Advantage and disadvantage of LHD heliotron divertor


National Institute for Fusion Science

Outline of the talk
1. Introduction: divertor optimization toward DEMO
2. The divertor geometry of LHD heliotron
3. Particle exhaust
4. Impurity screening
5. Power exhaust
6. Summary and discussion
Introduction: Optimization of divertor functions toward helical DEMO

Divertor functions:
1. Pumping
   Effects of 3D geometry of divertor structure on neutral compression and manufacturing of pumping system
2. Impurity control
   Role of edge stochastic layer on impurity screening
3. Heat load mitigation
   Divertor heat load distribution in the 3D divertor structure, Detachment stability with the edge stochastic layer
4. Compatibility with core plasma performance?

This contribution presents current achievements and understandings of LHD heliotron divertor, for further discussion of critical issues for divertor optimization toward helical DEMO.

<table>
<thead>
<tr>
<th></th>
<th>FFHR-d1 (DEMO)</th>
<th>ITER</th>
<th>JA Tokamak DEMO[^3]</th>
</tr>
</thead>
<tbody>
<tr>
<td>R / a [m]</td>
<td>15.6 / 2.5</td>
<td>6.2  / 2.0</td>
<td>8.5 / 2.42</td>
</tr>
<tr>
<td>B_e [T]</td>
<td>~5</td>
<td>5.3</td>
<td>5.94</td>
</tr>
<tr>
<td>P_{div} [MW]</td>
<td>3000</td>
<td>500</td>
<td>1462 (1694)**</td>
</tr>
<tr>
<td>f_{He} / f_{de} [%]</td>
<td>5 / 0</td>
<td>&lt;5  / NA</td>
<td>7 / 0.25 (0.6)**</td>
</tr>
<tr>
<td>P_{rad} [MW]</td>
<td>200</td>
<td>~70</td>
<td>82 (177)**</td>
</tr>
<tr>
<td>P_{aux} [MW]</td>
<td>0</td>
<td>73</td>
<td>84 (96)**</td>
</tr>
<tr>
<td>P_{div} (P_c + P_{aux} + P_{rad}) [MW]</td>
<td>400</td>
<td>~100</td>
<td>294 (258)**</td>
</tr>
<tr>
<td>P_{div}/R [MW/m]</td>
<td>35</td>
<td>16</td>
<td>35 (30)**</td>
</tr>
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</table>
The divertor geometry of LHD heliotron divertor

Heliotron
(Helios: the god of the sun in Greek mythology)

R = 3.9 m
a ~ 0.6 m
B = 2.8 T

Heating Systems
- n-NBI x 3 (180-190keV), H16MW, D8MW
- p-NBI x 2 (40-80keV), H6MW, D18MW
- ECH (77GHz x 3, 154 x 2, 82.7, 84) 5.5MW

Helical coils

Dashed lines: Open magnetic field lines

Purple surface: Magnetic surface of confinement region

Green: Divertor plate arrays

10 field periods
Formation of edge stochastic layers: island chains of various modes

Connection length ($L_C$) distribution in poloidal cross section

Mode structure $n/m$

- 10/2
- 10/3
- 10/4
- 10/5
- 10/6
- 10/7
- 10/8

Edge surface layers

Stochastic region

LHD

Helical coils

Connection length (LC) distribution in poloidal cross section

- 3.9 m

Radial

Poloidal
Particle exhaust in LHD helical divertor
The divertor heat (particle) load distribution is not uniform in helical direction. The heat load tends to localize at inboard side (and up & bottom). Correlation with $L_C$ distribution is observed.
In-out asymmetry of divertor neutral pressure

- Higher inboard neutral pressure than outboard by one order of magnitude.
- The rather low pressure (0.01 ~ 0.1 Pa) is due to low divertor density, < 1x10^{19} m^{-3} (Absence of high recycling regime).
- Loss of pressure conservation along flux tubes due to enhanced cross-field transport (3D effect).

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Pressure profile along flux tube (EMC3-EIRENE)

- Edge surface layers
- Stochastic region

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Diagram showing the relationship between neutral pressure and density.
Closed Divertor since 2010

Dome

Cryogenic pump is installed under domes.

Divertor plates
Closed divertor successfully increases divertor neutral pressure by a factor of ~10

Particle exhaust with the divertor pump installed under the dome structure

- Approximately 50% of the fueled gas is exhausted in the divertor pumping.
- Slight degradation of pumping efficiency observed in high density range.

Development of divertor cryo-sorption pump in 3D geometry

The main characteristics of the development:

(1) Development of new activated cryo-panel → high pump speed and capacity
(2) The water-cooled blinds are no longer needed → high conductance
(3) The area of the cryo-sorption panel is enlarged → high capacity

New type

Pumping speed of 96.5 m³/s, capacity of 86,000 Pa m⁻³ have been achieved so far. To be operated in next experiments.


G. Motojima IAEA 2018.
Prediction of particle exhaust in helical DEMO

Prediction of EMC3-EIRENE for size-scaled computation (Preliminary)

The plasma size is scaled by a factor of 2 and 4.
(Plotted in normalized scale.)

By courtesy of G. Kawamura

The results suggest favorable situation for divertor pumping.

Combination with outboard pumping will improve the pumping efficiency further.
Replacement of cryogenic pump to TMP will be an issue.
Edge impurity transport in LHD helical divertor
Numerical analysis of impurity screening in LHD stochastic layer:
high $n$ $\rightarrow$ friction force $\uparrow$, thermal force $\downarrow$ $\rightarrow$ screening

Increasing density $\rightarrow$ Enhances friction force in edge surface layer with flow acceleration by short flux tubes $\rightarrow$ Suppresses thermal force in stochastic region

Increasing density $\rightarrow$ Enhances friction force in edge surface layer with flow acceleration by short flux tubes $\rightarrow$ Suppresses thermal force in stochastic region

$n_{\text{carbon}}$ distribution

Simulations

$n_{\text{LCFS}}=2 \times 10^{19}$ m$^{-3}$

$3 \times 10^{19}$

$4 \times 10^{19}$

Increase $n_e$

Impurity emission measurements and comparison with synthetic diagnostic of EMC3-EIRENE

Qualitative agreement between simulation & experiments

Ionization potential
CIII (C^2+): 48 eV
CIV (C^3+): 65 eV
CV (C^4+): 392 eV

Proxy for source
Proxy for C in confinement region

Reduction of C in confinement region

SOL thickness dependence of impurity screening: thicker stochastic SOL \(\rightarrow\) better screening already at low density

- Stochastic layer width \(\lambda_{st}\) relative to neutral impurity penetration \(\lambda_{imp}\) 
  \[\lambda_{st}/\lambda_{imp} \uparrow \rightarrow\) better screening

In DEMO, stochastic layer width becomes larger, \(\lambda_{st} \sim 1\) m, while \(\lambda_{imp}\) (atomic process) remains unchanged.

\[\lambda_{st}/\lambda_{imp} \uparrow\uparrow\uparrow\]

Screening in the stochastic layer can be more effective in DEMO
Impurity screening against high Z materials

First wall of LHD is stainless steel. However, no significant core iron accumulation is observed.

In a frame of edge impurity transport model (friction vs thermal force balance), first ionization potential of impurity is one of key parameters:
Radial position of impurity ion launching ~ mfp of impurity ionization

<table>
<thead>
<tr>
<th></th>
<th>C</th>
<th>Ne</th>
<th>Ar</th>
<th>Fe</th>
<th>W</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>11.3</td>
<td>21.6</td>
<td>15.8</td>
<td>7.9</td>
<td>7.9</td>
</tr>
</tbody>
</table>

- Further investigation against W is ongoing by replacing divertor plate to W-coated tiles.
- Replacement of one toroidal section (36 degrees) is complete.
- No remarkable impact on core plasma has been observed so far.

Typical iron density in core (EUV & VUV spectroscopy): $< 10^{14} \sim 10^{16} \text{ m}^{-3}$ ($n_{Fe} / n_e < 10^{-3}$)

S. Morita et al. NF 53 (2013) 093017.
Power exhaust in LHD helical divertor
Crude estimation of “AVERAGED” divertor heat load in helical DEMO

“Averaged” divertor heat load: $\Gamma_{\text{div}}^{\text{ave}}$

$$\Gamma_{\text{div}}^{\text{ave}} = \frac{P_{\text{div}}}{S_{\text{div}}}$$

Power to SOL: $P_{\text{div}} (= P_a + P_{\text{aux}} - P_{\text{rad}}) = 400$ [MW]

Wetted area: $S_{\text{div}} = S_{\text{div,LHD}}(R_c/R_{\text{c,LHD}})^2$

$$S_{\text{div,LHD}} = 2 \text{ m}^2$$

The local maximum can be several times larger due to the non-uniformity in helical direction.

Needs heat load mitigation

See [46] T. Goto (M. Kobayashi)
Divertor foot-prints of magnetic flux tubes & power load in various configurations

**Single peak**: Good correlation between long flux tubes and peak power load.

**Multi-peak**: Foot-print width becomes broad, power peak does not necessarily correlate with $L_c$ peak.

Multi-peak strike lines could widen the wetted area.

Edge magnetic field structure, plasma parameter profiles, and impurity radiation

$L_C$ changes from a few meters to more than 1km. $T_e$ ranges from a few tens to a few hundreds eV.

Density around LCFS is larger than at the divertor region.

Impurity radiation: the stochastic layer > divertor region

The edge stochastic layer has potential of various impurity emissions of different charge states.
Impurity seeding experiments: Ne and N

Ne seeding

Toroidal profile of div. particle flux

N seeding

L_C & div particle flux profile at div plate (N seeding)

In N seeding, div flux reduction is strongly affected by L_C structure.

Sustainment of detached phase for longer duration is still to be explored.

For recent experiments with mixture seeding Ne + Kr, see [48] K. Mukai.
Detachment control with RMP application

R = 3.9 m, $\bar{a} \sim 0.7$ m, 10 field periods (toroidal)
Divertor: carbon, First wall: Stainless steel

RMP coils (m/n=1/1)
Helical coils
Plasma shape

With RMP
Without RMP
Resonance value

$\frac{b_{r coil}}{B_0} \approx 0.1\%$

Connection length (m)

Rotational transform $\iota$

RMP coils (m/n=1/1)
Helical coils
Plasma shape

Divertor legs
Edge surface layers
Stochastic region
Magnetic island O-point

Connection length (m)

Divertor: carbon, First wall: Stainless steel
With RMP → Stable sustainment of radiative divertor operation
Without RMP → Radiation collapse due to thermal instability

Application of RMP leads to stable sustainment of detached plasma near density limit.

The radiation profile qualitatively agrees between experiments & simulation.

The magnetic island structure “catches” the radiation and prevents it from penetrating inward!?!
Divertor heat load distributions (Langmuir probe): attached & detached phases

- Nearly uniform toroidal distribution without RMP
  - Toroidal modulation with RMP due to change of $L_C$

- After detachment transition, heat load decreases at most of divertor plates (HYDROGEN).
- Slight increase is observed at certain sections (2L, 8L), where $L_C$ profile is split by RMP.

- In DEUTERIUM plasma, heat load decreases at all toroidal sections at detachment. Isotope effects? Or due to amount of carbon?
The LHD heliotron divertor needs to be optimized toward helical DEMO

**Advantage (Control of transport)**
- Effective impurity screening with stochastic layer
  To be confirmed for high-Z impurity
- Flexibility of edge magnetic field structure
  Thicker stochastic layer → better screening
  Controllability of detachment

**Disadvantage (Complexity of transport & engineering)**
- Neutral compression
  Further improvement is foreseen in next experiments
  (could be improved in DEMO)
- Non-uniform heat deposition on divertor plates
  Needs of development of energy dissipation scheme
- Technological challenge in complex 3D shaping
  Pumping, magnet system etc.

What is the most critical issue toward helical DEMO among above issues?