

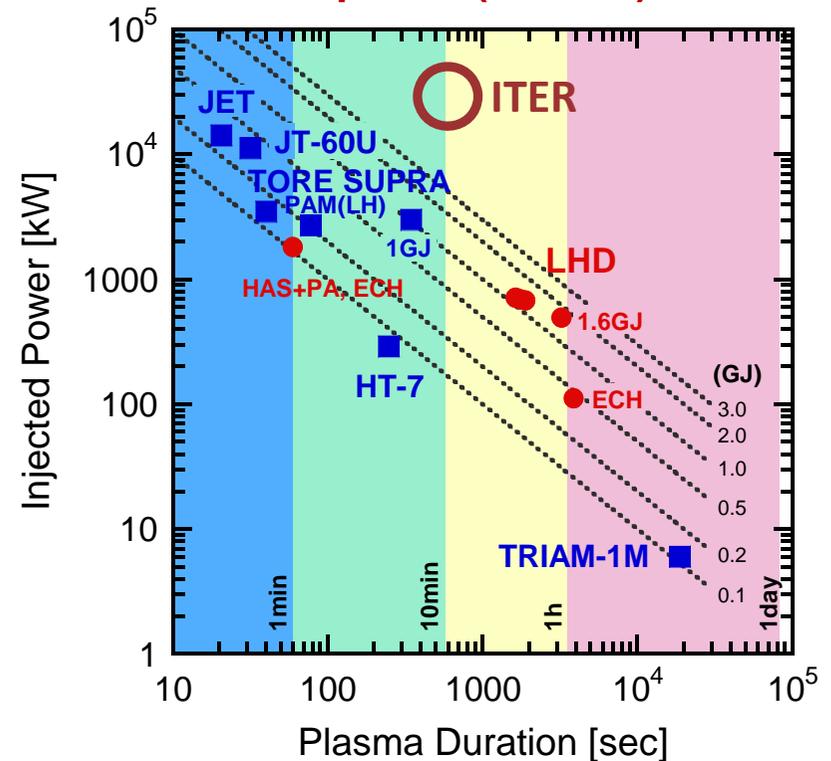
Abstract

- The steady state operation (SSO) of high-performance plasma in LHD has progressed since the last IAEA conference (2010) by means of a newly installed ICH antenna (HAS antenna) and an improved ECH system.
- HAS antenna could control the launching parallel wave number and heated a core plasma efficiently.
- The heating power of steady state ICH and ECH exceeded 1 MW and 500 kW, respectively, and the higher-density helium plasma with minority hydrogen ions was maintained by using the HAS antenna and new 77 GHz gyrotrons.
- As a result, plasma performance improved; e.g., an electron temperature of more than 2 keV at a density of more than $2 \times 10^{19} \text{ m}^{-3}$ became possible for more than 1 min.
- Heat flow balance and particle flux balance of steady-state operation are evaluated. Particle balance analysis indicates that externally fed helium and hydrogen particles are mainly absorbed by a chamber wall and divertor plates, even after the 54-min operation.

One of the Major Goals of LHD is to Demonstrate the Scientific Feasibility of Steady State Helical Reactor

- Heliotron plasma is net current free and disruption free, and it is suited to SSO
- LHD achieved SSO of an hour : A record of the highest input energy to plasma
- Physics and technology development for high performance plasma is important for SSO
- 3MW/ 1hour is target of SSO in LHD

Previous SSO in LHD was low density and low power (< 1 MW)



Key physics and technology elements of SSO

- Heat removal and mitigation of local heat load of divertor and vacuum vessel
- Understanding and control of particle balance in SSO
- Stable CW operation of heating devices

Progress of ICH and ECH

- Poloidal array antennas (PA antenna) has been installed and used. PA antenna is single current strap type and has a large plasma coupling. From the power modulation experiment, 20 to 30% was lost at the edge or outside of plasma column.
 - New improved ICRF antenna (HAS antenna) has been installed to heat the core plasma efficiently. Two single current strap antennas are inserted separately from upper and lower port. The parallel wave number of launched wave can be controlled by changing the phase of two current straps.
 - To reduce an RF field outside of plasma which can cause impurity contamination induced by an RF sheath. The RF electric field intensity near the antenna section is calculated by using electromagnetic simulation code HFSS™ for detailed LHD wall and antenna structure models.
- ECH system is also improved to sustain higher density plasma and to keep steady-state plasma stably.
 - Three 77-GHz high-power gyrotrons were newly installed for high-power ECH and also steady state heating experiment.
 - For ECH In LHD, 4MW for several second and 500kW for steady state operation are available. The ECH frequency of 77-GHz is best to heat the plasma core region for the wider plasma operation condition in LHD and also good match with usual ICRF heating frequency.
 - 77GHz gyrotron has been developed in collaborations with University of Tsukuba , JAEA and Toshiba.



New HAS antenna has good performance for SSO by controlling launched wave number $k_{//}$ (HAsu Seigyo)

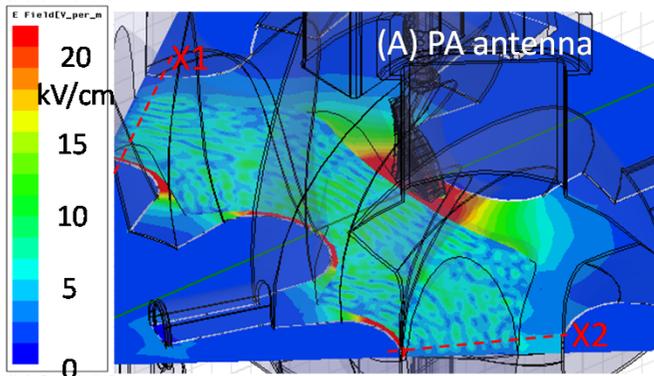
Poloidal Array (PA) antenna



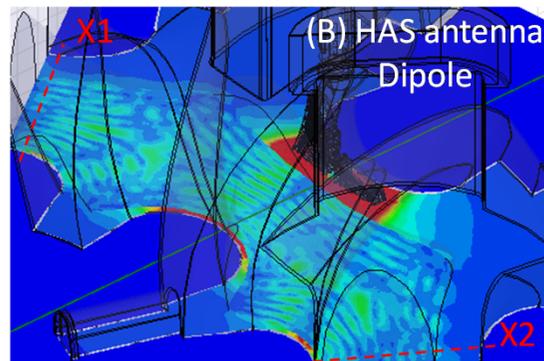
HAS antenna (Toroidal Array)

- ICRF wave with a large $k_{//}$ can heat core plasma effectively.
- HAS antenna can control $k_{//}$ by phasing of two current straps.
- PA antenna has a large plasma coupling resistance due to low $k_{//}$.

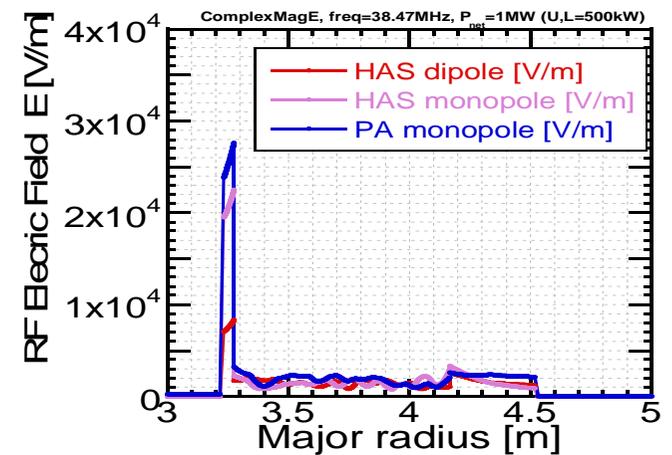
HFSS code shows that outside RF fields at next toroidal sections are reduce by 1/3 with dipole phasing



(A) PA antenna



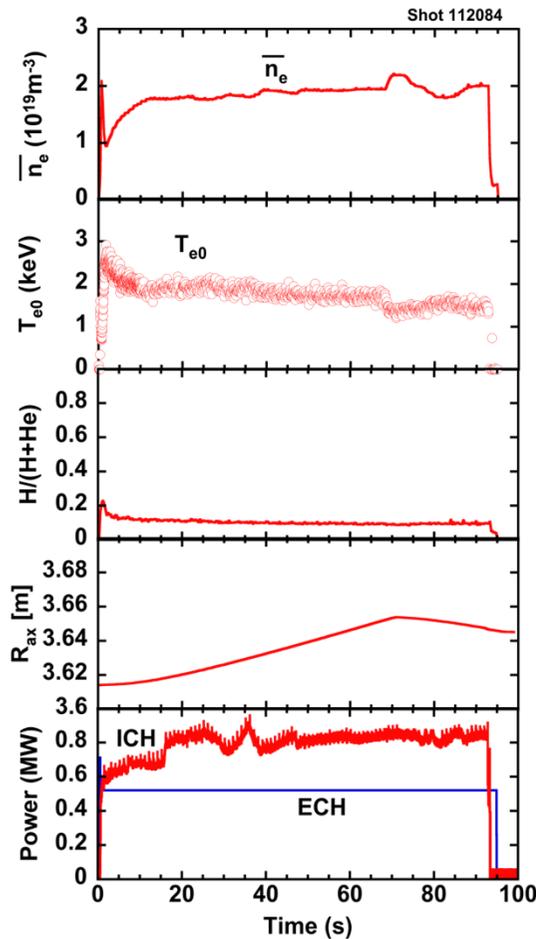
(B) HAS antenna Dipole



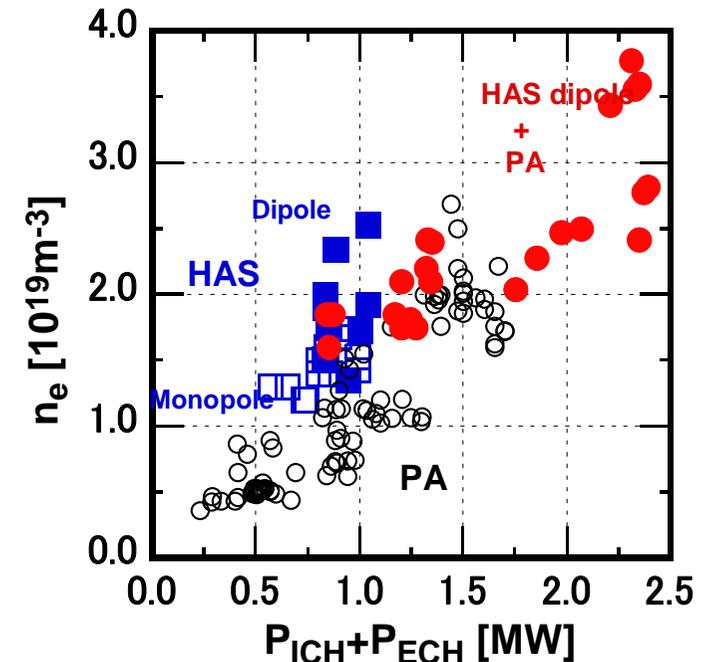
Radial position along X1 and X2⁵



Plasma parameters of SSO is steadily improved from last IAEA



HAS (dipole mode) antenna has better performance than HAS (monopole) and Poloidal Array antennas.

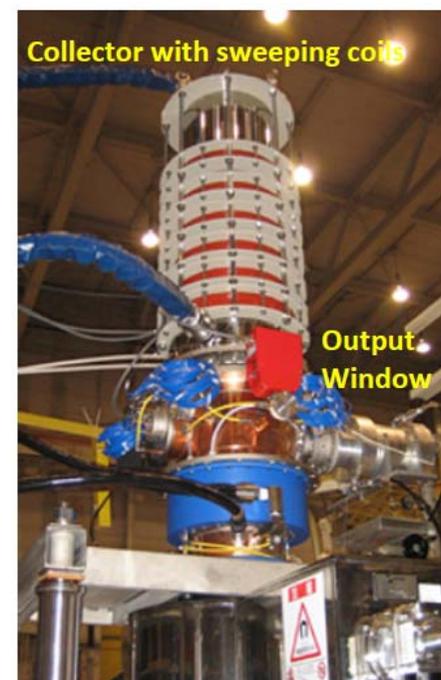
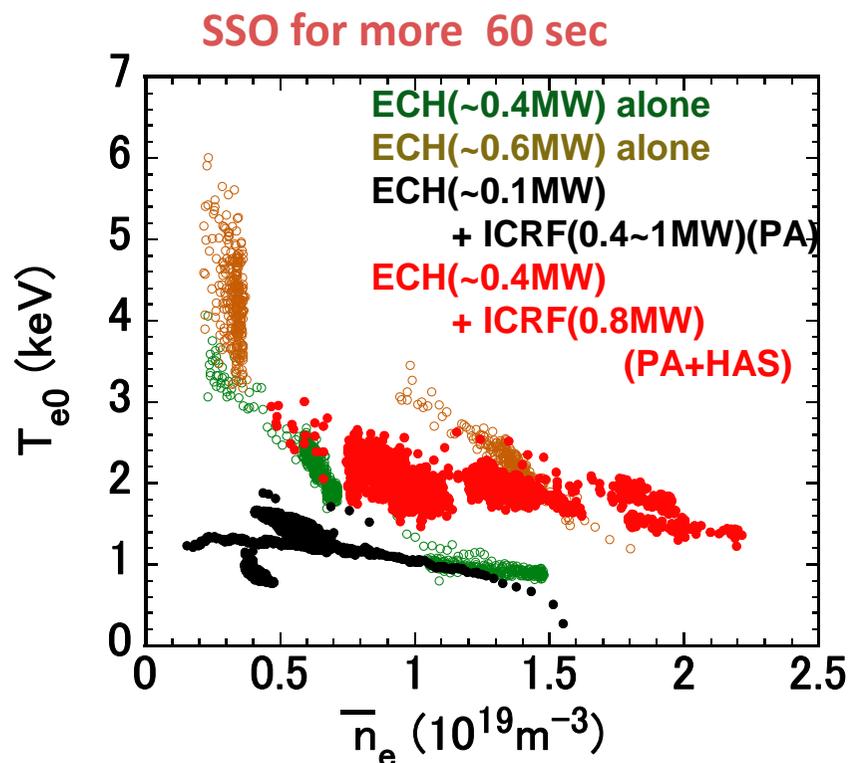


B = 2.75T (@R=3.6m)
P_{ICRF} = 800kW (freq. = 38.5 MHz)
P_{ECH} = 500 kW, P_{total}=1300 kW

- Higher density plasma with $n_e=3.6 \times 10^{19} \text{m}^{-3}$, $T_e \sim T_i \sim 1 \text{keV}$ was sustained with $P_{\text{ICH}}=2 \text{MW}$ and $P_{\text{ECH}}=0.37 \text{MW}$
- Plasma density was increased almost proportionally to $P_{\text{RF}}(P_{\text{ICH}}+P_{\text{ECH}})$.



Plasma parameters of SSO is improved using newly 77 GHz gyrotrons from last IAEA



Design parameters of 77GHz gyrotrons

ECH: Three 77 GHz Gyrotrons are installed.
 4 MW for 5 sec
 0.5 MW for CW
ICH: New HAS antennas and PA antenna are used to sustain higher density plasma

Items	Design parameters
Frequency	77GHz
Power/Pulse	1 st tube: 1.0MW/5sec, 0.3MW/CW
	2 nd tube: 1.2MW/5sec, 0.3MW/CW
	3 rd tube: 1.5MW/2sec, 0.3MW/CW
Beam Current	< 60A
Oscillation Mode	TE18,6
MIG Type	Triode
Collector Type	Collector Potential Depression
Output Window	CVD Diamond

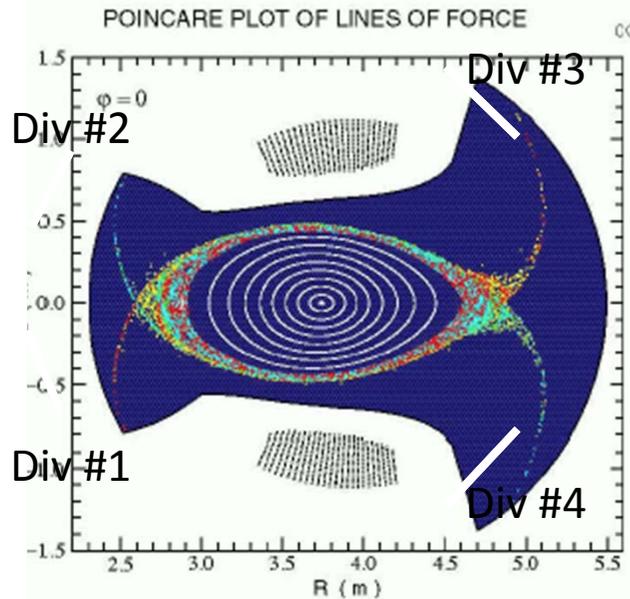
Heat Flow and Particle Balance of ICH SSO in LHD

- Heat flow to divertor channel is estimated by temperature rise of cooling water. Cooling channels of divertor are divided to 40 sections of toroidal and poloidal section.
- Wall heat load which includes radiation loss and charge exchange loss is estimated by bolometers.
- Other local heat load at wall caused by high energy particle prompt loss or ECH beam transmission is estimated from the residual amount.
- About half of the input energy injected by ICRF and ECH goes to the divertor plates, and around 10% goes to the ICRF antenna carbon protectors.
- Heat flow to the chamber wall is around 10% at low electron density and it increased to 30% by increasing electron density.
- The residual part should be due to prompt particle loss of ICRF heating or ECH microwave transmission, and it decreased from 30% to 15% as plasma density increased.

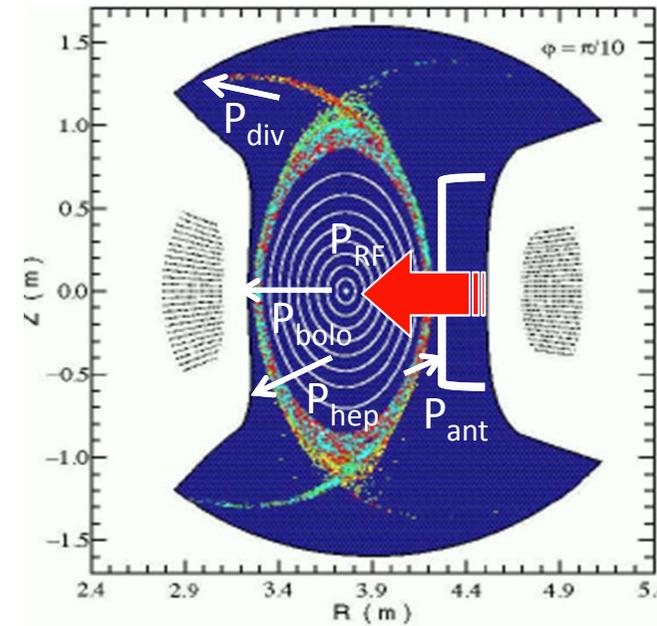
- Particle balance inside of LHD vacuum chamber is estimated. The majority ions of plasma are helium and the minority ions are hydrogen.
- The ratio of the total supplied particles (helium and hydrogen) to the externally pumped particles is around 20 times, which indicates that wall pumping is a dominant particle sink during the SSO of 320 sec. The vacuum chamber works as a large particle sink in LHD.
- In the case of 54-min plasma operation in 2006, the LHD chamber wall also worked as a particle sink even after the very long operation time.
- Helium is majority ions of 90 % and hydrogen is minority ions in plasma. Major part of feeding gas is hydrogen (> 90 %) and this shows the low recycling rate of hydrogen atoms.



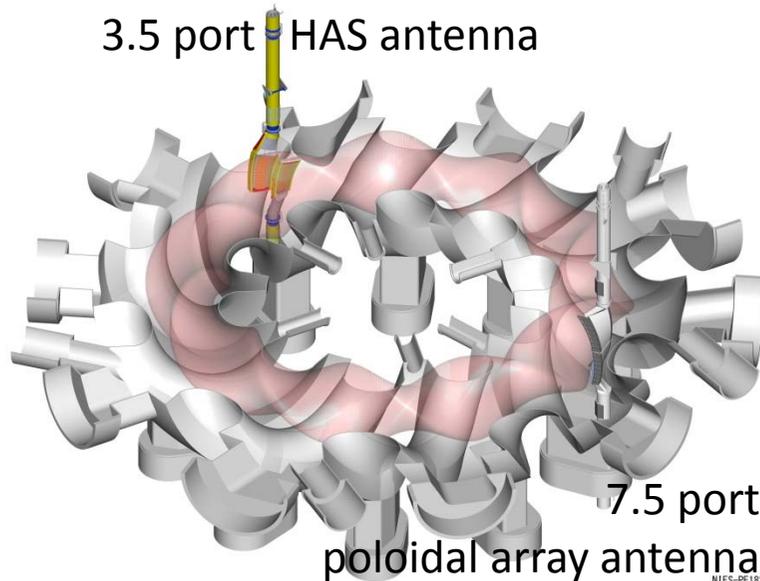
Heat flows through divertor, wall and antennas are estimated for long pulse discharge



Particle out flow distribution through four divertor legs depends on plasma axis position



3.5 port HAS antenna



$$P_{RF} = P_{bolo} + P_{div} + P_{ant} + P_{other}$$

P_{bolo} : radiation losses to wall

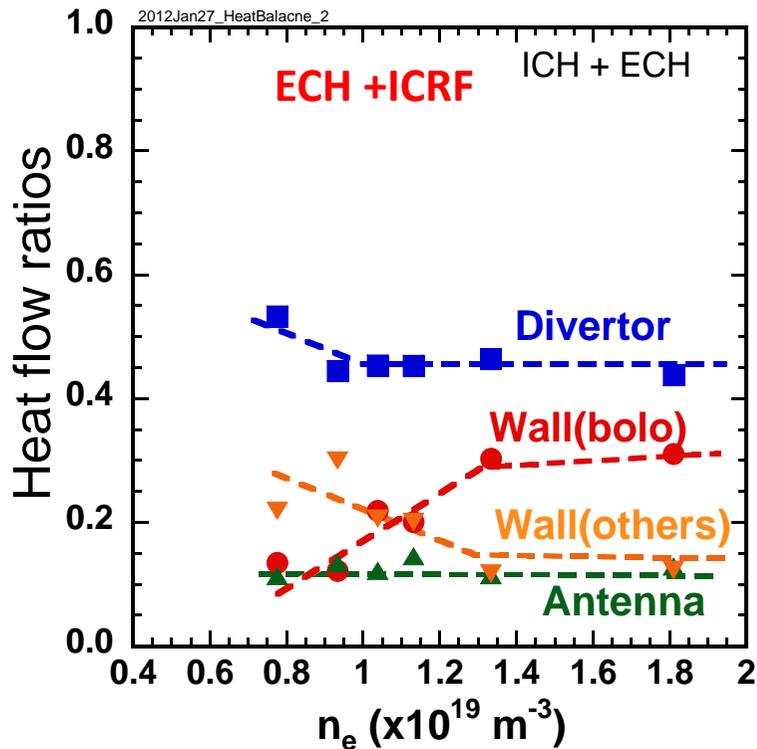
P_{div} : divertor losses

P_{ant} : antenna protector and coaxial line losses

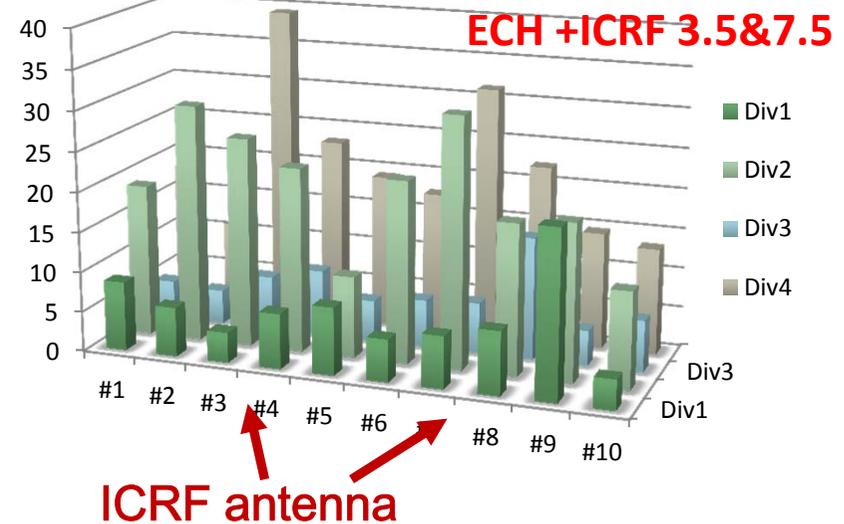
P_{other} : particle orbit loss, other ... to wall



Around Half of Input Energy Goes to Divertor Plates



#112073 $P_{RF} = 1255\text{kW}$ (ICH:1134kW, ECH:121kW)
 $P_{div.} = 568.3\text{kW}$, $n_e = 1.13 \times 10^{19} \text{ m}^{-3}$



Heat Flow balance is estimated from Integrated water removal power and bolometer in the discharge.

- $r_{\text{bolo.}} = P_{\text{bolometer}} / P_{RF}$
- $r_{\text{div.}} = P_{\text{div. water cooling}} / P_{RF}$
- $r_{\text{ant.}} = P_{\text{antenna water cooling}} / P_{RF}$
- $r_{\text{other}} = 1 - (r_{\text{bolo.}} + r_{\text{div.}} + r_{\text{ant.}})$

- Heat flow to divertor plates is around half of the total heating power.
- ICRF antennas absorb around 10%
- VV wall absorbs 10 to 30%, and it increases as n_e
- Local heat load by prompt ion loss is large in low density regime.



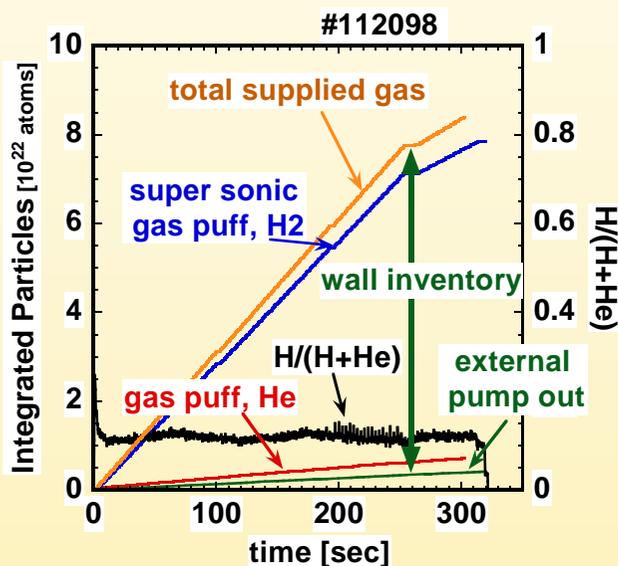
Particle Balance in Vacuum Vessel is Evaluated at SSO in LHD

$$dN_p/dt + dN_0/dt = \Gamma_{\text{fuel}} - \Gamma_{\text{pump}} - \Gamma_{\text{wall}}$$

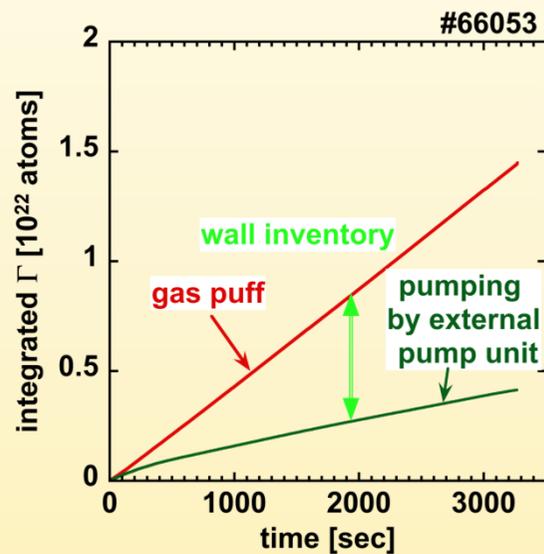
N_p : ions in the plasma, N_0 : neutral atoms in the chamber

Γ_{fuel} : fueling rate, Γ_{pump} : pumping rate, Γ_{wall} : net wall pumping rate

LHD 5min discharge



LHD 54min discharge

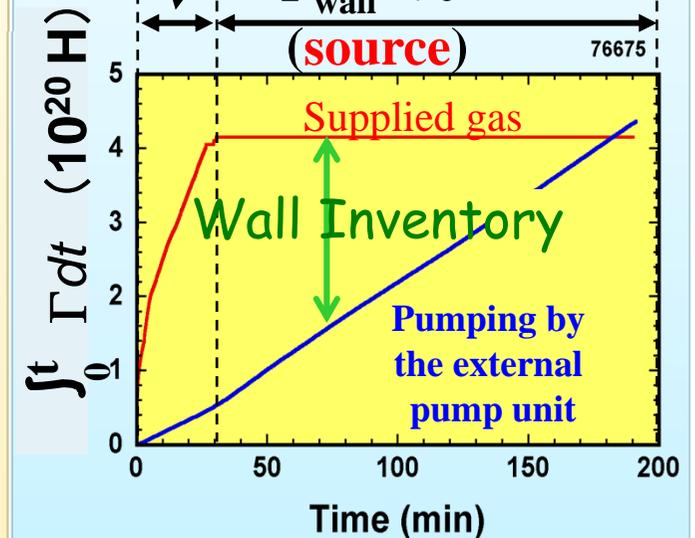


TRIAM -1M 3hrs discharge

$\Gamma_{\text{wall}} > 0$ (sink)

$\Gamma_{\text{wall}} < 0$

(source)

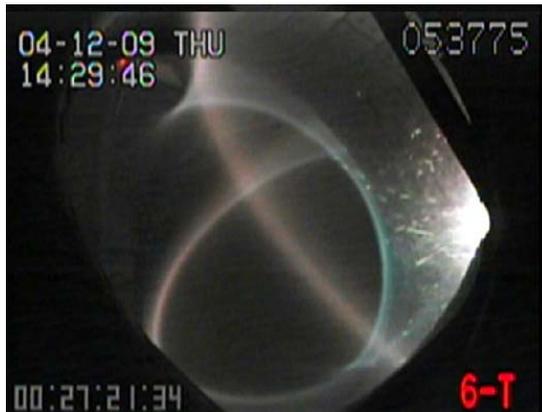


(By M. Sakamoto, Univ. of Tsukuba)

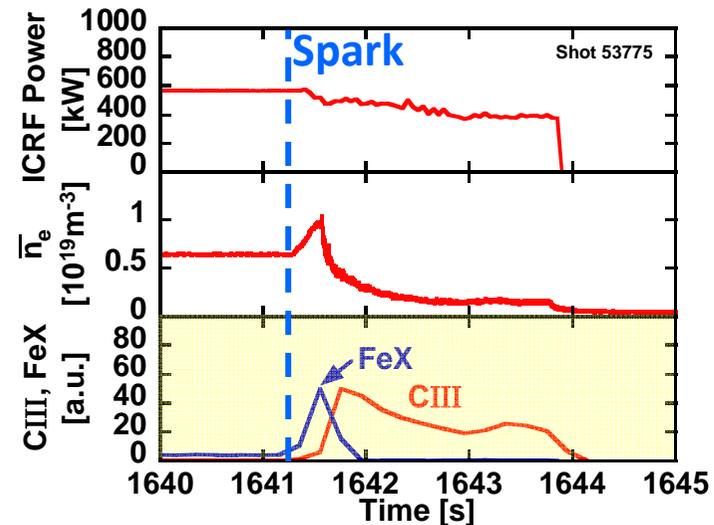
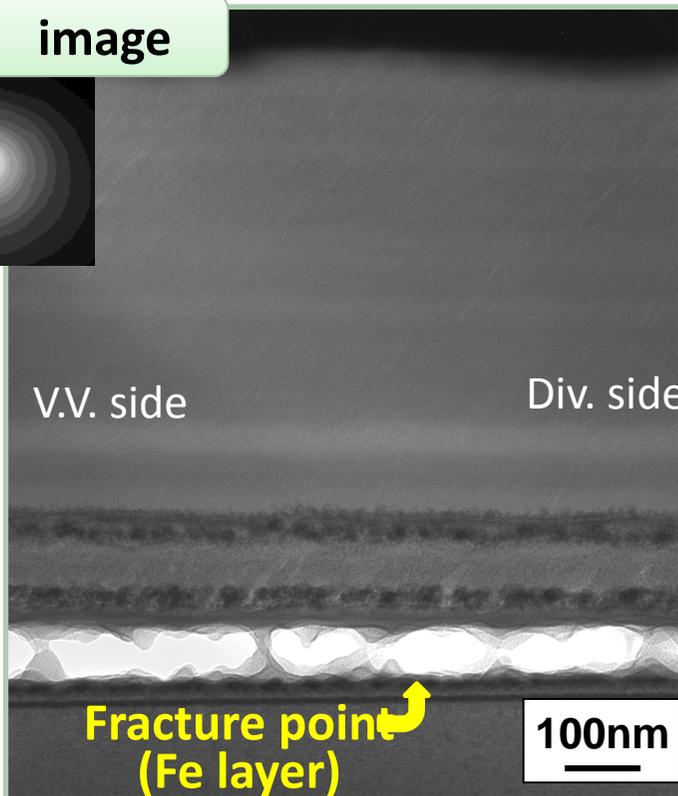
- High recycling for He and low recycling for H
- VV Wall works as particle sink even after 54 minutes plasma operation in LHD

Deposited mixed-material can cause radiation collapses

Visible camera image during long pulse discharge in LHD



TEM image



- Plasma was terminated due to the sudden increase of Fe impurity.

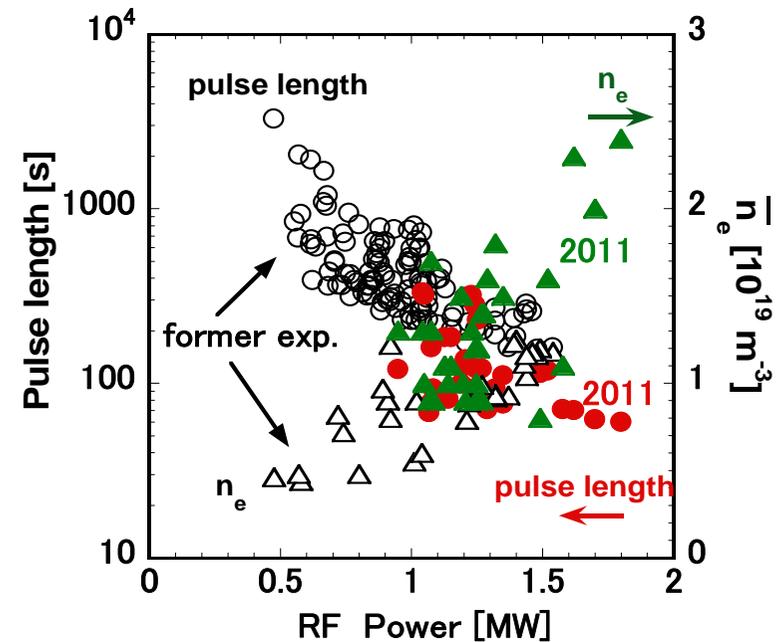
- Mixed-material deposition layer formed on the periphery of divertor plates.
- Fractured mixed-material flake is a main candidate of impurity influx which can terminate the SSO.



Summary and Future Plan

- The steady state operation regime has extended to higher-power region since the last IAEA conference.
- Steady-state operation using HAS antenna and 77 GHz gyrotrons has just started in 2011 and an operation time is limited less than 5 min mainly due to the hardware problems of heating systems.
- In previous steady-state operation, plasma operations were terminated by uncontrollable density rise or impurity flake drops from the wall.
- To reduce local heat load, the operation of HAS antenna is important and the injection power from HAS antenna and 77 GHz ECH should be increased to the higher power level up to 3 MW as the target of LHD.
- These experiences of steady state operation are expected to give us useful information for ITER and future fusion devices.

Duration Time vs. P_{RF}



After the last IAEA conf., steady state operation regime is extended to the higher power and higher density regime.