ITER BASELINE SCENARIO INVESTIGATIONS ON TCV AND COMPARISON WITH AUG

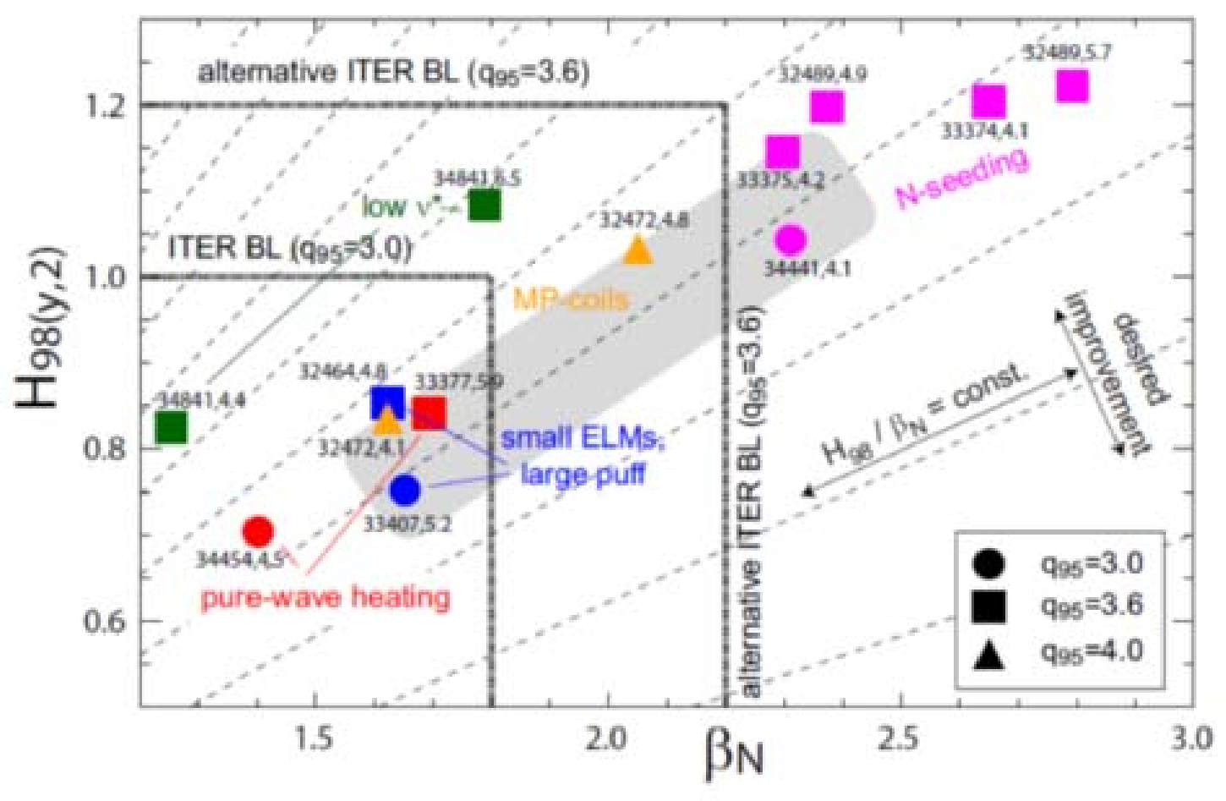
O. Sauter[1], T. Pütterich[2], I. Voitsekhovitch[3], M. Vallar[1], B. Labit[1], Y. Camenen[4], F. Eriksson[5], E. Fransson[5], A. Karpushov[1], F. Widmer[3], F. Bagnato[1], V. Bobkov[2], S. Coda[1], M.G. Dunne[2], P.T. Lang[2], M. Mantsinen[6], M. Maraschek[2], R.M. McDermott[2], A. Merle[1], Ph. Neubert[2], J. Stober[2], W. Suttrop[2], M. Willensdorfer[2], TCV team[a], ASDEX Upgrade Team[b] and EUROfusion MST1 team[c]

[1]Ecole Polytechnique Fédérale de Lausanne, Swiss Plasma Center (EPFL-SPC), Lausanne, Switzerland*; [2]Max-Planck-Institut für Plasmaphysik, Garching, Germany*;
[3]EURATOM/CCFE Fusion Association, Culham Science Centre, Abingdon OX14 3DB, UK; *[4]CNRS, Aix-Marseille Univ., PIIM UMR7345, Marseille, France;*
[5]Chalmers University of Technology, Gothenburg, Sweden; *[6]Barcelona Supercomputing Center (BSC), Barcelona, Spain; ICREA, Barcelona, Spain*; *[a]See author list of "S. Coda et al 2019 Nucl. Fusion 59112023"*; [b]See author list of "H. Meyer et al. 2019 Nucl. Fusion 59 112014"; *[c]See author list of "B. Labit et al 2019 Nucl. Fusion 59086020"; Max-Planck-Institut für Plasmaphysik, D-85748 Garching, Germany*

Conclusions:

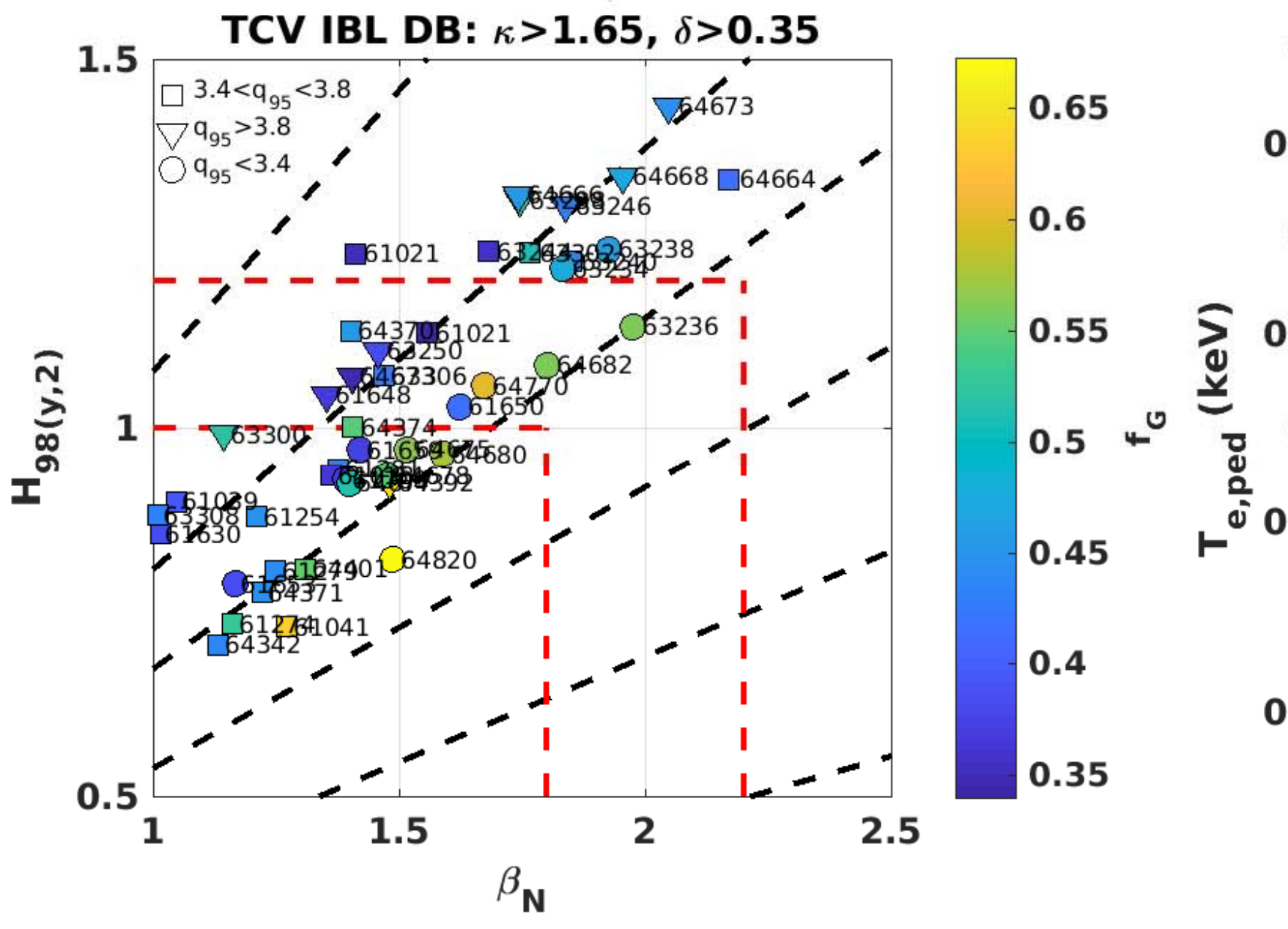
TCV ITER baseline scenarios have been successfully developed and analysed within the EUROfusion WPMST1 campaigns, starting first with a similar shape as the AUG IBL and then moving towards higher edge triangularity and elongation. TCV spans the ITER target values (H_{98}~1, β_N~1.8 at q_{95}~3 and H_{98}~1.2, β_N~2.2 at q_{95}~3.6), and slightly better confinement properties, consistent with previous findings with carbon wall. Integrated modelling using ASTRA-GLF23 quasi-linear drift mode based transport model predicts the observed heat and particle transport, with ITG dominant regime in most of the radial extent. In particular, it also predicts the mainly turbulent-driven significant density peaking observed in TCV IBL discharges. AUG IBL cases with similar good confinement properties, at low ν^*, also exhibit density peaking contrary to the standard AUG IBL discharges. The TCV IBL high performance and low q_{95} cases are limited by the occurrence of 2/1 modes, occurring typically after 1-2 current redistribution time, which is only a few ELM periods in TCV. It has been shown that broad current density profile, induced by density peaking, as well as elongation, high β_N and low q95 combine to lead to more unstable plasma to "both" classical and neoclassical tearing modes. Both in the sense that these combined parameters lead to more unstable q profiles to classical tearing onset, and to larger perturbation due to type I ELMs. TCV IBL can avoid these modes at medium β_N and/or high q_{95} with X3 EC heating, and also at lower elongation. We have also shown that lower elongation helps in reaching IBL discharges at high Greenwald fraction. We have used the benefit of controlled elongation and power source during AUG IBL termination phases (in feedforward). Safe ramp-down scenarios, inspired by off-line optimization results using RAPTOR, have been demonstrated on AUG including the q_{95}=3 scenario. The combination of I_p and κ ramp-down with a pre-defined H-L transition timing keeps the time evolution of li and of the density within a safe operating range. Contrary to the flat top part, where high elongation leads to low li and more unstable profiles, in the ramp-down phase too high li needs to be avoided. Note that both can lead to higher magnetic shear near q=2, similar to impurity accumulation or edge cooling respectively. Analyses will be continued to test this overall consistent picture.

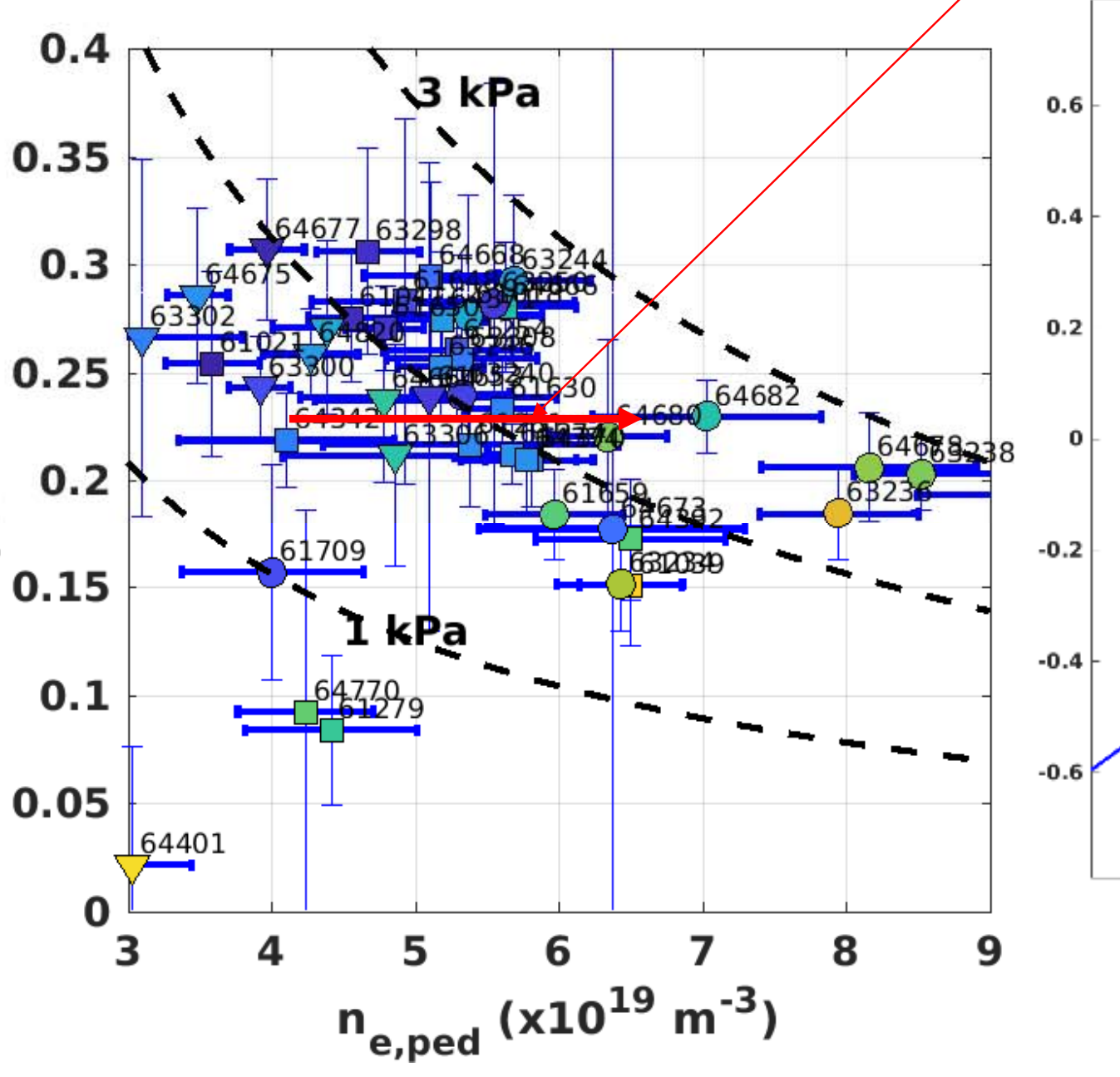
ITER baseline main parameters and performance

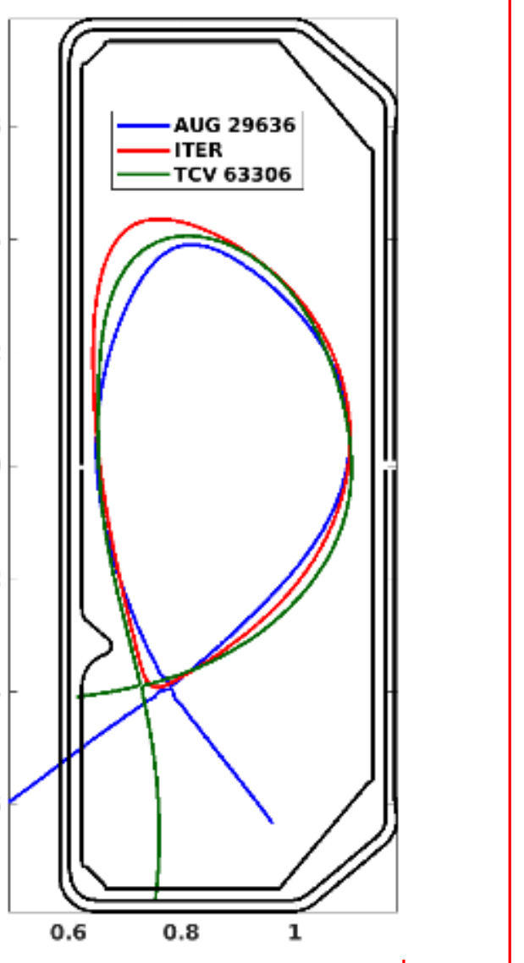


AUG: H_{98} vs β_N as shown at last IAEA 2018 conference. Typical behavior for W wall machines with confinement properties slightly lower than needed for ITER Q=10 [1,4]. Low collisionality cases have better confinement despite MP yielding edge pump-out and allowing low overall density to be reached. These cases have density peaking, as do TCV cases which also have better confinement properties

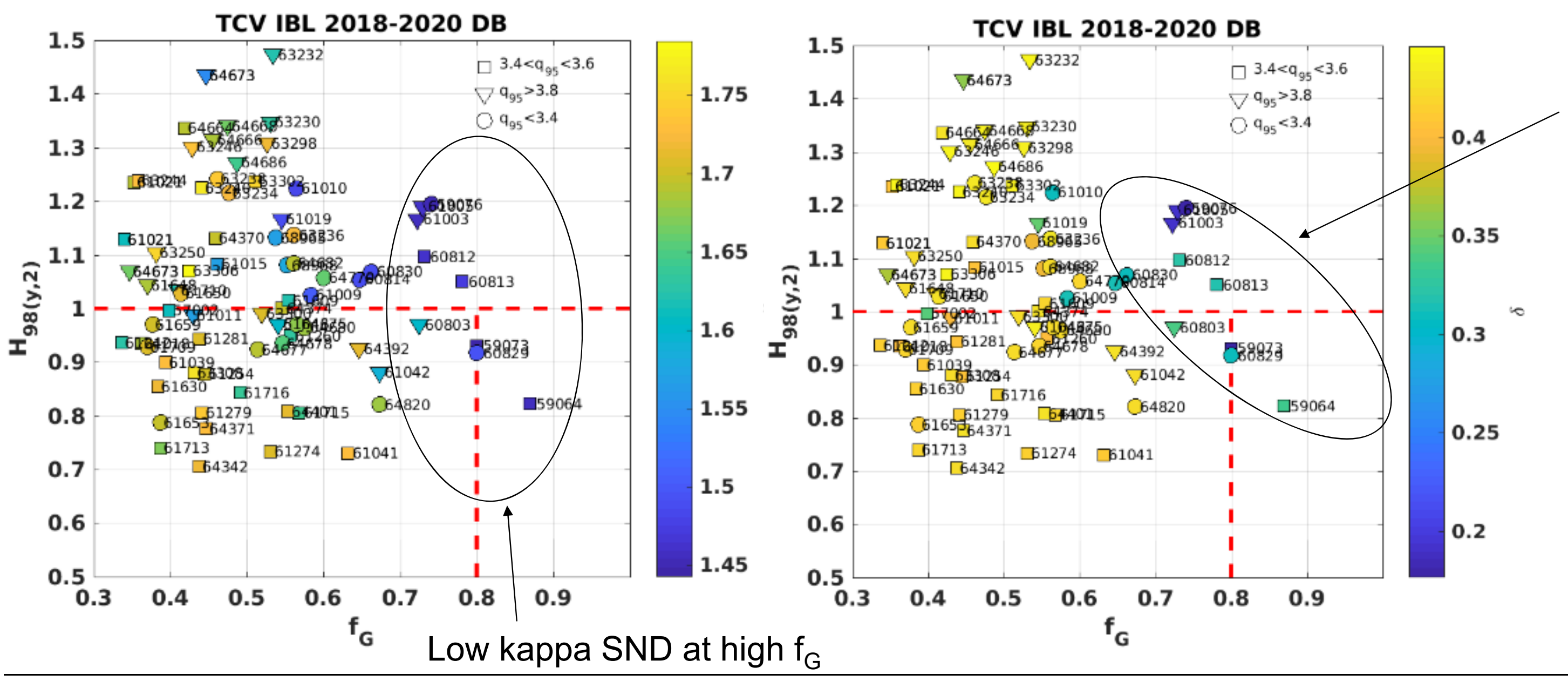
TCV: - IBL span (β_N,H_{98}) region with slightly better conf. properties as in other carbon wall machines [1, 6]
- H98 improves with β_N as in IBL scenarios in other machines [1]
- Improvement of H_{98} with β_N, high f_G shows $n_{e,ped}$ ⇑ at cst $T_{e,ped}$
- ITER values reached with f_G~0.65







TCV cases: High elongation limits achieved f_G

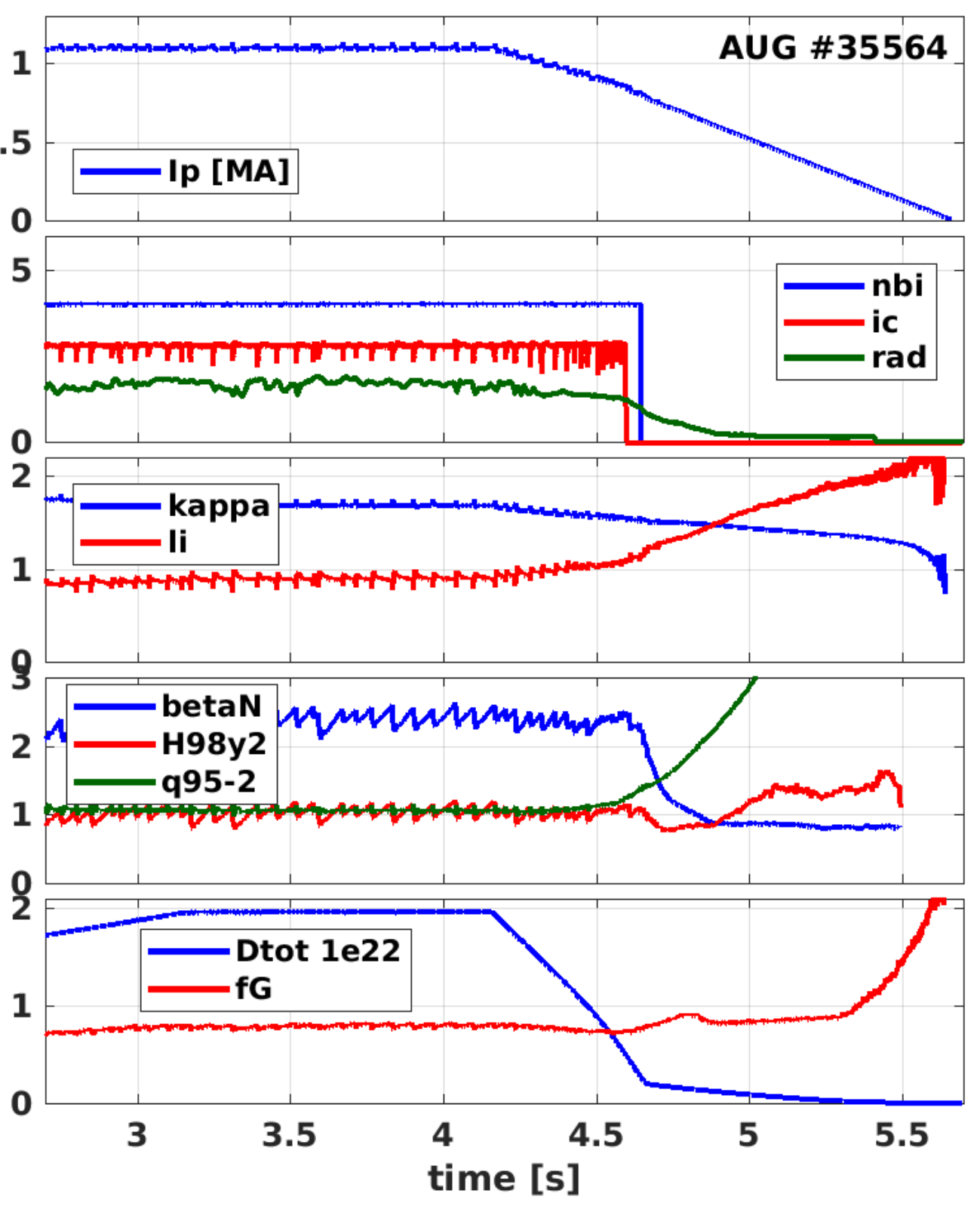


Low delta SND

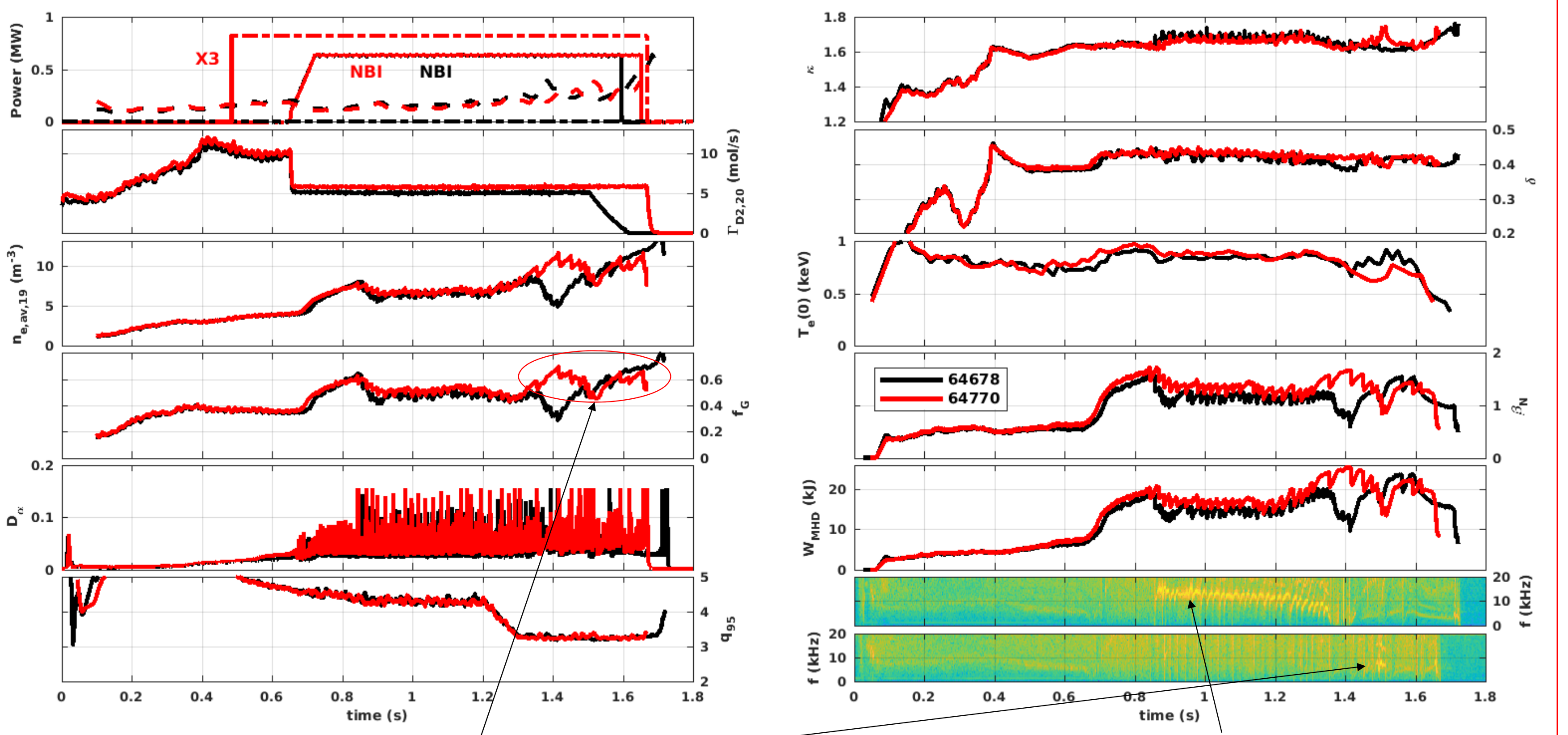
Low kappa SND at high f_G

IBL safe termination design:
AUG demonstration at q95=3

- Full integrated simulations of AUG ramp-down IBL cases performed with RAPTOR to validate the transport model, including H-L transition
- Optimization of the ramp-down trajectory with I_p ramp-rate, kappa(t) and H-L transition timing as parameter
- Proposed strategy: I_p and kappa decreasing (k down to value compatible with IC antenna coupling). Decrease gas, keep power in ramp-down, trigger H-L transition about 1/3 in ramp-down, keep P_L-P_{rad}>0
- Strategy implemented as new segment on AUG, needed to develop shape control to safely and effectively reduce elongation
- All cases with this new ramp-down safely landed down to 0 current as in this q95=3 example
- Reduce shape (κ, δ) for overall and ELM stability, lower pedestal controls impurities, keep l_i(t) under control and H-L to avoid too high density at low I_p



2/1 (N)TM in TCV IBL: - Can be avoided with X3 at low β_N, high q_{95}
- Always ends high performance after few ELMs~$\tau_{resistive}$



High performance interrupted by short-lived 2/1
τ_E~40ms, Δt_{ELM}~30-60ms, τ_{crt}~100ms
Timescales long on TCV as compared to resistive time => full current evolution

64678 without X3, 2/1 mode from 0.85s
64770 with X3

ASTRA results from KER, summary at 1.4s

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ASTRA results for TCV#64770@1.401sec; model:"TCV NBI FAST MEQ Hmode TiAs"
     Electron density ...................... 15.7127 (10^{19}m^{-3})
     Bulk ion density ...................... 13.5458 (10^{19}m^{-3})
     Fast ion density ...................... 0.2500 (10^{19}m^{-3})
     Max. fast ion density ................. 0.2500 (10^{19}m^{-3}) fast/bulk 1.8%
     Electron temperature .................. 0.7540 (keV)
     Ion temperature ....................... 0.6058 (keV)
     Electron energy ....................... 11.5125 (kJ)
     Ion energy ............................ 12.9340 (kJ)
     Bulk plasma energy .................... 24.4466 (kJ)
     OH power .............................. 0.2059 (MW)
     ECH power ............................. 0.0000 (MW)
     Electron to ion power ................. -0.4142 (MW)
     NB injected power ..................... 0.5562 (MW) 100%
     Fast ion to ion power ................. 0.2249 (MW) 40.4%
     Fast ion to electron power ............ 0.1067 (MW) 19.2%
     NB heating power ...................... 0.3316 (MW) 59.6%
     NB conf. power ........................ 0.5468 (MW) 98.3%
     Fast ion CX-loss & thermalization power 0.2152 (MW) 38.7%
     NB shine-through & orbit loss power ... 0.0095 (MW) 1.7%
     Plasma current ........................ 0.2787 (MA) 100%
     OH current ............................ 0.2304 (MA) 82.7%
     Total currentdrive .................... 0.0042 (MA) 1.5%
     ECCD currentdrive ..................... -0.0000 (MA) -0.0%
     NBCD currentdrive ..................... 0.0042 (MA) 1.5%
     Bootstrap current ..................... 0.0443 (MA) 15.9%
     NB injected current ................... 0.0064 (MA)
     BetaN total (bulk)..................... 1.8006 (1.7456)
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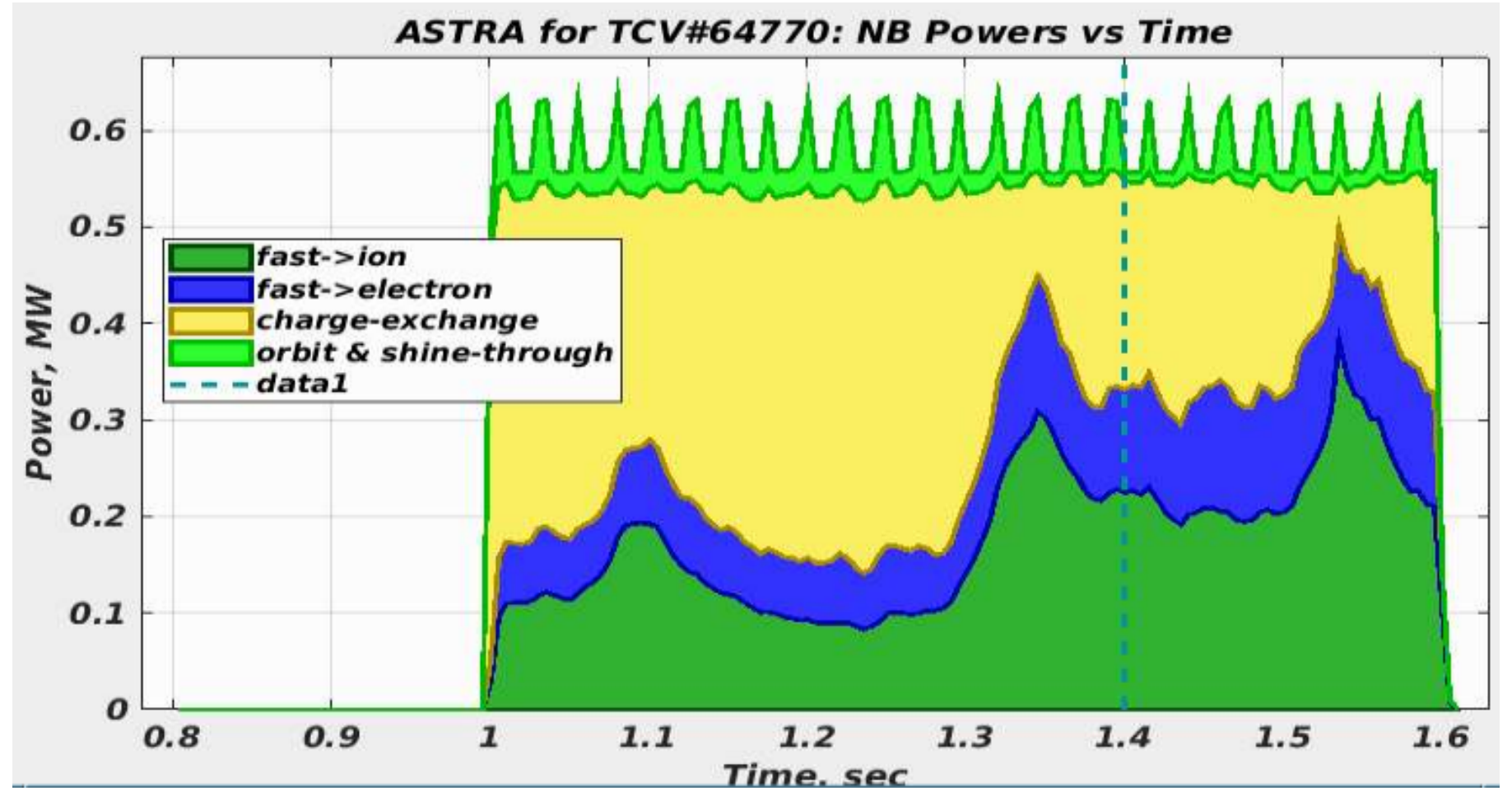
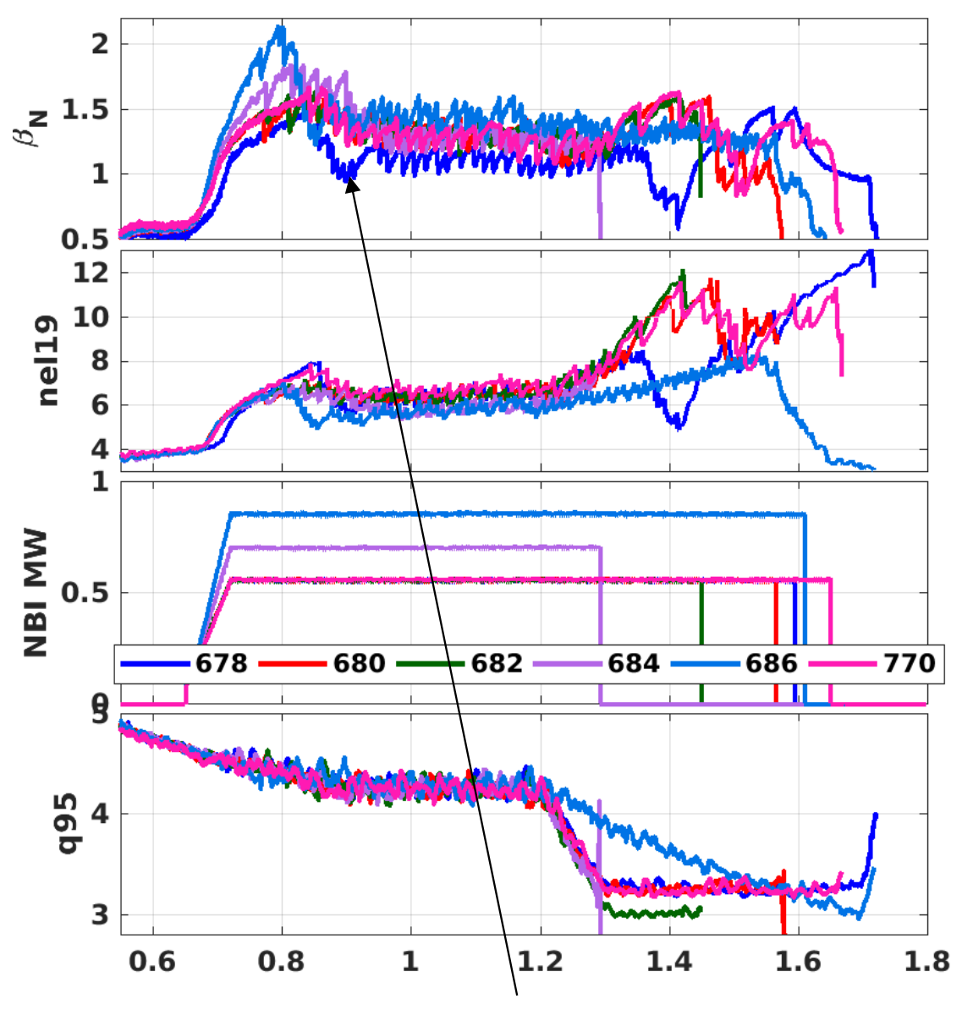
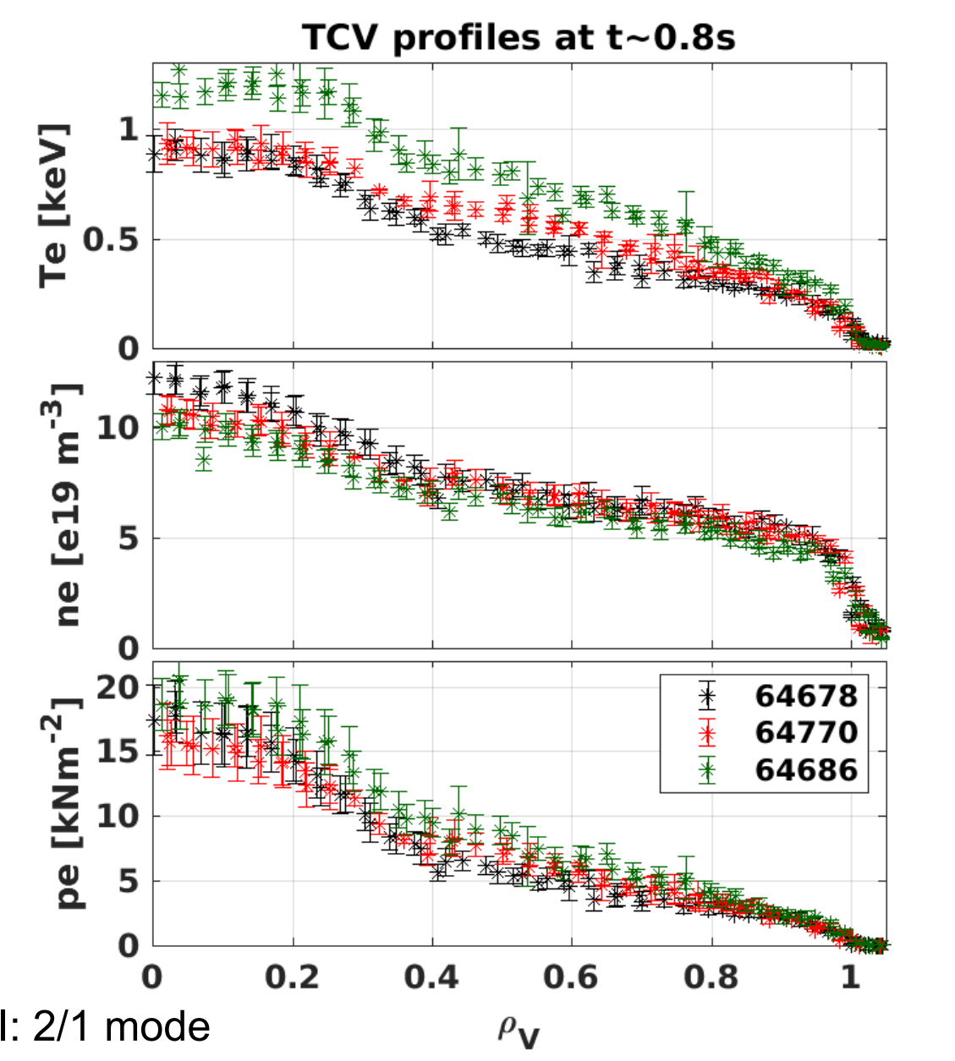
1.4s:
NBI->el: 110kW
NBI->ion:220kW
EC: 80kW
(2-3x at 1.2s)



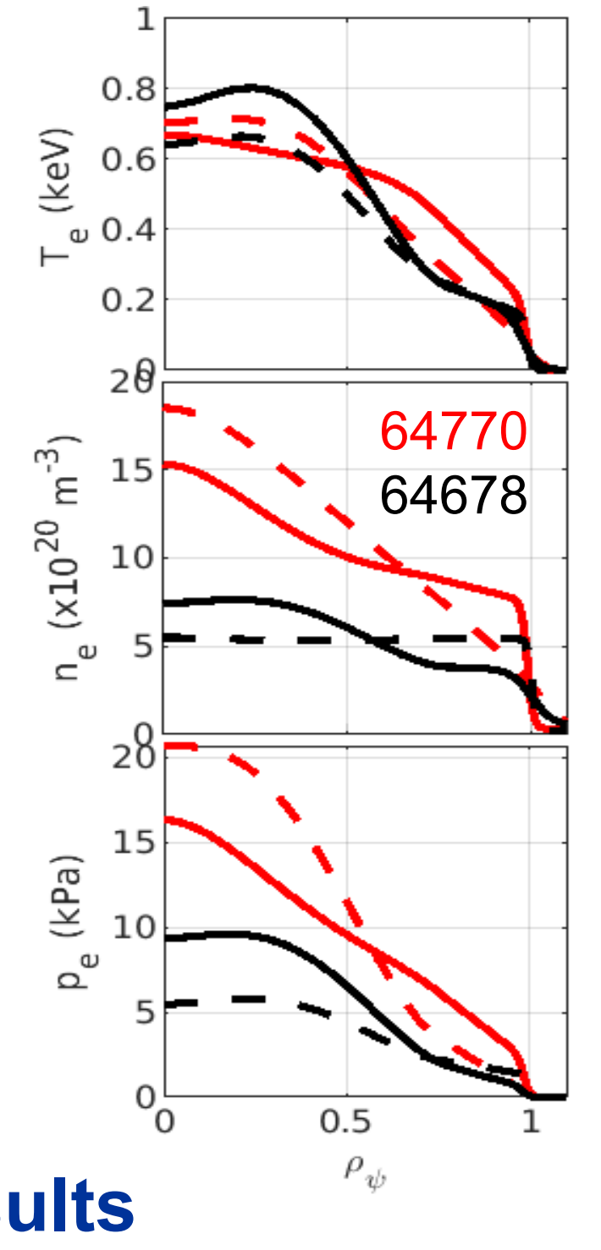
Power scan and profiles before 2/1 onset and due to ELM crash





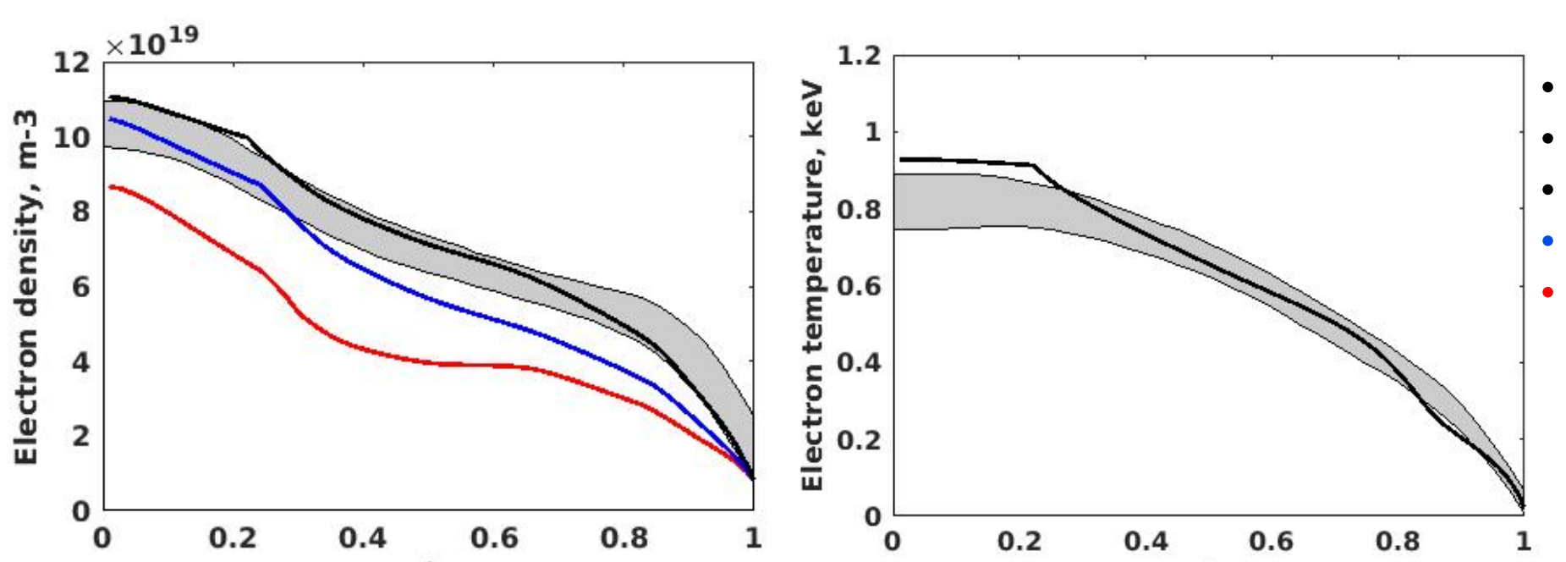
64678 no X3, 600kW NBI: 2/1 mode
64770, 64680, 64682: with X3 same NBI: no mode
64684, 64686: with X3 higher NBI: 2/1 mode

before(solid)/after(dashed)
ELM crash at 1.41s

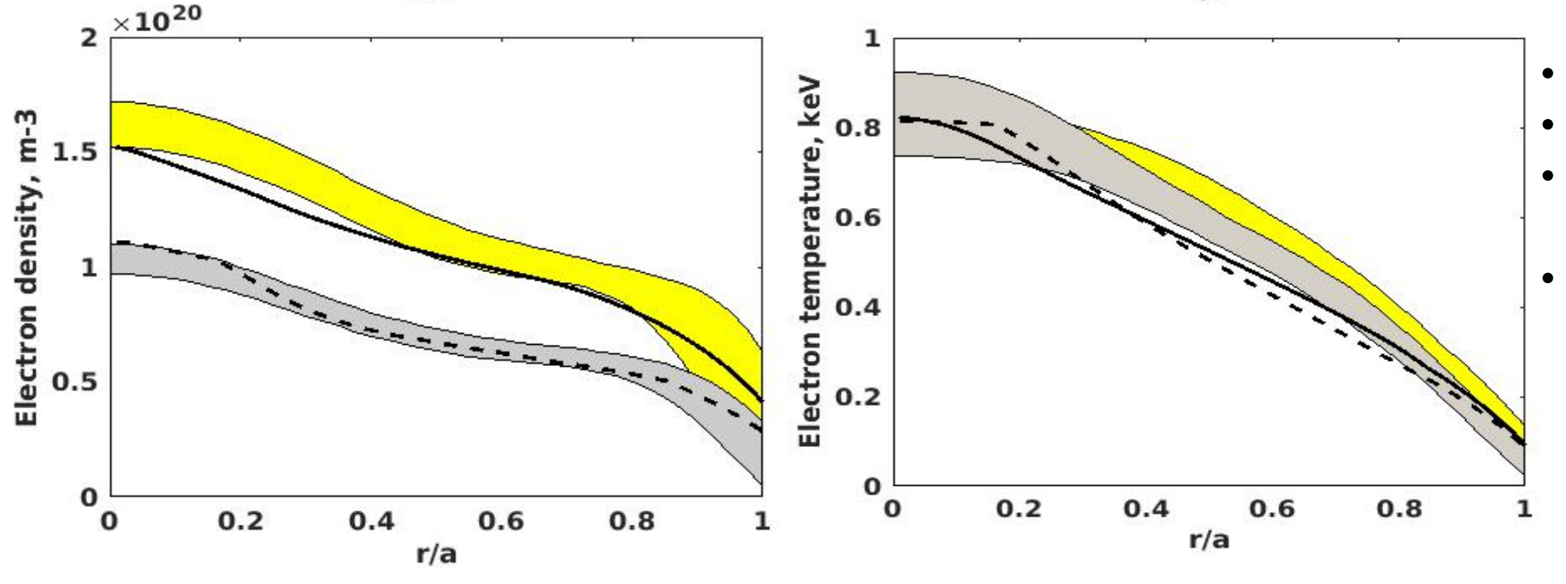


Predictive transport simulations consistent with experimental results

- GLF23 and GENE find ITG most unstable in most part of minor radius. GENE finds similar growth rates in AUG and TCV
- ASTRA-GLF23 heat/particle transport predictive simulations consistent with measurements for both q95~3.2 and 3.7 cases



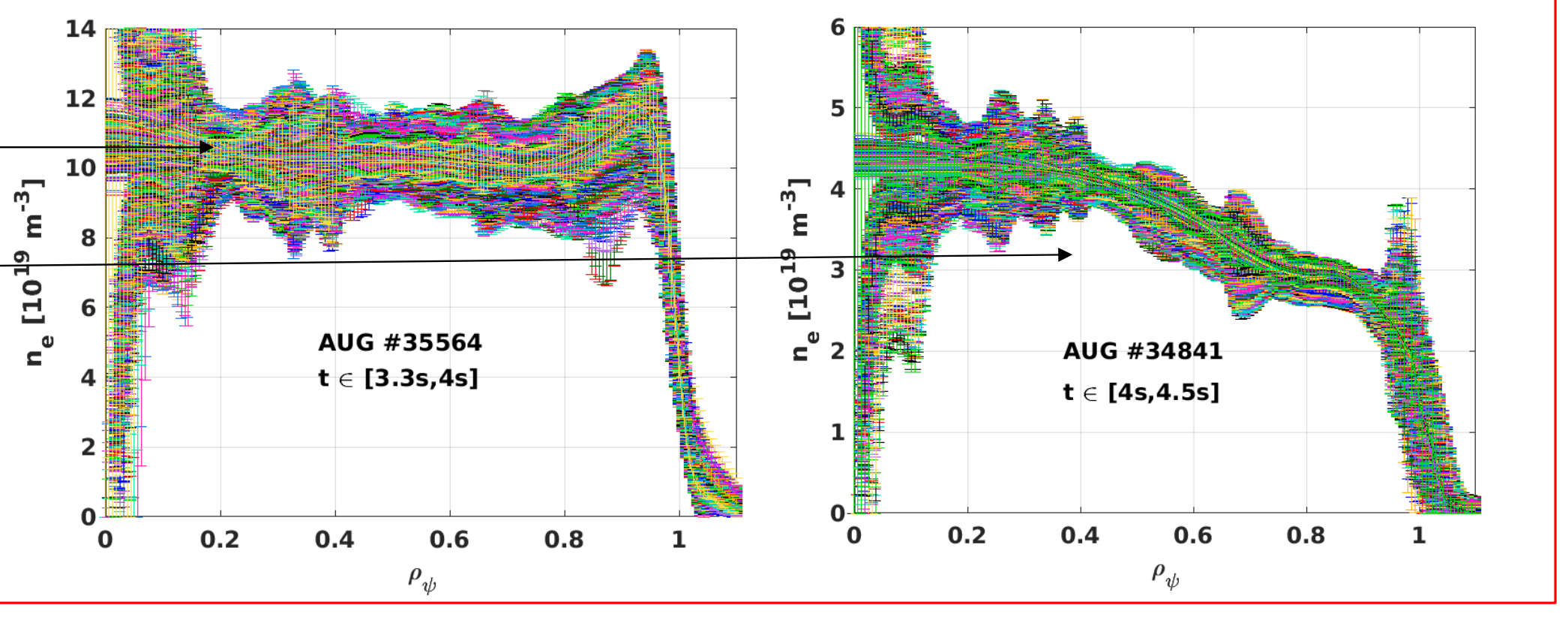
- 63306, q95=3.7, 1.2s
- Shaded regions: TCV data with error bars
- Solid black: ASTRA-GLF23 predictions for n_e and T_e
- Blue: removing neutral gas flux and waiting for stationary state
- Red: removing NBI fueling source. Strong overall decrease but remains with peaked n_e due to ITGs



- 64770, q95=4.2/1.2s (dashed, grey) and q95=3.2/1.4s (solid, yellow)
- Solid black: ASTRA-GLF23 predictions for n_e and T_e
- n_e and T_e well reproduced over full discharge, ne peaking at 1.4s slightly underestimated
- Reaches n_{e0}=1.5 10^{20}!! (=> cut-off for central X3)

AUG density peaking:

- AUG IBL have flat density profiles contrary to all TCV IBL case
- Except for low ν^* cases, with edge pump-out and low edge density (e.g. 34841)
- Peaked density and related good confinement are consistent with TCV cases, albeit at different ν^* values: to be studied further



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