An integrated view on high density operation and fuel cycle

Part I

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Motivation

High density operation is desirable for maximizing fusion power

$$P_f = \int n^2 < \sigma v > E_f dV$$

at T_i = 10 – 15 keV $$< \sigma v >= c_{\sigma v} T^2$$

with $$\beta = \frac{p}{B^2/2\mu_0}$$

$$P_f = 2\mu_0 c_{\sigma v} E_f \int \beta^2 B^4 dV$$

- thus, below β-limit increase of density in order to stay in the optimum fusion reaction range (at 10 – 15 keV)
- Cost of electricity (in tokamaks) drops with increasing n/n_{GW}

$$coe \propto \left(\frac{1}{A}\right)^{0.6} \frac{1}{\eta^{0.5}} \frac{1}{P_e^{0.5} \beta_N^{0.4} \left(\frac{n}{n_{GW}}\right)^{0.3}}$$

D. Ward et al.

Motivation

In addition

- decrease of population of fast particles (of particular importance for stellarators)
  - . $\tau_s \propto \frac{T_e^{3/2}}{n_e} \propto \frac{p_e^{3/2}}{n_e^{5/2}}$
  - avoid fast particle driven instabilities altogether?

- for stellarators high density required for high Q_{DT} or ignition, because of

$$D \sim \varepsilon_{eff} T^{7/2} = \varepsilon_{eff} \left(\frac{p}{n}\right)^{7/2}$$

- improve lifetime of plasma facing components / divertor; higher densities / lower temperatures
  - reduce local heat fluxes due to increased radiation / detachment
  - reduce high energy ion tail impinging on target

- relation between plasma density, neutral density, plasma fuelling and fuel cycle
  - maximize core density, divertor density and neutral density at the pumps
  - minimize tritium turn-over

Density limits: tokamaks and stellarators

- In tokamaks density empirical density limit given by Greenwald scaling

$$n_{GW}[10^{20}m^{-3}] = \frac{I_p[MA]}{\pi a^2[m^2]}$$

  - limit associated with loss of confinement (H to L transition)

  - disruptions

- In stellarators density limit

  - no Greenwald limit (e.g. LHD super dense core plasma, up to 5 × n_{GW})

  - theoretically given by bremsstrahlung

  - in practise often radiation limit is observed (Sudo-limit)

$$\bar{n}_{Sudo} \propto \frac{P \cdot B^{0.5}}{V}$$ associated with impurity accumulation

Comparison stellarator and tokamak

Tokamaks:

- Temperature screening counteracts effect of density peaking

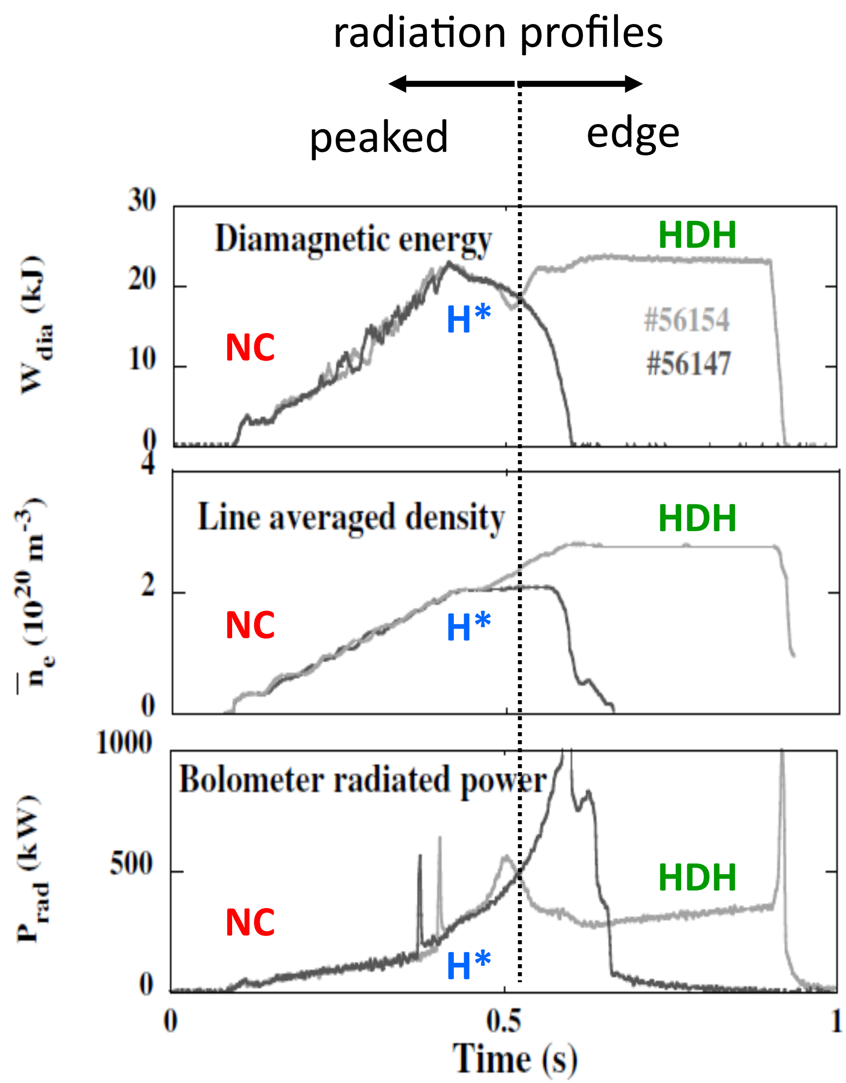
- Density peaking increases with decreasing collisionality, also considering central heating by fusion α's (next slide)

Stellarators

- Thermodynamic forces are predicted to support accumulation in the standard case with negative radial electric field, the so-called ion-root regime

- Suitable confinement regimes have to be found (→ HDH)

- Test of high-Z (tungsten) still has to be done



Example W7-AS

Comparison stellarator and tokamak

Tokamaks:

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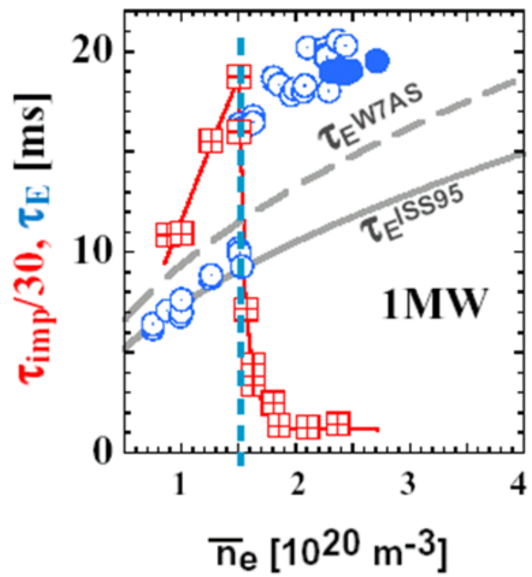
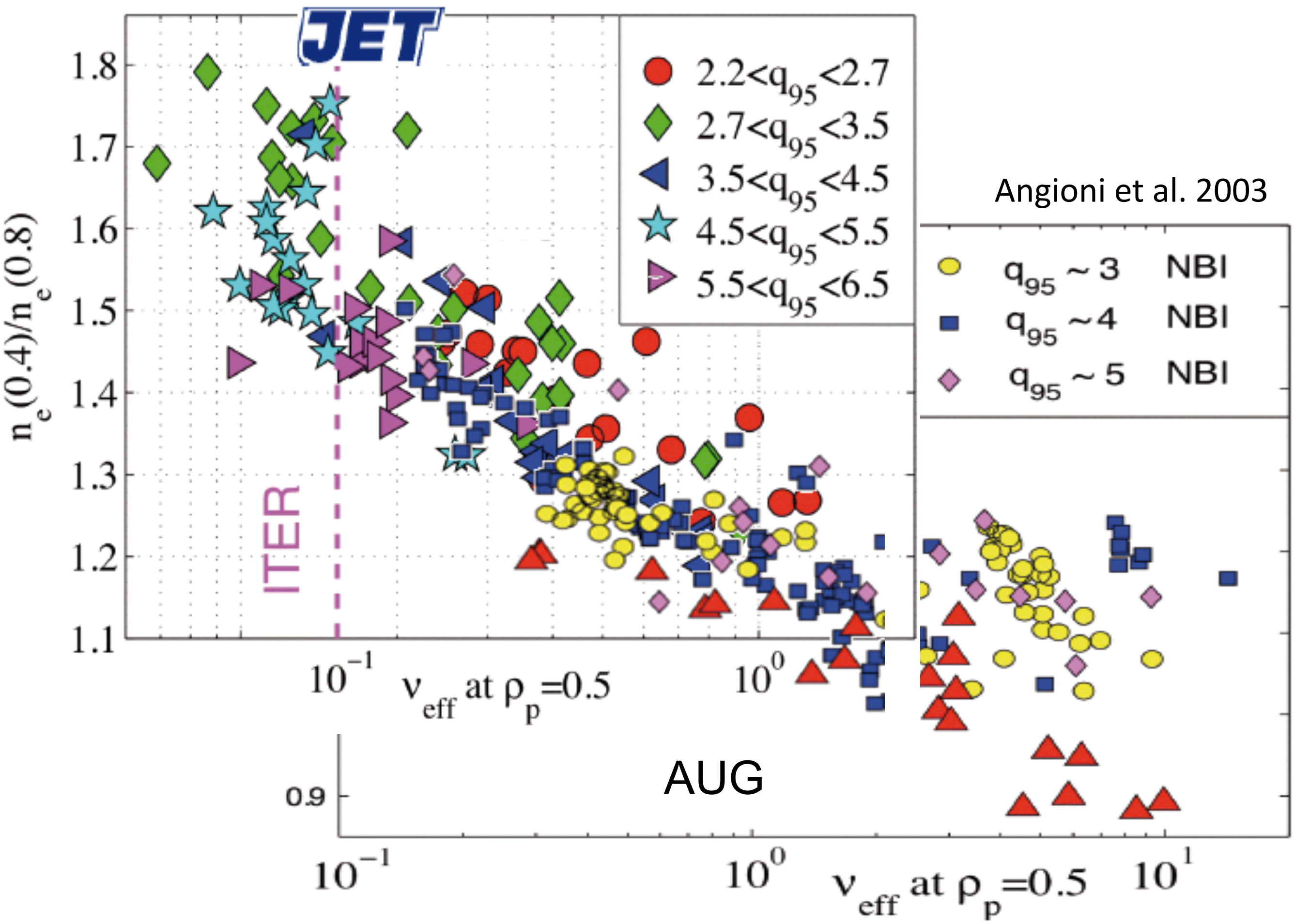
HDH mode in W7-AS
characterized by steep edge ∇n

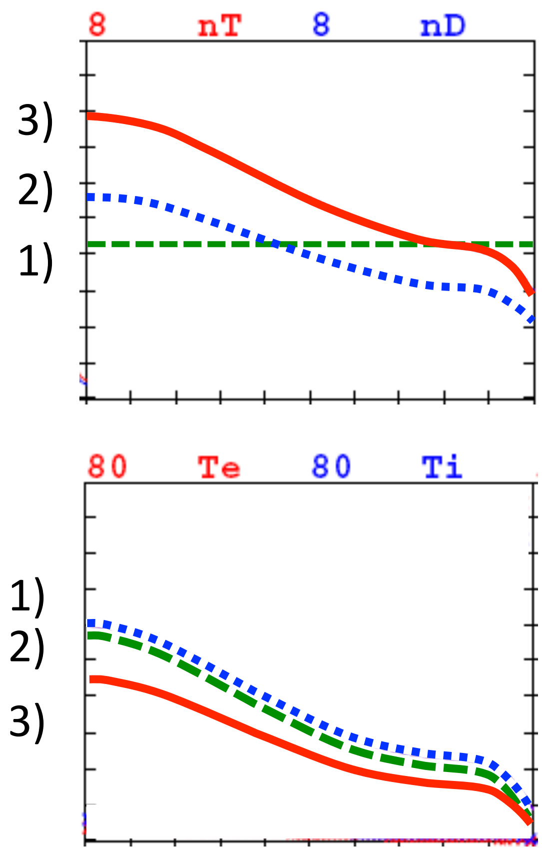


Tokamak: density peaking scales with collisionality



Effect of density peaking for a tokamak DEMO

- Hypothesis: Greenwald limit is a pedestal limit
- ASTRA simulation of DEMO (D. Ward: R/a = 8.5/2.83, 5.74 T, 23 MA, $\beta_{N,th}$ = 2.95)



1) $\int n\, dl/l = n_{GW}$
P_{fus} = 2.7 GW

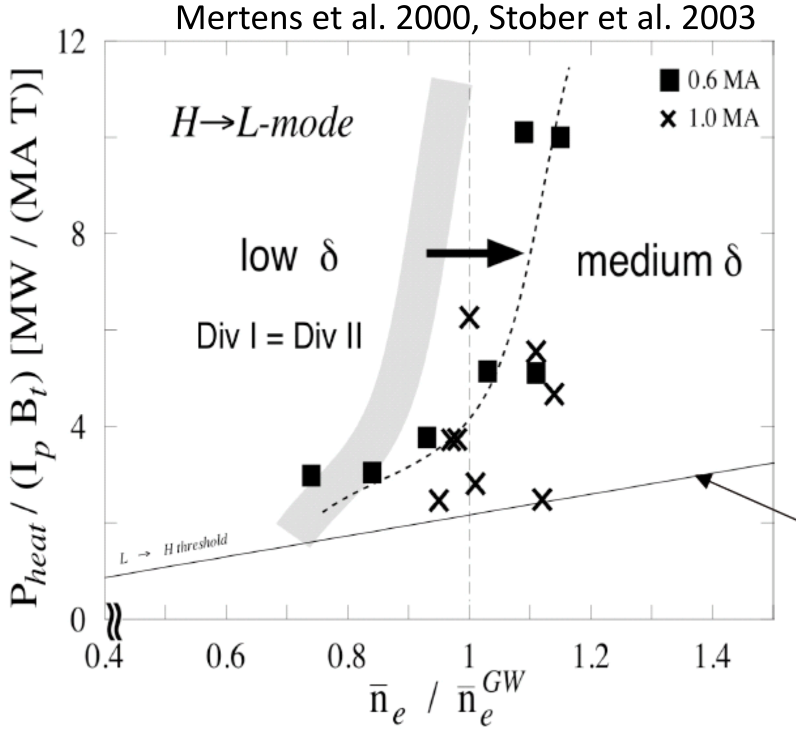
2) $\int n\, dl/l = n_{GW}$ P_{fus} = 2.7 GW

3) $\int n\, dl/l = 1.4\, n_{GW}$
$n(\rho=0.9) = n_{GW}$
P_{fus} = 3.7 GW

H-mode density limit

Increase of density → ELM characteristic changes → H to L-transition → MARFE → disruption

Mertens et al. 2000, Stober et al. 2003



$P \propto \bar{n}_e B_T$

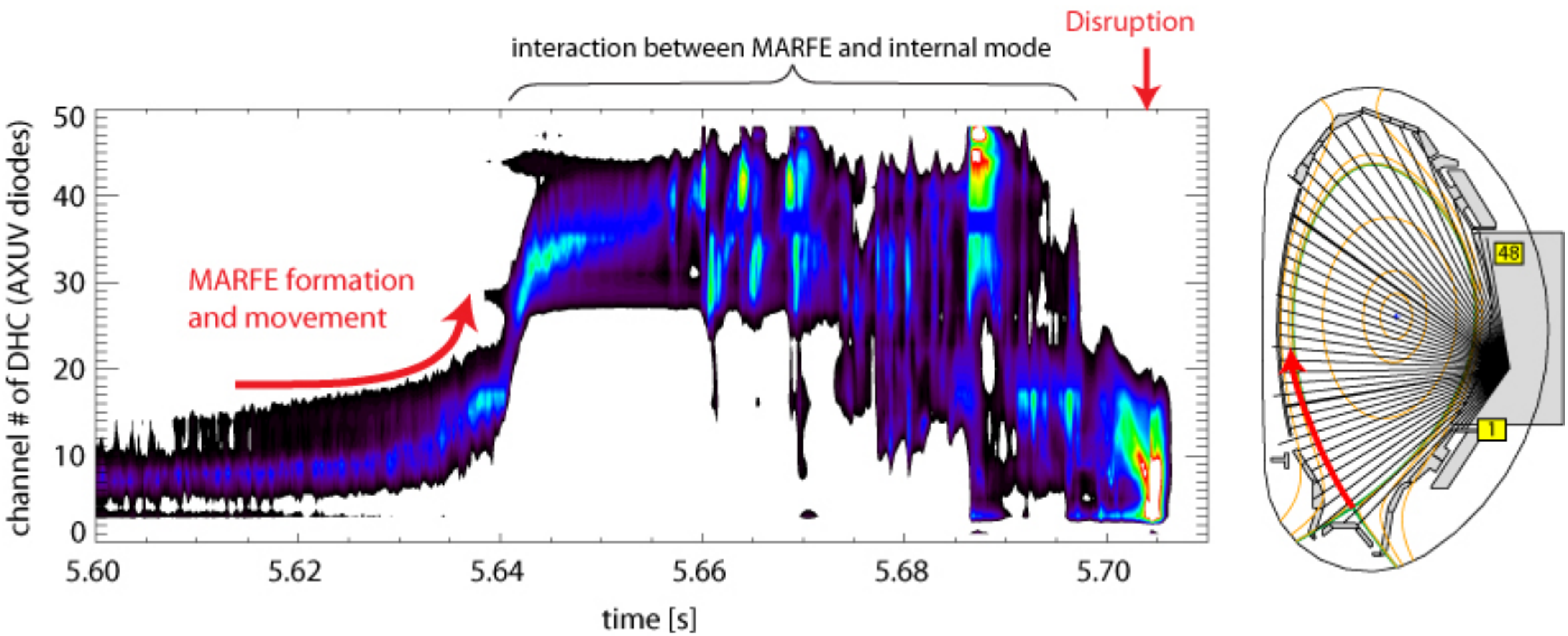
Power threshold at medium densities

H-mode density limit

Increase of density → ELM characteristic changes → H to L-transition **→ MARFE → disruption**

In the end MHD event, locked mode and disruption:

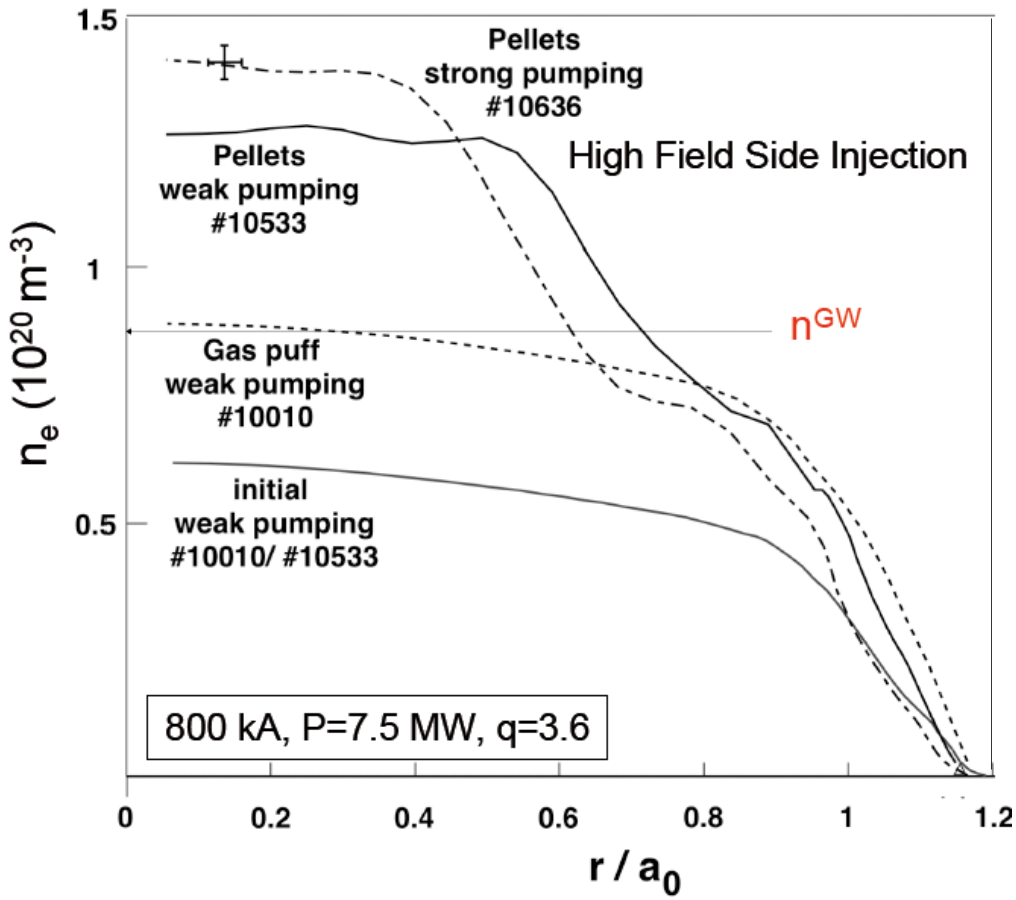
m/n = 2/1 mode suggests loss of electrical conductivity and unstable current density profile



Core density can exceed Greenwald limit

Pellet fuelling allows central $n > n_{GW}$

Pedestal density stays below n_{GW}



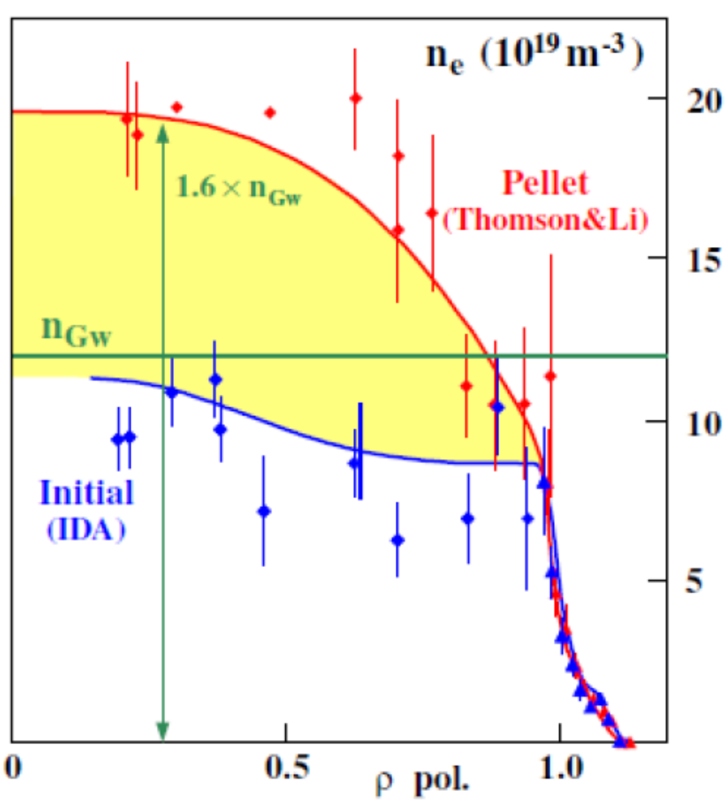
Stober et al. 2003

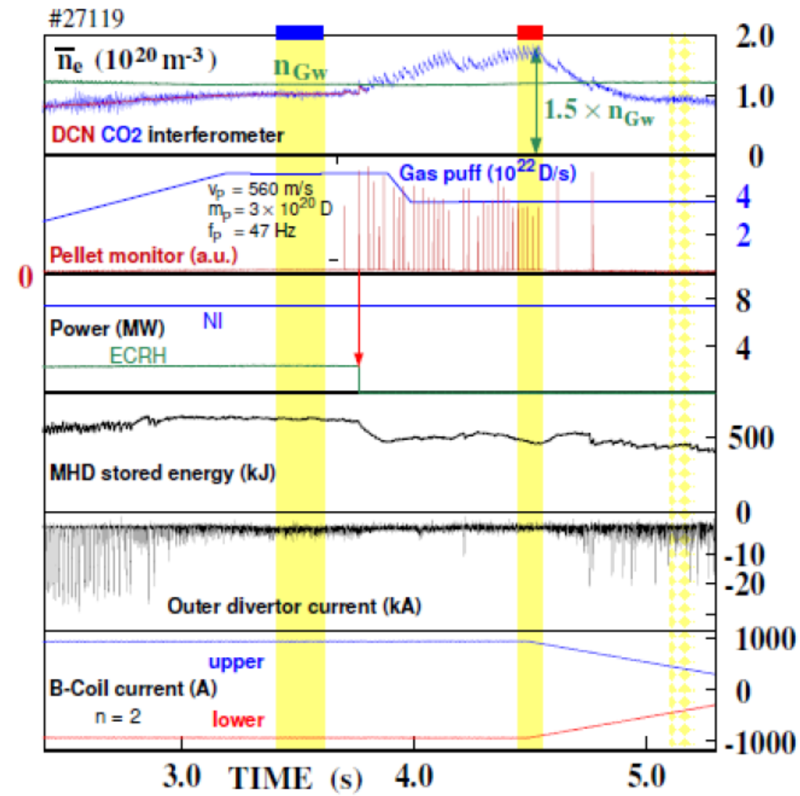
Core density can exceed Greenwald limit

Pellet fuelling allows central n > n_{GW}

Pedestal density stays below n_{GW}, modest confinement degradation

ELMs suppressed with perturbation coils, pellets for HFS fuelling

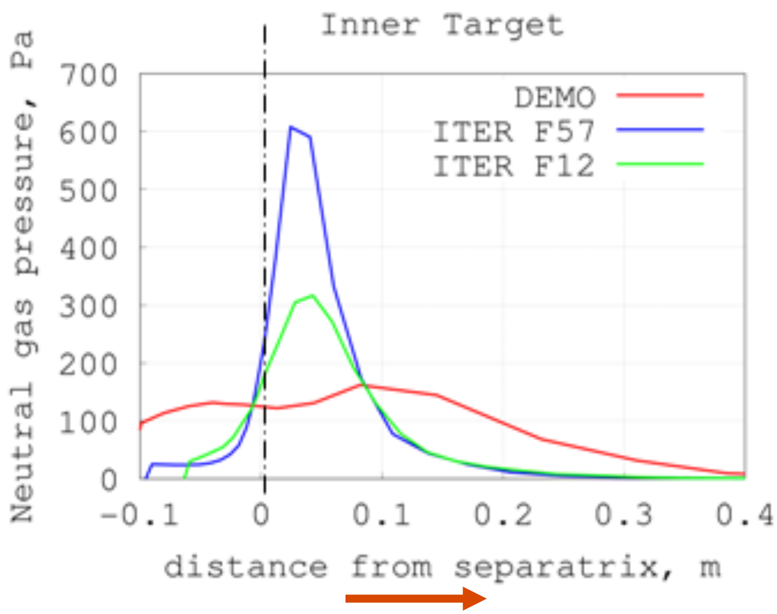




Lang et al., EPS 2011

Divertor gas pressure in ITER and DEMO

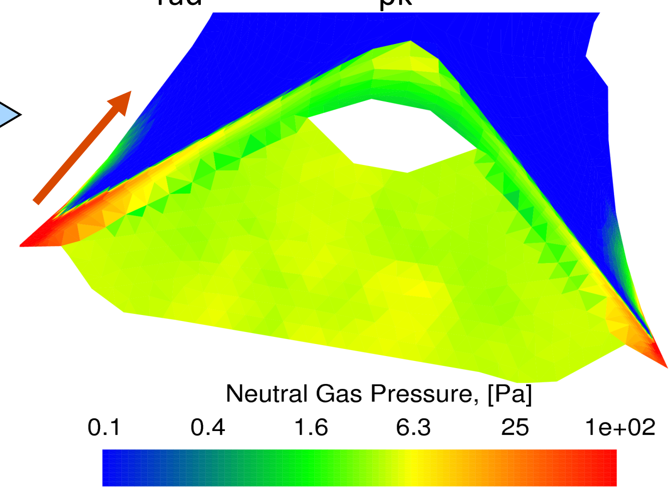
B2-EIRENE (SOLPS 4.3) modeling, (A.S. Kukushkin, H.D. Pacher)



DEMO #092

R=8.1 m, P_{SOL}=300 MW

f_{rad}=0.71, q_{pk}=5.6 MW/m^2



The pressure is determined by
- upstream plasma pressure;
- magnetic configuration;
- plasma-neutrals interaction in divertor

Similar sub-divertor pressure
1-15 Pa in ITER and DEMO

Is it possible to increase it significantly?

Can inter-cassette gaps be used for pumping? He de-enrichment?

Summary & work plan

- Further verify that in tokamaks density limit is a pedestal limit / not a core limit
- Improve density scaling (scaling parameters not independent, 0D approach too simple)
- Apply methods to increase core density above Greenwald limit
  - Pellet fuelling – is pellet fuelling applicable in a tokamak DEMO?
  - Investigate density peaking at low collisionality – how far can we go on present day tokamaks?
- Radiation limit in stellarators
  - Impurity control is not an optimization criterion of W7-X – *see C. Beidler et al.*
  - HDH in W7-AS (or SDC in LHD) is a starting point, but not understood how it extrapolates to e.g. W7-X
- Divertor & fuelling
  - High density / detachment required for staying below critical heat flux (≤ 5 MW/m^2?) – *see L. Boccaccini, A. Kallenbach*
  - High neutral pressure desired for "simple" pumping solution – *see C Day et al.*
  - Are geometrical solutions (e.g. pumping close to strike points) feasible?
  - Balance between neutral pressure and upstream plasma pressure?