MAX-PLANCK-INSTITUT
FÜR PLASMAPHYSIK

Small ELM / no ELM regimes in tokamaks and their way to reactor relevance

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EUROfusion

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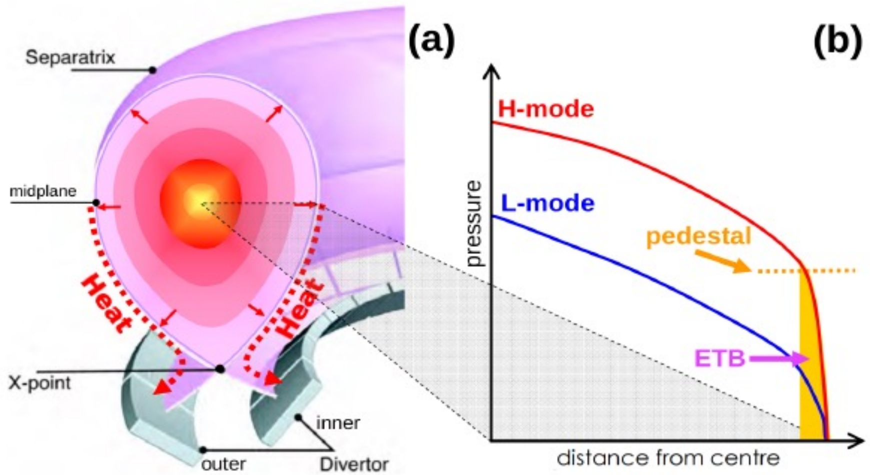
H-mode – the way to a power plant

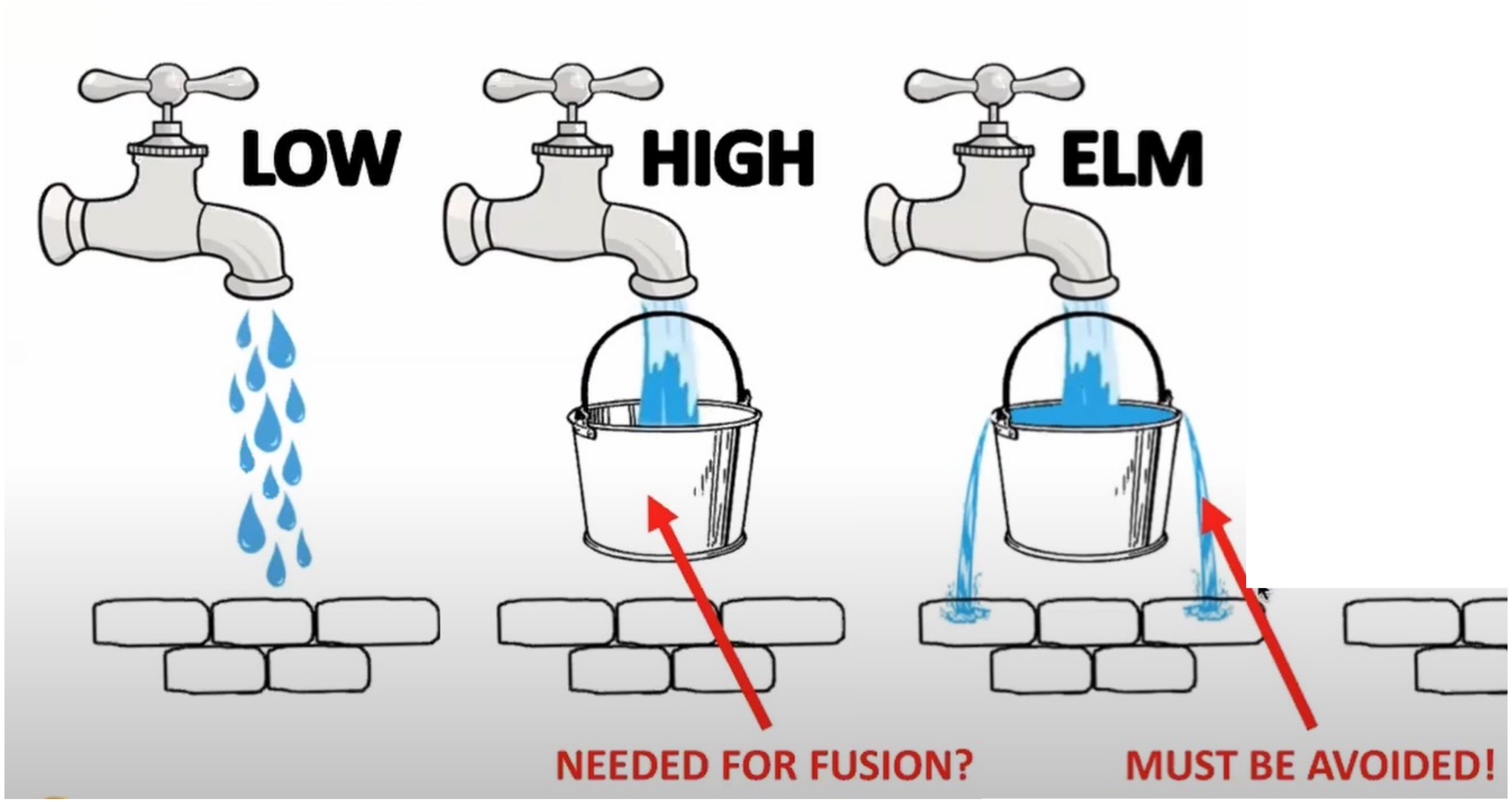
- Cookbook for a fusion power plant: have high $n \cdot T \cdot \tau_e$
- 1982: High confinement mode (H-mode) at ASDEX
- Made possible by divertor configuration and high heating
- Features:
  - Overall pressure ($p = nT$) increase
  - Edge transport barrier (ETB) → pedestal



Did we really just solve fusion?

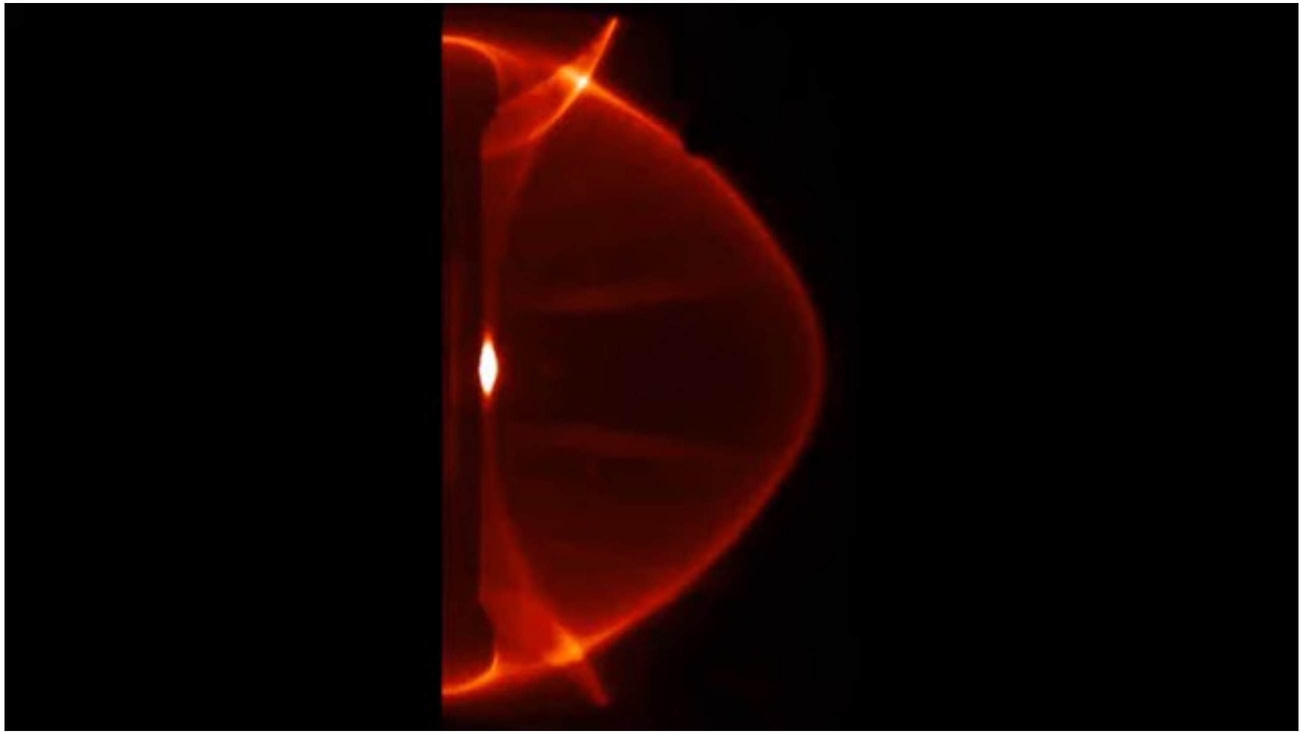
Cathey Cevallos, A.(2021). Non-linear magnetohydrodynamic simulations of edge localised modes (ELMs) (IPP 2021-14). Garching: Max-Planck-Institut für Plasmaphysik. doi:10.17617/2.3344034.

Tale of the buckets



https://www.youtube.com/watch?v=S9QQEA3jhlE&t=1818s&ab_channel=FusionEPtalks

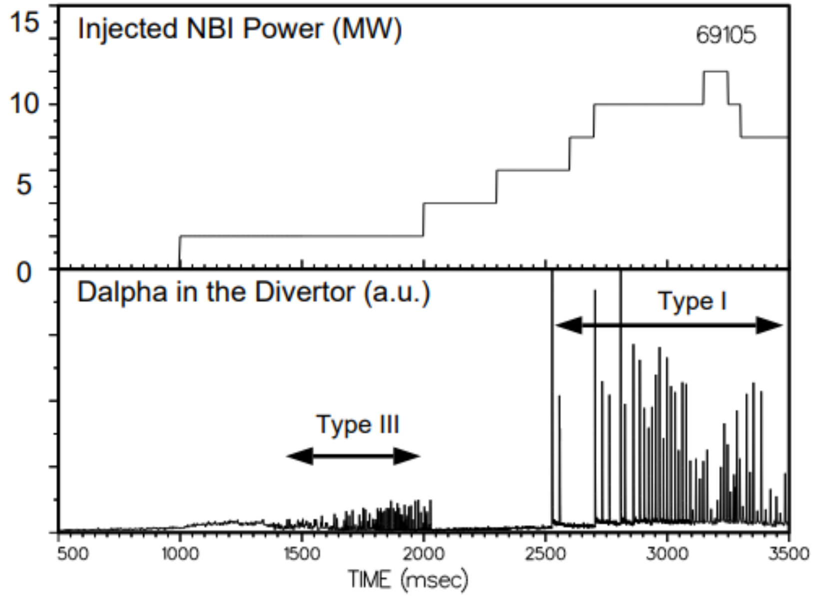
Dangers of H-mode - ELMs



https://www.youtube.com/watch?v=0uPzwN939VE&ab_channel=StevenLisgo

Dangers of H-mode - ELMs

- Pedestal continues to build up without losses
- Degrades with sudden flushing out of plasma – Edge Localized Mode (ELM)
- Quasiperiodic: pedestal build up -> ELM -> build up -> ELM …
- Categorized based on frequency and plasma energy loss
- Type-1 ELMs can expel up 5-15% of plasma stored energy
- In present devices OK
- For ITER plasma-facing components (PFCs): fatal



H Zohm 1996 Plasma Phys. Control. Fusion 38 105

- MUST be avoided in a reactor-size machine

Solutions to ELMs

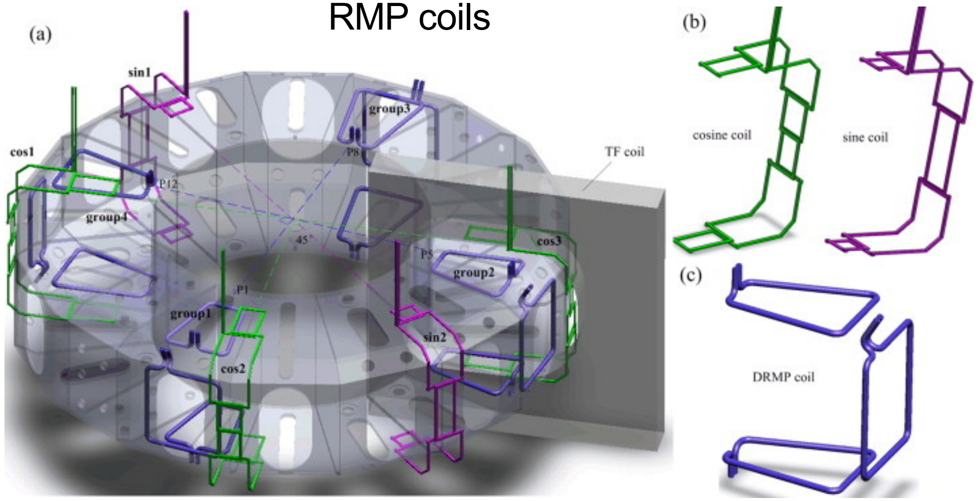
Mitigation

- Resonant magnetic perturbation (RMP)
- Pellet pacing
- Buffering with impurities

Small ELM / no ELM regimes

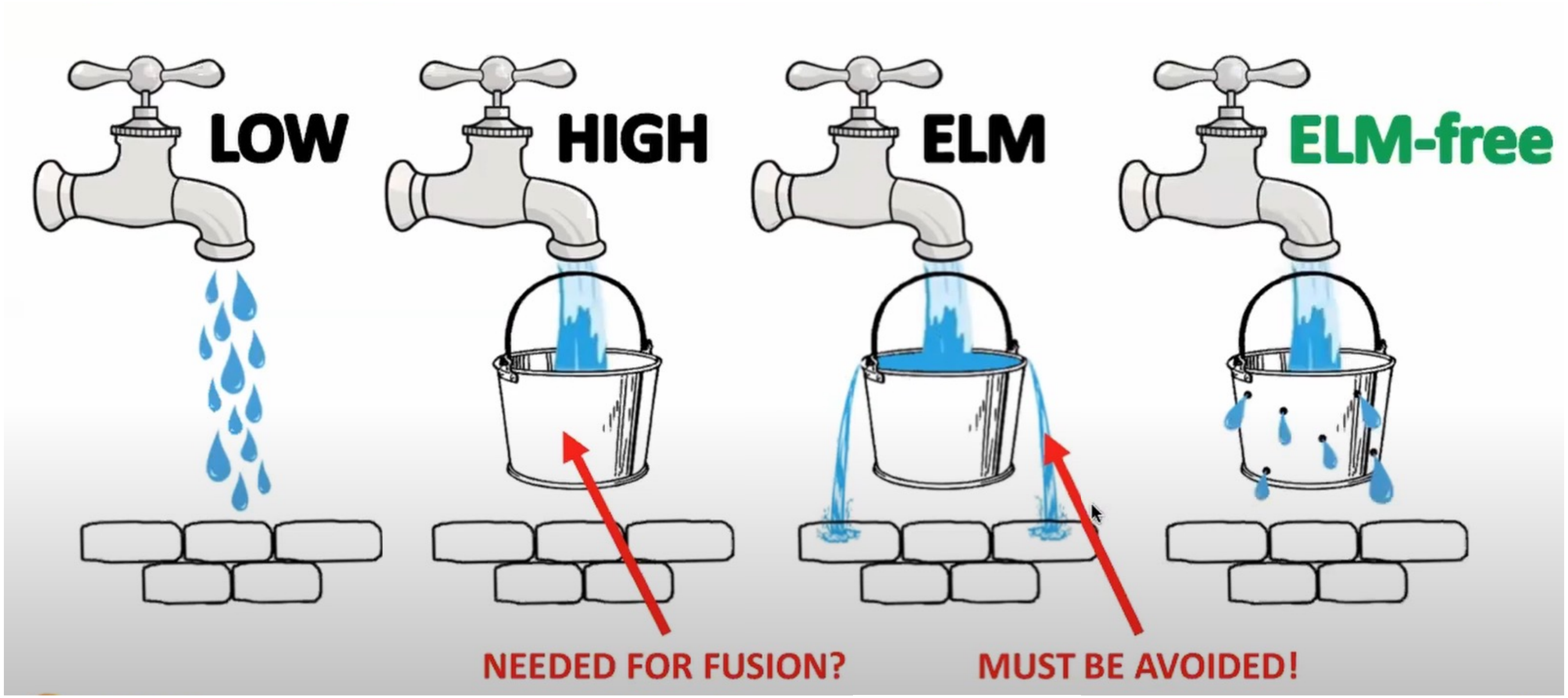
- **Enhanced D-alpha H-mode (EDA H-mode)**
- ..etc

RMP coils



B. Rao, G. Wang, Y.H. Ding, K.X. Yu, Q.L. Li, N.C. Wang, B. Yi, J.Y. Nan, Y.S. Cen, Q.M. Hu, W. Jin, J.C. Li, H. Jin, M. Zhang, G. Zhuang, Introduction to resonant magnetic perturbation coils of the J-TEXT Tokamak, Fusion Engineering and Design, Volume 89, Issue 4, 2014,

Tale of the buckets – part 2



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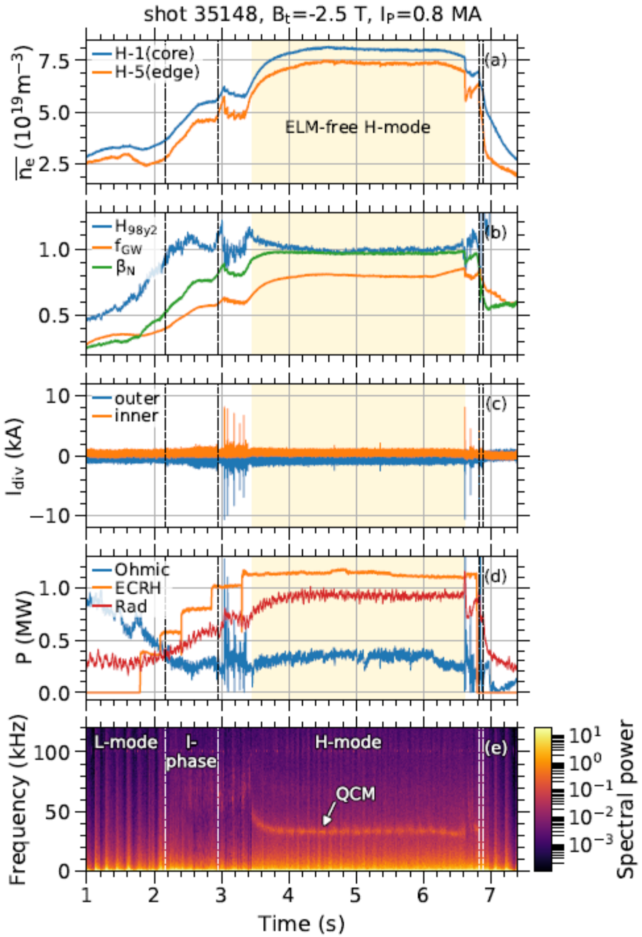
EDA H-mode history

- Power ramp (with ECRH) performed in ASDEX Upgrade (AUG)
- Plasma undergoes several confinement regime transitions
- Finally, a stationary ELM-free phase is found

- Features:
  - High density, confinement
  - No ELMs
  - Relatively low heating needed
  - Quasi Coherent Mode – edge instability

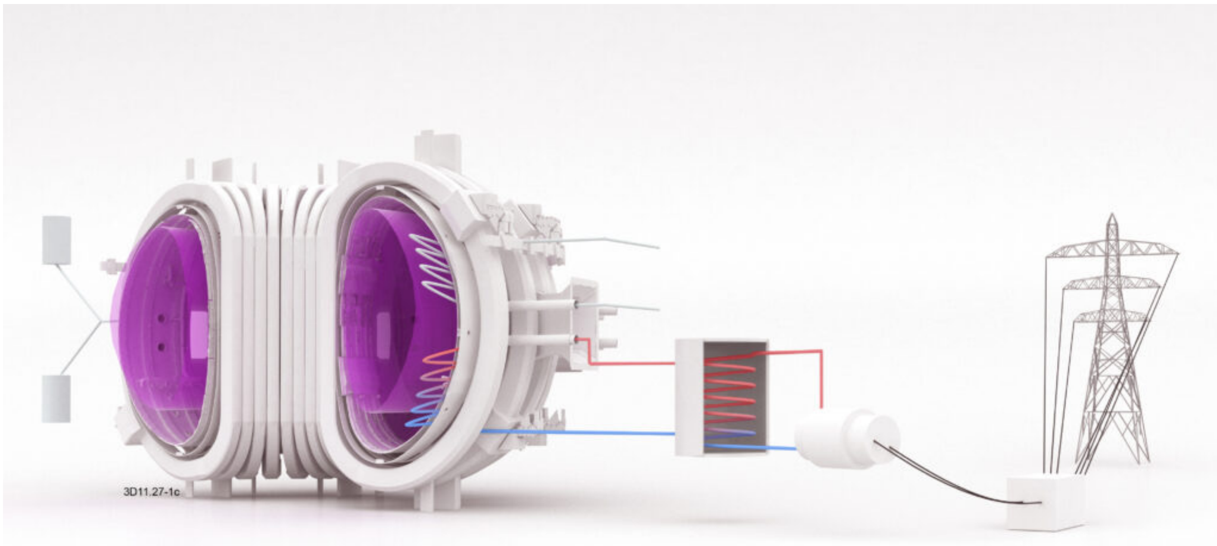


Gil, Luís Manuel Cerdeira. Stationary ELM-free H-mode in ASDEX Upgrade. 2021. Universidade de Lisboa, Instituto Superior Técnico, PhD Dissertation.

Tailoring for reactor relevance

For reactor relevance, we need (not complete):

- High power window
- Low heat loads on PFCs



https://euro-fusion.org/programme/demo/

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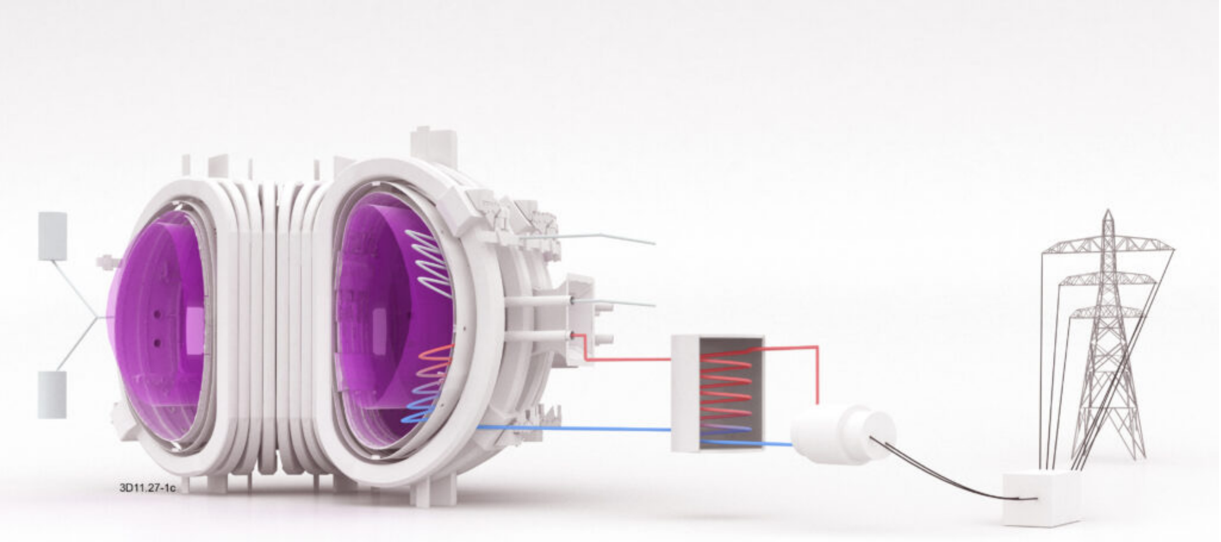

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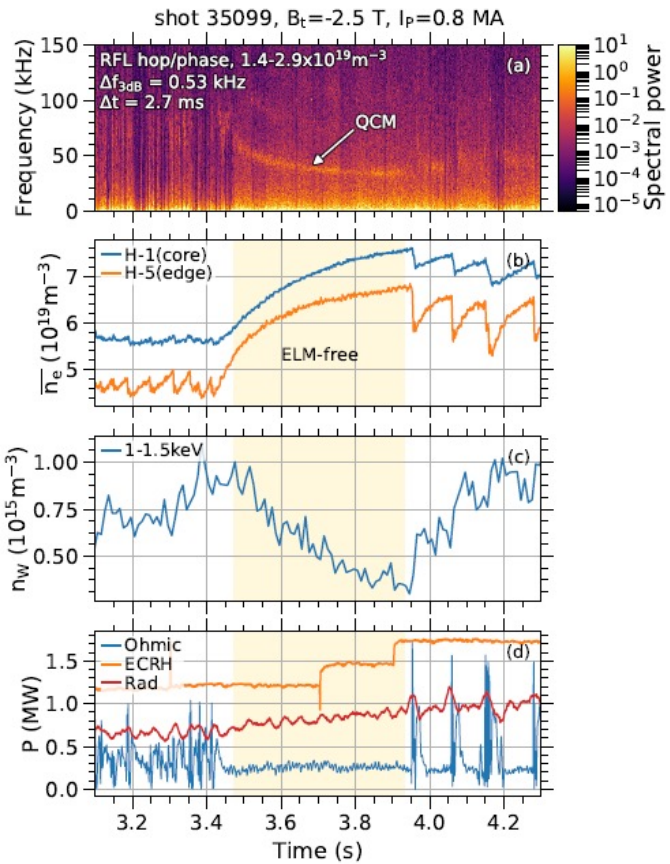
Reactor relevance

- Reactor scenario needs long duration, stable no ELM plasma
- A few ELMs can melt the PFCs
- Extending the power window is extremely important

- In EDA H-mode, reappearance of ELMs at high-heating
- No ELM power window is only ~0.2 MW
- Would need fine control of heating to maintain
  (not robust to for example alpha particles)



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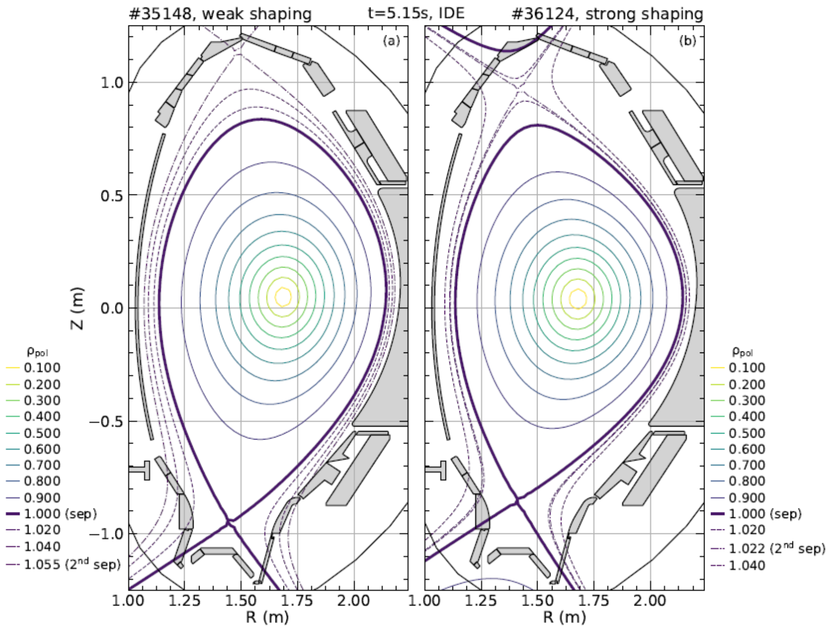
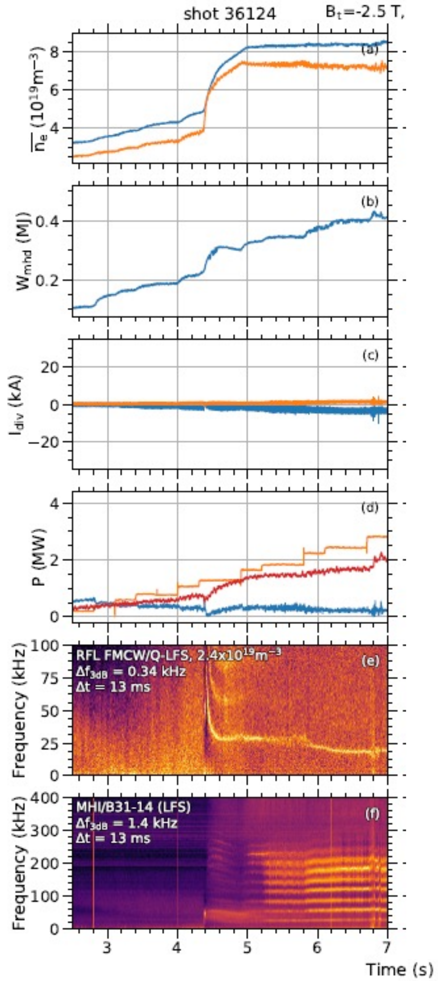
Extending the power window - shaping

- Idea: make it less unstable to underlying instability
- Stability limit can be extended by strong plasma shaping
- Also, instant transition from L- to EDA H-mode





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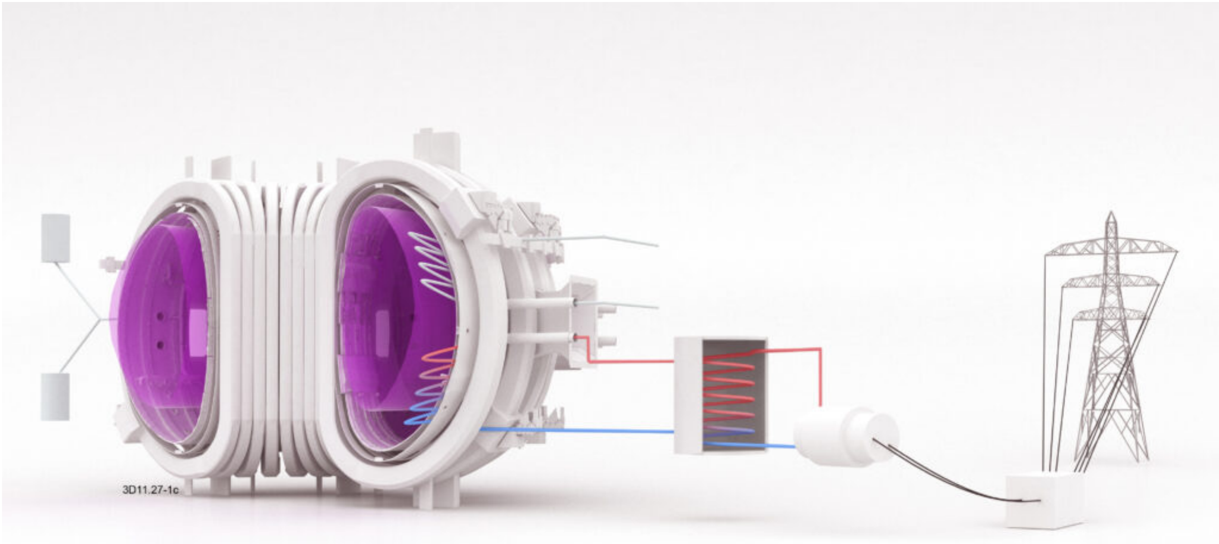

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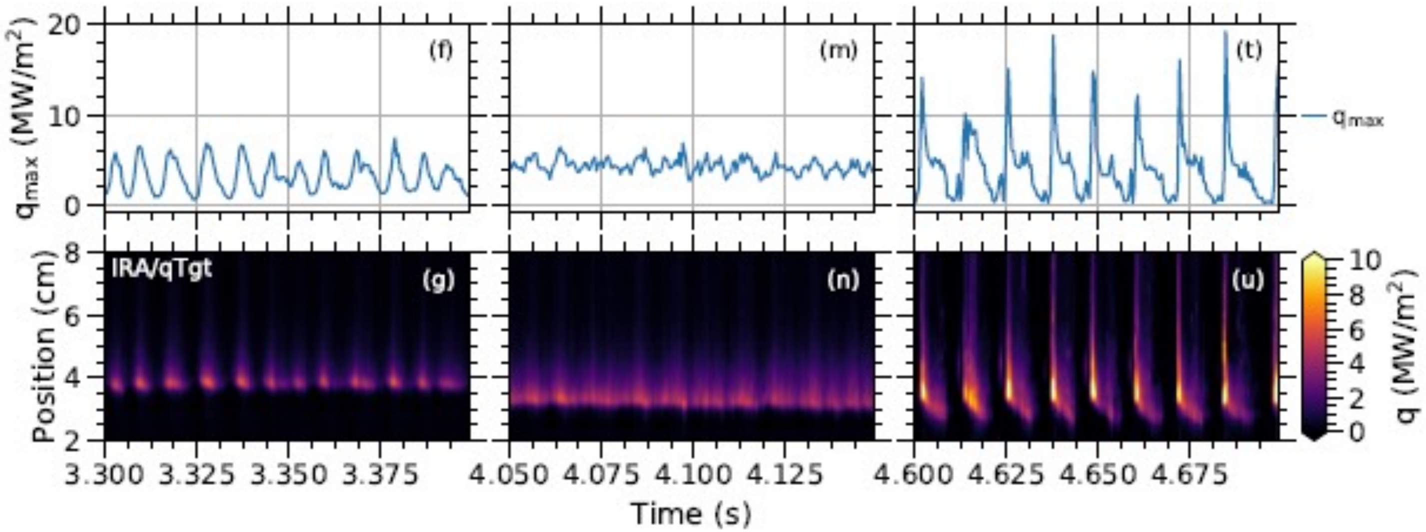
Addressing heat loads

- Heat loads can be large without ELMs
- Need low peak AND time-averaged heat load for reactor



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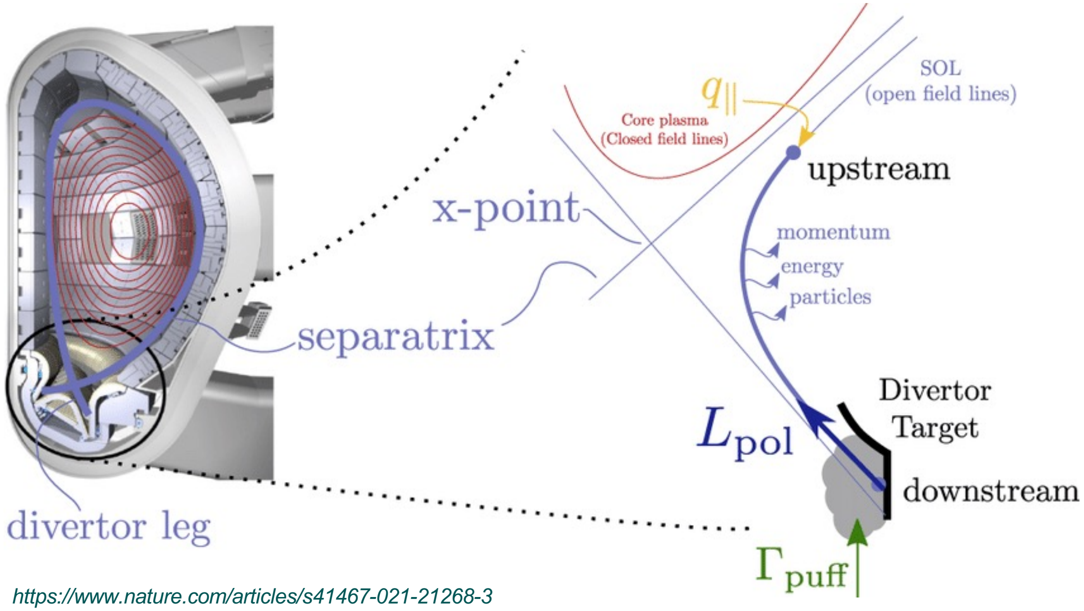
Lowering heat loads with detachment

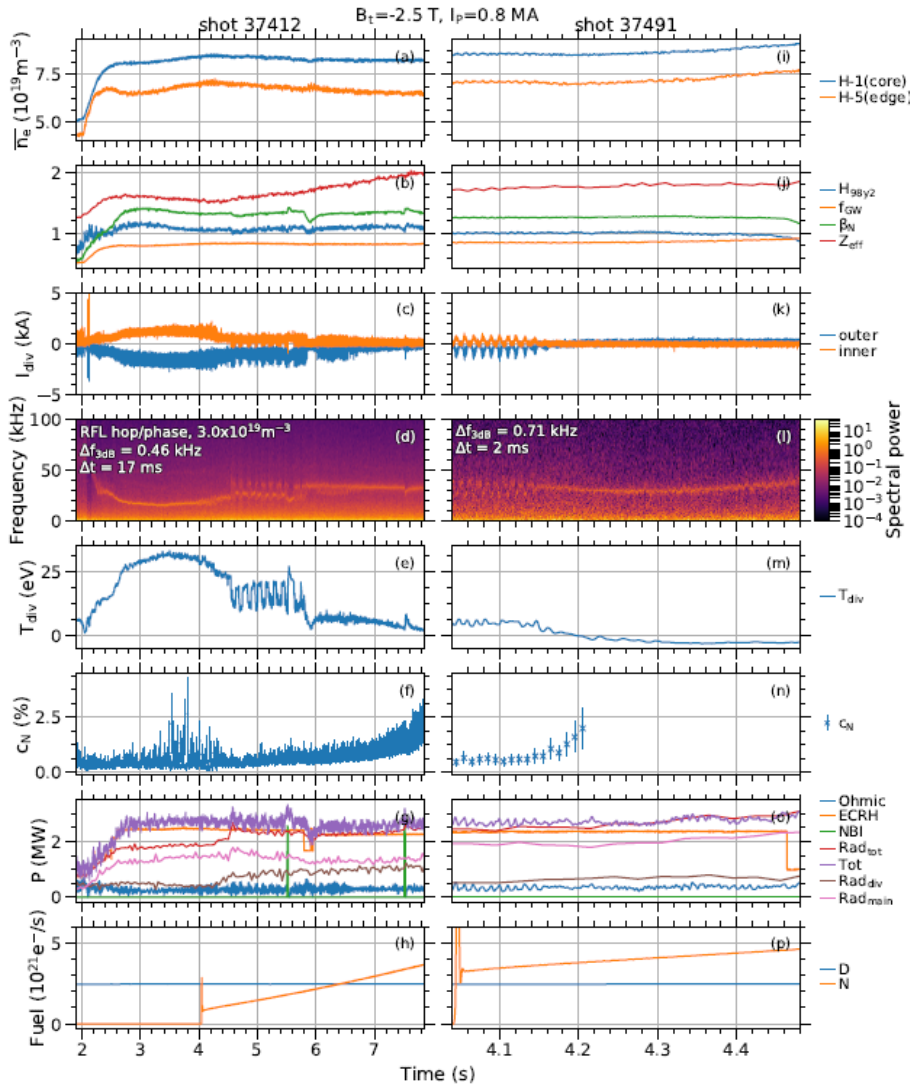
- Mitigate heat fluxes by puffing D or impurities
- Lowers the temperature of the divertor plasma
- Cold, dense layer of plasma at divertor targets
- Large volumetric losses radiate power away
- Very desirable for a reactor



https://www.nature.com/articles/s41467-021-21268-3

Detachment in EDA H-mode

- Heating kept constant
- Combined N and D gas puff
- Radiated power increased
- Divertor legs cool down to 5-10 eVs
- Impurities come with a tradeoff:
  - Increased in Z_eff in the core
  - Cool divertor but don't radiate in core
- Here, density limits further development (ECRH cutoff)



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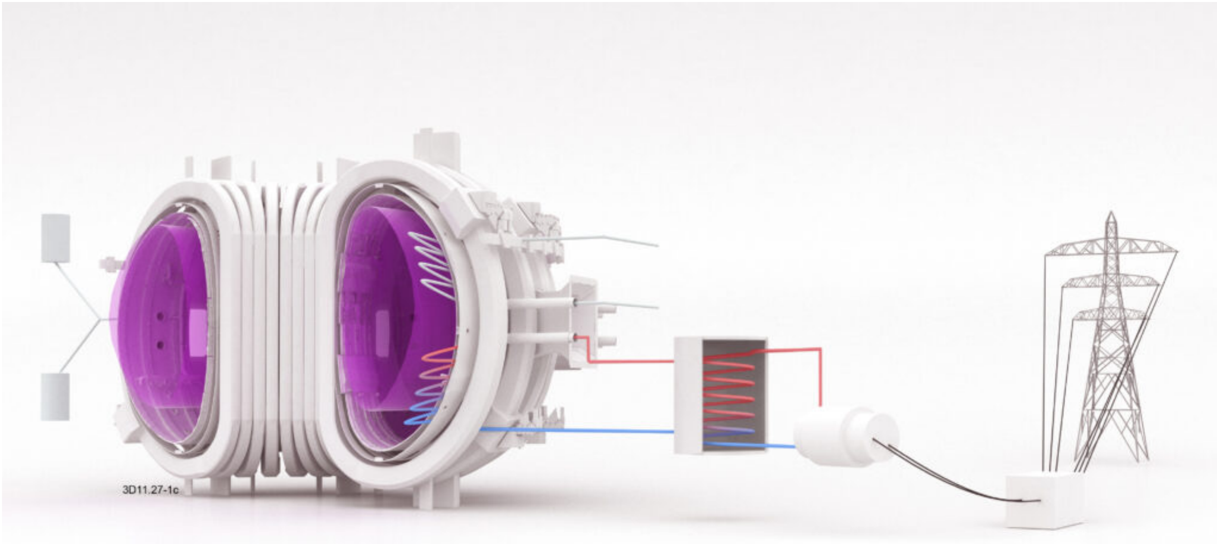

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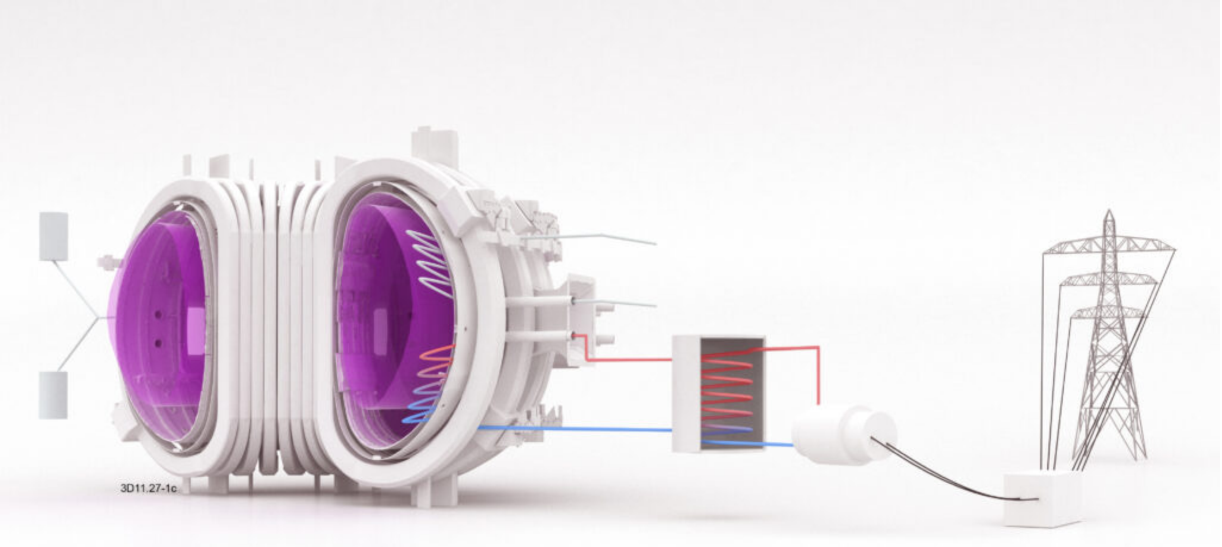

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Can we achieve both with one method?

Argon seeding

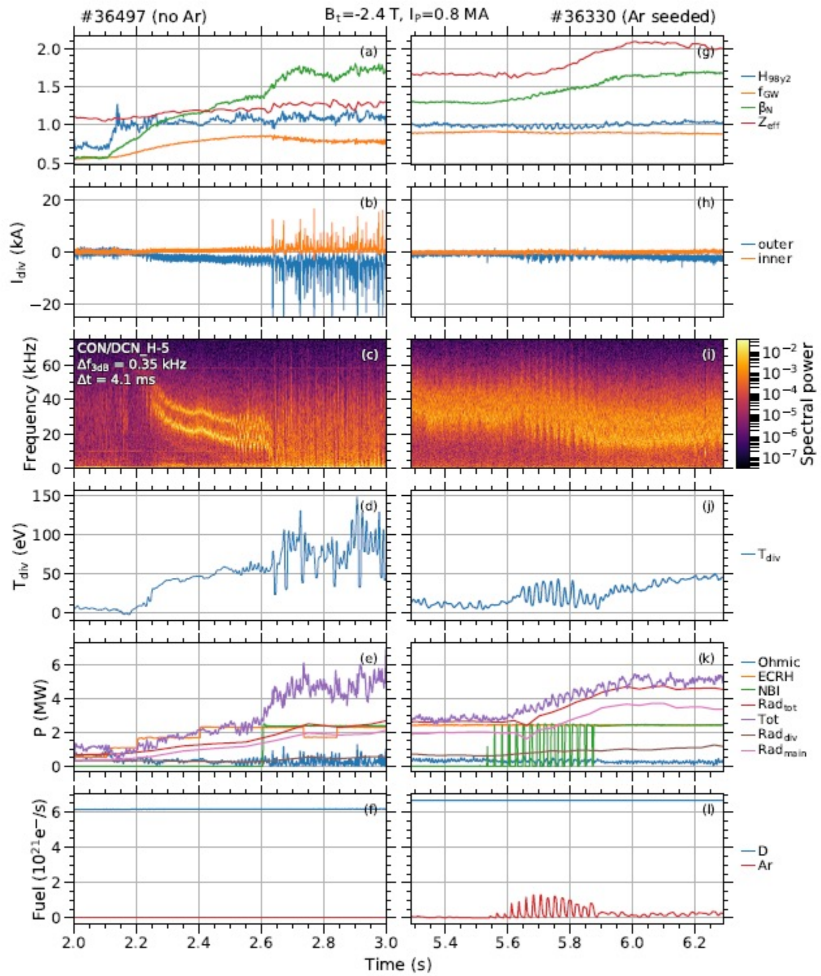
- Yes, with Argon

- Pedestal build up –> ELMs
- Radiating power away with impurities -> decreased divertor heat fluxes
- What if we radiate power away at the pedestal?
  - Pedestal cools down -> no ELMS
  - Power radiated

- Avoid radiation in core by choosing the right impurity
- Argon, peak ionization at 10-40 eV, separatrix region
- No ammonia formation and wall sticking like for nitrogen

Argon seeding

- No Argon vs with Argon
- No argon:
  - ELMs at 4 MW
  - Divertor temperature keeps increasing
- With argon:
  - Stationary no ELM period
  - No increase in divertor temperature
  - Broadening of QCM
  - High Z_eff



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Summary

- H-mode is the desired regime for a fusion reactor
  - Large increase in confinement thanks to ETB
- Pedestal build-up excites ELMS
  - Fatal heat fluxes on large machines, must be avoided
- EDA H-mode shows H-mode level confinement without ELMs
  - QCM acts as transport channel regulating pedestal
- For this to be reactor relevant we need:
  - Longer power window: shaping
  - Low heat fluxes at divertors: detachment (nitrogen seeding)
  - Each can also be achieved with argon seeding: pedestal and divertor cooling