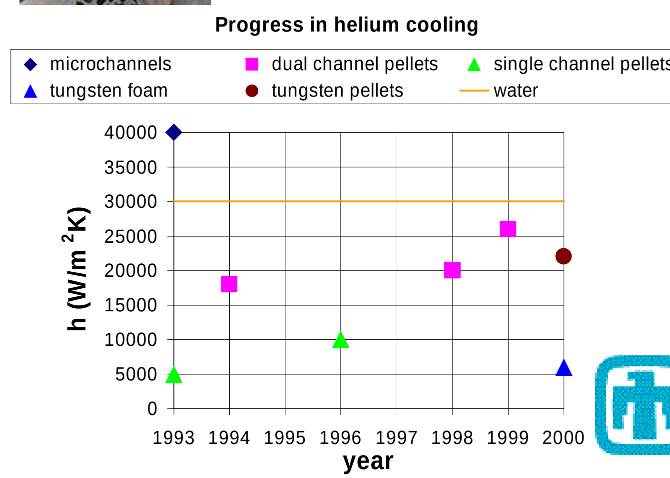
Porous Metal Heat Sinks (He)

- Promising designs have been found for Cu alloys
- Heat removal is approaching water values
- Pressure drop is ok.
- Refractory metal research just starting.
- Helium gas purity is a key issue but there appear to be solutions.
- Refractory alloy development is needed.







Status of Refractory He Cooled R&D

- Development of irradiation resistant refractory materials is a key issue
- Refractory PFM to refractory heat sink joining techniques remain to be proven
- Demonstration of He gas purity must be done
- Requires low T edge plasma because the sputter erosion can be eliminated.
- High temperature gas produced (up to 1100C) implying high electrical efficiency.

Impact of ELMS

- ELM energy deposition severely limits the operating heat flux
- The thermal fatigue caused by ELMs has not been experimentally verified (could be very severe)
- ELMs will severely limit the lifetime of PFCs and may reduce reliability.
- Reducing ELM energy to less than 0.5 MJ/m^2 is sufficient to increase the margin for failure.

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Liquid Surface PFCs

- Liquids being considered are: Lithium, Gallium, Tin (SnLi mixture)
- Flowing Liquids have high heat flux capability (up to ~50 MW/m^2)
- Key Issues are:
  - Magnetohydrodynamic effects on flowing conducting liquids (much modeling needed)
  - Materials compatibility (corrosion)
  - Practical methods
  - Particle pumping capability (mostly He)

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Opportunities for Research Summary

- Refractory Materials development including joining to heat sinks
- Gas cooled refractory heat sink inventions
- Off-normal event mitigation methods and detection methods
- Liquid metal PFC MHD modeling, methods for injection and control, and materials development