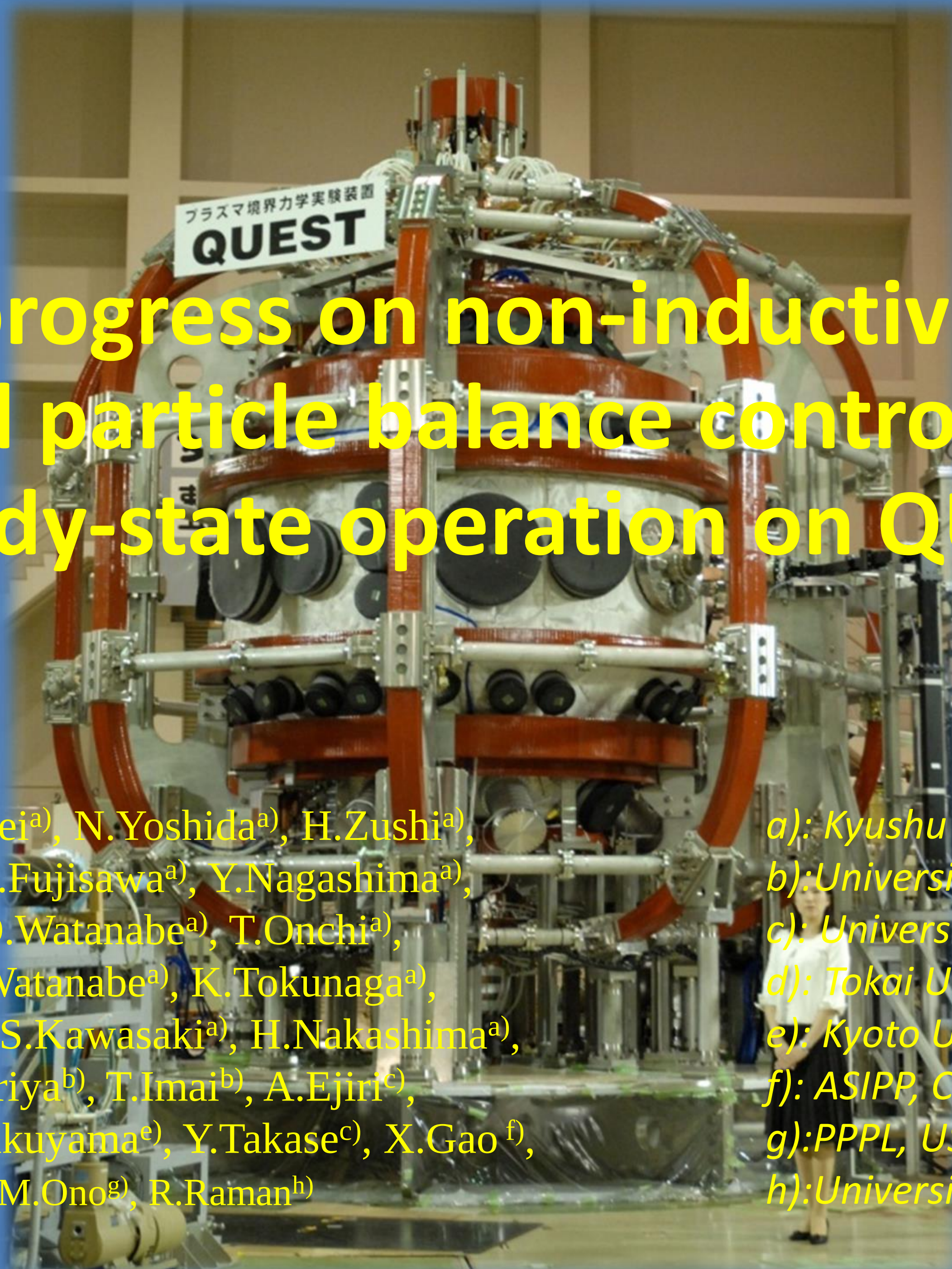


Recent progress on non-inductive current drive and particle balance control towards steady-state operation on QUEST

K.Hanada[a], H.Idei[a], N.Yoshida[a], H.Zushi[a], K.Nakamura[a], A.Fujisawa[a], Y.Nagashima[a], M.Hasegawa[a], O.Watanabe[a], T.Onchi[a], A.Kuzmin [a], H.Watanabe[a], K.Tokunaga[a], A.Higashijima[a], S.Kawasaki[a], H.Nakashima[a], T.Nagata [a], T.Kariya[b], T.Imai[b], A.Ejiri[c], O.Mitarai[d], A.Fukuyama[e], Y.Takase[c], X.Gao [f], H.Liu[f] J. Qian[f], M.Ono[g], R.Raman[h]

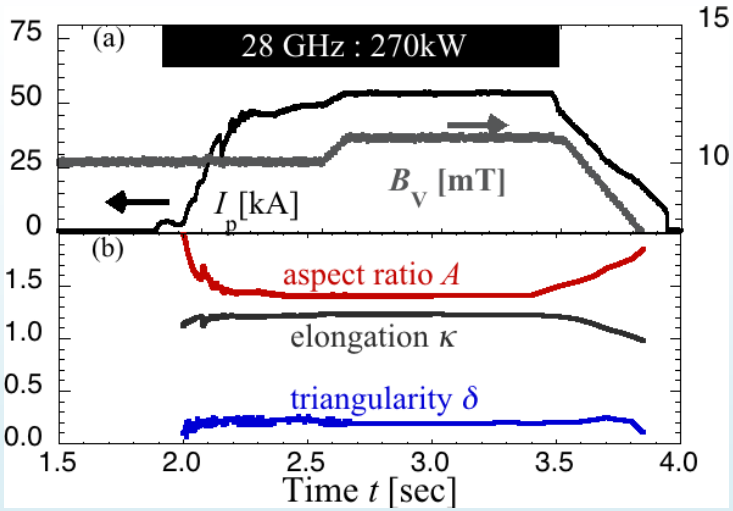
a): Kyushu University, Japan,
b):University of Tsukuba, Japan,
c): University of Tokyo, Japan,
d): Tokai University, Japan,
e): Kyoto University, Japan
f): ASIPP, China.
g):PPPL, USA,
h):University of Washington, USA

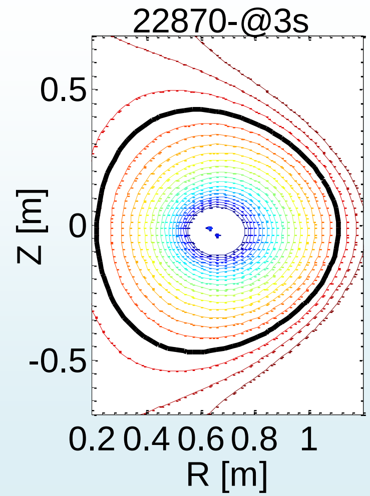
Plasma start-up with a 28GHz gyrotron and 8.2GHz klystrons

Fully Non-inductive Current Drive Experiments using 28 GHz and 8.2 GHz Electron Cyclotron Waves in QUEST

筑波大学 University of Tsukuba
九州大学 KYUSHU UNIVERSITY
QUEST Advanced Fusion Research Center

54 kA Plasma Sustainment in Low Aspect Ratio Configuration by 28GHz Injection





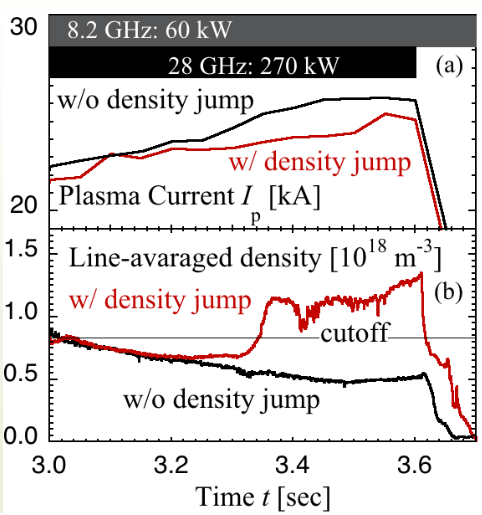
Plasma current of 54 KA was non-inductively sustained for 0.9 sec by only 28 GHz injection.

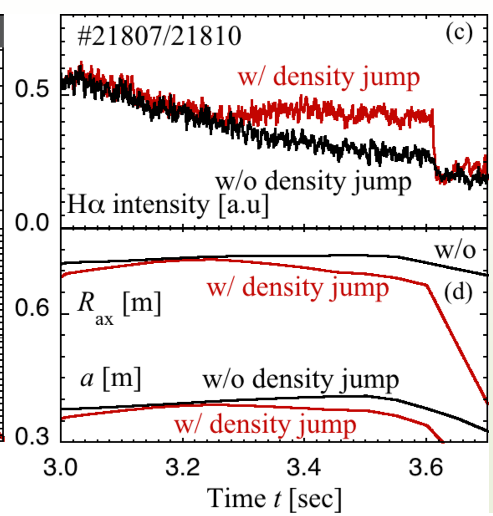
Plasma shaping was almost kept for 1.3 sec.

Higher current of 66 kA was non-inductively obtained by slow ramp-up of vertical field also.

Non-inductive high current plasma start-up by 2nd ECH/ECCD has been demonstrated.

Over Dense Plasma Sustainment by 28 /8.2 GHz Injections after Spontaneous Density Jump



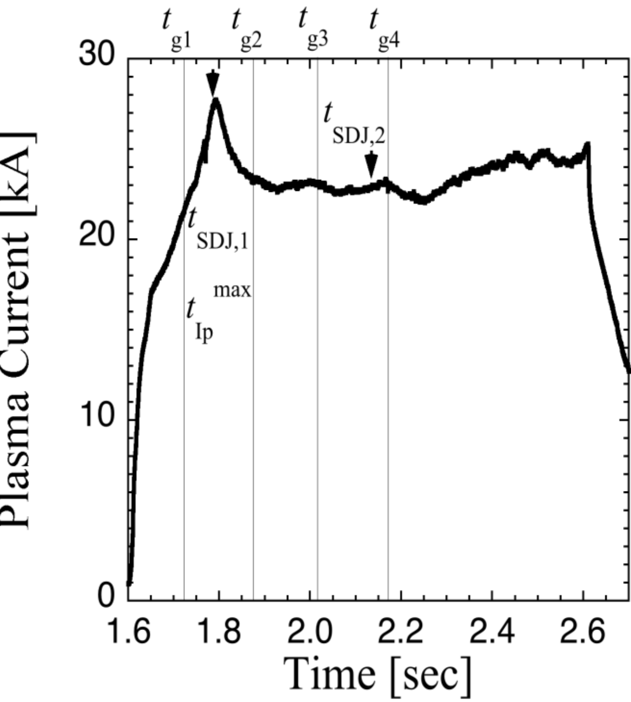


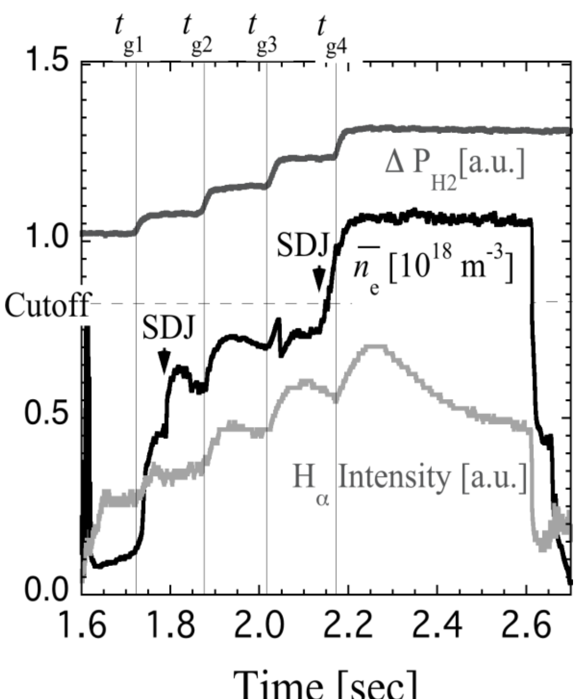
Spontaneous density jump across the cutoff density was observed in superposed 28 and 8.2 GHz injections.

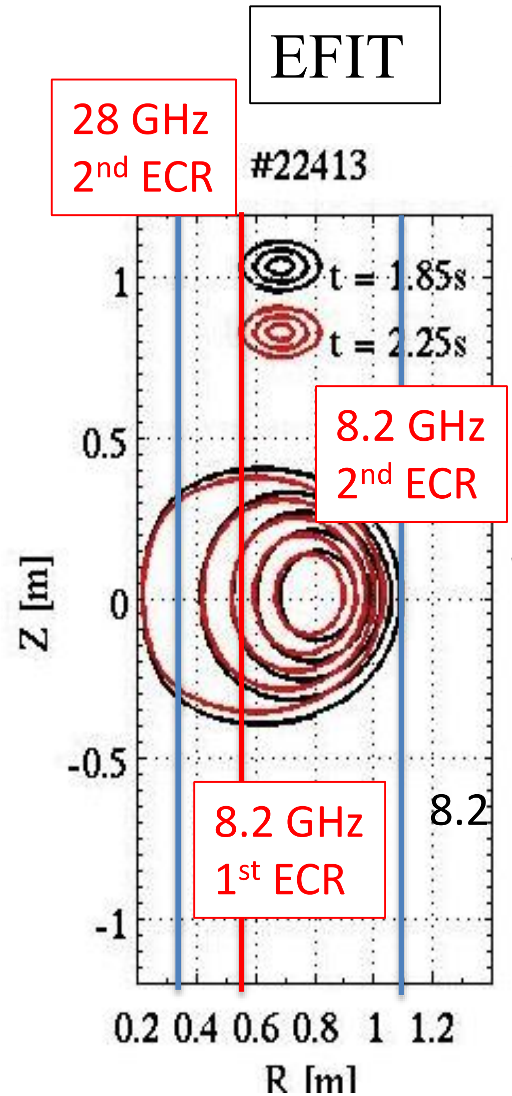
Hα intensity was kept, magnetic axis R_{ax} and minor radius a were slightly decreased in the density jump case.

Plasma current I_p was once decreased, but was recovered after the plasma shaping became more stable.

Experimental proof of EBWH [8.2 GHz + 28 GHz]

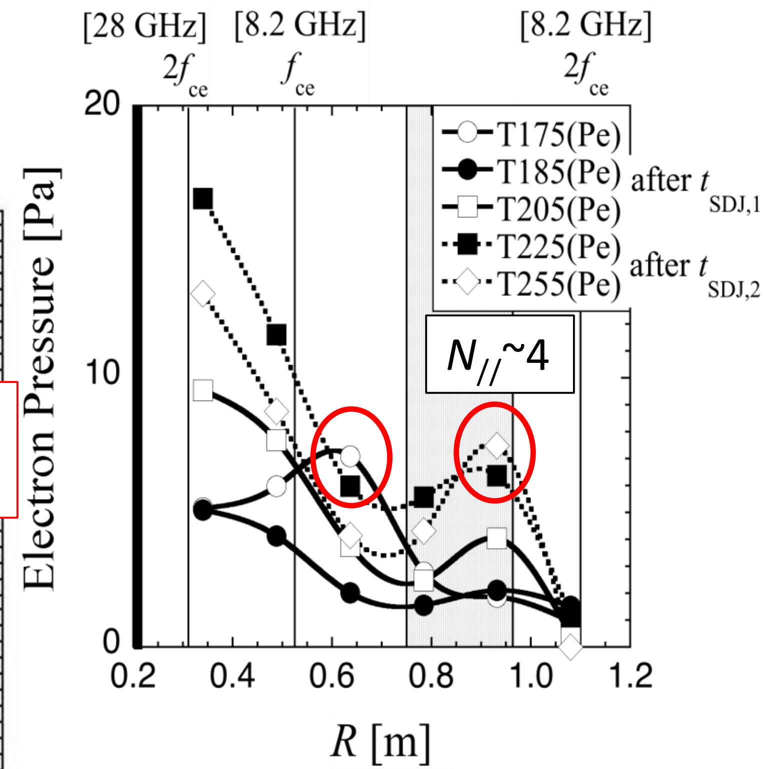






Large Shafranov Shift

R_0~0.8m



In low density, 8.2 GHz 1st can work around the plasma center. (see a left red circle) Effective ECH

In higher density, 8.2 GHz 1st can also work well at the shifted plasma center. (see a right red circle) $N_{//}$~4 EBWH

8.2GHz microwave is still difficult to reach UHR for EBWCD in low density

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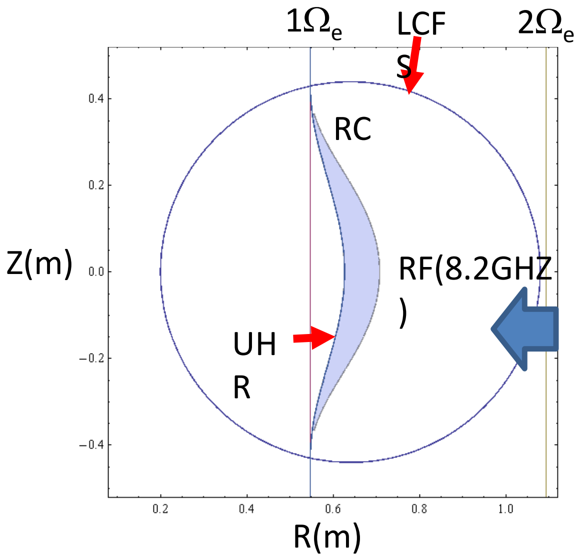
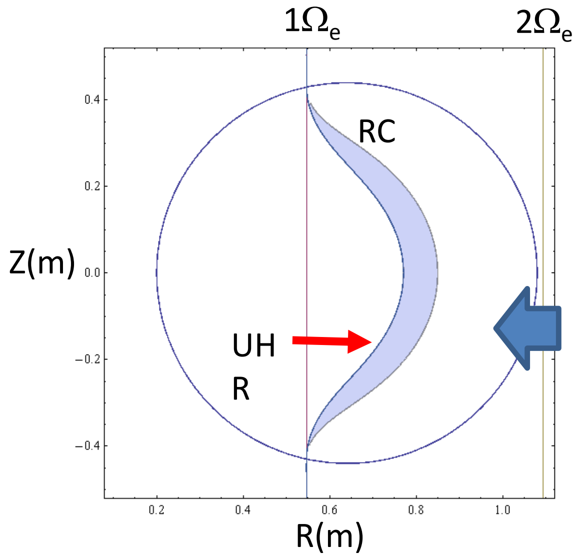


$$n_e = 2\times10^{17}\, m^{-3}\left(1-\frac{(R-0.64)^2+Z^2}{(0.44)^2}\right)^2$$

$B_T = 0.25T\ @\ R = 0.64m$

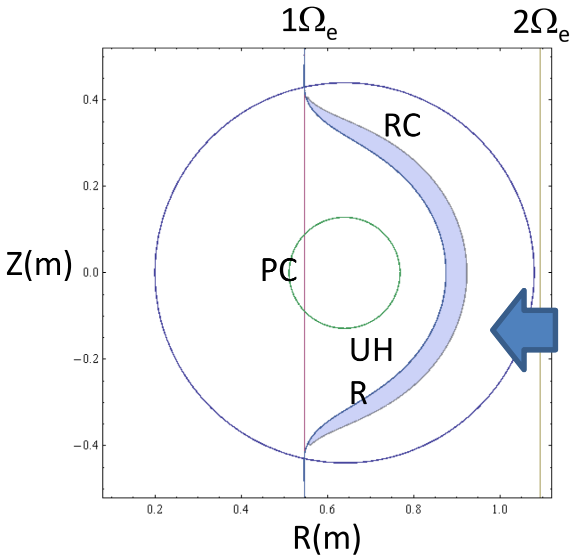
$N_z = 0$



$$n_e = 5\times10^{17}\, m^{-3}\left(1-\frac{(R-0.64)^2+Z^2}{(0.44)^2}\right)^2$$

$B_T = 0.25T\ @\ R = 0.64m$

$N_z = 0$



$$n_e = 1\times10^{18}\, m^{-3}\left(1-\frac{(R-0.64)^2+Z^2}{(0.44)^2}\right)^2$$

$B_T = 0.25T\ @\ R = 0.64m$

$N_z = 0$

Typical waveforms of a slow oscillation from 20 to 30 Hz has been observed in 28GHz+8.2GHz.

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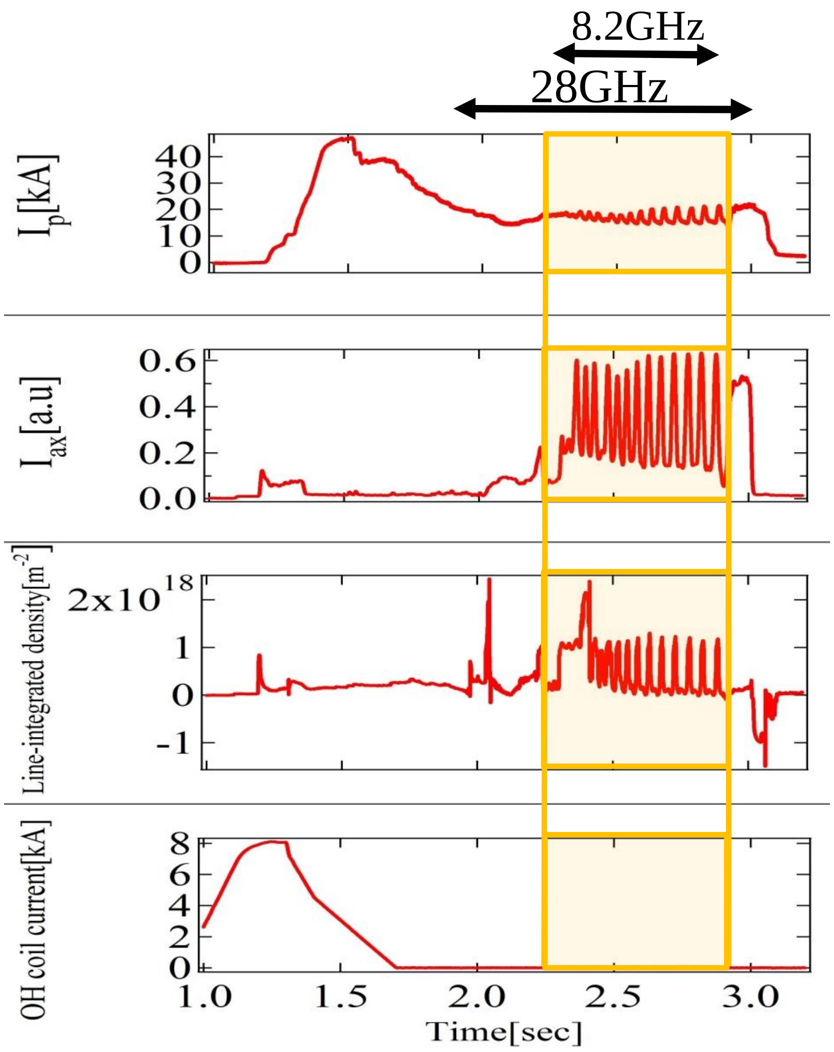
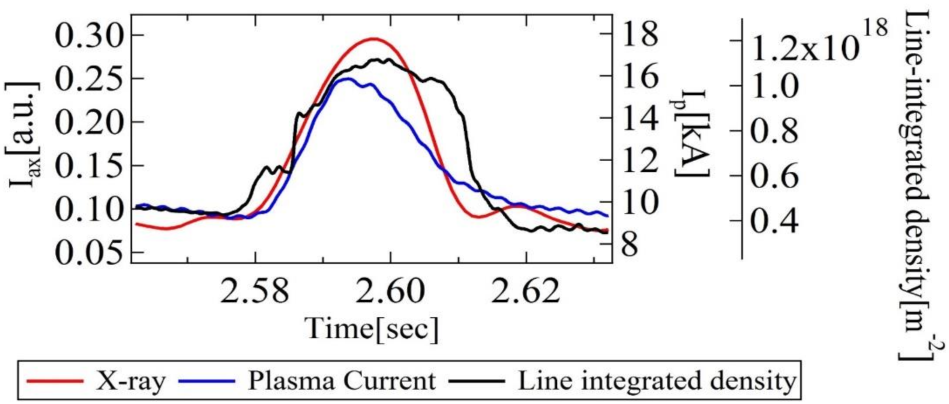
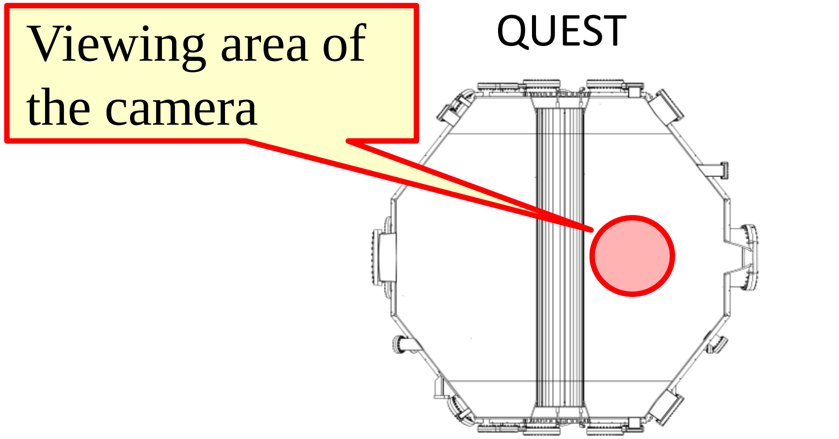


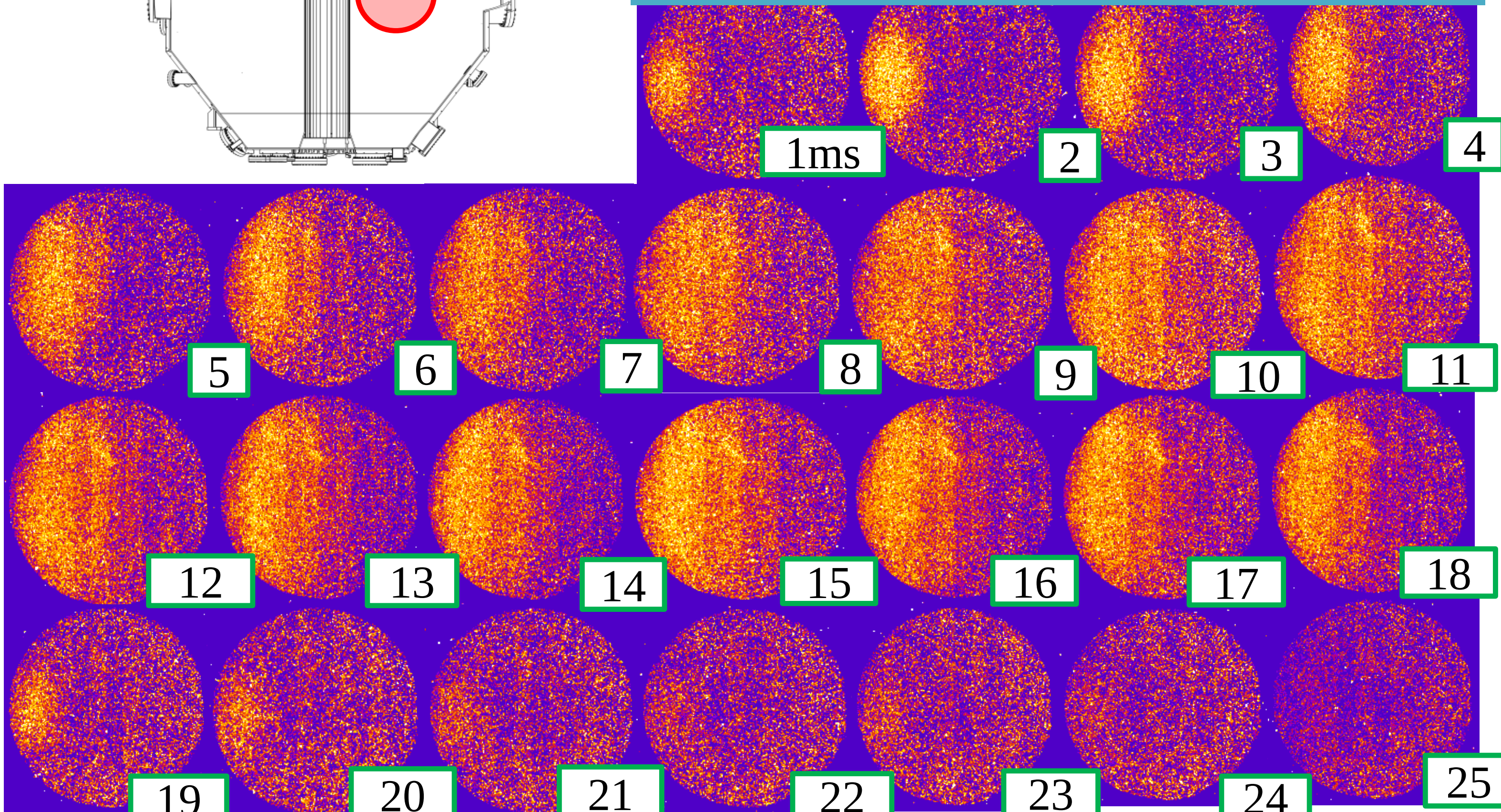


- The oscillation of 20-30 Hz took place in the plasmas with combination of 28GHz and 8.2GHz.
- Both Ip and ne oscillate in the same frequency which is comparable to current diffusion time.

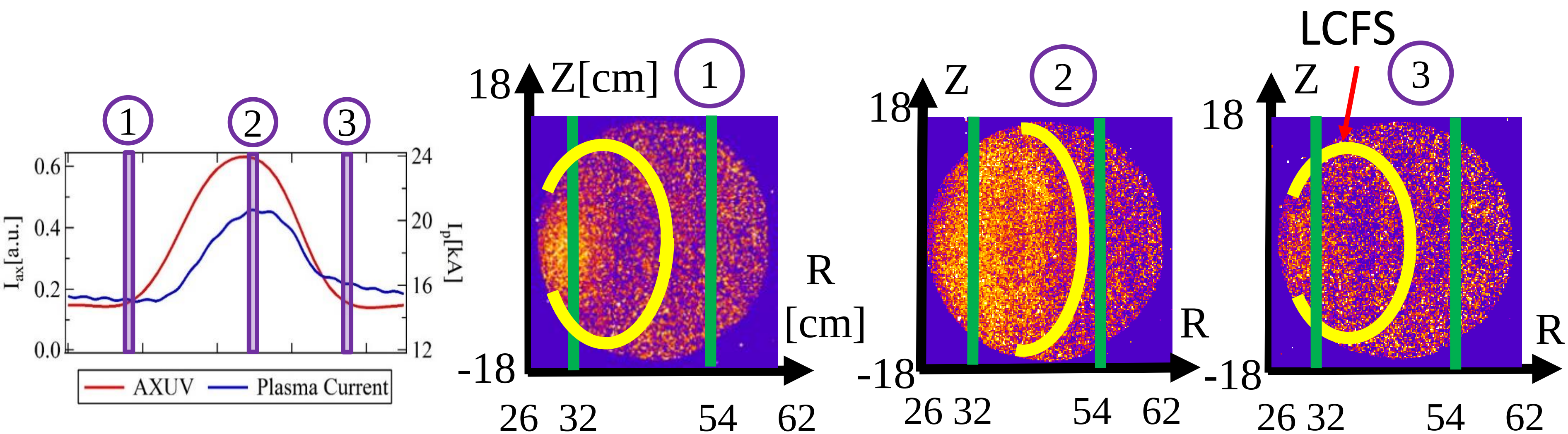
The 2D SXR camera can catch the modification of the core plasma.



The position of the intense SXR signal repeats to expansion and shrink.



The oscillation is relating to modification of LCFS and starts to shrink it around 2nd resonance of 8.2 GHz.



Two green lines show a location of a second harmonic resonance layer of 28GHz at R=32cm and a fundamental resonance layer of 8.2GHz at R=54cm

LCFS is likely to expand to low filed side and starts to shrink when it looks to reach 2nd resonance of 8.2GHz.

- The intense SXR was emitted from 2nd ECR layer of 28GHz and spread with the expansion of last-closed flux surface.
- The SXR oscillation can be partially explained by the modification of LCFS.

Spontaneous rotation and Flow reversal

Spontaneous toroidal rotation was observed in higher mirror ratio configuration.

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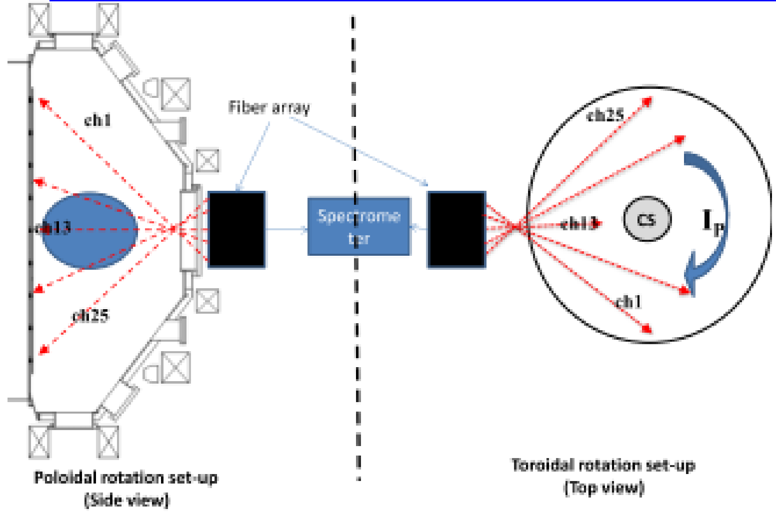


Fig. 1. Schematic set up of 25 channel optical fiber and spectrometer system on QUEST to measure toroidal and poloidal plasma rotation profile. Approximate viewing chords are shown as broken arrow.

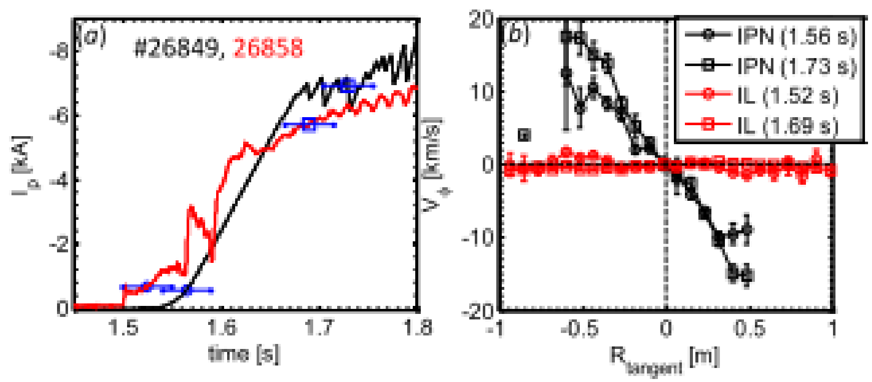
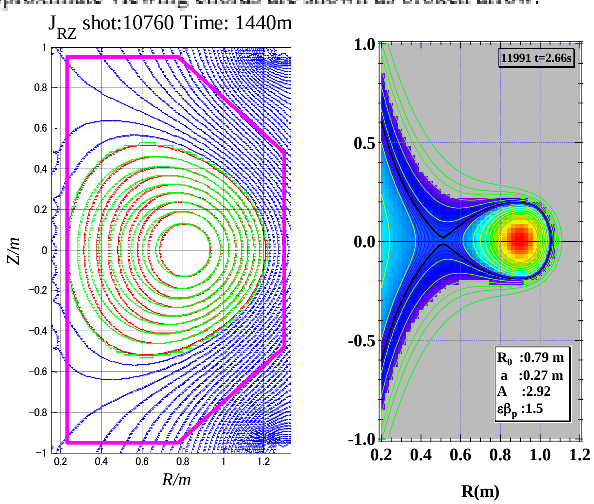


Fig. 5. Plasma current (I_p) and rotation (V_ϕ) evolution in time for two most similar plasma discharges at two different are shown. Red color traces are for the discharge at $M = 1.2$ (IL plasma) and in black traces are at $M = 2$ (IPN plasma). Spectrometer exposure time is shown as horizontal bars on the I_p traces. Finite rotation is observed only in IPN plasma. Error bars on V_ϕ traces shows 95% confidence level in Gaussian fittings of raw line spectra.



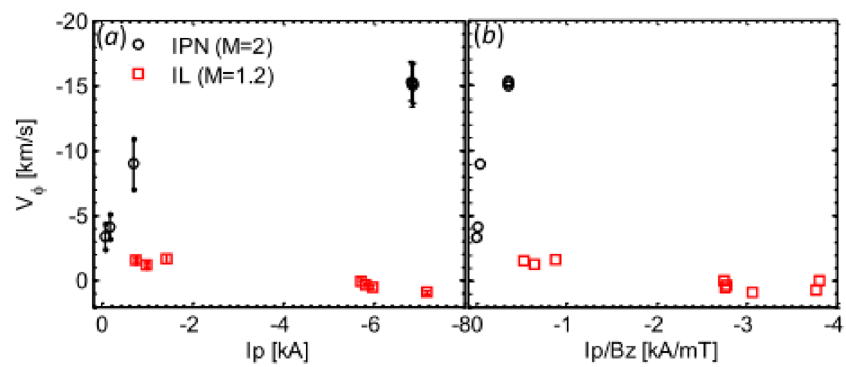
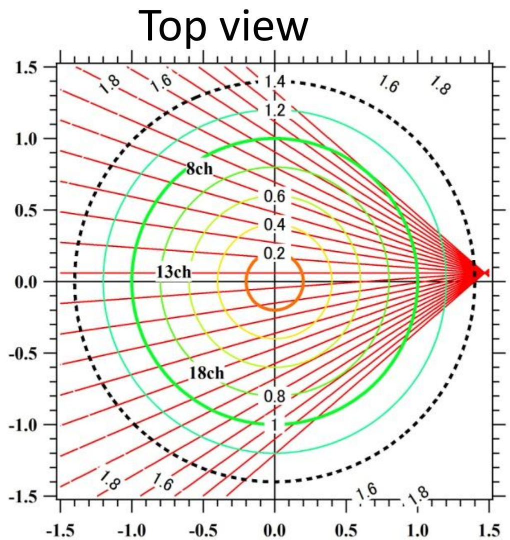


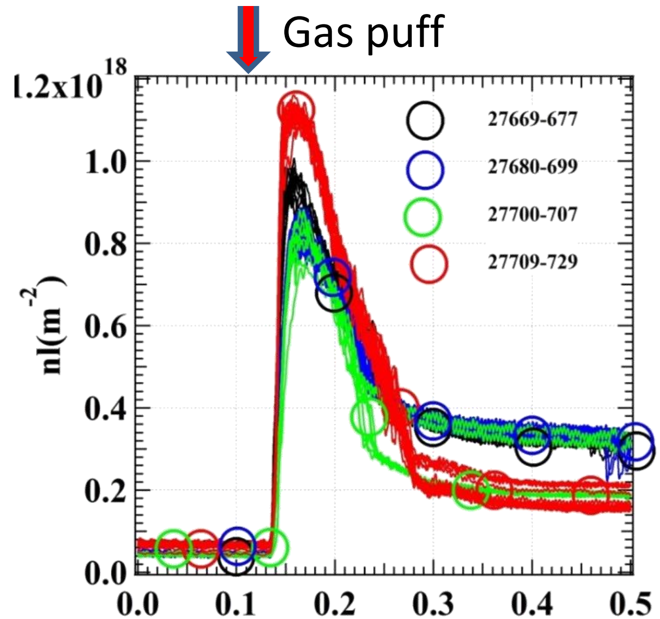
Fig. 6. $V_\phi \sim I_p$ and $V_\phi \sim I_p / B_z$ relation are shown for the two types of plasma IL and IPN under different M = 1.2 and 2 respectively.

In particular configuration (high mirror ratio) co-current toroidal flow is found to be generated by a hidden torque without closed magnetic surfaces. The sign and magnitude depend on the sign of Bz and Bz/Bt.

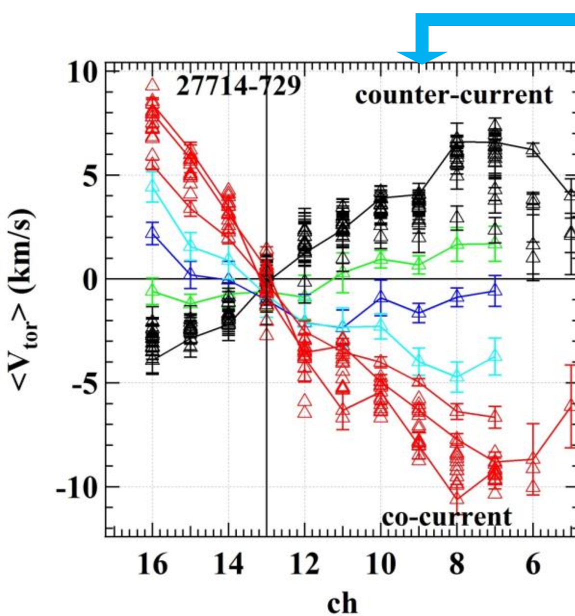
Strong gas-puff induces modification of plasma rotation

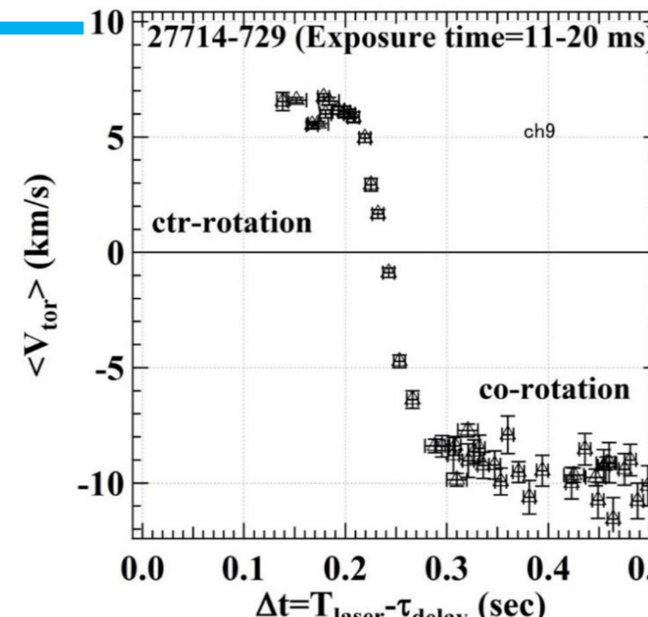
Intrinsic rotation has been investigated using passive line HeII, CIII emissions both in toroidal & poloidal direction with a visible spectrometer attached with 25 channel fiber array.





Flow shear is formed near the edge in the low density regime. A rigid rotation in the ctr-direction is triggered by intense density rise and the relaxed to the co-direction rigid rotation.





Spontaneous rotation can maintain during SSTO of Non-inductive Plasma

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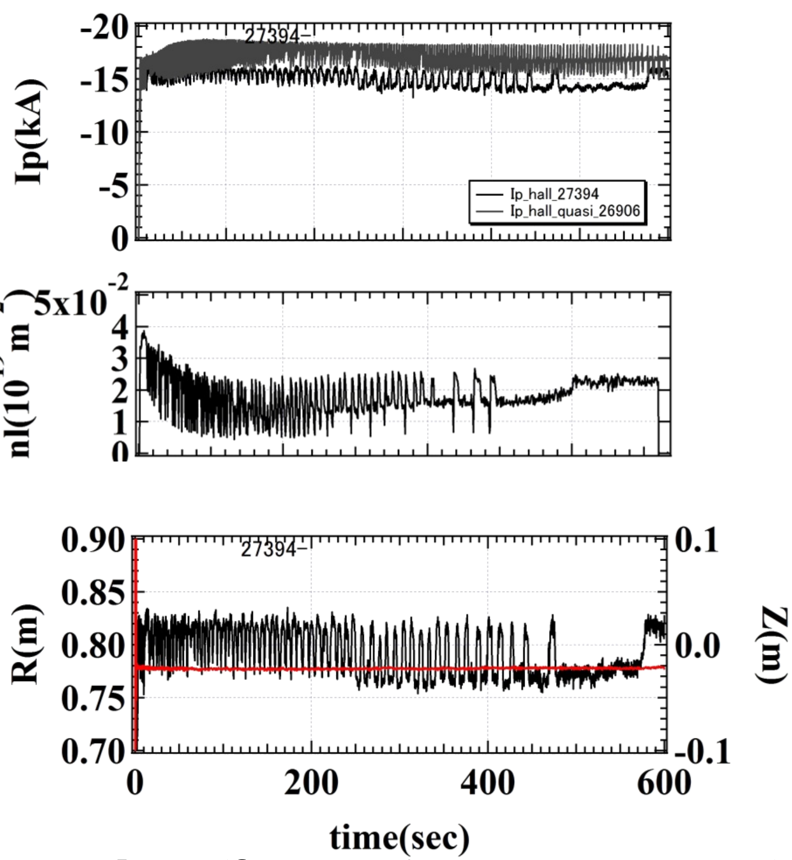
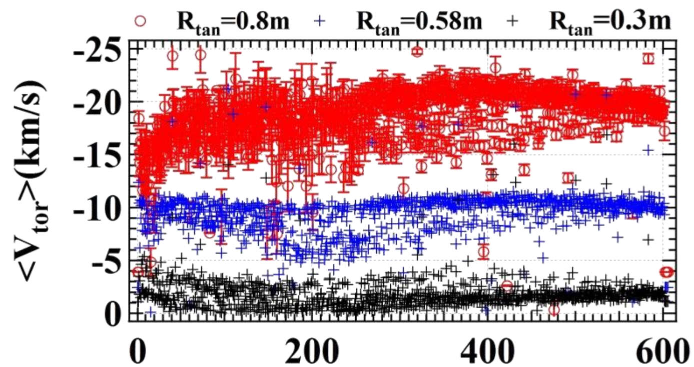
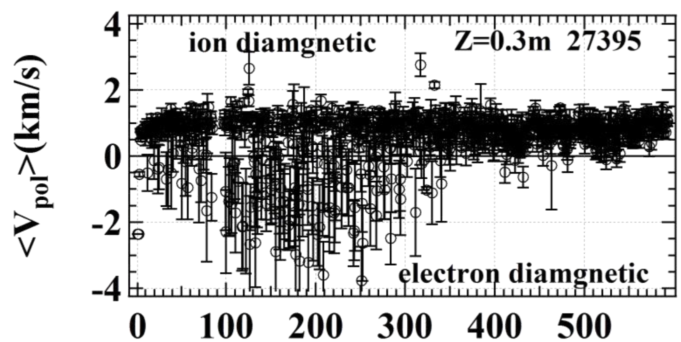
Fully NI plasma sustained by FB control of recycling flux



Co-current toroidal (20km/s)& ion diamagnetic poloidal (1km/s)flows



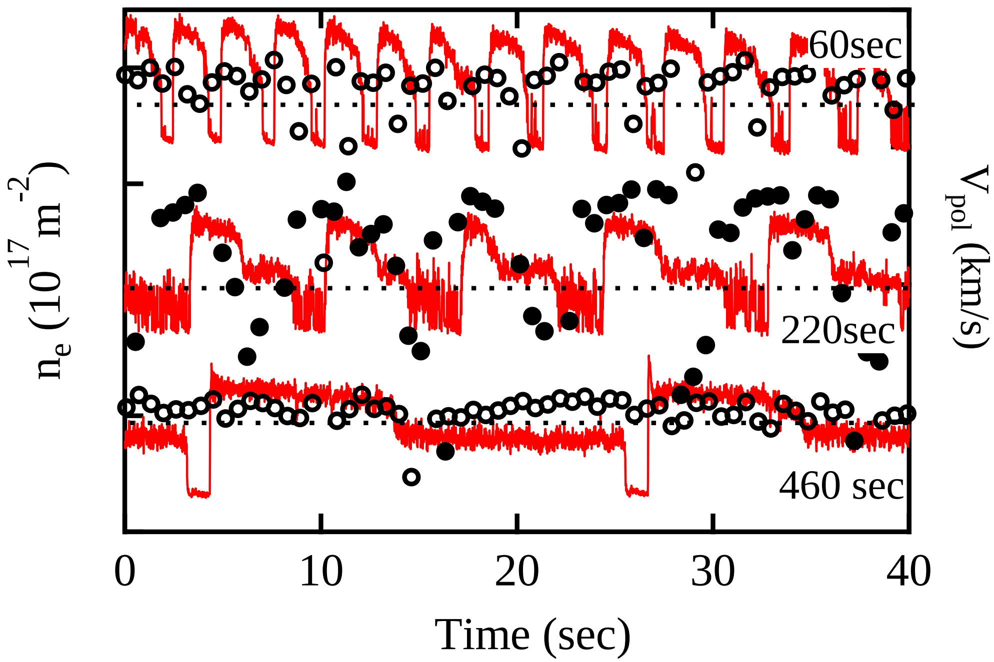


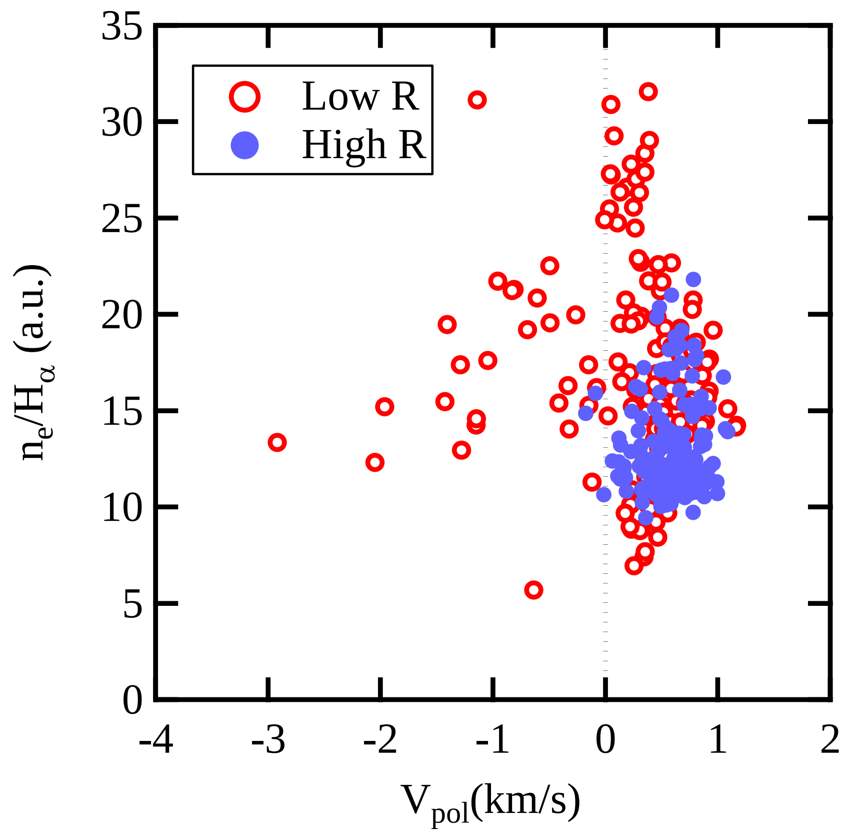
Two shots (for rotation measurements) are presented.

Puff width(amount of H2) is fixed, the repetition frequency is FB controlled to keep Ha constant

![Kyushu University logo]

Poloidal rotation reversal was observed relating gas puffing and the effect becomes to be week in R~1

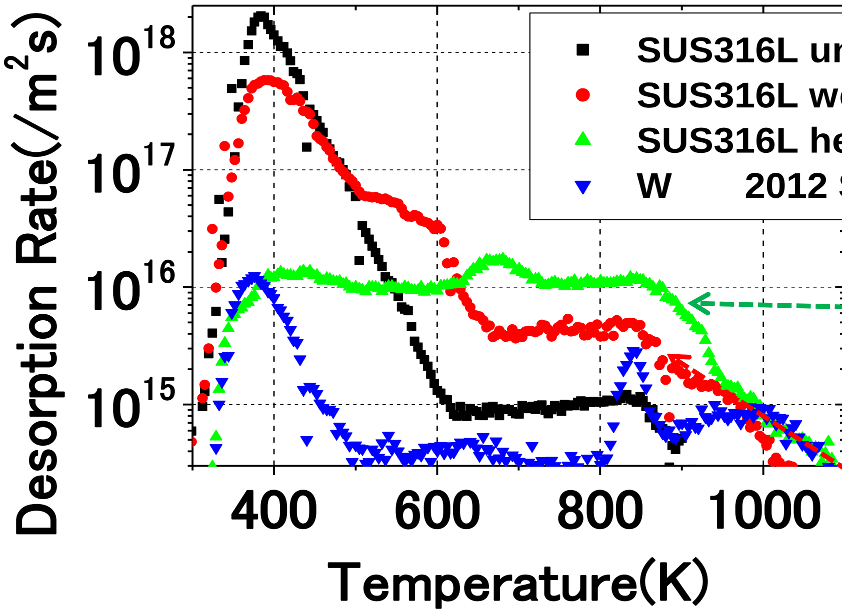


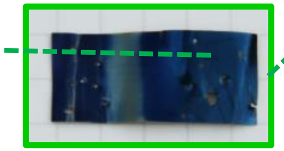


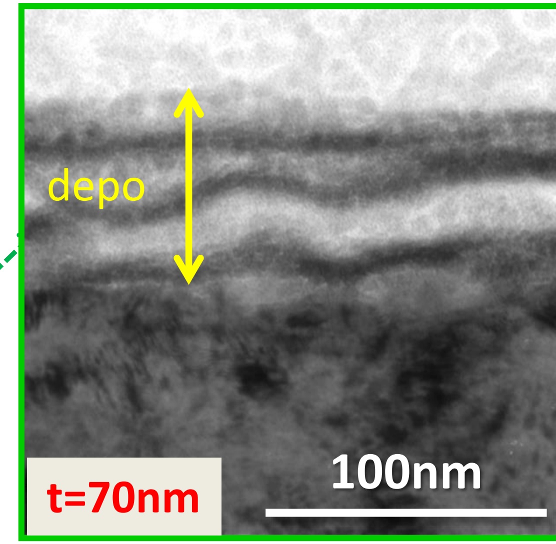
Hydrogen recycling during long duration discharges

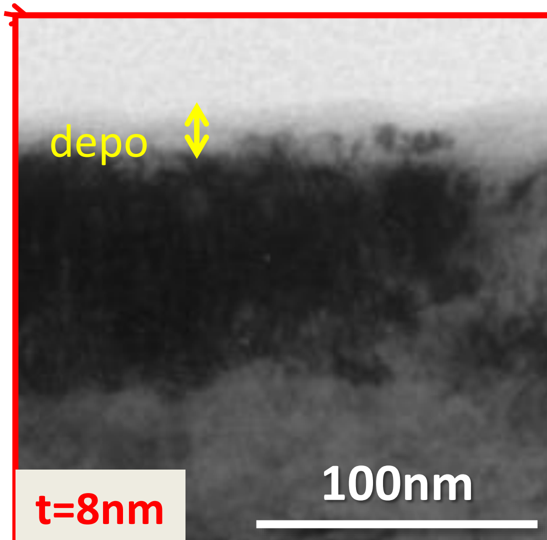
Wall property for H storing is significantly affected by the presence of deposition layer

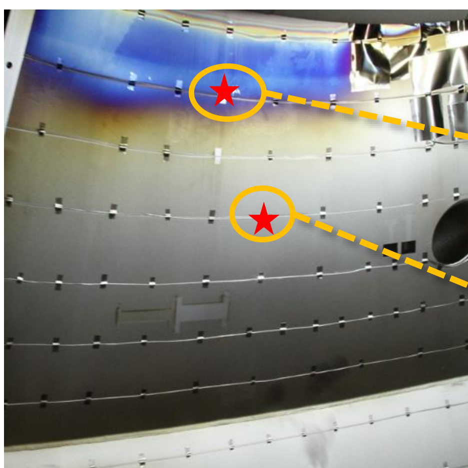
The details can be discussed in today's poster (Z.Wang)











SUS316L plate for fixing of magnetic probe

Heavily colored region

Slightly colored region

Collaborated with Prof. Yoshida

Deposition profile was decided by TRIM calculation based on TEM & GD-OES measurement

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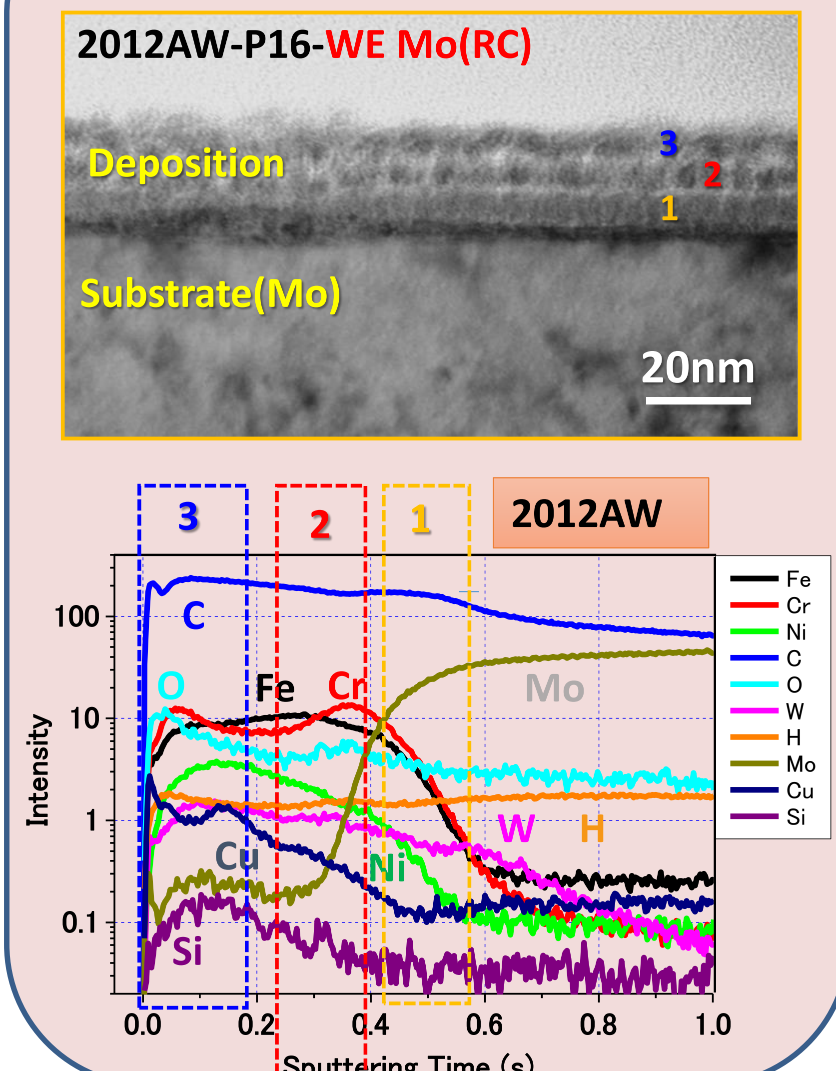
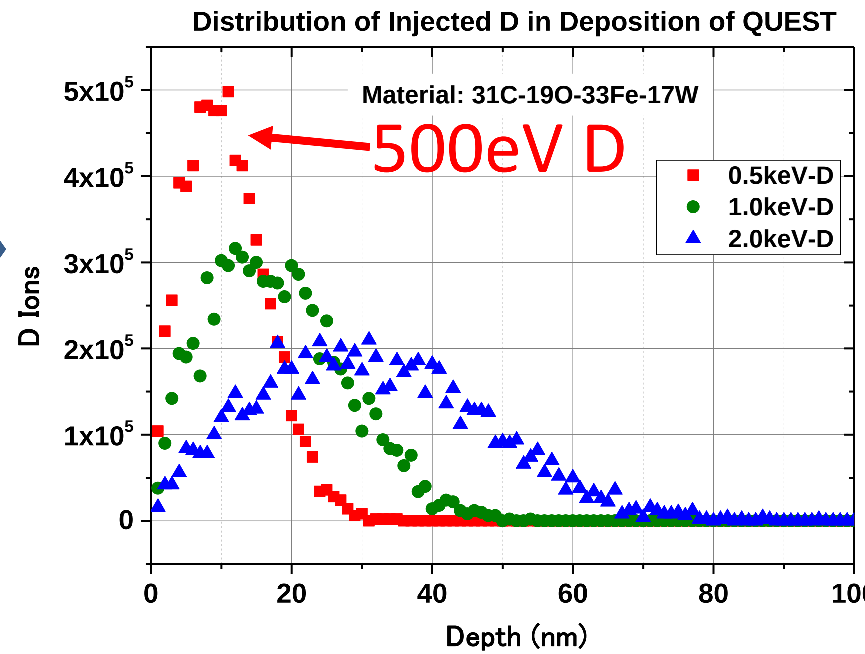
TEM & GD-OES



TRIM Calculation



$$G\left(x,t\right)=G_0 e^{-\left(x-x_D\right)^2/x_W^2}$$

Nuclear reaction analysis can indicate the presence of H barrier between deposition layer and substrate.

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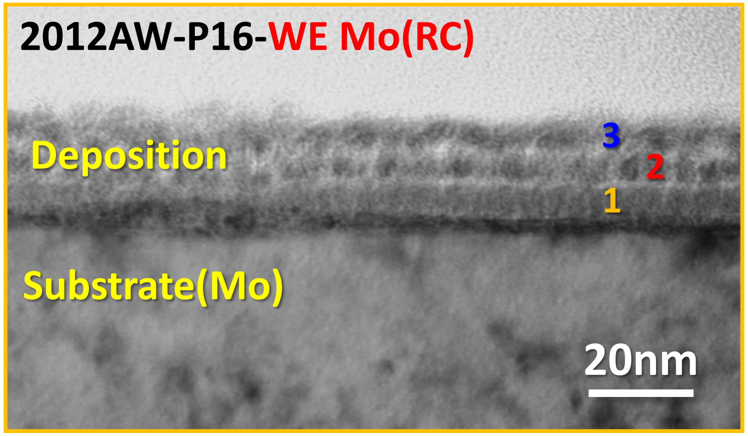
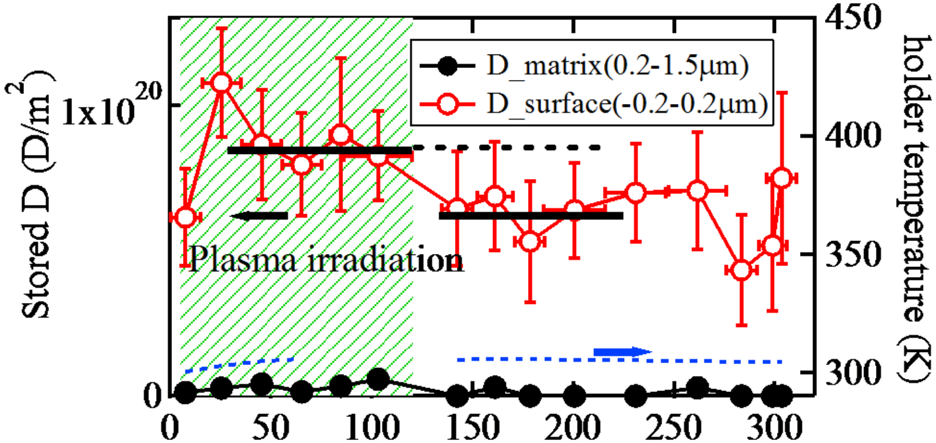
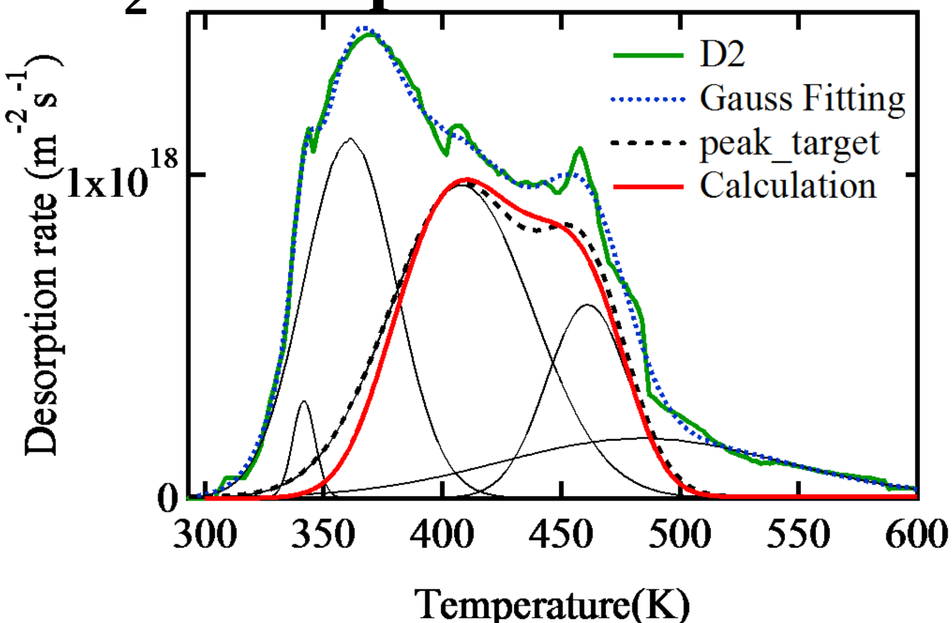
TEM Collaborated with Prof. Yoshida



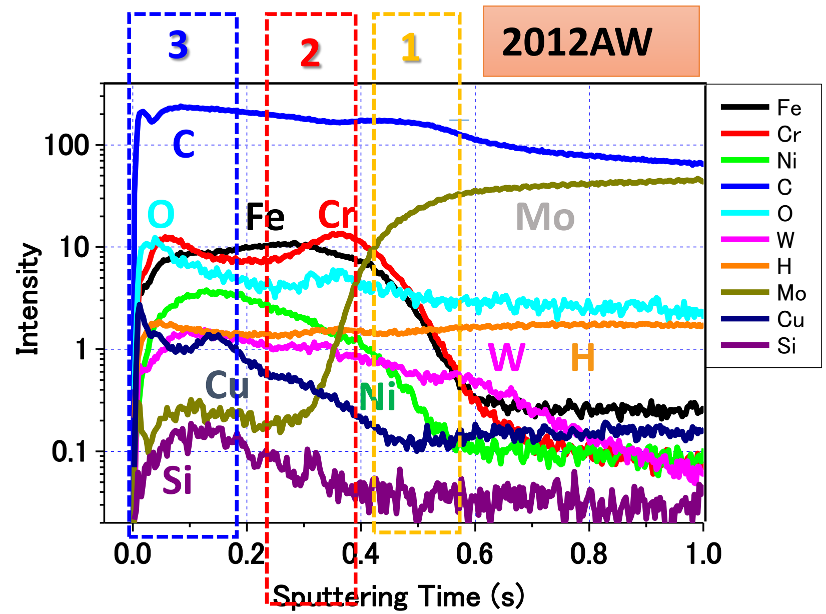
NRA Collaborated with Prof. Takagi



D_2 ion implantation & TDS



GD-OES Collaborated with Prof. Ohya



QUEST wall model can reconstruct micro and macroscopic observations.

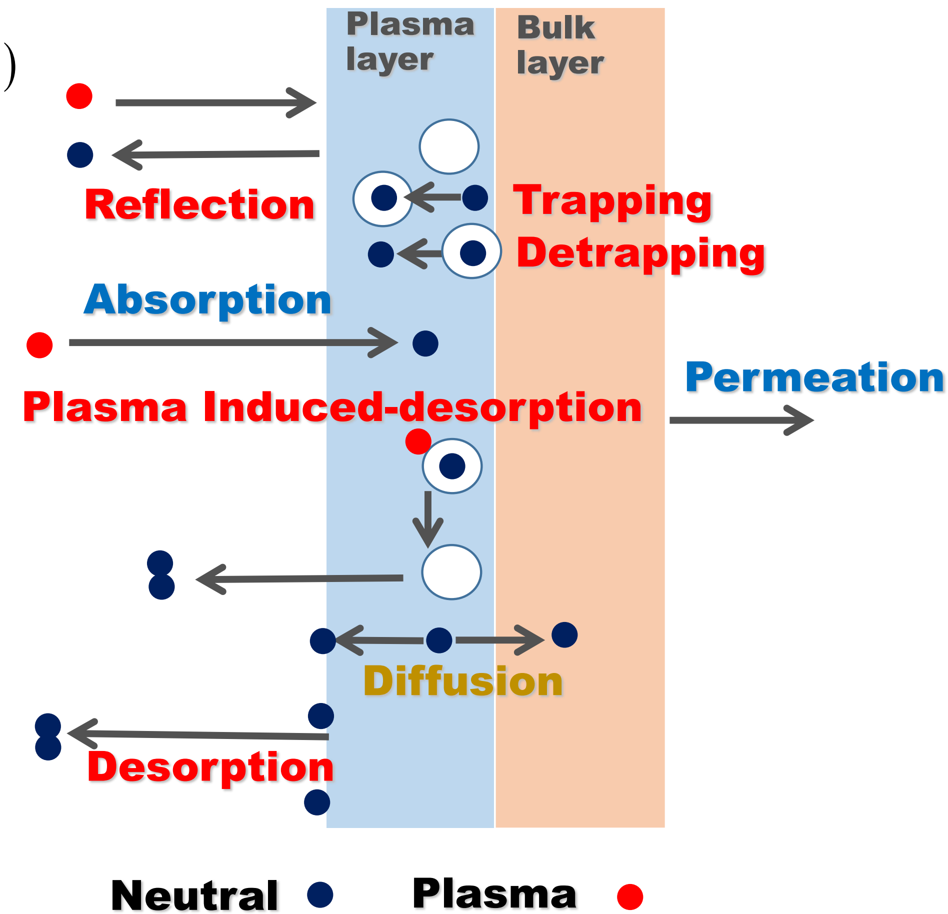
$$\begin{cases} \dfrac{\partial C_W(x,t)}{\partial t} = D\dfrac{\partial C_W(x,t)}{\partial^2 x} + G(x,t) - \dfrac{\partial C_{TA}(x,t)}{\partial t} - \dfrac{\partial C_{TB}(x,t)}{\partial t} - k_A C_{TA}(x,t)G(x,t) - k_B C_{TB}(x,t)G(x,t) \\ \dfrac{\partial C_{TA}(x,t)}{\partial t} = \beta_A C_W(x,t)F_A(x,t) - k_A C_{TA}(x,t)G(x,t) \\ \dfrac{\partial C_{TB}(x,t)}{\partial t} = \beta_B C_W(x,t)F_B(x,t) - k_B C_{TB}(x,t)G(x,t) \end{cases}$$

$$\begin{cases} \left.\dfrac{\partial C_W(x,t)}{\partial x}\right|_{x=0} = kC_W^2(0,t) \\ \left.\dfrac{\partial C_W(x,t)}{\partial x}\right|_{x=x_{\max}} = 0 \end{cases}$$

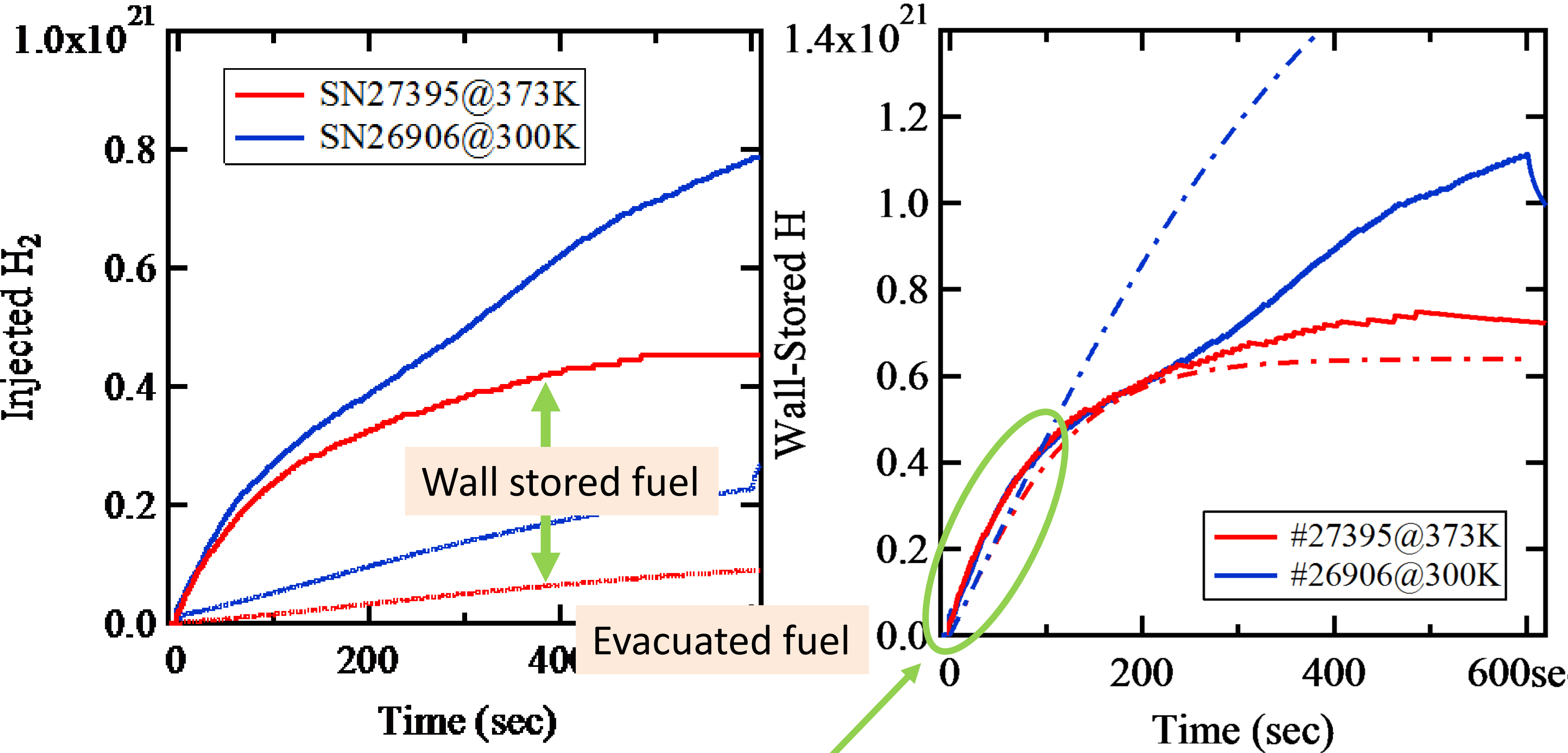
$$G(x,t) = G_0 e^{-(x-x_D)^2/x_W^2}$$

$$F_A(x,t) = \begin{cases} 1 - \dfrac{C_{TA}(x,t)}{C_{TA}^0} & C_{TA}(x,t) < C_{TA}^0 \\ 0 & C_{TA}(x,t) \geq C_{TA}^0 \end{cases}$$

$$F_B(x,t) = \begin{cases} 1 - \dfrac{C_{TB}(x,t)}{C_{TB}^0} & C_{TB}(x,t) < C_{TB}^0 \\ 0 & C_{TB}(x,t) \geq C_{TB}^0 \end{cases}$$



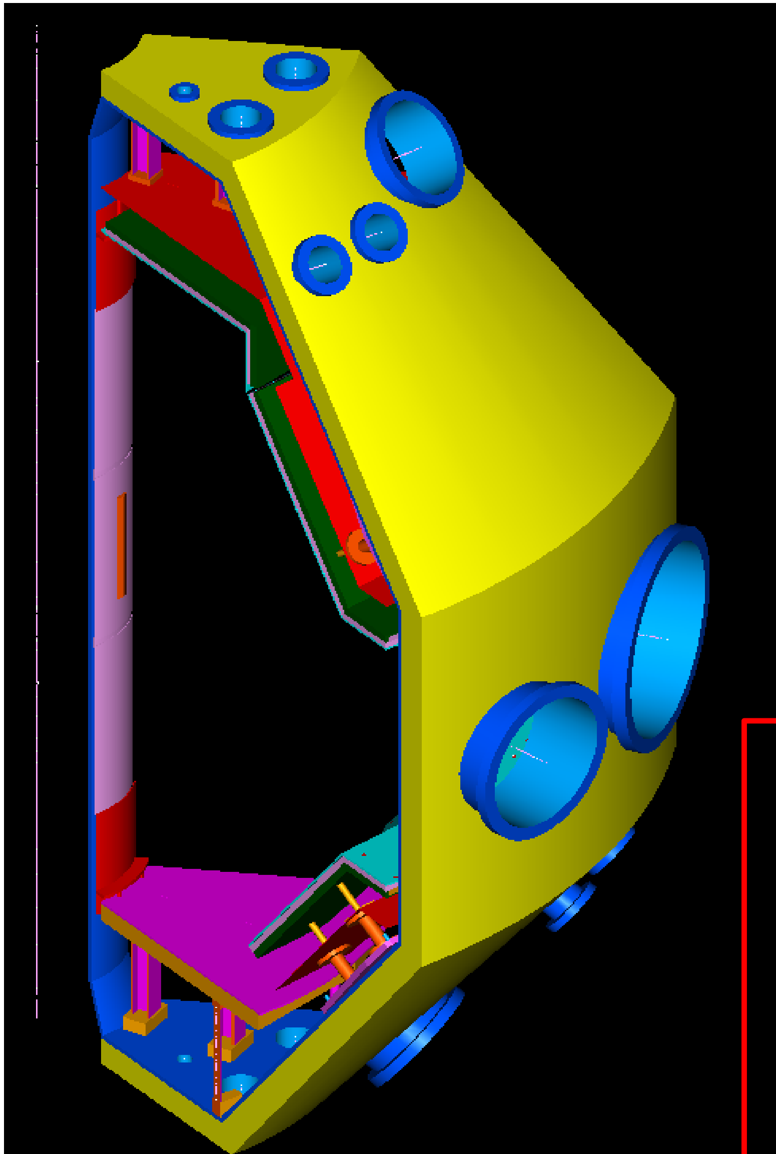
Wall temperature dependence can be reconstructed by QUEST wall model.

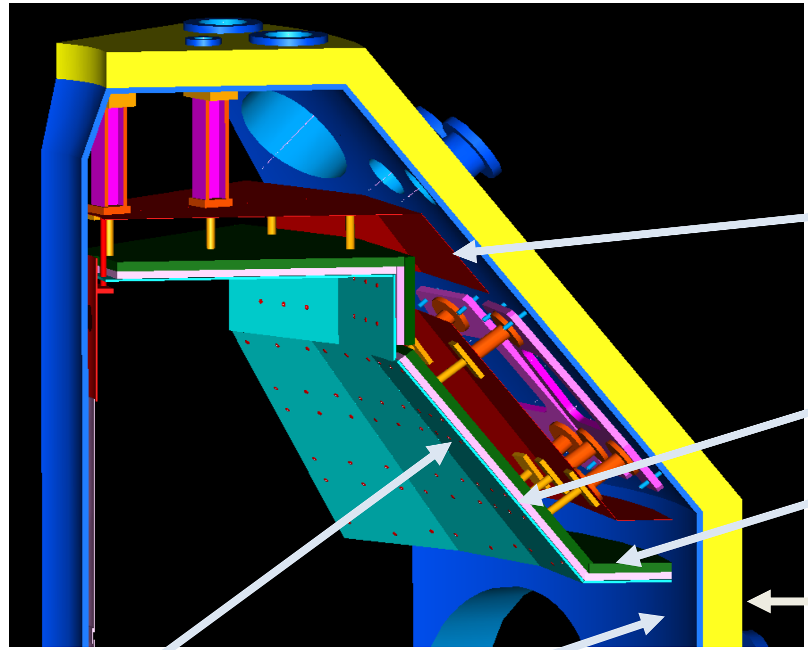


Wall stored particle is decided by only fuel flux to the wall.

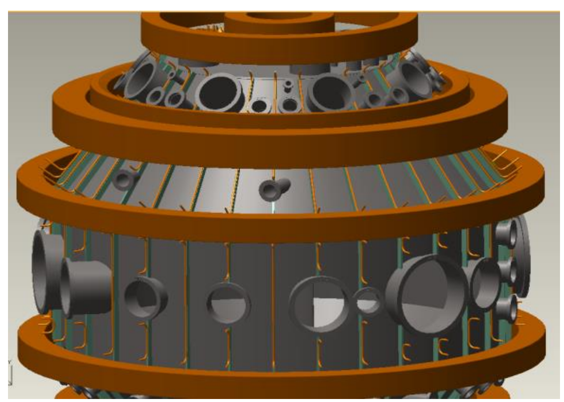
Hot wall installation and its impact to plasma.

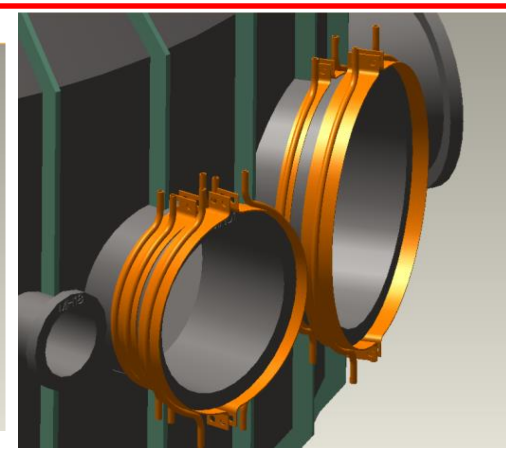
Hot wall has already prepared.





2015 Summer

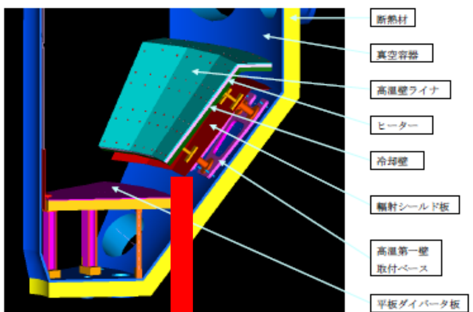


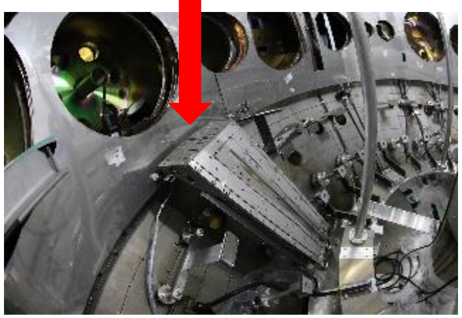


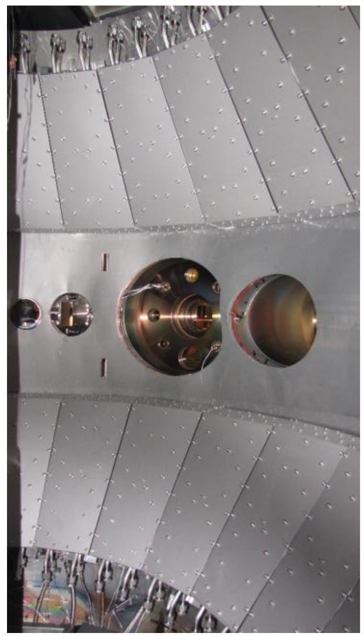
Some cooling channels will be installed on the vessel

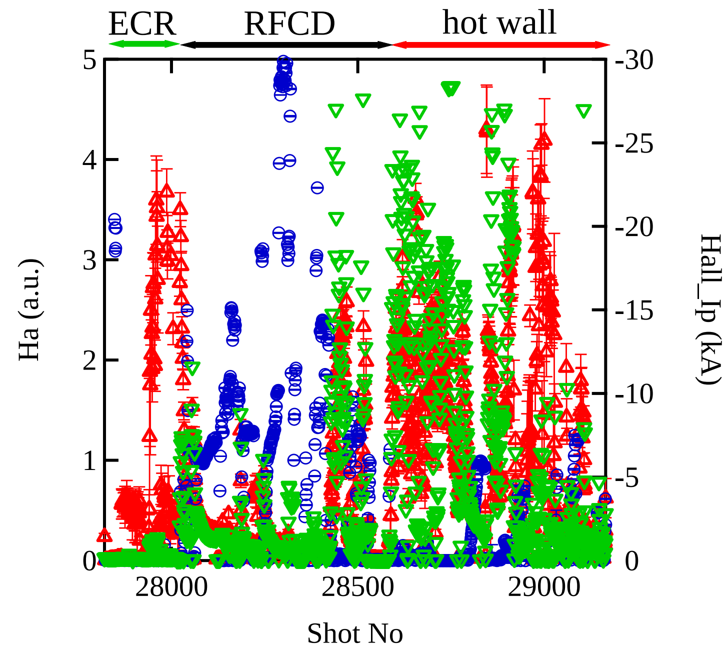
Hot wall installation and its impact to the plasma parameters

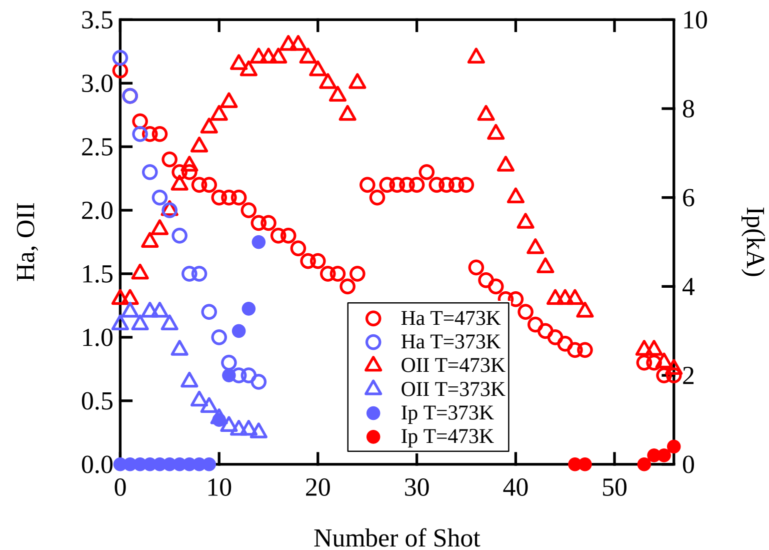
The hot wall has been installed since 2014.





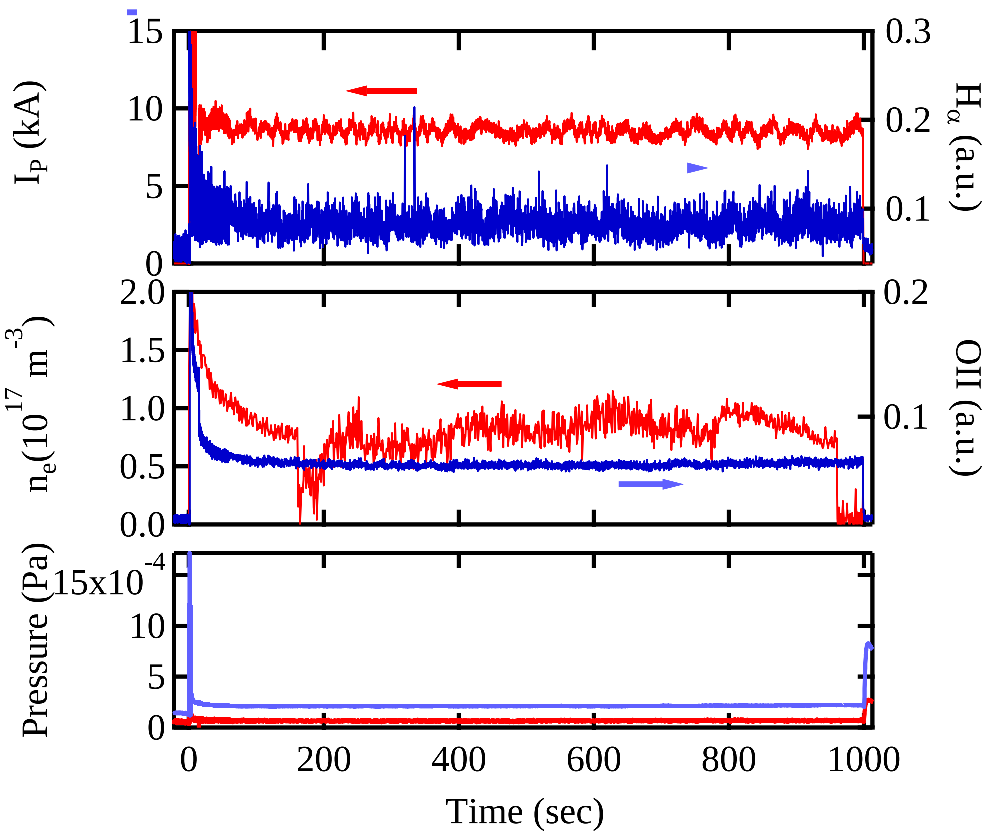






Just after the installation of hot wall, plasma parameters have no serious differences, but after the temperature went up to 473K, significant outgases disturb making good plasmas.

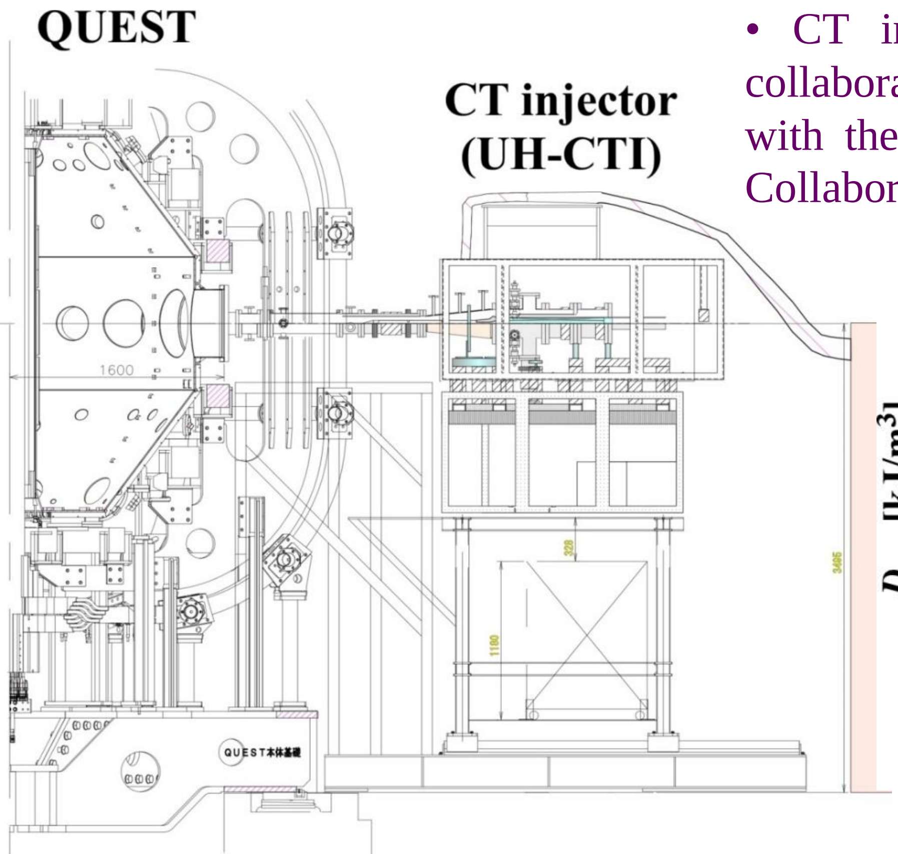
A long duration discharge for ~ 1000 s with R>1 was obtained.



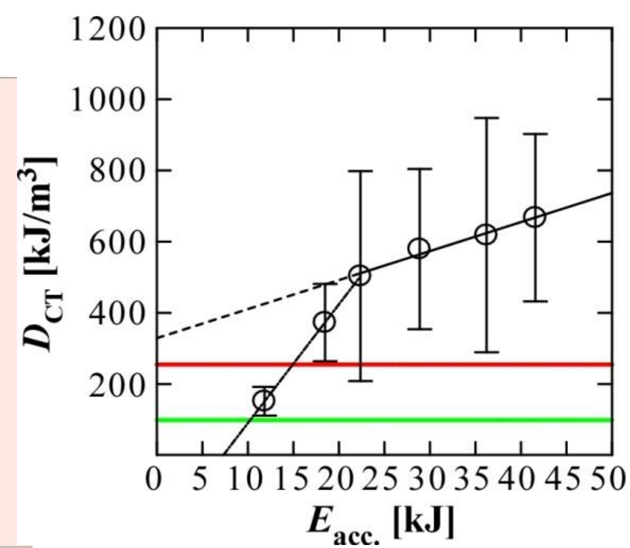
Very long discharge of 1000 s with Ip can be maintained without gas-puffing. It means that all the fuel hydrogen can be supplied from the wall recycling.

Advanced Fueling
CT injection on QUEST

CT injection experiment for advanced fueling in ST with Thomson scattering system on QUEST



- CT injection experiment has been performed in collaboration between Kyushu Univ. and Univ. of Hyogo with the support and under the auspices of the NIFS Collaboration Research Program.



- The kinetic energy density of the CT exceeds the magnetic field energy density of the target plasmas.

JFT-2M
B_T=0.8 T
W_B = 255 kJ/m^3

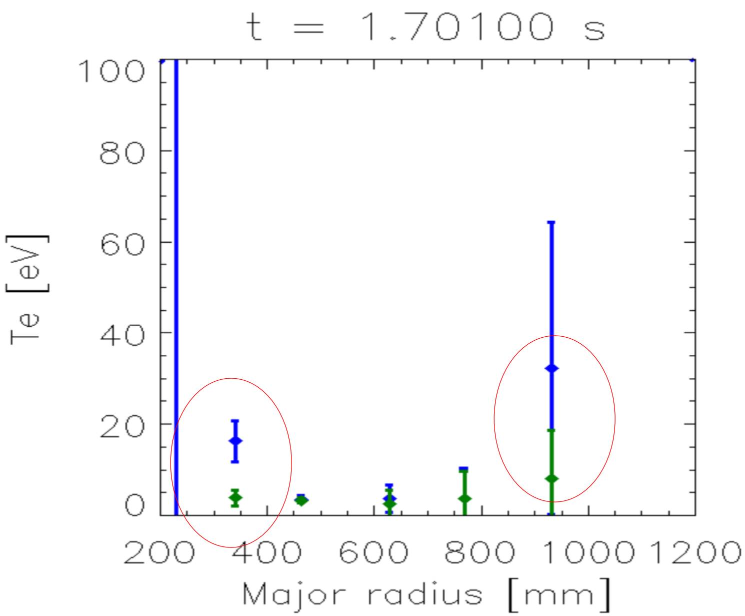
QUEST
B_T = 0.5 T
W_B = 99 kJ/m^3
for a pulse mode

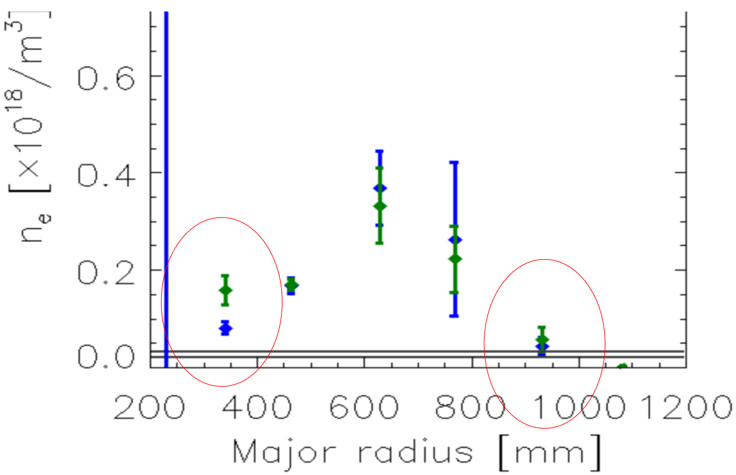
- The UH-CTI, which was designed for central fueling in the JFT-2M tokamak, has a sufficient performance to penetrate a CT plasma deeply into a ST plasma on QUEST.

- CT parameters at $V_{ct.acc.}$ of 16 kV～30 kV
  > v_{ct} : 170 km/s - 250 km/s,
  > $\bar{n}_{ct}$: 3×10^{21} m^{-3} - 7×10^{21} m^{-3}
  （V_{bias} = 0.8 kV, $V_{form.}$ = 17 kV, $\tau_{acc.}$ = 3μs）

T_e and n_e at the only peripheral region change just after the CT injection to an Ohmic plasma (I_p~30 kA)

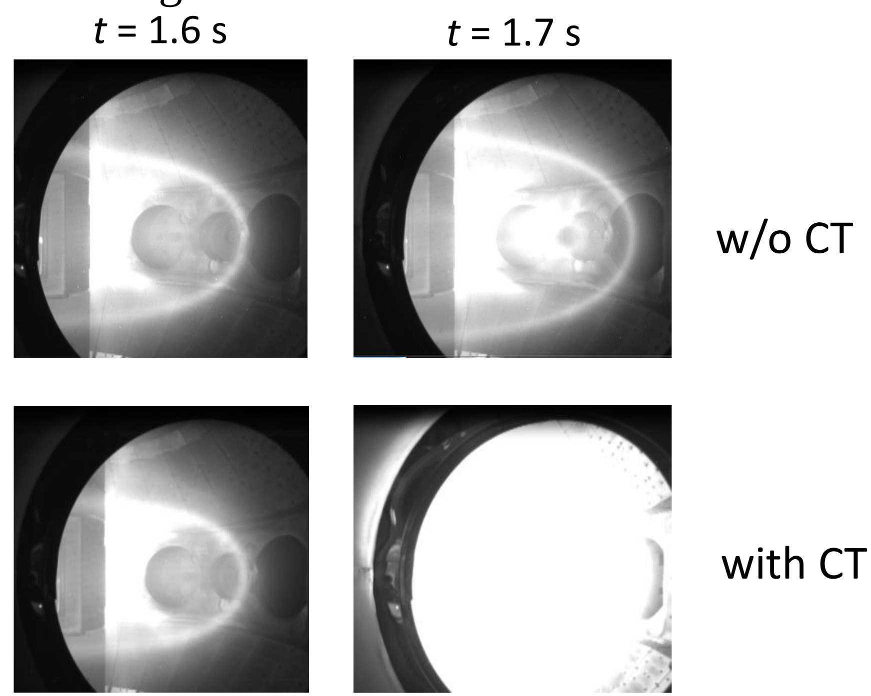
Temperature and density profiles 0.5 ms after CT injection





With and without CT injection

- Quick (0.5 ms) temperature decrease and density increase at the peripheral region.
- Slow (<100 ms) density increase at the whole region.



Tangential camera view

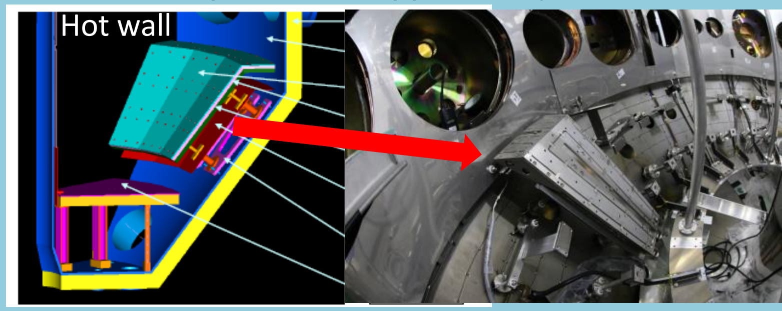
Summary

- Plasma current start-up can be obtained up to 66 kA with 2nd ECCD of 28 GHz. The 2nd ECR of 8.2 GHz significantly disturb plasma current increment.
- Magnetic configuration (M>2) can produce toroidal rotation spontaneously and a strong gas puffing make a flow reveal.
- High recycling plasma (R~1) cannot make a response of flow reversal induced by gas puff.
- Micro-scopic observation can be reconstructed by a model with hydrogen barrier and the model can predict a time evolution of recyecling ratio during long duration discharges.
- Compact toroid (CT) injection is successfully demonstrated as an advanced fueling and its deposition at the peripheral region can be detected by timing-adjusted Thomson scattering.

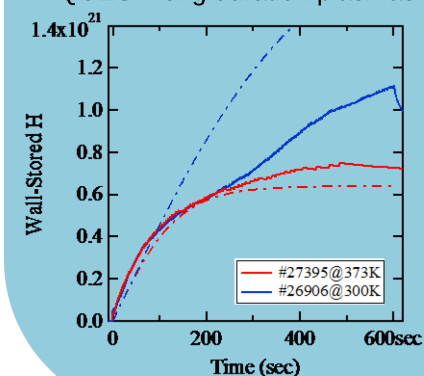
Future Plan of QUEST

Improvement of controllability of wall-pumping

Hot wall experiment supported by JSPS



Dependence of wall-pumping rate on wall temperature in QUEST long duration plasmas



QUEST wall model decided by reconstruction of TDS after D_2^+ ion implantation

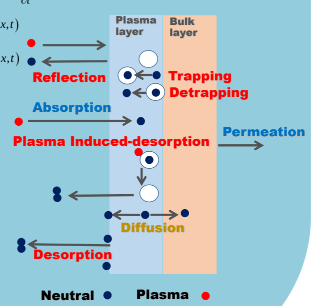
$$\begin{cases} \frac{\partial C_W(x,t)}{\partial t} = D\frac{\partial C_W(x,t)}{\partial^2 x} + G(x,t) - \frac{\partial C_{TA}(x,t)}{\partial t} - \frac{\partial C_{TB}(x,t)}{\partial t} - k_A C_{TA}(x,t)G(x,t) - k_B C_{TB}(x,t)G(x,t) \\ \frac{\partial C_{TA}(x,t)}{\partial t} = \beta_A C_W(x,t)F_A(x,t) - k_A C_{TA}(x,t)G(x,t) \\ \frac{\partial C_{TB}(x,t)}{\partial t} = \beta_B C_W(x,t)F_B(x,t) - k_B C_{TB}(x,t)G(x,t) \end{cases}$$

$$\begin{cases} \left.\frac{\partial C_W(x,t)}{\partial x}\right|_{x=0} = kC_W^2(0,t) \\ \left.\frac{\partial C_W(x,t)}{\partial x}\right|_{x=x_{\max}} = -kC_W^2(x_{\max},t) \end{cases}$$

$$G(x,t) = G_0 e^{-(x-x_D)^2/x_W^2}$$

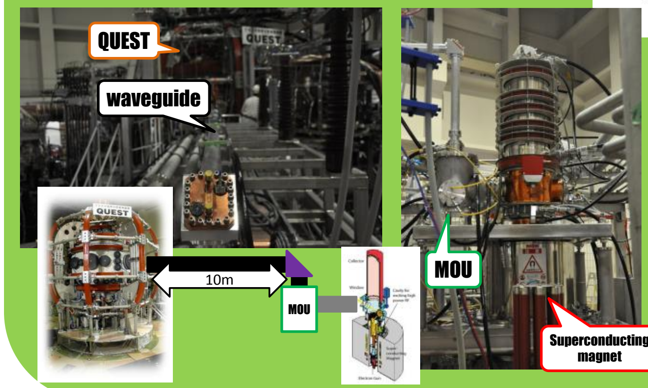
$$F_A(x,t) = \begin{cases} 1-\frac{C_{TA}(x,t)}{C_{TA}^0} & C_{TA}(x,t) < C_{TA}^0 \\ 0 & C_{TA}(x,t) \geq C_{TA}^0 \end{cases}$$

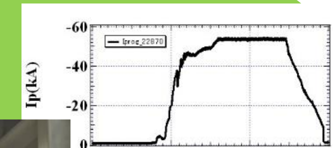
$$F_B(x,t) = \begin{cases} 1-\frac{C_{TB}(x,t)}{C_{TB}^0} & C_{TB}(x,t) < C_{TB}^0 \\ 0 & C_{TB}(x,t) \geq C_{TB}^0 \end{cases}$$

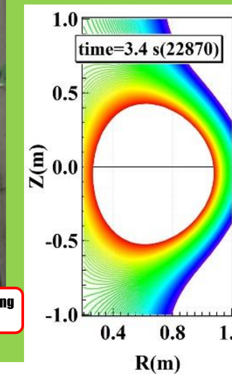


Improvement of controllability of core and SOL plasma

28GHz ECCD experiment with Tsukuba University and NIFS







CHI experiment supported by DoE