Physics of Core-Edge in Tokamaks

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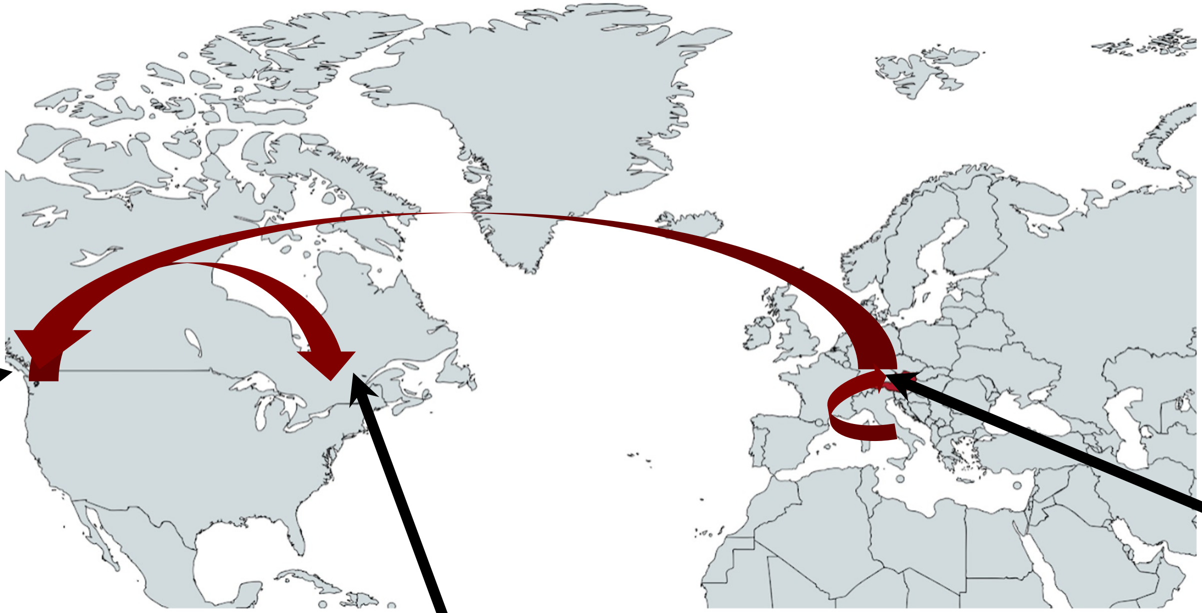
SULI June 21 2022

Moving around the globe

Staff Scientist at
General Atomics

DIII-D
NATIONAL FUSION FACILITY

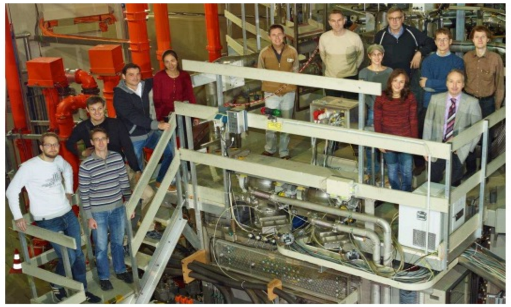
San Diego 🇺🇸



PhD from the
Max Planck
Institute for
Plasma physics

ASDEX Upgrade IPP

Munich 🇩🇪



Faculty at the
University of
Tennessee
Knoxville
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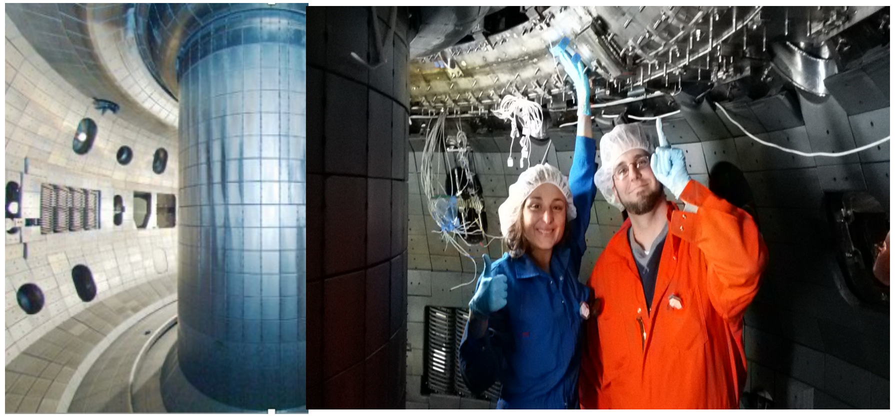
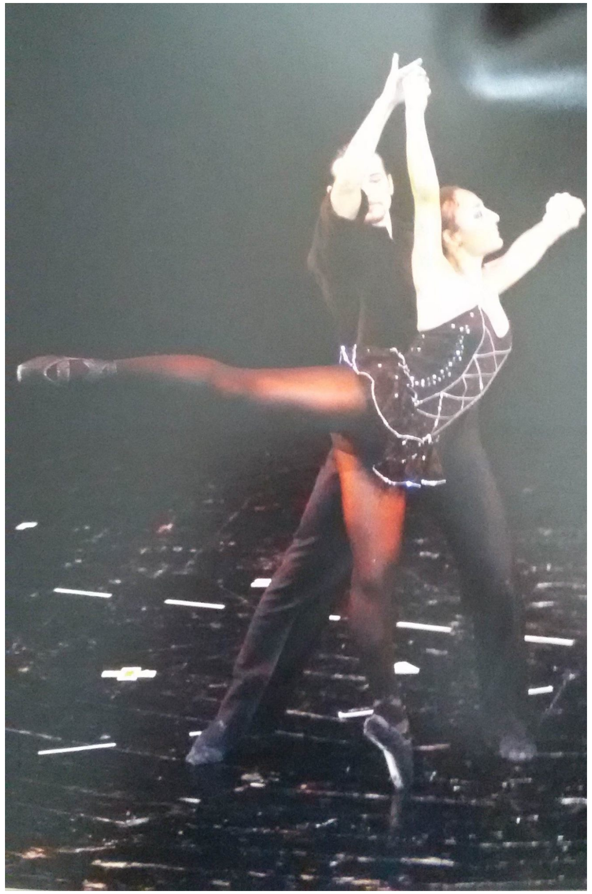
Graduated in 🎓
nuclear and
subnuclear
physics at the
University of
Rome, Italy 🇮🇹



Interesting facts about me



I graduated at the ballet academy of Rome and I was a professional ballet dancer.

A lot of the skills I acquired back then have been very useful for my career in science!

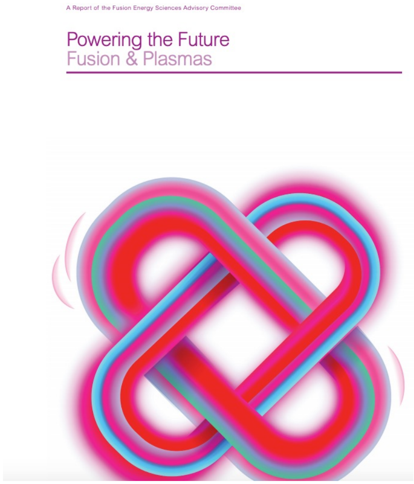
DIII-D work

Panelist at the APS Conference for Undergraduate Women in Physics (CUWiP), Irvine, January 2020

Outreach

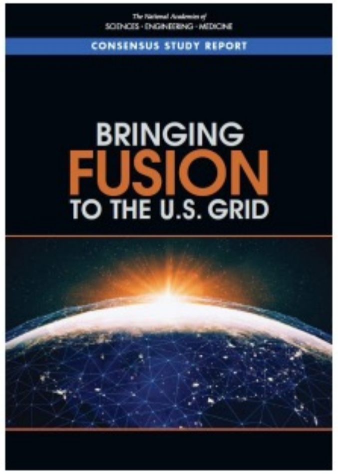
ITER Fellow

“Core-Edge Integration” is currently the grand challenge in fusion energy science



- **2020 DOE FESAC Report on Fusion**

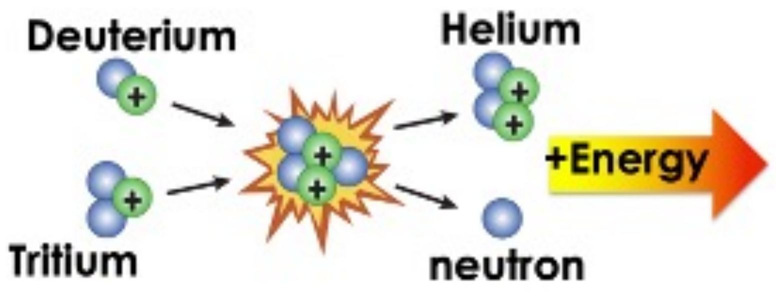
“The long-range plan to deliver future energy and plasma science” recently released identifies as priority #1 “Addressing the core/exhaust integration challenge which is needed for generation of significant fusion power”

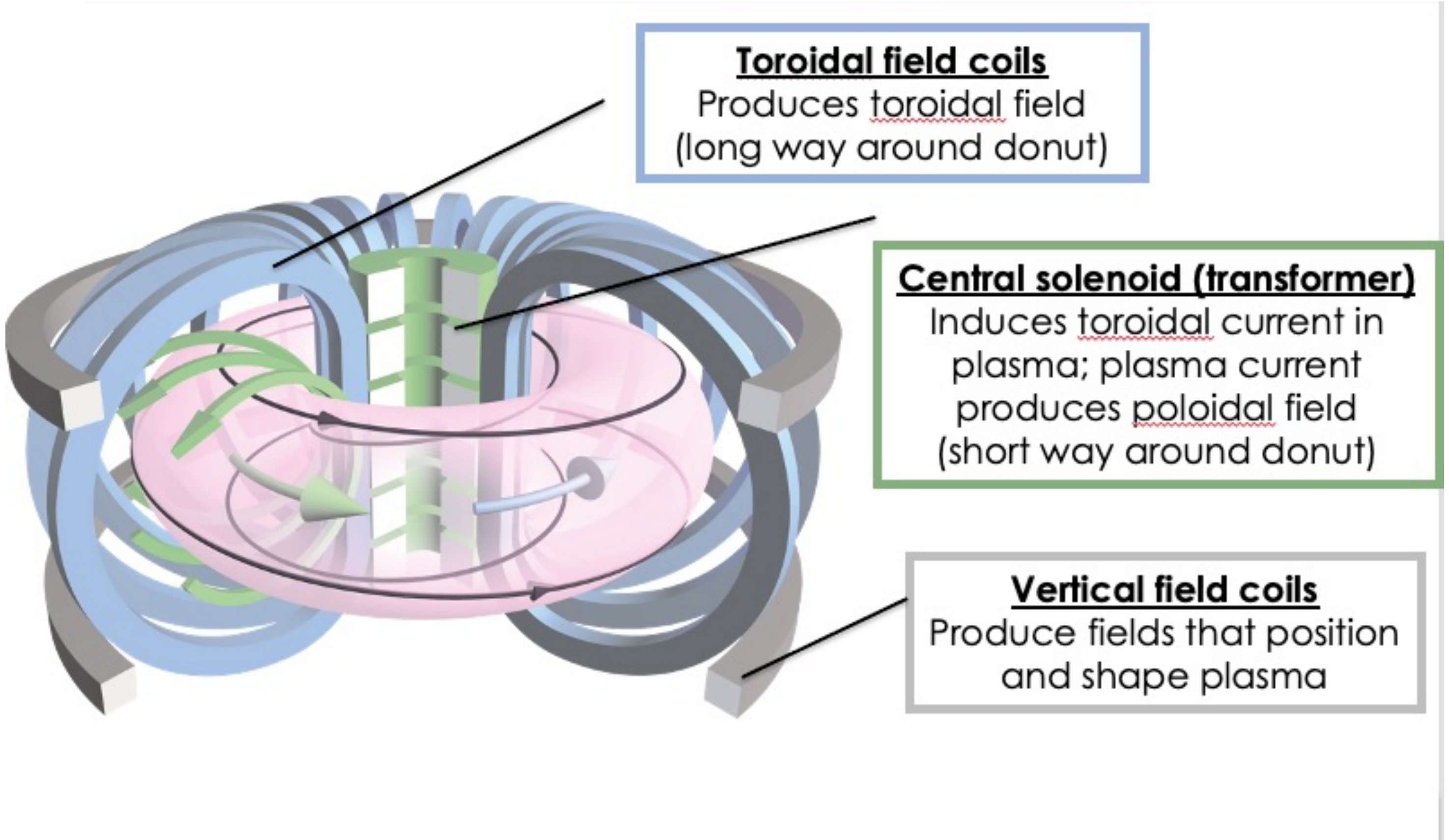


- **2021 National Academies of Science Report on Fusion**

“Integrated understanding of the plasma core-edge integration with the materials science of the divertor and first-wall is an ongoing research area that will benefit burning plasma experiments in ITER and contribute to U.S. efforts toward an attractive compact fusion pilot plant”

A Tokamak confines plasma using a helical magnetic field in extreme operating conditions





Condition for Fusion:

– High temperature (~ 10 KeV) to overcome the Coulomb barrier

– Such high T must be maintained for a sufficient confinement time τ_E

– With a sufficient ion density in order to obtain a net yield of energy

$$Triple\ Product = n * T * \tau_E$$

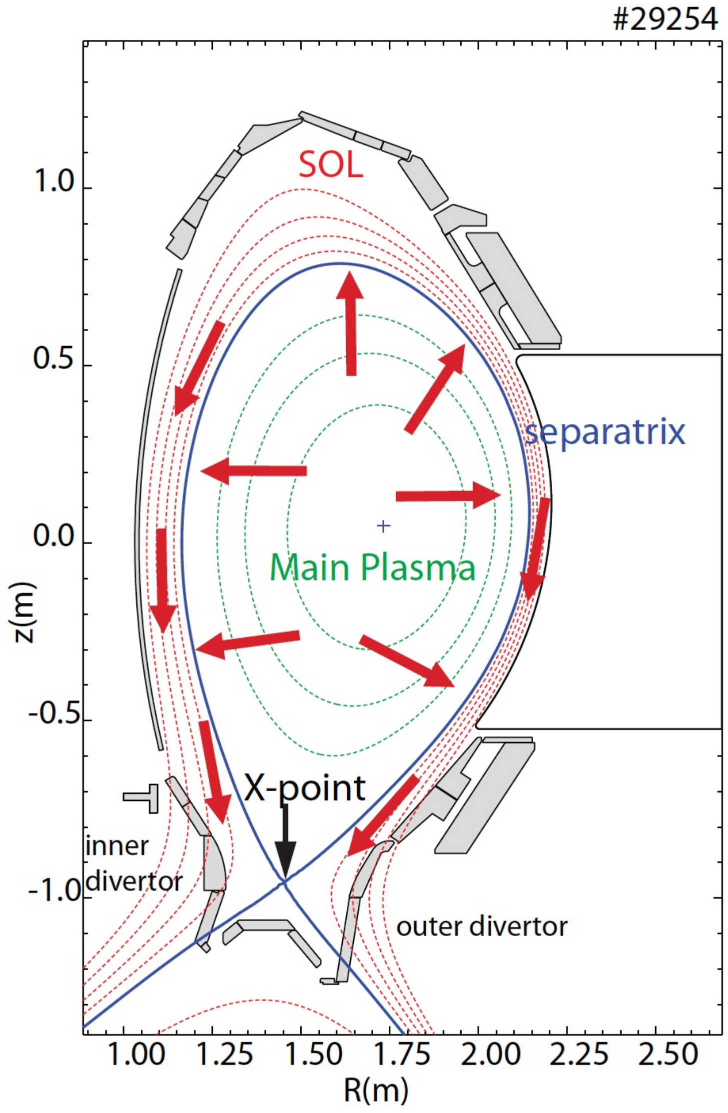
Plasma confinement is limited by heat transport

Plasma confinement:
key factor for the design of a future fusion reactor

$$\tau_E = \frac{W}{P_{heat}} = \frac{\int \frac{3}{2} n(T_i + T_e) dV}{P_{heat}}$$

But is it limited by heat transport

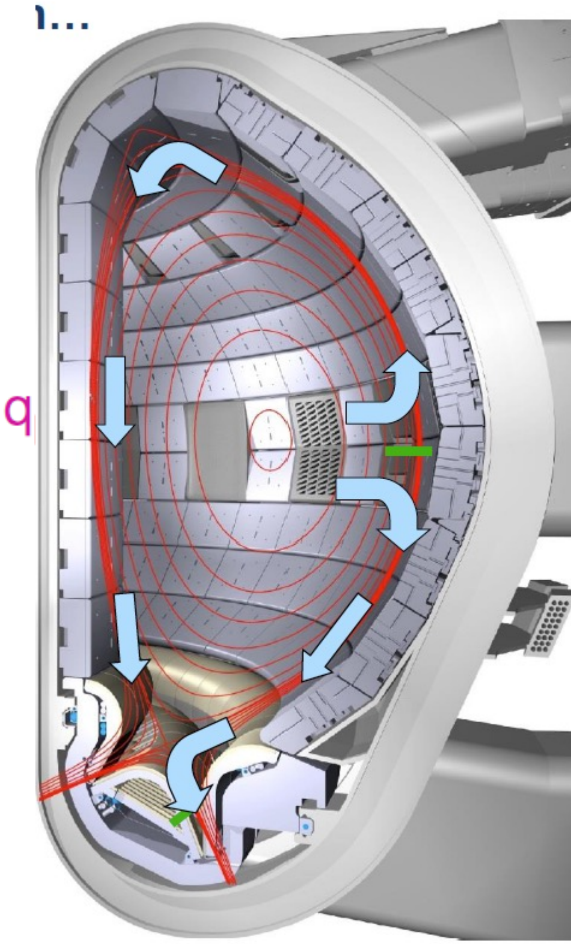
- Heat is deposited in the center
- Heat and particles diffuse towards the edge
- Divertor –Main Region of Plasma Exhaust

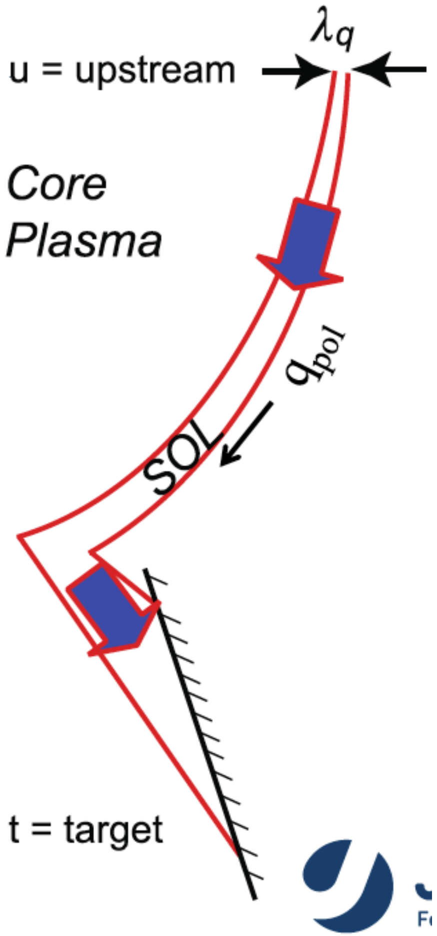


Handling the power flowing out of the plasma is a serious challenge

Heat conductivity || B much higher than ⊥ B

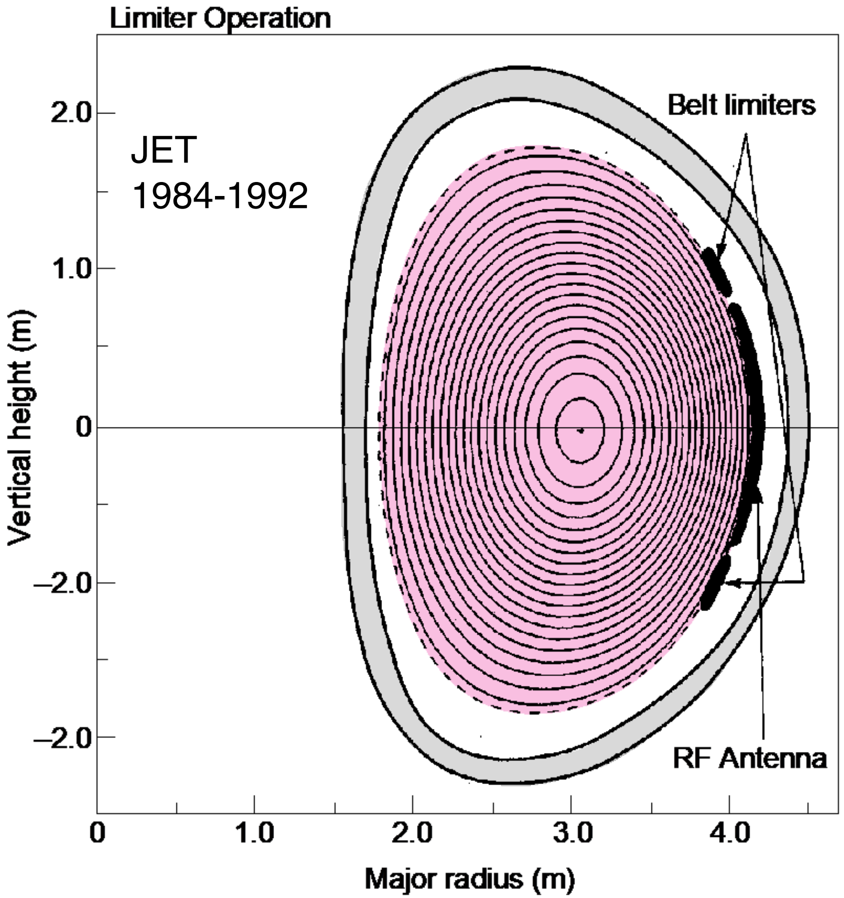
→ Heat flows in narrow flux bundle (λ_R < 1 cm)

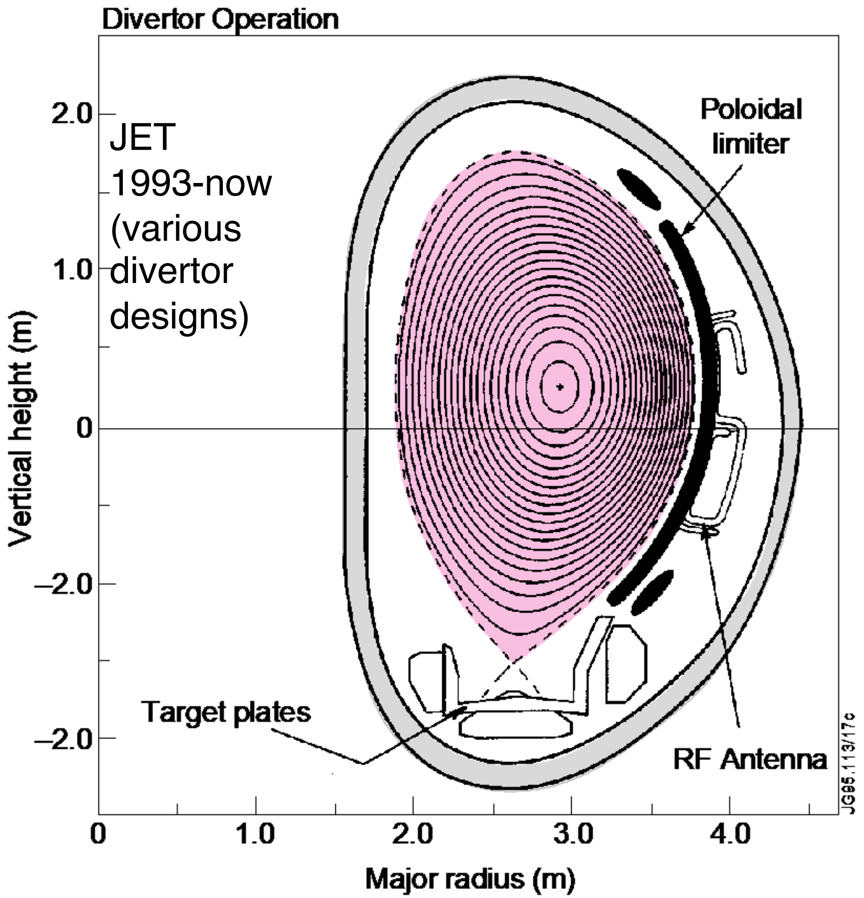




The large ratio of || and ⊥ heat conduction leads to a spatial concentration
The heat load on wall components → needs for methods of amelioration

Limiters and divertors used to exhaust plasma





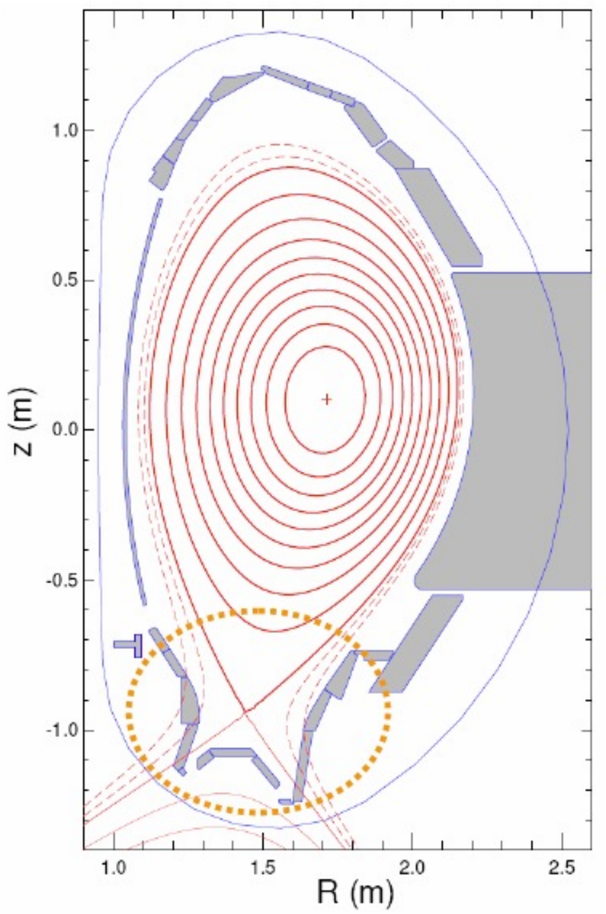
•A **limiter** is a surface in contact with the plasma

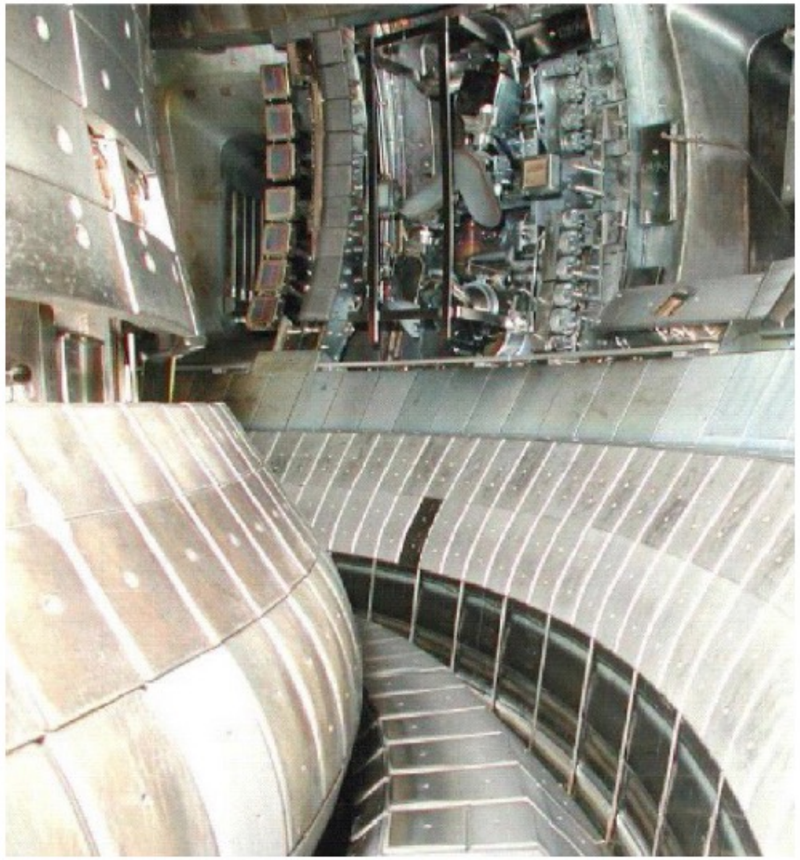
–Can be inserted (sacrificial) or as part of surrounding wall structure

Divertor geometry plasma-material interaction moved away from the confined plasma

If external current is run in the same direction as plasma current *outside* of the confined plasma, then one component of the field can be canceled, creating an **X-point divertor**

Divertor is the main region of power Exhaust





- The poloidal field goes to zero at the X-point
- Power flux along the filed line towards divertor targets
- De-coupling the region of strong plasma-wall interaction and core plasma

Heat fluxes on material surface can exceed those of a rocket nozzle

- **In future reactors unmitigated power fluxes > 300 MW/m^2**
- **Localized power deposition at the divertor challenge the material limit:**

  - Divertor target heat load: $q_t \leq 10$ MW/m^2
  - Divertor target $T_t \leq 5$ eV ➡ *to suppress erosion*

Material research

Increase power dissipation to more than 95 %

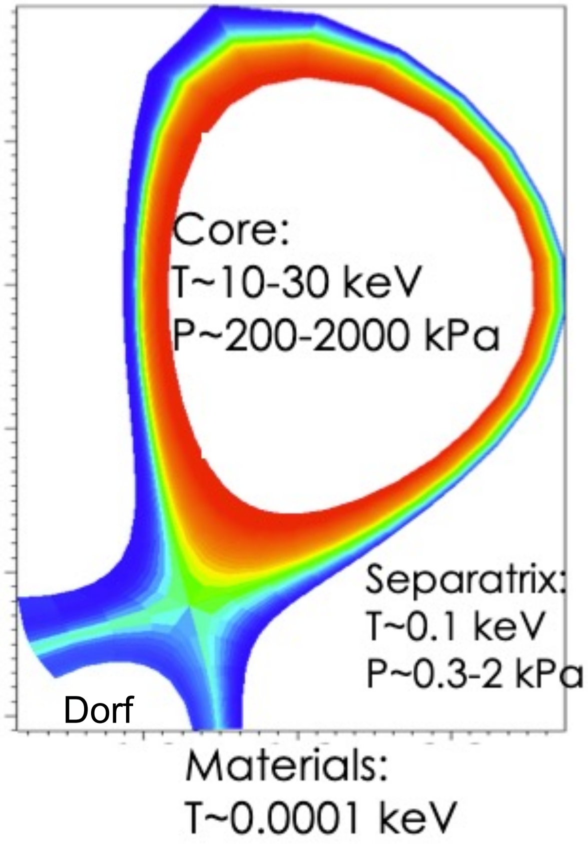
Melted W tile, Lipschultz, et al. NF (2012)

Integrating the hot core with the cool edge is the greatest challenge in tokamak research

In simple words: How can we keep a hot core and a cold edge?

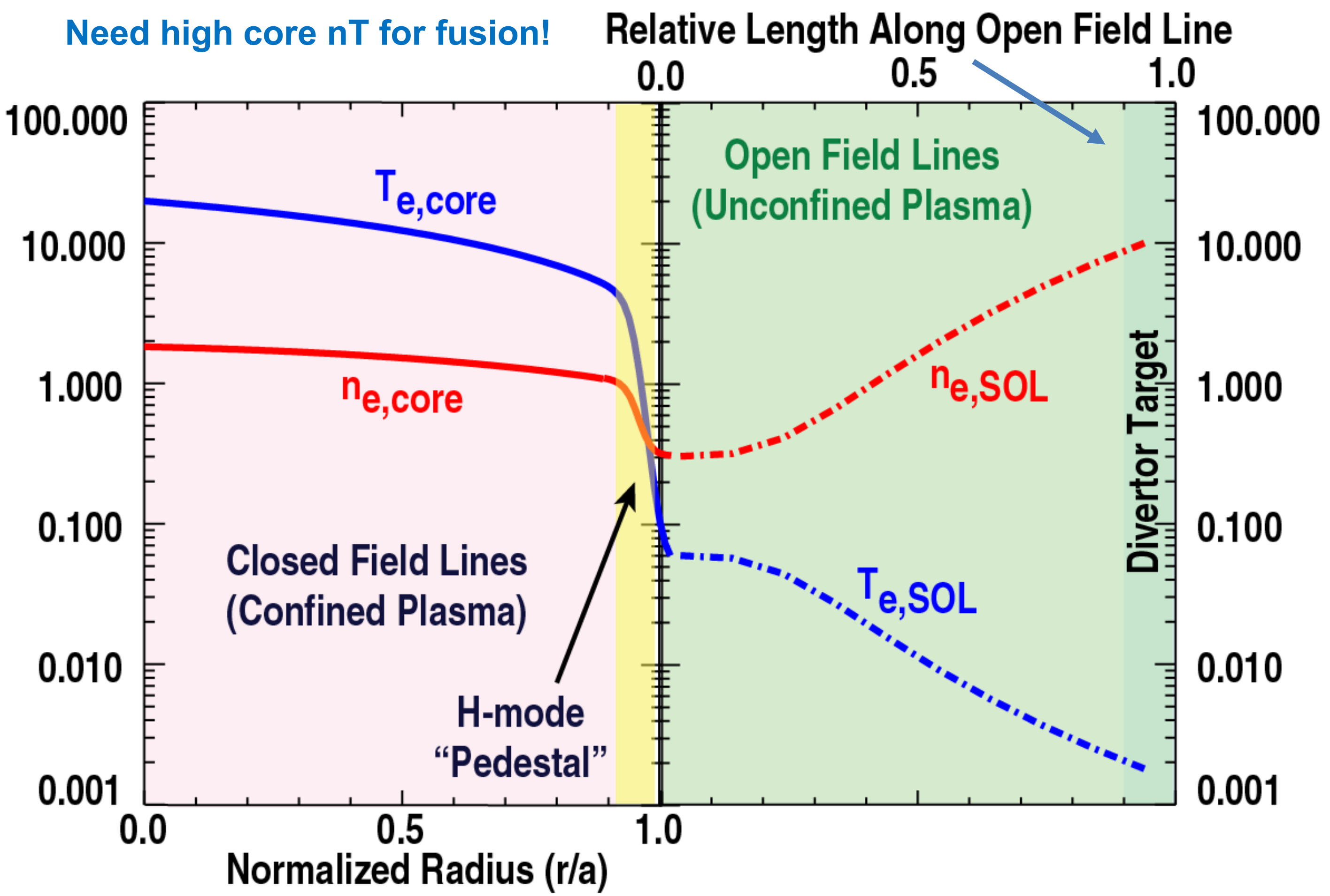
Divertor design must simultaneously accommodate core plasma as well as divert target constraints

- Challenge: **Achieve high confinement compatible with power handling solutions**
- Challenge: **Controlling divertor heat flux without degrading core performance**



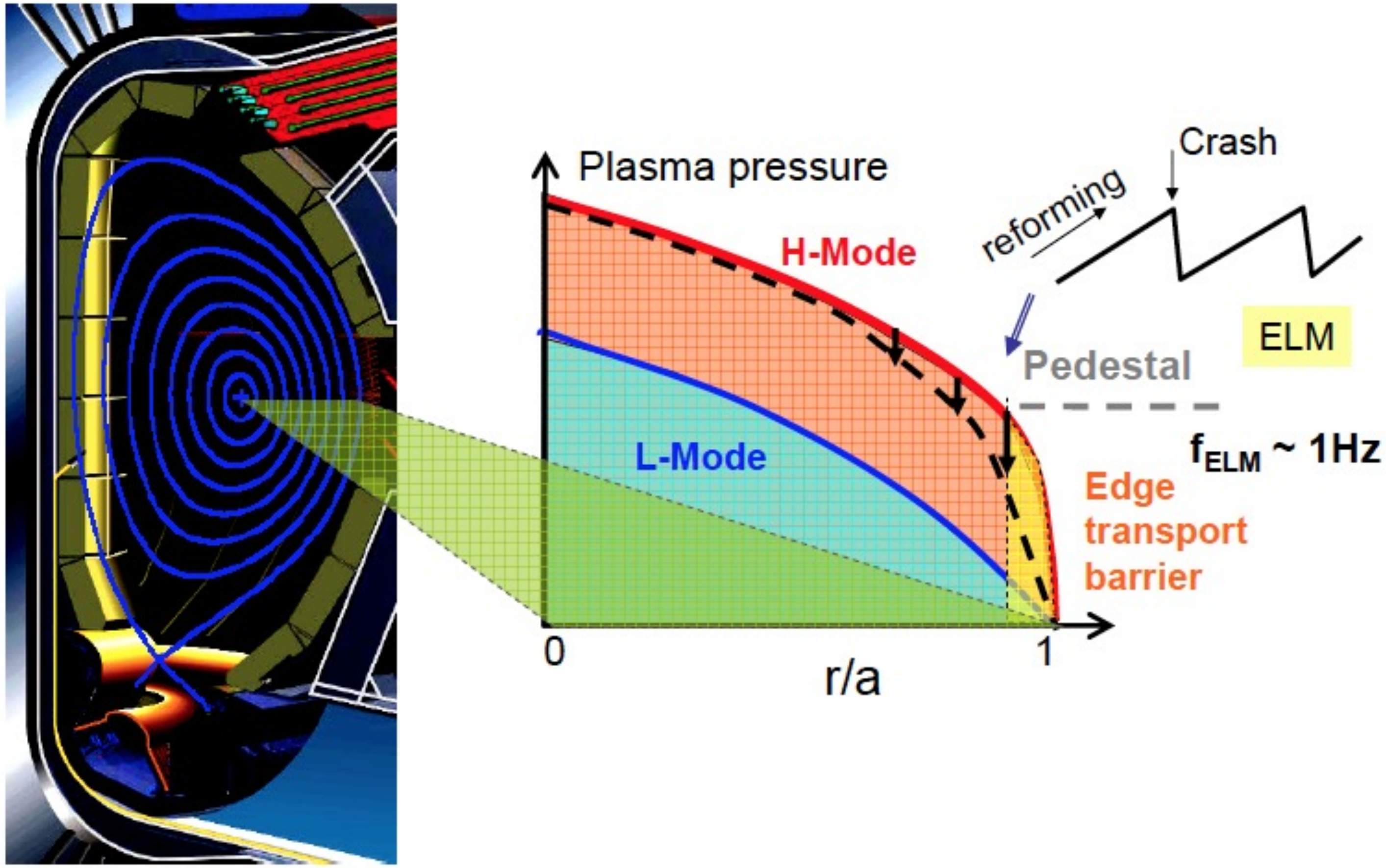
Physics understanding, establish a basis for integrated core and divertor scenario optimization, development of predicting capability

Fundamental Challenge: Conditions in the core needs to be compatible with the plasma edge and materials



H-mode pedestal: mediates the tension between the core and the edge and influences the performance of both

H-mode pedestal is the critical region of interaction between the core and the edge



H-mode = high confinement mode

- Edge transport barrier: Region of reduced radial transport at the plasma boundary
- Formation of edge transport barrier and suppression of turbulence is key to high confinement in tokamaks
- ELMs (Edge Localized Instabilities): expel particle and energy from the plasma

  -Unacceptable heat loads on PFCs for future devices

Active area of research!

The core and the edge are guided by different physics

Core ↔ Pedestal

Low collisionality, $\nu^{*} \sim n^3/P^2$

⬇

PERFORMANCE

— Separatrix —

n_{sep}

$n_{e,sep}$ constrains both core and divertor performance

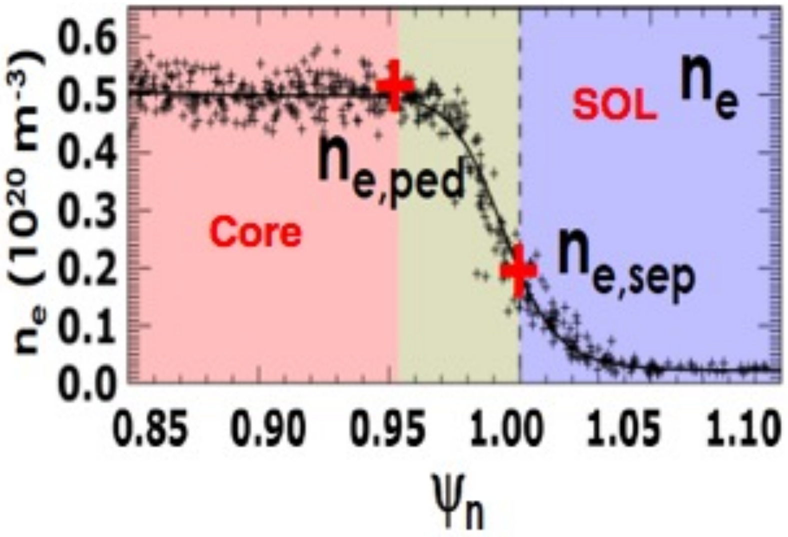
Divertor, $q_{||}$ ↔ Wall

High n_{div} + *impurities*

⬇

DISSIPATION

- **Core**: Hot - tens of keV
- **Core**: fully ionized



- **SOL**: Cold – few tens of eV
- **SOL:** not fully ionized

SOL region involves plasma interaction with solid materials (PMI) - the first wall, plasma facing components (PFC), the divertor plates (erosion)

…. and interaction with neutral particles

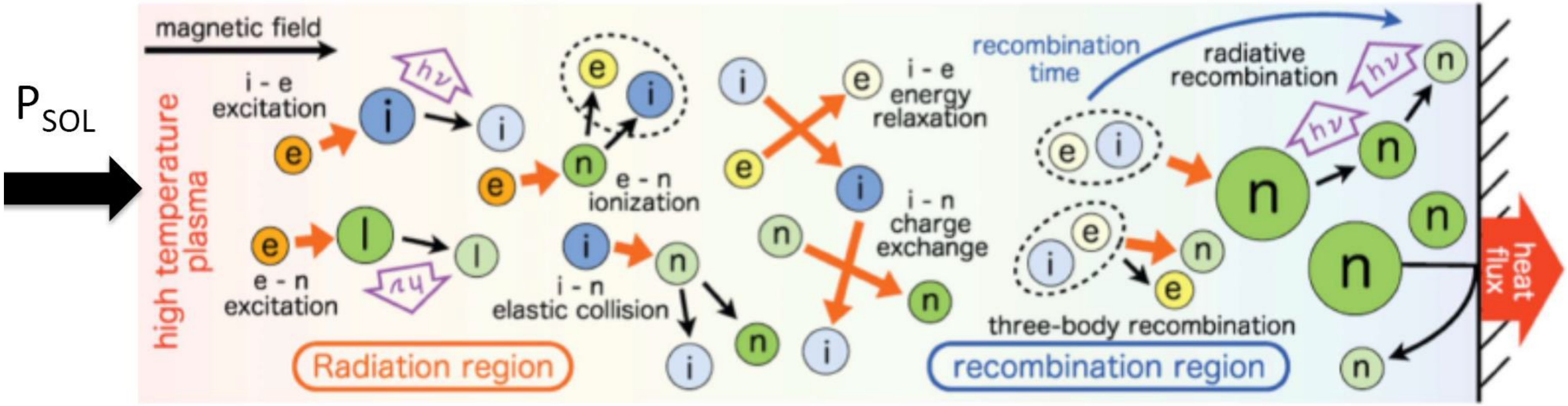
What processes control power dissipation?

Impurity radiation

Ionization and dissociation of recycling Atoms and molecules

Recombination

P_{SOL}



Wall geometry: divertor, baffling of neutrals…

$$q_{\|}^{t} = q_{\|}^{u} - q_{rad}^{imp} - q_{recy}^{rad} - q_{\perp} - q_{recom}$$

Complex atomic physics- > obstacle to scaling approaches

Complex physics -> coupled fluid-kinetic 2D/3D edge plasma codes (SOLPS-ITER, UEDGE, EDGE2D-EIRENE etc)

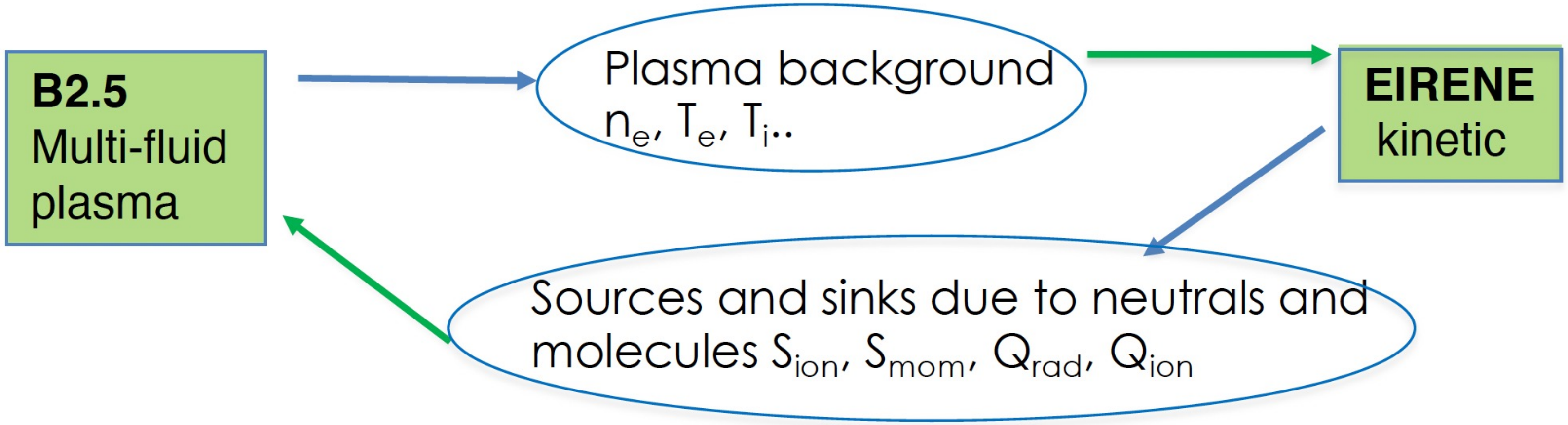
What processes control power dissipation?

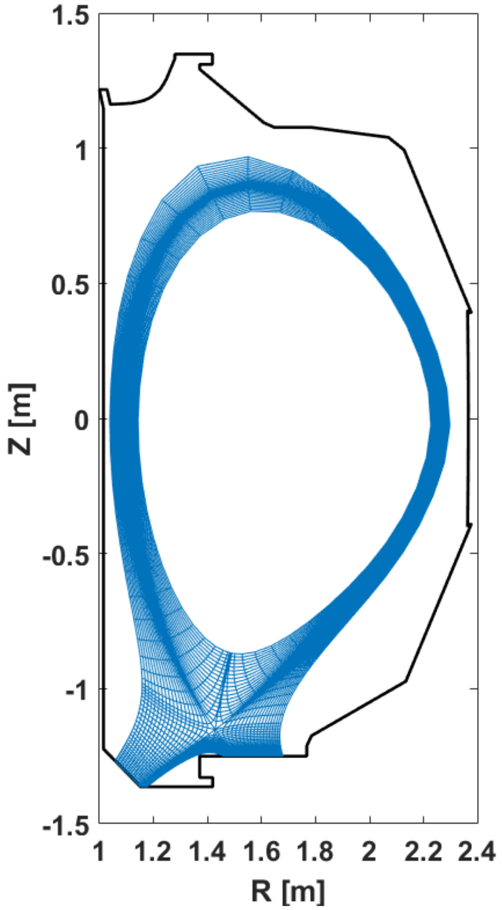
Complex physics -> coupled fluid-kinetic 2D/3D edge plasma codes

SOLPS-ITER, UEDGE, EDGE2D-EIRENE etc.

SOLPS-ITER (Scrape Off Layer Plasma Solver)

- B2.5: 2D multi-fluid plasma
- EIRENE: 3D Monte-Carlo neutral kinetic (ion-molecules and neutral-neutral collisions)





Comprehensive atomic reaction rates (ionization, radiation, etc)

How can we reduce divertor power loads to match the technological limit?

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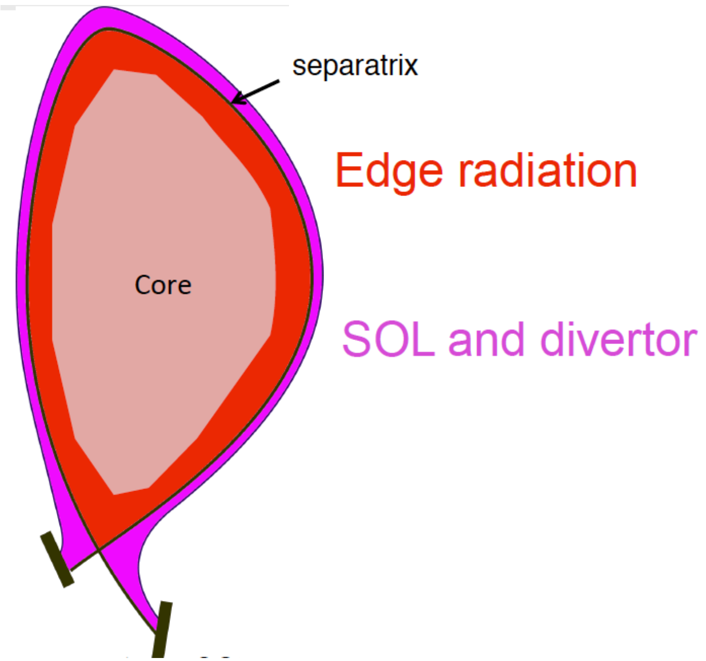
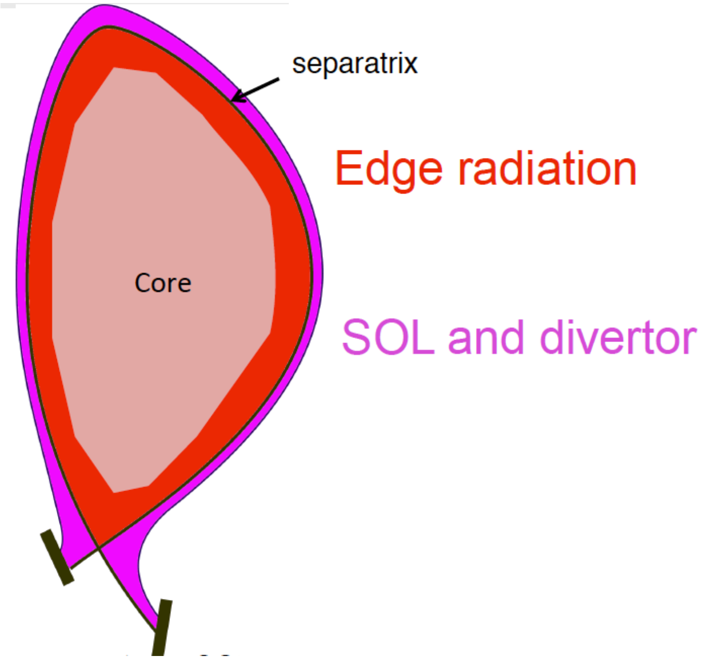
- **Radiative cooling to promote radiation while minimizing core contamination**
  Radiation needs to be compatible with dilution, MHD, divertor impurity leakage and core accumulation

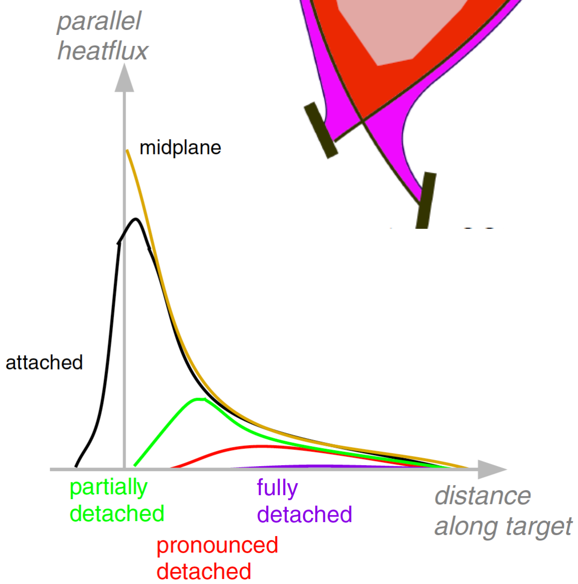


How can we reduce divertor power loads to match the technological limit?

- **Radiative cooling to promote radiation while minimizing core contamination**
  Radiation needs to be compatible with dilution, MHD, divertor impurity leakage and core accumulation

- **Divertor detachment:**
  cold dissipative divertor (T_e< 2 eV) with reduced heat and particle flux
  Detachment obtained with high gas puff often associated with decreased confinement





A. Kallenbach NF 55, 5 (2015)

Radiative cooling by impurity seeding to convert power flux into radiation

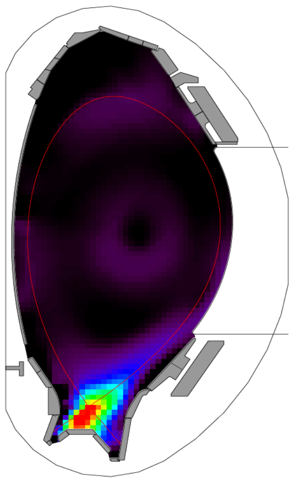
How do I choose the right seeding impurity?

L_z: radiative loss function for impurities (ADAS)

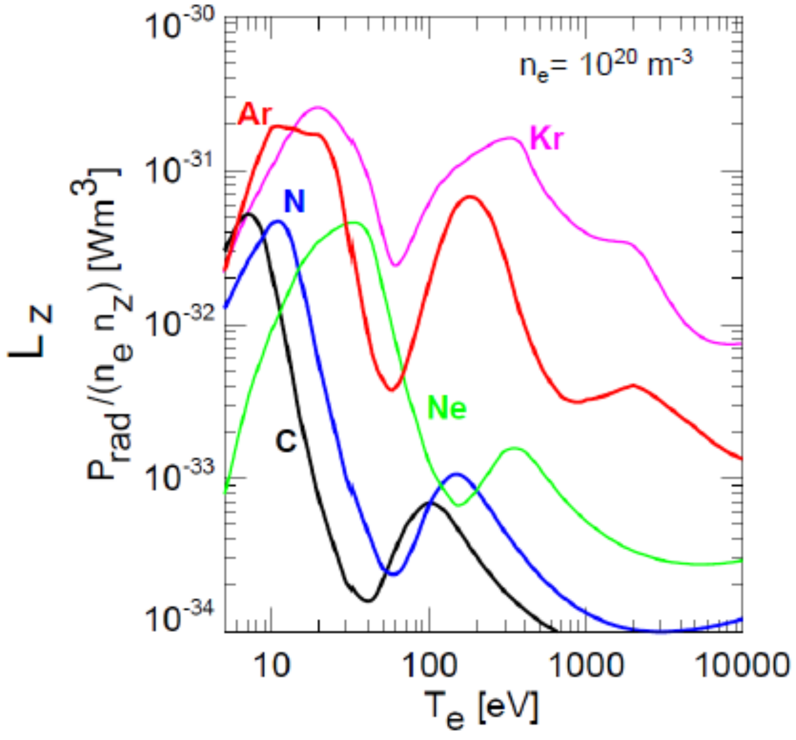
- C, N the most suitable edge and divertor

- Ar and Kr are the best candidate for radiation

N seeding



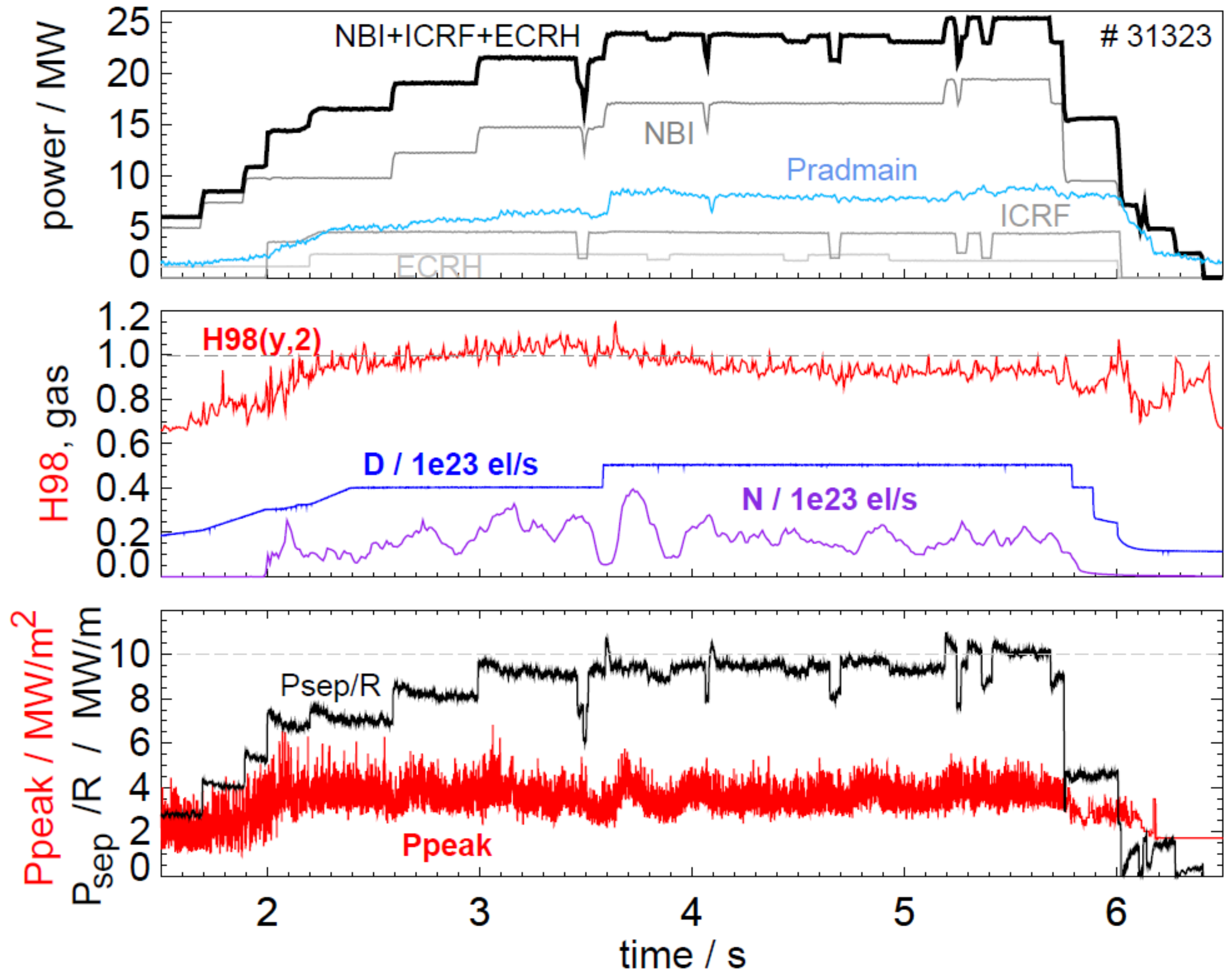
Atomic Data



A. Kallenbach et al. PPCF 2013

Impurity seeding:
- Already required in W machines
- Mandatory in future reactors:
maximum divertor radiation + strong mantle radiation

Divertor heat flux kept low with N seeding



A. Kallenbach et al.,Nucl. Fusion (2013)

ASDEX Upgrade discharge applying N-cooling at 2/3 of Normalised ITER power flux (P_{sep}/R=10 MW/m)

Feedback control N seeding, divertor heat flux is kept < 5MW/m^2 at high n_{sep}
Unmitigated divertor heat flux would be ~ 40MW/m^2

Non coronal treatment necessary for radiation at the plasma edge

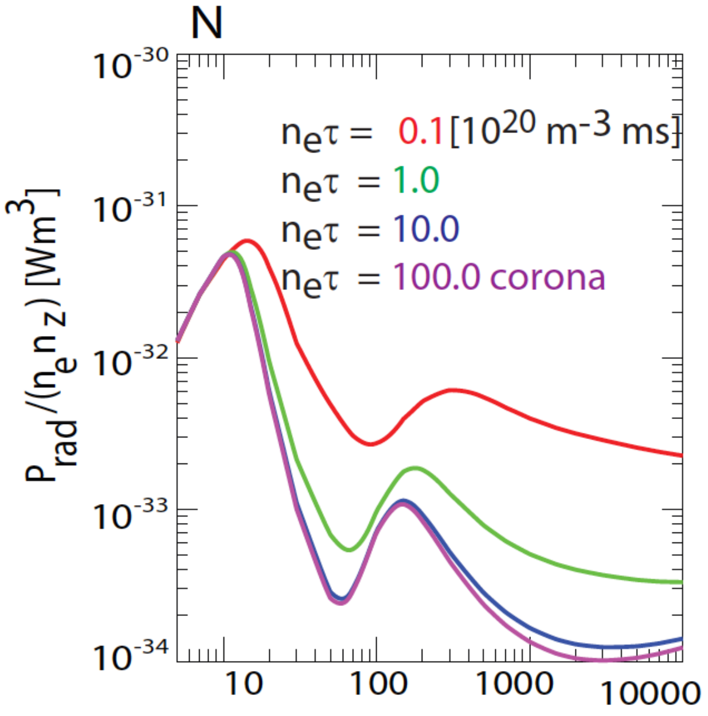
Neglecting plasma transport: coronal equilibrium
Balance between ionization and recombination, as in the solar corona (plasma core)

$$P_{rad} = n_e \cdot n_z \cdot L_Z\,(Te)$$

At the plasma edge: steep gradients + ELMs (Edge Localized Instabilities)
radial transport cannot be neglected

→ **Non Coronal Equilibrium** $L_z\,(T_e\,, n_e\,{*}\tau)$

τ : resident time of an impurity

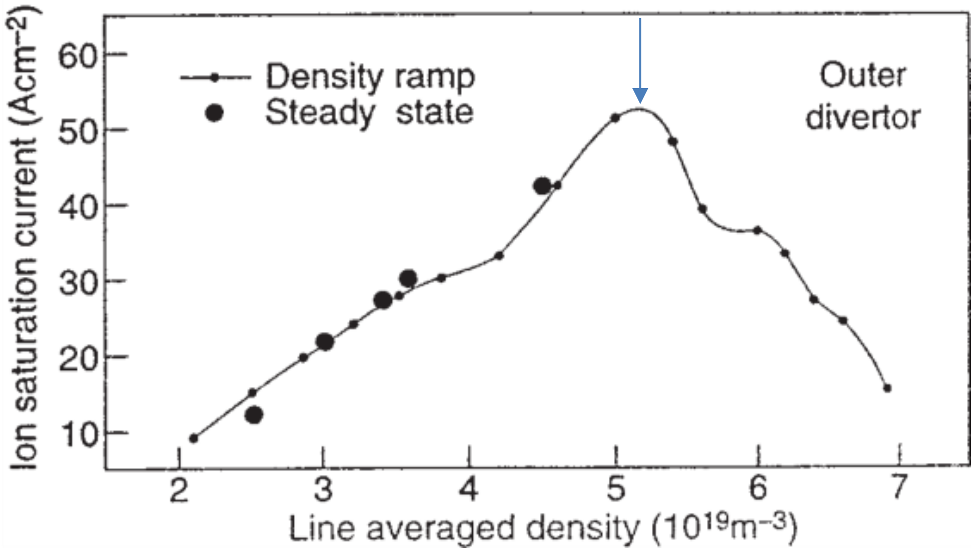


- Transport increases effective cooling rate and makes it less temperature dependent
- Self-consistent model (plasma transport code + radiation model)

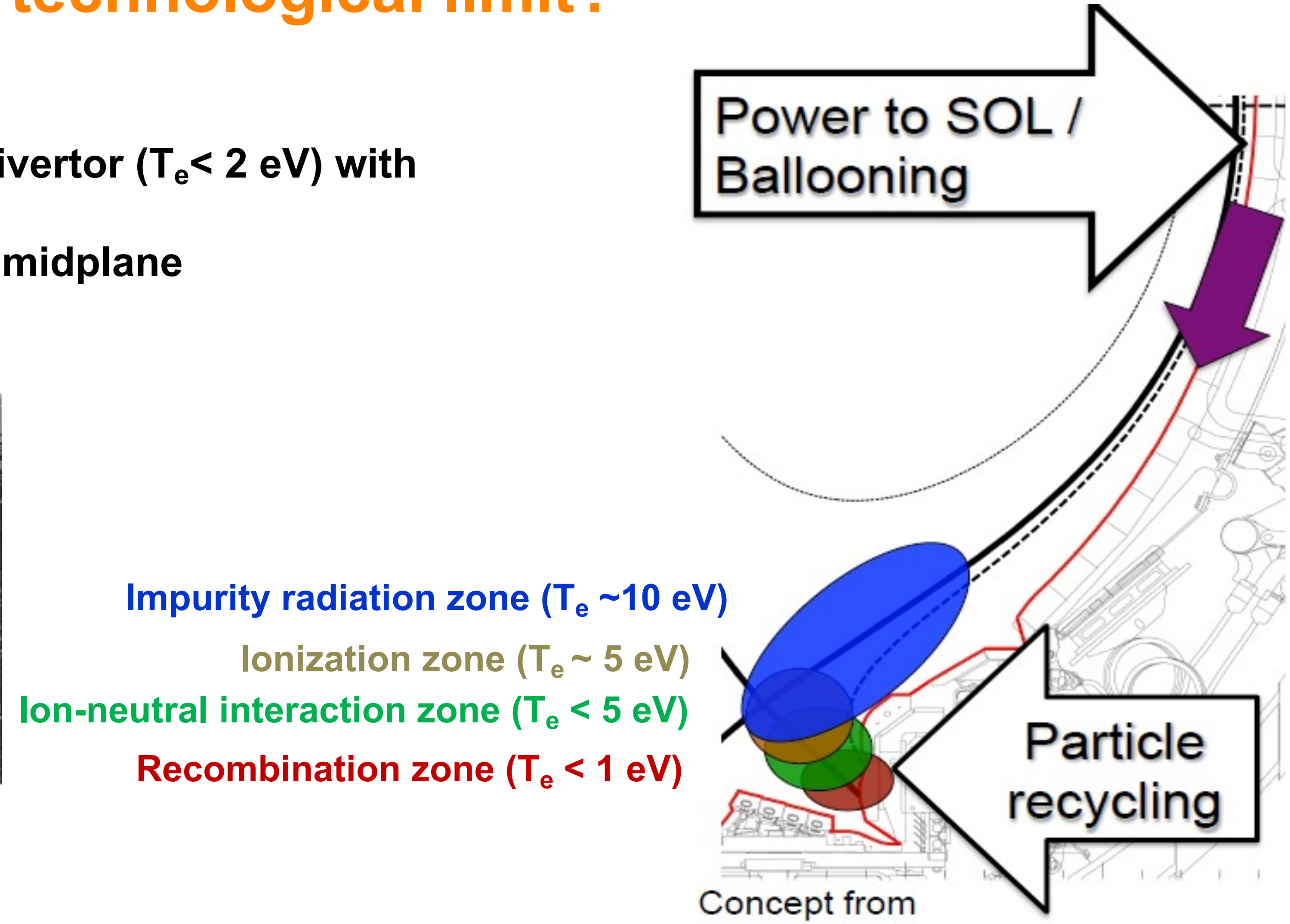
L. Casali, Phys. Plasmas 25, 032506 (2018)

How can we reduce divertor power loads to match the technological limit?

- **Divertor detachment cold dissipative divertor (T_e< 2 eV) with reduced heat and particle flux**
- **Pressure in the divertor well below the midplane**



Loarte, et al. Nucl. Fusion (1998)

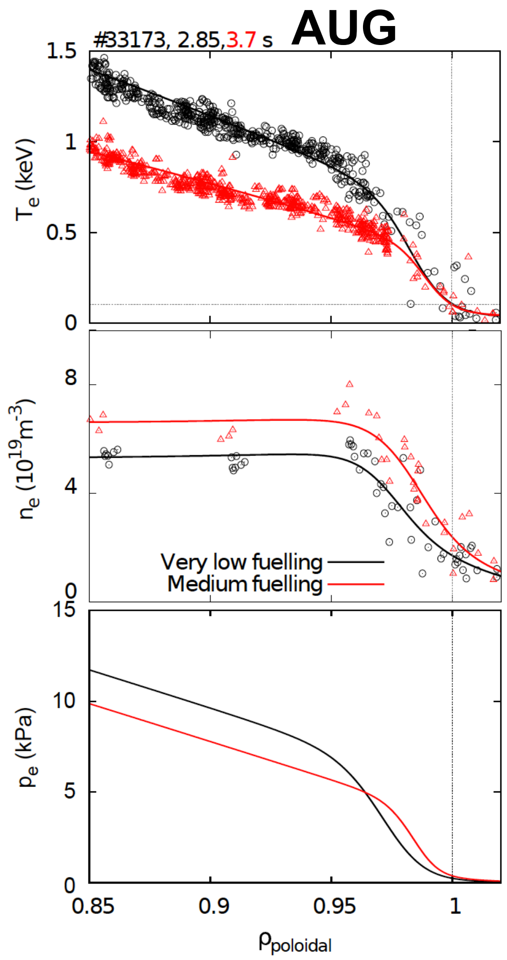


Concept from
[M. E. Fenstermacher, PPCF 1999]

Detachment often associated with decreased confinement in existing devices

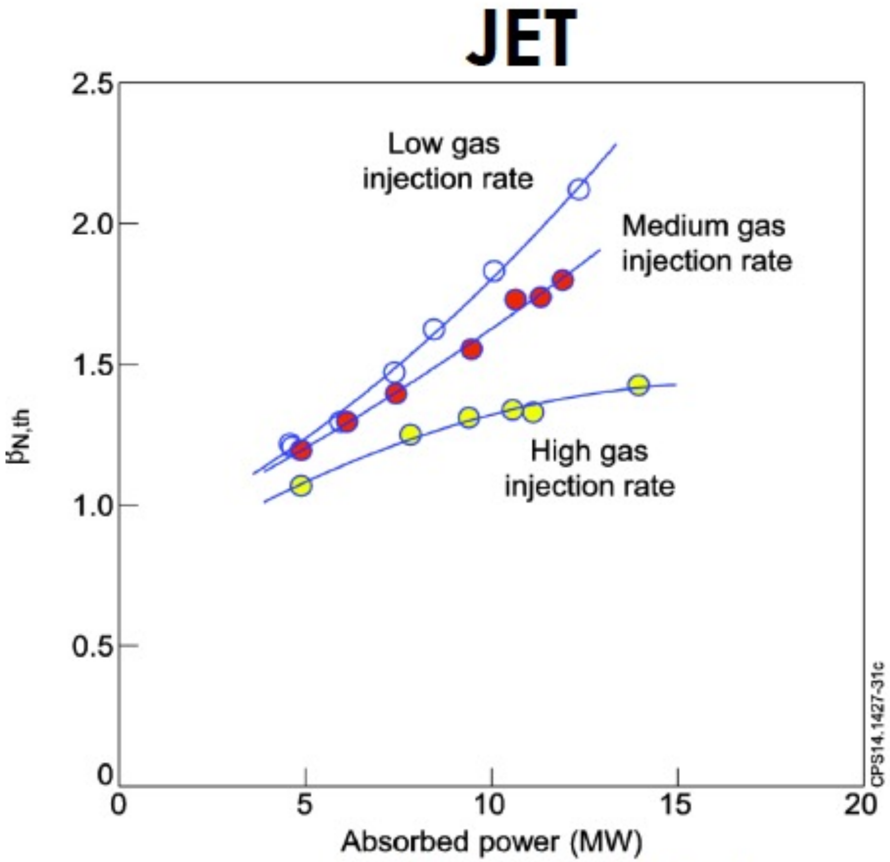
High D fueling required for detachment leads to high upstream density/ collisionality

Reduction in H-mode confinement as density is increased to access detachment



High n_{sep} (D fueling)

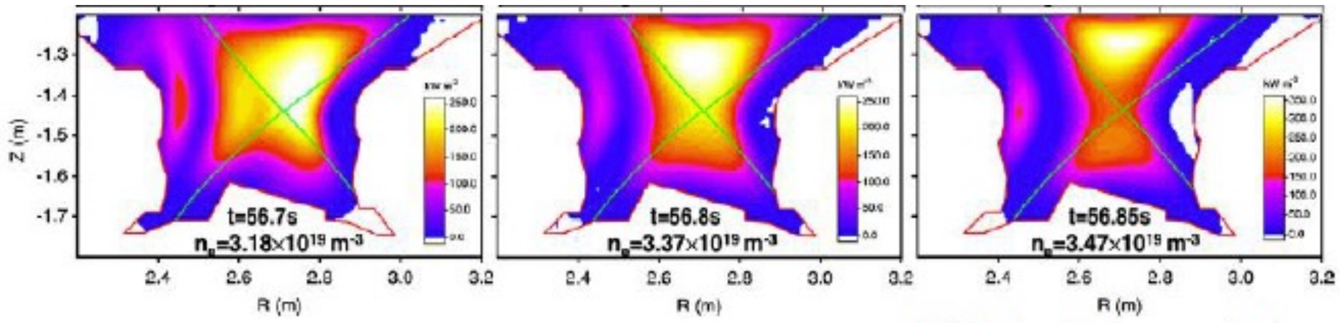
Dunne PPCF 2016



Challis NF **55** 053031 (2015)

Detachment often associated with decreased confinement in existing devices

Full detachment can also lead to radiation instabilities (MARFE)



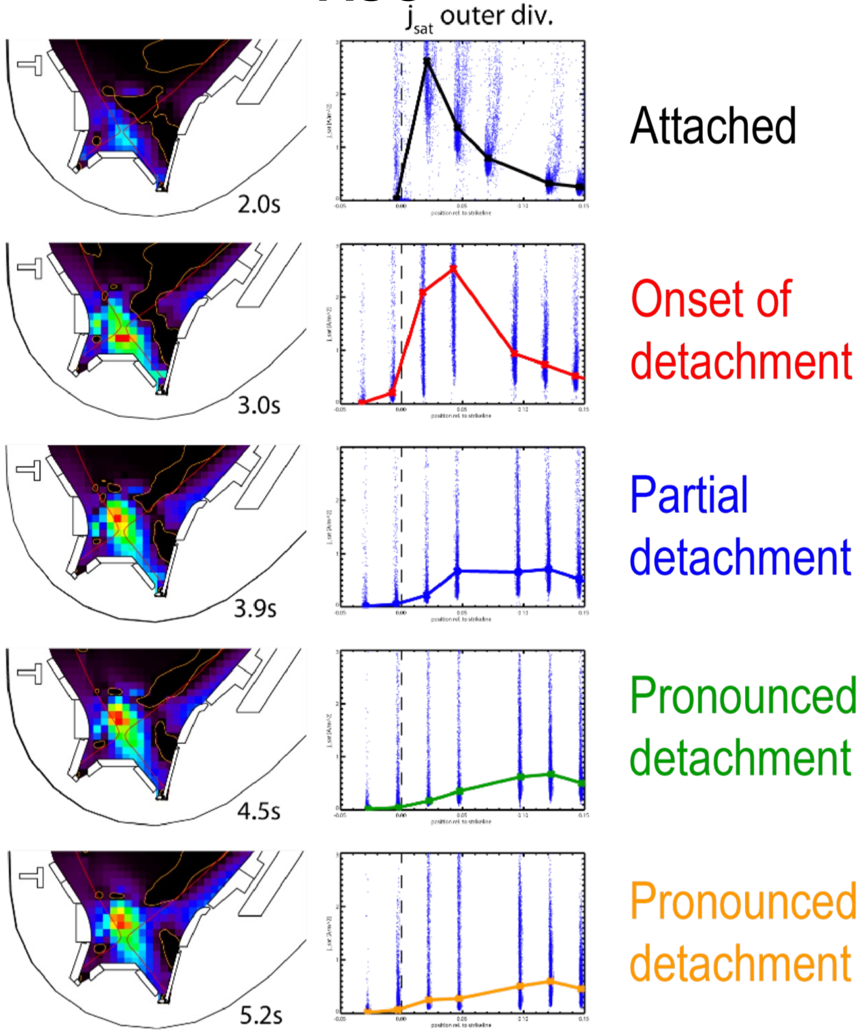
JET, A. Huber, et al.

- MARFE formation can drive a transition from H to L-mode (H-mode density limit) or disruption
- Limit detachment to regions where it is needed most

How to achieve this?

Divertor closure | Target orientation | Impurity seeding

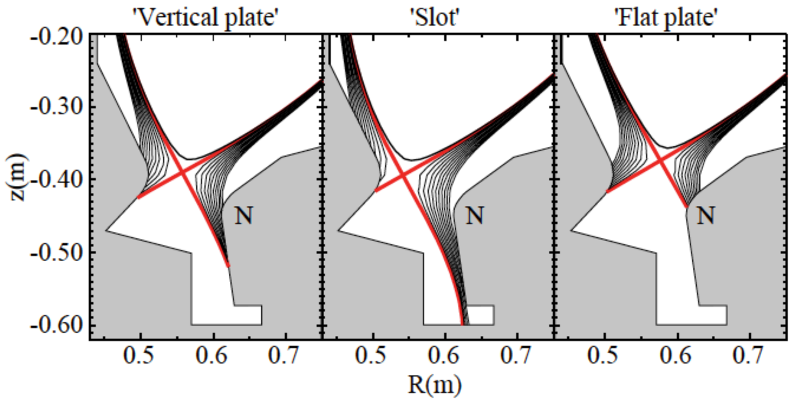
AUG



Bernert NF 61 024001 (2021)

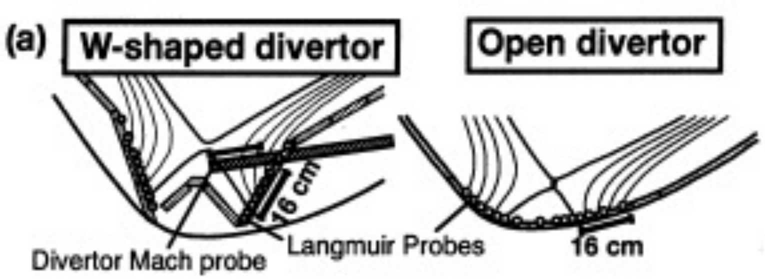
Detachment Onset is Influenced by Divertor Baffle Geometry

C-Mod



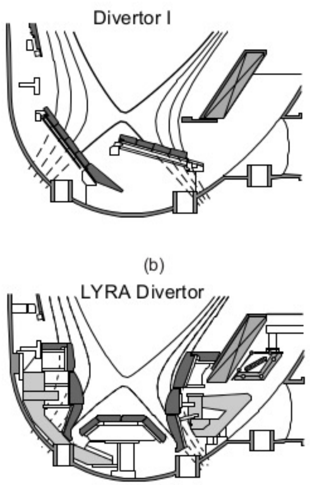
Lipschultz, et al. 16th IAEA (1996)

JT-60



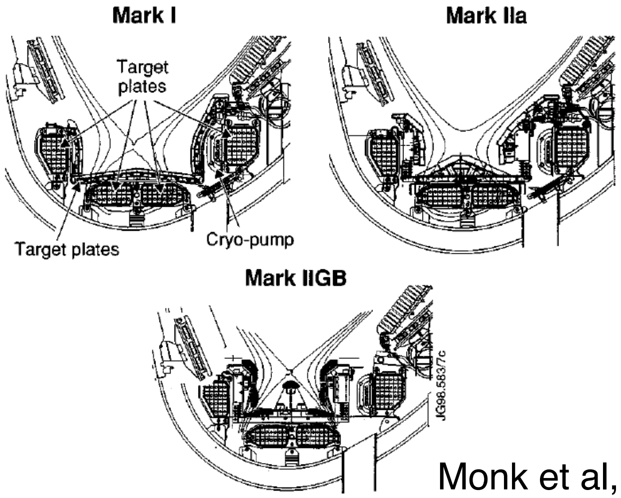
Asakura, et al., Journal of Nucl. Mat. (1999)

AUG



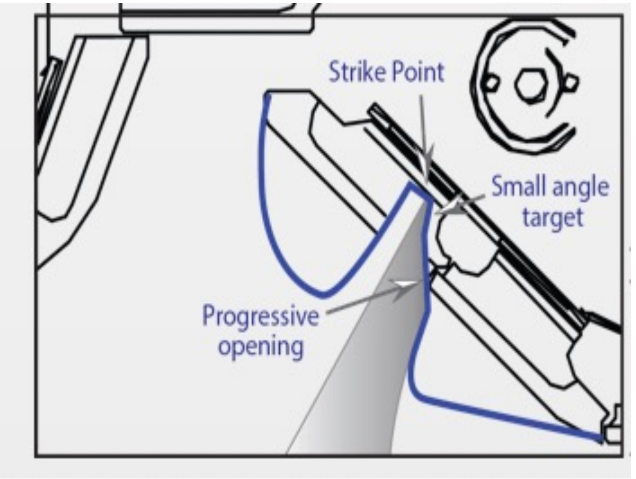
Kallenbach, et al. Nucl. Fusion (1999)

JET



Monk et al, Nucl. Fusion (1999)

DIII-D

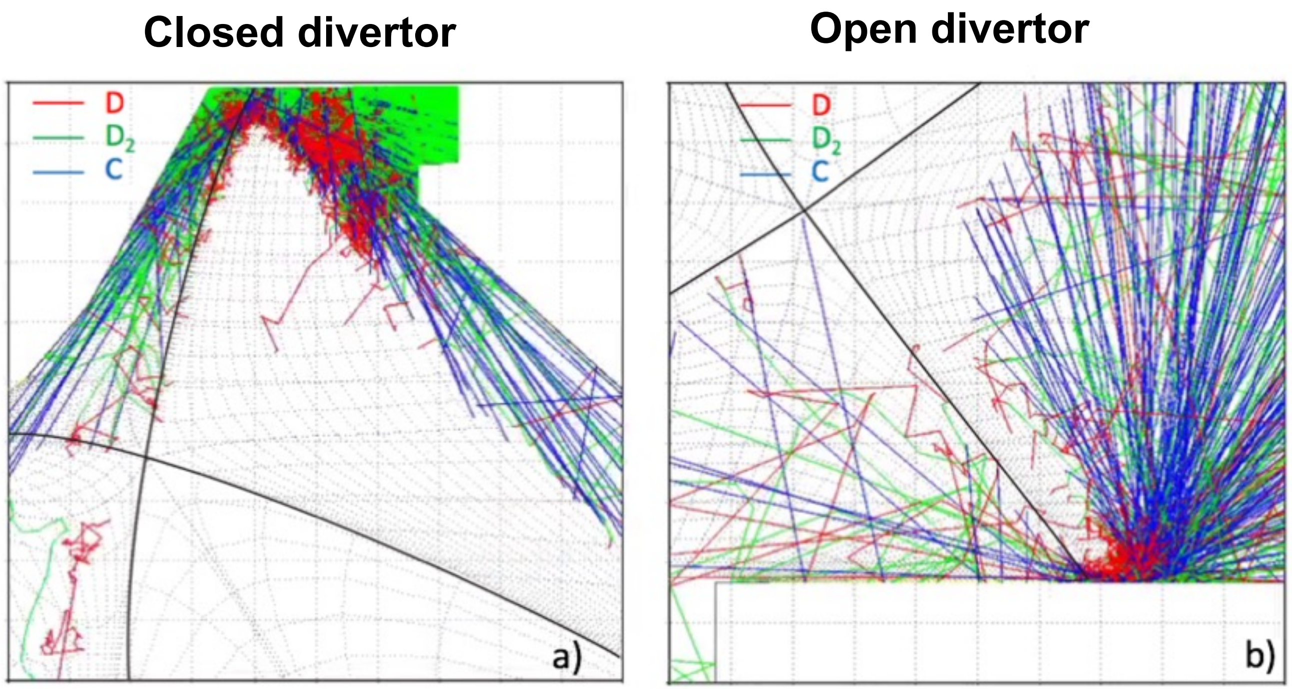


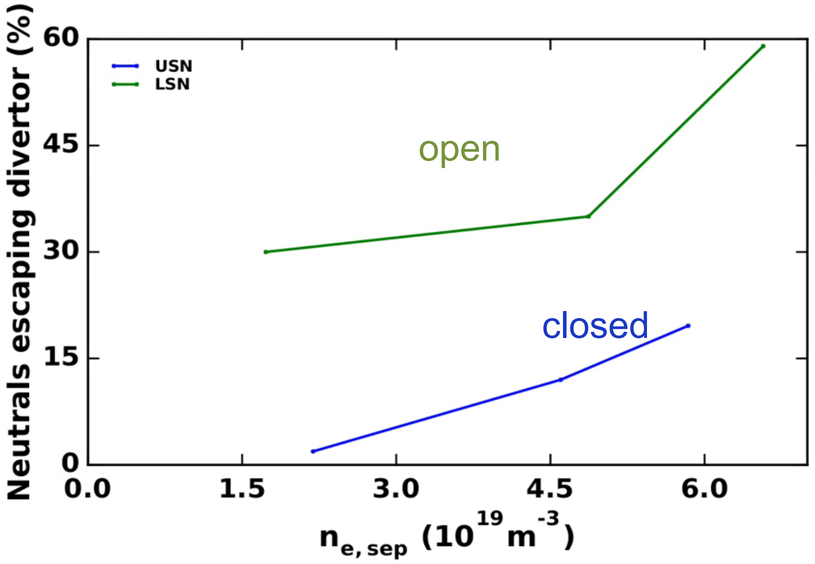
H. Guo et al. NF 59 (2019)
L. Casali et al. NME 19 (2019)

What is divertor closure?

“Closure” refers to the degree in which recycling neutrals at the target can escape the divertor

MC trajectories of neutrals calculated by EIRENE





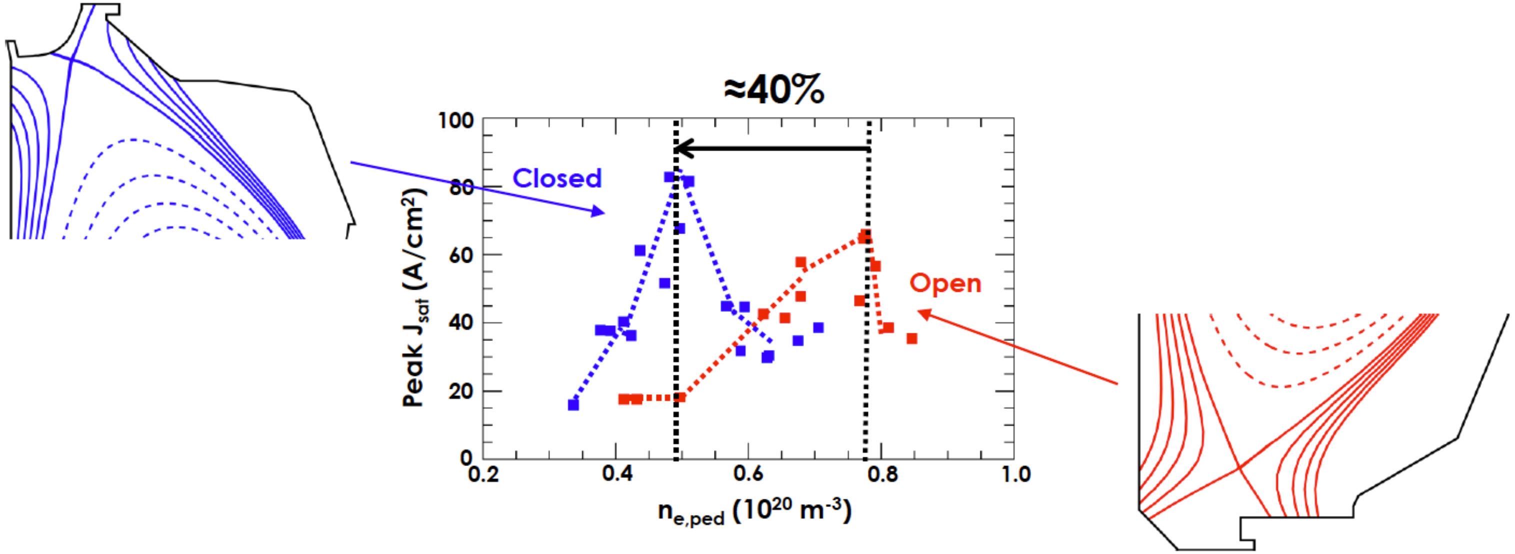
- Closed divertor: neutrals accumulate at target
- Open divertor: scatter into the SOL -> Low neutral accumulation

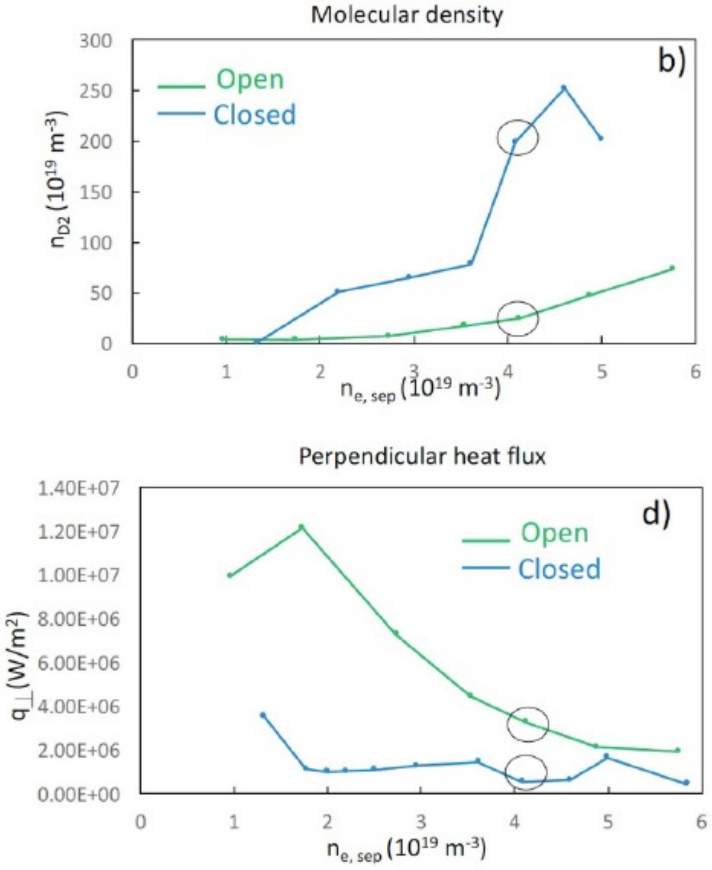
L. Casali et al. Nucl. Fusion 60 076011 (2020)

Closed divertor detaches at lower upstream density than the open divertor

SOLPS

DIII-D upper closed divertor vs lower open divertor



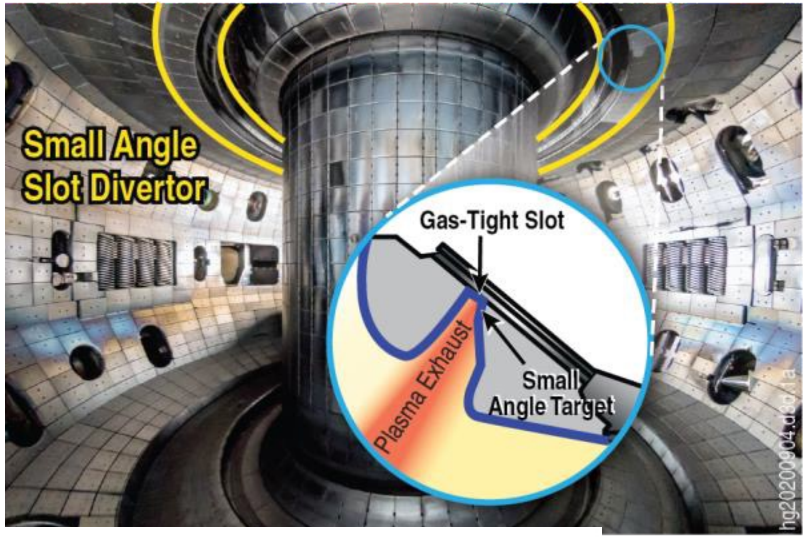


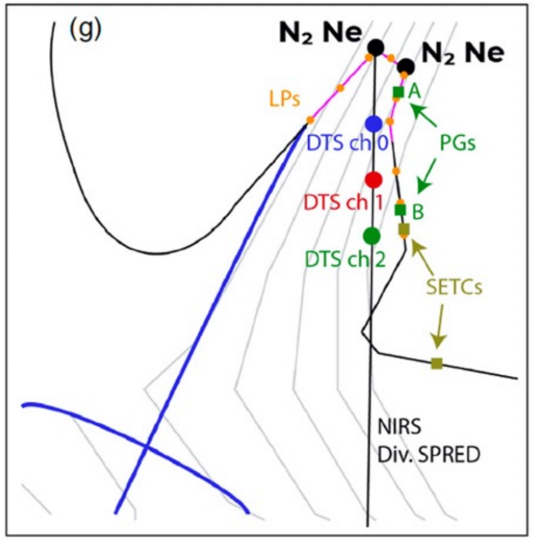
A . Moser et al. PoP (2020)

- Closed divertor has higher SOL dissipation (increased neutral trapping, radiation losses etc)
- Divertor closure change the pedestal structure

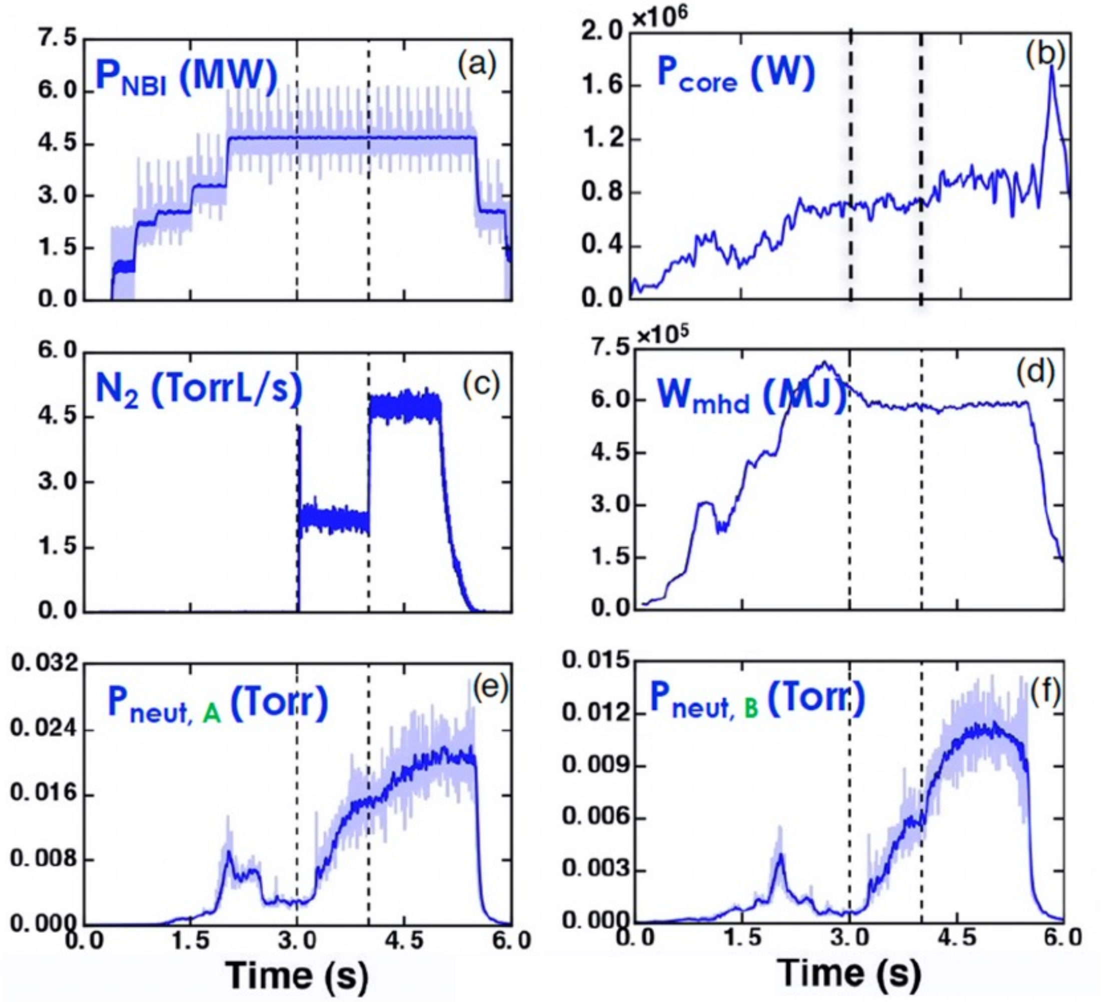
L. Casali et al. CPP 58 (2018)
L. Casali et al. NF (2020)

First Impurity seeding studies in the SAS divertor at DIII-D





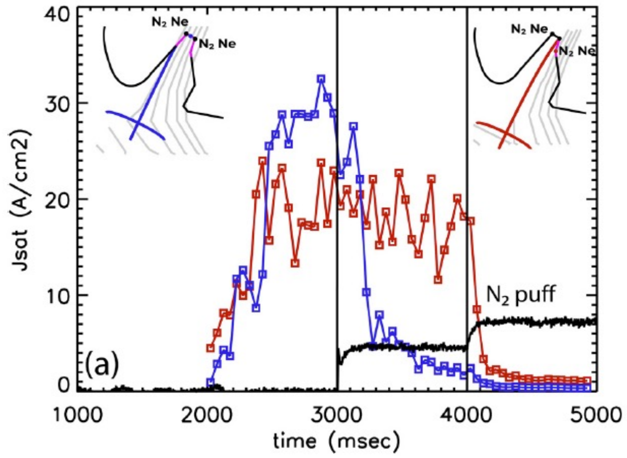
L. Casali et al. POP (2020)
L. Casali et al. NF (2022)

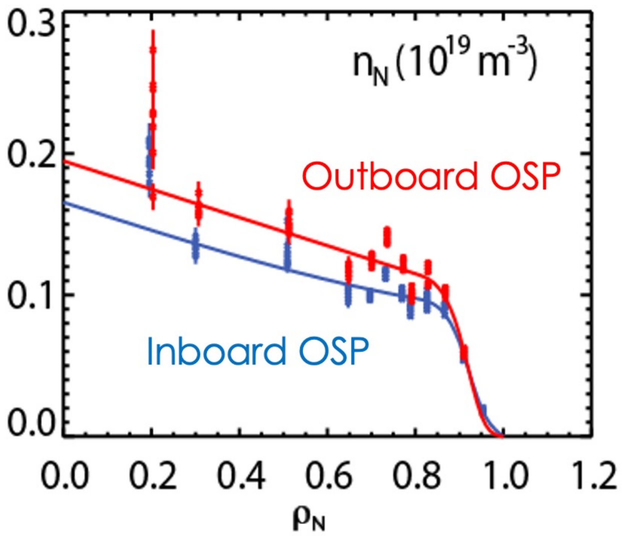


High neutral pressure indicating deep detachment

No core confinement degradation

Divertor closure/ target shaping + impurity seeding: better core-edge compatibility





With the strike point at inboard side:

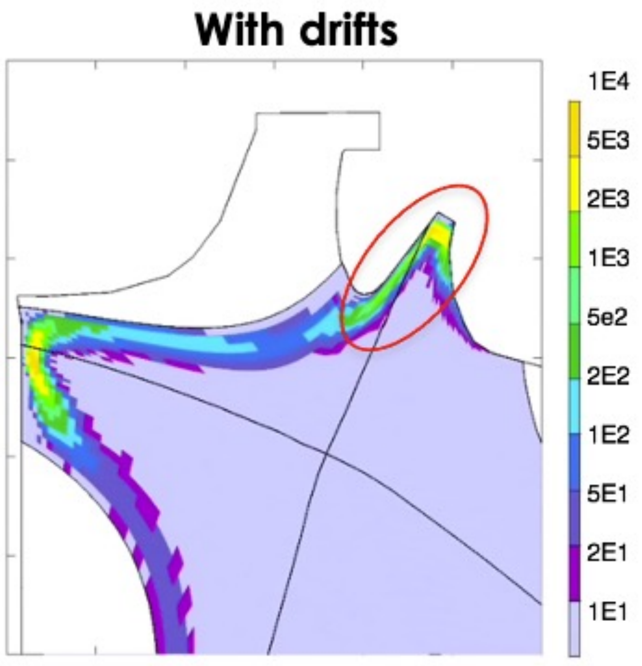
- Detachment at lower density

- Reduced core impurity contamination

-> improved core-edge integration

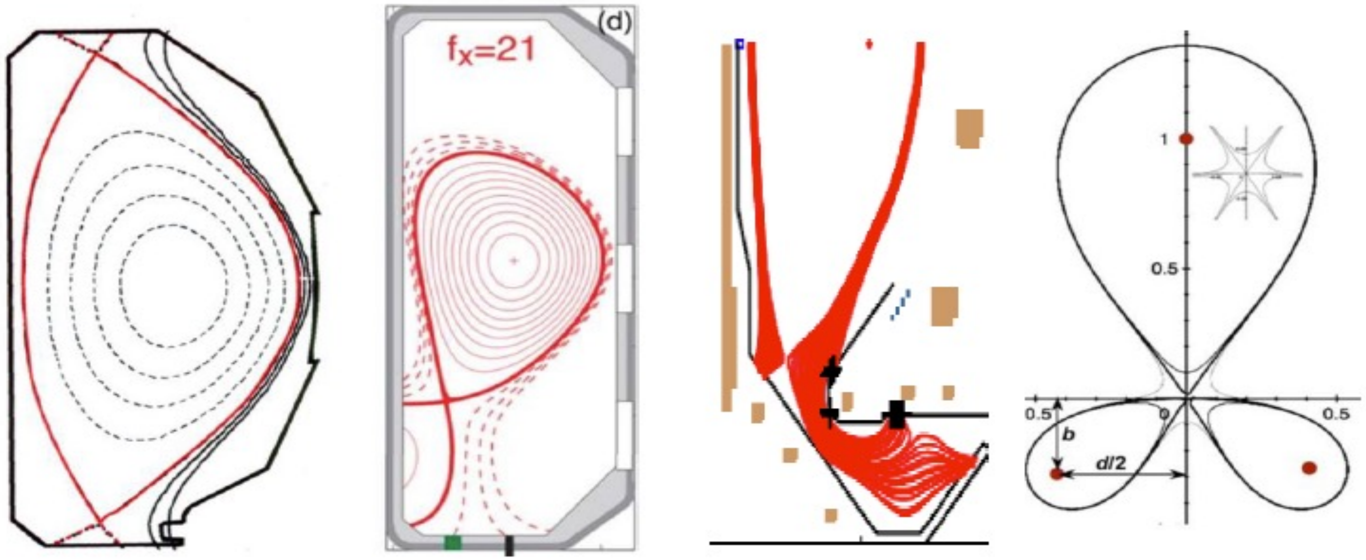
L. Casali et al. Physics of Plasmas 27, 062506 (2020)

SOLPS-ITER



Plasma Drifts and Divertor Geometry play an important role for core-edge

Advanced divertor configuration can provide improved control of detachment front



Alternative divertor geometries may lead to higher allowable P_{sep}

- increase (dissipative) divertor volume
- increase wetted area on target plate
- stabilise detachment front…

H. Reimerdes et al., 27th IAEA Fusion Energy Conference (2018), TH/P7-18

Has become a very active research field across the globe

The core-boundary solution represents a critical challenge for fusion

- It represents a critical gap in fusion tokamak research worldwide
- Requires understanding of how these regions interact & can be married together
- It requires cross fertilization and innovation (radiation, divertor geometry, materials)
- Be able to project solutions for future reactors
- -> Ultimately the solution is likely a combination of the presented concepts

This is an exciting area for current and future research ! (i.e. for you)

Casali Research Group: Power Exhaust & Core-Edge Physics

Mission: Integrated core-edge solutions to achieve high core performance scenarios with mitigated power exhaust solutions in magnetically confined fusion devices

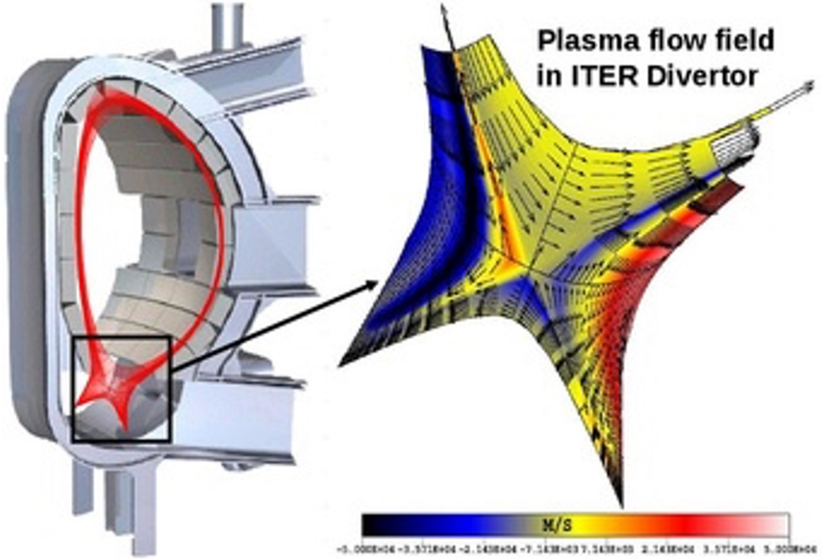
Design and execute experiments as well as state of the art computational modeling such as SOLPS-ITER, STRAHL, TRANSP, ASTRA, ELITE, EIRENE etc.

DOE Early Career Award 2022 – Innovative core-edge solution for tokamaks

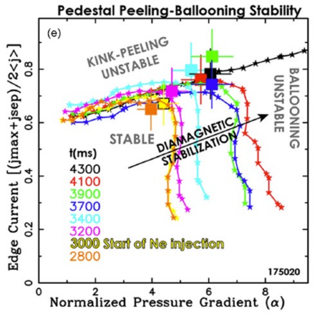
ITER Fellow - work on Core-Edge for ITER

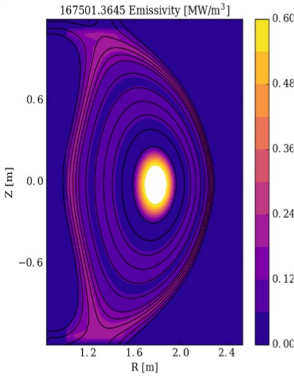
DIII-D Control Room

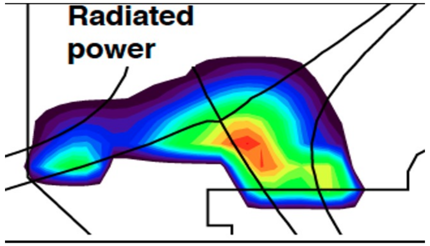
Experiments



State-of-the-art computational modeling







Contact: lcasali@utk.edu

THE UNIVERSITY OF TENNESSEE KNOXVILLE

Plasma Physics, Fusion Technology, Nuclear materials UTK courses

Plasma Physics and Fusion Energy

Introduction to Fusion Technology

Edge Physics for Power and Particle Exhaust (from 2023)

Diagnostics for Plasma Physics and Fusion Technology

Boundary Plasma Physics and Plasma-Material Interactions

Introduction to Nuclear Fuels and Materials

Fundamentals of Irradiation Effects in Nuclear Materials

Advanced Characterization Methods Applied to Nuclear Materials

Defect Physics in Materials Exposed to Extreme Environments

Gas Dynamics in Nuclear Materials

Interested in this field?

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