Topics from New Approaches in Plasma Confinement Experiments in Helical Devices

presented by
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NEW APPROACHES IN PLASMA CONFINEMENT EXPERIMENTS IN
HELICAL SYSTEMS
Nov. 13-15, 2006

Heliotron J

• F. SANO, Overview of Recent Experiments in Heliotron J
• D. ANDERSON, Overview of HSX Results
• S. OKAMURA, Topics from CHS experiment
• S. KOBAYASHI, Experimental Studies of NBI-heated plasmas in Heliotron J
• W. GUTTENFELDER, Turbulence measurements and theory-based transport modeling of ECRH plasmas in HSX
• T. MINAMI, High density edge transport barrier during reheat mode on CHS
• Y. SUZUKI, MHD Equilibrium Analyses of Advanced Helical Configurations
• T. RAFIQ, Microinstabilities and resistive ballooning modes in helically symmetric stellarators
• D. SPONG, Shear flow generation in stellarators - configurational variations
• S. KITAJIMA, Dependence of ion viscosity on ripple structures of magnetic configurations in Tohuku University Heliac and CHS
• K. MATSUOKA, Effect of magnetic configuration on electron energy transport in CHS
• M. ZARNSTORFF, Physics research plans for NCSX
• N. POMPHREY, Magnetic Flux Loop Design for NCSX
• J. HANSON, Progress in 3-D equilibrium reconstruction in stellarators
• R. MAINGI, The edge physics program during initial NCSX operation
• T. MIZUUCHI, Dynamic shift of divertor plasma position during a discharge in Heliotron J
• T. OISHI, Edge Harmonic Oscillations measured using Beam Emission Spectroscopy in CHS
• K. NAGASAKI, ECCD experiments in helical systems
• G. MOTOJIMA, Toroidal current control in ECH plasmas on Heliotron J
• T. OKADA, Fast ion study using ICRF heating in Heliotron J
• C. DENG, Studies of energetic electron-driven Alfvénic modes in HSX
• J. BERKERY, Confinement of Pure Electron Plasmas in CNT

• S. KNOWLTON, Overview of CTH experiments
• W. REIERSSEN, Promising Innovations for Future Compact Stellarators
• A. WELLER, Progress of W7-X
• S. OKAMURA, Discussion on stability and confinement in LHD

http://www.auburn.edu/cosam/events/plasma/usj06/
Topics from New Approaches in Plasma Confinement Experiments in Helical Systems

– Outline –

- Advanced Helical (Stellarator/Heliotron) Concepts
  - Quasi-Symmetry
  - Quasi-Isodynamic (Quasi-Omnigeneous)

- Topics from Recent Plasma Experiments in Helical Devices
  - Configuration effects on NC/turbulent transport
  - Progress in high-\(\beta\), high density steady state operation
  - Divertor relevant experiments
Evolution of Helical (Stellarator/Heliotron) Concepts

Helical Heliotron
Helical Windings w/o TFC
Planar Axis System

Optimized Helical Heliotron
(H-E, CHS) U-3M

Helical-Axis Heliotron
Helical Winding + TFC
Quasi-Isodynamic
(Quasi-Poloidally Symmetric)

Kyoto Original

Stellarator Concept

Spatial Axis System

Heliac
Helically displaced
TFC + CC

Helias
Quasi-Isodynamic
Quasi-Pol. Symmetric
Quasi-Axisymmetric

Quasi-Helically Symmetric

1950s
today

Planar Axis System

Stellarator
Helical Windings with TFC

Modular Coil System

TJ-II, H-1NF TU-Heliac

W7-AS

W7-X
(construction)

QPS
(designed)

NCSX
(construction)

H-J

LHD

HSX

IAE, Kyoto University
Helical ripple leads to high transport in conventional stellarators.

→ How to reduce it?

- Particles trapped in helical ripple have net radial drift in conventional stellarators.
- Electric field can mitigate scaling.
  - Ambipolarity constraint on NC fluxes can create $E_r$.
- Advanced helicals reduce the ripple losses through recovering of symmetry or tailoring the field harmonics.
## World-wide research activities for optimization of helical systems

<table>
<thead>
<tr>
<th>Concept</th>
<th>Modular Coils</th>
<th>Continuous Helical Coil(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Quasi-Axisymmetric</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Quasi-Toroidally Symmetric)</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Quasi-Helically Symmetric</strong></td>
<td></td>
<td><strong>LHD</strong> (NIFS, 1998~)</td>
</tr>
<tr>
<td><strong>Quasi-Poloidally Symmetric</strong></td>
<td></td>
<td><strong>Heliotron J</strong> (Kyoto, 2000~)</td>
</tr>
<tr>
<td><strong>Quasi-Isodynamic</strong></td>
<td></td>
<td><strong>Helical axis heliotron</strong></td>
</tr>
<tr>
<td>(Quasi-Omnigeneous)</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Heliac</strong></td>
<td>TJ-II (CIEMAT, 1997~)</td>
<td>H1-NF (ANU, 1993~)</td>
</tr>
<tr>
<td></td>
<td>H1-NF (ANU, 1993~)</td>
<td>TU-Heliac (Tohoku, 1988~)</td>
</tr>
<tr>
<td><strong>Others</strong></td>
<td></td>
<td><strong>U-3M</strong> (Kharkov, )</td>
</tr>
<tr>
<td></td>
<td></td>
<td><strong>CTH</strong> (Auburn, 2006~)</td>
</tr>
</tbody>
</table>

- **Heliotron J** (Kyoto, 2000~)
- **LHD** (NIFS, 1998~)
- **Helical heliotron**
- **Helical axis heliotron**
## Helical-Axis Helical Devices in the World

### Heliotron J

<table>
<thead>
<tr>
<th>Plasma Device</th>
<th>H-1NF</th>
<th>TJ-II</th>
<th>HSX</th>
<th>Heliotron J</th>
<th>NCSX</th>
<th>QPS</th>
<th>W7-X</th>
</tr>
</thead>
<tbody>
<tr>
<td>Country</td>
<td>Australia</td>
<td>Spain</td>
<td>USA</td>
<td>Japan</td>
<td>USA</td>
<td>USA</td>
<td>Germany</td>
</tr>
<tr>
<td>Research Lab</td>
<td>Max Planck Institute</td>
<td>Oak Ridge National Laboratory</td>
<td>Princeton University</td>
<td>Kyoto University</td>
<td>Princeton University</td>
<td>Oak Ridge National Laboratory</td>
<td>Max Planck Institute</td>
</tr>
<tr>
<td>Coils Form</td>
<td>M=3 H(1HF+2 TFC)</td>
<td>M=4 H(1HF+2 TFC)</td>
<td>M=4 H(1HF+2 TFC)</td>
<td>M=4/L=1 H(1HF+2 TFC)</td>
<td>M=3 H(QA)</td>
<td>M=2 H(QPS)</td>
<td>M=5 H(1HF+2 TFC)</td>
</tr>
<tr>
<td>Major Radius R (m)</td>
<td>1.0</td>
<td>1.5</td>
<td>1.2</td>
<td>1.2</td>
<td>1.4</td>
<td>0.95-1.0</td>
<td>6.5</td>
</tr>
<tr>
<td>Minor Radius a (m)</td>
<td>0.22</td>
<td>0.1-0.25</td>
<td>0.15</td>
<td>0.18</td>
<td>0.32</td>
<td>0.3-0.4</td>
<td>0.65</td>
</tr>
<tr>
<td>Volume (m³)</td>
<td>0.96</td>
<td>1.43</td>
<td>0.44</td>
<td>0.82</td>
<td>3</td>
<td>2-3</td>
<td>54</td>
</tr>
<tr>
<td>Confinement Time (s)</td>
<td>1.0</td>
<td>1.0</td>
<td>1.37</td>
<td>1.5</td>
<td>1.2-1.7</td>
<td>1.0</td>
<td>3.0</td>
</tr>
<tr>
<td>Aspect Ratio R/a</td>
<td>4.5</td>
<td>6-15</td>
<td>8</td>
<td>7</td>
<td>4.4</td>
<td>2.7</td>
<td>10</td>
</tr>
<tr>
<td>Heating Power</td>
<td>ECH: 0.2 MW</td>
<td>ECH: 0.6 MW NBI: 4 MW</td>
<td>ECH: 0.2 MW</td>
<td>ECH: 0.4 MW NBI: 1.5 MW ICRF: 2.0 MW</td>
<td>RF: 6 MW NBI: 6 MW</td>
<td>ECH/EBW: 1 MW ICRF: 1 MW</td>
<td>ECH+NBI: 20-30 MW</td>
</tr>
</tbody>
</table>

### Characteristics

- High aspect ratio, low beta, and magnetic field configurations are possible.
- Research focuses on beta limit studies and high magnetic field experiments.
- Innovative methods for plasma confinement and heating.
- Advanced materials and engineering for plasma devices.

### Diagrams

- Various diagrams illustrating the helical-axis helical devices in the world.
- Detailed representations of plasma configurations and experimental setups.
Topics from New Approaches in Plasma Confinement Experiments in Helical Systems

– Outline –

- Advanced Helical (Stellarator/Heliotron) Concept

- Topics from Recent Plasma Experiments in Helical Devices
  - Configuration effects on NC/turbulent transport
  - Progress in high-β, high density steady state operation
  - Divertor relevant experiments
The electron-root condition is found inside $\rho \sim 0.6$ creating the large $E_r$-shear regime.

- Steep $T_i$-gradient is found in $E_r$-shear regime.
- $T_e$-gradient also increases inside $\rho \sim 0.4$.
- HIBP measurements showed suppression of turbulent transport with the internal transport barrier formation.
**Effects of Configuration on NC transport: Exp. from HSX**

Significant differences have been measured between plasma profiles w/ & w/o QHS. (I)

- Mirror fields are added for symmetry breaking in HSX.
- Density profiles are peaked w/ **Quasi-Helical Symmetry (QHS)**, hollow when symmetry is broken.
  - Discharges shown: 
    ~50 kW of ECH power, central deposition
  - higher temperature, more peaked density profile with QHS.
- Hollow/flat $n_e$-profile in w/o QHS is due to thermodiffusion, which is **reduced** with QHS.

\[
\Gamma = -n \left( D_{11} \left( \frac{n}{n} - \frac{qE_r}{T} \right) + D_{12} \frac{T'}{T} \right)
\]

$D_{12}$ is smaller due to quasi-symmetry

*D. Anderson, et al*
Thermal diffusivity is reduced in QHS.
- at \( r/a \sim 0.25 \),
  \( \chi_e : 2.5 \text{ m}^2/\text{s} \) in QHS,
  \( 4 \text{ m}^2/\text{s} \) in Mirror
- Difference is comparable to neoclassical reduction
  \( (~2 \text{ m}^2/\text{s}) \)

Two configurations have similar transport outside of \( r/a \sim 0.5 \).
\( \Rightarrow \) anomalous transport dominant
Soft X-ray, Hard X-ray Emissions indicate fast electrons are better confined in QHS.

- Soft X-ray (600 eV-6 keV) emission; QHS >> Mirror
- Hard X-ray flux: QHS>>Mirror; decay time longer
- Indicates these fast electrons drive Alfvénic modes.
  - No mode observed in Mirror Configuration.
Bumpy (mirror) component is essential to realize the **quasi-isodynamic feature** in Heliotron J.

- To investigate the bumpiness effects on fast-ion confinement,
  - the bumpiness was varied by controlling the current ratio of the two toroidal coil sets under the fixed condition of \( \nu(a)/2\pi = 0.56 \).
  - The fast-ions are created by ICRF or NBI.

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**Diagram:**

- Poloidal profiles of \(|B|\) along a field line (upper) and \(|B|\) contour plots (lower) in Boozer co-ordinate (r/a = 0.52)
- \( B_0 / B_{00} = 0.15 \) (High)
- \( B_0 / B_{00} = 0.06 \) (STD config.)
- \( B_0 / B_{00} = 0.01 \) (Low)

---

- Better
- Worse
Better confinement of fast ions by ICRF in higher bumpiness configuration

- For ICRF heating, the high-energy ion tail temperature increases with $\varepsilon_b$.
- Power-moderation experiments indicate lower loss-rate for higher $\varepsilon_b$ configuration.
- Due to better confinement of fast-ions, higher increment of the bulk ion-temperature is observed for higher $\varepsilon_b$ configuration.
The $\varepsilon_b$-dependence of BS current is consistent with the predictions from SPBSC calculations.

For ECCD, the ripple structure at the resonance region is important.
turbulence transport and improved modes

$P_{\text{NBI}}$-Dependence of Delay Time of L-H Transition

Comparison between CHS and Heliotron J

- Delay time of $H\alpha$ spontaneous drop after the start of NBI becomes longer as decreasing NBI power.
- The edge field structure (rationals?) might be important for the transition.

T. Minami, S. Kobayashi, et al
Positioning a low order rational (e.g. 3/2, 4/2, 4/3) near the core (using, e.g., induced OH current or ECCD) triggers an ITB in a controllable way.

The rational must be inside the plasma to trigger the transition.

Change in $E_r$ is observed near the rational.

So far no cases found where the e-ITB triggered by 5/3.
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Observation of Internal Diffusion Barrier and super dense core plasma in LHD

Central density: $5 \times 10^{20} \text{m}^{-3}$
Central temperature: 0.85 keV
→ exceeding 1 atmospheric pressure
Magnetic field: 2.64 T
→ Central beta: 4.4 %
: > 5 % at B of 1.5T

Super Dense Core operation enables a new reactor scenario.
progress in high-\( \beta \) performance

High \( \beta \)-plasma studies in LHD

Goal : 5 \%

\(<\beta> > 4 \% \) was sustained for $>> 10\tau_E$

Degradation can be attributed to the change of effective helical ripple due to Shafranov-shift, not on MHD effect.

self-stabilization
\( \Rightarrow \) realization of high-\( \beta \) plasma,
\( \Rightarrow \) needs 3D equilibrium reconstruction technique.

Degradation in high \( \beta \) regime will be improved by dynamic \( R_{ax} \) control in nearest future.
Request for 3-D Equilibrium Reconstruction is Increasing in Helical Experiments. ⇒ V3FIT

- Equilibrium reconstruction is invaluable for tokamaks
  - Equilibrium Control
  - MHD Stability and Confinement Studies
    ⇒ Example: EFIT code

- Helical Trends
  - Higher beta
  - Bootstrap current

⇒ Equilibrium flux surfaces are not vacuum flux surfaces.

MHD Equilibrium
- Input:
  - External B Field
  - Current profile
  - Pressure profile
  - Toroidal flux

- Output:
  - Flux surface geometry
    (Key to further computations)

Equilibrium Reconstruction:
- Use observed diagnostic signals to determine:
  - External B Field
  - Current profile
  - Pressure profile
  - Toroidal flux
3-D Equilibrium Reconstruction requires a sophisticated flux loop system.

- Design of Ex-Vessel Flux Loops in NCSX
- Both SS fields with $n=3 \cdot j$ and periodicity-breaking non-SS fields with $|n|=1, 2, 4, 5, \ldots$ must be diagnosed.

N. Pompherey, et al
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  - Divertor-relevant experiments
Several Divertor Concepts are proposed for Helical Devices

Heliotron J

Helical Field Coil

Divertor Probe Array

Edge Magnetic Fields

#14-pin

#1-pin

Helical Field Coil

Local island divertor: LHD

island divertor: NCSX, W7-X

core plasma

LCFS

m/n=1/1 island separatrix

Separatrix (disappeared)

LID head

to pump

Field-line tracing in SOL

divertor

pumps

baffle
progress in long-pulse operation

Steady State Operation in LHD

- Record of input energy to high temperature plasmas in FY2005
  1.6GJ : 490kW × 3268s
- Planning longer pulse with higher heating power
  3 MW for 1 hour

- Steady state operation by ICRF demonstrates the high potential of helical systems towards a currentless steady state reactor.
- Minority heating ICRF accelerates perp. component of ion velocity effectively up to MeV range.
  - demonstrates the high capability of LHD to confine high energy ions.
Particle/heat load on the divertor plates are dispersed by $R_{ax}$ sweeping.

Main divertor trace is switched from inboard to outboard side by a small change of $R_{ax}$ ($\Delta R/R \sim 0.8\%$)

Temp. of div. tiles saturates at a tolerable level
The shift of the diverted plasma footprints is observed during a single discharge.

- The shifts of $R_{\text{target}}$ and $R_{\text{DPA}}$ are closely related to the change of plasma current.
  - In #23624, $W_p$ and $I_p$ were kept increasing up to almost the end of discharge, but in #23635, $I_p$ started to decrease at $t \sim 240$ ms while $W_p$ did not decrease and was kept almost the same value until the end of the NBI pulse.
  - For #23635 discharge, the inward shifts of $R_{\text{target}}$ and $R_{\text{DPA}}$ were observed until $t \sim 240$ ms and they started to change the direction of shift for $t > 240$ ms, i.e. coming back to the values at the initial phase of the discharge.

- This experiment points out
  - the importance of current control to fix the divertor plasma position in a low shear helical device,
  - the possibility of "divertor swing" for the divertor particle/heat load reduction by controlling a small amount of plasma current.
Since the value of vacuum rotational transform is close to the natural resonance condition, even a small change in the edge rotational transform by a small current can make a big change in the plasma radius, i.e. in the x-point.
Divertor swing by a small current drive in W7-X or other helicals?

Predictive Modelling Example
- X-point (thermal load) control by feed forward ECCD...

...involves various physics software modules:
- Equilibrium recovery
- Flux surface mapping
- Power deposition (ECRH, NBI)
- Transport (neoclassical)
- Current drive

additional modules:
- Thermal loads
- SOL + divertor physics (not yet clear)

Yu. Turkin, A. Werner, ...
Topics from New Approaches in Plasma Confinement Experiments in Helical Systems

Summary

Advanced Helical (Stellarator/Heliotron) Concept
- Several advanced concepts are experimentally examined.
  » Topics from recent plasma experiments in helical devices are reported.
    • Configuration effects on NC/turbulent transport
    • Progress in high-\(\beta\), high density steady state operation
    • Divertor-relevant experiments

Helical research activities in the world contribute to
- assess the attractiveness of helical systems
  » a disruption free, high density (no GW-limit) steady-state reactor
- advance understanding of 3-D plasma
  » for basic fusion science relating also to tokamaks & ITER
  » for physics of non-linear/complex-systems in the natural world
Thank you very much for your attention!

Please enjoy the Heliotron J tour this afternoon.