Control Issues for Integrated Steady-State Operation

- First principle:
  - Steady state operation is not conceivable without active control

- Plan of the talk
  - Some Definitions
  - Integration
  - Core control
  - Particle control
  - MHD and beta limits
  - Energetic Particles
  - Pedestal
  - Summary
Some definitions for advanced or steady state scenarios

- **Hybrid Scenarios**
  - high beta, high confinement, high bootstrap, steady current profile but not full current drive and not steady-state
    - Permit very long burn in ITER
  - Require to have $q_0 > 1$

- **ITER Steady State Scenario:**
  - High confinement, high beta, $f_{BS} = 50\%$, full current drive with well-aligned currents
  - Scenario very dependent upon current profile

- **Ideal Steady State Scenario:**
  - High confinement, high beta, $f_{BS} = 80\%$ and full current drive
General Issues

- So far, all hybrid and steady state scenarios are H-modes and share the same essential control issues
  - Normal plasma control: current, position, shape,…
    - Better accuracy on plasma shape possibly needed
    - Loop voltage control likely to be added
  - Disruptions mitigation
  - MHD control (NTMs, sawteeth,…)
  - Pedestal: ELMs compatibility, core control
  - Particle control
  - …. 
- Although some constraints are different, most notably for
  - core control
  - MHD
Meaning of integration:

- All dimensionless parameters to be similar to the target ITER scenario?
- Selected dimensionless parameters similar to the target ITER scenario?
  - Criteria for selection?
- Other real dimension parameters to be taken into account?
  - For instance ELMs
    - Question not yet resolved
Integration: Favourite JT60-U Diagram

- Missing
  - ELMs quality
  - $q_{\text{edge}}$
  - other dimensionless parameters: $\nu^*$, $\rho^*$,...

#E37964 0.9 MA, 2.5T, deuterium
Specific Aspects to Steady State Operation

- Core control
- Particle and impurity control
- MHD and beta limits
- Energetic Particles
- Pedestal control
Complex core control for Steady State Scenarios with ITB

Current Profile

Good alignment required
Increase bootstrap

Modify shear

Excite EP modes

Impurity accumulation

Stabilise turbulence

Control ITB location

Increase ∆P

Increase some MHD modes

Produce ITB
Initially, demands on control were extreme:

- Control of shear flow
  - Momentum
  - Pressure gradients
- Control of temperature gradients
- Control of ITB foot localisation:
  - minimum q?

To day, demands appear more feasible

- Minimum demand:
  - Control q profile
- Probable:
  - Control temperature gradients
Less Complex core control for Hybrid Scenarios: Preliminary

Maintain $q_0 > 1$

Modify shear

Current Profile

Not clear on how to do it

Impurity accumulation

Rough alignment required

Increase bootstrap

Increase $\Delta P$

Stabilise turbulence

Increase some MHD modes

Not clear on how to do it
Actuators for core control

- Off-axis Current Drive main actuator for steady state scenarios
  - Large experimental effort (JET, Tore Supra, JT60-U)
  - Current alignment needs specific modelling (development of model-based control algorithm: Moreau)
  - Tools: ECCD, NBCD, LHCD
- On and off-axis CD important for Hybrid scenarios
  - Tools: ICCD, ECCD, NBCD, LHCD
- Core heating
  - Might act on pressure control
Particle and impurity control (1)

- Core fuelling is still an open question, in particular if ITBs are needed
  - Pellets
    - Experiments on course: JT60-U, JET
  - Anomalous inward pinch:
    - Create?
    - Control?
Particle and impurity control (2)

- Impurity accumulation
  - Neo-classical confinement + density gradients = impurity accumulation (helium ashes and intrinsic impurities)
    - Central ECRH seems to increase impurity transport compared to deuterium and electrons transport (AUG)
    - Controlled temporary loss of ITB to clean the core (sawteeth like effect)
    - Control of electron and/or ion temperature gradients (used as an effective tool in JET)
  - In JET (Zastrow): $5 < \tau^*_P(\text{He})/\tau^\text{th}_E < 8$ (10 required for ITER)
    - Pumping required?
    - Scenario dependent?
MHD and beta limits

- By definition, steady state and hybrid scenarios have to operate at high $\beta_N$
- Domain of operation is limited by the various links between MHD limits, pressure gradients, bootstrap current and current profile
  - From mapping done in DIII-D (T Luce), clear dependences of $\beta_N$ have been established with:
    - $\text{ITB}_{\text{width}}$, $\text{ITB}_{\text{radius}}$, $q_0$, $q_{\text{min}}$
- NTMs seems to be less severe than in standard scenarios (absence of sawteeth), but rationale q surfaces might be closer to the plasma edge
- Resistive wall modes appears to be the ultimate limit in present scenarios
  - Active control needed (T Srait)
Energetic Particles: more important than in Standard Scenario

- Current profile has to be compatible with containment of energetic ions (NBI and ICRF) and more over with alphas
  - Strong or weak radial diffusion of alphas?
- Some control of central and minimum q values might be required to avoid large radial diffusion from EP modes.
  - Other indicators/actuators to be installed (Fasoli)
- All ITBs have been produced so far with core heating within the ITB:
  - Alpha heating in a BPX experiment has to be contained within the ITB:
  - control of ITB width?
- Use of energetic particles to “minimise” some MHD modes: sawteeth, NTMs
  - Control location of ICRF?
Pedestal and ELMs control

- Some constraints are common to standard scenarios, namely ELM and edge compatibility with divertor plates
- Some specificities:
  - Link between pedestal height and core confinement
    - clearly different in steady state scenarios,
    - possibly similar in hybrid scenarios
  - In most present steady state and hybrid scenarios, type II (AUG) or mild ELMs (JET, JT60-U) are achieved but at somewhat too low density
  - Type I ELMS with high pedestal pressure incompatible with some ITBs (JET)
  - Possible ELMs control (JET)
    - Edge current
    - Neon injection
Development of “real-time” central controller probably needed

See A. Becoulet et al 15th RF Top. conf. 15\textsuperscript{th} (Moran, USA, 2003)

- **Input:**
  - real-time diagnostics (very long list: see Joffrin, Moreau)

- **Inside:**
  - various targets and limits:
    - current profile, density, loop voltage, beta, energetic particles beta, …
  - Model-based algorithms or even a simplified model

- **Output:**
  - Actions on core actuators
  - Actions on edge actuators
Integrated control of steady state scenarios start now to have a firmer basis

- Long time duration experiment use an increasing number of real-time feedback loops
- Substantial work still clearly needed. Among them:
  - Better specifications for ITB control needed
  - Current alignment control requires further demonstration
  - Particle control, including fuelling
  - ELMs control
  - Compatibility between scenarios and Energetic Particles
Summary (2)

- Steady state and hybrid scenarios are now more mature:
  - Experimental efforts shall also take into account the development of scenarios with minimum control requirements
- Controlling steady state operation in ITER is clearly a very challenging but a very worthwhile task:
  - We are learning rapidly