Prevention of the H-mode density limit by various heating schemes through control of the plasma state space

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IAEA Technical Meeting on Plasma Disruptions and their Mitigation, 20-23 July, 2020 (Virtual Meeting)

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 and 2019-2020 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

Prevention of the H-mode density limit by various heating schemes through control of the plasma state space

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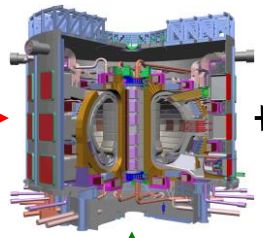
ASDEX Upgrade team, TCV team, MST1 team

- Integrated disruption prevention scheme
- State space description of HDL in D_2 at ASDEX Upgrade and TCV
- State space based controller at ASDEX Upgrade and TCV
- Influence of $N_2 \Rightarrow$ alternative sensor and controller setup
- Summary and outlook

Outer flow diagram for all disruption path$_i$'s, controlling handler$_i$

hierarchy of actions: I: recovery II: avoidance III: mitigation



critical plasma condition for path$_i$

{**sensor$_{i,j}$**} detect path$_i$

supervisor, which starts, interrupts, switches between and combines handlers, manages competing requests and availability

handler$_1$ for **I**, **II**

handler$_2$ for **I**, **II**

handler$_n$ for **I**, **II**

III: DMS managed by CIS

success

yes

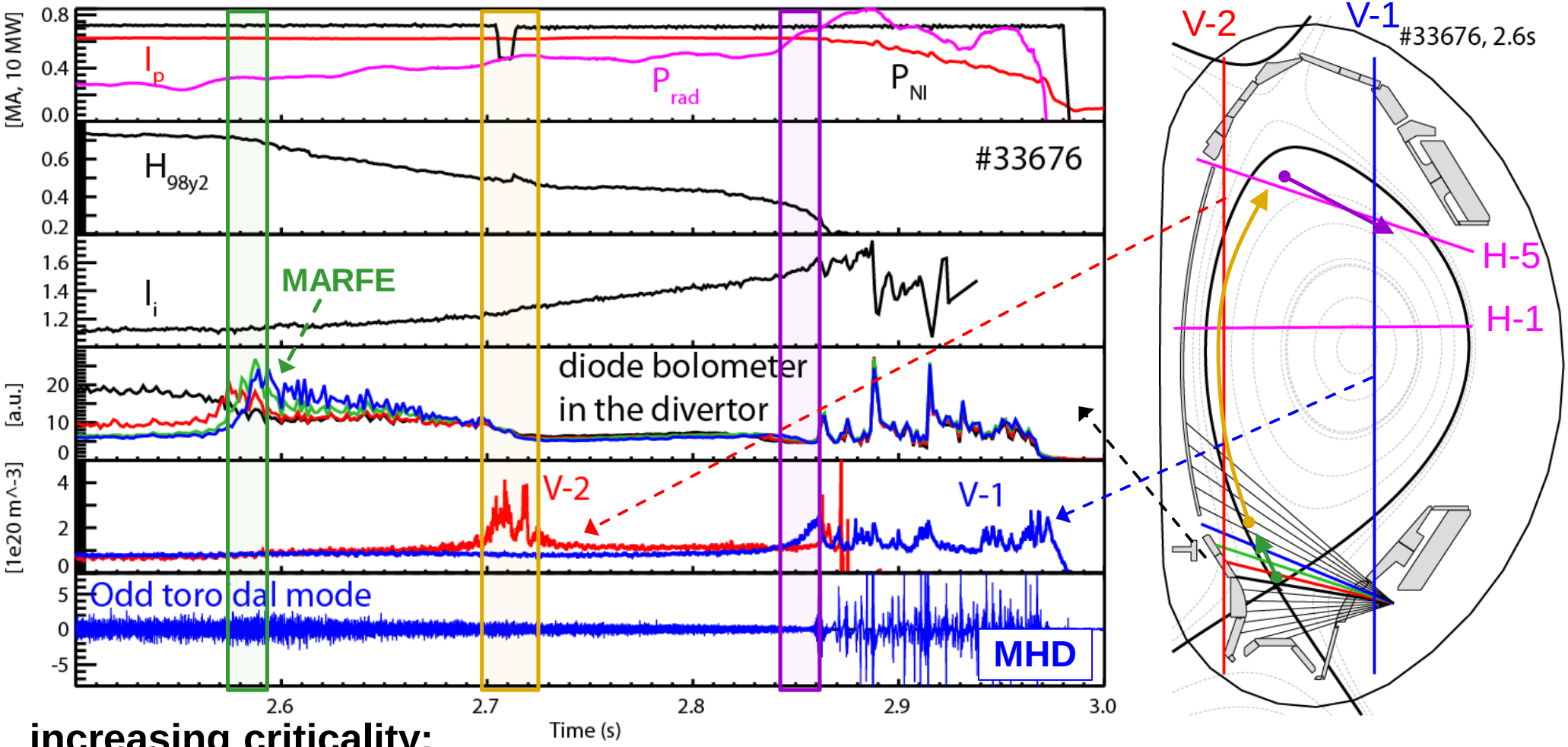
original or backup scenario

no

controlled shutdown

[Maraschek, PPCF 60(2018) 014047, EPS 2017 Belfast]

ASDEX Upgrade and TCV : H-mode density limit



increasing criticality:

- MARFE enters confined plasma (seen on div. bolometer, with / after HL-transition)
- migration from X-point to top on HFS (bolometer, HFS interferometer)
- movement towards plasma LFS (bolometer, HFS interferometer)

Consideration for the start of prevention actions

- Strong W_{mhd} and H_{98y2} drop with MARFE formation before MHD:
  - In present devices early MARFE can be recovered with heating
  - In future devices $P_{fus} \sim \beta_N^2$ loss makes plasma unrecoverable

    $\Rightarrow$ action required significantly before MARFE
- With lower q_{95} the time between MARFE and disruption might shrink

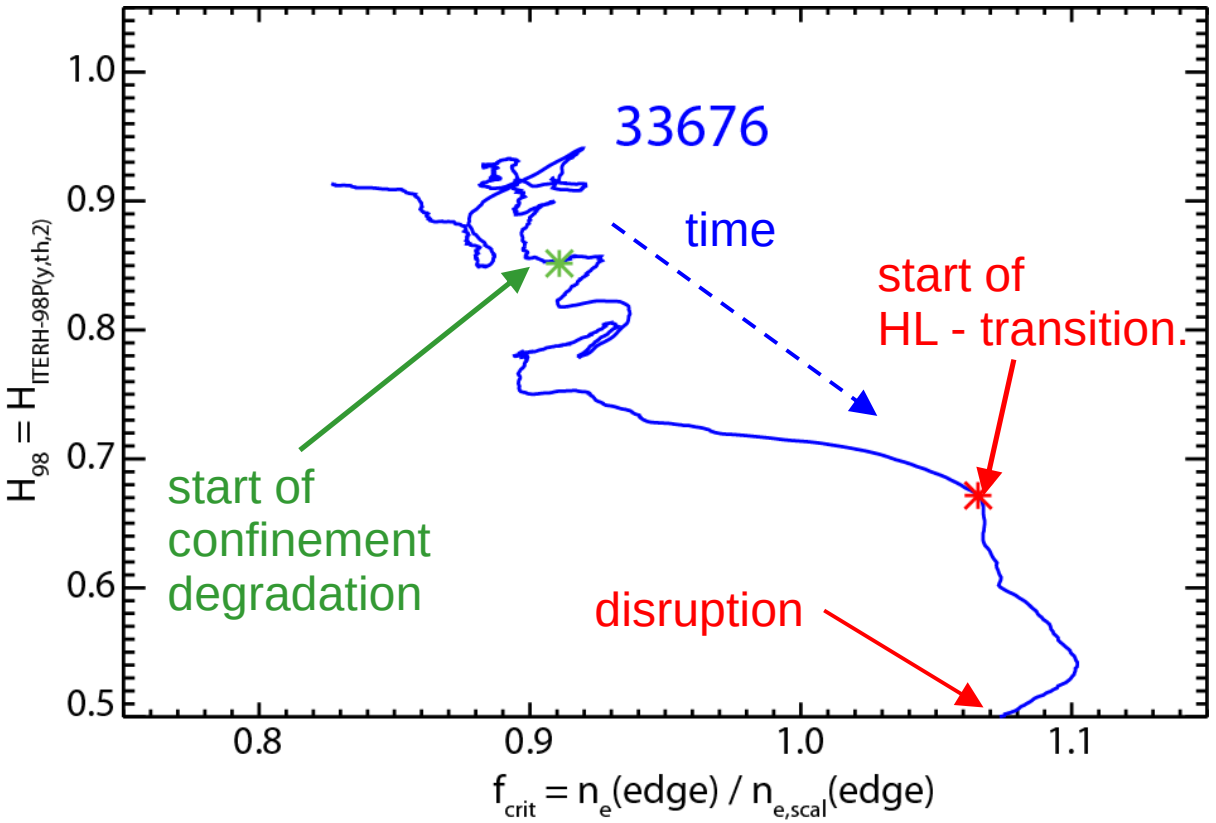
- Scaling for start of H to L – transition:

  $n_{e,scal}(edge) = 0.506\ P_{heat}^{0.396}\ I_p^{0.265}\ q_{95}^{-0.323}$

  determined from state space: $W_{mhd} - n_e(edge)$

[Bernert, PPCF 57(2015) 014038]

Normalized state space: $H_{ITER-98P(y,th,2)} - n_e/n_{e,scal}$



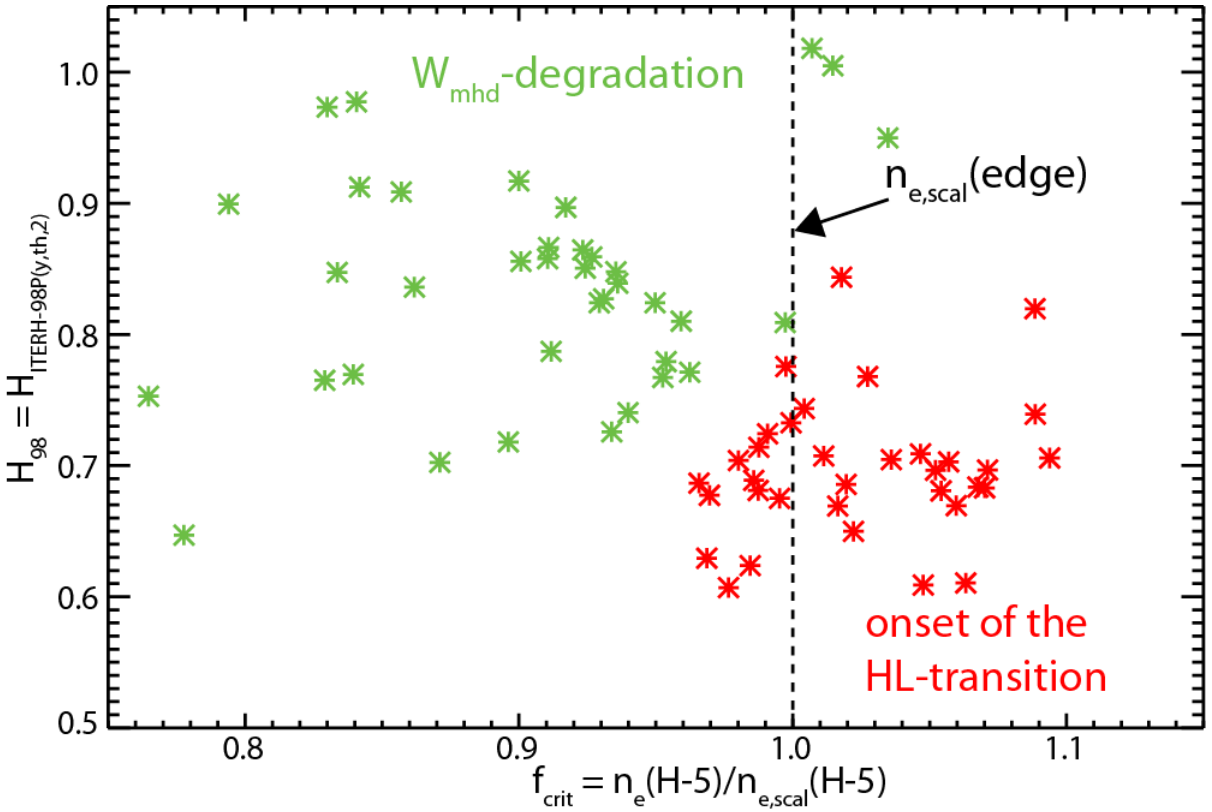
start of "HL-transition" : (shortly) before MARFE moving into confined plasma region

⇒ identifiable point, which should never be reached during safe operation

- generalized coordinates:

$$H_{98} = H_{ITER-98P(y,th,2)} \quad - \quad f_{crit} = n_e(edge) / n_{e,scal}(edge)$$

Deuterium H-mode density limit in H_{98} – f_{crit} space

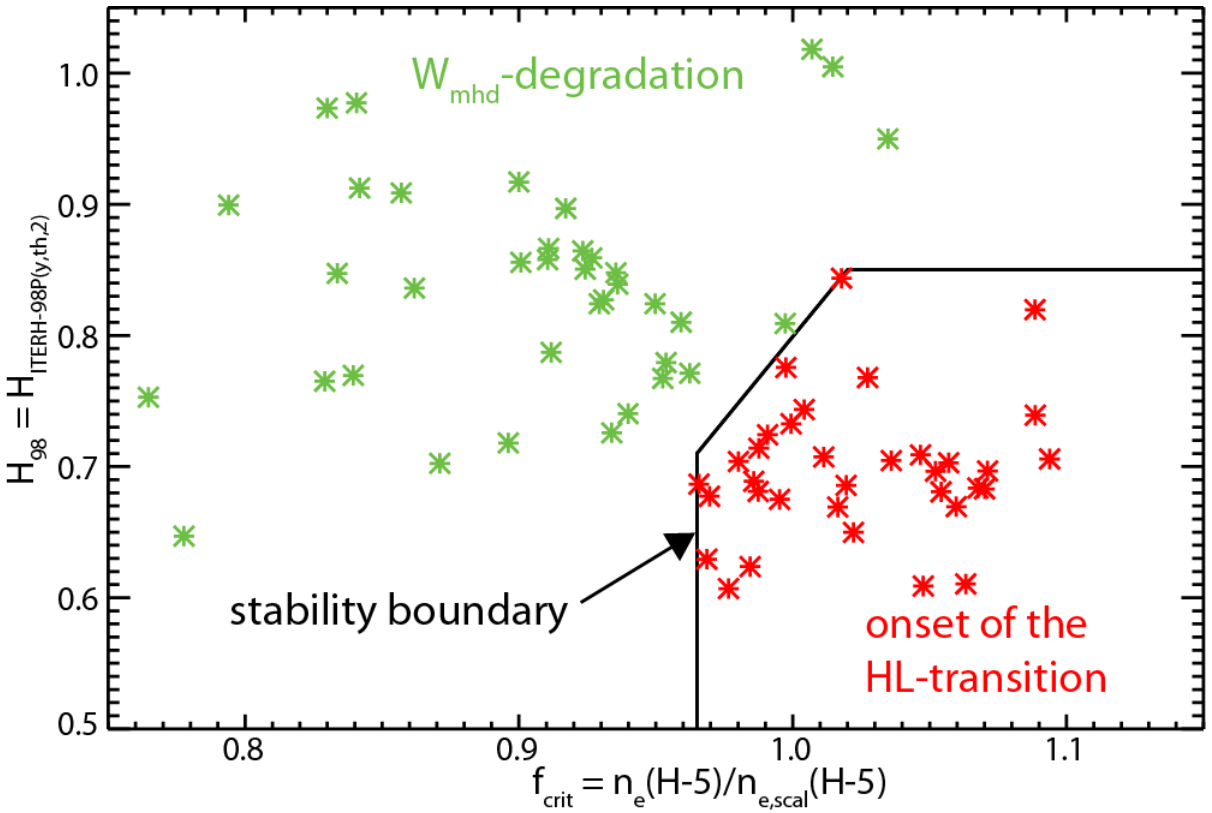


data range:

pure deuterium gas
6MW $\leq P_{NBI} \leq$ 12.5MW
0.6MA $\leq I_p \leq$ 1.2MA
3.5 $\leq q_{95} \leq$ 7

- Begin of confinement degradation and start of HL-transition / MARFE entering confined region dissociate in H_{98} – f_{crit}

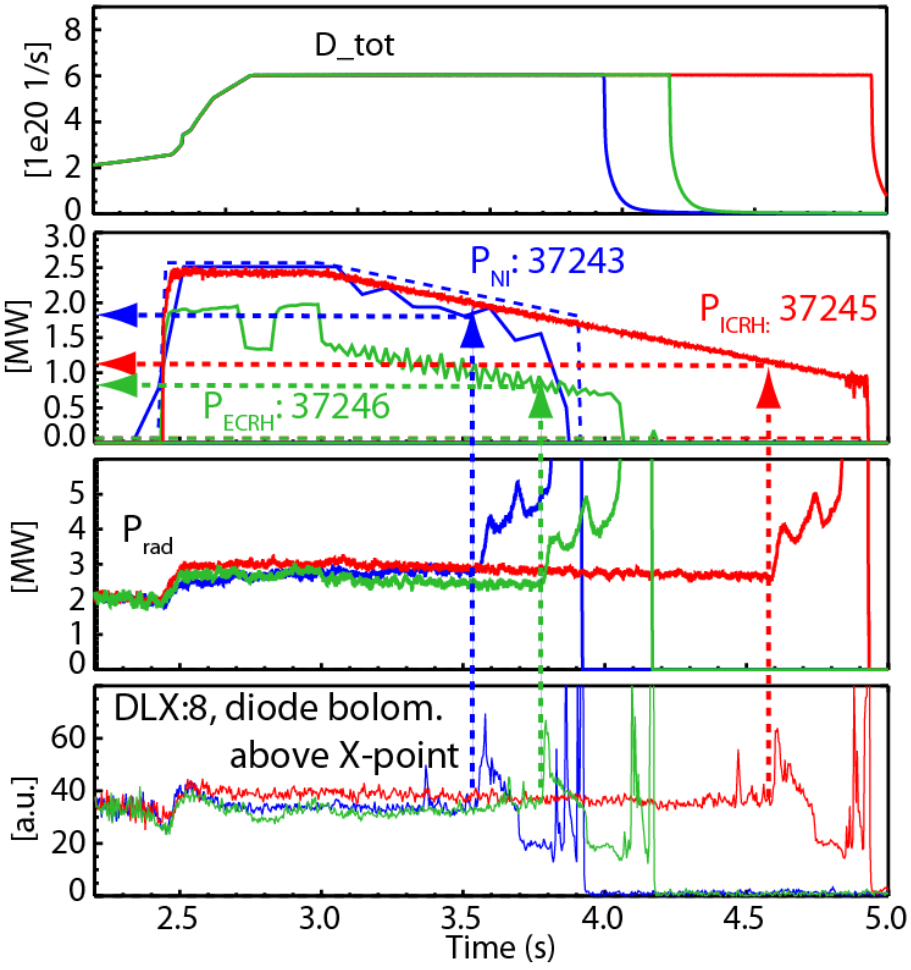
Danger boundary in H_{98} – f_{crit} state space



- empirical boundary for D in $H_{ITER-98P(y,th,2)}$ – $n_e/n_{e,scal}$ plasma-state
- possible actuators: gas flux reduction, particle confinement reduction, additional heating, …

[Maraschek, PPCF 60(2018) 014047]

Feedforward actuator comparison: NBI, ICRH, ECRH

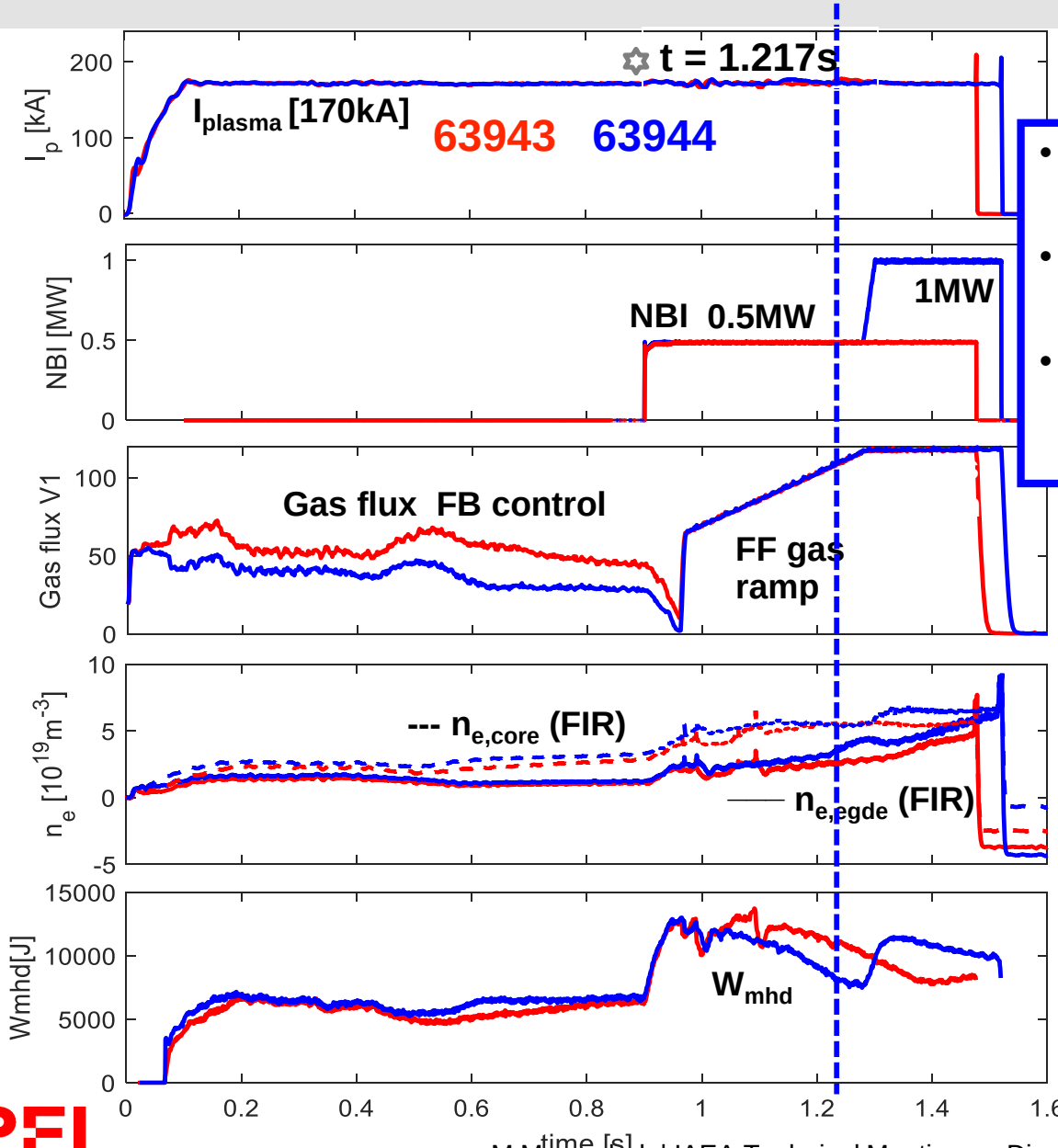


- 0.8 MA, -2.5 T, q_{95}=5.5, P_{NI} = 5.5 MW,
- stabilize discharge with additional ff actuator power → P-ramp to measure marginal actuator power, P_{marg}, for MARFE formation
  - $P_{marg,NBI}$ = 2.0 MW
  - $P_{marg,ICRH}$ = 1.2 MW
  - $P_{marg,ECRH}$ = 0.84 MW
- comparison co-ECCD at q=2 ↔ ↔ central ECRH (not shown)

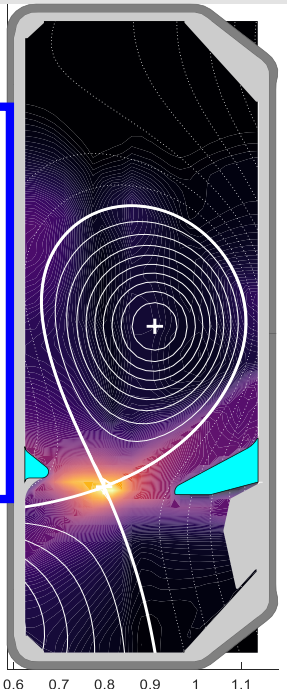
⇒ central heating most effective in terms of required actuator power, P_{act}

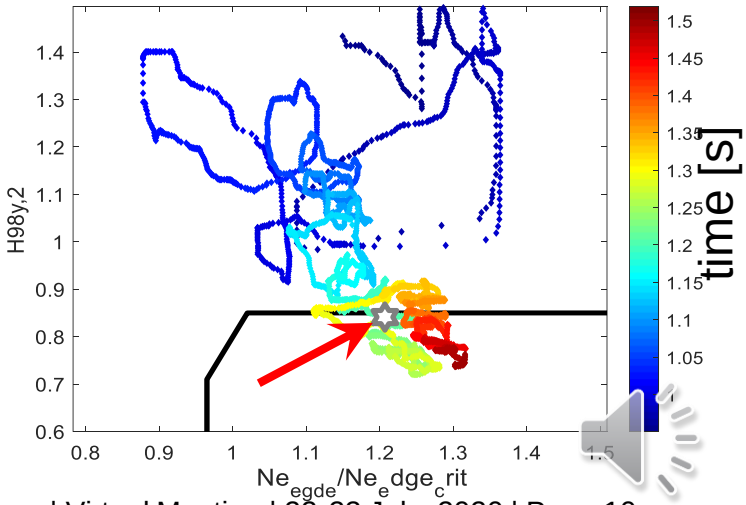
$T_e(0)$ assumed to play central role

TCV: 0.17MA with initial MARFE at AUG! boundary

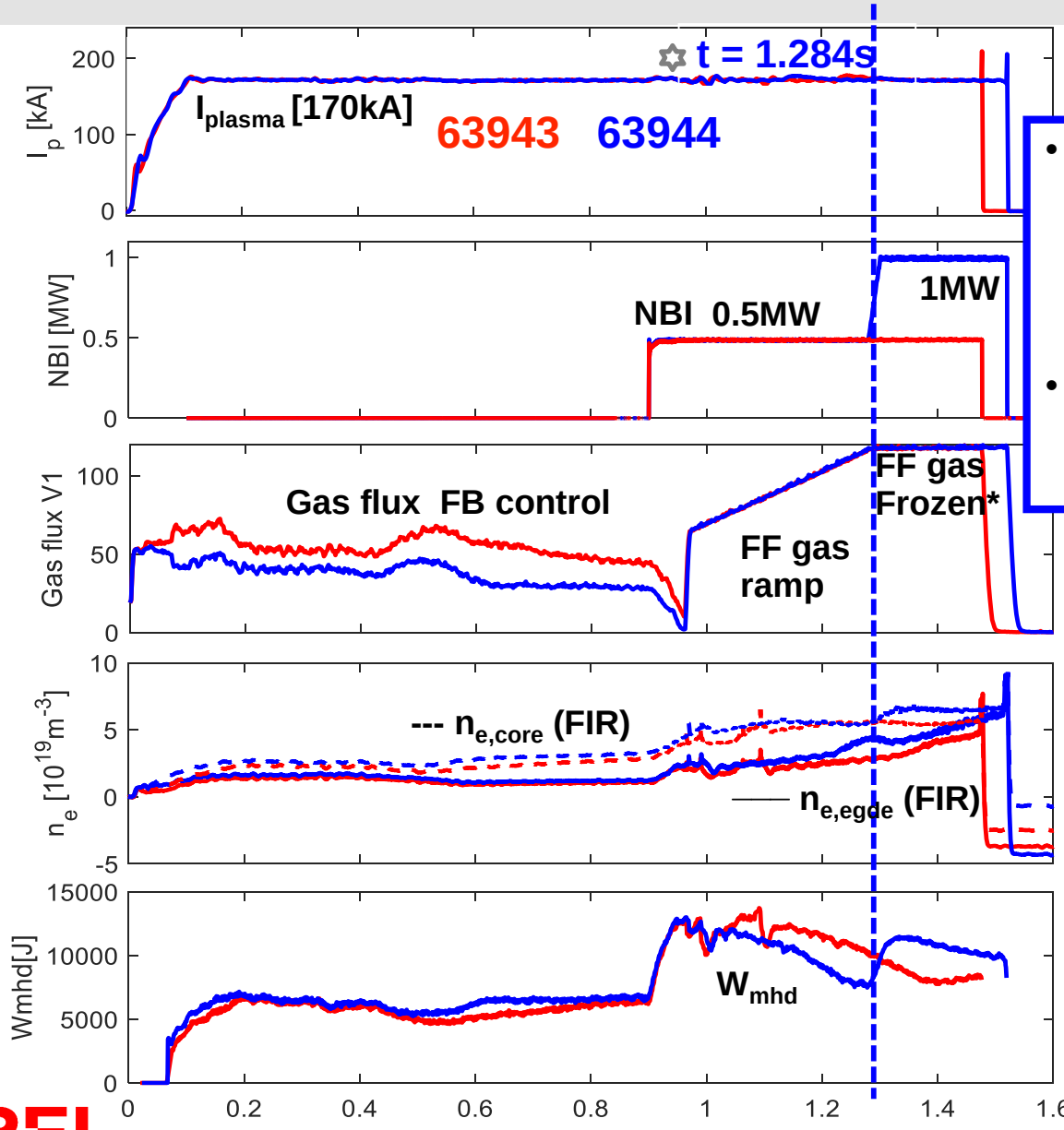


- Radiation moves to **X-point** and increases;
- Sharp increase of the **HFS n_e**;
- Operating point in the state space reaches the **boundary**.

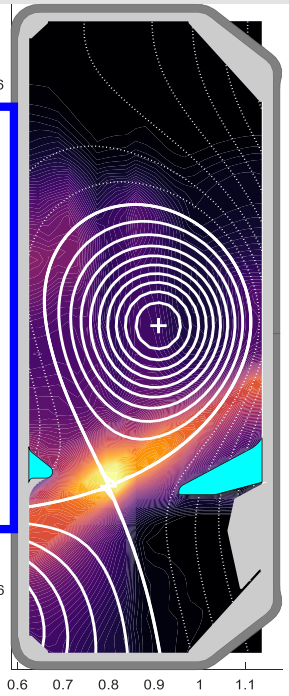




TCV: developed MARFE in danger zone



- H_{98} keeps degrading until additional NBI power is applied, whereas f_{crit} is increasing;
- **Radiation** begins to leave the X-point moving upwards.



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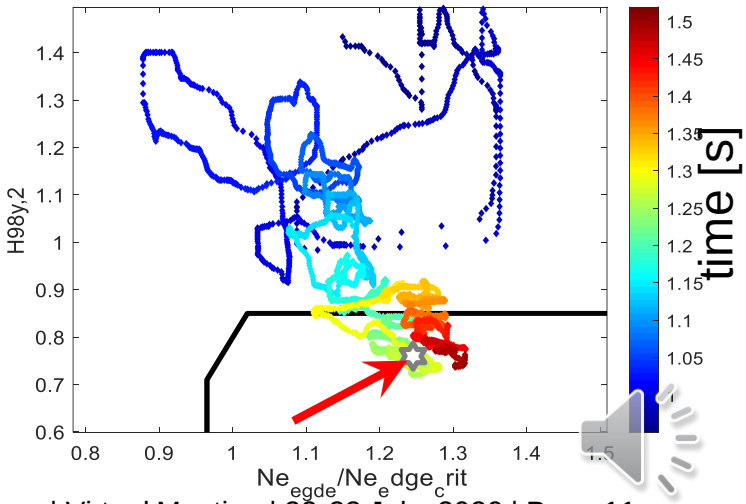
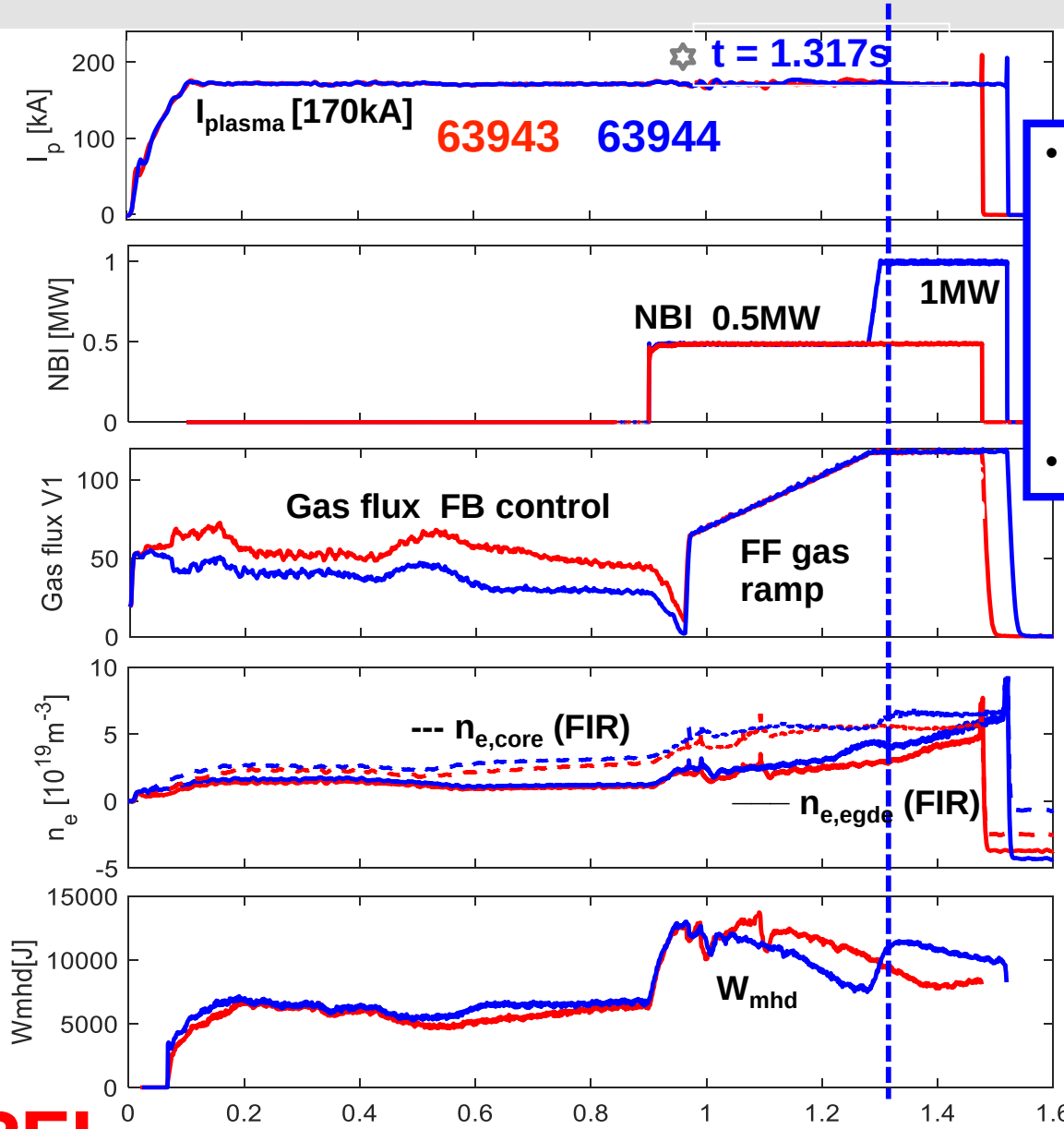
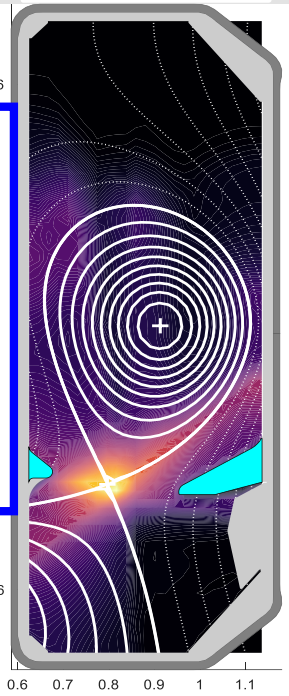


TCV: NBI suppressed MARFE, back in safe zone



- **Stepping up NBI** power the **MARFE** is temporarily suppressed (radiation pushed back towards the X-point and H_{98} improves)
- NBI heating works



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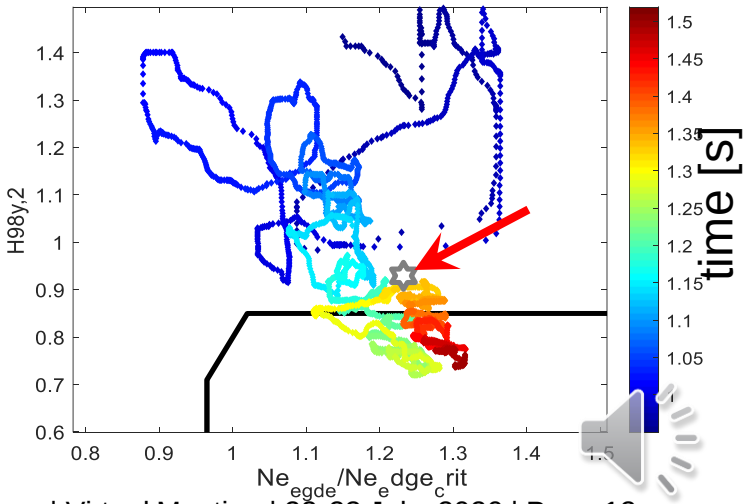
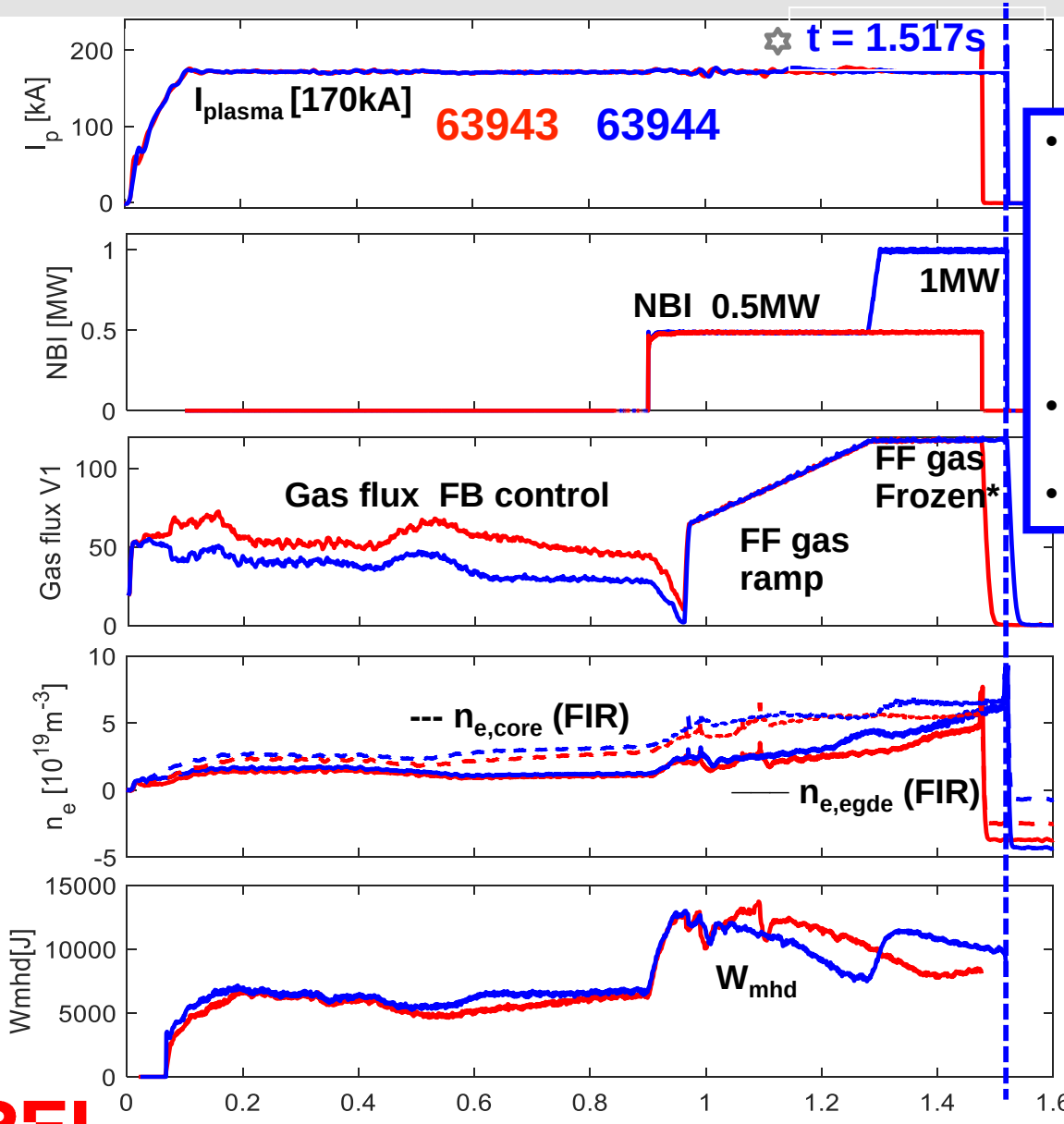
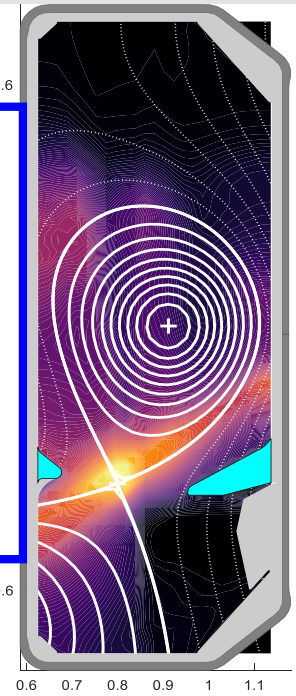


TCV: re-developed MARFE in danger zone, higher n_e



- At constant gas flux f_{crit} starts again to slowly increase with H_{98} degrading.. until plasma disrupts!
- **state space transferable !**
- **vertical: P_{act}**



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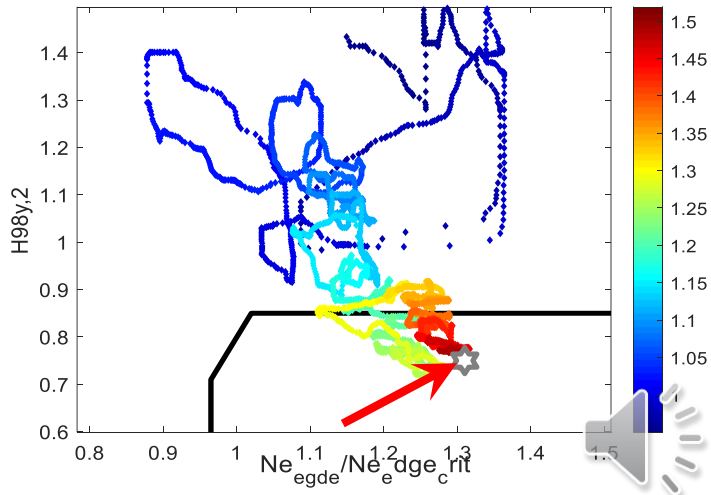
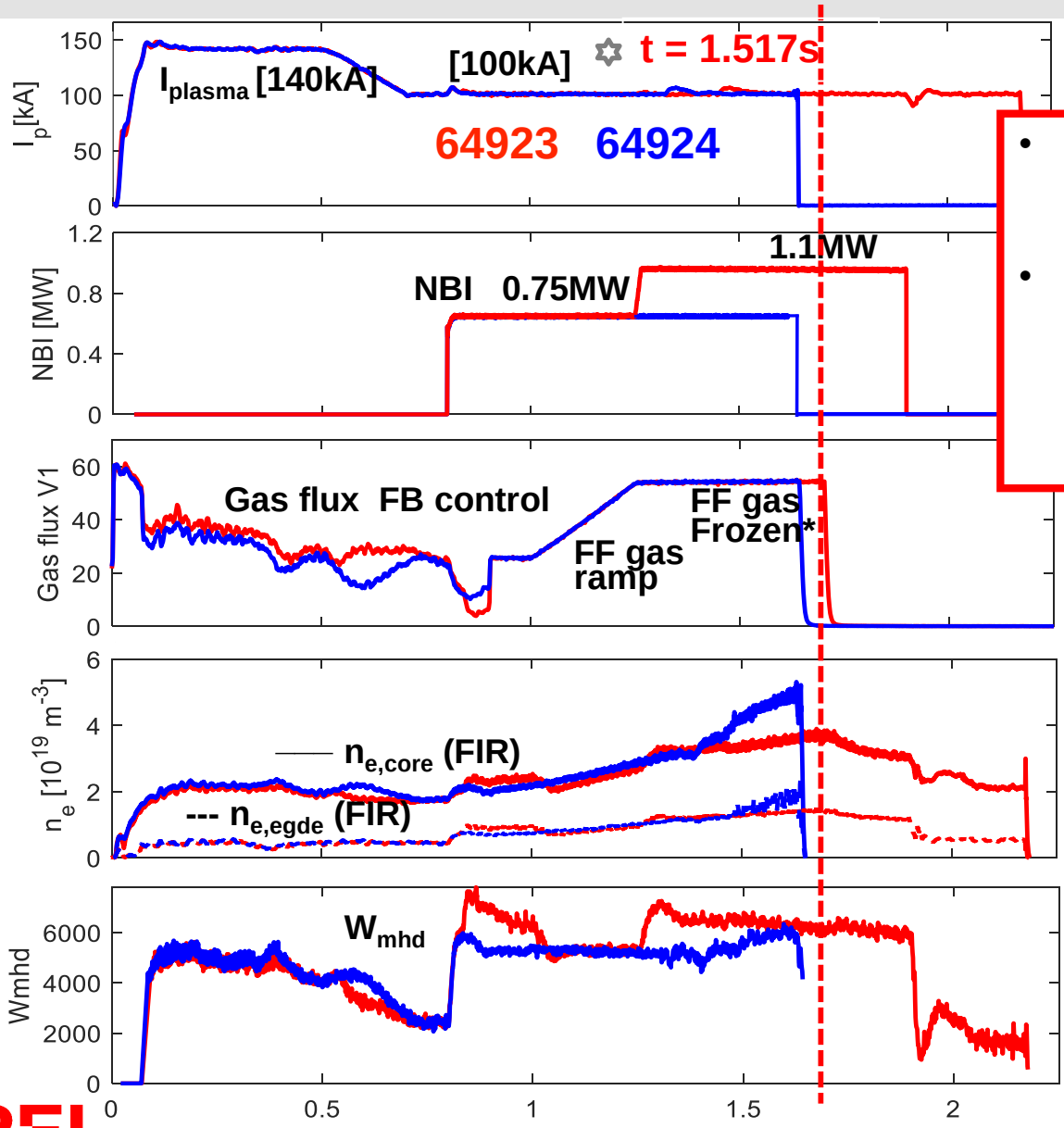
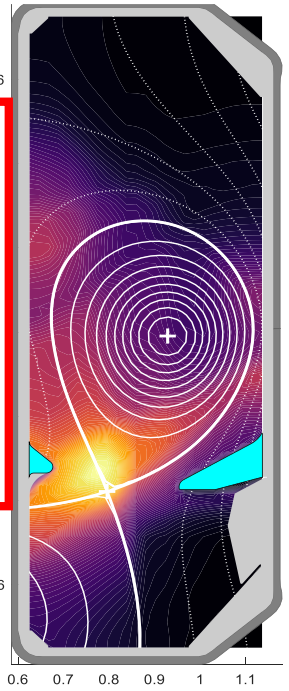


TCV: 0.1MA with developed MARFE at boundary



- At constant gas flux f_{crit} increases with H_{98} slowly degrading;
- **MARFE** starts developing with radiation leaving the X-point (operating close to the boundary!



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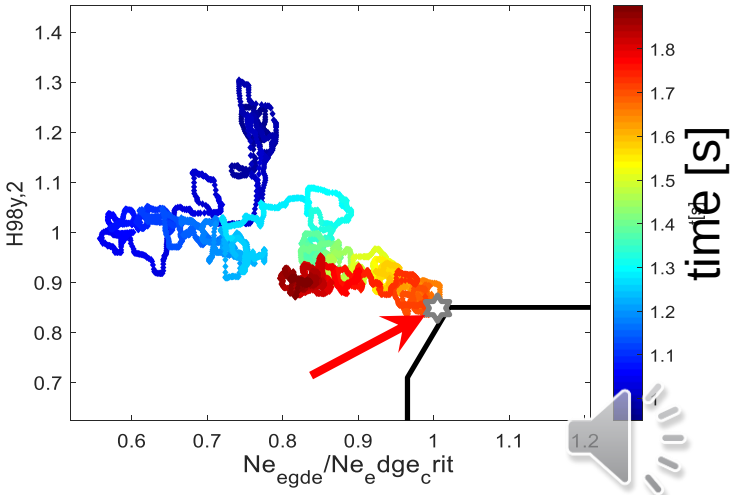
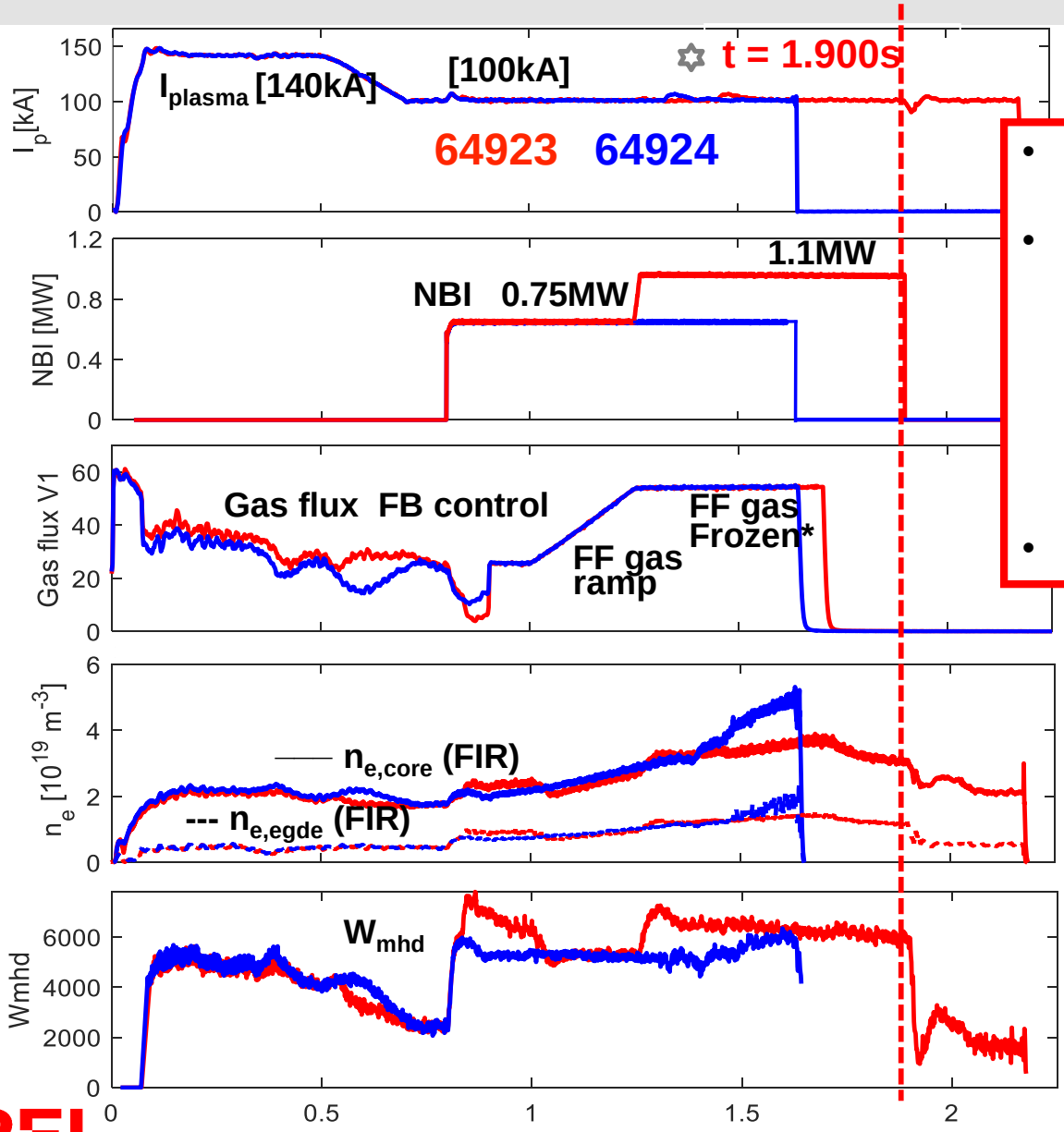
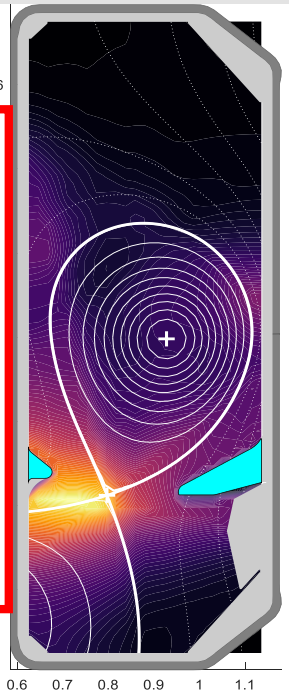


TCV: 0.1MA with remove MARFE by gas reduction



- Cutting the gas the disruption is avoided!
- f_{crit} is reduced with H_{98} slowly improving until we switch the **NBI off** (the discharge disrupts later because of the **OH limit**).
- horizontal: gas flux



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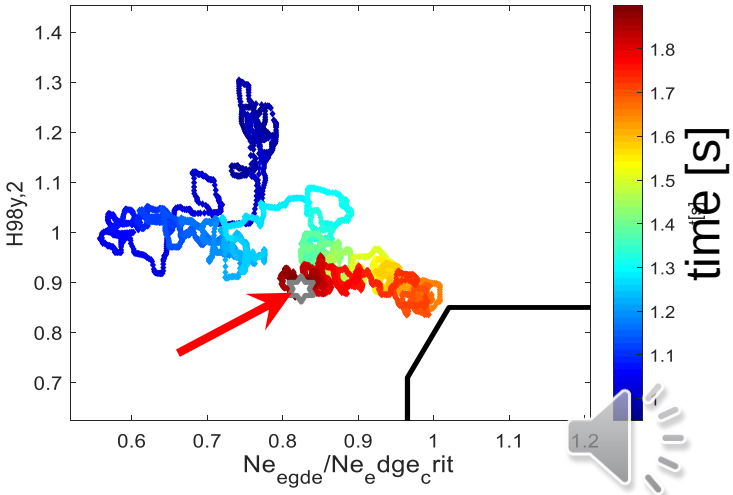
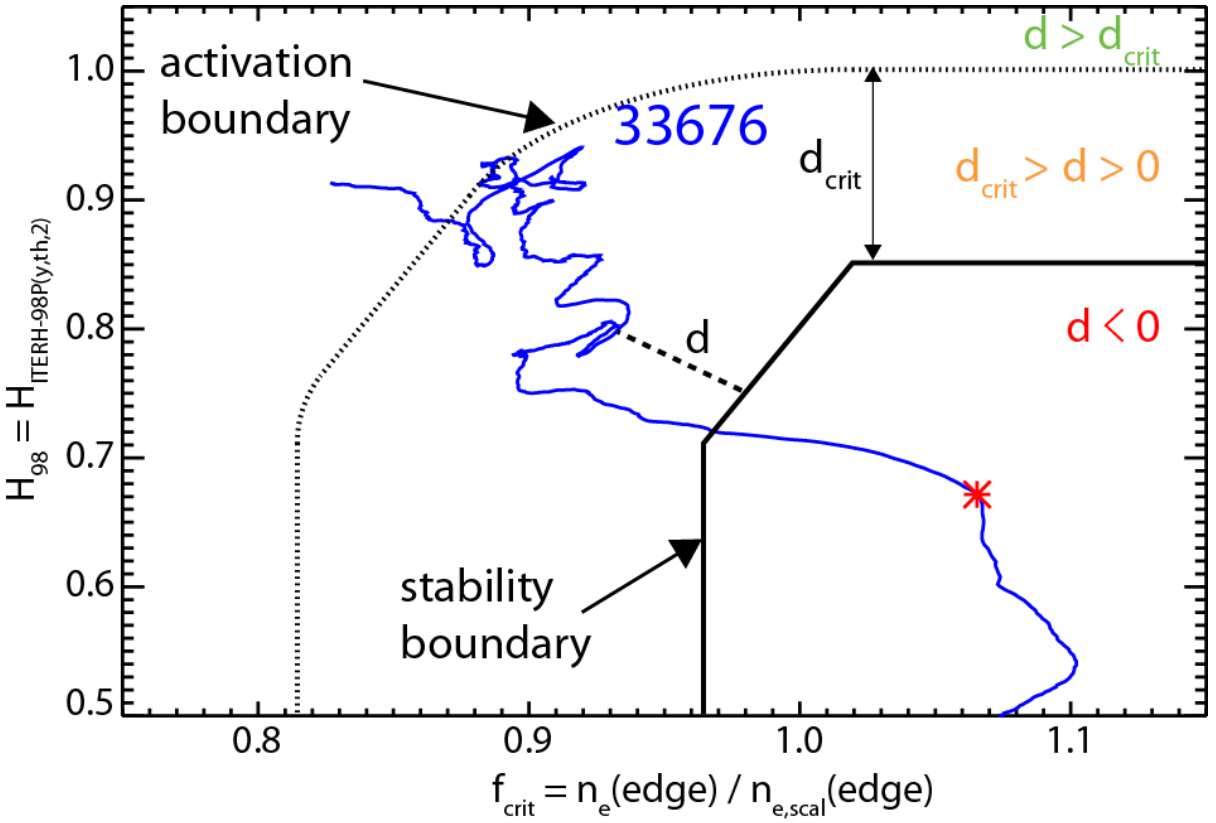
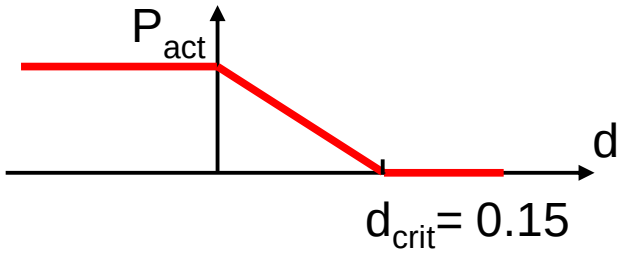


Controller scheme at ASDEX Upgrade





normalized 2D distance d:

$d > d_{crit}$, safe region

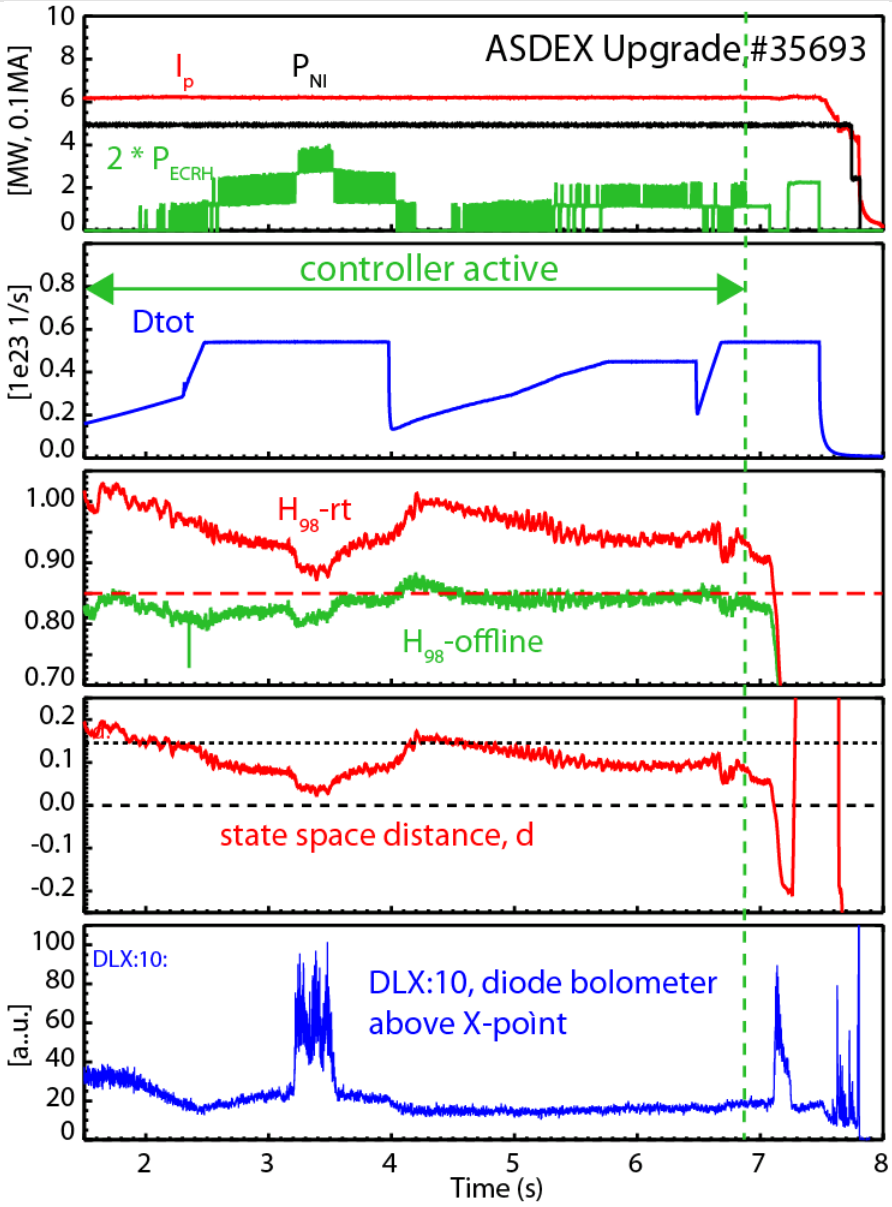
$d_{crit} > d > 0$, activation

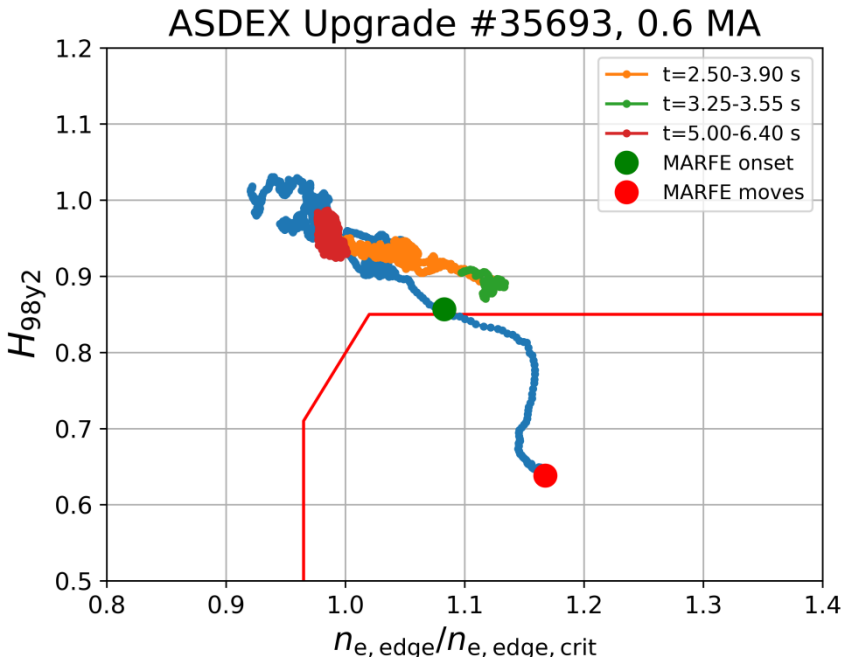
$d \leq 0$, danger zone

- soft controller activation before reaching danger zone : actuator reaction = f(d)
  - different weight of H_{98} and f_{crit} could be considered

[Sieglin, FED. 146-B, 2019, p.1737]

Feedback controlled ECRH at ρ=0 with rt-signals

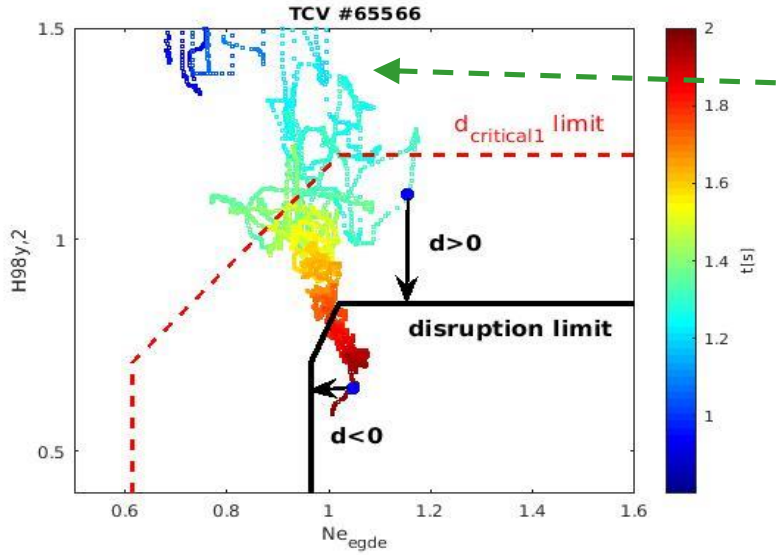




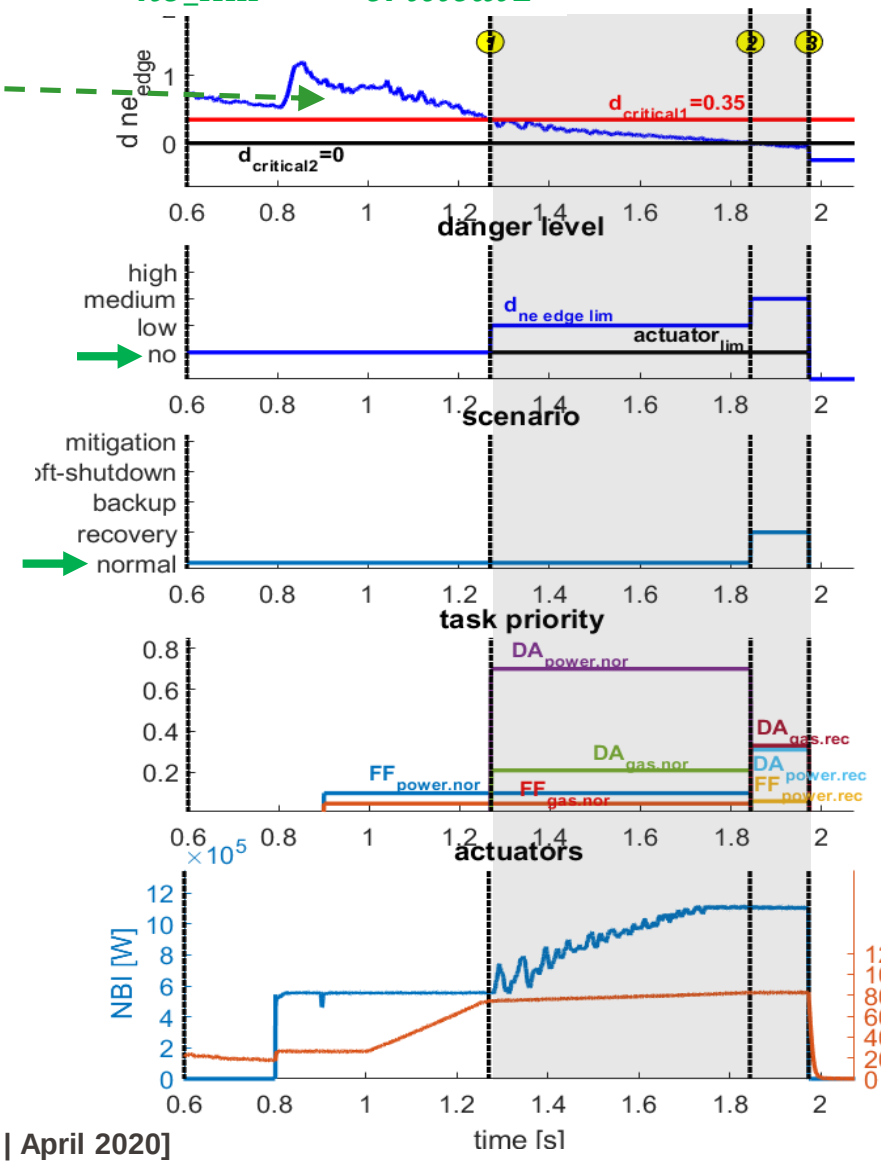
- ECRH starts already approaching the disruptive zone and keeps discharge safely away from it
- MARFE and disruption after ECRH is off
- distance d as sensor, note: with corrected rt-H_{98}, the actuator would start even earlier

[Sieglin, FED. 146-B, 2019, p.1737]

Controller with 2 actuators, NBI and gas flux, and hierarchical reaction at TCV

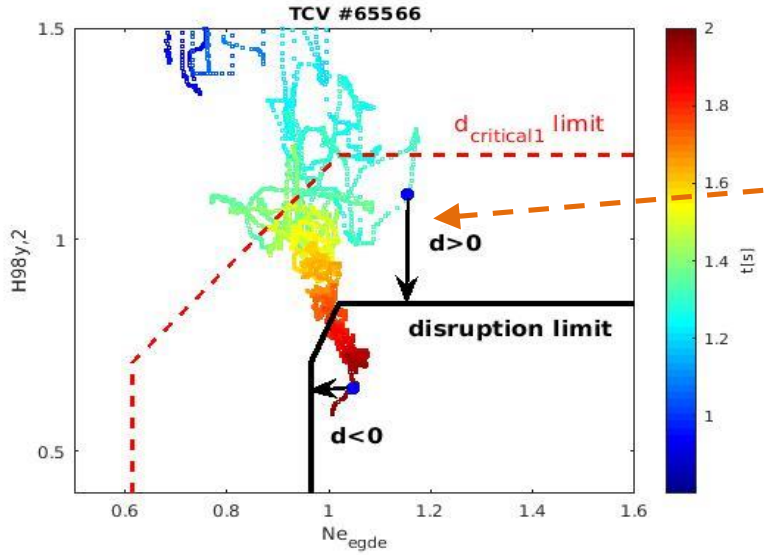


$d_{ne\_lim} > d_{critical1}$

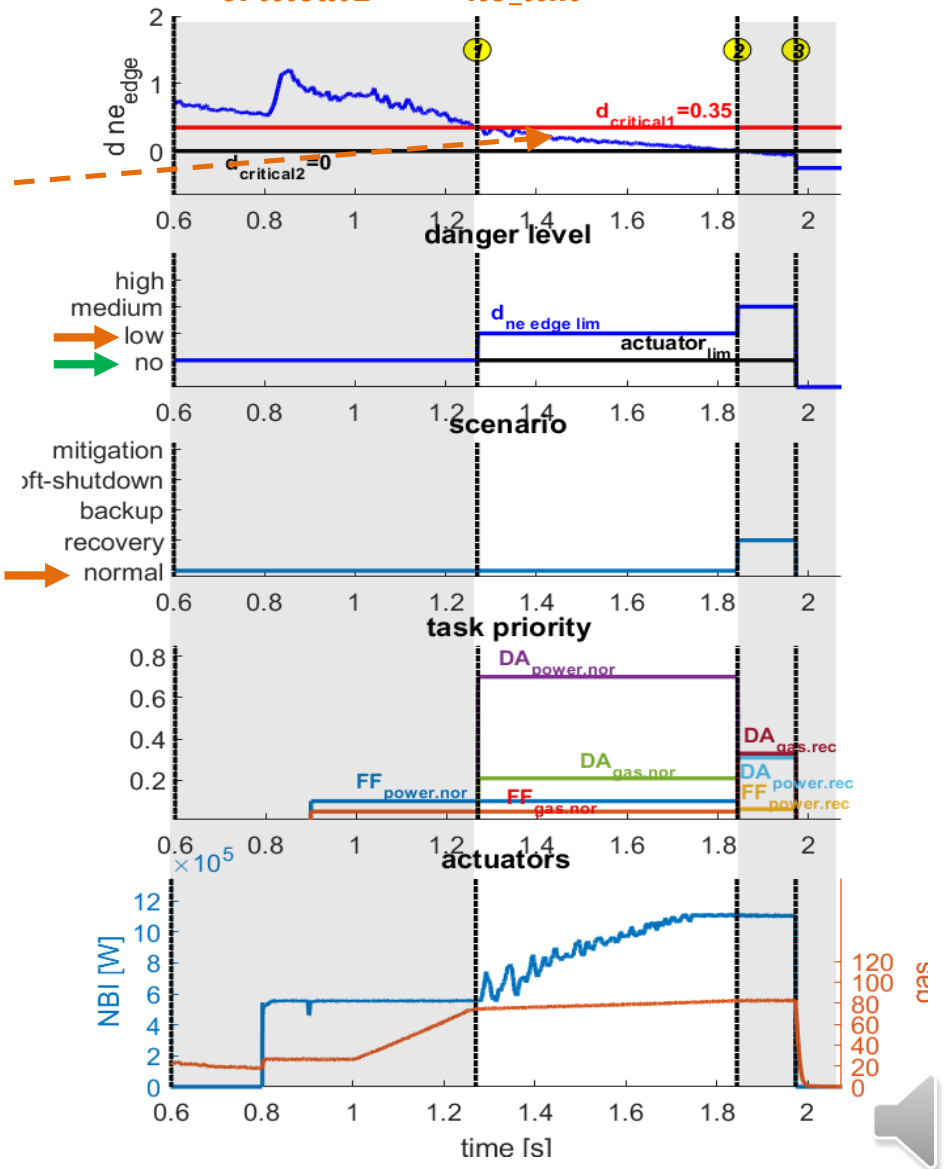


- ***no* danger** for $E_{d\_ne\_lim}$ and E_{act_lim}
- ***normal* scenario**:
  - NBI and gas valve are controlled by the feedforward tasks

Controller with 2 actuators, NBI and gas flux, and hierarchical reaction at TCV



$d_{critical1} < d_{ne\_lim} < disr.limit$



- ***low* danger** for $E_{d\_ne\_lim}$ and still ***no* danger** for $E_{act.lim}$

- ***normal* scenario**:
  - NBI and gas valve are controlled by the feedforward tasks
    + $DA_{power.nor}$ asks for linearly increasing power
    + $DA_{gas.nor}$ reduces the gas flux

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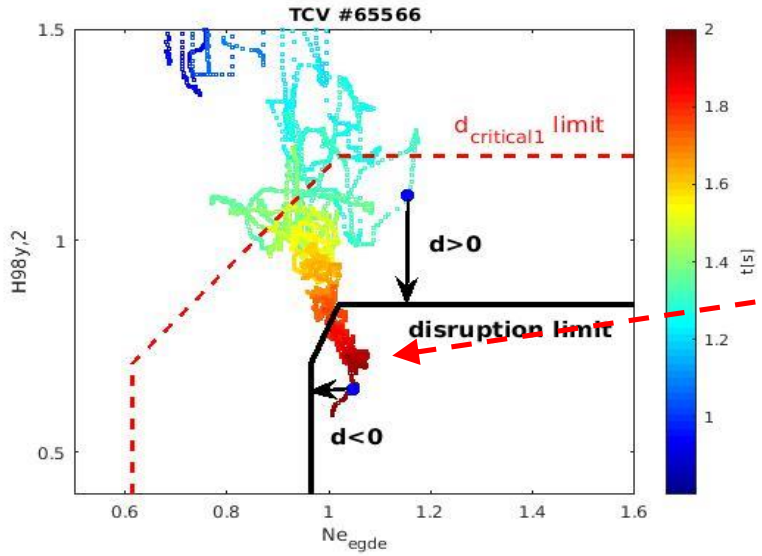
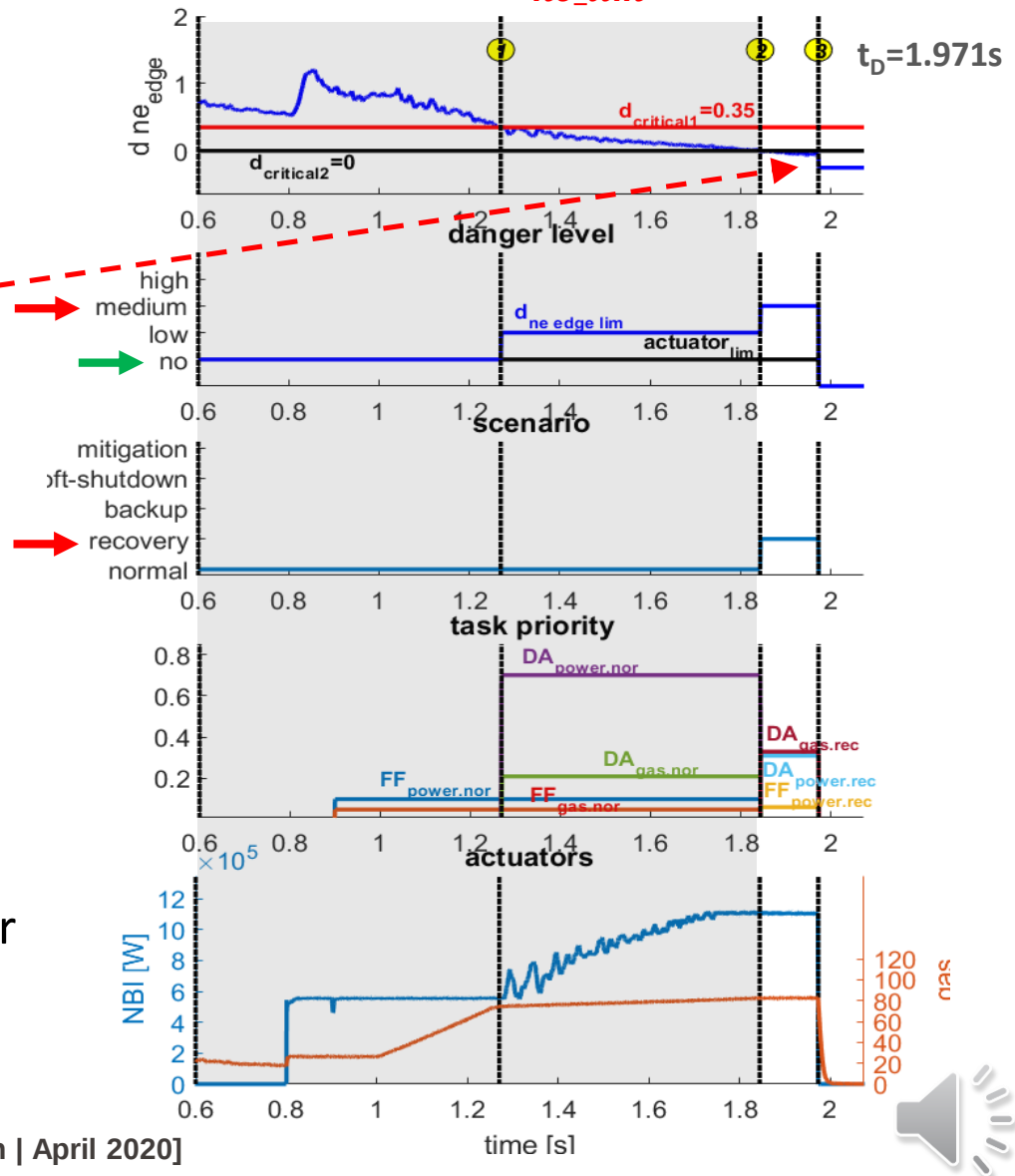
Controller with 2 actuators, NBI and gas flux, and hierarchical reaction at TCV



$d_{ne\_lim} < disr.limit$



- ***medium* danger** for $E_{d\_ne\_lim}$ and still ***no* danger** for E_{act_lim}

- ***recovery* scenario**:
  - NBI is controlled by the feedforward
    + $DA_{power.rec}$ asks for maximum power
    + $DA_{gas.rec}$ freezes the gas flux

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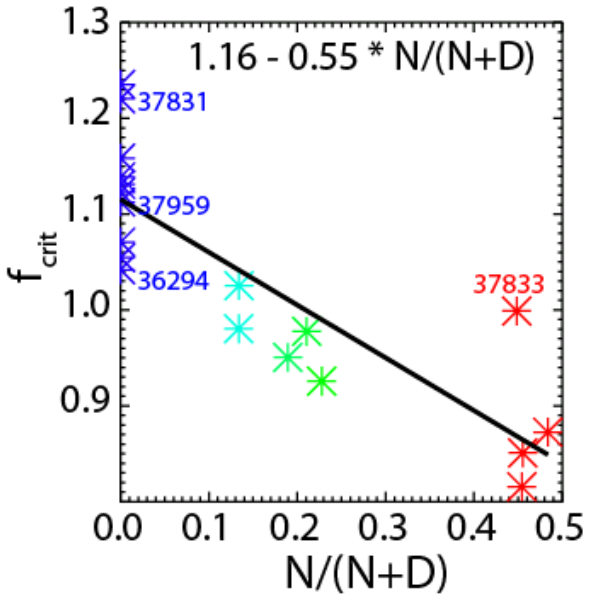
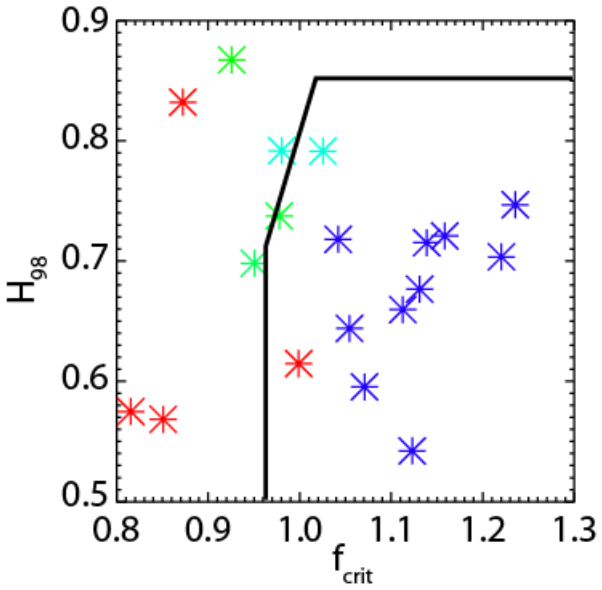
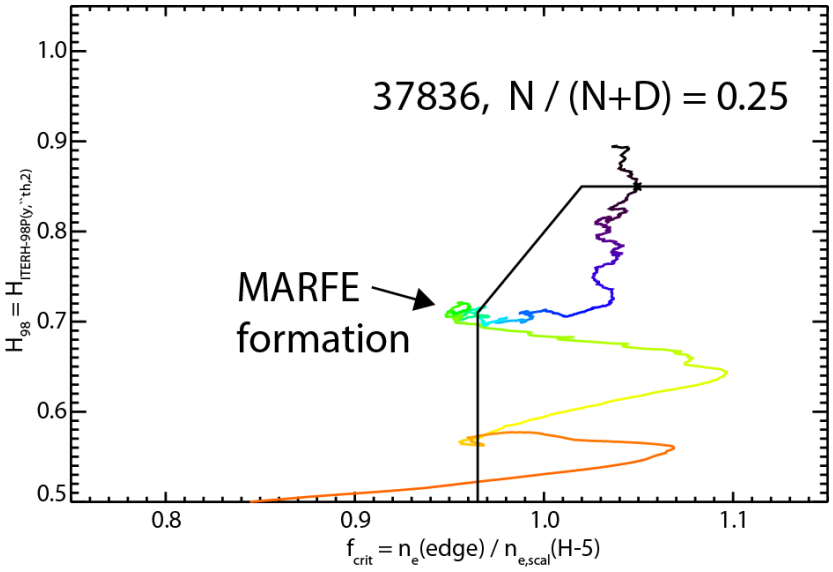
MARFE formation with additional impurities (N_2)

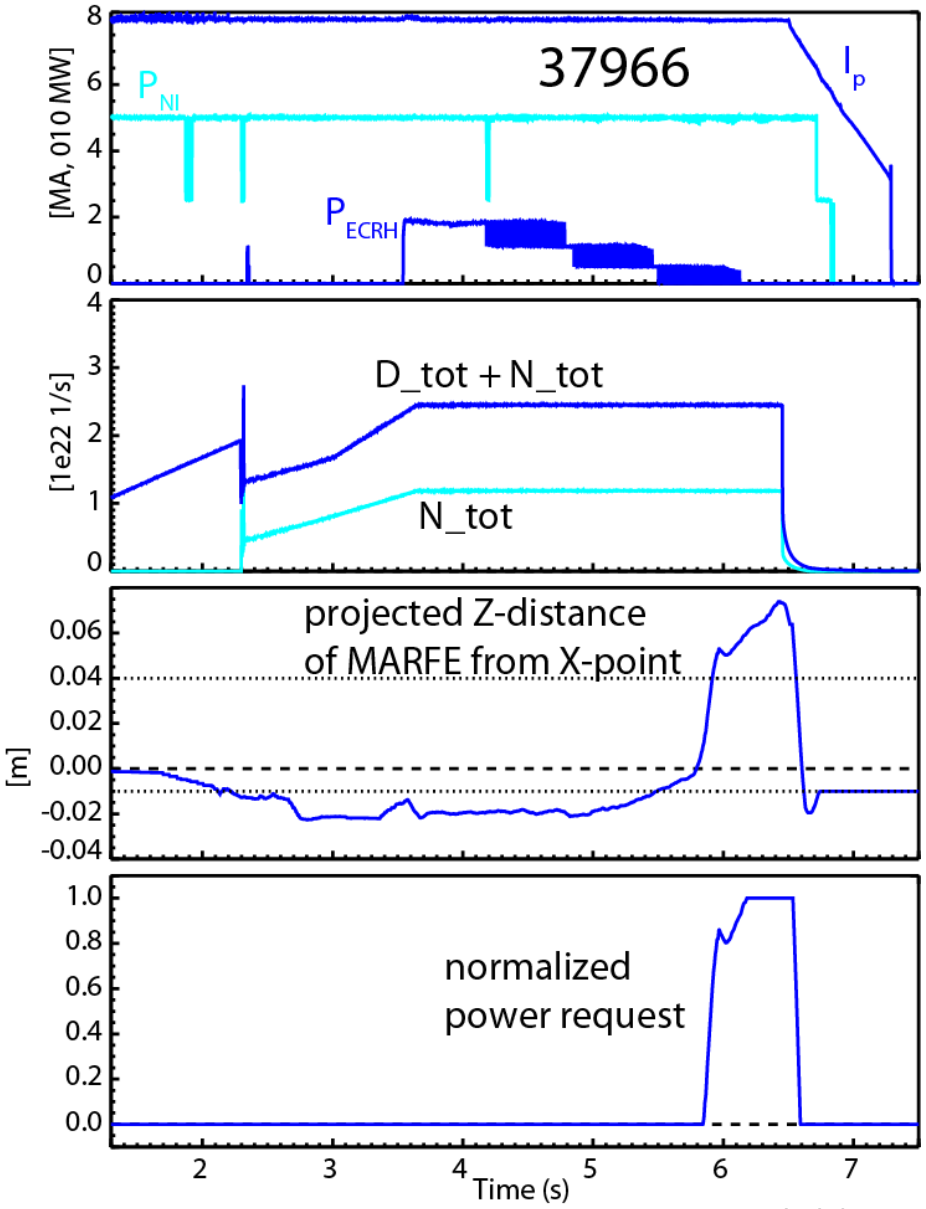




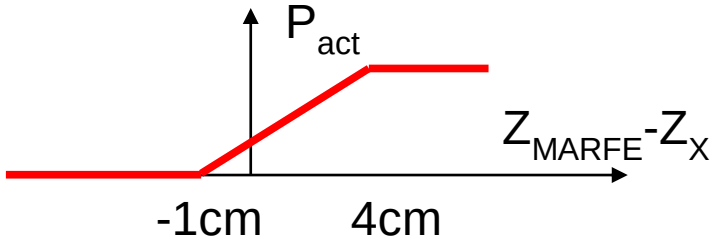


- f_{crit} and n_e typically lower with increasing nitrogen content,
  $\Rightarrow$ modified scaling for f_{crit} including impurities could help
- H_{98} possibly higher, but large scatter
- trajectory behaves differently $\Rightarrow$ boundary modification insufficient !
  $\Rightarrow$ not applicable with impurities
- complementary sensor, such as a MARFE detector desirable

MARFE observer and alternative controller



- realtime observer of Z-position of X-point radiator above X-point as complementary direct detector for MARFE and as control quantity
- transfer function for actuator :



Summary

- state space based controller for the H-mode density limit established for deuterium at ASDEX Upgrade and ported to TCV

ASDEX Upgrade:

- different efficiencies of heating actuators (co-ECCD, central ECRH, central ICRH, NBI): further analysis and understanding needed
- include seeded impurities, such as N_2 (for divertor protection): at least f_{crit} adaption needed, but different behaviour in state space with N_2 needs further work

TCV:

- combined actuators controller extended by including gas control
- application to achieve stable high density ELMy H-mode (not shown)

Outlook and next steps

- data base analysis at JET could provide:
  - behaviour with impurities (different impurity for divertor protection)
  - behaviour at higher T_e(edge) (test for ITER and DEMO)
  - portability to larger devices

- modified state space (f_{crit}) and MARFE behaviour with impurities
- physics based derivation of scaling and boundary desirable

- manage competing requests from prevention schemes for other disruption paths, such as NTM's (presentation by A.Pau)