Third Technical Meeting on Divertor Concepts
IAEA Headquarters, Vienna, Austria
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Advantage and disadvantage of LHD heliotron divertor

M. Kobayashi, T. Goto, Y. Hayashi, G. Kawamura, G. Motojima, S. Morita, K. Mukai, S. Masuzaki, T. Oishi, C. Suzuki, T. Morisaki, and the LHD experimental group

National Institute for Fusion Science

Outline of the talk

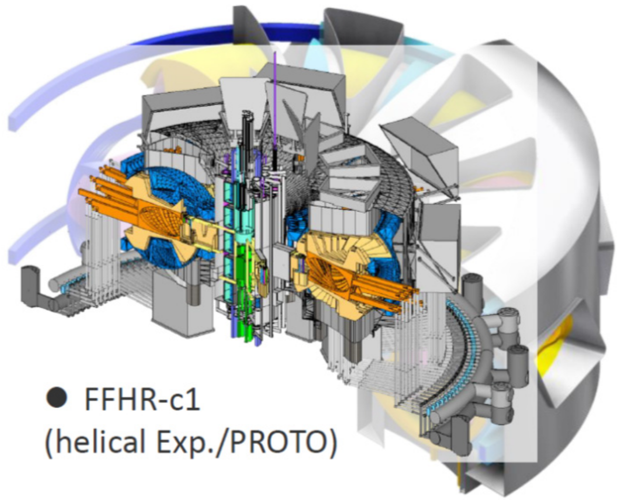
1. Introduction: divertor optimization toward DEMO
2. The divertor geometry of LHD heliotron
3. Particle exhaust
4. Impurity screening
5. Power exhaust
6. Summary and discussion

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?



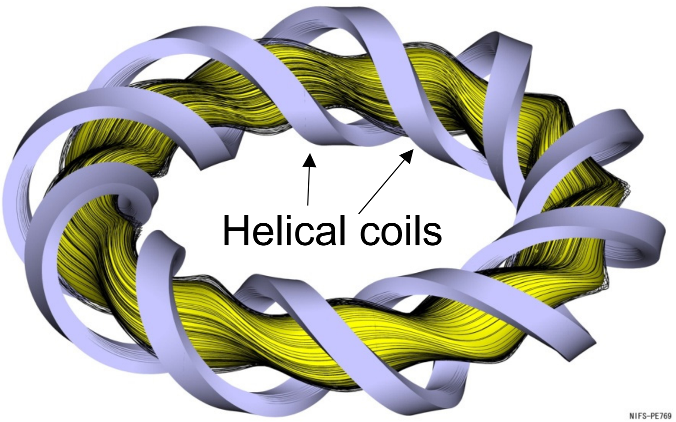
	FFHR-d1 (DEMO)	ITER	JA Tokamak DEMO[5] ** w/ increasing elongation and seeding
R / a [m]	15.6 / 2.5	6.2 / 2.0	8.5 / 2.42
B_c [T]	~5	5.3	5.94
P_{fus} [MW]	3000	500	1462 (1694)**
f_{He} / f_{Ar} [%]	5 / 0	<5 / NA	7 / 0.25 (0.6)**
P_{rad} [MW]	200	~70	82 (177)**
P_{aux} [MW]	0	73	84 (96)**
P_{div} $(= P_\alpha + P_{aux} - P_{rad})$ [MW]	400	~100	294 (258)**
P_{div}/R [MW/m]	35	16	35 (30)**

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

The divertor geometry of LHD heliotron divertor

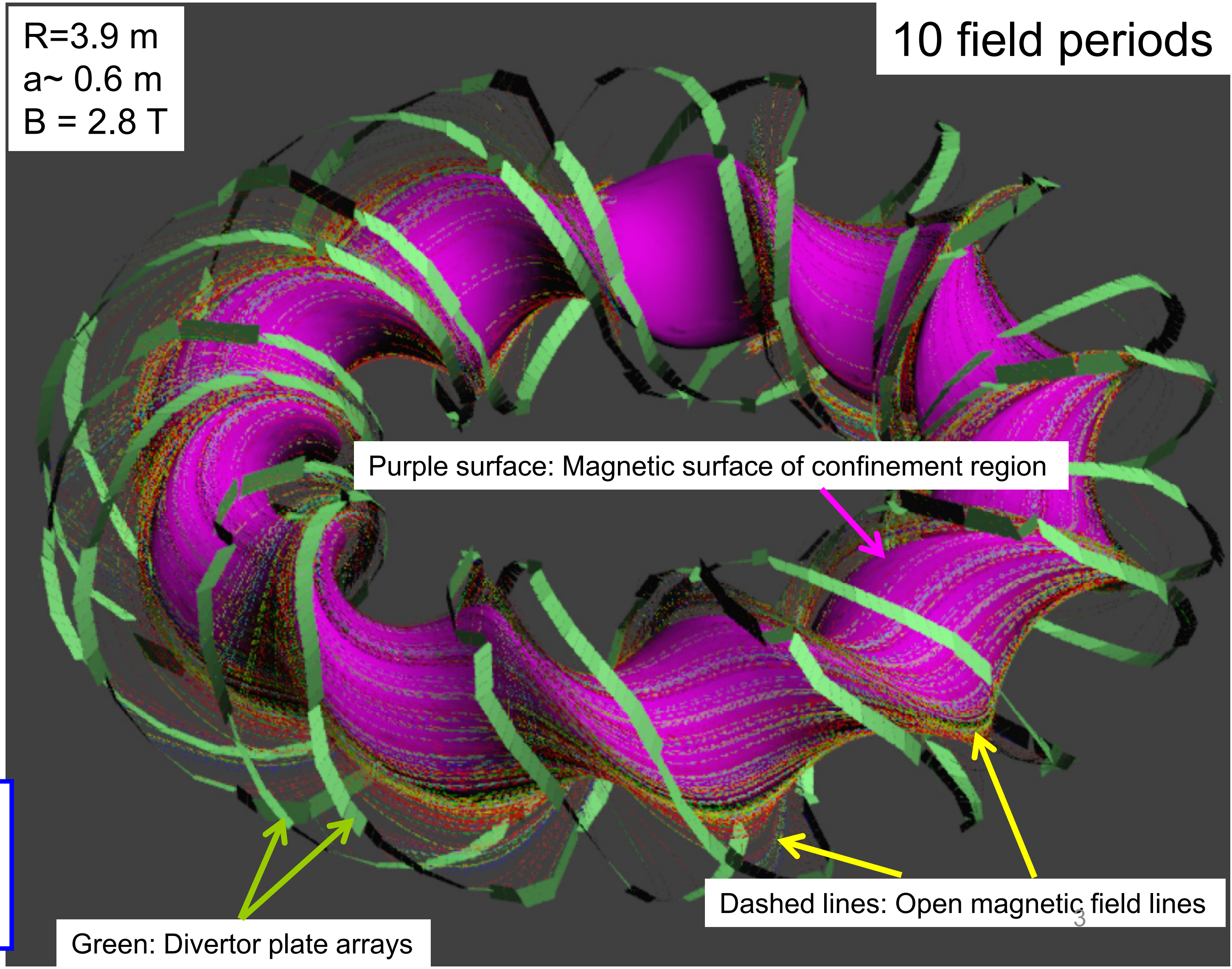
Heliotron

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



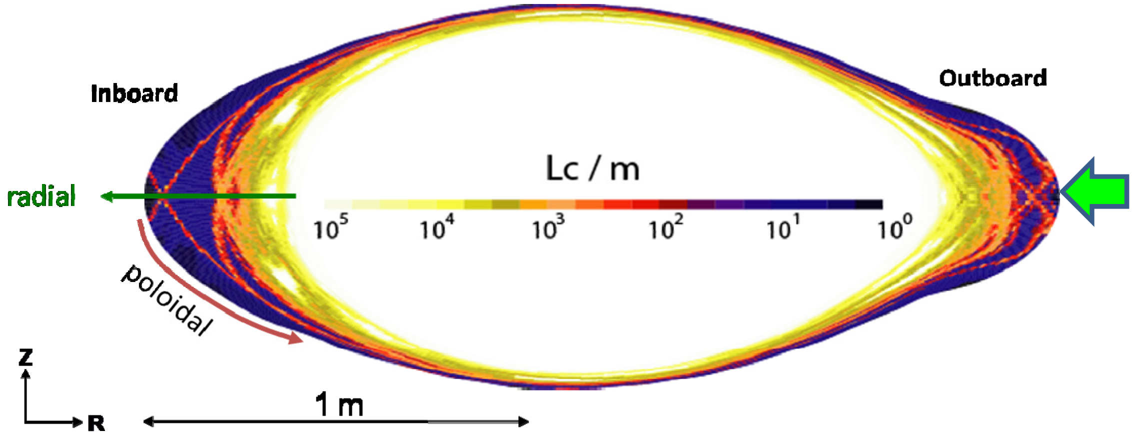
Heating Systems

- 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

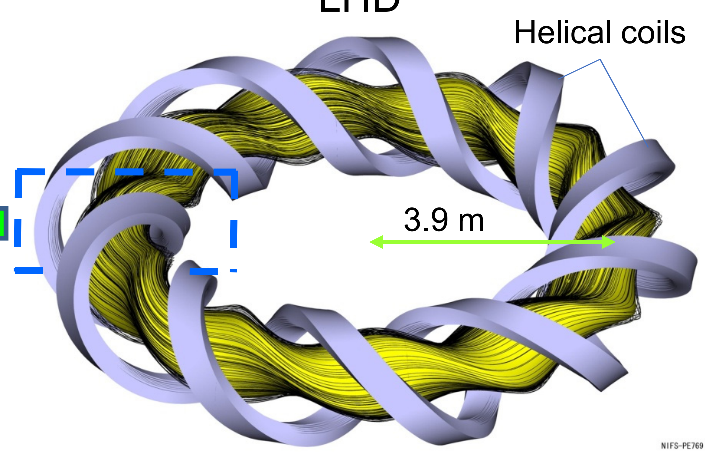


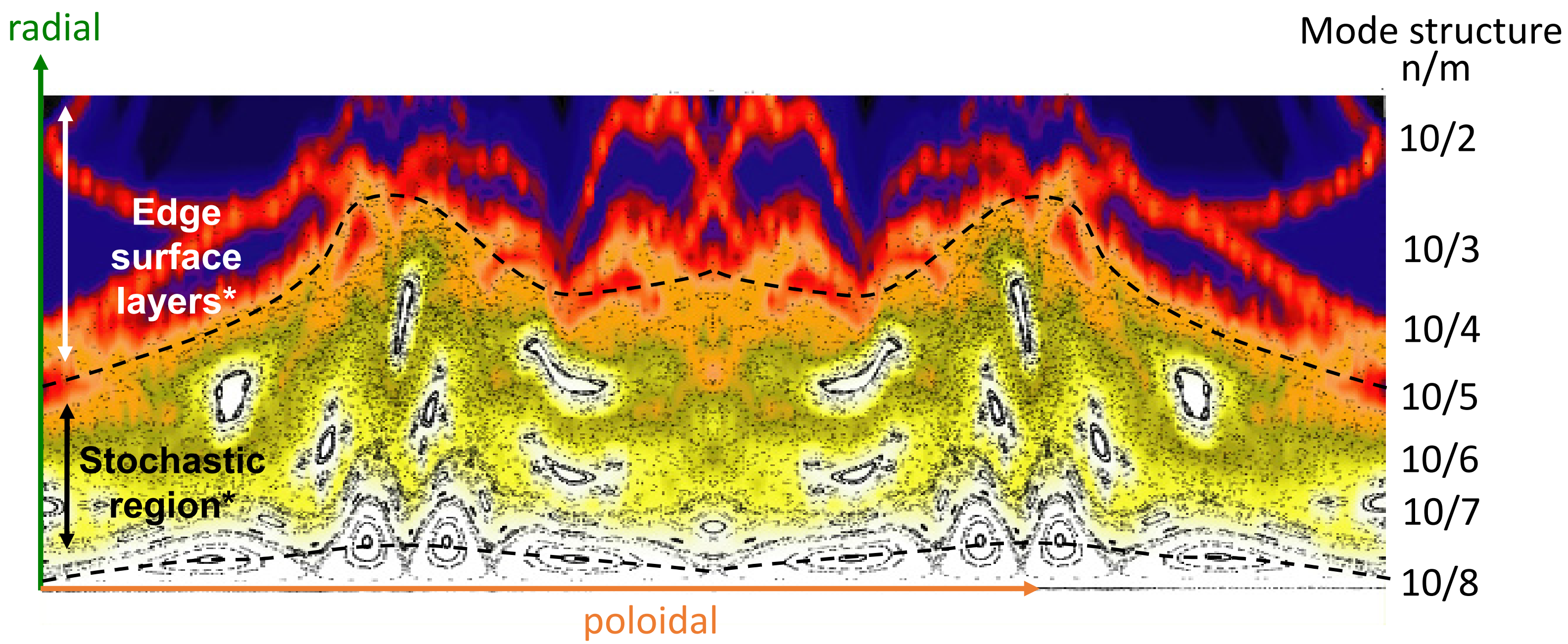
Formation of edge stochastic layers : island chains of various modes

Connection length (L_C) distribution in poloidal cross section



LHD

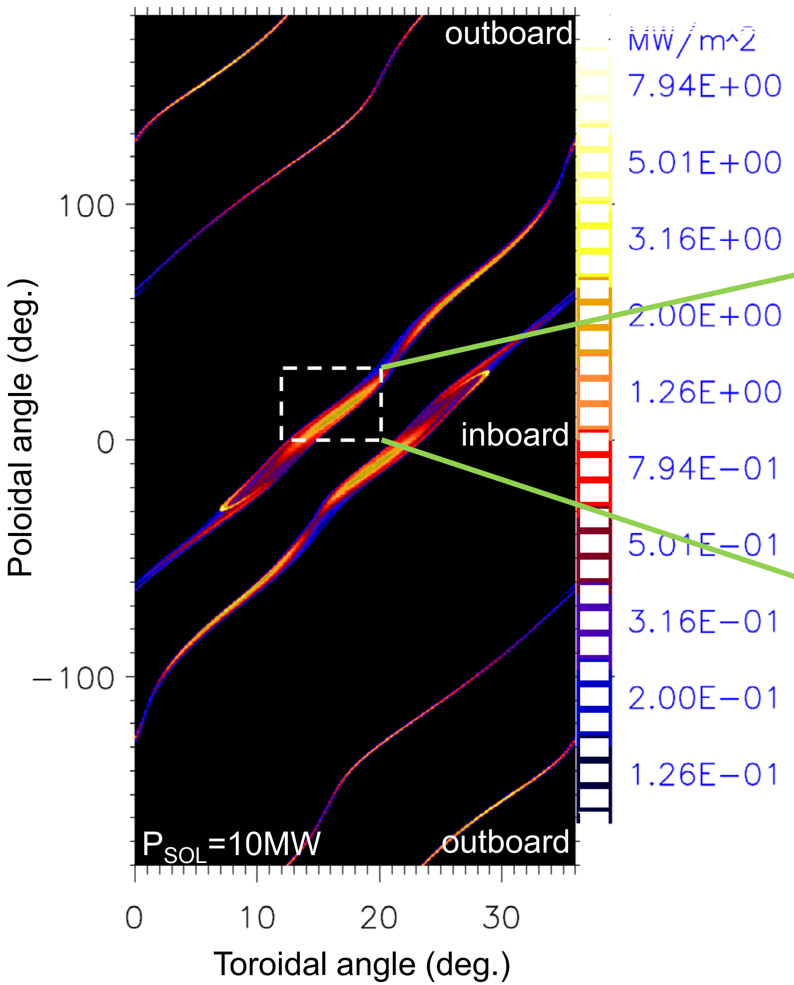




Particle exhaust in LHD helical divertor

Non-uniform plasma heat/particle deposition at divertor plates

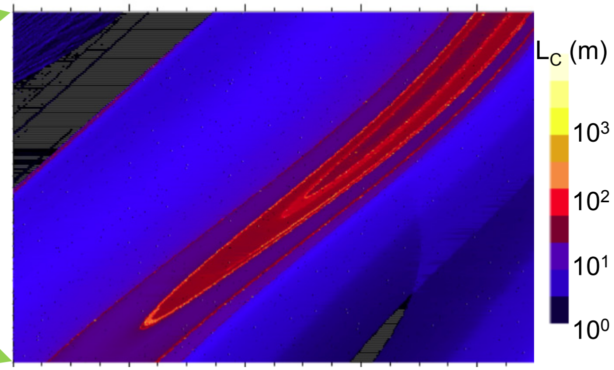
Divertor heat load distribution (EMC3-EIRENE)



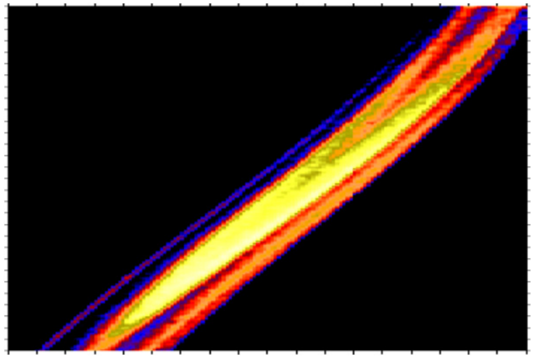
The divertor heat (particle) load distribution is not uniform in helical direction.

The heat load tends to localize at inboard side (and up & bottom).

Magnetic footprint at divertor plate



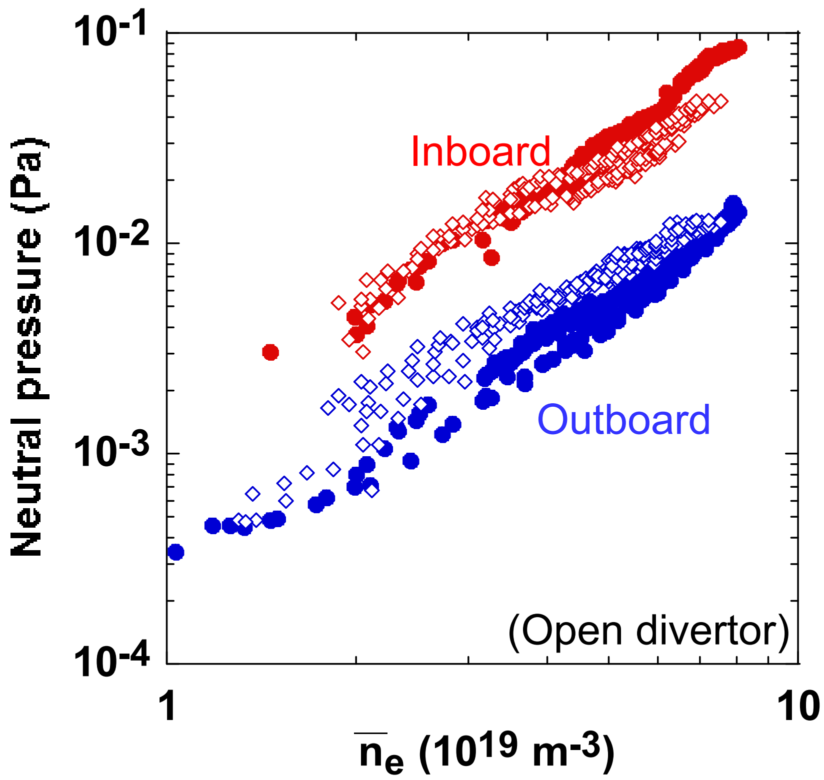
Divertor heat load distribution (EMC3-EIRENE)



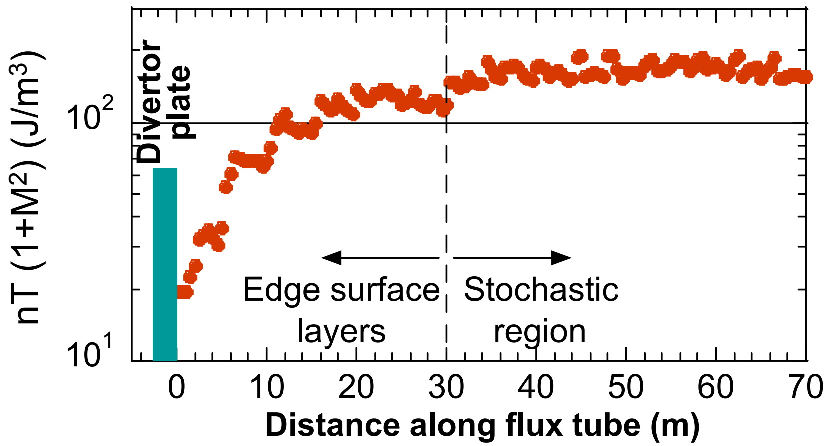
Correlation with L_C distribution is observed

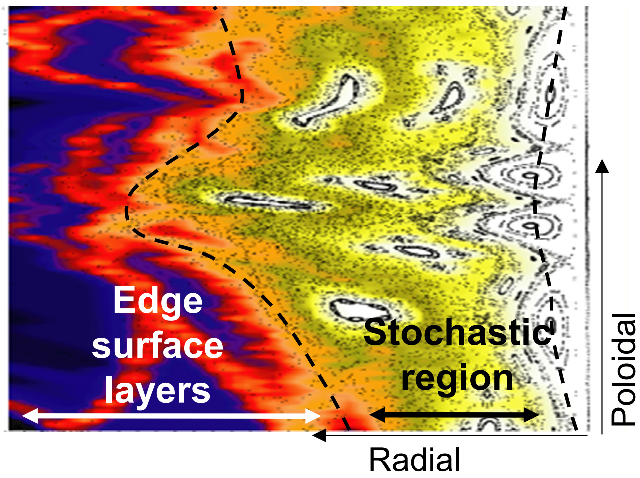
In-out asymmetry of divertor neutral pressure

- 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, < 1×10^{19} m^{-3} (Absence of high recycling regime).
  ← loss of pressure conservation along flux tubes due to enhanced cross-field transport (3D effect).

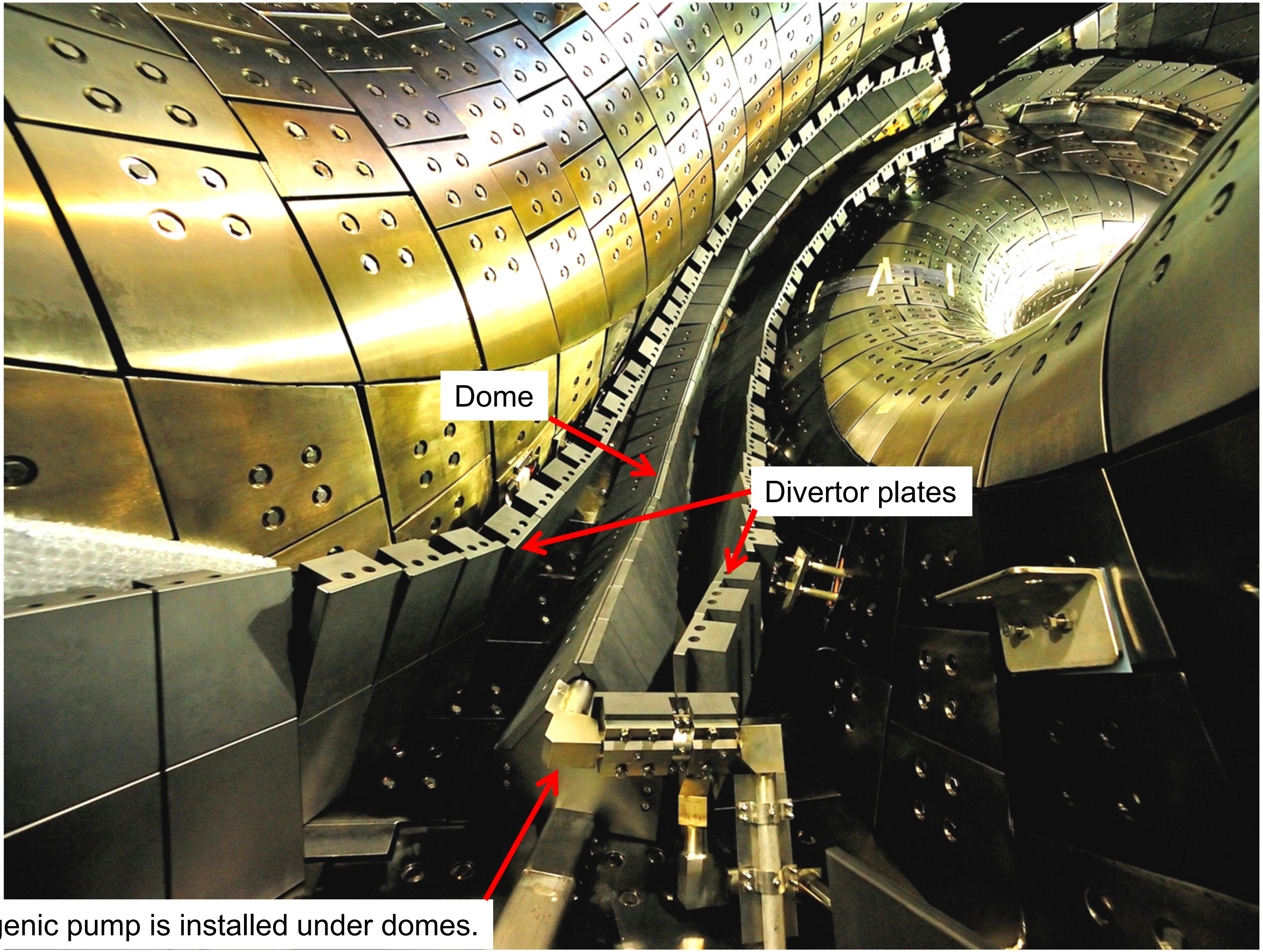


Pressure profile along flux tube (EMC3-EIRENE)



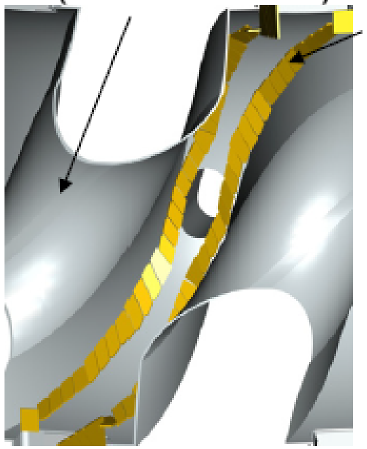


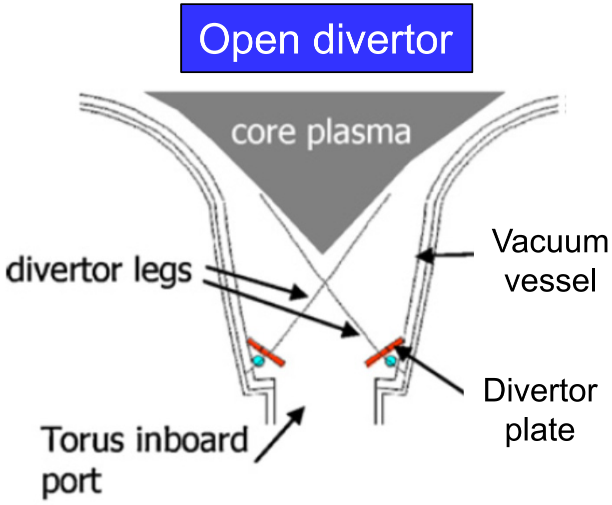
Closed Divertor since 2010

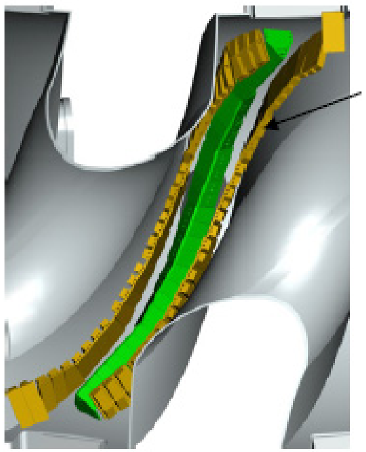


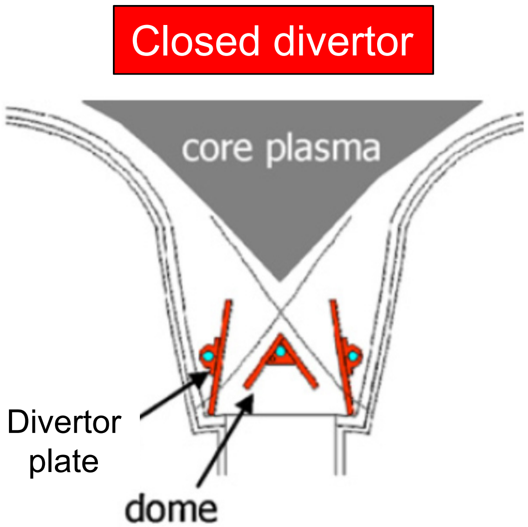
Cryogenic pump is installed under domes.

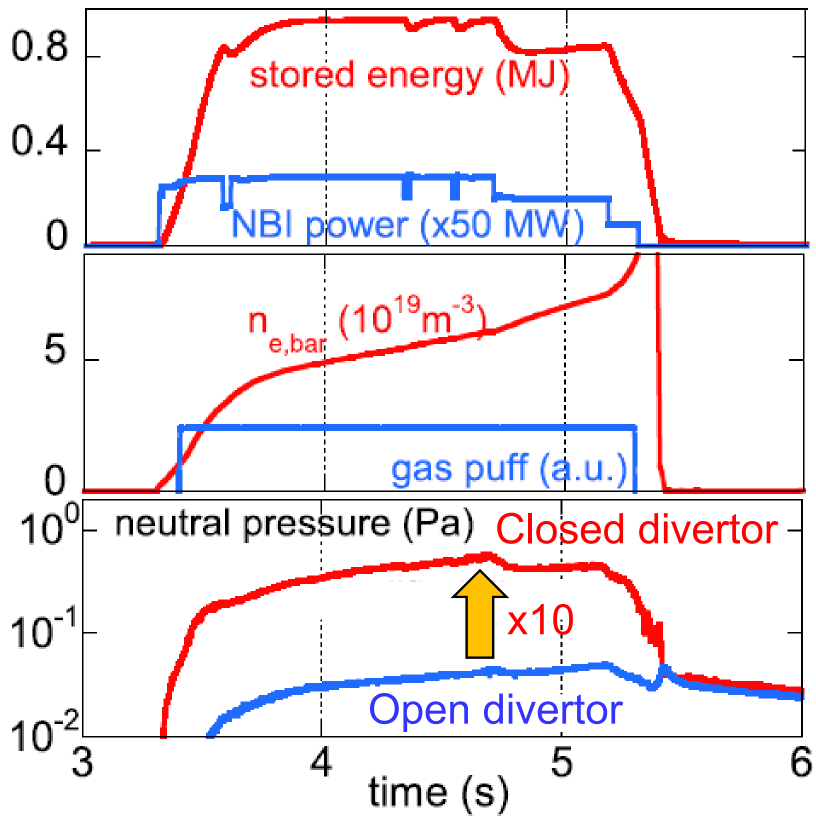
Closed divertor successfully increases divertor neutral pressure by a factor of ~10





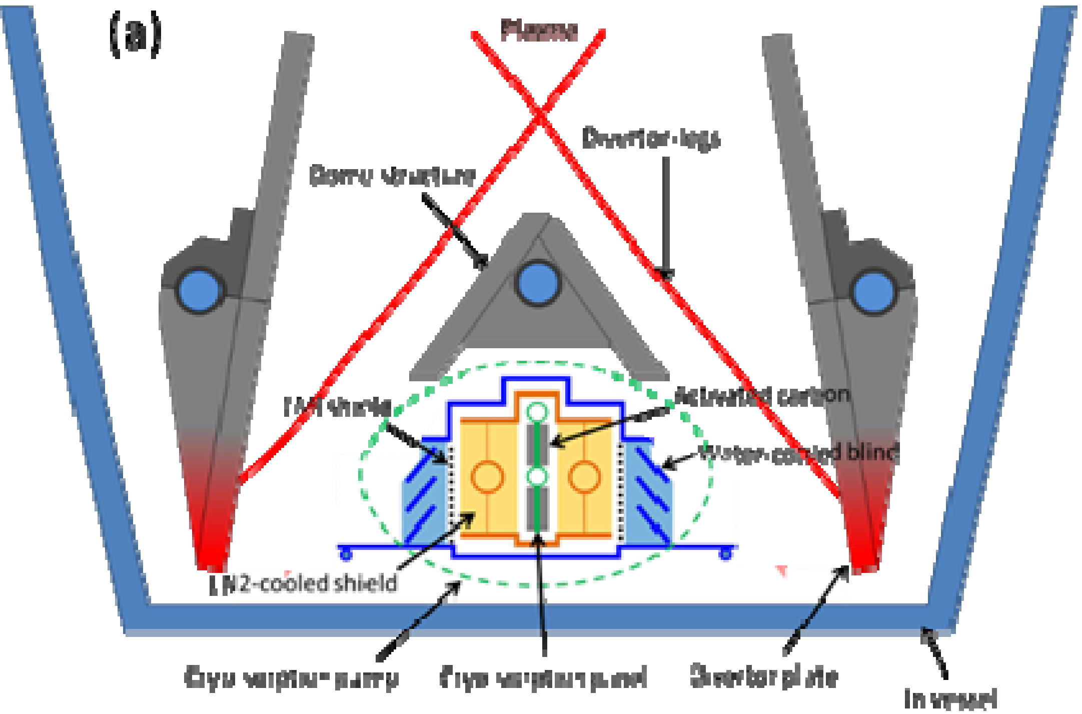


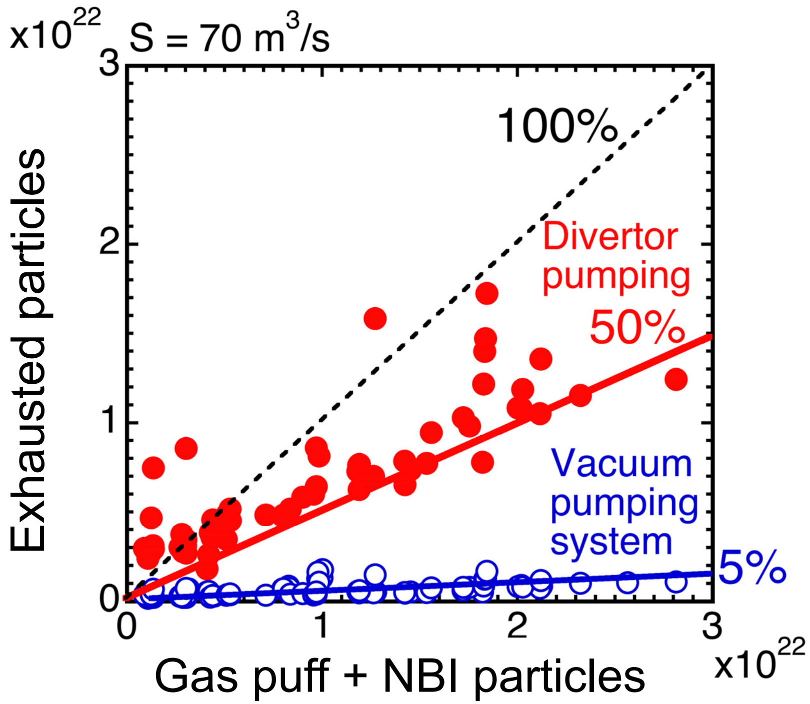




S. Masuzaki et al., Plasma and Fusion Research **6** (2011) 1202007.

Particle exhaust with the divertor pump installed under the dome structure



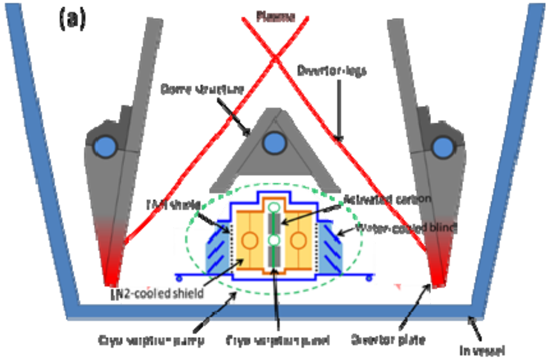


- ✓ **Approximately 50% of the fueled gas is exhausted in the divertor pumping.**
- ✓ **Slight degradation of pumping efficiency observed in high density range.**

G. Motojima NF **59** (2019) 086022.

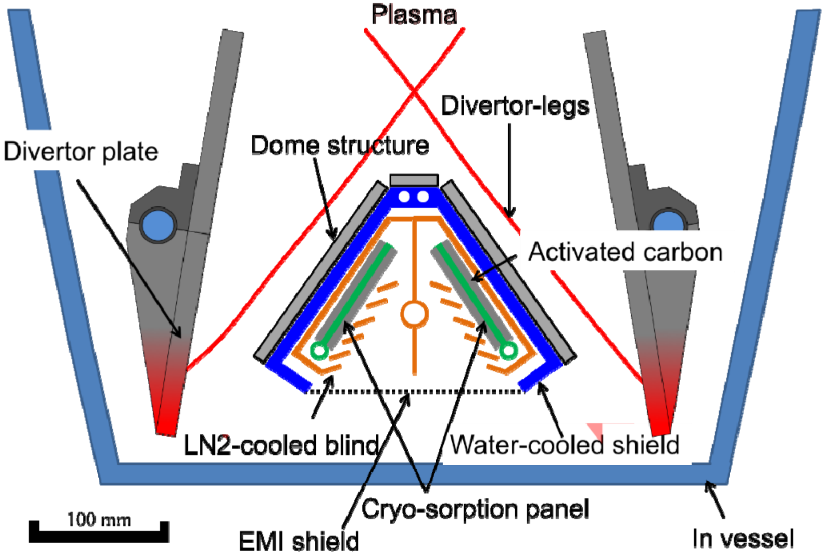
Development of divertor cryo-sorption pump in 3D geometry

Old prototype



T. Murase *et al.*, Plasma. Fus. Res. **11**, (2016) 1205030.

New type



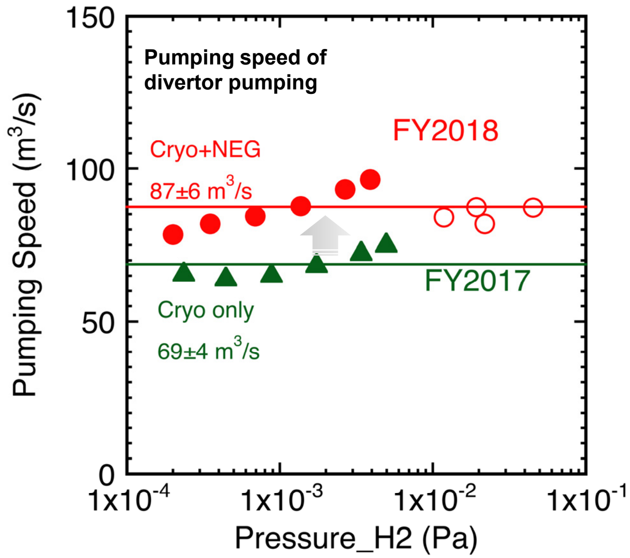
The main characteristics of the development:

(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

3D shaping and compactness

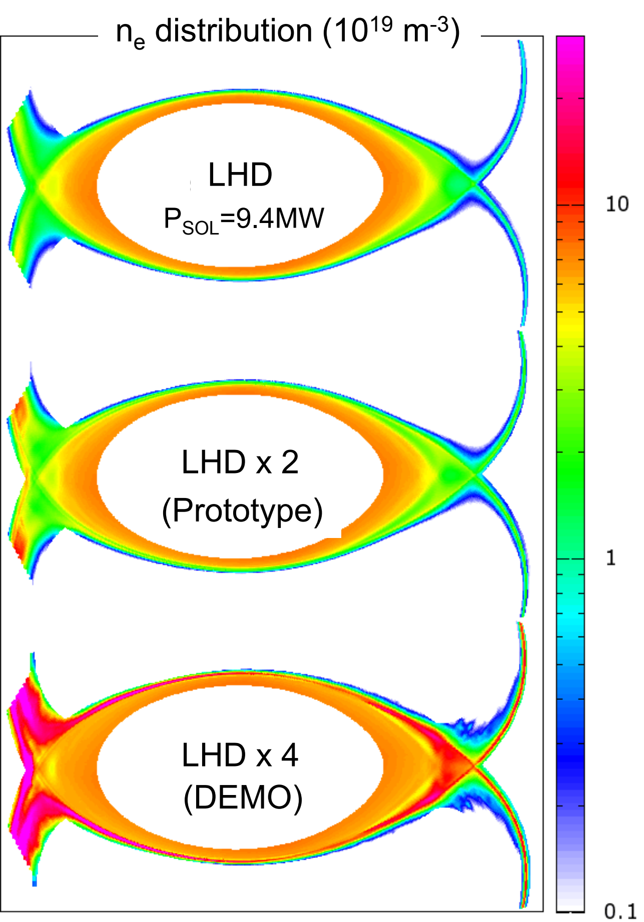


G. Motojima IAEA 2018.

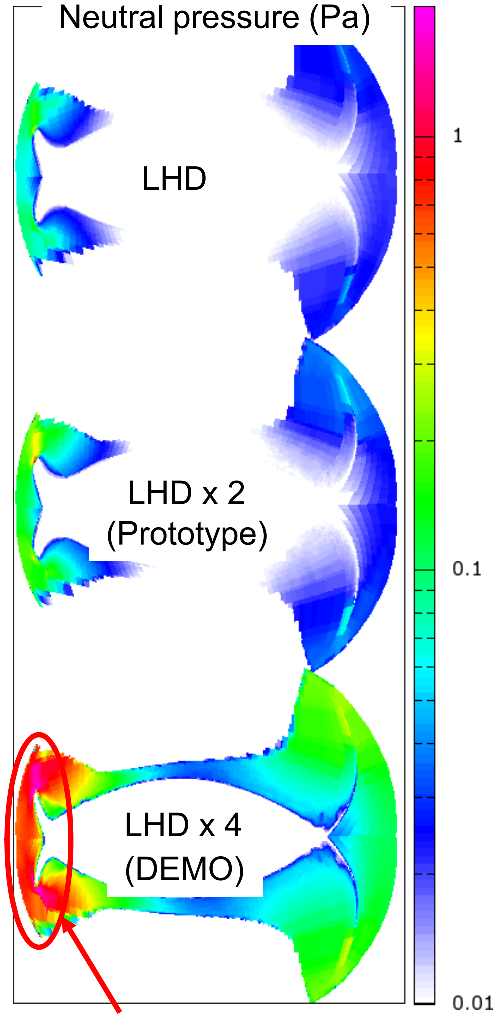
Pumping speed of 96.5 m^3/s, capacity of 86,000 Pa m^{-3} have been achieved so far. To be operated in next experiments.

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.)



Exceeds 1 Pa at DEMO size.

By courtesy of G. Kawamura

	LHD	LHD x 2 (Prototype)	LHD x 4 (DEMO)
R_{ax} (m)	3.6	7.2	14.4
D/χ (m²/s)	0.5/1.0	0.5/1.0	0.5/1.0
n_{up} (10^{19} m^{-3})	7	7	7
P_{SOL} (MW)	9.4	75	600

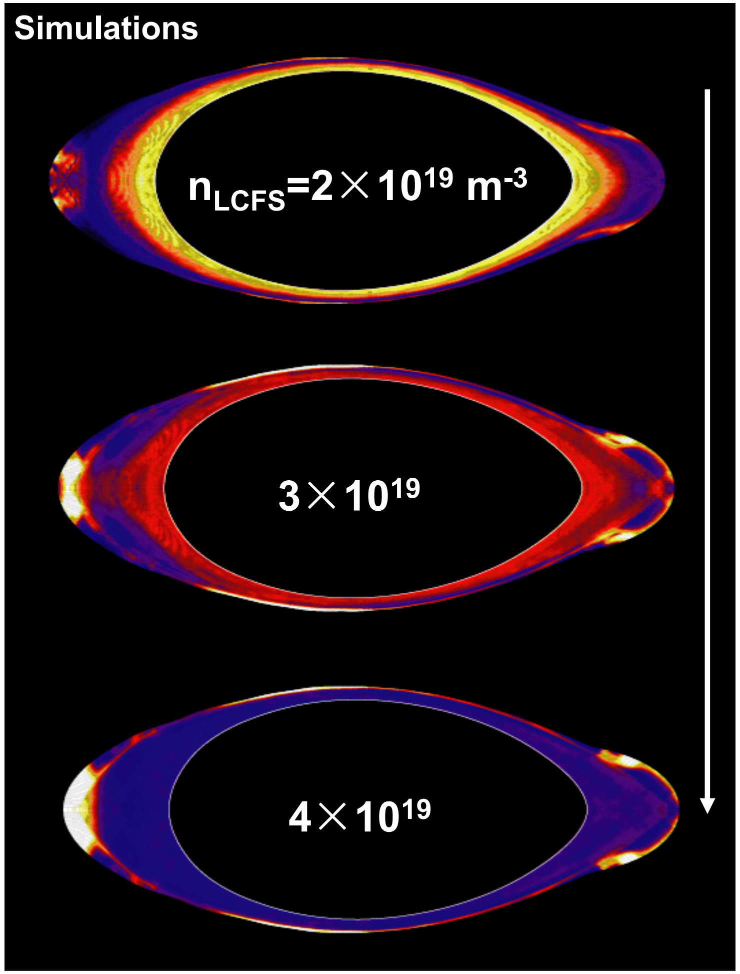
Prediction of EMC3-EIRENE with simply size-scaled computations shows increase in divertor density and neutral pressure
← due to change of relative scale of neutral mfp against plasma size + higher plasma pressure

The results suggest favorable situation for divertor pumping.

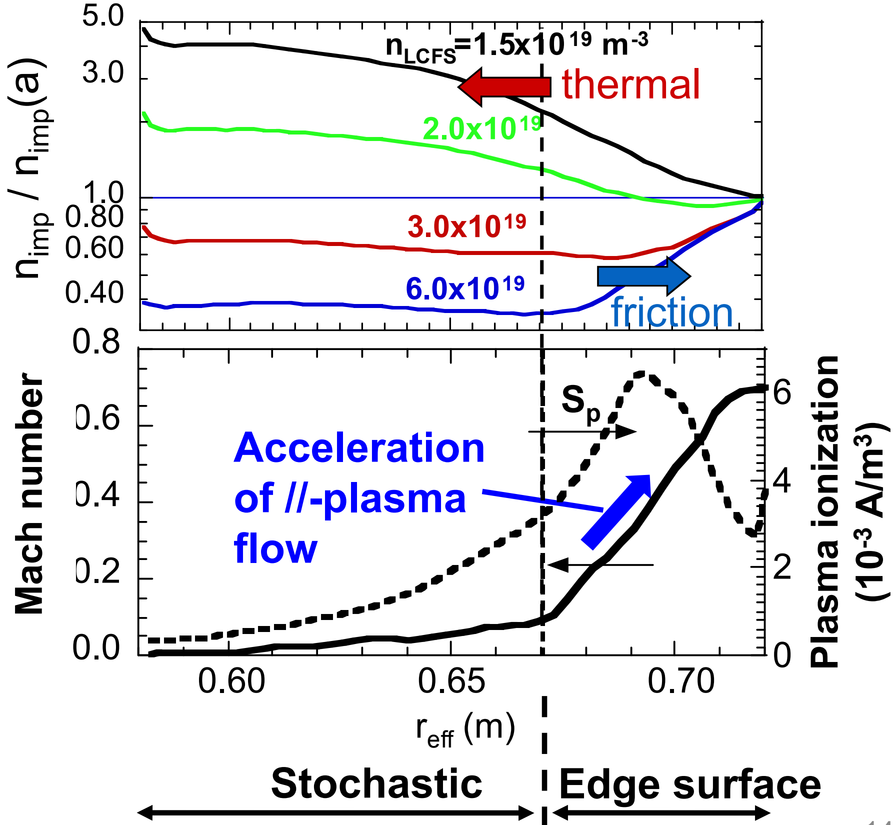
Combination with outboard pumping will improve the pumping efficiency further.
Replacement of cryogenic pump to TMP will be an issue.

Edge impurity transport in LHD helical divertor

Numerical analysis of impurity screening in LHD stochastic layer : high n → friction force ↑, thermal force↓ → screening

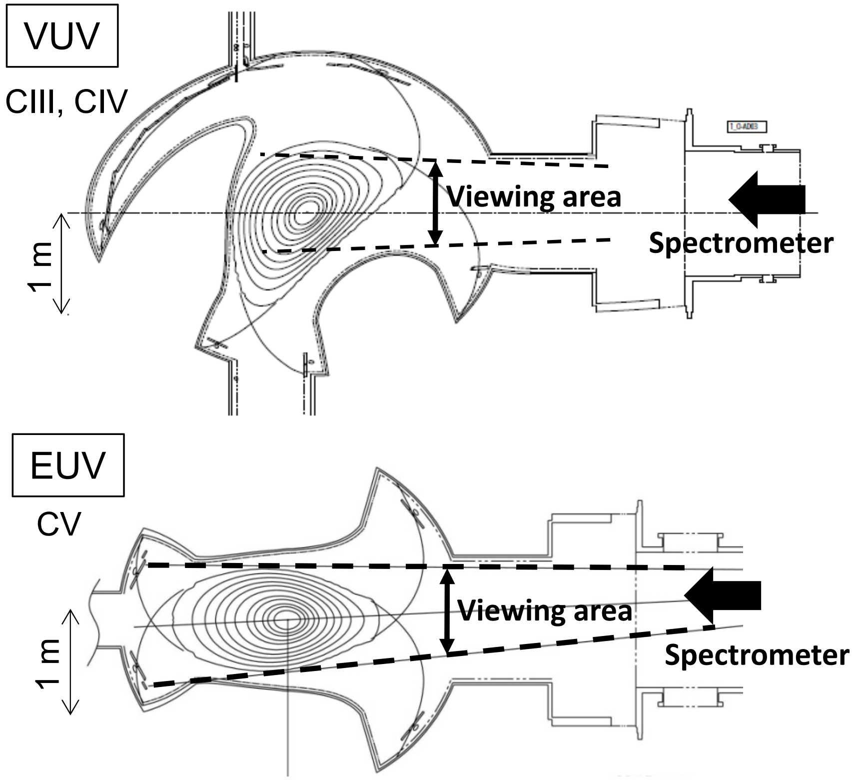


Increasing density
➔ Enhances friction force in edge surface layer with flow acceleration by short flux tubes
➔ Suppresses thermal force in stochastic region



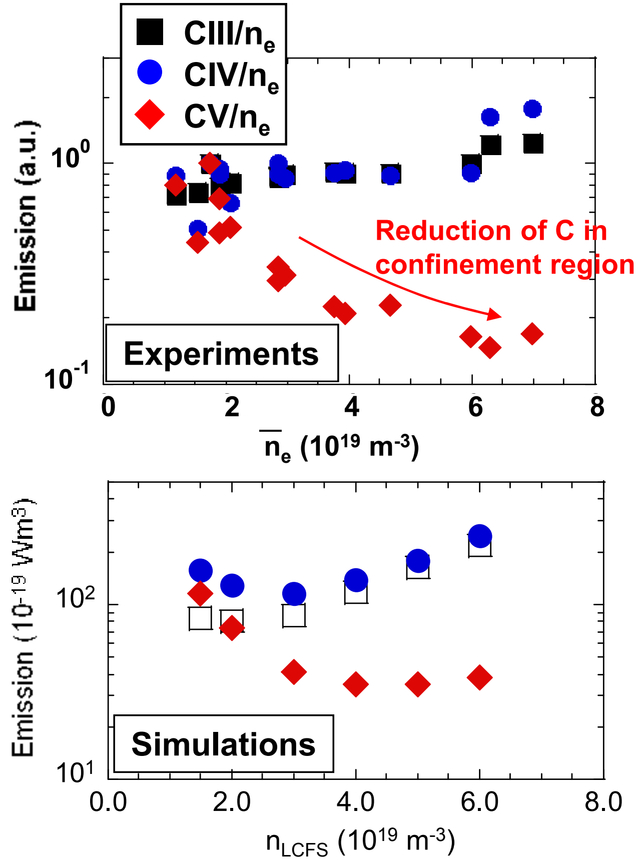
M. Kobayashi NF **53** (2013) 033011.

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 → **Proxy for source**
CV (C^{4+}): 392 eV → **Proxy for C in confinement region**

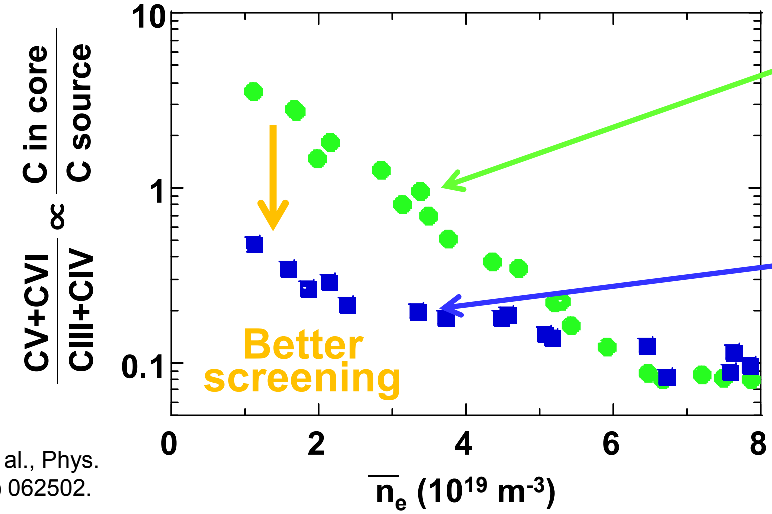


M. Kobayashi NF **53** (2013) 033011.

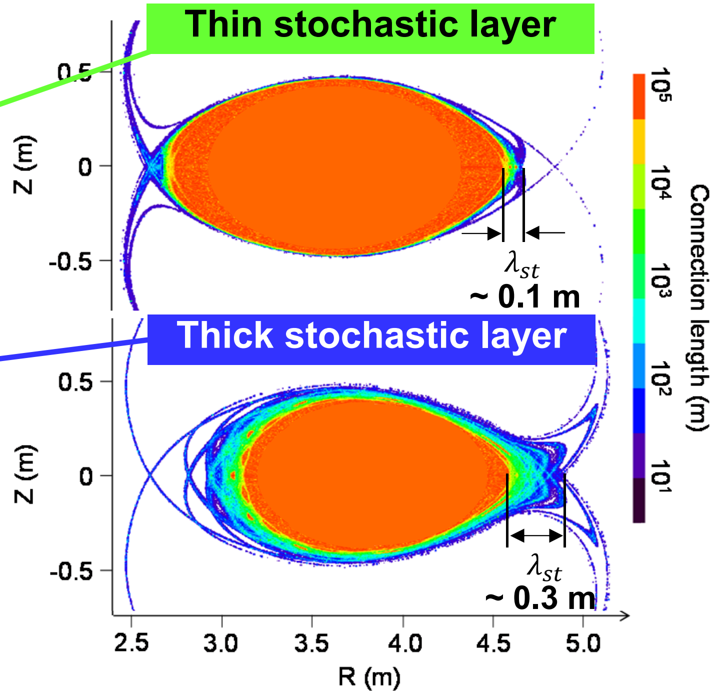
SOL thickness dependence of impurity screening: thicker stochastic SOL → better screening already at low density

- Stochastic layer width (λ_{st}) relative to neutral impurity penetration (λ_{imp})

  $\lambda_{st}/\lambda_{imp}$ ↑ → better screening

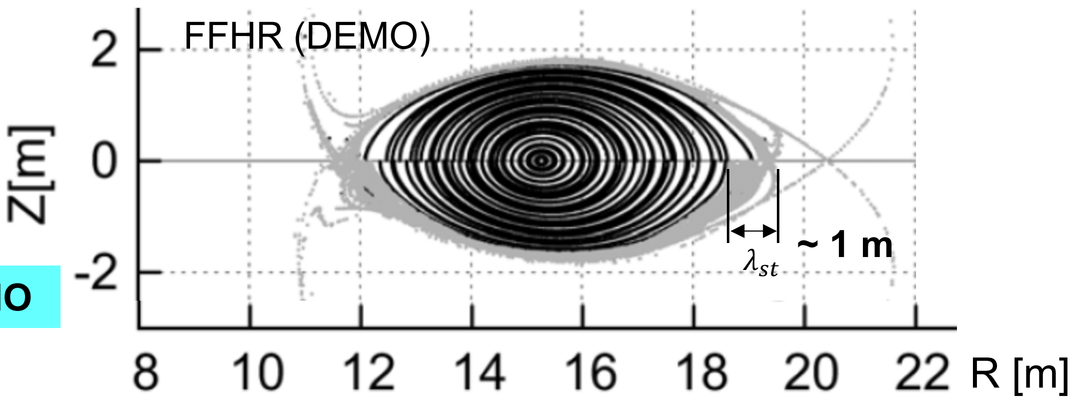


M.B. Chowdhuri et al., Phys. Plasmas **16** (2009) 062502.



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

$\lambda_{st}/\lambda_{imp}$ ↑↑↑

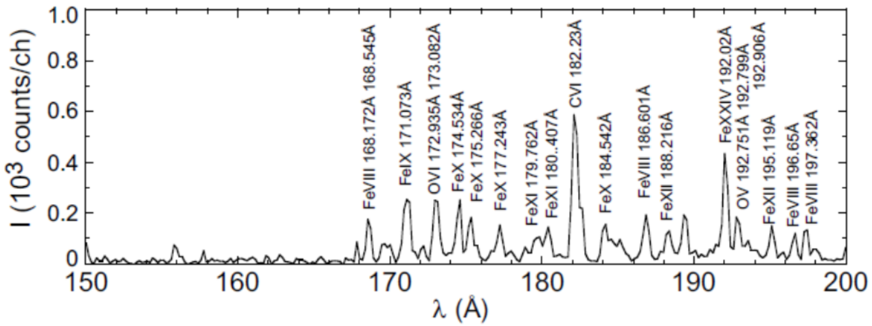


Screening in the stochastic layer can be more effective in DEMO

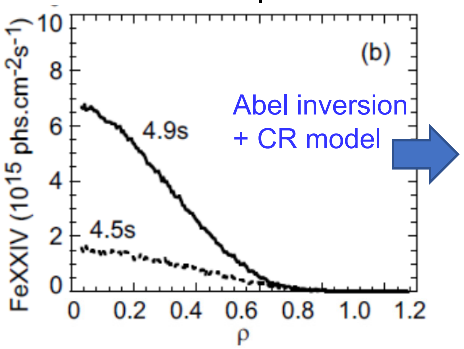
Impurity screening against high Z materials

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

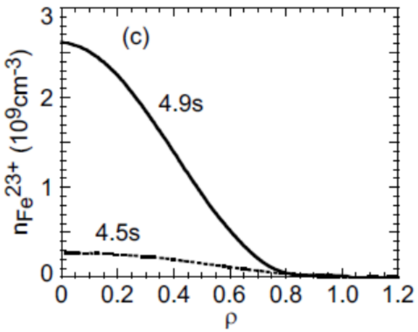
EUV Spectra of iron emission



Line integrated emission profile



Radial profiles of iron density



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

First ionization potential (eV)

C	Ne	Ar	Fe	W
11.3	21.6	15.8	7.9	7.9

- 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} ~ 10^{16} 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: $\Gamma_{\text{div}}^{\text{ave}}$

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

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

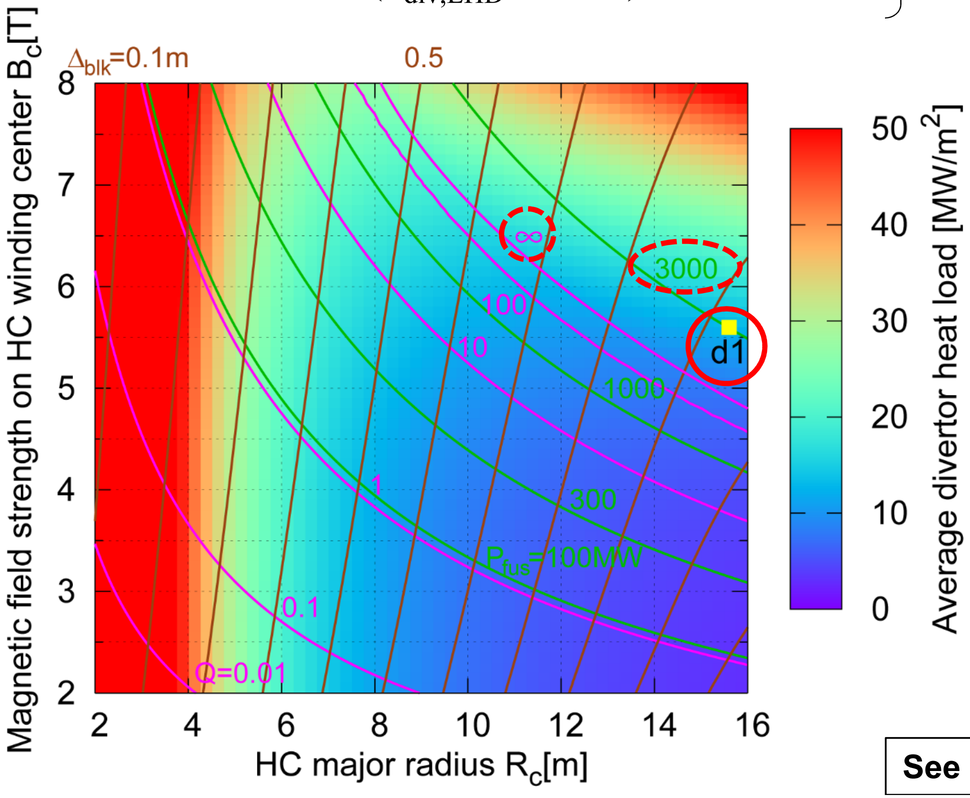
Wetted area: $S_{\text{div}} = S_{\text{div,LHD}}(R_c/R_{c,\text{LHD}})^2$

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

$\Rightarrow\ \Gamma_{\text{div}}^{\text{ave}} \sim 13\ \text{MW/m}^2$

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

Needs heat load mitigation



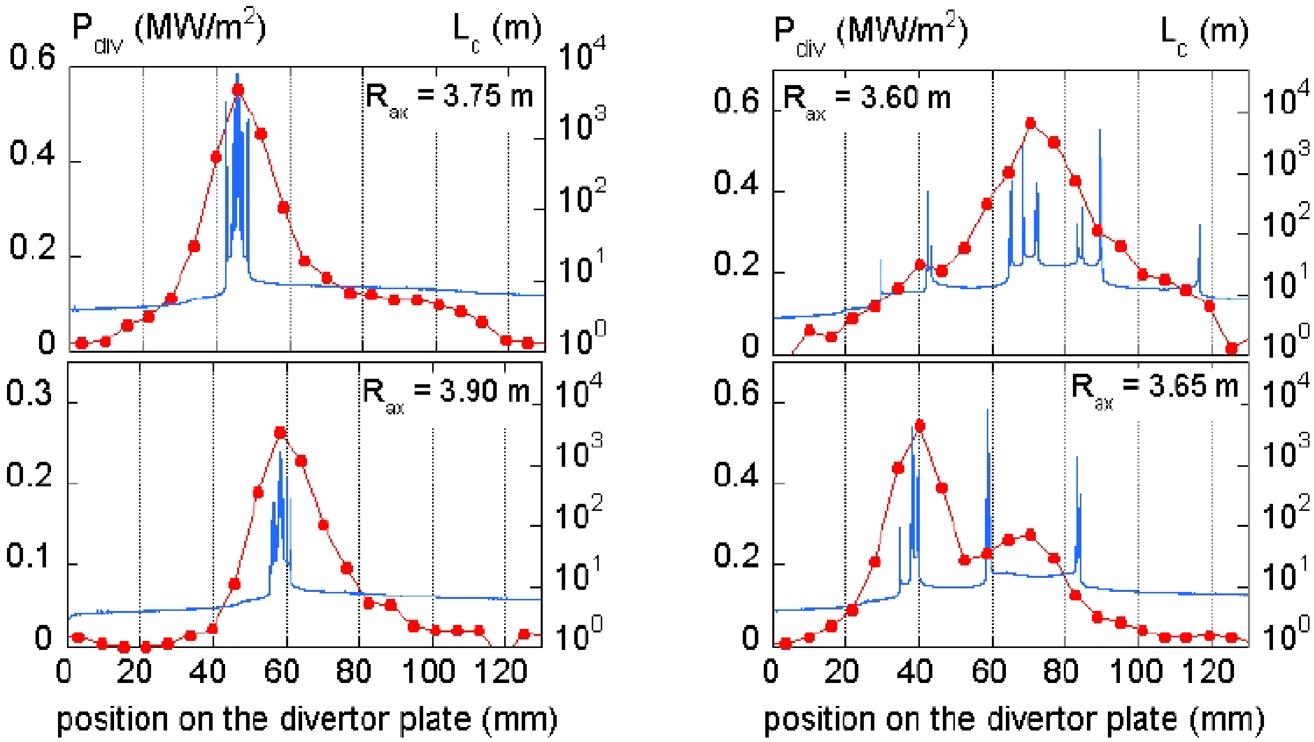
	FFHR-d1 (DEMO)
R / a [m]	15.6 / 2.5
B_c [T]	~5
P_{fus} [MW]	3000
f_{He} / f_{Ar} [%]	5 / 0
P_{rad} [MW]	200
P_{aux} [MW]	0
P_{div} $(= P_{\alpha} + P_{\text{aux}} - P_{\text{rad}})$ [MW]	400
P_{div}/R [MW/m]	35

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 Lc peak.

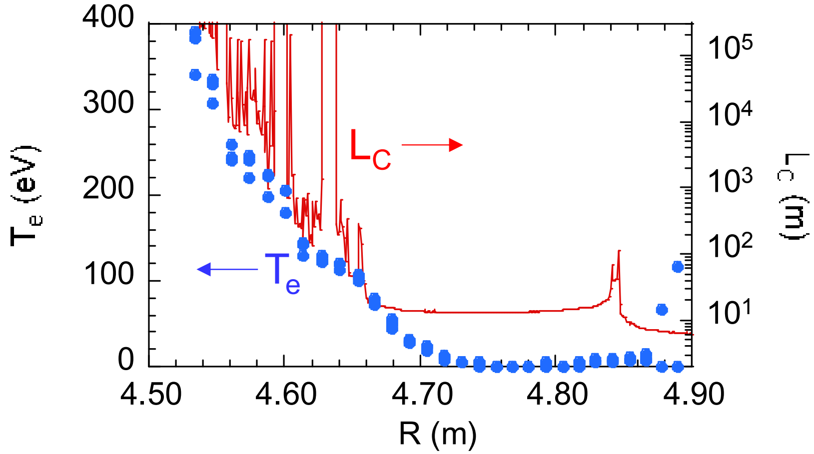


Multi-peak strike lines could widen the wetted area.

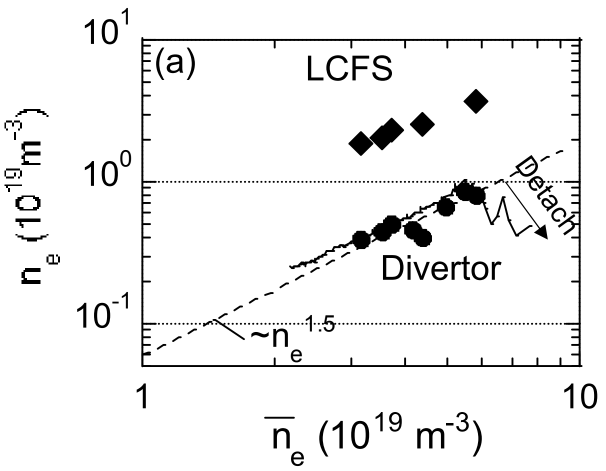
S. Masuzaki et al., CPP **50** (2010) 629.
S. Masuzaki et al., JNM **390-391** (2009) 286.

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

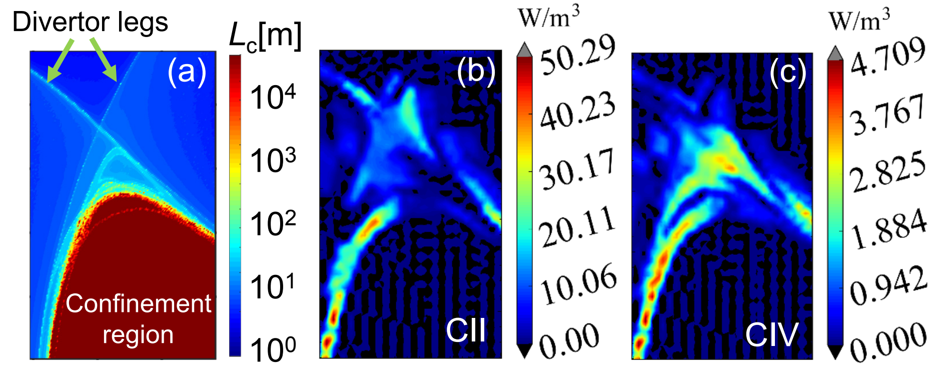
L_C changes from a few meters to more than 1km.
T_e ranges from a few tens to a few hundreds eV.



Density around LCFS is larger than at the divertor region.



Tomographic inversion of carbon emission



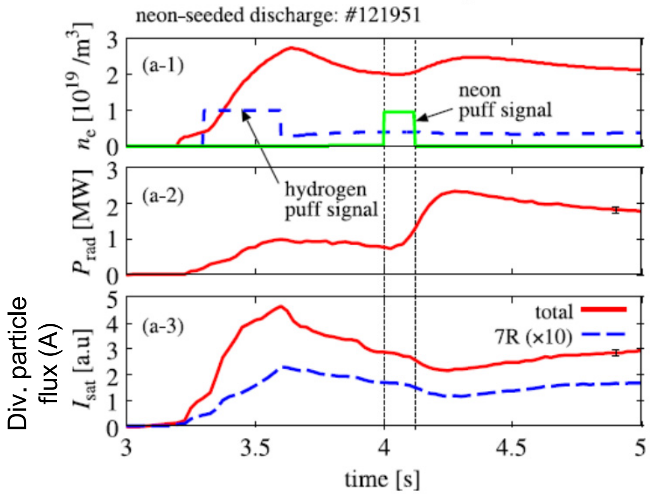
Impurity radiation: the stochastic layer > divertor region

T. Kobayashi et al. NME **19** (2019) 239.

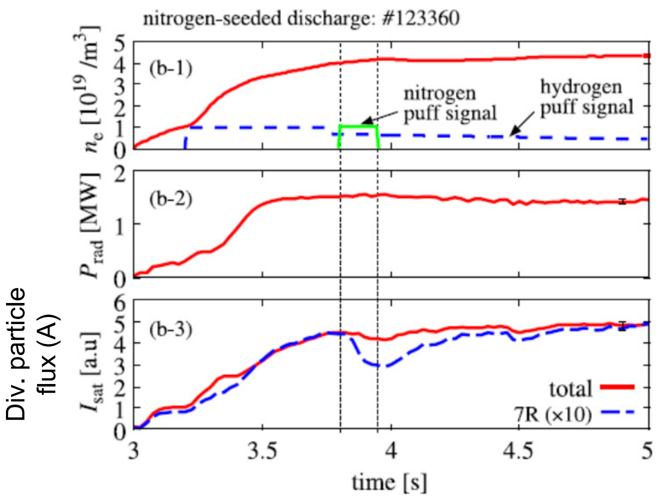
The edge stochastic layer has potential of various impurity emissions of different charge states.

Impurity seeding experiments: Ne and N

Ne seeding

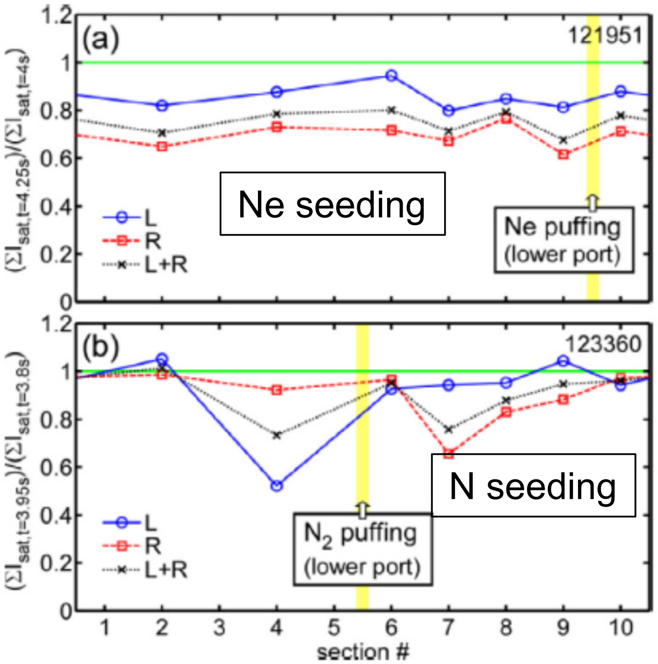


N seeding



G. Kawamura et al. PPCF **60** (2018) 084005.
K. Mukai et al. NF **55** (2015) 083016.

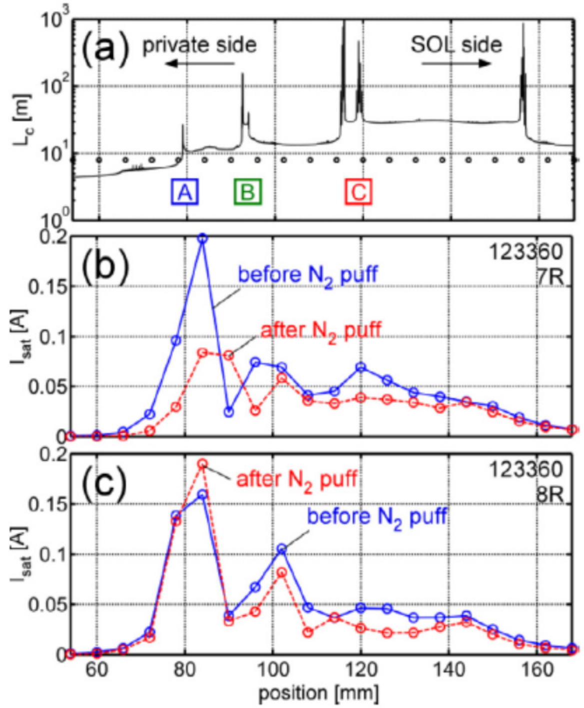
Toroidal profile of div. particle flux



Ne: Toroidally uniform reduction
N: Toroidally asymmetric profile

H. Tanaka et al. NME **12** (2017) 241.

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



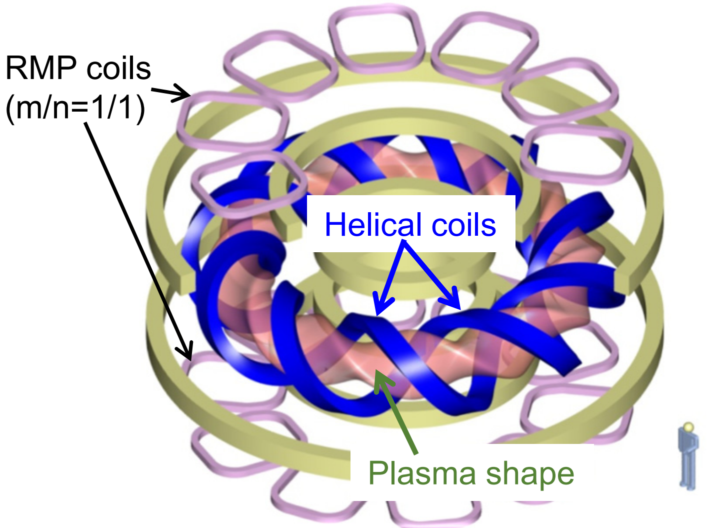
In N seeding, div flux reduction is strongly affected by L_C structure.

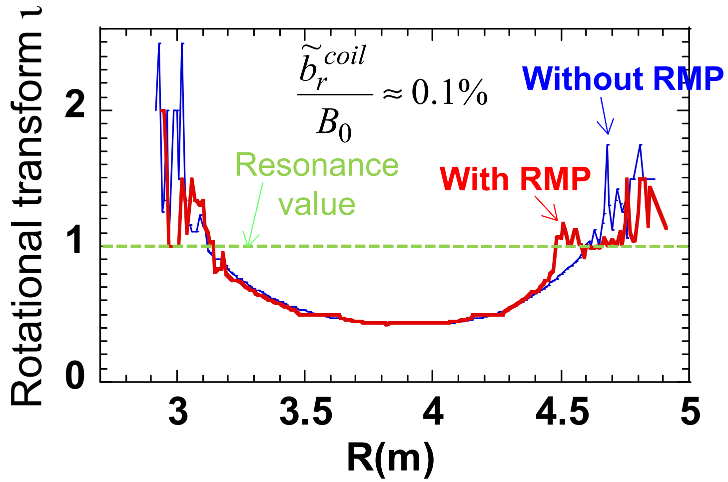
Sustainment of detached phase for longer duration is still to be explored.

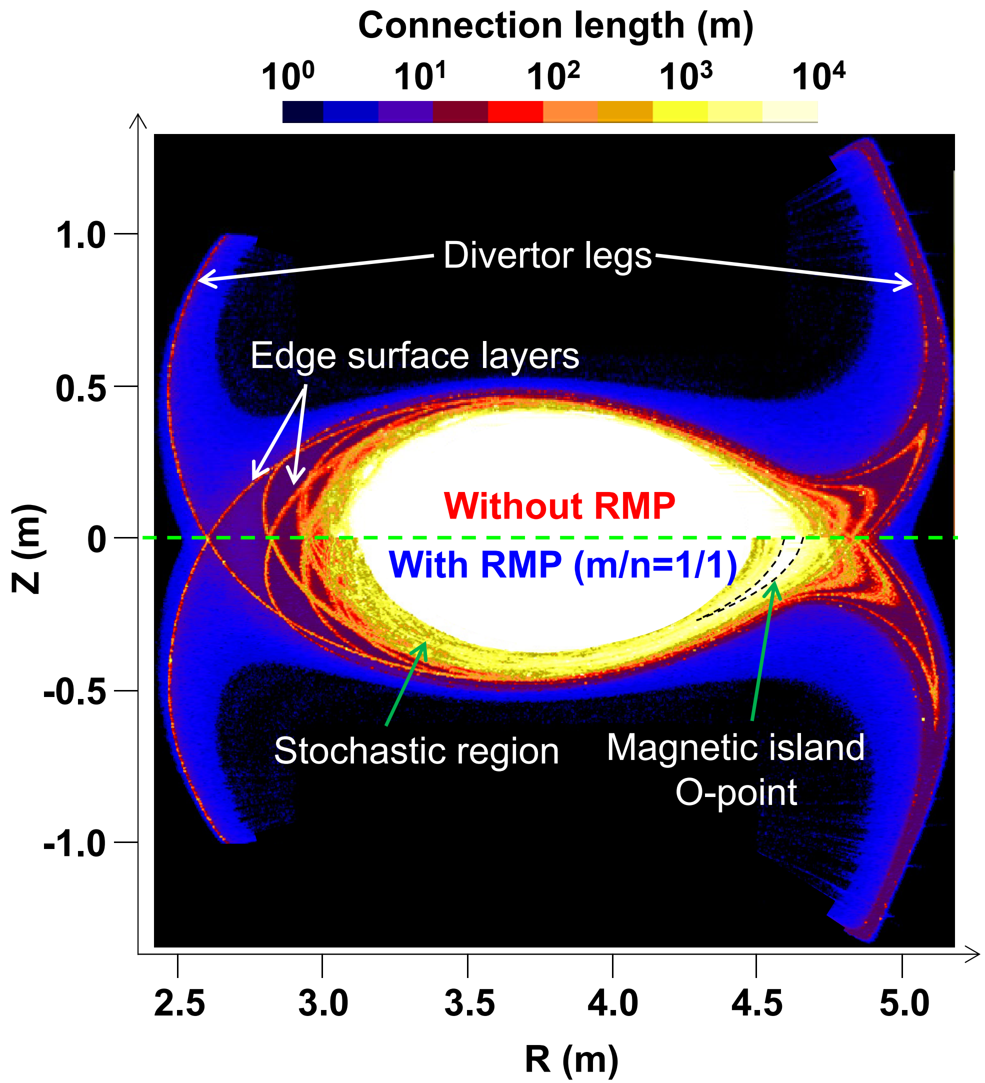
For recent experiments with mixture seeding Ne + Kr, see [48] K. Mukai

Detachment control with RMP application

R = 3.9 m, $\overline{a}$ ~ 0.7 m, 10 field periods (toroidal)
Divertor : carbon, Fist wall : Stainless steel

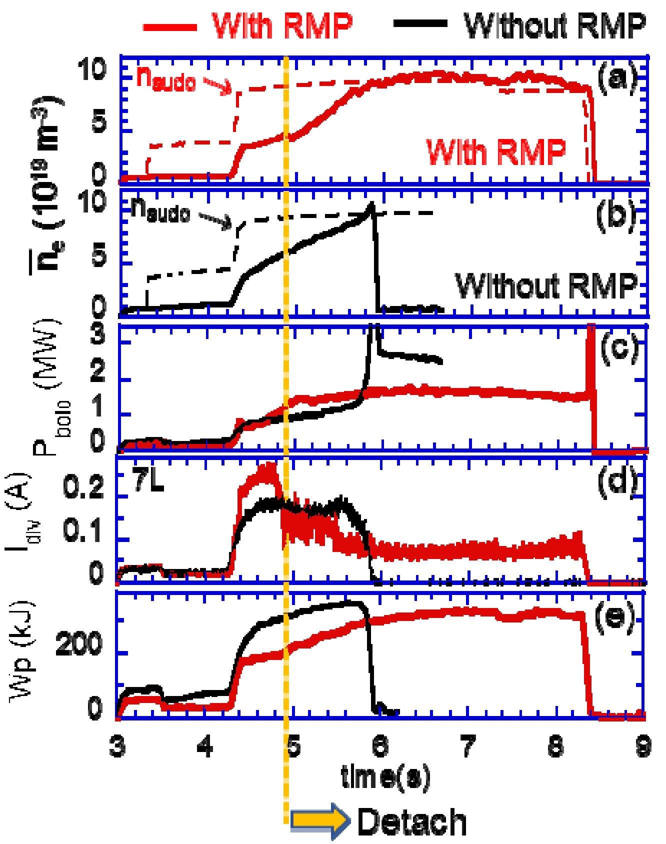


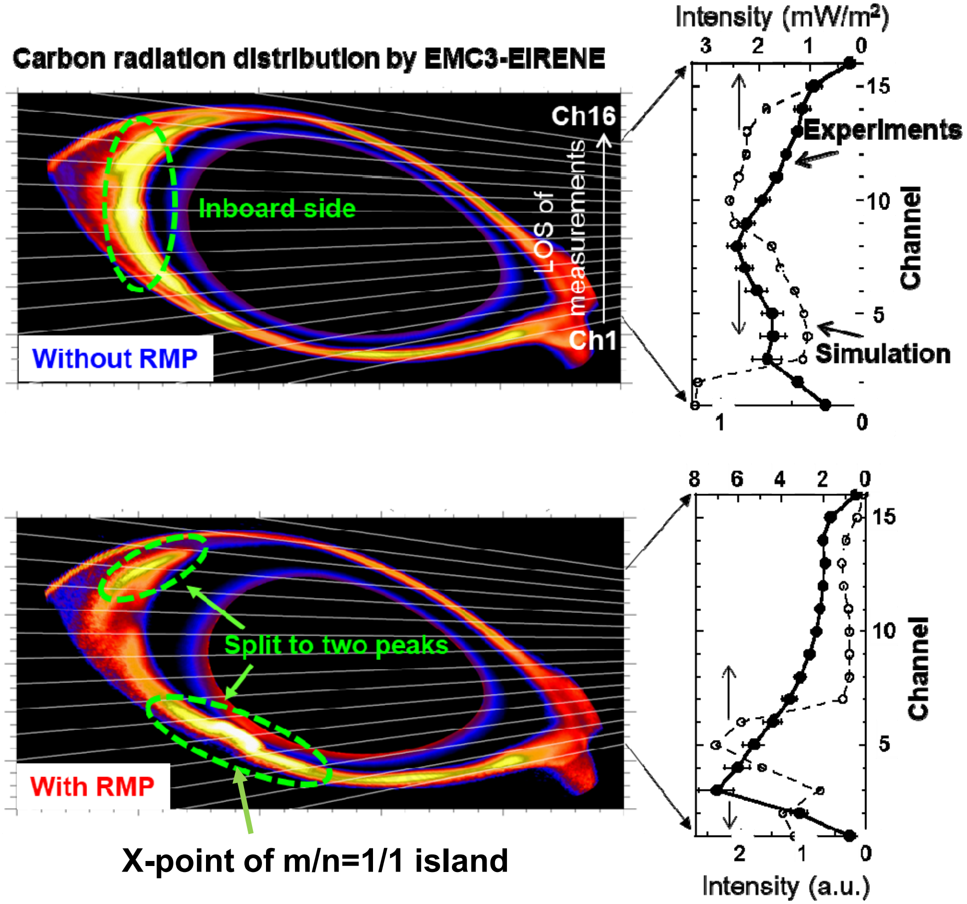




With RMP → Stable sustainment of radiative divertor operation
Without RMP → Radiation collapse due to thermal instability

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

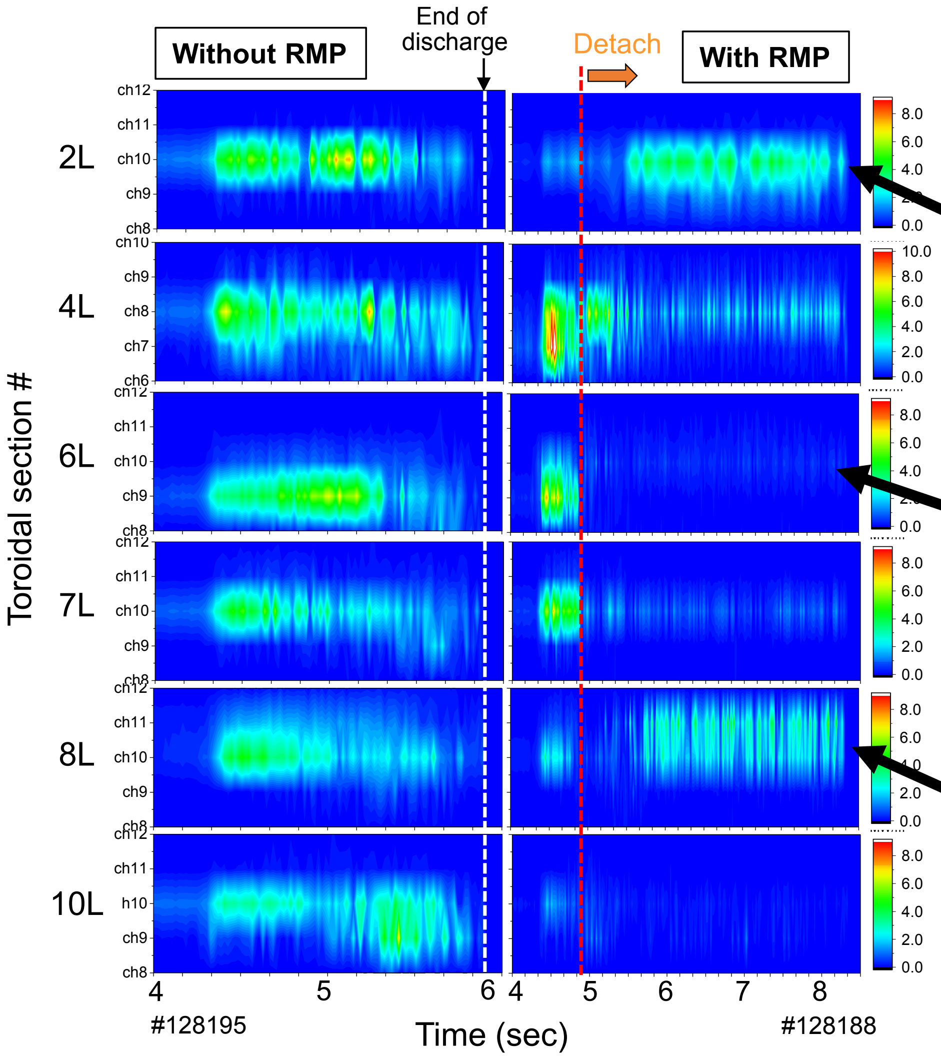




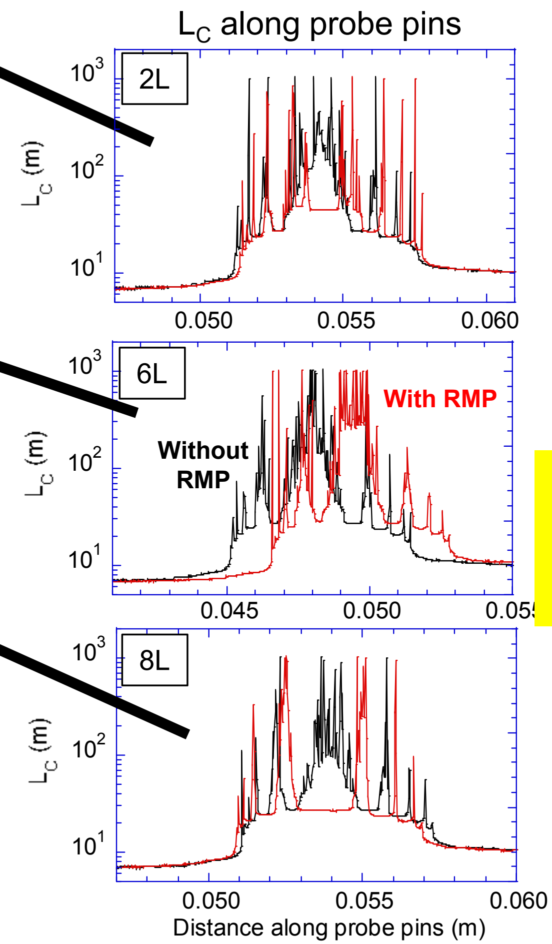
- The radiation profile qualitatively agrees between experiments & simulation.
- Results implies selective cooling at X-point of m/n=1/1 island in experiments.
- The magnetic island structure "catches" the radiation and prevents it from penetrating inward?!

M. Kobayashi et al., NF **59** (2019) 096009. M. Kobayashi et al., NF **53** (2013) 093032.

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?**

Summary

The LHD heliotron divertor needs to be optimized toward helical DEMO

Advantage (Control of transport) ⟷ **Disadvantage (Complexity of transport & engineering)**

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 issues toward helical DEMO among above issues?