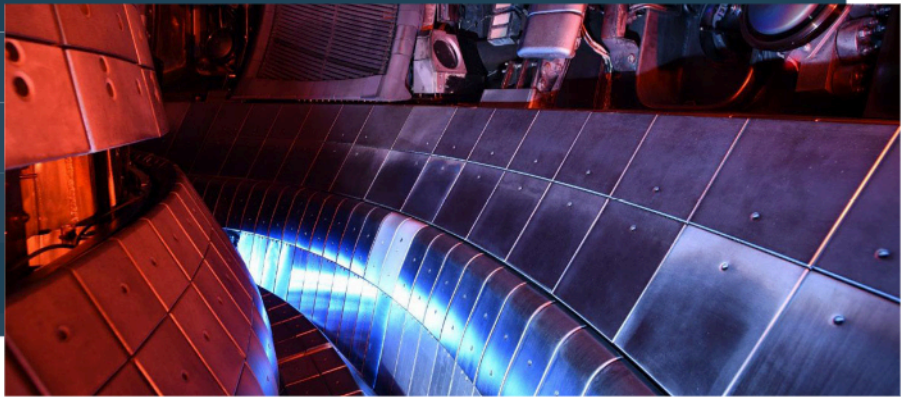
MAX-PLANCK-INSTITUT FÜR PLASMAPHYSIK

Power exhaust in ELM-free regimes

M. Bernert

With material by D.R. Ernst, M. Faitsch,
D. Fajardo, F. Scotti, W. Suttrop, E. Viezzer, …



EUROfusion

This work has been carried out within the framework of the EUROfusion Consortium, funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No 101052200 — EUROfusion). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them.

Normal ELM regimes and why to avoid them

- ELM energy fluence as material limit 0.15-0.5 MJ/m²

[J. Linke *et al* 2011 *NF* **51** 073017]
[J. Gunn *et al* 2017 *NME* **12** 75-83]

- Scalings predict 10-30 MJ/m² at ITER

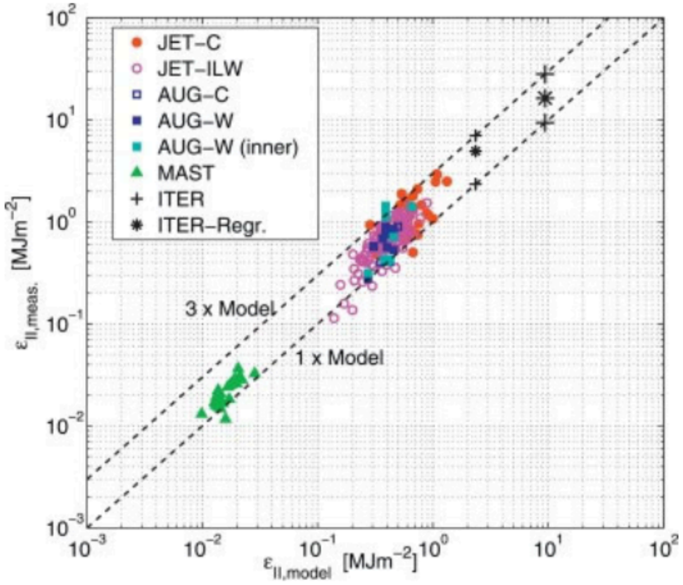
[T. Eich *et al* 2017 *NME* **12** 84-90]

→ Relative ELM size $\Delta W_{MHD} < 0.5\%\ W_{MHD}$

  – Type I ELMs are ~5-20%

- ELM buffering is usually not sufficient
  – In the best case 60% buffering
  – ELMs lead to reattachment
  – Better chances in ADCs

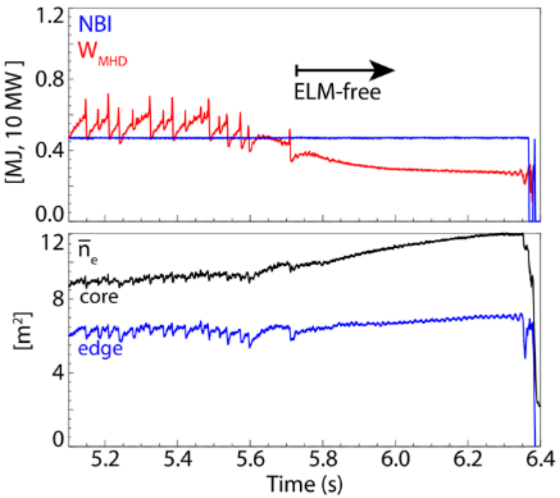
[M. Komm *et al* 2023 *NF* **63** 126018]

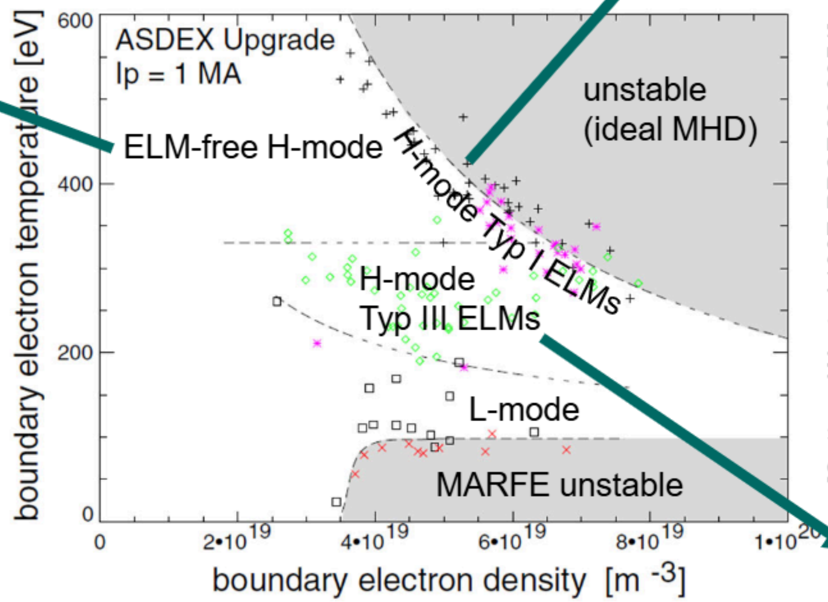


„normal“ ELM regimes in H-mode

Not stationary!

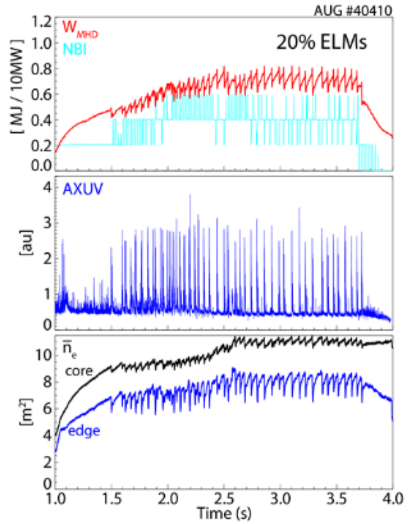
No density control



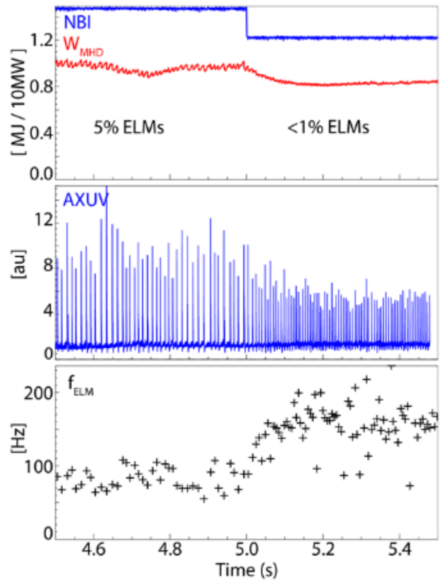


[Suttrop W *et al* 1997 *PPCF* **39** 2051]

Too big!



Bad power scaling



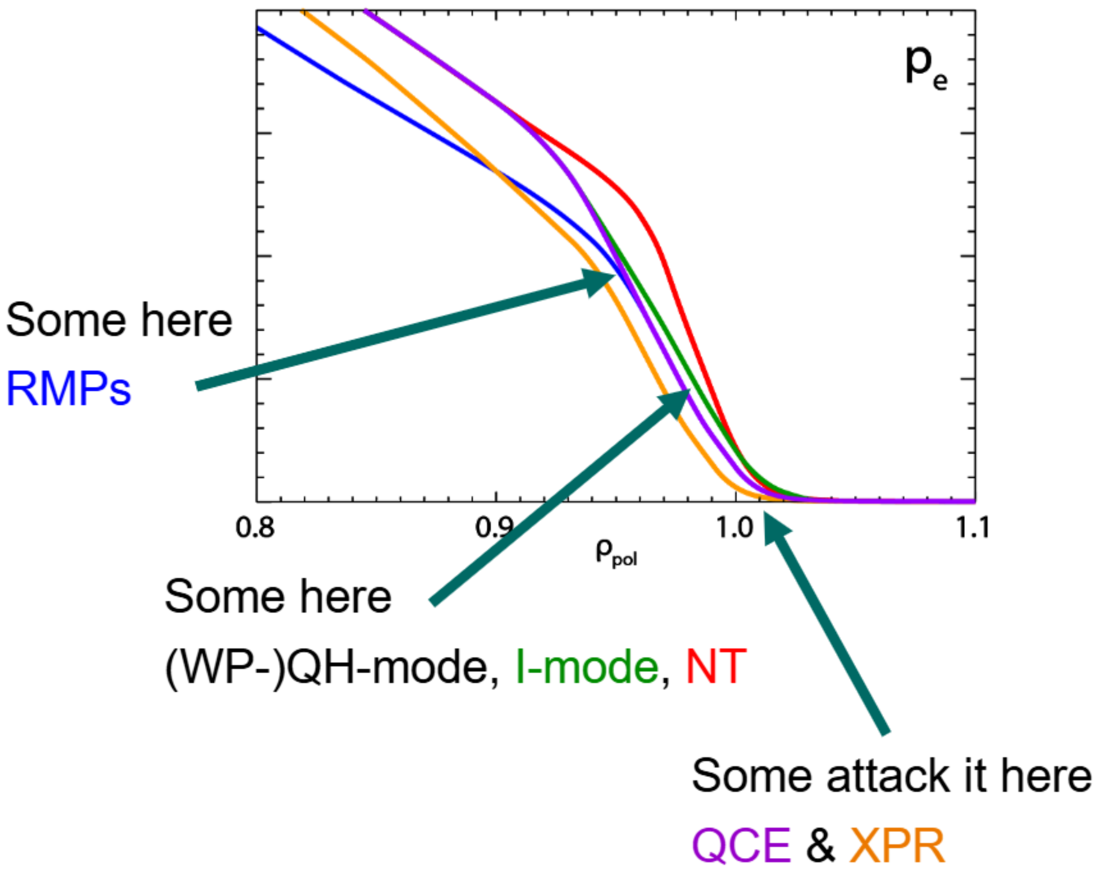
Limiting the pressure gradient

To avoid ELMs, the pedestal pressure gradient needs to be reduced
➔ An additional transport channel needs to be established, other modes destabilized

To be exhaust compatible, a conventional divertor tokamak needs (rough numbers):

- ○ High separatrix density (not high f_{GW})
  $n_{e,sep} >> 1\cdot10^{19}m^{-3}$
- ○ High radiated power fraction
  $f_{rad} > 70\%$
- ○ Unsusceptible to impurities and beneficial imp. transport
  $Z_{eff} < 2.5$

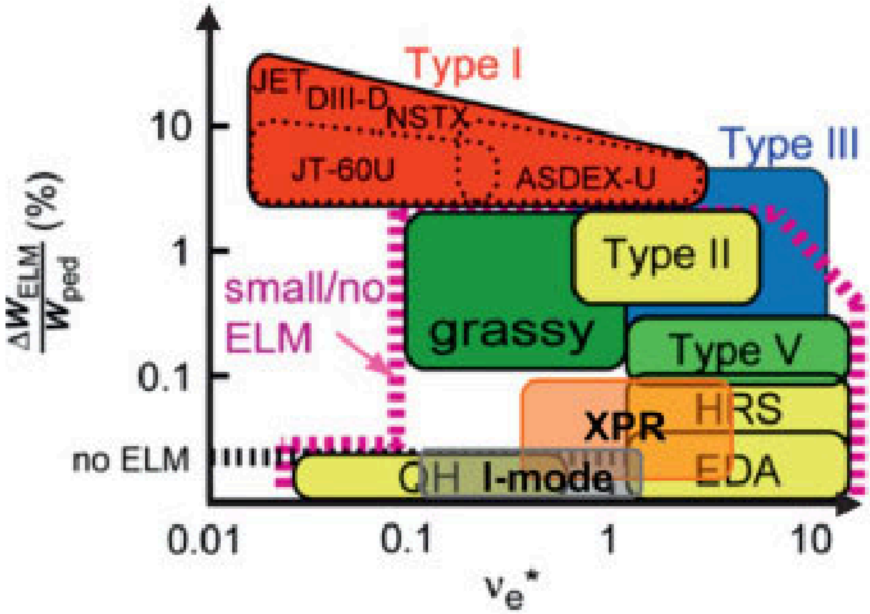
+ Still at high confinement ($H_{98}\approx1$)
+ Fitting in an affordable reactor (shaping, q_{95}, …)



Regimes without big ELMs

along EU-US joint working group on small/no ELM regimes

- QH-mode
- I-mode
- RMPs
- Negative triangularity
- QCE / small ELMs / type II ELMs / EDA H-mode
- XPR



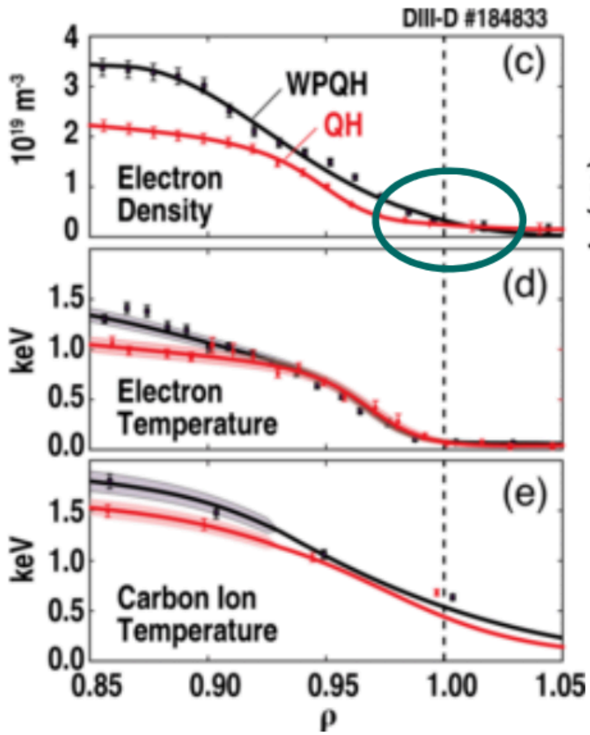
[K. Kamiya *et al*, PPCF 2007 **49** S43]
[E. Viezzer *et al*, 2023 NME **34** 101308]

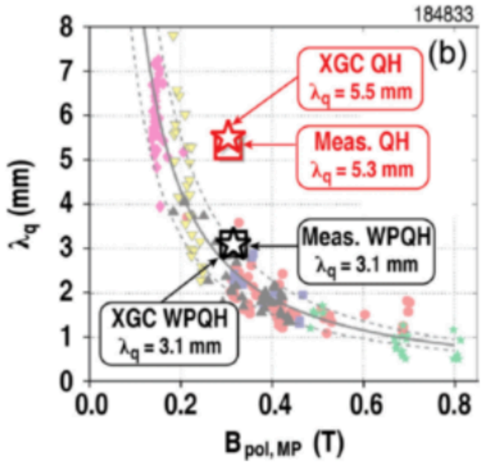
<u>Recent overview papers:</u>
C Paz-Soldan and the DIII-D Team 2021 *PPCF* **63** 083001
E. Viezzer *et al*, 2023 NME **34** 101308
G.S. Xu *et al* 2023 RMPP **7** 14

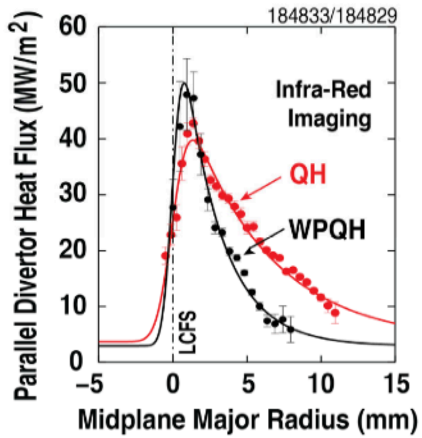
Quiescent H-mode (QH-mode) - the pros
Wide pedestal QH-mode

- ELM stabilization by edge harmonic oscillation (EHO) and turbulence in the pedestal
- Triggered by strong shear (/rotation) in pedestal
- Good confinement
- Separately attaining most ITER relevant parameters

➔ Increased λ_q by turbulence







[D.R. Ernst *et al* 2024 *PRL* **132** 235102]

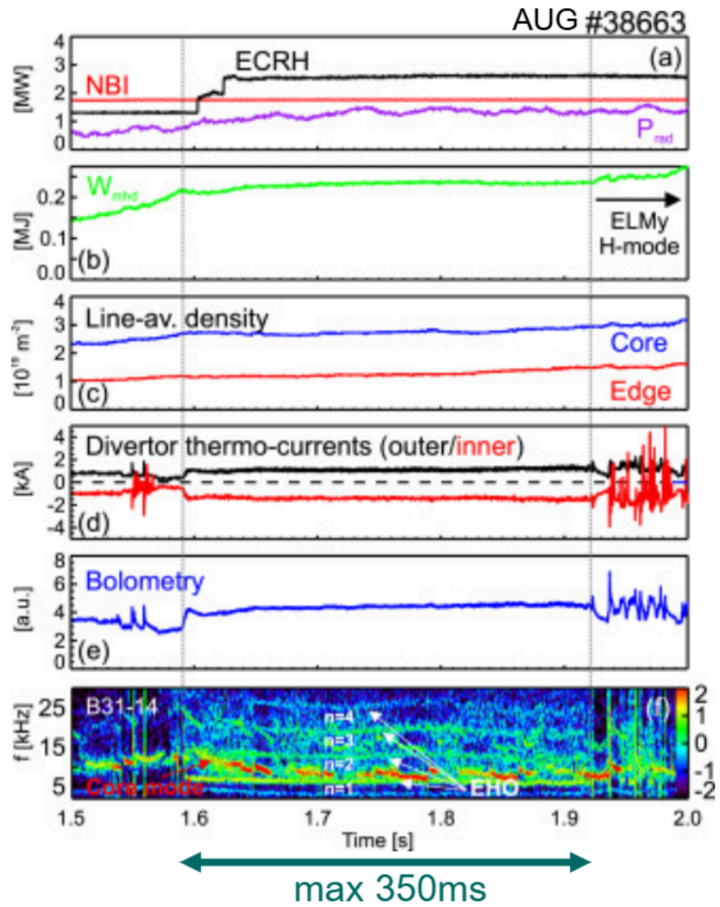
Quiescent H-mode (QH-mode) Wide pedestal QH-mode - the cons

- Only observed at low $n_{e,sep} < 0.15\ n_{GW}$
  - Sheath limited SOL – a killer for the divertor
- High impurity content (DIII-D: $Z_{eff} \sim 2\text{-}5$)

[C Paz-Soldan et al 2021 *PPCF* **63** 083001]

- In metal machines only observed transiently
  - Unbeneficial impurity transport

[E. Viezzer *et al* 2023 *NME* **34** 101308]



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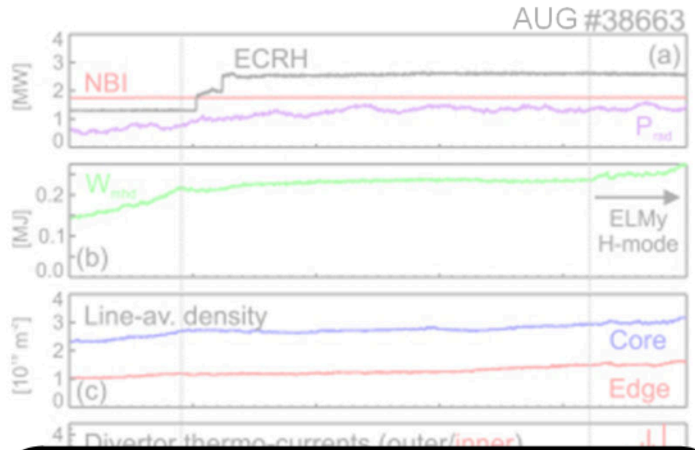


QH-mode/WPQH-mode is critical

\+ Fulfilling many requirements, but not yet in parallel

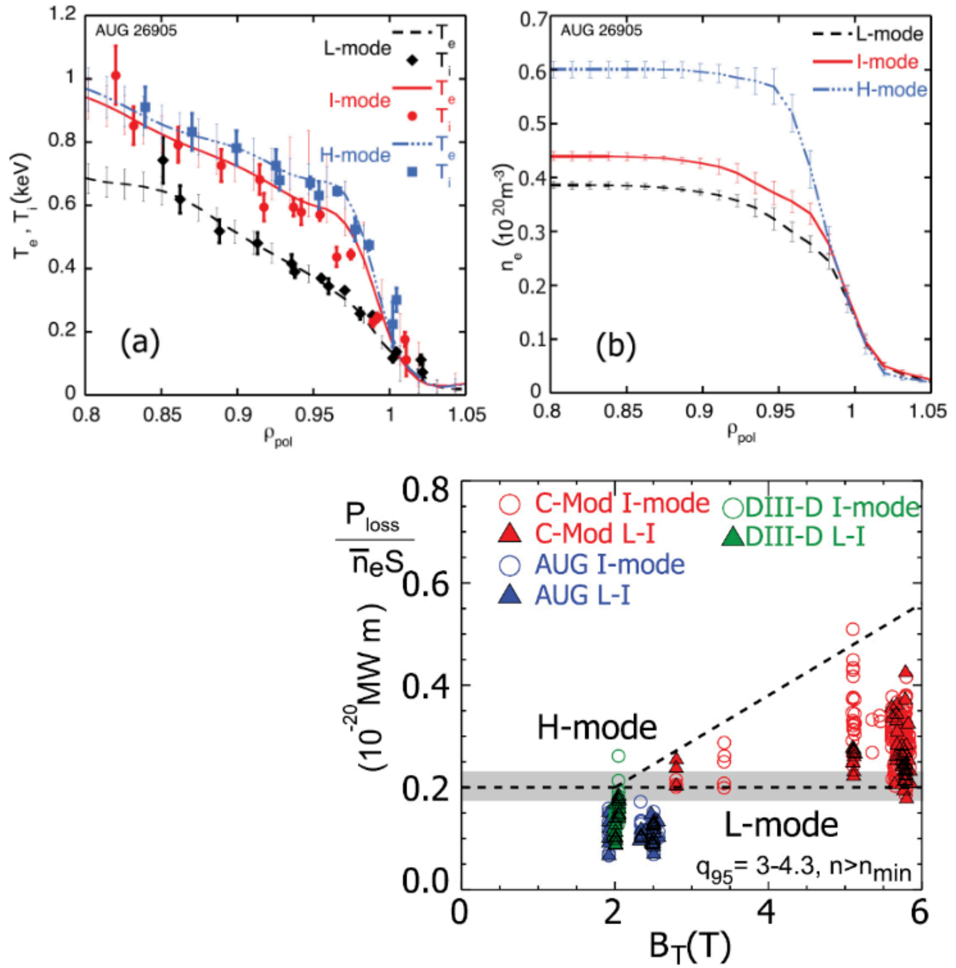
\- Not yet stable in metal devices

\- Impurity transport of concern

\+ Detachment challenging, but achieved!

I-mode

- Temperature pedestal
- No density pedestal
- Accessible in unfav. B_t
- Higher B_t increases operational space



Weakly Coherent Mode (WCM) in the middle of the pedestal

- Pedestal relaxation events (PREs) lead to ELM-like bursts of up to 1.5% W_{MHD}

[J.R. Walk *et al* 2014 *PoP* 21 056103]
[D. Silvagni *et al* 2020 *NF* **60** 126028]

[A.E. Hubbard *et al* 2016 *NF* **56** 086003]

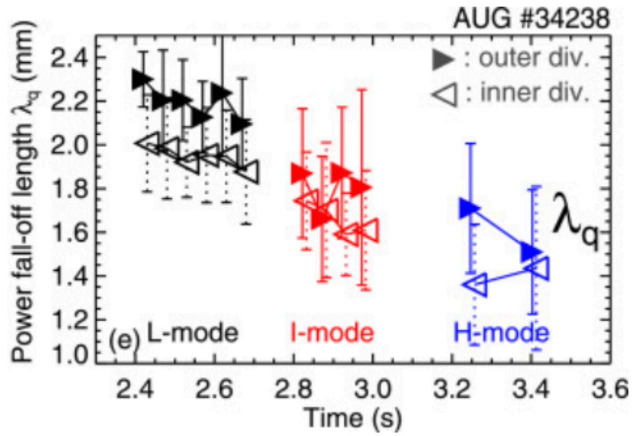
I-mode

- λ_q between L- and H-mode

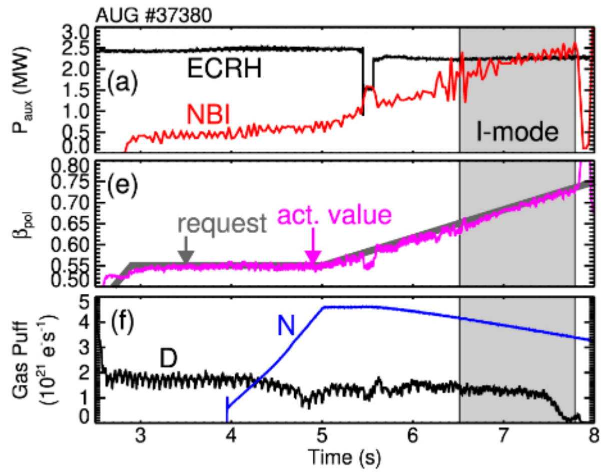
- N seeding leads to loss of I-mode
  - Can be compensated by increased heating power (β_{pol} operational space changed)

- Detachment only achieved at inner divertor
  - I-mode lost before detachment of outer divertor [Reinke NF 2019, Happel NF 2021]

➔ The end of the I-mode…



[T. Happel *et al* 2019 *NME* **18** 159]



[T. Happel *et al* 2021 *NF* **61** 036026]

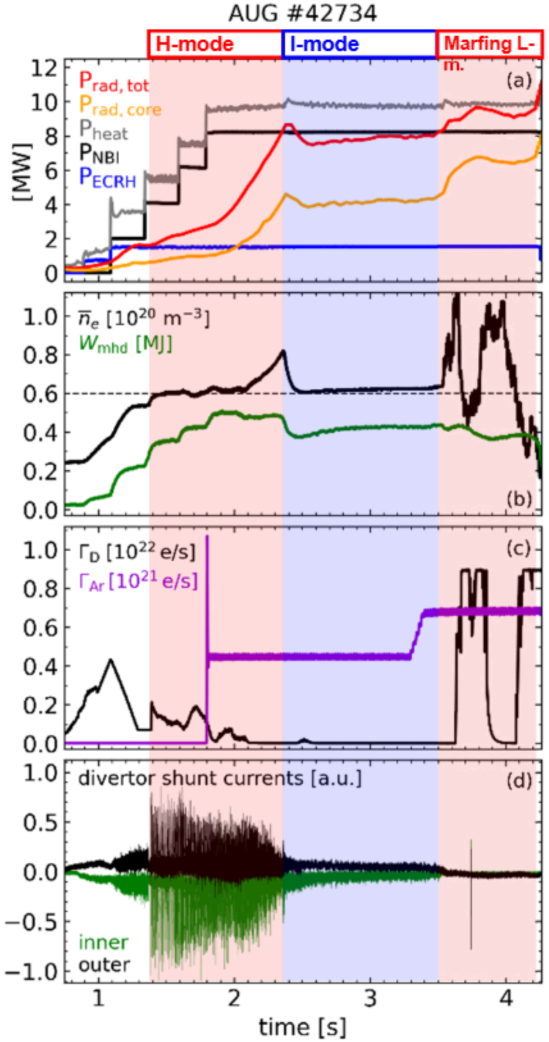
New detached I-modes

High-power Ar-seeding in AUG USN

- Potential I-mode in USN with detachment
  - Ar seeding
  - $\beta_{pol} \approx 1$ at slightly reduced confinement
  - WCM & transport analysis indicates I-mode

- I_p = 0.8 MA, B_t = – 2.6 T
- P_{NBI} = 8 MW, P_{ECRH} = 1.5 MW
- $\bar{n}_e = 6 \times 10^{19}$ m^{-3} (f_{GW} ~ 0.65)
- High radiated power fractions: 45% core, 85% total
- No large ELMs

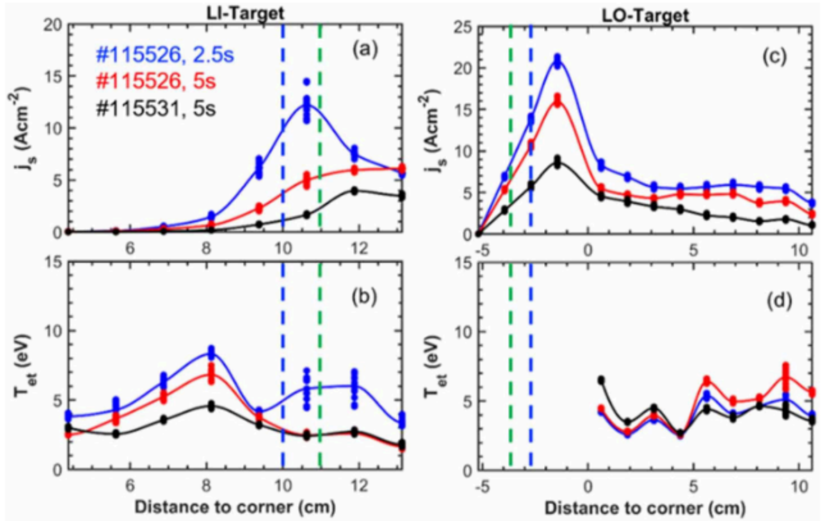
Courtesy of D. Fajardo



EAST Right-angled divertor

- Both divertors detached
  - At least in high recycling regime
  - New closed divertor structure beneficial

[L. Yu *et al* 2025 *Nucl. Fusion* **65** 07600]



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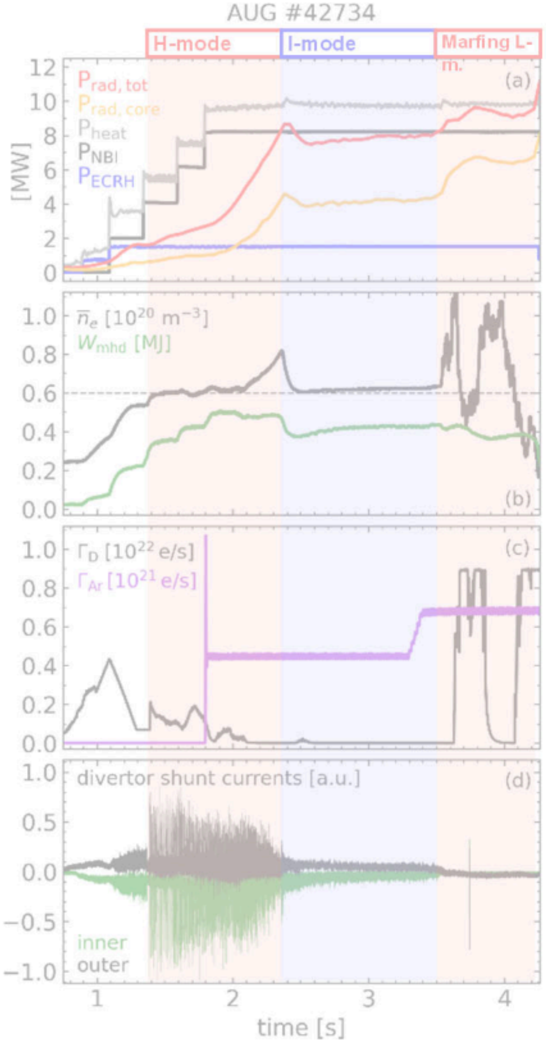

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[L. Yu *et al* 2025 *Nucl. Fusion* **65** 07600]

I-mode was dead, but there's new hope!

- Confinement could be higher
- Limited operational space
- PREs might still be a showstopper

\+ Potentially compatible with detachment (to be evaluated)

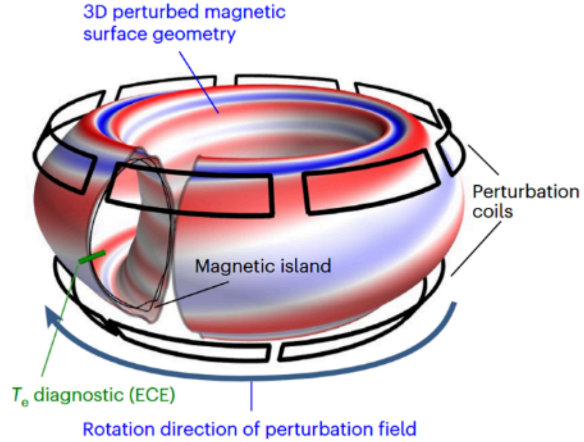
Resonant magnetic perturbations (RMPs)

- ELMs are suppressed by applying a resonant magnetic perturbation field

Creating island chains in the pedestal top

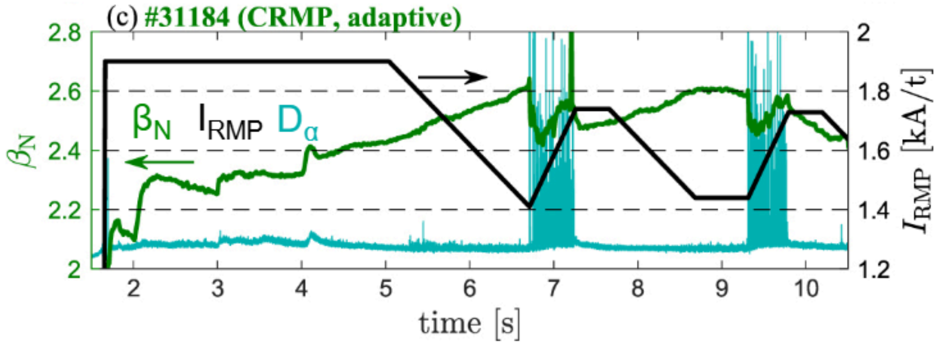
→ Reduction of pedestal top pressure by ~20%

  - Can be improved by adapting RMP currents (<10% @ KSTAR) [M. Kim *et al* 2023 *NF* **63** 086032]



[M. Willensdorfer et al. 2024 *Nat. Phys* **20** 1980]
[W. Suttrop *et al* 2018 *Nucl. Fusion* **58** 096031]

- ELM suppression occurs at low $n_{e,ped}/\nu^*_{ped}$
  - At higher densities, ELMs might be mitigated



[M. Kim *et al* 2023 *NF* **63** 086032]

Resonant magnetic perturbations (RMPs) – threshold & lobes

- Access parameter for suppression yet unclear:
  - If edge density needs to be below

    $n_{e,ped} < 3.3 \cdot 10^{19} m^{-3}$

  → $n_{e,sep} \ll 1.6 \cdot 10^{19} m^{-3}$ $(n_{e,sep,ITER} \geq 4 \cdot 10^{19} m^{-3})$
  - If edge collisionality needs to be below

    $\nu^* < 0.15 - 0.45$ $(\nu^*_{ITER} = 0.01 - 0.15)$

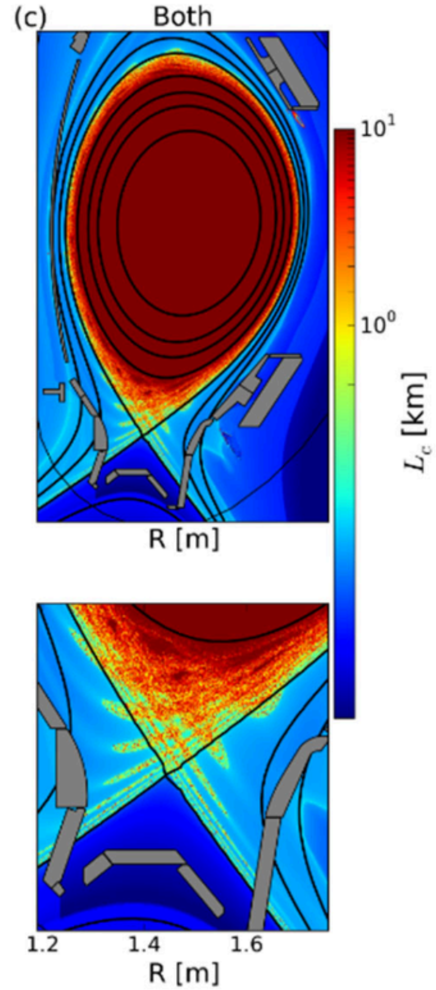
- Lobes in the divertor:
  - Higher heat fluxes in the far-SOL might cause burn through

  → Not observed at current experiments

  [D. Brida *et al* 2017 *Nucl. Fusion* **57** 116006]

  → Dependencies change at ITER (RMP pert. ↔ λ_q)

  [H. Frerichs *et al* 2020 *PRL* **125** 155001]



[D.Brida, PhD thesis, TU München 2017]

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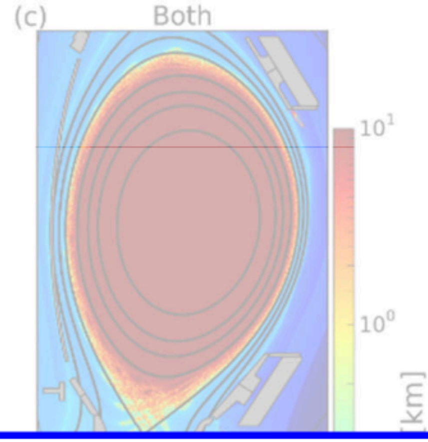

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    [H. Frerichs *et al* 2020 *PRL* **125** 155001]

RMPs could be compatible with exhaust

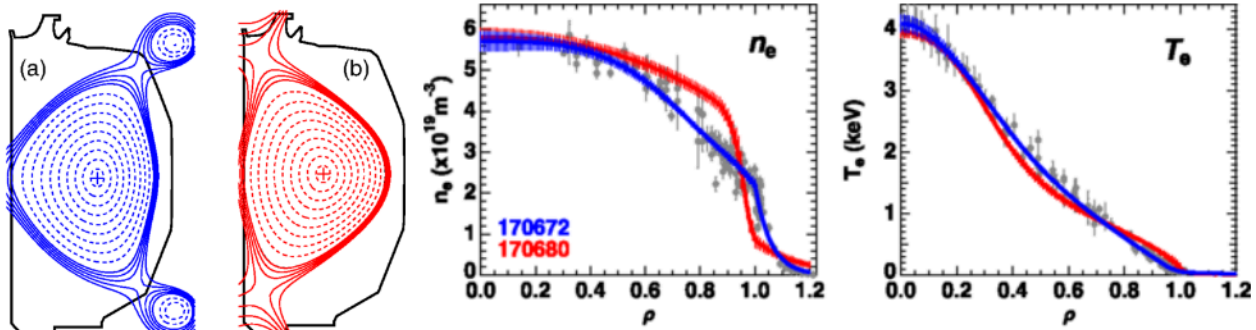
- Only if collisionality is the determining factor
- Reduction in confinement significant (~10-20%)
- Prediction for lobe detachment not conclusive for ITER

Negative triangularity (NT)

Avoiding ELMs by staying in L-mode

- Extreme shaping helps to avoid H-mode [A.O. Nelson *et al* 2023 *PRL* **131** 195101]

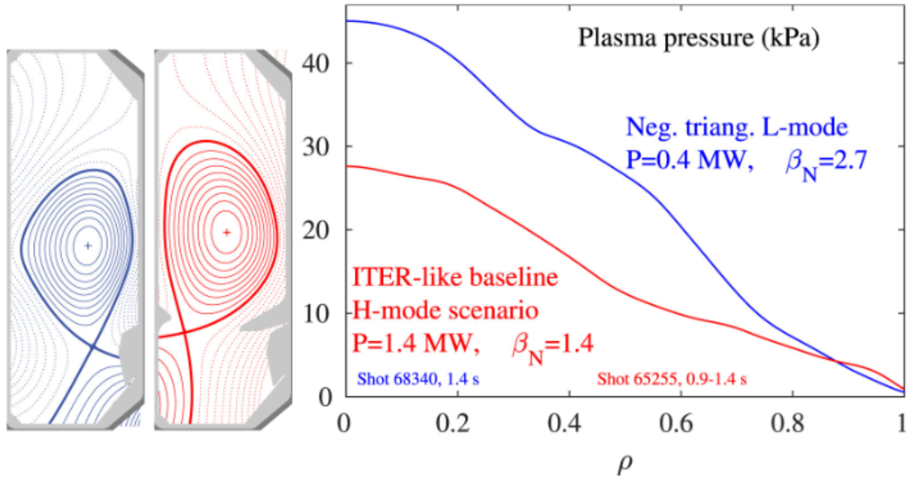
- Compensate reduced ped. top pressure by increased core gradients
  - Stability of core turbulence (TEM & ITG) improved in NT
  - Performance to be shown at full power



[M E Austin *et al* 2019 *PRL* **122** 115001]

Advantages are:

- Plasma can stay in L-mode:
  - No lower limit for P_{SOL}
  - Exhaust power can be radiated inside separatrix
- Divertor at bigger R_{maj} → higher flux expansion



[S Coda *et al* 2022 *PPCF* **64** 014004]

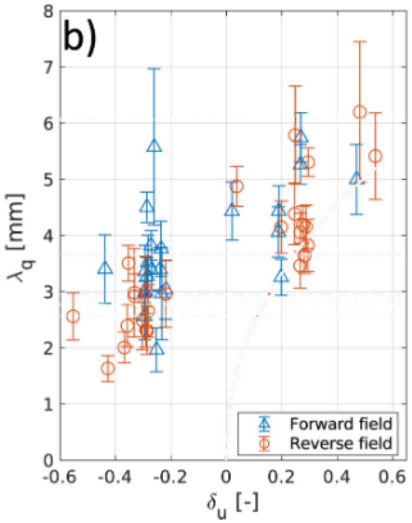
Negative triangularity – detachment challenges

- λ_q decreases with neg. δ
  - λ_q values similar to H-mode

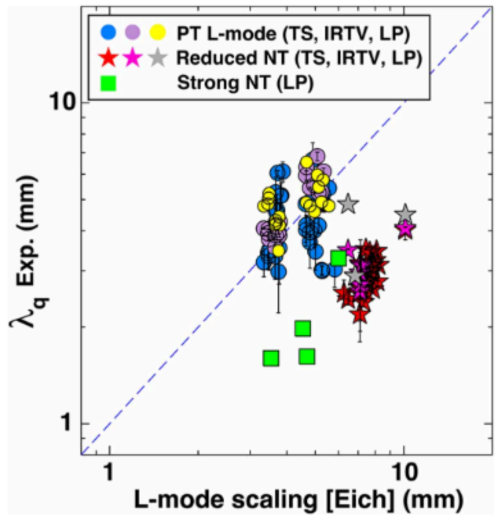
[M Faitsch *et al* 2018 *PPCF* **60** 045010]

- Connection length to divertor is shorter (factor 2-4)

[F Scotti *et al* 2025 *PPCF* **67** 095030]



[R.I. Morgan *et al* 2025 *NF* **65** 106030]



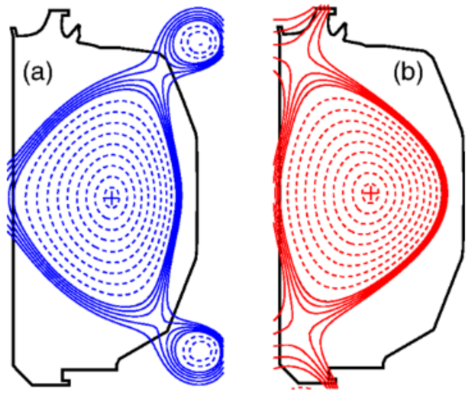
[F Scotti *et al* 2025 *PPCF* **67** 095030]

- H-mode has to be avoided
- “Bursty modes” might be observed

[T Cote *et al* 2025 *PPCF* **67** 035033]

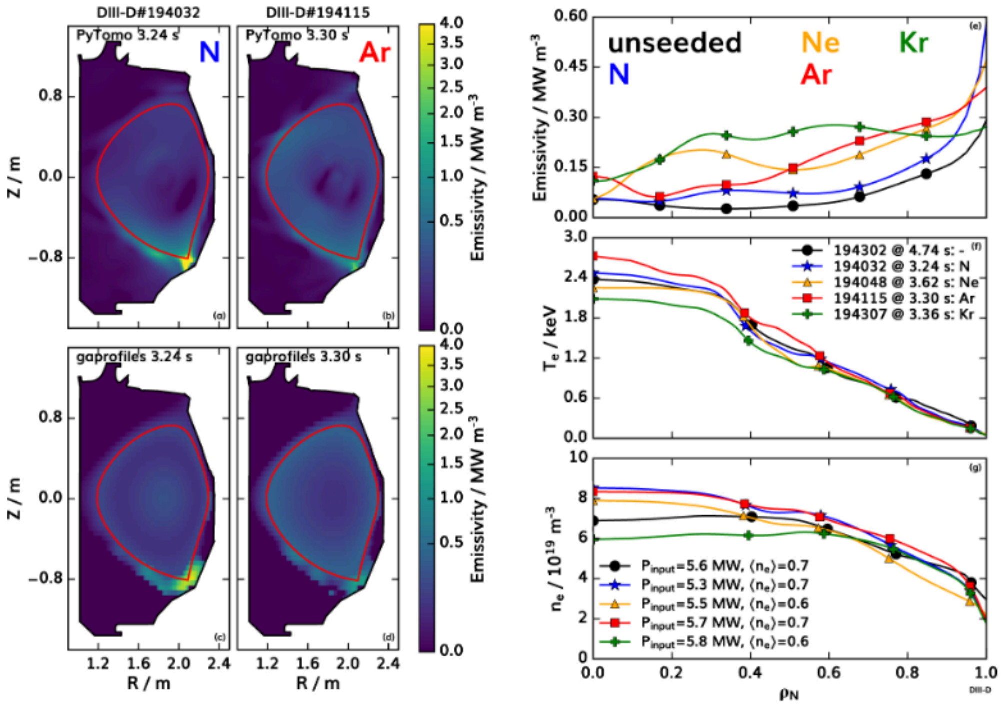
- Stronger power degradation of confinement

[C. Paz-Soldan *et al* 2024 *NF* **64** 094002]



Negative triangularity – chances

- Use of core radiation for power exhaust
  - Not yet combined with detached targets

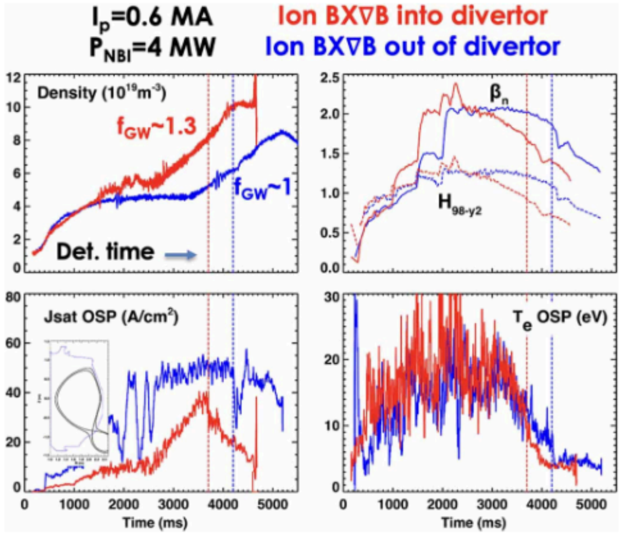


[D Eldon *et al* 2025 *PPCF* **67** 015018]
[L Casali *et al* 2025 *PPCF* **67** 025007]

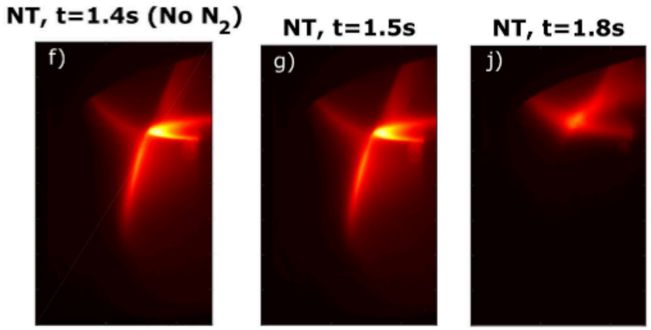
Negative triangularity – chances

- Use of core radiation for power exhaust
  - Not yet combined with detached targets

- Operating in unfav. B_t to ease outer divertor detachment
  - TCV: Full detachment with N seeding
  - DIII-D: Full detachment not yet achieved
  - Confinement reduction of ~10-20% (DIII-D & TCV)
  - XPR observed when detaching (DIII-D & TCV)



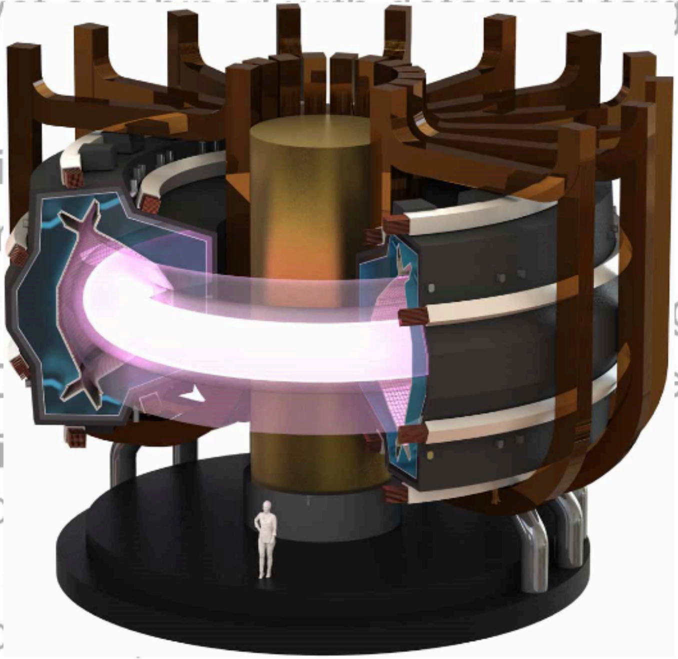
[F. Scotti *et al* 2025 *PPCF* **67** 095030]



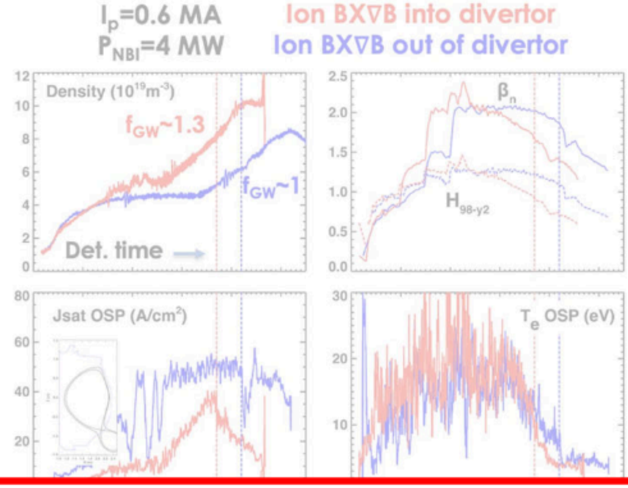
[O.Fevrier *et al* 2025 *IAEA FEC*]

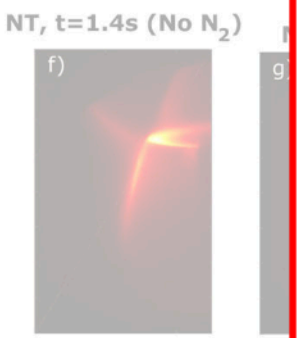
Negative triangularity – chances

- Use of core radiation for power exhaust
  - Not y… …jets
- Operati…
  divertor…
  - TCV: … …g
  - DIII-D … …eved
  - Confi…
    (DIII-D…
  - XPR …
    (DIII-D…



[The MANTA Collaboration
et al 2024 *PPCF* **66** 105006]





[O.…

NT is a promising option for future reactors

\+ Good confinement (at low power)

\+ Exhaust by core radiation

\- More experiments with optimised divertor and full power needed

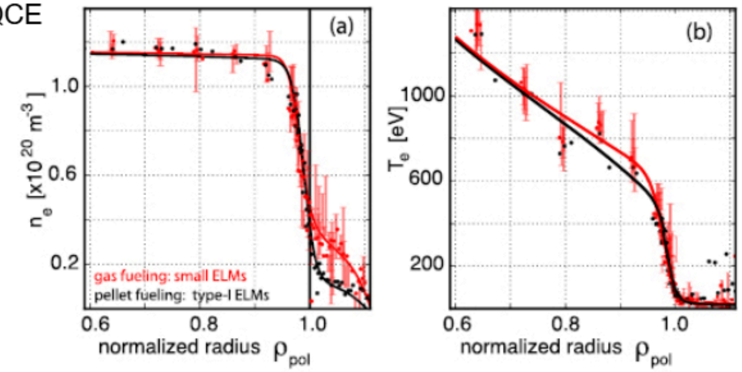
QCE / EDA / small ELMs / grassy ELMs / type II ELMs

- Zoo of similar regimes, at many different devices
- Most work is at high-ish density or have high separatrix density as prerequisite
- Partially detached scenarios exist at AUG, EAST, DIII-D & JET

- All scenarios still have small ELMs or filamentary bursts
  - To be ascertained that transients do not get bigger for a reactor scenario!

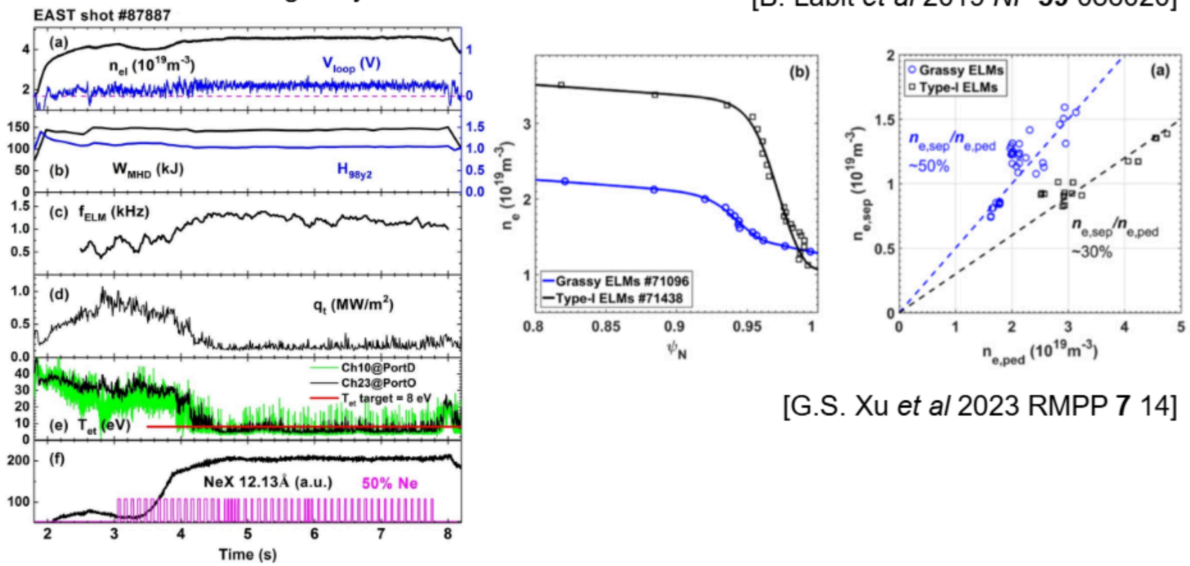
$$\frac{\delta W_{MHD}}{W_{MHD}} \overset{!}{<} 0.5\%$$

AUG QCE



[B. Labit *et al* 2019 *NF* **59** 086020]

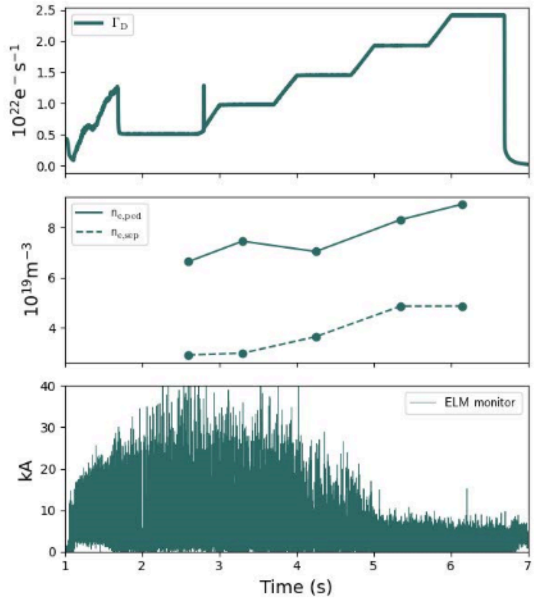
EAST grassy ELMs



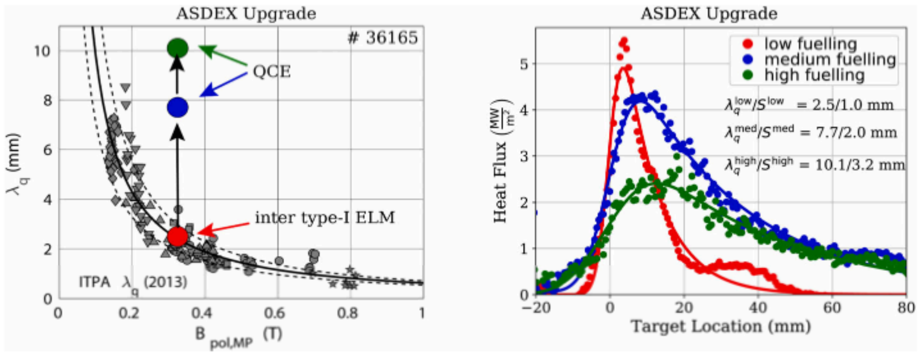
[G.S. Xu *et al* 2023 RMPP **7** 14]

Quasi continuous exhaust (QCE)

- Triggering filamentary transport (local ballooning) at pedestal bottom by high shaping and high density
  - λ_q increased by filament transport
  - Good confinement can be achieved
- Observed at AUG, TCV & JET
  - Scalable to a reactor



[M. Dunne *et al* 2025 *IAEA FEC*]

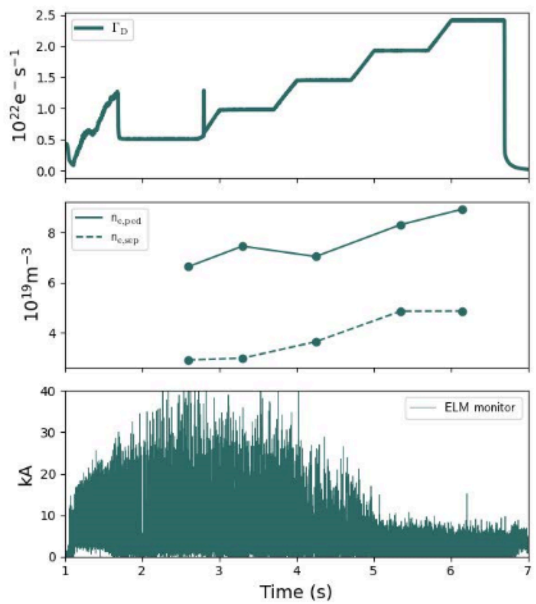


[M. Faitsch *et al* 2021 *NME* **26** 100890]

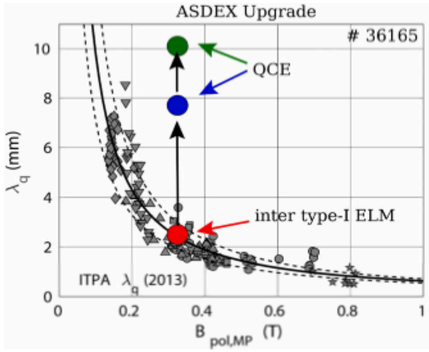
Quasi continuous exhaust (QCE) / Enhanced Dα (EDA) H-mode

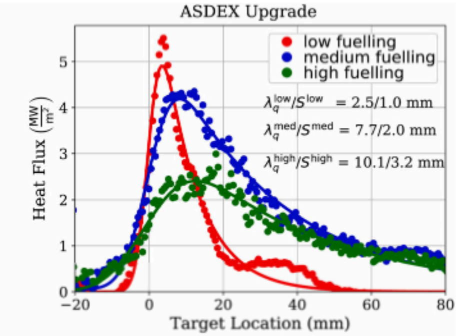
- Triggering filamentary transport (local ballooning) at pedestal bottom by high shaping and high density
  - λ_q increased by filament transport
  - Good confinement can be achieved
- Observed at AUG, TCV & JET
  - Scalable to a reactor

- Similar or identical to EDA H-mode
  [M. Greenwald *et al* 1999 *PoP* **6** 1934]
  [L. Gil *et al* 2020 *Nucl. Fusion* **60** 054003]
  - EDA has a smaller operational range
  - EDA can perform exhaust by core radiation
  [A. Kallenbach *et al* 2021 *Nucl. Fusion* **61** 016002]



[M. Dunne *et al* 2025 *IAEA FEC*]





[M. Faitsch *et al* 2021 *NME* **26** 100890]

QCE & detachment

Detachment experiments at AUG:

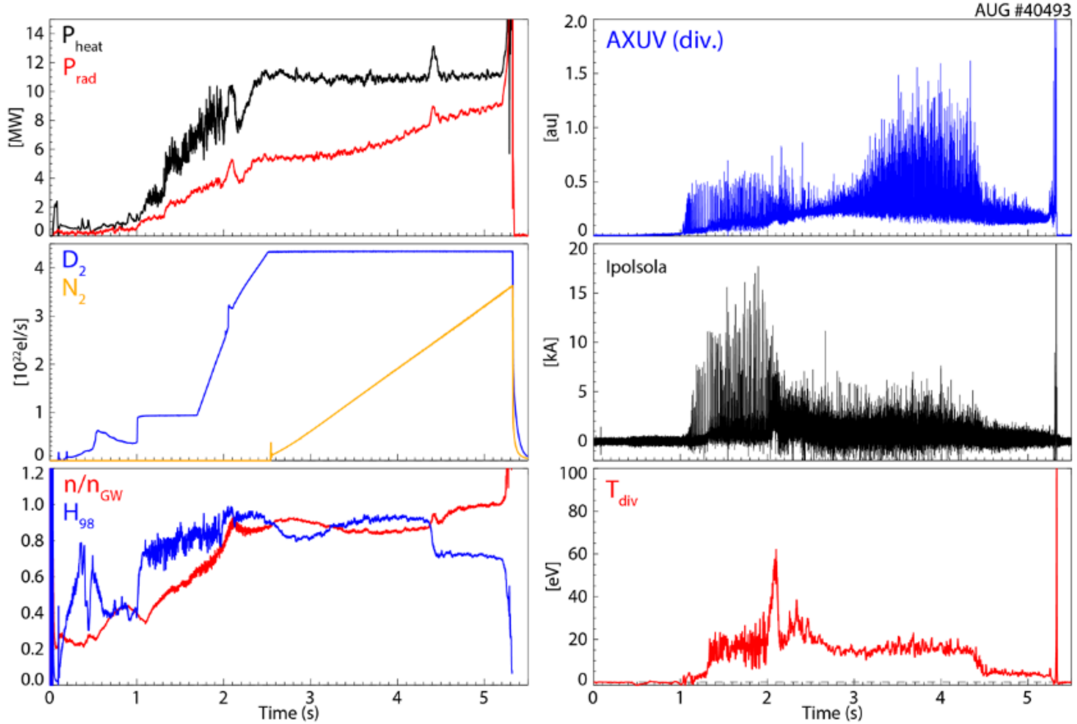
- Divertor is detached in-between filaments
- On average partial detachment is reached

[M. Faitsch *et al* 2023 *Nucl. Fusion* **63** 076013]

- Injection of N might increase filament losses
  - Loss of confinement before full detachment

- Our understanding increased since then
  → Attempt to combine QCE with XPR in next AUG campaign

→ Can filaments be fully detached?
  - Also far-SOL detachment is needed



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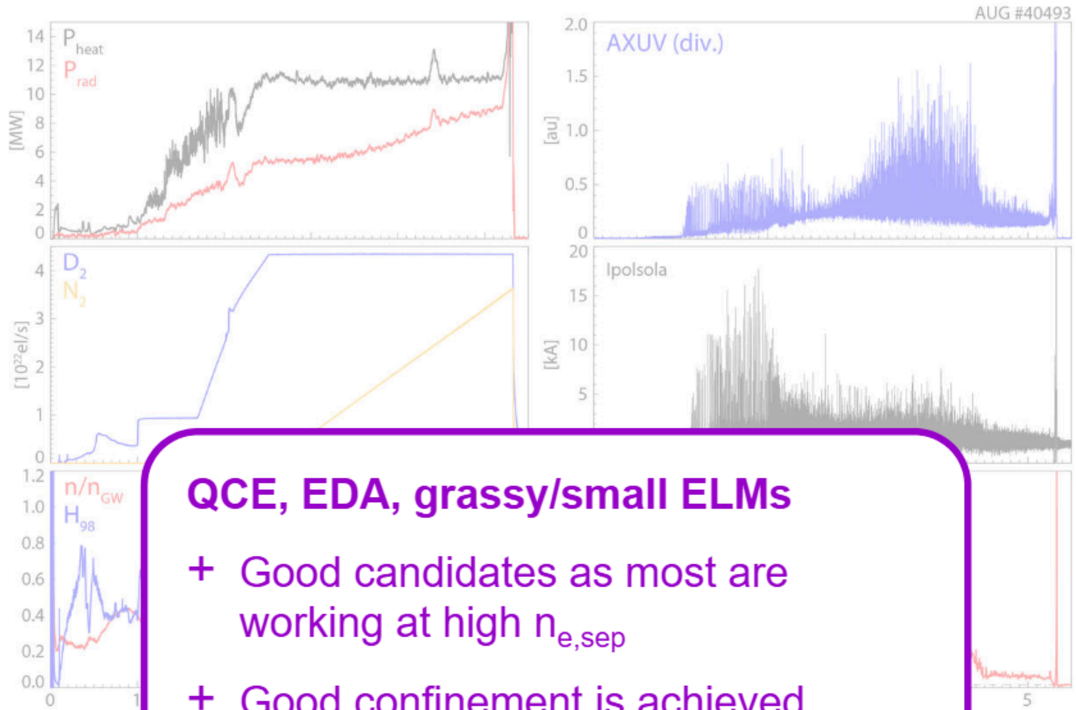


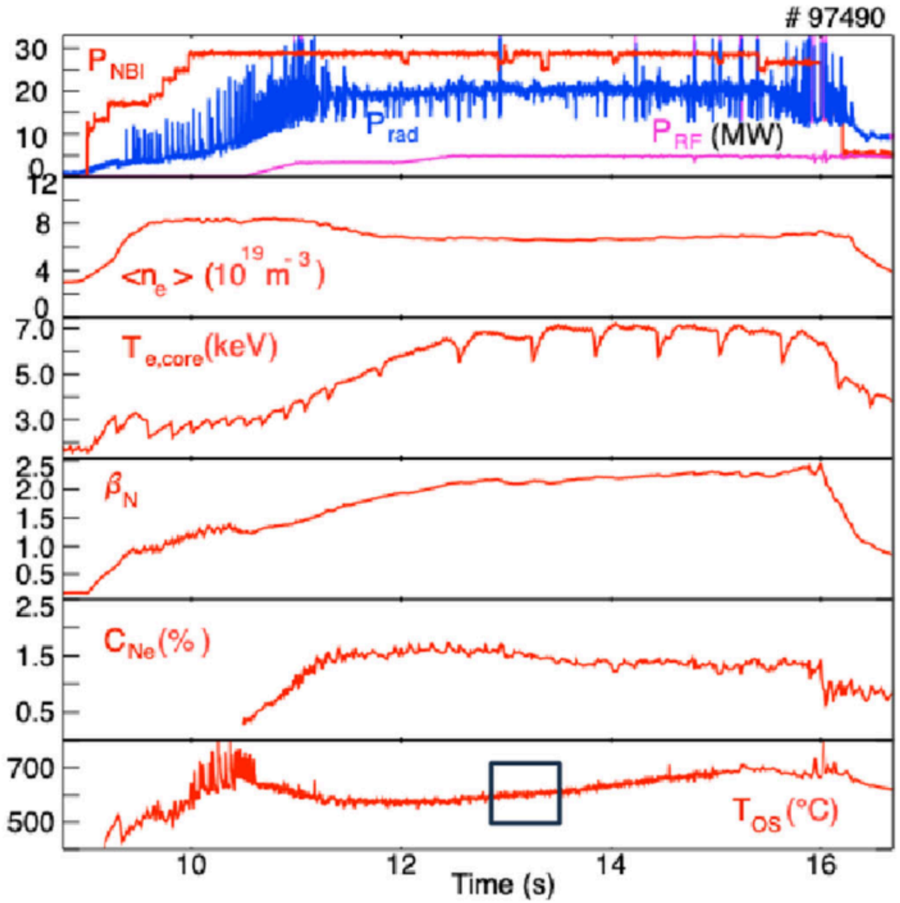
QCE, EDA, grassy/small ELMs

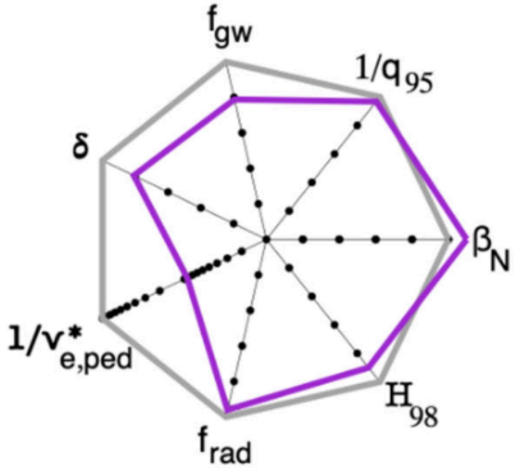
+ Good candidates as most are working at high $n_{e,sep}$
+ Good confinement is achieved
- Detachment of filaments (far-SOL) to be shown
- Transients must remain <0.5% W_{MHD}

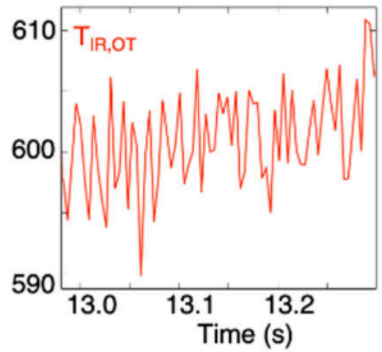
First demonstration of integrated ELM-free high-performance Neon-seeded plasma at JET

[C. Giroud, IAEA FEC 2025]

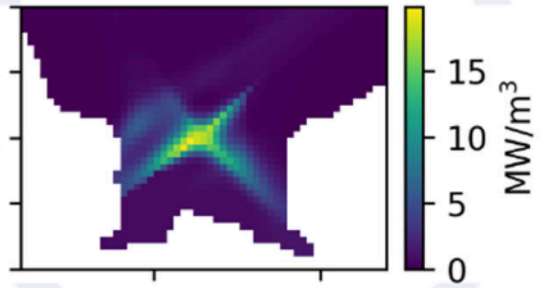
D-D operation 2.5MA/2.7T







ITER	#97490
$H_{98(y.2)}$=1	$H_{98(y,2)}$ =0.9
f_{GW}=0.85	f_{GW}=0.68
β_N=1.8	β_N=2.2
Z_{eff}=1.8	Z_{eff}=2.7
v^*_{ped} = 0.06	v^*_{ped} = 0.6
	$P_{sep}/P_{LH,Martin}$< 2



V Svoboda

$T_{e,OT}$< 5 eV

Transfer from D to D-T was straightforward.

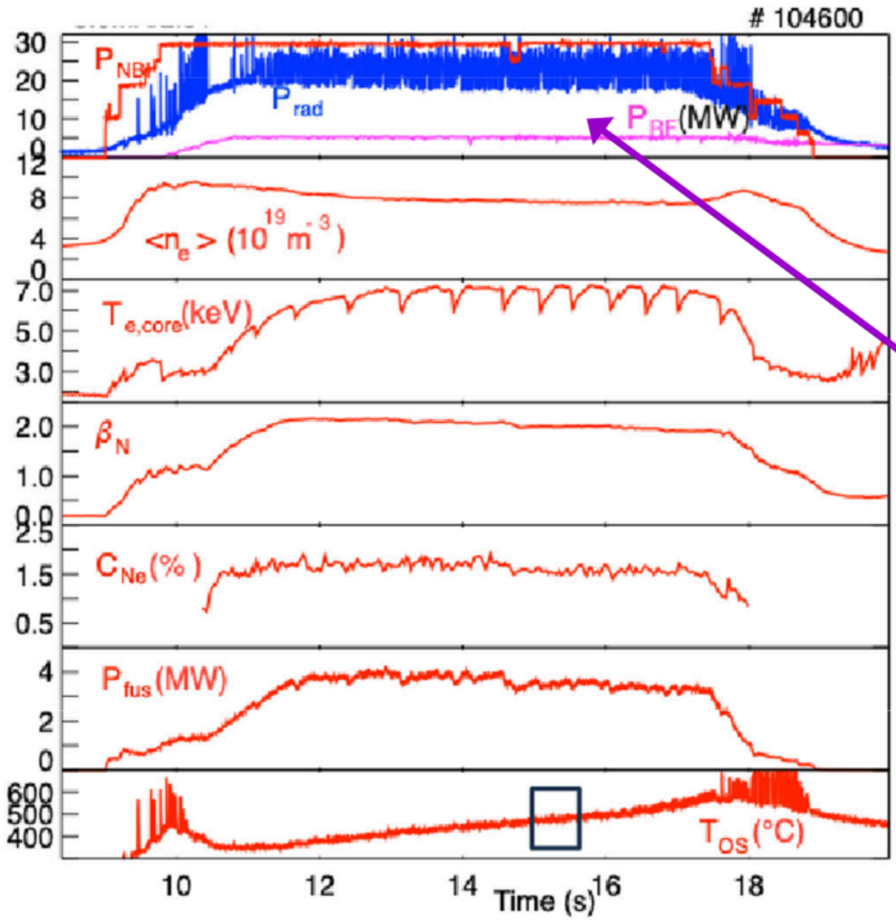
F_{rad} corrected to achieve energy balance

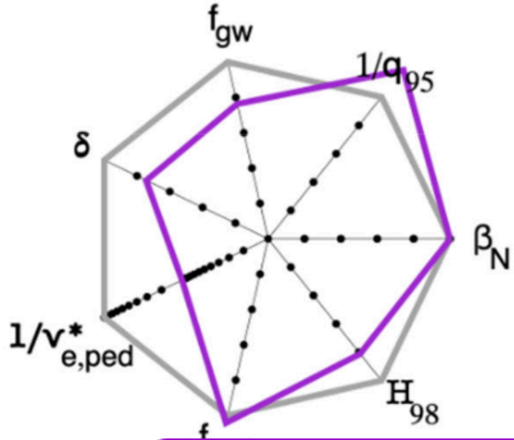
Successfully achieved in D-T at 3MA

[C. Giroud, IAEA FEC 2025]

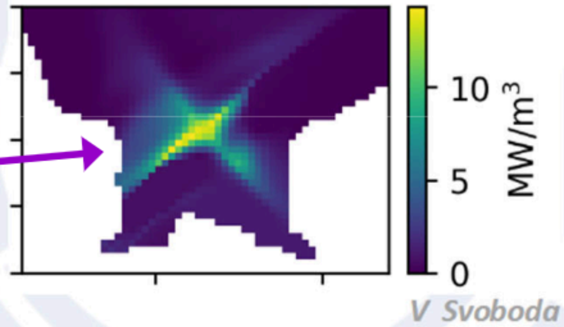
#104600

D-T operation 3.0MA/2.9T



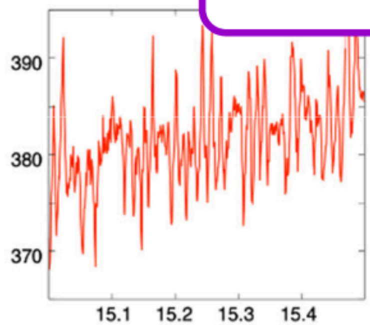


- $H_{98(y,2)}$ =0.85
- f_{GW}=0.68
- β_N=2.0
- Z_{eff}=3.2
- $v^*_{e,ped}$ = 0.5



Not a full XPR:

Disturbed by high frequency ELMs



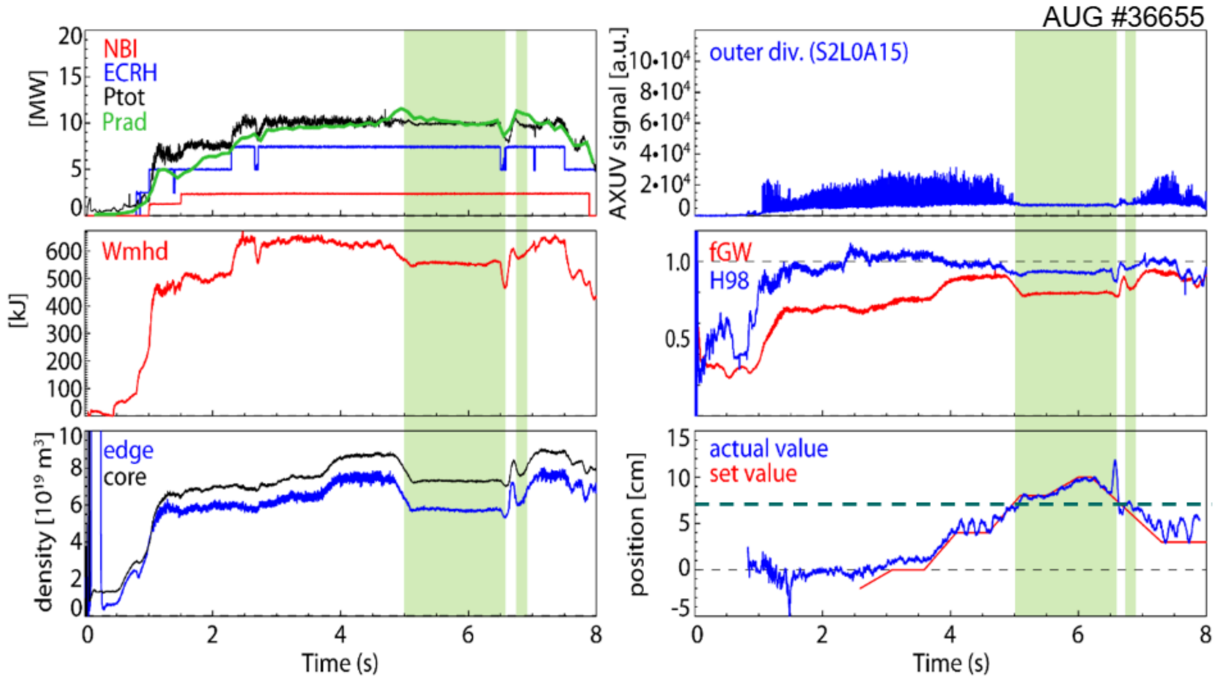
$T_{e,OT}$ < 5 eV

Best performance DT-seeded plasmas and achieved very long pulse (7.4s NBI at 30MW) **P_{fus} = 4MW**

XPR ELM suppression - AUG

XPRs are triggered with detachment
→ Inherent exhaust solution

- ELM signatures disappear at high XPR (dz_{XPR} > 7cm @ AUG)
- Sudden change of plasma behaviour
Characteristics between L- & H-mode
- Decent confinement at high density
$H_{98} \approx 0.95$, $f_{GW} \approx 0.8$
- High-ish impurity concentration
$c_N \approx$ 2-3%, $Z_{eff} \approx 2.5$ → should become better at ITER



[M. Bernert *et al* 2021 *NF* **61** 024001]

XPR ELM suppression - TCV

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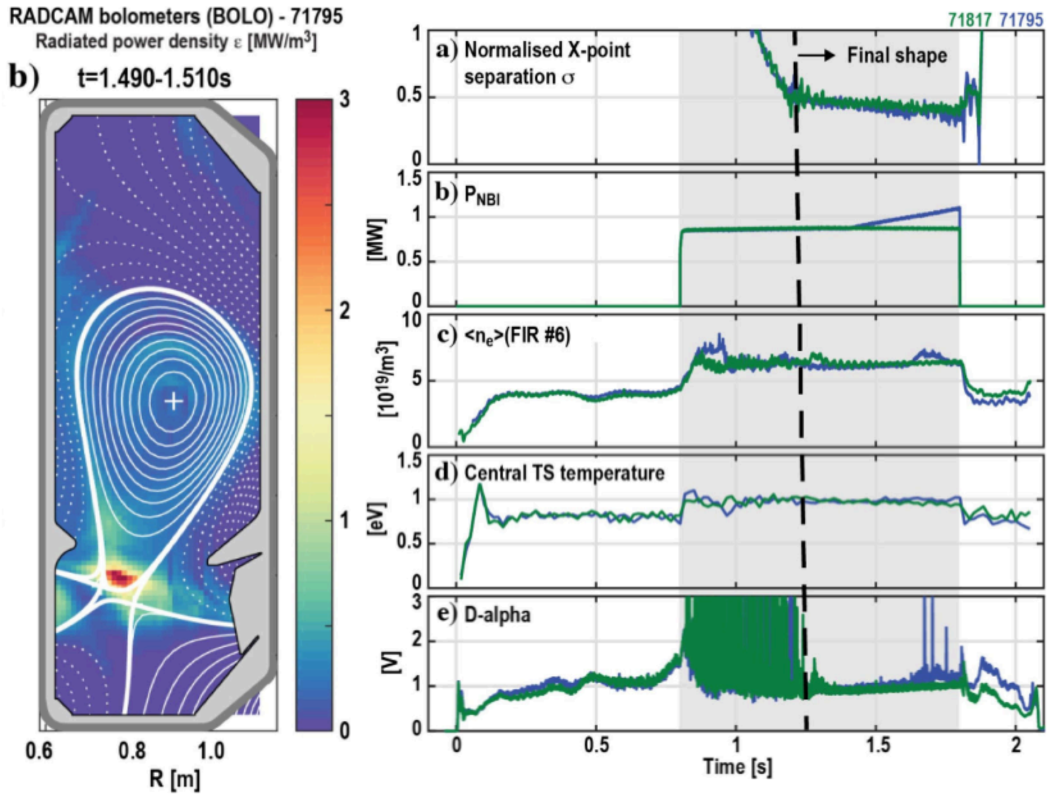
- Similar ELM-suppression also observed at TCV



[H. Reimerdes *et al* 2024 *NME* **41** 101784]

XPR ELM suppression - JET

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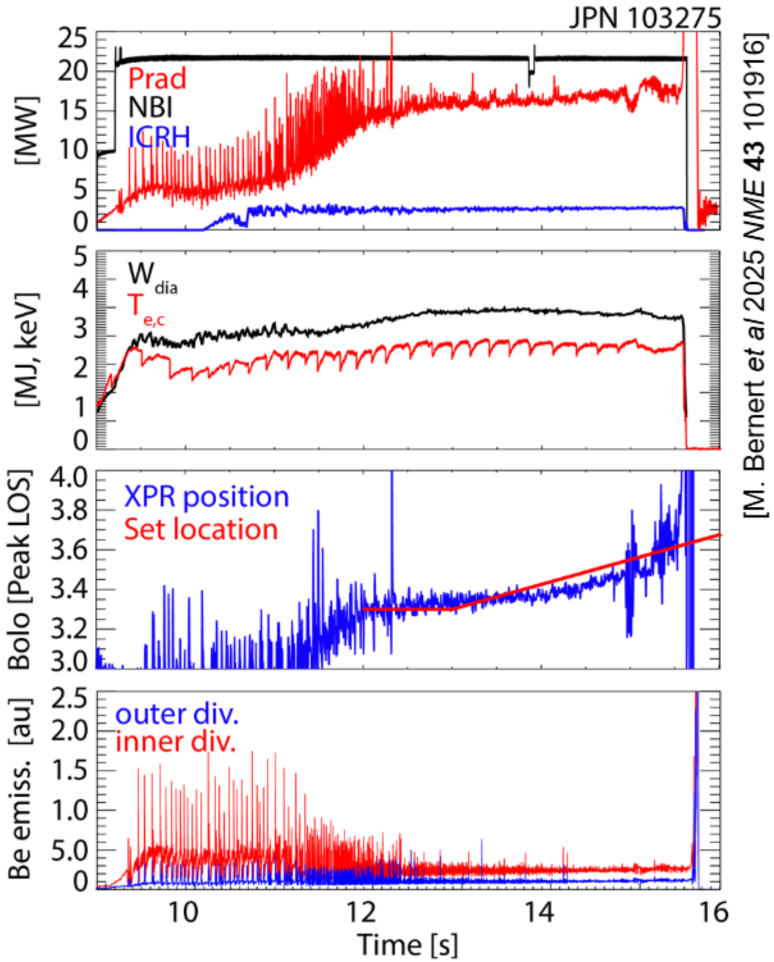
- Similar ELM-suppression also observed at TCV … and JET



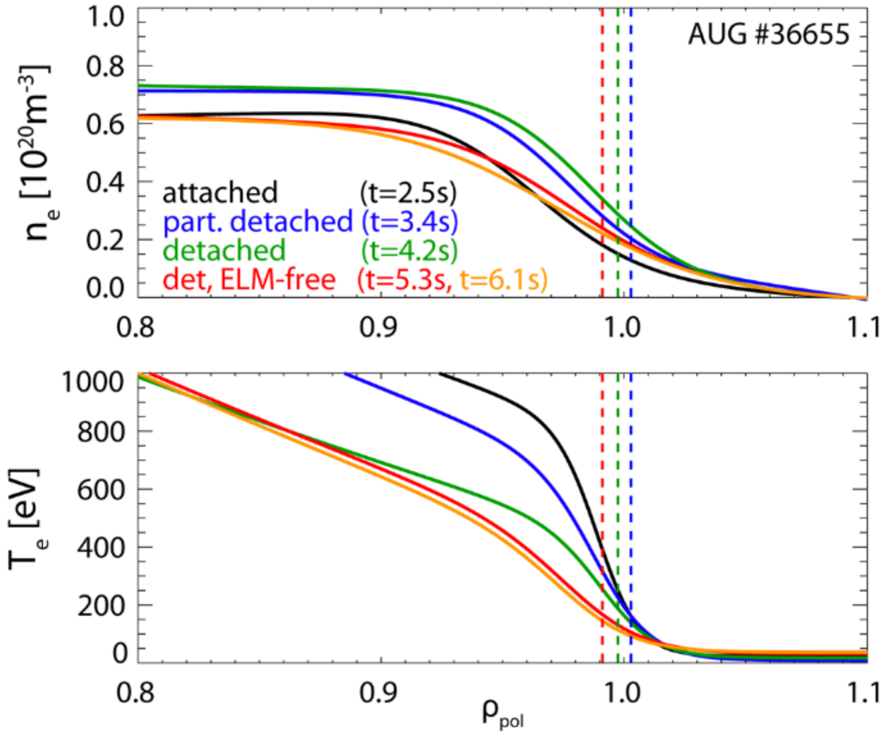
XPR ELM suppression – Pedestal

AUG:

- Pedestal profile gradients reduce further inside than XPR location

  → Peeling ballooning stable

  - Could, at least partially, be described by U.Stroth [PPCF 2025] → talk on Wed.
  - Rather abrupt transition to suppression



[M. Bernert *et al* 2021 *NF* **61** 024001]

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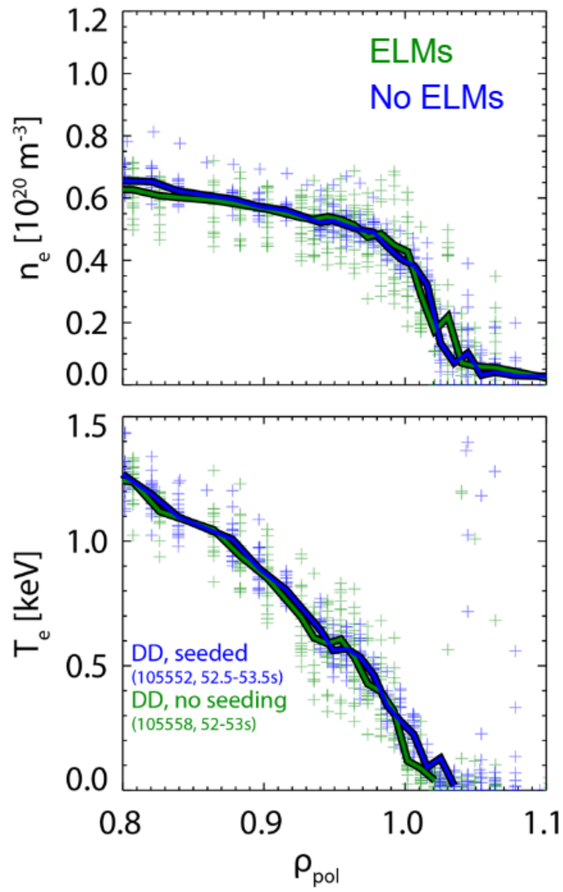
JET:

- No measurable impact on the pedestal (at $H_{98} \approx 0.65$-7)
  - ELMs gradually shrink but may not fully disappear

TCV:

- Less than 10% confinement reduction
  - ELMs vanish abruptly

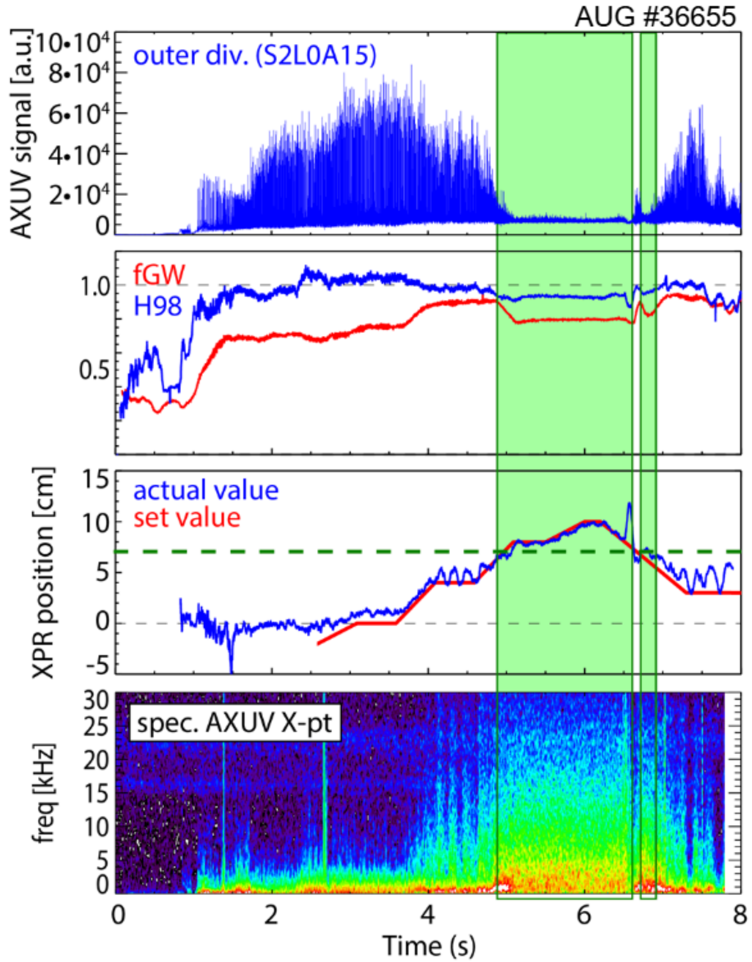


[M. Bernert *et al* 2025 *NME* **43** 101916]

XPR ELM suppression – Transport

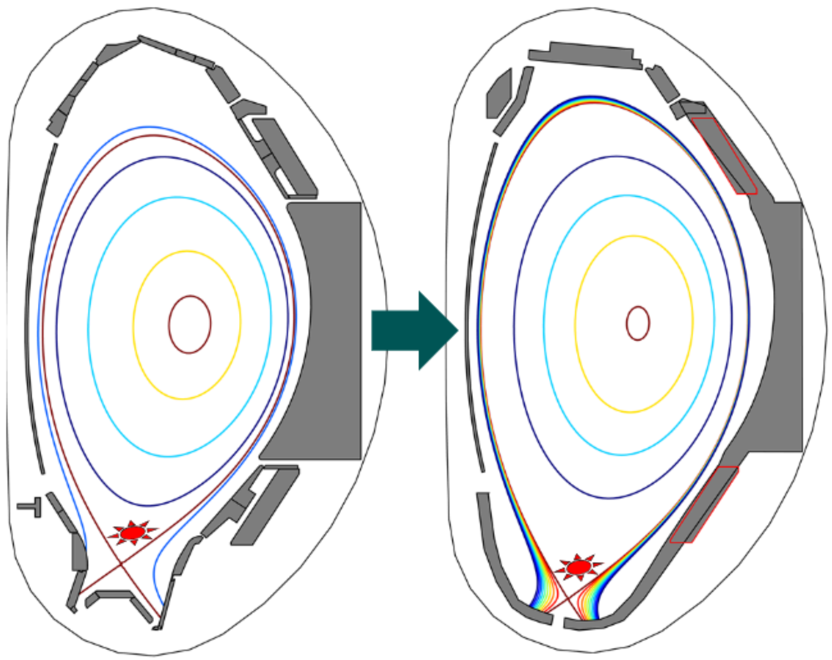
- Signs for increased transport
  - Fluctuations in X-point region increase
  - → Origin of incr. transport not yet identified

- Overall, reduction by up to 20% of confinement to be expected



XPR – The Compact radiative divertor (CRD)

- Compensate a loss of confinement by an increase of volume (40%!)
  - Reattachment has to be avoided at any price
  - No showstopper yet found (transients, impurity content, control, pumping & neutral compression)
  - Integrated design for reactor yet missing



[Lunt & Bernert et al 2023 *PRL* **130**, 145102]

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XPR ELM suppression is (obviously) a convincing regime for future reactors

\+ Inherent exhaust solution (incl. control!)

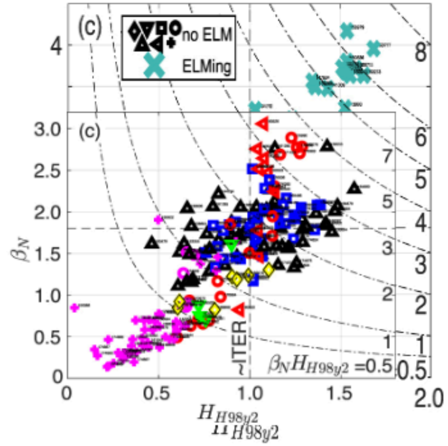
\+ Might also be combined with other ELM suppression methods (QCE, NT)

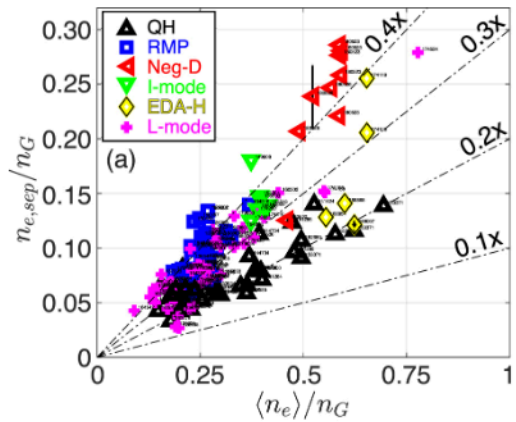
\- Reduced confinement and high-ish impurity content

\- Transport channel is not yet fully understood, hampering extrapolations

Common issues

- Almost all scenarios have reduced confinement vs type I ELMy H-modes
- Many have low edge densities (QH-mode, RMPs)
  - Not always a showstopper, but makes (detachment) life difficult
- Power fluxes might be shifted to the far-SOL (QCE, XPR, rev. B_t NT, RMP)
  → Full detachment is needed far out
  - High recycling (aka "power detachment") is not sufficient!
- Path into ELM suppression without ELMs needed
  - Exists for QCE, EDA, RMP, NT, I-mode & XPR ⇖ incl detachment ☺
- Impurity transport is an open issue for many scenarios
  → Requires integrated modelling with correct pedestal models





[C Paz-Soldan et al 2021 *PPCF* **63** 083001]

Summary and next steps to achieve ELM-free exhaust

QH-mode/WPQH-mode is critical, but significant improvements were done

- Not yet stable in metal devices
- High-ish impurity content

\+ Fulfilling many requirements, but not yet in parallel

→ **Stabilize in metal machines**
→ **Further improve impurity transport**
→ **Fully establish detachment**

I-mode was dead, but there's new hope!

- Confinement could be higher
- Limited operational space

\+ Potentially compatible with detachment

→ **Further evaluate full detachment cases**
→ **Improve confinement and avoid PREs**

RMPs could be exhaust-compatible

- Only if collisionality is the determining factor
- Reduction in confinement significant (~20%)
- Prediction for lobe detachment not conclusive for ITER

→ **Identify access parameter: edge collisionality or density**
→ **Evaluate lobe detachment for ITER**

NT is a promising option for future reactors

\+ Good confinement (at low power)
\+ Exhaust by core radiation
\- More complicated reactor design

→ **More experiments with optimised divertor and full power needed**

QCE, EDA, grassy/small ELMs are good candidates

• Many different scenarios
\+ Most are working at high $n_{e,sep}$
\+ Good confinement is achieved

→ **Detachment of filaments (far-SOL) to be shown**
→ **Transients must remain <0.5% W_{MHD}**

XPR ELM suppression is a convincing regime for future reactors

\+ Inherent exhaust solution (incl. control!)
\+ Might also be combined with other ELM suppression methods (QCE, NT)
\- Reduced confinement and high-ish impurity content

→ **Identify the ELM suppression mechanism/transport**
→ **Integrated modelling of a reactor design (CRD)**