Summary: Confinement, Plasma-wall Interaction, and Innovative Confinement Concepts

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Statistics of EX and IC

EX (Magnetic Confinement Experiments)  178
  EX-C (Confinement)              ~93
  EX-D (Plasma-wall Interaction)  22
IC (Innovative Confinement Concept)  22

Total: 441
Outline

1. Tokamak Regimes Extended towards ITER
2. Scenario Optimization
3. Global Confinement Physics
4. Transport Physics
5. Plasma-wall Interaction
6. Innovative Confinement Concepts
1. Tokamak Regimes Extended towards ITER

Long Pulse Operation
1.1 Long Pulse Operation: high $\beta$ & G sustained $\gg \tau_R$

High $\beta$  &  AT (self regulating) regime $> \tau_R$
Particle control $> \tau_W$

*JT-60U: extended high-$\beta$ duration $=13\tau_R$

*DIII-D: 9.5s ITER baseline scenario
$\sim 9\tau_R$, $\langle \beta \rangle =4\%$, G$\sim 0.55$

*JET: 20s reversed shear
1.2 Long Pulse Operation: Excellent Heat Removal

JET:
  20s RS, 326MJ
JT-60U:
  30s ELMy-H, 350MJ
LHD:
  2min, 115MJ
HT-7:
  4min, $T_{\text{limiter}}$ still rising
TORE-SUPRA:
  6min, 1GJ
TRIAM-1M:
  5 hrs, No wall saturation
2. Scenario Optimization & Extrapolation

ITER Baseline Scenario
- Long Sustainment: DIII-D
- Integrated exhaust scenario (Ar + pellet): AUG, (Ar or N): JET

Steady-state / Hybrid Scenarios
- Full CD approaches: JT-60U, DIII-D, JET
- WS Long Sustainment: NTM-stabilization: JT-60U, DIII-D, JET, AUG
- High Integrated Performance: JT-60U, JET, DIII-D, AUG

High Density & High Radiation: DIII-D, JET, JT-60U

Extension of Improved Regimes
- H-mode with small / no ELMs
- Core Improvement eITB without central heating etc.
2.1 ITER Baseline Operation

Increased confidence in reaching the ITER performance

DIII-D: Long sustainment

\[ G \approx 0.55 \times 9 \tau_R \]

Integrated Exhaust Scenario

AUG: divertor temperature control by Ar + ELM control by pellet

JET: impurity seeding (Ar or N)
2.2 Steady-state / Hybrid Scenarios: Full Non-inductive approaches successful

JT-60U (bootstrap+NBCD)

- $f_{CD} > 90\%$
- WS: $f_{BS} \sim 45\%, 2.8 \tau_R$
- q(r) $> \sim 1.5$, q=2 at small $\nabla P$
- RS: $f_{BS} \sim 75\%, 2.8 \tau_R$

DIII-D (bootstrap+NBCD+ECCD)

- $f_{CD} \sim 100\%, \beta_N < 3.5, \sim 1 \tau_R$

High BS Full CD without inductive current control
2.2 Steady-state / Hybrid Scenarios: Improved Integrated Performance & ITER access

JT-60U

\[ \rho^* \sim 0.006 \]
\[ \nu^* \sim 0.06 \]

\[ q_{95} \sim 4.5 \]

Good probability for achieving high fusion gain in ITER at reduced current (~13MA) with a pulse length longer than 2000s.
2.2 Steady-state / Hybrid Scenarios. Extended to High Density & High Radiation

DIII-D

JET
LHCD+Pellet+NBI
=ITB, \( T_i \sim T_e, n_{e0} > n_G \),
low Rotation

JT-60: \( n_e/n_{GW} > 1 \),
\( n_{e(0)}/n_{GW} \sim 1.5 \)
Ne, Ar, D-pellet

\( q_{95} = 3.2 \)
\( q_{95} = 4.5 \)
2.3 Extension of Improved Regimes

H-mode Improvements
- Small - no ELM: AUG, C-Mod, DIII-D, JET, JFT-2M, JT-60U
- Low-A MAST: high beta DB, CNTR-NB
- NSTX: parametric dependence of confinement established

Helical: CHS, Heliotron-J, Tohoku-Heliac

Core Improvement
- Electron ITB without central fueling: TCV, TJ-II
- ITB with rotation: MAST

Pellet Enhanced Performance: FTU
2.3 Extension of Improved Regimes(2)

HANBIT: A stable high density mode found at $\omega<\Omega_{ci}$.

Mirror

GOL-3: Complete multimirror: $T_e~T_i~2$keV at $10^{21}/m^3$

GAMMA-10: ion-confining potential up to 2.1kV
3. Global Confinement Physics
3.1 Scaling Studies of Global Confinement

- JET and DIII-D: $\beta$ scan with fixed $\rho^*$ and $\nu^*$ in ELMy H-mode show $\beta$ independent (electrostatic) energy transport.
- Would predict improved confinement for high $\beta$ operation.

International stellarator database has been extended and new gyro-Bohm scaling has been extracted.

\[ \tau_{E}^{ ISS04v3} = 0.148a^{2.33} R^{-0.64} P^{-0.61} n_{e}^{-0.55} B^{0.85} \tau_{2/3}^{0.41} \]
\[ \propto \tau_{Bohm} \rho^{-0.90} \beta^{-0.14} \nu_{b}^{-0.01} a^{0.04} \]
3.2 L/H transition and its power threshold

C-MOD: distance between primary and secondary separatrix has large influence to toroidal rotation and L/H power threshold $P_{L/H}$ (low at LSN).

MAST: factor 2 reduction of $P_{L/H}$ in connected DN.

Biased H-mode in TCABR ($R=0.615m$, $r=0.18m$), ISTTOK and TU-Heliac ($R=0.48m$, $r=0.07m$).

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NSTX: HFS gas puffing reduces $P_{L/H}$ (less momentum drag of HFS neutral).

Heliotron J: H-mode with edge iota windows.
3.3 ITB

**Electron ITB (eITB)**

**MAST:** ITB with steep $T_e$-gradient and peaked $n_e$ profile was formed with counter-NBI where $M_\phi \sim 1$ in core.

**NSTX:** eITB (+ion ITB) formed with early NBI and fast Ip ramp (negative shear).

**FTU:** high density eITB. $T_{e0}$ up to 5keV at $n_{e0}>1 \times 10^{20} m^{-3}$ with LHCD+ECRH

**TCV:** Control of eITB with inductive CD (negligible power variation).

**TJ-II:** eITB was formed at low order rational surfaces ($\rho<0.3$) with strong positive $E_r$ by loss of ECH superthermal electrons.

**JET:** ion ITB with small momentum input and ExB shear.

**ITB w. no/small momentum input**
4. Transport Physics
## 4. Transport Physics

### Highlighted topics

<table>
<thead>
<tr>
<th>No.</th>
<th>Topics</th>
<th>Device/paper No.</th>
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</table>
| 1   | Zonal flow  
Reynolds stress, GAM, Zonal flow | HT-7, Extrap-T2R  
JFT-2M, CHS, T-10 |
| 2   | Electron transport  
Critical $\nabla T_e$, non-linear $\chi_e \sim (\nabla T_e)^\beta T_e^\alpha$ | AUG, JET, JT-60, DIII-D, LHD, TCV |
| 3   | Particle transport  
$G \sim -D[c_q\nabla q/q - c_T\nabla T_e/T_e], n_e^* \text{ dep.}$ | Tore-Supra, FTU, AUG, JET,  
LHD, MAST, ET |
| 4   | Momentum transport  
Rotation without torque | Tore-Supra, C-Mod, FTU, DIII-D,  
TEXTOR |
| 5   | Radial electric field  
$E_r$ control, Flow damping | LHD, GAMMA-10, TJ-II, HSX  
ISTTOK |
4.1 Zonal flow: measurement of Reynolds stress

Direct measurements of Reynolds stress reported from tokamak and RFP

\[ \frac{\partial \langle v_E \rangle}{\partial t} = -\frac{1}{r^2} \frac{\partial}{\partial r} r^2 \langle \tilde{v}_E r \tilde{v}_E \theta \rangle + \frac{\beta}{n_{eq}} \frac{1}{r^2} \frac{\partial}{\partial r} r^2 \langle \tilde{B}_r \tilde{B}_\theta \rangle - \frac{2}{n_{eq} R} \langle p \sin \theta \rangle \]

- Zonal flow
- Electrostatic Reynolds stress
- Electromagnetic Reynolds stress
- GAM term

\[ \text{(10^8 m/s^2)} \]

\[ \Delta r \text{ (cm)} \]

HT-7 (Tokamak)

Extrap-T2R (RFP)

\[ V_\theta \text{ [km/s]} \]

Radially inward

\[ [10^8 \text{m/s}^2] \]
4.1 Measurement of GAM and Low Frequency Zonal Flow

The modulation of $n_{e,\text{ambient}}$ correlates with GAM (JFT-2M).

Measurement of GAM (T-10)

Identification of low frequency Zonal flow (CHS)

Zonal flow profile

Zonal flow ($f < 1\text{kHz}$)
4.2 Electron transport:

Critical $\nabla T_e$, non-linear $\chi_e \sim (\nabla T_e)^\beta T_e^\alpha$.

- Critical $\nabla T_e$
  - JET, JT-60U => YES, DIII-D => NO
  - LHD => NO
- Non-linearity
  - JET, JT-60U => YES, DIII-D => NO
  - LHD => YES but on Te

$\chi_e^{tr} = C T_e^{\alpha} (\nabla T_e)^\beta$

Strong $T_e$: $\alpha \sim 1-2.5$
Weak $\nabla T_e$: $\beta \sim 0$

Exp. of effect of plasma shape and shear (TCV)
4.3 Burning Plasma Physics

JET: Thermal Tritium transport

• Turbulence dominates thermal particle transport for most regimes
  – Large inward \( \nu_T \) correlates with high \( D_T \)
  – Neo-classical only for high \( n_e \) ELMy H & in ITBs.

• Dimensionless parameters scans show:
  – Gyro-Bohm particle transport \( (D_T \sim \rho \star^3) \) for Inner plasma;
  – Bohm particle transport \( (D_T \sim \rho \star^2) \) for Outer plasma;
  – when q scans are included scaling is more like Gyro-Bohm in outer plasma \( (D_T \sim \rho_{POL} \star^3; \rho_{POL} = q \times \rho \star) \);
  – particle transport has an inverse \( \beta \) and \( \nu \star \) dependence.
4.3 Particle transport: dependent on $1/L_T, 1/L_q, v_e$

- Evident turbulent pinch observed in Tore Supra and FTU. Both the thermodiffusion ($\nabla T_e/T_e$) and curvature ($\nabla q/q$) pinches co-exist.
- Density peaking increases with decreasing collisionality, consistent with quasi-linear ITG/TEM model (AUG, JET)

⇒ could lead to higher fusion power in ITER

Confirmation of extrapolation to ITER requires further experiments.

Concern for mpurity accumulation (JT-60U, JET and AUG)
4.4 Momentum transport: Rotation without torque

- Rotation without torque is important for transport and stability (RWM).

⇒ More reports of rotation without torque input (C-mod, DIII-D, TEXTOR, Tore Supra)

C-Mod: rotation changes with USN, LSN (ICRF)

DIII-D: CTR rotation with ECH

TEXTOR: control by 3/1 DED

Cf. AUG; -400km/s for QH mode with counter NBI
4.5 Radial electric field
E_r control, flow damping

Combination of magnetic geometry with E_r produce interesting phenomena (Gamma-X, LHD, TJ-II, HSX, ISTTOK)

HSX
Viscous flow damping

TJ-II
Turbulence suppression

Radial Electric field

GAMMA-10
Turbulence suppression

LHD
E_r control
5. Plasma-wall Interaction
5.1 Active Control of Edge Plasma

- Higher confinement of $\tau_E = 1.2 \tau_{E, ISS95}$ due to sharp edge (large Te gradient) with a Local Island Divertor (LID) in LHD.
- Onset of 2/1 and 3/1 tearing modes by Dynamic Ergodic Divertor (DED) and reduction of the edge poloidal rotation.
- Configuration effects (USN, DN, LSN) on particle control in DIII-D.

[Graphs and diagrams showing confinement and divertor configurations]
5.2 Recycling/Wall retention

- Wall saturation in JT-60U (30s NB heating, $T_{vv} = 150, 300^\circ C$)
- No wall saturation in TRIAM (5h 16min, $T_{vv} = 30-40^\circ C$) and Tore Supra (6min., $T_{Limiter} = 120^\circ C$)
- Wider retention area than the area directly interacted with plasma (JT-60U, TRIAM, Tore Supra, JET, ASDEX-U. TEXTOR).

![Graph showing wall saturation in JT-60U and TRIAM/Tore Supra](image)
Tungsten Wall

- 65% of all PFC are W coated in ASDEX.
- High performance discharge with moderate W concentrations feasible.
- W concentration is controllable with central ele. heating and pellet triggering of ELMs.
- Blisters and bubbles are formed on the surface of W irradiated with low energy (~100 eV) H beam.

Further experiment in large tokamaks with high power heating.
Carbon Migration

- C migration toward the inner target and its main origin is the main chamber (DIII-D, JET, AUG, JT-60U)

$^{13}$CH$_4$ injection exp.

- SEM analysis
  - Divertor pumping

JET

- 10cm Divertor pumping

DIII-D

- Inner Strike Point
- Outer Strike Point

JT-60U

- Thickness (um)
- Major Radius (m)

Re-deposition layer thickness
Estimated erosion depth
Tritium Retention

T retention much lower with vertical target in JET: Geometry effect?

D/C ratio and dust much lower in JT-60: better alignment? Higher temperature?

<table>
<thead>
<tr>
<th>T(D) retention</th>
<th>D/C</th>
<th>dust</th>
</tr>
</thead>
<tbody>
<tr>
<td>JET</td>
<td>3%</td>
<td>0.4 - 1.0</td>
</tr>
<tr>
<td>ASDEX</td>
<td>3%</td>
<td>0.4 - 1.0</td>
</tr>
<tr>
<td>JT-60</td>
<td>&lt;2%</td>
<td>7 g</td>
</tr>
</tbody>
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6. Innovative Confinement Concepts
6 Innovative Confinement Concept

Experiments:
• SC levitated internal ring in ECH heated plasma on Mini-RT
• Measurement of axial flow shear in the ZaP flow Z-pinch
• CD by Helicity injection in the HIT-II & HIT-SI
• FRC plasmas, produced and sustained by the RMF, and for MTF (FRX-L, TCS)
• Sequence of spheromak formation (CALTECH), supersonic rotation with centrifugal confinement (MCX)
6 Innovative Confinement Concept

Numerical studies:
• Nonlinear evolution of MHD instability in FRC
• Design of magnetic measurement for 3D equilibrium and model of ambipolar plasma flow for NCSX
• Simulation of liner compression using two fluid model
• Optimization of quasi-poloidal stellarator

New Concept:
• Burning spherical tokamak by pulsed high-power heating of magnetic reconnection
• Selective heating using LH for He ash removal
• Solenoid-free start-up for spherical torus using outer poloidal field coils and conducting center-post
• Spherical tokamak configuration using spherical snow-plug
I am very much pleased that fusion community has made significant progress in confinement and plasma-wall interaction research areas. These results will greatly contribute to ITER.