ITER and Pedestal Physics

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Acknowledgements:

Members of ITER Organization and Domestic Agencies together with many experts in the international fusion community

Outline

- ➢ ITER : Goals and design basis description
  - ✓ Plasma confinement & fusion production
  - ✓ Integration with fluxes to plasma facing components
- ➢ Basic H-mode and pedestal physics concepts
- ➢ Key Pedestal & Transport Physics Issues in ITER
  - ✓ Access to high τ_E H-mode
  - ✓ Pedestal physics in ITER
  - ✓ ELMs and ELM control
  - ✓ W impurity control
- ➢ Overview of ITER Operation & Research Plan
- ➢ Conclusions

ITER – Objectives

- ITER's overall programmatic objective:
  - to demonstrate the scientific and technological feasibility of fusion energy for peaceful purposes
  - to design, construct and operate a tokamak experiment at a scale which satisfies this objective

- ITER is a tokamak designed to confine a DT plasma in which α-particle heating dominates all other forms of plasma heating

  $\Rightarrow$ an experimental nuclear fusion reactor

  ✓ Designed to achieve P_{fusion} = 500 MW with gain $Q \geq 10$ for 300-500 s

  ✓ Aims to achieve $P_{fusion} \geq 350$ MW with $Q \geq 5$ for 1000-3000 s

  ✓ Aims at exploring "controlled ignition" ($Q \geq 30$)

  $D + T \rightarrow \alpha + n$ $\qquad$ $Q = P_{fusion}/P_{add} \rightarrow P_{\alpha}/P_{add} = Q/5$

- ITER is a unique worldwide collaboration in research involving the EU (plus Switzerland), China, India, Japan, Russian Federation, South Korea and United States

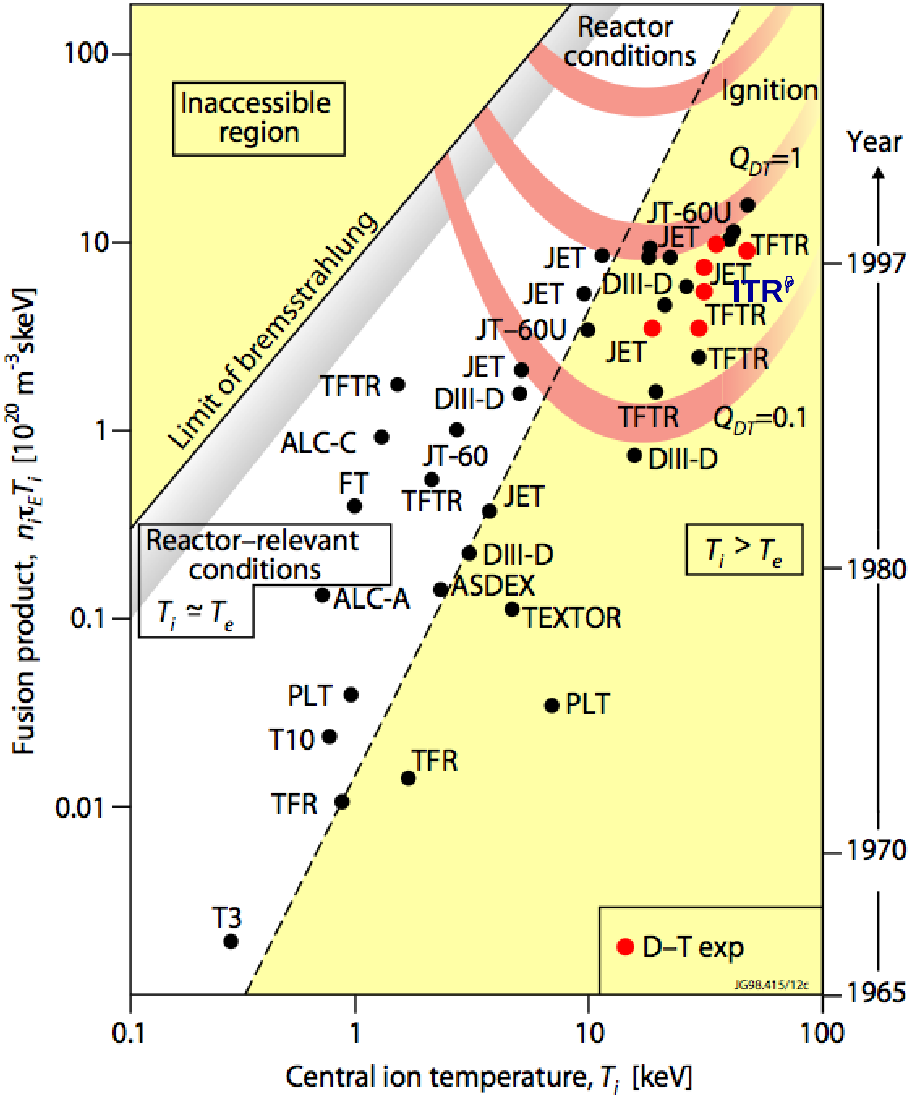
ITER Goals and Design Basis Description

Fusion performance

$$Q = \frac{Fusion\ Power}{Input\ Power}$$

Existing experiments have achieved $nT\tau_E \sim 1\times10^{21}\ m^{-3}skeV$ and $Q_{DT} \sim 1$

JET and TFTR have produced DT fusion powers >10MW for ~1s



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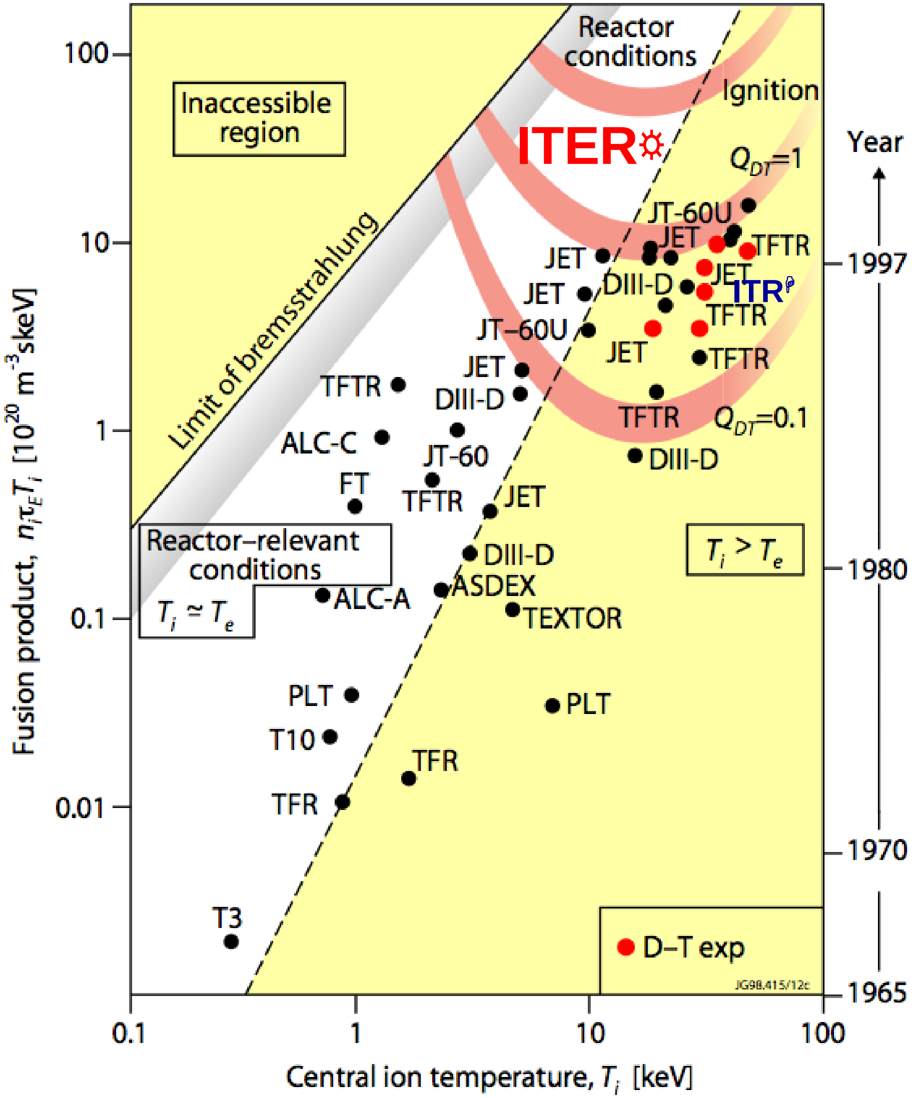
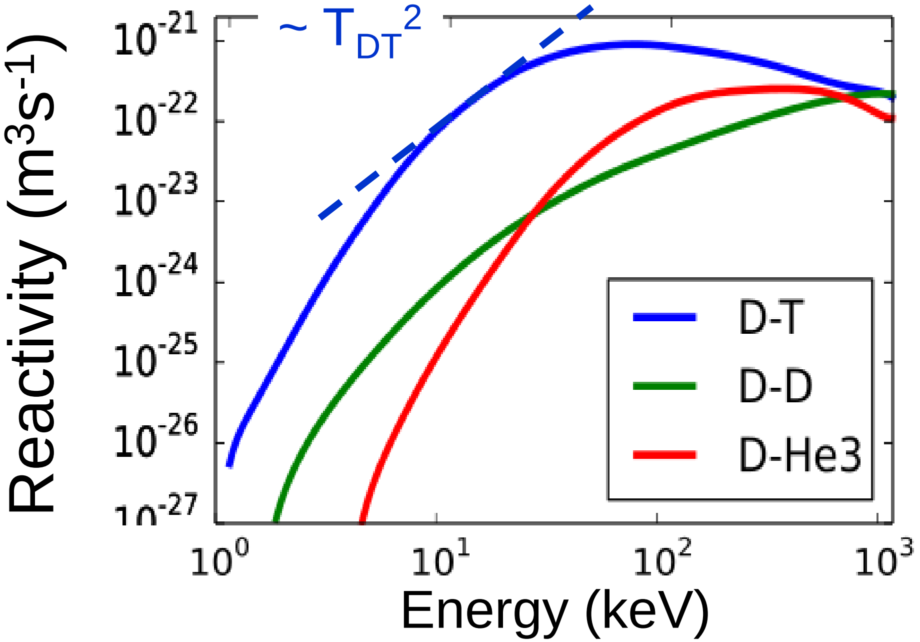
ITER is designed to a scale which should yield $Q_{DT} \geq 10$ at a fusion power of 400 – 500 MW for 300 – 500 s → Baseline scenario



Energy Confinement : L-mode and H-mode

Energy confinement → $\tau_E = W_{plasma}/P_{input}$

- To achieve T_i ~ 20 keV required for fusion the plasma must be strongly heated (large P_{input})
- $P_{fusion} \propto n_{DT2} \langle \sigma v_{DT} \rangle \sim (n_{DT} T_{DT})^2 \sim W_{plasma}{}^{\alpha}$ (α ~ 2-3) → high Q requires high W_{plasma}
- Achieving highest possible τ_E is required for high Q reactor



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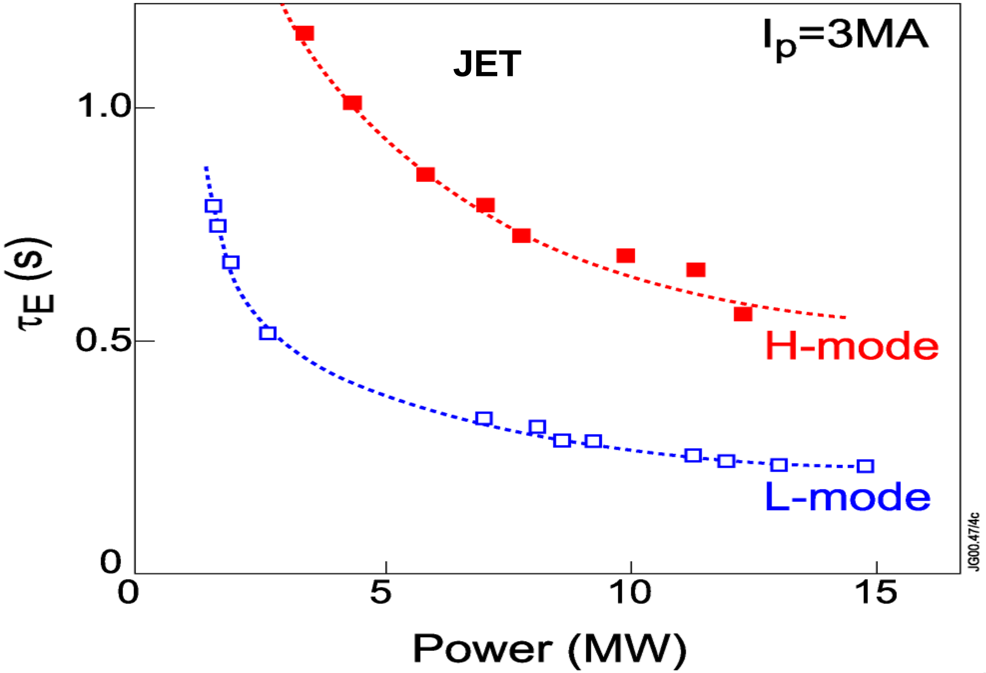
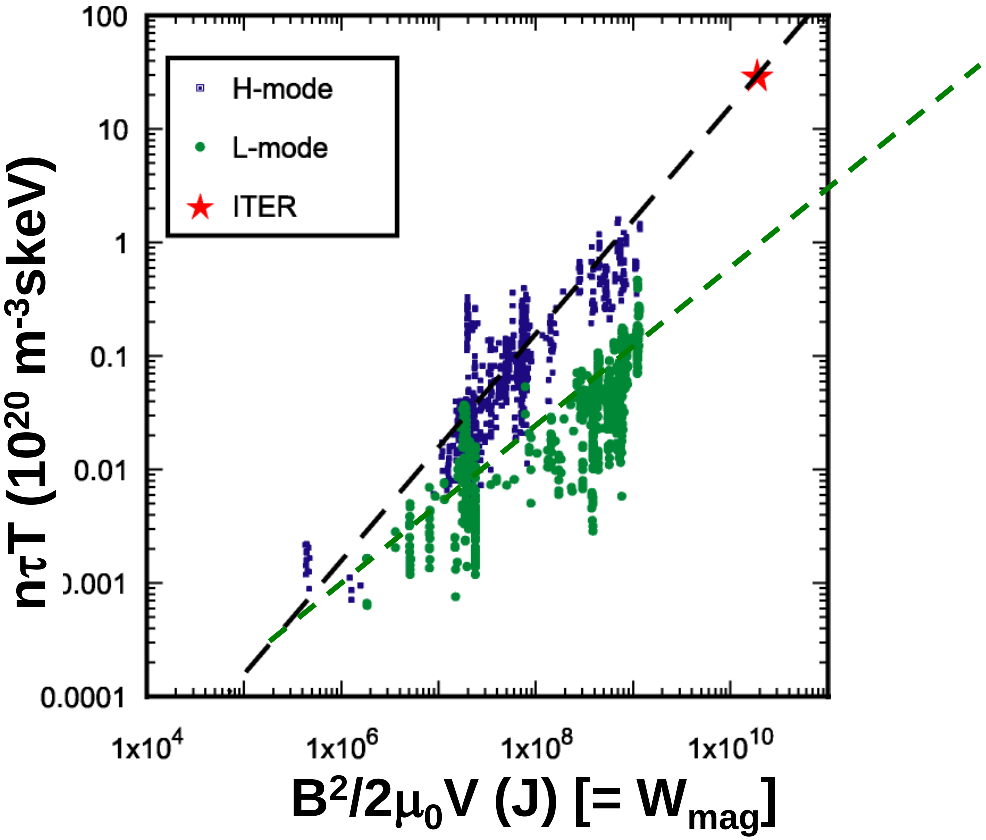
- Achieving highest possible τ_E is required for high Q reactor
- H-mode regime → $\tau_E^{H\text{-}mode} = 2 \times \tau_E^{L\text{-}mode}$ for same P_{input} → P_{fusion} ↑ (x 4-8)



ITER Size and Parameters



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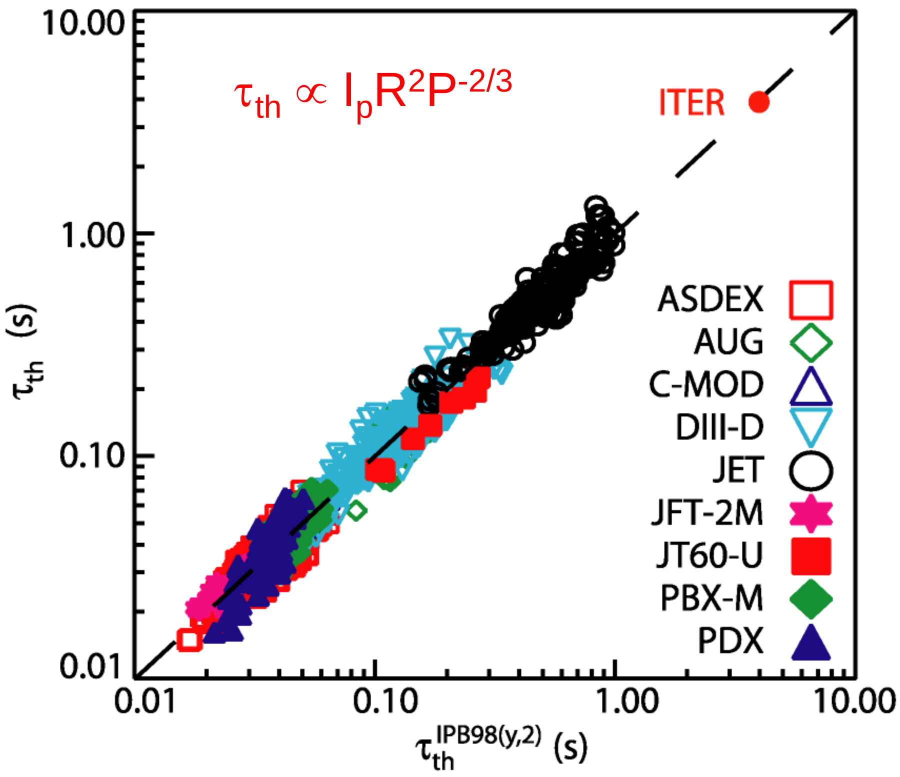
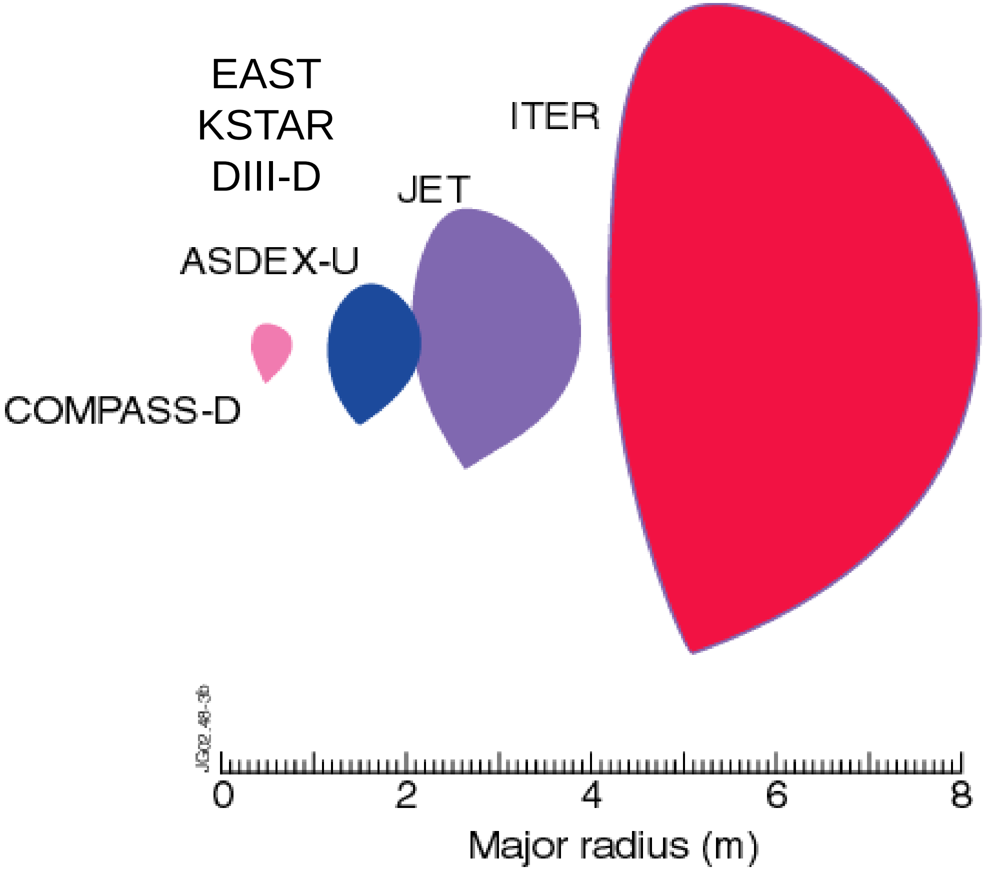


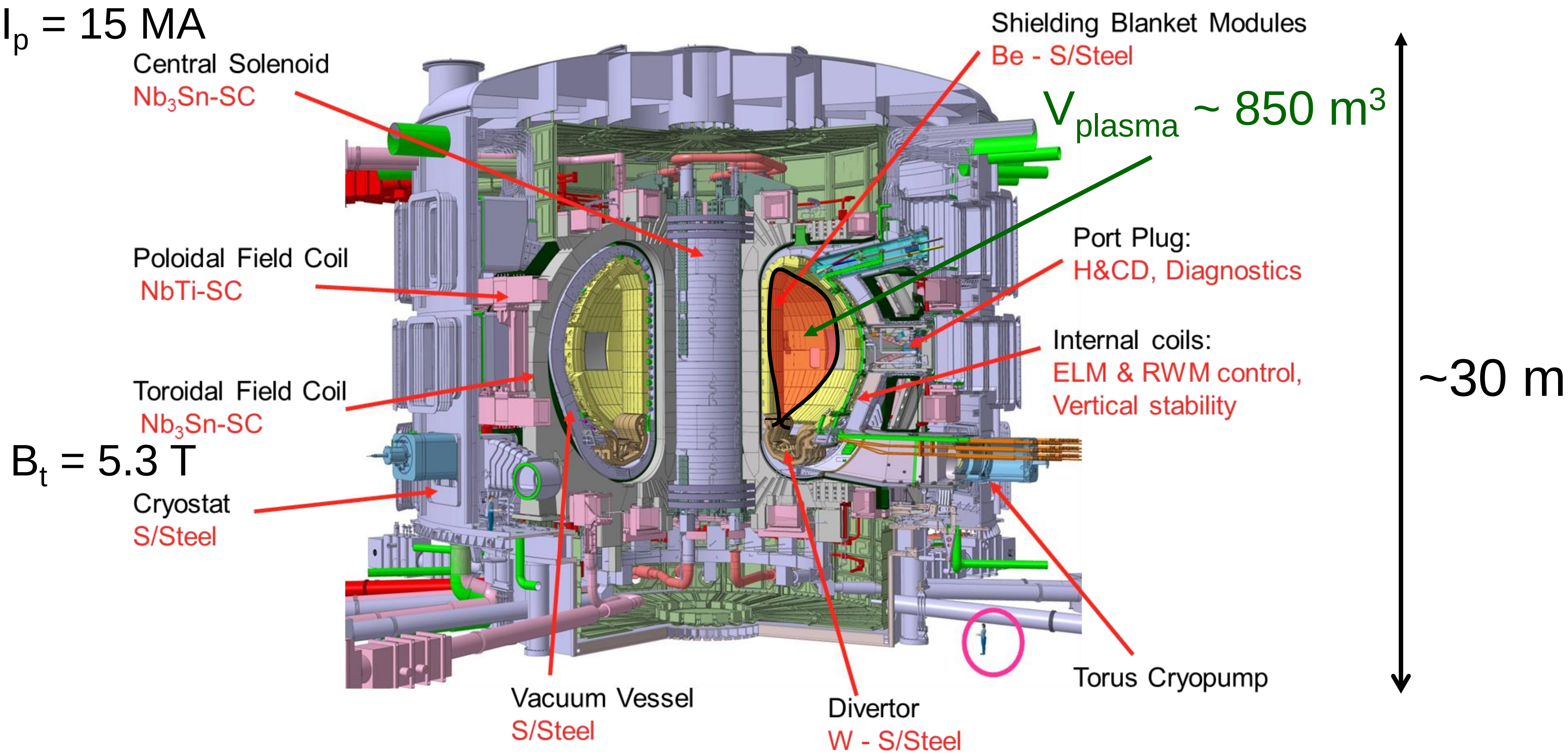


- ➢ H-mode confinement scaling studies (+ known operational limits in tokamaks) provide a robust approach to determining ITER’s size

Q requirement → τ_E → I_p, R, … + operational limits → B_t, …

Q = 10 → R = 6.2 m, a = 2 m, I_p = 15 MA, B_t = 5.3 T,….

ITER - Main Features



I_p = 15 MA

Central Solenoid
Nb_3Sn-SC

Poloidal Field Coil
NbTi-SC

Toroidal Field Coil
Nb_3Sn-SC

B_t = 5.3 T

Cryostat
S/Steel

Vacuum Vessel
S/Steel

Divertor
W - S/Steel

Torus Cryopump

Shielding Blanket Modules
Be - S/Steel

V_{plasma} ~ 850 m^3

Port Plug:
H&CD, Diagnostics

Internal coils:
ELM & RWM control,
Vertical stability

~30 m

NBI (1 MeV)	ECH (170 GHz)	ICH (40-55 MHz)	LH (5 GHz)	Total
33 MW (+16.5 MW)	20 MW (20 MW)	20 MW (20 MW)	0 MW (20 MW)	73 MW (130 MW-110 MW simultaneous)

ITER Fuelling Systems Configuration

Gas Injection System (GIS)

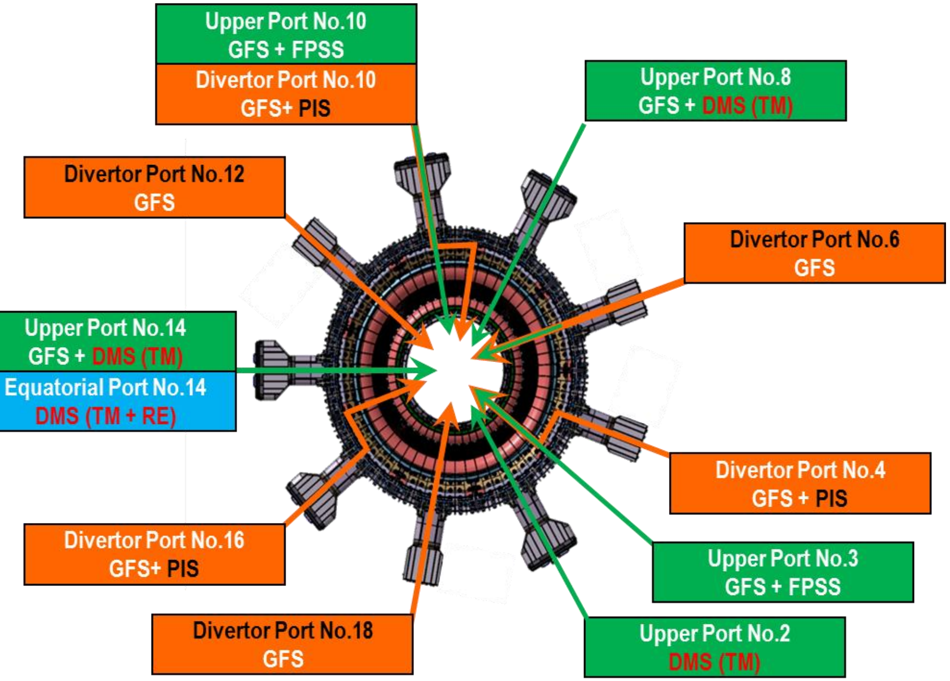
Upper port level GIS : 4 ports

Divertor port level GIS : 6 ports

Pellet Injection System (PIS)

Three divertor ports

Two injectors at each port



Upper Port No.10
GFS + FPSS

Divertor Port No.10
GFS+ PIS

Upper Port No.8
GFS + DMS (TM)

Divertor Port No.12
GFS

Divertor Port No.6
GFS

Upper Port No.14
GFS + DMS (TM)

Equatorial Port No.14
DMS (TM + RE)

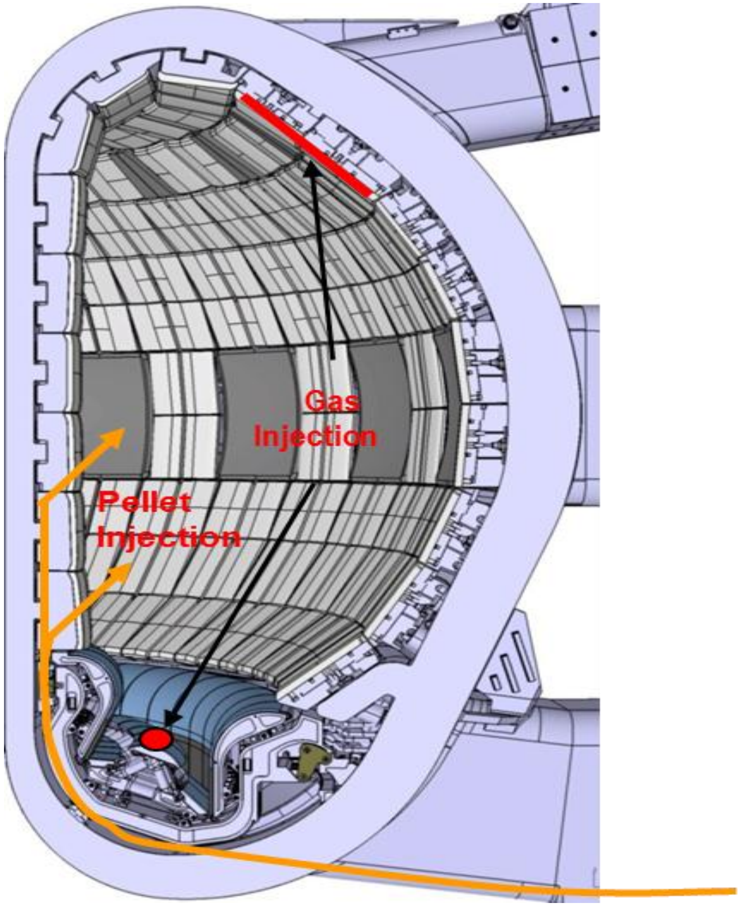
Divertor Port No.4
GFS + PIS

Divertor Port No.16
GFS+ PIS

Upper Port No.3
GFS + FPSS

Divertor Port No.18
GFS

Upper Port No.2
DMS (TM)



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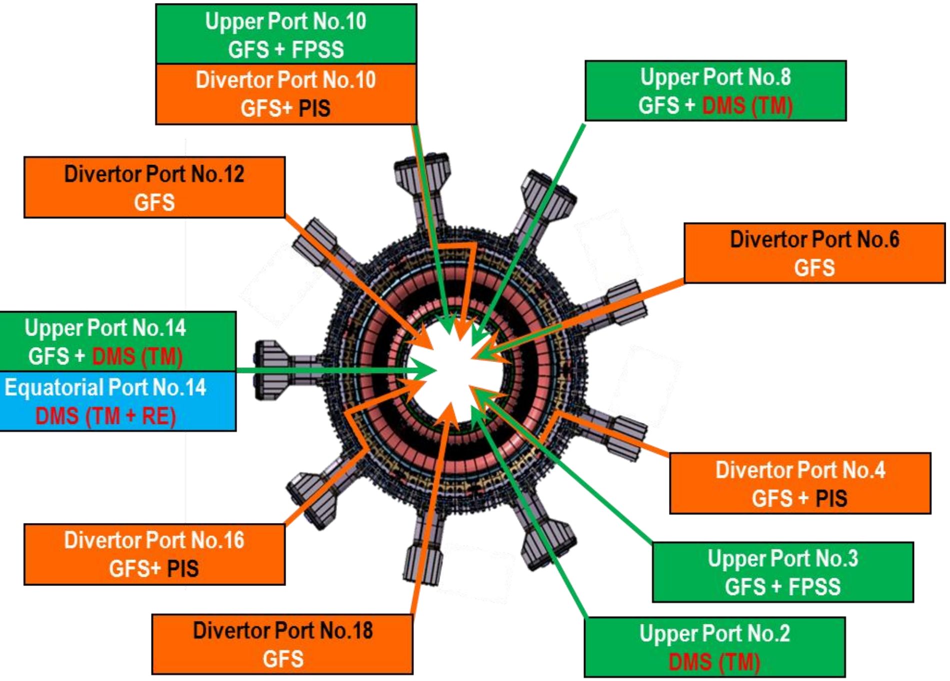

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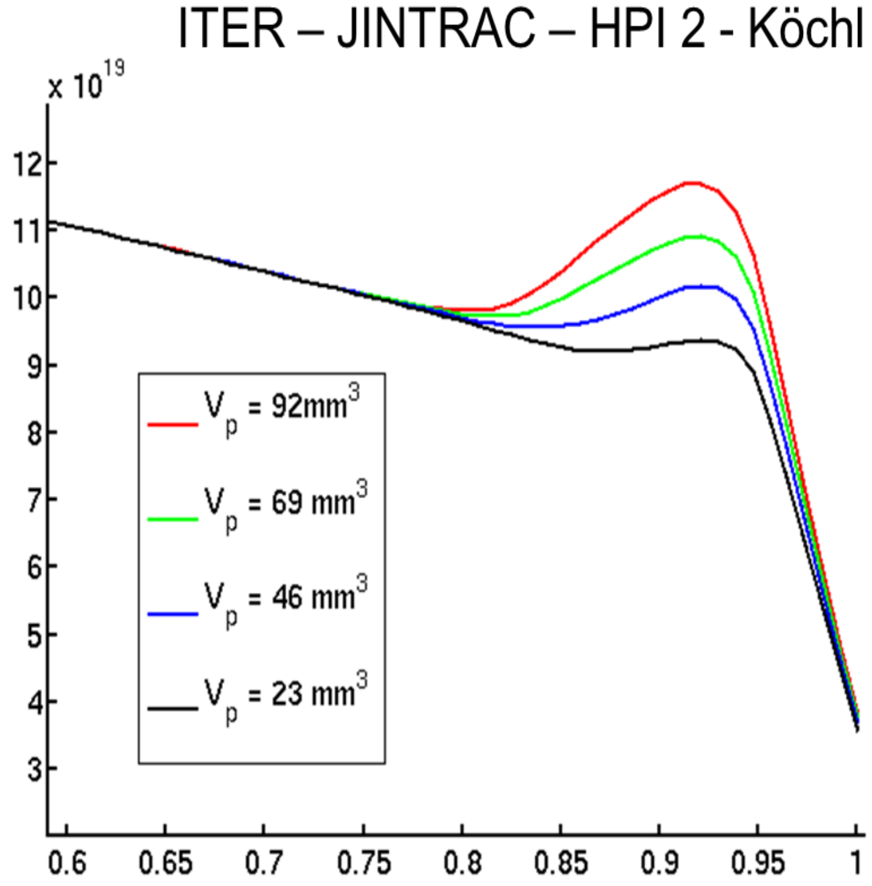
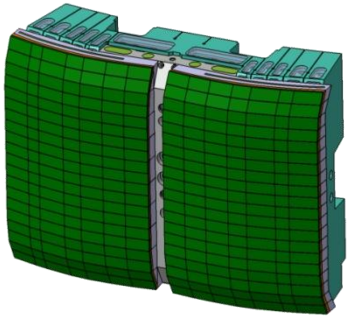


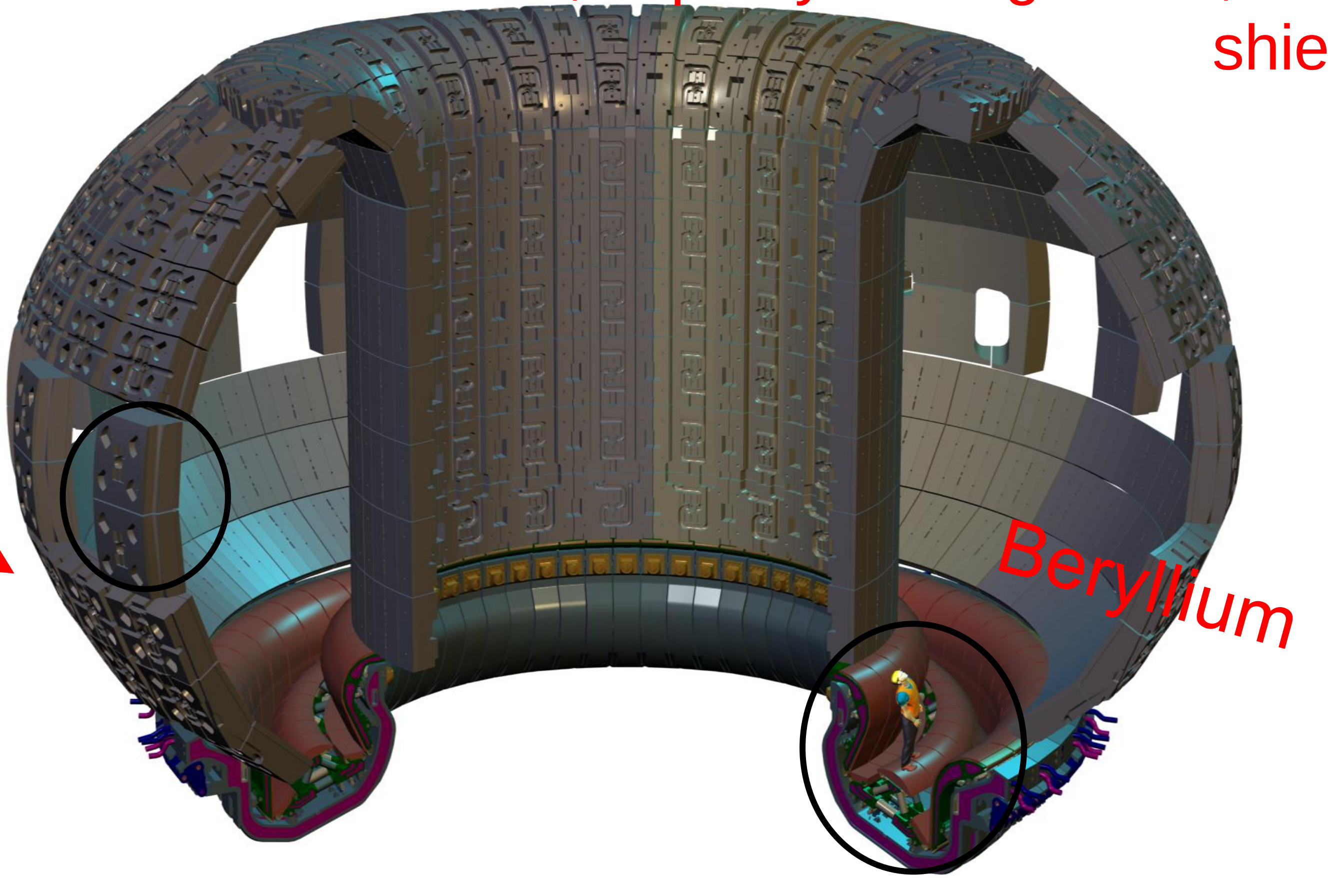
ITER – JINTRAC – HPI 2 - Köchl

ITER In-Vessel Components : Design

First wall/blanket → heat exhaust, impurity management, nuclear shielding



Blanket modules $2\text{-}5\ \mathrm{MWm^{-2}}$

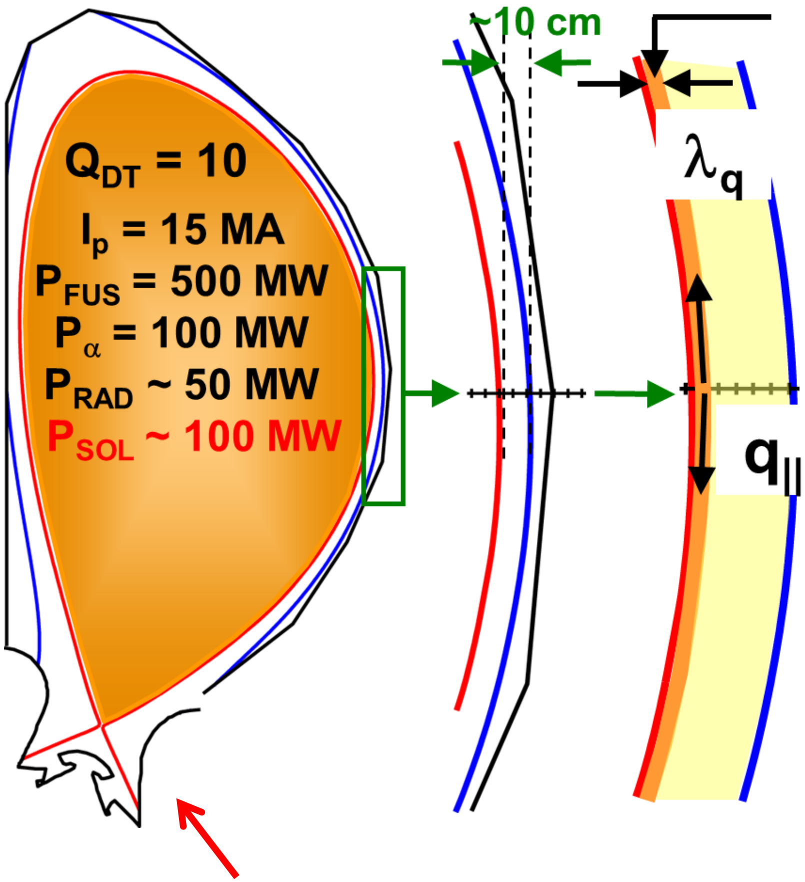


Divertor (W) $10\text{-}20\ \mathrm{MWm^{-2}}$ → Heat and He ash exhaust

W → favourable features (low erosion/T retention, high T_{melt}) but n_Z must be kept low (~ 0.001%) to prevent large radiation → challenge for ITER plasmas

Integration Fusion Performance ←→ Walls

- ITER's demonstration of fusion power requires integration:
  - ✓ "Clean" and high τ_E (H-mode) plasmas
  - ✓ Acceptable power/particle fluxes to plasma facing components



Integration

- ✓ Avoid direct contact between confined plasma and walls (divertor)

$q_{div}^{unmitigated}$ ~ 40 MWm^{-2} (q_{sun} ~ 60 MWm^{-2})

Integration Fusion Performance ←→ Walls

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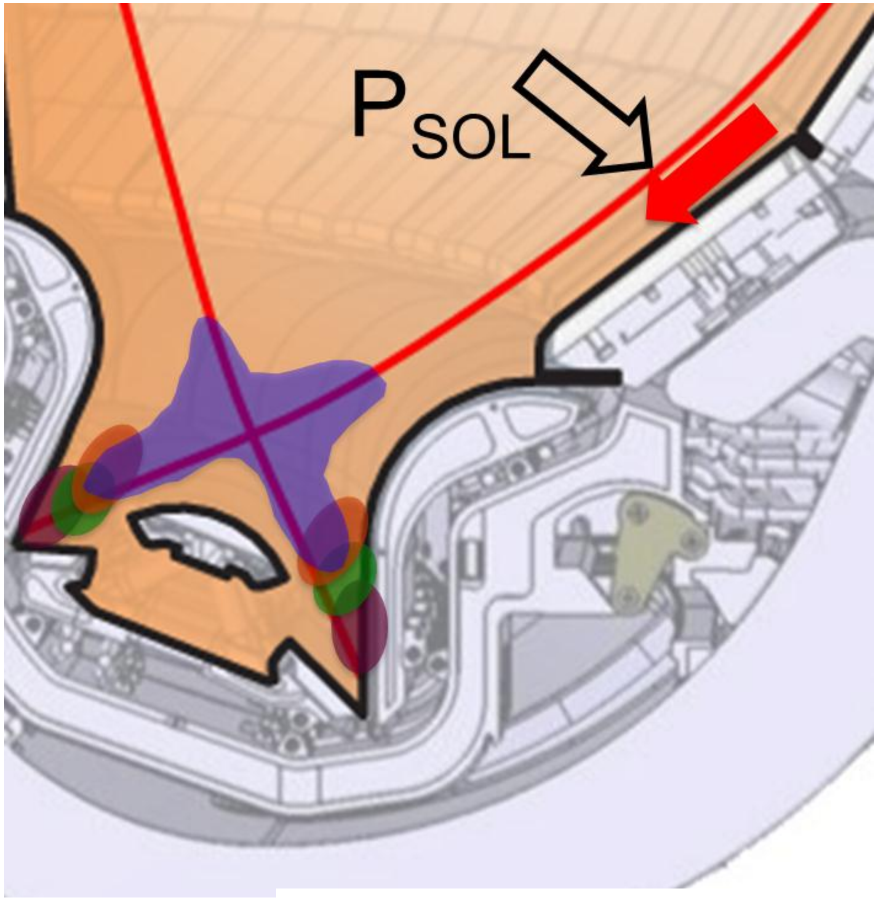


Integration

- ✓ Avoid direct contact between confined plasma and walls (divertor)
- ✓ Power dissipation by radiation in plasma periphery

Loss of integration

- ✓ Termination of fusion reactions by impurity contamination (dilution + radiation)
- ✓ Plasma facing component damage (melting)

40 $\mathrm{MWm^{-2}}$ → ~ 10 $\mathrm{MWm^{-2}}$ by radiation + ionization losses

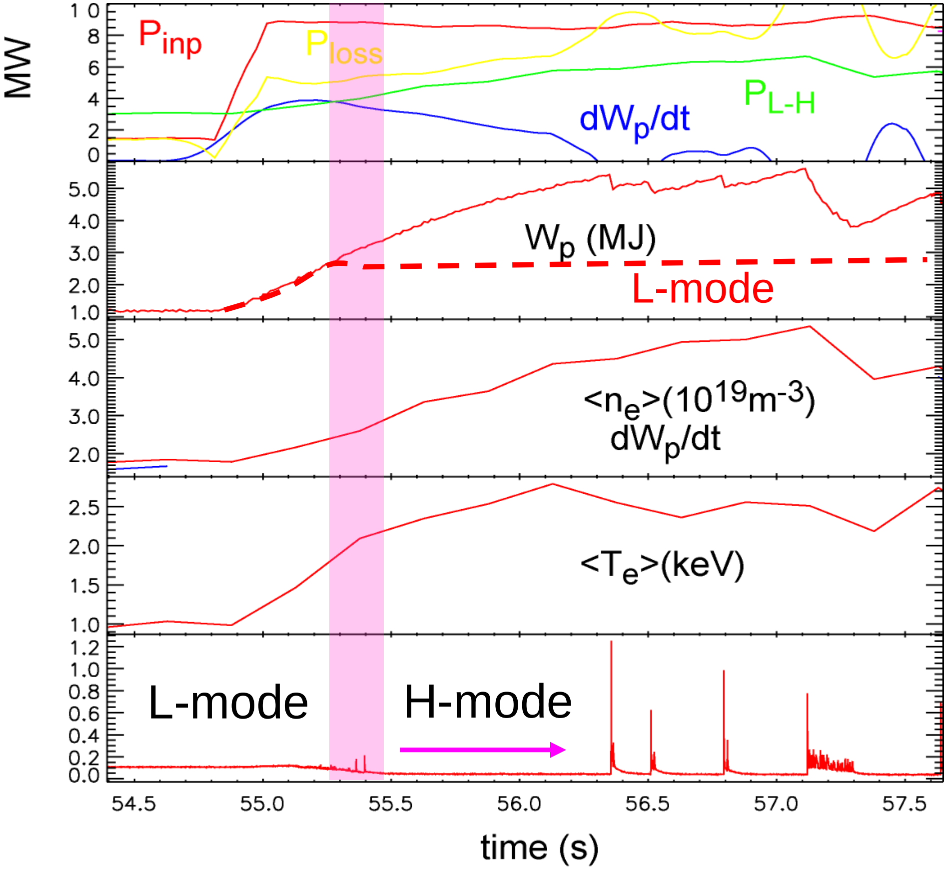
Basic H-mode and pedestal physics concepts

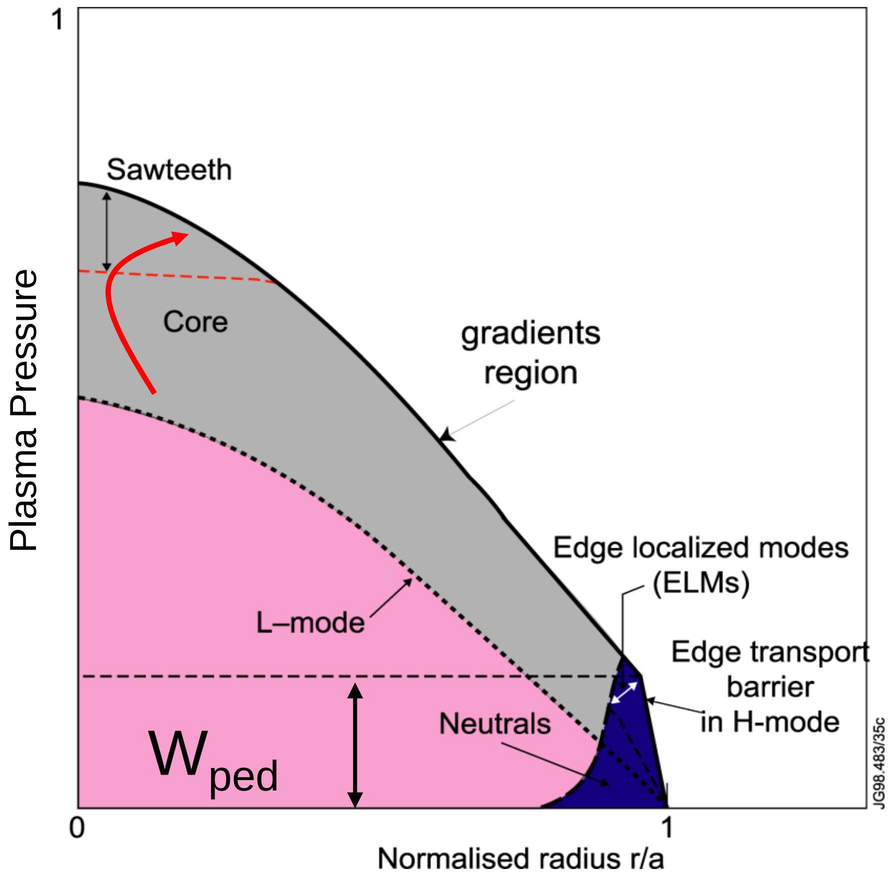
Energy Confinement : H-mode – Transport Barrier

- H-mode confinement “naturally” achieved in certain conditions (magnetic configuration when $P_{input} > P_{L\text{-}H}^{threshold}$)

H-mode ←→ Edge Transport Barrier (➔ Pedestal)

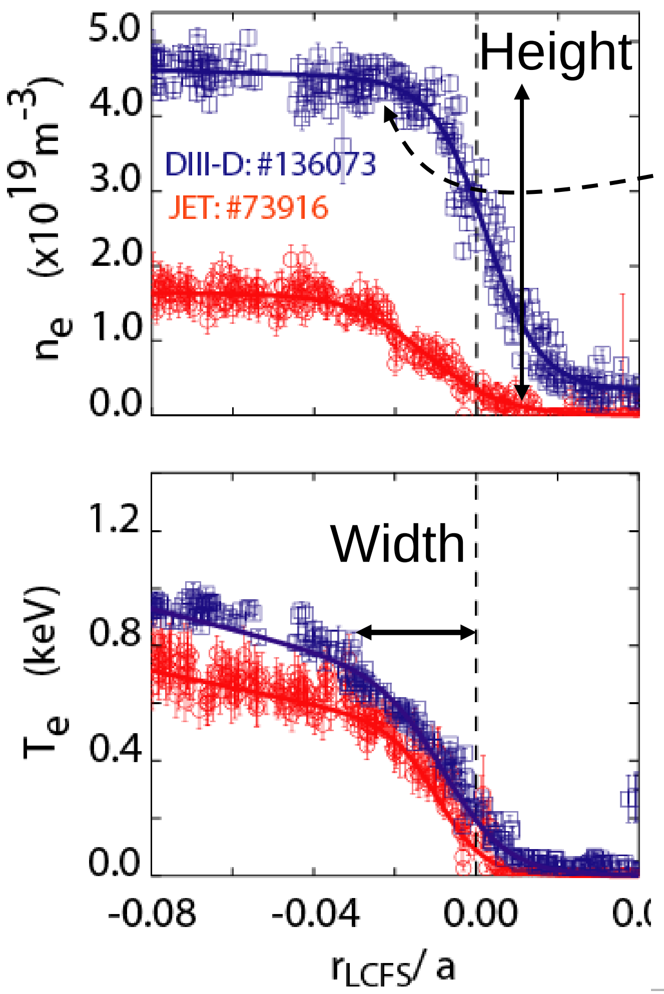
JET





What is the pedestal ?

- Pedestal → region of low energy and particle transport leading to large n and T gradients
- Core gradients ≤ 10 keV/m ←→ Pedestal gradients ≤ 100 keV/m



Pedestal top

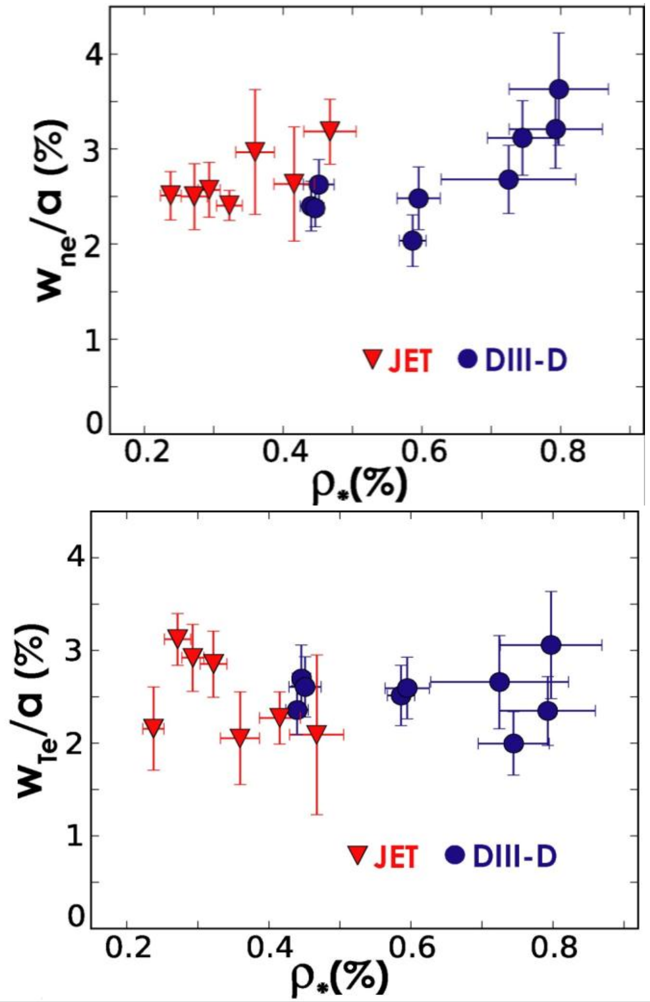
P_{ped}

The pedestal is a very small region but key for fusion energy development

JET + DIII-D

M. Beurskens

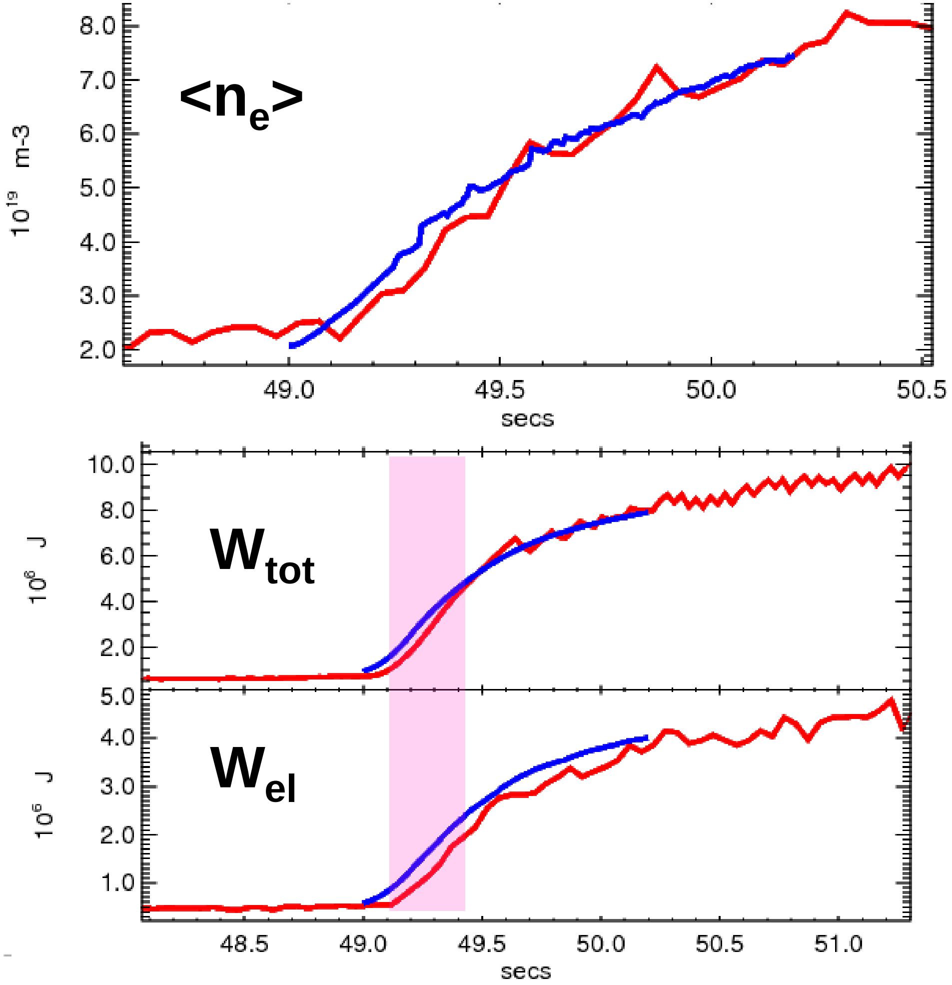
T. Osborne



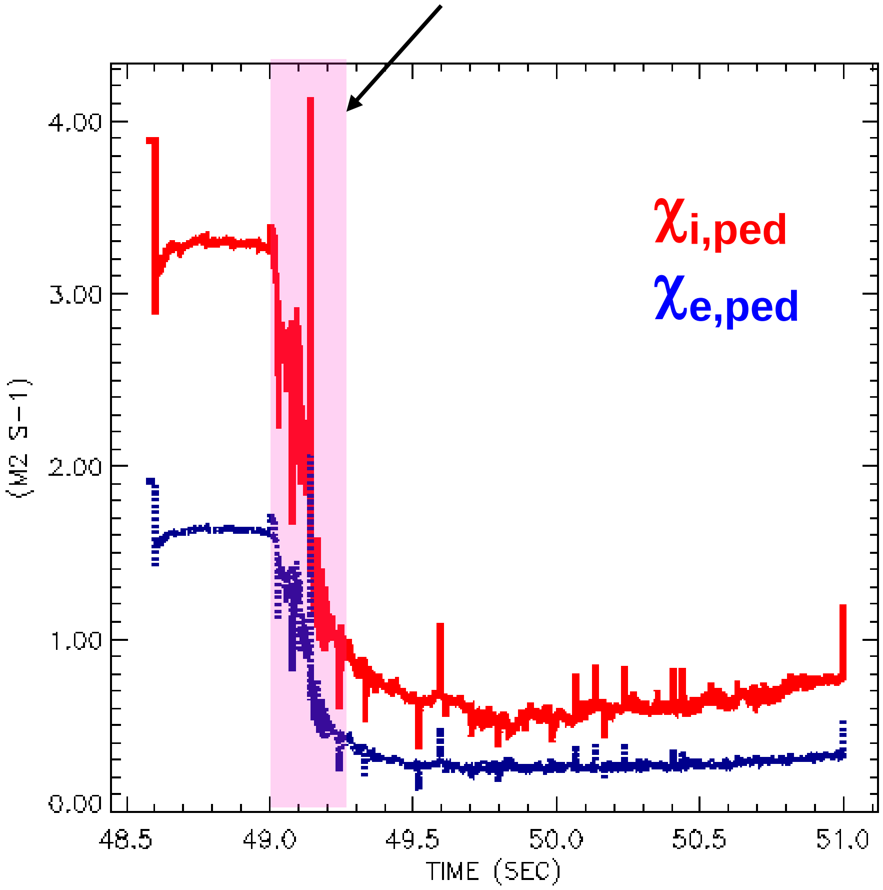
Level of plasma transport in pedestal ?

- Typically anomalous transport reduced to ion-neoclassical levels for both ions and electron ($\chi_e^{neo} <<< \chi_i^{neo}$ → residual turbulent electron transport)

JET – JINTRAC – F. Köchl



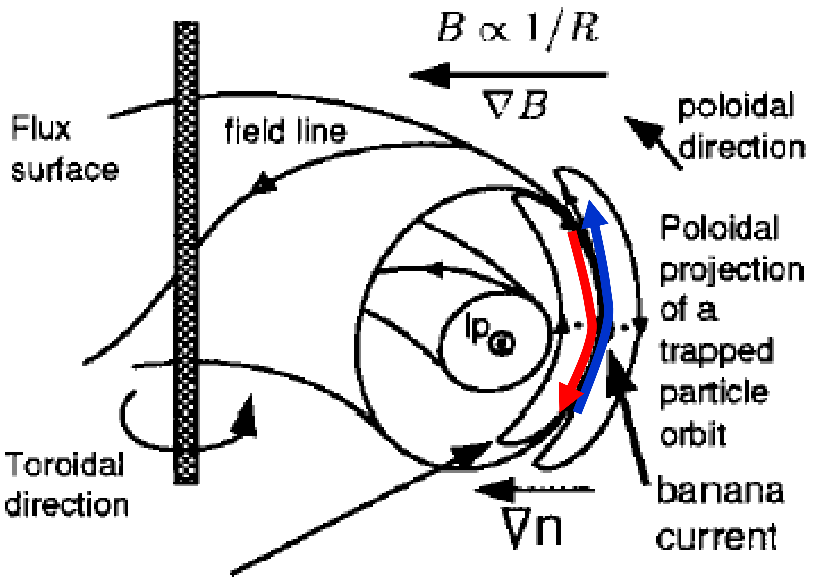
H-mode transition



Implications of neoclassical transport - $j_{bootstrap}$

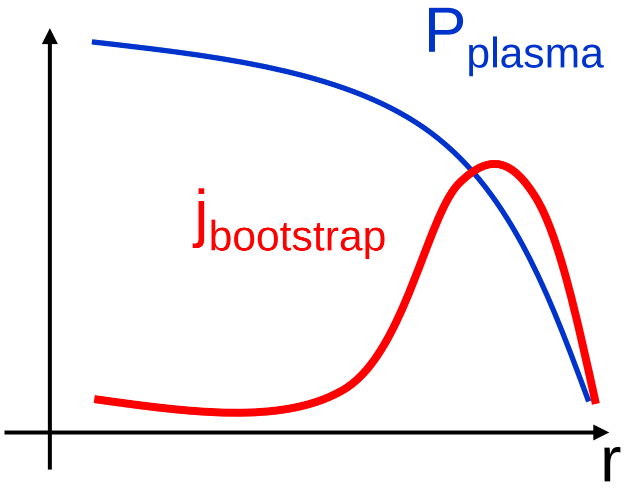
Large edge bootstrap currents due to large grad-P_{ped} → Edge MHD stability?

$$\boxed{j_t = e n_t(a) v_{\parallel}(a) - e n_t(a+w_b) v_{\parallel}(a+w_b)}$$



This orbit lies further inside more particles follow this orbit than the orbit further out.

$$\boxed{j_{bootstrap}^{max} \sim -\frac{1}{B_\theta}\frac{dp}{dr}}$$

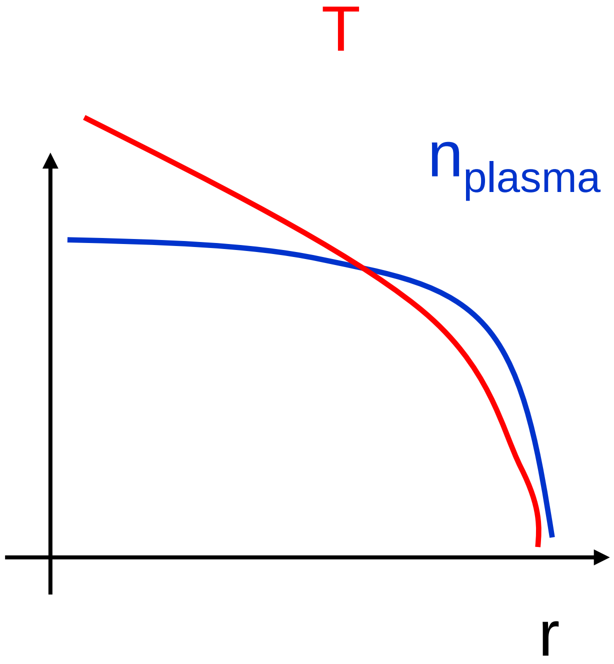


Particle collisions → $j_{bootstrap} < j_{bootstrap}^{max}$

Implications of neoclassical transport – pedestal impurity peaking

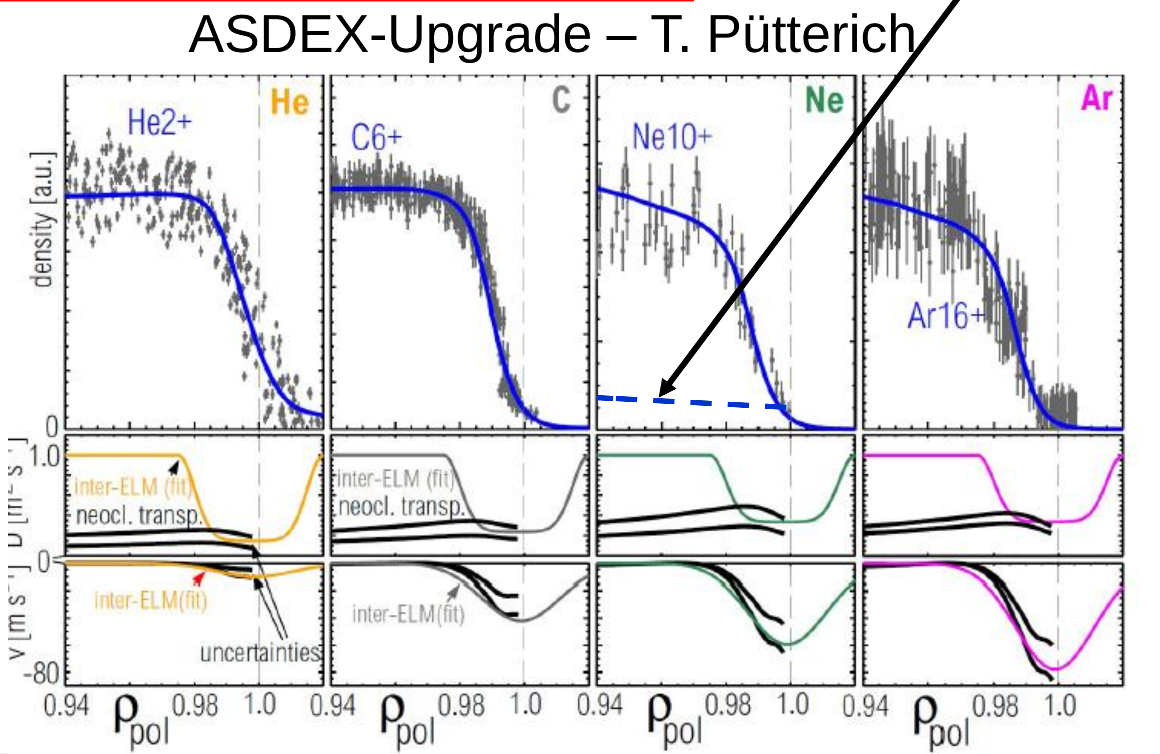
- Collisions between ions and impurities leads to appearance of impurity v_{pinch} in pedestal → can cause large increase of n_z^{core} !
  - ✓ Sign determined by L_n/L_T (small L_n/L_T → v pinch inwards)
  - ✓ Magnitude dependent on Z

$$\boxed{\frac{\nabla n_z}{n_z} \sim Z\left(1 \quad - \quad H\,\frac{\nabla T_{DT}/T_{DT}}{\nabla n_{DT}/n_{DT}}\right)\frac{\nabla n_{DT}}{n_{DT}}}$$



ASDEX-Upgrade – T. Pütterich

$V_{pinch} = 0$



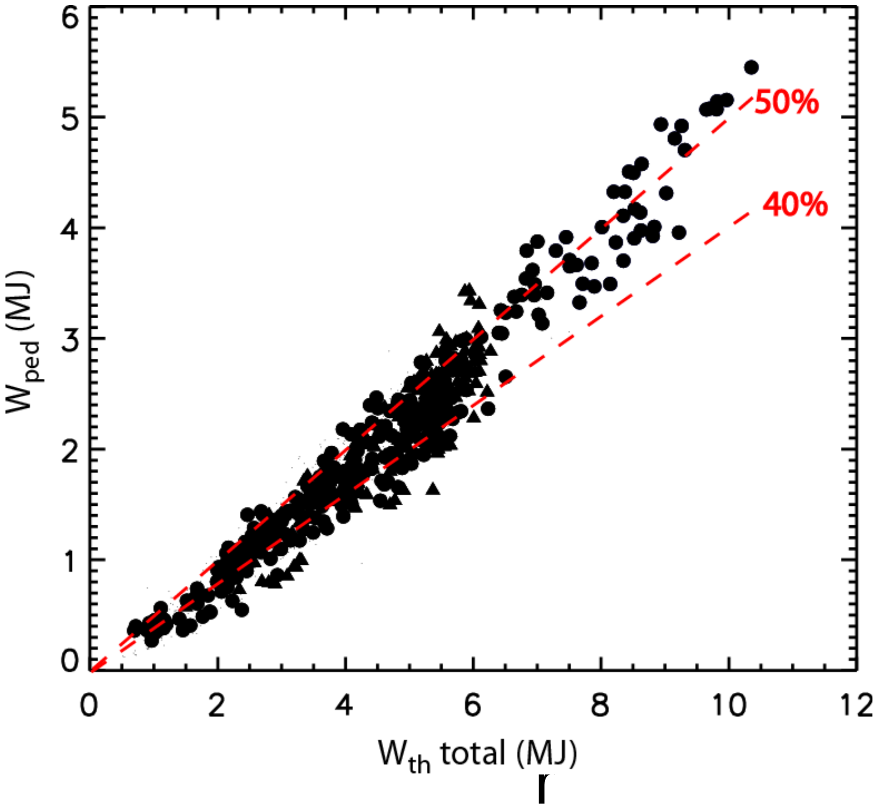
Why is the pedestal so important for fusion and ITER?

- In H-mode plasmas W_{tot} ($P_{fusion} \sim W_{tot}^2$) directly correlated with

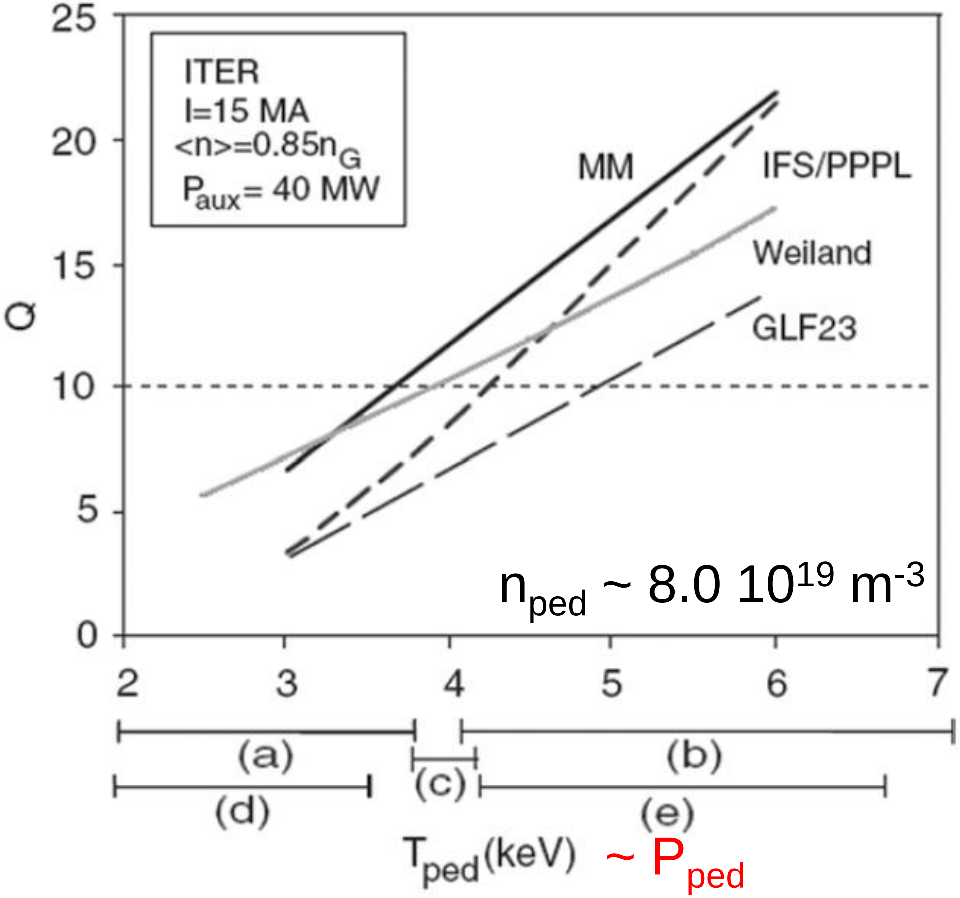
$$W_{ped} = 3\ P_{ped}\ V_{plasma}$$

- Maximum achievable Q in ITER determined by P_{ped}

JET - Beurskens



ITER - PIPB



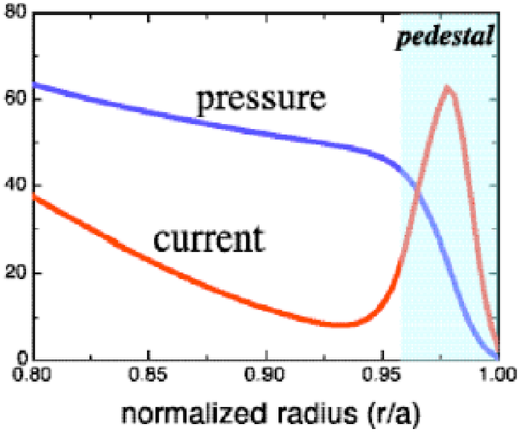
$n_{ped} \sim 8.0\ 10^{19}\ m^{-3}$

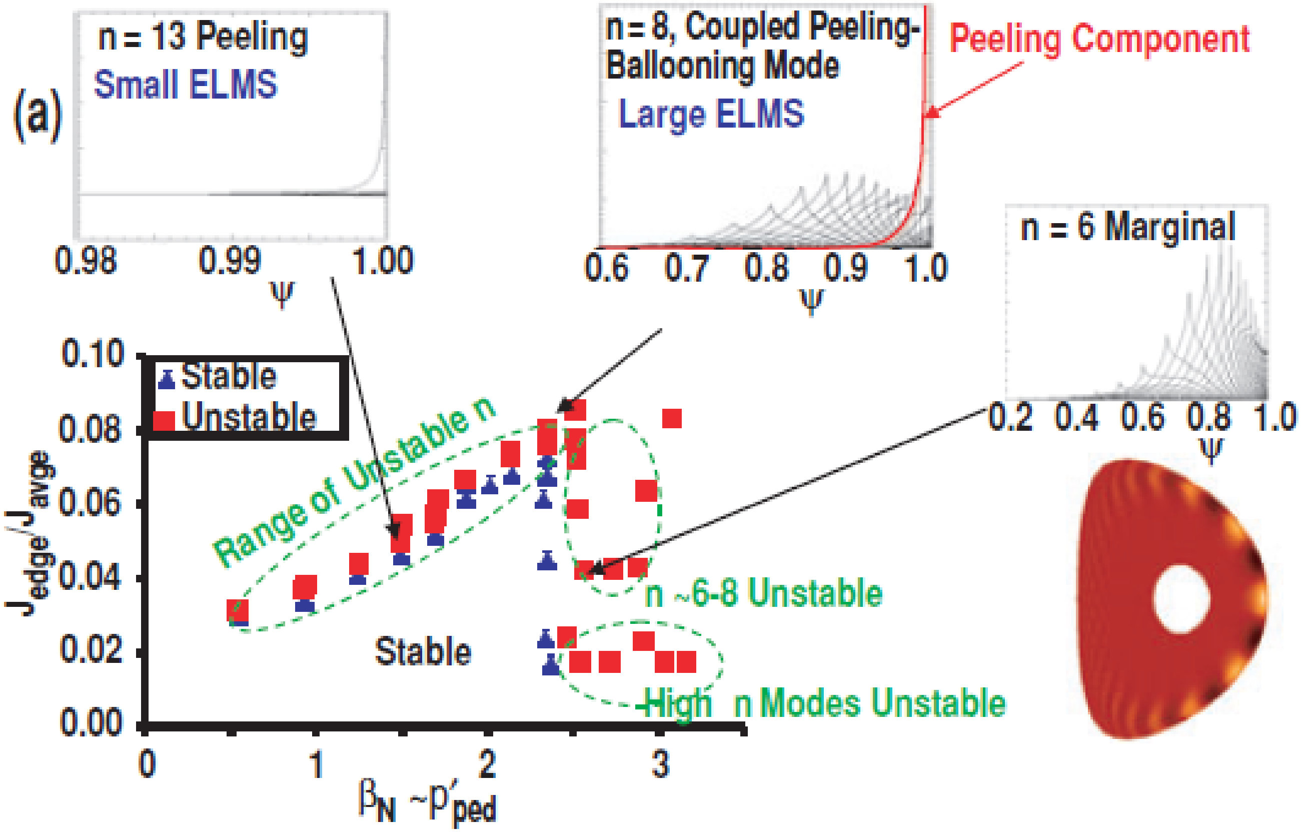
$\sim P_{ped}$

What limits the pedestal pressure magnitude ?

- Edge MHD stability limits pedestal pressure gradients & j_{edge} (~grad-P_{ped})

ELITE – P. Snyder



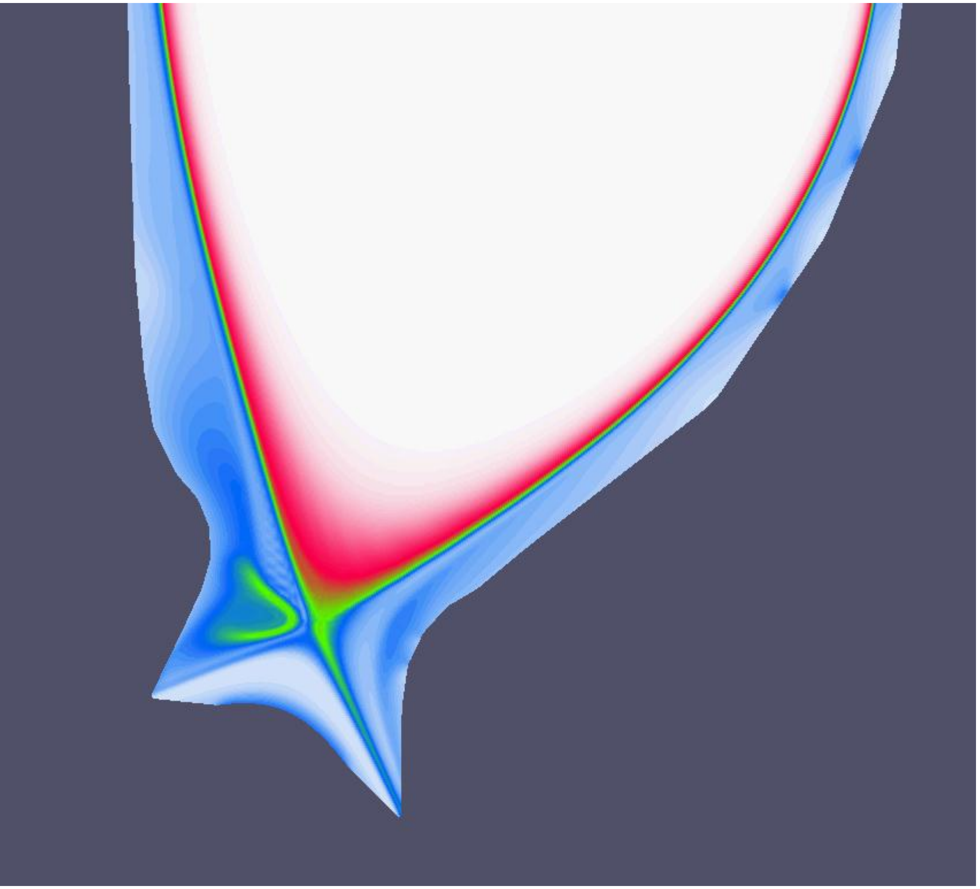


- Increasing Δ_{ped} → increases P_{ped} at same grad-P_{ped}

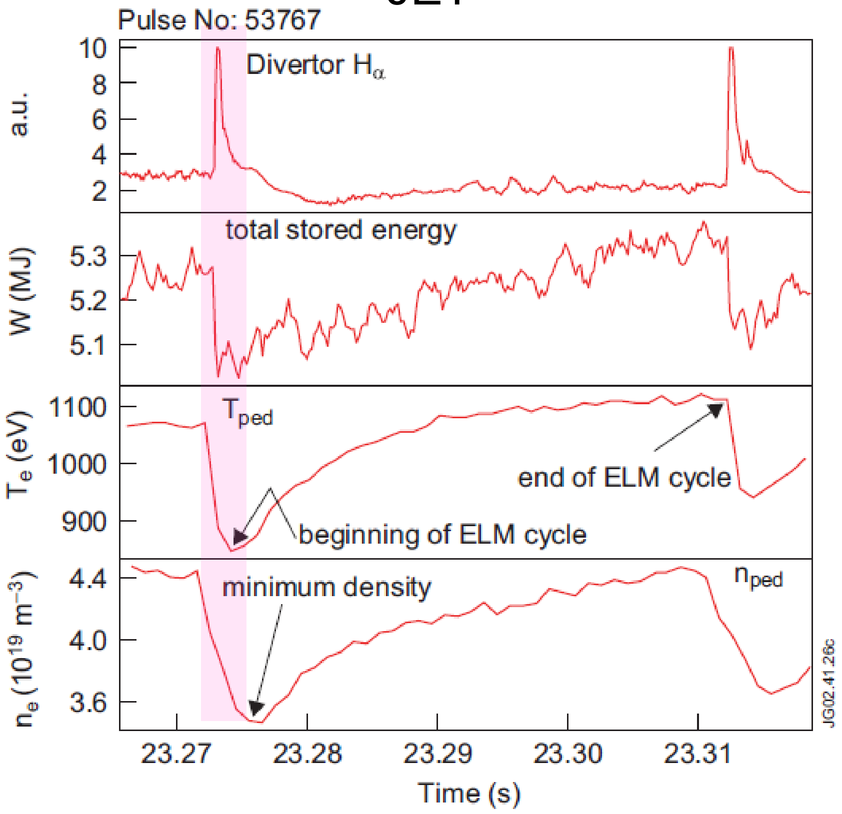
What happens when the edge MHD limit is reached ?

- MHD modes grow and lead to expulsion of plasma (ELMs = Edge Localized Modes) → edge pressure relaxes (100 μs) in and cycle repeats

ITER – JOREK – G. Huijsmans

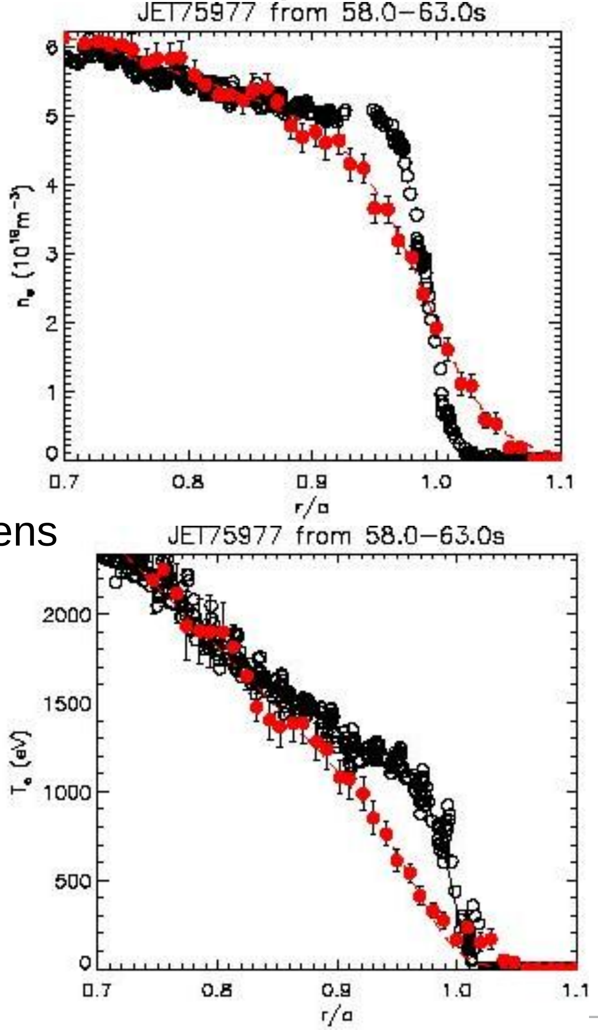


JET



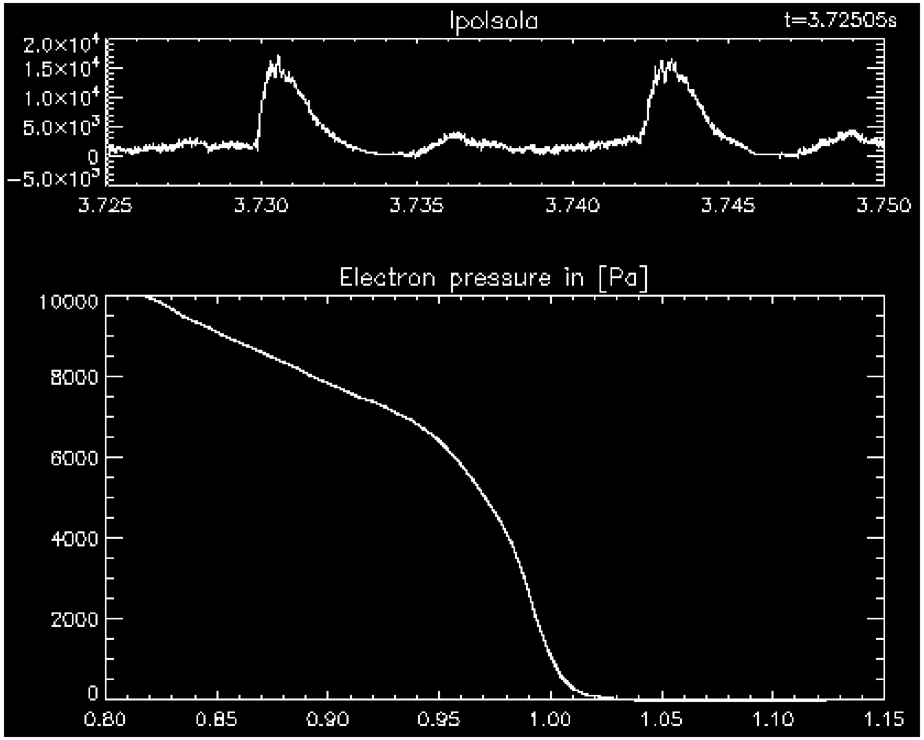
Effects of ELM on the confined plasma

- Expulsion of plasma by ELMs limited to edge and relatively small ($\Delta W_{ELM} \leq 10\% \, W_{tot}$) → $P_{ELM} = f_{ELM} \, \Delta W_{ELM}$ ~ 30% of P_{SOL}
- Strong effect on impurities due to peaking in pedestal



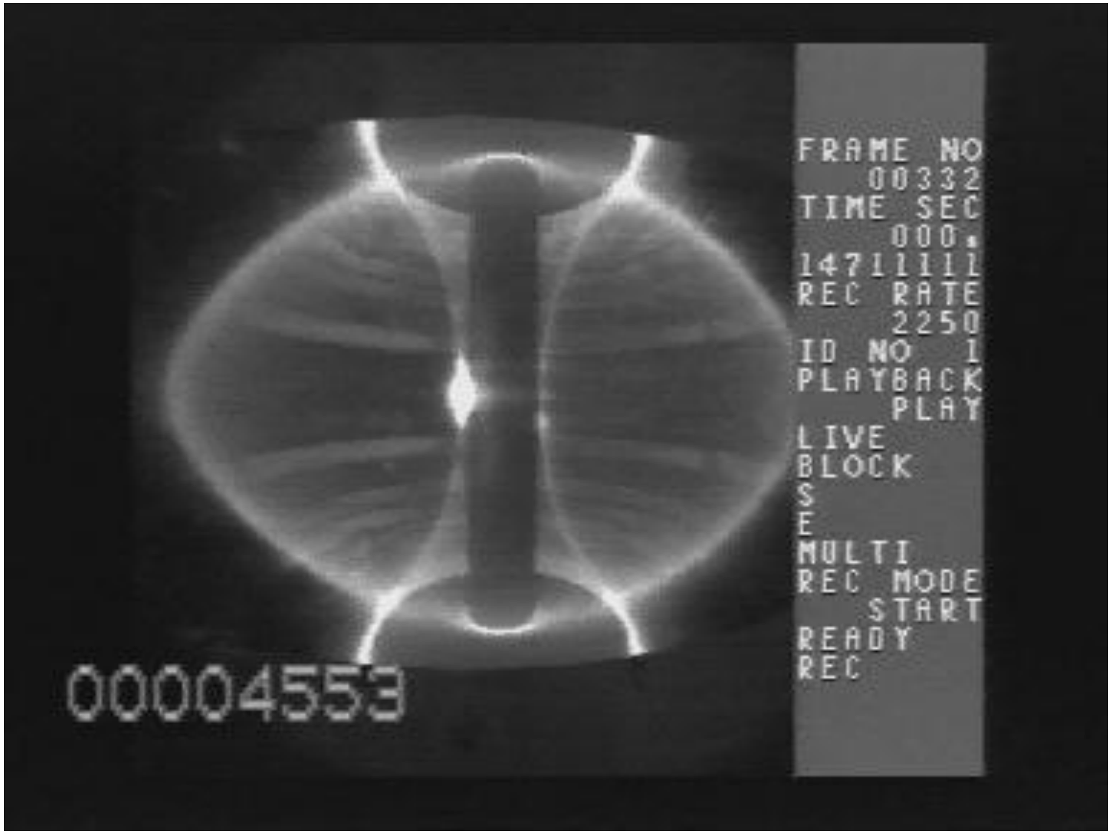
JET
M. Beurskens

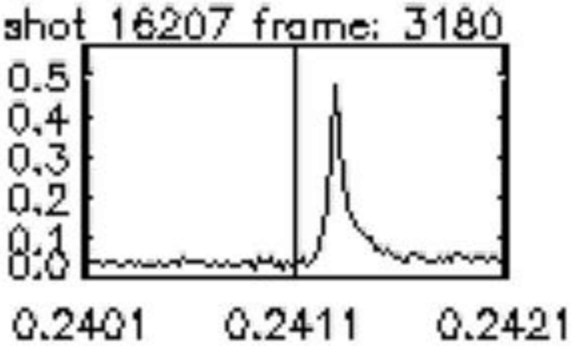
ASDEX-Upgrade-E. Wolfrum

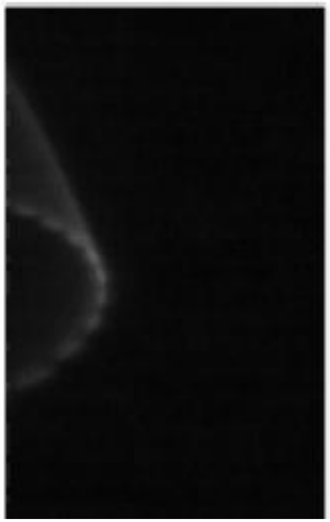


Effects of ELM on the edge plasma and PFCS

- ΔW_{ELM} is only a small fraction of W_{tot} but it is lost very fast
  - ✓ Large edge power and particle fluxes
  - ✓ Localized deposition of energy and particles on PFCs (heating and erosion-impurity production)







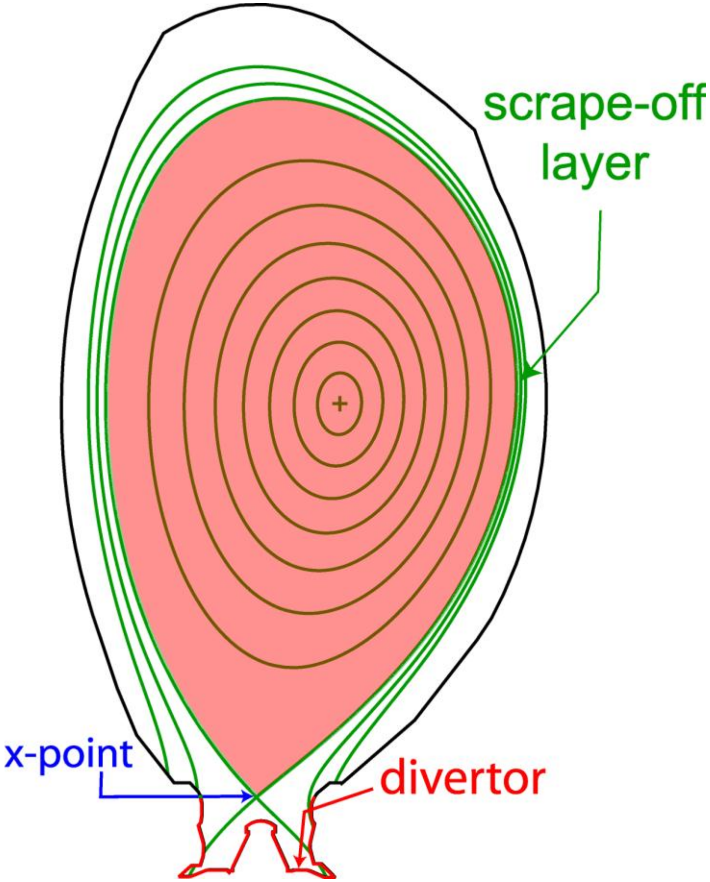
Key Pedestal & Transport Physics Issues in ITER

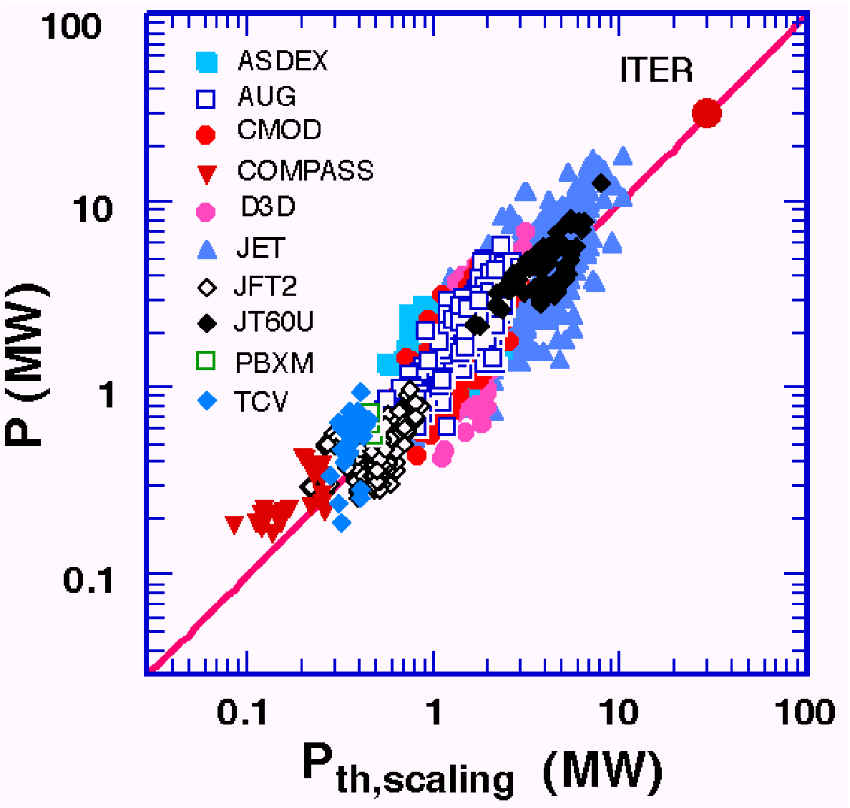
Access to H-mode

How can we access H-mode confinement ?

$$P_{input} > P_{L\text{-}H}\,(n_e, R, a, B_t)$$

$$P_{Thresh}\,(MW) = 2/A \times 0.0488\, e^{\pm 0.057}\, n_{e20}^{\;0.717\pm 0.035}\, B_T^{\;0.803\pm 0.032}\, S^{0.941\pm 0.019}$$





Power requirements for H-mode access in ITER

- Expected power required to access H-mode in ITER is comparable to (or higher) than the installed auxiliary power for Q = 10 operation (P_{aux} = 73 MW)
- ITER operation in non-DT plasmas cannot cover full operational range
- For high $I_p/B_t/<n_e>$ (required for high Q operation) P_α contribution is key ($P_\alpha = 2\ P_{aux}$) complex feedback loop

$$\begin{tikzcd}\text{H-mode confinement} \arrow[r] & W_{tot} \arrow[r] & P_\alpha \arrow[ll, bend left]\end{tikzcd}$$

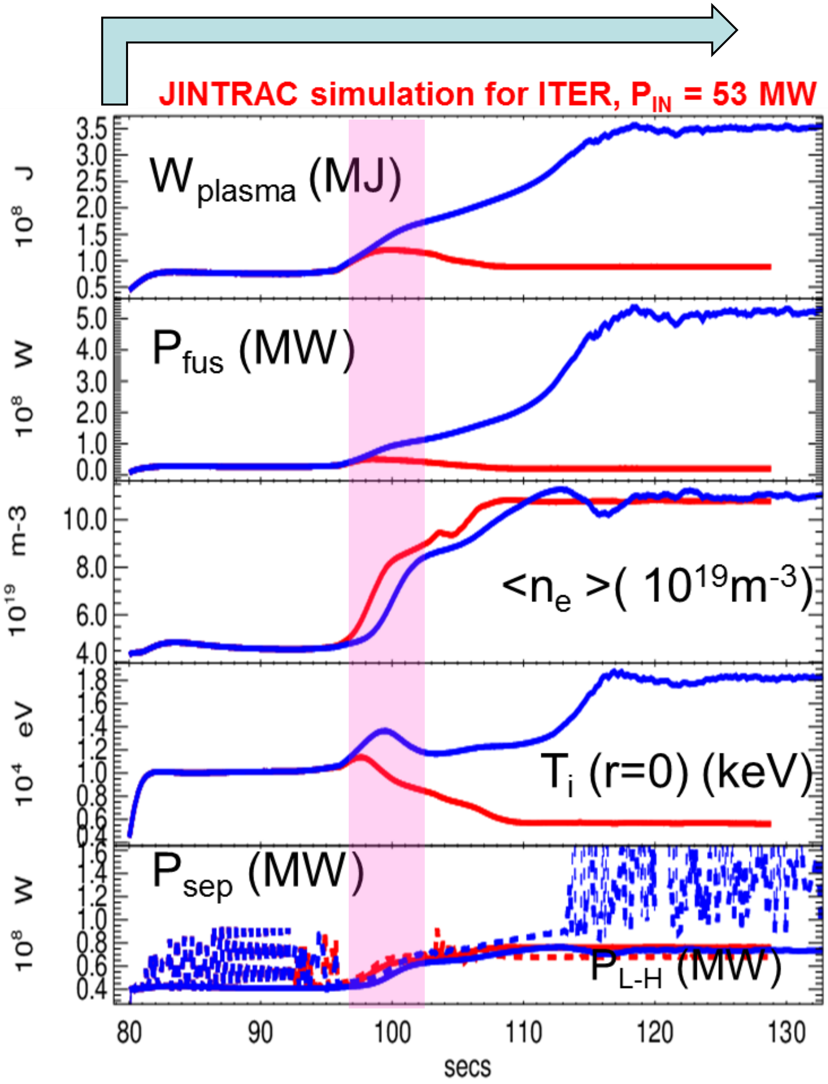
n_e (10^{20} m^{-3})	B_T (T)	S (m^2)	P_{th} - H_2 (MW)	P_{th} - He (MW)	P_{th} - D_2 (MW)	P_{th} - DT (MW)
0.5	2.65	683	61	31 - 46	31	24
0.5	5.3	683	106	53 - 80	53	43
1.0	5.3	683	175	88 - 132	88	70

Q=10

Access to Q = 10 H-mode in ITER - I

- ☐ Q = 10 H-mode access not straightforward → density evolution is key to optimum Pa and path from L-mode to Q = 10 H-mode

P_{aux} = 53 MW

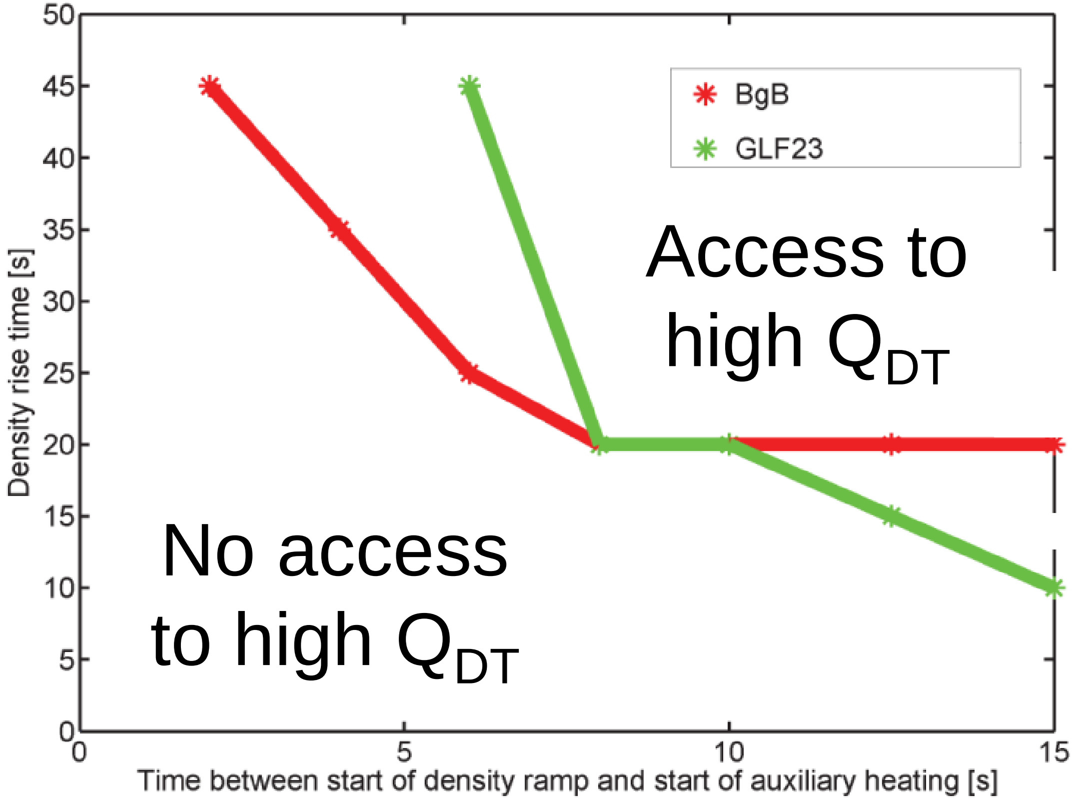


Köchel

- ✓ P_{L-H} ~ n_e → increasing ne requires more power to maintain H-mode
- ✓ For fusion to occur (significant Pa) → T_i > 10 keV a too high ne leads to low T_i for same W_{tot}

Access to Q = 10 H-mode in ITER - II

- ☐ Optimum access to Q = 10 :
  - ➢ Increase of P_{aux} while applying only gas fuelling for 5-15s to maintain n_{sep}
  - ➢ Followed by increase of n_{ped} using pellets in 10-30 s + gas fuelling

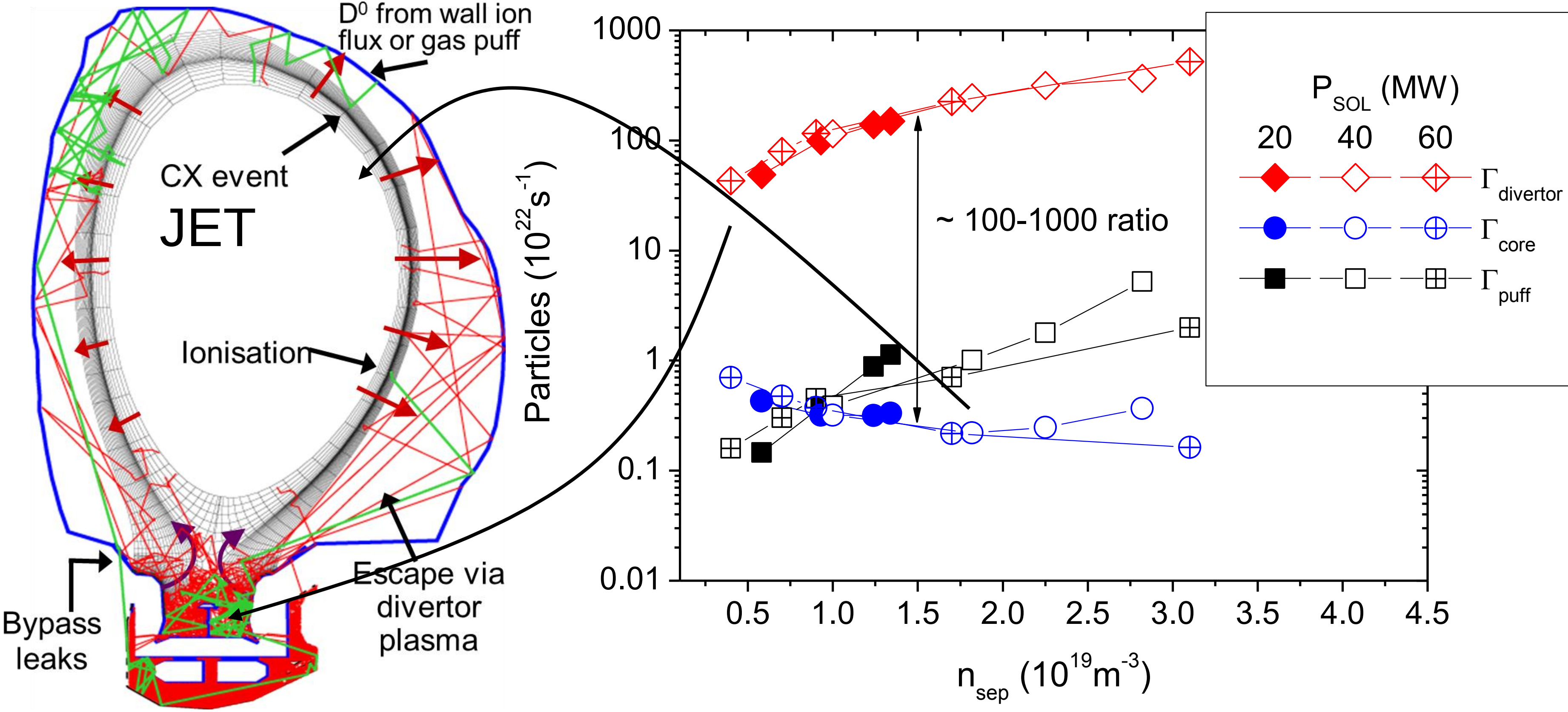


Key issues → H-mode density behaviour in ITER and reduction of D, χ_{ped} as $P_{edge} > P_{SOL}$

Fuelling of H-mode plasmas in ITER

- Fuelling of plasma by DT neutrals required to increase plasma density and to replenish burn DT fuel : gas puffing + DT frozen pellets
- Large ionization probability makes gas fuelling in ITER ineffective (typically 10 to 10^4 times more ineffective than in present experiments) but opens possibility for independent control of separatrix and pedestal density

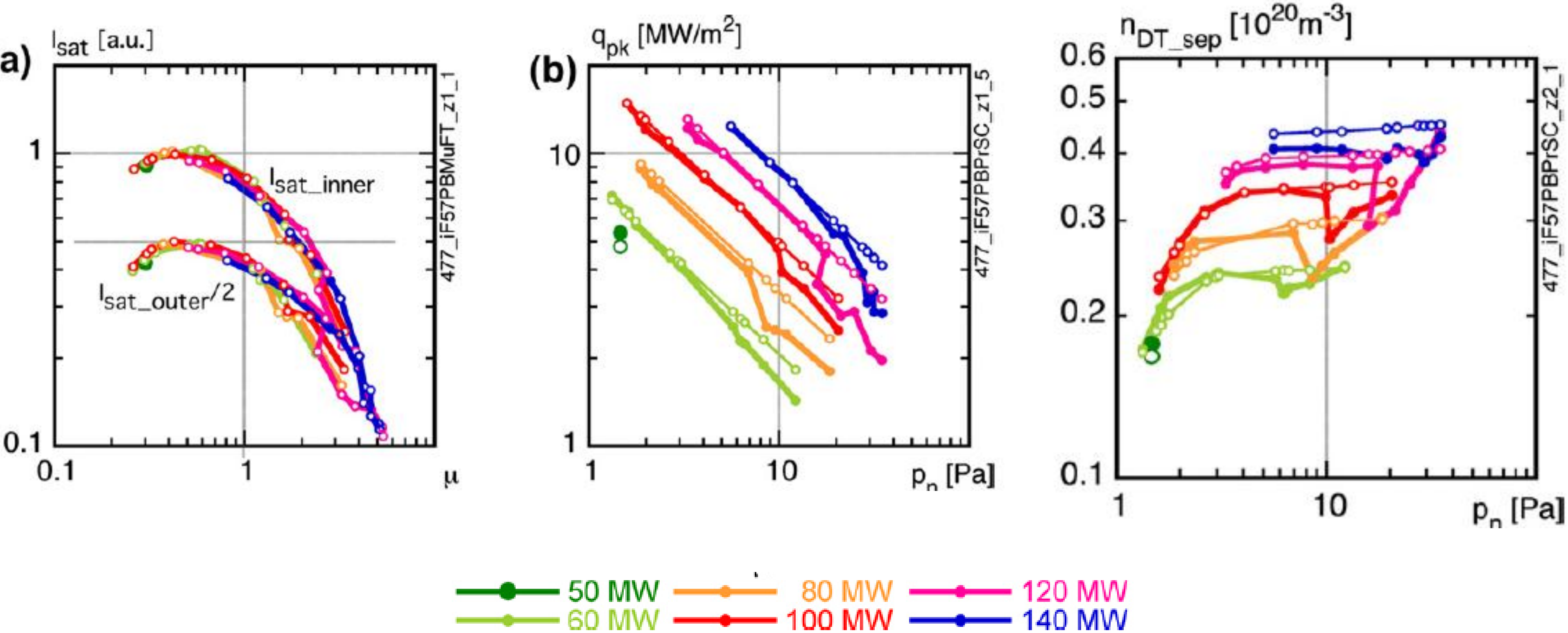
ITER- SOLPS – A. Kukushkin



Pedestal density behaviour in ITER - I

- Separatrix density requirement limit set by divertor power load control (incl. extrinsic impurity seeding to increase $P_{rad}^{divertor}$)
- Maximum separatrix density determined by plasma detachment

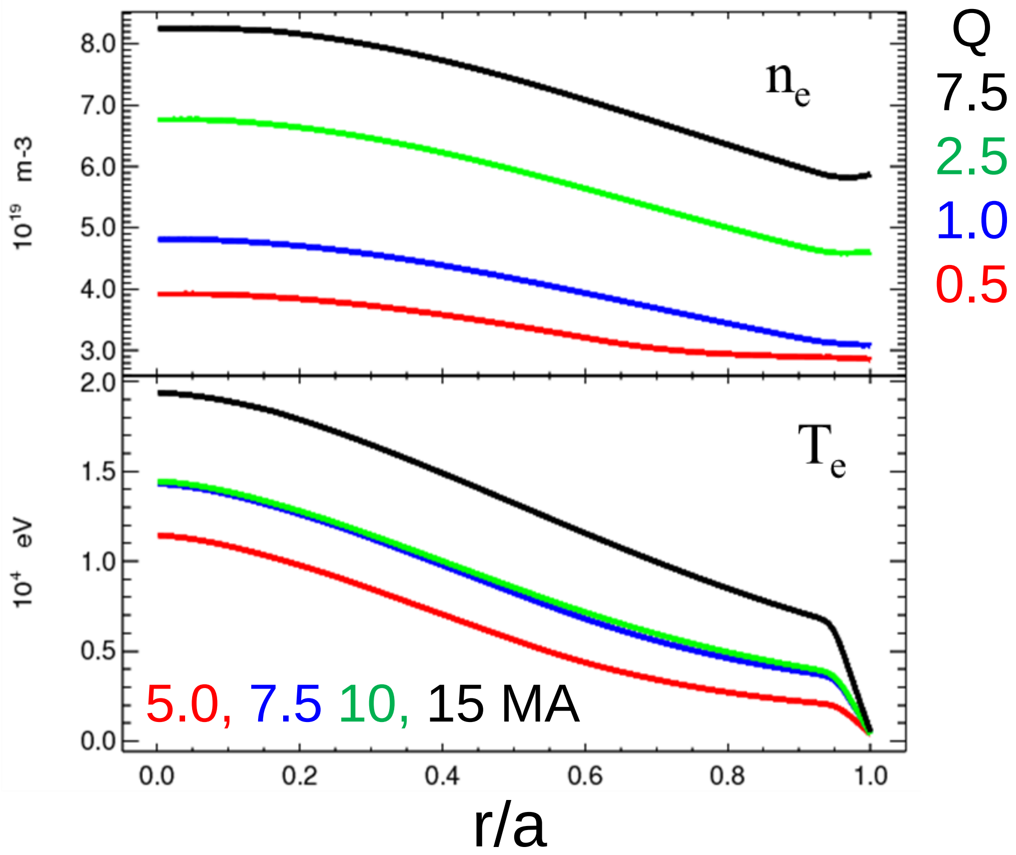
ITER SOLPS – H. Pacher and A. Kukushkin

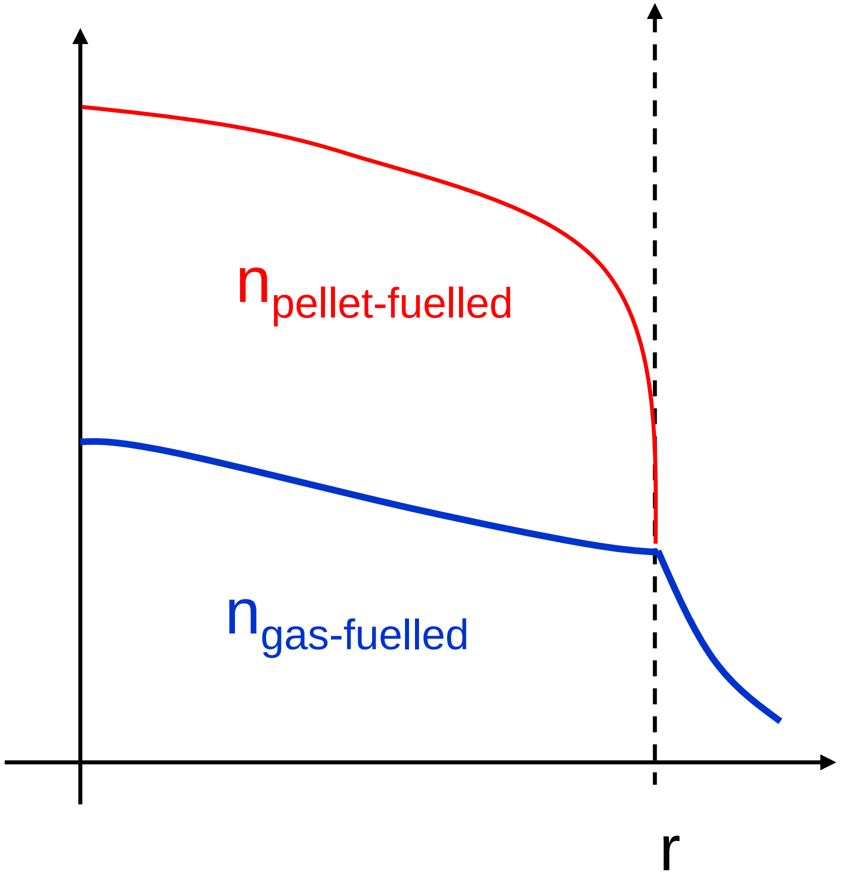


Pedestal density behaviour in ITER - II

- Low S_o with gas puffing → $n_{ped} \sim n_{sep}$ despite reduction of transport in ETB → high T_{ped} → high Q with gas fuelling only – key for Q = 10 H-mode access
- Possibility to adjust n_{ped} vs. n_{sep} by pellet fuelling (diffusive ETB transport)

ITER P_{ECRH} = 20 MW + P_{NBI} = 33 MW
JINTRAC – M. Romanelli





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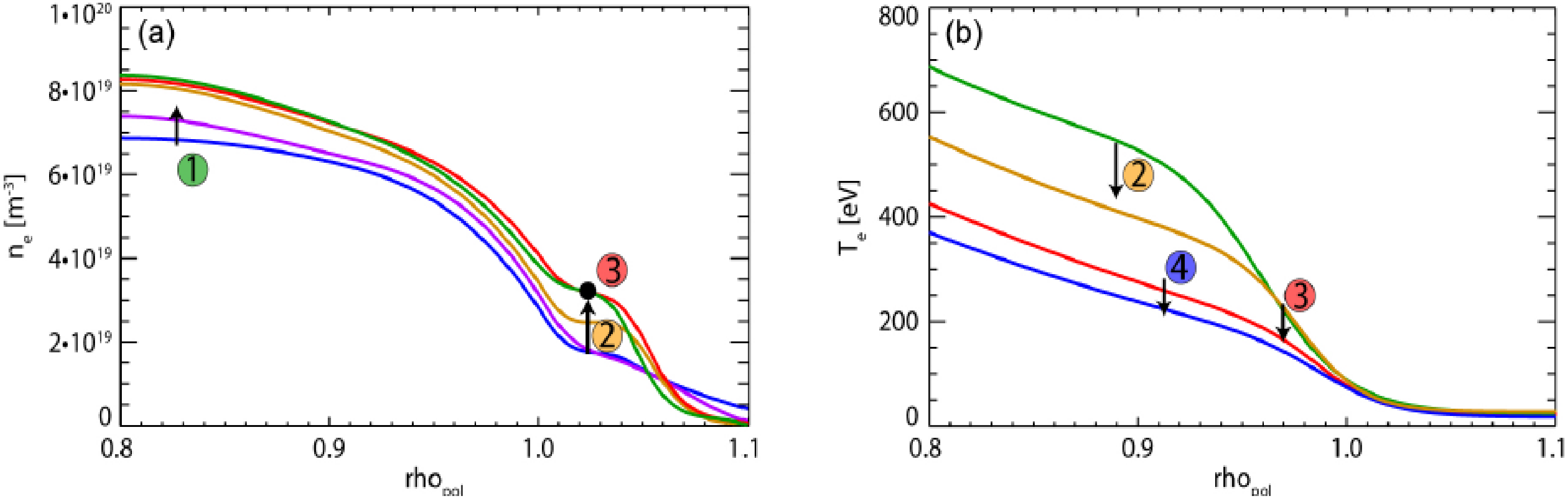
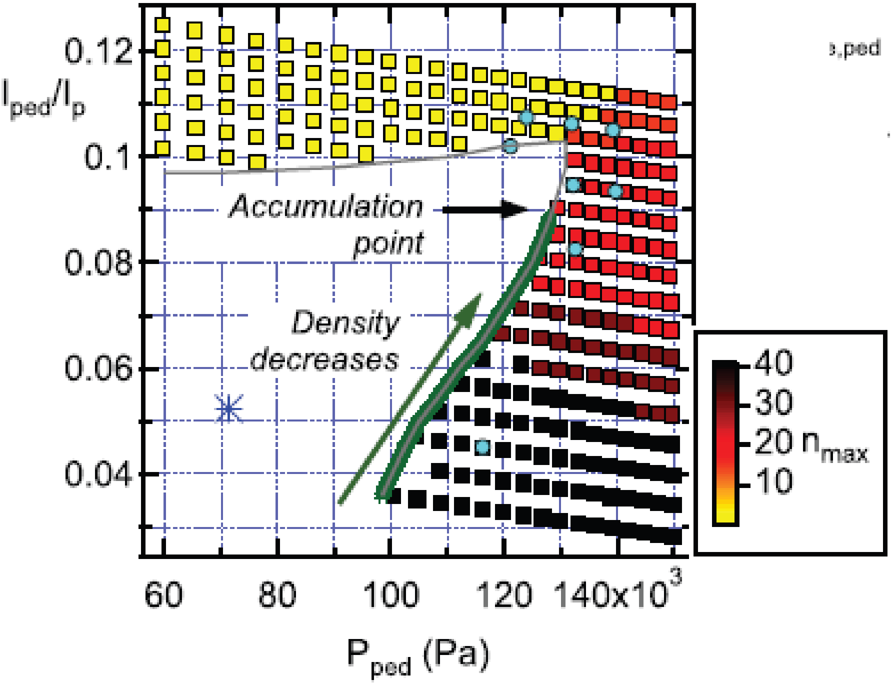
ASDEX-Upgrade – M. Bernet



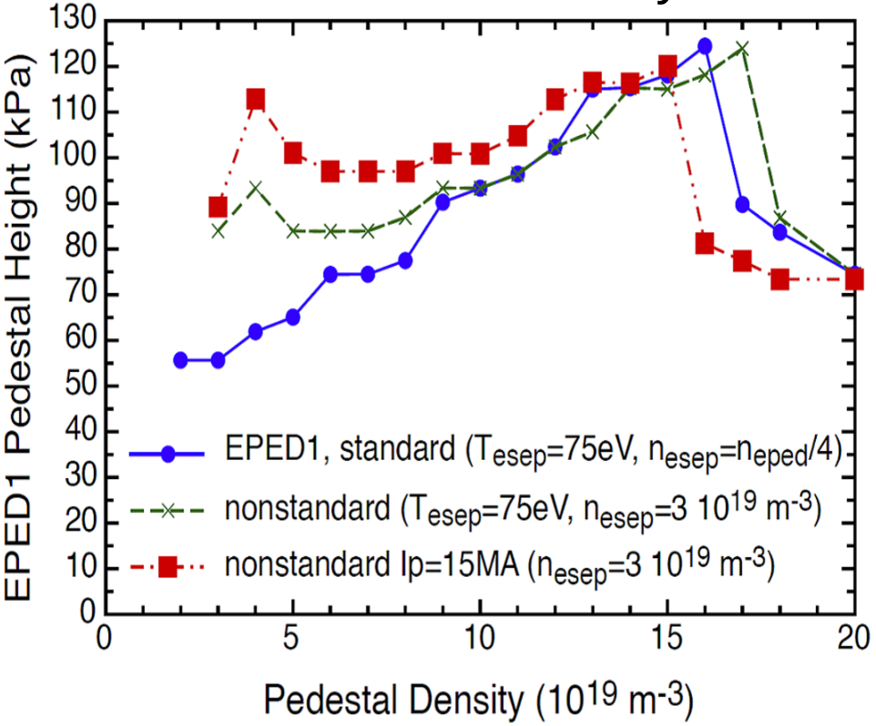
Edge MHD stability of ITER

- Edge MHD stability predicted to be regulated by same principles of todays experiments
- W_{ped} ~ 30-40% W_{tot}
- Due to high T_{ped} (low ν^*_{ped}) → $j_{bootstrap}$ ~ $j_{bootstrap}^{max}$
- Nature of MHD limit could be different dependt on limiting instability

ITER - MISKHA – Ph. Maget



ITER – ELITE – P. Snyder



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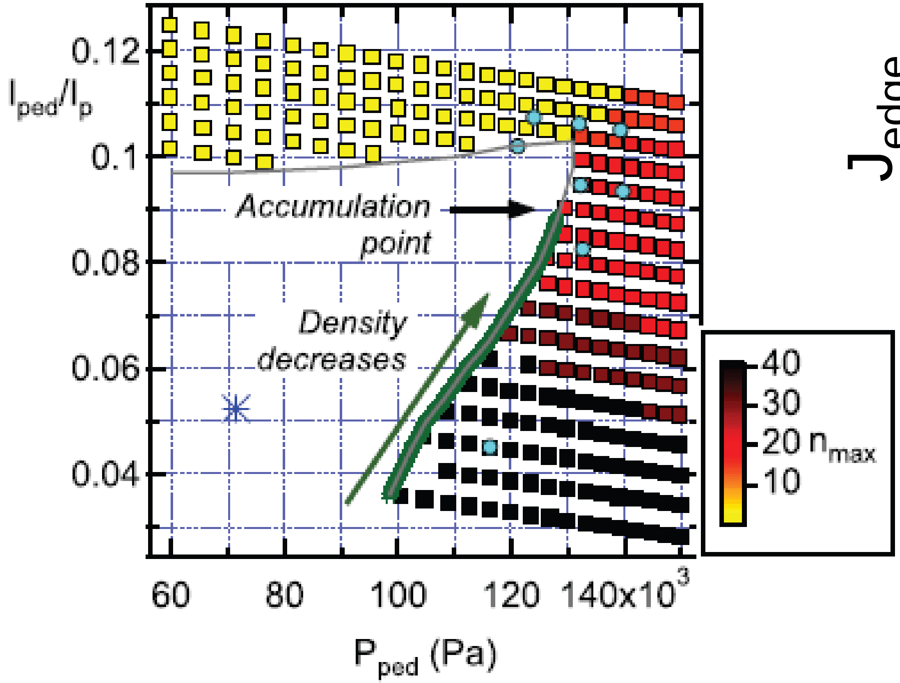

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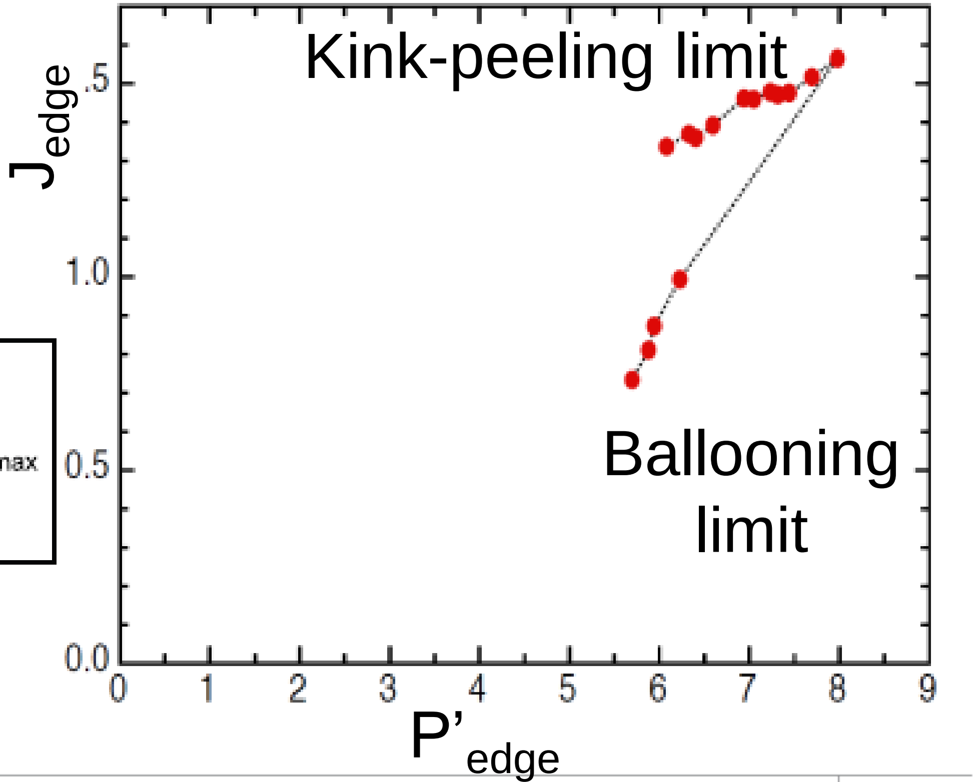
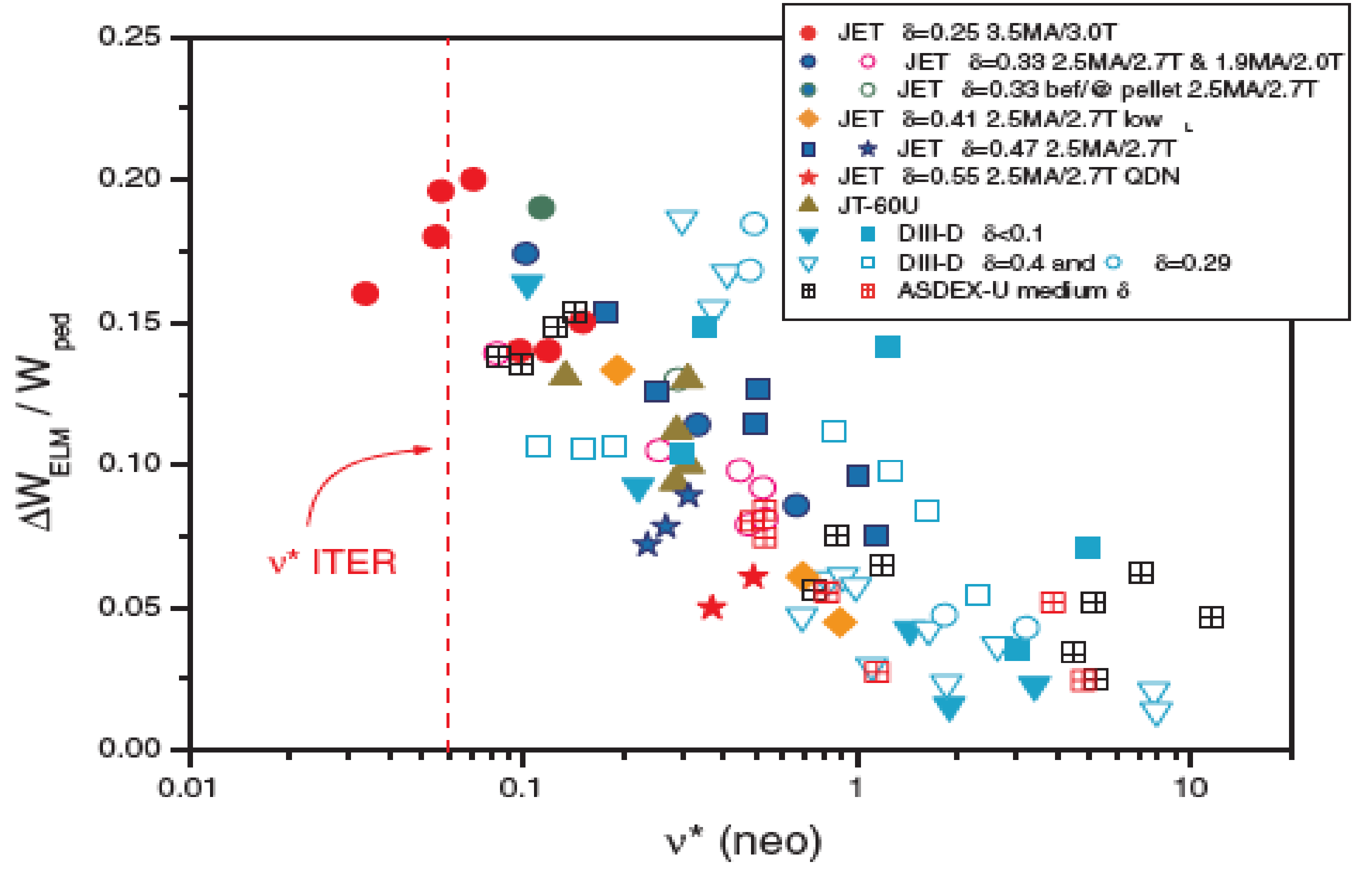


ELMs in ITER

- In normalized sense ELMs are not expected to be very different to those in present experiments
- The problem is that ΔW_{ELM} is LARGE (> 20 MJ) and it is lost very fast (~ 100's μs) → ~ multi GW power fluxes during ELMs (~ multi-MJ/m^2 on PFCs)



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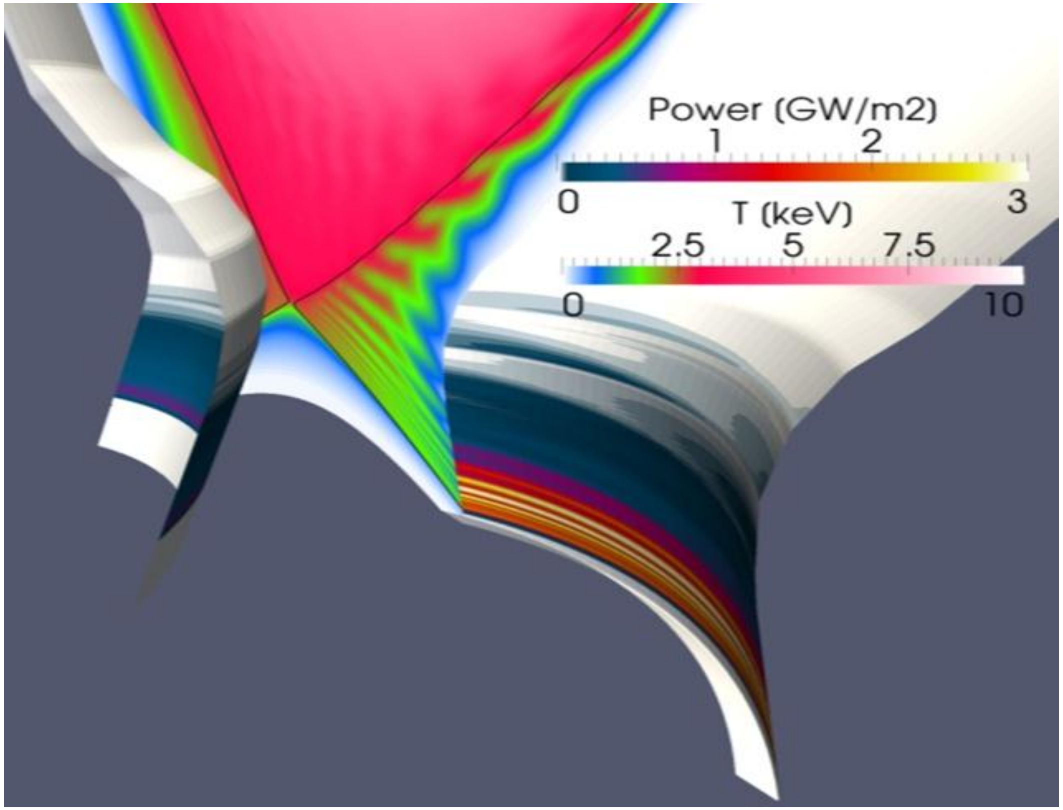
ITER – 4 MJ ELM – G. Huijsmans

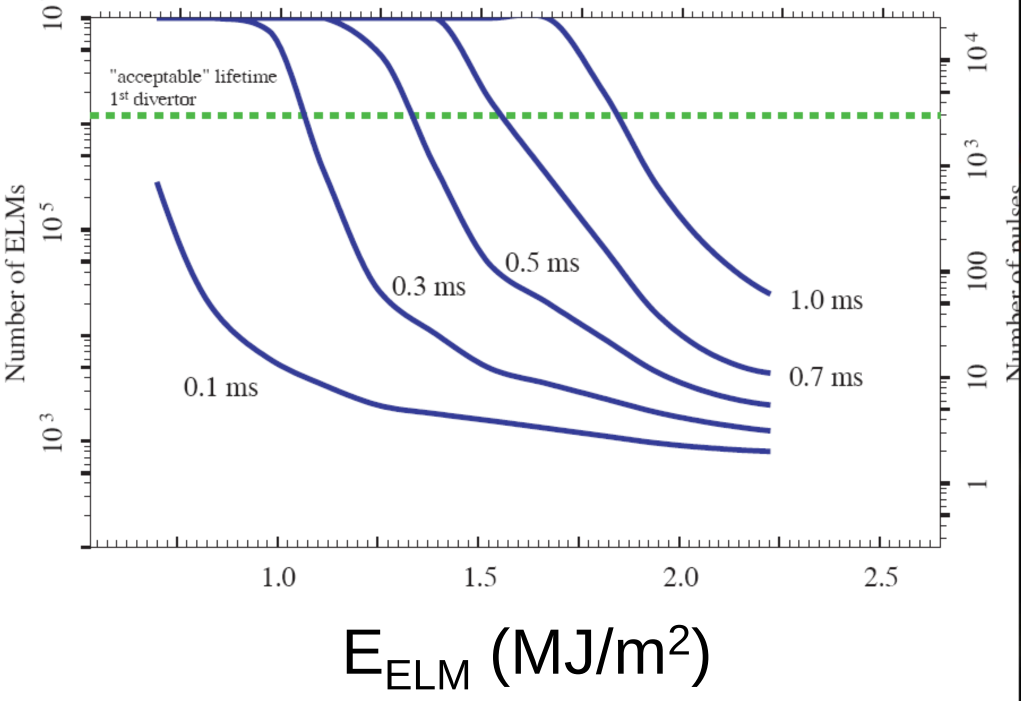


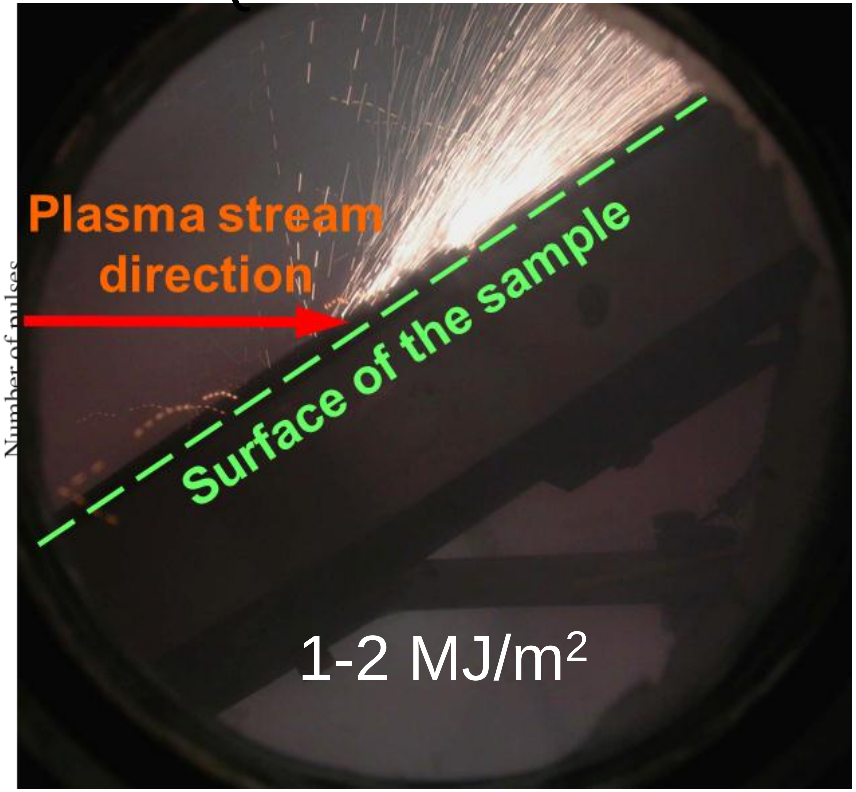
Effects of ELM power loads on ITER PFCs

- If uncontrolled ELMs are allowed to occur in ITER consequences for PFCs are serious
  - ✓ Lifetime reduced to very low number of discharges
  - ✓ Significant melting leading possibly leading to disruptions and difficultly to operate on molten surfaces

QSPA-Zhitluhkin

Raclette - Federici





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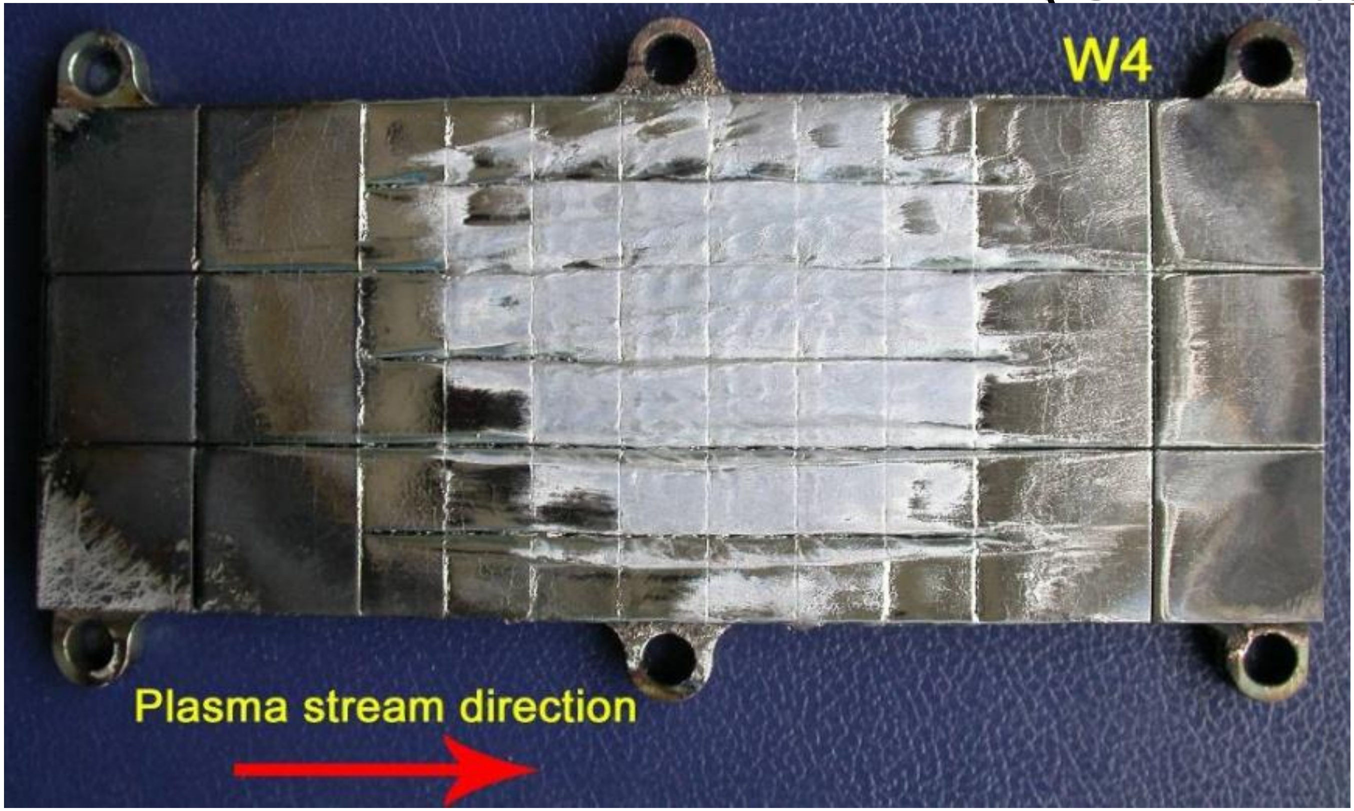


Control of ELM loads is mandatory for I_p> 9 MA operation in ITER

Approaches to ELM control in ITER

- Two basic approaches

ELM pacing

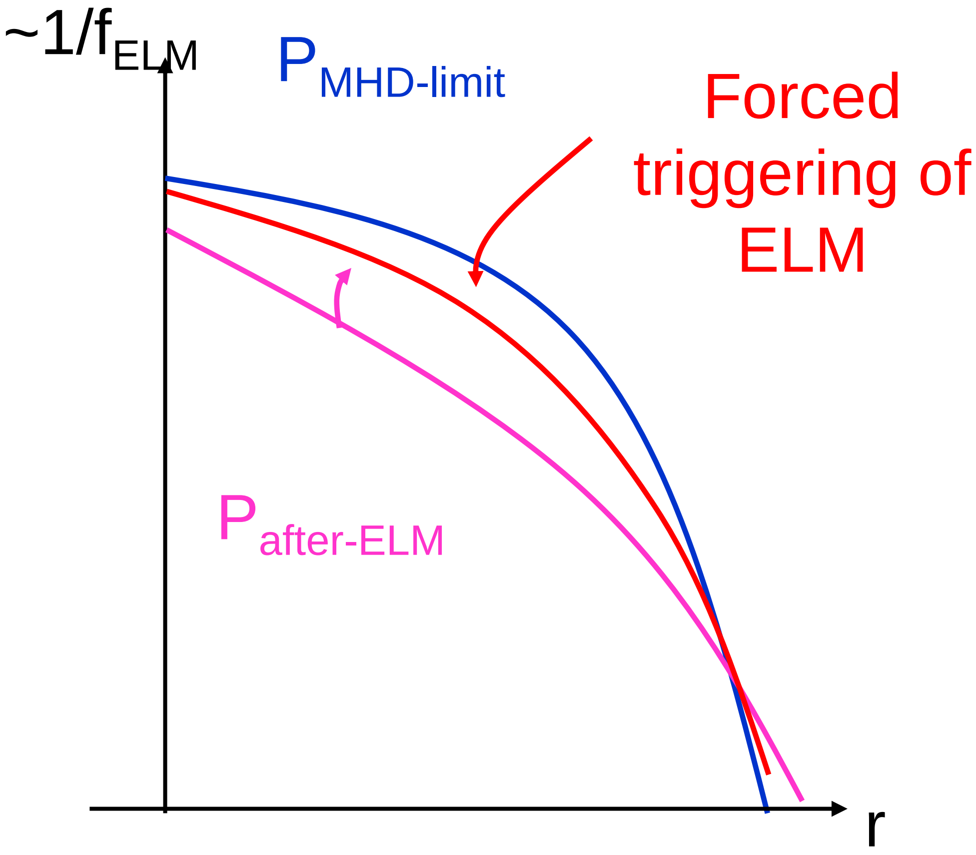
ELM suppression

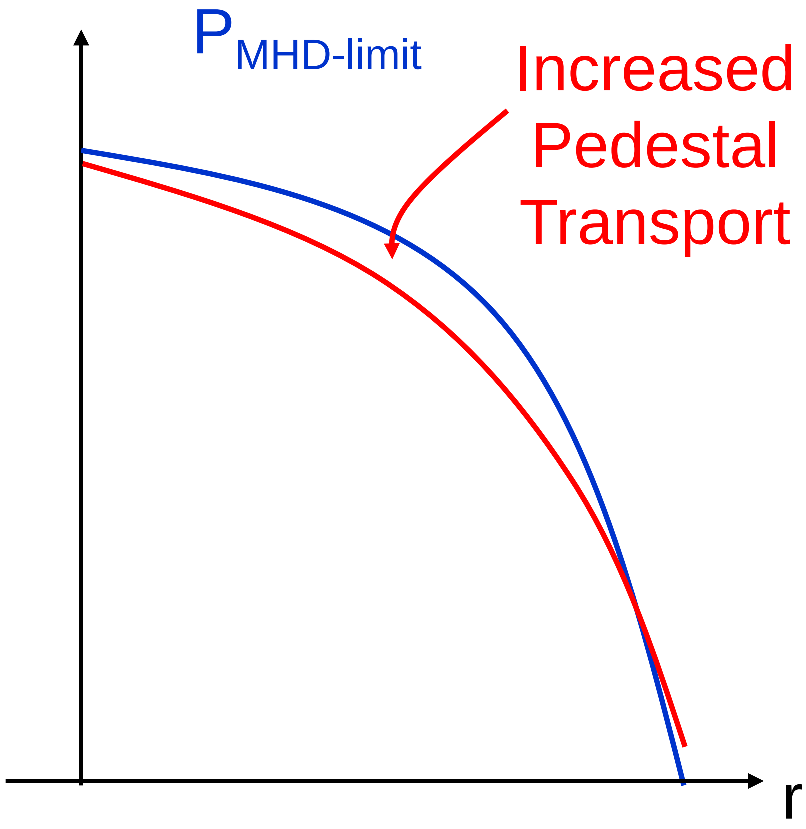
Controlled triggering of ELMs

$\Delta W_{ELM} \sim 1/f_{ELM}$

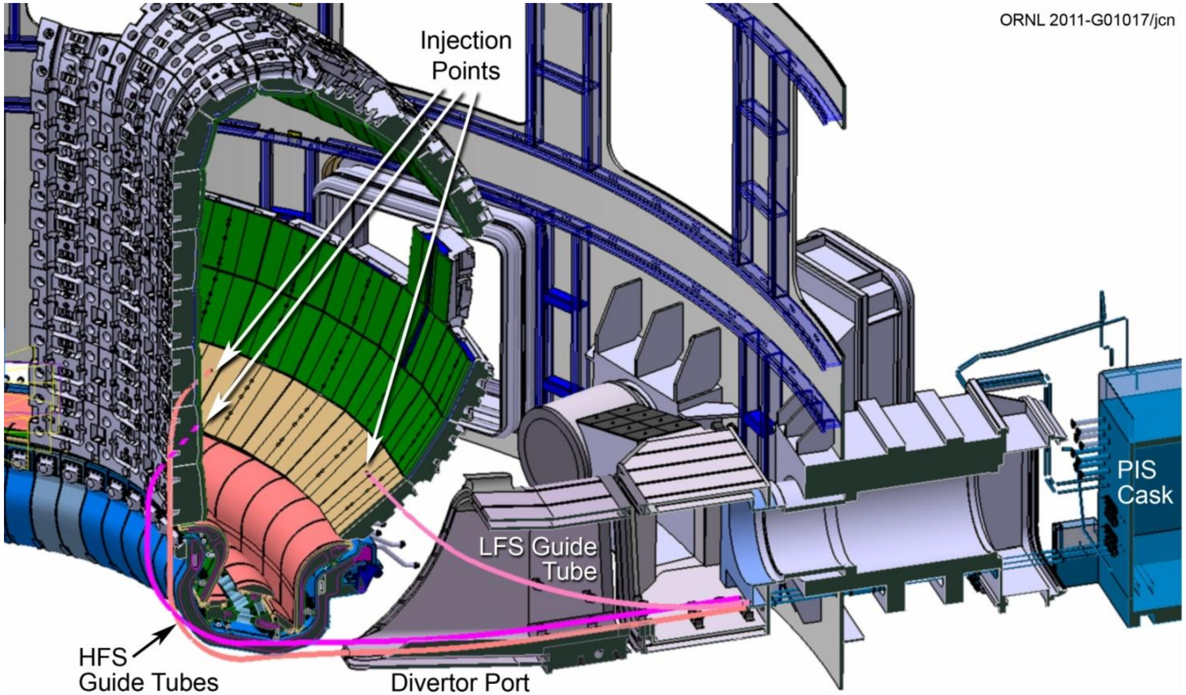
Enhanced pedestal transport

MHD limit avoidance $\Delta W_{ELM} = 0$



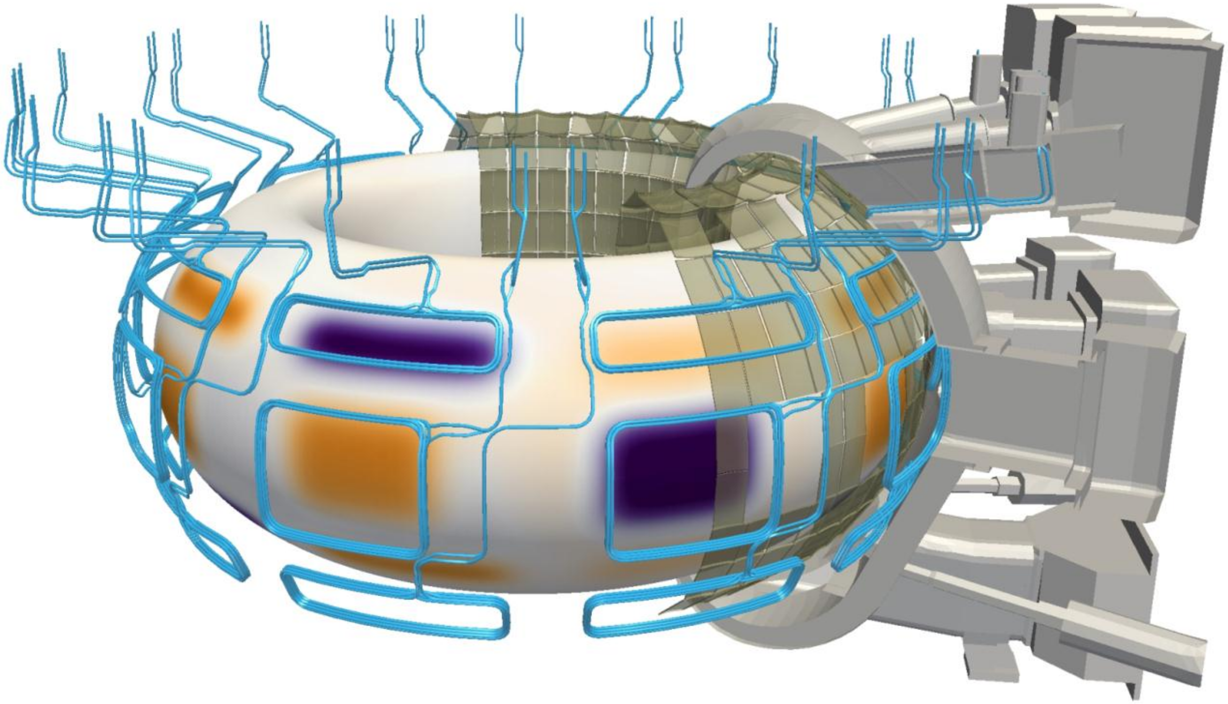


Pellet injector for ELM control



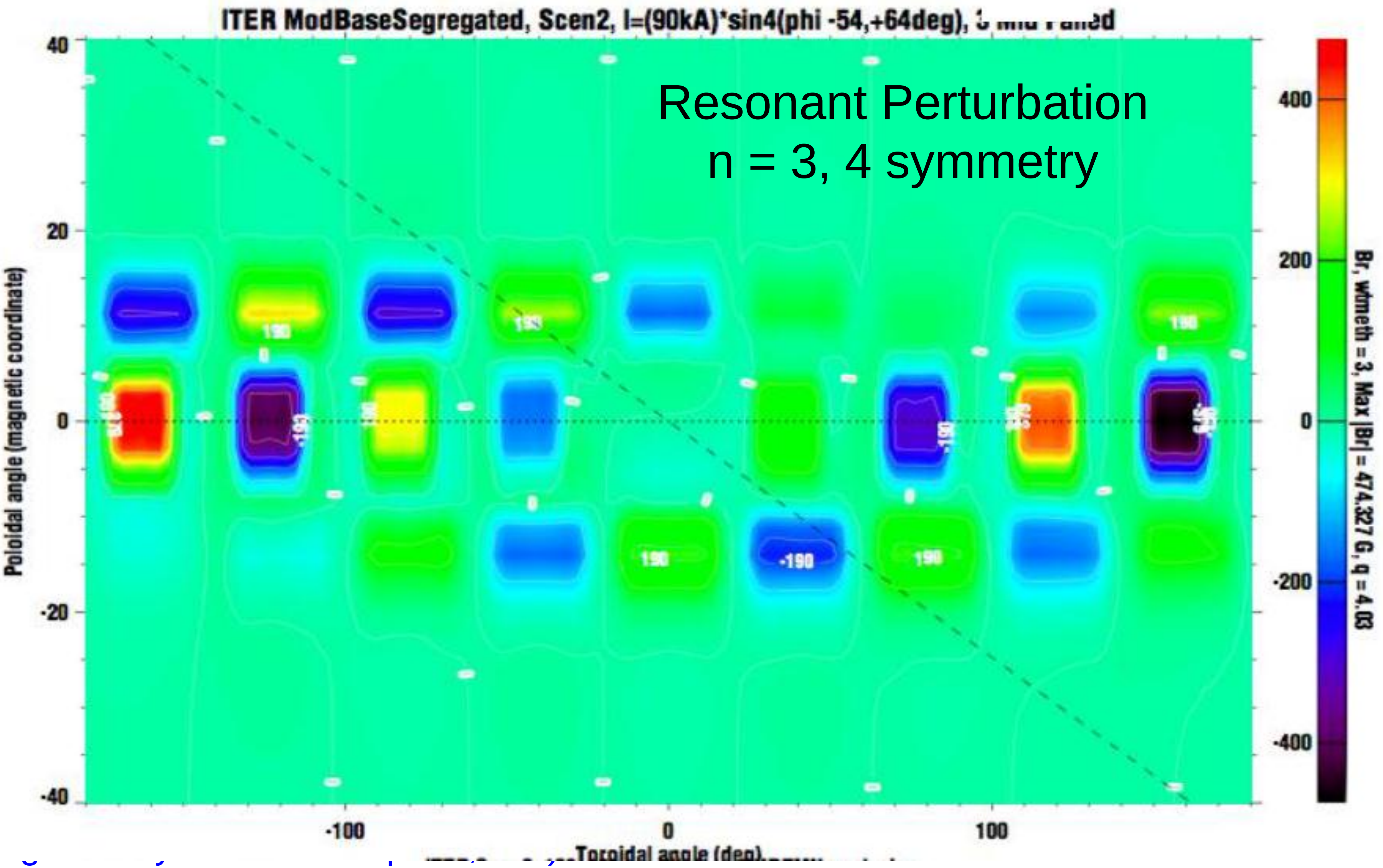
- Pacing pellets :
  - Geometry: one LFS, two HFS injectors
  - Species: D, DT or H
  - Speed: nominal 300m/s *(limited by geometry of guide tubes)*
  - Size: 17-33 mm^3 (*maximum ablation at top of pedestal)*
  - Frequency: nominal 45 Hz, maximum 60 Hz (max 16Hz / injector)

ELM Control Coils (3-D magnetic fields)



- Water-cooled "picture frame" coils
  - mineral (MgO) insulated conductor
- Geometry : 9x3 coils (powered independently)
  - toroidal symmetry n =3 or 4
- Current: max 90 kAturns (6 turns)
- Undergoing engineering design finalization (incl. materials (SS+OFC) & conductor geometry circular or square, etc.)

ELM Control Coils (3-D magnetic fields)

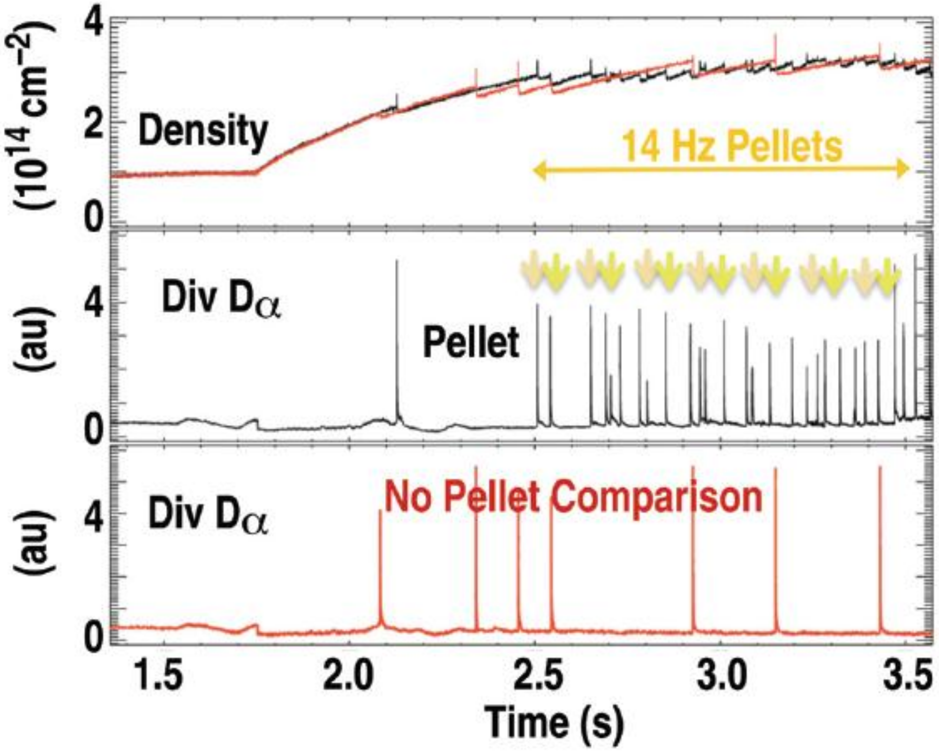


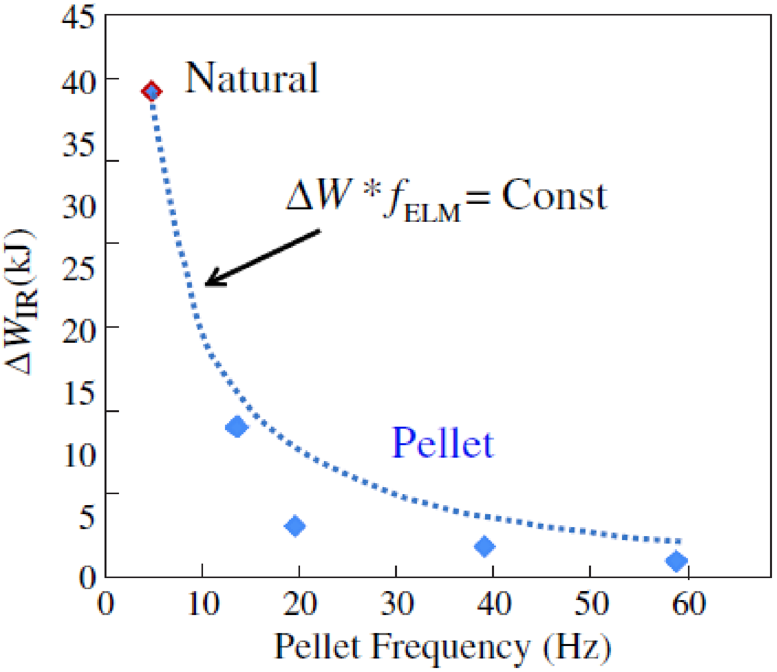
Resonant Perturbation
n = 3, 4 symmetry

ELM control by Pellet Pacing - Experiment

- Injection of pellets can increase f_{ELM} and decrease power fluxes due to ELMs

DIII-D – L. Baylor



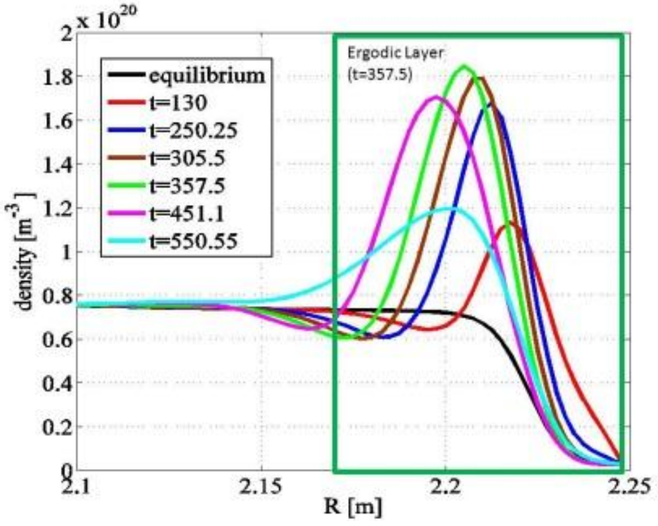


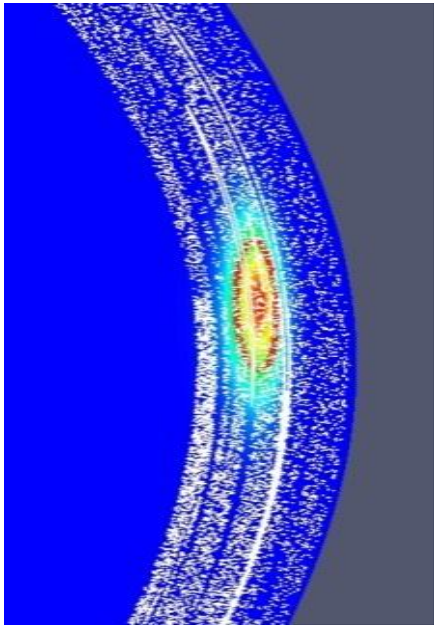
- Reliable technique with sound physics basis
  - ❑ Maximum $f_{ELM}^{controlled}$ achievable?
  - ❑ Required edge fuelling compatible with detachment + T throughput?

a)

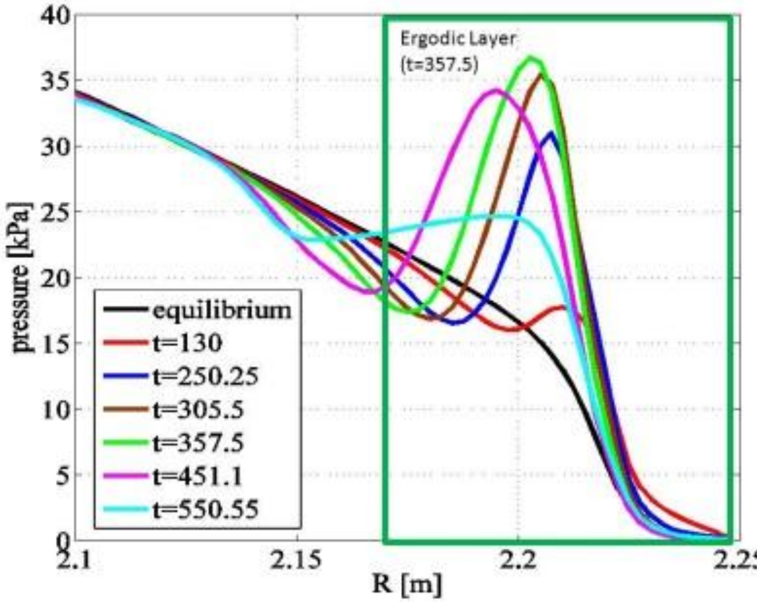
ELM control by Pellet Pacing - Modelling

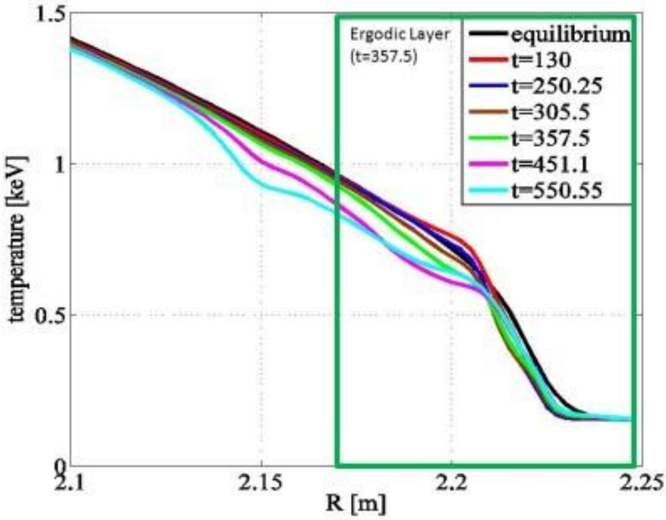
- ELM triggered by local overpressure caused by pellet thermalization





DIII-D – JOREK – S. Futatani





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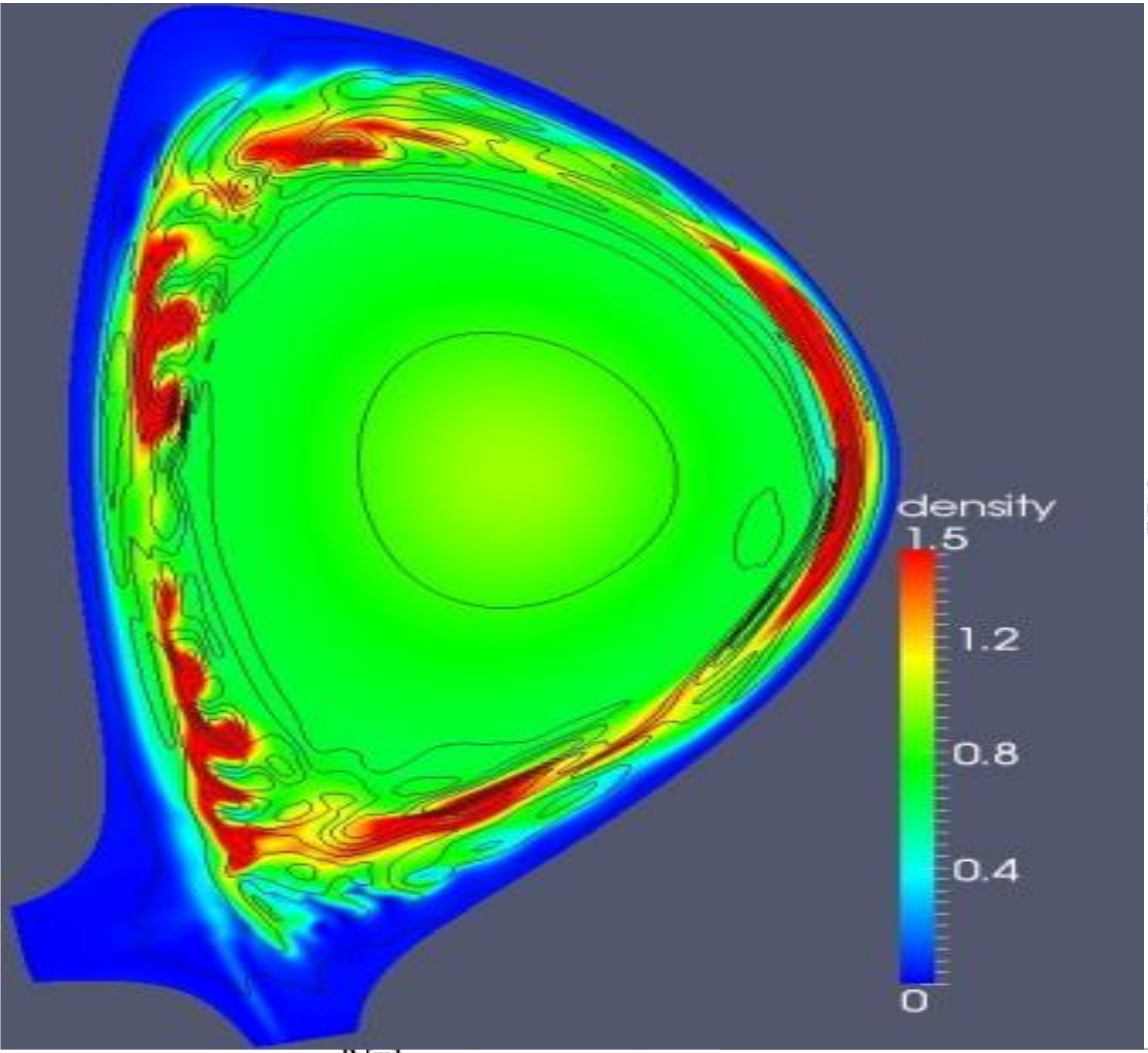
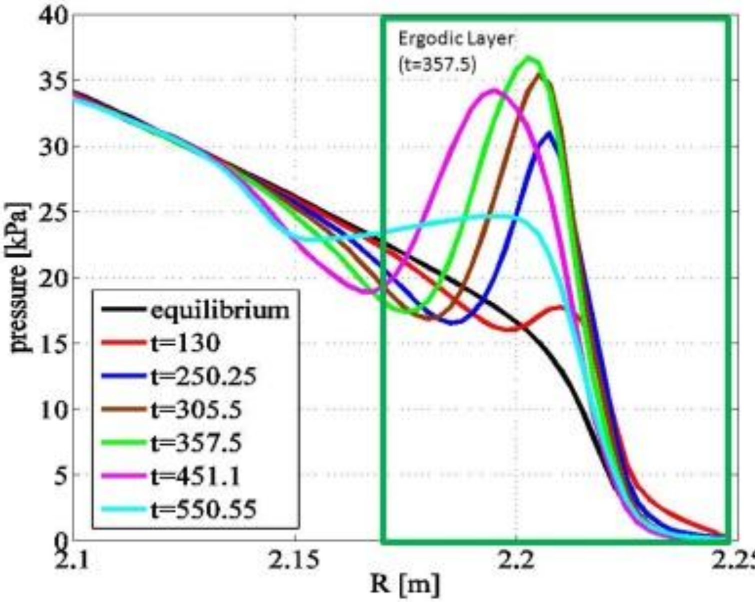
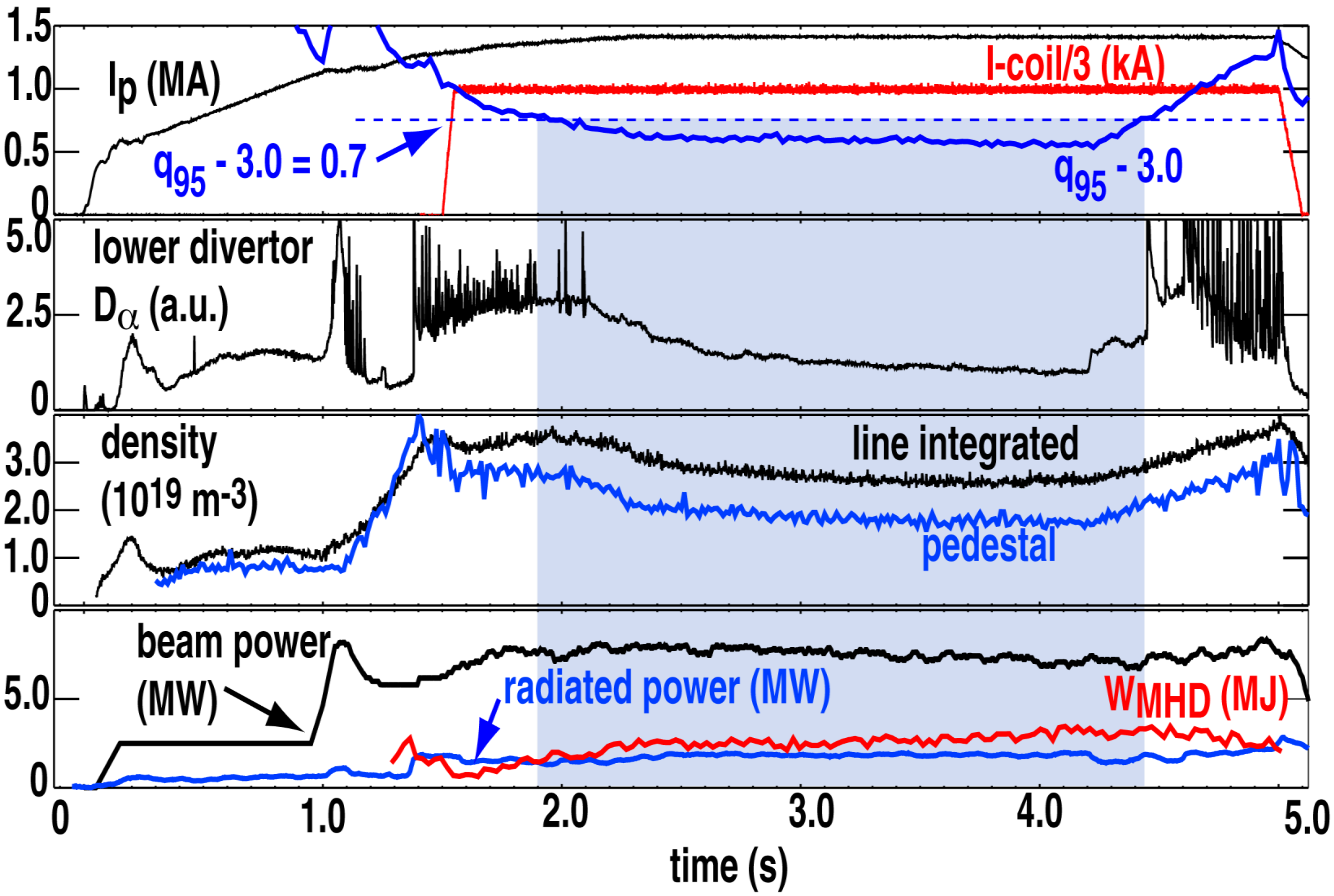
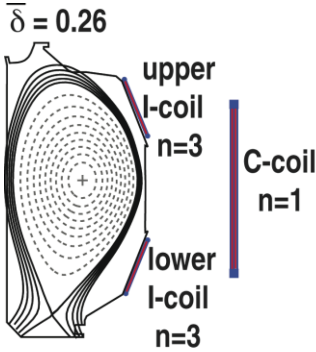


DIII-D – JOREK – S. Futatani



ELM control by 3D Fields – experiment - I



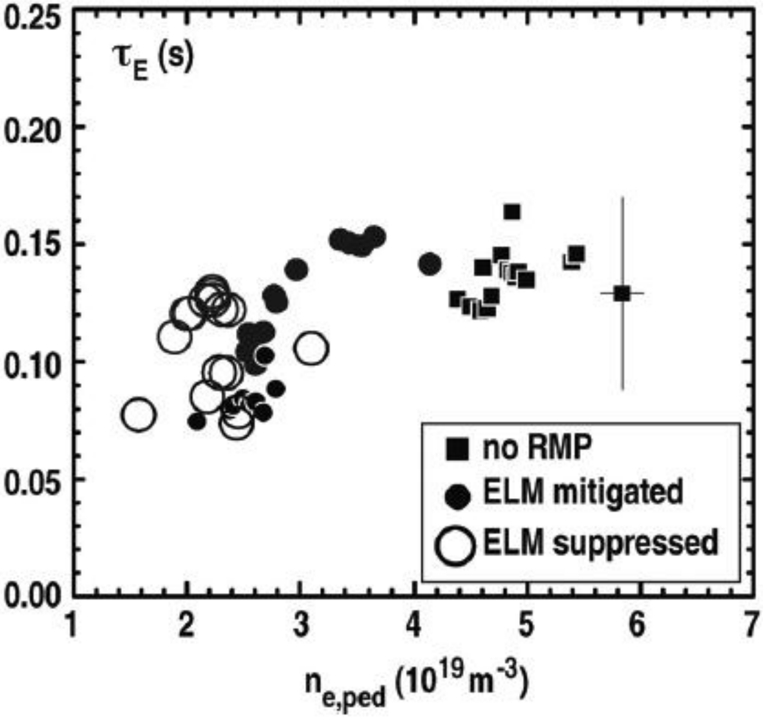


Low triangularity LSN shape

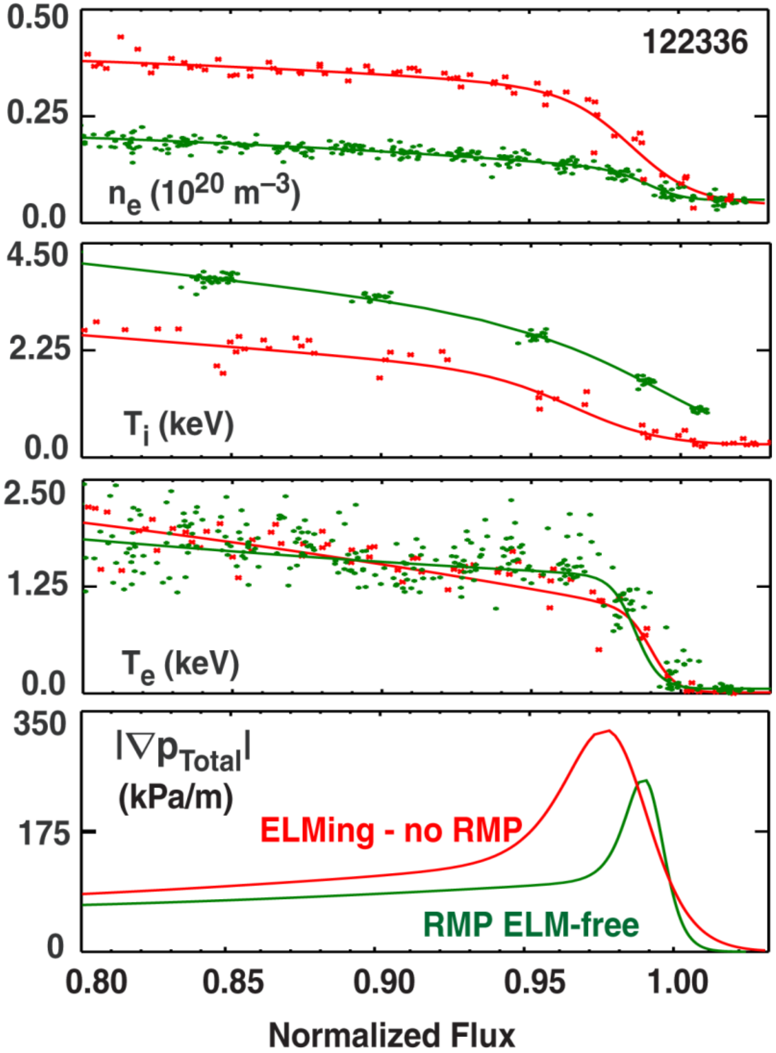
122338
7.9 MW

ELM control by 3D Fields – experiment - I

DIII-D - Nazikian

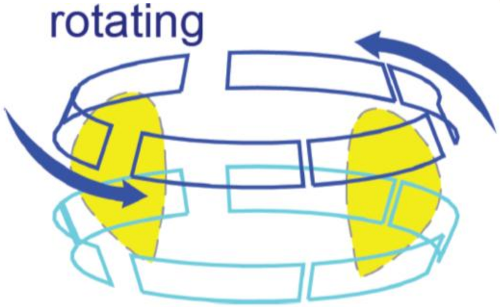


DIII-D - Evans

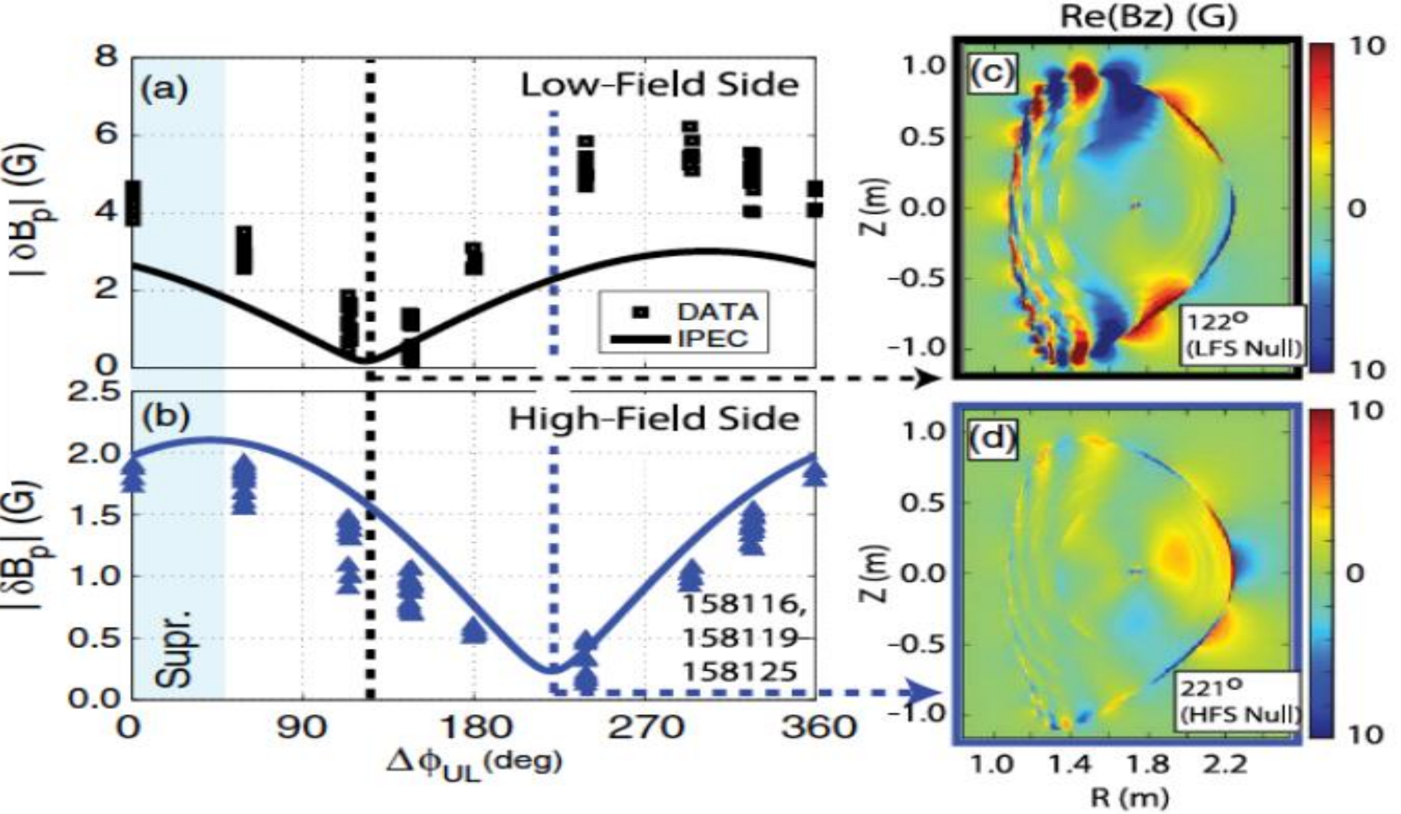


ELM control by 3D Fields – experiment - II

- Applied fields have effect on ELMs and lead to ELM suppression when:
    - ✓ Applied field is large enough
    - ✓ Applied field is properly aligned to maximize edge plasma response



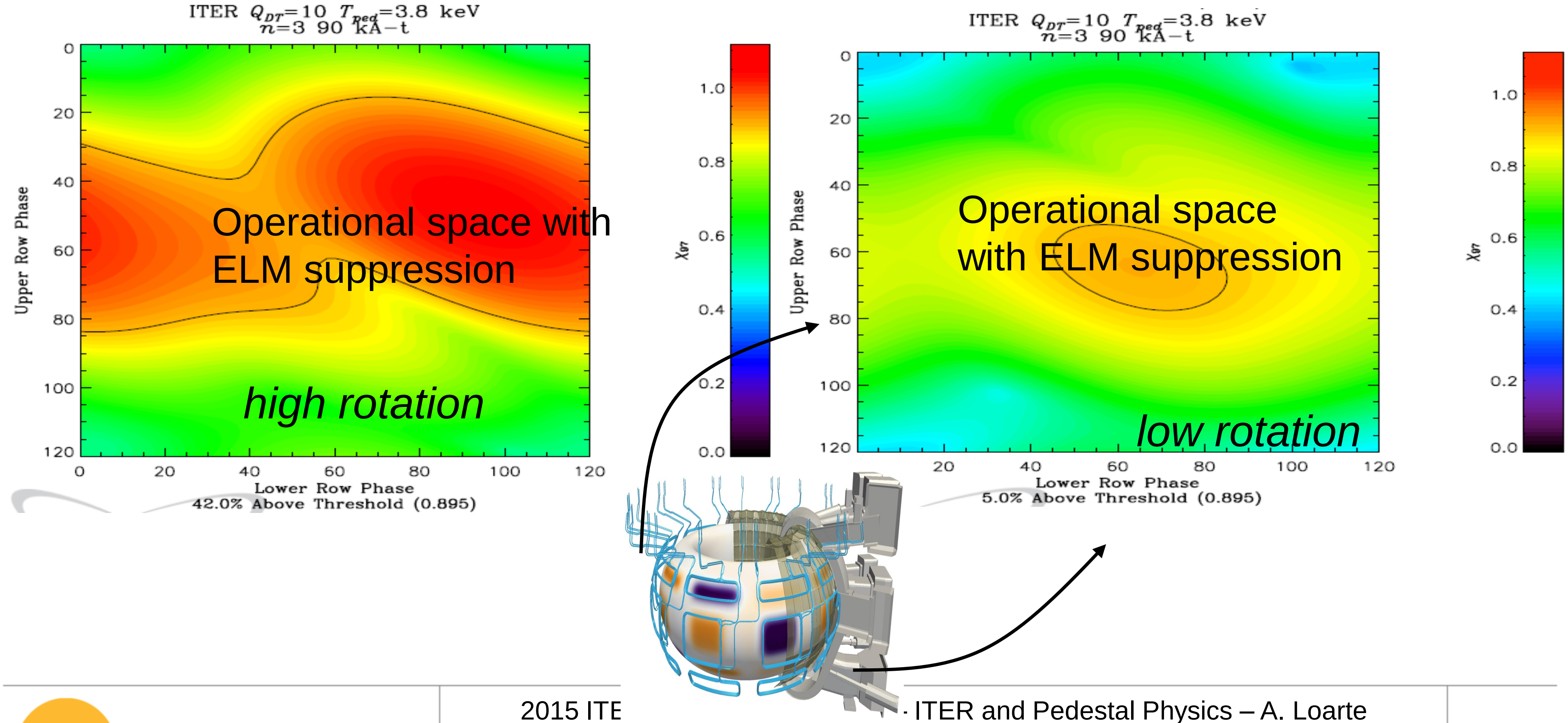
DIII-D – Paz-Soldán



Modelling of ELM control by 3-D fields in ITER

- Physics basis and computational codes not yet developed to predict effects of 3-D on ELM behaviour in ITER
- Modelling studies to evaluate if ITER design has appropriate capability to achieve ELM suppression compared with empirical criteria

ITER – M3D-C1 – N. Ferraro



Operational space with ELM suppression

high rotation

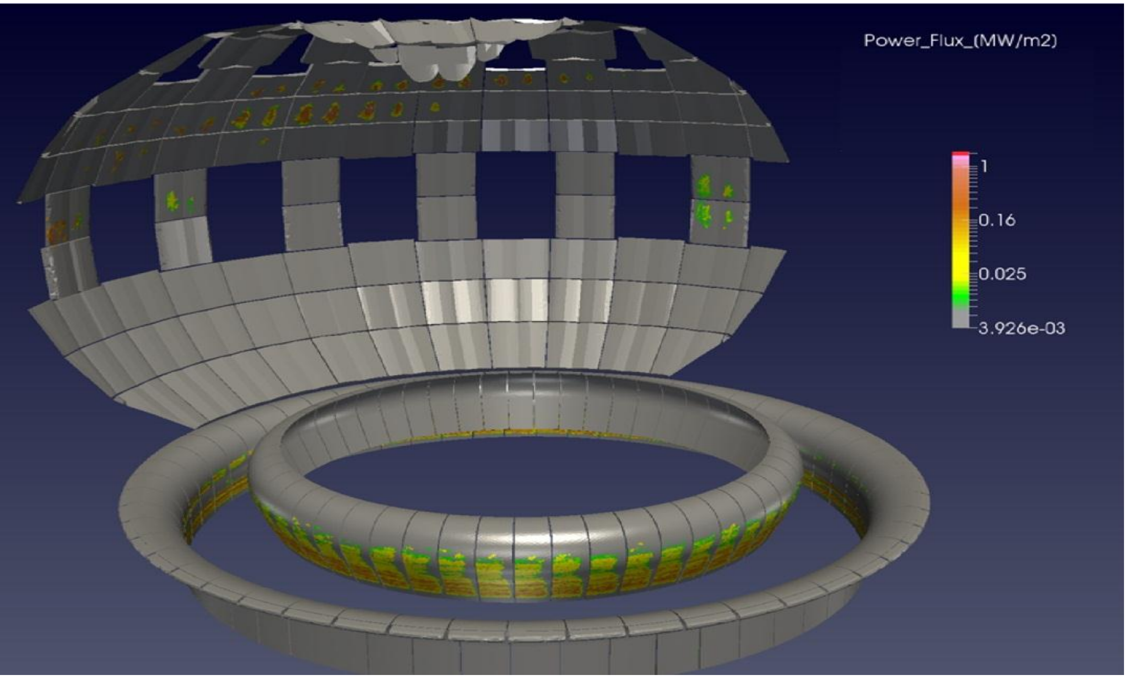
Operational space with ELM suppression

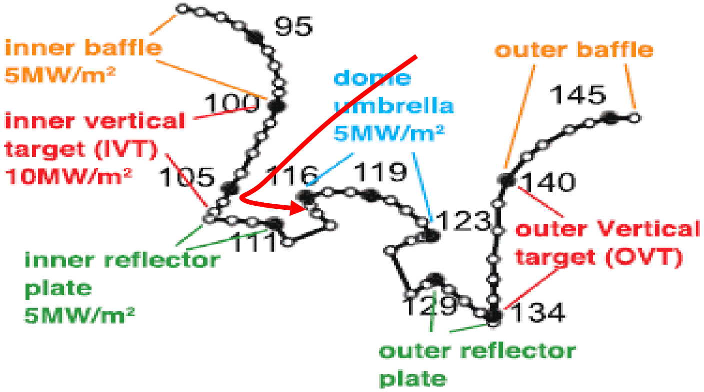
low rotation

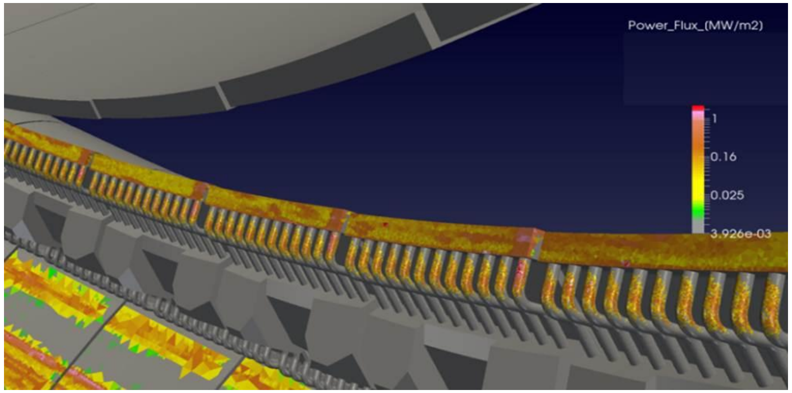
Effects of 3-D fields at ITER plasma edge – Fast Particles

- 3-D fields for ELM control affect profoundly plasma edge → 2-D to 3-D plasma edge → effects on losses of energetic particles

NBI-loss-ITER – LOCUST – R. Akers



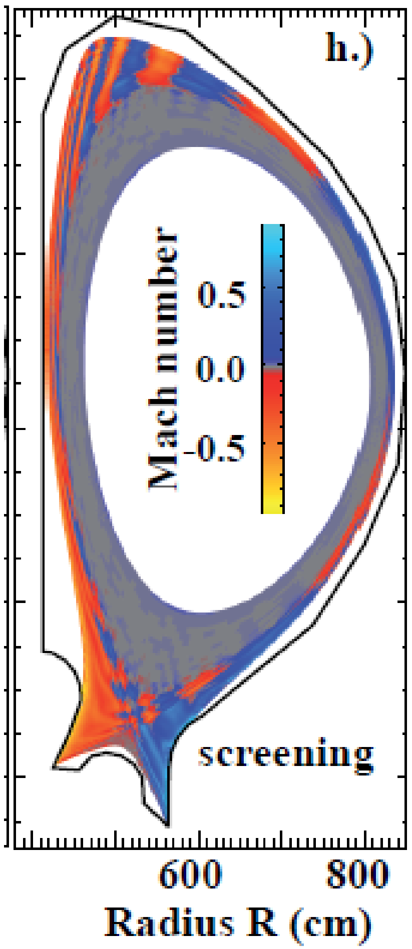


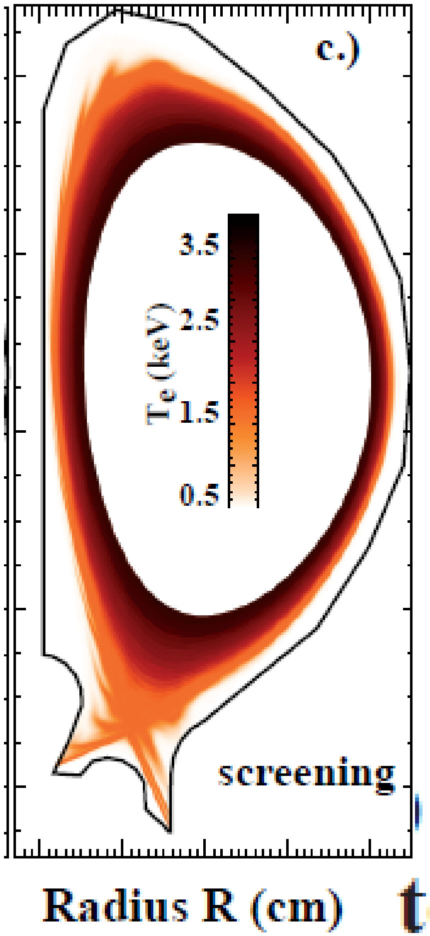


ELM suppression by 3-D fields <u>must not</u> lead to unacceptable losses of energetic particles by supressing ELMs

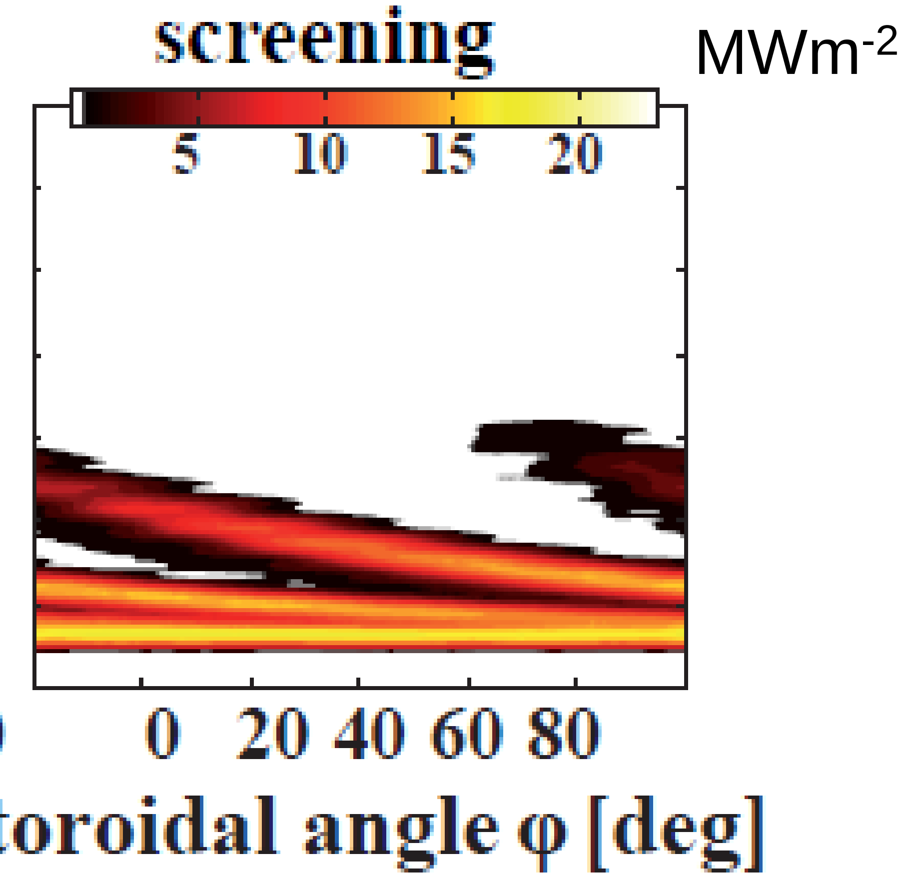
Effects of 3-D fields at ITER plasma edge – Thermal Particles

- ➢ 3-D fields for ELM control affect profoundly plasma edge → 2-D to 3-D plasma edge → effects on thermal plasma
- ➢ Main effect on particle confinement time and power fluxes to PFCs





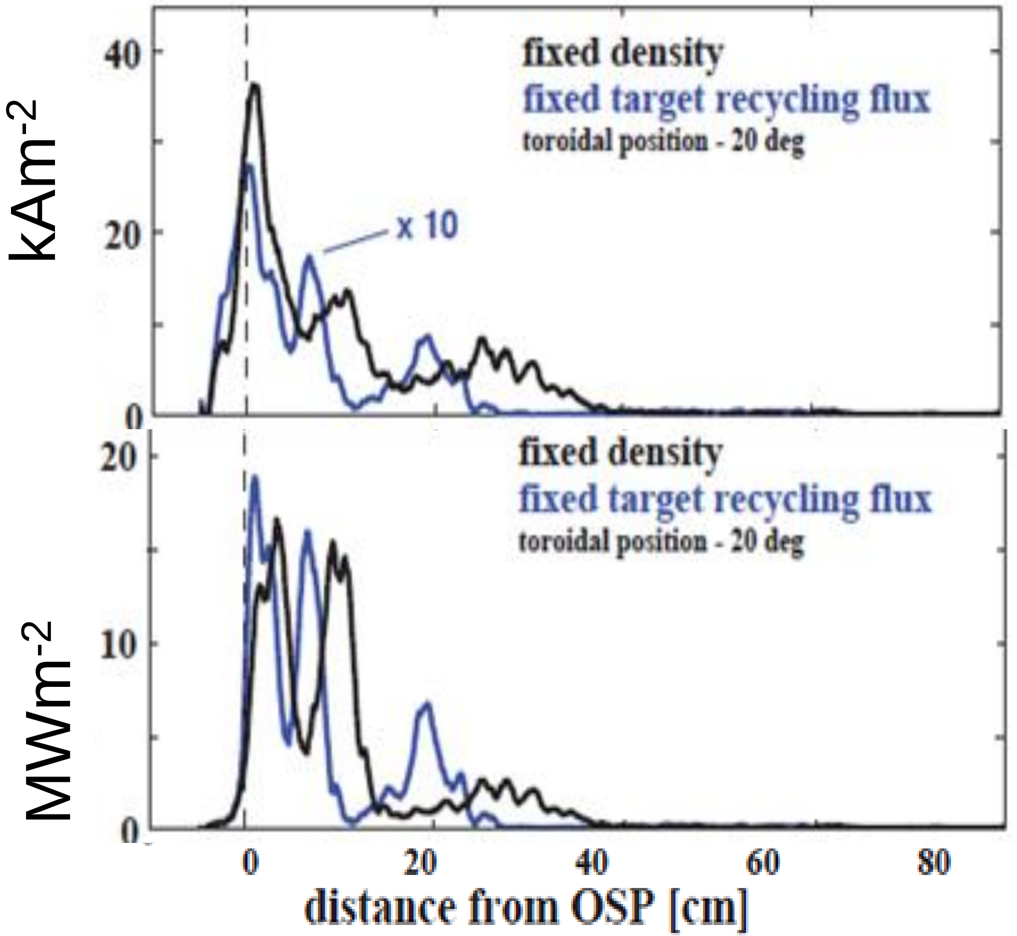
ITER – EM3C – Eirene – O. Schmitz



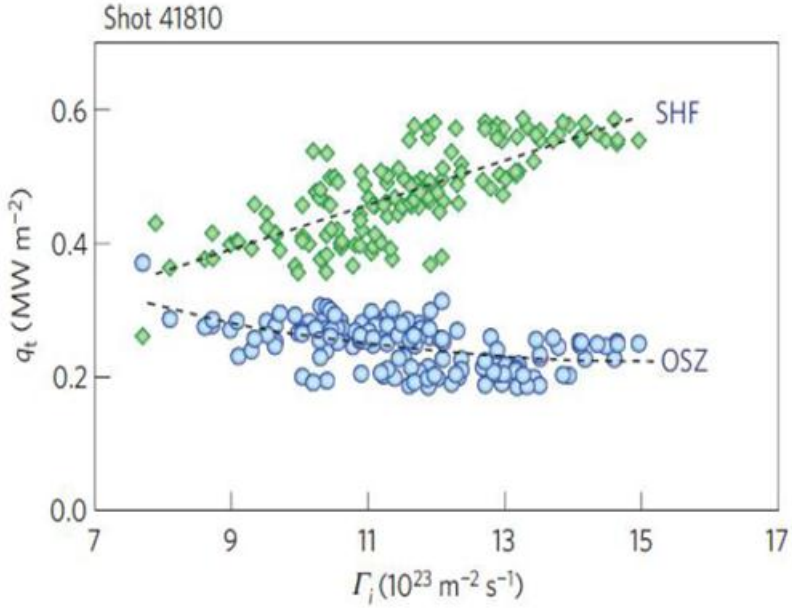
Effects of 3-D fields at ITER plasma edge – Radiative Divertor

- 3-D fields for ELM control affect heat flux at plasma edge and behaviour of power fluxes with divertor conditions
- Radiative divertor & q_{div}^{asym} <10 MWm^{-2} remains to be demonstrated

ITER – EM3C – Eirene – O. Schmitz



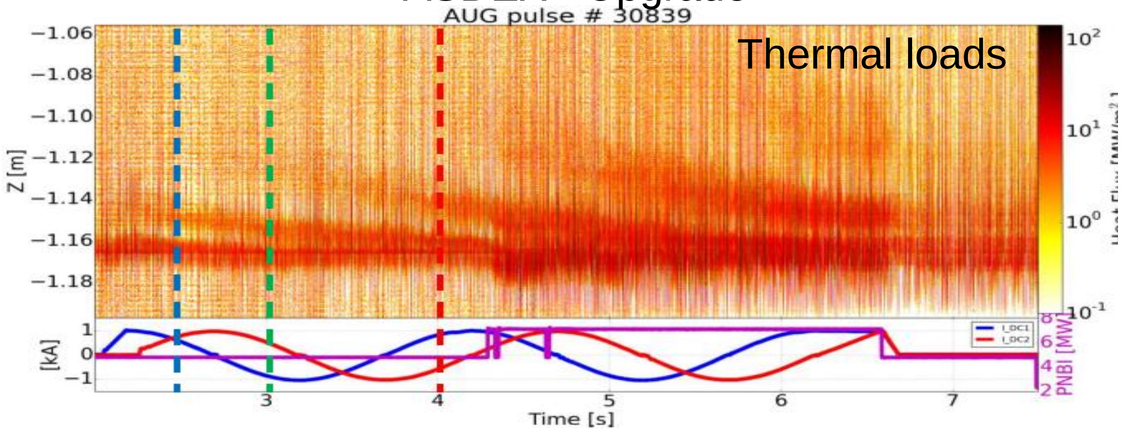
EAST – J.G. Li

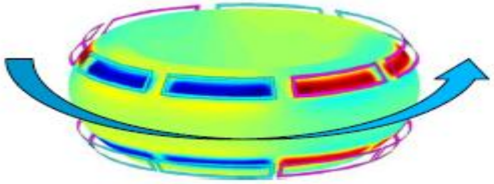


Control of power fluxes to PFCs caused by 3-D fields

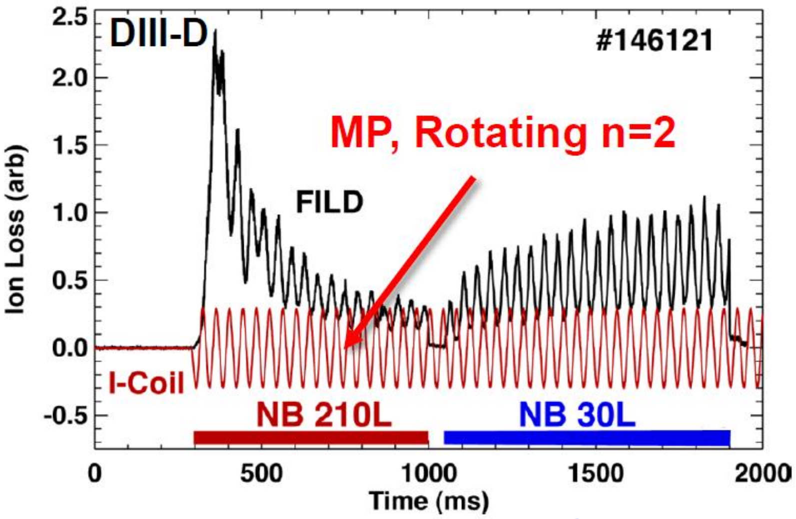
- Time variation of ELM control coil current be used to changed 3-D field move heat flux pattern to reduce time average-flux for thermal plasma and fast particle loads
- Technique proposed by ITER and demonstrated in several tokamaks (ASDEX-Upgrade, DIII-D, EAST) by rigid rotation of 3-D field structure → alignment with B_{edge} maintained
- Optimization for ITER to minimize ΔI_{coil} in progress

ASDEX - Upgrade





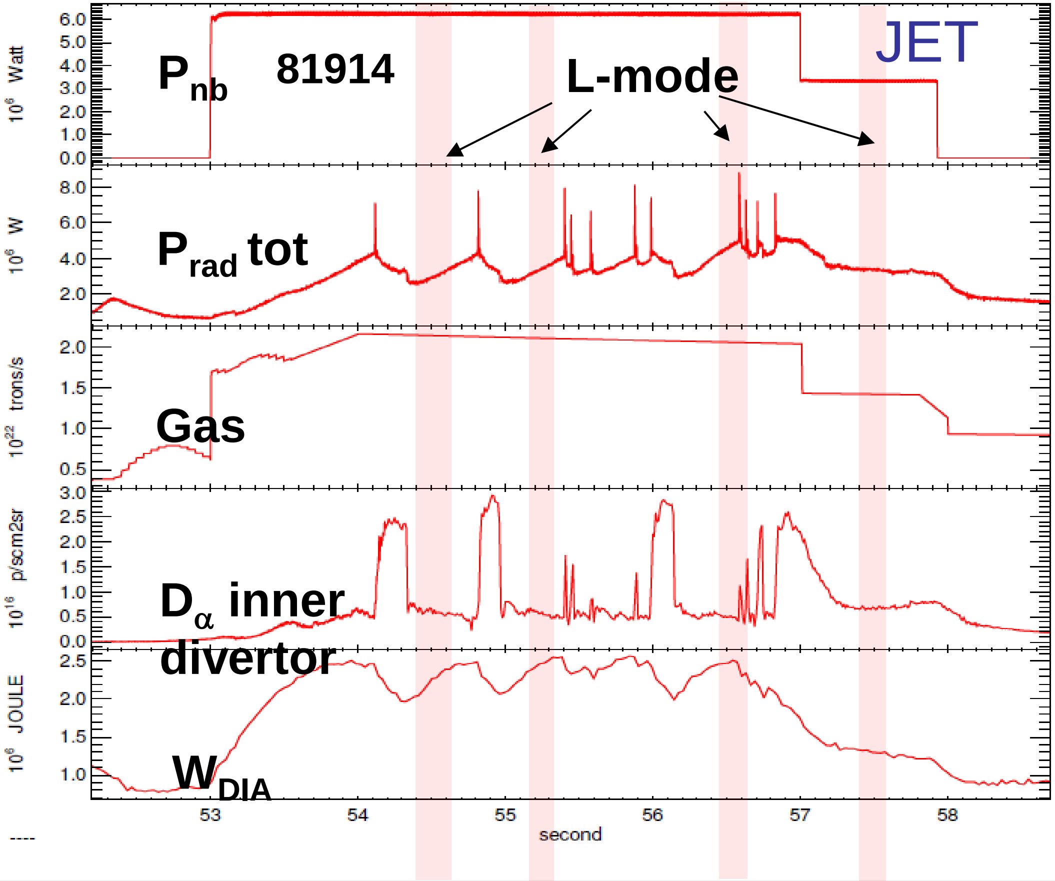
Fast particle loads



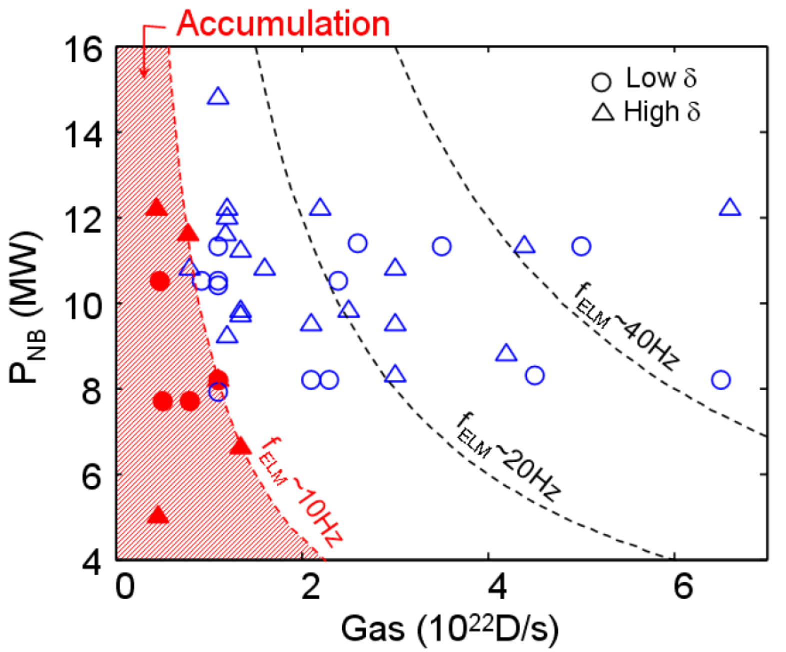
Counter I_p **Co I_p**

H-mode operation with W divertor

- ITER operation with W divertor introduces additional challenges to edge pedestal transport and ELM control
- Lack of ELM control leads to W accumulation and loss of H-mode (+ disruption in some cases)

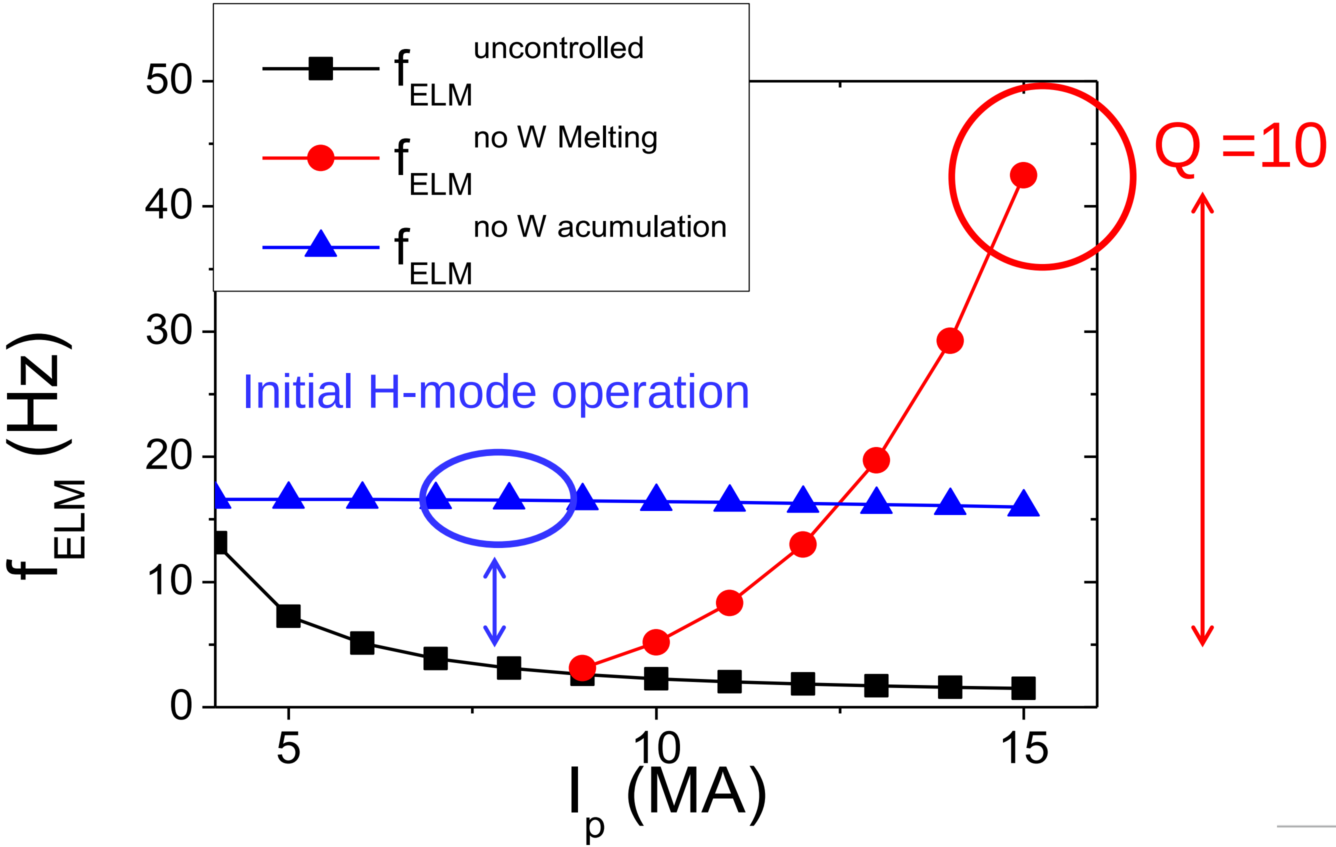


JET - Bucalossi



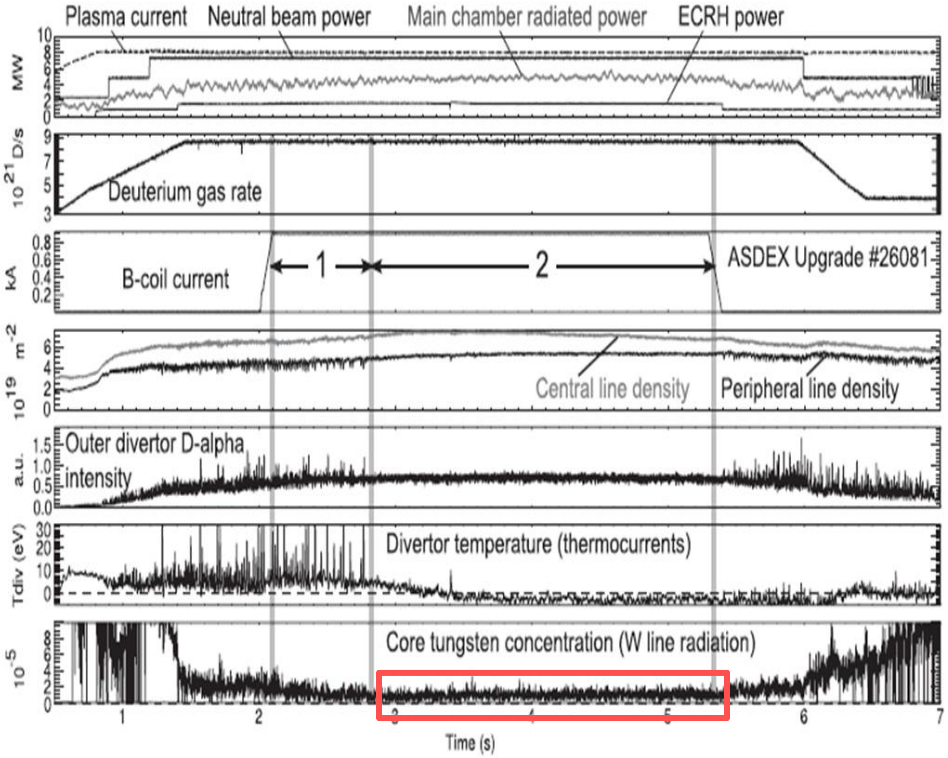
Requirements for ELM control & W exhaust in ITER

- **ITER will require ELM control throughout H-mode operation:**
  - ✓ Control of power loads to PFCs by ELMs was only required for plasma current I_p > 9 MA to avoid excessive erosion
  - ✓ ELMs also to be controlled/suppressed to prevent W contamination of ITER plasmas in H-mode for any level of I_p



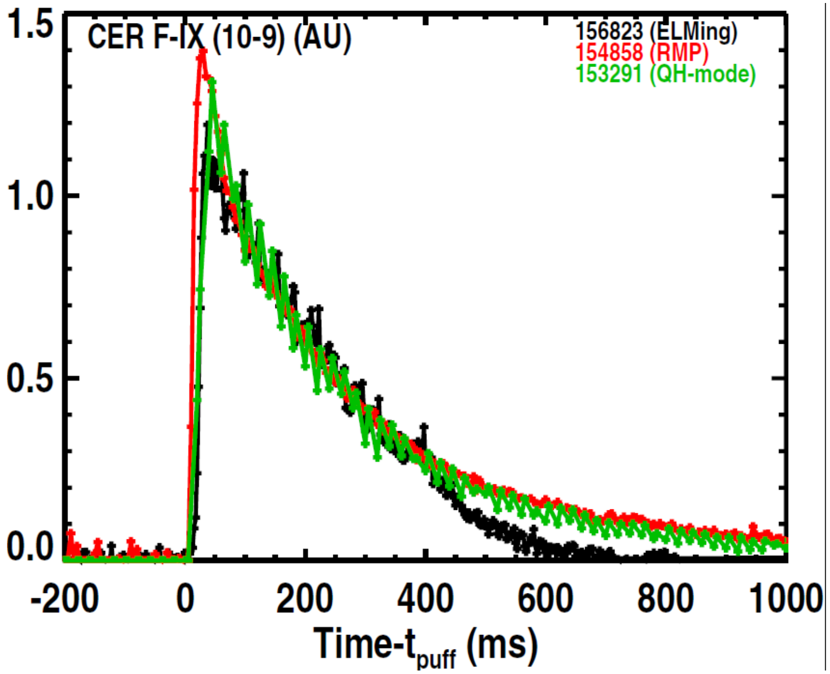
ELM control & W exhaust : experiment

- ELM mitigation by 3-D fields compatible with W control in high n_e H-modes in AUG
- ELM suppressed H-modes in DIII-D have demonstrated a similar impurity exhaust capability to Type I ELMy H-modes


AUG – Suttrop - PRL - 2011

High n_e/n_{GW} AUG

DIII-D
B. Grierson

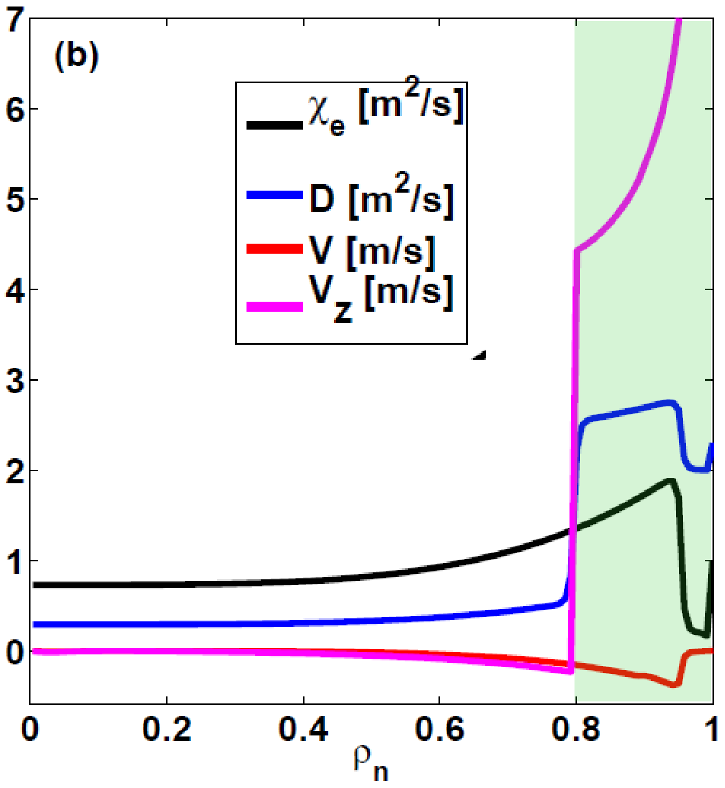


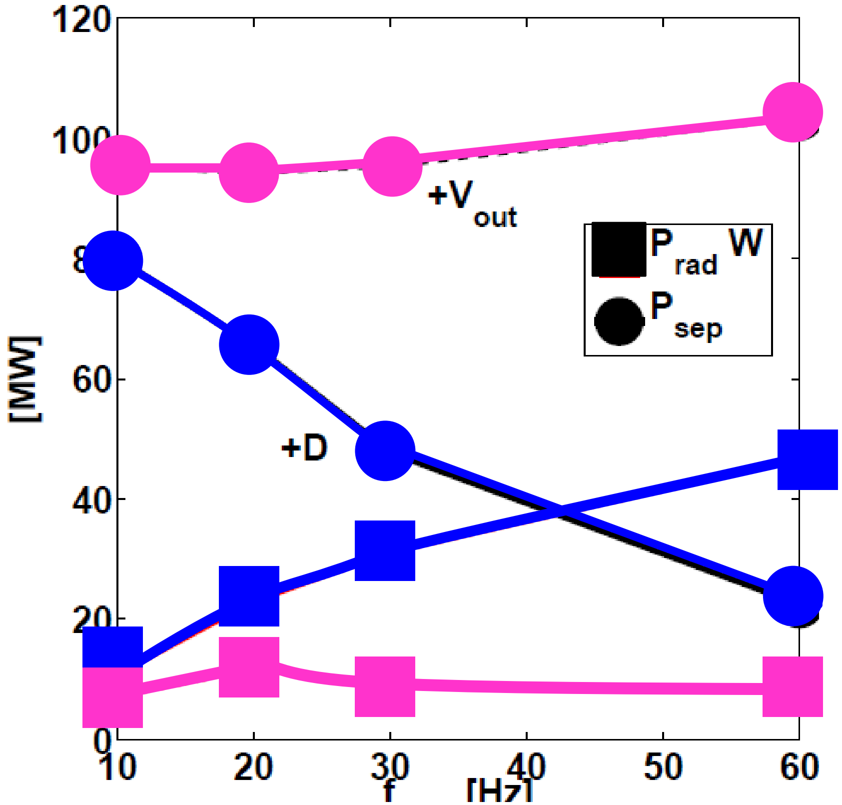
Optimization of impurity exhaust versus ELM power load mitigation ?

ELM control & W exhaust: ITER

- ELMs above a given frequency are found to be required to control n_{ped}^{W}/P_{rad}
- Effectiveness of ELMs to expel W in ITER depends on "effective" particle transport during the ELM (diffusive vs. convective) → ELMs can increase n_W → Optimum between power load control and W control required

ITER- STRAHL+NEOART+ASTRA - E. Fable & Dux





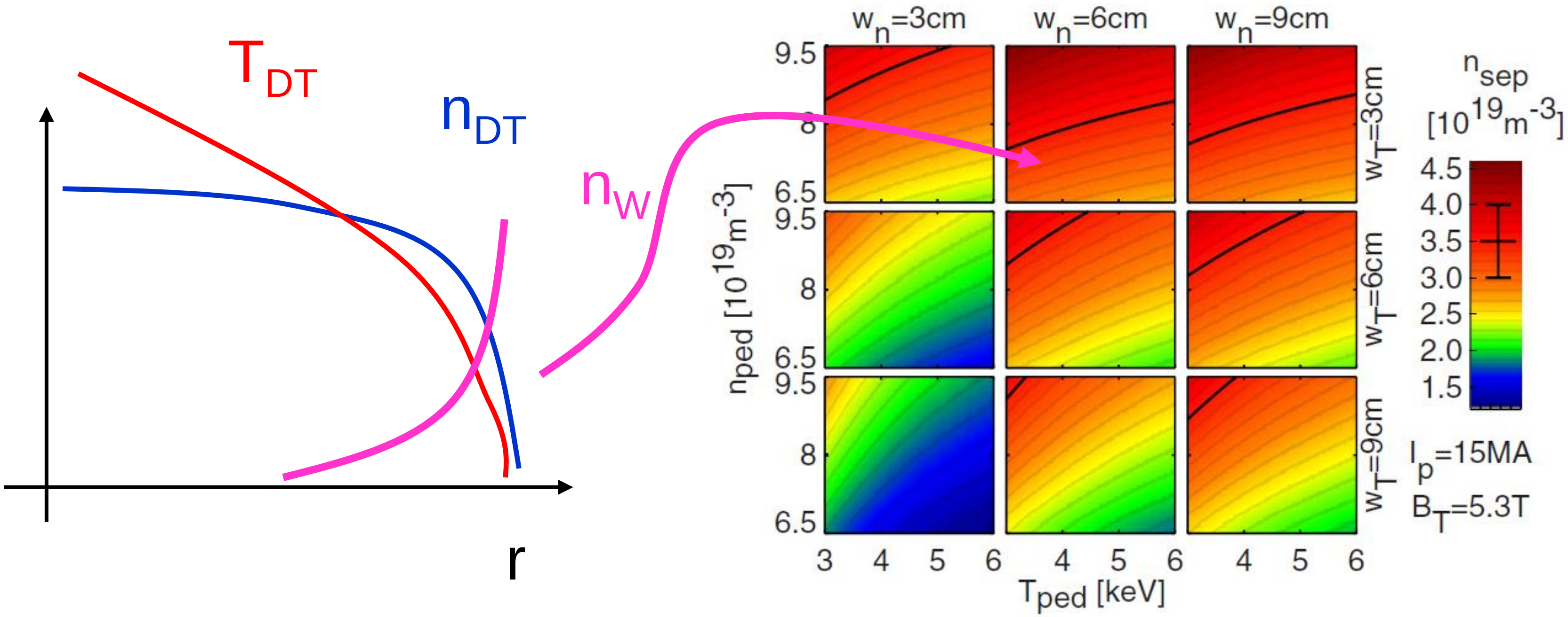
W transport in ITER pedestal

- ITER operation with radiative divertor requires high n_{sep} → $\text{gradn}|_{ped}$ is low

< 0

$$\frac{\nabla n_z}{n_z} \sim Z \boxed{\left(1 \quad - \quad H \frac{\nabla T_{DT}/T_{DT}}{\nabla n_{DT}/n_{DT}}\right)} \frac{\nabla n_{DT}}{n_{DT}}$$

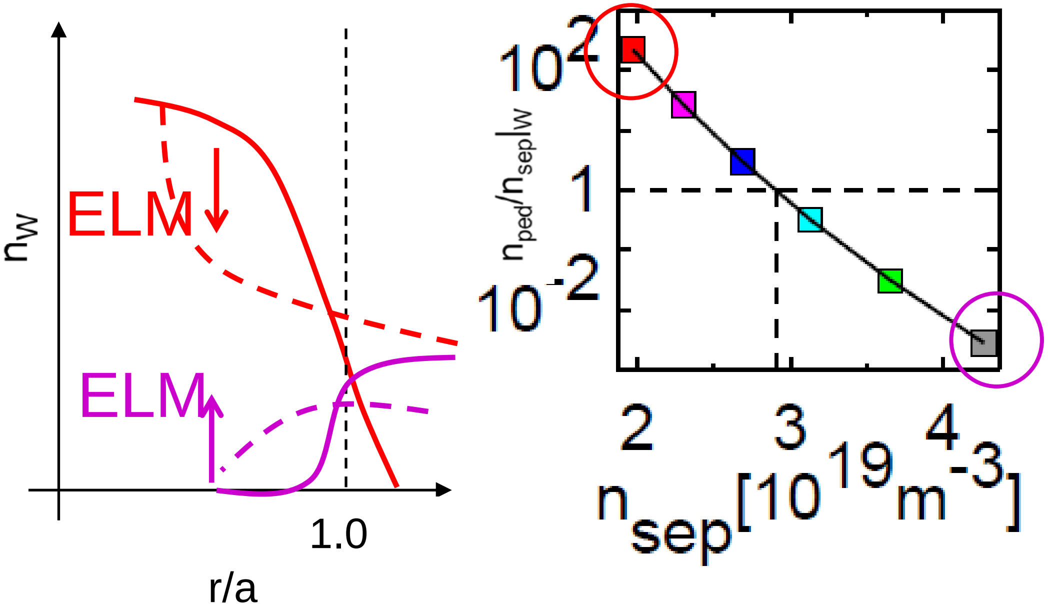
ASDEX-Upgrade – T. Pütterich



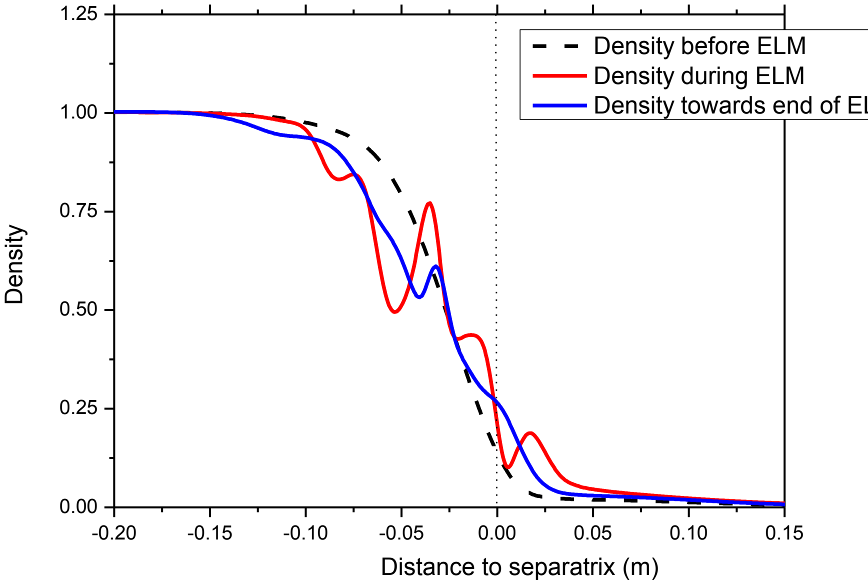
Edge W transport by ELMs in ITER

- Effectiveness of ELMs to expel W in ITER for $n_{ped}^{W} \ll n_{sep}^{W}$ depends on “effective” particle transport during the ELM (diffusive vs. convective)
- Expulsion of particles by ELMs associated with edge ergodization and radial expulsion of plasma filaments by MHD instability → Not yet clear if controlled ELMs can provide W exhaust

ITER – R. Dux

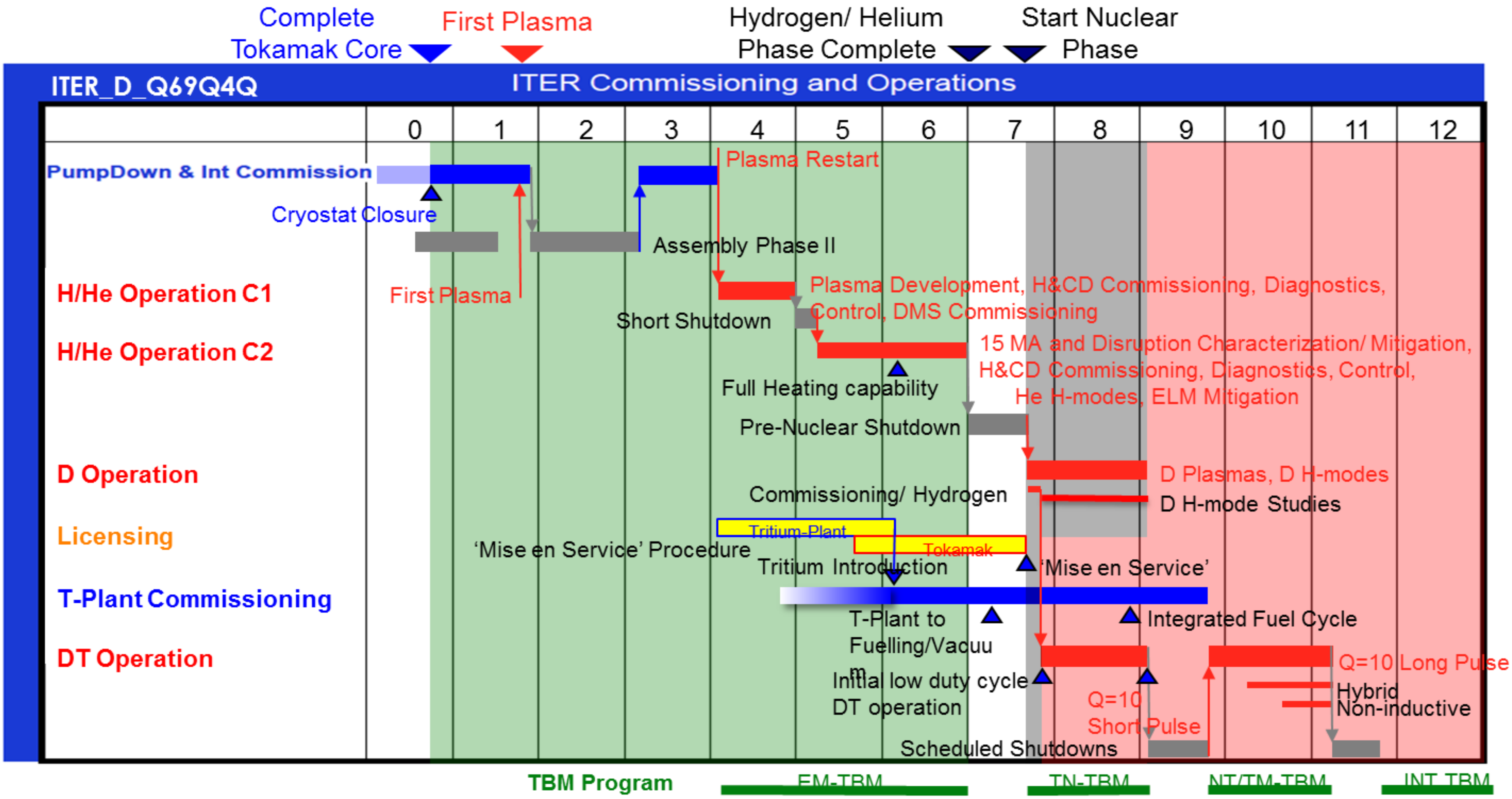


ITER-JOREK- G. Huijsmans

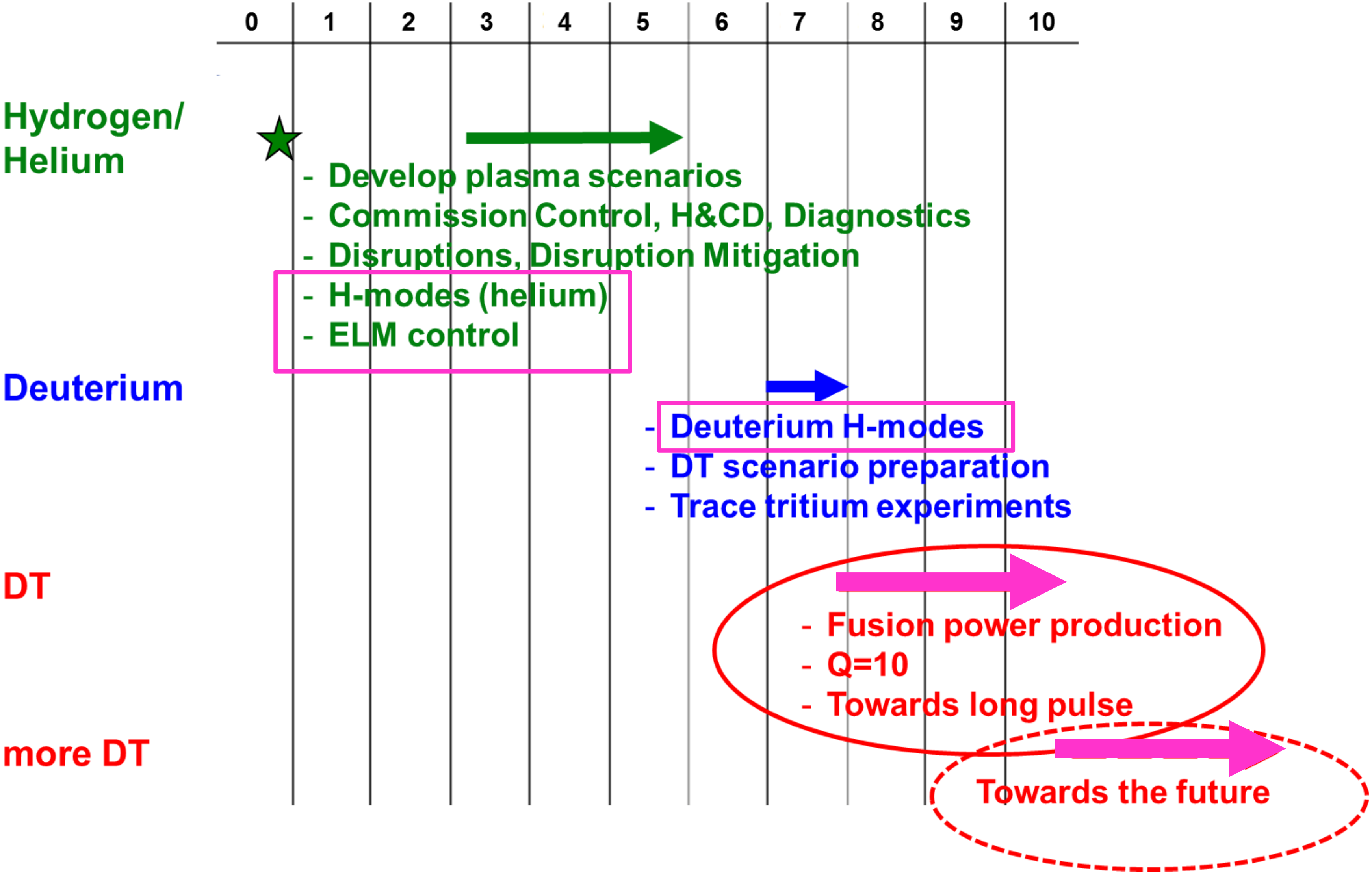


Overview of ITER Operational and Research Plan

ITER Research Plan - I



ITER Research Plan - II



Hydrogen/ Helium

- Develop plasma scenarios
- Commission Control, H&CD, Diagnostics
- Disruptions, Disruption Mitigation
- H-modes (helium)
- ELM control

Deuterium

- Deuterium H-modes
- DT scenario preparation
- Trace tritium experiments

DT

- Fusion power production
- Q=10
- Towards long pulse

more DT

Towards the future

Conclusions

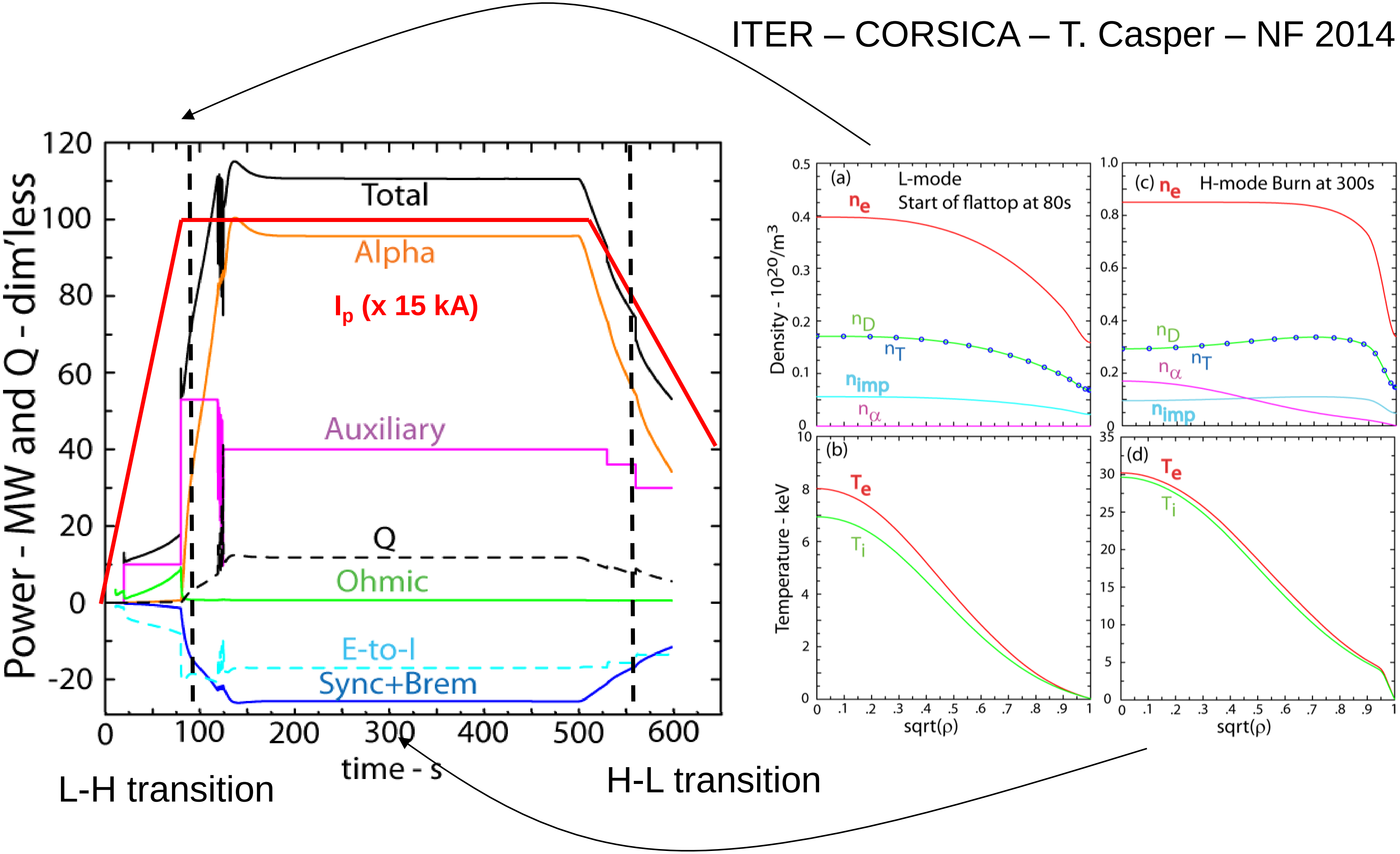
ITER design and plasma performance based on existing H-mode experiments and models → pedestal physics plays a major role in ITER's design and expected plasma performance

- ➢ Optimization of pedestal plasma is key to high plasma performance
- ➢ Low neutral penetration in ITER may open new pedestal physics due to low n_{ped} gradients (assuming transport is diffusive)
- ➢ ELM control is mandatory in ITER H-modes
  - ✓ At low I_p to exhaust W
  - ✓ At high I_p to control ELM power loads to PFCs (and W exhaust)
- ➢ Achievement of ITER performance requires integration of core plasma with SOL plasma through the pedestal → same physics as in todays experiments produces unexpected results
  - ✓ Solving ELM power load problem with 3-D fields complicates radiative divertor operation
  - ✓ W transport can be opposite to todays experiments (out between ELMs, inwards during ELM)

Reserve Material

An ITER high Q discharge

ITER – CORSICA – T. Casper – NF 2014

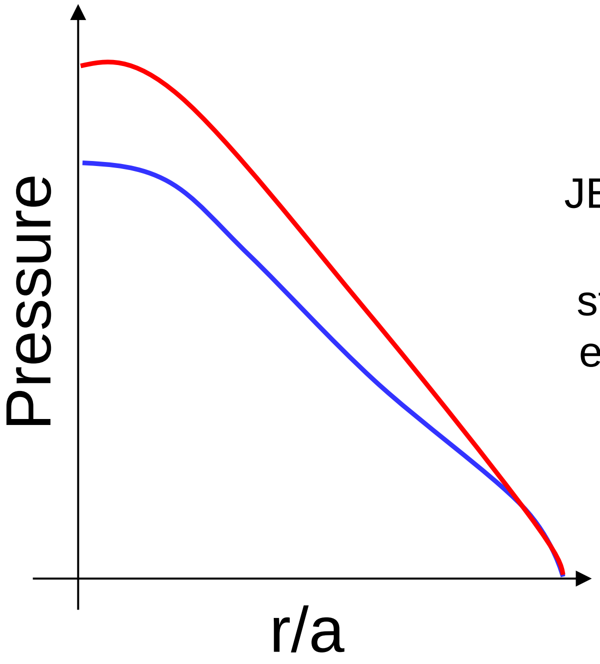


L-H transition

H-L transition

Core Transport in Stationary Phases – I

- ITER fusion performance is based on empirical scaling of τ_E and will depend on achievable core pressure for given edge pressure (MHD limited) → which ∇T and ∇n can be established in the core plasma in ITER ?
- ITER plasma conditions differ from present experiments (high n/low ν^*/low ρ/a) → extrapolation of experimental through physics understanding of turbulent transport
  - NBI 1 MeV in ITER compared to ≤ 100 keV in present experiments → 10 time less core fuelling per MW and 3 times less momentum input (rotation)
  - Dominant electron heating → $P_e/P_i \geq 2$

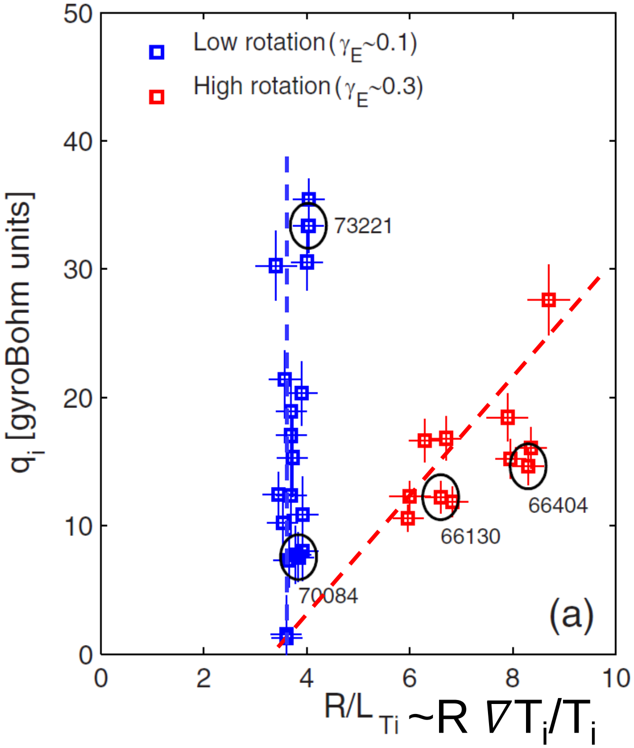


$$q \sim \chi \nabla T$$

JET-GENE-J. Citrin NF 2014

Core plasma turbulence stabilized by fast-particles + electromagnetic effects and not rotation as originally thought

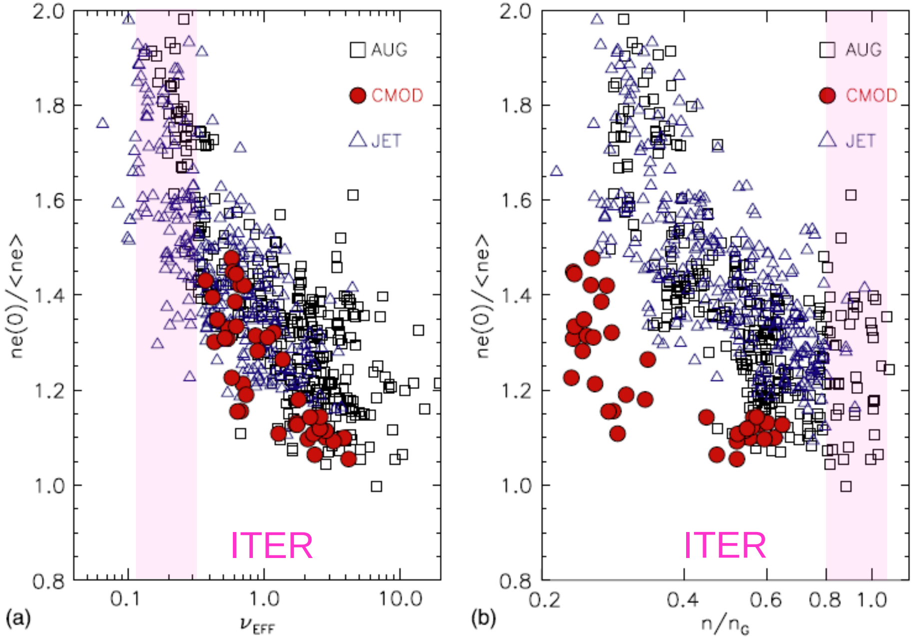
JET – P. Mantica – PRL 2011



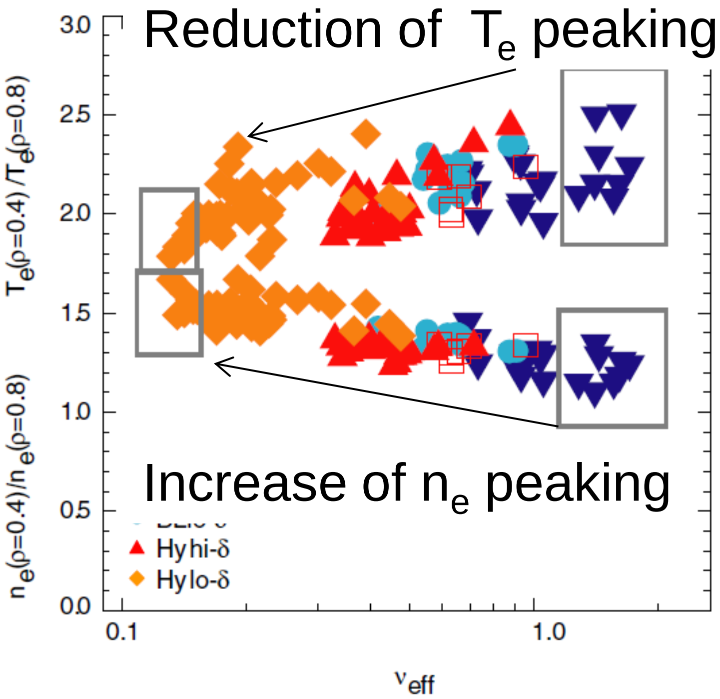
Core Transport in Stationary Phases – II

- Increased fusion performance requires high pressure (high core n_i and T_i) → understanding and optimization of inter-relation between core energy and particle transport in the absence of sources is required ITER
- Relative peaking of ion density/temperature → implications for W (Z = 74) transport if turbulent transport is low $\frac{\nabla n_Z}{n_Z} \sim Z\left(1 \quad - \quad H\frac{\nabla T_{DT}/T_{DT}}{\nabla n_{DT}/n_{DT}}\right)\frac{\nabla n_{DT}}{n_{DT}}$

AUG+C-Mod+JET – M. Greenwald + C. Angioni + H. Weisen – NF 2007



JET - Beurskens – NF 2013



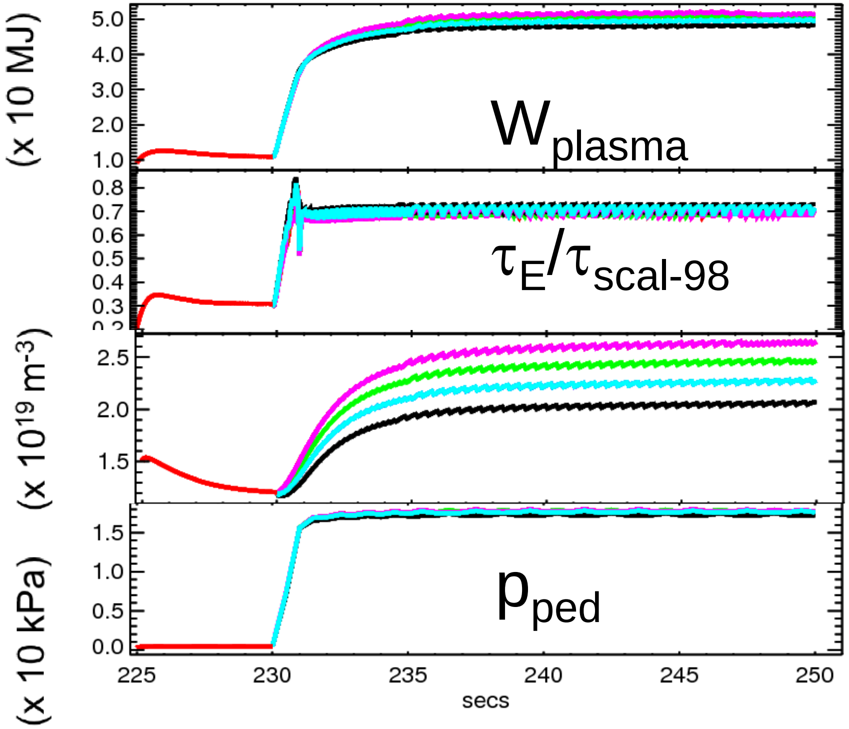
Reduction of T_e peaking

Increase of n_e peaking

Degree of core plasma density/temperature control in ITER with dominant P_α ?

Fuelling of ITER H-mode plasmas - II

- If ion transport in pedestal is neoclassical with low/no edge inwards convection for DT → density reachable by gas fuelling in ITER is limited (He plasmas)
- Fuelling of ITER plasmas DT will rely on pellet fuelling over large operational H-mode range but new control opportunities for ITER (n_{ped}/n_{sep})
- Initial experimental results consistent with physics picture → further experimental R&D and model validation required



He: 10^{22}/s, W: $5{\cdot}10^{18}$/s
He: $7.5{\cdot}10^{21}$/s, W: $5{\cdot}10^{18}$/s
He: $5{\cdot}10^{21}$/s, W: $5{\cdot}10^{18}$/s
He: $2.5{\cdot}10^{21}$/s, W: $5{\cdot}10^{18}$/s
He: 10^{22}/s, W: $1.5{\cdot}10^{19}$/s
He: $5{\cdot}10^{21}$/s, W: $1.5{\cdot}10^{19}$/s

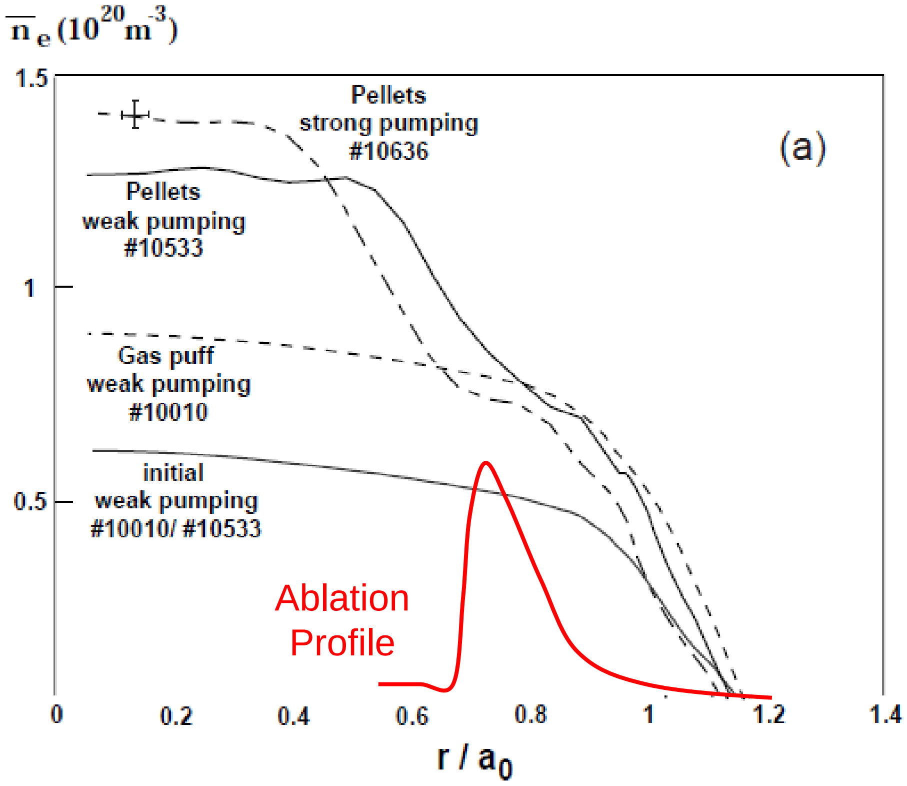
JETTO-SANCO
He: 7.5MA/2.65T
P_{ECRH} = 20 MW
P_{ICRH} = 20 MW
$P_{LH}^{He} = P_{LH}^{D}$
F. Köchl/V. Parail

$\langle n_e \rangle / n_{GW}$ ~ 0.4-0.5

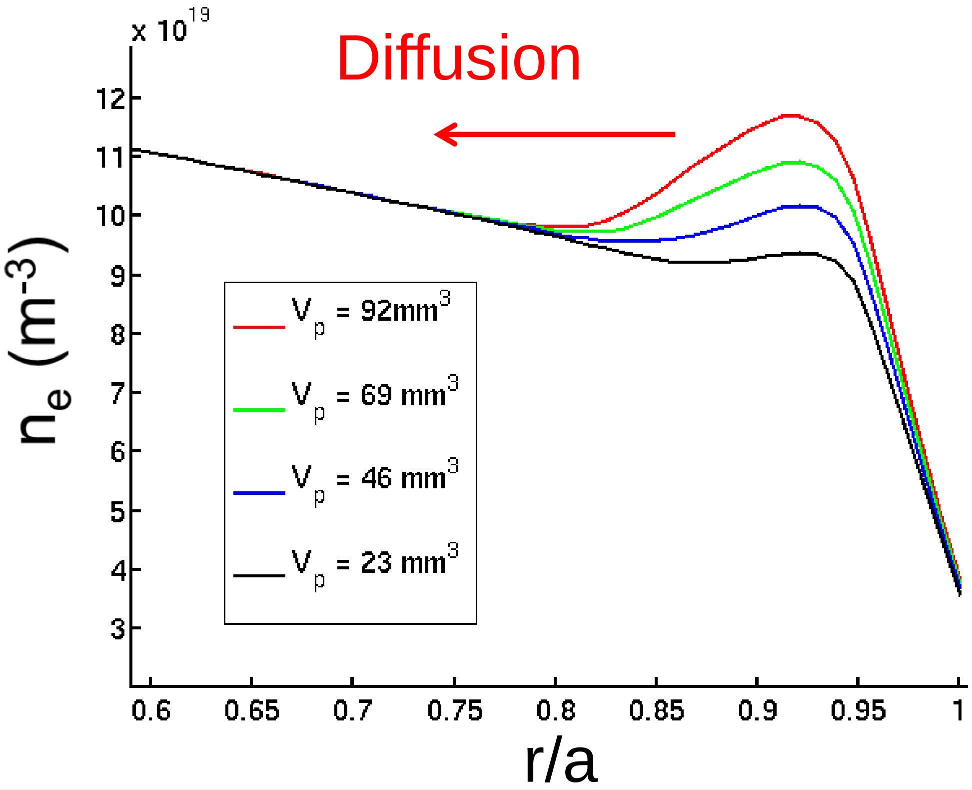
Fuelling of ITER H-mode plasmas - III

- Fuelling of plasmas by injecting solid DT pellets has been demonstrated in present experiments
- Due to high T_e pellets do not penetration deep in plasma → effectiveness of fuelling determined by transport processes (short + long timescales)

AUG – P. Lang – NF 2007



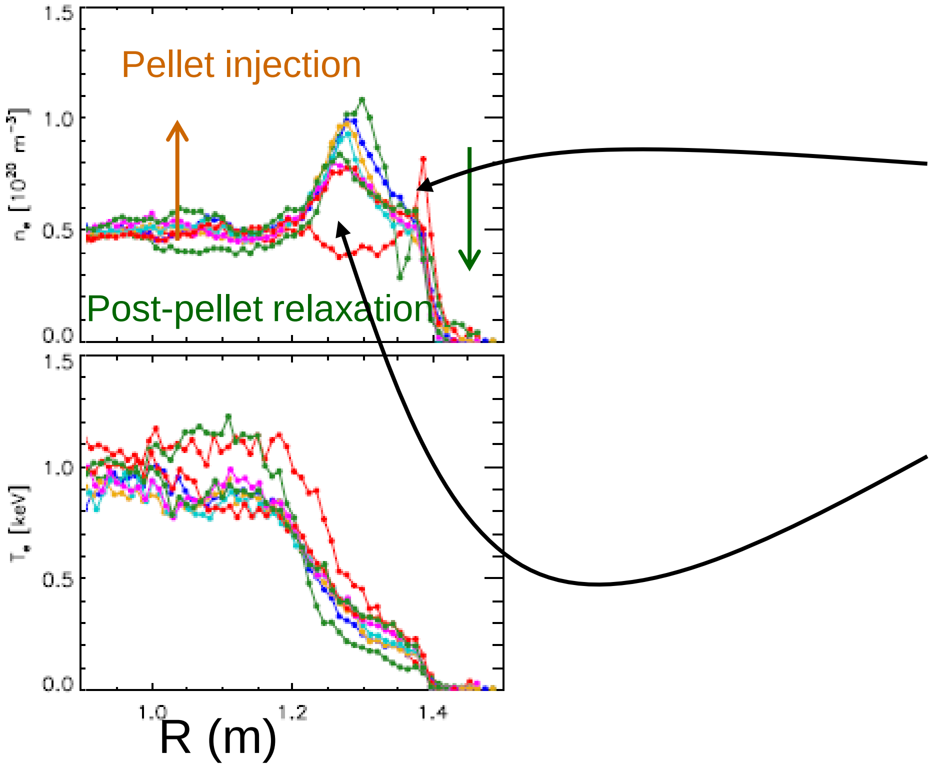
ITER – JINTRAC + HPI2 – F. Koechl

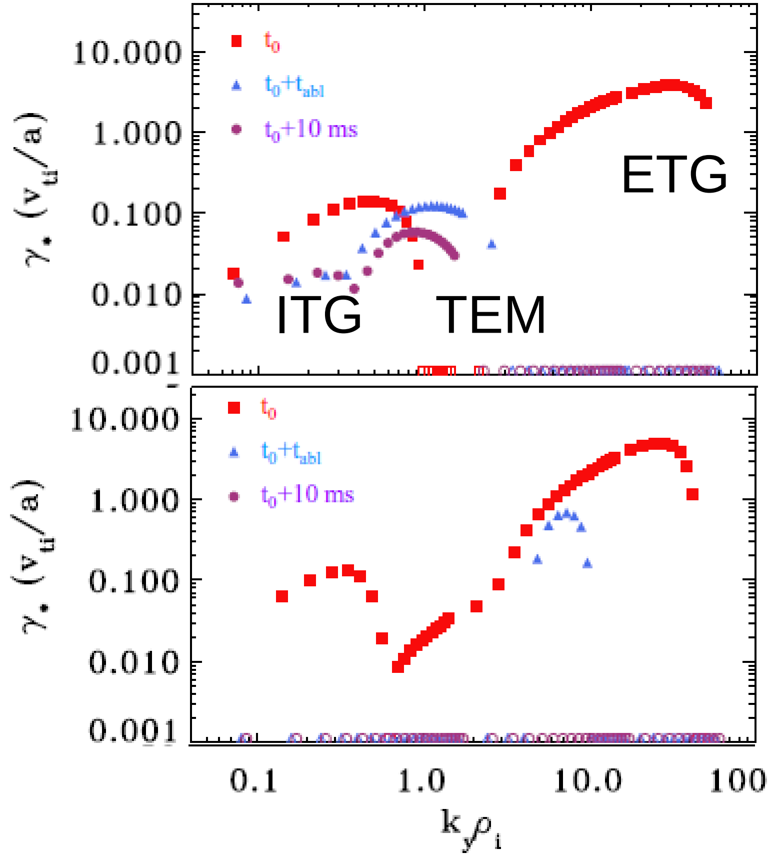


Fuelling of ITER H-mode plasmas - IV

- Injection of pellets → regions with "hollow" n_e profiles → significant modification of anomalous transport → reduction of net inwards particle flux after pellet
- R&D required to optimize pellet characteristics (size + velocity + frequency) for optimum inwards transport after pellet (L_n, L_T)

MAST + GS 2 Garzotti – PPCF 2004



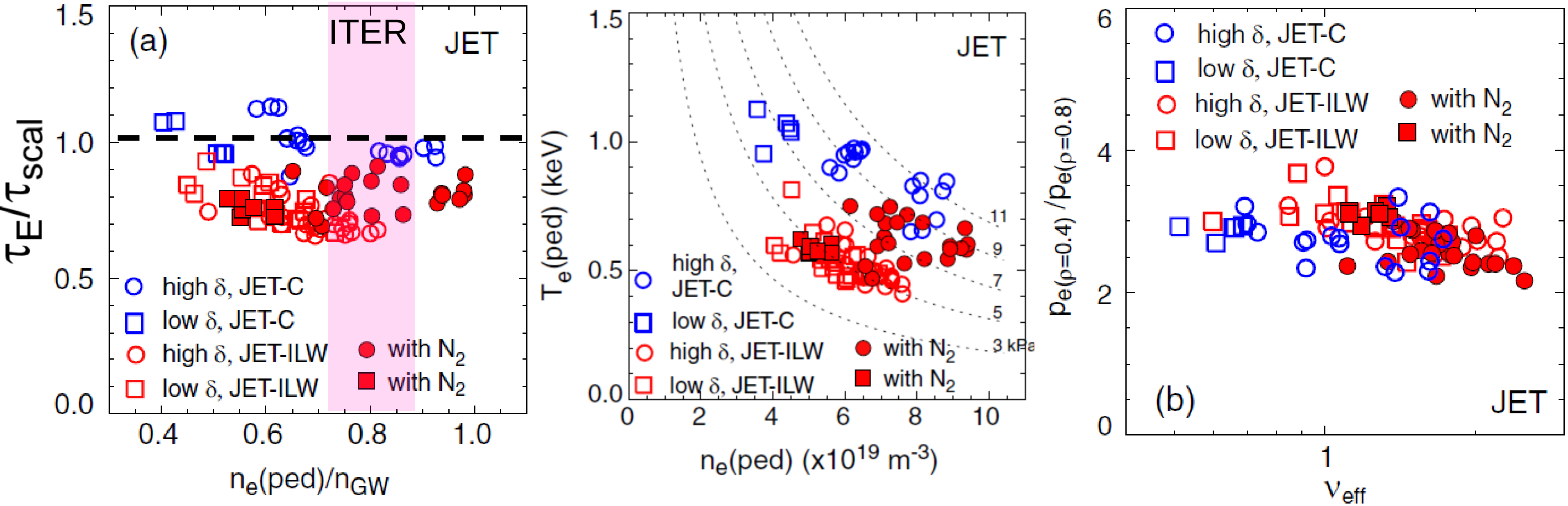


R&D on anomalous transport with "unusual" (L_n, L_T) formed when the plasma enters of exits the H-mode in ITER is required

Operation with W PFCs & energy confinement - I

- Operation with W leads to lower τ_E in H-modes in present experiments mostly through a reduction of pedestal pressure
  - Reduction of W sputtering between ELMs requires low T_{div} → high n_{edge} → strong gas fuelling
  - Avoiding penetration of W through pedestal into core plasma requires $f_{ELM} > f_{ELM}^{min}$
  - Adding low Z impurities (N) can affect confinement in positive way

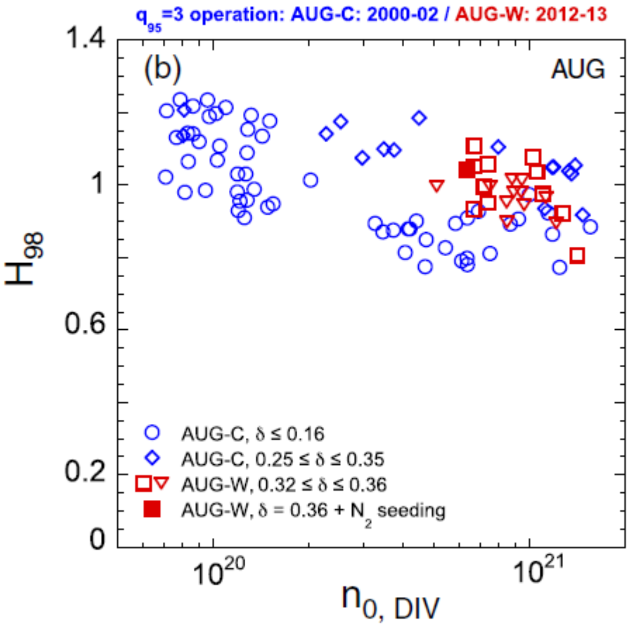
Beurskens, Schweinzer EPS 2013 & PPCF 2013

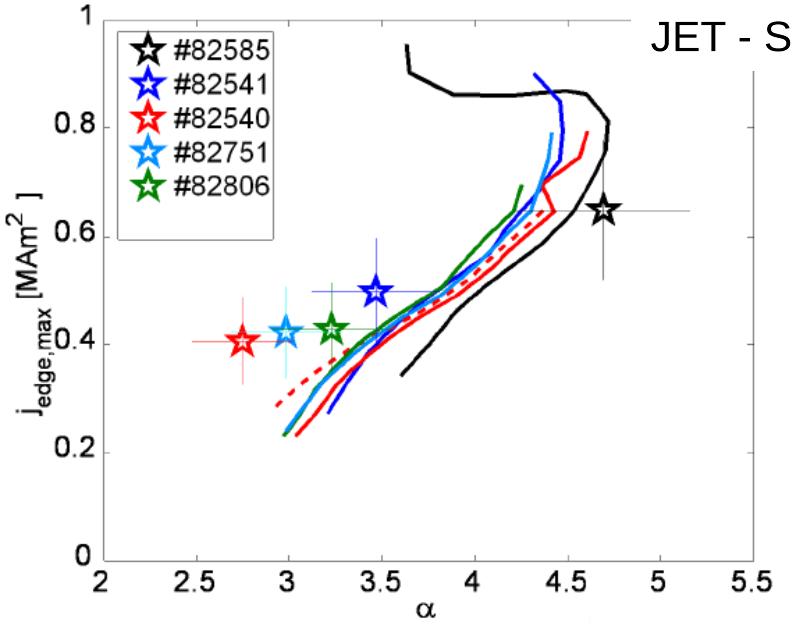


Operation with W PFCs & energy confinement - II

- Further R&D required to understand what physics processes lead to observed behaviour and their extrapolability to ITER
  - Consequences for fusion performance in ITER are sizeable Q/Q+5 ~ $(\tau_E/\tau_{scal})^3$
  - Are effects of neutral particles on H-mode pedestals extrapolable to ITER ? (low neutral penetration in edge transport barrier)
  - ITER plasmas will have low ν* even if $\tau_E/\tau_{scal-98}$ ~ 0.8 → is the reduction of edge plasma MHD stability (P_{ped}) extrapolable (j_{edge} decreased by ν*) ?
  - Low Z Impurities will be required in ITER for divertor power load control → will they have the same effect as in present experiments ?

Beurskens-Schweinzer EPS 2013 & C. Giroud EPS 20014



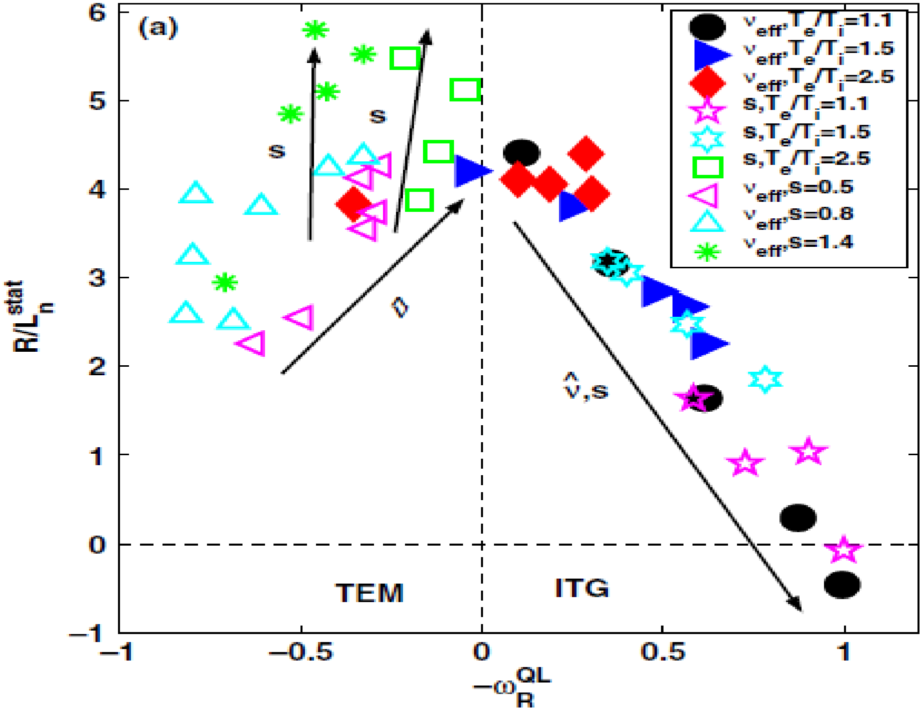


JET - Saarelma

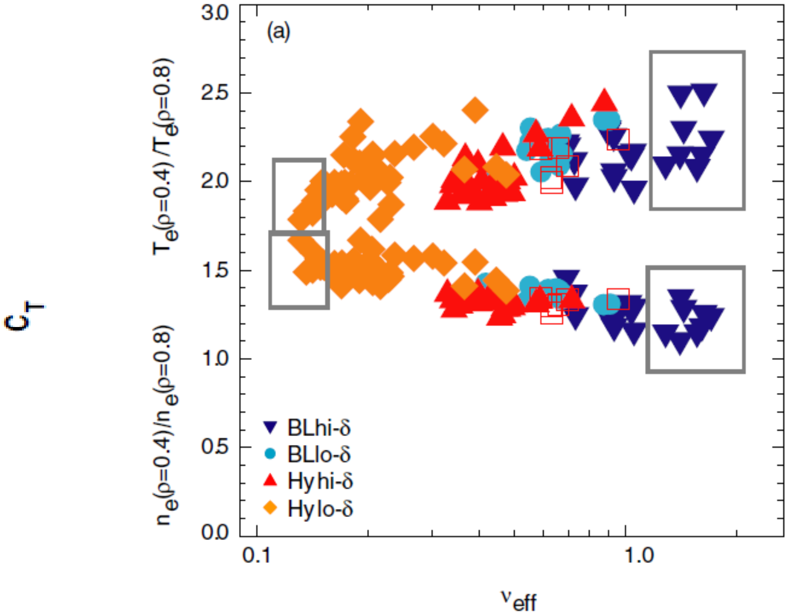
Core Transport in Stationary Phases – reserve

- Increased fusion performance requires high pressure (high core n_i and T_i) → understanding and optimization of inter-relation between core energy and particle transport in the absence of sources is required ITER
- Relative peaking of ion density/temperature → implications for W (Z = 74) transport if turbulent transport is low $\frac{\nabla n_Z}{n_Z} \sim Z\left(1 \quad - \quad H\frac{\nabla T_{DT}/T_{DT}}{\nabla n_{DT}/n_{DT}}\right)\frac{\nabla n_{DT}}{n_{DT}}$

GYRO + GS2 – E. Fable – PPCF 2010



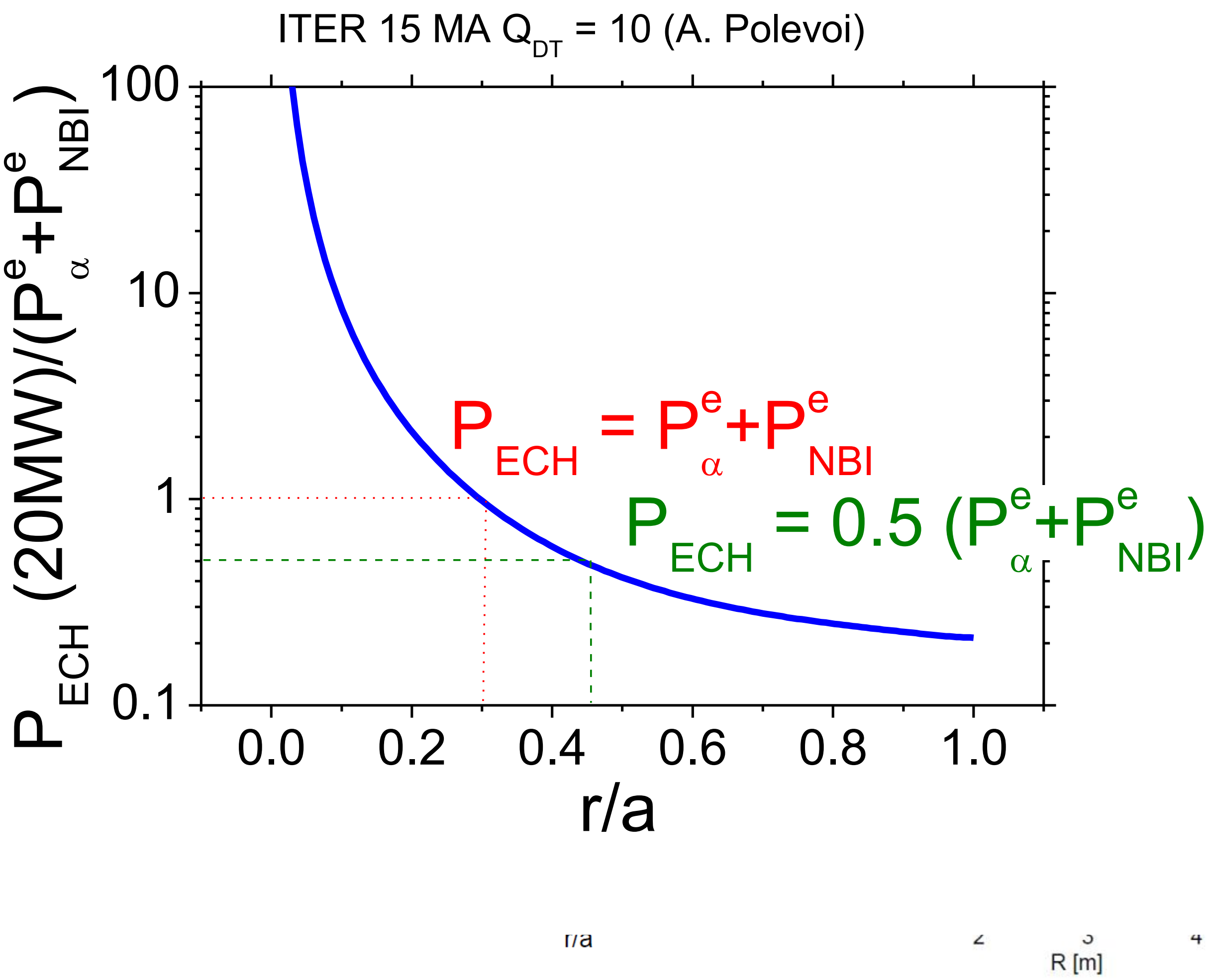
JET - Beurskens – NF 2013



ontrol in ITER with dominant P_α ?

Core Transport in Stationary Phases – reserve

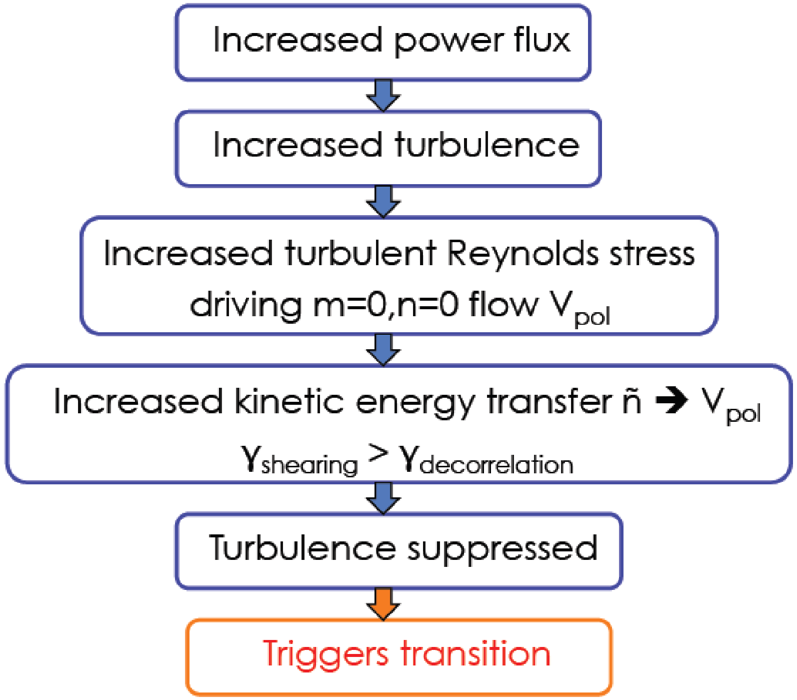
Despite dominant alpha heating ITER RF heating systems have sizeable capabilities to increase core electron heat flux



ITER 15 MA Q_{DT} = 10 (A. Polevoi)

H-mode access/exit R&D - reserve

- Physics paradigm for L-H transition may offer possibilities for its triggering with other actuators (not only P_{input}) ITER → quantitative assessment required (perturbation required, gain in P_{input} and back transition to L-mode)



Increased power flux

Increased turbulence

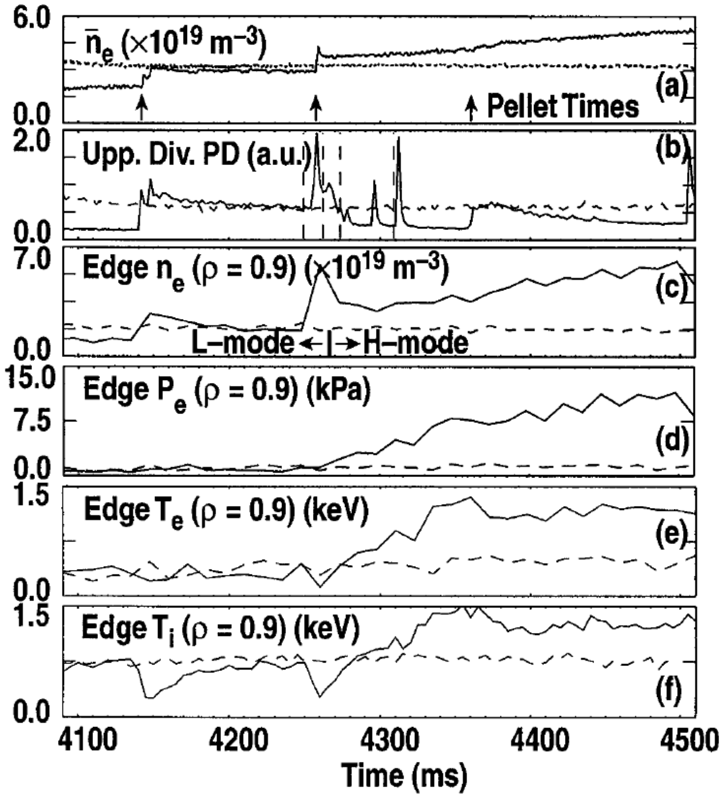
Increased turbulent Reynolds stress driving m=0,n=0 flow V_{pol}

Increased kinetic energy transfer $\tilde{n} \rightarrow V_{pol}$
$\gamma_{shearing} > \gamma_{decorrelation}$

Turbulence suppressed

Triggers transition

DIII-D - P. Gohil – PRL 2001

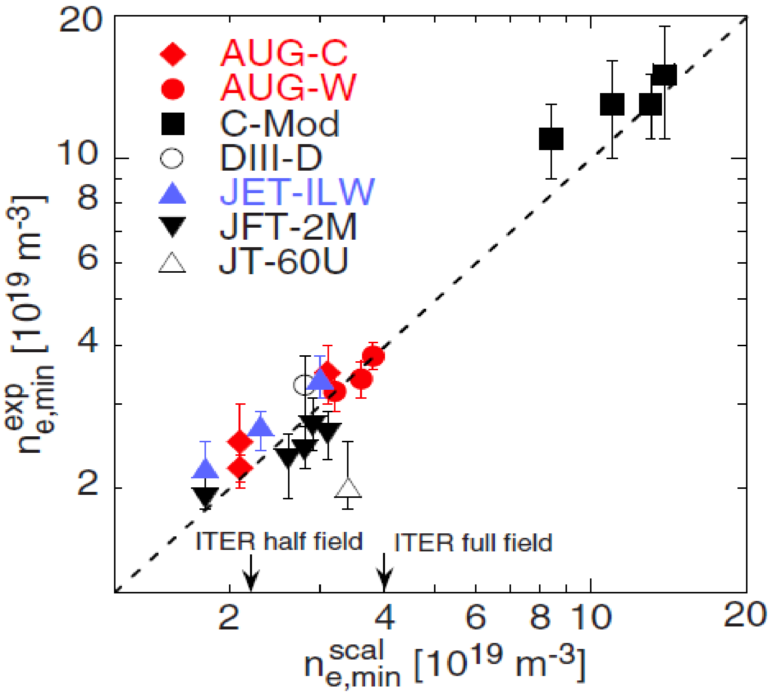


Most likely of use for regimes with high Q_{DT} in which P_α growth in H-mode provides significant increase of edge power flow

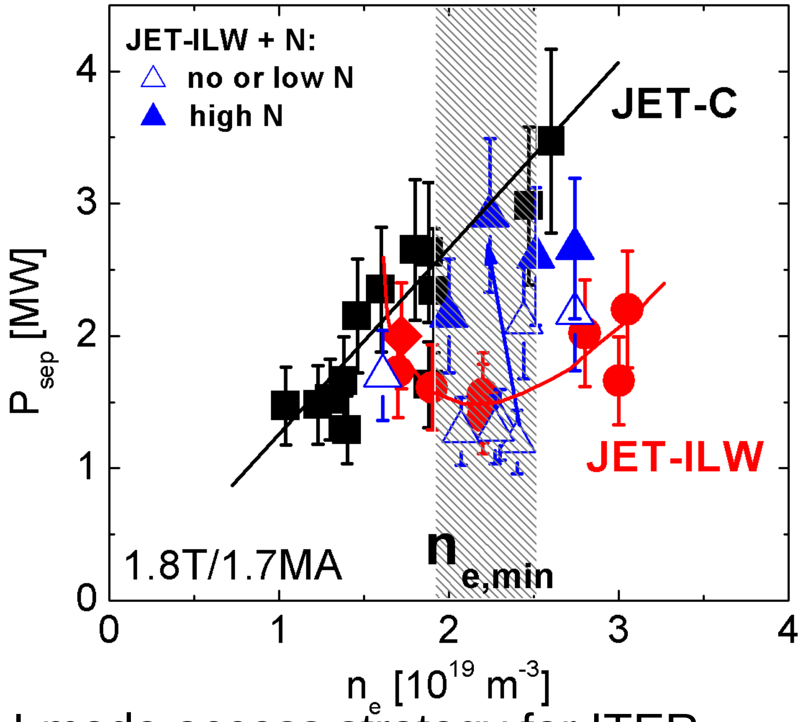
H-mode access/exit R&D - reserve

- Typical densities for H-mode access in ITER assumed to be above "minimum" density but physics basis not developed
- Recent developments identify physics effects that determine power threshold and minimum density →ion heating and decoupling of electron and ion heat channels and influence of Z_{eff}

ASDEX-Upgrade – F. Ryter NF - 2014



JET - C. Maggi - EPS 2014



- Understanding required to determine optimum H-mode access strategy for ITER
- Minimum density in He H-modes ?

High Performance access and exit - reserve

- Access to H-mode does not guarantee access to Q_{DT} = 10 in ITER ($P_{L\text{-}H}$ (Q_{DT} = 10) = 70-80 MW ~ $P_{add}^{installed}$) → alpha heating is a key player both in access and sustainment of Q_{DT} = 10 in ITER
- Evolution of n_e ($P_{L\text{-}H}$) and P_α are key to Q_{DT} = 10 access

ITER – JINTRAC
F. Köchl – IAEA 2014

GLF23 : Q_{DT} ~ 10
P_{AUX} = 53 MW from 80s
10s delay in n_e ramp

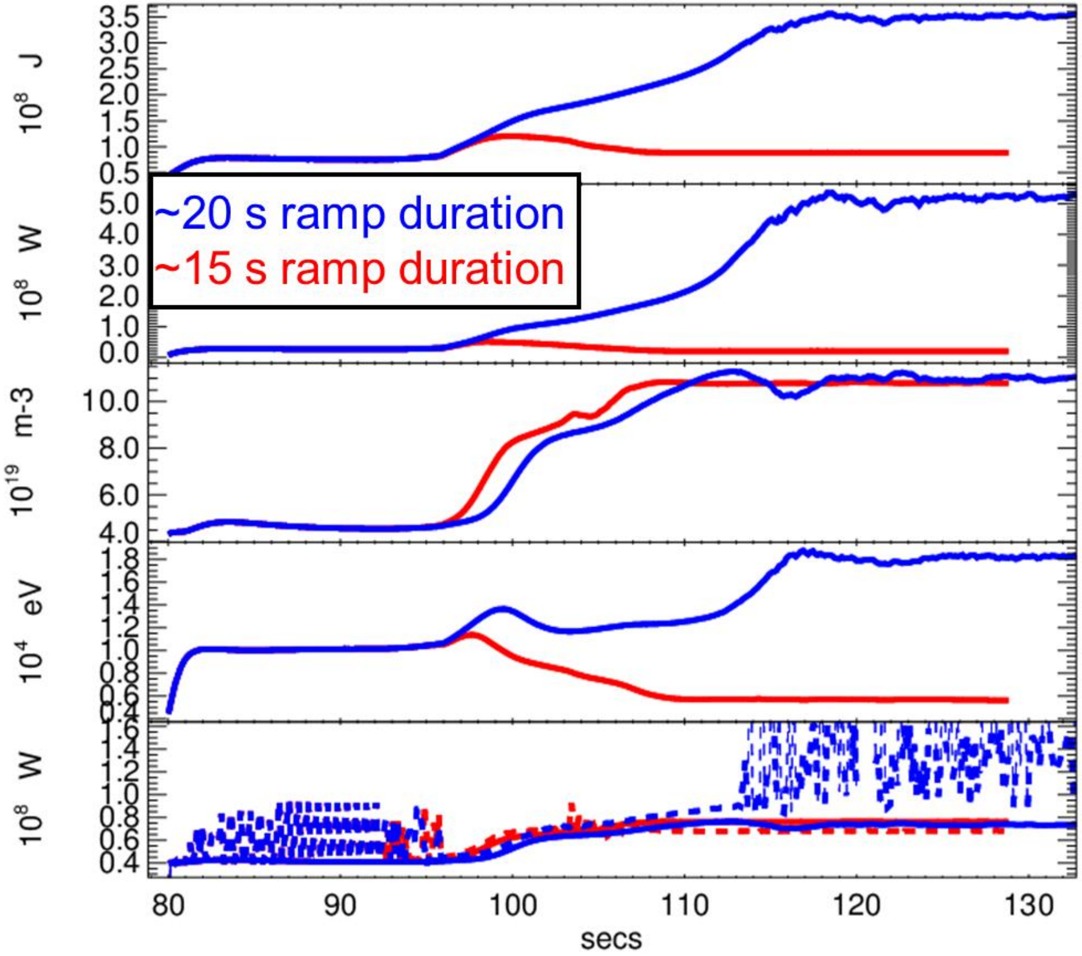
W_{th}:

P_{fus}:

$n_{el.lin.avg.}$:

$T_{i,ax}$:

P_{net} (dashed)
$P_{L\text{-}H}$ (solid):

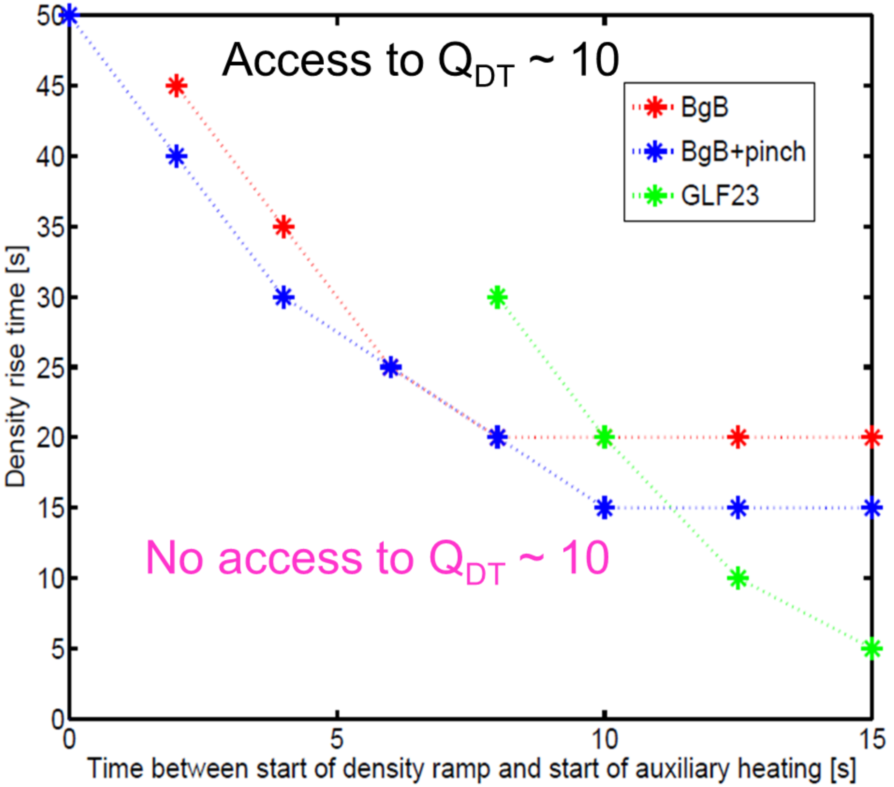


~20 s ramp duration
~15 s ramp duration

High Performance access and exit - reserve

- Low n_e pre-heated phase and slow ne ramp-up from L-mode to H-mode value required to access Q_{DT} = 10

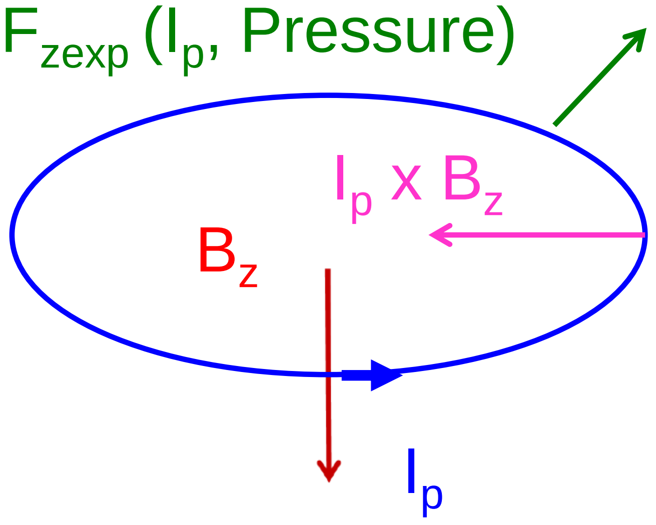
ITER – JINTRAC - F. Köchl – IAEA 2014



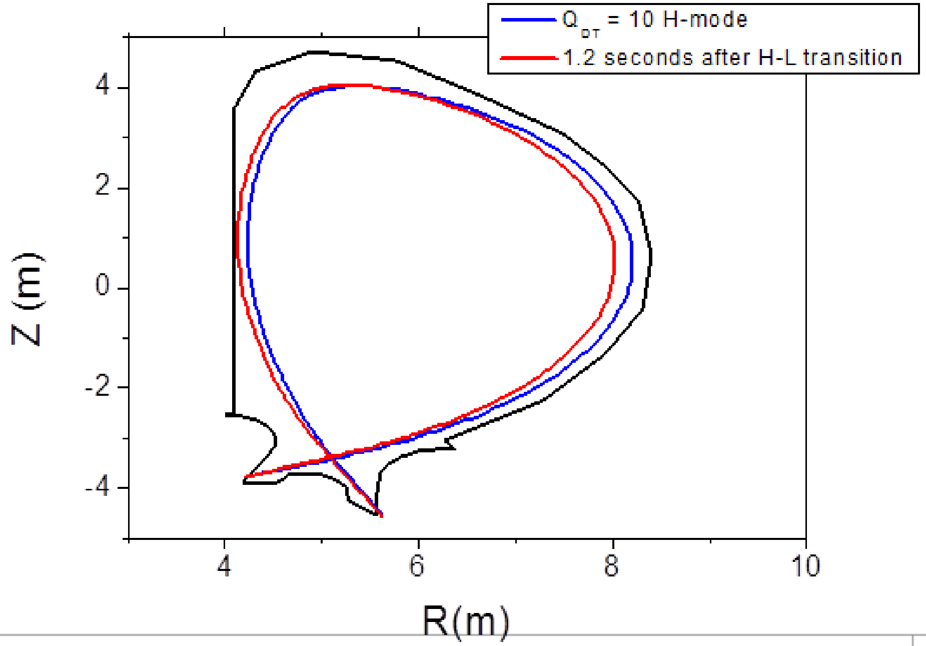
- Can initial low n_e H-mode phase be maintained in ITER ?
- How good is our transport physics understanding of core n,T evolution in H-mode transients ?

High Performance access and exit – reserve

- Fast H-L transitions (instantaneous H_{98} = 1 → L-mode) in ITER can lead to large power fluxes on inner-wall due to the plasma radial inwards shift associated with it
  - $\tau_E^L \sim 2$ s vs. $\tau_{Bz} \sim 5$ s → Large superconducting coils (except CS) and thick conductive vessel
  - $I_p \times B_z$ force larger than expansion force from plasma for τ_{Bz}
  - Plasma moves inwards and approaches inner wall → large power fluxes



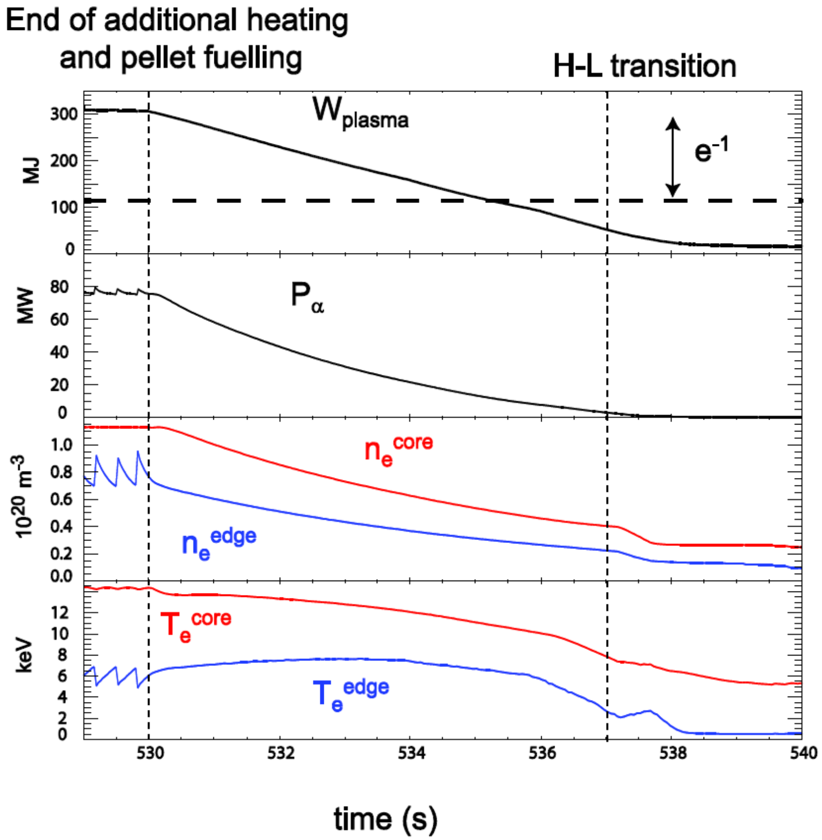
ITER – J. Lister – DINA - EPS 2013

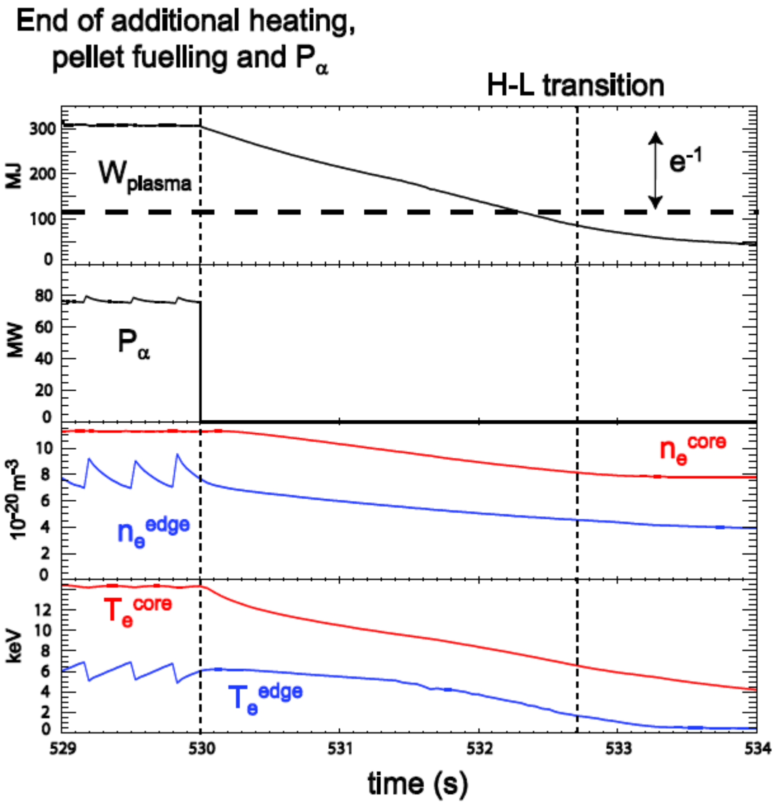


High Performance access and exit - reserve

- Timescale of energy collapse determined by duration of H-mode phase after end of additional heating
- Key factors: P_α and n_e ($P_\alpha+P_{H\text{-}L}$) behaviour in H-mode collapse phase

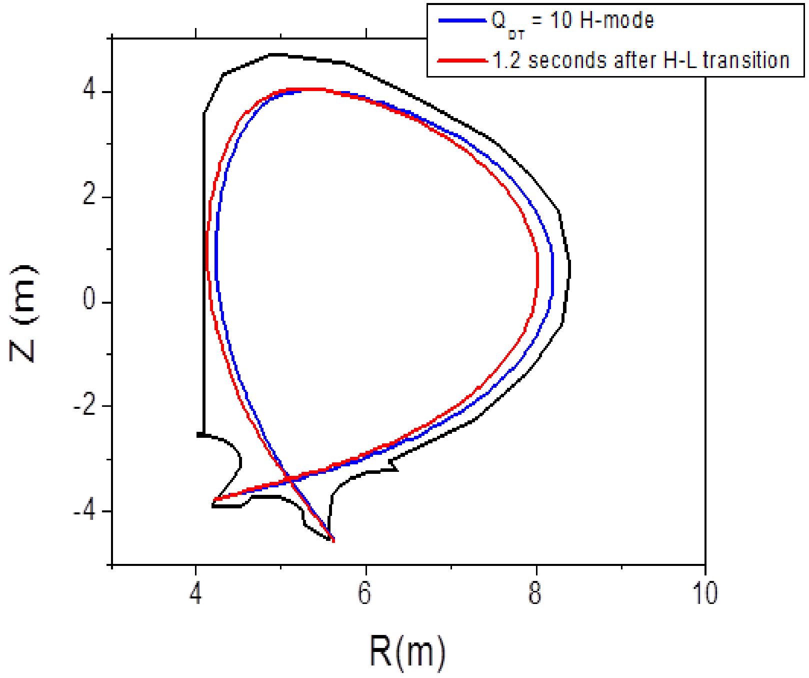
ITER JINTRAC simulations with JET-validated assumptions – F. Köchl
A. Loarte sub. NF 2014





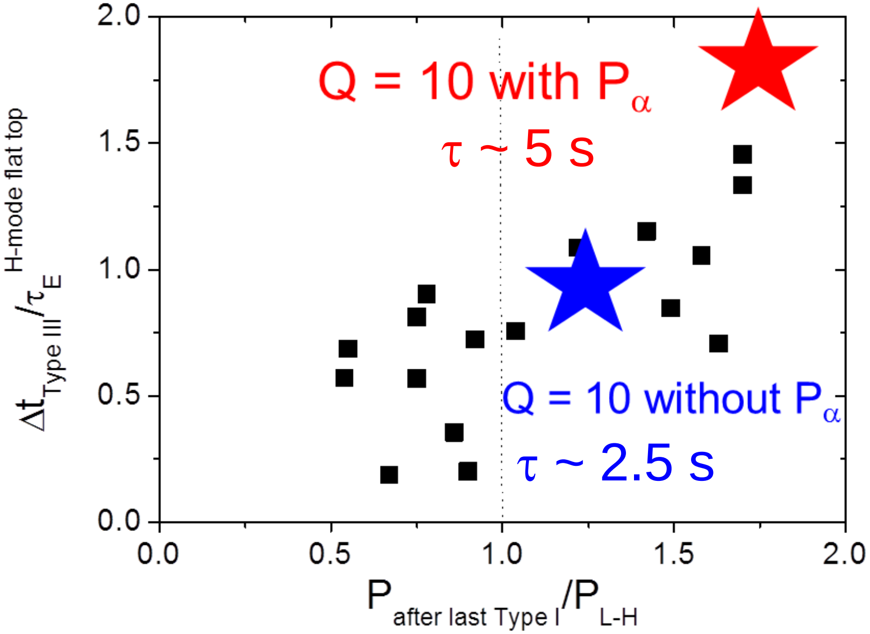
H-Mode Exit

- **Low or no hysteresis on edge parameters (ASDEX-U) nor edge & global parameters (JET):**
  - implications for H-mode back-transition in ITER (duration of type III H-mode phase and timescale of W_{plasma} collapse)
- **Important to characterize and understand timescales of energy and particle transport (including W) in H-L transition to evaluate risk of radiative collapse in ITER**



EPS 2013

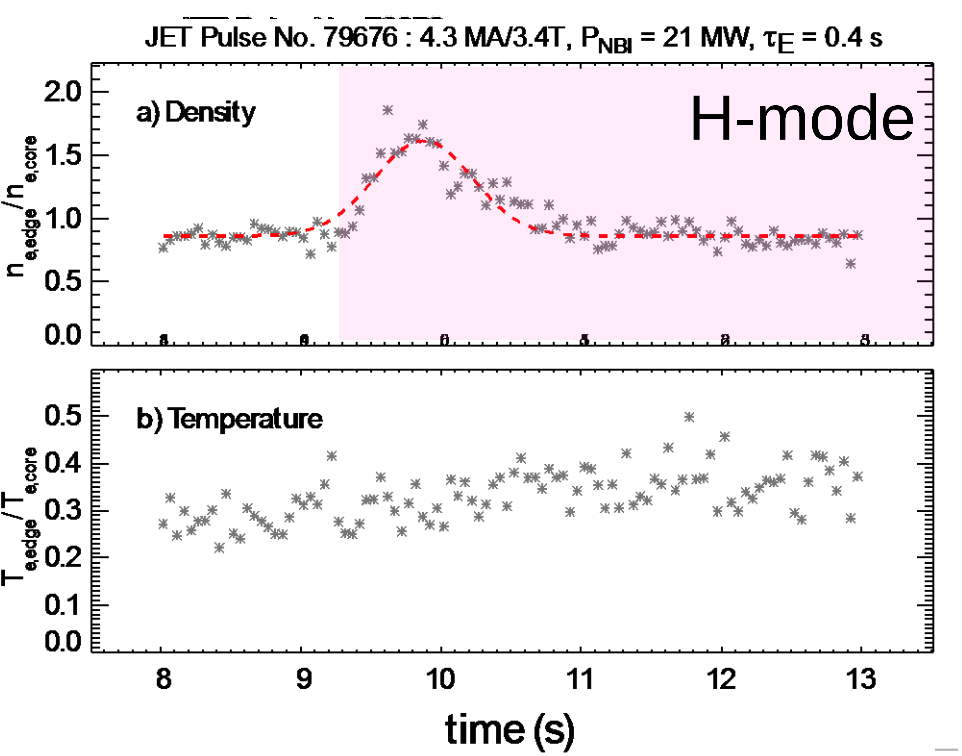
JET + ITER modelling

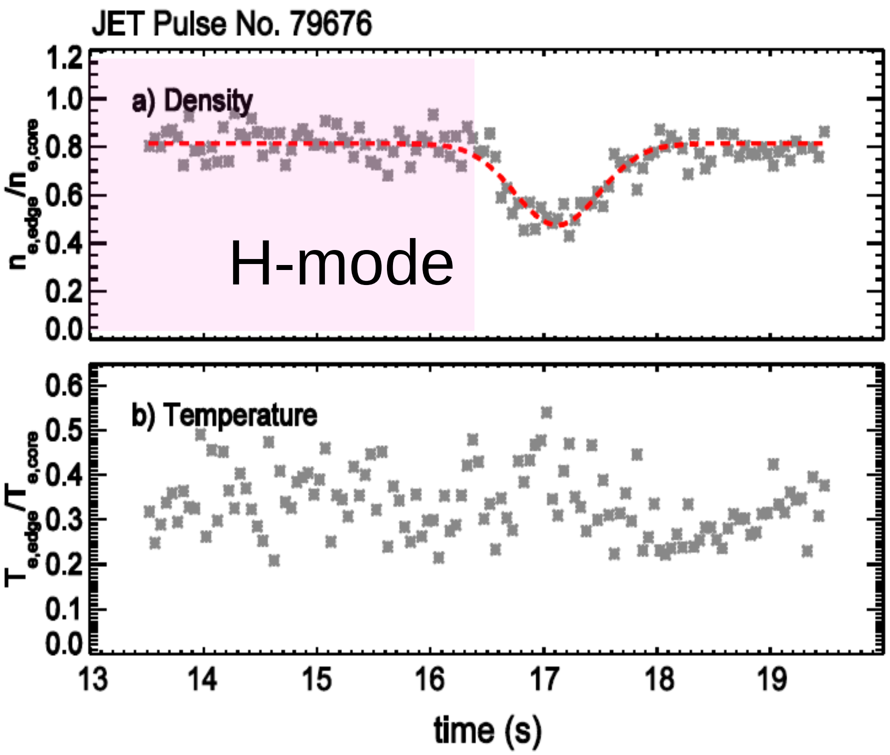


Transport in Transient H-mode Phases - reserve

- Understanding of transport in H-mode transients and H-mode sustainment in these phases is key to predict and control ITER plasma on access/exit → effect on P_{α}, P_{L-H} and high Z core impurity accumulation (evolving T profiles with non-stiff n_e profiles)

Hollow n_e formed in H-mode access and peaked n_e in H-mode exit
A. Loarte – NF 2013 + Sub. NF 2014

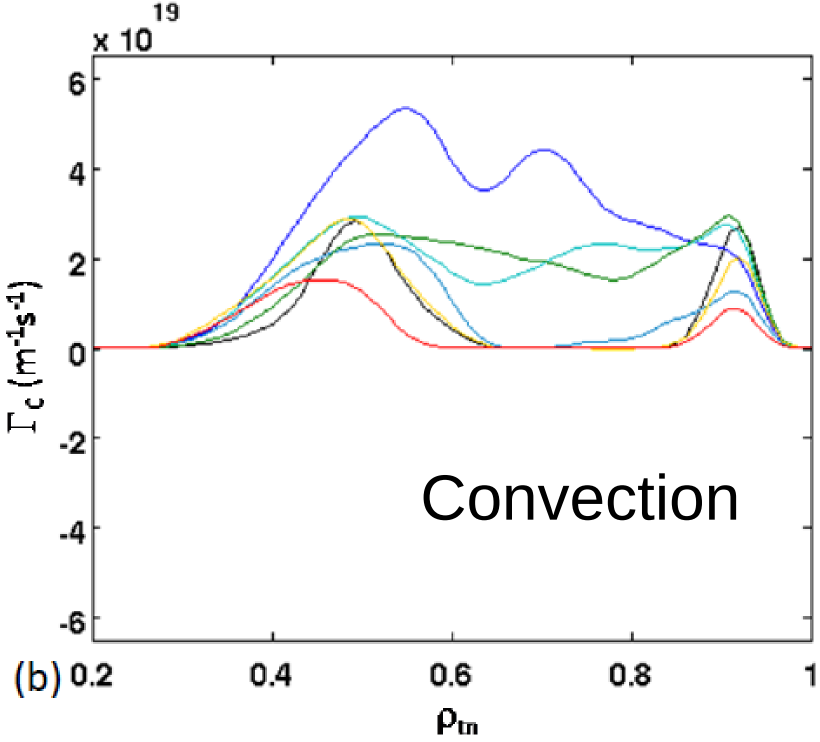


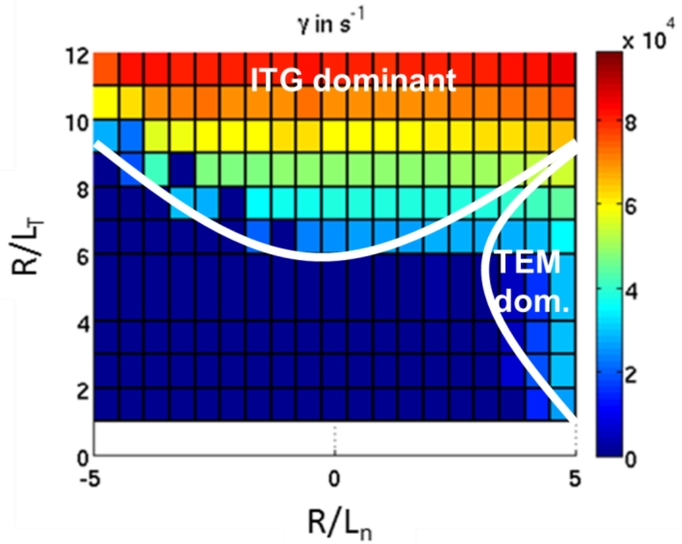


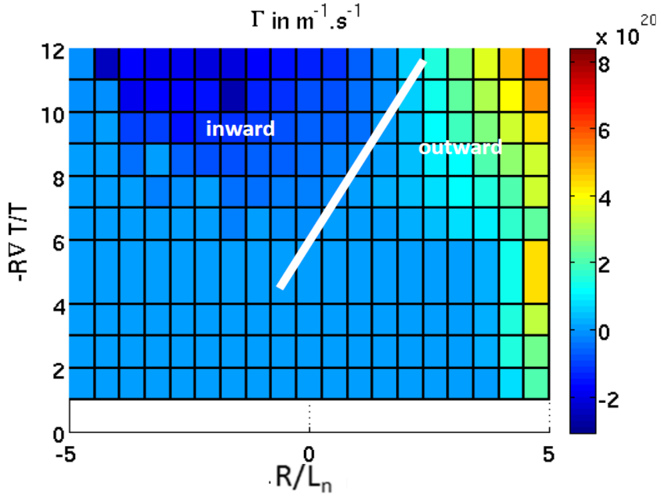
Transport in Transient H-mode Phases - reserve

- Particle transport in transients cannot be correctly modelled by effective diffusion and pinch values that describe stationary conditions → turbulent transport changes with grad-n

JET – CRONOS + Qualikiz – Baiocchi in preparation



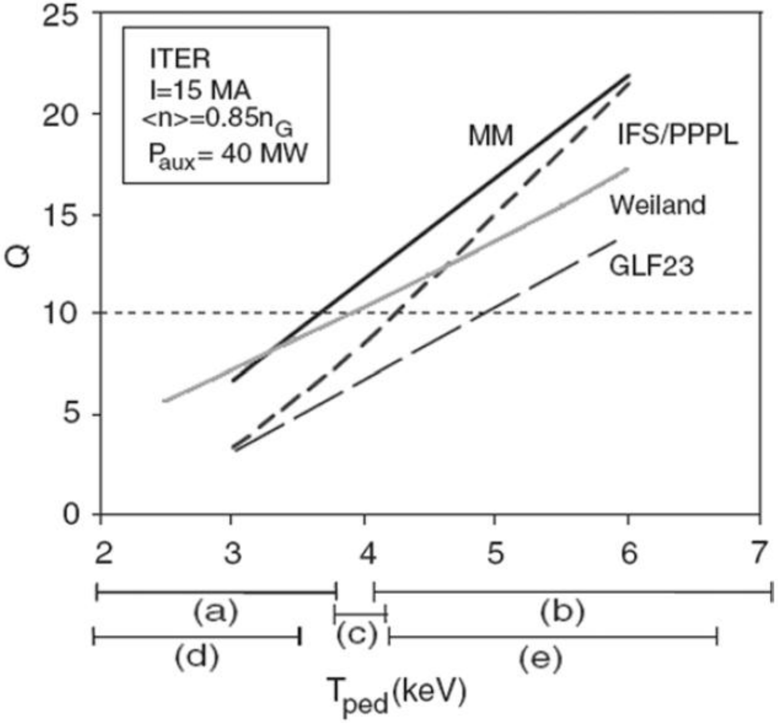




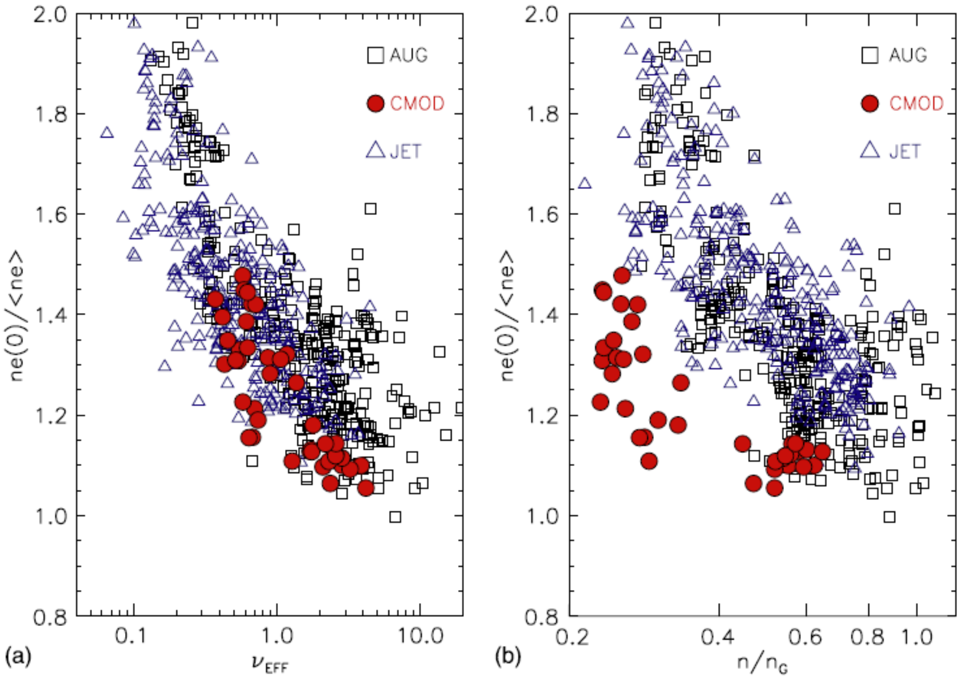
Core Transport in Stationary Phases – reserve

- Core transport studies have been focused on determining stiffness of T profiles and ITER fusion performance in ITER plasmas

ITER – Progress on IPB NF 2007



C-Mod-AUG-JET – M. Greenwald - NF 2007

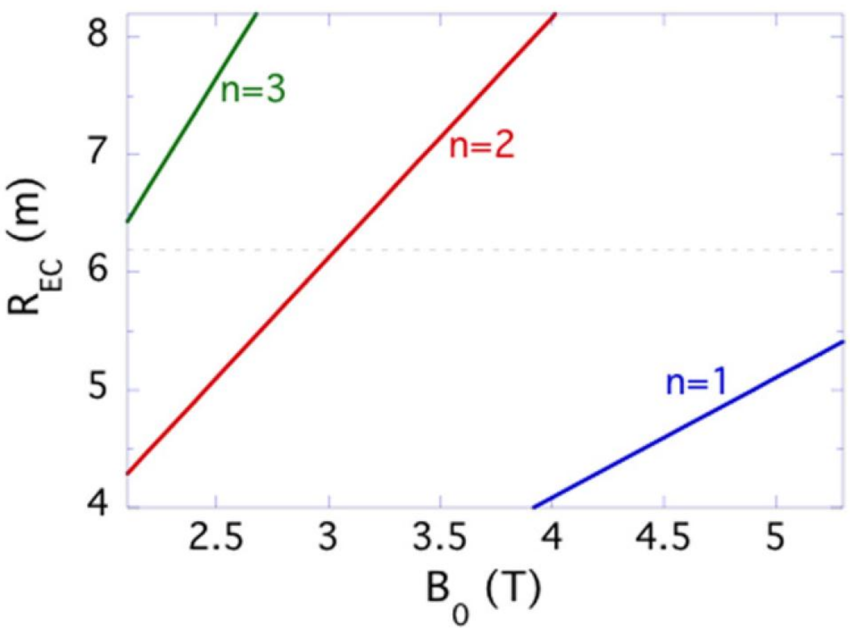


- Continued R&D with emphasis on ITER-like plasma conditions : dominant electron heating, low momentum input, fast particle population, etc.
- Further R&D required to address transport in He plasmas and edge integration issues → ITER capabilities/strategies of core transport control

Core Transport in Stationary Phases – reserve

- Requirements for electron heating for core transport control can also affect the H-mode scenario development strategy in ITER from low I_p to high I_p/Q_{DT} plasmas

ITER - D. Farina – NF 2012



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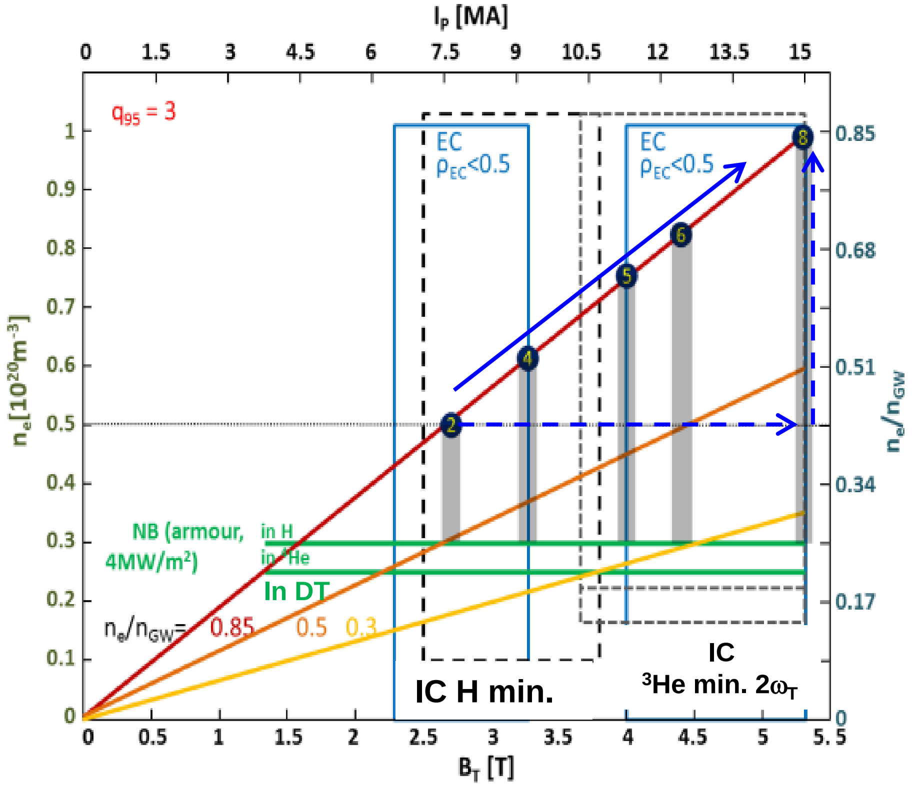
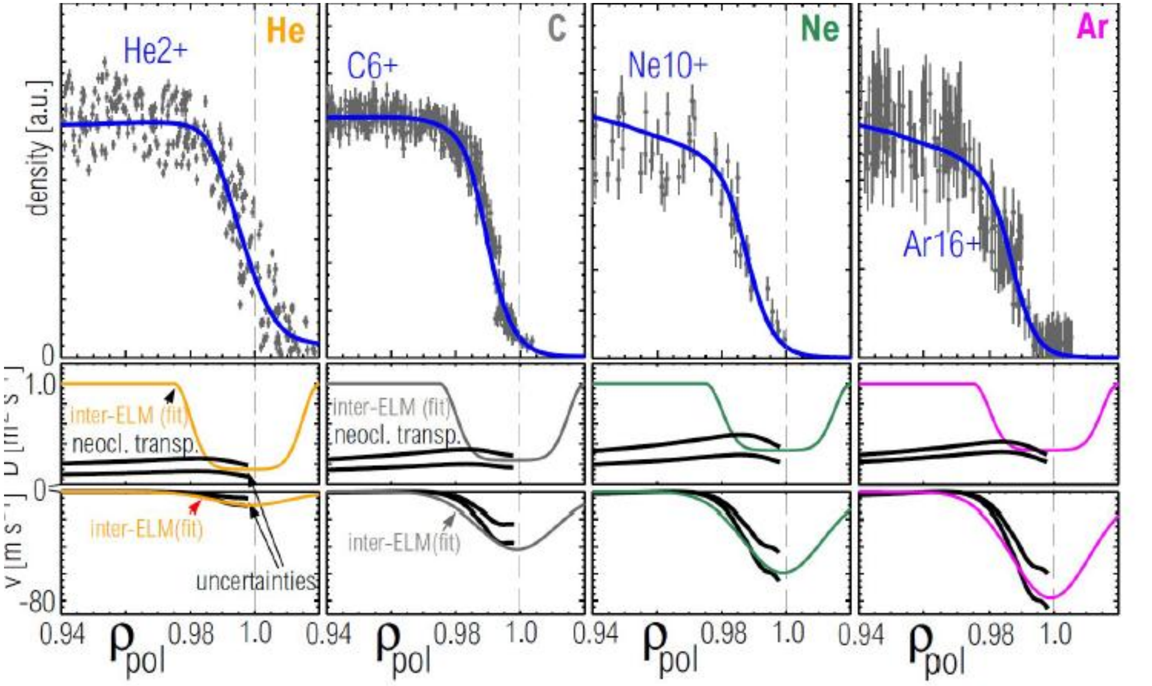


- How much central ECH is required in plasmas without alpha heating ?
- Are requirements the same for D (DT) and He plasmas ?

Edge Transport in H-mode – reserve

- ➢ Usual findings for pedestal transport → reduction to ~ ion neoclassical transport for main ions and impurities in edge transport barrier

ASDEX-Upgrade - T. Pütterich JNM 2011

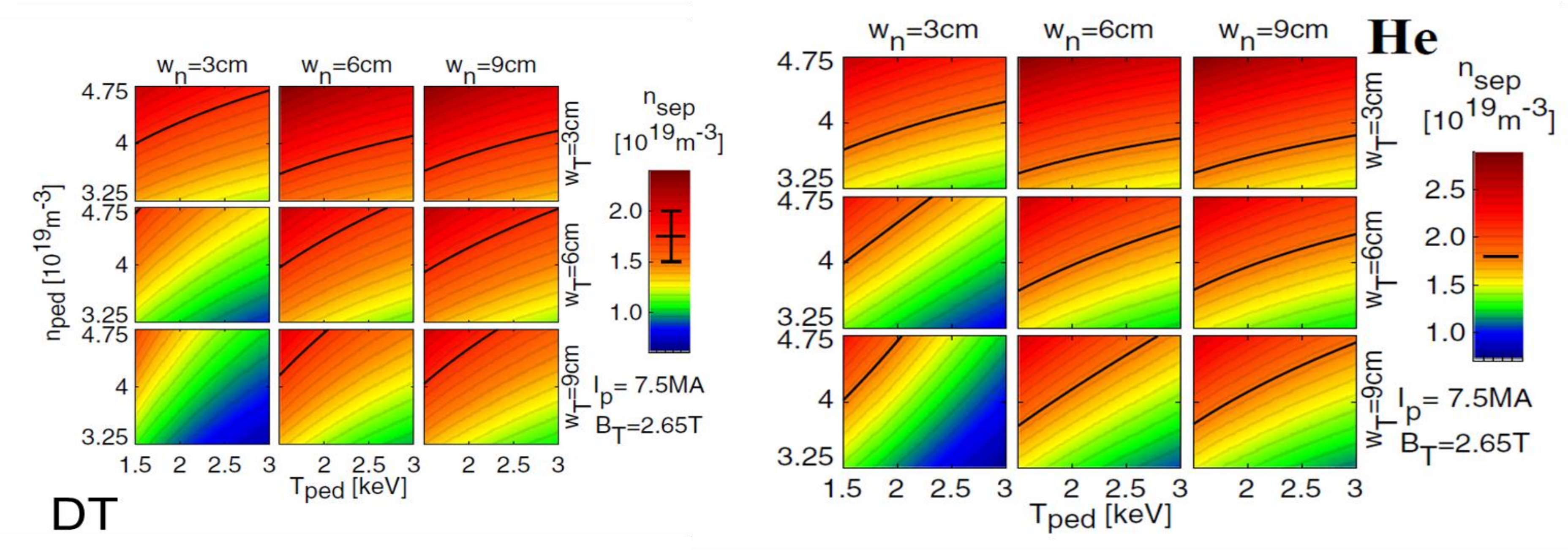


- This physics picture has important implications for edge impurity transport and its control in ITER (as well as for fuelling by gas puffing) → further R&D to confirm it

Edge Transport in H-mode – reserve

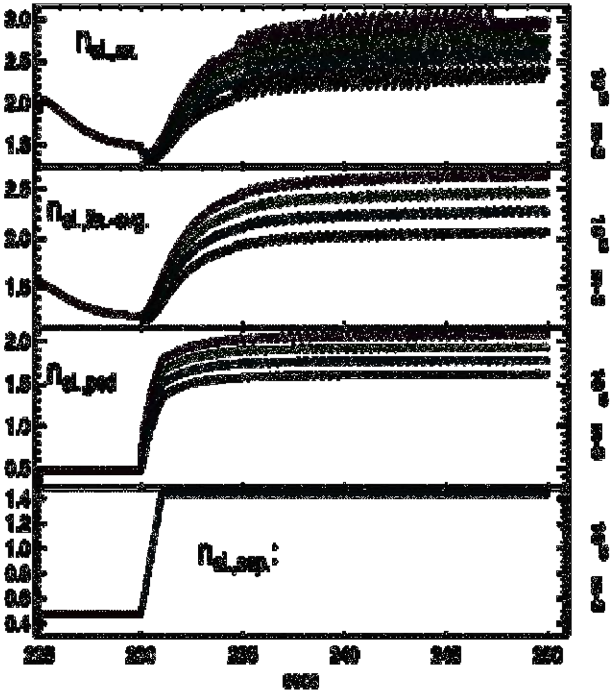
- He transport in pedestal is more unfavourable than in D (stronger inwards pinch)
- He is expected to sputter W more effectively than DT between ELMs and at ELMs → larger W influx → larger W radiation → more stringent ELM control requirements than in D plasmas

ITER- STRAHL+NEOART - R. Dux – sub. PPCF



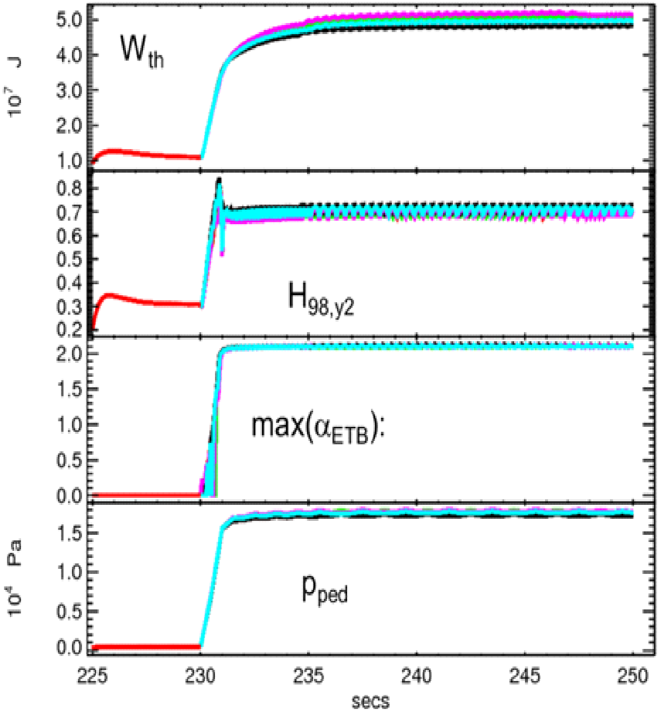
Edge Transport in H-mode and Plasma Fuelling – reserve

- He H-modes may have a narrow operational density range
  - He H-mode access robust for $P_{add} \geq 40$ MW → $\langle n_e \rangle^{H\text{-mode}} \sim 2.5\text{-}3.0 \times 10^{19}\ m^{-3}$ (above NBI shine-through limit) due to low core He source
  - Low $\langle n_e \rangle^{H\text{-mode}}$ → hollow W pedestal profile and low core n_W
  - Will this low $\langle n_e \rangle$ be the minimum threshold density ?



He: 10^{22}/s, W: $5\cdot10^{18}$/s
He: $7.5\cdot10^{21}$/s, W: $5\cdot10^{18}$/s
He: $5\cdot10^{21}$/s, W: $5\cdot10^{18}$/s
He: $2.5\cdot10^{21}$/s, W: $5\cdot10^{18}$/s
He: 10^{22}/s, W: $1.5\cdot10^{19}$/s
He: $5\cdot10^{21}$/s, W: $1.5\cdot10^{19}$/s

JETTO-SANCO
He: 7.5MA/2.65T
P_{ECRH} = 20 MW
P_{ICRH} = 20 MW
$P_{LH}^{He} = P_{LH}^{D}$
F. Köchl/V. Parail

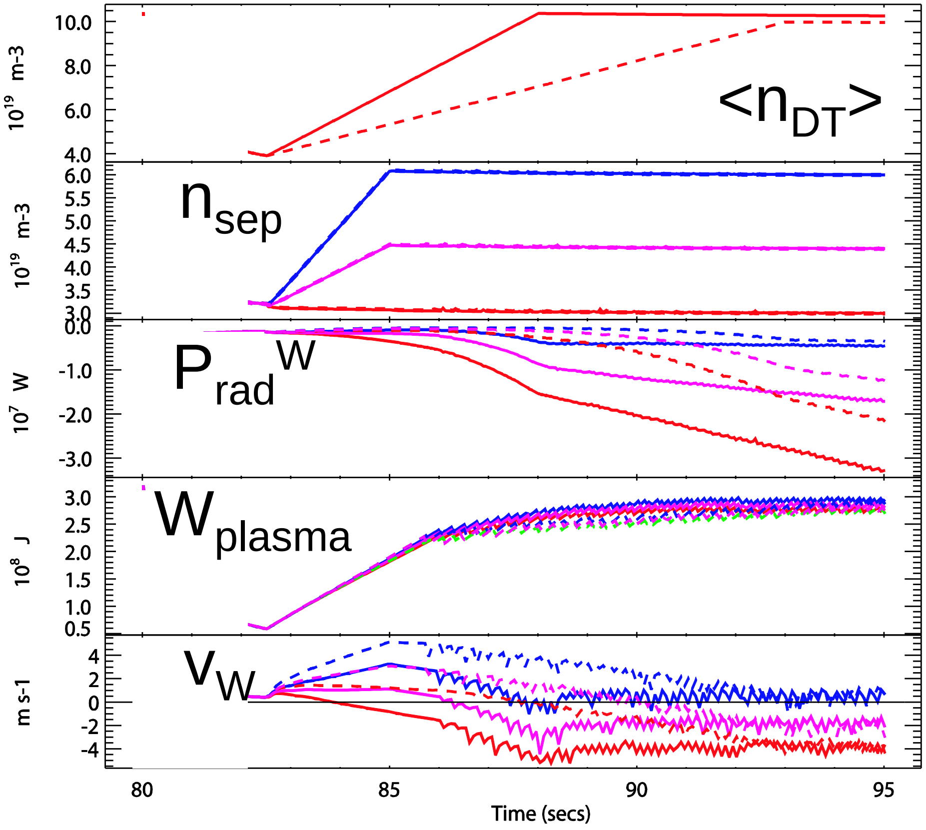


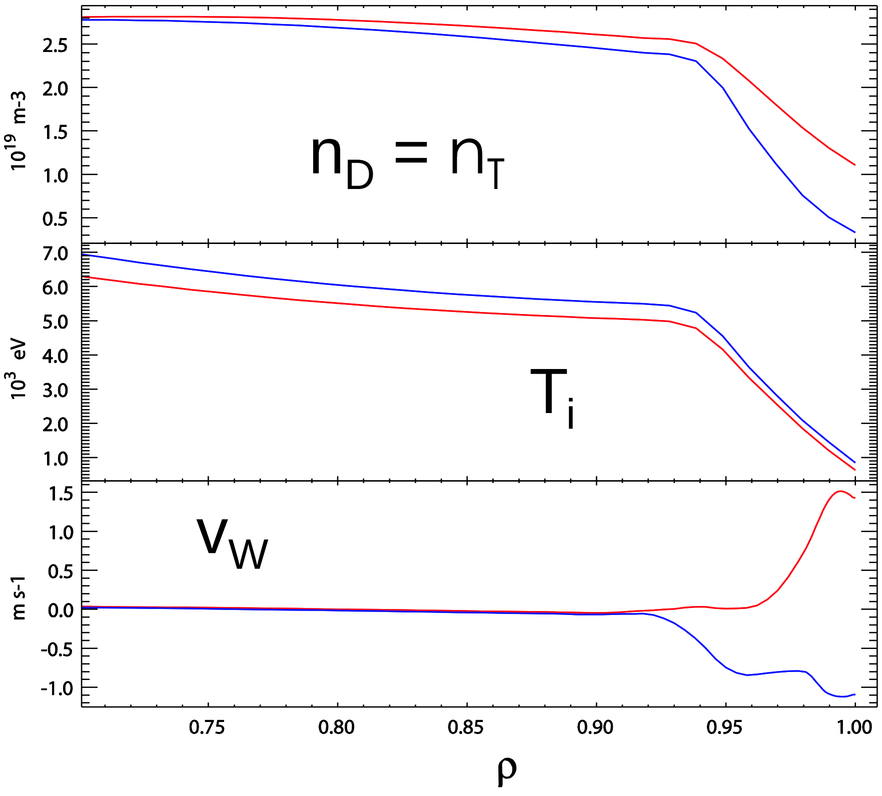
- R&D on core and edge main ion and impurity transport in He H-modes required

Optimization of high Z impurity control in ITER - reserve

- ✓ Optimization of separatrix (gas fuelling) and pedestal density (pellet) can be applied to keep W pinch outwards in the pedestal → is this a solid physics basis ?

ITER – JETTO-SANCO- Parail

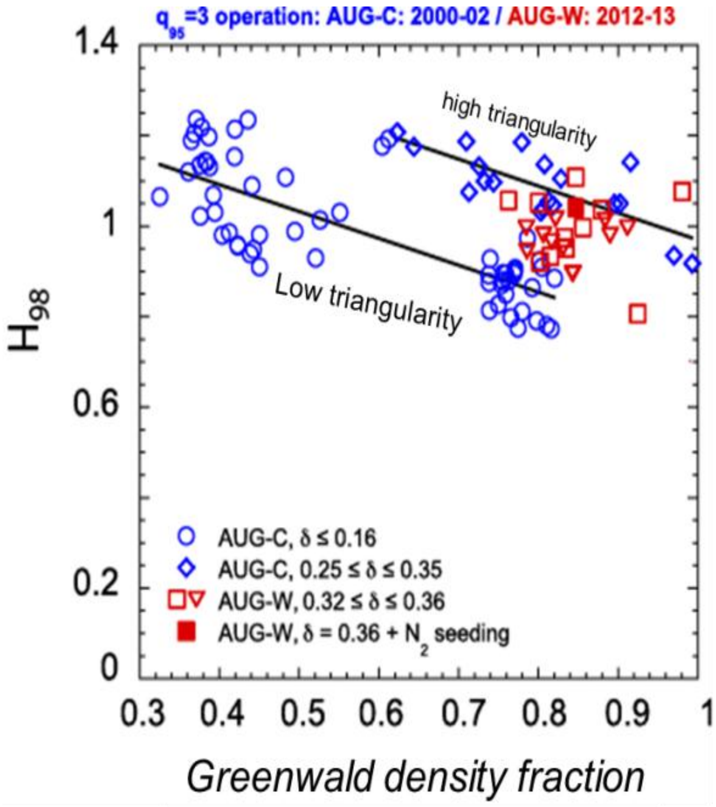


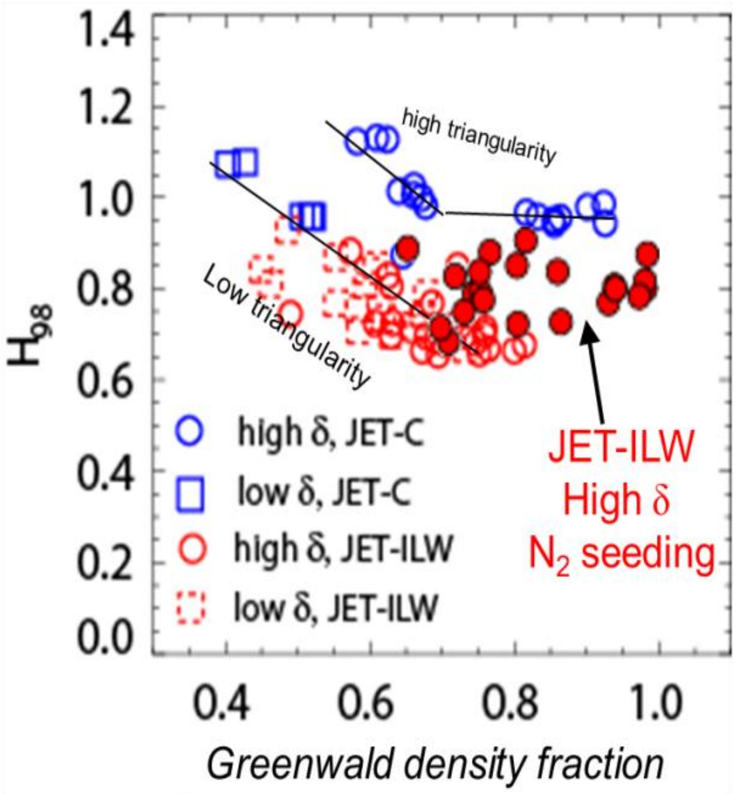


Compatibility of PFCs and energy confinement - I

- Compatibility with W leads to lower p_{ped} and lower H_{98} → is the direct empirical extrapolation to ITER relevant ?
  - Reduction of W sputtering between ELMs (high n_{sep} & high ν^*_{ped}) may not extrapolate to ITER (decoupling of n_{sep} and n_{ped} → low ν^*_{ped})
  - Impurity seeding required for q_{div} control over large operational range (narrow λ_p)

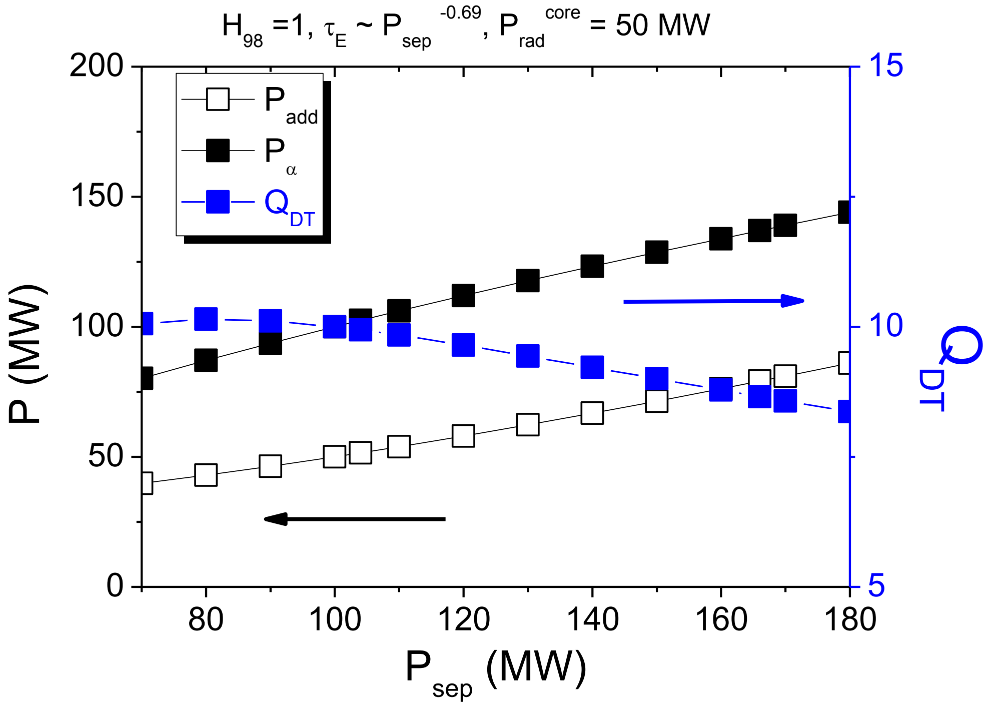
Beurskens, Schweinzer EPS 2013 & PPCF 2013

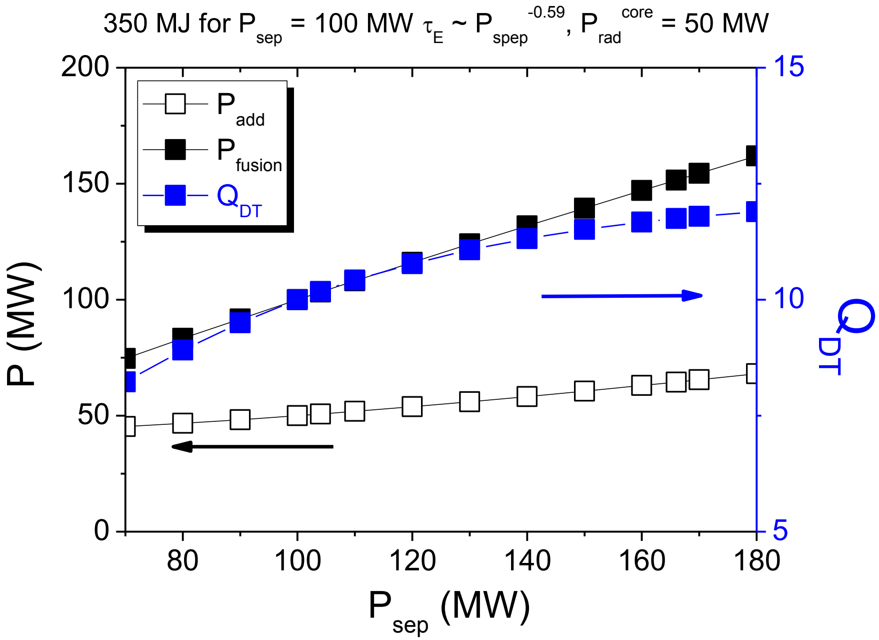




Compatibility of PFCs and energy confinement - reserve

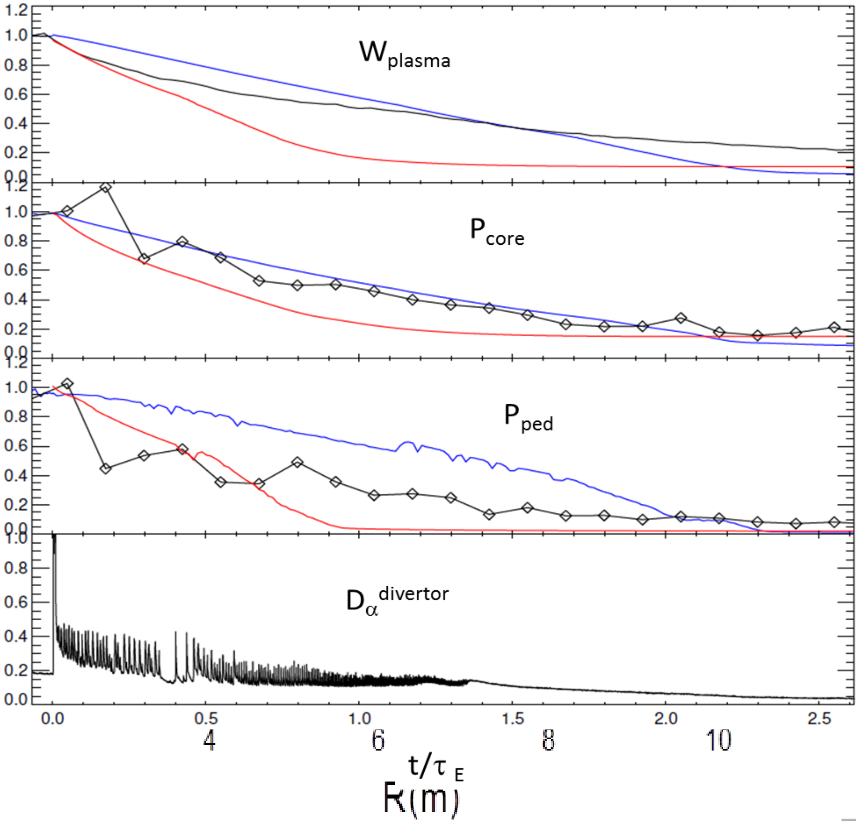
- Increasing β leads to recovery of H_{98} ($W_p \sim P^{0.5}$ instead $W_{p\text{-}98} \sim P^{0.3}$) → physics needs to be understood (core – pedestal integration)
- Consequences for ITER operation and fusion power control are significant : $Q_{DT} \sim P_{add}^{-1}$ (for $Q_{DT} >> 5$) and H_{98} while Q_{DT} does not depend on P_{add} (for $Q_{DT} >> 5$) with $W_p \sim P^{0.5}$

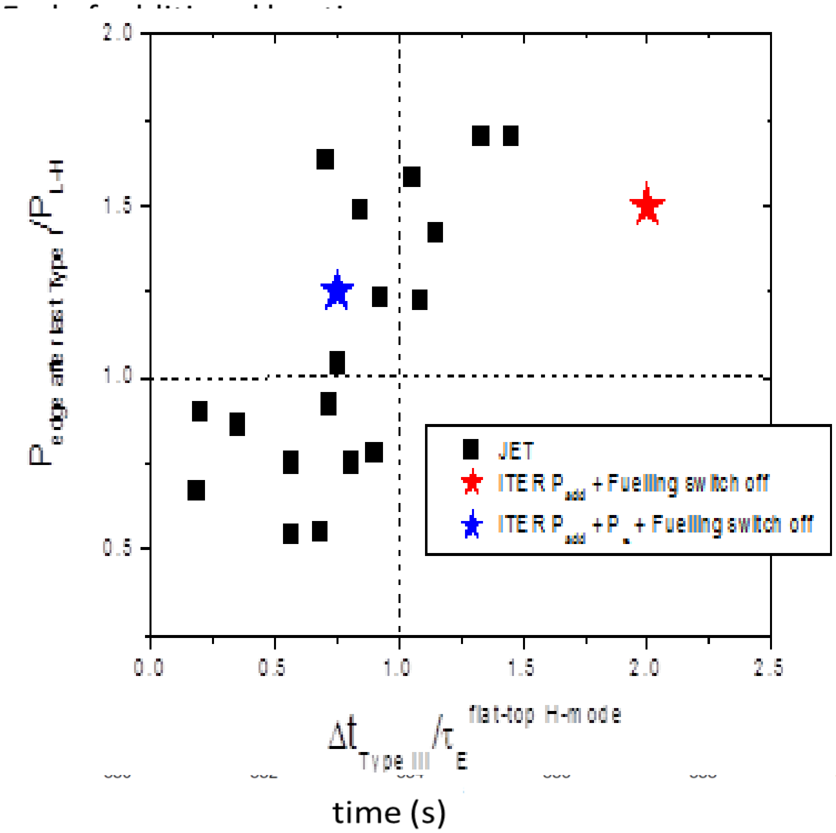




Transport in Confinement Transients

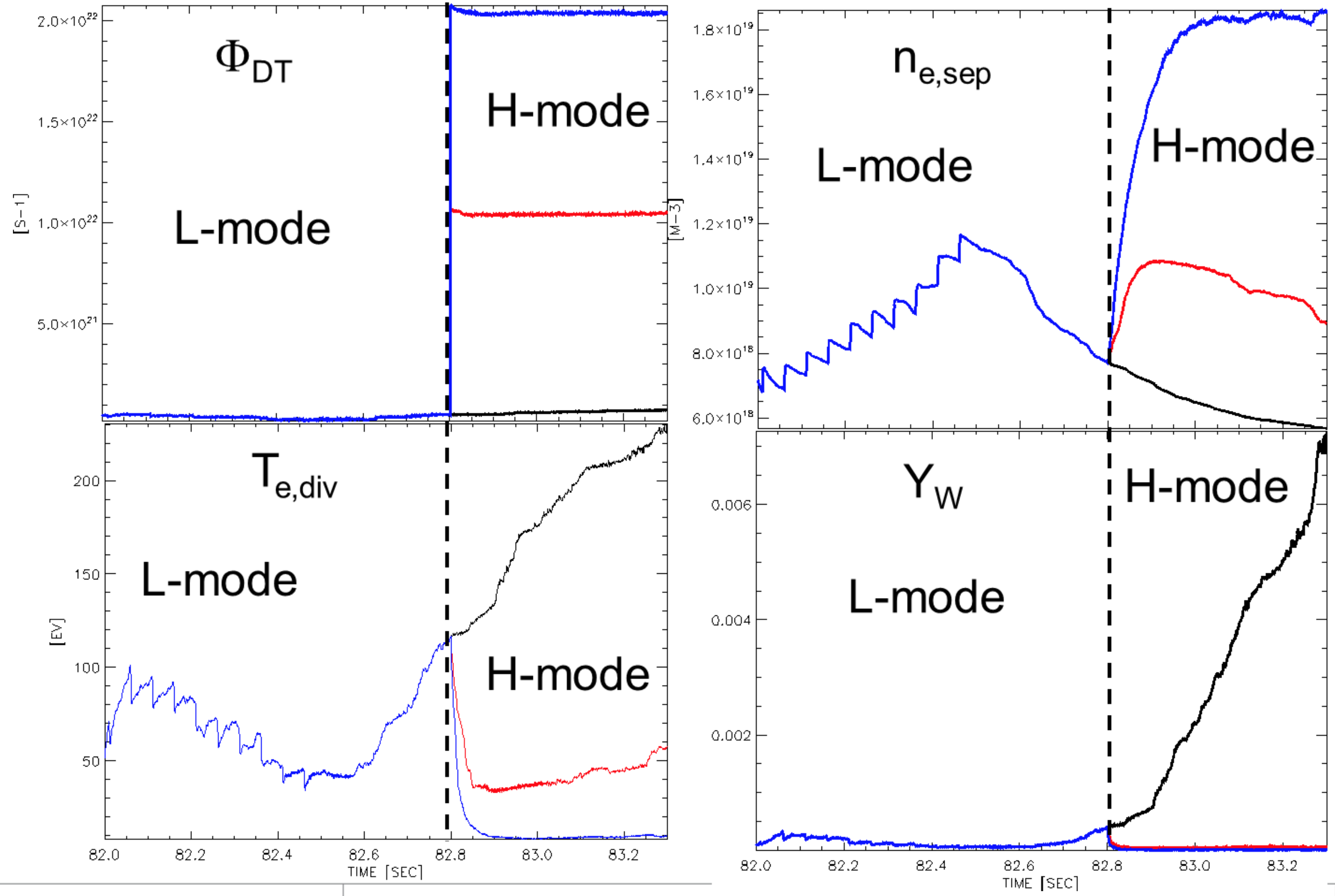
- Understanding transport in H-mode collapse phase is key to develop soft-landing strategies and to avoid uncontrolled contact of plasma with HFS first wall
- Timescale of energy collapse in ITER dictated by : alpha heating, density decay (alpha heating and H-mode threshold) and length of “Type III ELMy H-mode”





H-mode access with W control

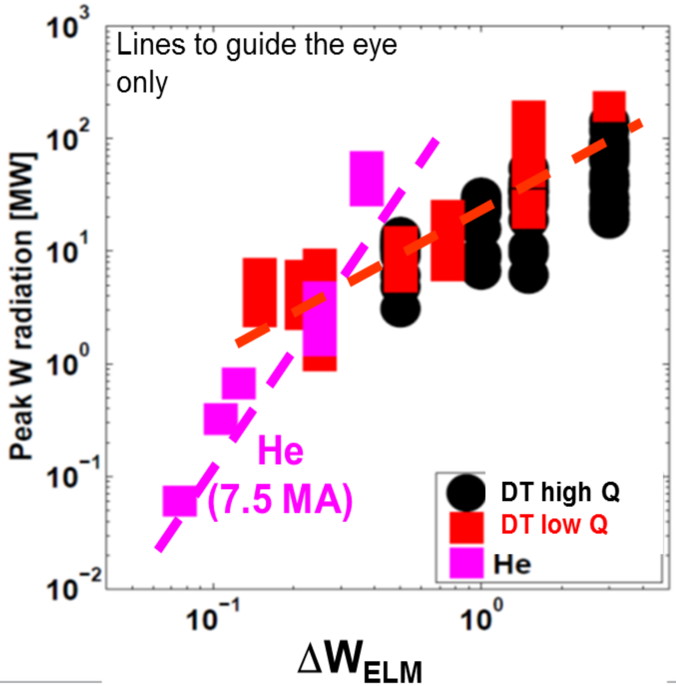
ITER – JINTRAC – V. Parail



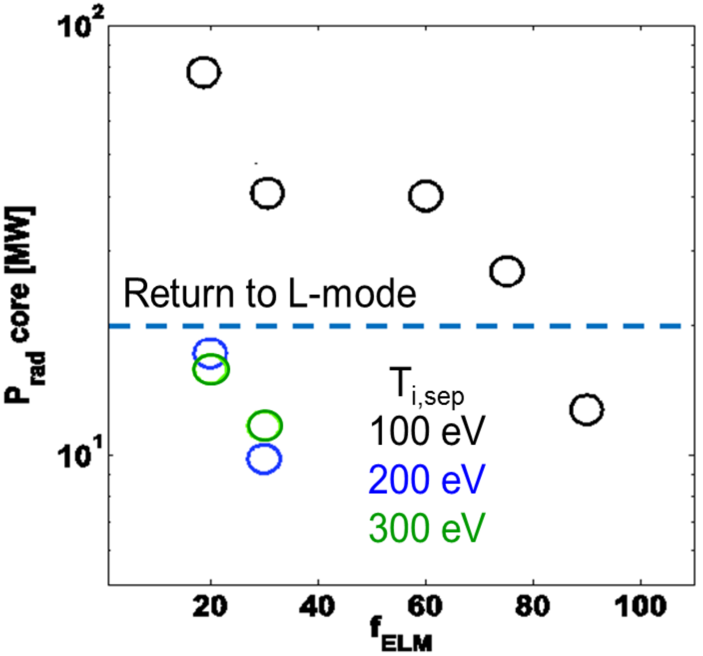
He H-mode Operation in non-active Phase

- He H-modes may present specific features that question their appropriateness as basis to develop DT scenarios in ITER
  - Fuelling of He plasmas must be done with gas fuelling only
  - W production and penetration through the pedestal may be more unfavourable than for DT plasmas
  - ELM characteristics and the response to (RMP) ELM control techniques could be very different in He plasmas and in DT plasmas
  - W divertor with He plasmas has specific PWI issues that have to be investigated

Post-ELM radiation



Average P_{rad} in He



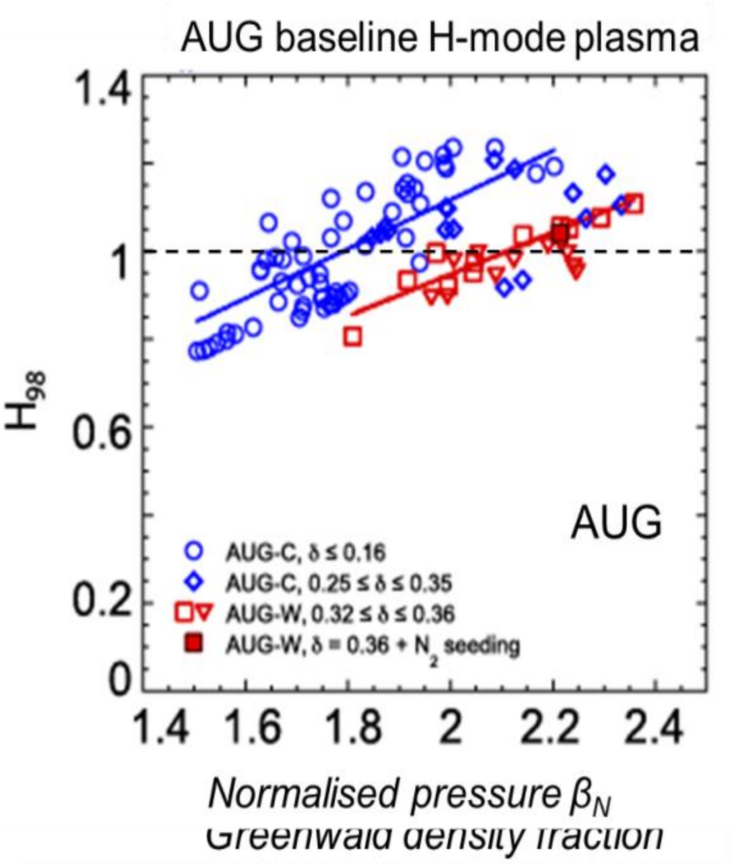
ITER

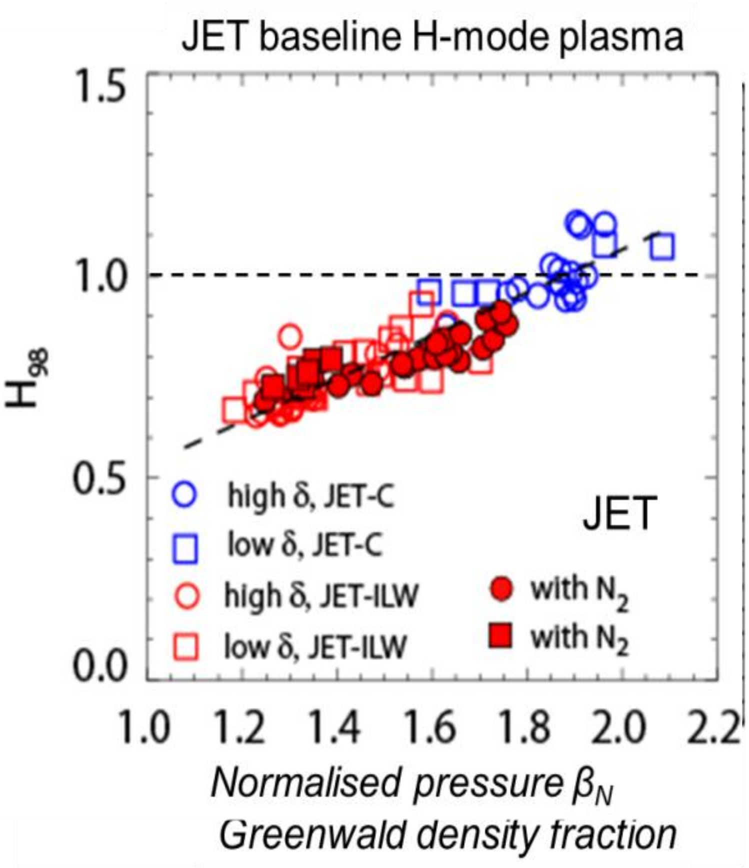
Fable/Dux/Coster

Effect of PFCs on Confinement

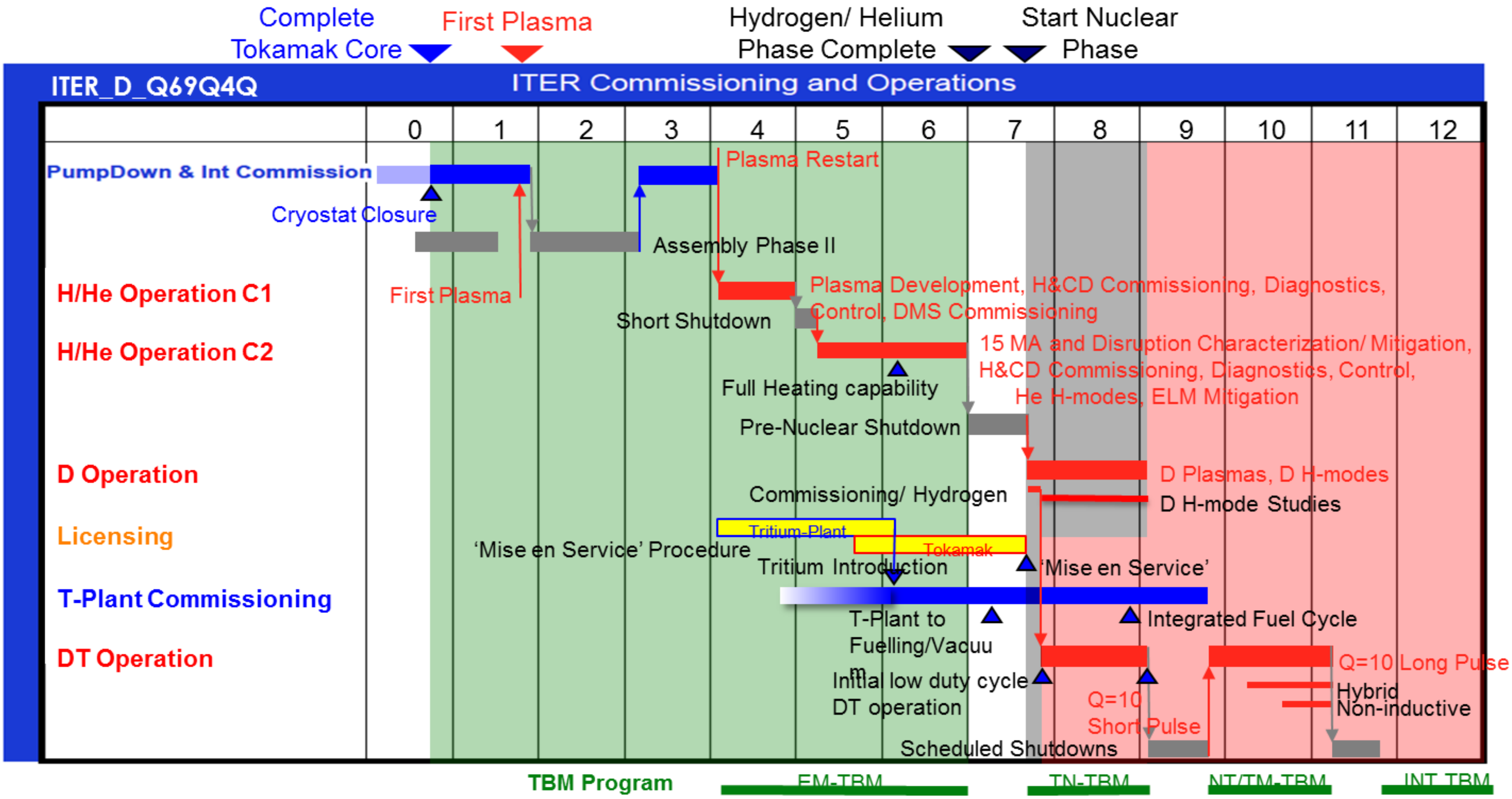
- **W PFCs do not lead to obvious operational restrictions in L-mode**
- **Compatibility with W leads to lower P_{ped} and lower H_{98} - Increasing β leads to recovery of H_{98} ($W_p \sim P^{0.5}$ instead $W_{p\text{-}98} \sim P^{0.3}$) → ITER ?**

Beurskens, Schweinzer EPS 2013

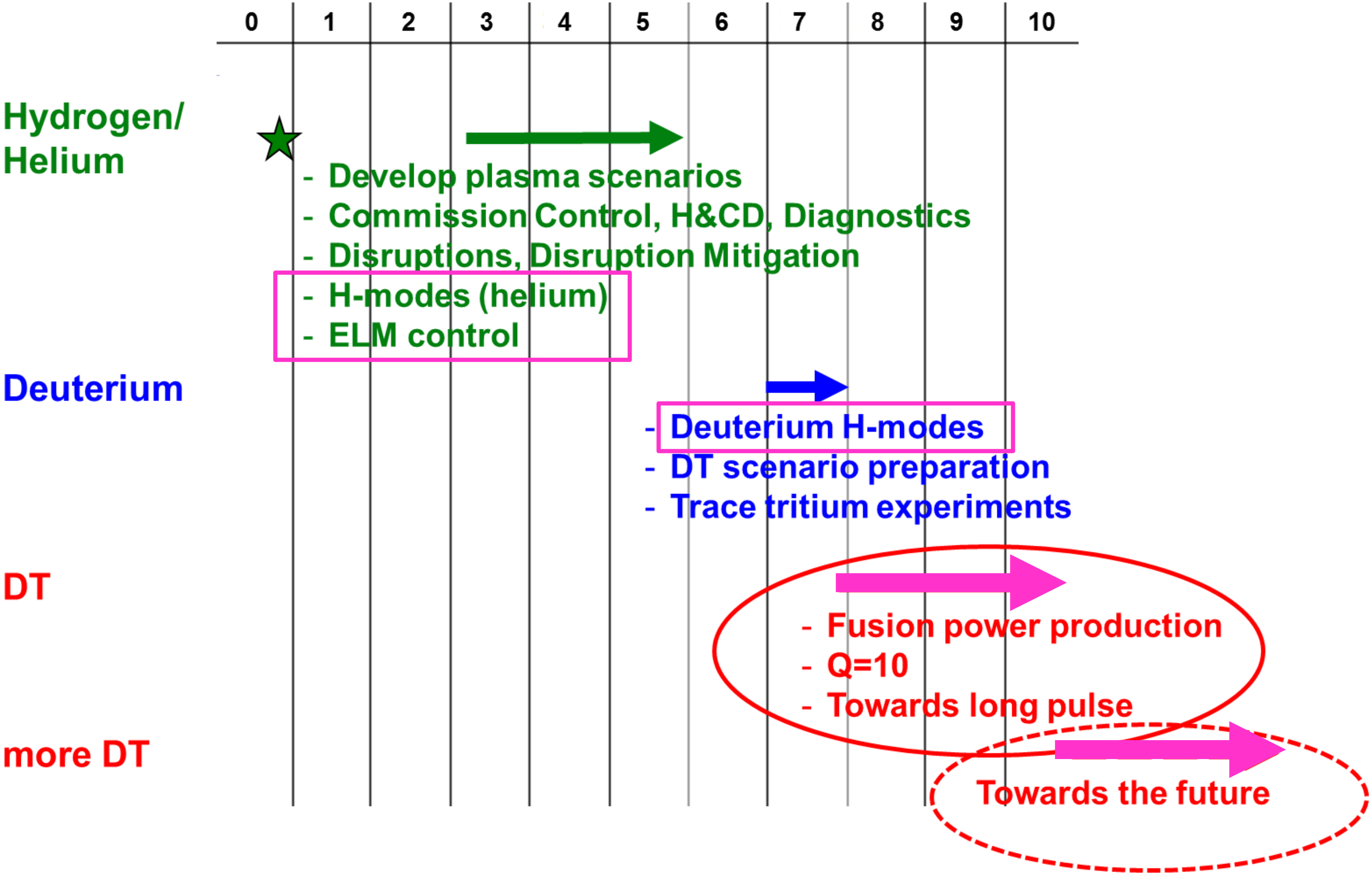




ITER Research Plan - I



ITER Research Plan - II



Hydrogen/ Helium

- Develop plasma scenarios
- Commission Control, H&CD, Diagnostics
- Disruptions, Disruption Mitigation
- H-modes (helium)
- ELM control

Deuterium

- Deuterium H-modes
- DT scenario preparation
- Trace tritium experiments

DT

- Fusion power production
- Q=10
- Towards long pulse

more DT

Towards the future