Divertor pumping for steady state operation in LHD experiments

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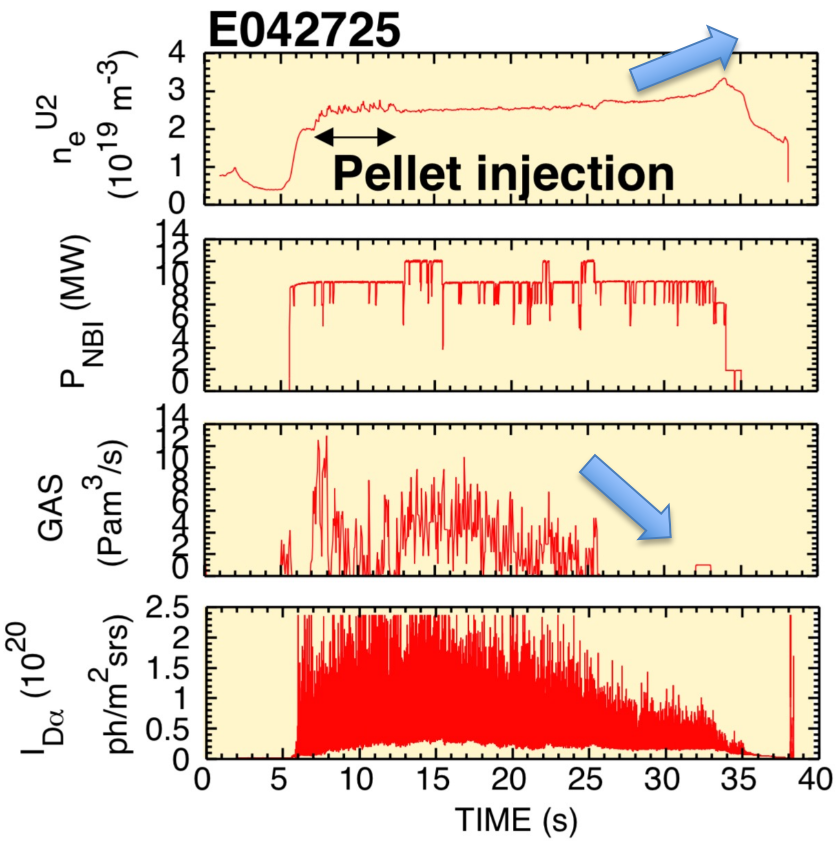
Contents

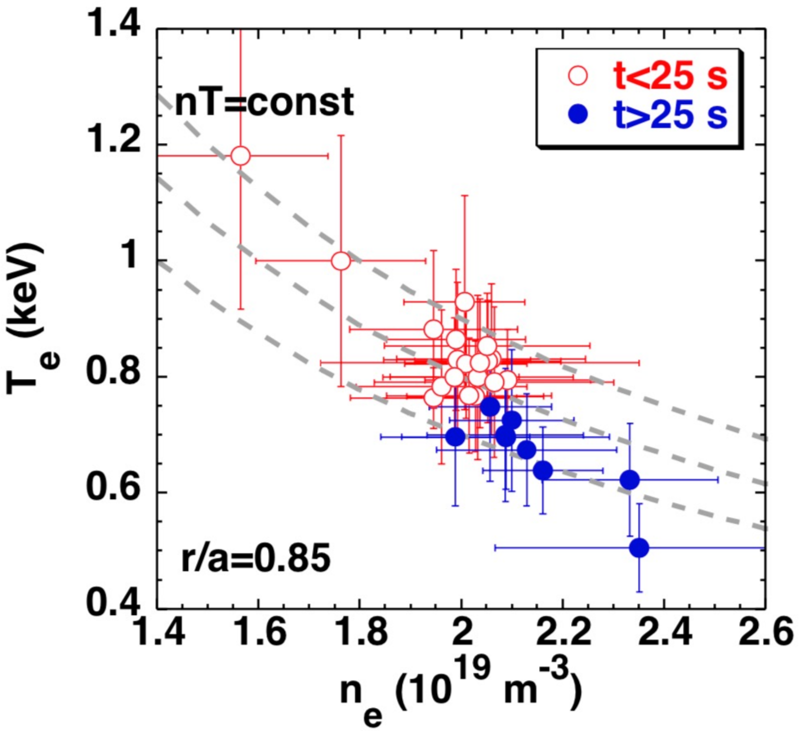
1. Importance of recycling control
2. Development of divertor pumping in LHD
3. Density control and new physics findings using divertor pumping
4. Development of neutral pressure gauge
5. Development of activated carbon for cryo-sorption pump and its to multi-purpose development
6. Summary

Importance of recycling control

JT-60U

Kamada, Atomic Energy Society 2004





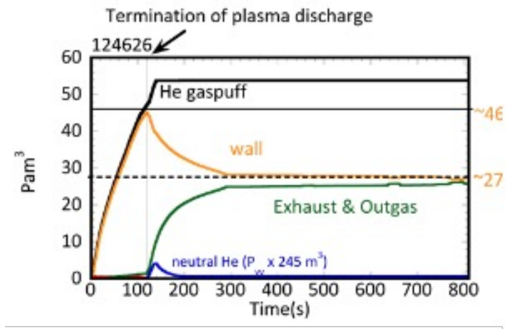
Edge plasma pressure is degraded at the wall saturation.

Wall saturation was observed.
Gas feed was not required in the latter phase.

Phased wall retention is observed in long pulse discharge of LHD plasma

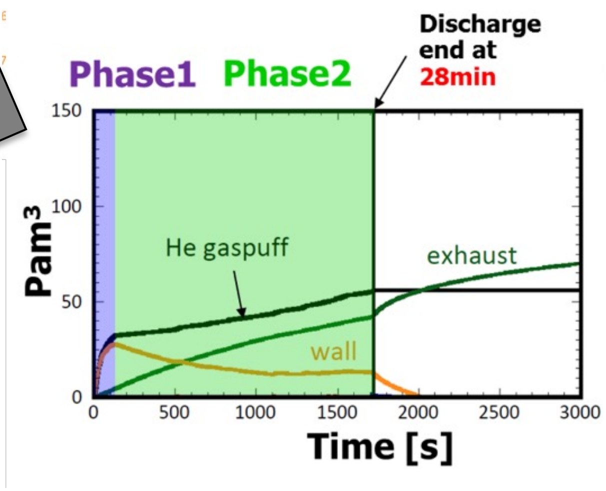
G. Motojima+, J. Nucl. Mat. **463** (2015) 1080.

2min. discharge



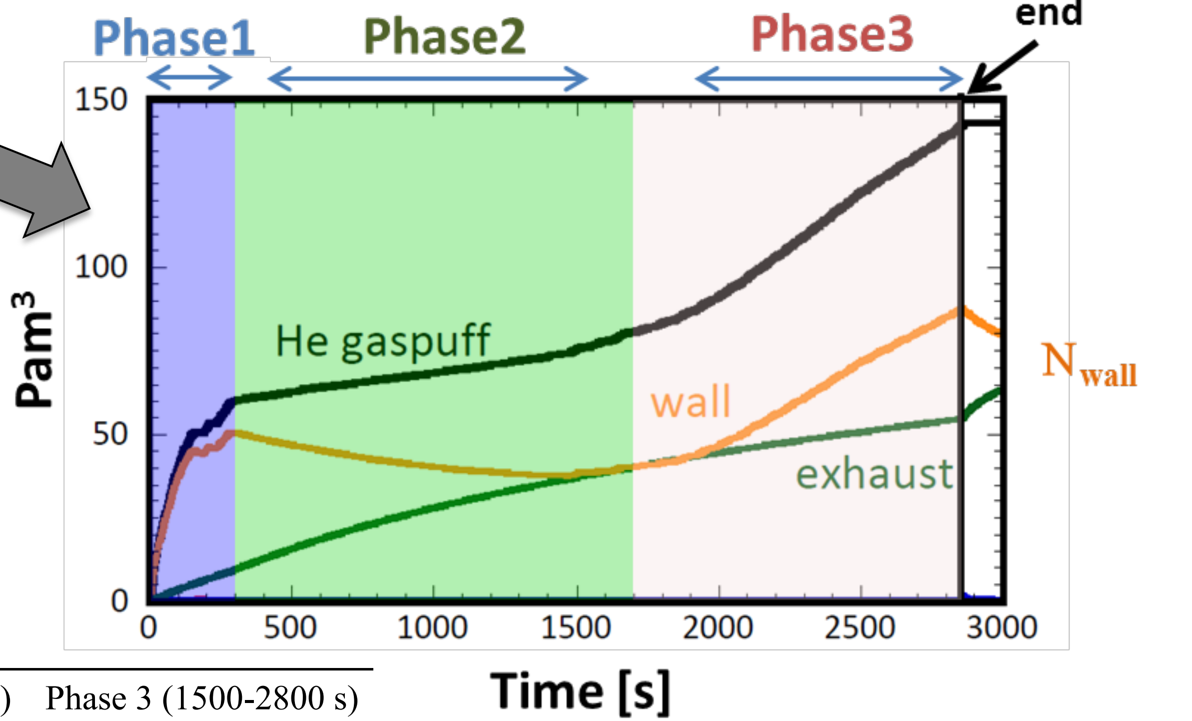
He sink @Phase1

28min. discharge



He source @phase2

48min. discharge

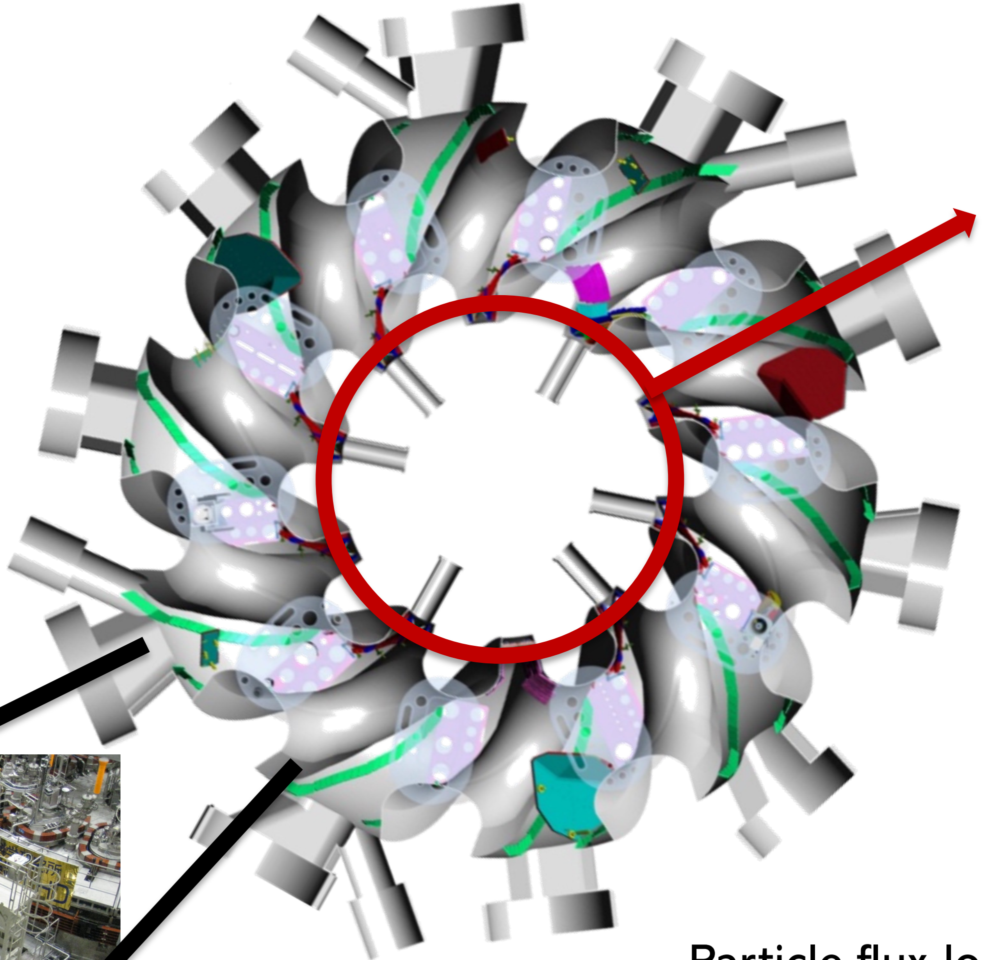


He sink@phase3

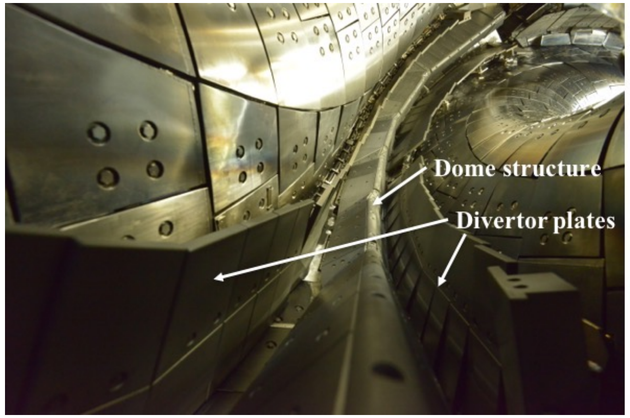
	Phase 1 (0-300 s)	Phase 2 (300-1500 s)	Phase 3 (1500-2800 s)
Γ_{fuel}	~1.0 × 10^{20} He/s	~3.2 × 10^{18} He/s	~1.6 × 10^{19} He/s
Γ_{wall}	~1.0 × 10^{20} He/s	~−3.5 × 10^{18} He/s	~1.4 × 10^{19} He/s
Total fuel	~1.6 × 10^{22} He	~2.0 × 10^{22} He	~3.7 × 10^{22} He
Total wall	~1.3 × 10^{22} He	~9.6 × 10^{21} He	~2.2 × 10^{22} He

The difference of the retention characteristics of deposition layer on the plasma facing wall qualitatively explain the phased wall retention.

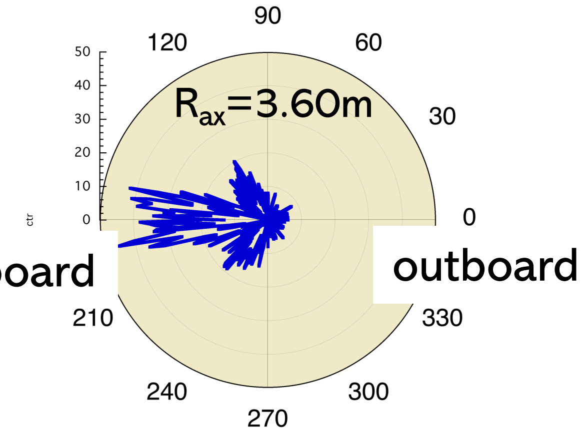
Vacuum pumping system in LHD



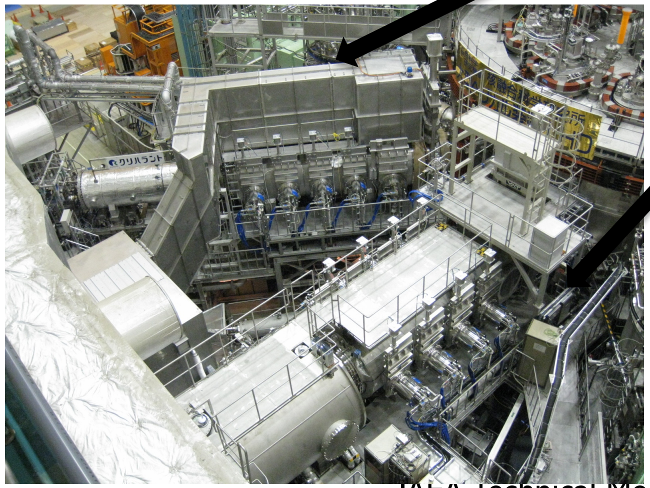
Divertor pumping system



T. Morisaki+, NF 2013



Main pumping system
~250 m^3/s
< 10^{-3} Pa
low neutral compression



Particle flux localized in inner toroidal section
~80 m^3/s (Cryo-sorption + NEG pumps)
< 1 Pa
High neutral compression possible in divertor pumping

General global particle balance

$$\boxed{\int \Gamma_{\mathrm{fuel}} dt \sim \int \Gamma_{\mathrm{wall}} dt + \int \Gamma_{\mathrm{Ex}} dt}$$

Currently, wall pumping is predominant in LHD. However, in DEMO reactors, wall recycling should be 1 in terms of tritium inventory and in steady state conditions.

$$\int \Gamma_{\mathrm{fuel}} dt \sim \int \Gamma_{\mathrm{Ex}} dt$$

$$\int \Gamma_{\mathrm{Ex}} dt = \int \Gamma_{\mathrm{Ex_{main}}} dt + \boxed{\int \Gamma_{\mathrm{Ex_{div}}} dt}$$

Main exhaust system pumps
Low compression

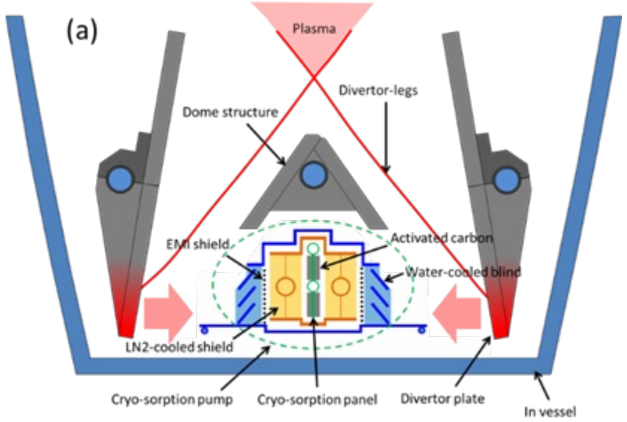
Divertor pumps
High compression

Divertor pump is important tool for density control

Contents

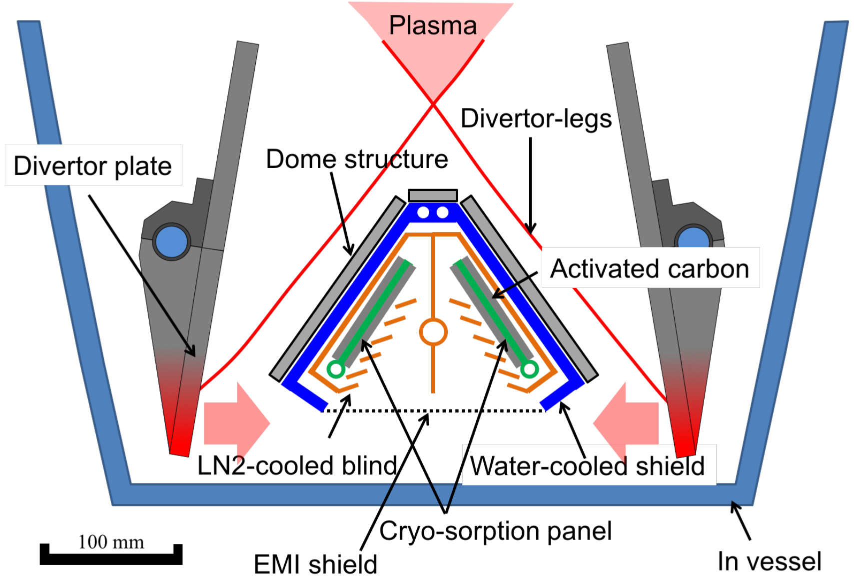
Improved in-vessel cryo-sorption pumps installed inside the divertor

Old prototype



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

Newly improved type



G. Motojima *et al.,* 2018 Nucl. Fusion **58** 014005.

The main characteristics of the development:

(1) Finding of new activated carbon → high pump speed and capacity

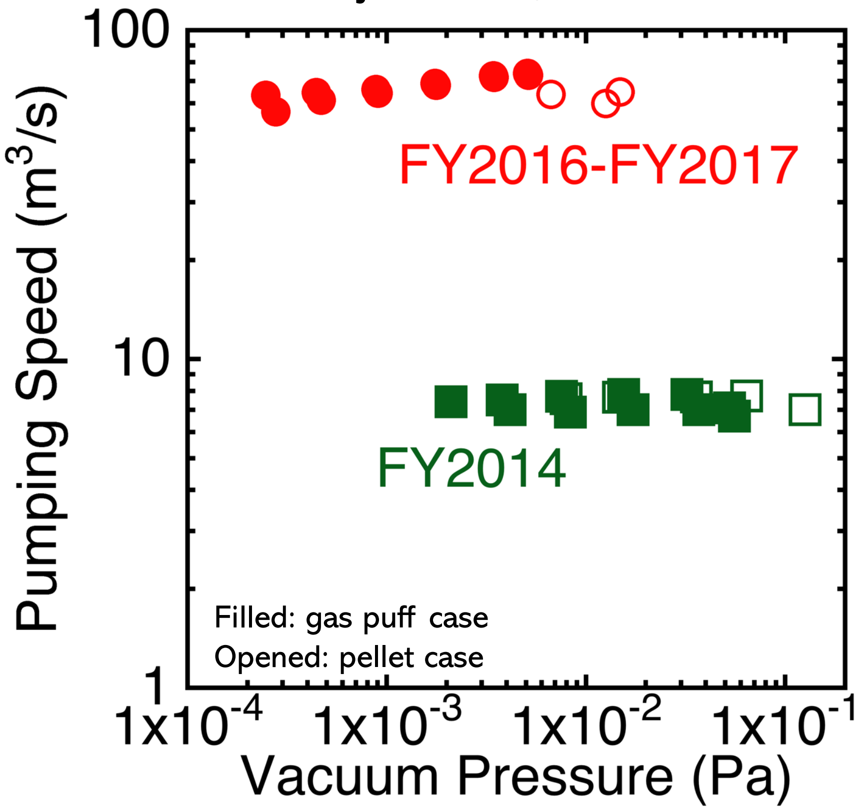
(2) The water-cooled blinds are no longer needed → high conductance

(3) The area of the cryo-sorption panel is enlarged → high capacity

Cryo-sorption pumps have been installed in five sections

High performance of divertor pumping

G. Motojima *et al.*, 2018 Nucl. Fusion **58** 014005.



Cryo-sorption pumps have been installed in five sections.

- ✓ Compared with FY2014, the pumping speed was seven times higher in hydrogen, which is close to the initial design target of 100 m^3/s in ten toroidal sections.
- ✓ The pumping capacity is identical to 20 days of fuel amounts for high density experiments in the LHD.

	Pumping capacity [Pa m^3]	Pumping speed [m^3/s]
FY2014 (18th cycle)	3,320	10
FY2016-Now (19th cycle-)	~58,000	67±5

Specification of divertor pumping in ITER, JT-60SA

ITER

R.J. Pearce+, FED 2013.

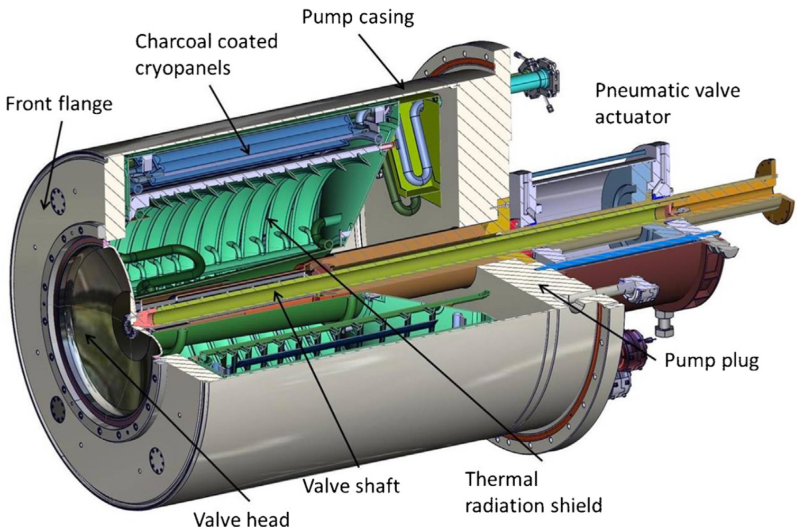


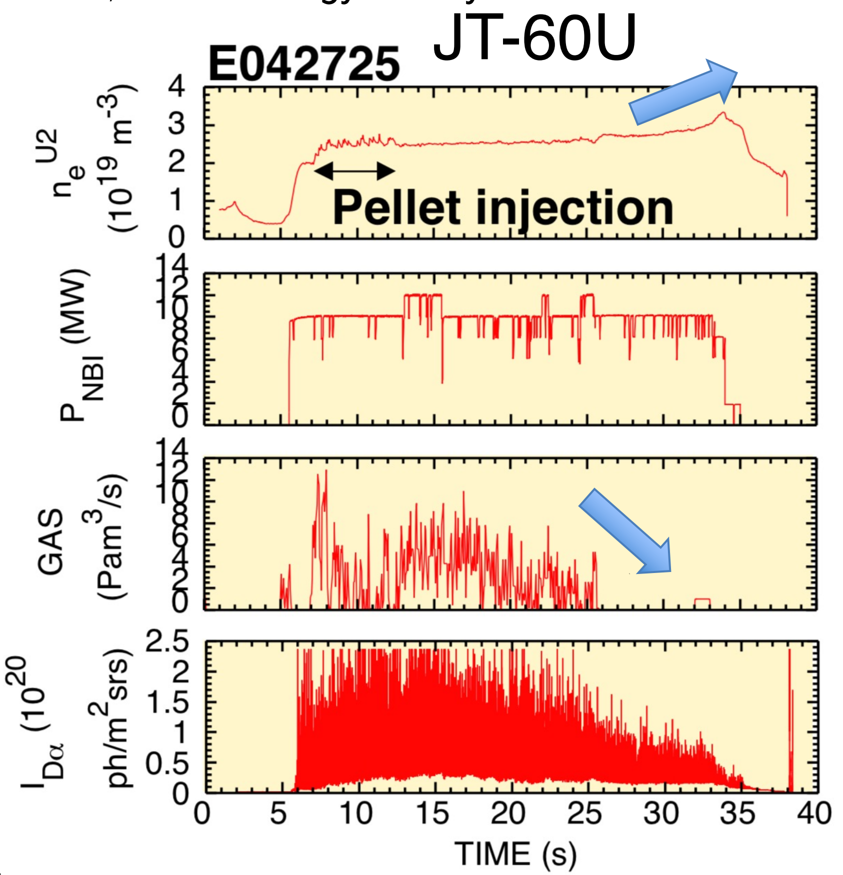
Fig. 3. View of the torus cryopump.

H. Nakamura+, FED 1998.

- ✓ In terms of He exhaust, the total gas throughput (H2, D2 and T2) is 50 Pa m^3 s^{-1} (assuming 10% concentration).
- ✓ However, in steady state conditions, 200-500 Pa m^3 s^{-1} is required
- ✓ **200 m^3 s^{-1} required (assuming divertor pressure of 1 Pa).**

JT-60SA (JT-60U)

Kamada, Atomic Energy Society 2004



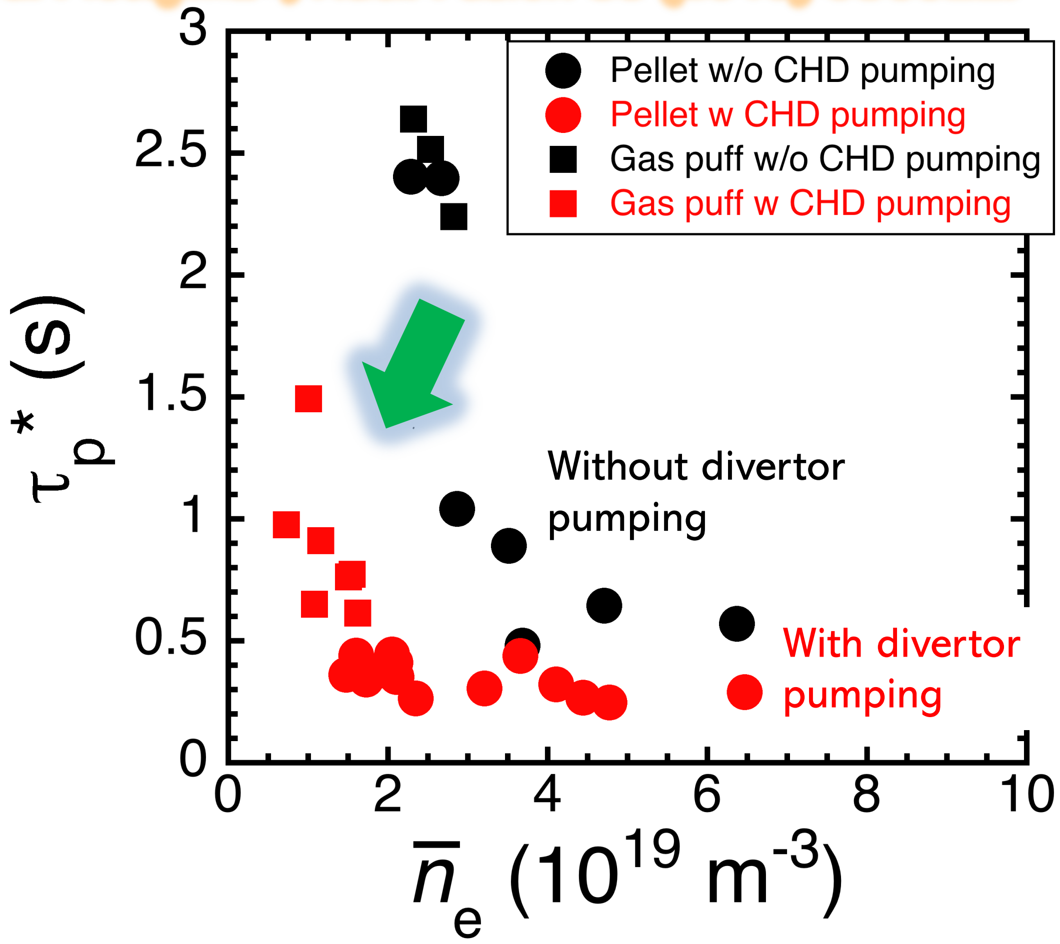
- ✓ Wall saturation observed.
- ✓ No gas puffing required in the second half of the discharge phase. ->Decreased plasma pressure around JT-60SA, up to 100 m^3/s planned.

JT-60SA Plant Integration Document (PID) V3.9

Contents

Low recycling state was observed by high-performance divertor pump.

G. Motojima+, Nucl. Fusion **59** (2019) 086022.



- ✓ The effective particle confinement time (τ_P^*) was evaluated from the decay of plasma density.

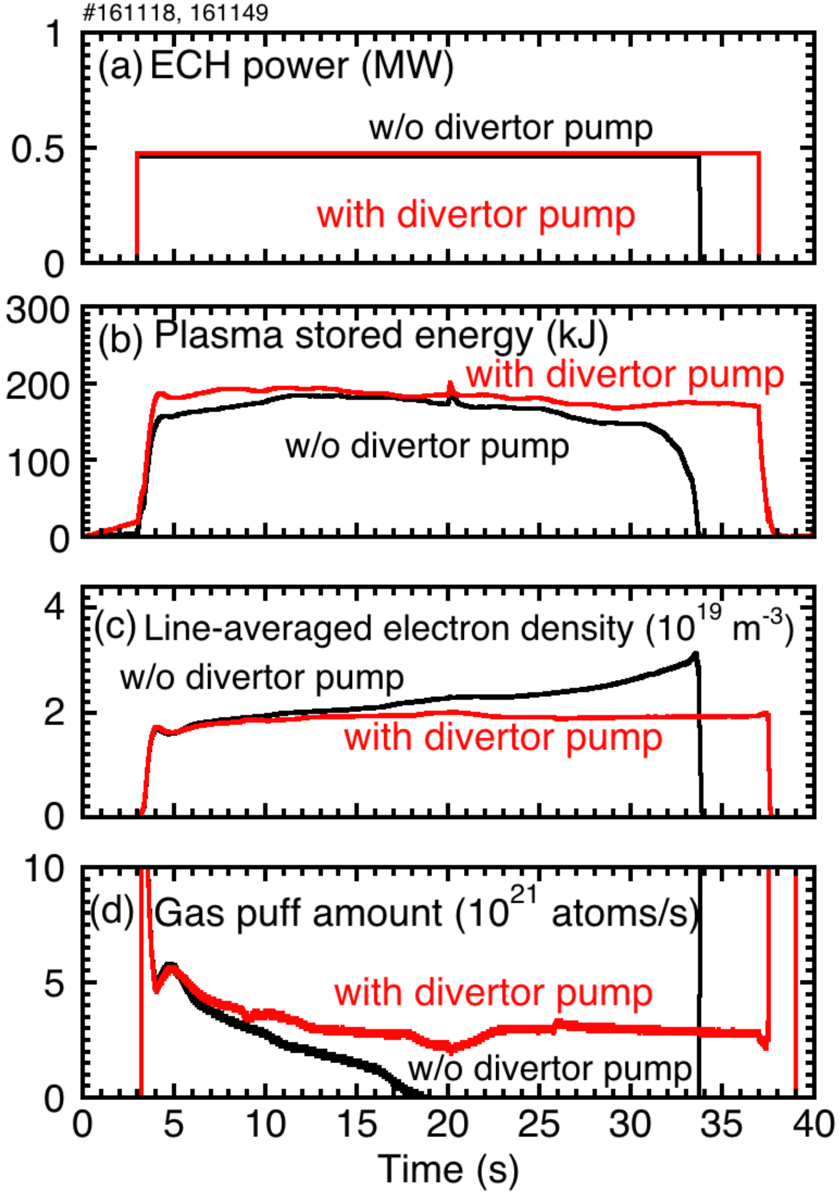
$$\tau_p^* = -\frac{\bar{n}_e}{\frac{d\bar{n}_e}{dt}}$$

- ✓ A lower τ_P^* was obtained with the divertor pump than without divertor pumping.

Low recycling state is possible by the divertor pump.

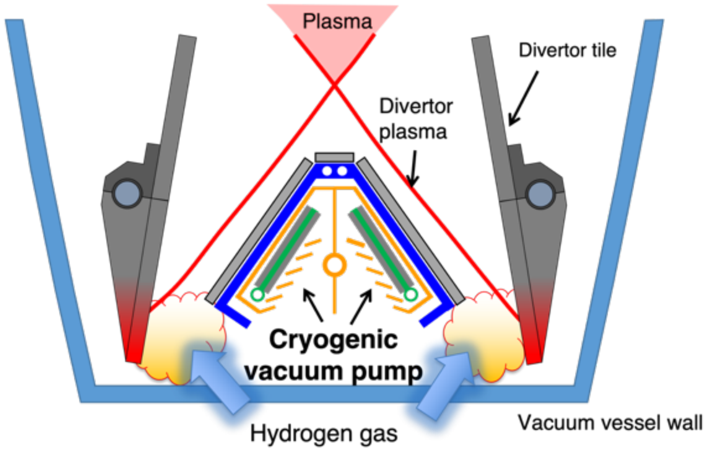
Application of divertor pumping to 40 seconds plasma discharges

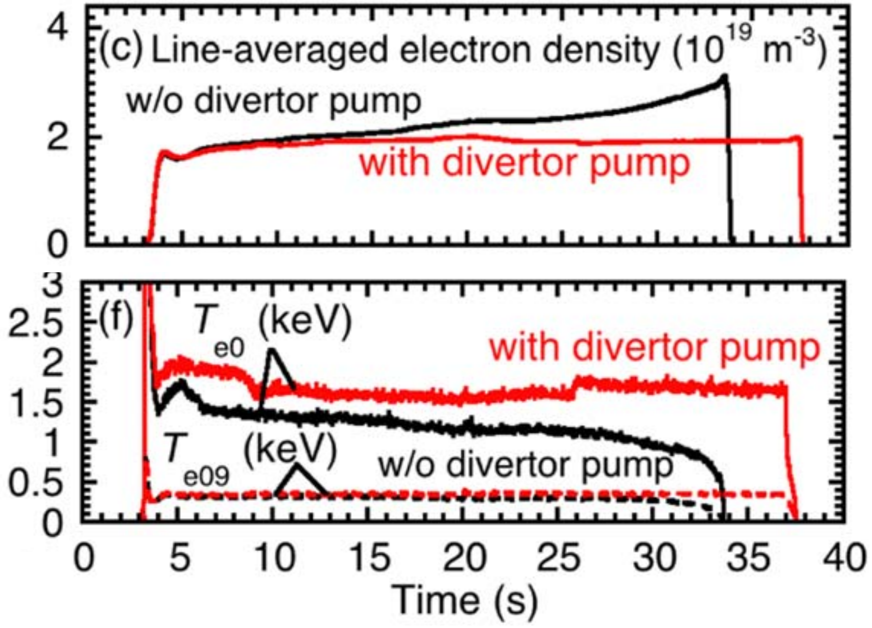
G. Motojima+, 2021 Plasma Fusion Res. 16 1202014.



- ✓ The magnetic configuration was selected at R_{ax} = 3.6 m.
- ✓ In the absence of the divertor pumping, even without gas puffing, the plasma density was increasing, and the density was not controlled well by density feedback, leading to plasma radiation collapse.
- ✓ On the other hand, if the divertor pumping is working, density feedback control is well operated with a stable hydrogen gas puff.

Control of plasma particles by powerful vacuum pumping

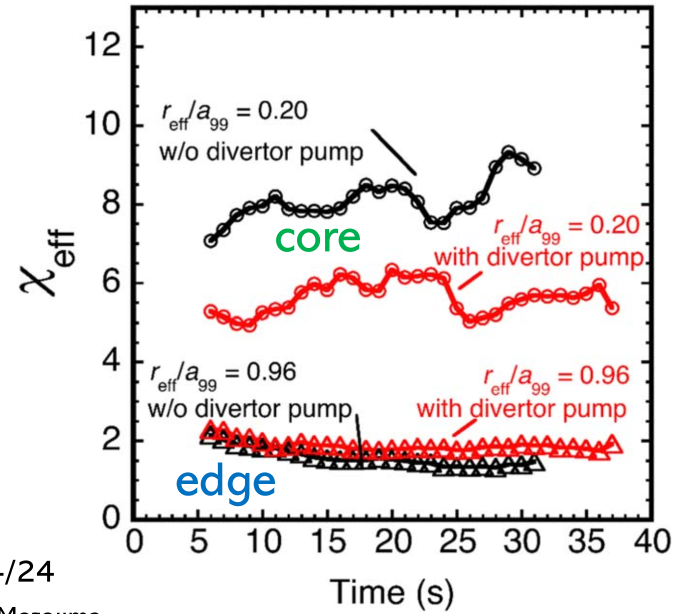




Divertor cryogenic vacuum pump contributes a better density control in the long pulse discharge.

Without divertor pump
→ Plasma collapse at 34 sec

Without divertor pump
→ No collapse until the end of discharge



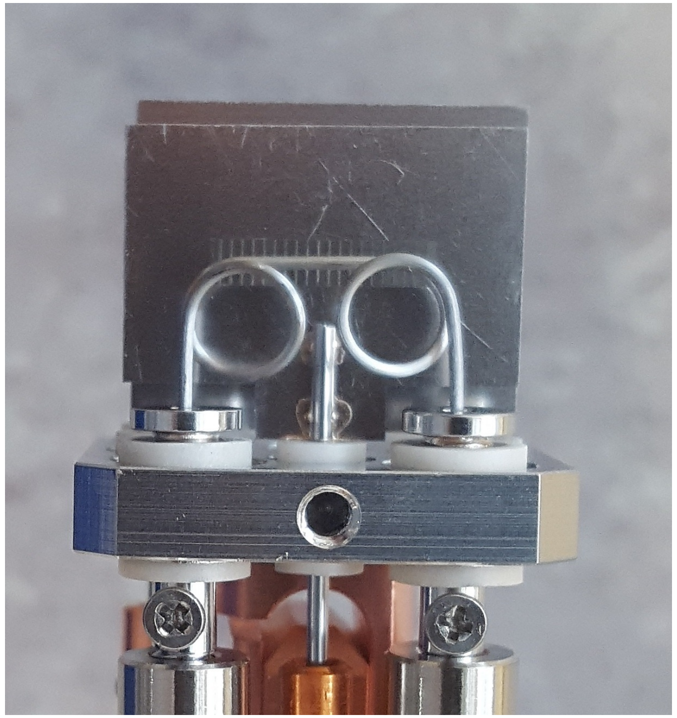
No impact of divertor pump on edge transport
But strong impact on core transport
(reduction of thermal diffusivity in the core)

→ Clear edge-core transport coupling
(evidence of non-local transport)

G.Motojima, *et al.*, Phys. Scr. **97**, 035601 (2022)

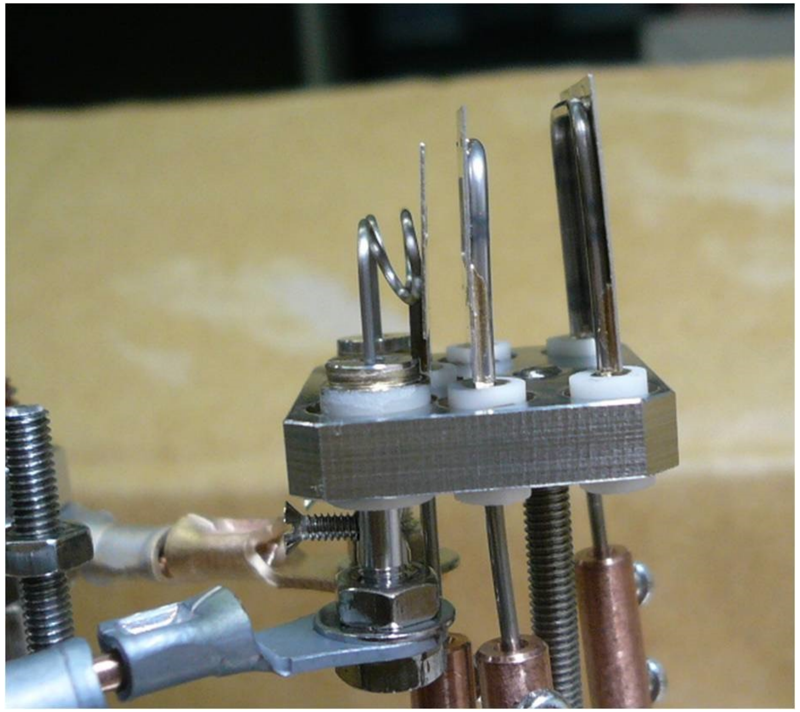
Contents

Bad performance of pressure gauges during long-pulse operation



Standard version used in the LHD

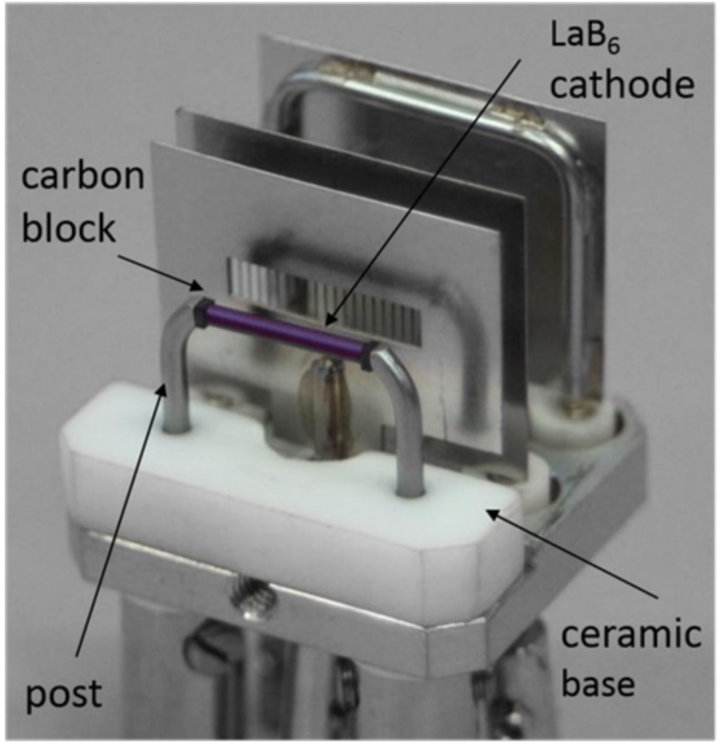
but the cathodes are frequently deformed by the j x B force



Analysis of the bad performance of Ohmically heated cathodes shows the need for a better design[1]

1) U. Wenzel+, Rev. Scient. Instrum. 92, 083510 (2021).

New designs are currently tested in the LHD

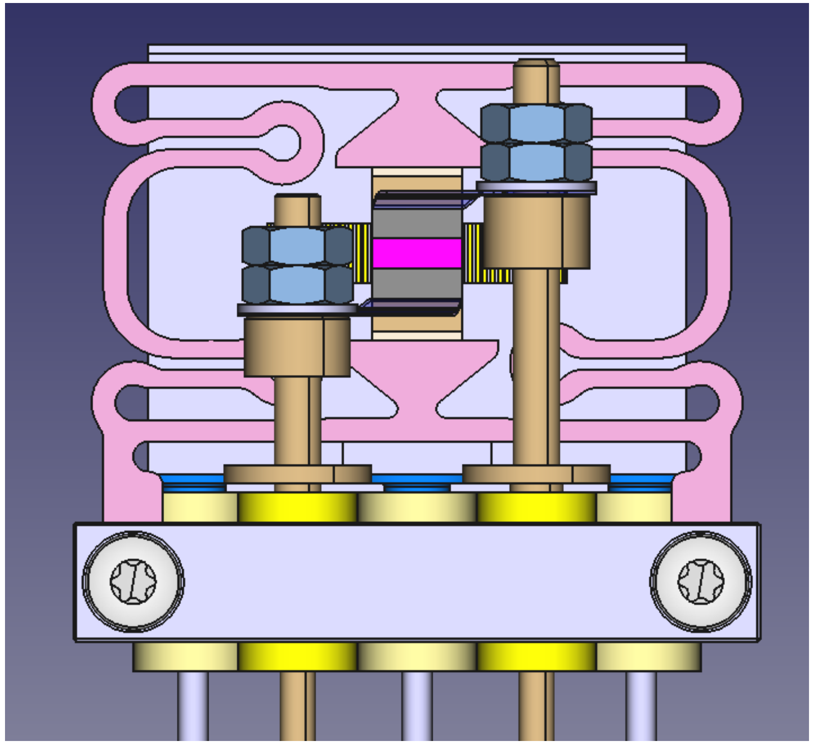


Wendelstein 7-X design
rod cathode
with LaB6 emitter

For long pulse operation:

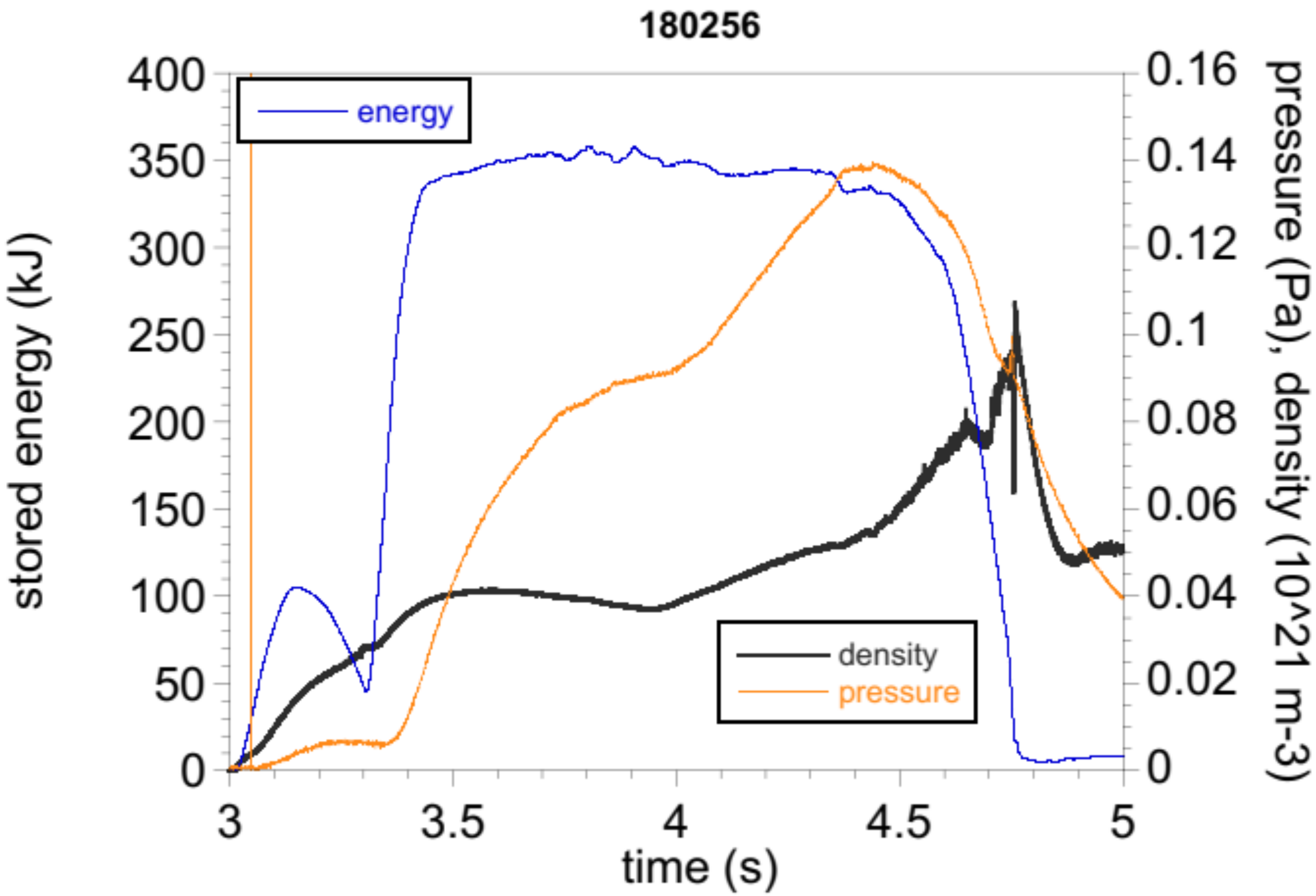
Indirectly heated cathodes for better stability in strong magnetic fields

Carbon blocks Ohmically are heated.
They heat the emitter.



ITER design
sandwich cathode
with ZrC emitter

Stable behaviour of the ITER design in the divertor of LHD



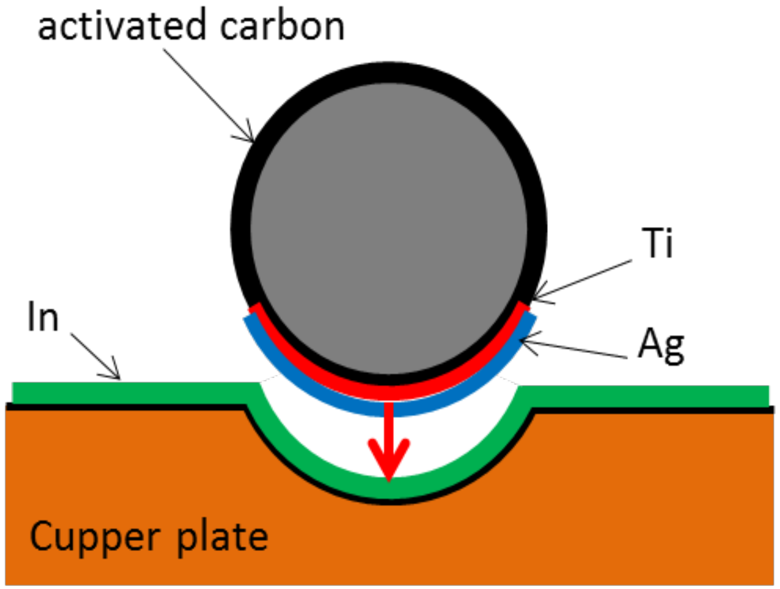
Optimum pressure range for long-pulse operation around the pressure maximum

G. Motojima

Contents

Development of adhesion technique with inorganic of indium

The contamination of vacuum vessel by outgassing from cryo-sorption pump is a problem.

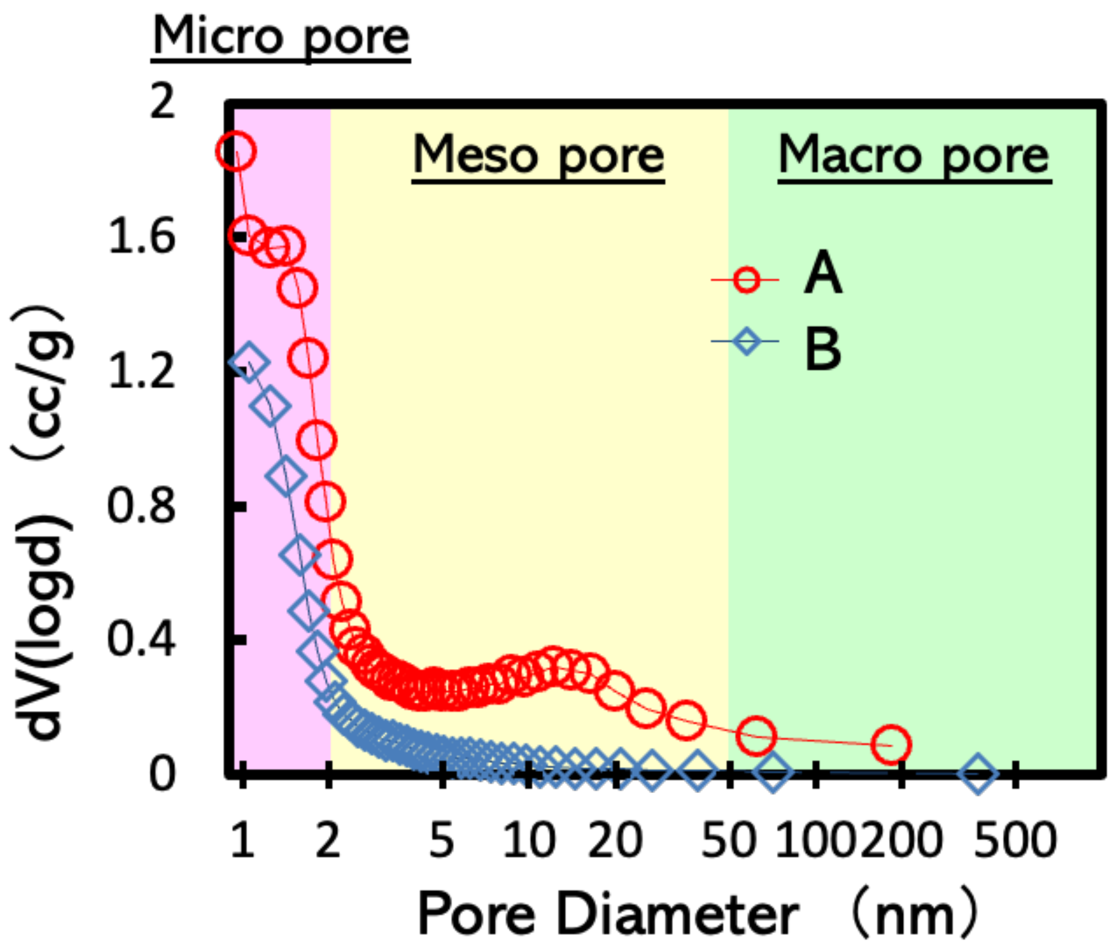


Out gassing by organic adhesion -> developed of adhesion technique with inorganic of indium.

Inorganic adhesion technique is one of the solution.

Further development of activated carbon

Pore distribution of activated carbon

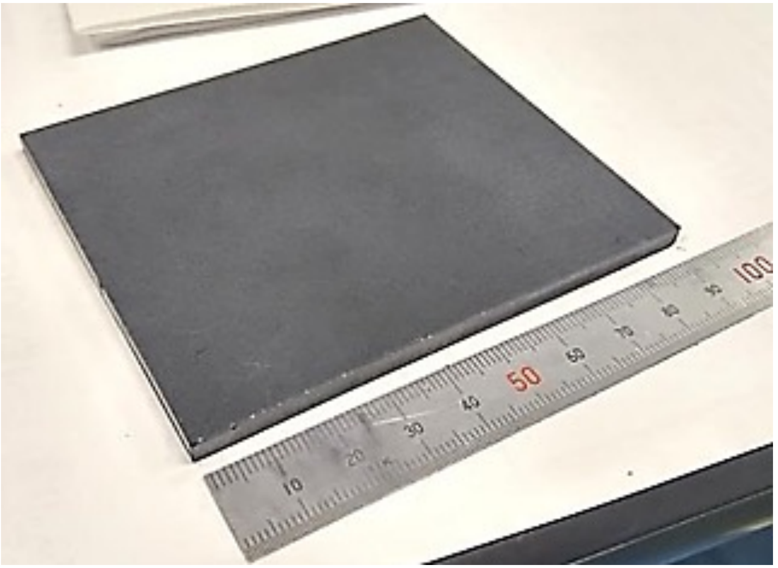


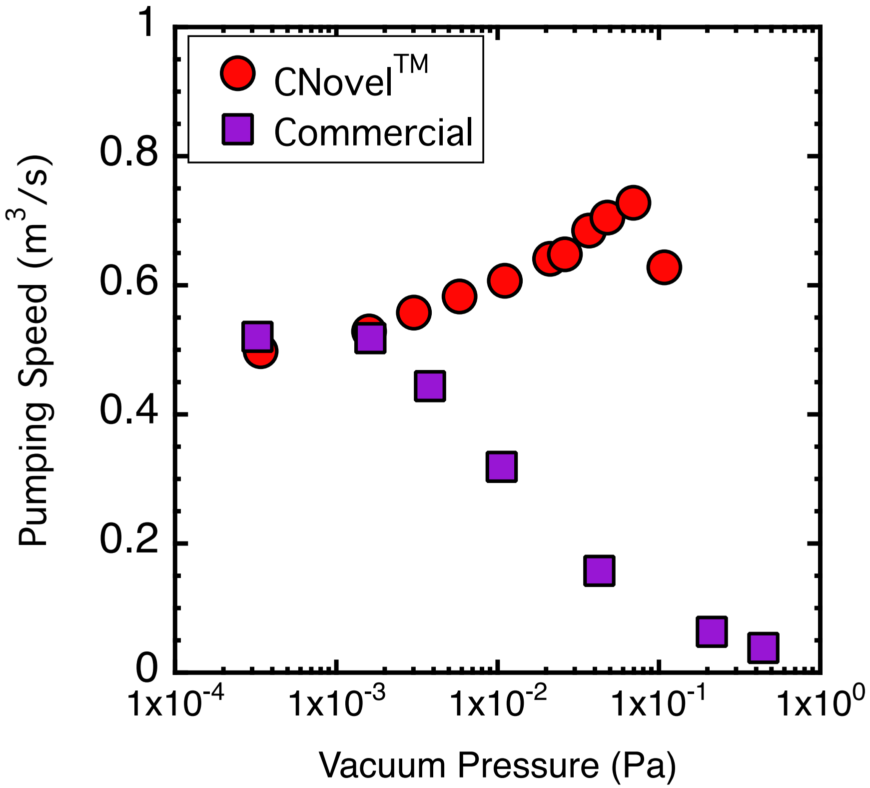
- ✓ The characteristics of pumping speed depends on the area of micro pore, which is related to a physical absorption.
- ✓ The characteristics of pumping capacity depends on the area of meso-macro pore.

The control technique of the distribution of pore diameter suitable for activated carbon is being established in NIFS.

Utilization of pore-controlled activated carbon

Manufacturing methods to produce porous structures have been established industrially such as CNovel™.





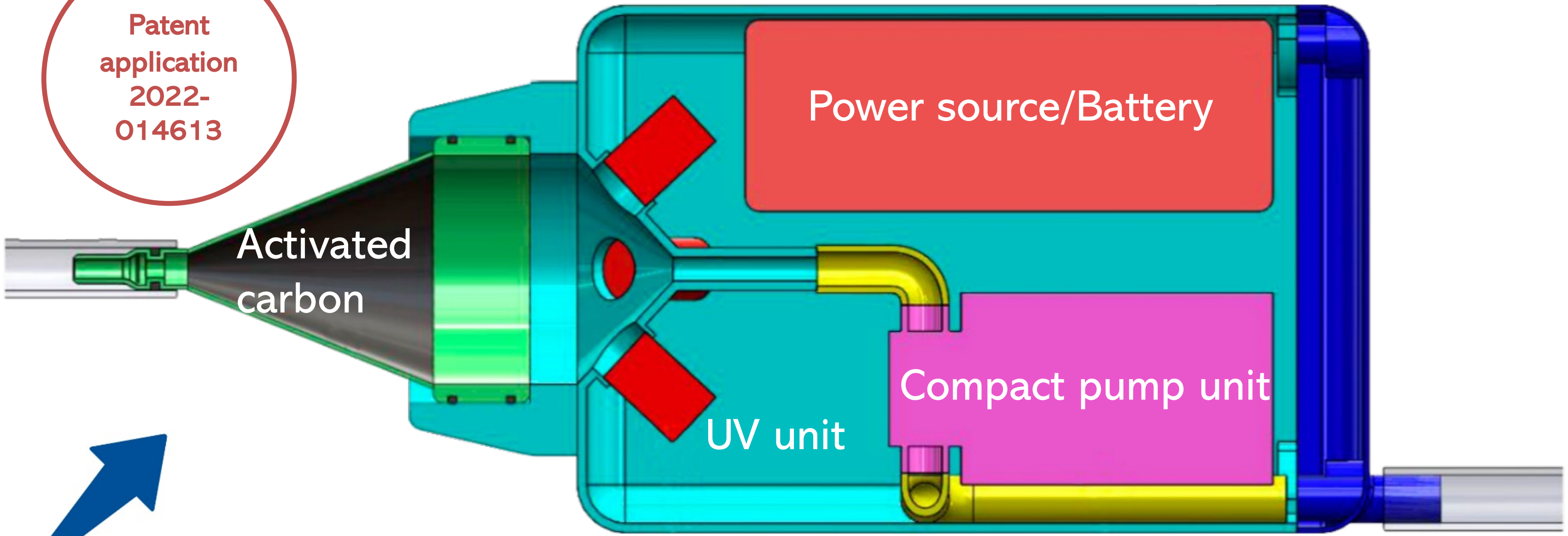
- ✓ The pumping rate of CNovel™ was maintained higher than that of the commercial activated carbon.
- ✓ This suggests that **pore-controlled activated carbon such as CNovel™ could be used as activated carbon in cryo-sorption pumps**.

Spin-off of activated carbon study

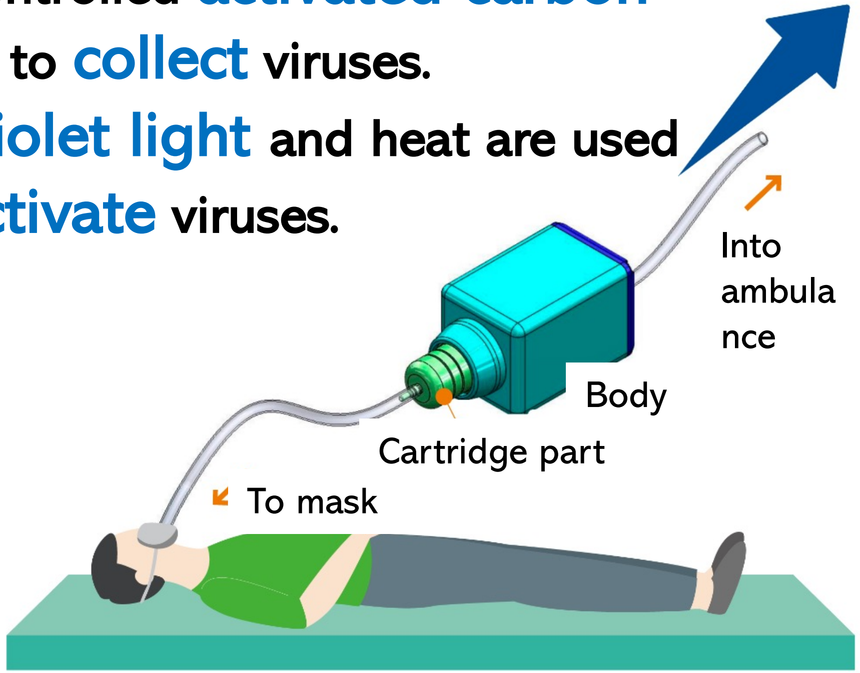
Supported by JST Score, 2021

Activated carbon& Ultraviolet light Virus inactivation equipment

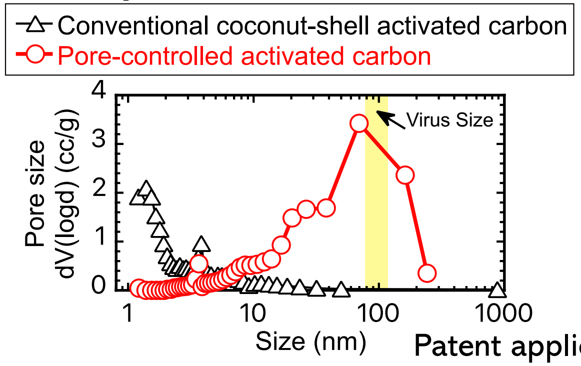
Patent application 2022-014613



Pore-controlled activated carbon is used to collect viruses.
Ultraviolet light and heat are used to inactivate viruses.

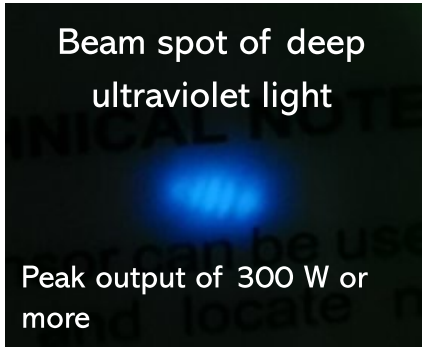


POINT 1 Freely molded activated carbon suitable for virus adsorption



Patent application 2018-178743

POINT 2 High power deep ultraviolet Laser light



Patent application 2021-4189

G. Motojima

IAEA Technical Meeting on Long-Pulse Operation of Fusion Devices, Nov14-16, 2022, Vienna, Austria

Summary

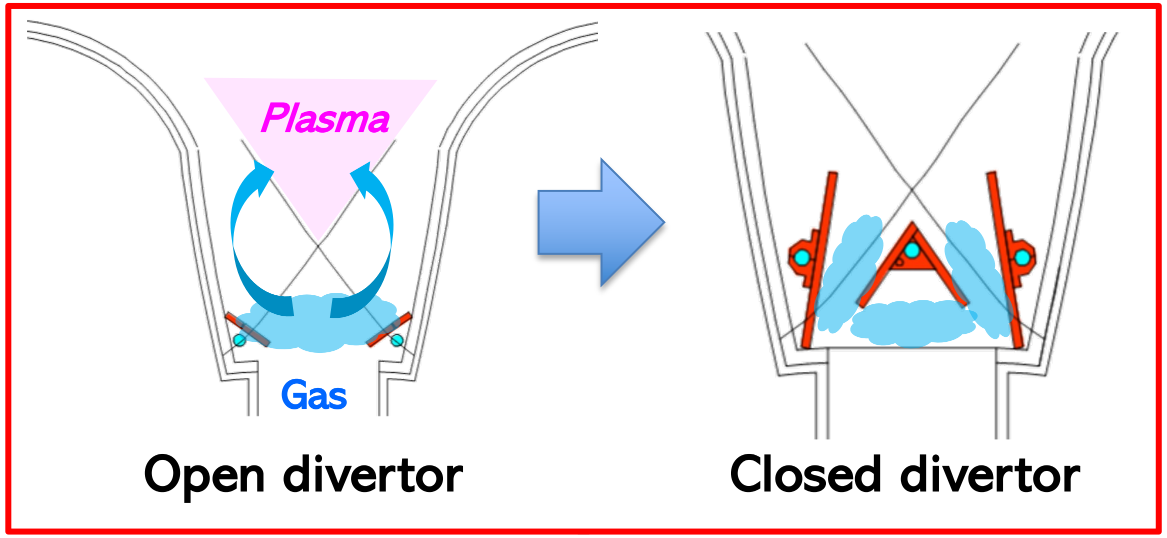
✓ In LHD, **development of divertor pumping has been strongly enhanced**. Low recycling state has been achieved.

- ❖ Divertor pumping was applied to 40-second long pulse ECH. Density was well-controlled by gas puffing using the feedback signal.
- ❖ A heat transport analysis shows that divertor pumping did not affect edge electron heat conductivity, but it led to low electron heat conductivity in the core region with the formation of the electron-internal-transport-barrier. The results suggest emergence of the core-edge coupling caused by the divertor pumping.

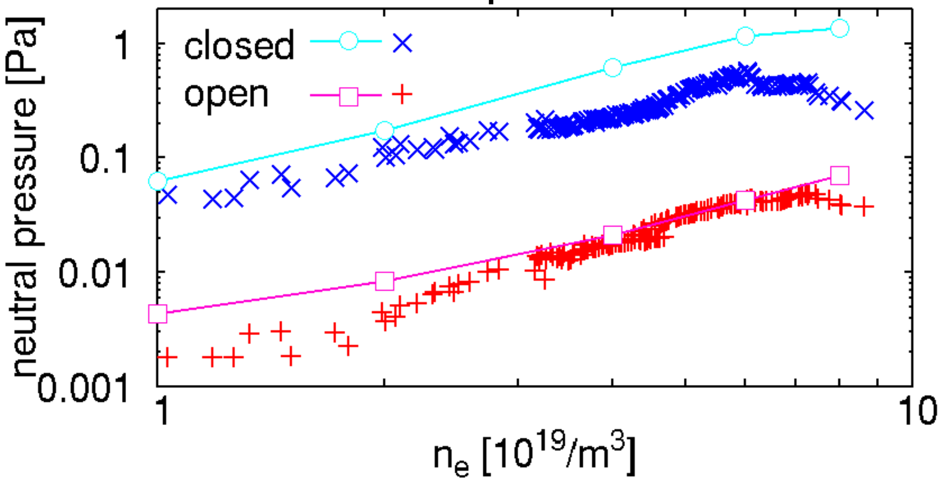
✓ Technical development in divertor pumps which is essential for the steady state operation is shown.

- ❖ An organic adhesive-free bonding technique, which enables outgassing-free, was developed for divertor cryo-sorption pump in LHD. The technique, which avoids the contamination of vacuum vessel by outgassing, is acceptable in future fusion devices.
- ❖ The pore size is optimized for the cryo-sorption pump. R&D shows that the pumping capacity with optimized activated charcoal is higher than that in commercially available activated charcoal. The technique contributes to the high performance of the vacuum pumps.

Neutral particle compression by closed divertor (inner toroidal section)



Neutral pressure in closed and open divertor

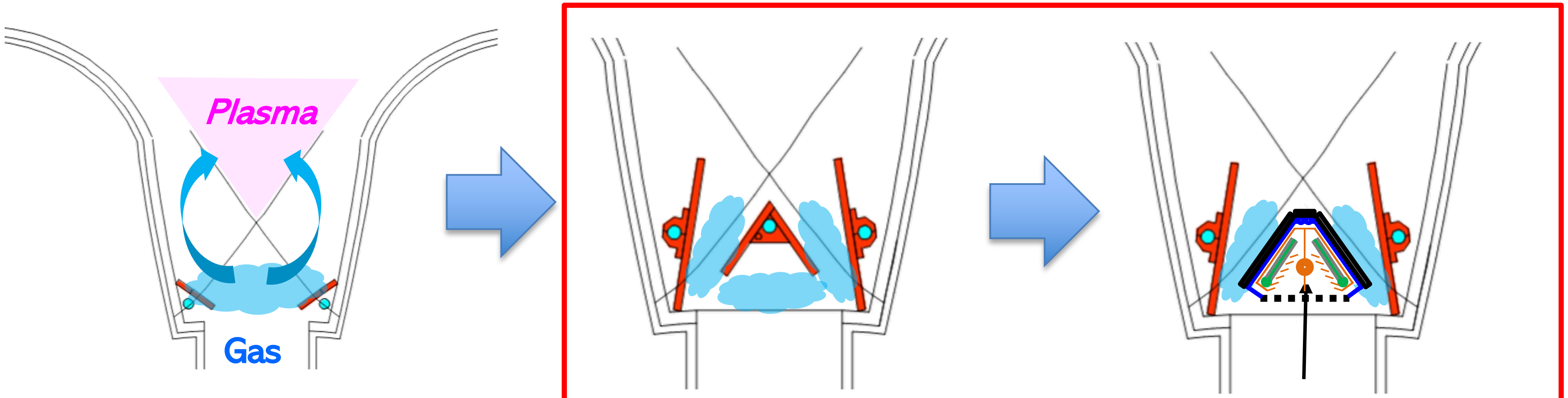


Significant pressure increase in the closed divertor

Compression is 10~20 times higher than that in the open divertor.

S. Masuzaki *et al.,* PFR **6**, (2011) 1202007.
G. Kawamura *et al.*, Contrib. Plasma Phys. **54**, (2014) 437.

Installation of cryo-sorption pump in closed divertor

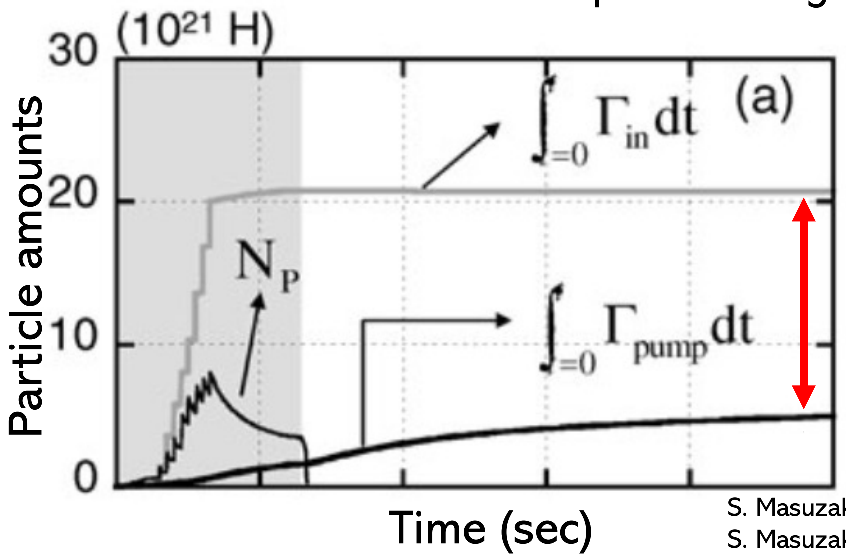


Open divertor

Closed divertor

Cryo-sorption pump in dome structure

Particle balance in 10 Hz pellet fueling



Wall retention is dominant

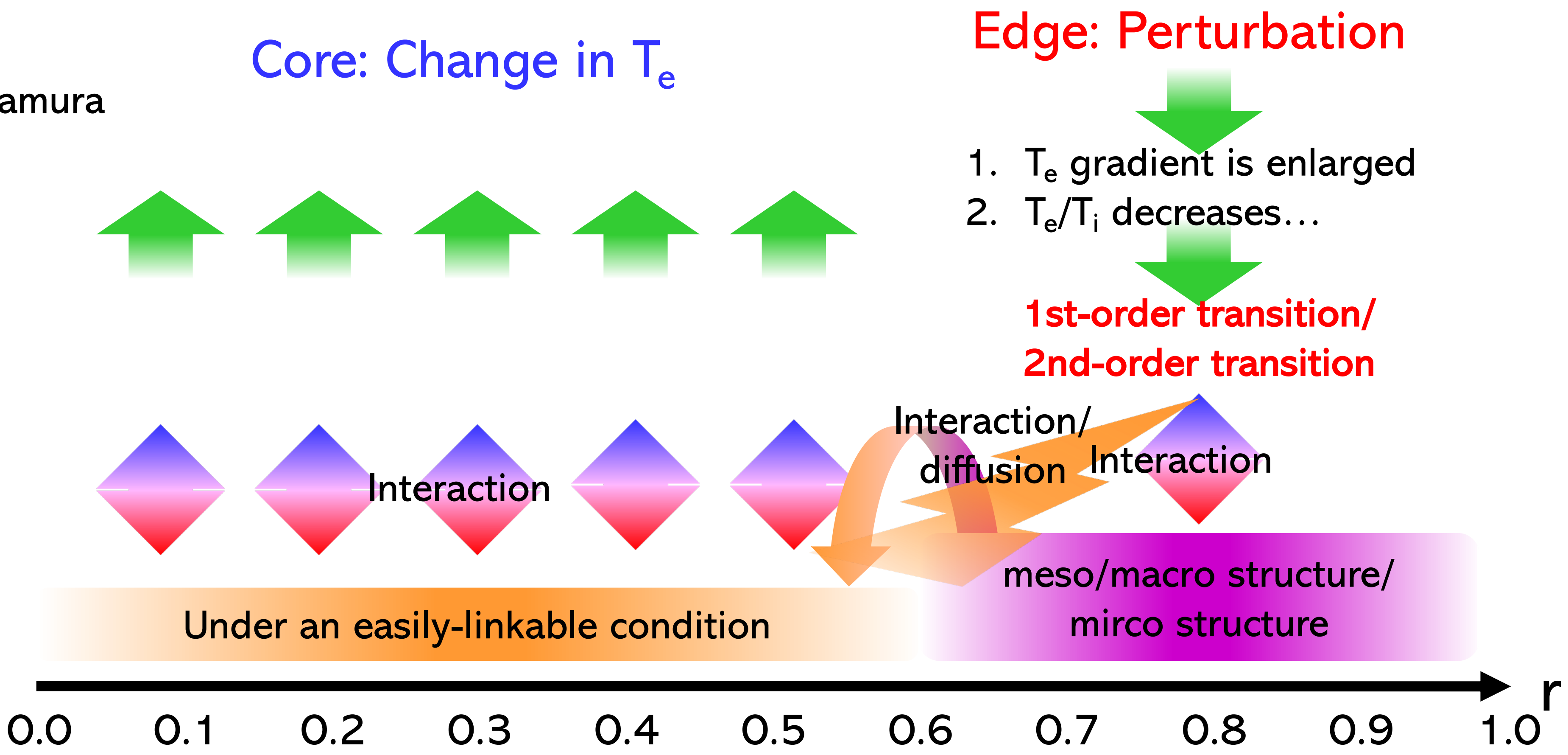
S. Masuzaki *et al.*, FED **85**, (2010) 940.
S. Masuzaki *et al.*, FST **58**, (2010) 321.

Outcome expected:
Improvement of control of edge neutral particles by strong pumping
⇒ Confinement improvement
⇒ Stable sustainment of high density plasma

Goal of pumping speed
Total 100 m^3/s
(Fueling rate of 10 Hz pellet 10 Pa m^3/s at ~0.1Pa)
⇒10 m^3/s per section

Physical Mechanism for Nonlocal Transport Phenomenon

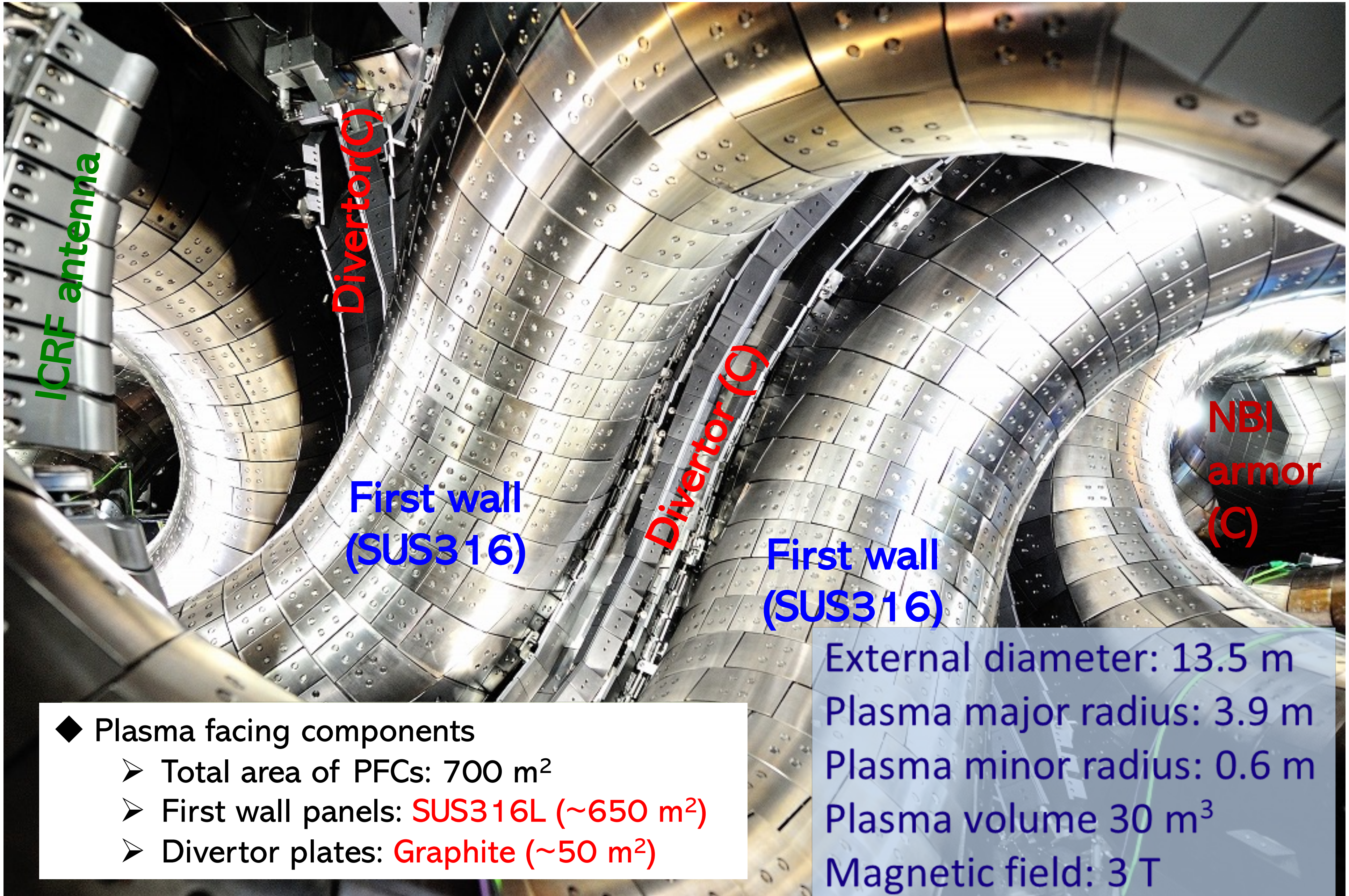
Courtesy of N. Tamura



Understanding of a formation condition of the unstable transport state(easily-linkable condition) and a coupling mechanism between the edge and the core could be a key issue!

Divertor pumping changes the edge plasma?

Inside the LHD vacuum vessel



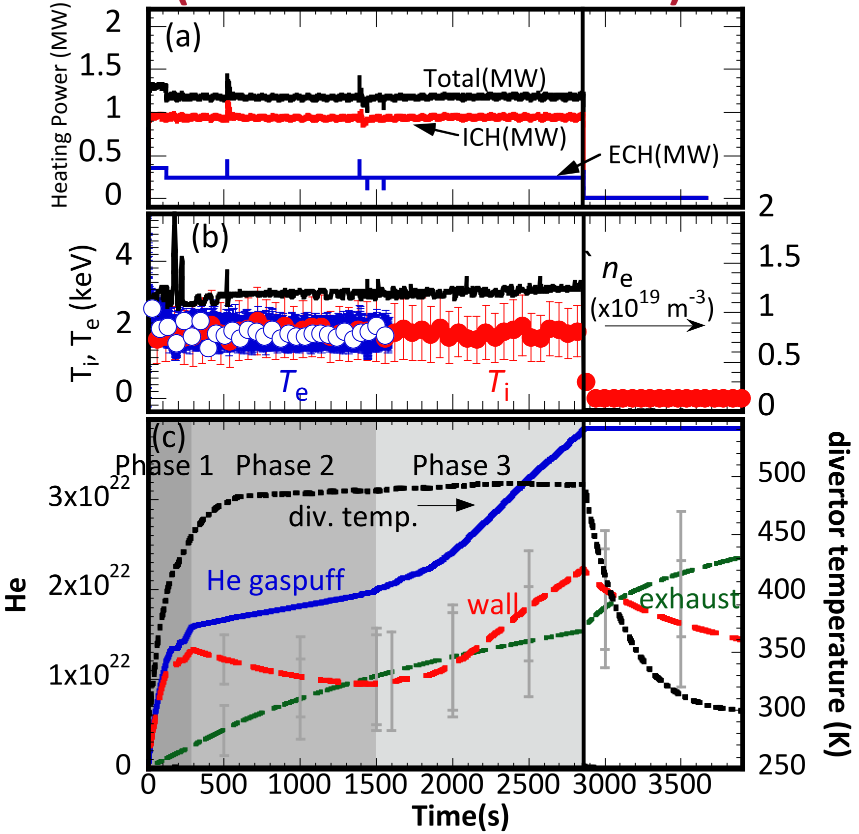
- ◆ Plasma facing components
  - ➢ Total area of PFCs: 700 m^2
  - ➢ First wall panels: SUS316L (~650 m^2)
  - ➢ Divertor plates: Graphite (~50 m^2)

External diameter: 13.5 m
Plasma major radius: 3.9 m
Plasma minor radius: 0.6 m
Plasma volume 30 m^3
Magnetic field: 3 T

Long pulse discharge in LHD

G. Motojima et al., IAEA 2016.
G. Motojima et al., JNM 2017.
M. Oya et al., JNM 2017.

Phased wall retention observed in 48 min discharge (sink → source → sink)



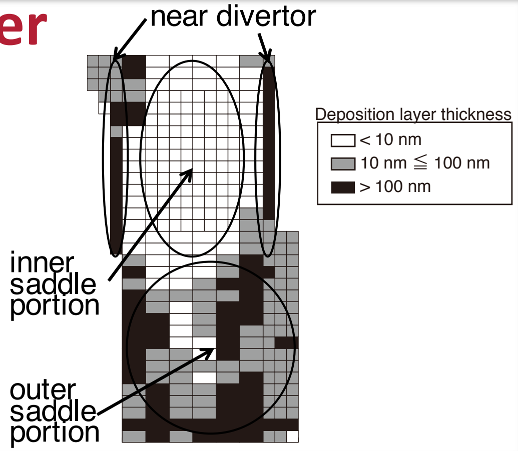
Co-deposition layer (on First wall)

< 348 K

- Sample analysis
- Deposition layer quantification by optical reflection measurement

Constant retention

Color analysis

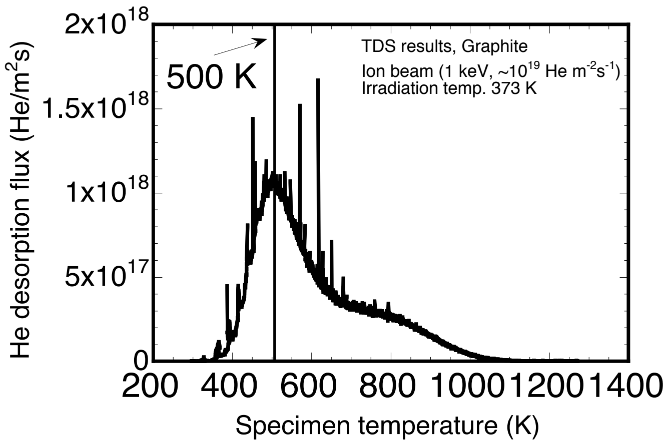


Graphite (Divertor)

< ~500 K

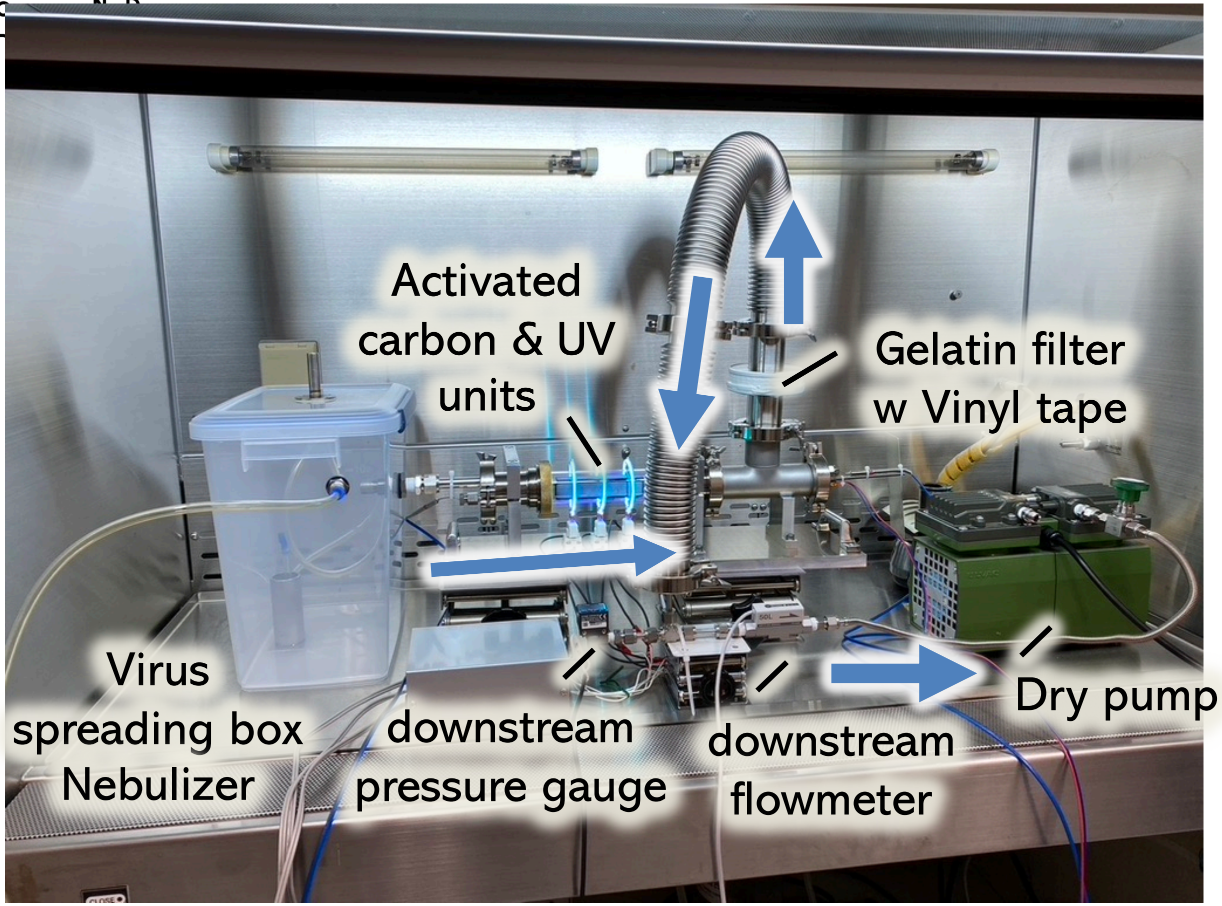
- Sample analysis

Desorption of retained helium with increase of temperature

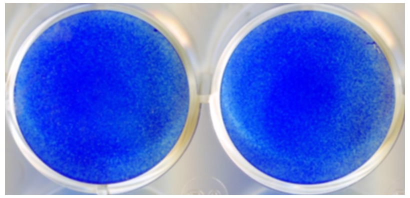


The difference of the retention characteristics in the plasma facing materials and the difference of their temperature may qualitatively explain the phased wall retention.

Demonstrated viral inactivation

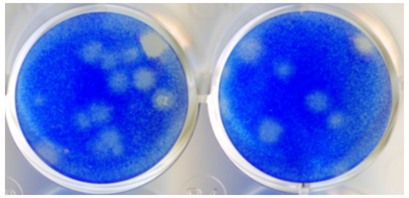


活性炭(+)　検出限界以下



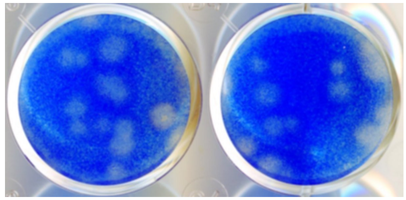
No viruses detected (below detection limit) if an activated carbon cartridge is **present**

活性炭(−)　1.1 x10^6 PFU/ml



Viruses detected in the **absence** of activated carbon cartridges

薬液ボトル　1.3 x10^8 PFU/ml



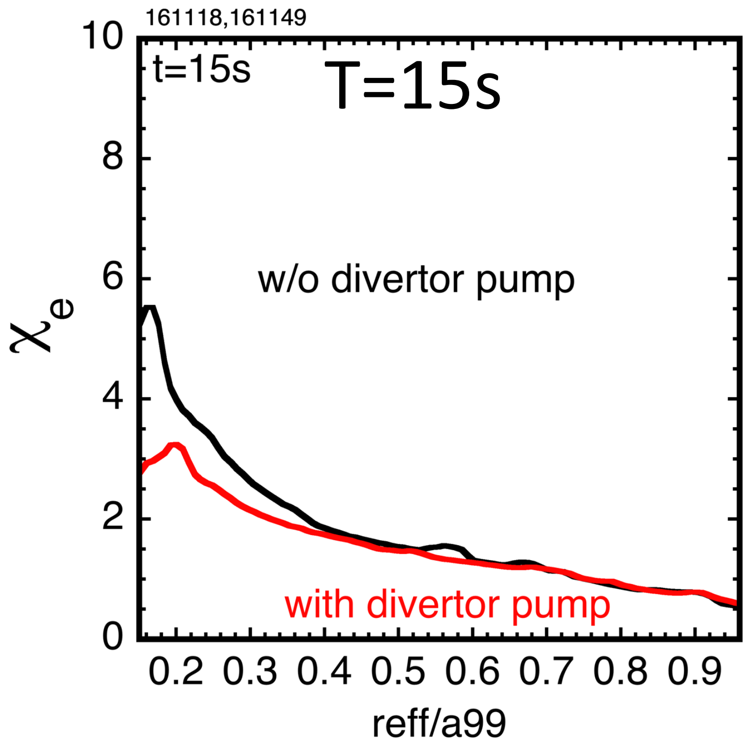
Undiluted solution

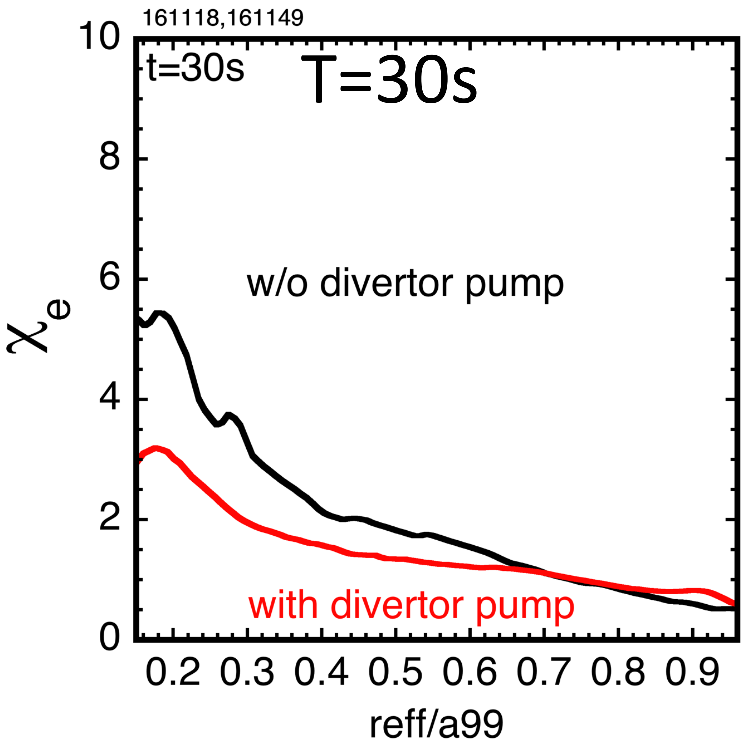
評価 well: 10^{-6}

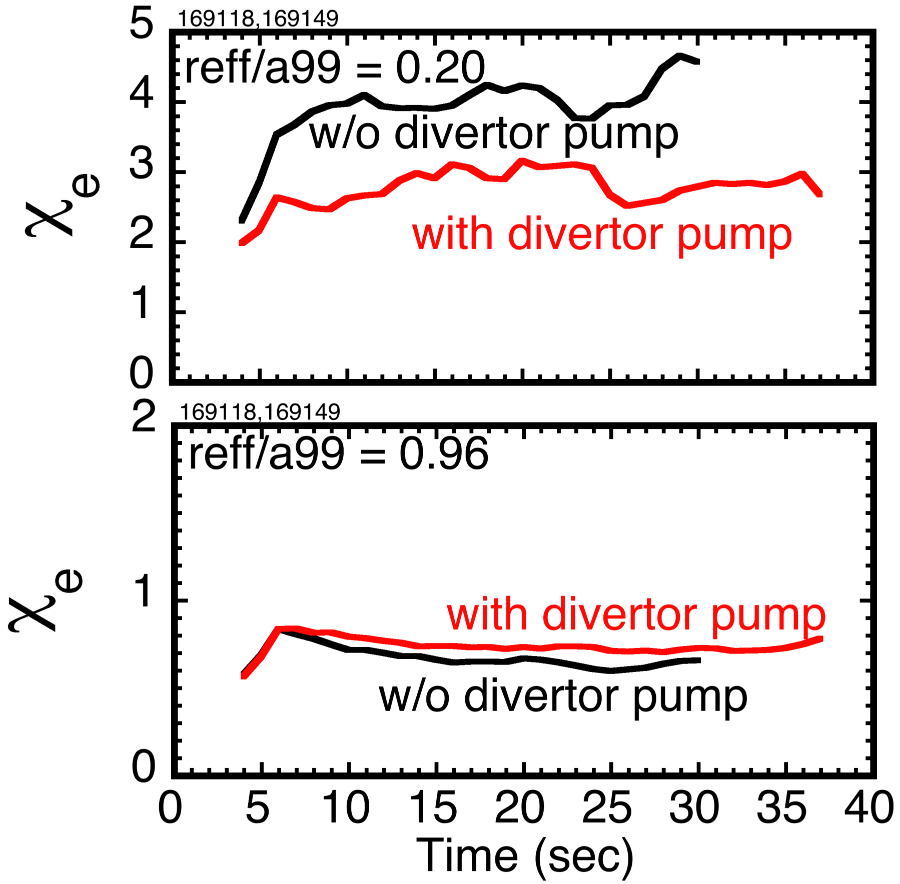
- ✓ Experimental infection of MDCK cells with influenza A virus (strain H1N1/PR-8)
- ✓ **The cleaners have demonstrated that they can inactivate viruses (>99.99%)**

Radial profile and time evolution of χ_e

G. Motojima+ Phys. Scr. 2022







- ✓ Core χ_e is lower in the case with divertor pumping, although there is no differences in edge χ_e with and without divertor pumping, which suggest the strong coupling between core transport and boundary condition controlled by divertor pumping.
- ✓ These results are consistent with the fact that high ion temperature plasma with ion-ITB has been achieved by reducing the wall recycling in LHD.

Utilized In-vessel cryo pump

- Cryo-Condensation
  Used in DIII-D and EAST
  A huge system of liquid helium is required

- Cryo-Sorption
  Applied in LHD
  Out gassing by organic adhesion
  -> developed of adhesion technique with inorganic of indium.

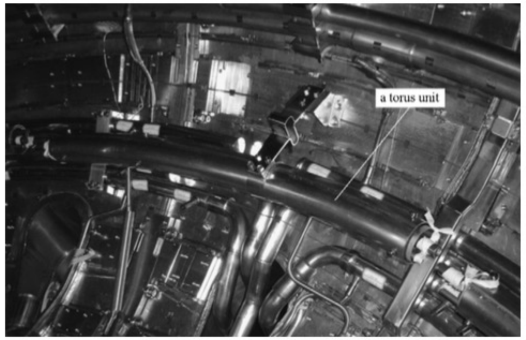
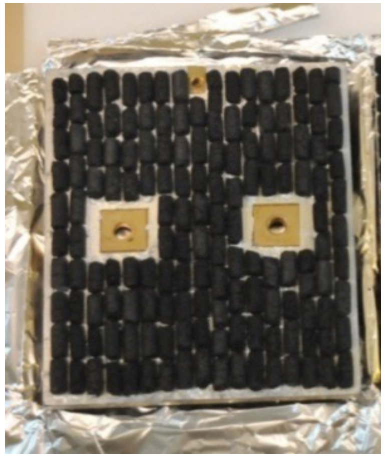


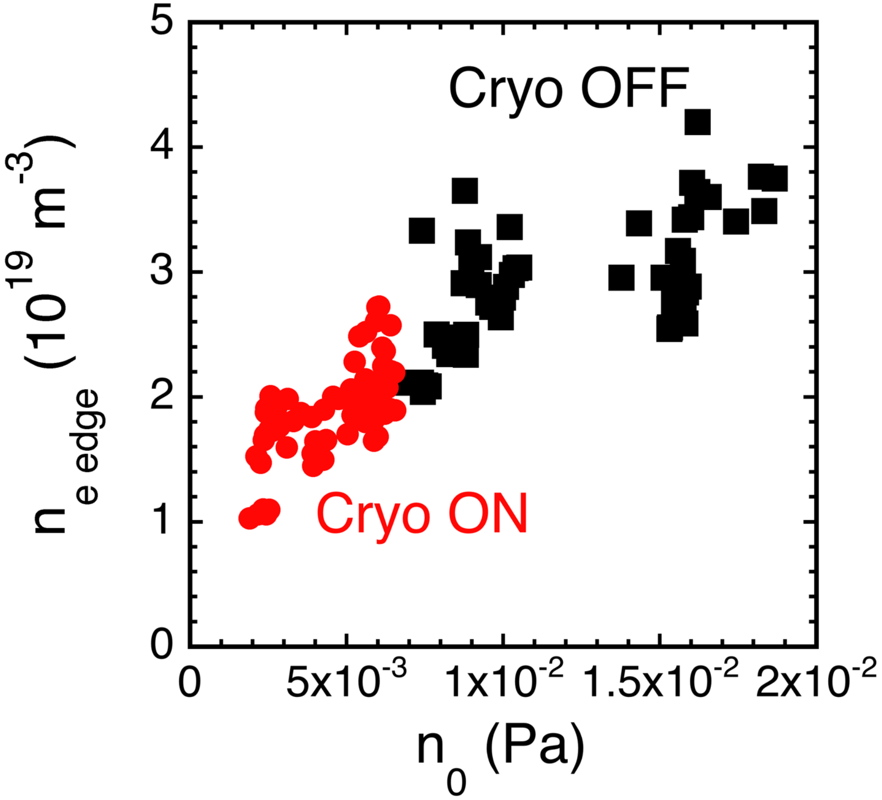
Fig. 6. A torus unit being installed in vacuum chamber.

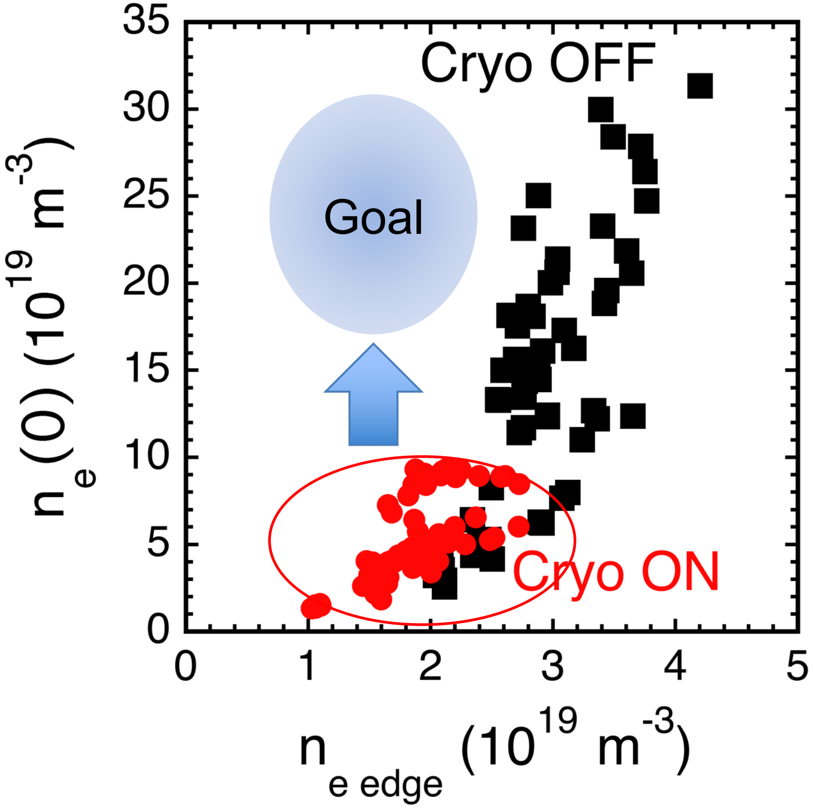
Q.S. Hu *et al.*, Fusion Eng. Des. **85** (2010) 1508.

Activated carbon used in sorption.



3. Application to density profile control in high density plasmas by pellet injection and divertor pumping

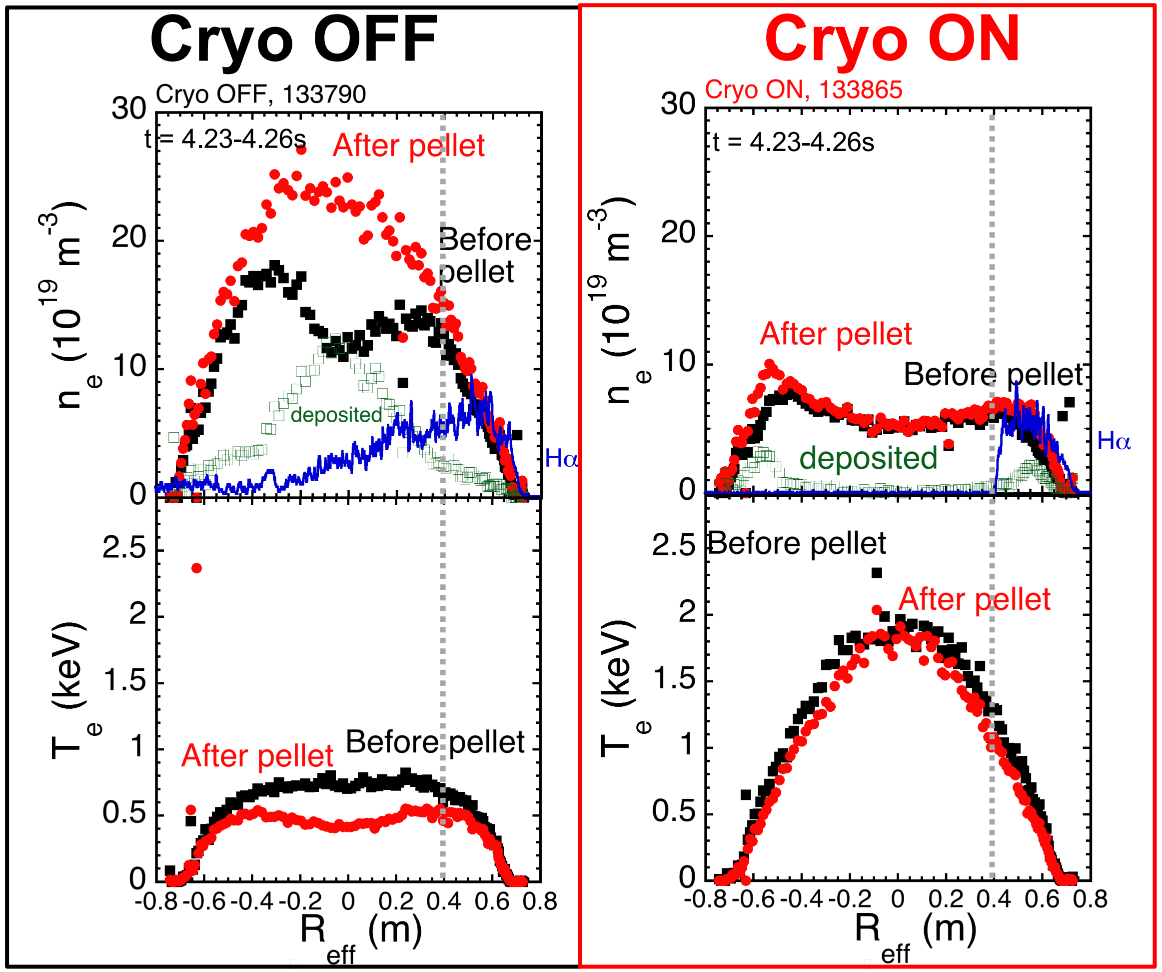


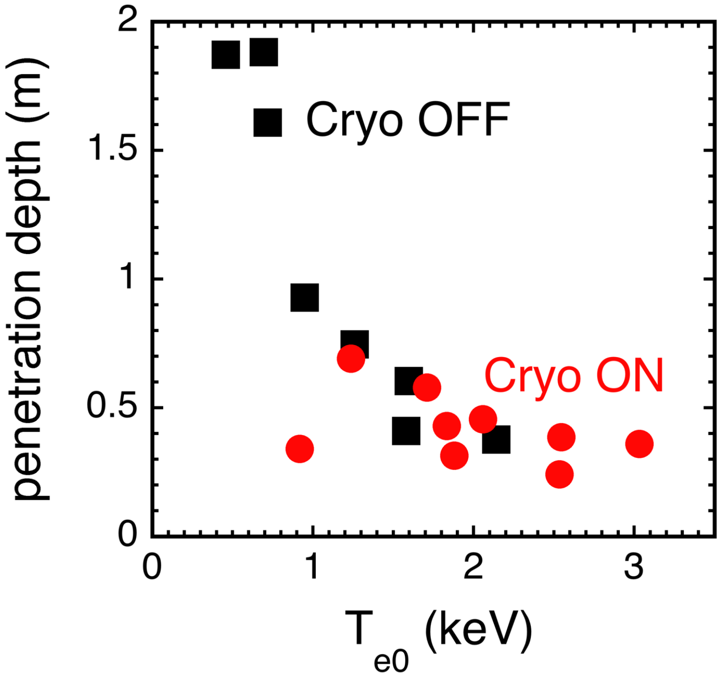


- ✓ High line averaged density plasma over 1×10^{20} m^{-3} is produced by pellet fueling.
- ✓ Neutral pressure and edge density can be reduced in divertor pumping under the similar pellet fueling condition. However, core density is also reduced.

Discussion regarding the reason

3. Difference of profiles

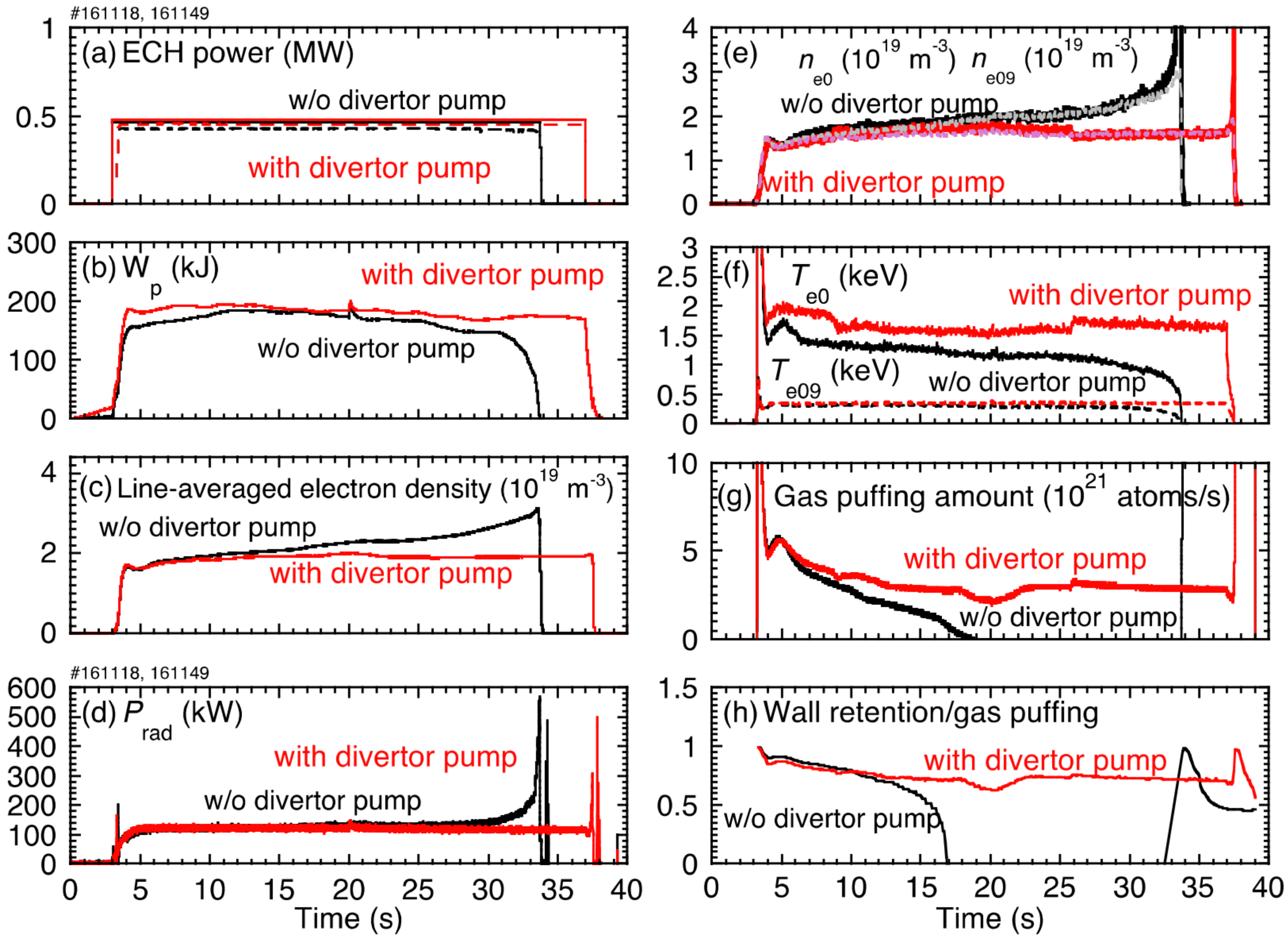




Pellet penetration depth is different.

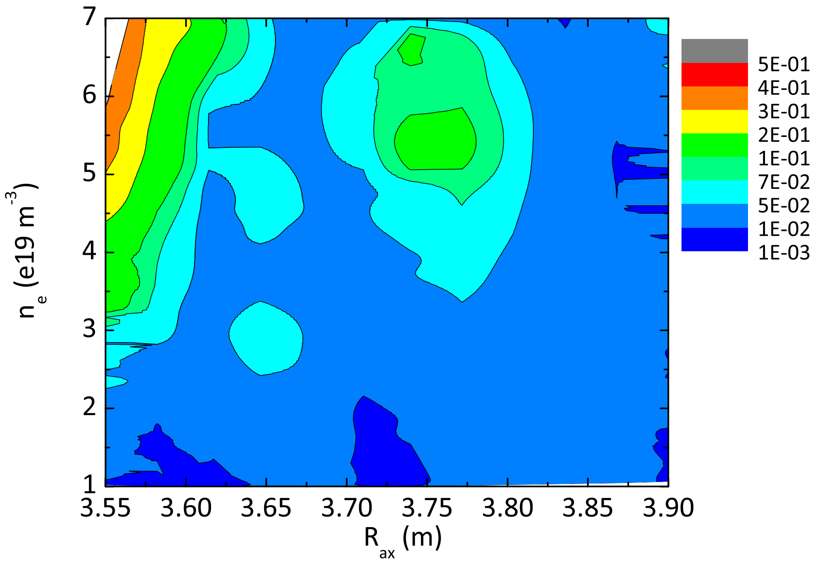
- ✓ Edge density is lower with divertor pumping. On the other hand, electron temperature is higher.
- ✓ Higher temperature causes the shallow pellet penetration.

  The control of neutral particle is important, considering the control of the pellet penetration depth. -> **The short time gas puffing and steady divertor pumping likely will be a candidate for the dynamic edge density control tool**.

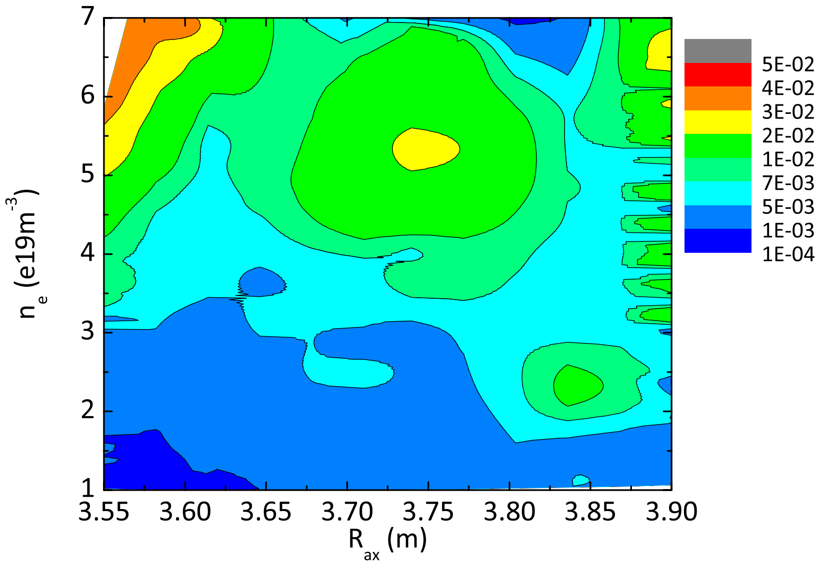

#161118, 161149
(a) ECH power (MW)
w/o divertor pump
with divertor pump
(b) W_p (kJ)
with divertor pump
w/o divertor pump
(c) Line-averaged electron density (10^{19} m^{-3})
w/o divertor pump
with divertor pump
#161118, 161149
(d) P_{rad} (kW)
with divertor pump
w/o divertor pump
Time (s)
(e) n_{e0} (10^{19} m^{-3}) n_{e09} (10^{19} m^{-3})
w/o divertor pump
with divertor pump
(f) T_{e0} (keV)
with divertor pump
T_{e09} (keV)
w/o divertor pump
(g) Gas puffing amount (10^{21} atoms/s)
with divertor pump
w/o divertor pump
(h) Wall retention/gas puffing
with divertor pump
w/o divertor pump
Time (s)

Neutral particle dependence of magnetic axis position

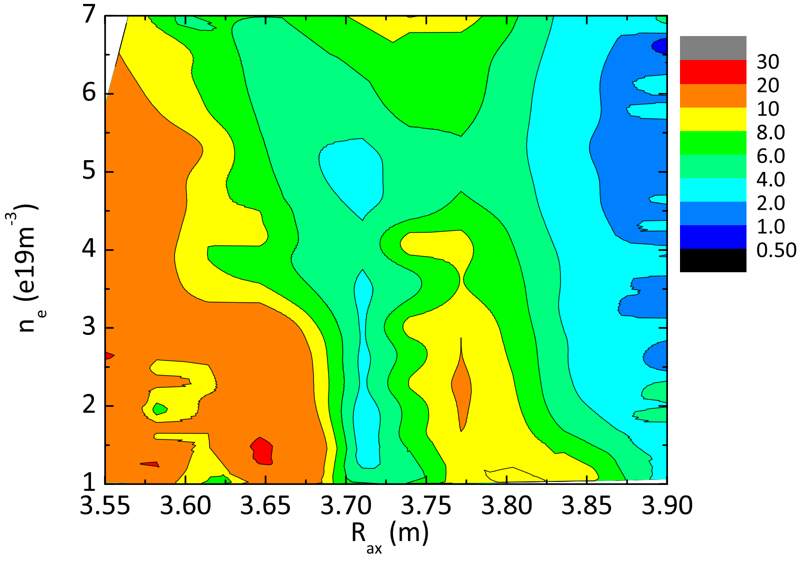
Divertor pressure P_{div} (Pa)



Out of divertor region P_{out} (Pa)



Compression (P_{div}/P_{out})



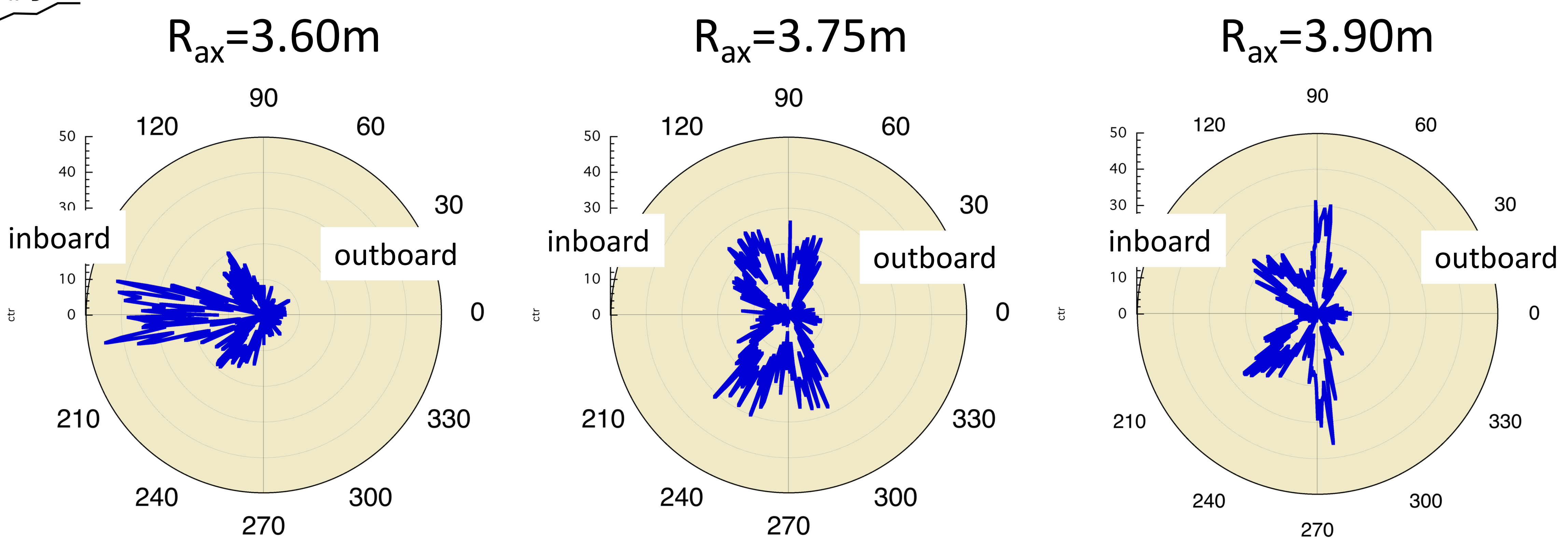
✓ Divertor pressure is 10 times higher than the pressure out of divertor region.

✓ Divertor pressure increases in inner magnetic axis configuration.

✓ Neutral compression is higher in inner magnetic axis configuration (10-20).

Particle flux distribution

T. Morisaki+, NF 2013

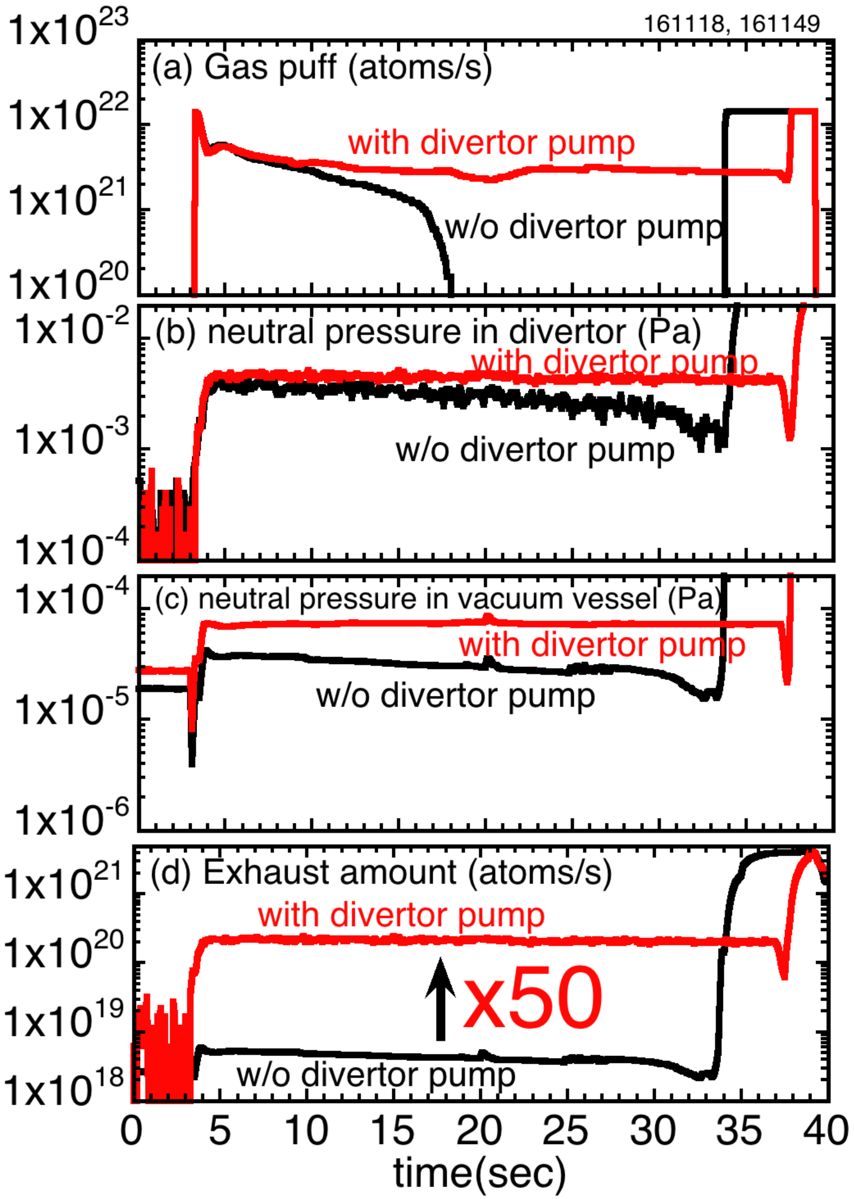


- ✓ 90% of the diverted particles in the inward shifted configuration at R_{ax} = 3.60 m go to the inner half of the torus.
- ✓ On the other hand, at R_{ax} = 3.90 m, only 60% of the diverted particle flow to the inner half of the torus.

Inward shifted-configuration is preferable for neutral particle control, if divertor pumping can work efficiently.

Particle exhausted amount

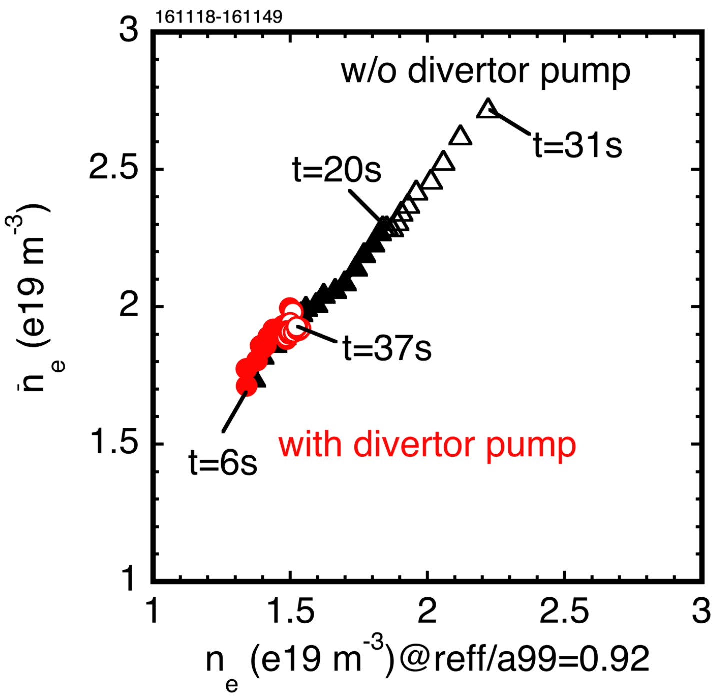
G. Motojima+, 2021 Plasma Fusion Res. 16 1202014.



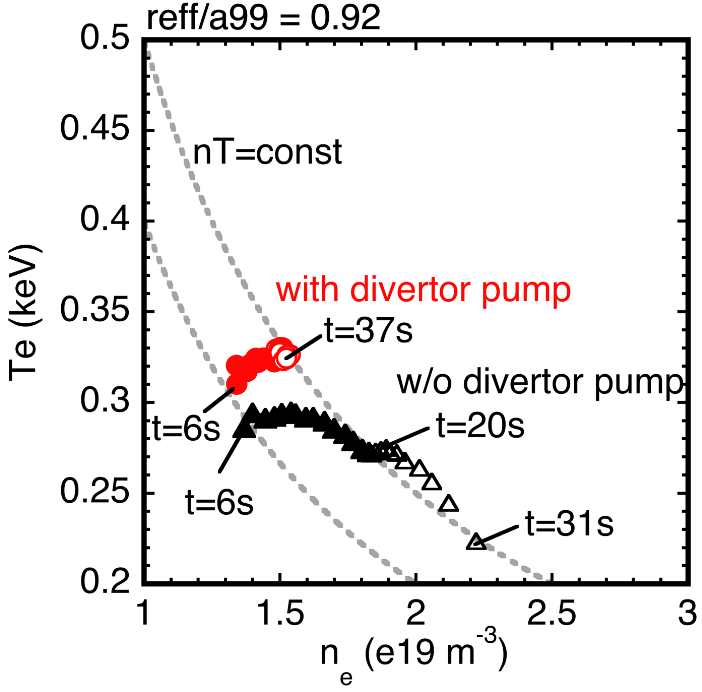
- ✓ In the case with divertor pumping, the exhausted amount increases up to 50 times larger than the case without divertor pumping.
- ✓ The results show that the efficient exhaust is attained by the divertor pump.

Edge pressure and heat flux analysis

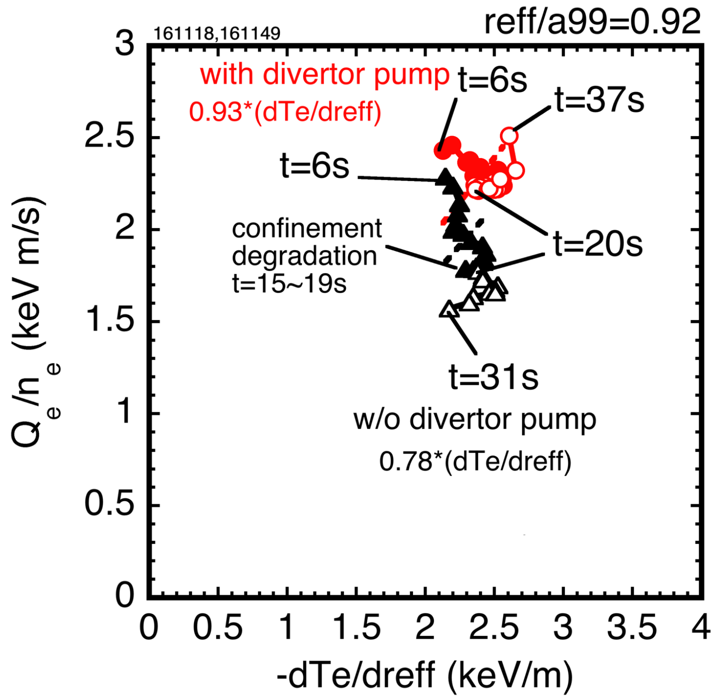
edge n_e vs. averaged n_e



edge n_e vs. edge T_e



edge heat flux

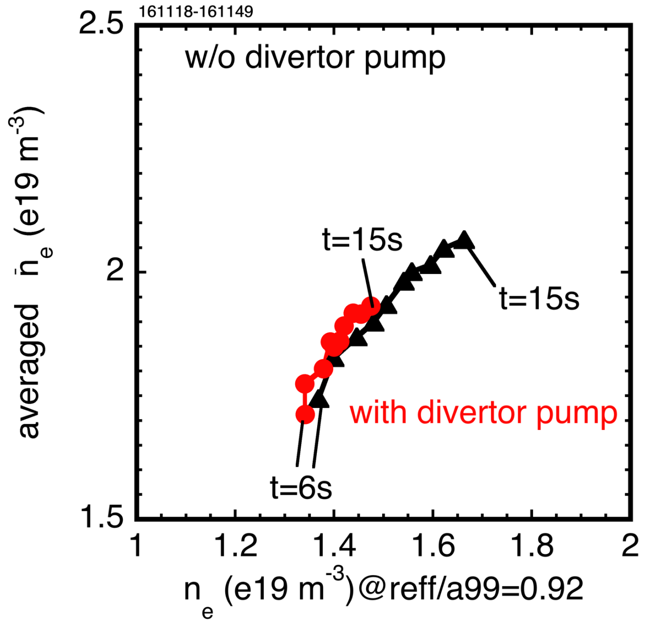


- ✓ Averaged n_e linearly increases with edge n_e. Edge density is a key to control averaged density.
- ✓ In both cases, edge pressure is increasing with time. This characteristics looks different from the result of JT-60U. In the case without divertor pump, density increase/temperature decrease is seen. On the other hand, in the case with divertor pump, stable density and temperature are sustained.
- ✓ A significant difference of T_e-gradient is not observed in edge.

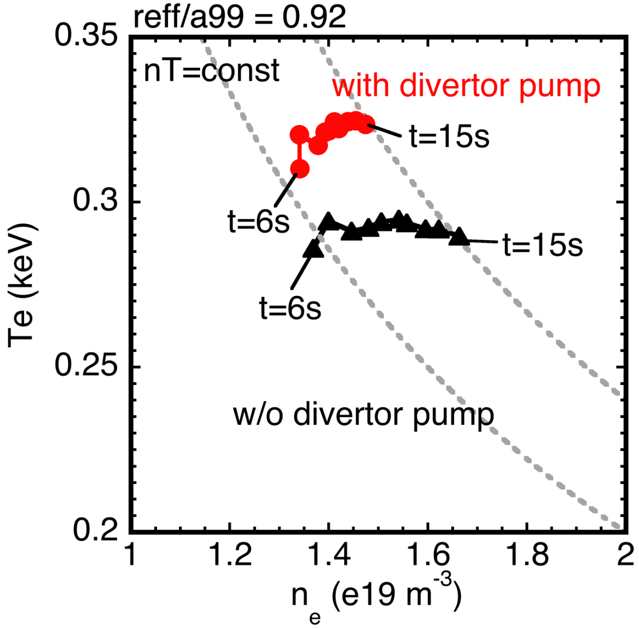
The relation between confinement and edge density control will be further investigated.

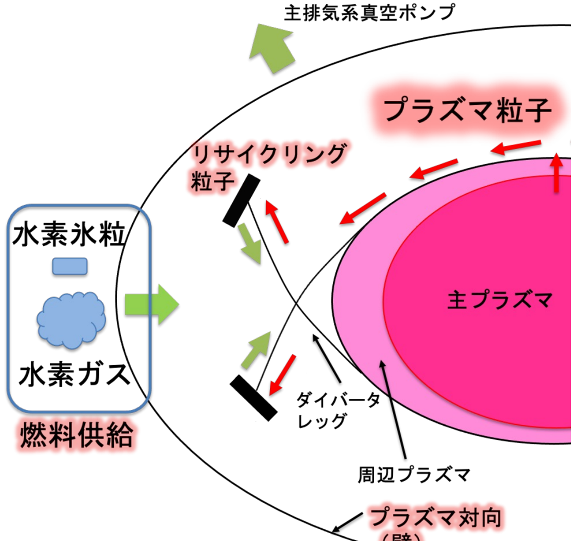
Discussion: comparison on timing of stable density

edge n_e vs. averaged n_e



edge n_e vs. edge T_e





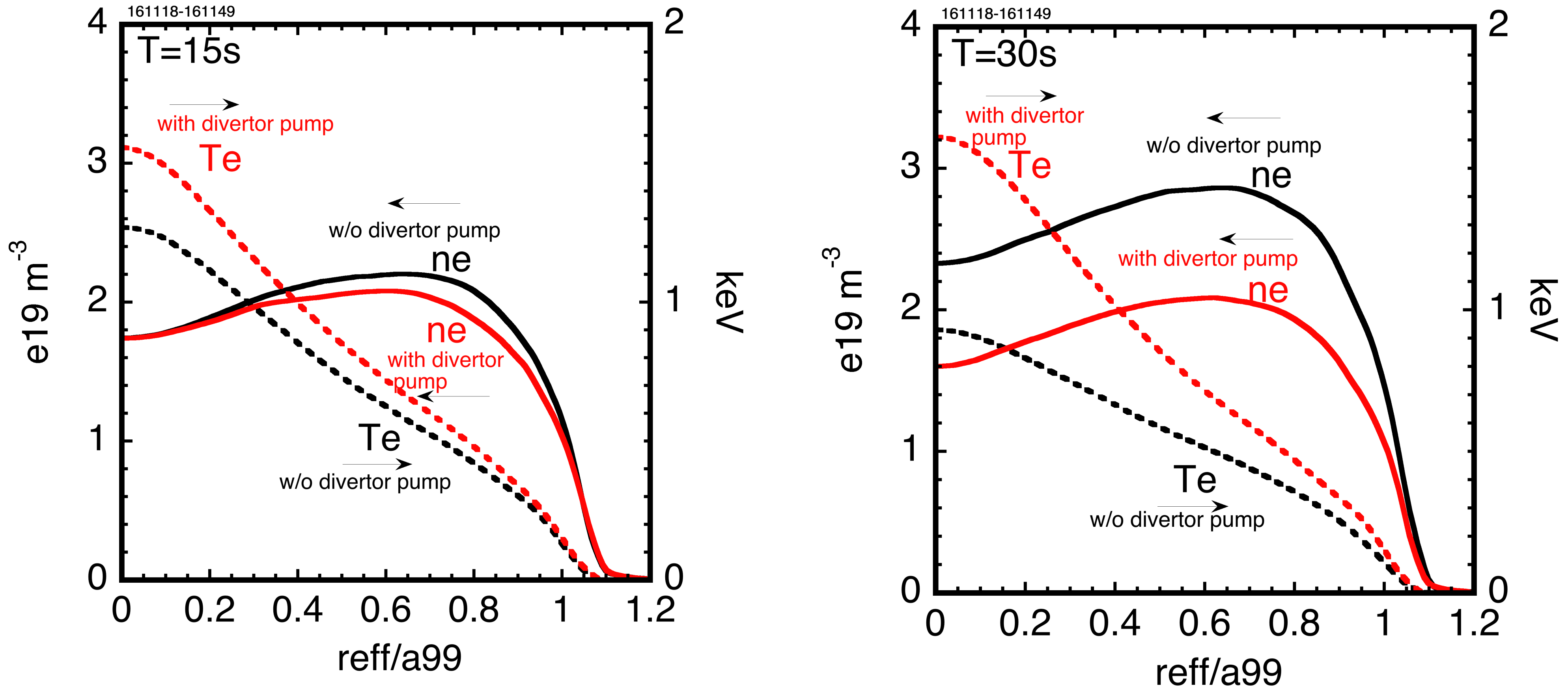
Fueling source

- ✓ Gas puff or ice pellet
- ✓ recycling

Confinement

change or not change?

Density and temperature profiles



G. Motojima