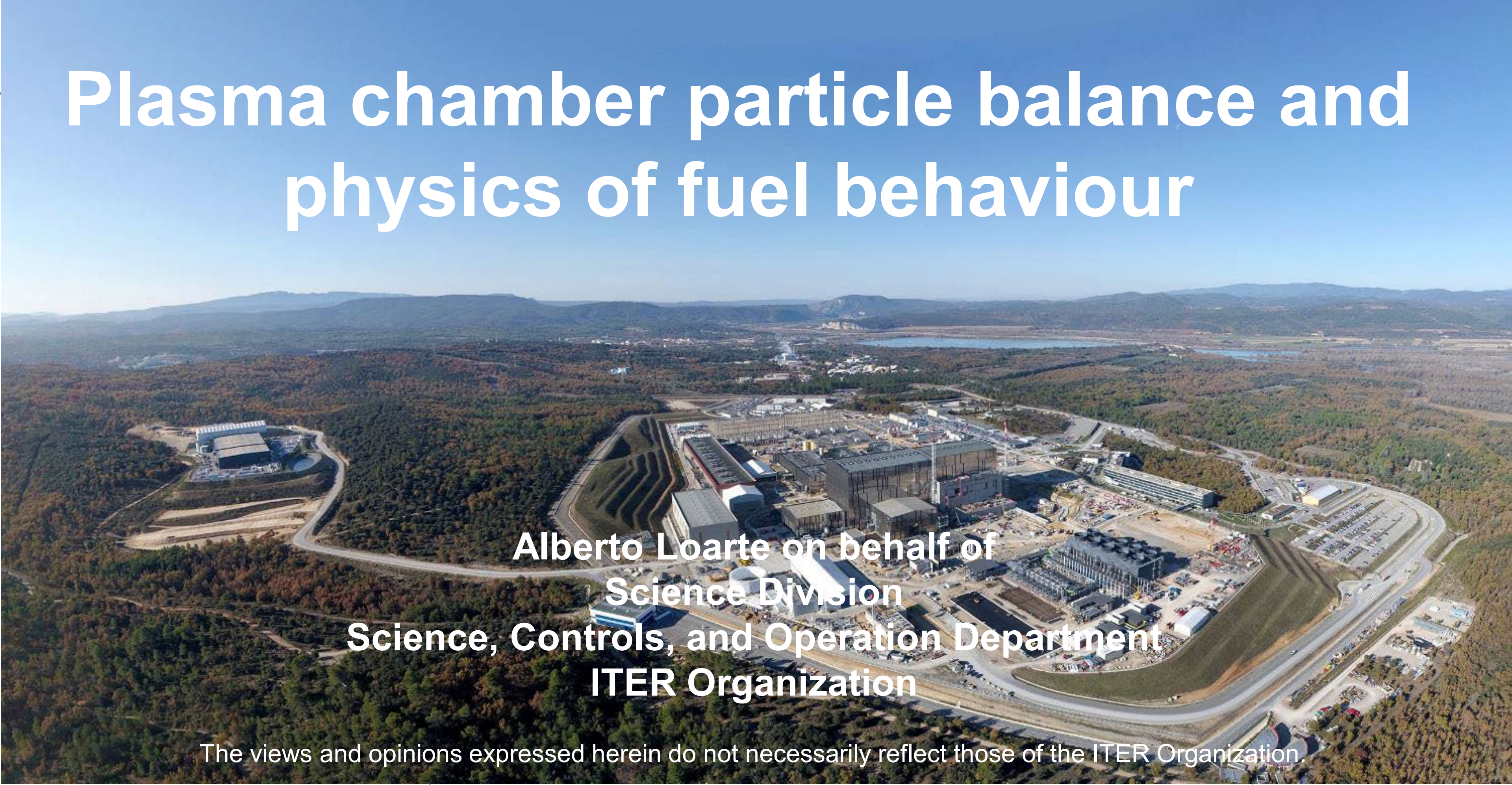


Plasma chamber particle balance and physics of fuel behaviour

Alberto Loarte on behalf of
Science Division
Science, Controls, and Operation Department
ITER Organization

The views and opinions expressed herein do not necessarily reflect those of the ITER Organization.

Outline

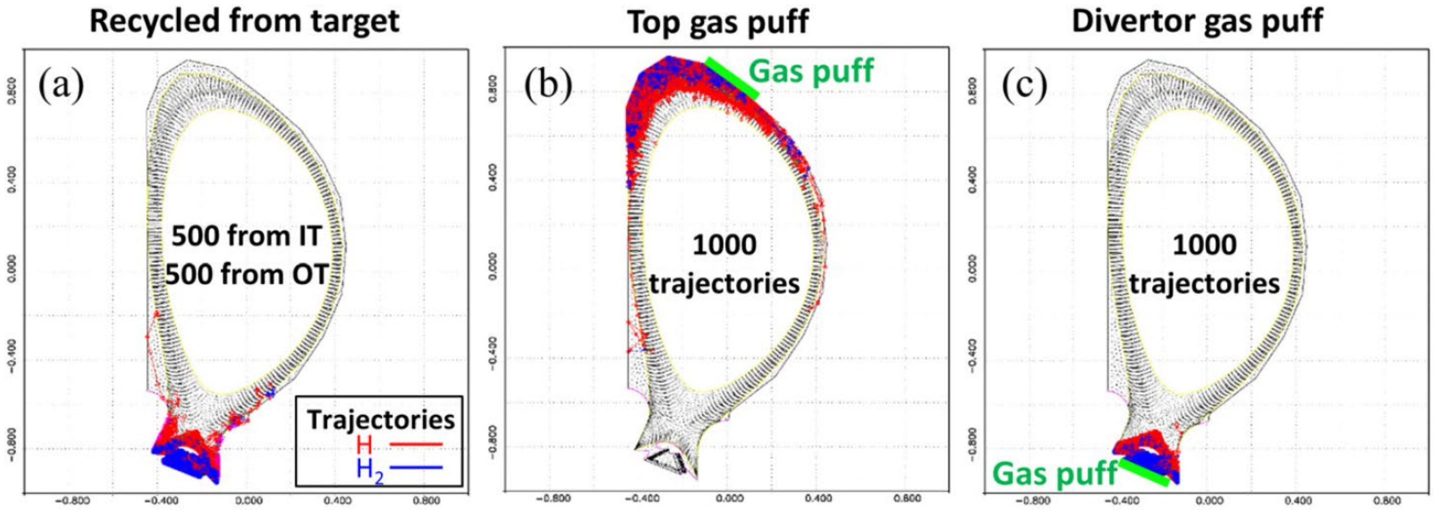
- Introduction
  - Plasma fuelling, particle exhaust and retention
  - Scenario integration aspects (power exhaust-particle exhaust, transient power load control)
- Plasma particle behaviour in ITER high Q plasma scenarios (incl. open issues to be resolved in ITER)
- Conclusions

Introduction

Plasma Fuelling and Exhaust - Neutrals

- Fuelling of the core plasma
  - Ionization of neutrals in periphery and inwards transport

J.S. Park 2021 Nucl. Fusion

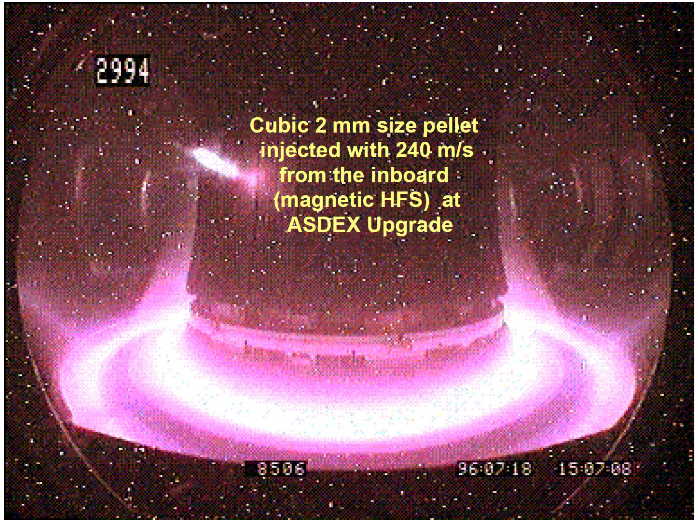


Fuelling by neutrals effective in present experiments but not in fusion reactors unless transport brings edge ions inwards

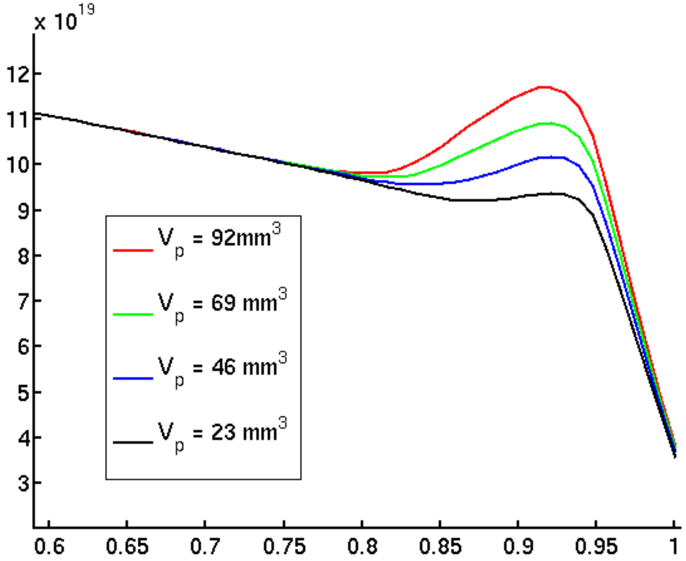
Plasma Fuelling and Exhaust - Pellets

- Fuelling of the core plasma
  - Ionization of pellet injected neutrals and inwards transport

P. Lang ASDEX Upgrade



ITER HFS – JINTRAC – HPI-2 – F. Köchl

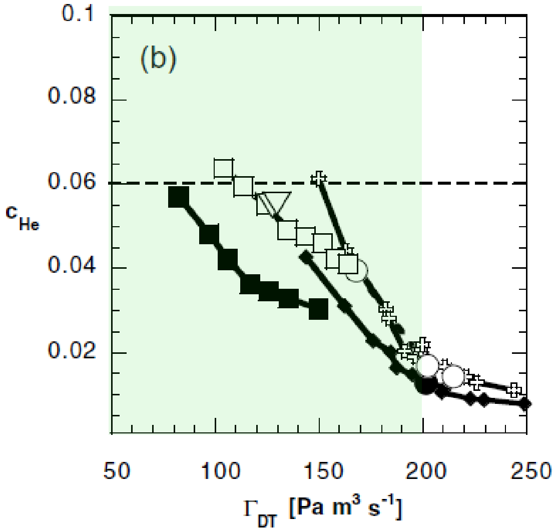


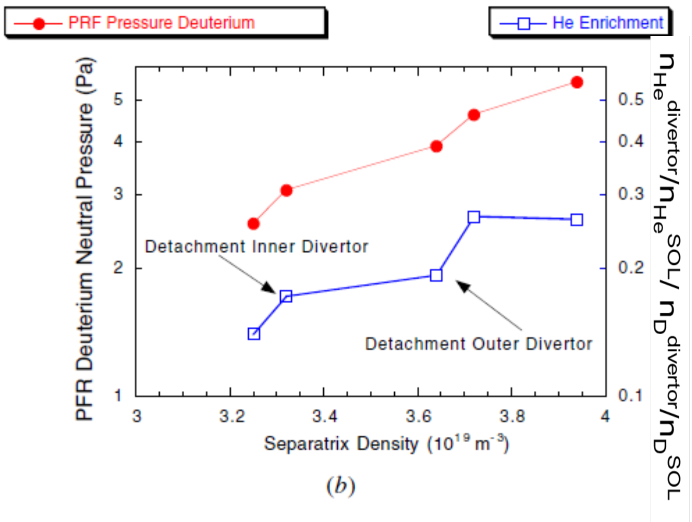
Pellet particle deposition can reach deep in the core plasma but not in fusion reactors

Plasma Fuelling and Exhaust – Particle Exhaust

- Plasma particle exhaust required to control plasma density and composition (impurities) + to exhaust He from DT reaction
- Pumping + transport from core plasma to pump determine exhaust rate

SOLPS ITER Modelling – A. Kukushkin

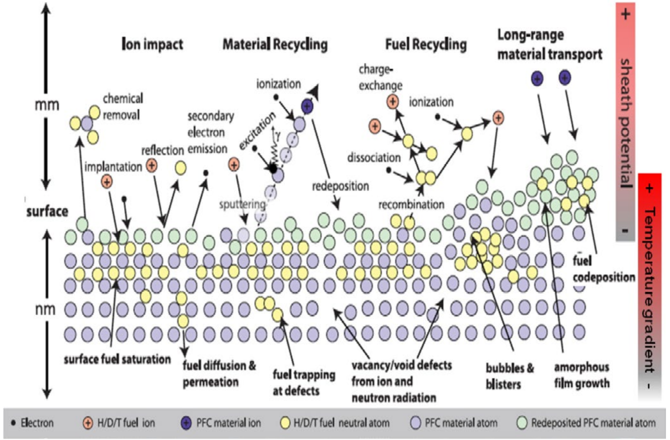


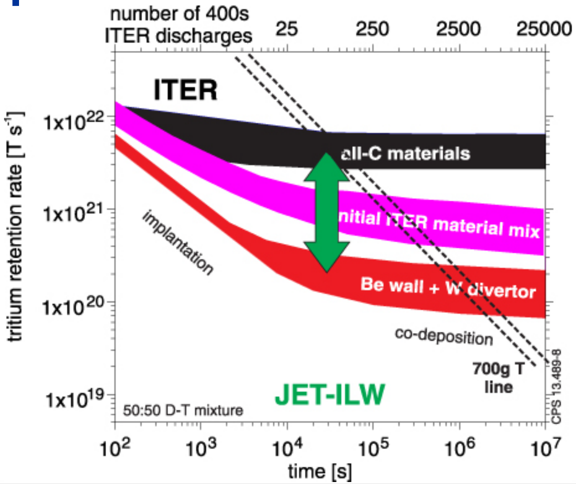


(b)

T retention and removal

- Plasma impacting PFCs leads to many processes: recycling, erosion, etc.
- Eroded material can react with plasma ions and trap T semi-permanently
  - ITER: Be-wall : Low plasma flux and some T retention (co-deposition possibly leading to dust)
  - ITER: W-divertor : High plasma flux and low T retention (implantation)
- T retention in-vessel must be kept to low values → strategies to minimize retention and schemes for in-situ removal required

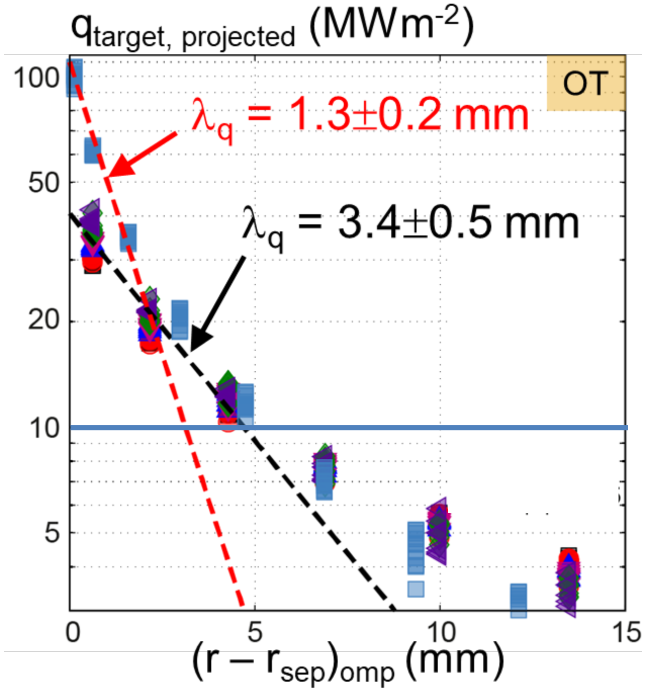




Roth/Schmid – ITER
Brezinsek – JET-NF 2013

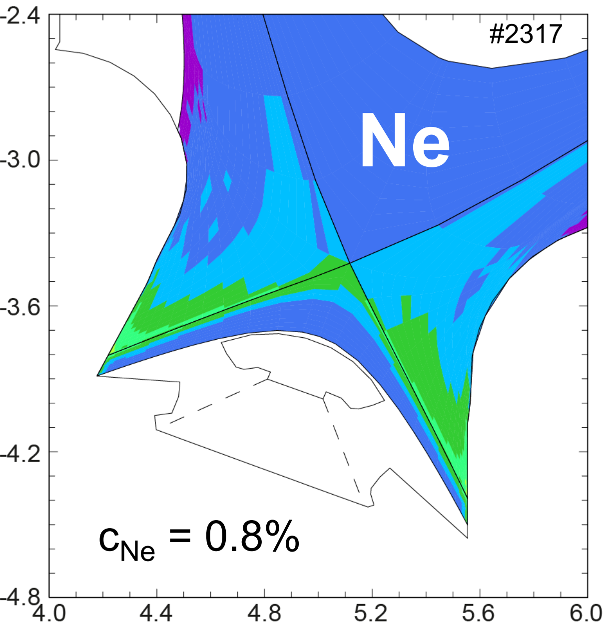
Core-edge integration (power exhaust-particle exhaust) - I

- **Power in charged particles similar for all ITER high Q scenarios**
  - **Q = 10 with P_{aux} ~ 50 MW → P_{total} ~ 150 MW**
  - **Q ~ 5 with P_{aux} ~ 70 MW → P_{total} ~ 140 MW**
- **Expectations**
  - **Narrow near separatrix e-folding length → 80 – 100 % of P_{SOL} power arrives divertor**
  - **Broad far SOL e-folding length (+ ELMs) → 20 - 0 % P_{SOL} arrives at first wall**
- **Burning plasma divertor power flux must be reduced by factors of 4 – 10 for compatibility with divertor target power handling capability**



R. Pitts NME 2019

Core-edge integration (power exhaust-particle exhaust) - II



$P_{RAD,DIV}$ = 56.6 MW

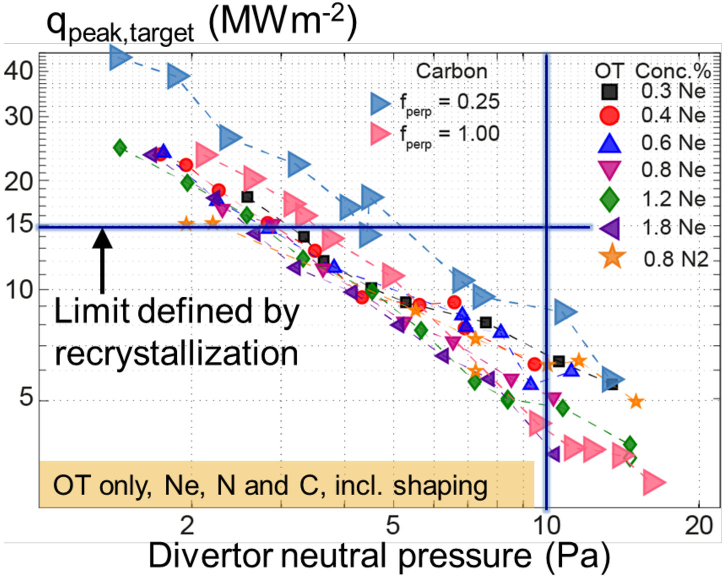
41.3 (Ne) + 15.3 (D)

R. Pitts NME 2019

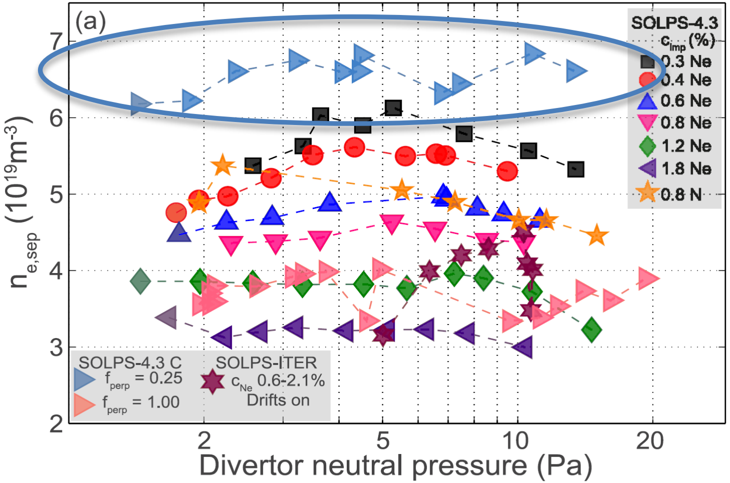
- Ne provides divertor radiation at ITER scale (N is also possible but issues with tritiated ammonia and, possibly Ar) → Ne favoured for ITER
- Up to 65% of P_{SOL} radiated at divertor → sufficient for power flux control
- **Power exhaust requires use of extrinsic impurities in metal PFC devices and appropriate edge plasma conditions → plasma edge fuelling intrinsically linked to power exhaust**

Core-edge integration (power exhaust-particle exhaust) - III

- ❑ Narrower λ_q → higher neutral pressures and detachment levels → edge transport in burning plasmas will be determined in ITER
- ❑ n_{sep} ~ 0.5 n_{GW} → impact on SOL and edge transport ?



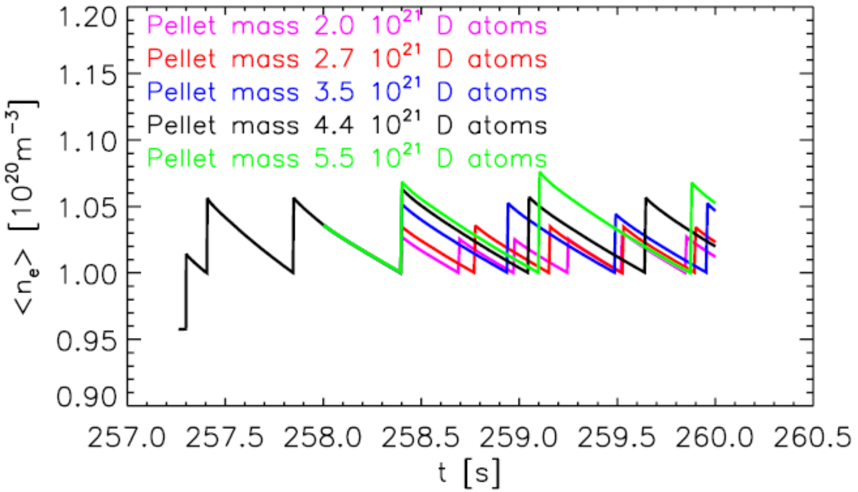
R. Pitts PSI 2018
NME 2019



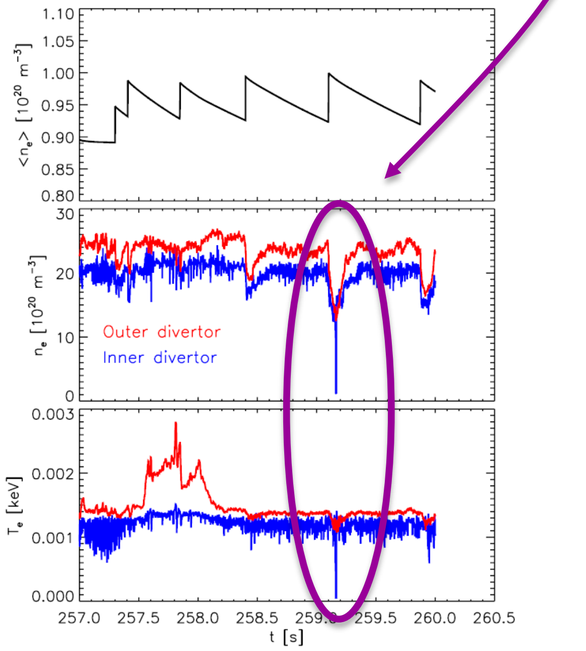
Narrow λ_q → faster reaction to loss of detachment

Pellet fuelling integration with radiative divertors

- Peripheral pellet deposition leads to edge n_e oscillations
- Edge n_e oscillations → divertor radiation and detachment
- Optimization of pellet size/frequency for effective fuelling compatible with stable divertor operation



L. Garzotti
ITER - JINTRAC
NF 2019

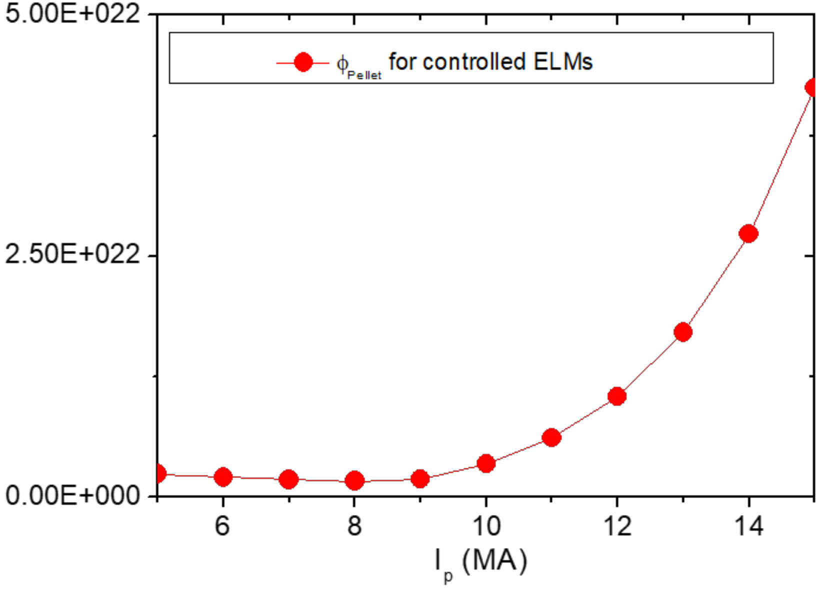


Optimization depends on ITER plasma post-pellet transport mechanisms

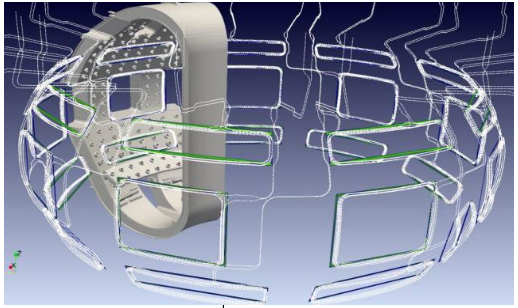
Core-edge integration (power exhaust-particle exhaust) - IV

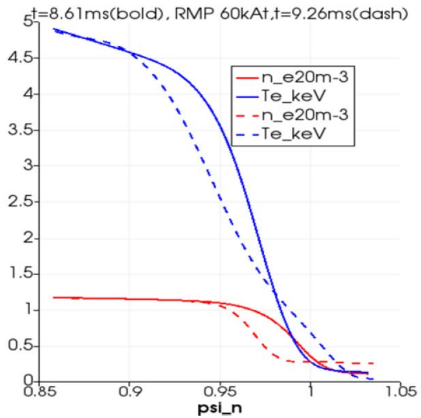
- Control of ELM transients impacts particle exhaust → additional fuelling required to trigger ELM or to compensate particle loss when suppressed

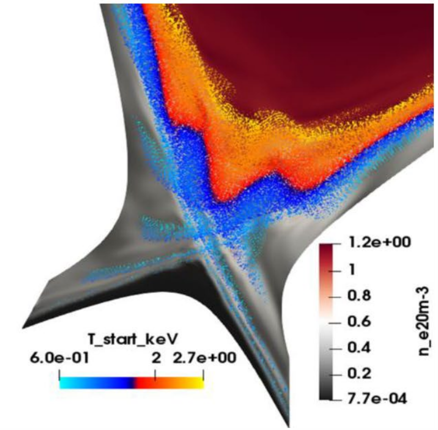
ITER – JOREK – Futatani – NF' 14



JOREK-Becoulet NF 2022





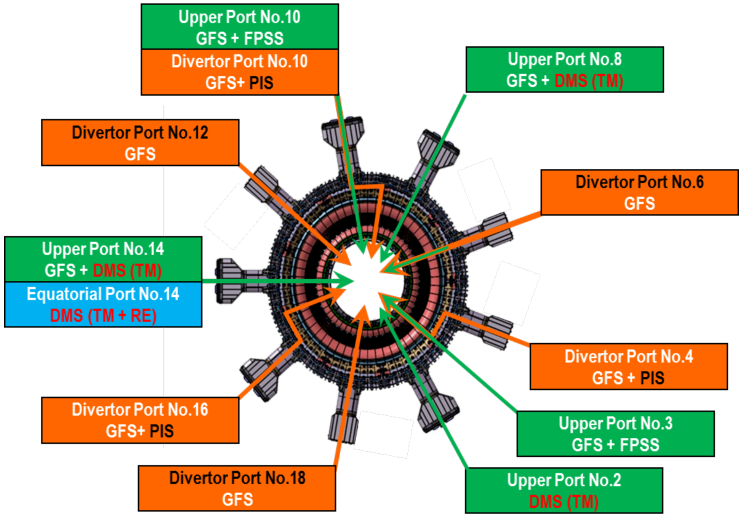


Plasma particle behaviour in ITER high Q plasma scenarios

Fuelling Systems in ITER

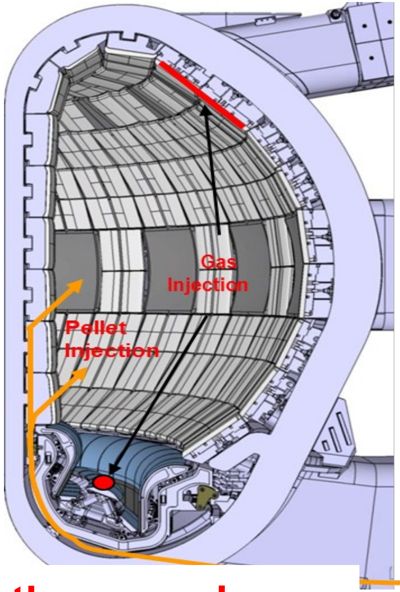
Gas Injection System (GIS)

- Upper port level GIS : 4 ports
- Divertor port level GIS : 6 ports



Pellet Injection System (PIS)

- Two divertor ports (Two injectors/port)

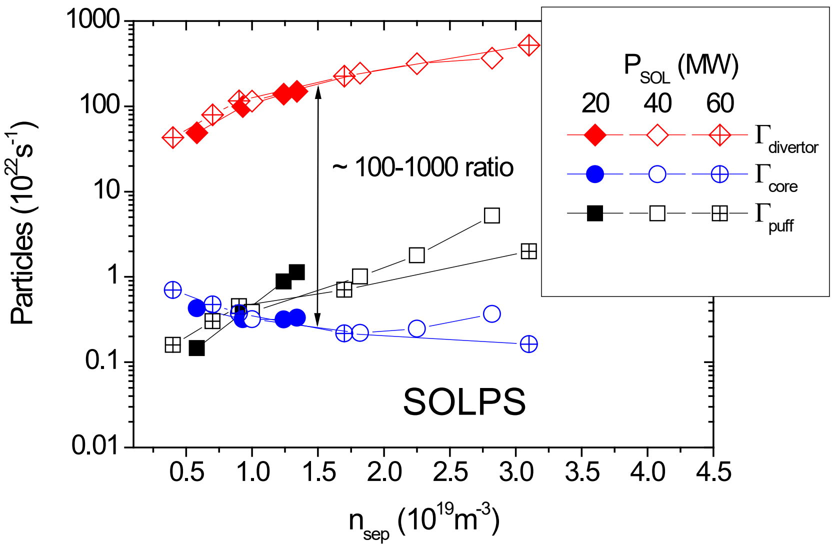


Fuelling gas	^4He (Pam^3/s)	H_2, D_2, T_2 (Pam^3/s)	Ne, Ar, N_2 (2 simult.) (Pam^3/s)
Bounding average/peak fuelling rate (gas puffing + pellet injection)		200/400	
Average/peak fuelling rate for Tritium for pellet injection		110/110	
Average/peak fuelling rate for other hydrogen species for pellet injection		120/120	
Average/peak fuelling rate for ^4He	60/120		
Average/peak fuelling rate for impurity			10/50

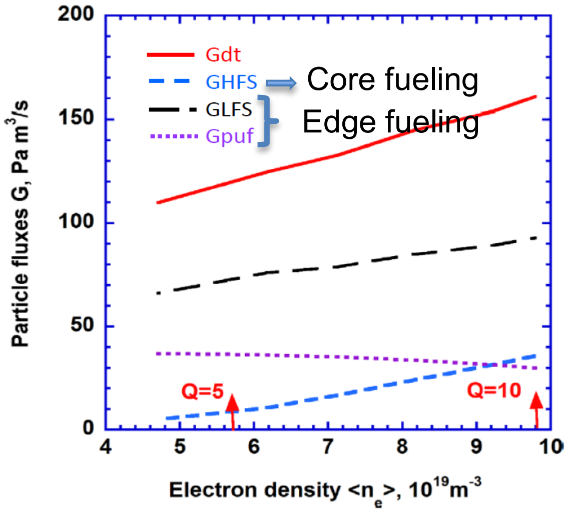
N.B. NBI system in ITER does not fuel the core plasma (Γ_{NBI} = 2 10^{20} s^{-1} = 0.8 Pam^3/s)

Core fuelling plasma fuelling (gas/pellet)

- **Neutral fuelling ineffective in ITER due to poor neutral penetration**
  - **Separate control of n_{sep} (gas fuelling) for power load control and n_{ped} (pellets) for core performance**



ASTRA+SOLPS b.c. Polevoi NF 2017



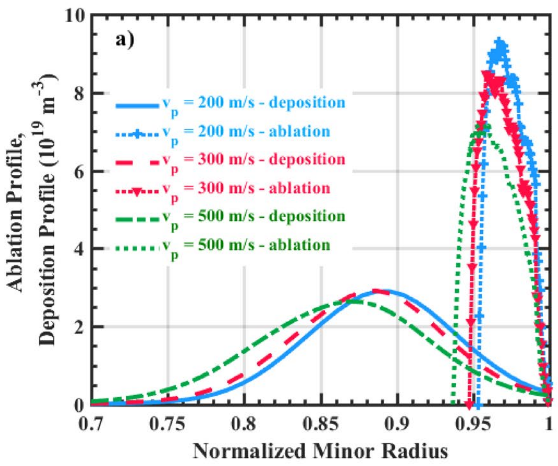
Assumes diffusive-like edge transport (no edge particle inwards pinch) → open issue to be resolved in ITER

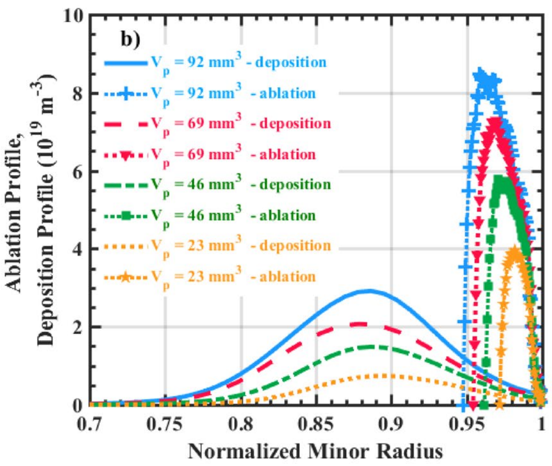
Pellet fuelling - I

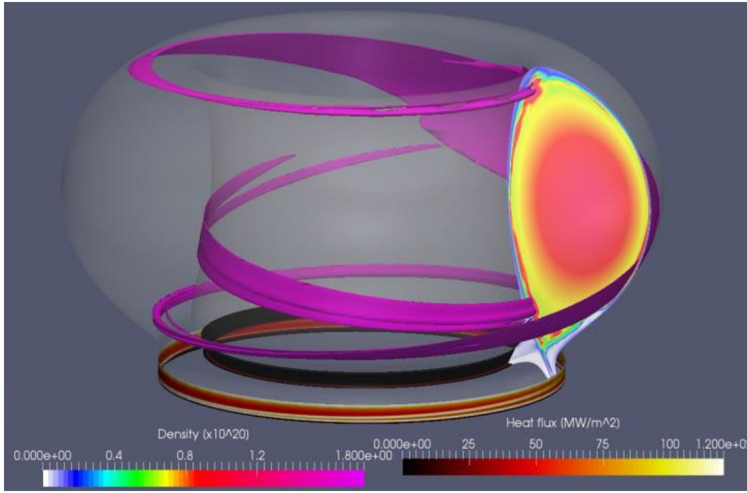
- Pellet penetration peripheral in ITER (high T_e) → Core fuelling driven by short time scale physics (ablation+drift) and long time scale inwards transport
- Peripheral pellets can trigger ELMs which expel pellet particles → contribution to edge fuelling as well (open issue)

N. Panadero HPI-2 sub. Nucl. Fusion 2022

S. Futatani IAEA FEC 2016





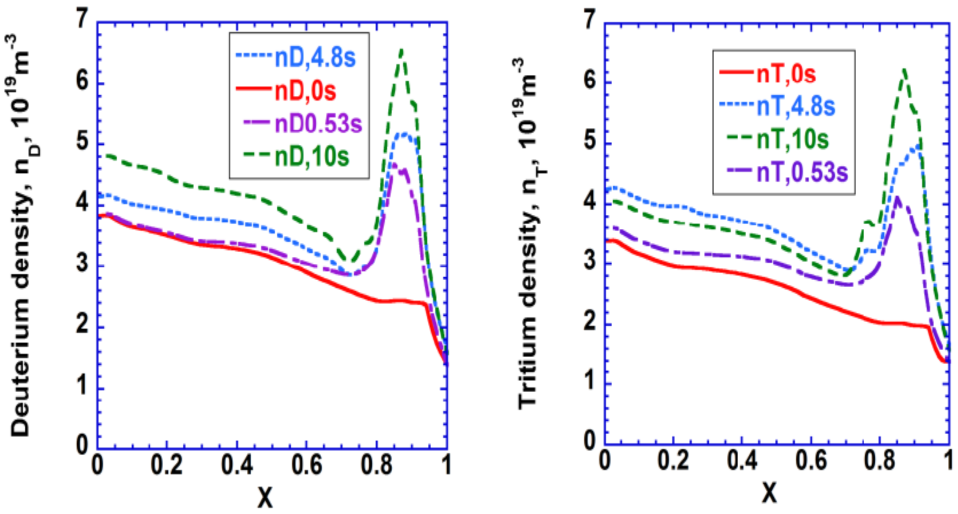


Pellet fuelling - II

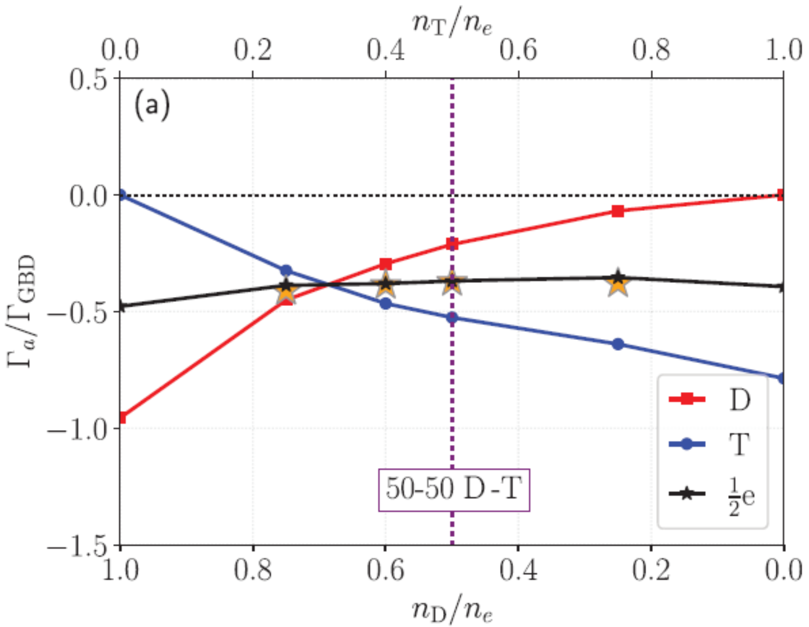
- Transport from pellet injected particles to core → turbulence (open issue)
- D & T inwards transport may be different → impacts D/T pellet fuelling rate

ASTRA-TGLF Polevoi EPS2018

DT pellets (90 mm^3, 4 Hz)

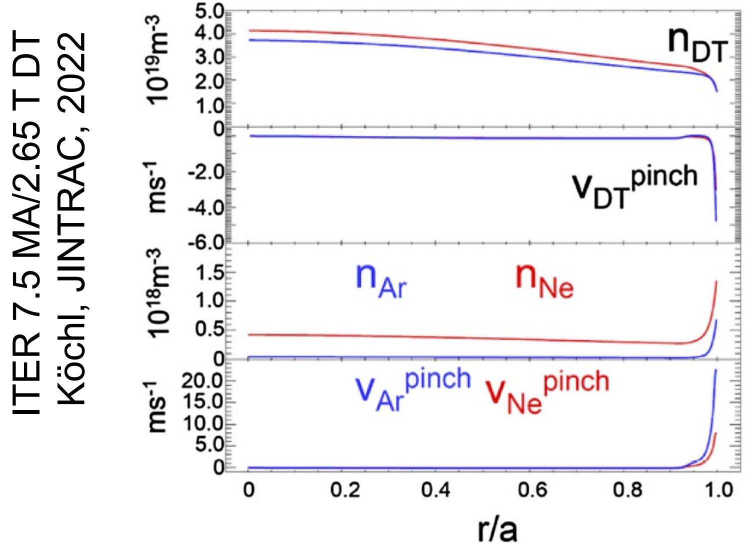


Belli, PoP 2021



Impurity ←→ Fuelling Impact

- **Presence of impurities can impact DT transport and fuelling efficiency**
- **P_{rad}^{core} ~ 60% P_{tot} achievable in ITER at low I_p shows large plasma driven edge fuelling if neoclassical transport dominates at the edge (open issue)**



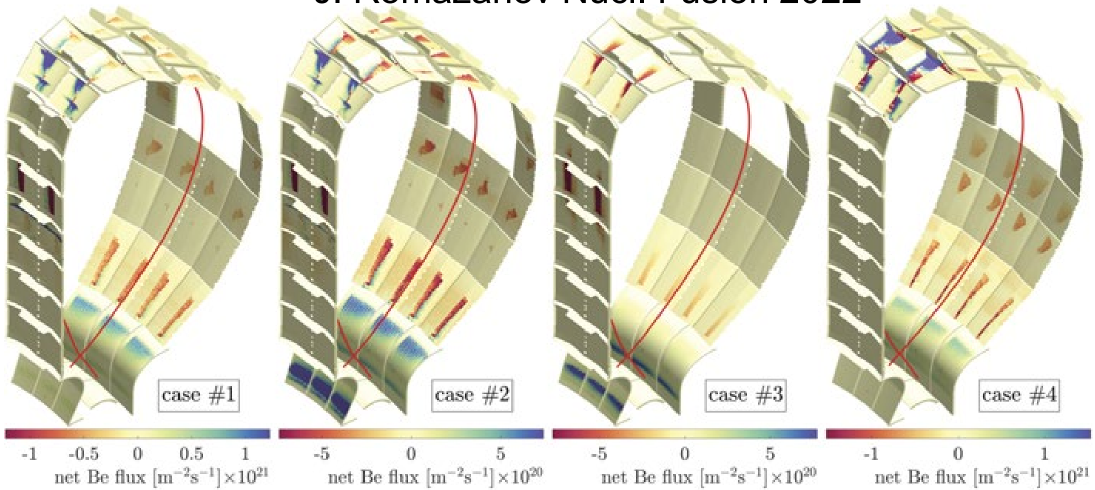
$\Gamma_{DT}^{in\text{-}sep}$ ~ 200 Pam³/s

ITER high Q → tolerable impurity levels are low (low allowed P_{rad}^{core}) but for DEMO high P_{rad}^{core} compatible with high Q

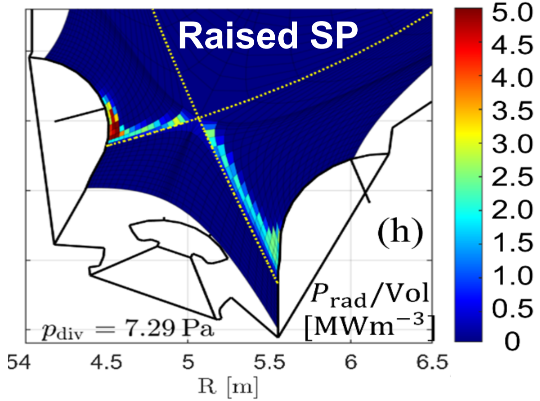
ITER T retention and removal strategy - I

- T retention driven by Be deposition → edge plasma conditions impacting magnitude (wall DT flux) and deposition location (SOL flows)
- Strategies to reduce (in-situ) T retention within/between pulses : ICWC/ECWC and plasma operation

J. Romazanov Nucl. Fusion 2022



J.S. Park PSI Conf. 2022

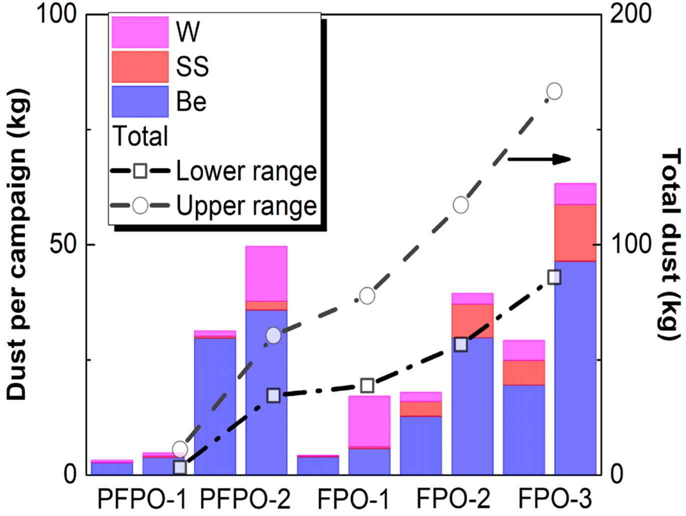


$$T_{\text{Be layer,pk}} = \begin{cases} 750 - 1050\ ℃\ (\text{DRSP 20MW}) \\ 1400 - 2000\ ℃\ (\text{DRSP 40MW}) \\ 2730 - 3930℃\ (\text{DRSP 60MW}) \end{cases}$$

T retention issues associated with high neutron fluence, high T_{wall}, permeation not fully addressed in ITER

ITER T retention and removal strategy - II

- Plasma based schemes not effective to remove T in non-exposed areas (where dust usually settles in)
- T removal (in-situ) to be implemented before shutdowns: GDC + baking (240 °C), divertor gas baking (350 °C), etc.
- Dust expected to be mostly Be and dominated by disruptions in PFPO (not T) and Be deposition in FPO

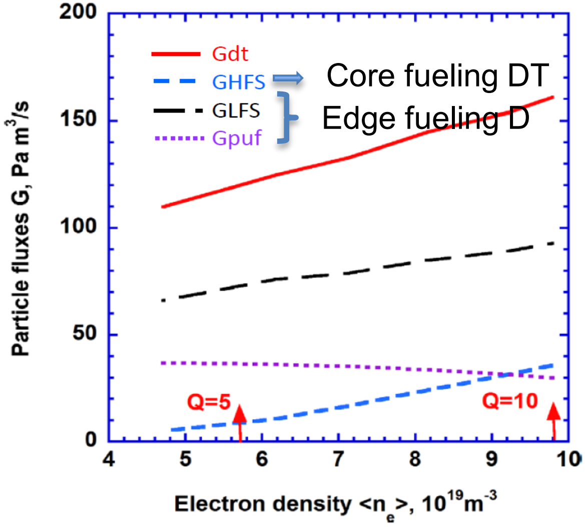


G. De Temmerman, R. Pitts

Integrated ITER simulations

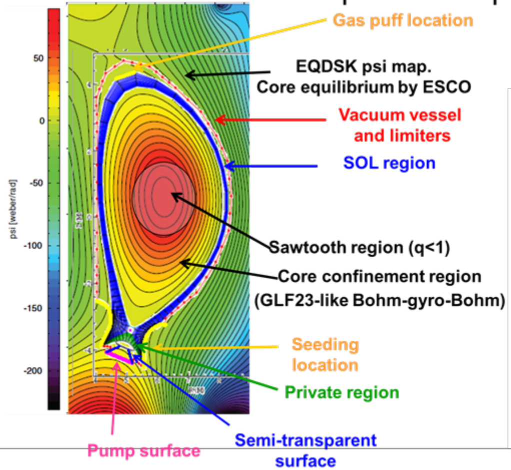
- Neutral penetration very ineffective in ITER due to poor neutral penetration
  - Separate control of n_{sep} (gas puffing by D) and n_{ped} (DT pellets)
  - Opportunity to minimize T throughput and increase burn fraction → full core-edge simulations

ASTRA+SOLPS b.c. Polevoi NF 2017

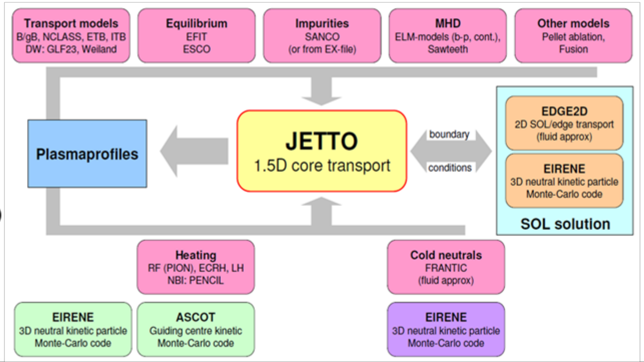


ITER modelling
E. Militello-Asp
(ITAC19TD53FE,F4E-OPE-1057 and RCUK EP/W006839/1)

Core to edge/divertor simulations including self-consistent description of transport in the pedestal and SOL (JINTRAC)



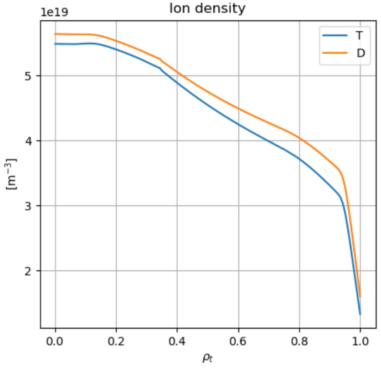
ITER- JINTRAC

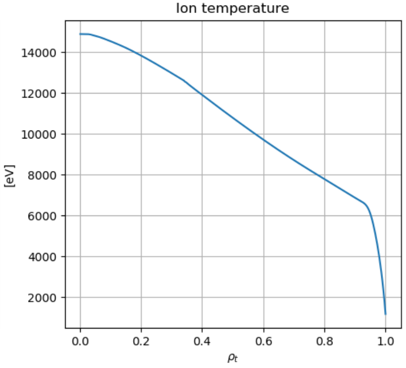


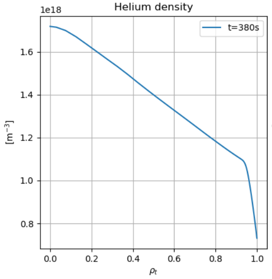
Integrated ITER simulation – stationary conditions I

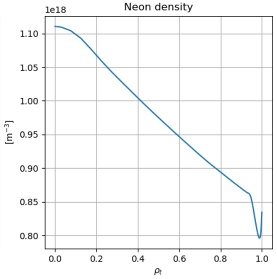
- Q = 10 simulations → 50 Pam^3/s[1] D gas fuelling + 44 Pam^3/s pellet fuelling (50-50 DT)
- Ne injection for divertor power load control and W impurities from divertor

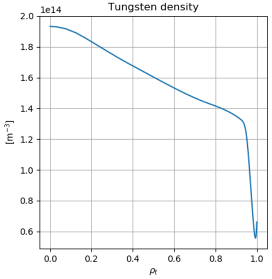
injected atoms 1 Pam^3/s but known underestimate by up to ~ 10 when comparing Ne rates in simulations and experiments

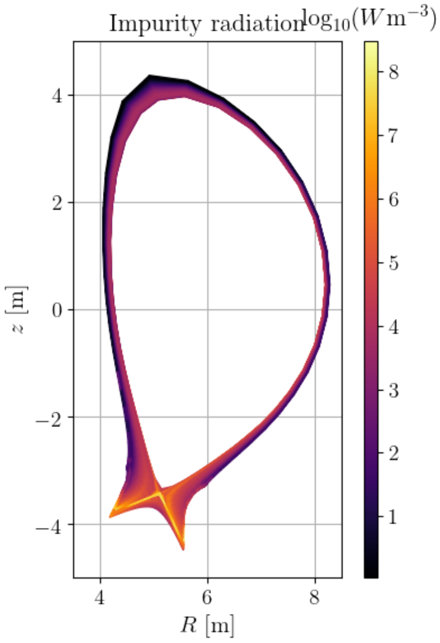












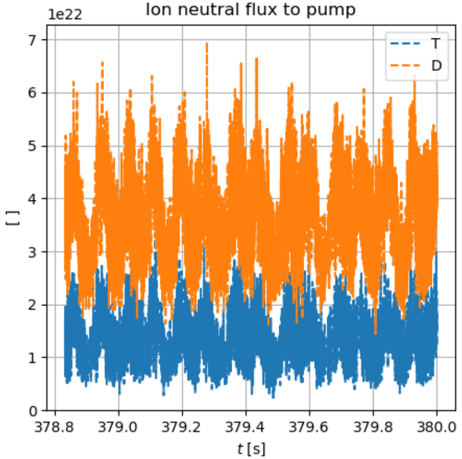
ITER modelling
F. Eriksson

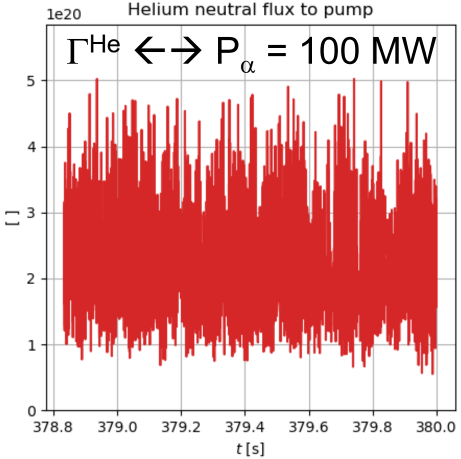
$P_{rad}^{core\text{-}Ne}$ = 20 MW
$P_{rad}^{edge\text{-}Ne}$ = 50 MW

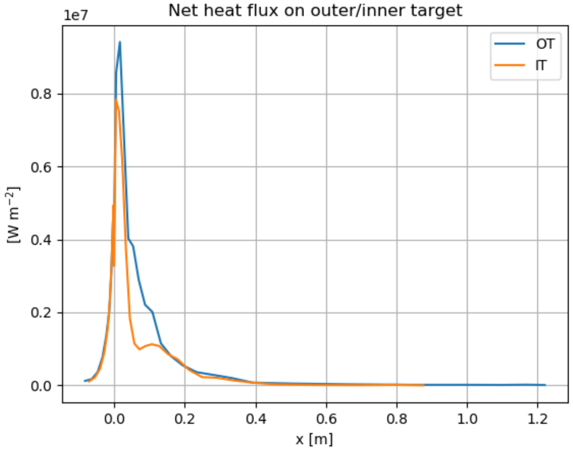
Integrated ITER simulation – stationary conditions II

- Q = 10 simulations → 50 Pam^3/s^1 D gas fuelling + 44 Pam^3/s pellet fuelling (50-50 DT)

ITER modelling - F. Eriksson







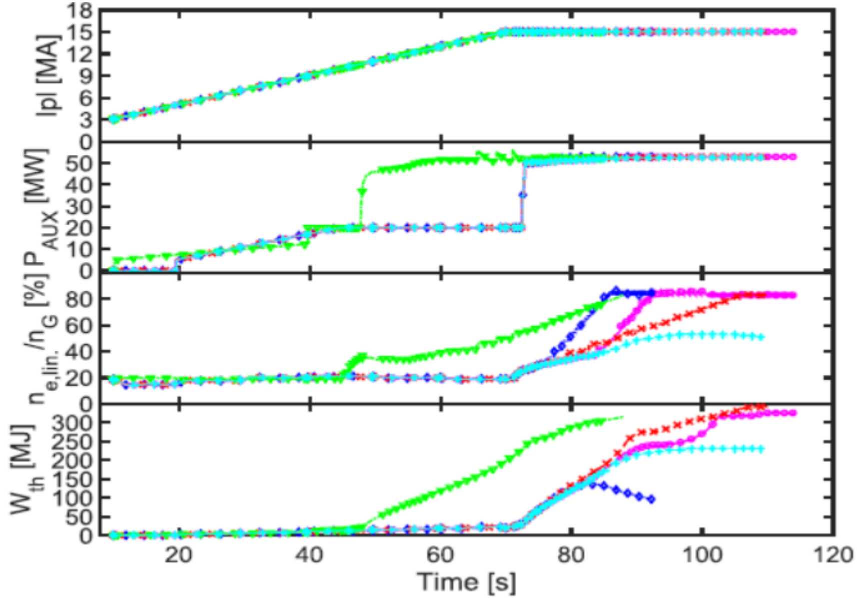
Q = 10 achievable with 94 Pam^3/s D-T fuelling = 23% T + 77% D
Demonstration of edge versus core isotopic fuelling in ITER

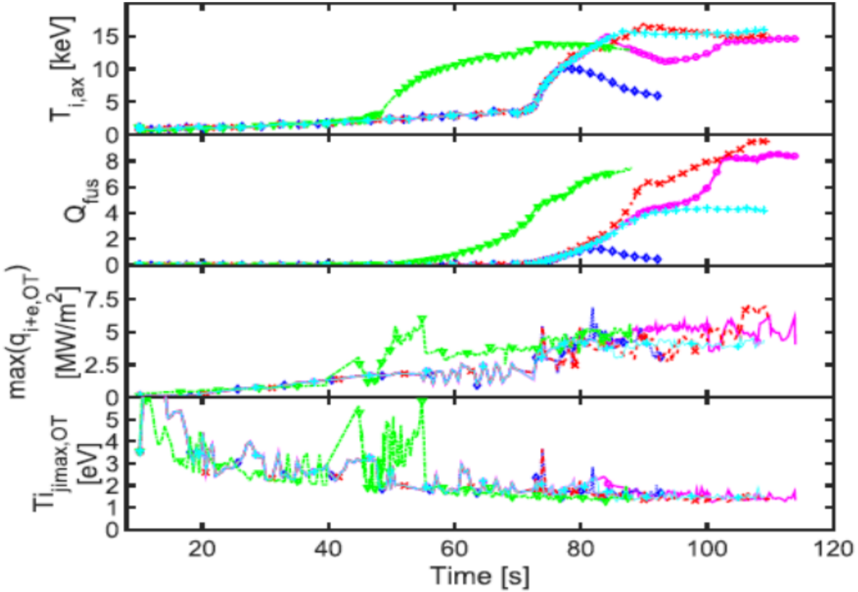
Integrated ITER simulation – transient conditions

- Access to high Q requires build-up of P_{alpha} since P_{aux} is moderate and $P_{L\text{-}H}$ is high
- Key to high Q access is density control (gas fuelling for n_{sep} and pellet fuelling for n_{core})

F. Koechl - ITER – JINTRAC - NF 2020

- Access in current ramp and low n_e allows high Q earlier in flat top





Conclusions

- Plasma fuelling/exhaust in fusion reactors has to be considered within the global scenario integration approach
  - Power exhaust (stationary and ELM transient load control)
  - Impurity exhaust
- Significant differences in neutral and plasma physics may be found in fusion reactors → Fuel cycle is (as far as possible) designed to be flexible in ITER
- Recycling fluxes and gas puffing expected to be very ineffective to fuel the core plasma in reactors → edge and core fuelling control may be independent
  - No impact of total D+T throughput but possibility to reduce T throughput for given Q
- ITER is expected to resolve most open issues in this area (except those related to high Q operation with high P_{rad}^{core} foreseen for DEMO and fuel retention in high Z metal PFCs at high neutron fluence and T_{wall})