Current density modelling in JET and JT-60U identity plasma experiments
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Outline
• ITER operational scenarios
• Advanced tokamak scenario
  JT-60U vs ITER
• Integrated scenario modelling
• JET & JT-60U identity plasma experiments
  experimental background modelling
• Conclusions
Definitions of ITER Operational Scenarios

Plasma parameters for characterising the operational scenarios

The ratio of the poloidal and toroidal magnetic field

**Safety factor** \( q = \frac{a B_\phi}{R B_\theta} \)

Magnetic shear \( s = \frac{dq}{d\psi} \)

Energy confinement scaling \( H_{98} = \frac{\tau_e}{\tau_{e,\text{ITER}}} \)

**Baseline scenario**

\( q_{95} = 3 \)
\( Q = 15 \)
\( I_p = 15 \text{ MA} \)
\( \sim 400 \text{ s} \)
\( H_{98} = 1 \)

**Hybrid scenario**

\( q_{95} = 4 \)
\( Q = 10 \)
\( I_p = 12 \text{ MA} \)
\( > 1000 \text{ s} \)
\( H_{98} = 1 - 1.2 \)

**Advanced scenario**

\( q_{95} \geq 5 \)
\( Q = 5 \)
\( I_p = 9 \text{ MA} \)
\( \sim 3000 \text{ s} \)
\( H_{98} \geq 1.3 \)

The ratio of the kinetic and magnetic pressure

**Normalised beta** \( \beta_N = \frac{2\mu_0 a(p)}{B_0 I_p} \)

**Poloidal beta** \( \beta_p = \frac{2\mu_0(p)}{B_\theta a} \)

**Self-generated bootstrap current**

\[ j_{bs} \sim \nabla p \]

BUT: different contribution from \( \nabla n_e, \nabla T_e, \nabla T_i \)!

Bootstrap fraction \( f_{bs} = \frac{I_{bs}}{I_p} \)

Non-inductive current fraction

\( f_{cd} = f_{bs} + f_{ext} \)
Advanced Tokamak (AT) Scenario

**Definition:**
high fusion efficiency and operation close to steady-state conditions

- Reverse q
- Negative magnetic shear
- High normalised beta
- High poloidal beta
- High bootstrap fraction (~50-75%)

Best results in AT scenarios have been achieved in JT-60U in early 2000's!

\[ H_{98}, f_{cd} \text{ and } \beta_N \text{ were close to ITER SS value} \]

Very high \( f_{bs} \) was achieved in JT-60U

Fuel purity is the challenge in AT scenarios

Integrated Scenario Modelling

Integrated Tokamak Modelling ITM

ACT1
Support to the validation and physics application of the ETS and ITM tools

ACT2
Developing and validating plasma scenarios simulations for existing devices

ACT3
Support to predictive scenario modelling for future devices (e.g. JT-60SA, ITER, DEMO)

1. Current diffusion and transport modelling for current ramp down
2. Predictive density modelling with first principle models for ITER, addressing the density peaking effect
3. ITER scenario modelling with METIS including simulation of the real time control of the fusion burn
4. Expansion of the operational domain of ITER hybrid scenario with q on-axis below one by controlling the sawtooth period
5. 1D scenario modelling: implementation of the JT-60SA H&CD configuration (NBI, ECRH) in EU transport codes in JT-60SA

1. Self-consistent modelling of current diffusion, temperatures and density, validation of first principle transport JET and ASDEX-Upgrade
2. H to L transition and current ramp down
3. Comparison and modelling of JT-60U and JET plasmas in typical operational domains
4. Comparison of current diffusion, transport and confinement in JET C and ILW discharges
5. Impurity transport in JET ILW discharges
6. Pedestal-SOL modelling for JET ILW discharges

1. Benchmarking of new modules integrated within ETS (European Transport Solver) workflows, following the ETS development
2. ETS validation and application of ITM workflows to physics studies
**Scenario Modelling Package**

**CREATE-NL**
Free boundary code

- **Transport models**
  - B/gB, ETB, NCLASS, ...

- **Impurities**
  - SANCO (or from EX-file)

- **Equilibrium**
  - EFIT, ESCO

- **MHD**
  - ELM-model: adhoc

- **Other models**
  - Fusion, radiation, ...

**JETTO**
1D core transport

- **Plasma profiles**
- **Heating**
  - NBI: PENCIL
- **Cold neutrals**
  - FRANTIC (fluid approx)
- **Fuelling**
  - Gas injection, pellets (NGPS)
- **EIRENE**
  - 3D neutral kinetic particle Monte-Carlo code

**EDGE2D**
2D SOL/edge transport (fluid approx)

**EIRENE**
3D neutral kinetic particle Monte-Carlo code

- **ASCOT**
  - Guiding centre kinetic 3D Monte-Carlo code

- **HPI2**
  - Pellet ablation and deposition code

(V. Parail, S. Wiesen, TF-T meeting 09)
Basic idea:
- Same-sized devices (JET a=0.9m R=3.1, JT-60U a=0.8m R=3.3m)
- Same initial conditions (T, n, q, plasma shape)

Main goals
Study the time evolution of plasma parameters in AT scenarios in two largest tokamak devices
- q current components (NBI, bs)
- forming the ITBs
- steady state properties...

Extrapolate the results to ITER SS scenarios


BEGINNING

Reverse-shaped q is same
Flat density profile with the different pedestal
Small differences in ion temperature profile in the ITB region

END

Reverse q was lost in JET
Strong electron density ITB was formed in JT-60U
The weak ITB can be obtained in ion temperature profile in JT-60U
Main experimental results

The matching of the plasma parameters was quite successful in the initial state
The **time evolution of q** was different
The **density peaking** was different
The **NBI current density** was different
Bootstrap current fraction is larger in JT-60U
Steady state is achieved in JT-60U

Objectives for the modelling

Understand the difference between JET and JT-60U
- What is the role of different density peaking in the q time evolution?
- Why the density profile is different?
Is the steady state achieved in JET (and under what kind of conditions)?
Simulation cases

- Effect of NBI current (shape)
- Effect of electron density

- Sensitivity of density gradient
- Effect of external current components
- Long time scale simulations (steady state)

Data & Model

Ion temperature from charge-exchange spectroscopy

Electron temperature and density from high-resolution Thomson scattering

Initial value of q from magnetic measurements with MSE

\[ \frac{\partial j_\varphi}{\partial t} = \nabla^2 \left( \eta \left( j_\varphi - j_{bs} - j_{nbi} \right) \right) \]

Current diffusion model: JETTO
Neoclassical resistivity and bootstrap current density: NCLASS
Plasma equilibrium: ESCO
Neutral beam current density: ASCOT

Structure of the modelling cases
Six steps from experimental data to modelling results

1. Analysis of the experimental data
   - find the interesting effects for the modelling
   - define needful simulation cases

2. Select suitable tools for the modelling
   - model
   - codes

3. Validation of the selected model with the experimental data
   - testing different options

4. Performing simulations

5. Analysis

6. Extrapolation

Validation of the JETTO model with experimental q data
The effect of NBI current density for the current density and q

Different shape but the same fraction

JT-60U current density simulation with different (JET) NBI current density

JT: On-axis
NBI fraction 22%

JT-60U: Off-axis
NBI fraction 24%

The effect of the different shape of NBI current density is negligible
- In AT scenarios the bootstrap fraction is aimed to be maximised.
- The density gradient is the most significant generator of bootstrap current density.

In JT-60U the density ITB has been formed and bs fraction is over 3 times larger (~80%) than in JET (~25%)

Significant but not only reason:
- Sensitivity of the density gradient?
- Effect of the temperature?

JET current density simulation with larger (JT-60U) electron density

The reverse q stays longer

BUT
It is not a steady-state
Summary of the simulations and results

Simulation cases

- Effect of NBI current (shape)
- Effect of electron density
- Sensitivity of density gradient
- Effect of external current components
- Long time scale simulations (steady state)

Results

Experimental-based analysis
- Impact of the different NB current density for the $q$ time evolution is negligible
- Bootstrap current driven by density gradient is significant but not the only reason for the different behaviour of $q$

Extended sensitivity tests
- The effect of the same density gradient is different in JET and JT-60U; it generates larger bootstrap current in JT-60U than in JET
- High current fractions are required for stationary $q$
- Based on the long (10-15-second) simulations (experimental pulse length in these scenarios is 2-4 seconds) stationary state is achieved in JT-60U but not in JET
Conclusions

GENERALLY
• The most promising results in AT scenarios have been achieved in JT-60U.
• ITER AT scenarios are topical in 2030’s. The first DT experiments will be done in baseline scenarios.

• Identity experiments in two largest existing tokamak devices JET and JT-60U in 2008 were the first identity experiments in advanced tokamak scenarios.

• In predictive current diffusion simulations the significant role of electron density gradient and bootstrap current is obtained:
  • But it does not explain all the differences in current density and q profile time evolution between JET and JT-60U.
  • Effect of differently shaped (but same current fraction) NBI current density profile is negligible.

• Extrapolation to ITER is challenging.

• The effects of different density gradients were tested: The producing the bootstrap fraction requires larger gradient in JET and in JT-60U.