The ITER plasma termination phase: physics constraints on control

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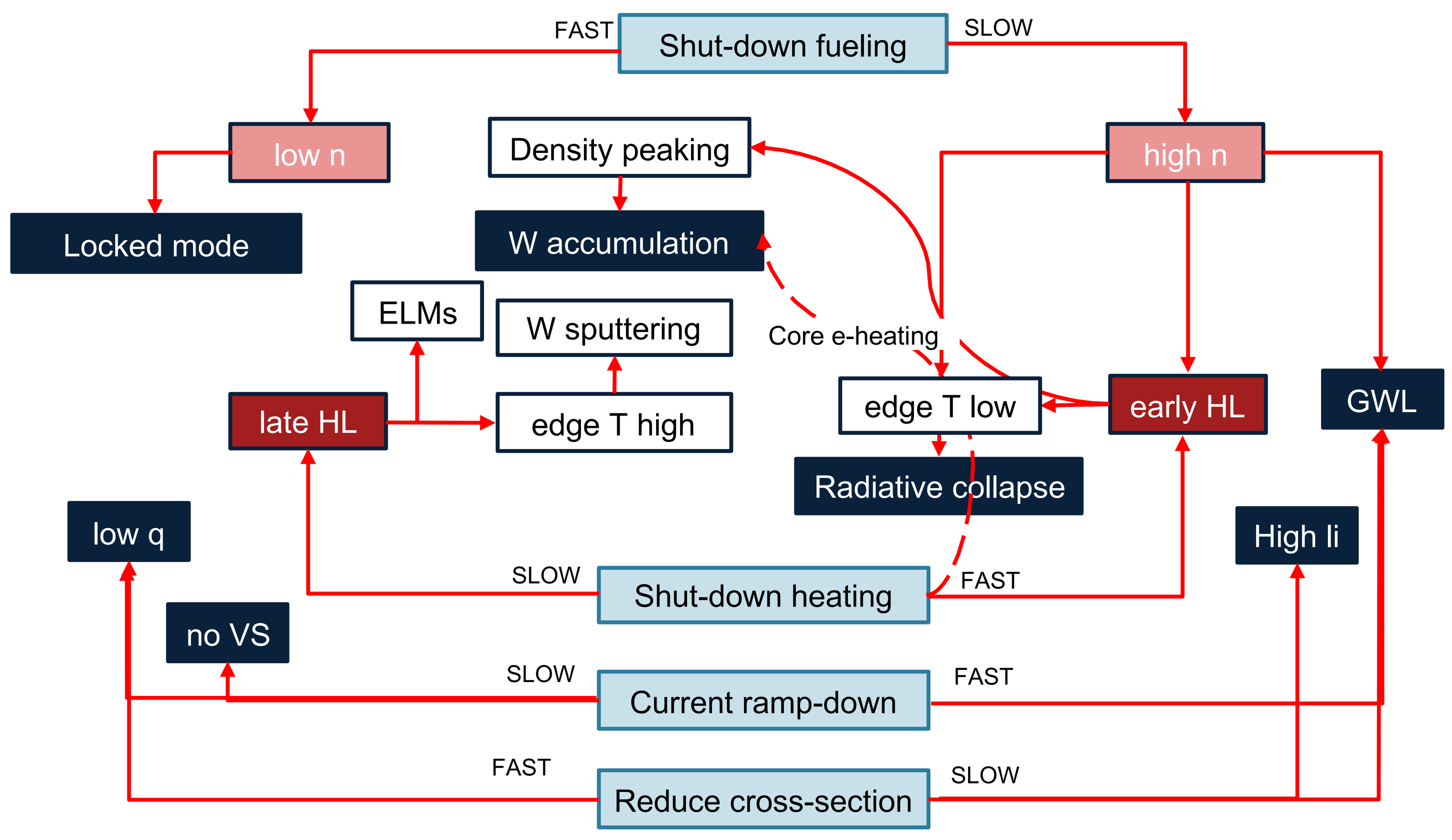
A controlled ramp-down should balance all responses



- Power step-down
  - Shut-down auxiliary power and fueling => IC coupling, EC, NBI shine-through, fast ions
  - Controlled exit from burn and H-mode => radial position control
  - Maintain control of impurities/radiation => seedling, core electron heating
- Current ramp-down
  - Avoid vertical instability due to increase of l_i (shape+heating) => reduce cross-section
  - Avoid additional flux consumption => reduce plasma current
  - Stay in X-point as long as possible to maintain particle and power handling => ~2MA

Use a parametrization for the edge as boundary condition for core transport

TRANSP calculates transport and outfluxes

edge input core output (@ψ=1)

Total input power P_{SOL}
DT ion outflux $\Gamma_{DT,sep}$
Helium ion outflux $\Gamma_{He,sep}$
$\xi_{ei}=P_e/P_i$

Edge input – external control

Pumping speed S_{ENG}
Gas puffing rate Γ_{puff}

SOLPS parametrization gives values at separatrix

Core+pedestal input edge output (@ψ=1)

Separatrix temperature $T_{i,sep}$ $T_{e,sep}$
Separatrix density n_{sep} $n_{He,sep}$
Neutral influxes $\Gamma_{DT,n,sep}$ $\Gamma_{He,n,sep}$
Neutral temperature $T_{DT,sep}$ $T_{He,sep}$
Impurity concentration

Core input – external control

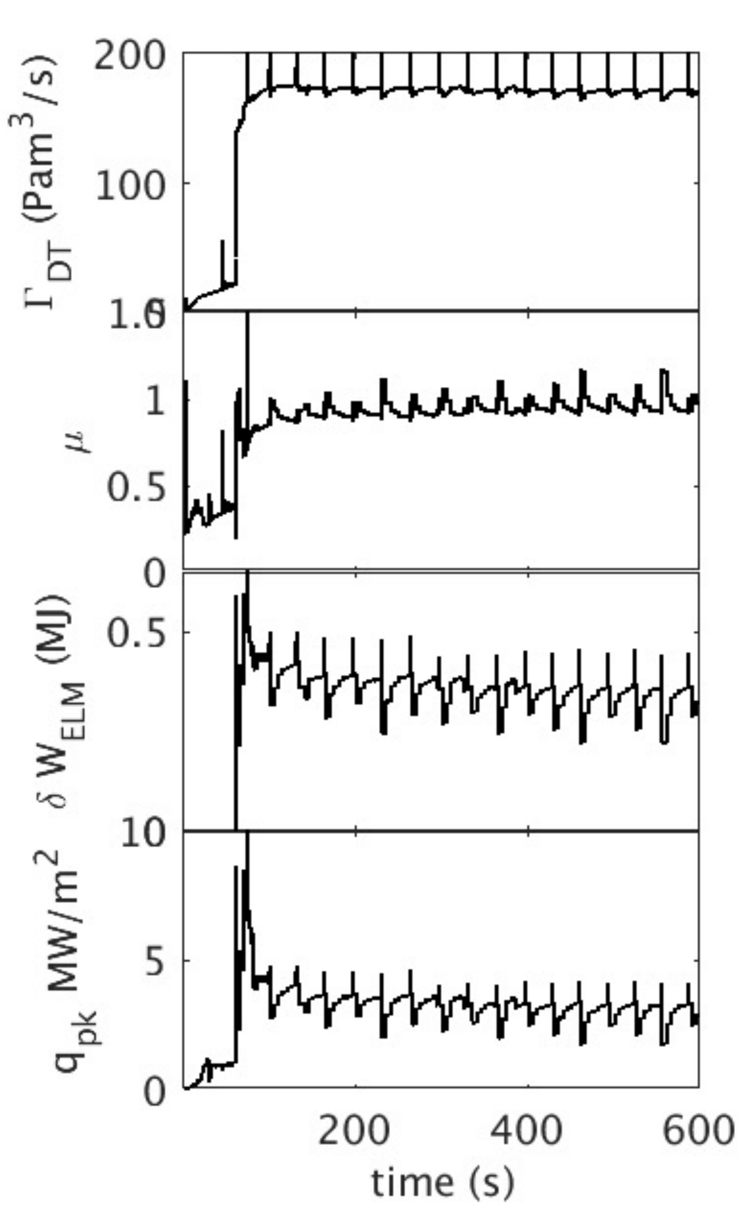
Auxiliary heating power P_{aux}
Core DT fueling Γ_{core}

Throughput $\Gamma_{DT}=\Gamma_{puff}+\Gamma_{core} \leq 200$ Pa m^{3}s^{-1} limited by cryopump and T inventory

Peak power loading $q_{pk} \leq 10$ MW/m^2 Limited by target design

*Edge parametrization from Pacher et al, JNM **463** (2015) 591*

Observables for control



$$\Gamma_{DT}=\Gamma_{SOL}+\Gamma_{ELM}+\Gamma_{LFS}$$

$$\mu=(\Gamma_{DT}/250S_{ENG})^{0.83}P_{SOL}^{-0.52}$$

$$\delta W_{ELM}=0.2P_{SOL}/f_{pel} \quad f_{pel}=35Hz$$

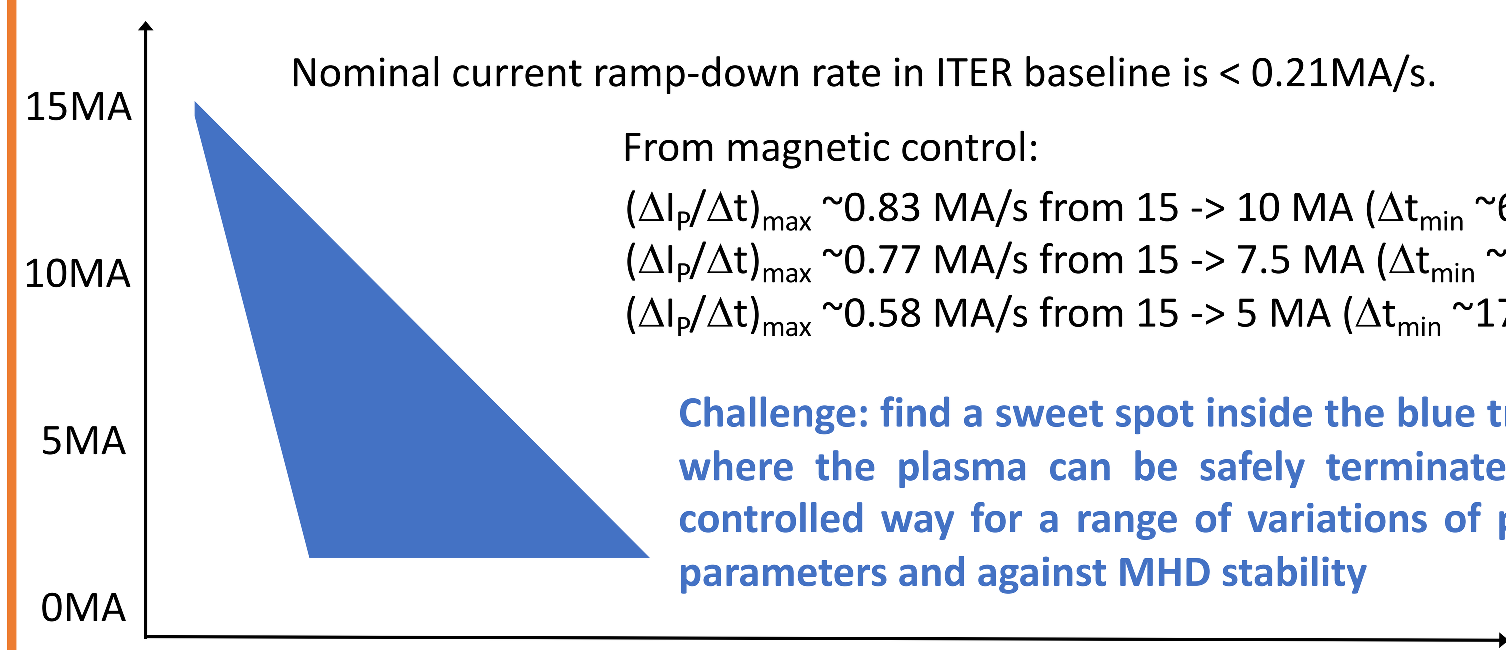
$$\Gamma_{ELM}=0.2n_{ped}P_{SOL}/1.5Vp_{ped}$$

$$q_{pk}=f(P_{SOL},\mu,c_{Z,sep},S_{ENG},P_{\alpha})$$

Limits of these simulations:

- Do not include ELM regimes
- H-L transition based on scaling
- Density peaking not realistic (either prescribed or based on semi-empirical)
- Uncertainties on dynamical variation of the Greenwald fraction

Simulations of the ITER termination phase need to satisfy all operational limits



Nominal current ramp-down rate in ITER baseline is < 0.21MA/s.

From magnetic control:
$(\Delta I_P/\Delta t)_{max}$ ~0.83 MA/s from 15 -> 10 MA (Δt_{min} ~6s),
$(\Delta I_P/\Delta t)_{max}$ ~0.77 MA/s from 15 -> 7.5 MA (Δt_{min} ~10s),
$(\Delta I_P/\Delta t)_{max}$ ~0.58 MA/s from 15 -> 5 MA (Δt_{min} ~17s),

Challenge: find a sweet spot inside the blue triangle where the plasma can be safely terminated in a controlled way for a range of variations of plasma parameters and against MHD stability

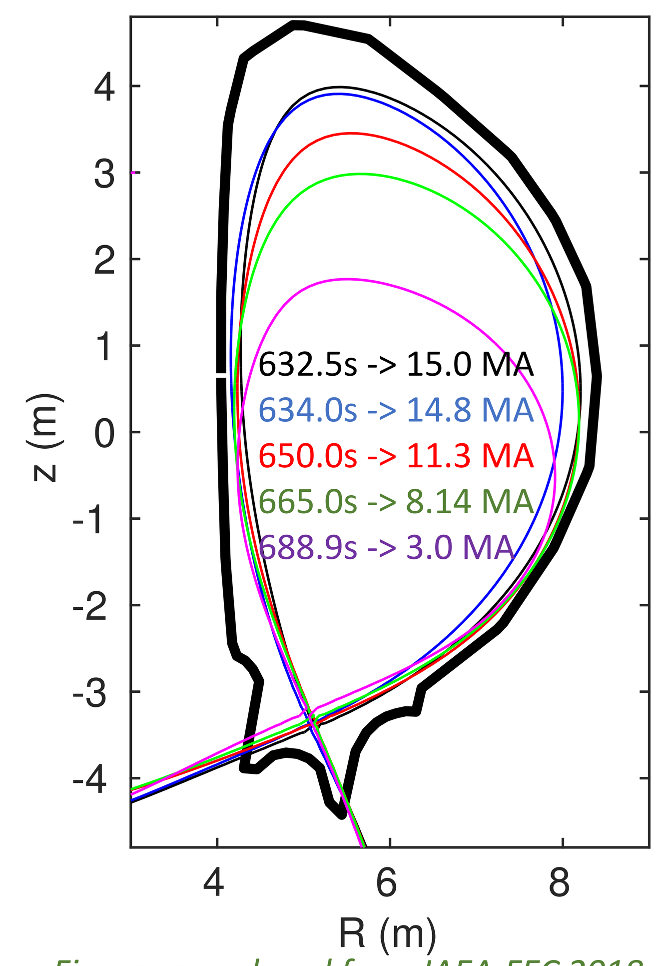
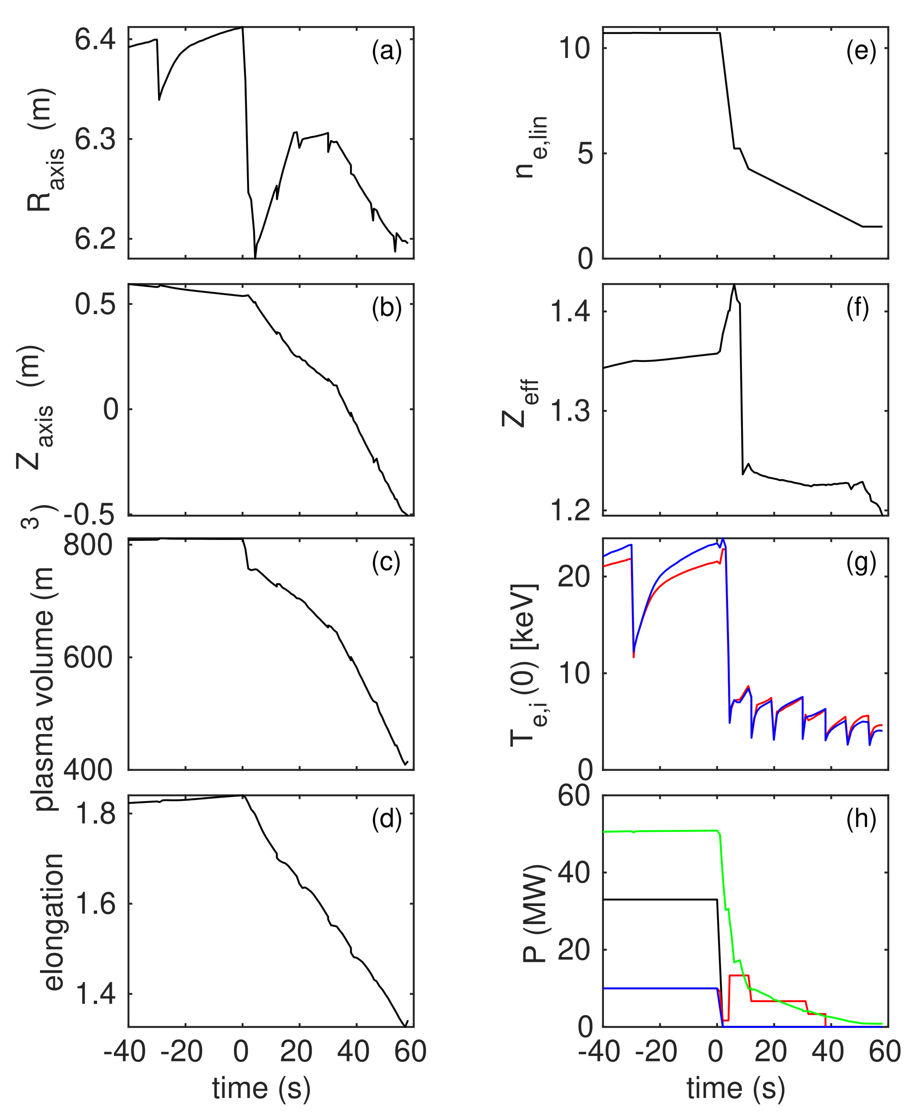


Figure reproduced from IAEA-FEC 2018

- PF/CS coil limits
- Vertical position control
  - reduce elongation to keep li low
- Shape/gaps control
  - Plasma diverted down to 2MA
  - Radial mid-plane gap > 7 cm
  - Min. gap between inner/outer separatrix > 4cm

Initial assessment of H-L transition time

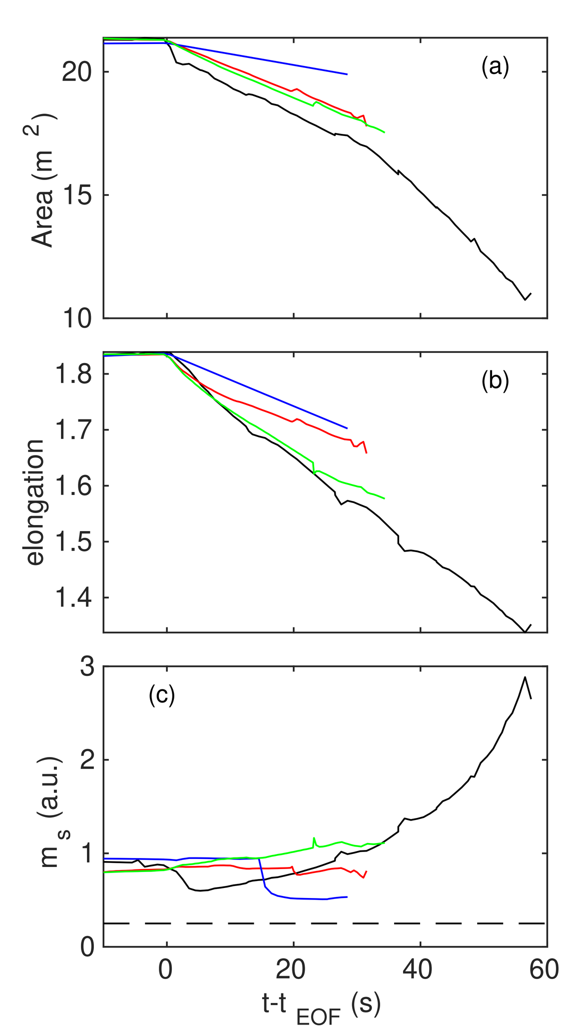


H-L transition at 15MA

- Let the controller do everything
- No NTMs in ramp-down

Risk assessment => high current disruptions

step-down everything together
⇒ in what sequence? what time scales?
⇒ Compatibility with DMS response time?



H-L transition around 10MA

Risk assessment => NTM control

w_{EC} naturally broadens => reduced CD efficiency

q=2 surface drifts => need to track (m,n)

Compatible with steering capabilities, but what about
⇒ ECE S/N ratio
⇒ magnetic equilibrium response

$$m_s=\left[\frac{1.47\left(1+e^{-2\ell_i+1}\right)}{2\left(\kappa-1.13\right)}-1\right]\left(1+0.6\left(\beta_P-0.1\right)\right)$$

Conclusions from initial assessment with reduced models and 0D parametrization:

- H-L transition at higher current is more controllable than transition at lower current
- Because is minimizes the number of combined operations for the PCS
- It minimizes risks with loss of NTM control and ELM heat loads

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