Non-inductive high-performance discharges on TCV on the path to steady state

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Background and motivation

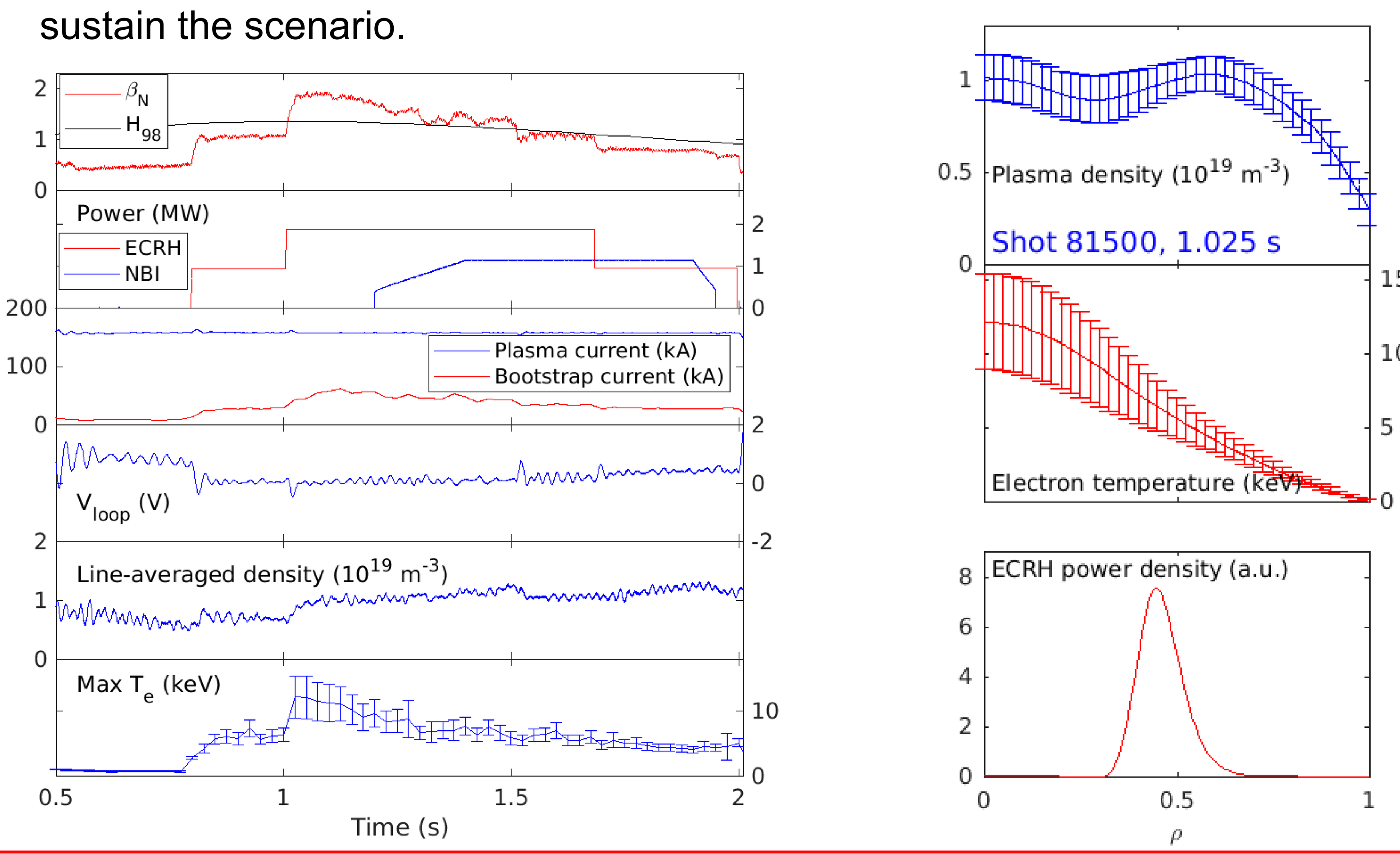
- Long-pulse operation is one of the conditions that appear necessary for a viable fusion reactor [1]. The present work, within the EUROfusion WPTE package, aims to achieve long-pulse operation while retaining good performance (e.g. high normalized β_N), in preparation for JT-60SA and ITER.
- True steady state requires fully non-inductive current drive; further, economics favors the "free" bootstrap current over external current drive.

The long-pulse quest on TCV

- R/a=0.88/0.23 m, I_p<1 MA, B_T<1.54 T; 2.6 MW ECRH, 2.6 MW NBI
- With pure electron heating from 1996 to 2015, TCV has a long history of steady-state (i.e., much longer than the current redistribution time), fully non-inductive discharges [2], a subset of which involved eITBs: this is a high-β_p scenario [3] (up to β_p>2) with bootstrap fraction up to 100%, *but cold ions*.
- With NBI, T_i~T_e is now common (e.g., H-mode).
- Merging the two conditions is challenging [4], especially because of a narrow usable density range (low enough for high ECCD efficiency, high enough for good NBI coupling and equipartition). The focus remains on **steady state**. Virtually all discharges in this study are with zero loop voltage, mostly by design.

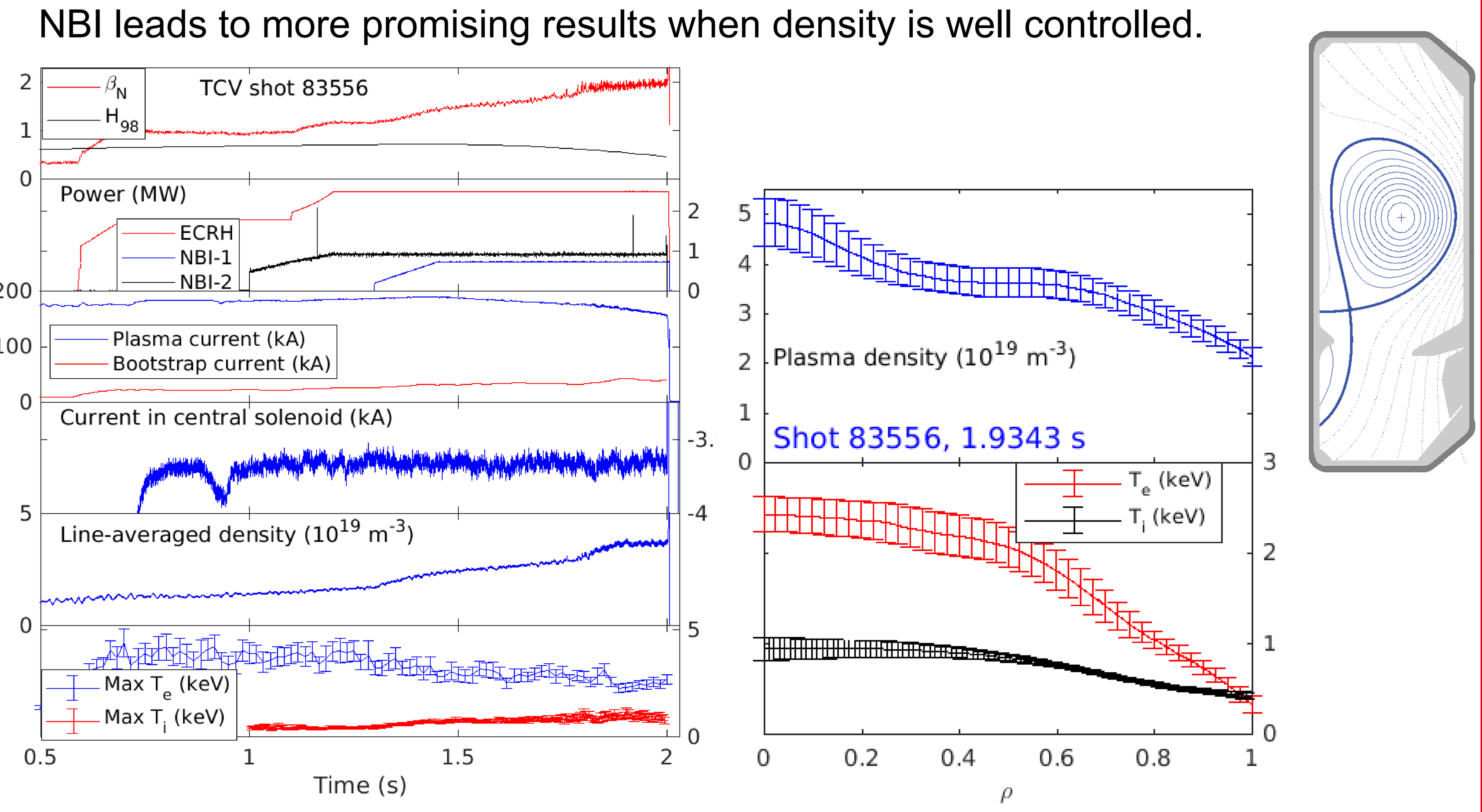
Extension of the eITB space

- One approach: establish the non-inductive conditions before applying NBI.
- In some cases an extended area of increased core confinement is seen rather than a barrier: record T_e~12 keV (only achieved before in inductive conditions) with one ECRH source moved slightly inward and in counter-ECCD mode.
- Good performance could not be maintained with NBI: confinement decreases, β_N descends to ~1, and T_i fails to rise.
- One conclusion: The current ECRH power *must all be used for off-axis ECCD* to sustain the scenario.

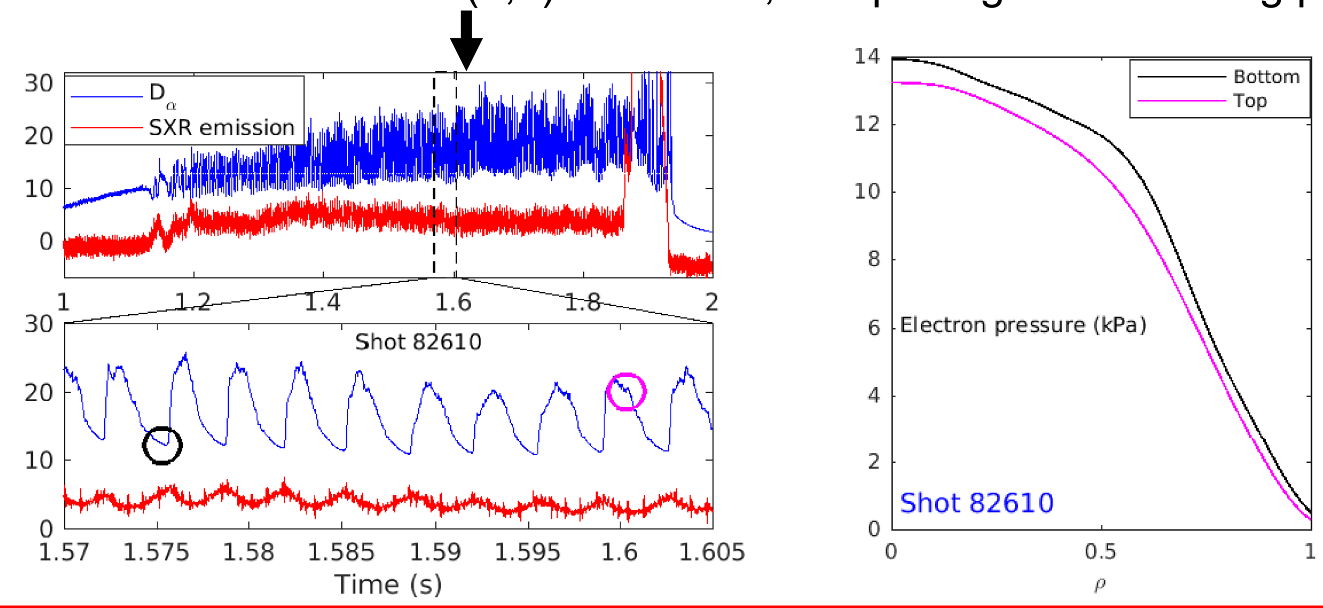


Flat-top non-inductive NBI-heated scenario

- More balanced application of all-off-axis co-ECCD and off-axis co- and counter-NBI leads to more promising results when density is well controlled.

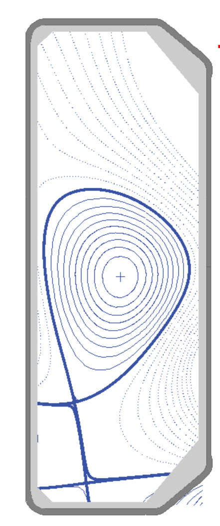


- Ohmic primary clamped to constant current: semi-stationary β_N reached during density ramp induced by NBI fueling, with plasma current slowly decreasing.
- MHD activity can be significant, but higher-energy (50-60 keV) NBI-2, injected counter-current, empirically limits its virulence.
- Bootstrap fraction still < 30%, T_i rising but still below T_e.
- *Extra gyrotron in 2026 could be a game-changer.*
- Reverse shear predicted by ASTRA and TRANSP, possibly confirmed by double (m,n)=(3,1) MHD mode.
- Often observed: 350-Hz (1,0) oscillation, steepening and flattening profiles.



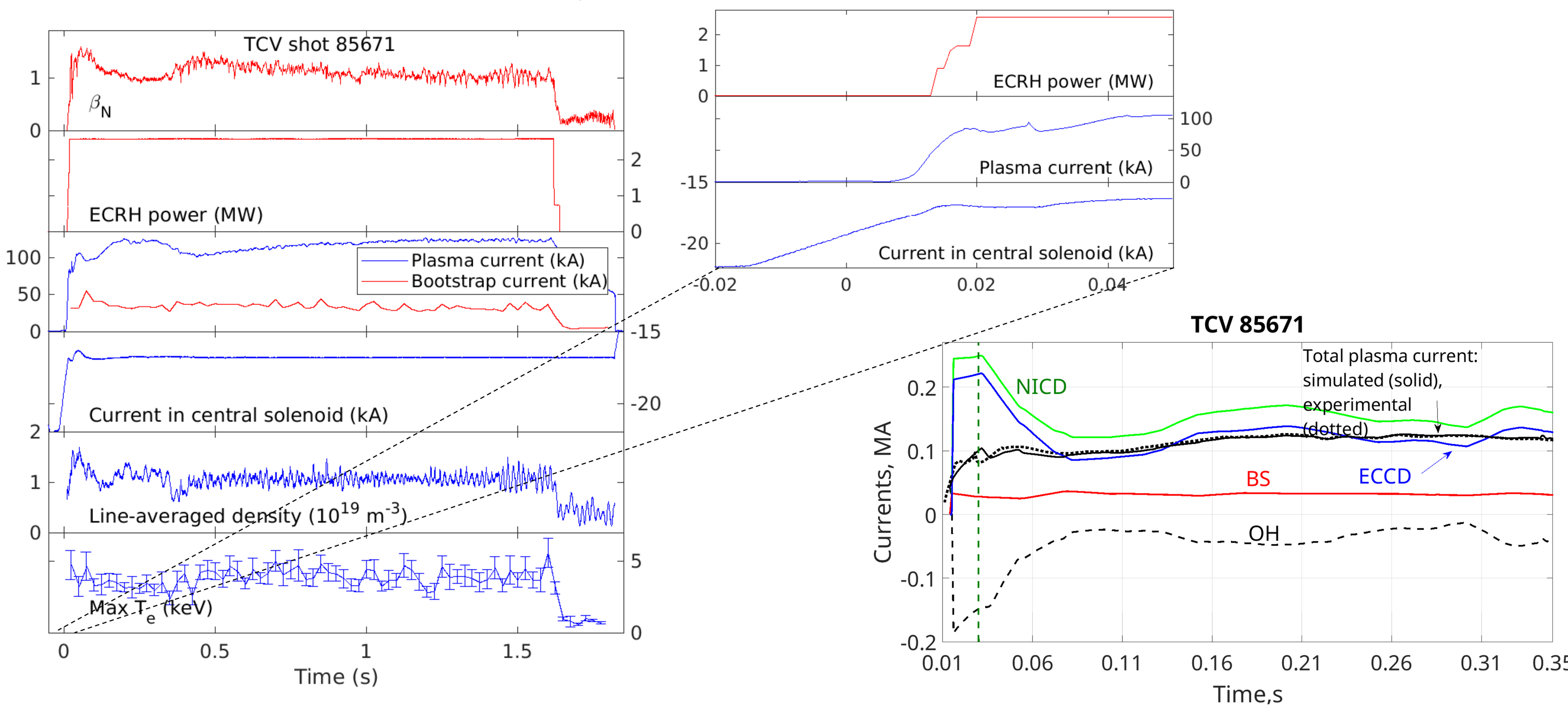
Preparation of X-point target divertor scenario

- Detachment appears difficult at our densities. An attempt will however be made with this particularly favorable configuration [5], with divertor baffles.
- Fully non-inductive XPTD scenario is ready for the upcoming campaign.

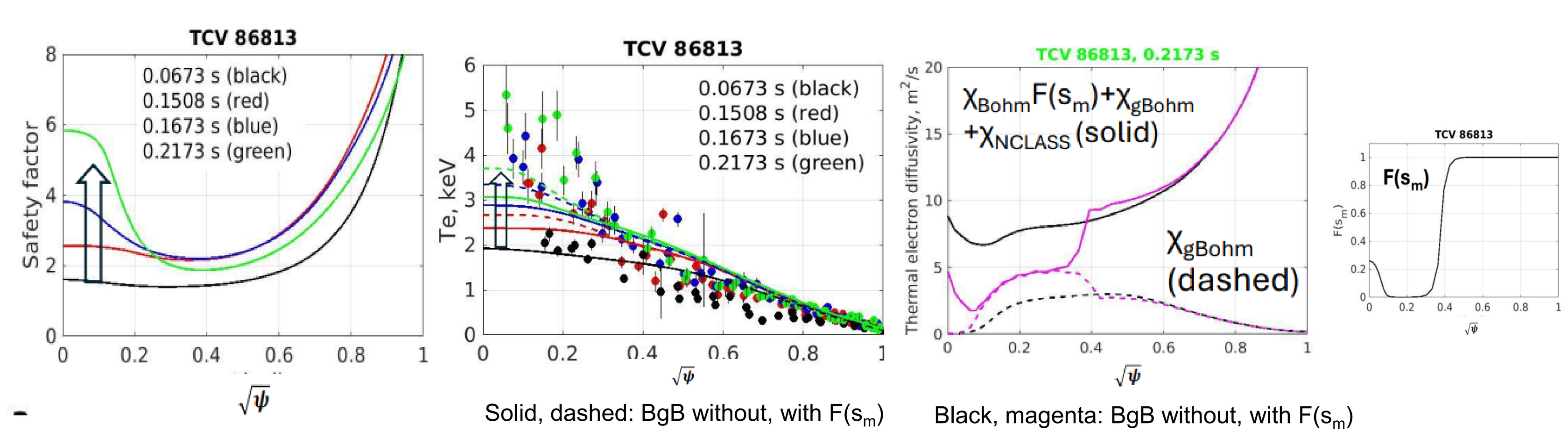


Central-solenoid-free ramp-up with eITB

- In the spirit of minimizing the inductive current component, we have explored a full ramp-up with the central solenoid (CS) clamped 30 ms after breakdown.
- This is also in support of the spherical tokamak program, represented in WPTE by MAST-U, which aims at eliminating the CS as an ultimate necessity.
- Successful scenario with only 10% of the available flux used for breakdown.



- Simulated in ASTRA with Bohm-gyroBohm (BgB) model [6] with and without shear stabilization multiplier $F(s_m)$ included in Bohm-like term.
- Reverse shear, ITB confirmed; BgB model underestimates thermal confinement.



Solid, dashed: BgB without, with $F(s_m)$ Black, magenta: BgB without, with $F(s_m)$

Outlook

- Attempt detachment in XPTD configuration.
- Identify smooth path from non-inductive ramp-up to non-inductive flat-top.
- An additional gyrotron will permit controlled core heating to address the question of the maximum achievable β_N in non-inductive steady-state TCV plasmas.

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