High Performance Operational Limits of Tokamak and Helical Systems

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Outline

1. Introduction
2. Achieved operational domain
3. Equilibrium Properties
4. Confinement
5. Stability Limit
6. Density Limit
7. Steady-State Operation
8. Reactor Prospect
9. Summary
INTRODUCTION

For the realization of attractive fusion reactors, plasma operational boundaries should be clarified, and be extended to the higher performance limit.

There are several plasma operational limits:

1. confinement Limit,
2. stability Limit,
3. density limit, and
4. pulse-length limit.

Here we would like to discuss on a variety of toroidal plasma operational limits focusing on the similarities and differences between TOKAMAK and HELICAL systems.
## Maximum Parameters Achieved

<table>
<thead>
<tr>
<th>Parameter</th>
<th>TOKAMAK</th>
<th>HELICAL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron Temperature ( T_e ) (keV)</td>
<td>25 (ASDEX-U, JT-60U)</td>
<td>10 (LHD)</td>
</tr>
<tr>
<td>Ion Temperature ( T_i ) (keV)</td>
<td>45 (JT-60U)</td>
<td>5.0 (LHD)</td>
</tr>
<tr>
<td>Confinement time ( \tau_e ) (s)</td>
<td>1.2 (JET)</td>
<td>0.36 (LHD)</td>
</tr>
<tr>
<td>Fusion Triple Product ( n_i \tau_e T_i ) ( m^{-3} \cdot s \cdot \text{keV} )</td>
<td>15x10^{20} (JT-60U)</td>
<td>0.22x10^{20} (LHD)</td>
</tr>
<tr>
<td>Stored Energy ( W_p ) (MJ)</td>
<td>17 (JET)</td>
<td>1.0 (LHD)</td>
</tr>
<tr>
<td>Beta Value ( \beta ) (%)</td>
<td>40 (toroidal) 12 (toroidal) (START) (DIII-D)</td>
<td>3.0 (average) (LHD,W7-AS)</td>
</tr>
<tr>
<td>Line-Averaged Density ( n_e ) ( 10^{20} \text{m}^{-3} )</td>
<td>20 (Alcator-C)</td>
<td>3.6 (W7-AS)</td>
</tr>
<tr>
<td>Plasma Duration ( \tau_{dur} )</td>
<td>2 min 3 hr. 10min. (Tore-Supra) (Triam-1M)</td>
<td>2 min 1 hour (LHD) (ATF)</td>
</tr>
</tbody>
</table>
Operation Regime and Reactor Requirements

\[ \beta = \rho s / a \sim \sqrt{T} / (aB) \]

\[ \nu_* = \nu_{ei} a / \nu_{th} \sim na / (\varepsilon^{5/2} T^2) \]

Normalized parameters

\[ \rho_* = \rho_s / a \sim \sqrt{T} / (aB) \]

\[ \nu_* = \nu_{ei} a / \nu_{th} \sim na / (\varepsilon^{5/2} T^2) \]

**TOKAMAK**

**HELICAL**
# Similarities and Differences between Tokamak and Helical Systems

<table>
<thead>
<tr>
<th></th>
<th>STANDARD TOKAMAK</th>
<th>STANDARD HELICAL</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Equilibrium</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Plasma Boundary</td>
<td>Shape</td>
<td></td>
</tr>
<tr>
<td>Shape</td>
<td>2D</td>
<td>3D</td>
</tr>
<tr>
<td>Magnetic Field</td>
<td>Components</td>
<td>Toroidal (1,0) + Helical (L,M) + Bumpy (0,M) Ripples</td>
</tr>
<tr>
<td>Components</td>
<td>Toroidal (m,n)=(1,0)</td>
<td></td>
</tr>
<tr>
<td>Plasma Currents</td>
<td>External + BS Currents</td>
<td>No net toroidal current or BS Current</td>
</tr>
<tr>
<td>q-profile</td>
<td>Normal or Reversed shear profile</td>
<td>Flat or Reversed shear profile</td>
</tr>
<tr>
<td>Divertor</td>
<td>Poloidal divertor 2D</td>
<td>Helical or island divertor 3D</td>
</tr>
<tr>
<td><strong>Physics</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Magnetic shear</td>
<td>Substantial Shear or Shearless in the core</td>
<td>Substantial Shear</td>
</tr>
<tr>
<td>Magnetic Well</td>
<td>Well in whole region</td>
<td>Hill near edge</td>
</tr>
<tr>
<td>Radial Electric Field</td>
<td>driven by toroidal rotation &amp; grad-p</td>
<td>driven by non ambipolar loss (Helical Ripple)</td>
</tr>
<tr>
<td>Toroidal Viscosity</td>
<td>Small</td>
<td>Large (Helical Ripple)</td>
</tr>
<tr>
<td>grad-j, grad-p</td>
<td>grad-j driven</td>
<td>grad-p dominant</td>
</tr>
<tr>
<td>Island, Ergodicity</td>
<td>near separatrix</td>
<td>Edge Ergodic Layer</td>
</tr>
</tbody>
</table>
Advanced Plasma Shapes

Core Symmetry
- QA: Quasi Axi-Symmetry
- QP: Quasi Poloidal Symmetry
- QO: Quasi Omunigenity
- QH: Quasi Helical Symmetry

Edge Symmetry
- M=2
- M=3

Standard Tokamak
- M=0 (n=0)

Helical Divertor
- M/L=4/1
- M/L=10/2

Standard Helical

Larger M
Magnetic Shear / Well

Tokamak:
Shear is changed by current profile.
Magnetic well.

Helical:
A variety of shears by helical coil.
Magnetic hill near edge.

Normal or Reversed Shear

Flat or Reversed Shear

\[ \text{TJ-II} \]
\[ \text{JT-60U Normal Shear} \]
\[ \text{LHD} \]
\[ \text{W7-AS} \]
\[ \text{JT-60U Current Hole} \]
Confinement Scaling Laws
Comparing between ITER ELMy-H Database and stellarator Database adding LHD data

\[ \tau^{ELMY}_E \propto \tau_B \rho^{-0.83} \beta^{-0.50} \nu^{-0.10} \]

\[ \tau^{ISS95}_E \propto \tau_B \rho^{-0.71} \beta^{-0.16} \nu^{-0.04} \]

\[ \tau_{ELMY}^{E} = 0.0365R^{1.93}P^{-0.63}\bar{n}_e^{0.41}B^{0.08}e^{0.23}I^{0.97} \]

\[ \tau_{ISS95}^{E} = 0.08a^{2.21}R^{0.65}P^{-0.59}\bar{n}_e^{-0.51}B^{0.80}t^{0.40}_{2/3} \]
Radial Electric Field & ITB

TOKAMAK
Er shear driven by toroidal rotation and grad-p (JT-60U, Shirai)

HELICAL
Positive electric field driven by ripple loss in low density regime predicted by Neo-Classical Theory
NC-ITB (CHS, Minami & Fujisawa)
Island, Ergodicity and Divertor

**TOKAMAK**
- Poloidal Divertor
- ITER

**HELICAL**
- Helical Divertor
- LHD
- Island Divertor
- W7-AS, LHD

Remote radiation

Short connection length
Rather clean separatrix
**Stability Limits**

**grad-j dominant or grad-p dominant?**

**Tokamak**

- Ideal beta agrees with Ideal MHD
- Resistive beta agrees with NTM & TM, RWM theories

**Helical**

- Beta obtained beyond Mercier mode
- Global mode is still marginal.

**LHD**

- Equilibrium limit
- Unstable
- Experiment

** JT-60U**

- q_{edge}/q_0 = 4
- q_{edge}/q_0 = 6
- High-\(\beta_N\) mode
- Large \(\rho_p/\langle p \rangle\)
- H-mode
- Medium \(\rho_p/\langle p \rangle\)
- Grad-j dominant or grad-p dominant?
Mode structure

TOKAMAK
(JT-60U, Takeji)
ERATO-J code
Global mode
driven by grad-j

HELICAL
(LHD, Nakajima)
CAS3D code
Localized mode
driven by grad-p

Low-n mode is
interchange-like.

High-n mode is
ballooning-like.
Effects of Wall

Tokamak

Kink-ballooning modes driven by grad-j & grad-p can be easily stabilized by the fitted wall.

Helical

Mode is localized and there is no strong wall effect on pressure-driven mode, but substantial effects on BS current-driven external mode.

Ballooning mode is stable in the area: $\beta_N < 6$.

Unstable $(b/a > 1.2)$

Stable
Operational Density Regime

**Tokamak**
- radiation collapse
- leading to current disruption

\[ n_{20\_GR} = \frac{I_{MA}}{\pi a_m^2} \]

**Helical**
- radiation collapse
- slow plasma decay

\[ n_{20\_hel} = 2 \cdot \min \left\{ 0.25 \frac{P_{MW} B_T}{R_m a_m}, 0.35 \frac{P_{MW}}{R_m a_m} \sqrt{B_T} \right\} \]
Disruption-Free in Helical System?

Tokamak - Helical Hybrid
(Current Carrying Stellarator)

W7-A

JIPP T-II

Tearing mode, even NCTM, can be stabilized in helical system?

LHD

\( m/n=1/1 \)

\( W_{ex}/a=0.085 \)

Fujita et al.,
IEEE Transaction on Plasma Science
Steady-state Operation

**Tokamak**

NB Current Drive
in JT-60U RS Elmy H-mode
(80% bootstrap current fraction)

Full non-inductive CD

LH Current Drive
in Triam-1M (3hr.10min.)

**Helical**

~1keV long pulse operation
In LHD (ICRF 0.8MW)

(Triam-1M, Sakamoto, this conference)
Progress on Reactor Designs

Lower-aspect designs are explored.
## Operational Limits

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<tr>
<th></th>
<th>STANDARD TOKAMAK</th>
<th>STANDARD HELICAL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Confinement</td>
<td>Gyro-Bohm</td>
<td>Gyro-Bohm (Global)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Helical Ripple Effect (Local)</td>
</tr>
<tr>
<td>Beta Limit</td>
<td>Kink-Ballooning Mode</td>
<td>Low-n Pressure-Driven Mode</td>
</tr>
<tr>
<td></td>
<td>Resistive Wall Mode</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Neoclassical Tearing Mode</td>
<td></td>
</tr>
<tr>
<td>Density Limit</td>
<td>Radiation &amp; MHD Collapses</td>
<td>Radiation Collapse</td>
</tr>
<tr>
<td>Pulse-Length Limit</td>
<td>Recycling Control</td>
<td>Recycling Control</td>
</tr>
<tr>
<td></td>
<td>Resistive Wall Mode</td>
<td>Resistive mode (?)</td>
</tr>
<tr>
<td></td>
<td>Neoclassical Tearing Mode</td>
<td></td>
</tr>
<tr>
<td>Beyond limit</td>
<td>Thermal collapse</td>
<td>Thermal collapse</td>
</tr>
<tr>
<td></td>
<td>Current quench</td>
<td></td>
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</tbody>
</table>
Summary

- For realization of attractive fusion reactors, **better confinement** and **longer-pulsed operations** should be achieved in addition to burning plasma physics clarification.

- In tokamak systems, critical issue is to avoid disruption and to demonstrate steady-state operation.
  - In helical systems, high performance discharges should be demonstrated with reliable divertor, and compact design concepts should be developed.

- Each magnetic concepts should be developed complementally focusing on above critical issues keeping their own merits, for realization of attractive reactors and for clarification of common toroidal plasma confinement physics.