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

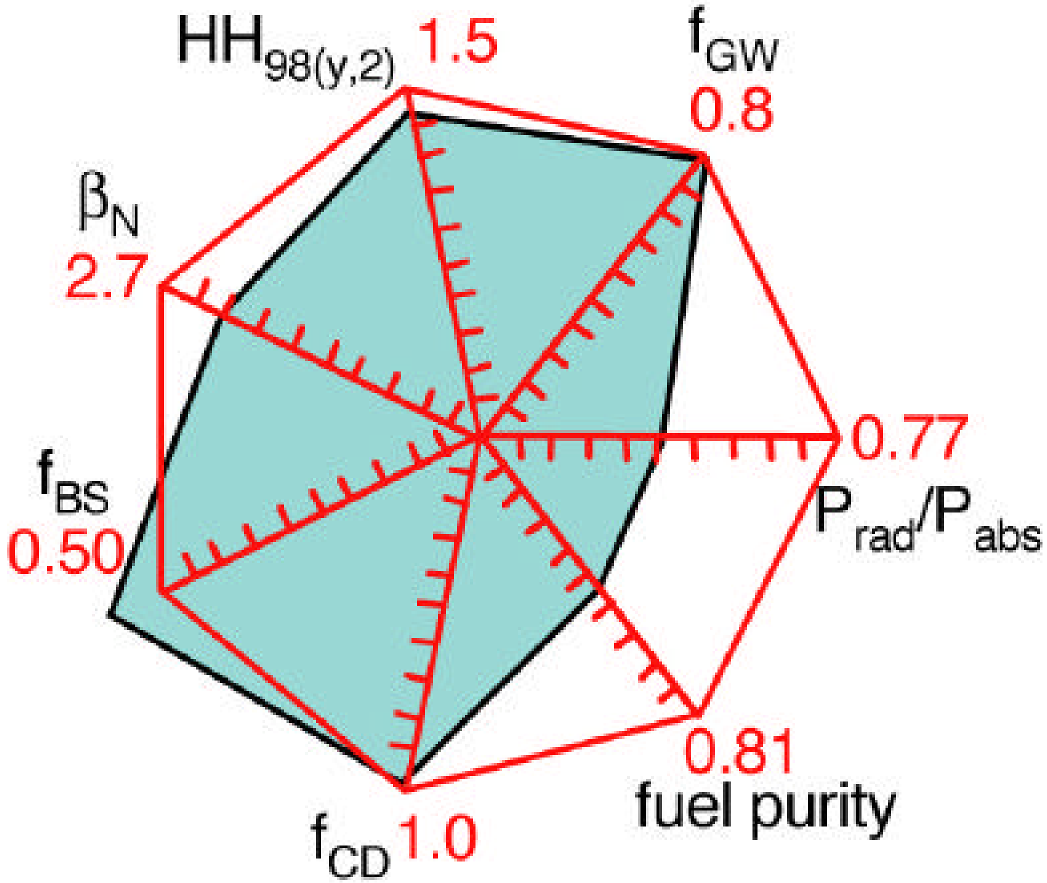
General Issues

- 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



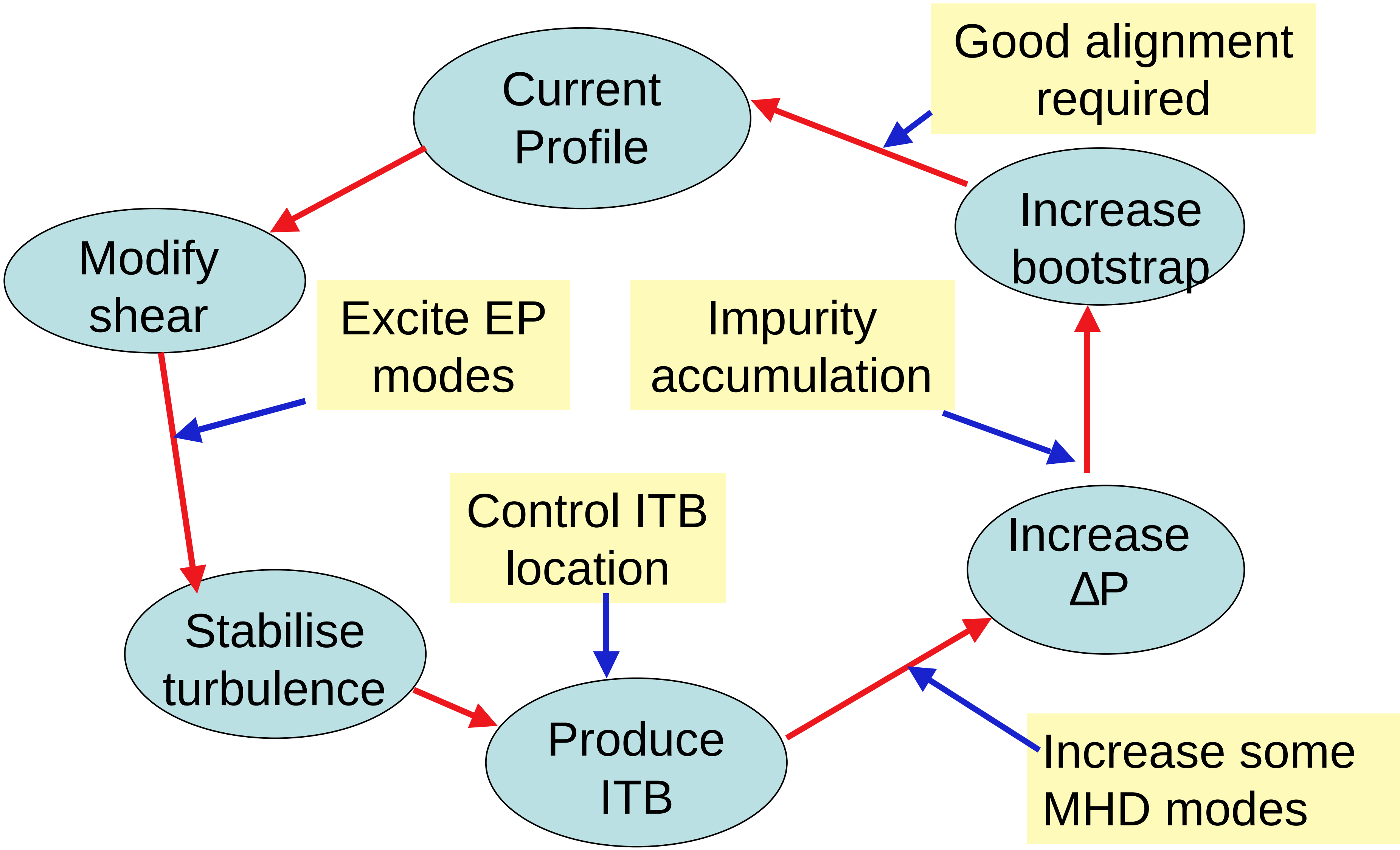
#E37964 0.9 MA, 2.5T, deuterium

- Missing
  - ELMs quality
  - q_{edge}
  - other dimensionless parameters: ν*, ρ*,…

Specific Aspects to Steady State Operation

- Core control
- Particle and impurity control
- MHD and beta limits
- Energetic Particles
- Pedestal control

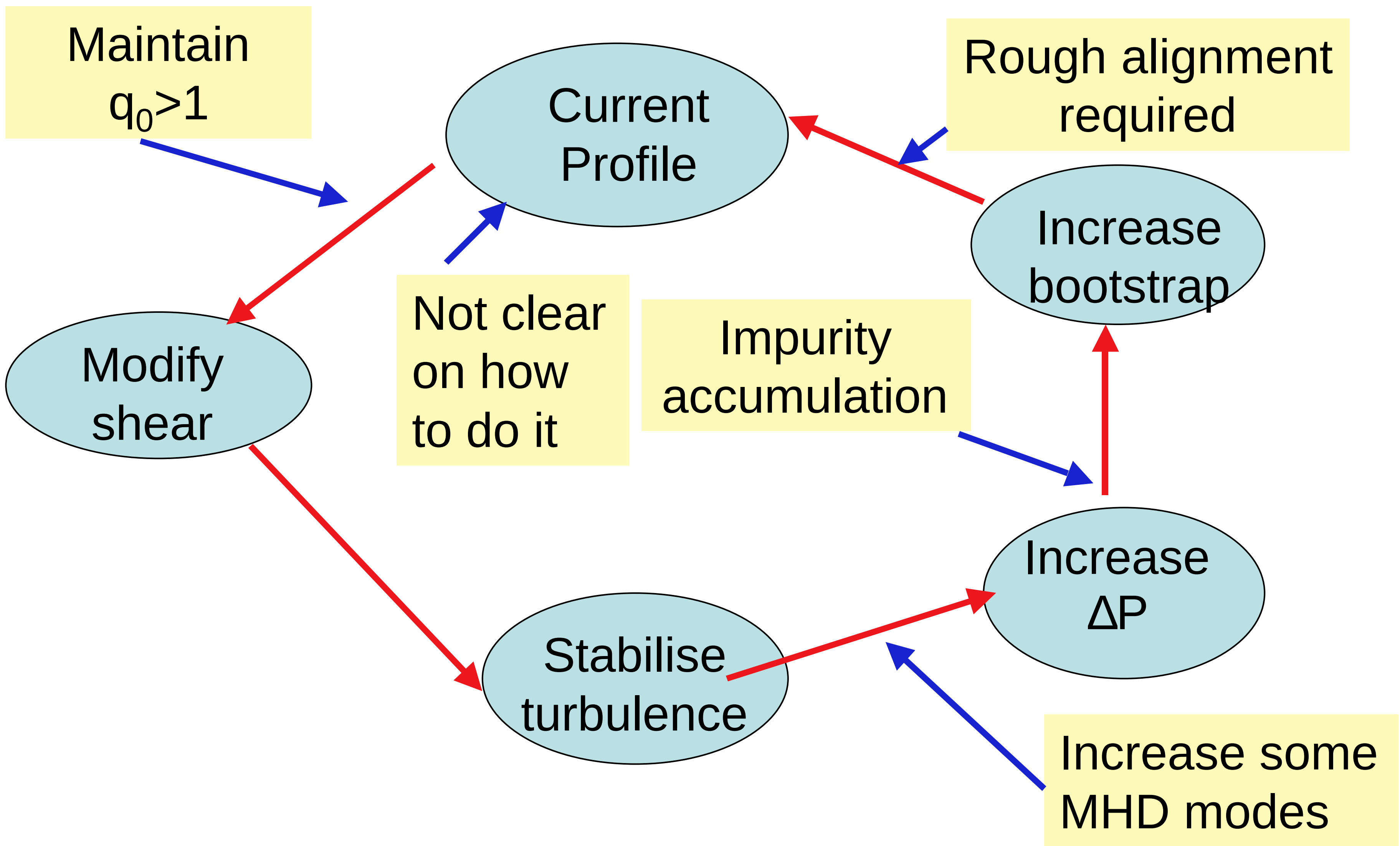
Complex core control for Steady State Scenarios with ITB



ITB control

- 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



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): $5 < \tau^*_P(He)/ \tau^{th}_E < 8$ (10 required for ITER)
    - Pumping required ?
    - Scenario dependent ?

MHD and beta limits

- By definition, steady state and hybrid scenarios have to operate at high β_N
- Domain of operation is limited by the various links between MHD limits, pressure gradients, bootstrap current and current profile
  - From mapping done in DIIID (T Luce), clear dependences of β_N have been established with :
    - ITB_{width}, ITB_{radius}, q_0, q_{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. 15th(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

Summary (1)

- 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