Progress & Challenges of CW operation

LHD

ITER
The challenge:
At reactor parameters (beta, n, H factor),
demonstrate and optimize:

– Burning plasmas
  • ITER after >2020

– Operation in CW or QCW (quasi CW, pulsed with high duty cycle)
  • LHD, TS, East, KSTAR, ST1, W7x + …but no QCW Tokamaks foreseen; When? rapid progress is essential!
“Steady-state” refers to a particular physics timescales

On present devices, it often refers to the Energy confinement time, sometimes to the current diffusion time

**CW demonstration requires:** $t > \text{largest time scales}$

They are set by erosion, deposition, flake formation

$\sim$ several hours
How?

• What counts is the engineering $Q_{\text{eng}}$

\[
Q_{\text{eng}} = \frac{P_{\text{fus}}}{(P_{\text{aux}} + P_{\text{inj}}) / \eta}
\]

\[
= \eta Q / (1 + \eta P_{\text{aux}} / P_{\text{inj}}) \quad \text{with } Q = P_{\text{fus}} / P_{\text{inj}}
\]

ITER:

$\eta < 0.5$; $P_{\text{aux}} \sim 200$ MW (cryoplant, pumps etc.)

$\Rightarrow Q_{\text{eng}} \sim 2!$

DEMO:

$\Rightarrow$ Must reduce $P_{\text{aux}}$ and $P_{\text{inj}}$

NB: Off axis power (e.g. CD) has lower $\eta$

$\Rightarrow$ advantage to Stellarators and Pulsed Tokamaks
A QCW Tokamak

- 1095 MWe (1.52 – 425 auxiliary)
- Helium cooled with a heat storage (560°C at He exit)
- Cycle: 5 hour on; 10 minutes off
- Smooth drop by 250 MWe at the end of the 10min dwell
- Grid: No need for de-phased plants
- Issues: thermal & creep fatigue (first wall and divertor)

Heat storage module
20m long, 850 tons cast iron
Belgatom study, W. D’haeseleer et al 1994

JET AC discharges 1991
Physics/Integration Issues

• Generic issues
  – Undesired bifurcations; Plasma control under $\alpha$ heating
    • UFO; TAE
  – Fuel inventory
    • Choice of 1st wall material
  – Overall engineering Q (impact of control auxiliaries)

• Specific to advanced tokamak issues
  – 90% bootstrap, MHD, NTM
    • Stabilisation requires auxiliary power
      ➔ too much of it?
Where are we? LPO experience

- **LHD:** $t \sim 54'$, $P_{\text{inj}} \sim 490$ kW, 1.6 MJ or 13', $P_{\text{inj}} \sim 1.1$ MW

- **TRIAM-1M:** $t = 5h\ 16'$, 0.28 GJ (Nov 03)

Very good progress but not at reactor $n$ and $\beta$!
Where are we? Long pulses in TS

- Large superconducting tokamak in operation
  - Cryo-magnetic system with trouble free operation for 20 years
  - All PFCs actively cooled
  - Powerful H/CD systems
- 6 min discharges (2003) with 1 GJ injected/exhausted energy
  - $P_{\text{LHCD}} = 3$ MW
  - $I_p = 0.5$ MA
  - $n_{e0} = 2.5 \times 10^{19} \text{m}^{-3}$

$\Rightarrow$ Missing $n$, $\beta$, bootstrap $\Rightarrow$ more H&CD power required

IAEA 2003
Towards long discharges at higher power

- Convective losses routinely handled by the TPL (3-5 MWm⁻²)
- Routine high power long duration discharges
- Studies of discharges in which
  - loop voltage is evanescent for duration much longer than current diffusion time
  - Stationary PFC surface temperature
- Testing key technologies in real Tokamak environment

Need longer CD power or bootstrap ➔ New klystrons being procured
Non-linear behaviour @ Vloop=0

- Oscillations of core electron temperature
- Complex coupling between q-profile, MHD (double tearing, e-fishbones), transport and heat sources

[Giruzzi PRL 03; Imbeaux PRL 06; Maget Nucl Fus 06]
Where are we? Non-inductive operation with RT control

Fully non-inductive regimes with large bootstrap over several resistive times achieved in many tokamaks

JT60-U (75%)

JET (30%-40%)

[Sakamoto, Nucl Fus 05]

[Litaudon, PPCF 03]
Impurity Issue

- Core impurity accumulation in negative magnetic shear configuration (Internal Transport Barrier)
- e-heating shows control capability (JET, AUG)

[Dux, Nucl Fus 04]

Ni radial profile

Minority ICRH

Mode conversion e-heating

[Puiatti PoP05; Giroud, IAEA 06]
A virtuous circle seems to exist, related to the intimate link between current density profile and heat transport

Only a partial solution so far: particle transport, rotation, edge, ..?

More modelling, theory, R&D and longer pulses needed

Will α heating preserve the loop?
Technology Issues

• Supra conductors
  – High $T_c$ ? $\Rightarrow$ Higher engineering Q

• Erosion/redeposition/T inventory
  – Choice of material
    • Carbon, Tungsten etc..

• Structural longevity
  – Radiation resistant material
  – Disruption (Tokamaks)
Progress in superconducting coil R&D

One of 1st SC magnets (courtesy Oxford Instruments) (1962)

Non-planar winding for W7-X (EU)

Winding machine of helical coils for LHD (JPN, 1998)

And now EAST and KSTAR

J. Jacquinot, ITC 18 Toki 2008
The $\text{Nb}_3\text{Sn}$ conductors of the ITER coils

CSMC
51 mm x 51 mm
40 kA, 13 T

TFMC
Φ 40.7 mm
80 kA, 9.7 T
Real time control of CW discharges

- IR Acquisition Unit
- Diagnostic

- APILOTE

- Need IR survey of T of all strategic places

- APOLO
- Poloïdal

- ICRH

- LHCD
- Power C2, C3

- 36143 – LPT Q6
- 36143 – Q1, Q2, Q5

- ScramNet

- Power modulation
- Safety interlock

J. Jacquinot, ITC 18 Toki 2008
Fuel retention: a major issue for C based PFC

- Long term constant retention rate observed (~50% injected flux) from particle balance of long discharges

Where does it go?
D inventory: the 5-hour marathon TS project

- **Three steps:**
  - Dedicated long discharge campaign in D
  - Dismantling one sector of TPL (20°) for samples extraction
  - Analysis of samples

- **The campaign**
  - **160 long discharges** (1 min < duration < 2 min)
  - Total of **5 hours of plasma**
  - no wall conditioning during the entire period
  - **10 g** \( (3 \times 10^{24} \text{ D}) \) retained of **19.3 g** \( (5.8 \times 10^{24} \text{ D}) \) injected
  - ~ 25 g of C redeposited on TPL

**Objective:**
Explore the erosion /re-deposition issue

J. Jacquinot, ITC 18 Toki 2008
B. Saoutic et al. SOFT 2008
Results of the 5hour marathon

- No sign of saturation
- First analysis conducted on 10 samples situated in 3 zones of interest: erosion, thin & thick deposition zones
- Includes analysis of inter-tile gap deposits
- Extrapolation to whole TPL:
  - 4.7 g of D trapped in TPL
  - 90% in deposits
- Great step toward closing the particle balance (50%)
  - Up to 70% if D losses in samples with time taken into account
  - Potentially D-rich deposits in other part of the machine
- Retention dominated by co-deposition (90%)
Preparing Long Pulse Operation of fusion devices is of strategic importance for the future of Magnetic Fusion

We are far from a demonstration of CW/QCW operation at reactor normalised parameters

- Slow equilibrium drifts, first wall material, Elm’s, $\alpha$ confinement (wall loading by $\alpha$ losses)

Long Pulse Steady-State developments deserve a worldwide coordinated effort:

- Joint Experiments *(short & long pulse, Tokamaks & Stellarators)*
- Theory / Simulation *(First principle; Integrated & Real Time)*
- Technology R&D programme
In summary

CW/QCW operation: A major challenge for fusion

Broad topics: Technology and physics

A world wide coordinated effort seems indispensable

Paris, 21 nov 2006