Access to AT modes: Generic Issues

- Difference between genuine steady-state modes and hybrid scenarios (very long pulses)
- Hybrid scenarios require as much CD as possible almost regardless of location.
  - Several scenarios without ITBs: high li modes(DIII-D), “improved H-modes” (AUG, DIII-D)
  - Requirement : $q_0 > 1$
- Steady-state scenarios require:
  - Full CD, including bootstrap > 50% (minimum for steady-state in ITER, preferably 70% for AT reactors)
  - Good alignment between I_{BS} and I_P
  - Likely a wide ITB (for the confinement)

Access to AT modes: Issues for ITBs

- Shear flow / rotation
- Electron ITBs at high collisionality (scenario important: enter ITB at low density and then increase density ?)
- Best configuration not clear
  - Weak positive shear
  - Weak negative shear
  - Strong negative shear
- MHD issues (control of pressure profile, NTMs ?)
- Energetic particles (magnetic configuration crucial)
- Fuelling: how to reach high densities without core beam fuelling (pellet fuelling just started)
- Impurity concentration : control of ITB gradient ?
- Elms and divertor compatibility
- Controllability

Access to AT modes in ITER :Tools (1)

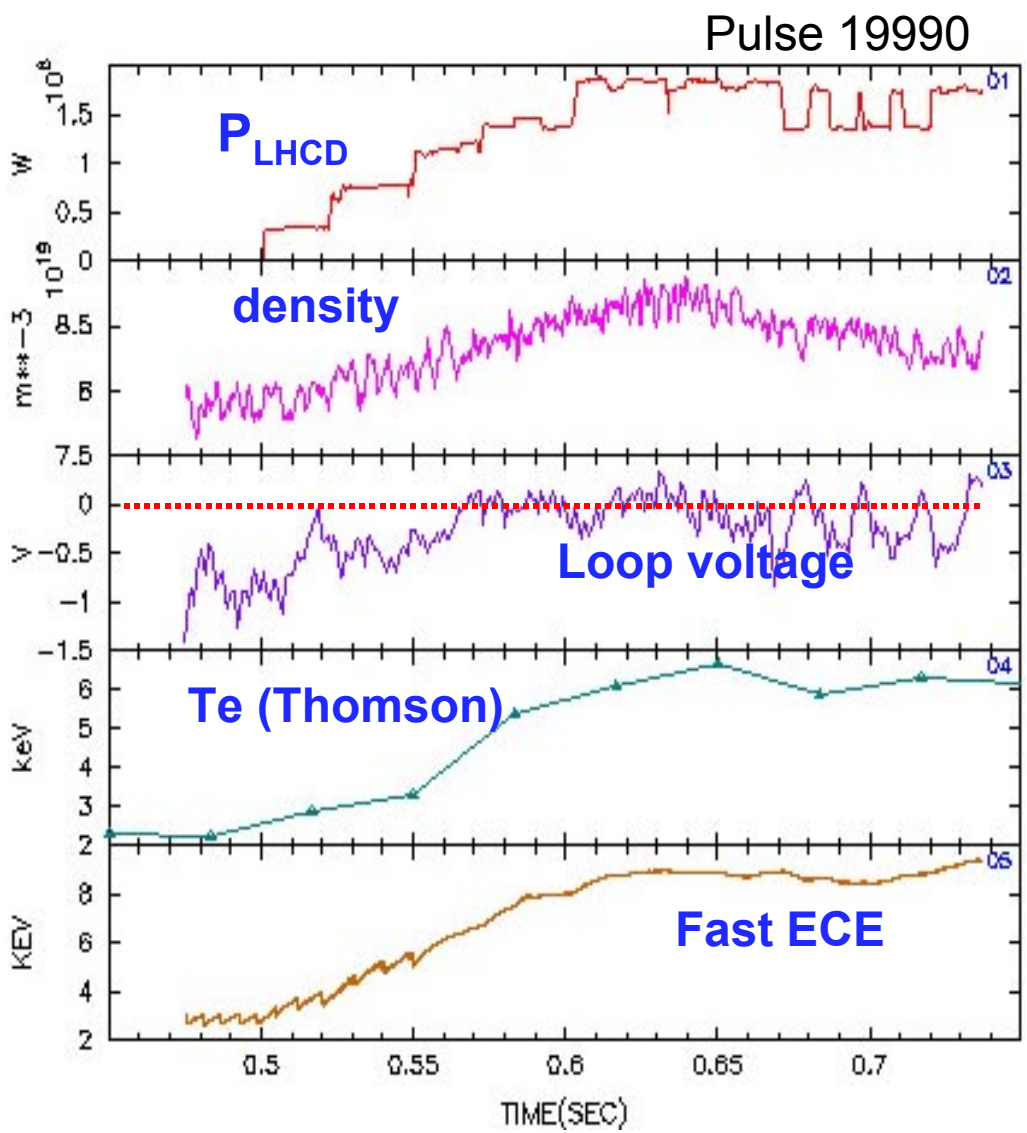
- NBCD: On-axis and off-axis CD achieved by tilting beam axis vertically: 0.38 - 0.95 m below plasma equatorial plane at the tangent point. Efficiencies depend upon scenario, temperature and density profile. In AT scenarios: 0.25 to 0.39 A/Wm^2 .NBCD peaked at r/a~0.2-0.3 (to be used with another outwards CD system for full CD)

- ICRH: Simultaneous slightly off-axis minority ^3H_e and 2nd harmonic tritium allows a very effective deposition on ions to be achieved (> 50%). Electron CD: efficiency ~0.10 A/W/m^2 (prop. to Te). Minority CD: do not provide main CD, but can be effective for local control: central seed current, MHD control on rationale magnetic surface.

Access to AT modes in ITER :Tools (2)

- ECCD: 20 MW at 170 GHz.One equatorial launcher with toroidally steered beam (20° to ~45° in a horizontal plane)for H&CD. One upper launcher for NTM stab. Power can be switched between launchers. Steerable mirrors in real time.
  - CD efficiency (Equatorial launcher): up to 0.2 A/Wm^2 at plasma center, down to 0.1 A/Wm^2 for r/a=0.42 (max range ~r/a=0.5). CD efficiency (Upper launcher): ~ 0.05A/W/m^2 at r/a=0.7, but poorly localised.
- LHCD: 5 GHz 20 MW, some N// flexibility (1.9-2.1). CD efficiency: 0.3 A/W/m^2 to 0.25 A/W/m^2 (at r/a ~2/3) *(fig).* Can be localised well off-axis (0.7<r/a<0.85):
  - In most scenarios, well localised at the foot of an ITB.
  - Unique system with significant off-axis CD efficiency well off-axis

Full Lower Hybrid Current Drive at High Density

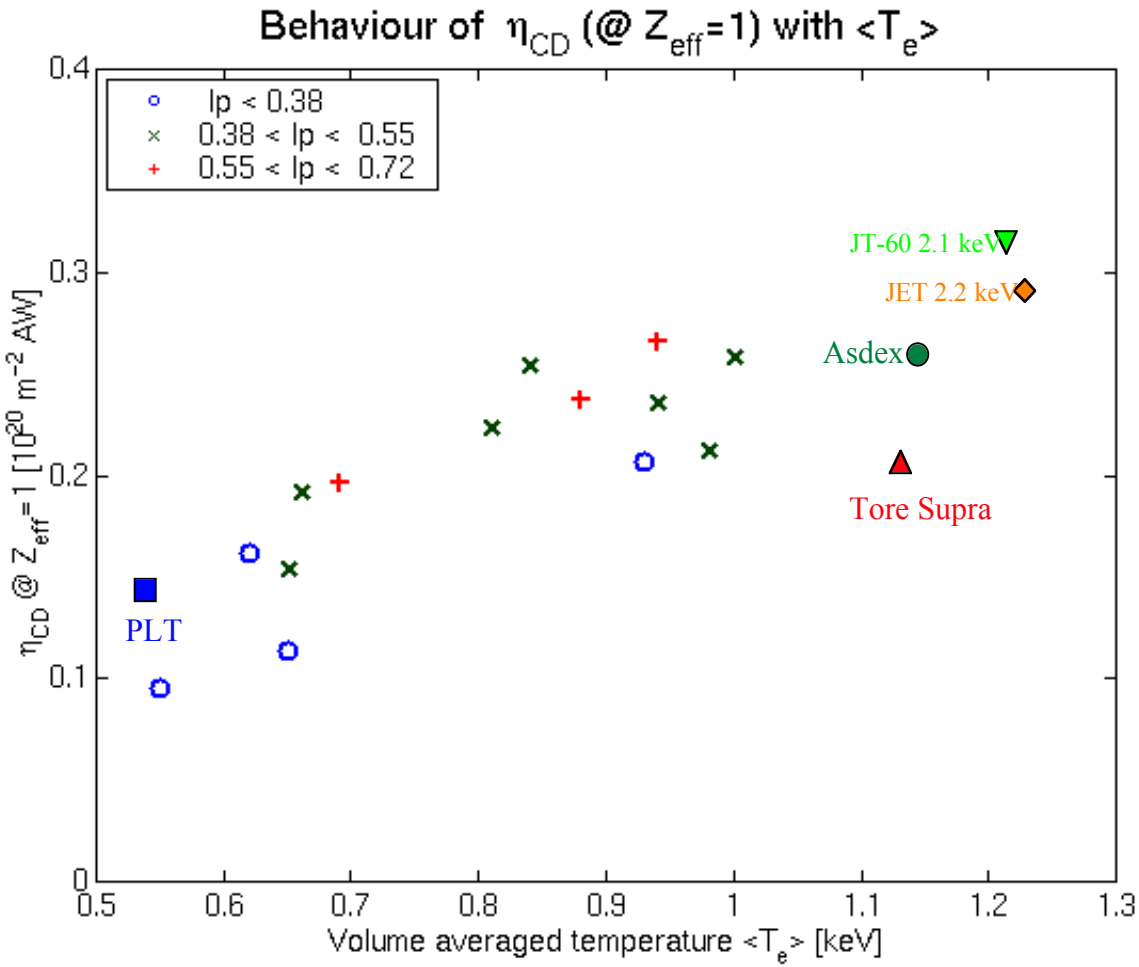


- P_{LHCD}= 1.8 MW, Ip=0.5 MA, n_e up to 8.5 $10^{19}m^{-3}$ Te up to 7 keV
- Zero loop voltage
- Reasonably steady
- Sawteeth are stabilised

LHCD localised about mid-radius

- Up to 2.2 MW launched at B=7.2 T, Ip=0.5 MA
- Close to max LHCD power on FTU (2.4MW)

η_{CD} (@ Z_{eff}=1) vs <T_e> from FTU data



- η_{CD} grows with <T_e> almost linearly up to ≈ 0.27 10^{20} m^{-2} A/W
- <T_e> appears to be the only ordering parameter

Steady-state scenarios in ITER

- Preferred scenario not yet chosen.
- As much flexibility as possible:
  - NNBI for off-axis CD and if momentum injection is needed for ITB production
  - Off-axis ICRH if rotation(as in C-MOD) is needed
  - Some off-axis ECCD
  - LHCD (upgrade).
- Aim
  - Ip=9 MA, q_{95}=5.2, β_N =3, $I_{BS} \cong$ 50%, P_{add}=60 MW (up to110 MW possible), Q=5 with P_{FUS}>400 MW.*(fig)*

Simulations at an early stage (ASTRA + NNBI+ “other”)

- Basically guide-lines on feasibility of a prescribed magnetic configuration.

Advanced Scenarios with NBCD + "other"

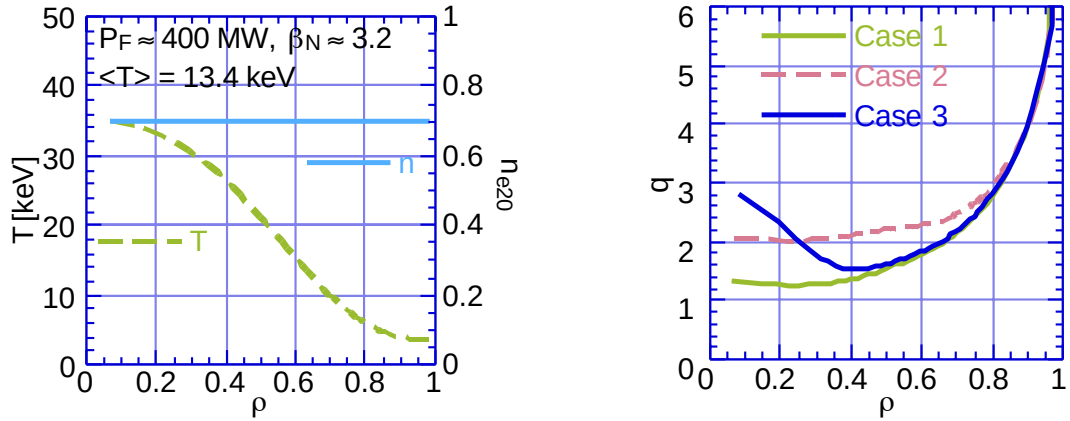


Figure 4.3-4 Plasma Temperature and Density (left) and q (right)

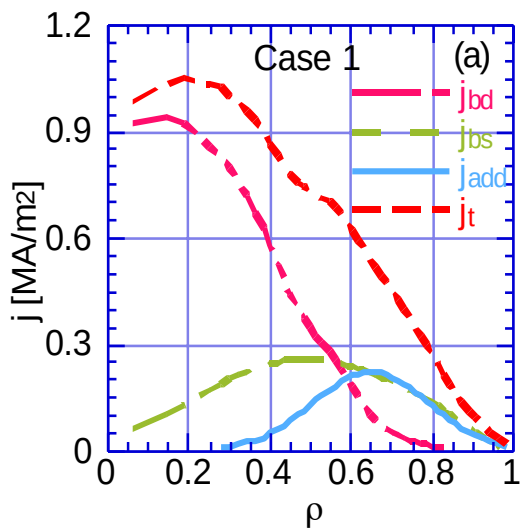


Figure 4.3-5 (a) Current Profiles

j_t: total current density, j_{bd}: bean-driven current density, j_{bs}: bootstrap current density, j_{add}: additional current density needed for q(r) profile shown in Figure 4.3-4.

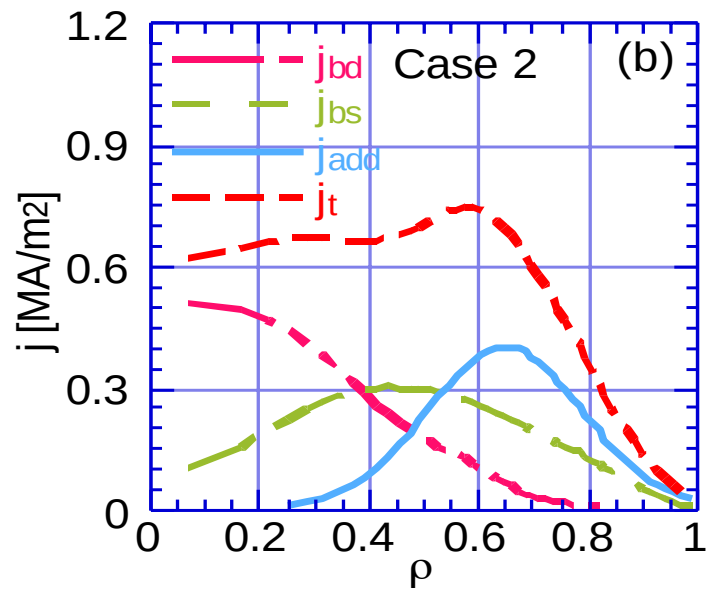
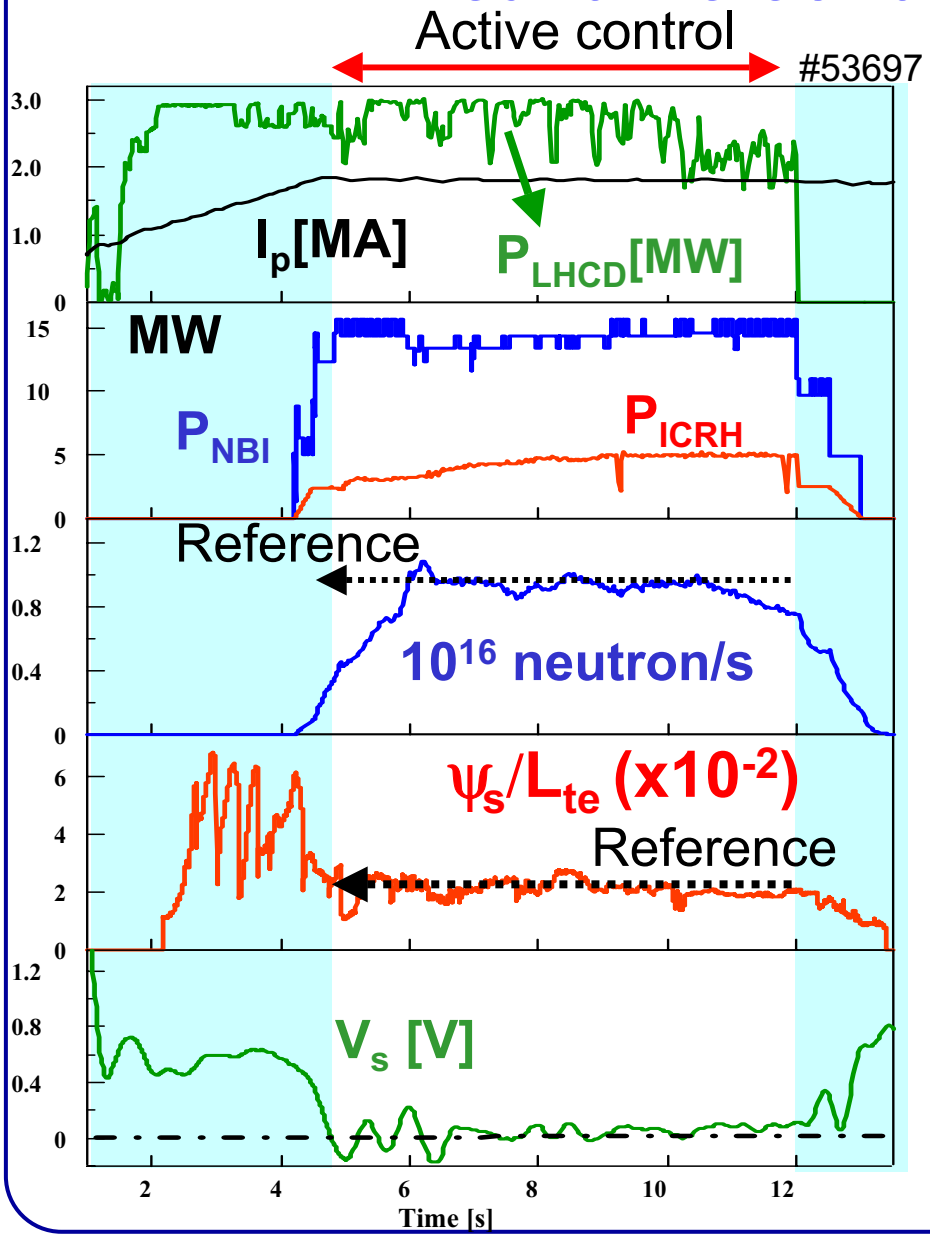


Figure 4.3-5 (b) Current Profiles

Steady-state scenarios in ITER: controllability

- Actuators: main H&CD systems + fuelling systems . Main recent developments:
  - Active ITB control (shear rotation) on JT-60U with NBI (unlikely inITER).
  - Active control on quasi steady-state ITBs in JET *(fig)* : ICRH for gradTe control, NBI for neutron control. Present attempt to use LHCD for current profile control (real time).
  - Active current profile control prepared on AUG.
- ***Main issue for ITER***: Bootstrap current alignment in particular in presence of a large alpha population. Demonstrate integrated real time controlled AT scenarios, in particular with high bootstrap fraction.

Real time control experiments



- Real time feedback loop on Te-profile (normalized gradient length control), plus on neutron rate.
- Highly non inductive current profile preventing ITB evolution, and strong ELMs

=> long pulse steady-state ITB far from MHD limits and with mild impurity accumulation.

- feasibility demonstration of a controlled AT regime.
- requires margins on actuators, and thus somewhat reduced performance.