Core-Edge Integration with Radiative Scenarios

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BOUT++ Workshop January 2023

Path to Optimized Core-Edge Integration Relies on Radiative Power Exhaust Balancing Core Contamination

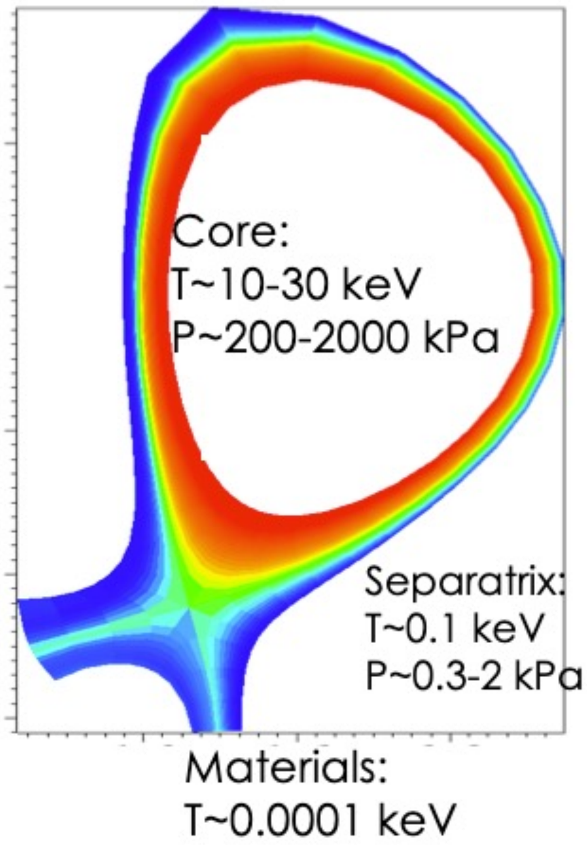
- The power exhaust and the core-edge integration challenge
- Radiation as the key element for the integrated scenario
- State-of-the-art: experimental observations, modeling
- The quest for power exhaust criteria
- Discussion

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

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

Core constraints must be translated into divertor/SOL design metrics
Separatrix values: Density, temperature, neutral flux, impurity density etc

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



The core and the edge are guided by different physics

Core ↔ Pedestal

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

⬇

PERFORMANCE

Current drive, $p_{e,PED}$

Separatrix

n_{sep}

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

Divertor, $q_{||}$ ↔ Wall

High n_{div} + *impurities*

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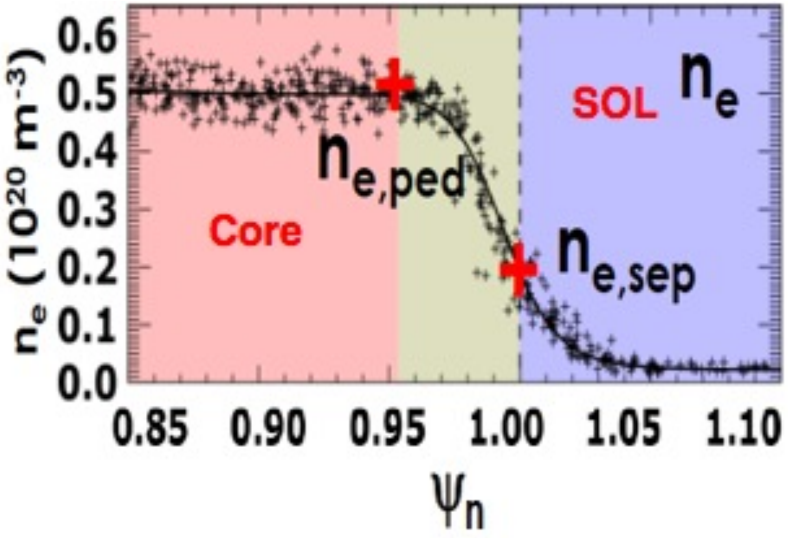
DISSIPATION

Radiation, detachment



Compatibility of core-edge solutions balances at the pedestal

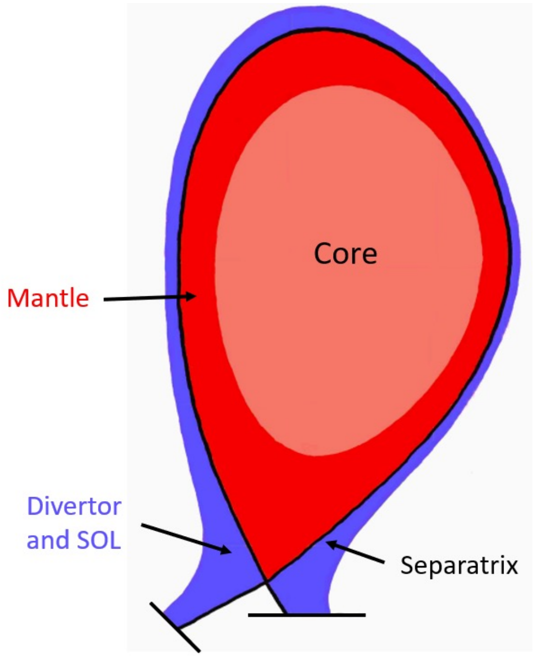
$n_{e,ped}$ set by core fueling and radial transport to separatrix density

$n_{e,sep}$ set by divertor detachment and parallel transport

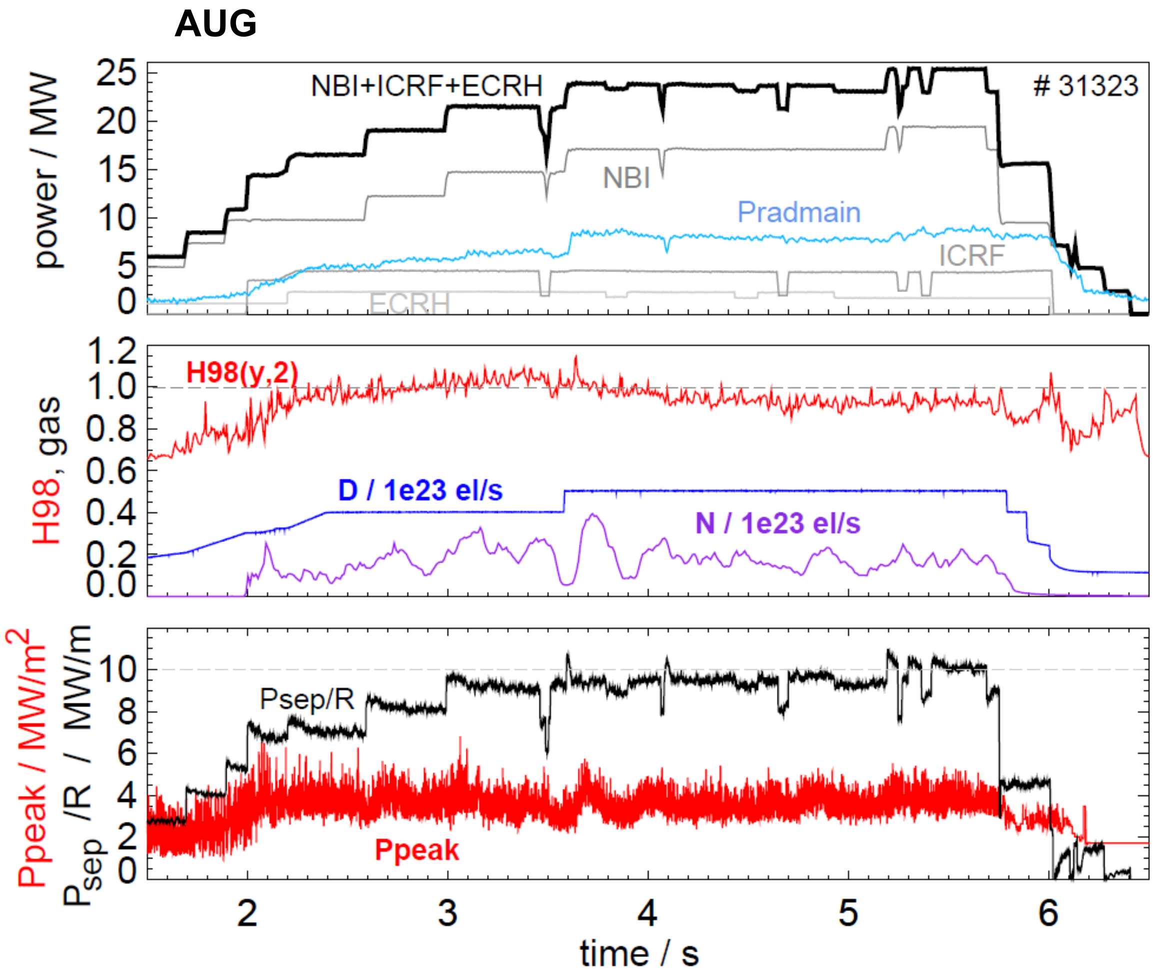
Radiation: key element for power exhaust and core-edge

Impurity seeding to promote radiation while minimizing core contamination

- Impurity gas puff
- Impurity powders



Divertor heat flux kept low with N seeding

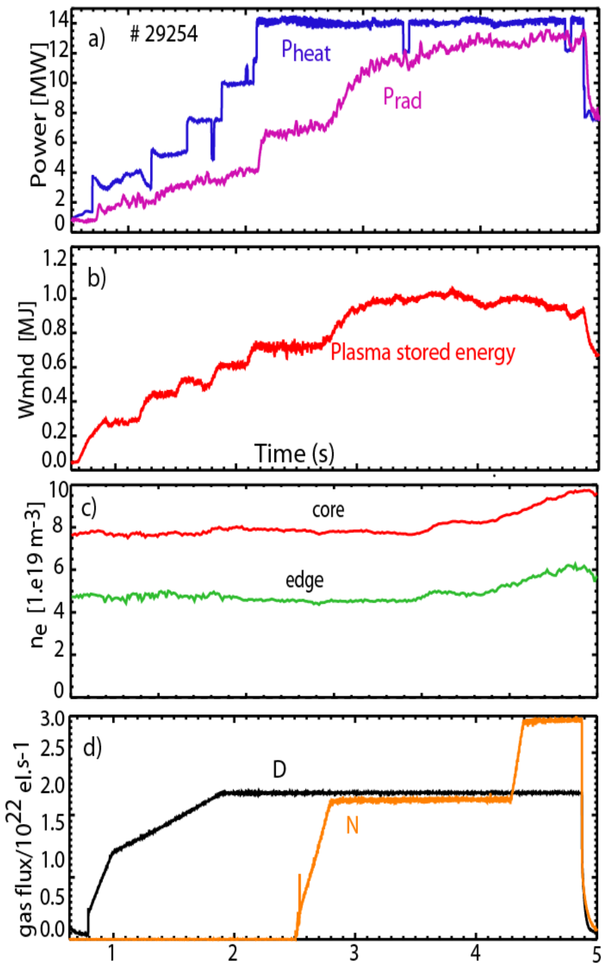


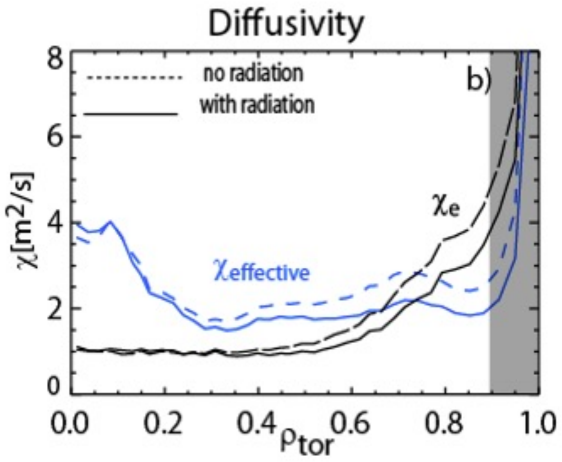
N-cooling at 2/3 of Normalized ITER power flux (P_{sep}/R =10MW/m)

A.Kallenbach Nucl. Fusion 2013

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

In ASDEX Upgrade confinement increases with nitrogen seeding

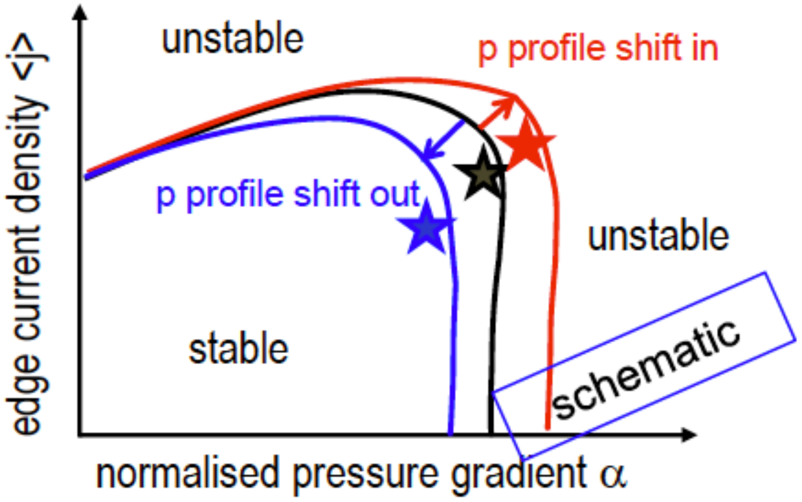




- **Pedestal effect through profile stiffness**
- **Density profile moves inwards**

  Decreases $n_{e,sep}$ and $n_{e,sep}/n_{e,ped}$

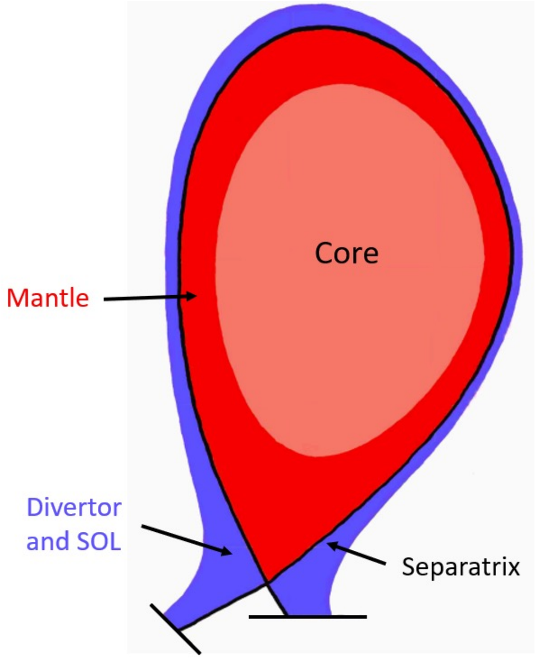
- **40% confinement improvement**
- **Losses are at the edge**
- **No significant change in core transport (TRANSP)**



L. Casali EPJ 79, 01007 (2014)

M. Dunne, PPCF 59 (2017) 025010

Radiation: key element for power exhaust and core-edge



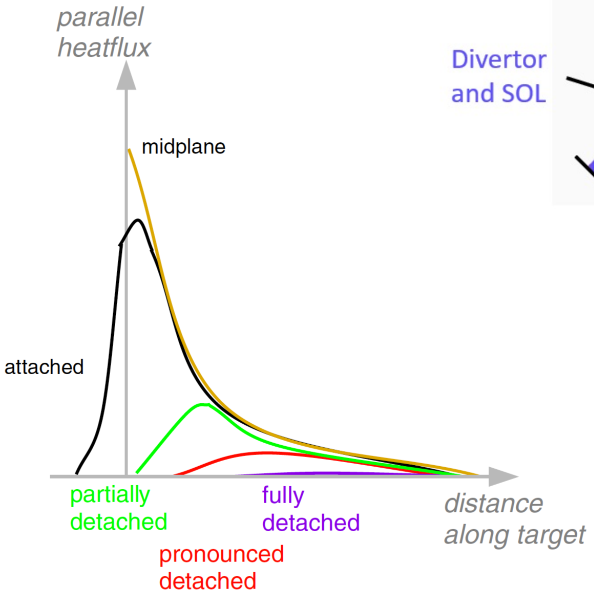
Impurity seeding to promote radiation while minimizing core contamination

Radiation needs to be compatible with dilution, MHD, divertor impurity leakage and core accumulation

Cool down divertor plasmas inducing detachment

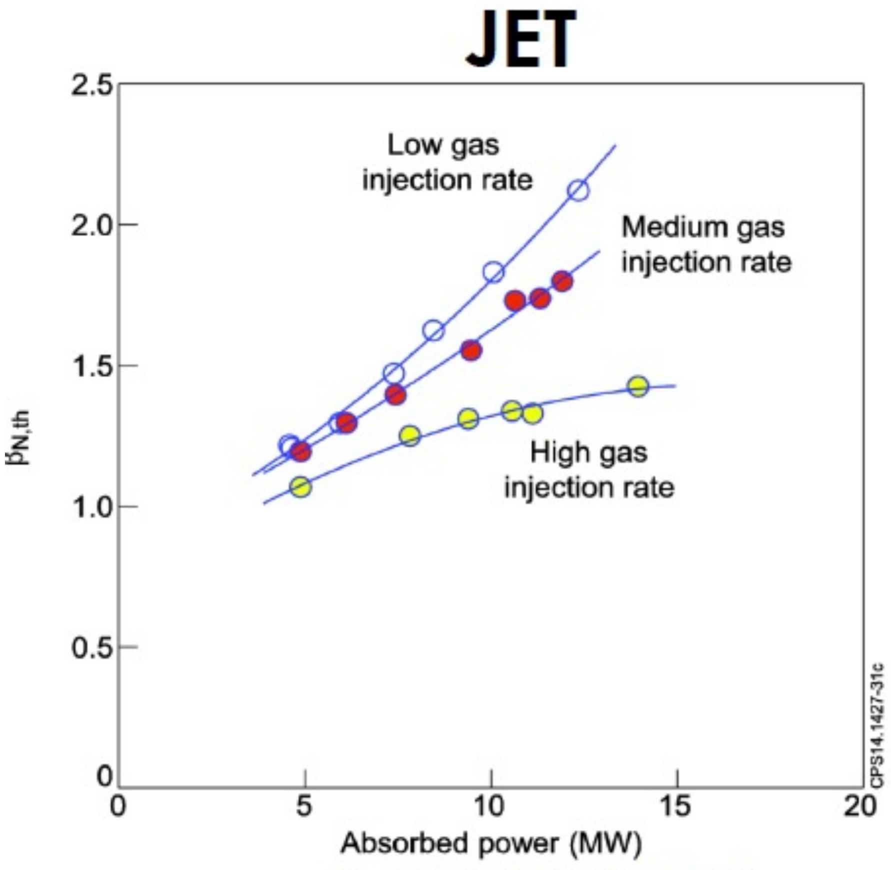
Cold dissipative divertor (T_e< 2 eV) with reduced heat and particle flux

Detachment obtained with high gas puff often associated with decreased confinement



A. Kallenbach NF 55, 5 (2015)

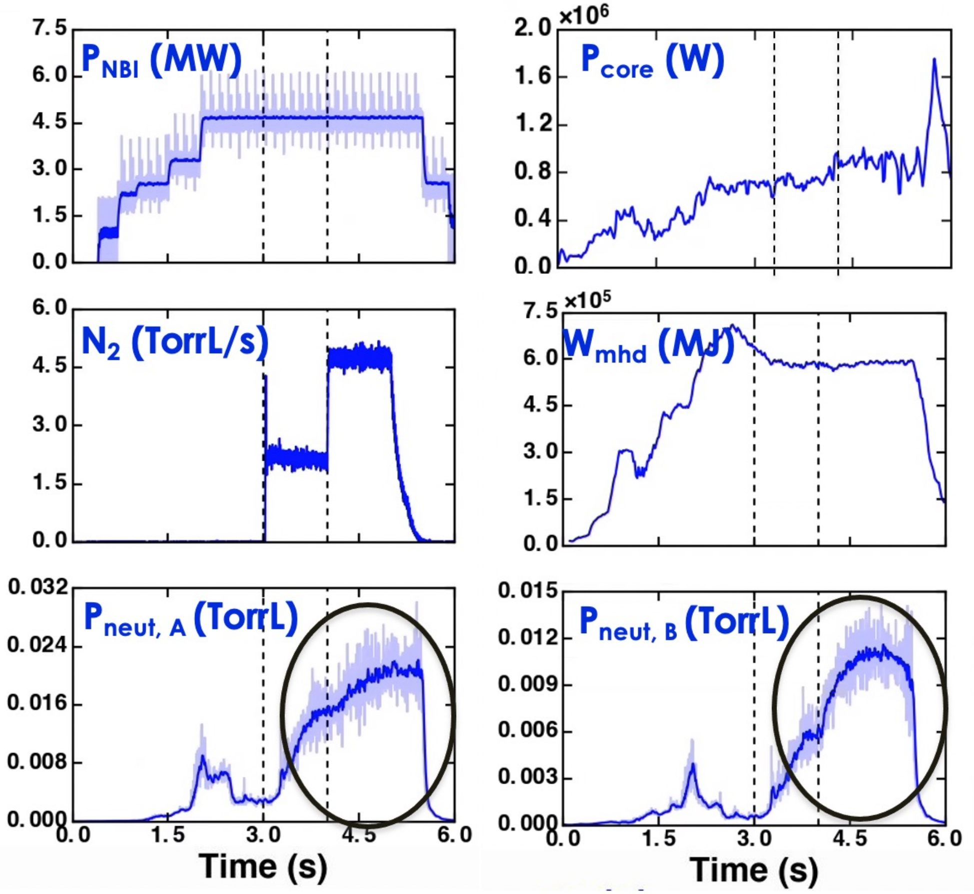
Compatibility of detachment and core performance

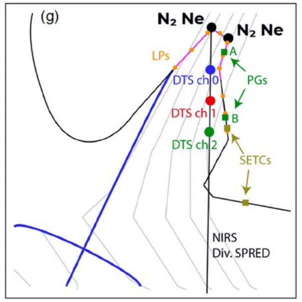


Challis NF **55** 053031 (2015)

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

SAS divertor at DIII-D



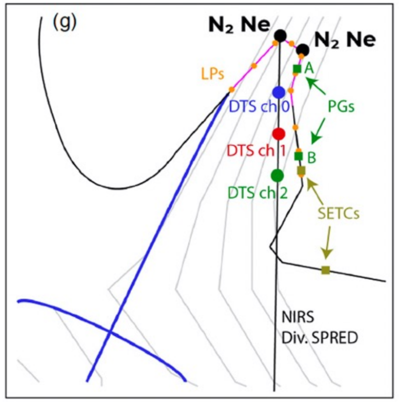


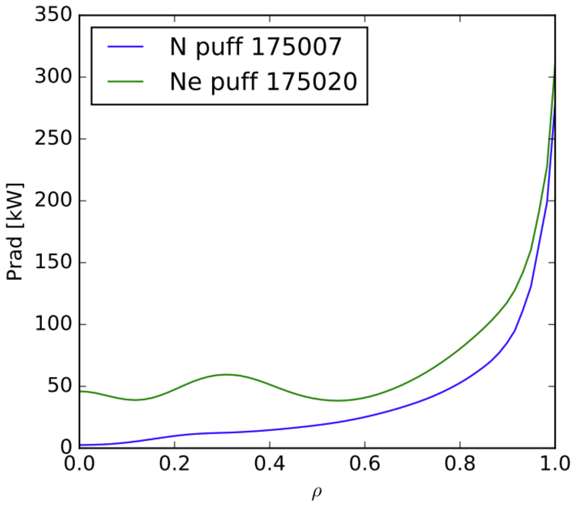
L. Casali et al. Physics of Plasmas 27, 062506 (2020)

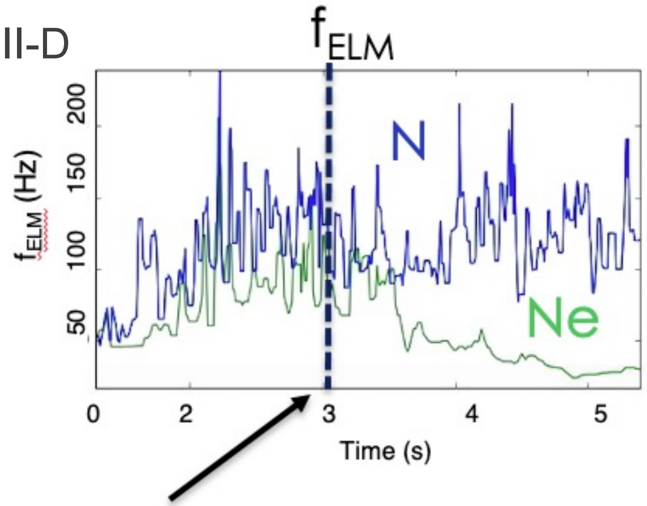
Divertor closure + Impurity seeding can improve core-edge compatibility

For N/Ne matched discharges, Ne increases radiation in the core reducing the ELM frequency

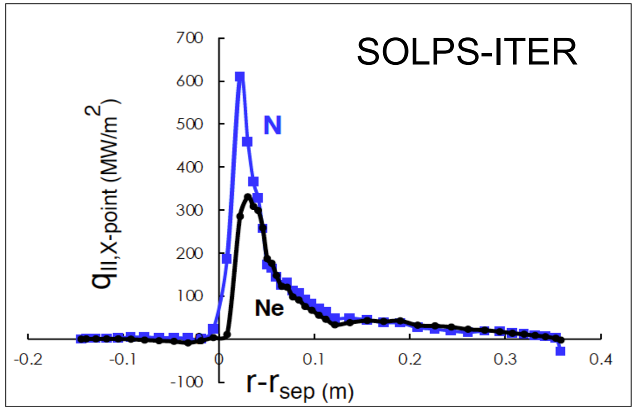
First impurity seeding experiments in the SAS divertor at DIII-D







Impurity seeding start



Ne dissipates more upstream than N

Two-point model (P. Stangeby 2000):

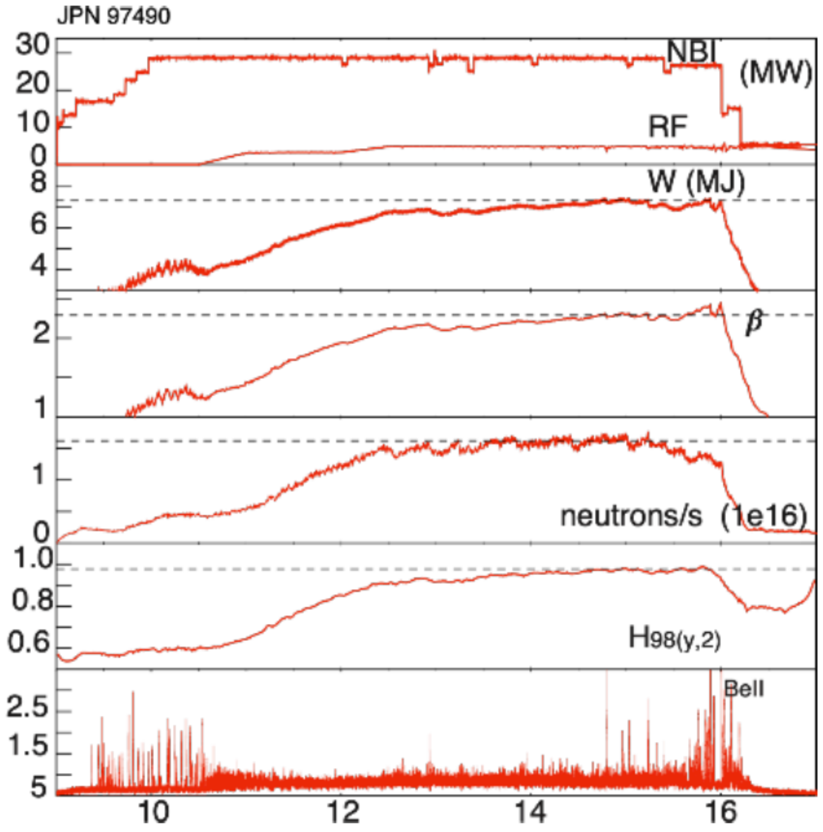
$$n_u \propto \frac{q_{\parallel}^{5/7}}{T_t^{1/2}} \frac{(1-f_{rad})}{(1-f_{mom})(1-f_{conv})^{2/7}}$$

Neon reduces both $q_{\parallel}$ and (1-frad) due to mantle radiation

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

Small/Non-ELM scenario with high confinement and detached state necessary for future reactors

In JET Stationary conditions obtained with Ne and no ELMs/small at highest radiation and good performance



f_{GWL}: 0.7

n_{ped}/n_{GW}: 0.46

f_{rad}: 0.8

Z_{eff}: 2.7

f_{rad}: 0.8

C_{Ne}=1.3 %

H_{98}: 1.0

β_N: 2.3

$T_i \backsim 1.2 \times T_e$

$P_{tot,ped}$ 17 kPa

ν_{eff} 0.9

C. Giroud IAEA FEC 2020

- Simultaneous small/no ELM stationary regime with Ne seeding and high thermal energy confinement with strong divertor radiation (start of partial detachment)

EDA H-mode in AUG Double radiative for high power, no ELM, detachment

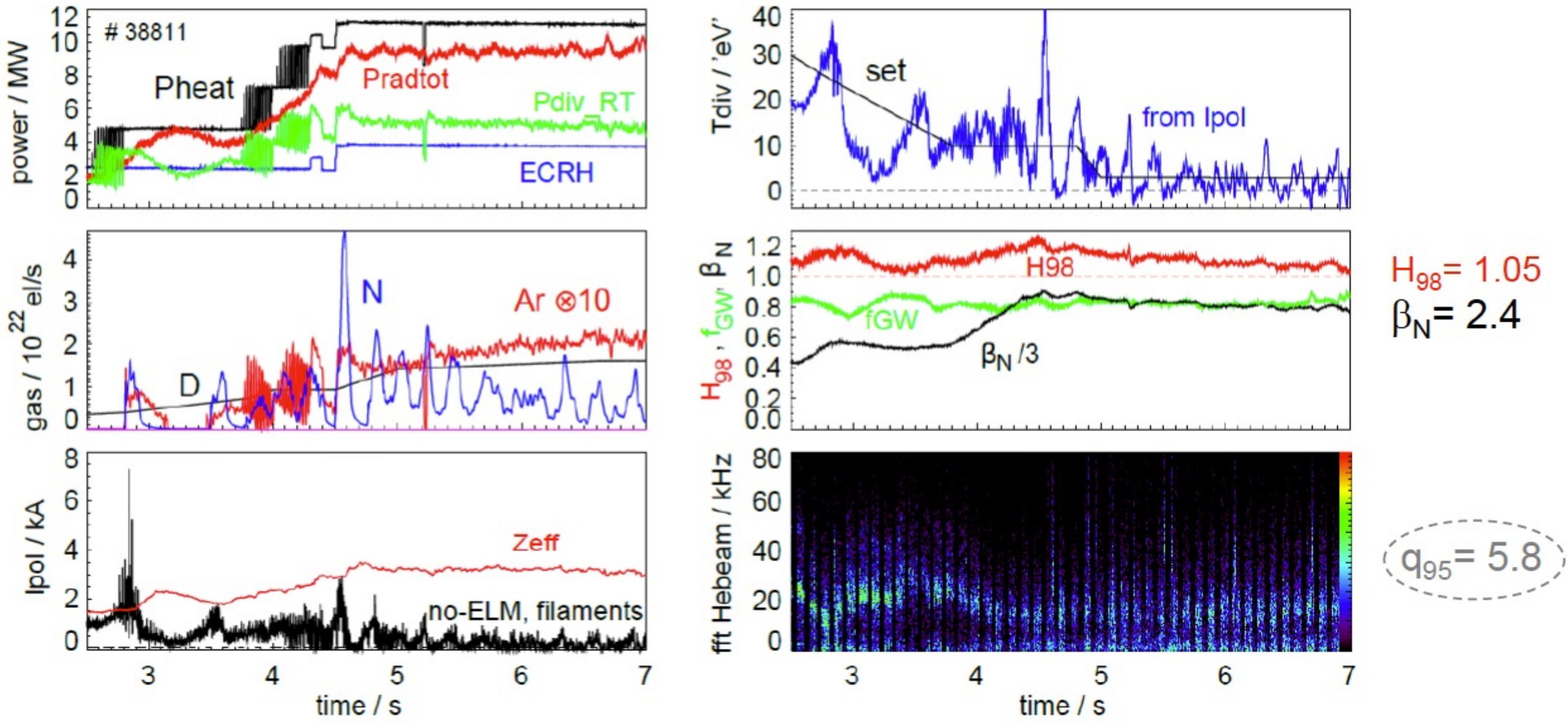
- Argon to maintain quasi-coherent mode and no-ELM state
- Nitrogen for divertor partial detachment

Quasi coherent mode leads to ELM suppression

Promising for non-ELM scenario

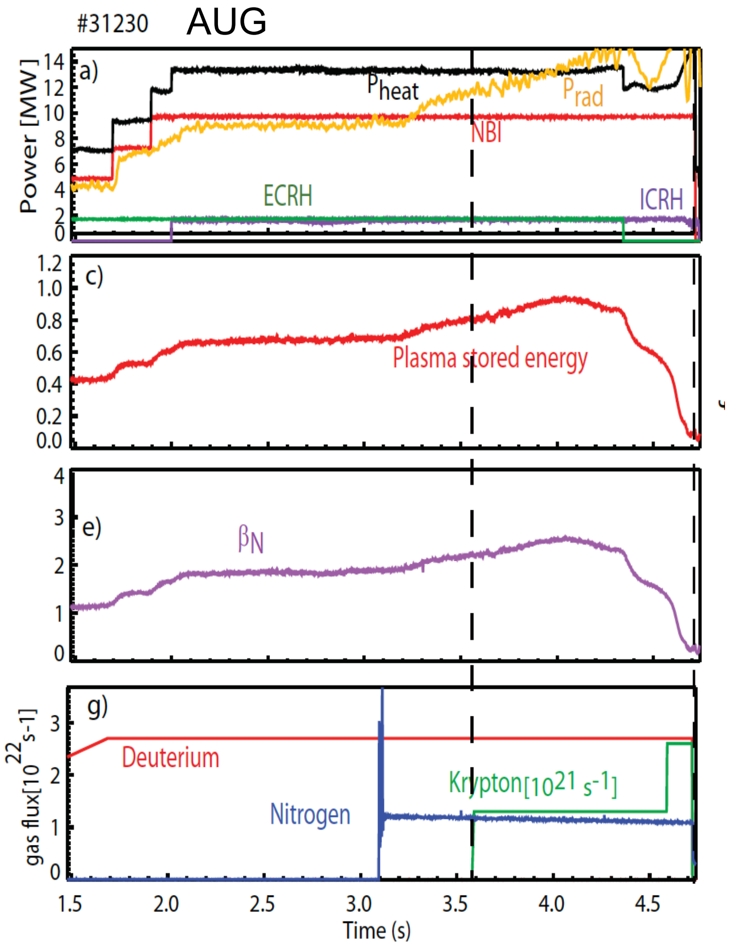
By controlling P_{sep}, EDA can be extended to higher power

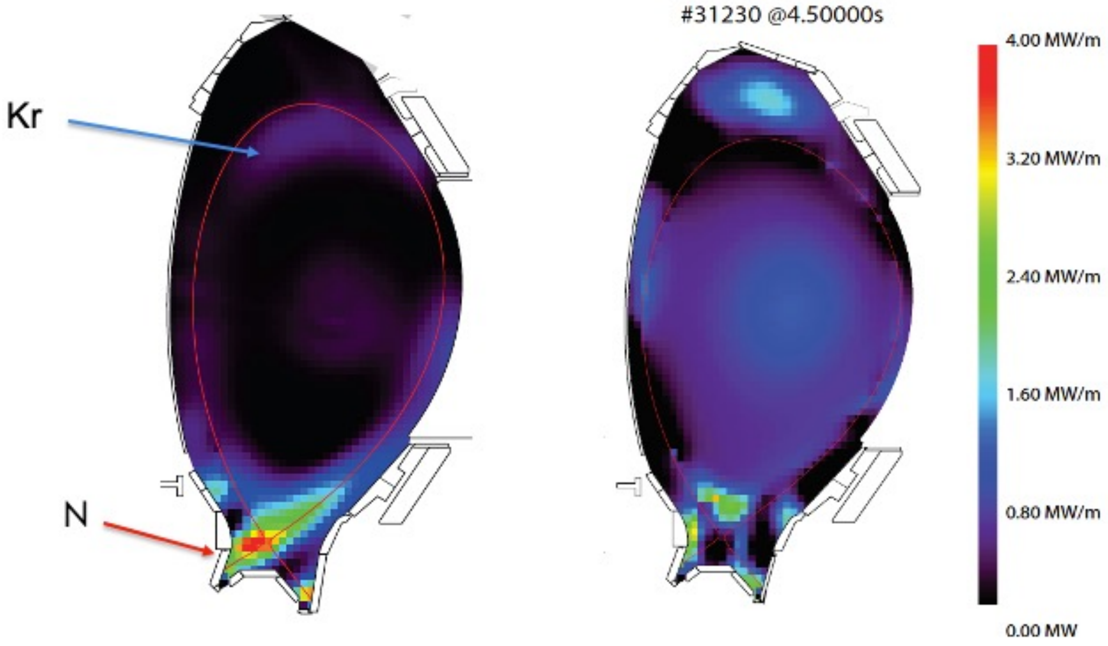
Typically accessed at high collisionality (compatibility in future reactors?)



A. Kallenbach et al. Nucl. Fusion 61 016002 (2021)

N (divertor)+ Kr (mantle) seeding experiments: c_{Kr} low to avoid radiation collapse



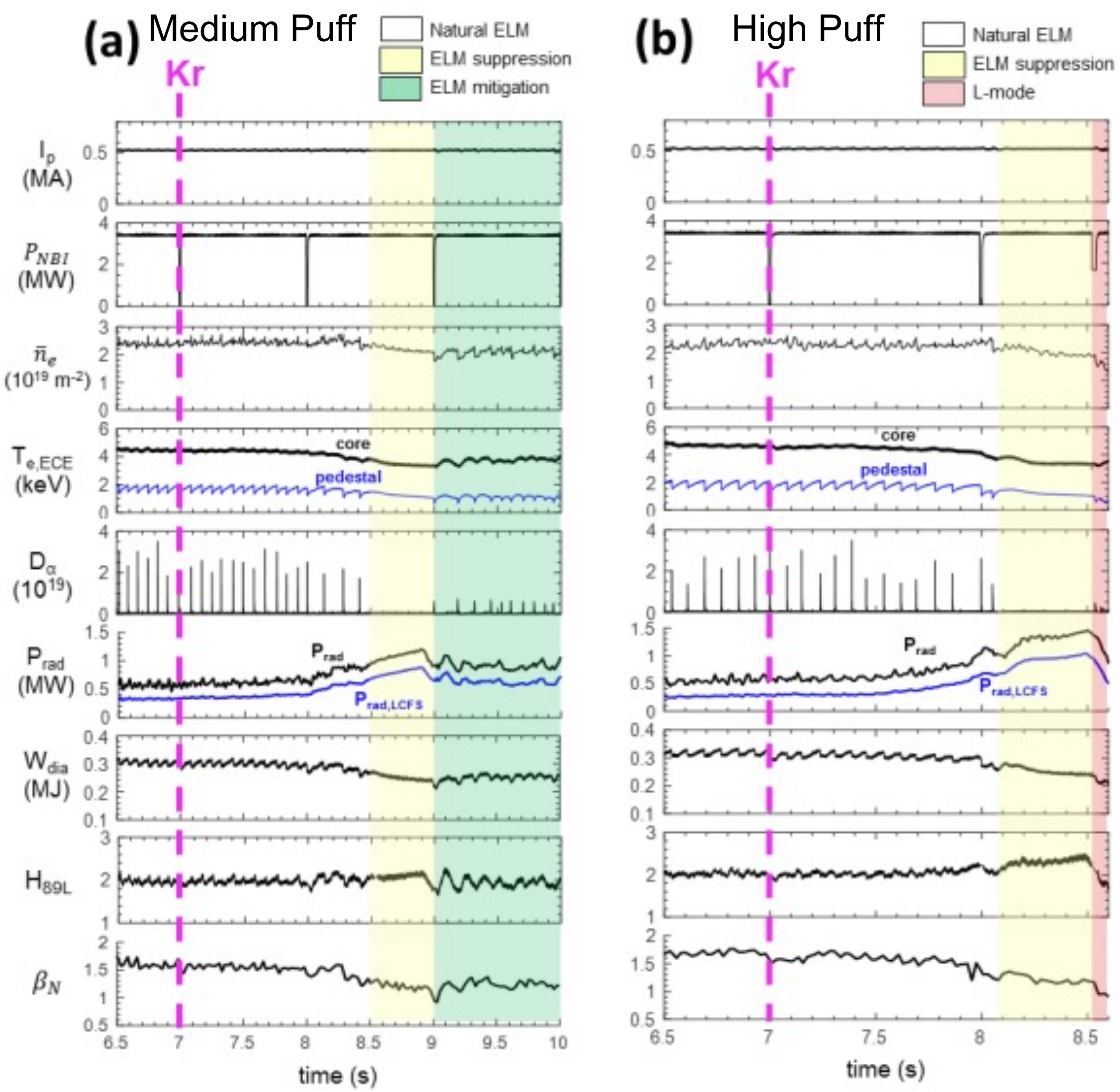


- At t = 4.5s strong radiation ring in the core: onset of radiative collapse

Kr concentration has to be low to avoid impurity accumulation (0.0002%)

L. Casali, PhD Thesis

KSTAR: Kr induces ELM free H-mode but needs tuning against H-L back transition



J. Jang et al. IAEA 2020

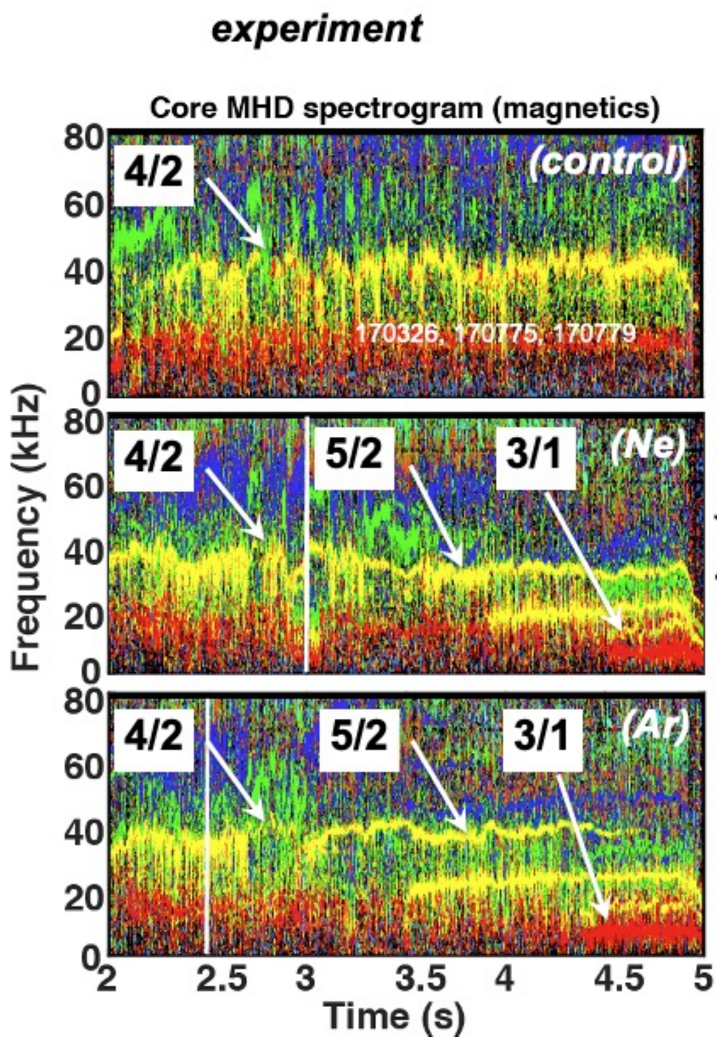
Impurity density may be limited below that for $P_{sep} \geq P_{LH}$

- Series of n=2 and n=1 core instabilities appear with larger injection rates (Ar, Ne)
- Loss of confinement is NOT due to core impurity radiation. Associated with deleterious tearing modes

What determines the operational limits of the AT scenarios with high $f_{rad,core}$ and P_{sep} close to P_{LH}?

For AT path compact plants: scenario development with elevated f_{BS}, Beta_N

What modification of the core current profile due to impurities is tolerable?



F. Turco IAEA 2020

X-point radiator achieved at AUG, JET, TCV

- Full detachment

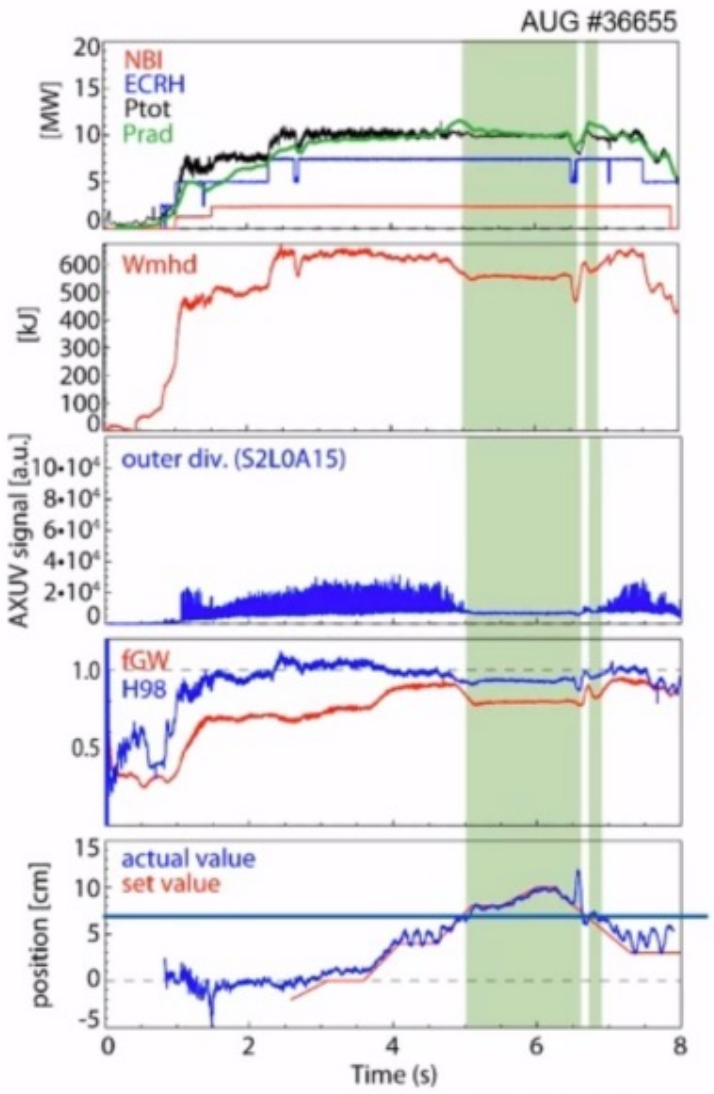
- Radiated power fraction close to 100%

- Controllability demonstrated (AUG, TCV)

- Location of XPR influence by impurity seeding level/heating power

- ELM suppressed regime accessible

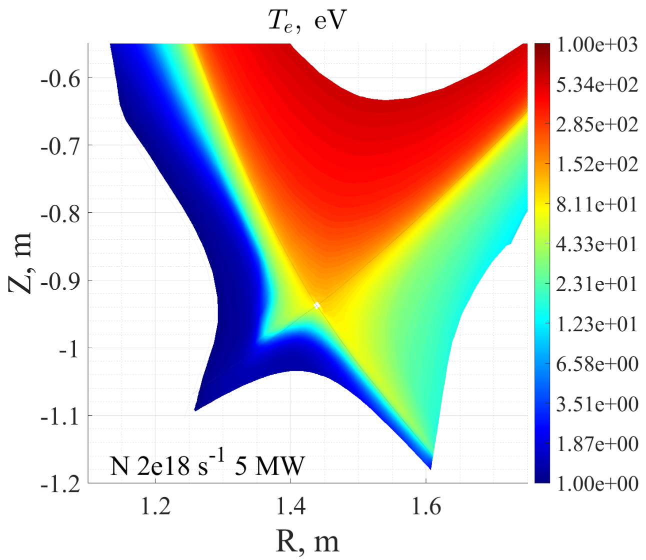
- Compatible with good confinement



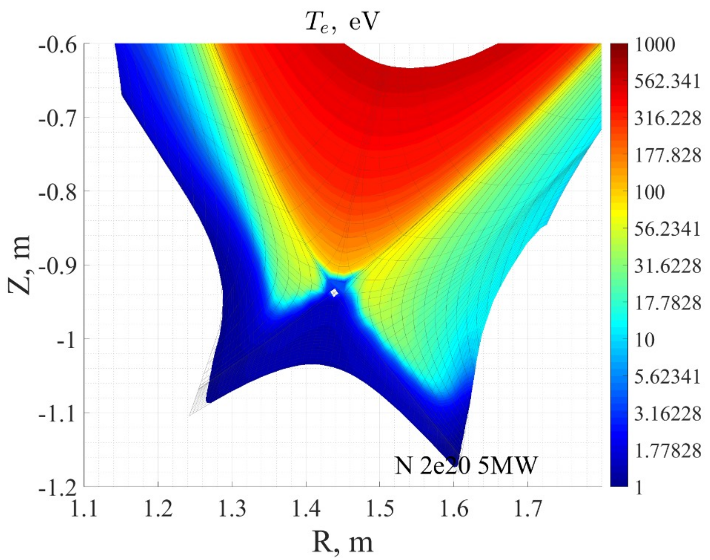
M. Bernert *et al*, NF **61** 024001 (2021)

SOLPS-ITER: from attached outer target to radiating X-point

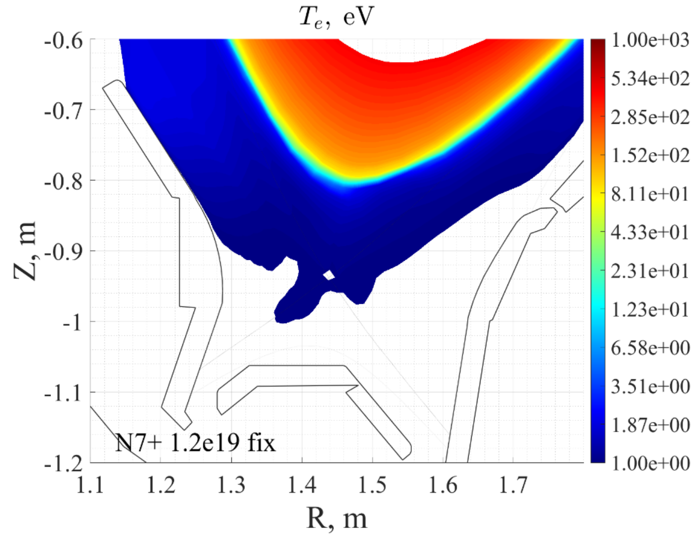
N concentration increase



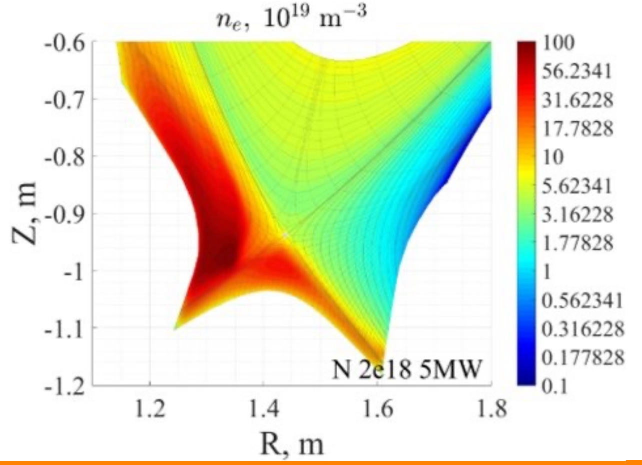
Attached (low seeding)

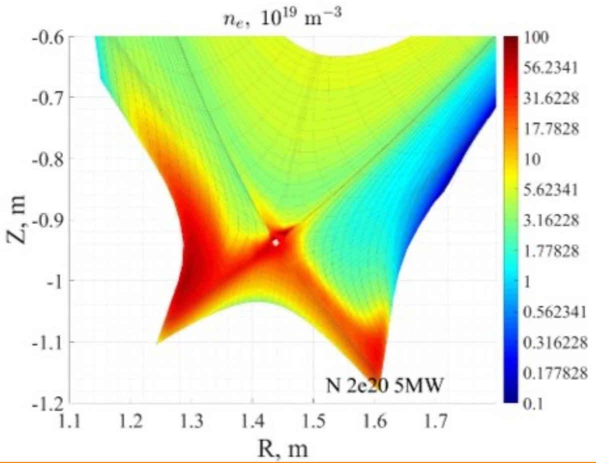


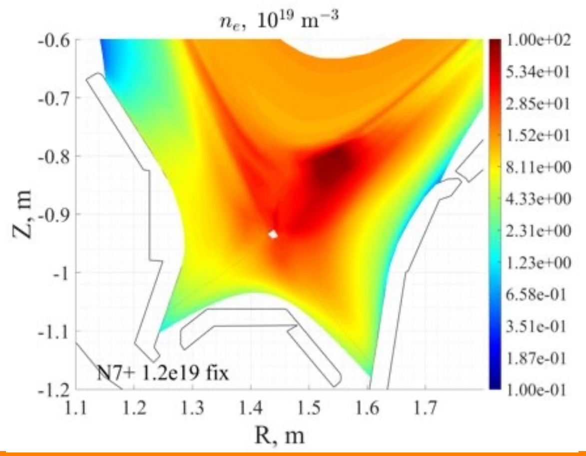
Pronounced detachment (high seeding)



Radiating X-point







What is the physics governing the impurity leakage mechanism?

Impurity distribution is the Result of the Parallel Force Balance:

Stationary Form

$$-\nabla_{\|} n_I T_i - eZn_I \nabla_{\|}\phi + R_I^{Fr} + R_I^{T} = 0$$

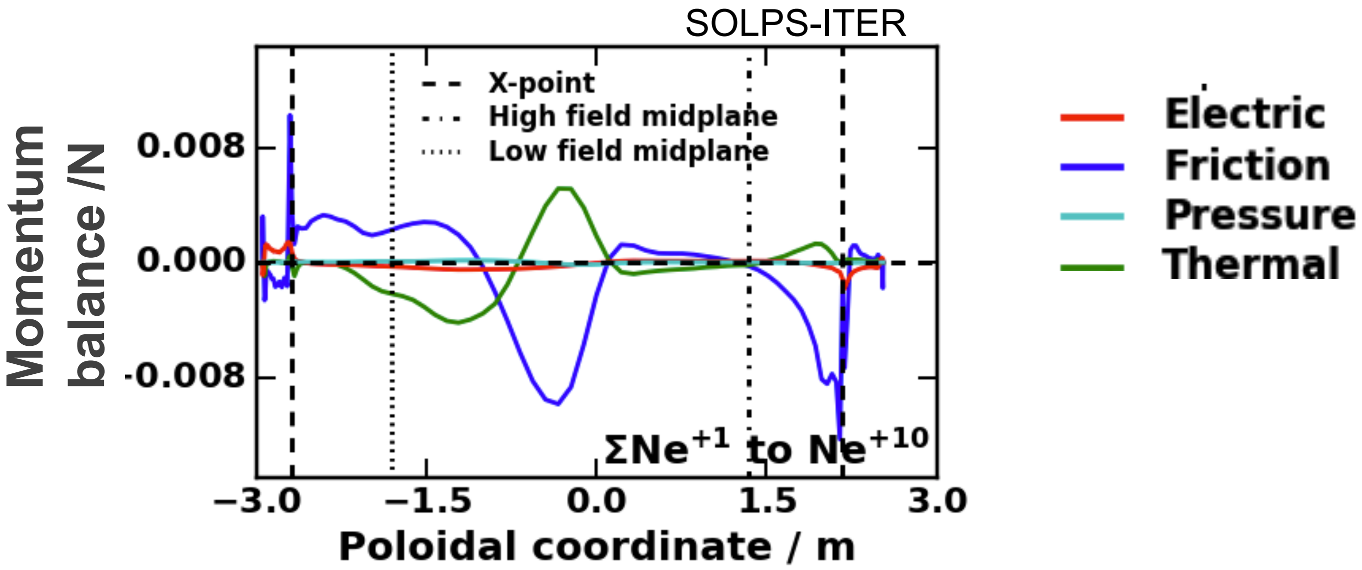
Pressure Electric force Friction Thermal force

E. Sytova et al. PoP 2020
(As implemented in SOLPS-ITER)

All the terms contributing to the impurity force balance equation include ionization, recombination, viscosity, inertia

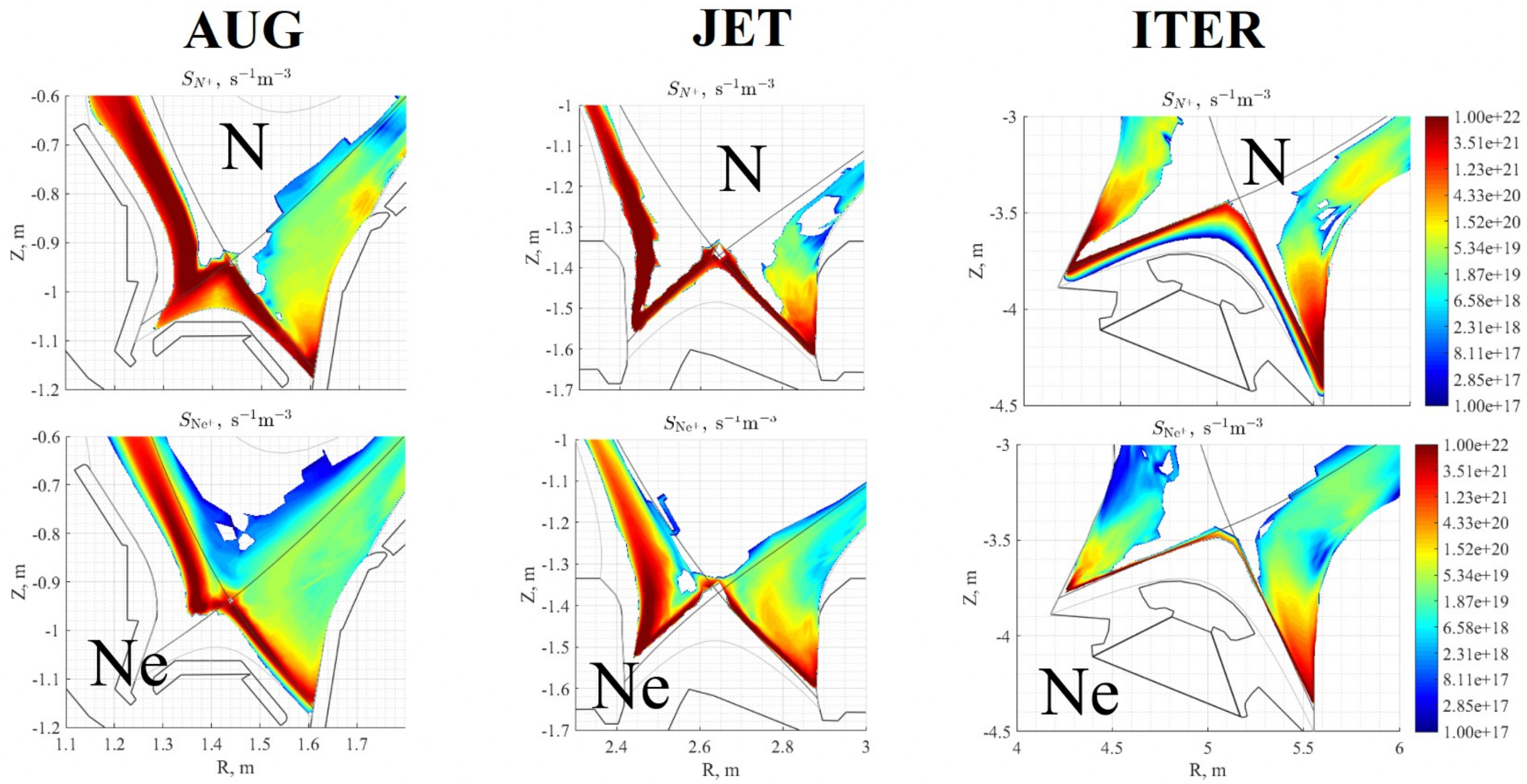
Dominant forces:

- **Thermal**
- **Friction with the main ions**



L. Casali et al. Nucl. Fusion 62, 026021 (2022)

Impurities With Low Ionization Potential Retained in the Divertor



Difference in Ionization potential of N (14.5 eV) vs Ne (21.5 eV) -> different leakage behavior

Similar findings in L. Casali Nucl Fusion 2022 for DIII-D

S_N higher for Ne that for N, reaches separatrix for Ne in AUG, in the divertor for Ne in ITER

V. Rozhansky et al, Nucl. Fusion **61** (2021) 126073

Occurrence of Flow Reversal Leads to Impurity Leakage

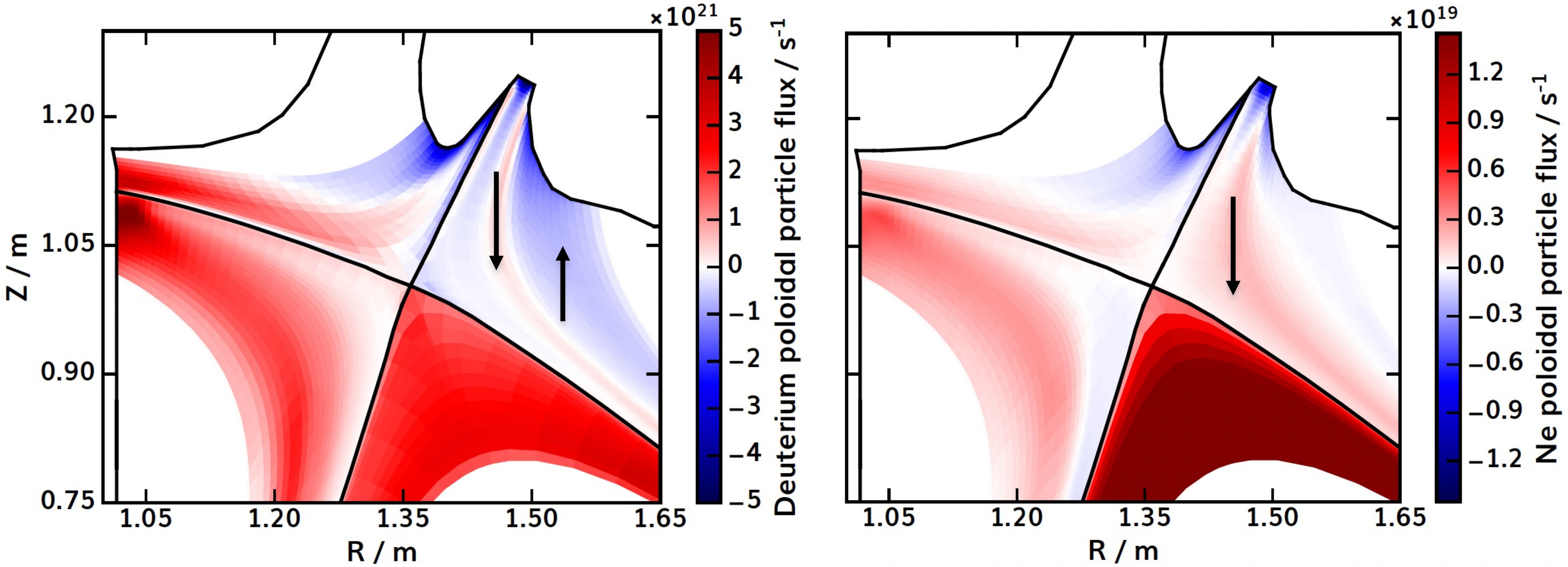
- **Flow reversal found in both main ions and impurities due to strong ionization source induced by closure**
  L. Casali et al. PoP (2020)

- **Impurity flow is directed upstream where:**

  - Main ion flow is directed upstream

  - Strong thermal force effect

Neon case



High Ne leakage out of the divertor

- Flow Toward the target
- Flow Away from the target

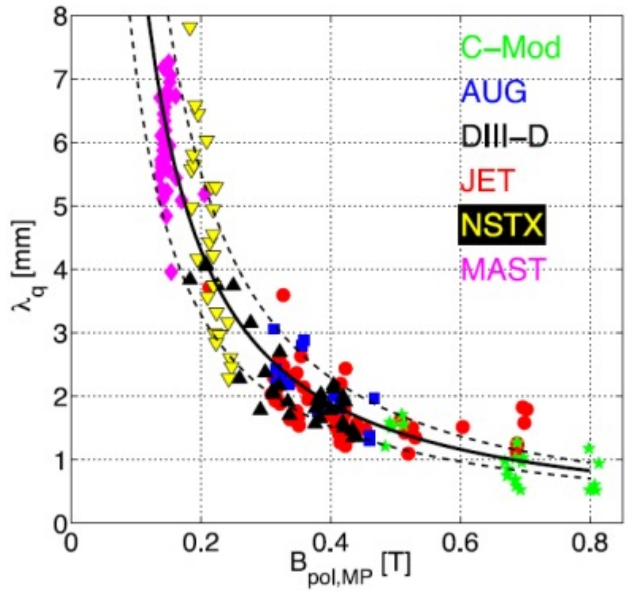
L. Casali et al. Nucl. Fusion 62, 026021 (2022)

There are limits to how much we can radiate…

Mantle radiation required in future devices but the limit is set by several factors

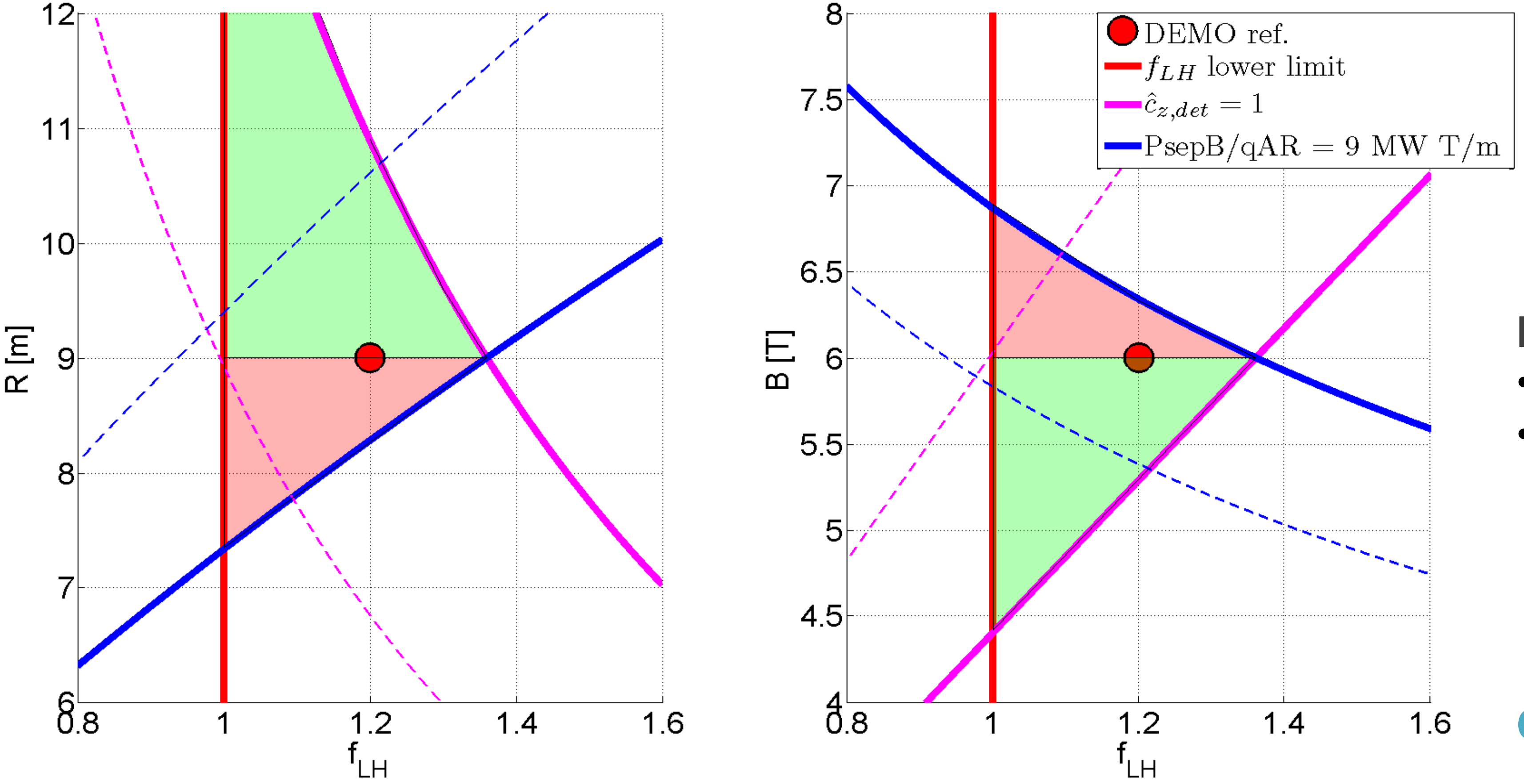
- Fuel dilution for fusion: $f_{imp} \leq 5\%$ for low-Z impurities, EU DEMO $c_{Xe} \sim 4*10^{-4}$
- Radiative collapse
- MHD due to core resistivity and current profile effects may limit Zeff below max allowable dilution - Z_{eff} effects on PB stability and turbulence growth rates
- Mantle radiation limited by the need to stay in H-mode $P_{SOL} \geq aP_{LH}$
  $P_{LH} \propto B_T^{0.8} R^2$, $q_{SOL} \propto P_{SOL}/(R\lambda_q) \propto B_T R/\lambda_q$

Ideal impurity level for a pilot plant will depend on operational scenario



T. Eich NF 2013

Operational space bounded by H-mode and detachment



Based on:

- **Martin scaling for P_{LH}**
- **Goldston & Reinke Scalings for c_Z and λ_q**

Conservative case:

$S = 0.5\lambda_q^{ref}$ $\hat{c}_{z,det} = 0.7$

M. Siccinio et al. Nucl. Fusion 59 (2019) 106026

The quest for Power Exhaust Criteria

What is the concentration of impurity required for detachment?

Goldston $c_Z \propto {P_{sep}}\big/{B_p(1+\kappa^2)^{1.5} f_{GW,sep}^2}$ → Upstream density, 2-point Model

Reinke $c_Z \propto B_T^{0.88} R^{1.33}$ → Machine size scaling
(assumes P_{sep} expressed in terms of f_{GW} & P_{LH}^{Martin} → $q_{||} \sim B_T^{2.52} R^{0.16}$)

Kallenbach $c_Z \propto {P_{sep}/R}\big/{p_{div} \lambda_{int} R^{rz}}$ → Momentum and energy loss

R J Goldston et al 2017 Plasma Phys. Control. Fusion **59** 055015
M.L. Reinke 2017 Nucl. Fusion **57** 034004
A Kallenbach et al 2016 Plasma Phys. Control. Fusion **58** 045013

Some fundamental physics mechanisms of divertor dissipation missing in Lengyel model often used in scalings

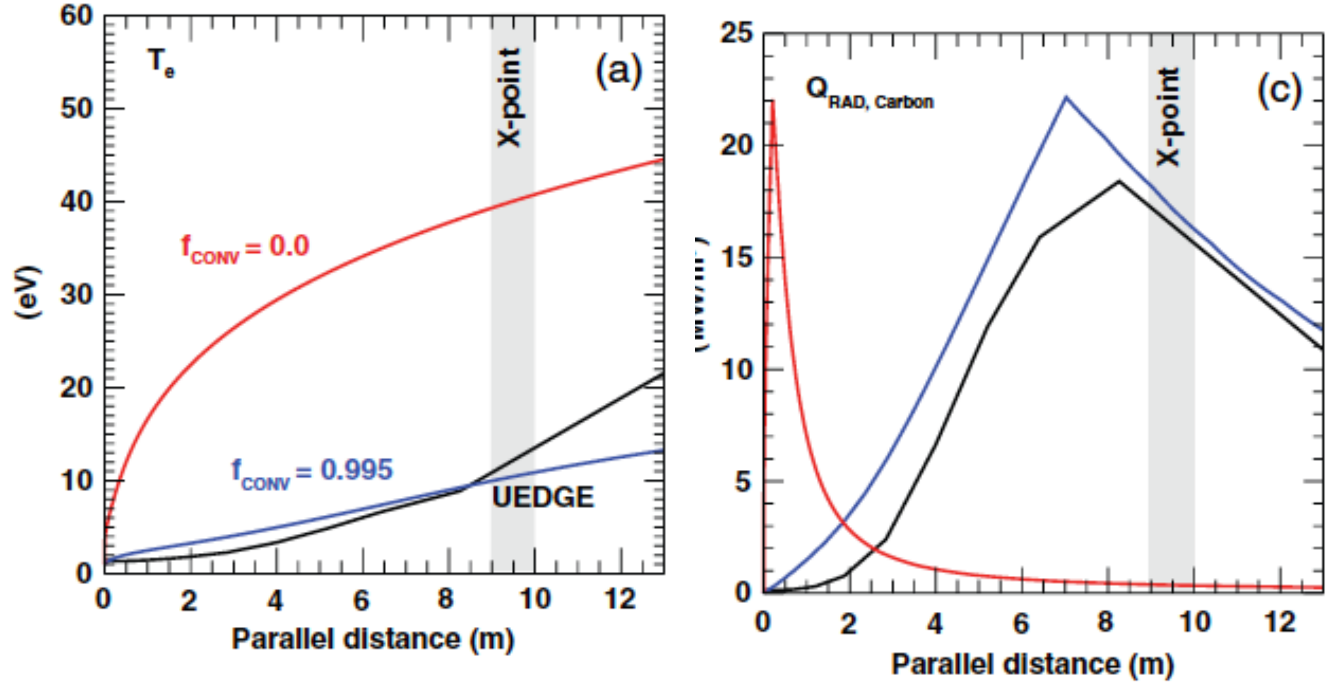
Assumptions in Lengyel model[1]:

- Heat transport by electron heat conduction $q = -\kappa_0 T_e^{5/2} \nabla_{||} T_e$
- Static pressure conserved on a flux tube
- Conservation of impurity concentration along a flux tube
- Neutral and radial losses are not included
- Constant $\mathbf{n_e}$ *τ for L_z

[1] Lengyel L L 1981 Analysis of radiating plasma boundary layers IPP Report1/191

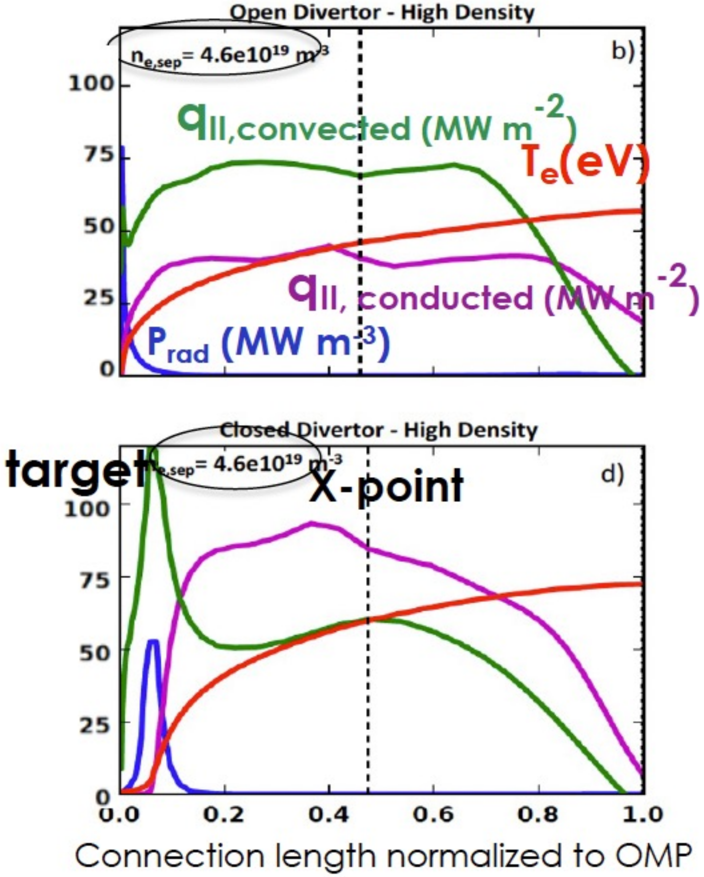
High fraction of heat is transported by convection/cross-field

UEDGE for DIII-D Plasmas



A. Jarvinen CPP 2019

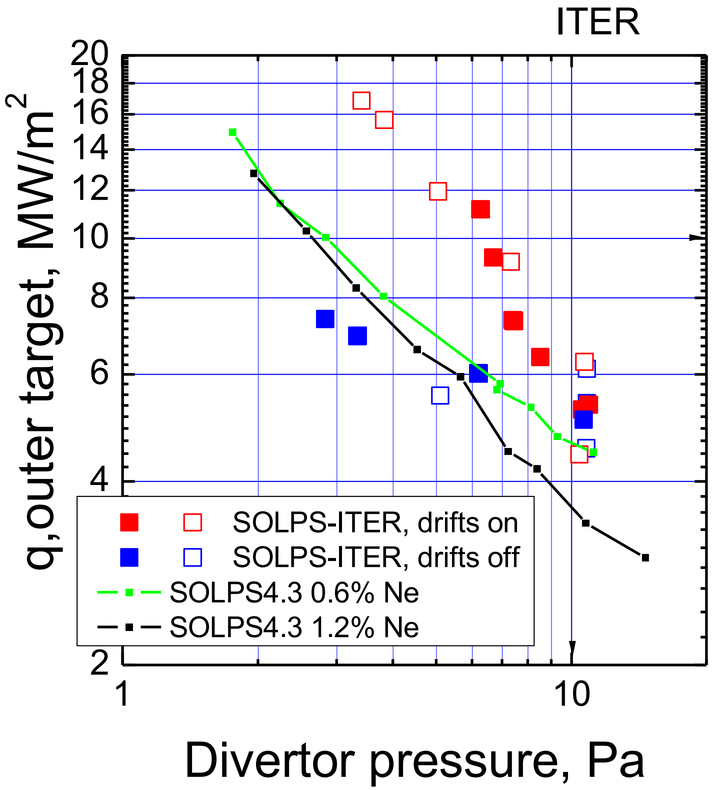
SOLPS for DIII-D Plasmas



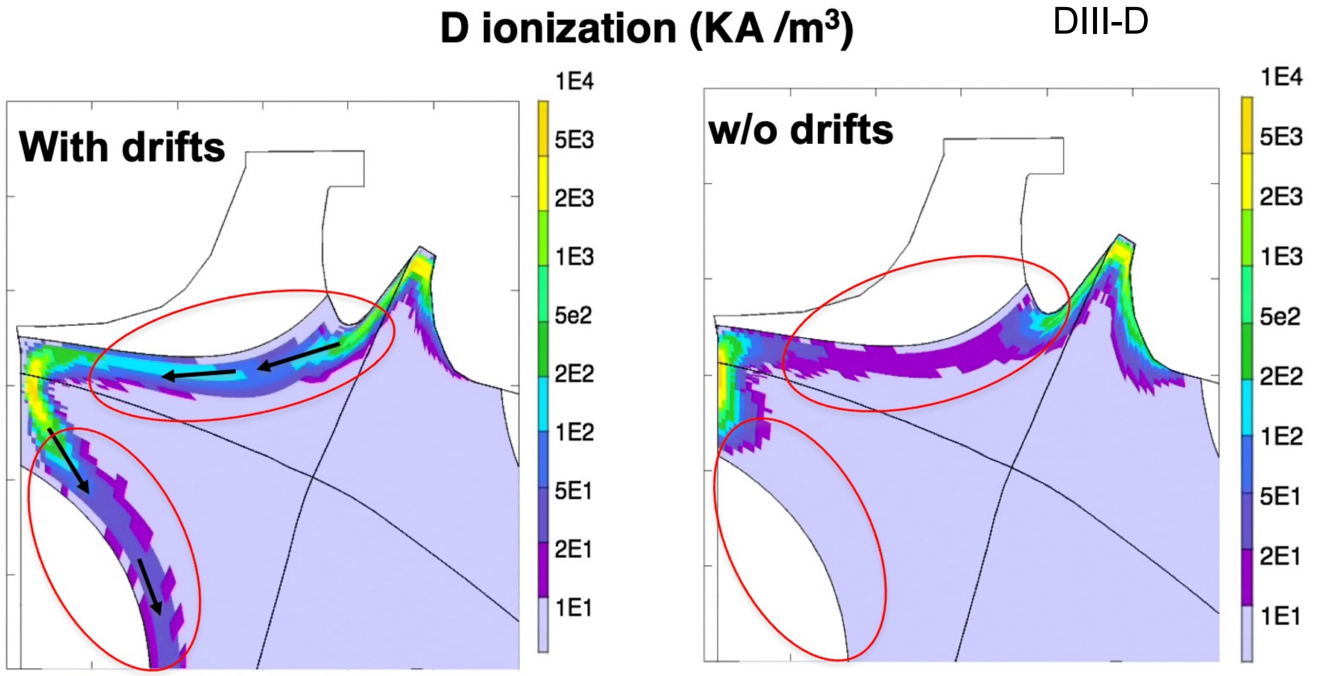
L. Casali Nucl. Fusion 2020

See also A. Leonard Physics of Plasmas 5, 1736 (1998)

Ionization Distribution and SOL impurity transport is affected by Plasma Drifts



E. Kaveeva *et al* 2020 *Nucl. Fusion* **60** 046019



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

Drifts changes parameter space of possible working regimes for ITER

Simplified detachment criteria (c_z) needs further development

- Lengyel model provides a pessimistic estimate for the radiative capability of impurities in the divertor
- Convective fraction decreases with increasing size and q_{SOL}
- T_e is invariant for atomic physics dissipation

→ Systematic study including drifts, measurements of c_z in the divertor (McLean PSI 2022, Henderson PSI 2022) and comparison with models that include plasma transport

Path to Optimized Core-Edge Integration Relies on Radiative Power Exhaust Balancing Core Contamination

- What is the required c_z for detachment?
- What is the amount of c_z that the core plasma can tolerate?

- Impurity transport from the wall to the core:
  - SOL impurity transport, leakage, pedestal impurity transport and core accumulation

- Validated 2D/3D edge models are required for future reactor predictions
- 0D/1D models need to be trained by high-fidelity models
- Predictive capability for pedestal density profile needed
- Integrated modeling through multi-physics and multi-scale integrated solutions

Challenge: establishing the physics basis for simultaneously balancing core and divertor solution

How can BOUT++ help us ?

- Prediction of particle and heat fluxes in tokamak edge is crucial. One of the uncertainties is the transport across the magnetic field.

- SOLPS, UEDGE etc: transport set artificially
- BOUT++:
  - Simulate edge plasma turbulence and transport, obtain the particle transport & heat transport coefficients spontaneously
  - Divertor heat flux width
  - SOL filamentary dynamics
  - Pedestal instabilities and turbulence

Self consistent simulations of transport and turbulence edge plasma are needed

Backup slides