QUEST experiments towards steady state operation of spherical tokamaks

K.Hanada[a)], H.Zushi[a)], H.Idei[a)], K.Nakamura[a)], M.Ishiguro[b)], S.Tashima[b)], E.I.Kalinnikova[b)], M.Sakamoto[c)], M.Hasegawa[a)], A.Fujisawa[a)], K.N.Sato[a)], N.Yoshida[a)], H.Watanabe[a)], K.Tokunaga[a)], Y.Nagashima[a)], A.Higashijima[a)], S.Kawasaki[a)], H.Nakashima[a)], H.Liu[b)], O.Mitarai[d)], T.Maekawa[e)], A.Fukuyama[f)], Y.Takase[g)], J. Qian[h)], S.Banarjee[b)], N.Nishino[i)]

a): Research Institute for Applied Mechanics, Kyushu University, Japan, b):Interdisciplinary Graduate School of Engineering Science, Kyushu University, Japan, c):Plasma Research Center, University of Tsukuba, Japan, d): School of Industrial Engineering, Tokai University, Japan e): Graduate School of Energy Science, Kyoto University, Japan, f): Graduate School of Technology, Kyoto University, Japan g): Graduate School of Frontier Science, University of Tokyo, Japan h): Institute of Plasma Physics, Chinese Academy of Sciences, China. i):Hiroshima University

We have been promoting characteristic steady state experimental devices

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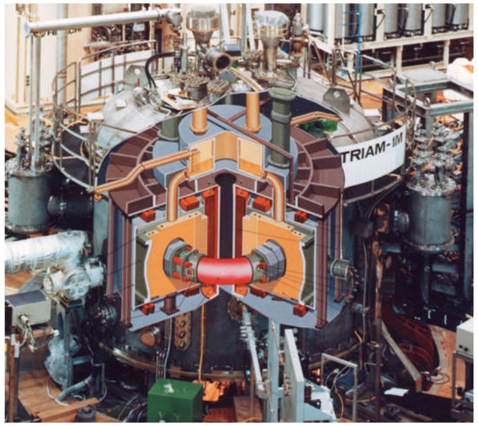

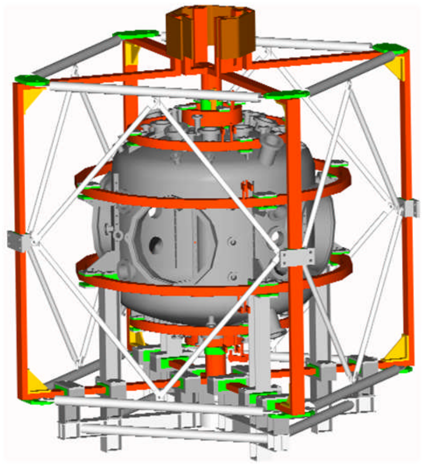

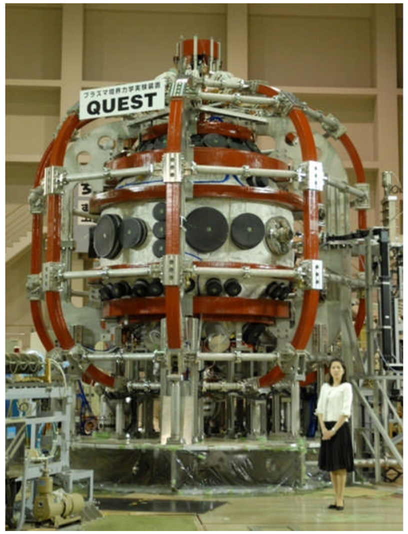

1983 — TRIAM-1M → 2006

CPD → 2008

QUEST →

What are issues to SSO?

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- **Non-inductive current drive**

  Ideally self-organized current such as BS current to alleviate less current drive efficiency

  neo-classical current in low n_e at present and EBWCD in near future on QUEST

- **Heat and particle handling**

  Heat handling; Detached divertor, Ar and Ne injection

  Particle handling; Closed divertor, Hot wall, Enhanced pumping, Advanced fueling

- **Integrated control including core plasma, PWI and wall.**

  Global plasma control, Turbulence control in core, Blob control in SOL, Wall conditioning

An example of 0-D heat balance in a steady state plasma

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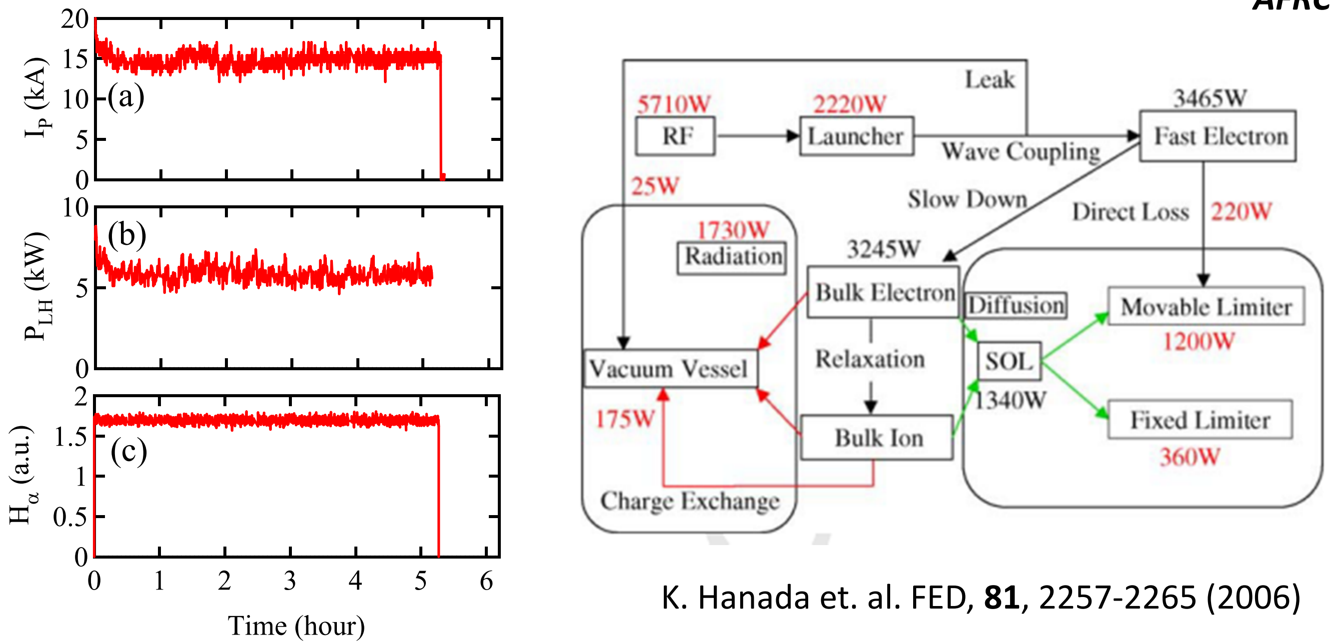

K. Hanada et. al. FED, **81**, 2257-2265 (2006)

- **Heat was completely balanced after about 30 min.**
- **Plasma termination was caused by unbalance of particle.**

What happen particle balance in steady-state?

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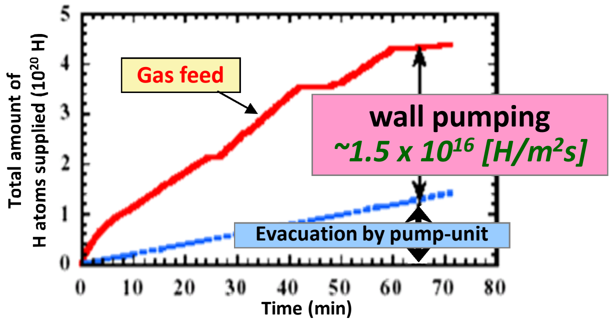
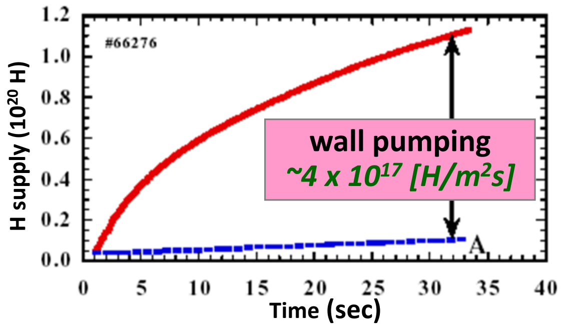
Wall pumping in long pulse operation

M. Sakamoto et al., Nucl. Fusion 42 (2002) 165

Low density (n_e~10^{18} m^{-3})



High density (n_e~10^{19})



- **The wall pumping rate strongly depended on the plasma parameters.**
- **The wall pumping was working for more than 5 hours.**
- **The abrupt termination of the plasma was caused by a lost of particle balance (may be wall saturation).**

Model of 0-D Particle balance

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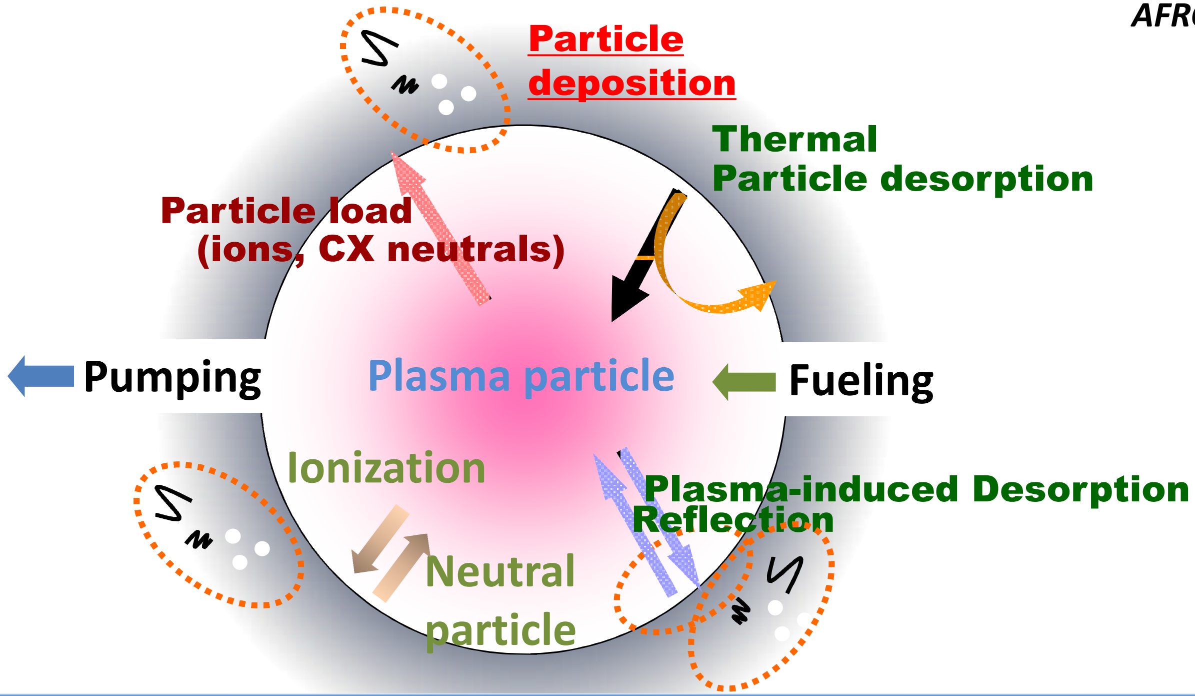

- Simple model for 0-D particle balance equations.
- Considered processes are illustrated on the schematic figure.

0-D particle balance eq.

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$$\frac{\partial N_p}{\partial t} = -\frac{N_p}{\tau_p} + \frac{N_n}{\tau_{ion}}$$

$$\frac{\partial N_n}{\partial t} = -\frac{N_n}{\tau_{ion}} - \frac{N_n}{\tau_{ab}} f_n(N_W) + r\frac{N_p}{\tau_p} f_p(N_W) + (1+C_1)\frac{N_p}{\tau_p}\frac{N_W}{N_{WSp}} + \frac{N_W}{\tau_W} + \Gamma_{in} - \Gamma_{out}$$

$$\frac{\partial N_W}{\partial t} = -\frac{N_W}{\tau_W} + (1-r)\frac{N_p}{\tau_p} f_p(N_W) - C_1\frac{N_p}{\tau_p}\frac{N_W}{N_{WSp}} + \frac{N_n}{\tau_{ab}} f_n(N_W)$$

$$f_{n,p}(N_W) = \begin{cases} 1 - \dfrac{N_W}{N_{WSn,p}} & N_W < N_{WSn,p} \\ 0 & N_W \geq N_{WSn,p} \end{cases}$$

$$\Gamma_{out} = \frac{N_n S_{pump}}{V_{Vessel}}$$

N_p, *number of plasma particle*

N_n, *number of neutral particle*

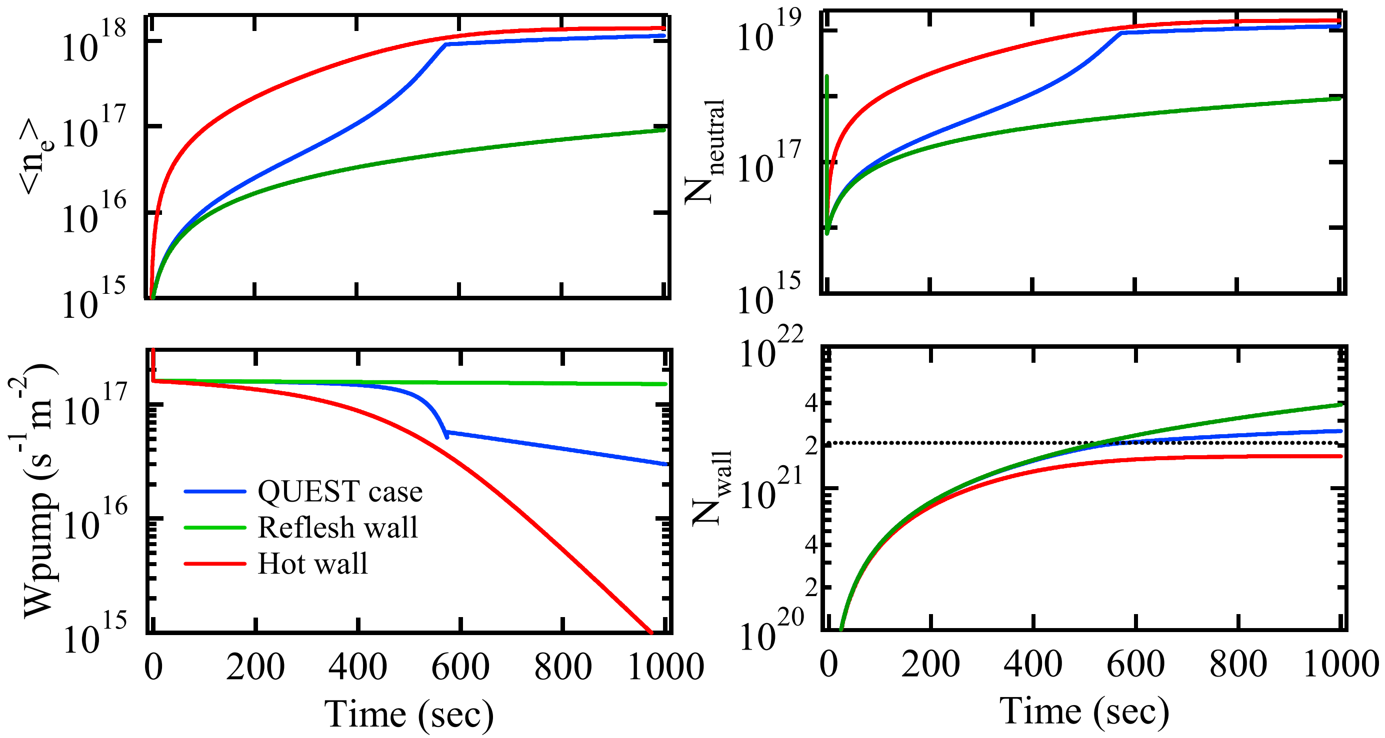
N_W, *number of neutral particle in wall*

$N_{WSp,n}$, *number at wall saturation*

r, *refrection coeffcient*

C_1, *plasma – induced desorption*

Steady state will be realized more than 1000s



τ_W=10sec, τ_{ion}=25ms, τ_p=10ms, nWSp=2.5x10^{22} (1x10^{21} m^{-2}), nWSn=nWSp/12
Vvessel=35m^3, Vplasma=4m^3 Svessel=25m^2, input=4x10^{18}/sec, Spump=10m^3/sec

τ_W can be controlled by T_{wall}. *QUEST*

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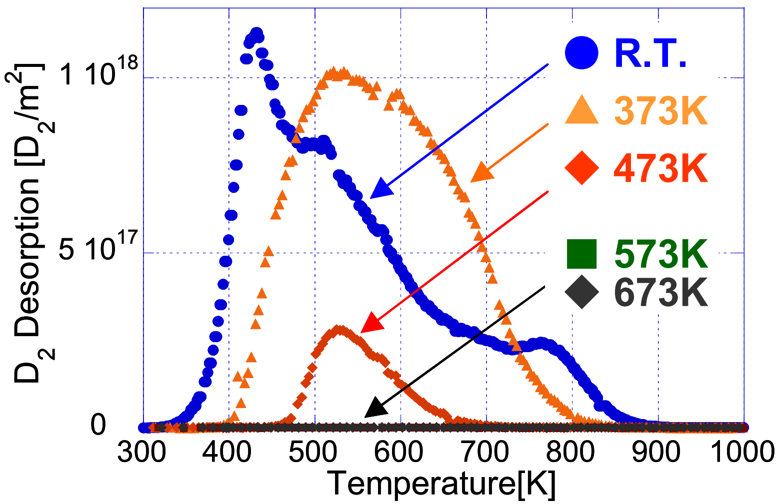

N.Yoshida et al.

- TDS spectrum for Mo implanted D (2keV-D+, $3x10^{21}$ D/m^2) at various temperature.
- At the high temperature region, D does not absorbed in the material.
- We consider the high temp. wall works as the reflector of the particle.

- **The number of stored particles depends on the targeted wall temperature.**
- **Hot wall around 673K could not have the property of pumping.**

Issues in particle balance eq.

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- Impurity production
- Re-deposition, Co-deposition
- Estimation of τ_W, τ_p, τ_{ab}, τ_{ion}, C_1, r, n_{WSp}, n_{WSn}
- Fusion reaction, D, T, and He balance
- 1-D model (inward pinch, density peaking, blob, divertor)

Need to 1-D model

Core plasma model

$$\frac{1}{n_e}\frac{\partial n_e}{\partial \rho} = \frac{1}{|\nabla \rho|}\frac{V_{ware}}{D(\rho)} + \underbrace{\eta q H \frac{\partial}{\partial \rho}\frac{1}{qH}}_{\text{Turbulent Equipartition}} + \underbrace{\alpha \frac{1}{T_e}\frac{\partial T_e}{\partial \rho}}_{\text{Thermodiffusion}} + \hat{\Gamma}_s(\rho) + \hat{\Gamma}_{in}(\rho)$$

Turbulent Equipartition

Thermodiffusion

SOL plasma model

$$\Gamma = \underbrace{-D\nabla n_e + C_s \cdot n_e}_{\text{To Divertor}} + \underbrace{V_{blob} \cdot n_e}_{\text{To wall}}$$

To Divertor

To wall

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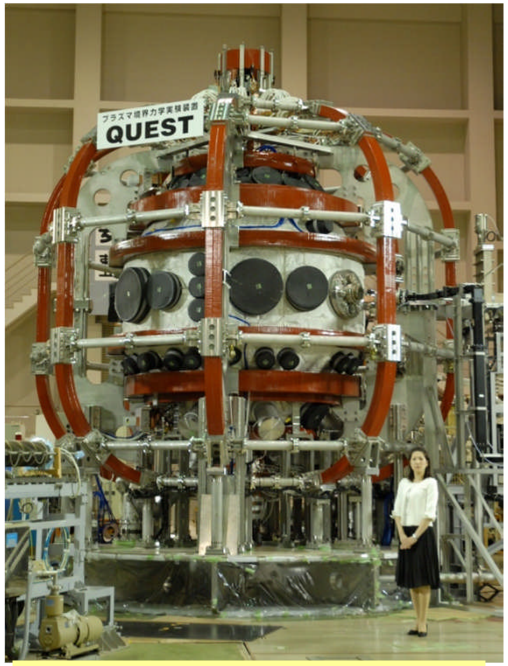
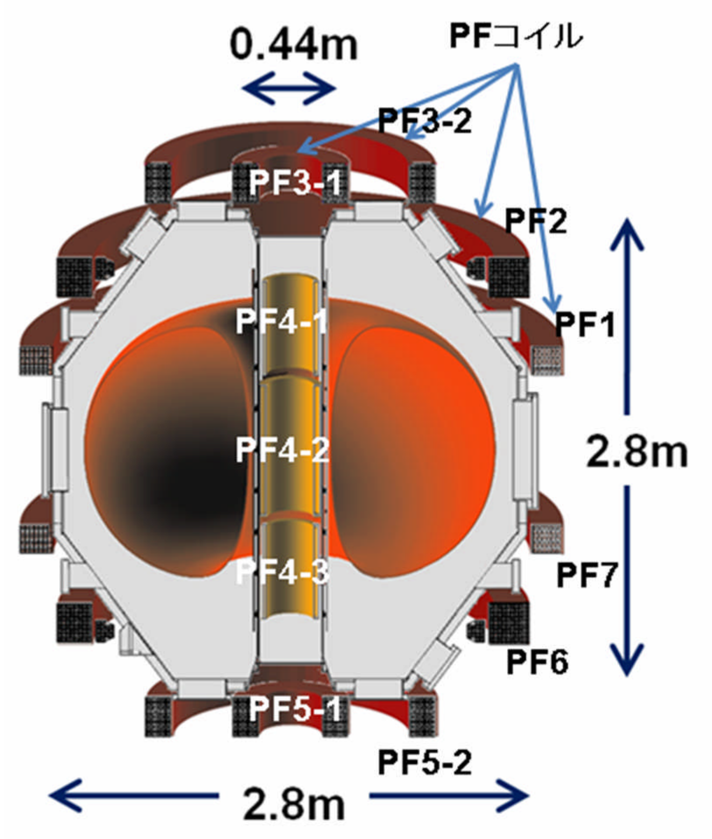


Bt 0.25 T at R=0.64 m (CW)
PF 4 pairs
CS 3 coils
RF systems
2.45GHz 50 kW(CW)
8.2 GHz 400 kW(CW)



Present status of QUEST

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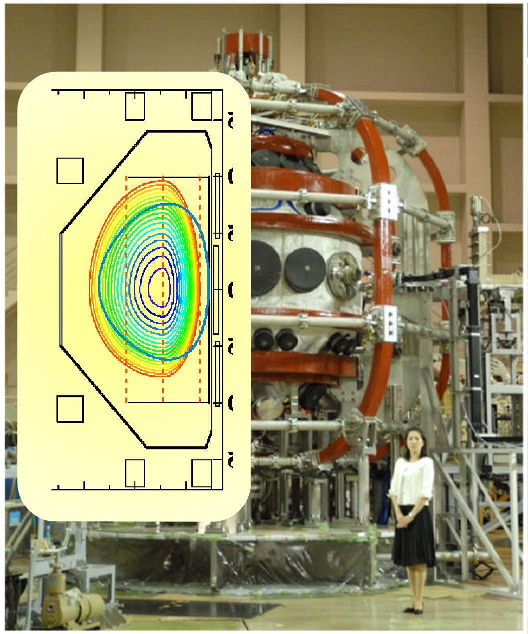

Non inductive current driven plasma
R=0.7m, a=0.48m, A=1.47

	Design	Achieved
R(m)	0.68	0.7
a(m)	0.4	0.48
A	1.6	1.47
I_p kA(OH)	300	110 (Bt=0.14T)
Ip kA (RF)	2~ 30(0.45MW) 100 (1MW)	25(60kW)
P_{rf} (kW)	400	~200
Bt(T)	0.25(CW)	0.25(CW)
n	4E18	<1E18
discharge	SS	37 s

Non-inductive current drive

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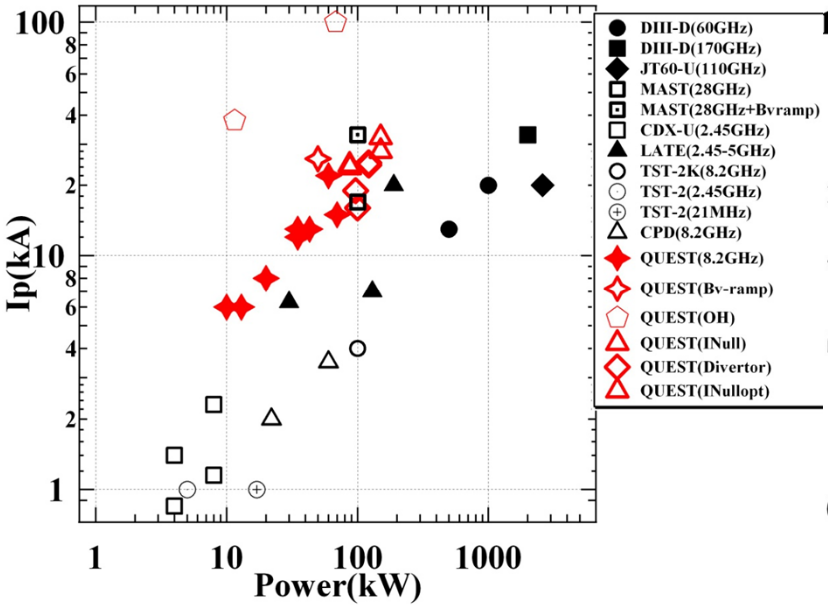
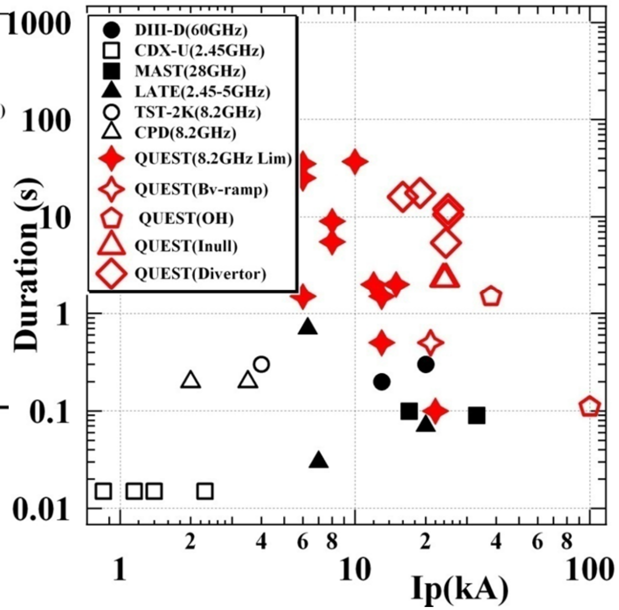
- Development of hardware of microwave heating system (presented by Prof. Idei)
- Plausible explanation of present experimental observation
- Future plans for current drive (presented by Prof. Idei)

Development of QUEST status





QUEST experiments are going well as previously scheduled and we have an opportunity to challenge for steady state operation of spherical tokamaks.

New type phased array antenna for EBWCD

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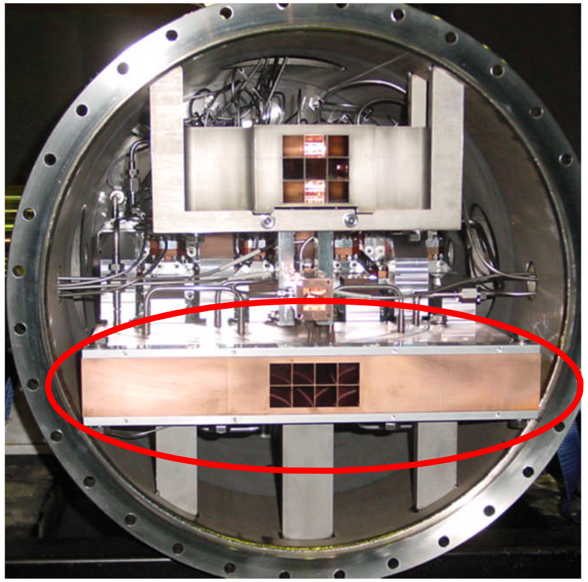

- Control of incident wave polarization and mode
- Control of incident angle and beam property
- Water cooling for CW operation up to 200kW

How wave should be injected depends on the way for current drive. This antenna will be used for EBW excitation and current drive, X and O mode ECCD.

The details will be presented by Prof. Idei in this meeting

H. Idei et al., Journal of Plasma and Fusion Research SERIES, Vol.8 (2009), pp. 1104-1107

Steady state operation

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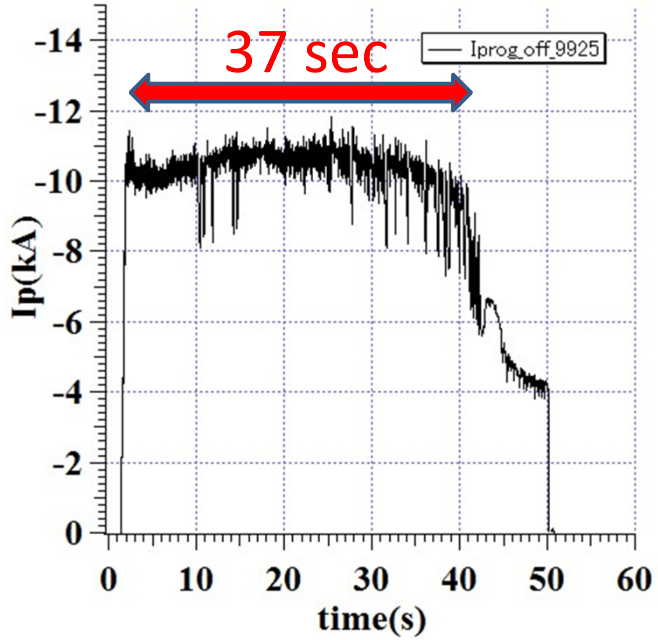
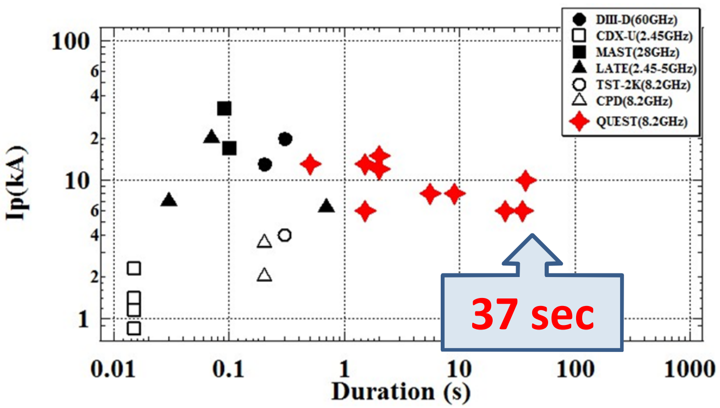


The plasma of more than 10kA, A~1.5 could be obtained by only 8.2GHz microwave on a limiter conf.



Magnetic surface and current profile

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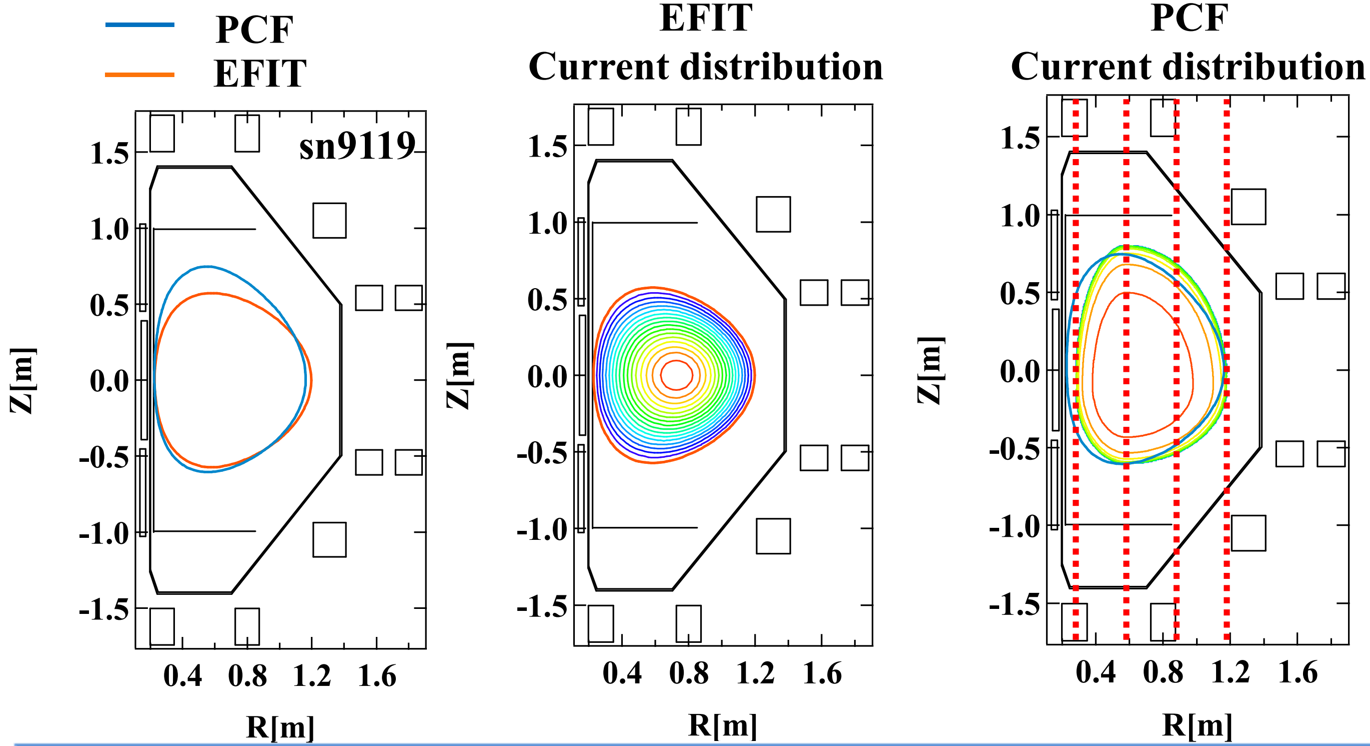
Magnetic surface | Current profile | Current profile *AFRC*



The current locates between 2Ωe and 3Ωe. A=1.45 on EFIT and 1.47 PCF. ST configuration was obtained.

EBWCD can drive?

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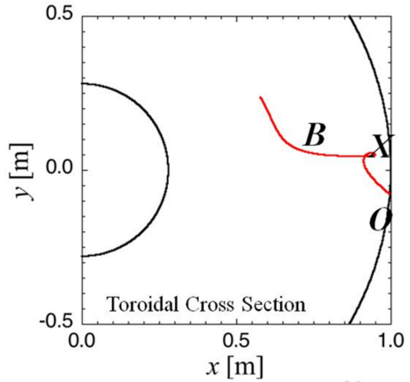
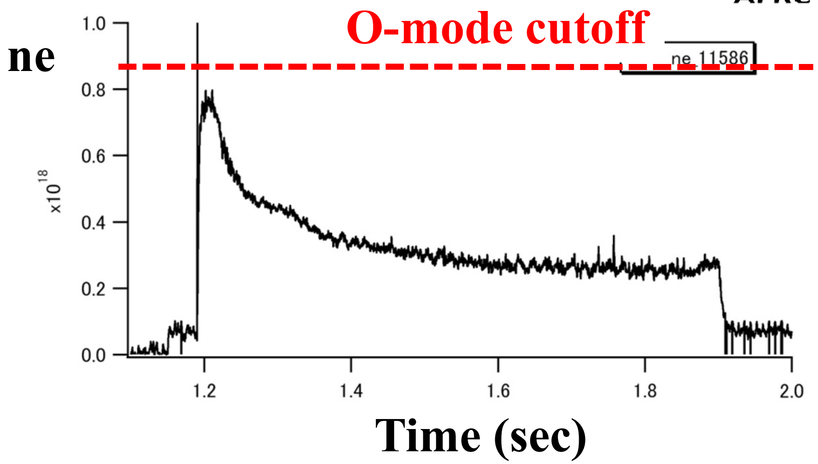
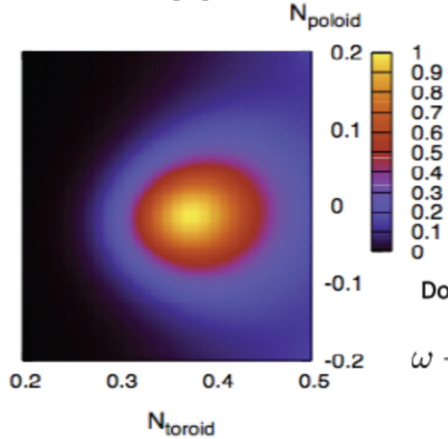
$n_{e0} = 2 \times 10^{18}$ m^{-3}, T_{e0} =100eV,
total current : 20kA



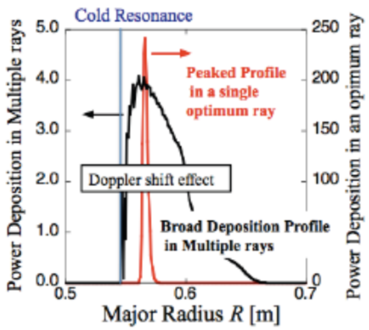


$P_{\text{absorb}} = TP_{\text{initial}}$



Doppler-shift resonance condition

$$\omega - k_{||}v_{||} - n\omega_c = 0$$



The details will be presented by Kalinnikova-san in this meeting

Wave mode, $N_{//}$, and B_T dependence

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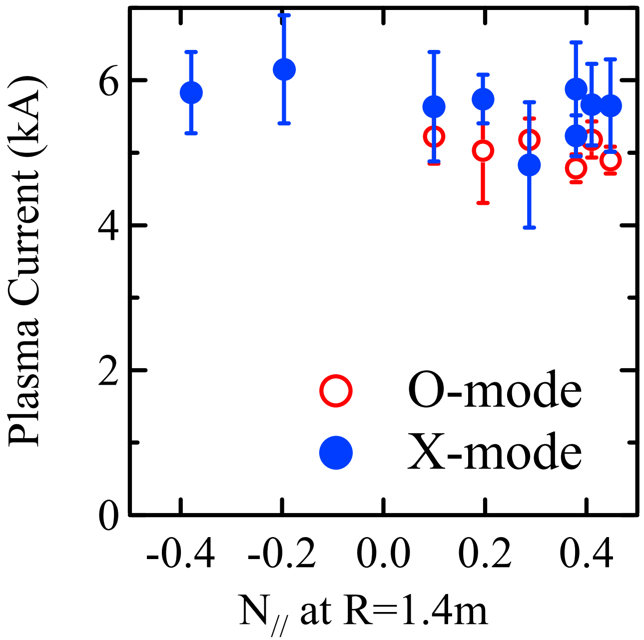
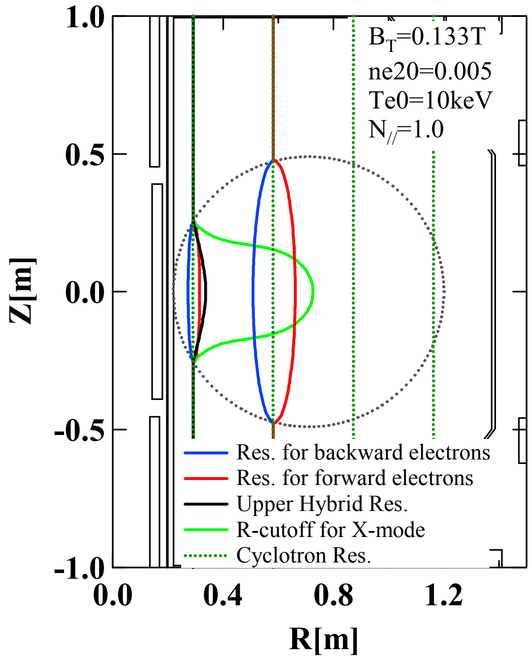
No mode and $N_{//}$ Dep.





- Difficult to understand how to drive the current using 1 and 2Ωe X and O mode ECCD and EBWCD.

How was the current driven?

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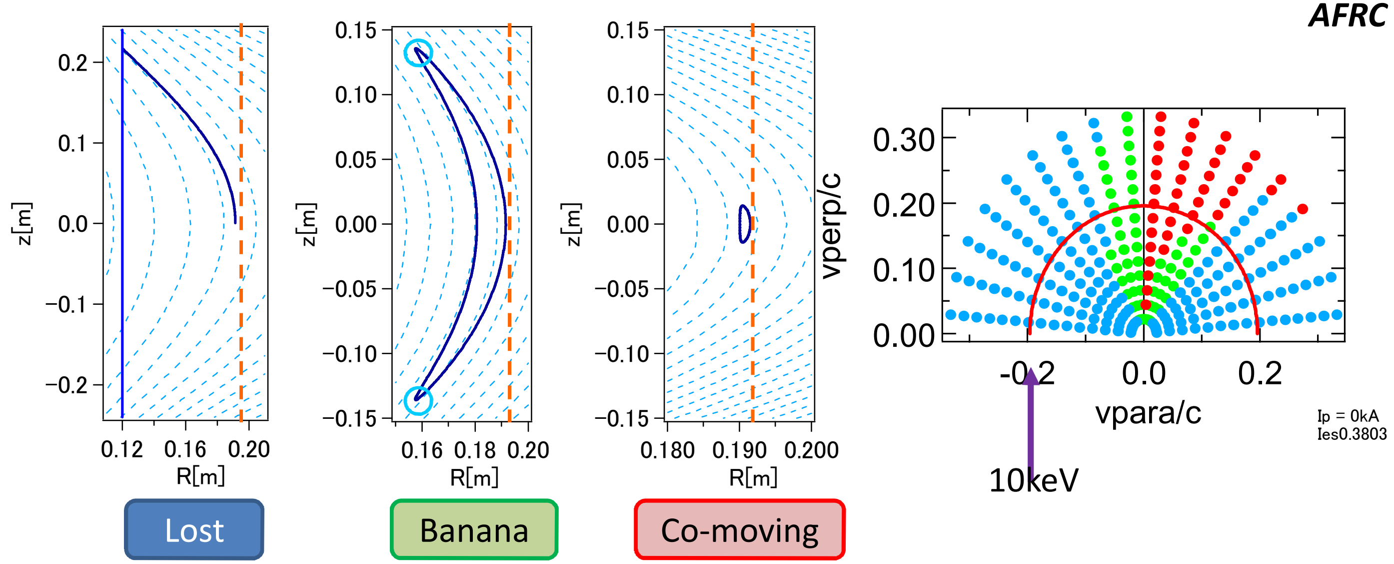

- **On open magnetic surface, the asymmetric orbit and the precession of banana electrons can drive the plasma current.**
- **The effect is enhanced with higher energy region.**
- **The momentum to electron fluid is supplied by the lost electrons. This is a kind of spontaneous current such as bootstrap current.**

Direct detection of driven current

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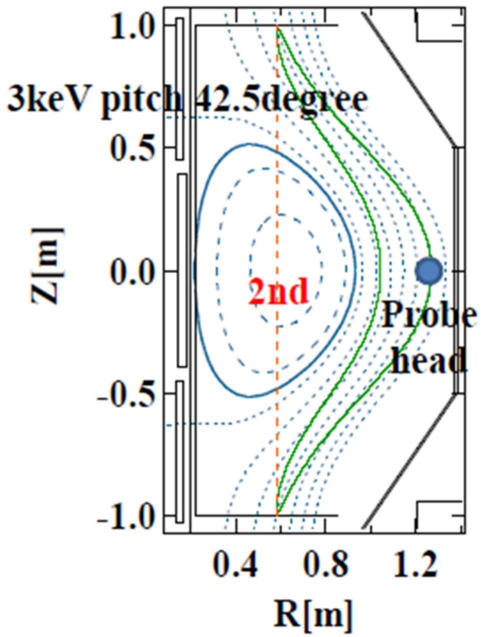

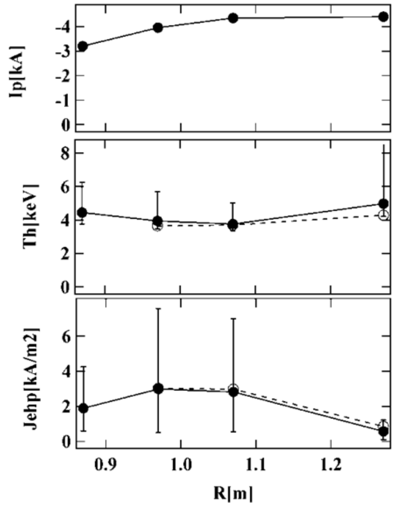

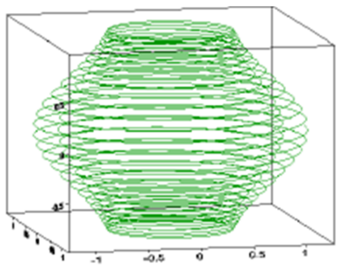

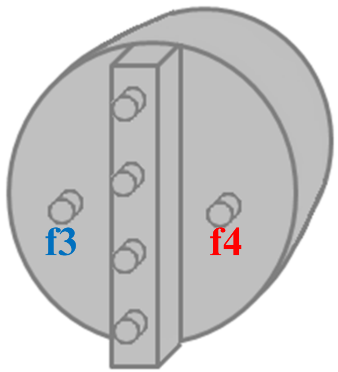

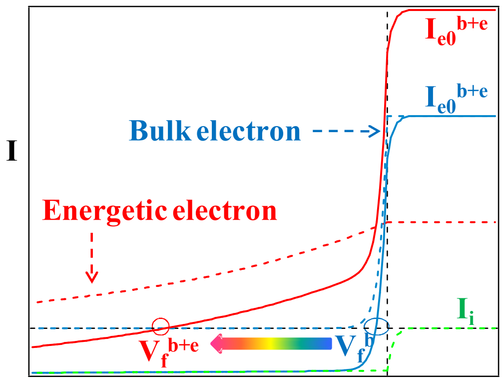

Neo-classical effect can drive the current

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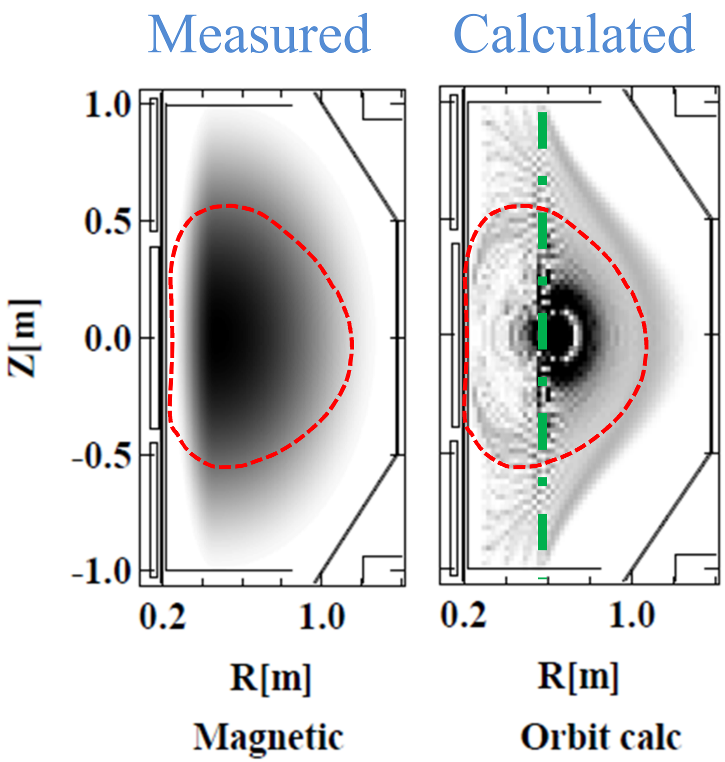

- **At the plasma current start-up, a part of the plasma current was driven outside of last closed flux surface.**
- **The current can be explained by the precession motion of banana electrons accelerated on 2Ωe ECR layer in open magnetic flux.**

Heat and particle handling

- Formation of Divertor conf.
- Divertor probe measurement
- Study of Blobs in ECRH plasmas

What is the reason of plasma termination?
Hot spot on the outer wall

QUEST

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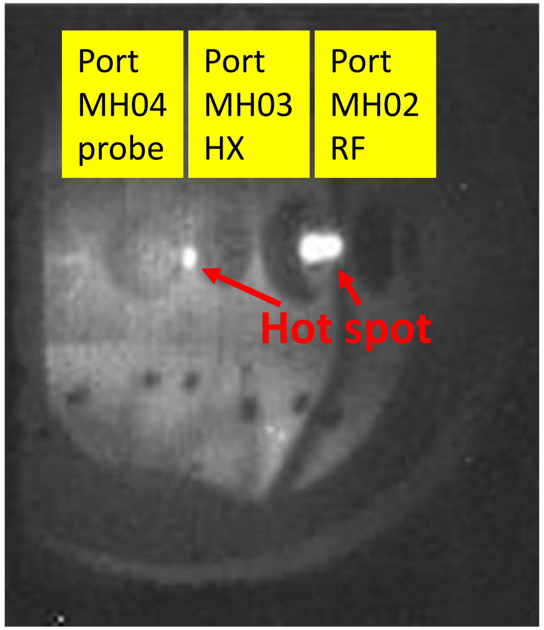

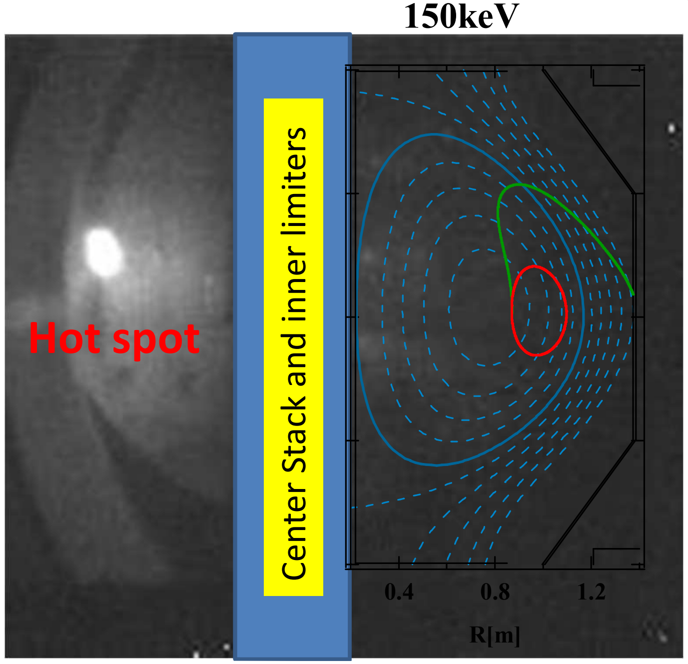

Hot spots mainly appeared on the outer wall, increasing P_{RF} and pulse duration. The plasma current was reduced by the increment of out-gassing caused by the presence of the hot spots.

Divertor Config. can be obtained

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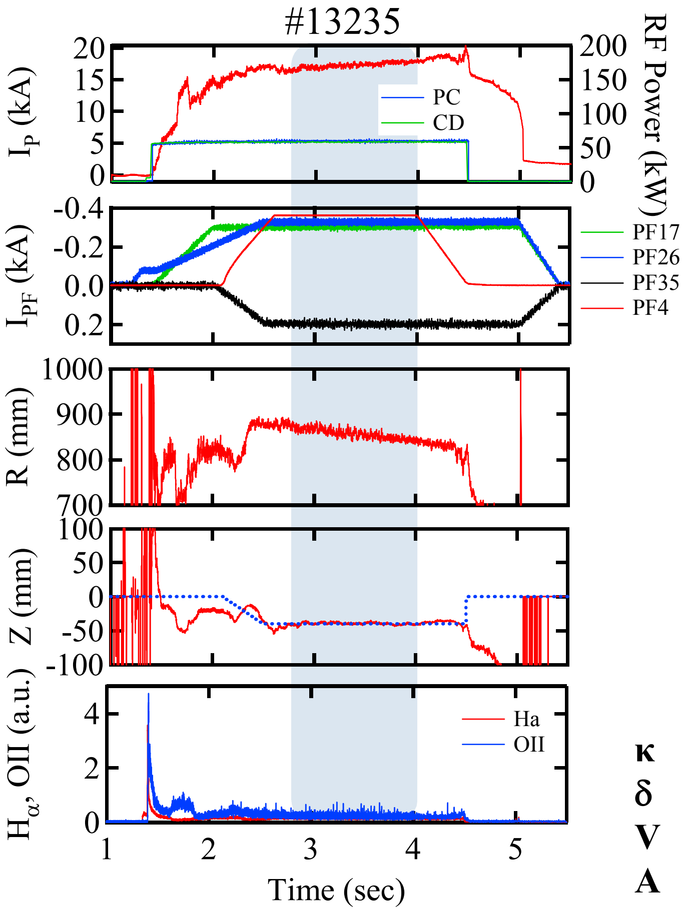

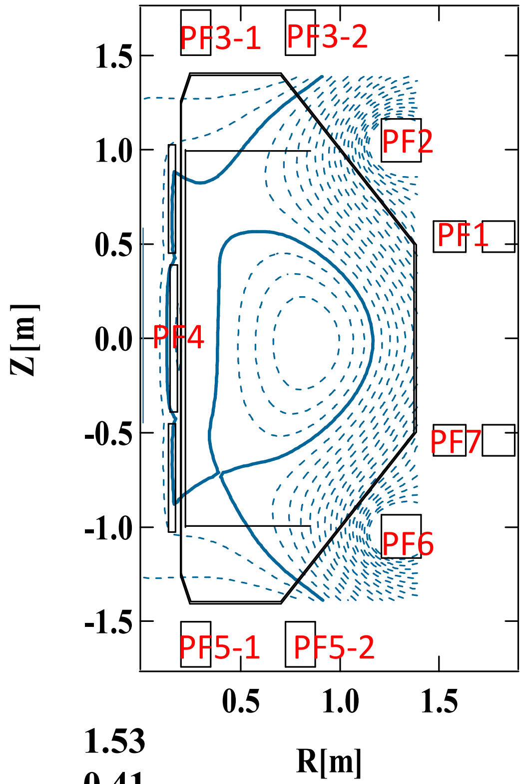

κ	1.53	
δ	0.41	
V	3.31	[m^3]
A	1.98	

Formation of divertor Conf.

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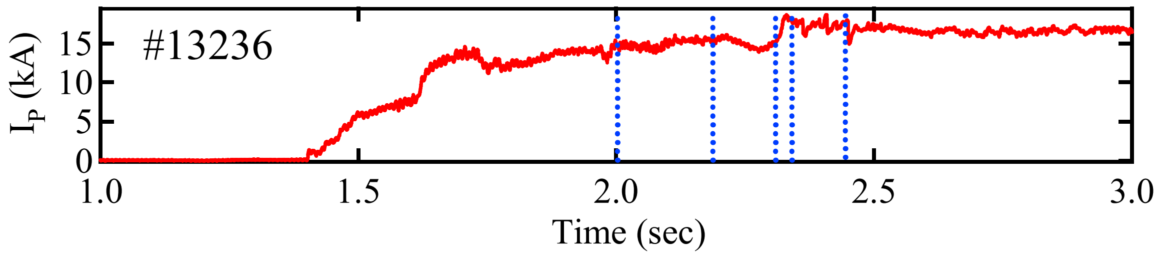

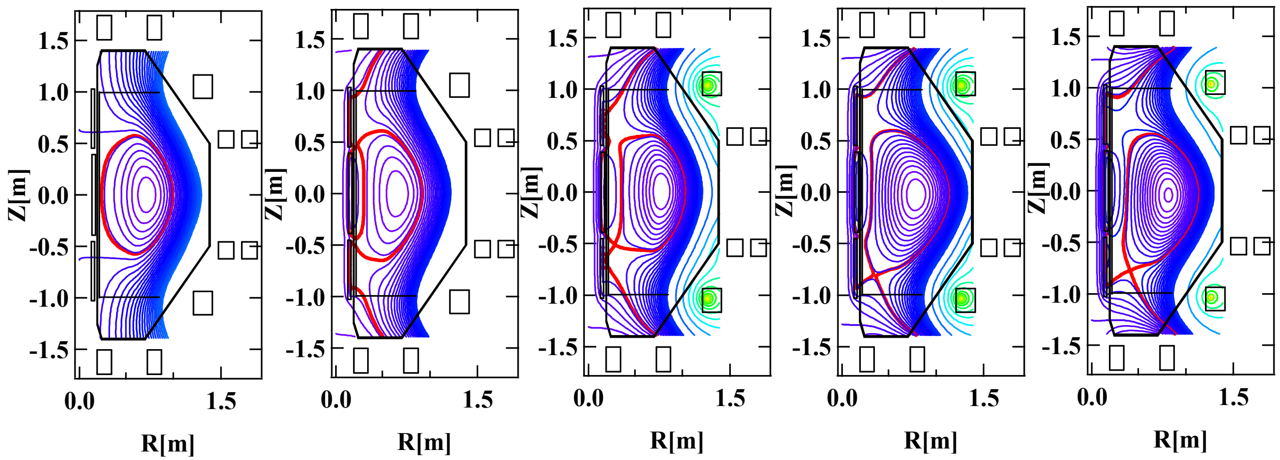

Divertor probe measurement

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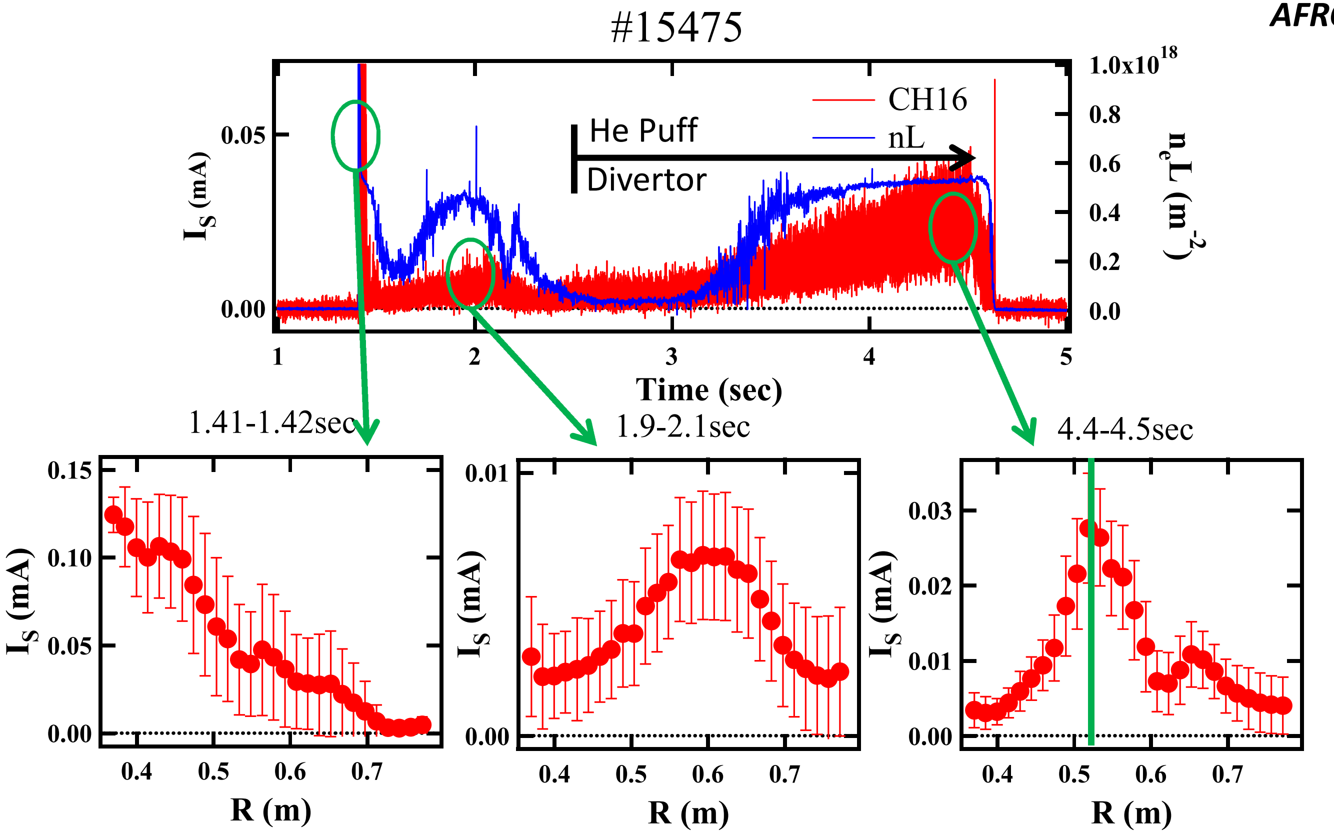

Distribution of Is strongly depended on magnetic conf. and peak position of Is agreed with position of a divertor leg measured with magnetic reconstruction.

Study of blobs is important to make 1-D model

QUEST

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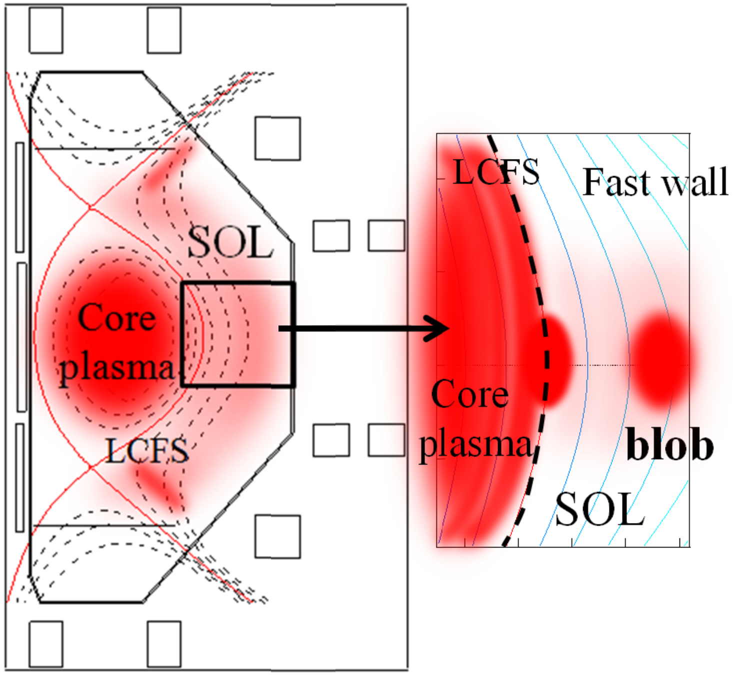

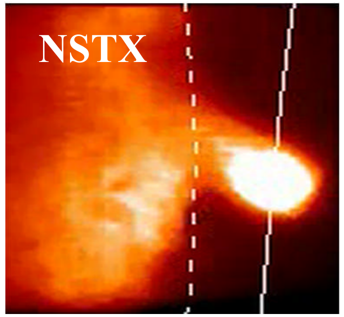

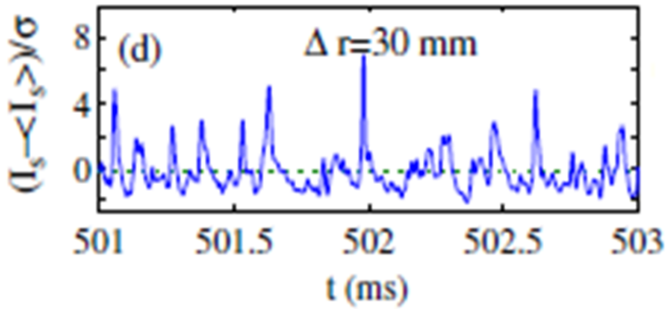

J.R.Myra and D.A.D'lppolito *et al*, Physics of Plasmas ,13 ,92509(2006)
J. Cheng et al., Plasma Phys. Control. Fusion, 52, 055003 (2010)

Particle flux in SOL region related to blobs is dominant . For 1-D model of particle balance, distribution of particle flux should be investigated.

Blobs in ECRH plasma on QUEST

QUEST

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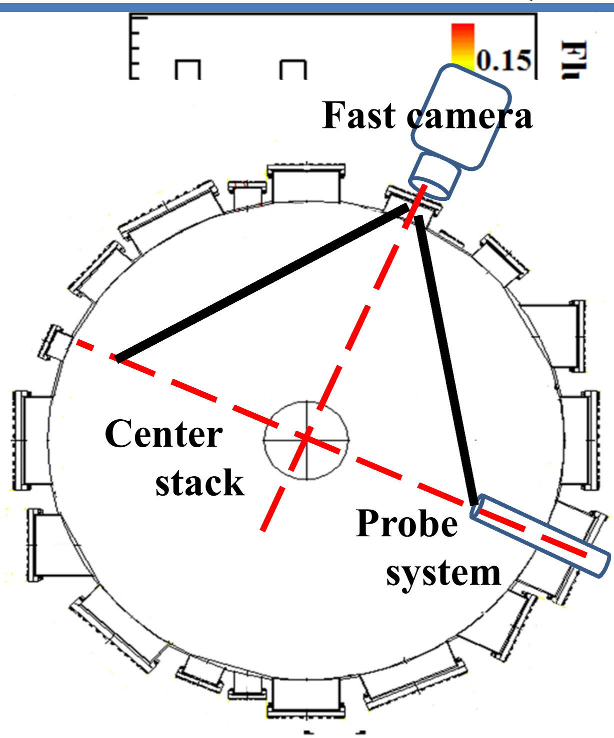

Blobs in ECRH plasma on QUEST are belonging to low collisional region like as ITER SOL.

Statistical Analysis will be reported by Santanu-san in this meeting

Blob induced particle flux

QUEST

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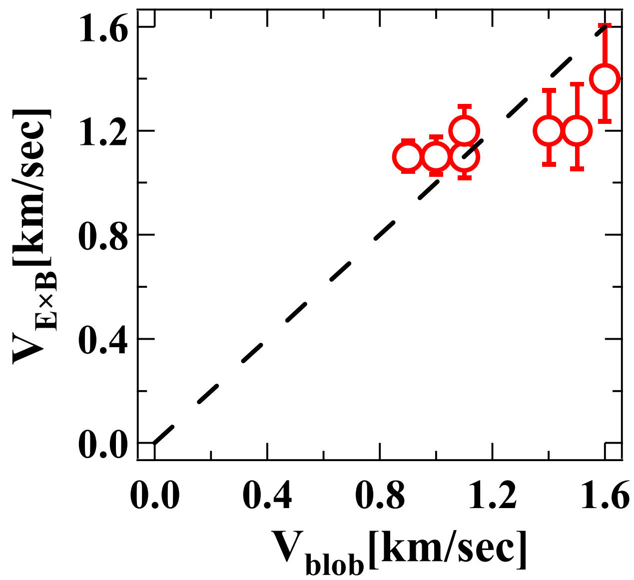

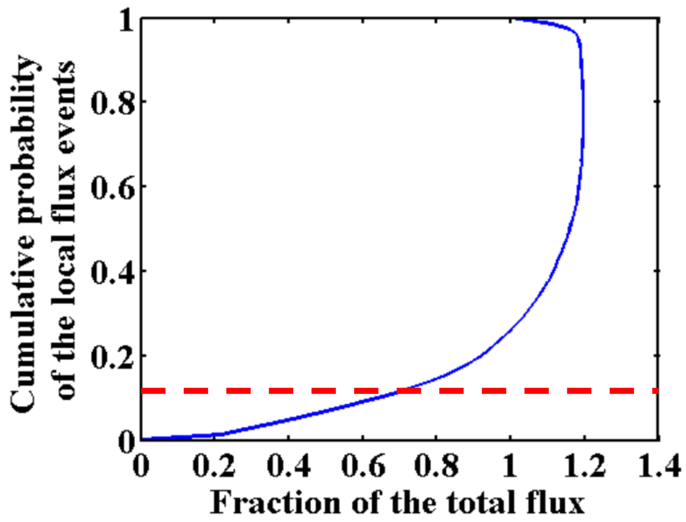

60% of particle flux was induced by blob-related convective flux and It should be investigated how many particles transport to the wall, not to the divertor.

Required conditions of the control system for steady state operation

QUEST

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- **At least 1kHz, if possible 3kHz for plasma**
  - Real time calculation; less than 1ms
- **Divertor leg position control (need to power supplies)**
  - Real time reconstruction of plasma shape
- **Application to wall control (installation of hot wall)**
  - Need to establish some reliable monitors;
  - Plasma density, neutral density, wall pumping rate
- **High scalability**
  - Extremely different time scale from 3kHz to more than hours

New current profile reconstruction is applied.
The reconstructed plasma shapes are reliable

QUEST

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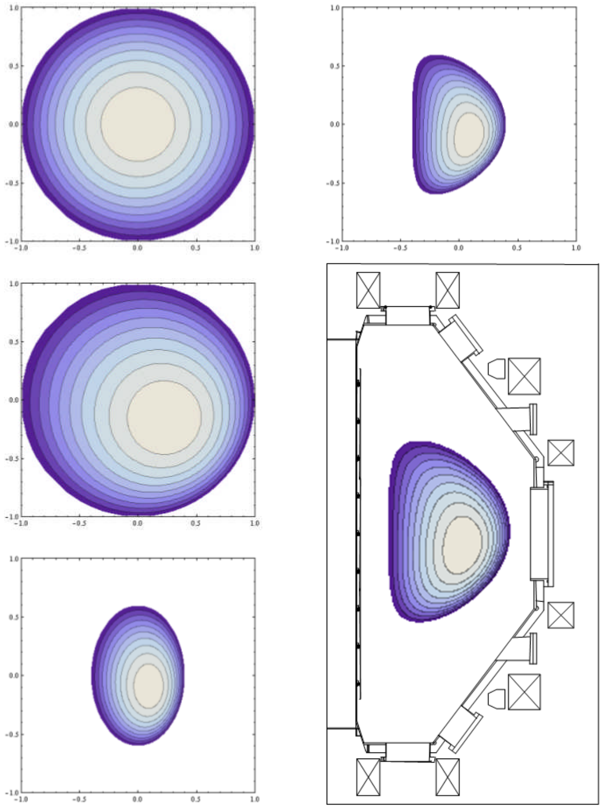
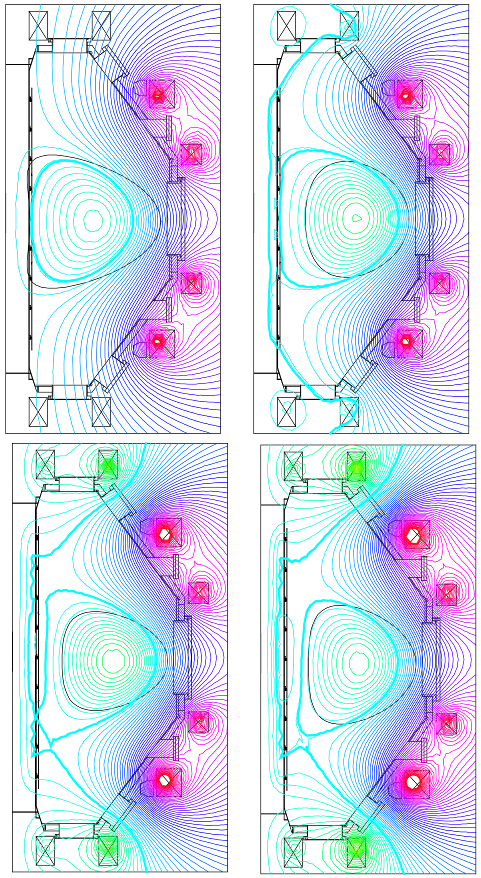




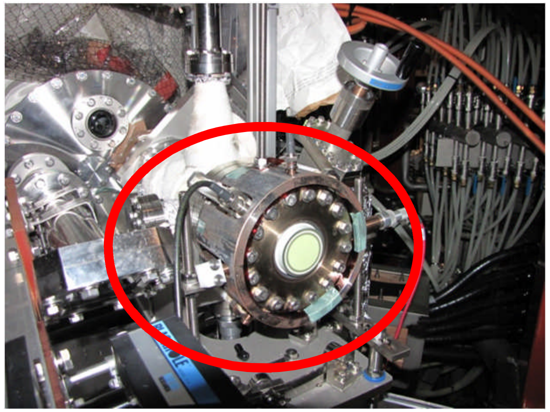
The details will be presented by Hasegawa-san in this meeting

How to monitor a plasma position

QUEST

AFRC

2D SXR camera



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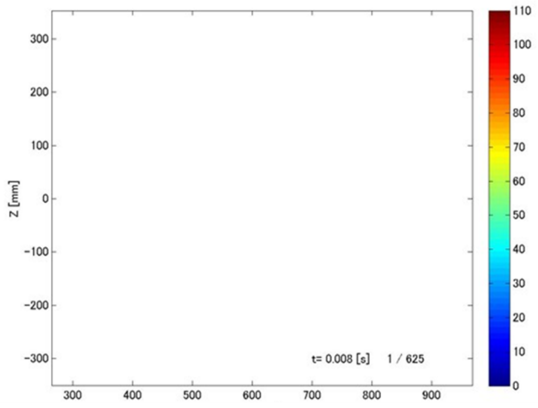
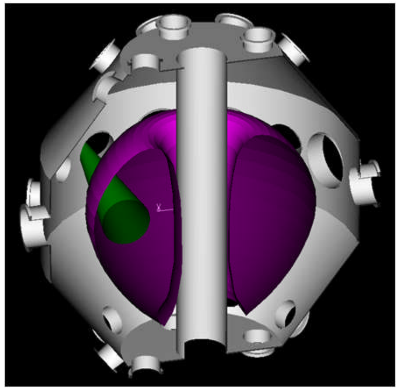
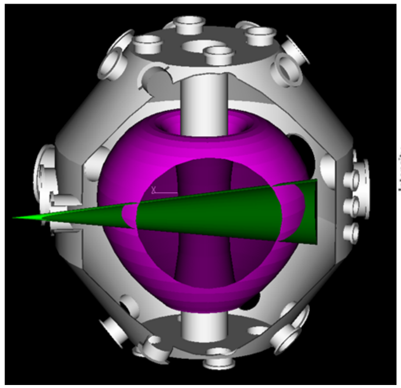
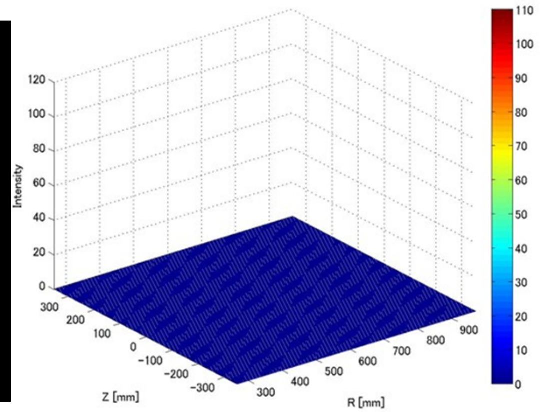






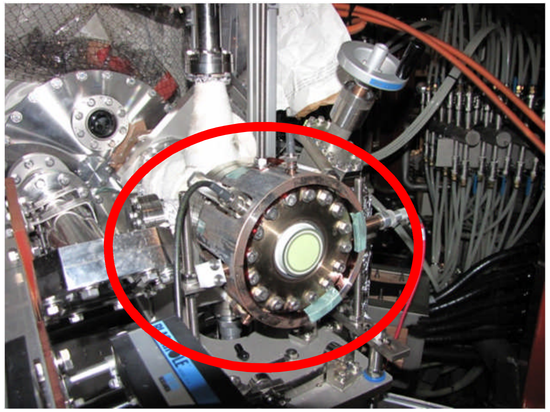


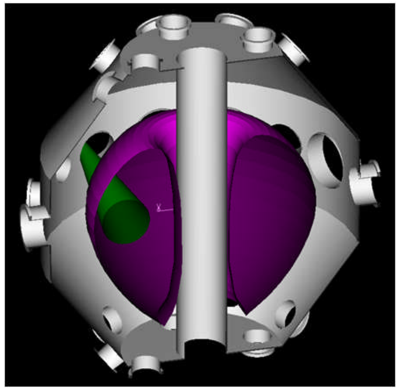
How to monitor a plasma position

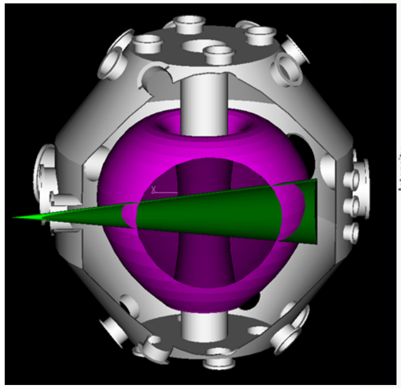
QUEST

AFRC

2D SXR camera







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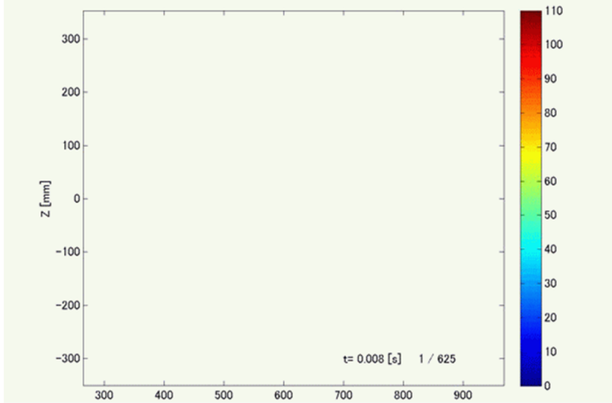
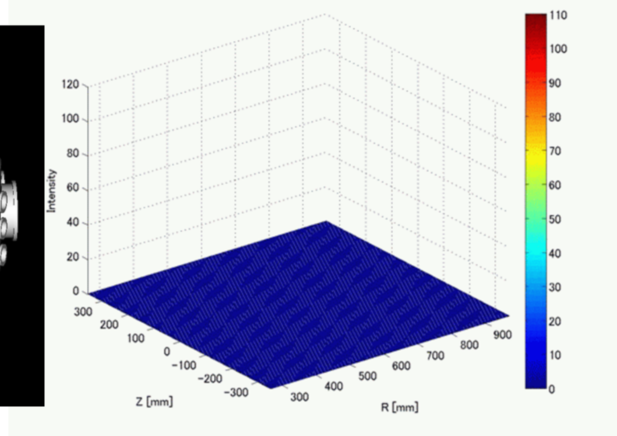
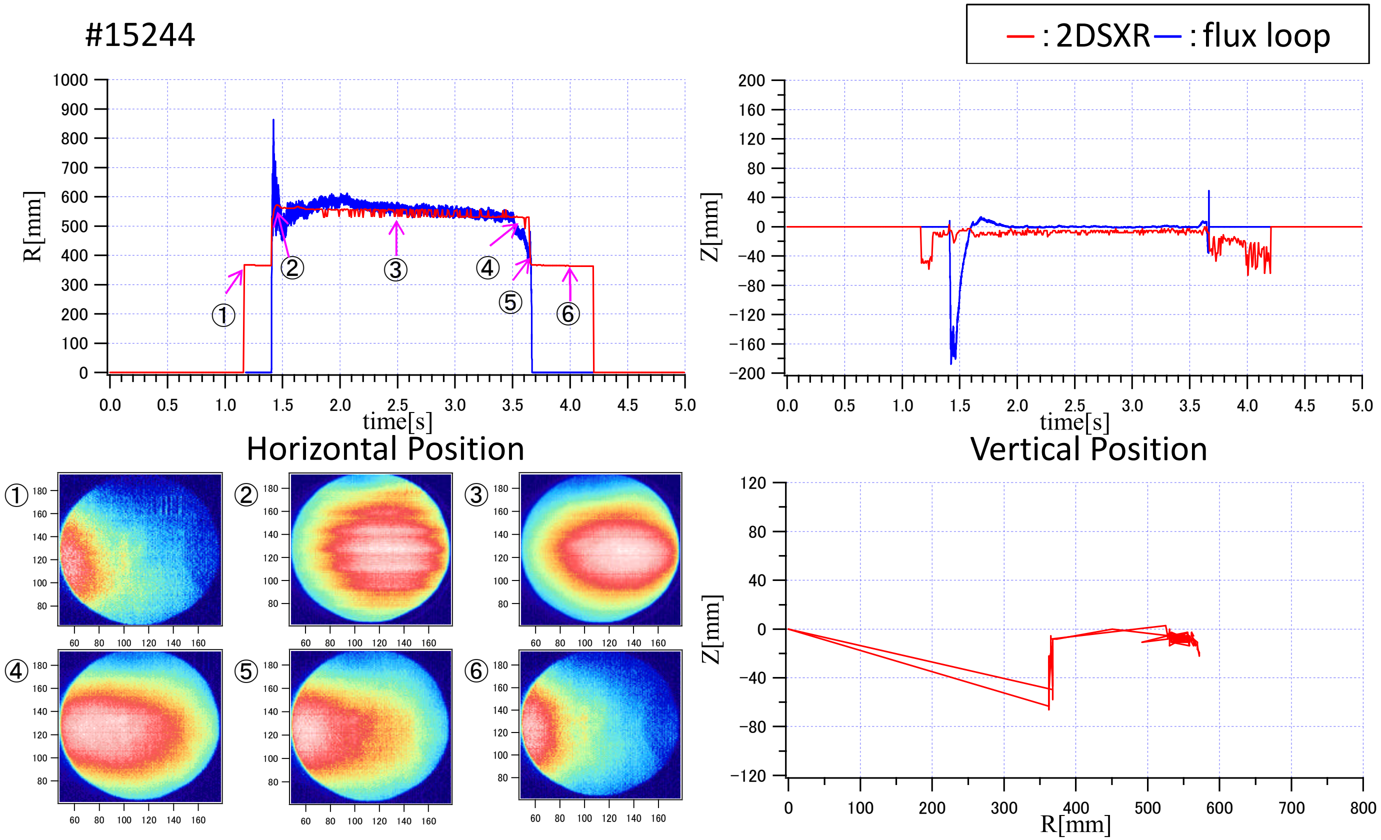




Comparison of the plasma axis position with magnetic measurement

QUEST

AFRC



Required conditions of the hot wall *QUEST*

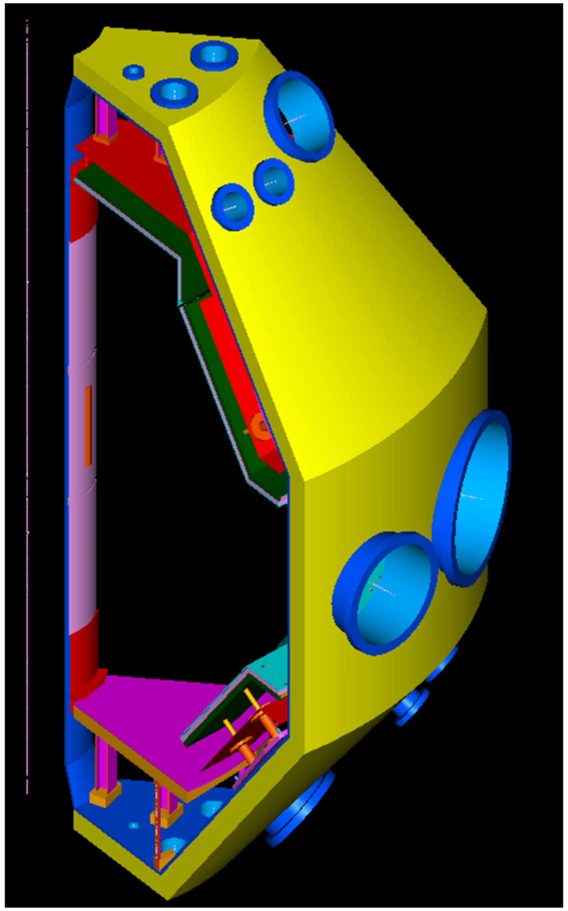
AFRC

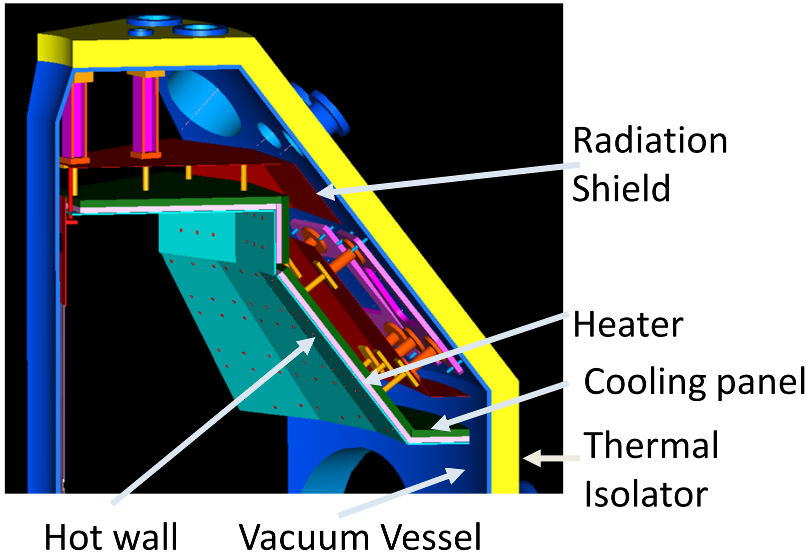
- **At least 573 K, if possible 773K on the hot wall surface**
  - H pumping out, based on ion irradiation experiments.
  - If carbon, at least 1000K
- **Less than 323 K on the surface of V.V.**
  - For diagnostics, for window, for GV and so on
- **Covered by W on the plasma-side surface at least**
  - PWI control, application to fusion power plants.
- **If possible , T_{wall} control**
  - For particle handling in steady state

Hot wall has been designed

QUEST

AFRC

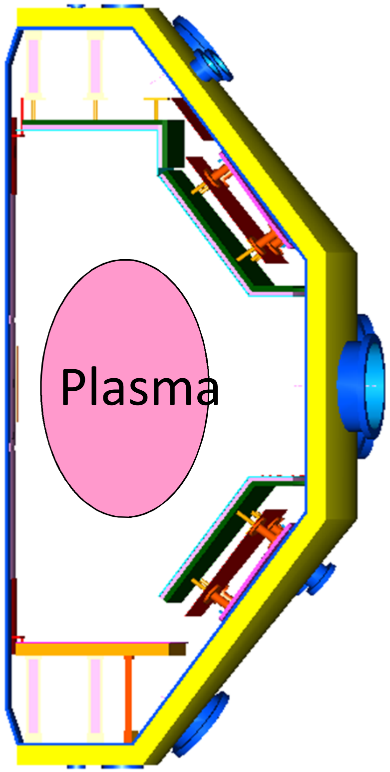




Modeling of plasma for heat balance calcu.

QUEST

AFRC

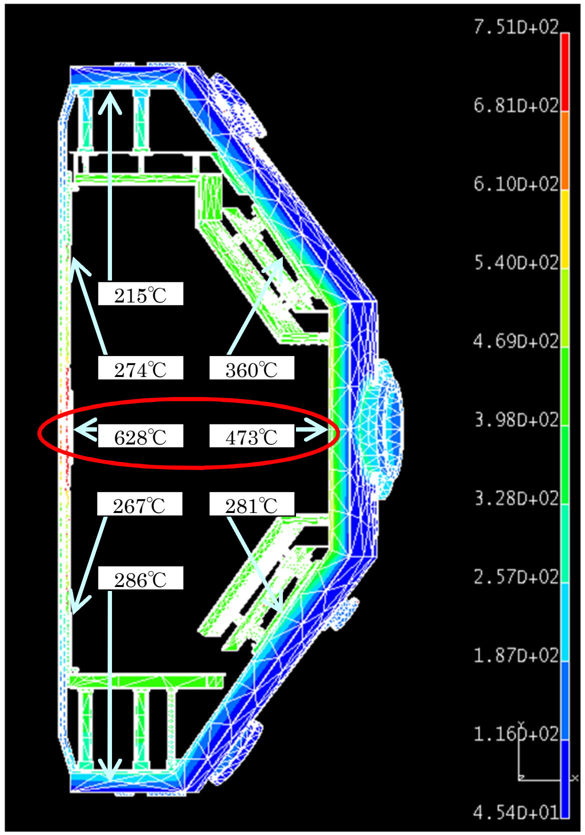


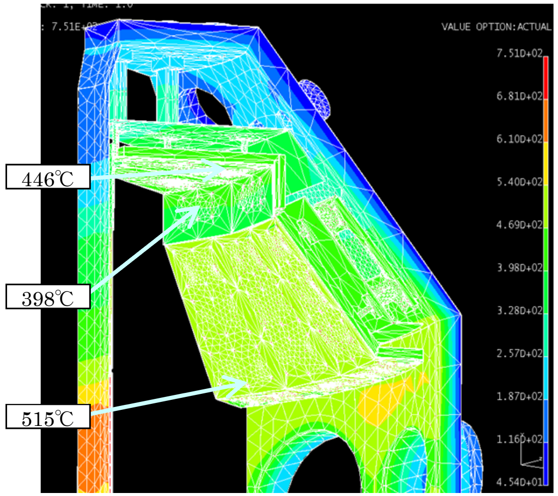
- Plasma was assumed as a toroidal-shaped flat radiation source.
- No heat flow to divertor plate from plasma.
- 100kW radiation in steady state (20 % of 500kW)

An example of calculation result

QUEST

AFRC



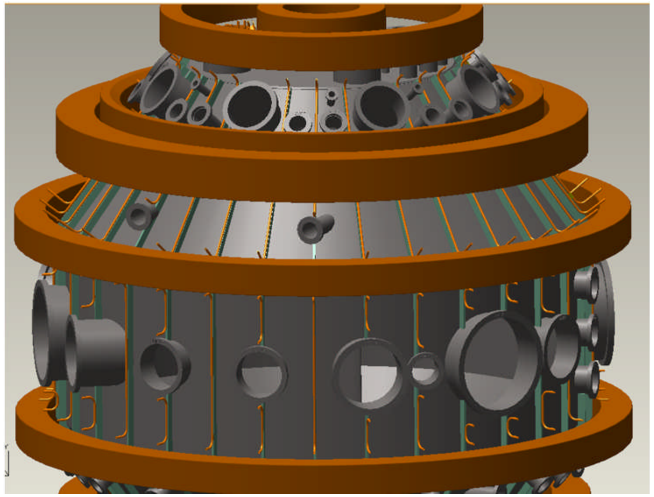


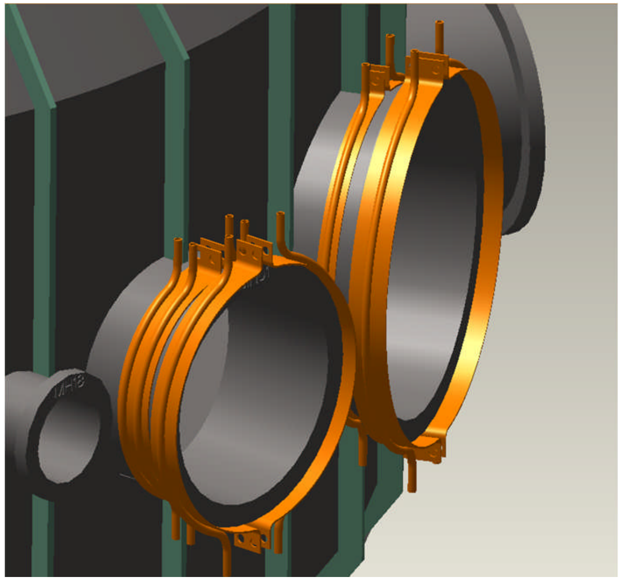
When the temperature of the hot wall surface is over 500 degree, a part of the vacuum vessel is going to be too high. This means some cooling channels are required.

Two types of cooling channels are investigated for cool-down of the vacuum vessel

QUEST

AFRC





Required flow rate of water is reasonable, however workability to install these channels is still concerns. Further investigations are necessary.

New developed diagnostics
Intrinsic plasma rotation with HeII images on QUEST

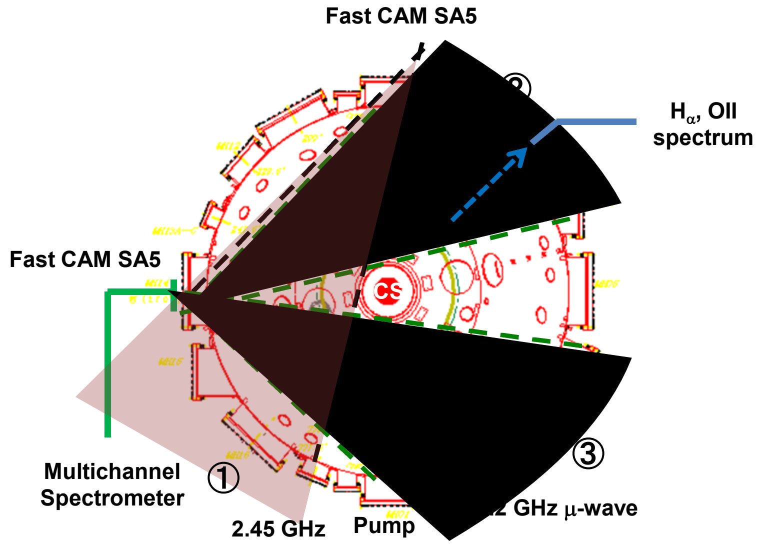
QUEST

AFRC

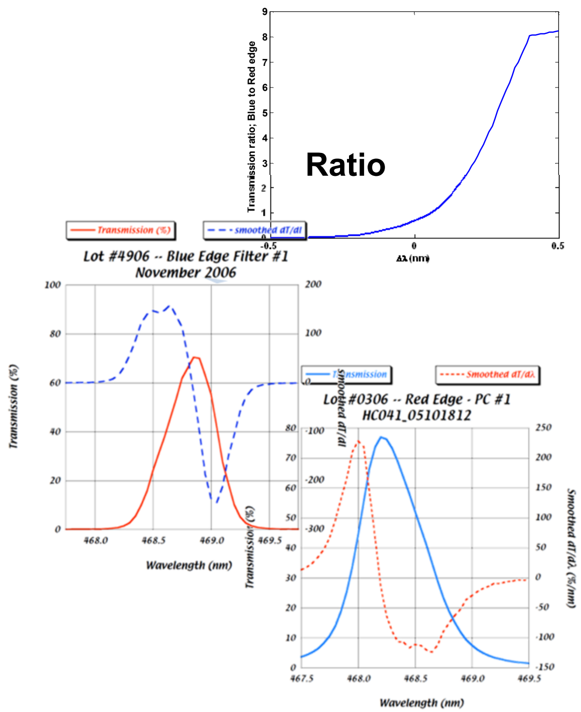
Images from both side view: Using fast camera and HeII edge and broadband filters:

1. Limiter configuration
2. Divertor configuration
3. Inboard null configuration

Velocity is: $v = \frac{\Delta\lambda}{\lambda} c$



Top View of QUEST

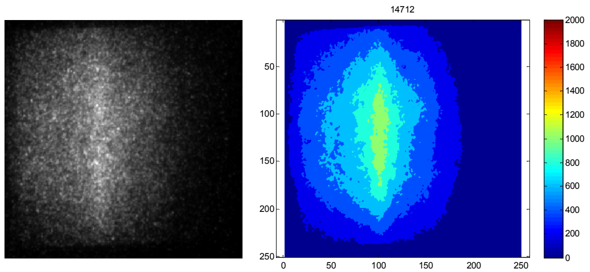


September 28th: Oral presentation by Prof. Nobuhiro Nishino

Slab plasma – no rotation case – angular effect

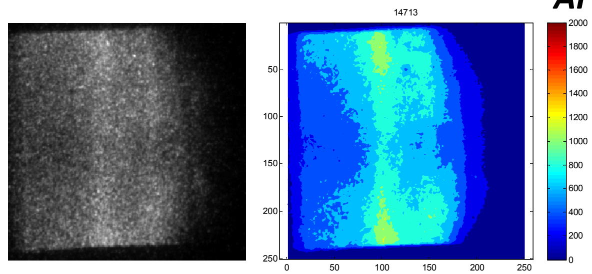
QUEST

AFRC



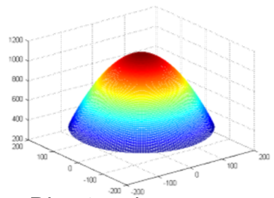
Blue shift

68% decrease from peak value; center to edge of image

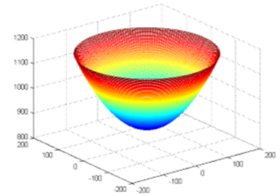


Red shift

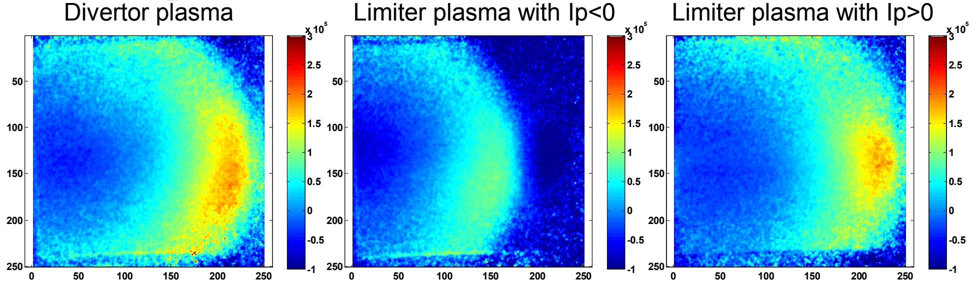
27% increase from minimum value; center to edge of image



Correction for angular effects required



Divertor plasma | Limiter plasma with Ip<0 | Limiter plasma with Ip>0



TFC 40 kA

2D – velocity profiles

More precise corrections necessary

September 28th: Oral presentation by Prof. Nobuhiro Nishino

Plasma current evolution – principal comp. analysis applied to fast camera images

QUEST

AFRC

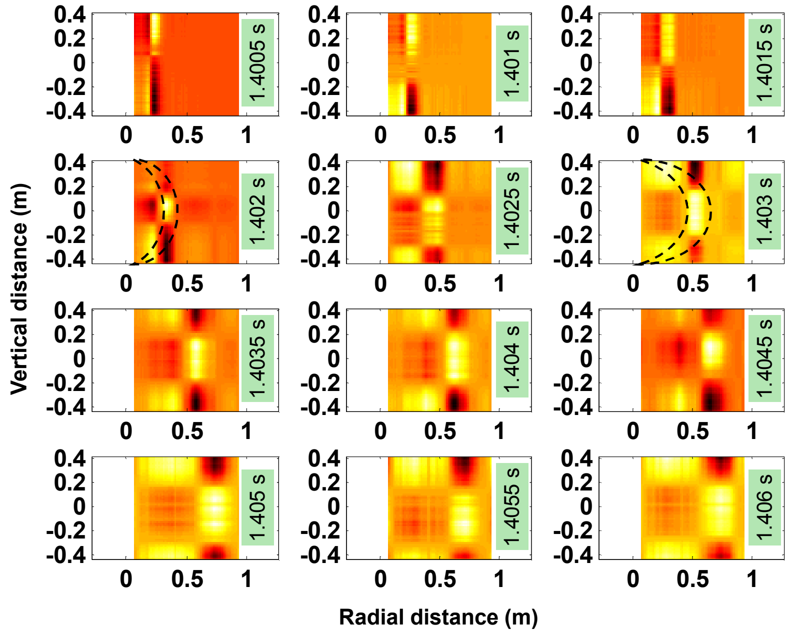
- Let A denote an $m \times n$ matrix of image data, where $m \geq n$
- Equation for SVD gives:

$$A = USV^T$$

Where U is a $m \times n$ matrix, S is a $n \times n$ diagonal matrix and V^T is a $n \times n$ matrix

- The first, second and third principal components are defined by $s_1v_1^T$, $s_2v_2^T$, $s_3v_3^T$ respectively

Temporal evolution of 2nd principal images showing banana orbit formation



September 28th: 28-3P-7 Poster presentation by Santanu Banerjee

Summary

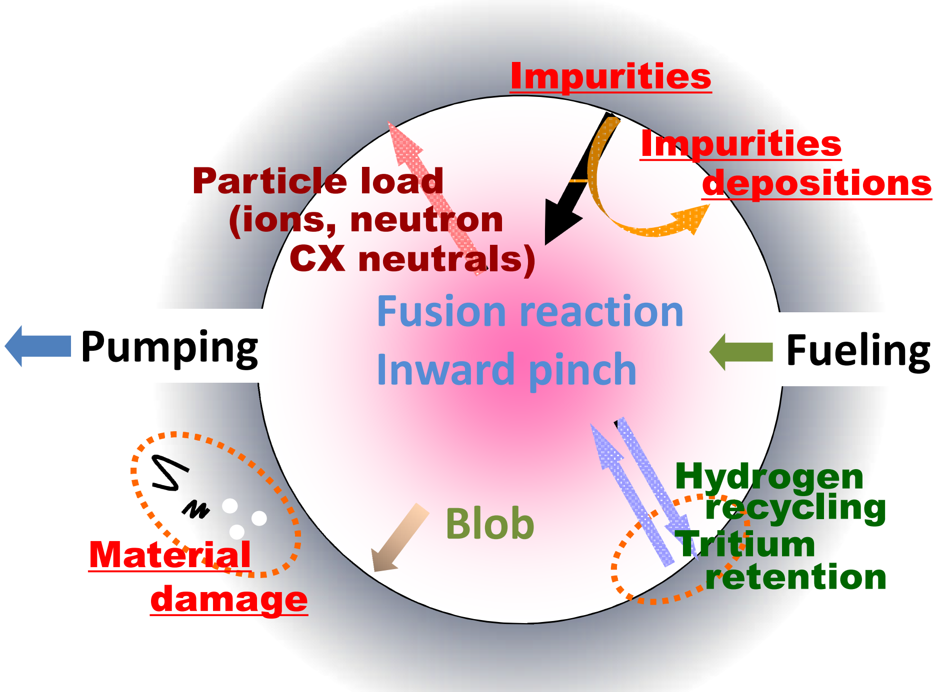
QUEST
AFRC

- On QUEST, a spherical tokamak configuration with the aspect ratio of less than 1.5, the plasma current up to 25kA could be obtained for 1s by fully non-inductive current drive using the well-controlled microwave of 8.2GHz, 120kW.
- The non-inductive current is driven by toroidally asymmetric orbit of energetic electrons accelerated by the microwave.
- The plasma current was reduced by the increment of out-gassing caused by the presence of the hot spots made by direct attack the energetic electrons on the wall.
- The single-null divertor configuration was formed and could be maintained for 20 sec. Ion saturation current measured on the divertor plate surface was increasing around the divertor leg.
- The real time plasma shape control for QUEST are preparing and the method to avoid a drift problem of magnetic signal (2D SXR) will try to apply to identify the plasma position..
- Several types of new developed diagnostics start to work.

Particle balance in Fusion plasma

QUEST

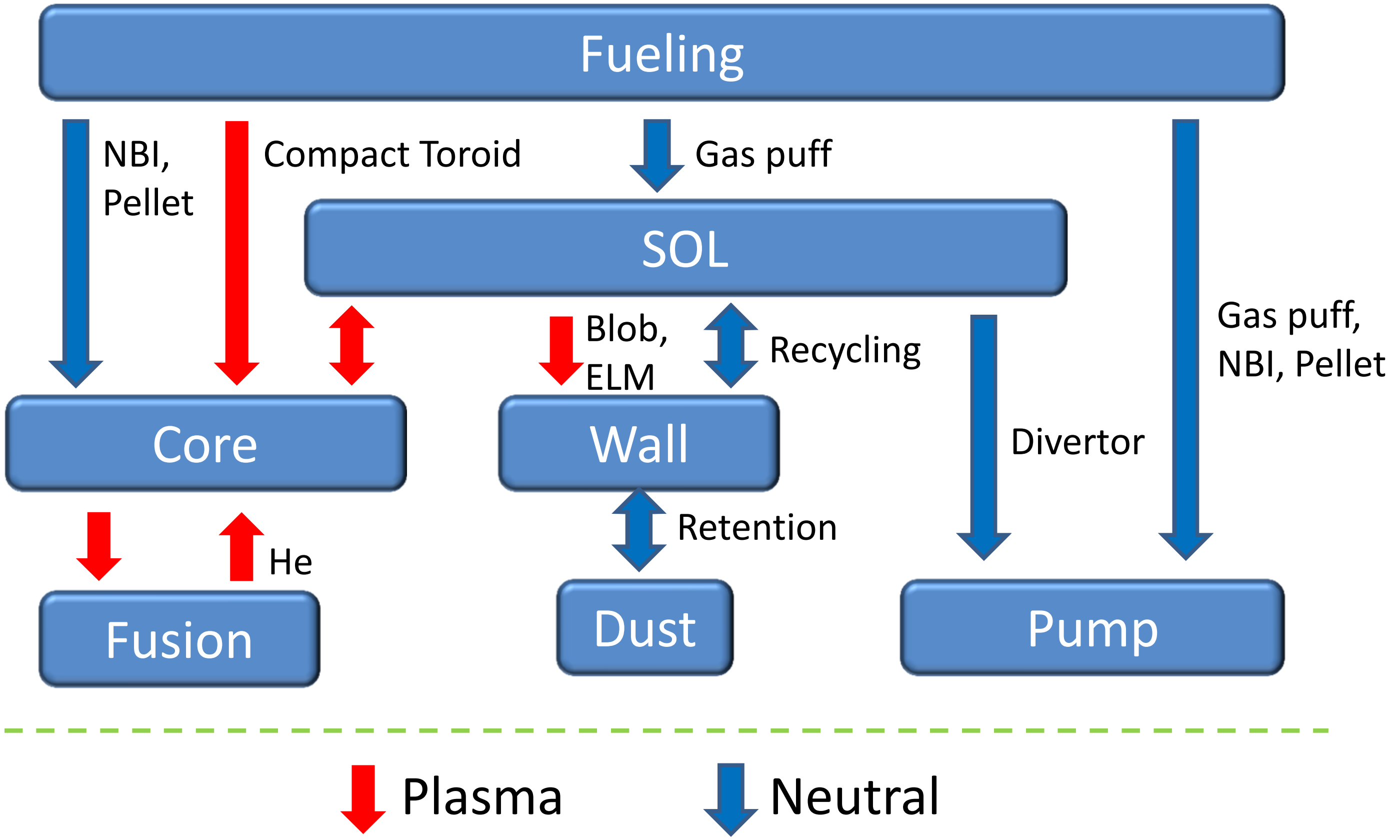
AFRC



- Everything has some complicated reciprocal relations and its integrated results make or mar fusion power plants.
- Several issues come to the front in steady state operation.

Particle Balance

What kinds of processes are working?



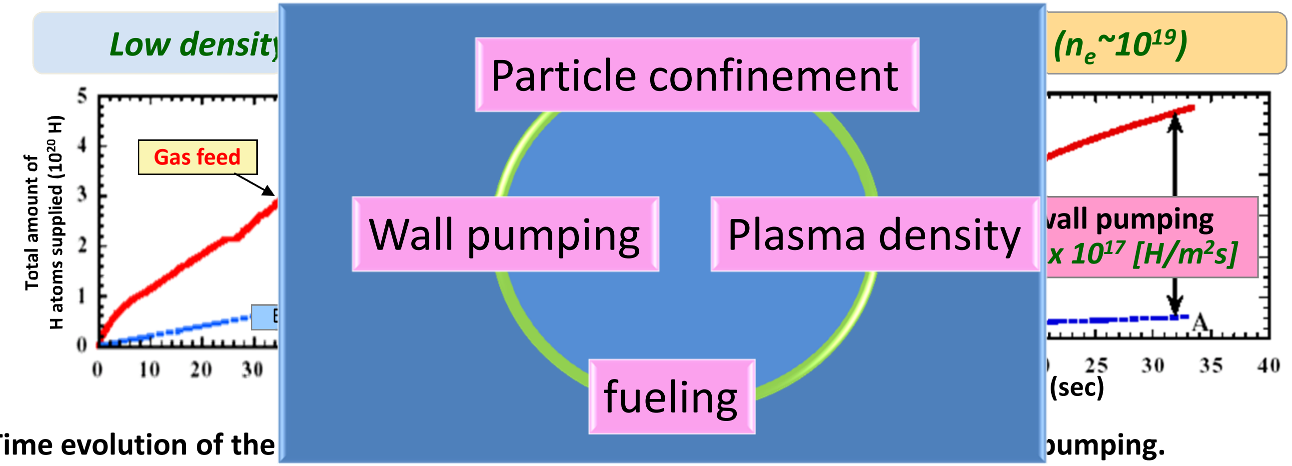
What is the matter with steady-state ?

QUEST

AFRC

Wall pumping in long pulse operation

M. Sakamoto et al., Nucl. Fusion 42 (2002) 165



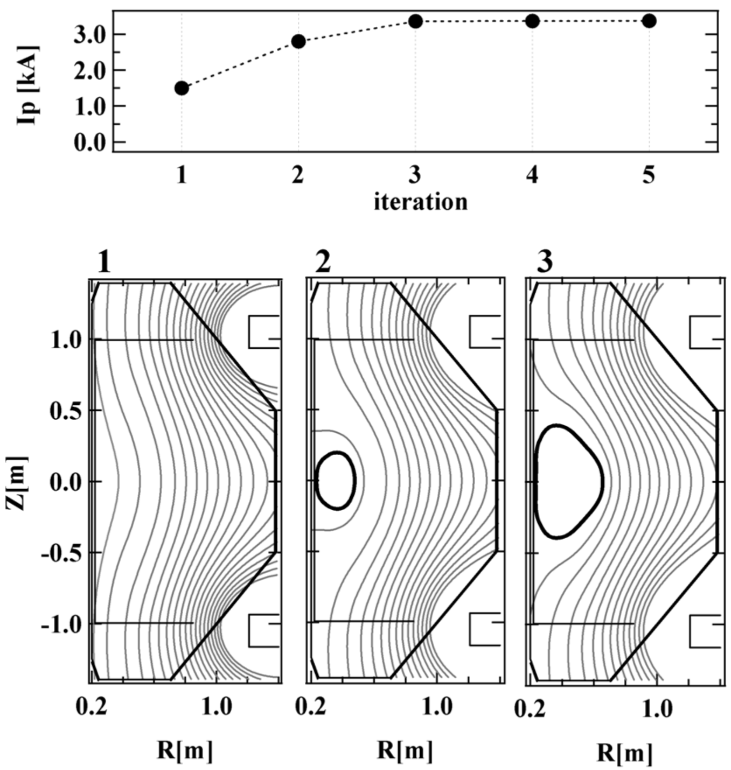
Time evolution of the … **pumping.**

- The wall pumping depends on the plasma parameters and it leads to be difficult to control of particle balance in steady state. The co-deposition process plays an essential role in the wall pumping rate.

Neo-classical current was enough to make CFS

QUEST

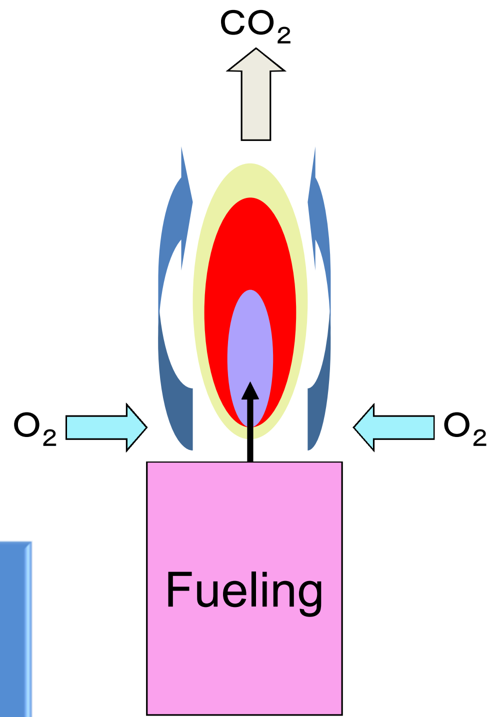
AFRC



Particle balance in chemical burning

QUEST

AFRC

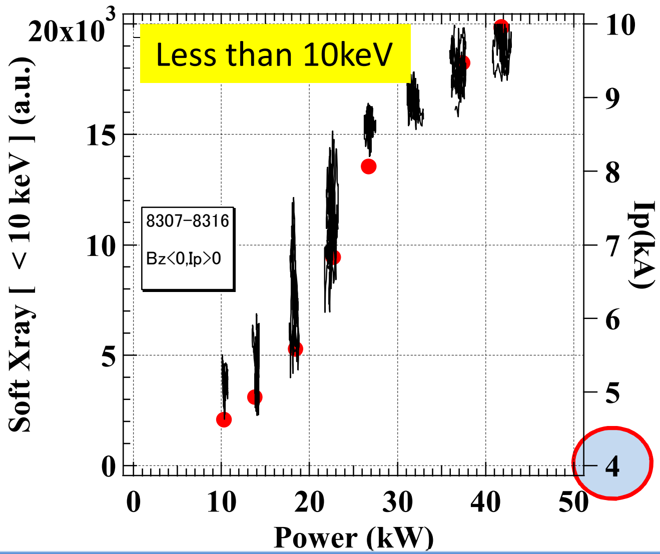


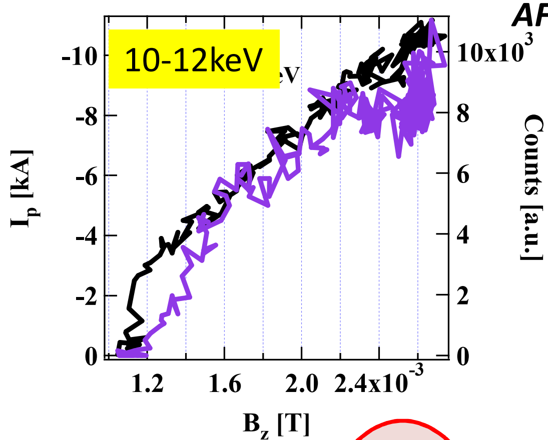
Automatic particle circulation can support steady state burning in chemical burning.

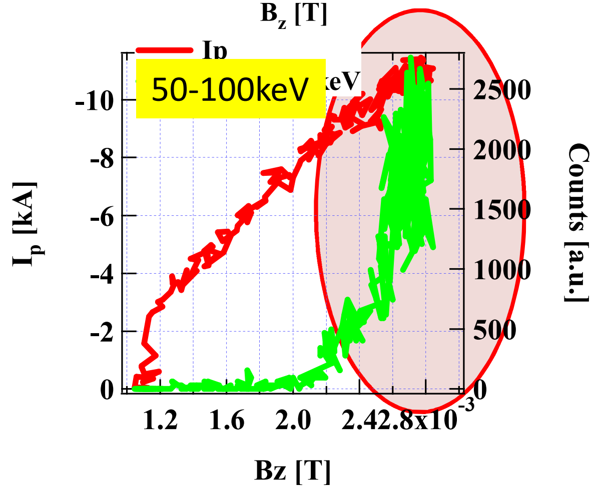
Properties of non-inductive current drive plasmas

QUEST

AFRC





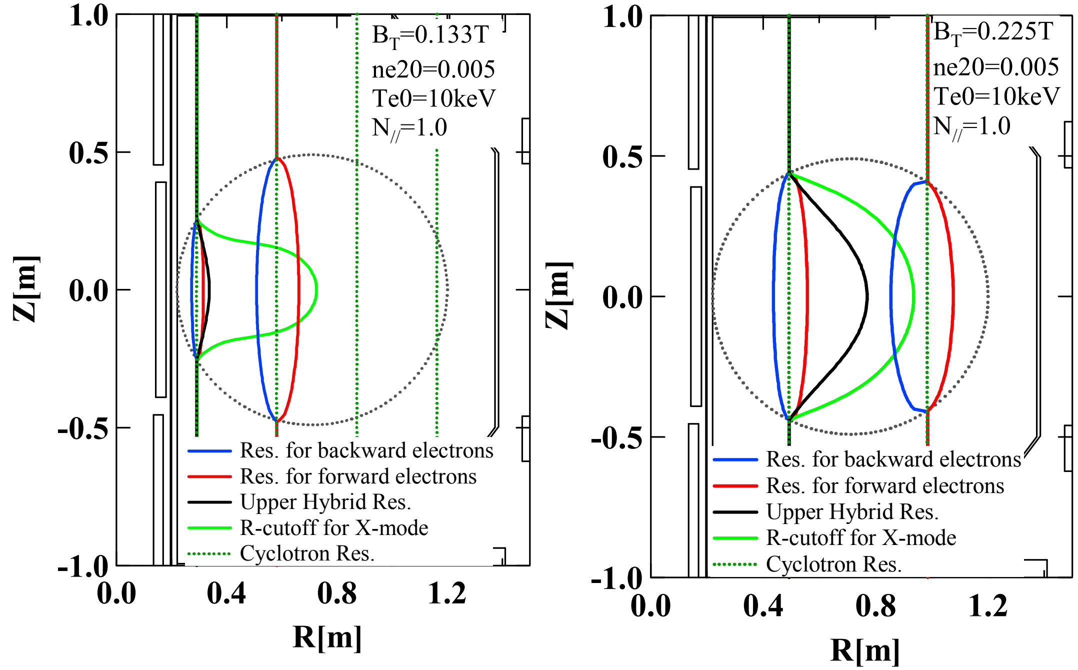


- **The plasma current more than 4kA was almost proportional to the number of photons 10-12keV.**
- **Electrons with higher energy are in higher current than 8-10kA.**

How was the current driven?

QUEST

AFRC



- 1Ωe X and O mode ECCD was impossible at low B_T even under the consideration of relativistic and Doppler effect.
- 2Ωe X ECCD had the possibility to drive the current because of avoidance of the cancel effect in a narrow density region.

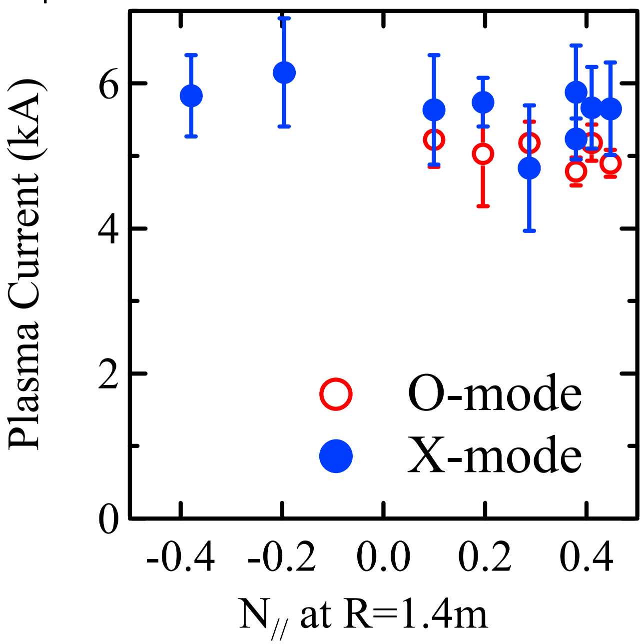
Wave mode, $N_{//}$, and B_T dependence

QUEST

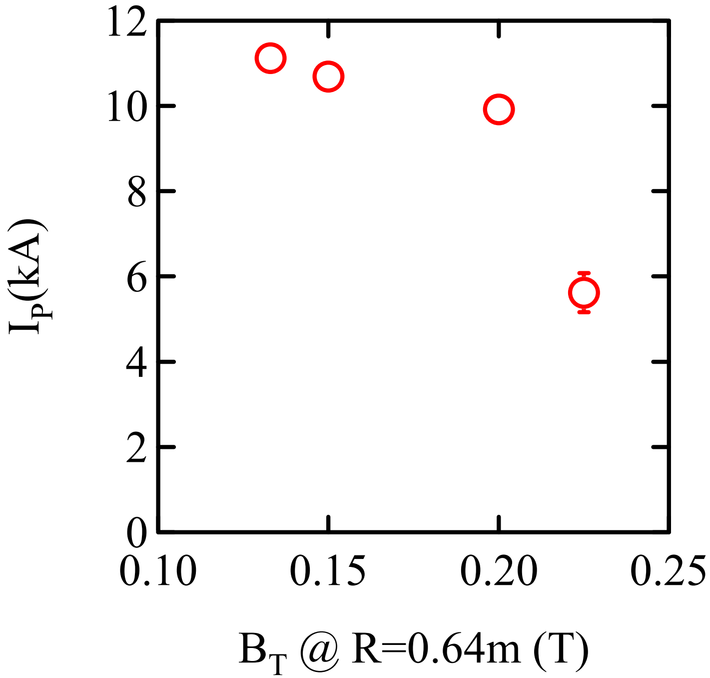
AFRC

No mode and $N_{//}$ Dep.

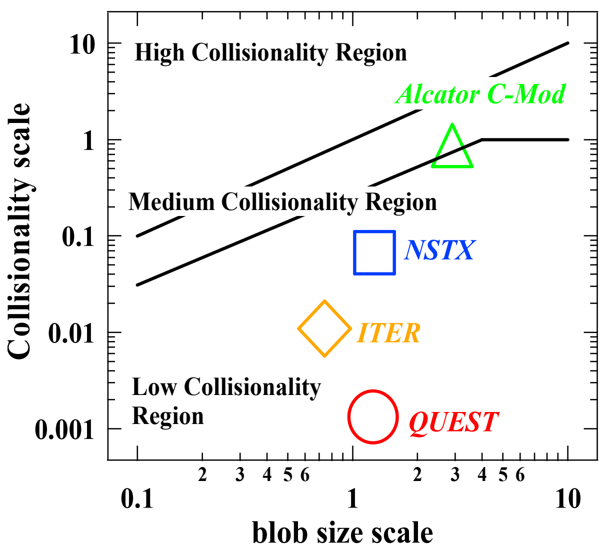
B_T = 0.2T



No B_T dep.



予測されるblobのパラメータ領域



Low Collisionality Region

$$V_{she} = \left(\frac{\rho_s}{a}\right)^2 \frac{L_C}{R} C_s \frac{\delta n}{n}$$

Medium Collisionality Region

$$V_{pol} = \sqrt{\frac{2a}{R}} C_s \frac{\delta n}{n}$$

High Collisionality Region

E×Bドリフト速度では、伝搬速
度が決まらない

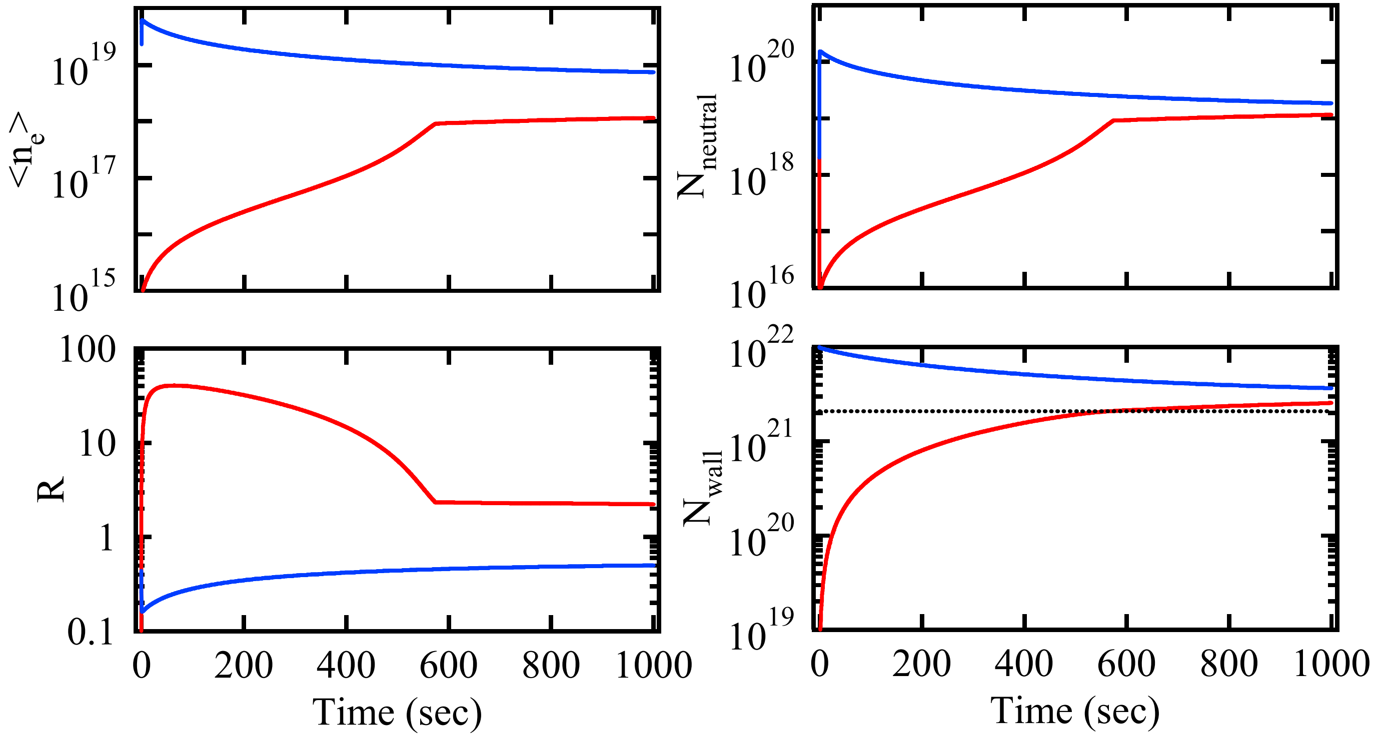
他の装置で発生するblobもこの領域にあると予想され、QUESTで観測されているblobも、同じ領域にいるのでQUESTでの研究は、他の装置での伝搬機構解明に役立つと考えられる。

S. I. Krasheninnikov, Phys. Plasma.,**74.** (2008)679
J.R.Myra and D.A.D'lppolito *et al*, Physics of Plasmas ,**13** ,(2006)92509

Why wall study?

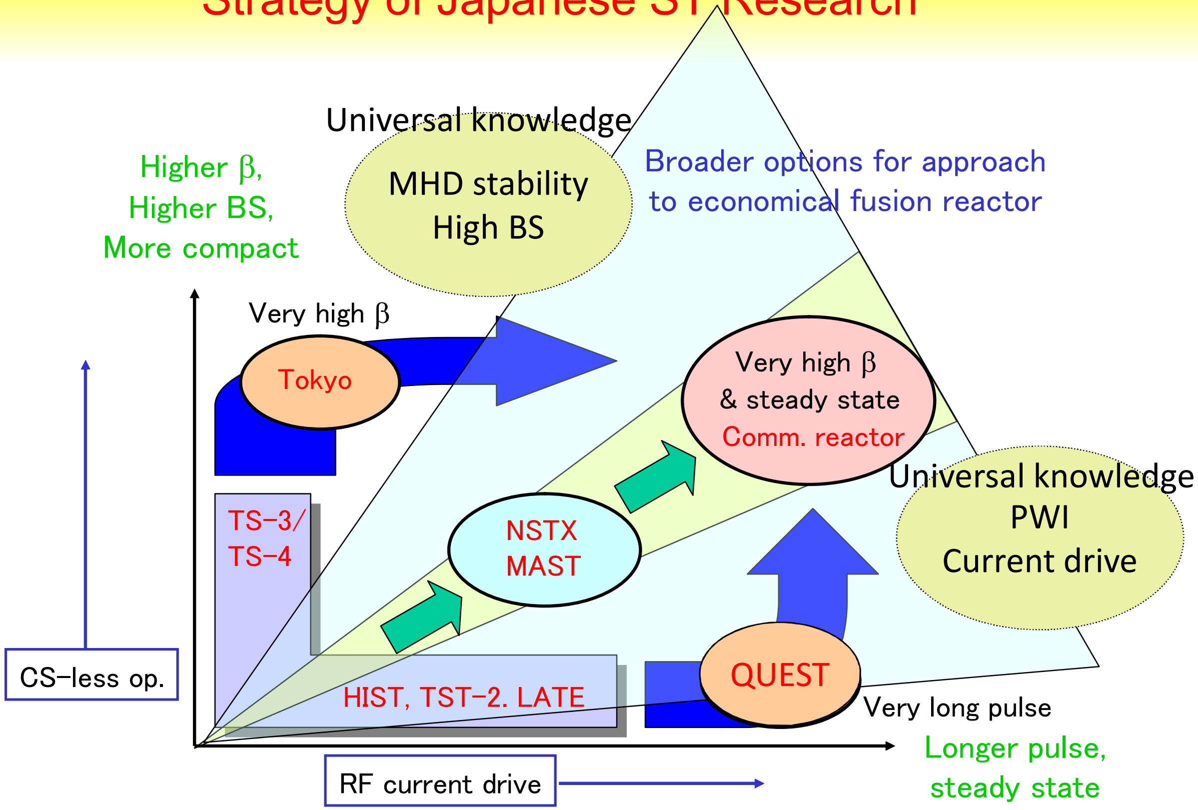
QUEST

AFRC



Wall store the number of particle ($1x10^{21}$) before the plasma turns on.
When this situation occurs in real experiments, the plasma do not turn on.

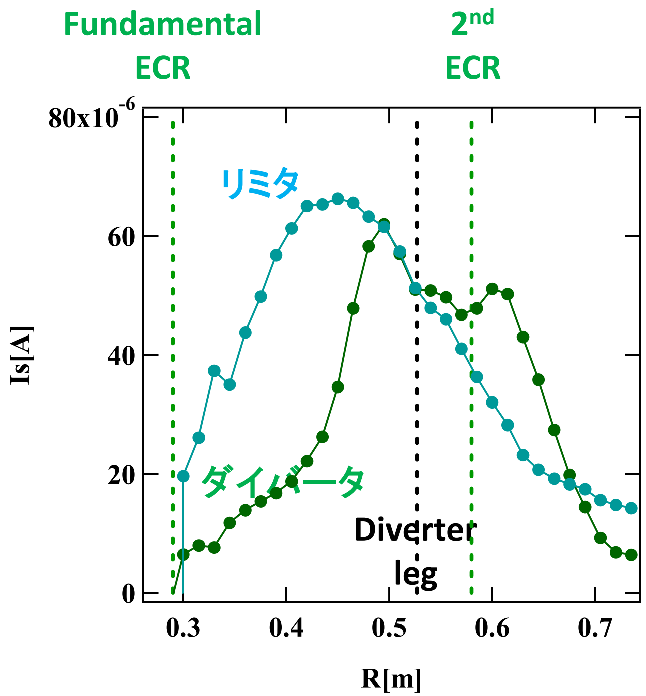
Strategy of Japanese ST Research

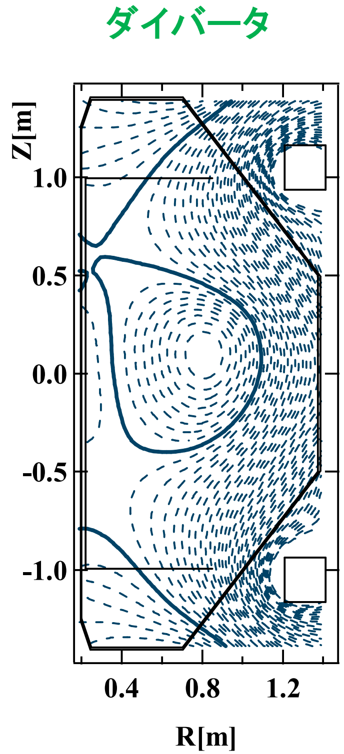


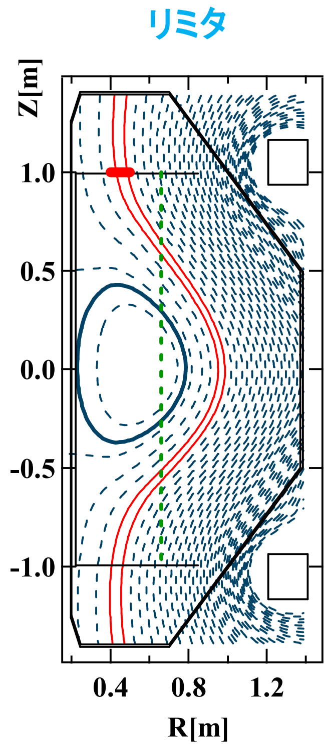
- QUEST is the main device for the research of steady state operation in this framework.

リミタ放電とダイバータ放電とでの違い

TF current : 26.6kA



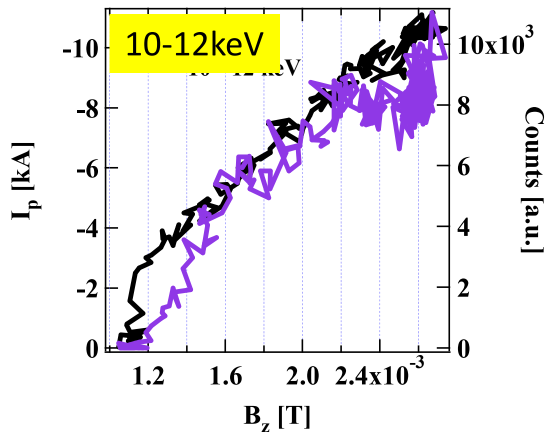


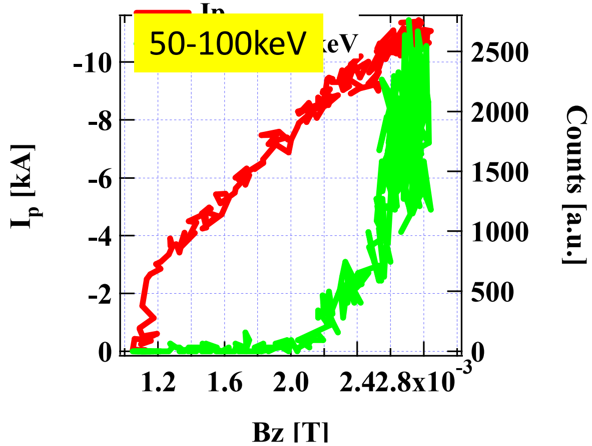


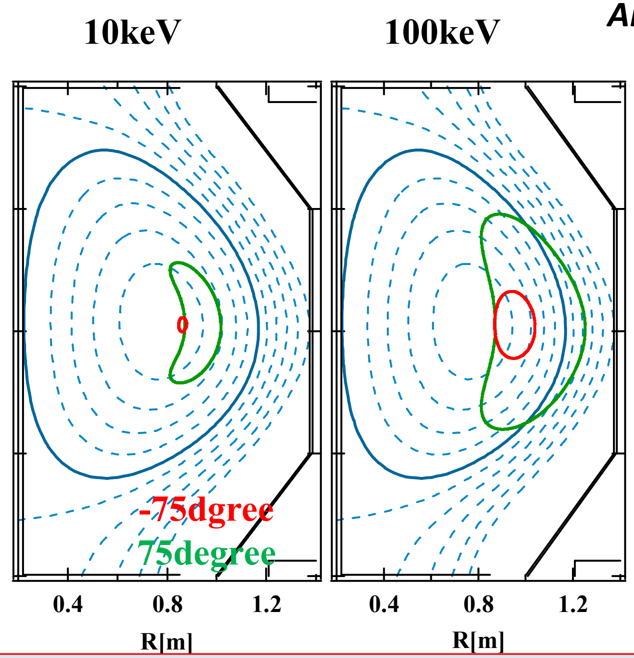
RF-accelerated electrons can drive plasma current

QUEST

AFRC

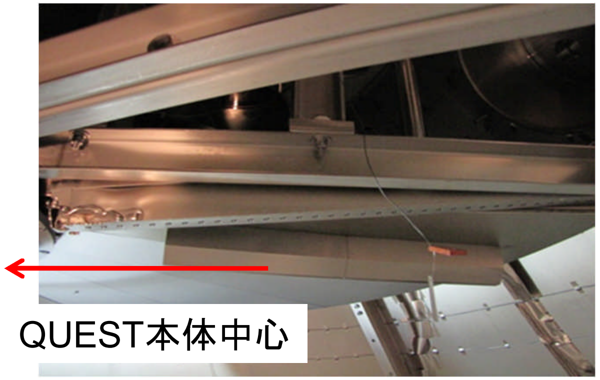


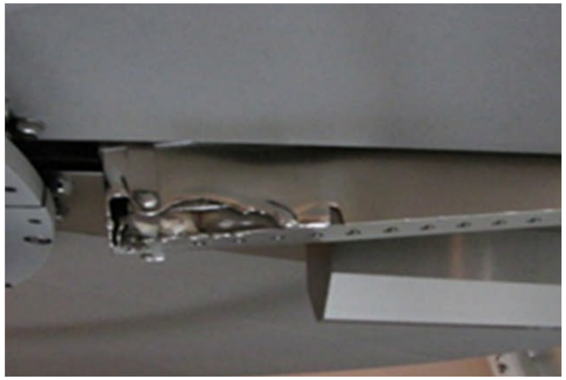


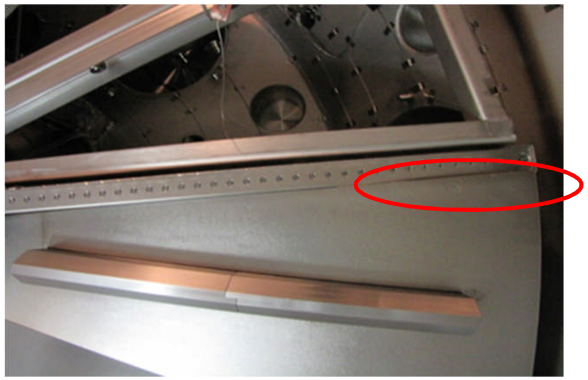


Strong asymmetry of energetic electrons makes net plasma current.

ダイバータプローブ破損状況

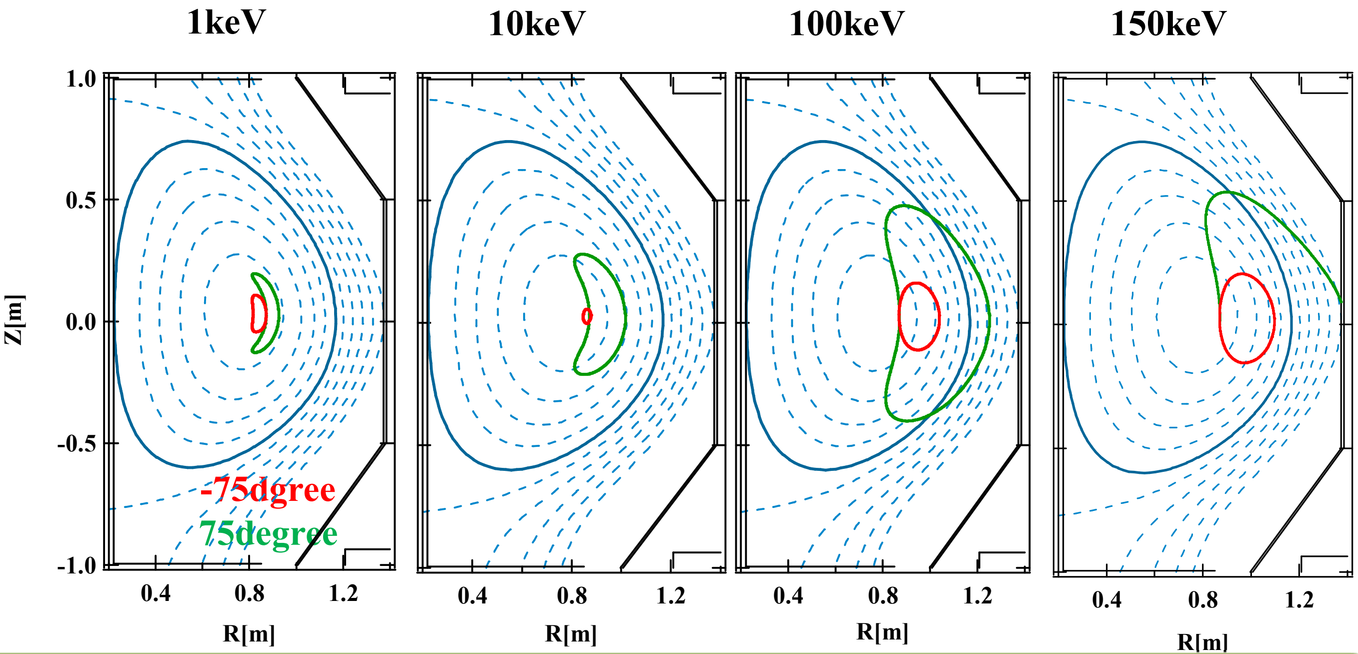






Asymmetric elec. orbit can drive the current in CFS

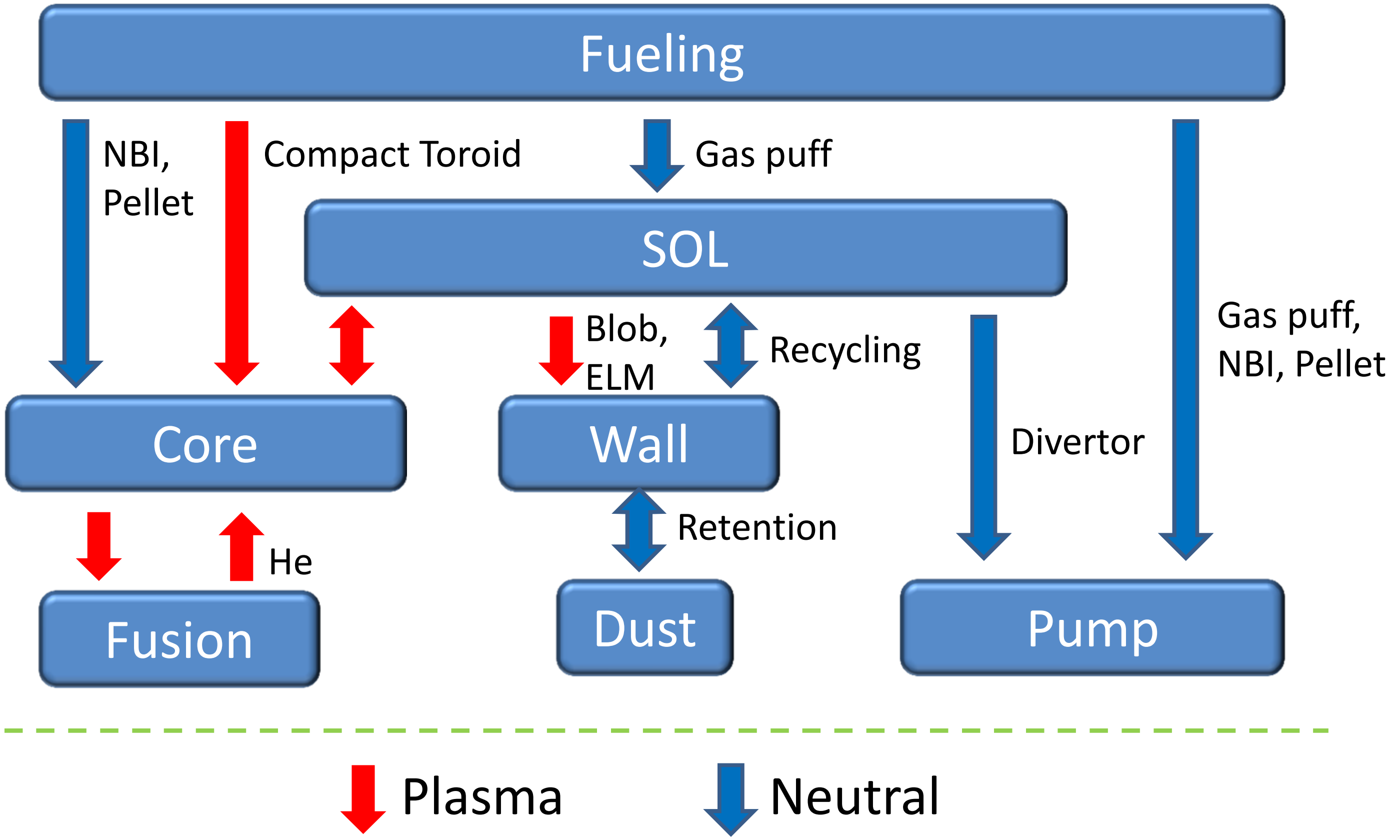
QUEST
AFRC



- A part of high energy elec. may directly attack to the outer wall.
- The asymmetric elec. orbit can drive the current in closed flux surface (CFS) spontaneously.

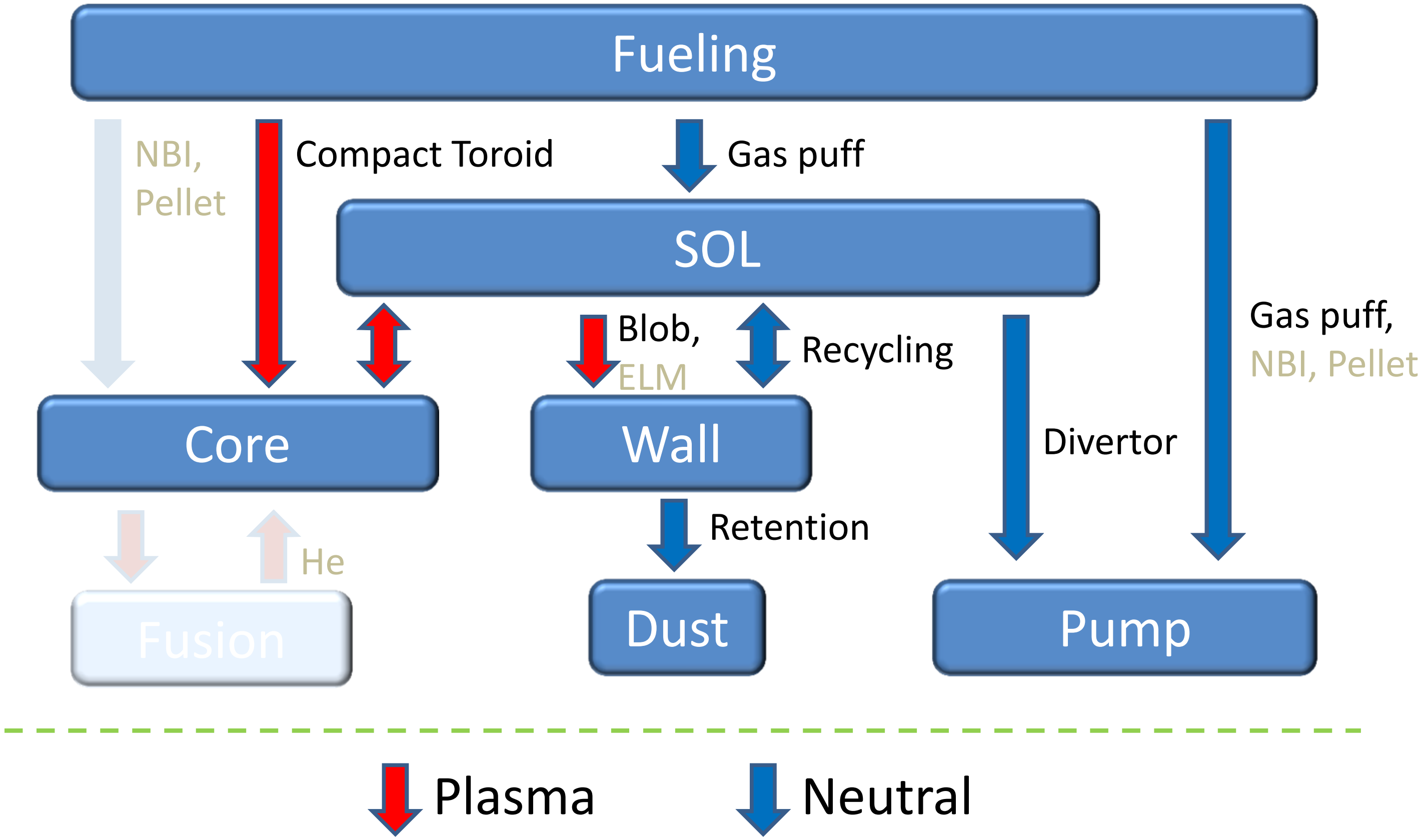
Particle Balance

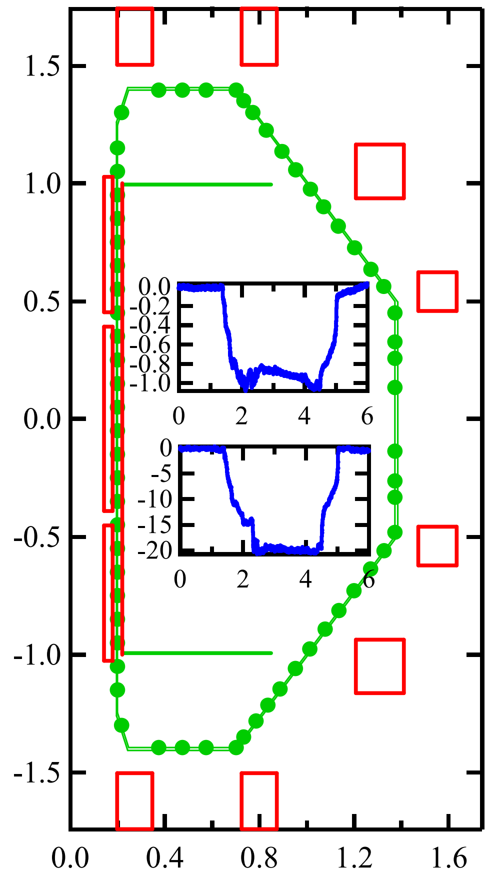
What kinds of processes are working?



Particle Balance in QUEST

Most of processes are common in various devices.

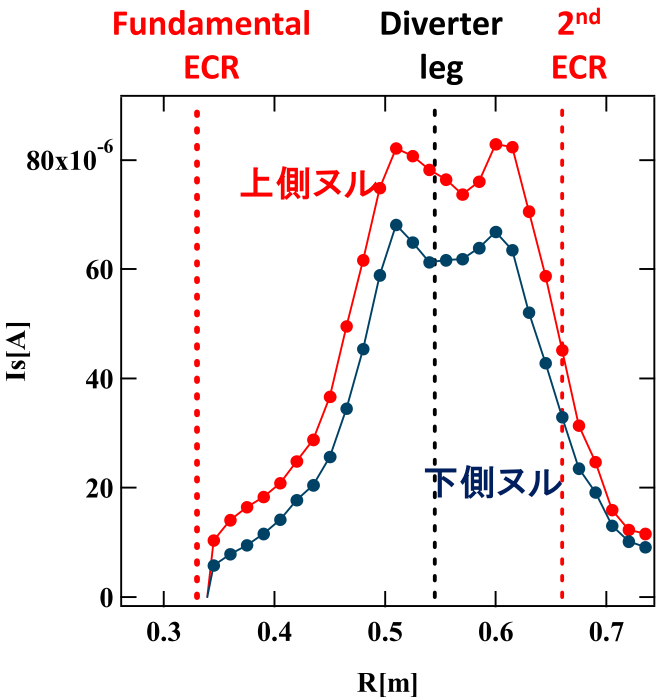


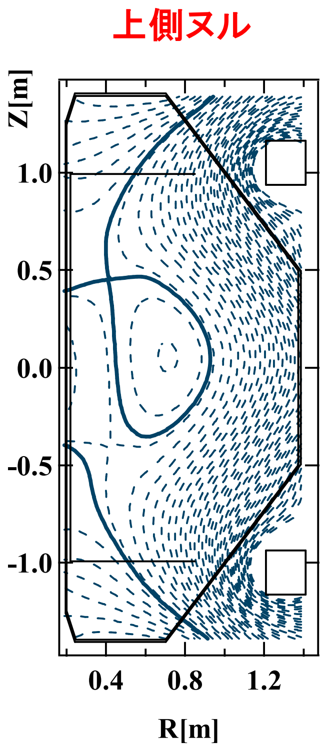


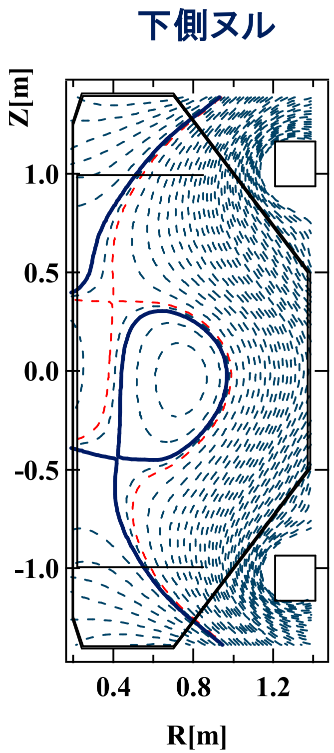
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
0.0
0.4
0.8
1.2
1.6
0.0
-0.2
-0.4
-0.6
-0.8
-1.0
0
2
4
6
0
-5
-10
-15
-20
0
2
4
6

上側ヌルと下側ヌルとでの違い

TF current : 30kA

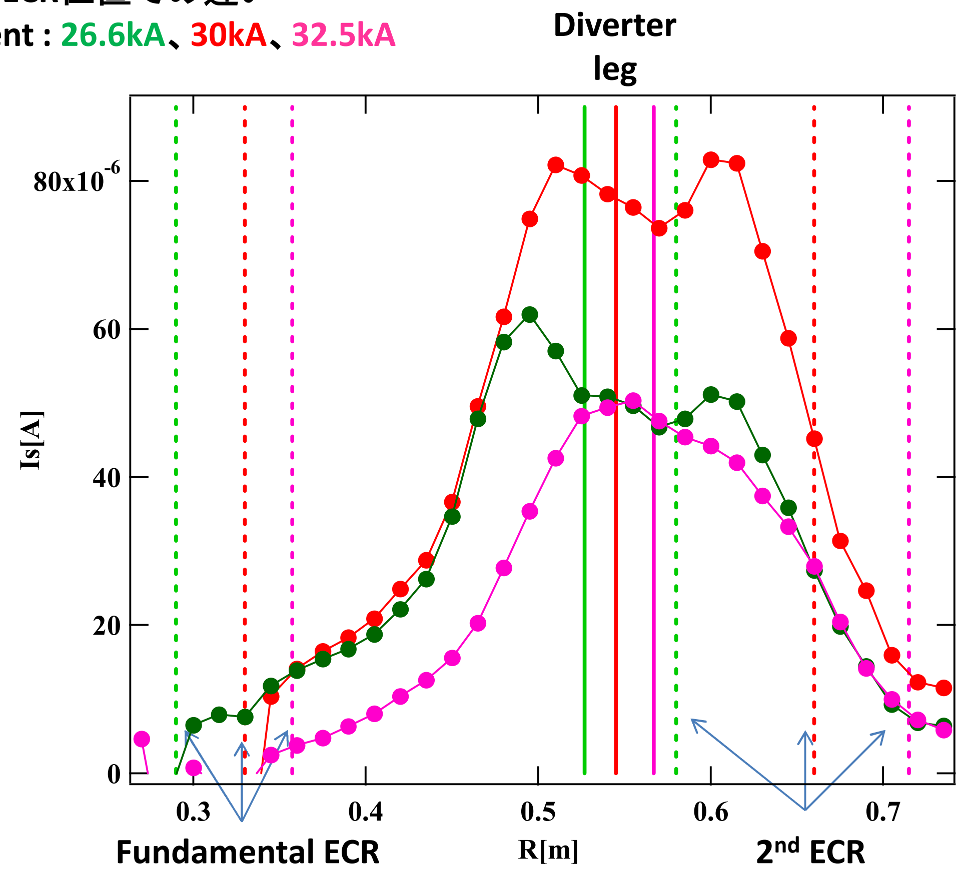


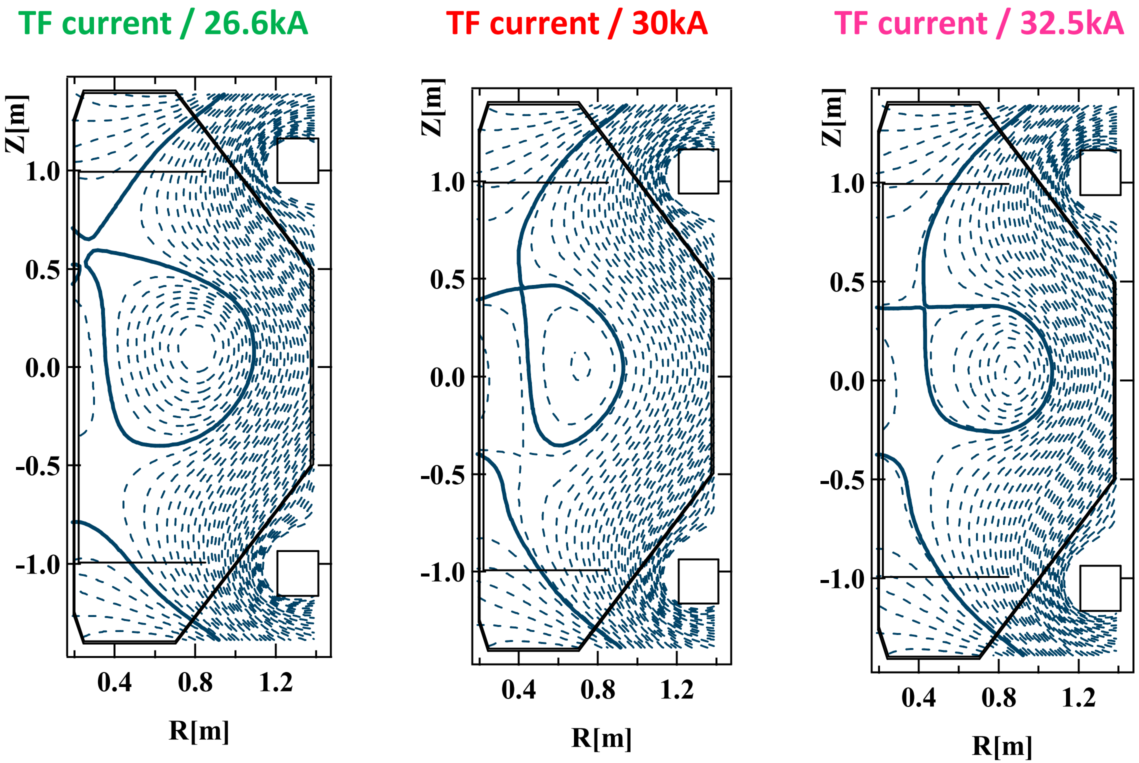




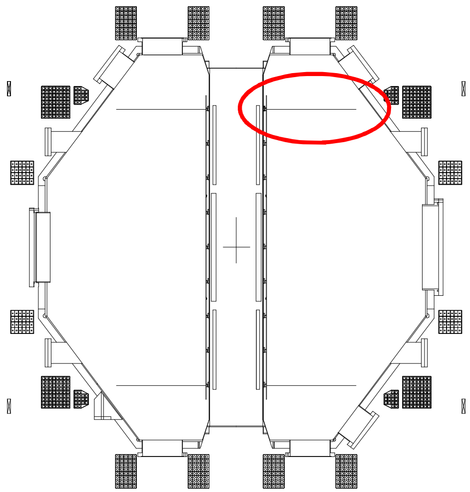
ECR位置での違い

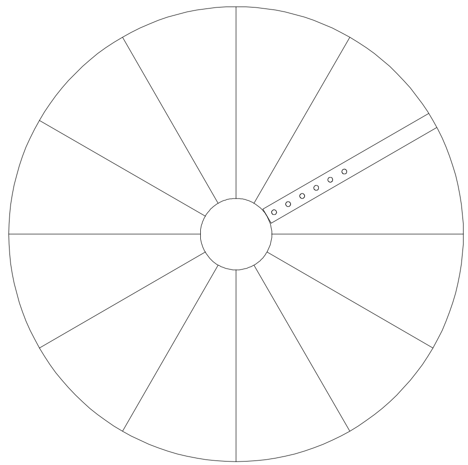
TF current : 26.6kA、30kA、32.5kA




TF current / 26.6kA
TF current / 30kA
TF current / 32.5kA
Z[m]
1.0
0.5
0.0
-0.5
-1.0
0.4
0.8
1.2
R[m]

ダイバータプローブ計測結果



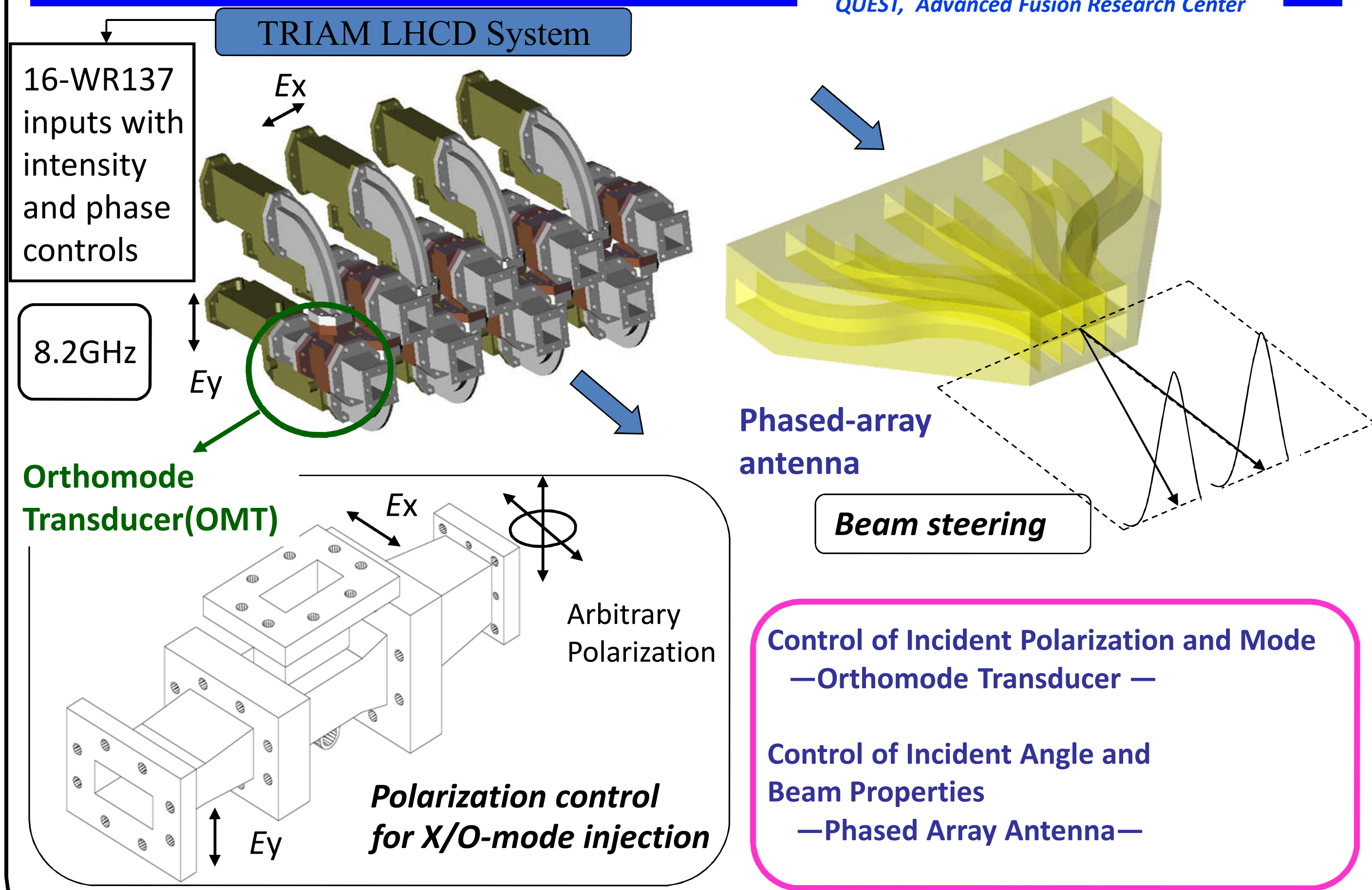


上側ダイバータ位置に、R方向にプローブアレイを設置（R=270mmから15mmおきに35チャンネル）。イオン飽和電流計測を行った。

•リミタ配位の場合とダイバータ配位の場合との違い
•（ダイバータ配位の場合）上側ヌルと下側ヌルとでの違い
•ECR位置での違い

New Concept of Phased Array Antenna

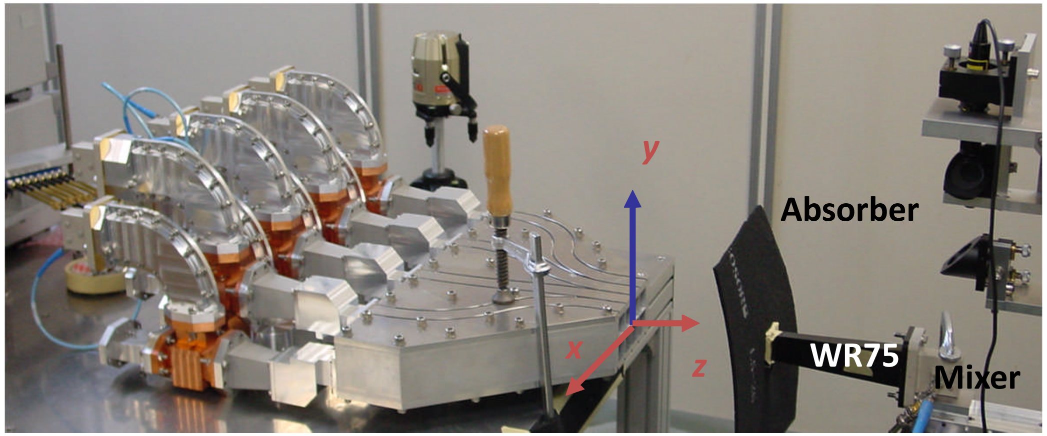
QUEST, Advanced Fusion Research Center

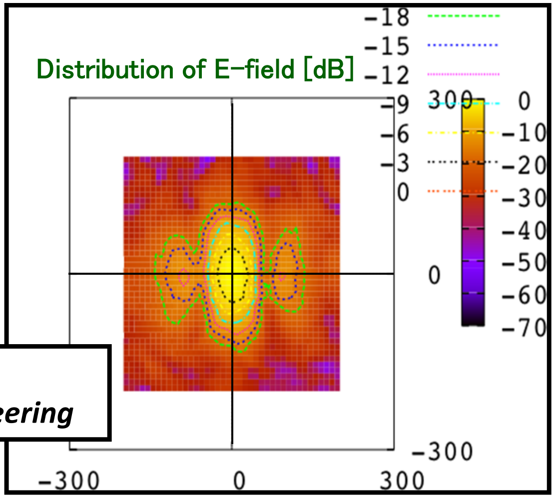


Development of Phased Array Antenna

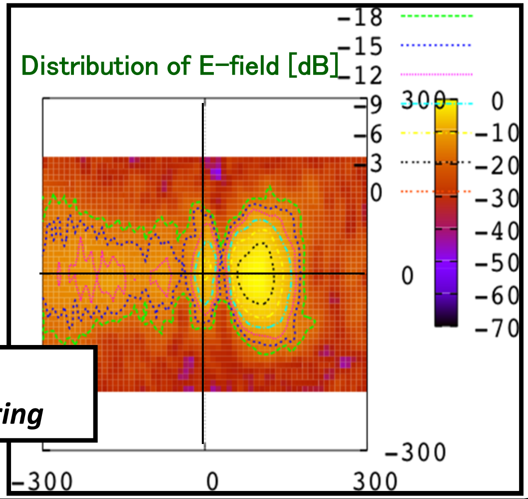
QUEST, Advanced Fusion Research Center

Experiment in
Low Power
Test Device





Ex
w/o steering



Ex
With steering