Challenges in
Operation and Control of ITER

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Synopsis

- **ITER goals, research planning and operational challenges**
- **Plasma scenarios and PF control issues**
  - ITER Plasma Control System
- **Power handling and transient heat load mitigation**
- **Control of magnetohydrodynamic instabilities**
- **Conclusions**

ITER Scope - Mission Goals

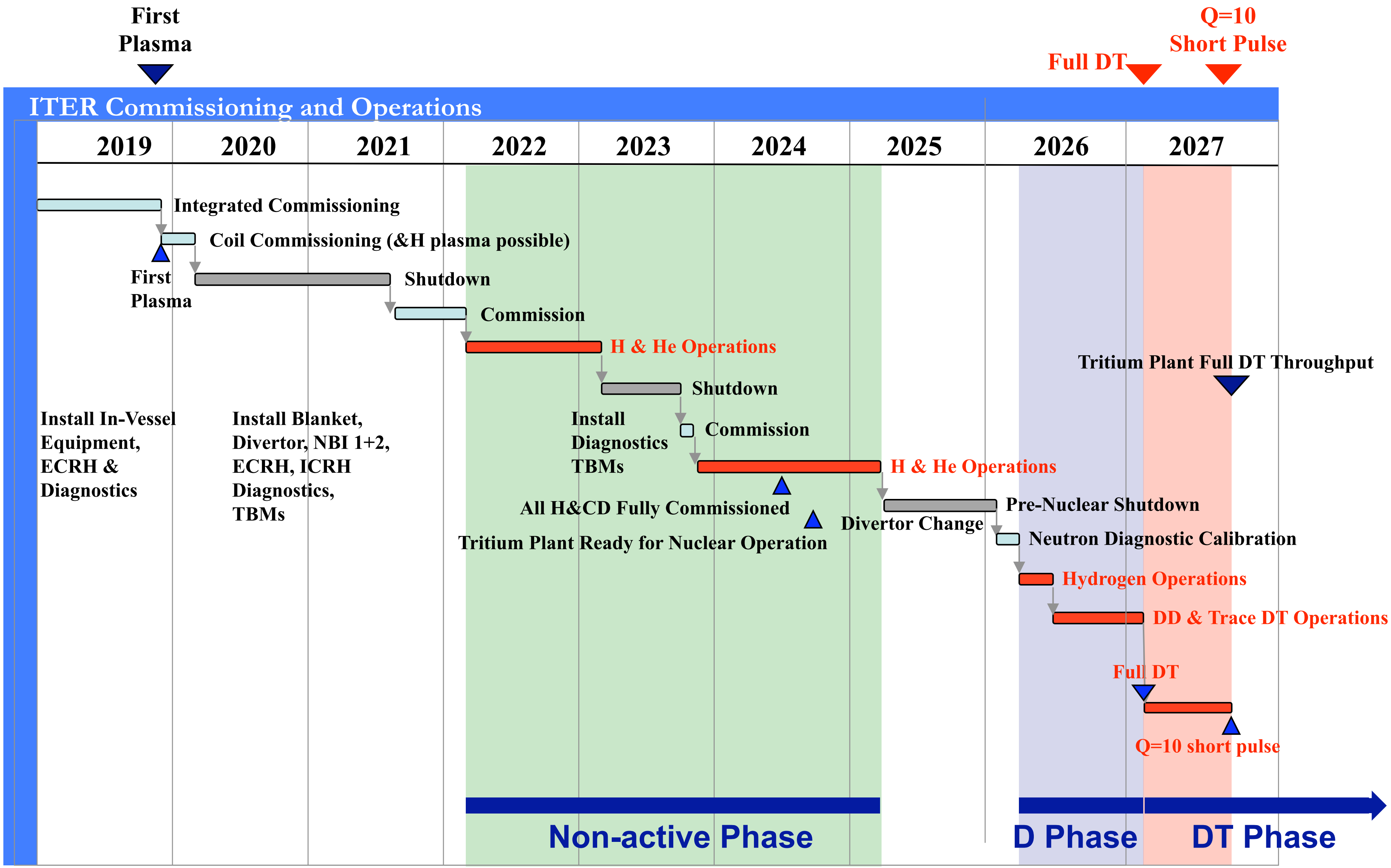
Physics:

- ITER is designed to produce a plasma dominated by α-particle heating
- produce a significant fusion power amplification factor ($Q \geq 10$) in long-pulse operation (300 – 500 s)
- aim to achieve steady-state operation of a tokamak ($Q \geq 5$/ $\leq$ 3000 s)
- retain the possibility of exploring 'controlled ignition' ($Q \geq 30$)

Technology:

- demonstrate integrated operation of technologies for a fusion power plant
- test components required for a fusion power plant
- test concepts for a tritium breeding module

ITER Experimental Schedule to DT



ITER Reference Scenarios

- The set of DT reference scenarios in ITER is specified via illustrative cases in the *Project Requirements*:

Parameter	1. Inductive operation	2. Hybrid operation	3. Non-inductive operation
R/a (m/m)	6.2 / 2.0	6.2 / 2.0	6.35 / 1.85
Toroidal field, B_T (T)	5.3	5.3	5.18
Plasma current, I_P (MA)	15.0	13.8	9.0
Elongation, κ_x/κ_{95}	1.85 / 1.7	1.85 / 1.7	2.0 / 1.85
Triangularity, δ_x/δ_{95}	0.48 / 0.33	0.48 / 0.33	0.6 / 0.4
Fusion power, P_{fus} (MW)	500	400	356
P_{add} (MW)	50	73	59
Energy multiplication, Q	10	5.4	6
Burn time (s)	300 - 500	1000	3000
Minimum repetition time (s)	1800	4000	12000
Total heating power, P_{TOT} (MW)	151	154	130
L-H transition power, P_{L-H} (MW) (note 1)	76	66	48
Plasma thermal energy, W_{th} (MJ)	353	310	287
Maximum fuelling input ($Pa\text{-}m^3/s$)	200	160	120

- In addition, a range of non-active (H, He) and D plasma scenarios must be supported for commissioning purposes to support rapid transition to DT operation

ITER Plasma Scenarios – Control Challenges

• **Inductive scenarios:**

Single confinement barrier

- ELMy H-mode:
  - reliable position/ shape control in end-to-end scenario (~600 s)
  - robust vertical position control
  - error field correction
  - ELM mitigation
  - kinetic control (density control, fusion burn control …)
  - exhaust power dissipation via radiative divertor
  - neoclassical tearing mode (NTM) suppression
  - disruption/ VDE/ RE mitigation
- Hybrid – additional:
  - maintain Q≥5 for up to ~2000 s
  - current profile control for enhanced confinement/ stability

• **Advanced scenarios:**

Multiple confinement barriers

- Steady-state - additional:
  - sustain scenario with Q≥5 for up to 3000 s
  - drive non-inductive currents to maintain:
    - 100% current drive
    - internal transport barrier and MHD stability
    - self-consistent equilibria
  - resistive wall mode (RWM) suppression

How can we control the plasma?

- **There are several "actuators" which can influence the plasma behaviour:**
  - magnetic geometry: changing the plasma equilibrium shape
  - plasma heating
  - injecting current – changing the current profile
  - rotation – injecting torque
  - fuelling – injecting particles (even impurities)
- **Detailed measurements (Diagnostics) of plasma parameters and an understanding of the influence of actuators on these parameters is required to provide the required control capability**
- **Over the years we have learned how to use these tools to expand the range of plasma scenarios which we can exploit**
  - in ITER must integrate all functionalities simultaneously with limited actuator set and integrate 'event handling' to provide robust operational framework

Heating the ITER Plasma

Heating System	Stage 1	Possible Upgrade	Remarks
NBI (1MeV –ive ion)	33	16.5	Vertically steerable (z at R_{tan} -0.42m to +0.16m)
ECH&CD (170GHz)	20	20	Equatorial and upper port launchers steerable
ICH&CD (40-55MHz)	20	20	$2\Omega_T$ (50% power to ions Ω_{He3} (70% power to ions, FWCD)
LHH&CD (5GHz)		20	$1.8<n_{par}<2.2$
Total	73	130 (110 simultan)	Upgrade in different RF combinations possible
ECRH Startup	>2		170GHz
Diagnostic Beam (100keV, H^-)	>2		

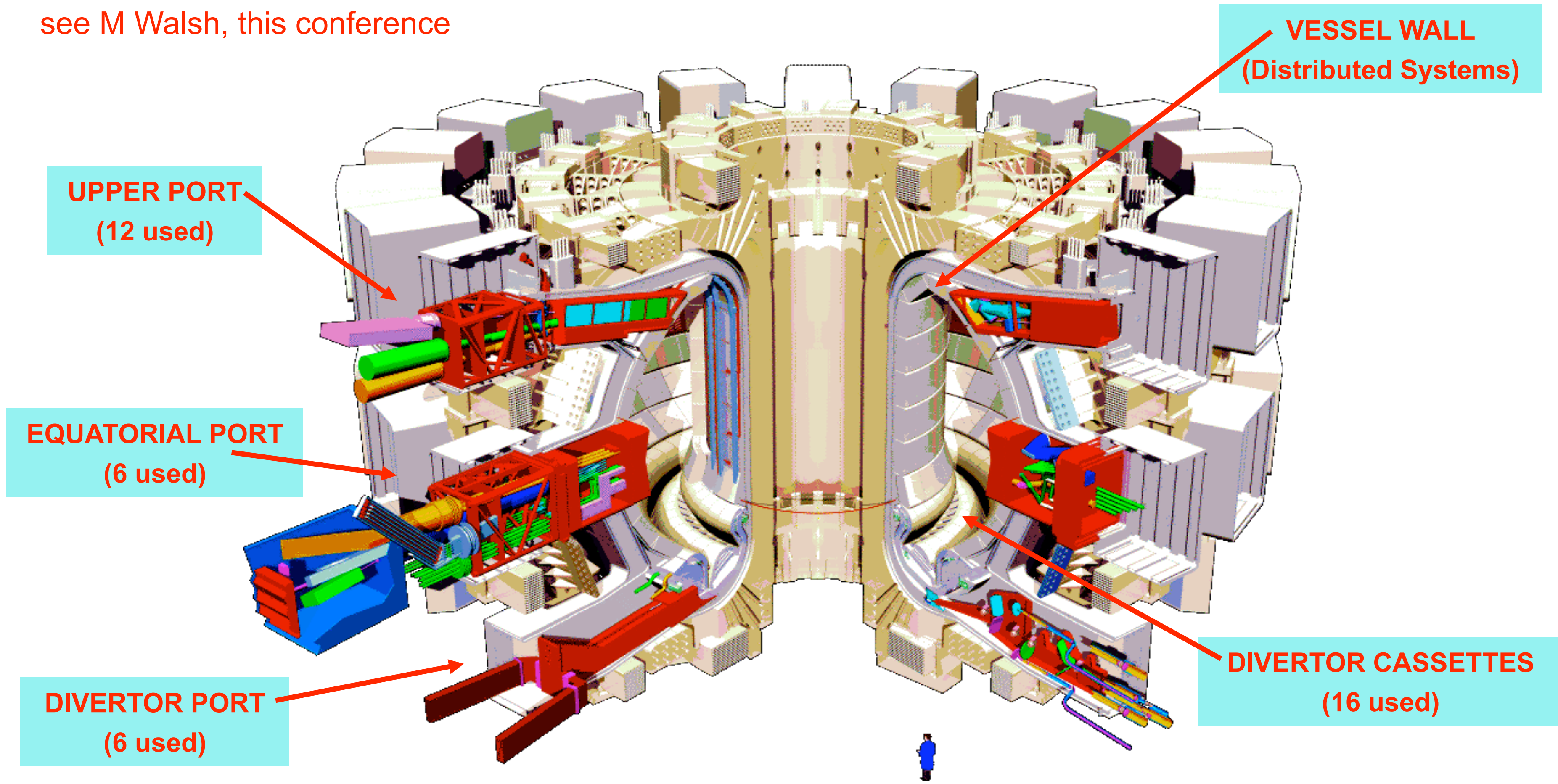
- **ITER's H&CD capability and upgrade options support:**
  - range of functionality
  - plasmas in H, He, D, DT

P_{aux} for Q=10 nominal scenario: 40-50MW

see P R Thomas, this conference
F Wagner et al, IAEA-FEC2010, ITR-1-2

Analyzing the Plasma - ITER Diagnostics

see M Walsh, this conference



- **About 40 large scale diagnostic systems are foreseen:**
  - Diagnostics required for protection, control and physics studies
  - Measurements from DC to γ-rays, neutrons, α-particles, plasma species
  - Diagnostic Neutral Beam for active spectroscopy (CXRS, MSE ….)

ITER Plasma Control System

PCS Architecture

system supervisor, cross-coupling, smooth transitions …

Wall Conditioning

ICWC, ECWC …

Axisymmetric Magnetic Control

plasma initiation, position current & shape, vertical position

Kinetic Control

power handling, non-inductive current, fusion burn …

Non-axisymmetric Control

NTMs, RWMs, ELMs, error field correction …

Disruption and Event Forecasting

prediction of disruptions, plasma transitions and events

Event Handling

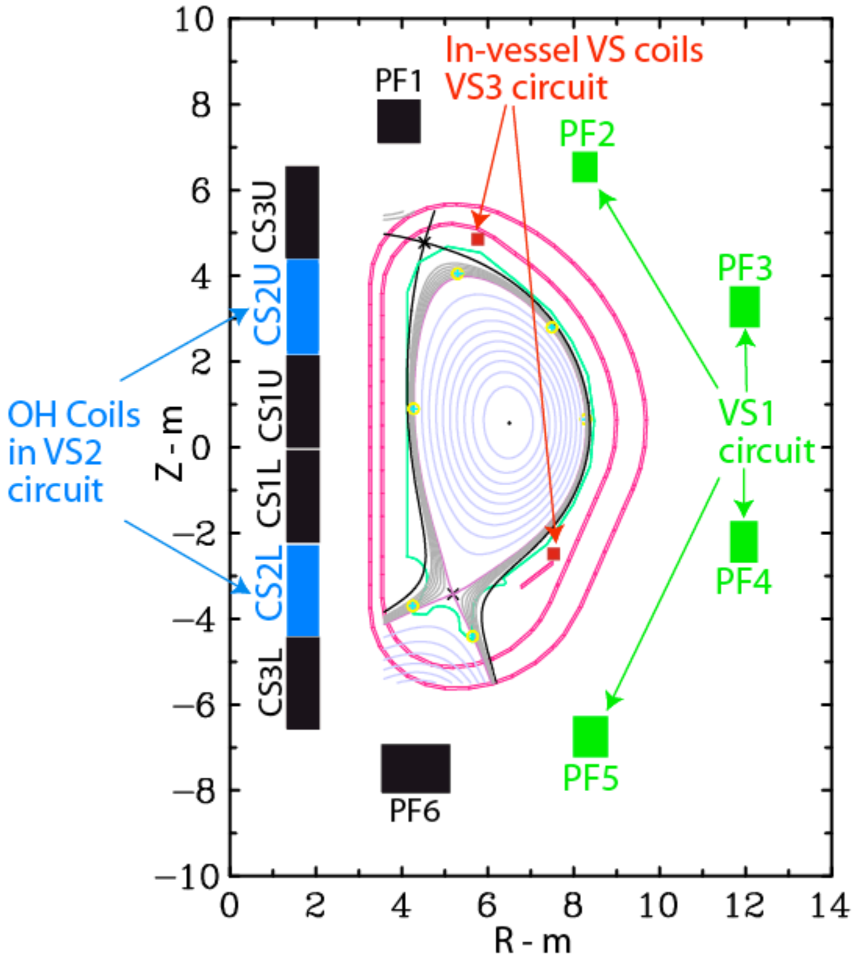
adaptive control, incl disruption mitigation

Plasma Control in ITER

- **Controlling a burning plasma in ITER will require an extensive set of control functions based on available measurement systems and actuators:**
  - Plasma equilibrium control: (routine and robust)
    - plasma shape, position and current
  - Basic plasma parameter control: (routine and robust)
    - plasma density
  - Plasma kinetic control: (ongoing research)
    - fuel mixture, fusion power, radiated power …
  - Control for advanced operation: (ongoing research)
    - current profile
  - Control of magnetohydrodynamic instabilities: (ongoing research)
    - several key MHD instabilities
- **All of these elements have been developed and demonstrated to varying extents in existing tokamak devices:**
  - integration and routine/ reliable operation required

Plasma Equilibrium Control

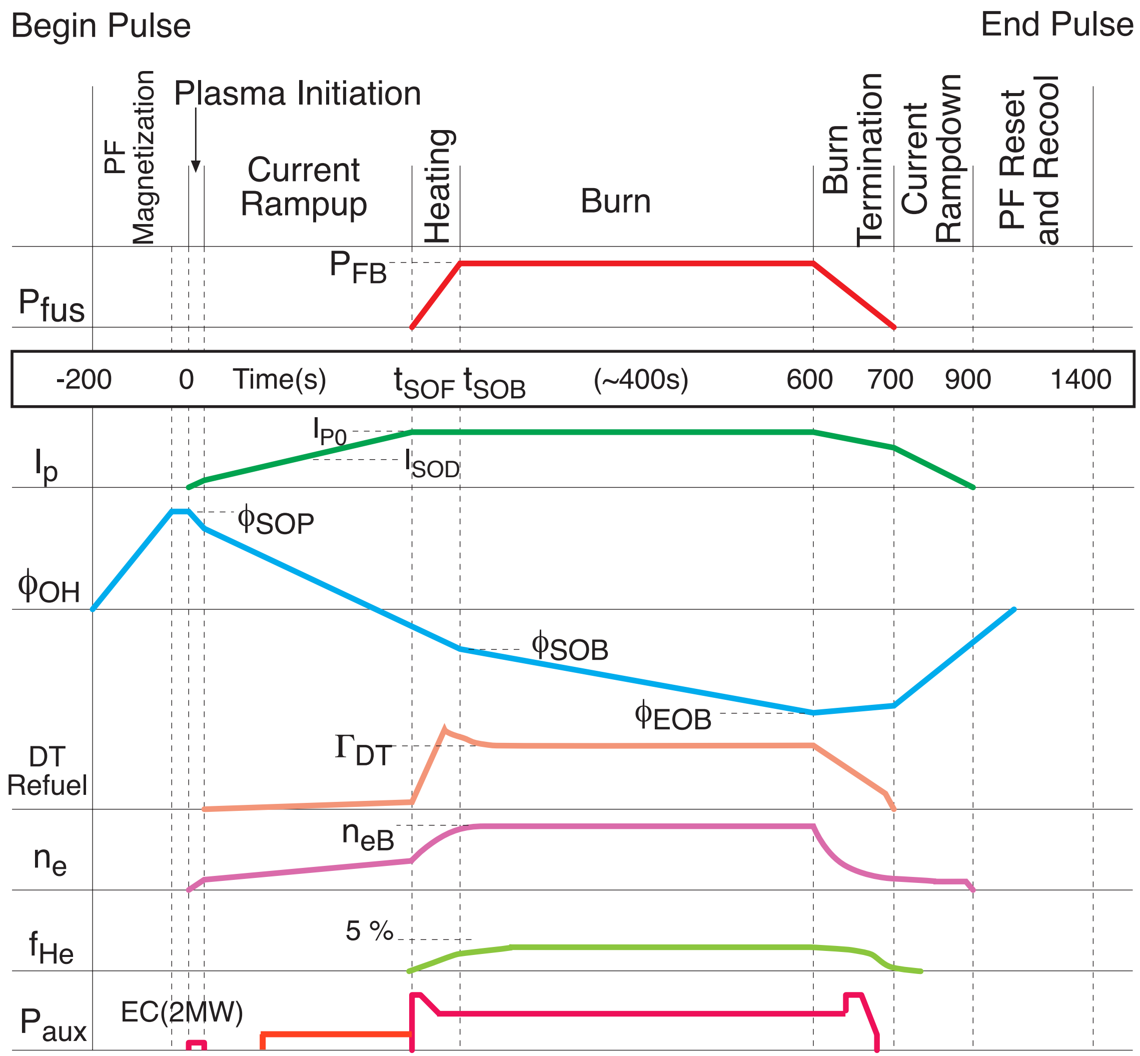
ITER PF layout



- **Plasma equilibrium control is routine in existing devices:**
  - based on magnetic sensors which provide signals to reconstruct plasma boundary or equilibrium
  - In ITER, care must be taken in developing scenario:
    - respect plasma-wall clearances
    - avoid coil current saturation
    - minimize flux consumption during current ramp-up
    - maintain plasma position control during transients
    - maintain vertical stability during current ramp-down
  - very long pulses require particular care to avoid drifts in magnetic diagnostic signals

15MA Inductive Scenario - Schematic

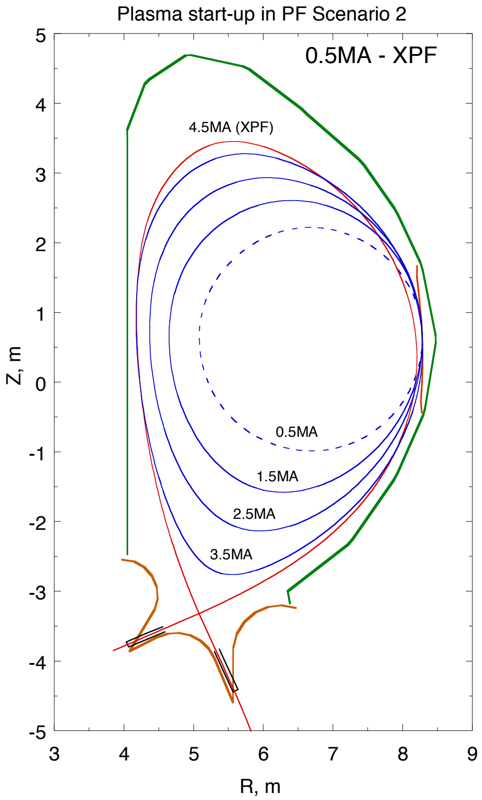
- **Typical 15MA Q=10 inductive scenario has:**
  - current ramp-up phase of 70-100s
  - heating phase of ~50s
  - burn phase of 300-500s
  - shutdown phase of 200-300s
- **Typical pulse repetition time ~1800s**
  - based on burn duty cycle of 25%

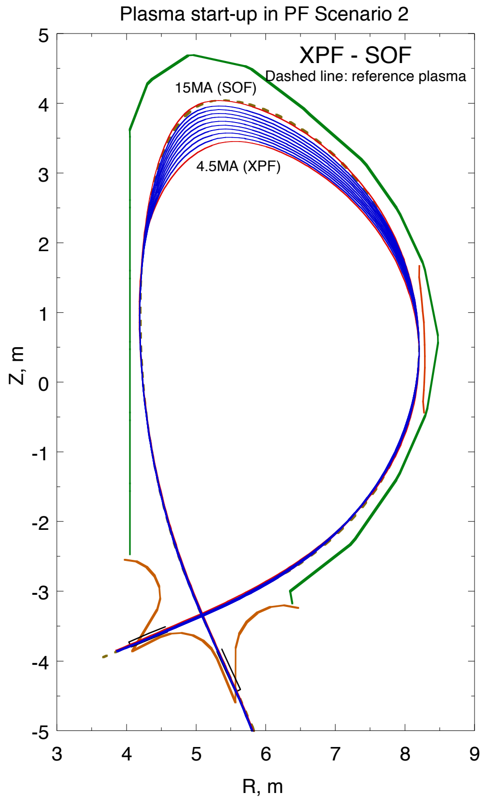


ITER Plasma Scenario: Q =10 H-mode

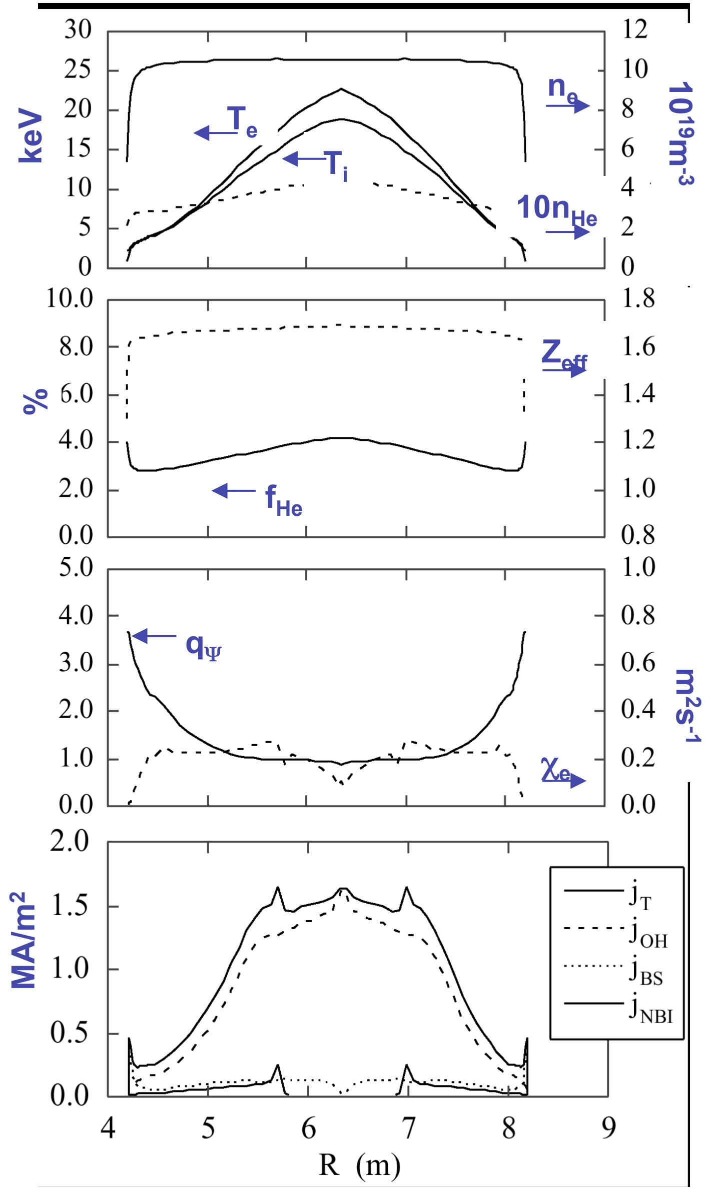
A Q=10 scenario with:

I_p=15MA, P_{aux}=40MW, $H_{98(y,2)}$=1





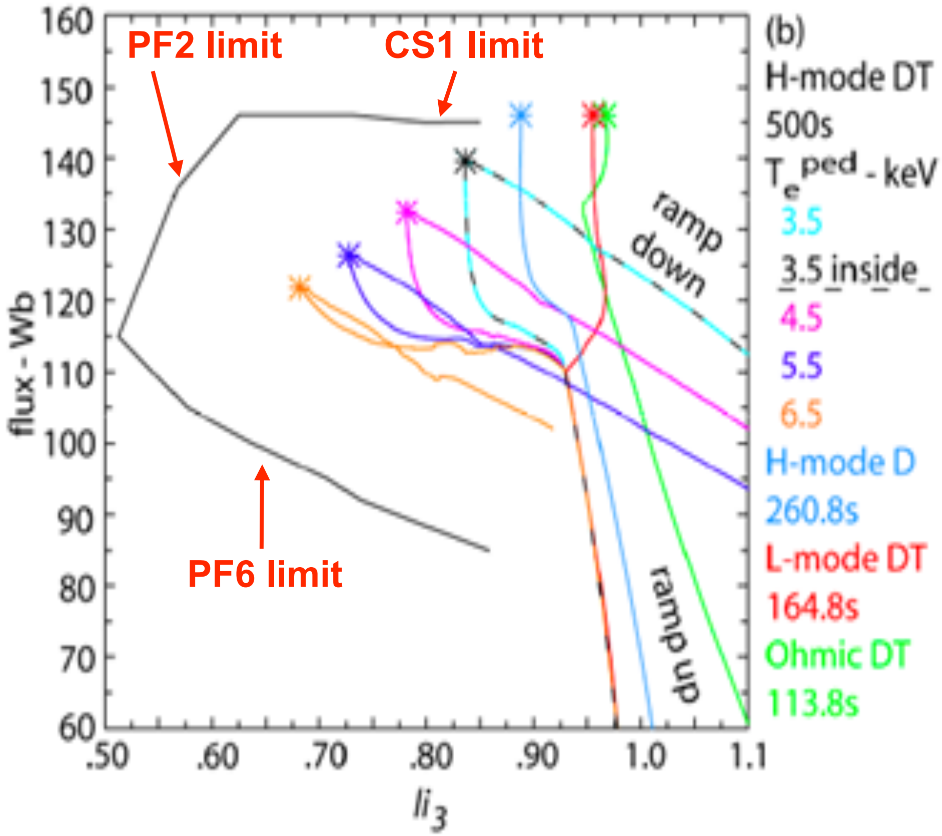
Current Ramp-up Phase



Flux Consumption in ELMy H-mode

- **Optimization of magnetic flux consumption is key issue for long-pulse operation in ITER:**
  - several limits must be respected in scenario development:
    - PF/CS coil current and field limits
    - saturation of PF6 ("divertor") and PF2 coils at low values of l_i
    - consumption of excessive magnetic flux during ramp-up at high l_i
    - Central Solenoid force limits
  - a wide range of scenarios has now been developed for 15MA operation in non-active and DT phases of operation, allowing up to 500 s burn duration

T Casper: CORSICA simulation



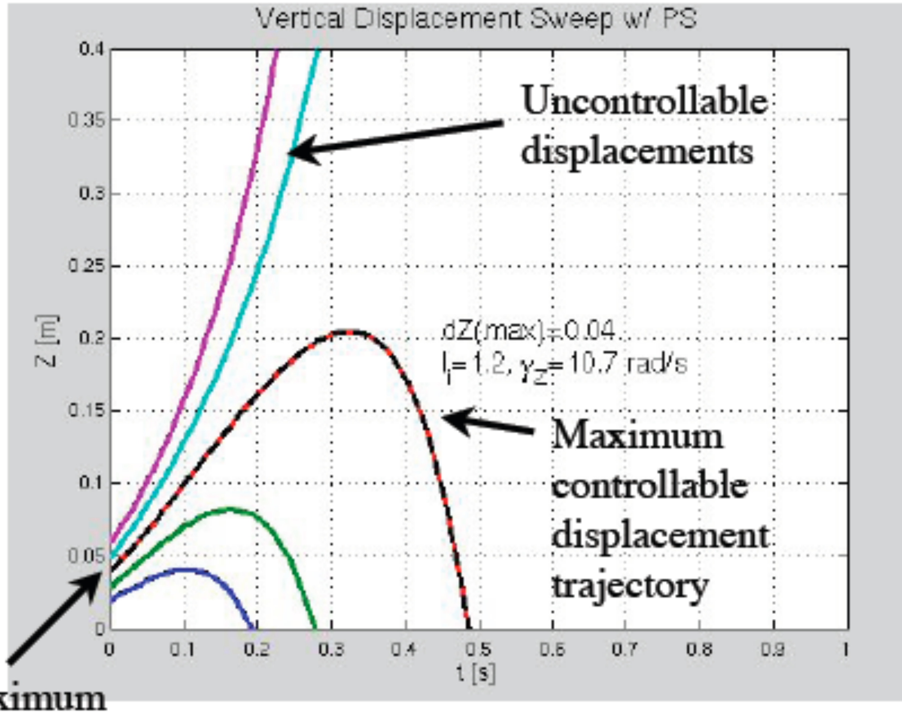
T Casper et al, IAEA-FEC2010, ITR-P1-19

Vertical Stabilization Performance

- **Performance of VS system characterized by ΔZ_{max}**
  - maximum controllable "instantaneous" vertical displacement
- **Experiments suggest that:**
  - $\Delta Z_{max}/a > 5\%$ is "reliable"
  - $\Delta Z_{max}/a > 10\%$ is "robust"
- **For "worst case" conditions ($l_i(3) = 1.2$), original ITER system:**
  - $\Delta Z_{max}/a = 2\%$
  - large overshoot in ΔZ due to vessel time constant

D Humphreys et al, IAEA-FEC2008, IT-2-4b
A Portone et al, IAEA-FEC2008, IT-2-4a

Example of Analysis and Gedanken Experiment to Calculate ΔZ_{max}



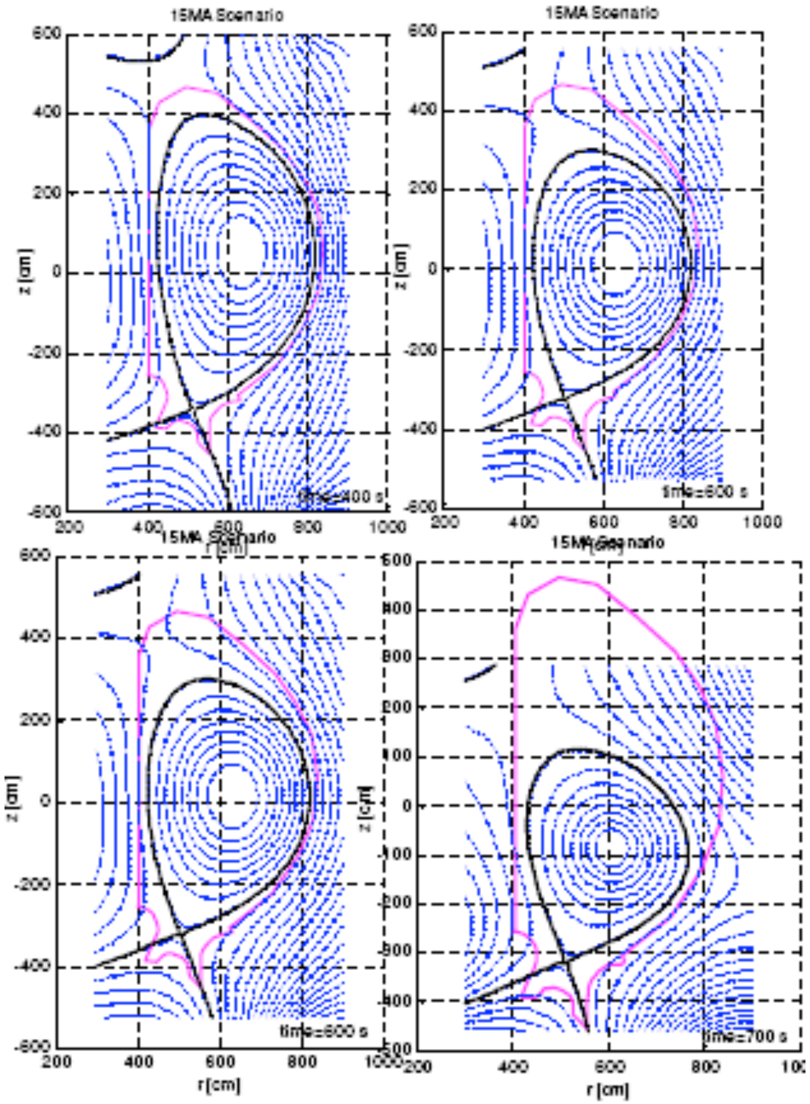
Maximum controllable displacement ΔZ_{max}=0.04 m

⇒ Internal coils for vertical stabilization to meet requirements

Equilibrium Control – Current Ramp-Down

- **Termination of fusion burn and current rampdown is demanding in ITER:**
  - particularly challenging in case of unplanned H-L transition
  - scenarios have been developed to deal with planned and unplanned H-L transitions:
    - CS provides additional capability for radial position control
    - elongation reduction during current ramp-down is key to successful plasma termination
    - reliable vertical stability control has been demonstrated using this strategy
  - approach to H-mode termination and ramp-down confirmed in several tokamak experiments

A A Kavin, V E Lukash: DINA simulation



Power and Particle Exhaust

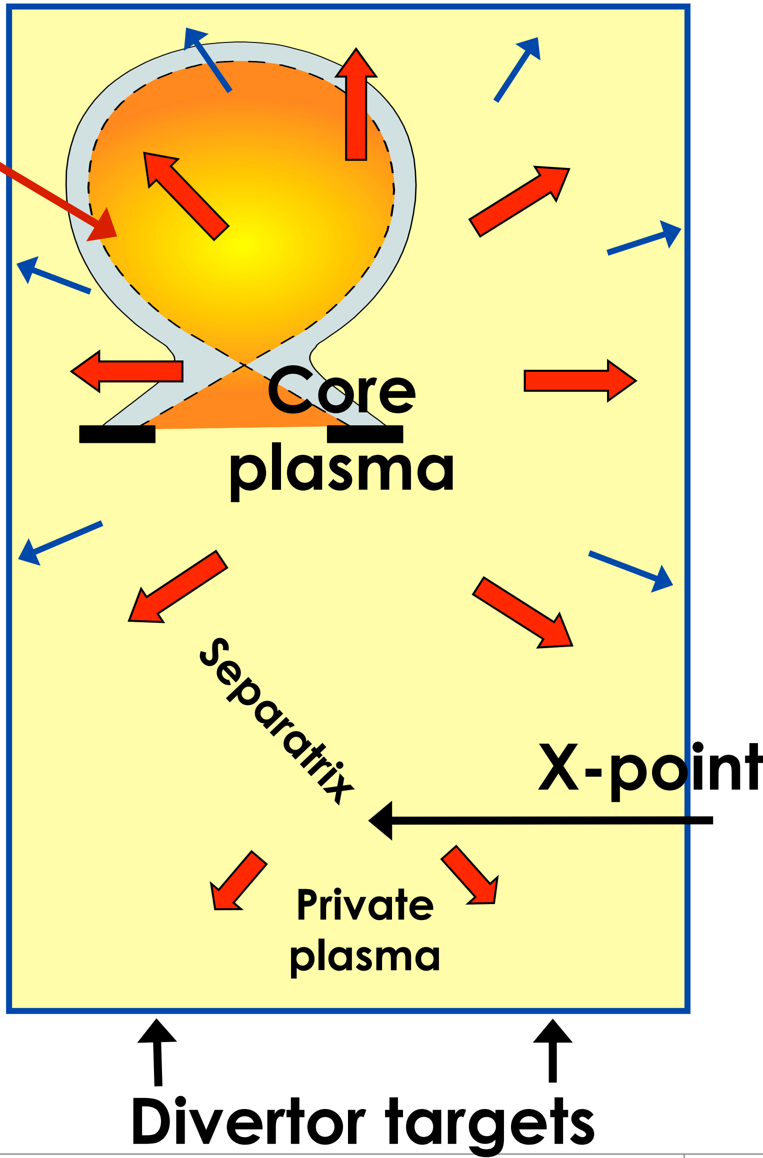
see S Lisgo, this conference

Scrape-off layer (SOL) plasma: region of open field lines

- **Essential problem is:**
  - handle power produced by plasma with (steady-state) engineering limit for plasma facing surfaces of 10 MWm^{-2}
  - extract helium from the core plasma to limit concentrated below ~6%
  - prevent impurities from walls penetrating into plasma core
  - ensure plasma facing surfaces last sufficiently long

  ⇒ **Use injected impurities to radiate a sufficiently large fraction of the exhaust power – radiative divertor/ partial detachment**

  ⇒ **Limit transient heat loads**



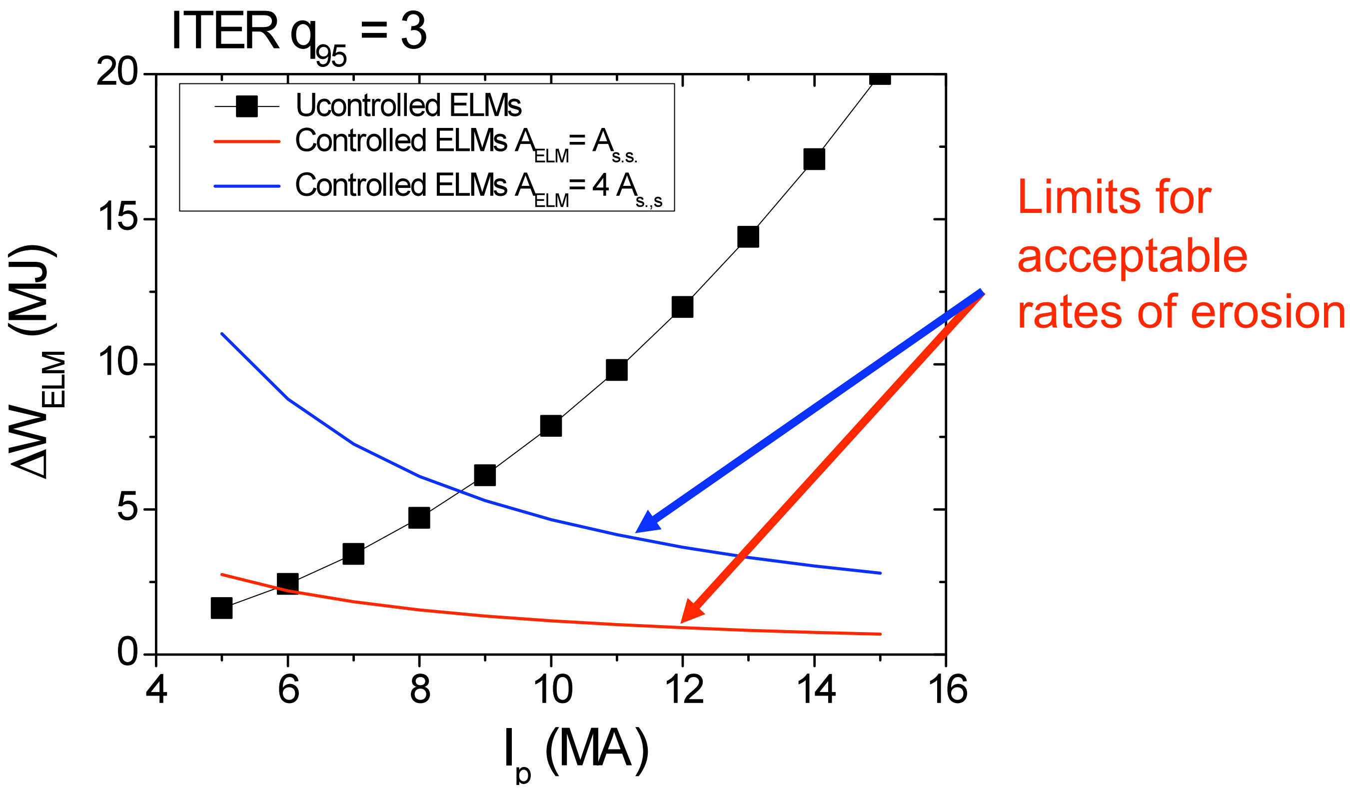
Control of MHD Stability

- **To assure reliable operation near stability boundaries, ITER is planning to implement several MHD control and mitigation methods:**
  - Error field correction: set of 18 external coils allows correction of multi-mode error fields to below the expected level at which MHD modes can grow
  - ELM correction: set of 27 internal resonant magnetic perturbation (RMP) coils plus a pellet injection system is designed to reduce transient heat loads below acceptable level
  - Disruption/ vertical displacement event / runaway electron mitigation: massive material injection will be used to mitigate heat and electromagnetic loads as well as to suppress runaway electrons
  - Neoclassical tearing modes: 4 steerable ECRH launchers in the upper ports allow control of (3,2) and (2,1) NTMs via localized current drive – sawtooth control is also foreseen as a technique for avoiding NTMs
  - Resistive wall modes: set of 27 RMP coils will also allow control of RWMs
- **Continued support from physics R&D programme is needed to optimize use of these control/ mitigation systems in ITER**

Uncontrolled ELMs Operation limited to: $I_p \leq 6$ - 9MA

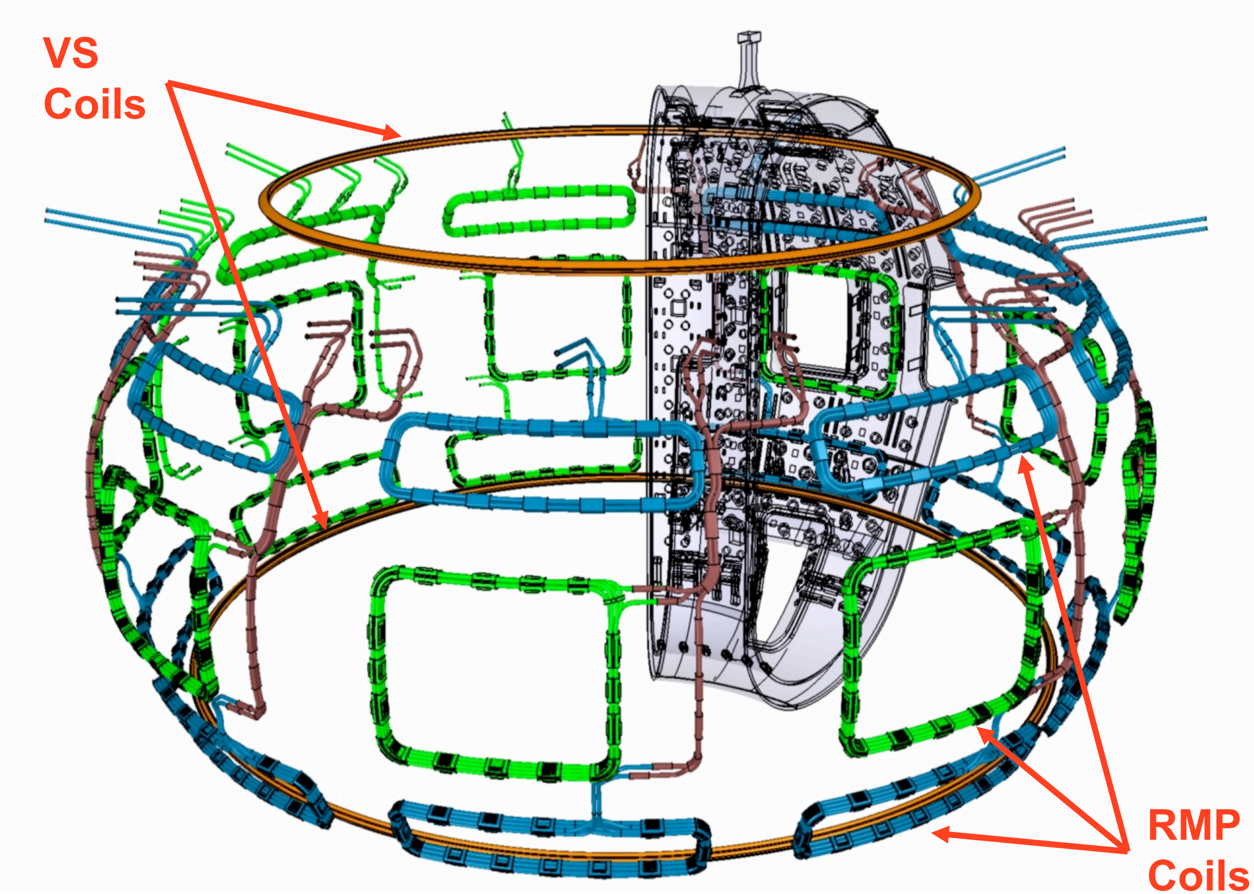
- **In ITER, uncontrolled ELM operation with low erosion possible up to I_p = 6.0–9.0 MA depending on $A_{ELM}(\Delta W_{ELM})$**

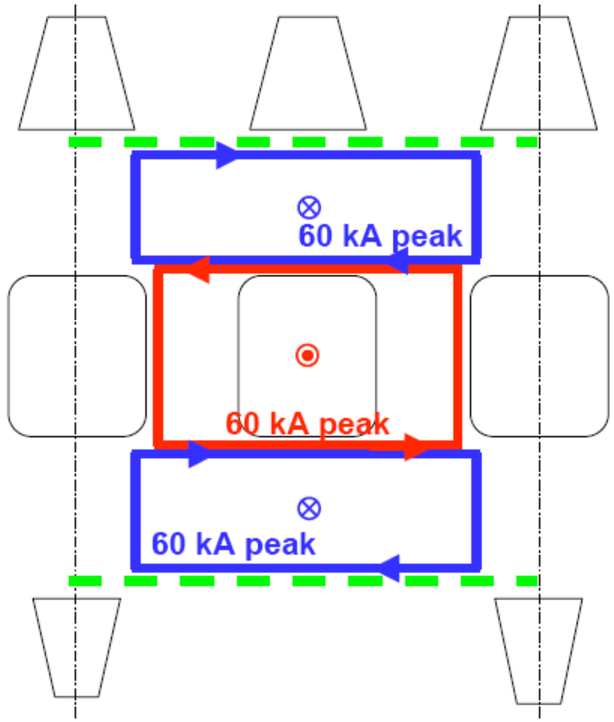
  ⇒ Mitigation of heat loads by factor of 10-20 required



A Loarte et al, IAEA-FEC2010, ITR-1-4

ELM Control via In-Vessel Coils

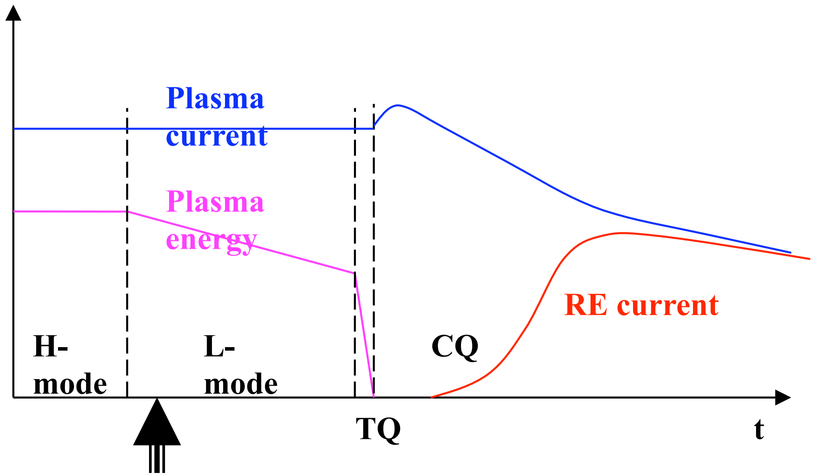




- **A set of resonant magnetic perturbation (RMP) coils under design:**
  - consists of 9 toroidal x 3 poloidal array on (outboard) internal vessel wall

Disruptions, VDEs, Runaway Electrons

S Putvinski et al, IAEA-FEC2010, IT-1-6



Typical chain of events during plasma disruption

Disruption/ VDE/ RE mitigation is essential for reliable operation of ITER

⇒ Massive material injection (MMI) is the most likely solution

- **Most serious thermal loads occur during Thermal Quench**

  ⇒ need to reduce by factor of at least 10 to limit impact on PFCs

- **Major mechanical forces act on VV and PFCs during Current Quench ⇒ eddy currents, "halo" currents**

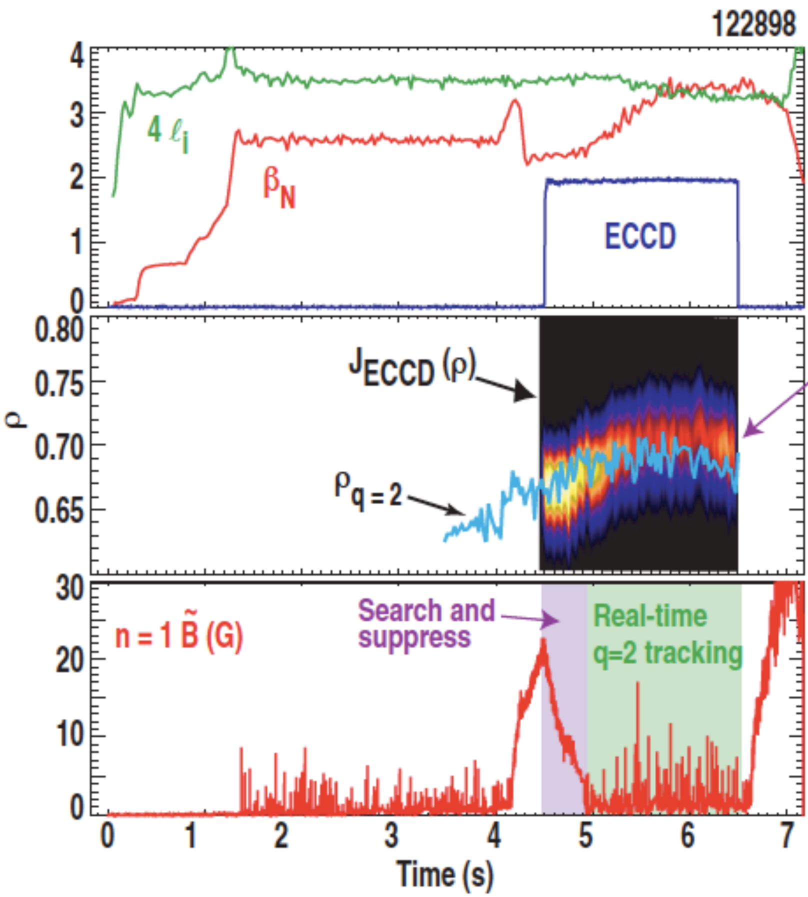
  ⇒ need to reduce by factor of at 2-3 to improve load margins

- **Runaway electrons can be generated during Current Quench**

  ⇒ need to reduce intensity and energy factor of at least 10

Control of Neoclassical Tearing Modes

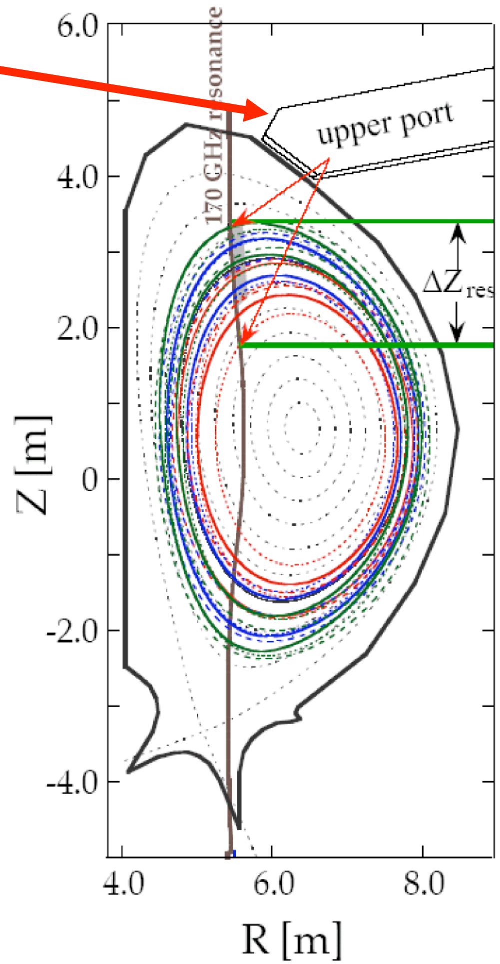
- **An MHD instability is detected (magnetically, SXR, ECE …):**
  - localized electron cyclotron current drive is used to suppress the instability
  - ITER has 4 steerable upper ECH&CD launchers launching 20 MW



M R Wade et al, FEC-2006, OV1-4

DIII-D

ECCD deposition location controlled by moving 2nd harmonic resonance

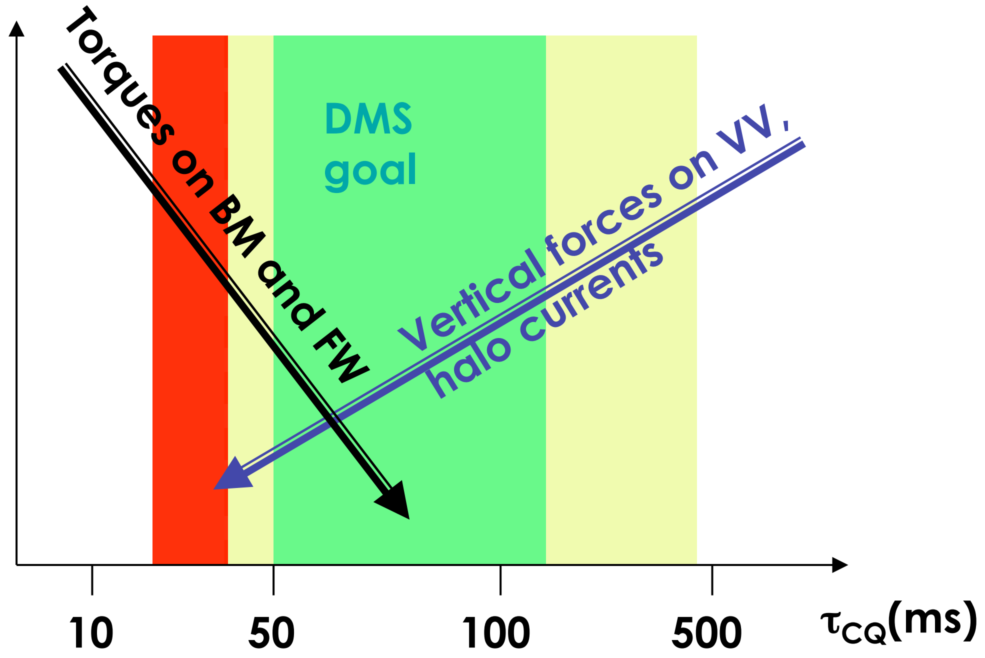


Conclusions

- **ITER is planning an ambitious programme of physics and technology R&D ranging across accessible burning plasma scenarios:**
  - ELMy H-mode inductive, “hybrid” and steady-state scenarios provide a reference basis for the tokamak design and the planning of exploitation
  - flexibility in device design and auxiliary systems provide scope to adapt research programme in response to ongoing R&D within fusion programme
- **Challenges in operation and control of ITER plasmas arise from:**
  - integrated control requirements to support operation over a range of plasma scenarios at high fusion gain
  - scale and parameter range of ITER plasmas which give rise to new demands in power handling, mitigation of transient heat fluxes etc
- **ITER challenges open many opportunities for exciting and innovative R&D in existing fusion experiments:**
  - we need to turn many of the “demonstration” control concepts currently being explored into robust techniques for routine control of ITER plasmas

Back-Up Slides

Forces constrain maximum amount of injected gas

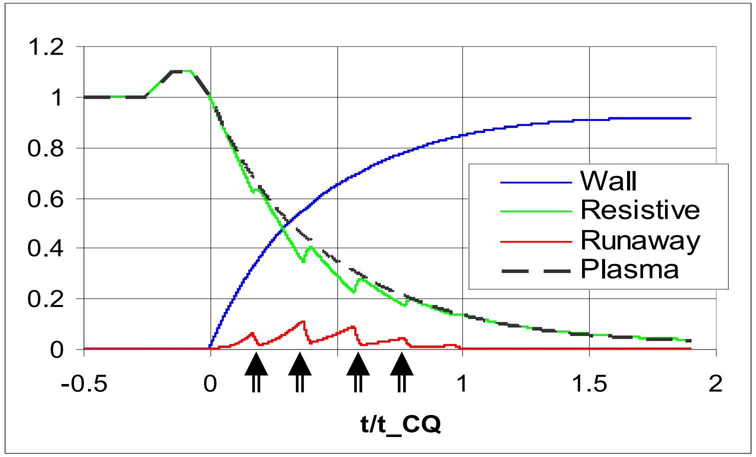


First tritium confinement barrier

- **Forces:**
  - Halo currents due to VDE dominate vacuum vessel forces – produce vertical and horizontal forces (JET data essential here)
  - Eddy currents due to current decay ultimately dominate forces on blanket and first wall ⇒ current quench time cannot be too short
- **Optimization of MGI involves striking a balance between these effects, while ensuring sufficiently high radiation**

Runaway electrons must be suppressed in ITER

- Massive runaway electrons can be produced during Current Quench of plasma disruptions in ITER. They must be suppressed by Disruption Mitigation System



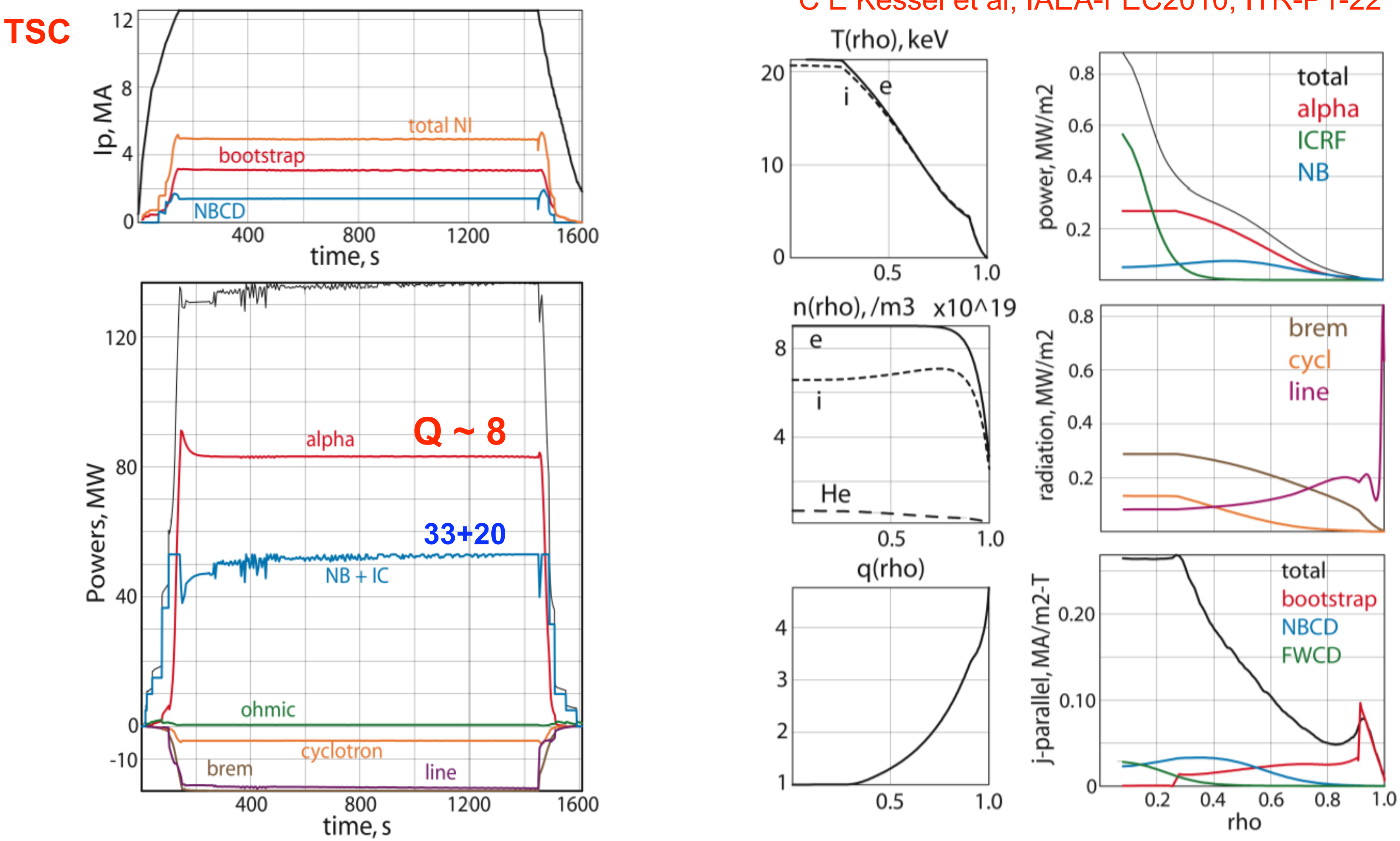
Modeling of CQ with repetitive gas injection show suppression of RE current at ~1 MA

- **A new scheme based on injection of dense gas jets in Current Quench plasmas could allow reduction of RE current to a tolerable level at a reduced amount of gas**

S Putvinski et al, IAEA-FEC2010, IT-1-6

End-to-End Hybrid Scenario

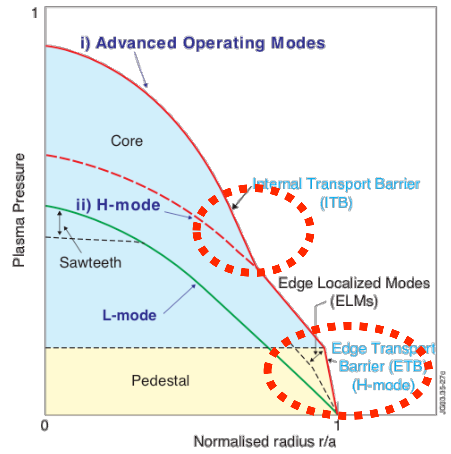
C E Kessel et al, IAEA-FEC2010, ITR-P1-22



- **Improved H-mode hybrid with burn duration of ~1300 s at I_p = 12 MA, H_{98} = 1.25, P_{aux} = 33 MW NB + 20 MW IC**

Steady-State Operation

- **Discovery of internal transport barriers ⇒ "advanced scenarios"**



plasma with reversed central shear + sufficient rotational shear

internal transport barrier
⇒ enhanced confinement

reduced current operation +
large bootstrap current fraction

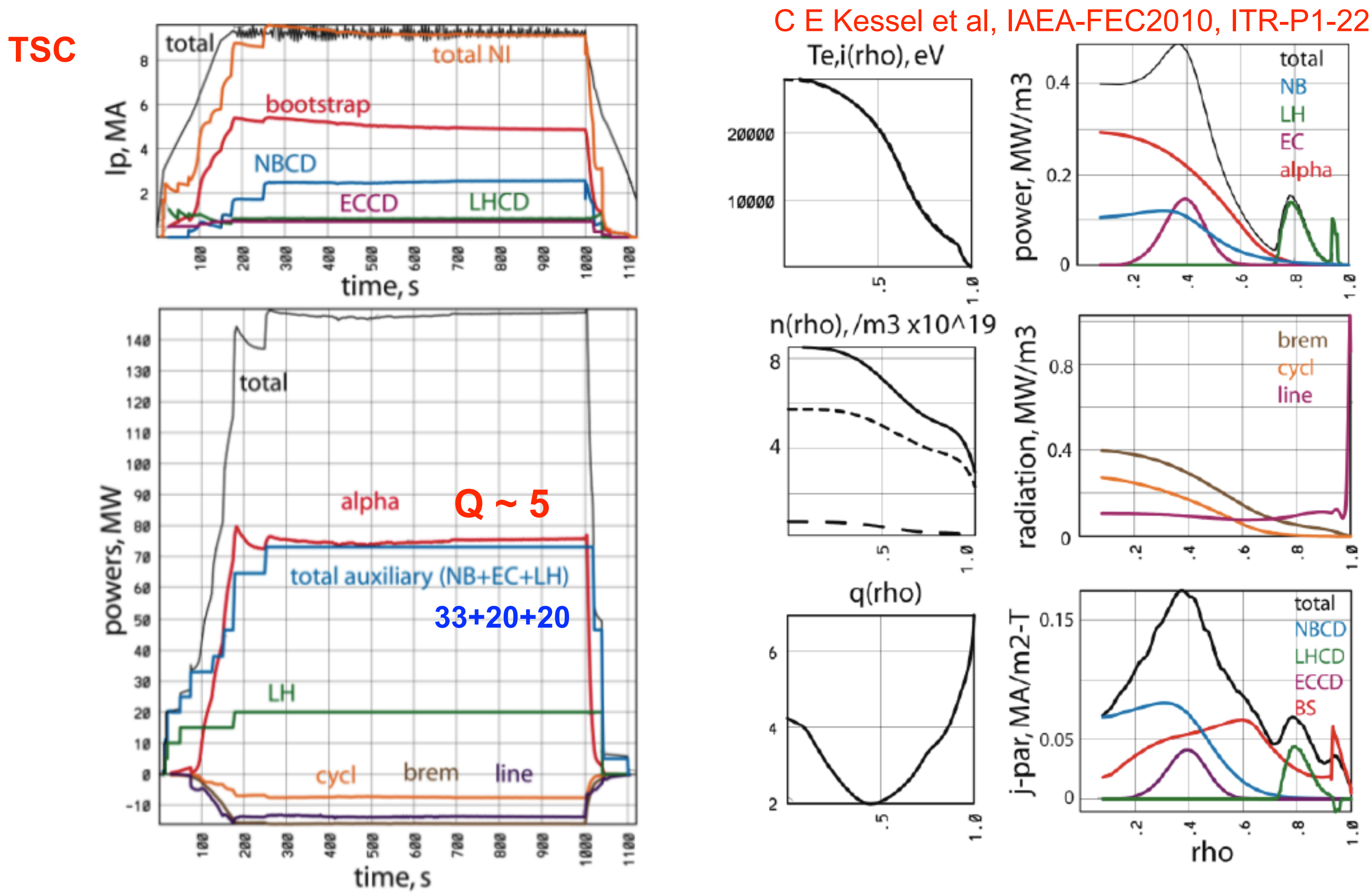
active mhd control

reduced external current drive +
current well aligned for mhd stability and confinement enhancement

Steady-state operation +
High fusion power density

- **But development of an integrated plasma scenario satisfying all reactor-relevant requirements remains challenging**

End-to-End Steady-State Scenario



- **Fully non-inductive steady-state scenario at I_p = 9.25 MA, H_{98} = 1.7, β_N = 2.8, P_{aux} = 33 MW NB + 20 MW EC + 20 MW LH**