Local Island Divertor Experiments on LHD


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(1) Introductions to LHD.

(2) LHD Divertor Strategy.

(3) LID Experiments.
   3-1) proof of the LID principle.
   3-2) modeling.
   3-2) impurity control.
   3-2) confinement properties.

(4) Summary.
**LHD (Large Helical System)**

- **Plasma Major radius**: 3.5 - 4.0 m
- **Plasma Minor radius**: ~0.6 m (average)
- **Plasma Volume**: ~30 m³
- **Coil minor radius**: 0.975 m
- **Magnetic field**: 2.893 T (at $R_{ax}=3.6$ m)
- **Heating power**:
  - ECH: 1.2 MW
  - N-NBI: 10 MW
  - ICRF: 3.0 MW

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Helical Divertor (HD)

**Advantage**
- * relatively wide wetted area.
  --> favorable for heat removal.
- * long distance from target to core.
  --> favorable for impurity screening.

**Feature**
- **Intrinsic double-null type divertor**
  * long legs.
  * short field lines (2-3m in LHD).
- **Nonaxisymmetric magnetic field**
  * 3-d structure.
- **Ergodic layer surrounding core**
  * thick (∼30cm in LHD).
  * no clear separatrix.
  * long $L_c$ (several 100m in LHD).

**Disadvantage**
- * complicated.
  --> inadequate for diagnostics, blanket.
- * difficult to construct (3D).
  --> high cost.
Local Island Divertor (LID)

**Features**
- Utilize m/n=1/1 island.
- Insert a divertor head locally.
- LCFS defined by island separatrix.
- No leading edge problem.
- Closed system.
- High efficient pumping.
- No ergodic layer.

\[ L_c = \sim 250 \text{m} \]

**Advantage**
- High efficient pumping.
- Easy to realize closed system.
  --> Superior cost performance.
- Compact and integrated
  --> Favorable for blanket, diagnostics.

**Disadvantage**
- Small wetted area.
  --> High heat load.
LHD Divertor strategy

Active edge control by LID.

Steep $T_e$ and $n_e$ gradient.

Confinement improvement.
Perturbation coils

10 pairs of normal conductor coils for m/n=1/1 island generation

m/n = 1/1 island
* surely exists as expected (calculation).
* confirmed by flux surface mapping with electron beam and probe.

\[ R_{ax} = 3.6 \text{m}, \quad B_q = 100\%, \quad \gamma = 1.254, \quad B_t = 2.75\text{T} \]
\[ I_{LID} = 0, \quad 0, \quad +1920\text{A} \]
**Divertor head**

water cooled heat sink (stainless steel) covered with carbon tiles.

$P < 7.5 \text{ MW/m}^2$ (5s).
Schematic of LID system

**Pumping system**
- 8 cryogenic pumps (42m$^3$/s each).
- Effective pumping speed $\sim$ 100m$^3$/s.
Experimental setup

- Spectroscopy
- CXRS
- NB#1
- NB#2
- Gas puff
- FIR interferometer
- Bolometer
- NB#3
- LID
- Gas puff
- Ice pellet
- Thomson scattering
In LID configuration,
- no ergodic layer.
- volume is reduced at 60%.
- steep $T_e$ gradient.
- while $n_e$ boundary is unclear.
  --> because of long $L_c$?

* LID functions as a divertor.
  --> because divertor head does not touch the core plasma.
Particle flux to the LID head and helical divertor

* w/o LID (open helical divertor)
  particle flux $\rightarrow$ helical divertor

* w/ LID (closed island divertor)
  particle flux $\rightarrow$ LID head
  $\rightarrow$ helical divertor $\sim 0$
Plasma flow predicted by EMC3-EIRENE

Parallel flow established.
(as expected)
- along separatrix of island
- to LID head (back side)

Unfavorable flow
- to leading edge
- to front side of LID head.

--> hot spot
Particle flux profile on the LID head

Head position scan (slit size=8cm=const.)

* At the appropriate position,
particle flux has its peak avoiding the leading edge.

probe array
backside view
$T_e$ and $n_e$ profile predicted by EMC3-EIRENE

* Parallel flow along the island separatrix.
* Highest density at outer island separatrix.
* High $n_e$ low $T_e$ plasma around LID head.
  --- high recycling
Pumping efficiency (head position dependence)

\[ \tau_p^* = \frac{\tau_p}{1-R} \]

- Gas puffing rate = const.
- Slit size = 8 cm (const.)
- \( n_e \) bar is minimum at \( R_{\text{head}} = 4.08 \sim 4.09 \) m

\[ \implies \text{Max. pumping efficiency} \]
H$_2$ density predicted by EMC3-EIRENE

* High particle flux.
* Closed system.
* High neutral confinement property (3 x $10^{21}$ m$^{-3}$)
* High recycling.
* High density.
* Detachment?
Screening / pump out effect of LID on impurities

In LID configuration,
* $P_{\text{rad}}$ is localized in island.
  --> accumulation at island?
* $P_{\text{rad}}$ is low in confinement region.
  --> lead to steep $T_e$?
* $P_{\text{rad}}$ at center increases as $n_e$.
  --> due to metallic impurity from LHD head.
  --> lead to degradation in $T_e$ gradient.

* Ne is injected by gas puffing.

\[
\Gamma_{\text{gas puff}} = \begin{cases} 
3.26 \text{ Pa m}^3/\text{s (HD)} \\
34.7 \text{ Pa m}^3/\text{s (LID)}
\end{cases}
\]

* $n_{\text{Ne}}$ profiles are measured with CXRS.

Low Impurity density in LID
  --> impurity screening
New outward shifted magnetic configuration ($R_{ax}=3.75m$)

In $R_{ax}=3.75m$ configuration,

* Confinement volume is almost the same as $R_{ax}=3.60m$.

* Foot positions of $T_e$ and $n_e$ are close (--> SOL is wide).

--> due to the stronger ergodicity around the island ?

--> due to the different $L_c$ ?
Parameter regime is extended

In $R_{ax} = 3.75\text{m configuration},$

* higher $n_e$ is achieved.

* $W_p \sim 757\text{kJ (LID)},$
  
  -- comparable to HD ---
Outward shifted configuration

* Energy confinement in LID confinement is improved in outward shifted configuration,
- which is superior to that in HD configuration.
- which is 1.2 times higher than that of ISS95 scaling.
Density decay time in two configurations

- In outward shifted configuration
  - ergodic
  - unfitted LID head shape
  - Degradation of collecting efficiency
  - Unfavorable recycling is enhanced.

No difference between gas puff and pellet
In outward shifted configuration.

- High recycling.
- Fueling strongly increased.
- Good plasma performance.
Summary

1) Fundamental functions of LID were confirmed, that is,
   * strong pumping effect,
   * formation of the steep edge gradients,
   * avoiding the leading edge problem.
   * impurities (Ne) screening effect.
     --> pump out effect?

2) Confinement property in LID configuration
   * follows the ISS95 scaling law.
   * improves in the outward shifted configuration,
     --> 1.2 times higher than that of ISS95.
     --> due to the enhanced recycling particles?
   * efficient fueling leads to high confinement regime?

3) First results from EMC3-EIRENE
Plans for next campaign

1) Control the $L_c$ to LID head.
   - by shifting $R_{ax}$.
   - by controlling the perturbation field strength.

2) Divertor gas puffing.

3) Potential control

4) Estimation of pumping efficiency

5) Analyses of impurity transport.

6) Edge modeling (EMC3-EIRENE)
Radial electric field

* Positive $E_r$ in the island region (LID).
* Negative $E_r$ (Limiter).
* Effect of $E_r$ on impurity behavior is unclear.
Time behavior of impurity quantity, $P_{\text{rad}}$ and $T_{\text{e0}}$

* In limiter configuration during high power discharge, impurities (carbon) are released from the leading edge.

--> $P_{\text{rad}}$ increase --> $T_{\text{e}}$ decreases
Confinement property with different fueling methods

- Low power region ($P<4\text{MW}$).
  - Little difference is seen in different fueling method.

- High power regime ($P\sim9\text{MW}$).
  - Pellet injection is superior to gas puff.

* Higher power + pellet injection
  --> higher $W_p$ is expected.
Rax=3.6m, Bt=2.75T, Bq=100%, gamma=1.25
gas=H,
ne_bar~2.8 x 10^{19} \text{ m}^{-3} \text{ (const.)}

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$T_e$ and $n_e$ profiles at $R_{ax}$=3.60m

HD

LID

Limiter

#46500
HD
$t$=1.975s

#46521
$R_{LID}$=4.09m / LID
$t$=1.325s

#46553
$R_{LID}$=4.09m / Limiter
$t$=0.525s
$T_e$ profile and separatrix position

* LID functions as a divertor.

--> because divertor head does not touch the core plasma.