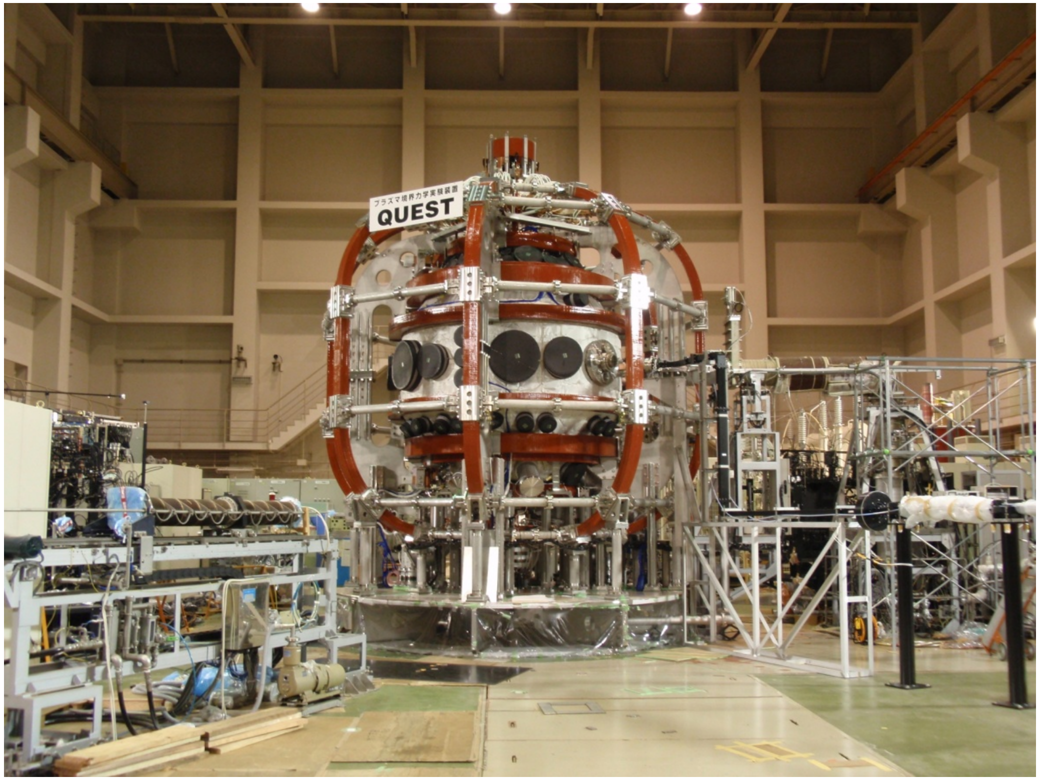
On 10, December 2008
18th International Toki Conference

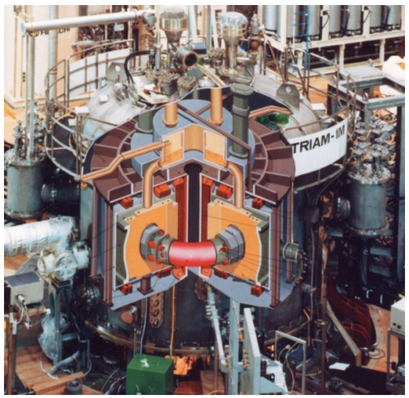
Steady-state operation scenario and the first experimental result on QUEST



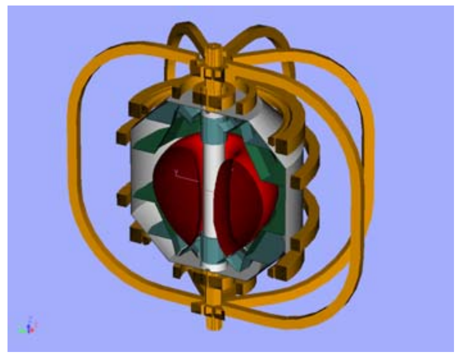
K.Hanada, K.N.Sato, H.Zushi, K.Nakamura, M.Sakamoto, H.Idei, M.Hasegawa, Y.Takase, O.Mitarai, T.Maekawa, Y.Kishimoto, M.Ishiguro, T.Yoshinaga, H.Igami, S.Kawasaki, H.Nakashima, A.Higashijima, Y.Higashizono, A.Ando, N.Asakura, A.Ejiri, Y.Hirooka, A.Ishida, A.Komori, M.Matsukawa, O.Motojima, Y.Ogawa, N.Ohno, Y.Ono, M.Peng, S.Sudo, H.Yamada, N.Yoshida, Z.Yoshida.

Domestic Collaborators and Map of QUEST

TRIAM-1M



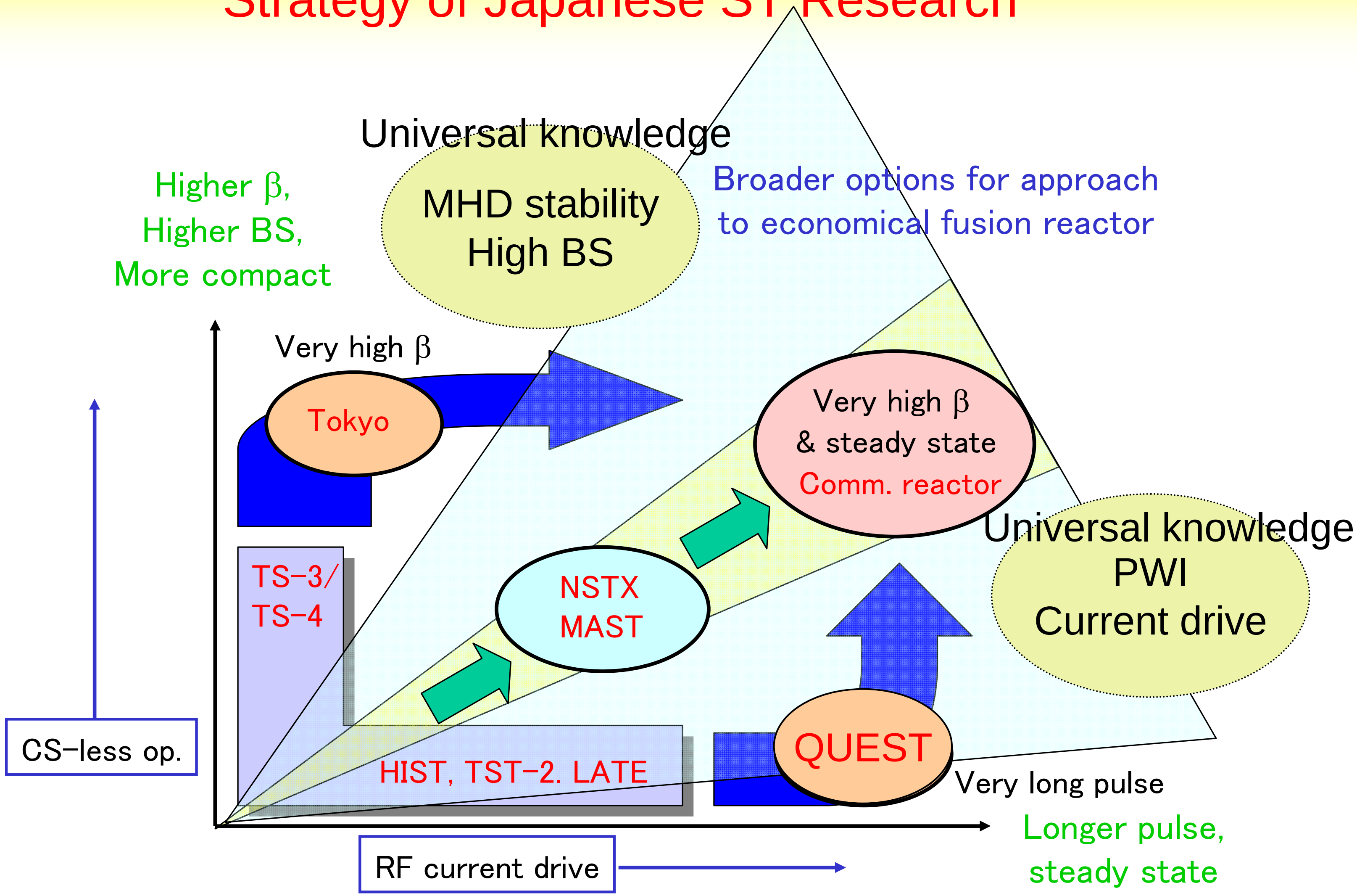
QUEST



Outline

- Purpose of QUEST project
- Plan for PWI research
- Plan for Current drive research
- Plan for Divertor research
- First experimental results

Strategy of Japanese ST Research

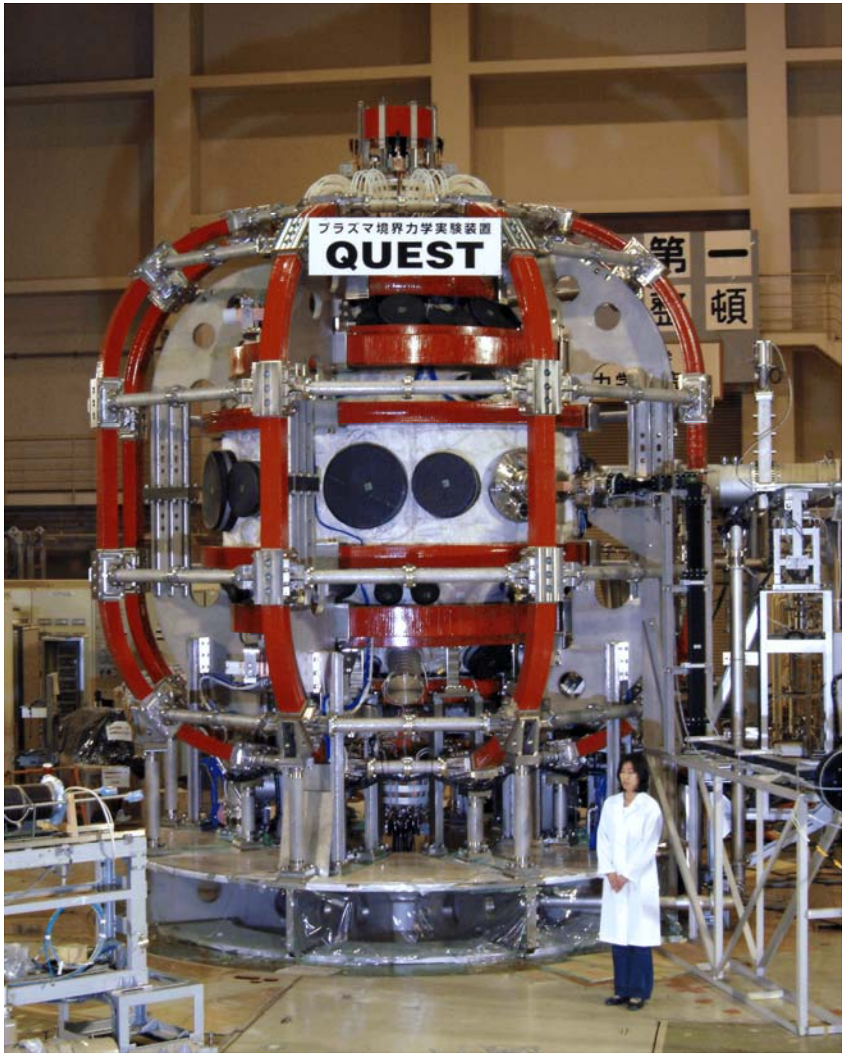


- QUEST is the main device for the research of steady state operation in this framework.

Mission of QUEST

- The mission of QUEST should be to develop the scientific basis for achieving a steady state condition at sufficiently high beta (~20%), with high confinement and low collisionality, in a longer term program that contains three Phases of R&D.
- The short-term goal of QUEST for Phase I (the first 2years) is to establish the basis for sustained operation at low density (~4x10^{18} m^{-3}) and low current (20-30 kA).
- In Phase II (5 years) , progress towards higher current (~100 kA) in steady-state, and towards higher beta (~10%) in the pulsed operation will be pursued with an upgraded heating system.
- The goal of Phase III research is to achieve steady state operation of ST at sufficiently high beta (~ 20 %) .

Specification and parameters



	Phase I	Phase II		Final aim
		SSO	Pulse	
R(m)	0.68			
a(m)	0.4			
A	1.78			
Radius of VV(m)	1.4			
Height of VV(m)	2.8			
BT(T)	0.25	0.25	0.5	0.25
IP(MA)	0.02−0.03	0.1	0.3	0.5
Pinj(MW)	0.45	1	3	3
k	2.5	2.5	2.5	2.5
d	0.7	0.7	0.7	0.7
<ne20>(m−3)	−	0.04	0.3	0.3
<Te>(keV)	−	0.32	0.33	0.54
<Ti>(keV)	−	0.32	0.33	0.54
τ_E(ms)	−	2.5	6.8	10.8
β(%)	−	1.6	13	21
β_N	−	1.5	3.9	3.8
β_p	−	0.33	0.29	0.17
q95	−	25	8.2	5
Γ_H (MW/m2)	−	6.5	10.1	13.6
F_{rad}(%)		20	40	40
Γ_P (Pa m3/s)	−	17.5	50	31.1
f_{GW}	−	0.16	0.41	0.24
I_{BS}(MA)	−	0.008	0.022	0.021
$\eta_{CD}10^{19}$(A/W/m^2)	−	0.026	0.19	0.32

Schedule and Research items

items \ fiscal year	05	06	07	08	09	10	11	12	13	14	further
construction											
High β						>10% (1sec)					20%
Plasma start-up				RF+OH		RF+OH+NBI					
Current drive				RF		RF(8.2GHz)+NBI					16GHz
PWI				W		W, high Temp. wall					Control of Recycling
Divertor				open			closed				advanced
fueling				Gas puff		CT injection					pellet

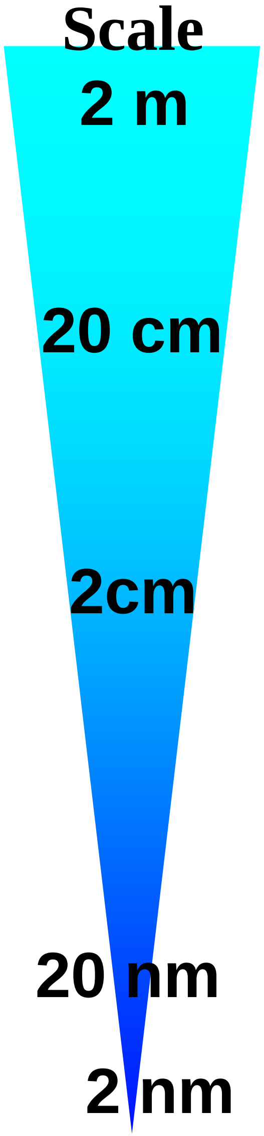
We are here.

Schedule and Research items

fiscal year / items	05	06	07	08	09	10	11	12	13	14	further
construction											
High β						>10% (1sec)					20%
Plasma start-up				RF+OH		RF+OH+NBI					
Current drive				RF		RF(8.2GHz)+NBI					16GHz
PWI				W		W, high Temp. wall					Control of Recycling
Divertor				open			closed				advanced
fueling				Gas puff		CT injection					pellet

We are here.

Multi-Scale of Plasma-Wall Interaction



Global particle balance

Transport of neutral particle

Transport of impurity

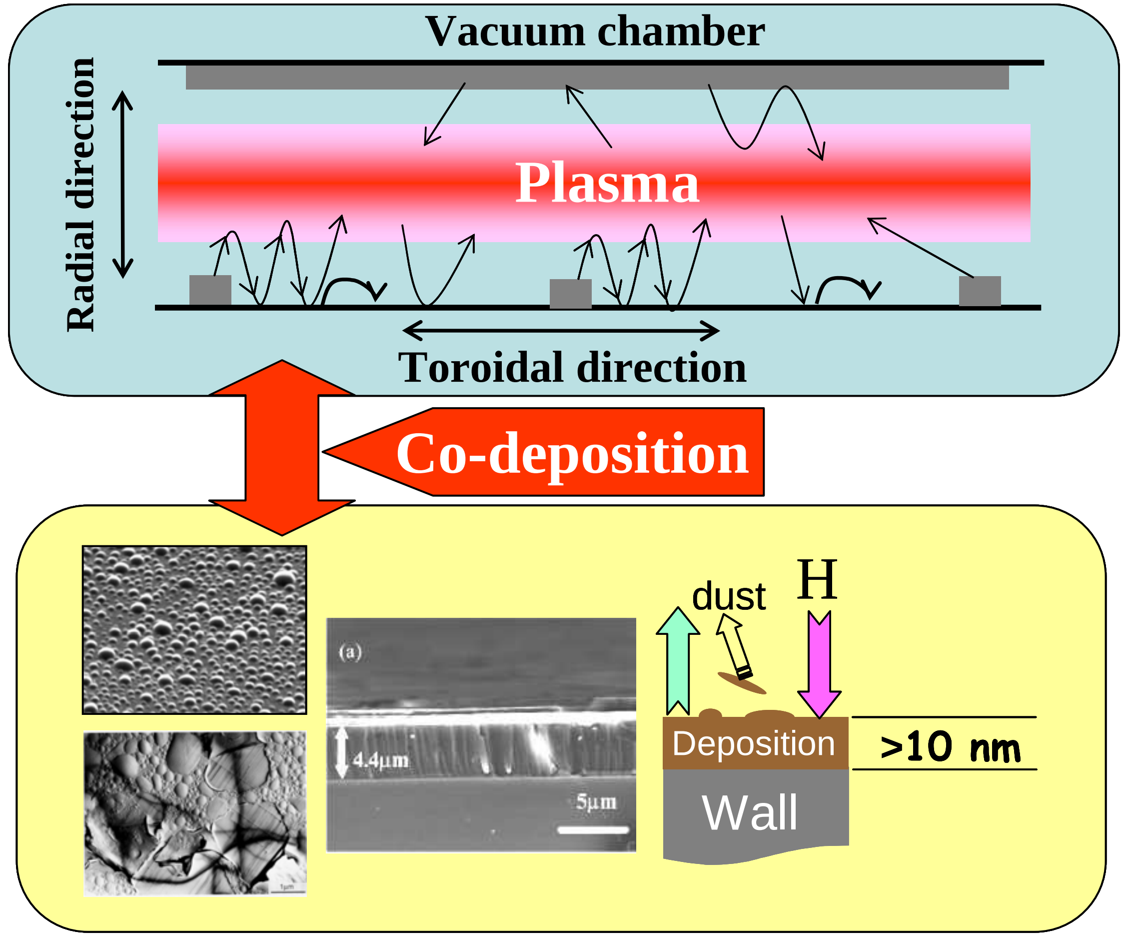
Re-deposition

Local recycling

Local heat load

Dust particles

Structure of deposit
Hydrogen absorption
Sputtering
Radiation damage

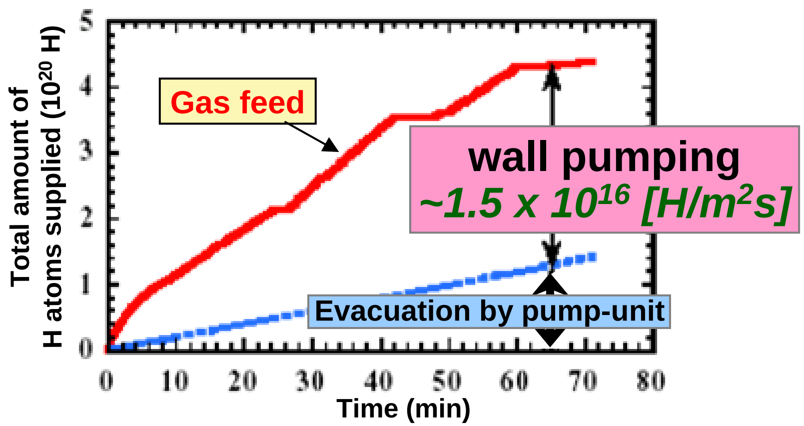


What is the main issue for steady-state ?

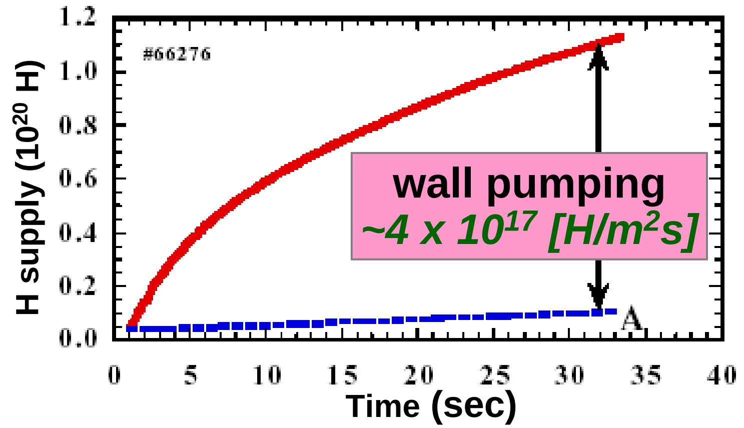
Wall pumping in long pulse operation

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

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



High density (n_e~10^{19})

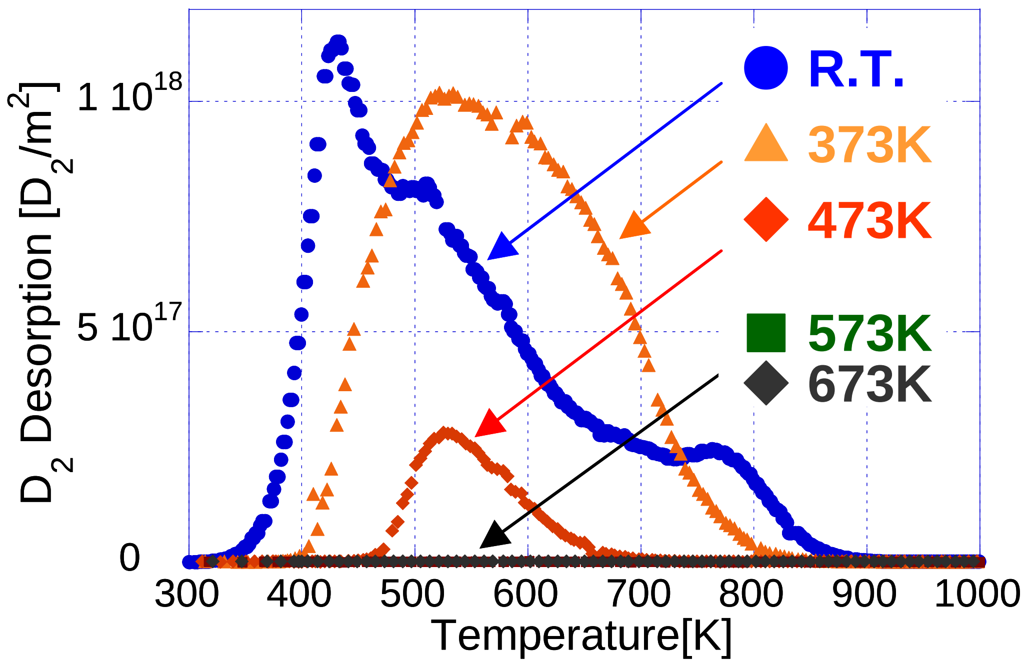


Time evolution of the total amount of gas feed and evacuation to the external pumping.

- 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.

How to resolve

The wall pumping should be controlled. It is difficult to control the co-deposition process on the wall, therefore R=1 is the unique solution.



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.

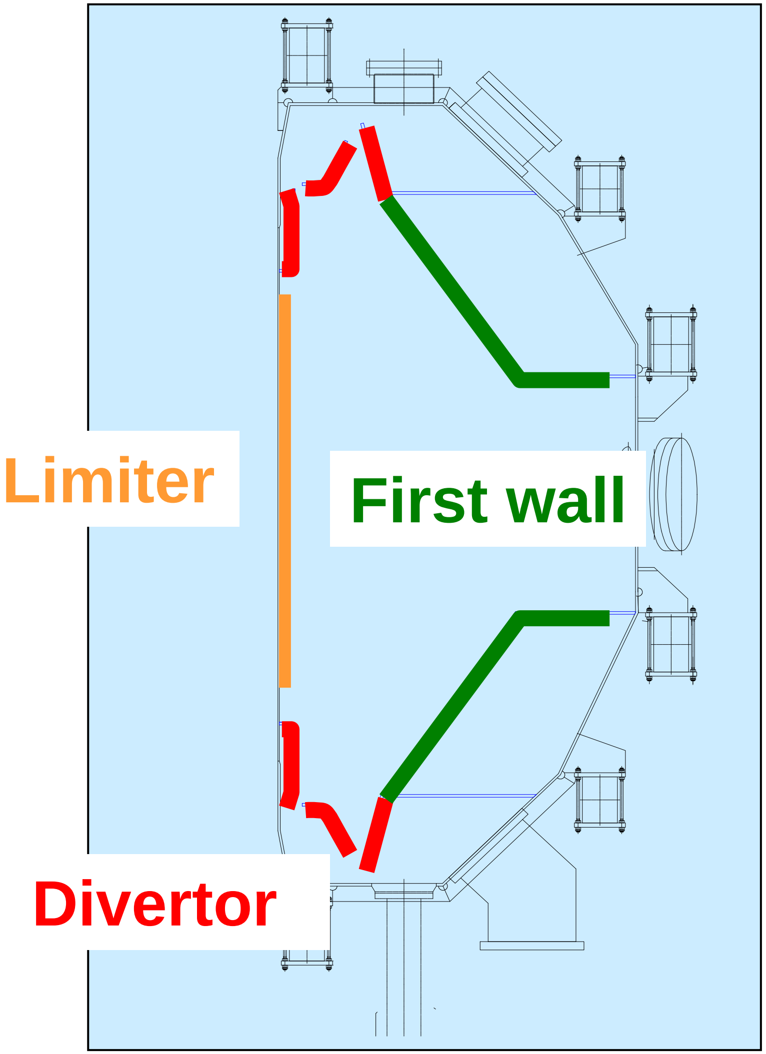
Proposed particle control in steady state

- Wall works sometimes as particle sink and sometimes as source.
- Wall pumping rate is comparable to pumping rate of external pumps.
- It is difficult to control wall pumping rate, because the effect of co-deposition is crucial.

- Recycling rate will become to unity under metal high temp. wall .

- It is necessary to investigate it in real-operated plasma confinement device.

Plan for high temp. wall and divertor



V.V. : SUS316L (~ 150℃)

First wall : W (300~500℃)

Divertor : W (400~500℃)

Limiter : SUS316L coated by

W (300℃)

Schedule and Research items

items \ fiscal year	05	06	07	08	09	10	11	12	13	14	further
construction											
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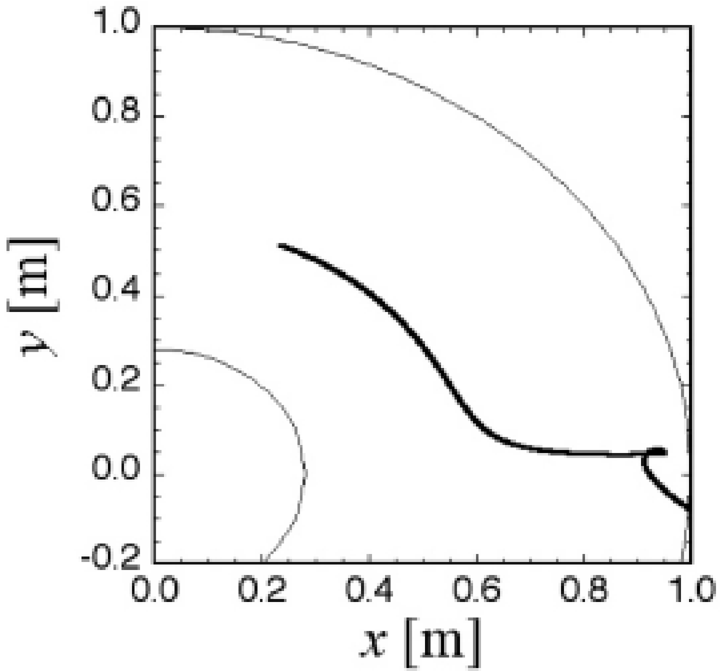
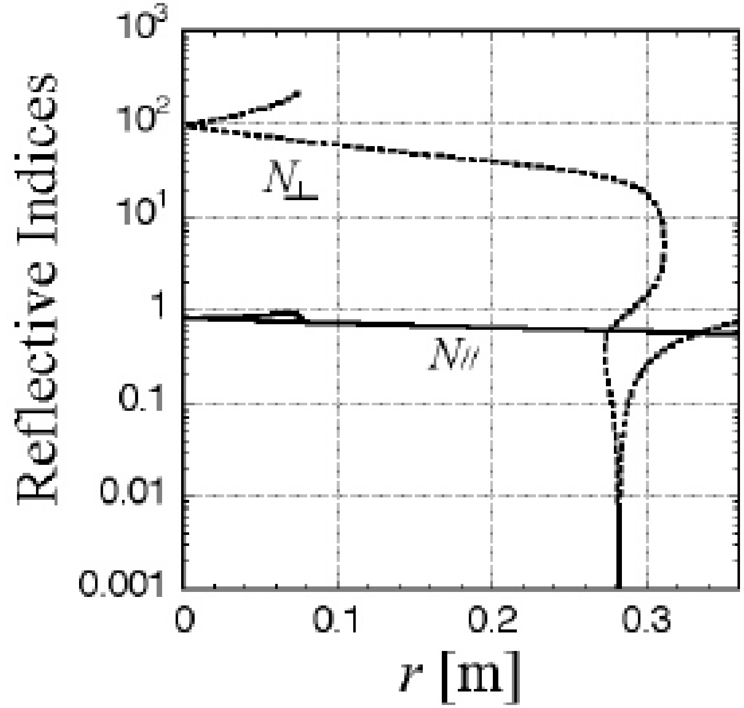
Current drive				RF		RF(8.2GHz)+NBI					16GHz
PWI				W		W, high Temp. wall					Control of Recycling
Divertor				open			closed				advanced
fueling				Gas puff		CT injection					pellet

We are here.

How to obtain steady state plasma
Ray Trace for EBCD

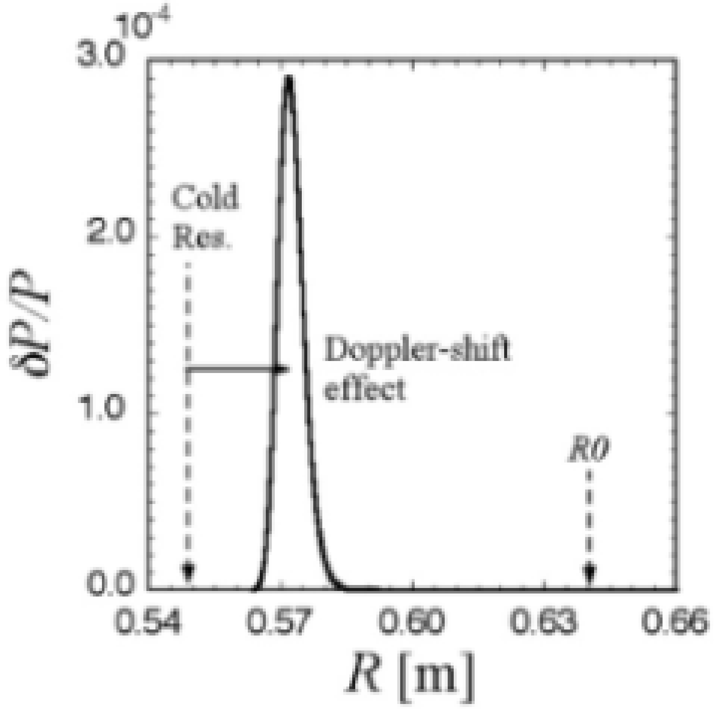


Wave trajectory at the toroidal cross section in the O-X-B conversion scenario at the QUEST.

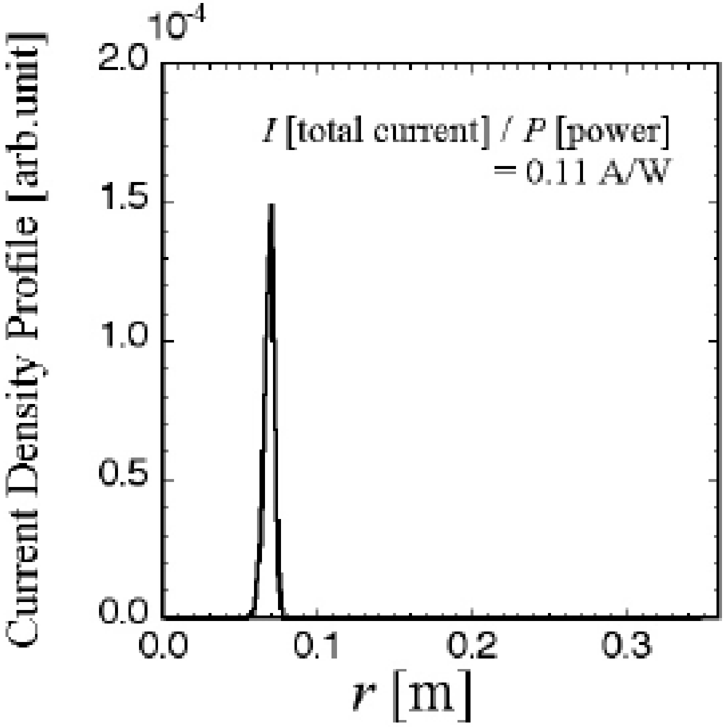


Evolutions of refractive indices *N⊥ and N// in perpendicular* and parallel to the magnetic field along the propagation.

Calculation of capability of current drive by use of TASK/FP



Power deposition profile in the *O-X-B conversion scenario*.

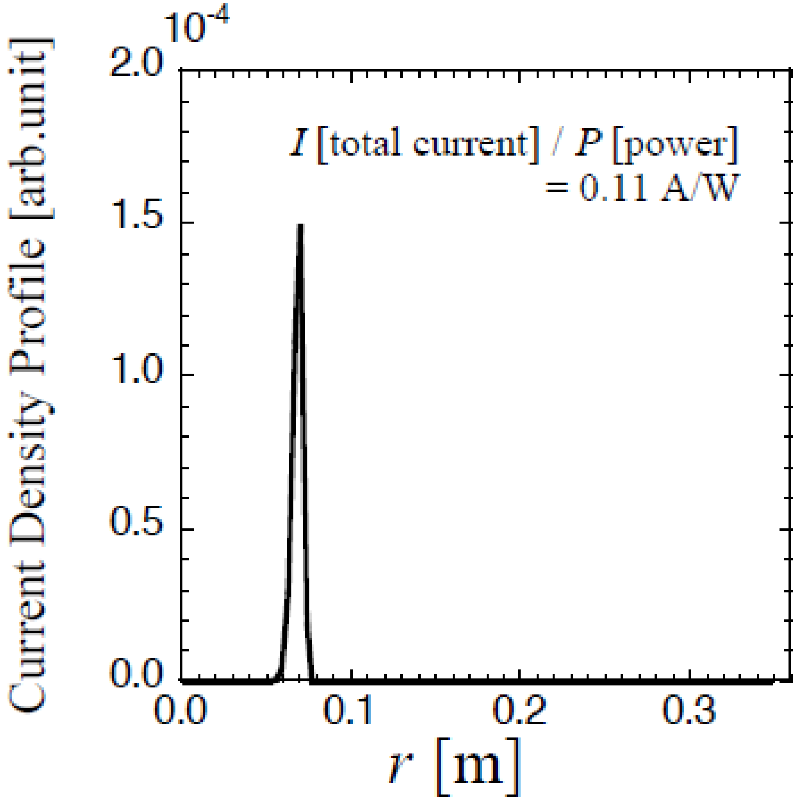


Current profile driven in the *O-X-B conversion scenario*.

$I_p/P=0.11$ A/W is obtained in 100eV, $0.4\times10^{19}m^{-3}$.

H. Idei *et al.* Proc. 32nd International Conf. on Infrared and Millimetre Waves, 2007.

Capability of EBCD on QUEST



EBCD in W-AS

[H. P. Laqua *et al*. Phys. Rev. Lett. **90**, 075003 (2003)] O-X-B from LHS,
n_e=10.5 x $10^{19}m^{-3}$, B_t=2.15T, f=70 GHz,
T_e = 0.8keV, I_{CD}=2 kA
Dimensionless CD efficiency :
$\boldsymbol{\eta = 33\, n_{20}\, I_A\, R_m / P(\mathrm{W}) / T_e(\mathrm{keV}) \sim 0.43}$

EBCD in QUEST

O-X-B from LHS,
n_e=0.2 x $10^{18}m^{-3}$, B_t=0.25T, f=8.2 GHz,
T_e = 0.1keV
Dimensionless CD efficiency :
$\boldsymbol{\eta = 33\, n_{20}\, I_A\, R_m / P(\mathrm{W}) / T_e(\mathrm{keV}) \sim 0.46}$

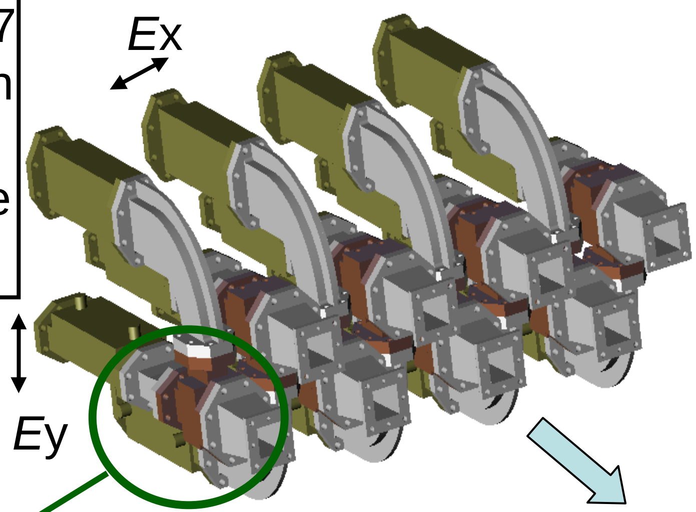
New Concept of Phased Array Antenna

QUEST, Advanced Fusion Research Center

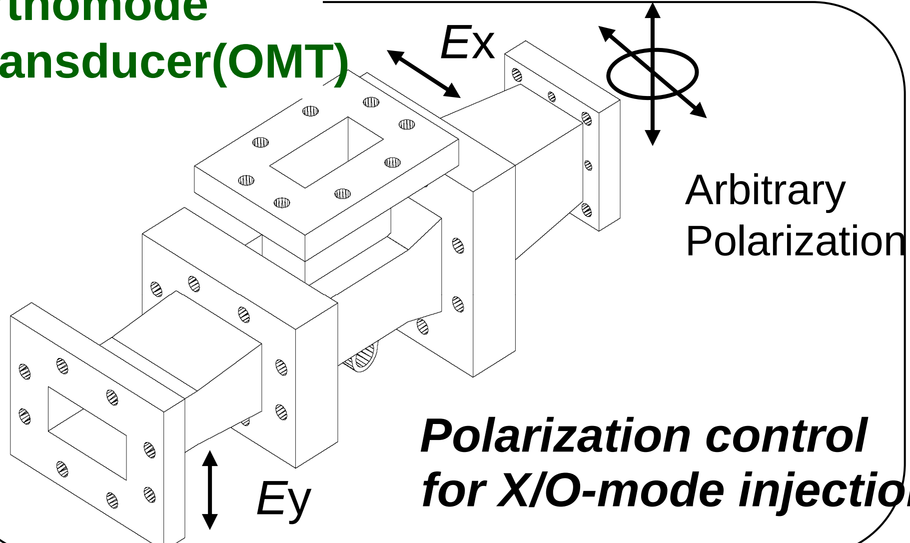
TRIAM LHCD System

16-WR137 inputs with intensity and phase controls

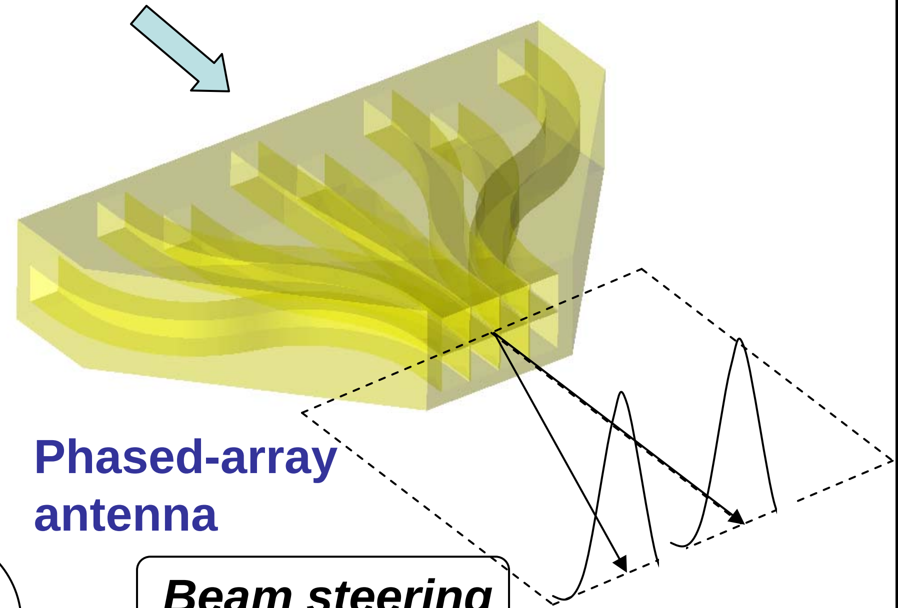
8.2GHz



Orthomode Transducer(OMT)



Polarization control for X/O-mode injection



Phased-array antenna

Beam steering

Control of Incident Polarization and Mode

—Orthomode Transducer —

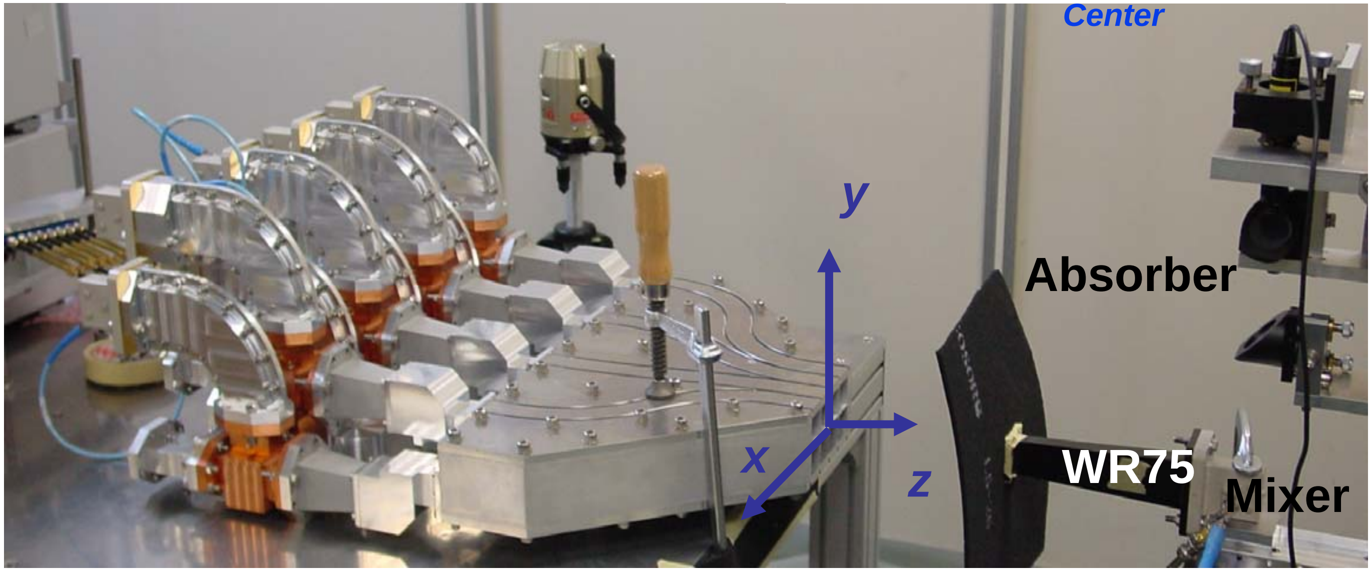
Control of Incident Angle and Beam Properties

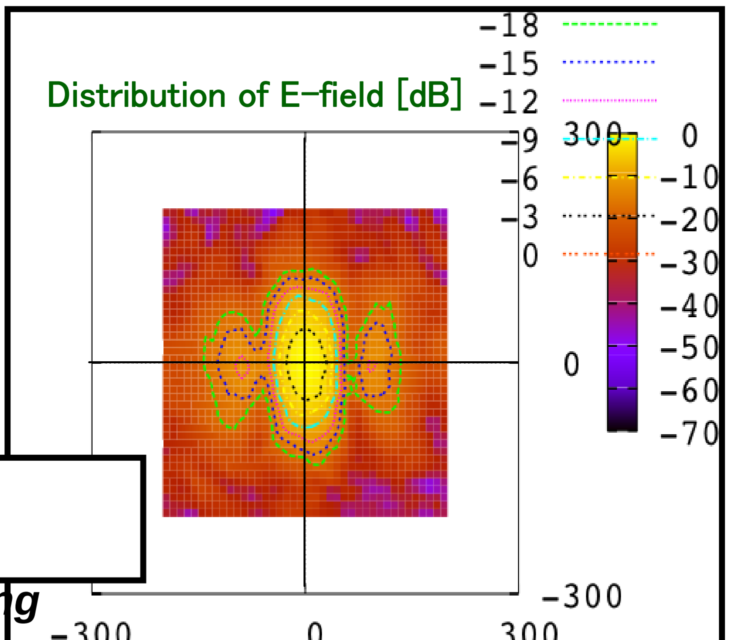
—Phased Array Antenna—

Development of Phased Array Antenna

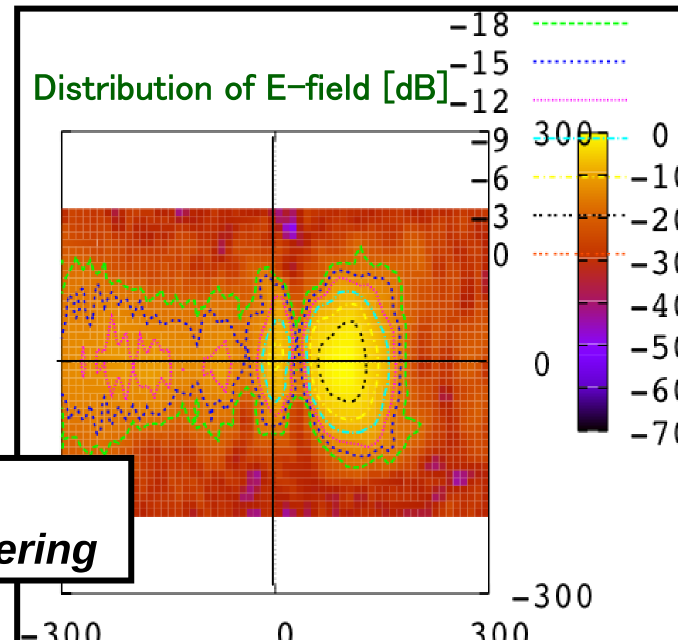
QUEST, Advanced Fusion Research Center

Experiment in Low Power Test Device





Ex w/o steering



Ex With steering

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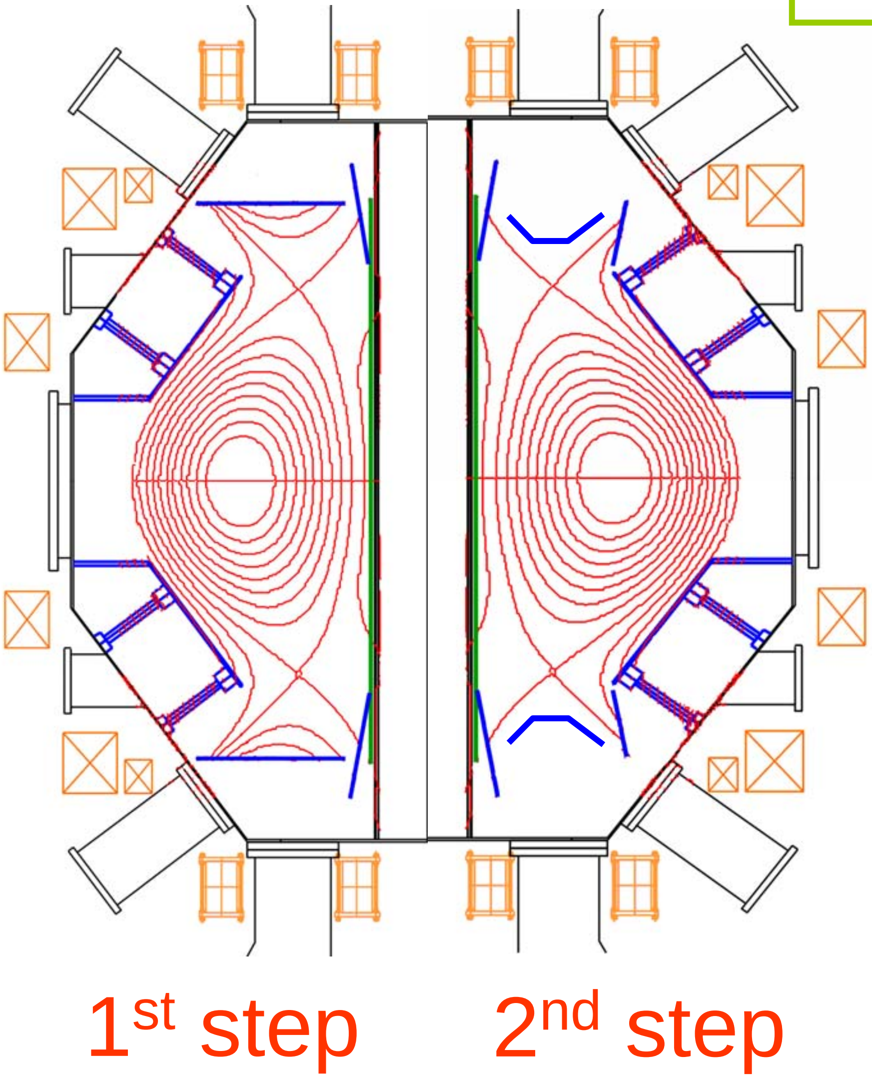
PWI				W		W, high Temp. wall					Control of Recycling
Divertor				open			closed				advanced
fueling				Gas puff		CT injection					pellet

We are here.

Plan for divertor and 1st wall

Vacuum Vessel（SUS316L）150℃



1st Step（2009-10）(300~500 ℃)

Flat Open divertor（W）
High temp. wall

Controllability of Magnetic flux

- Heat and Particle flux
- Diagnostics
- Simulation（SOLDOR）

2nd Step（2011- ）

Closed Divertor（W）
High temp. wall

Controllability of particle flux

- Heat and Particle flux
- Diagnostics
- Simulation（SOLDOR）

Simulation of design of divertor structure

Using SOLDOR/NEUT2D, Investigation of the divertor structure of QUEST has been executed.

Issues for divertor design

Heat handling

Heating of 1MW will be executed on QUEST in steady state and Heating of 3M is planned in pulsed discharge.

Need to estimated heat flux on the divertor plate

Particle handiling

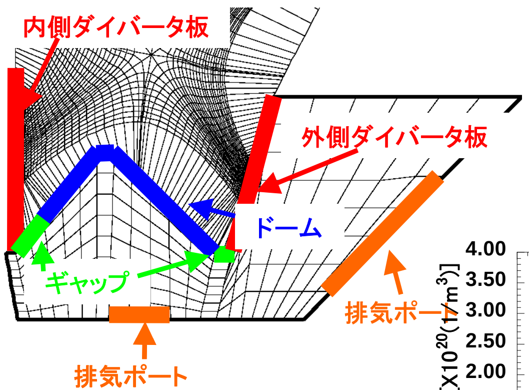
QUEST will be operated on the condition of R=1 due to high temperature wall and it is necessary to evacuate all of particle by pumping.

Need to estimated required particle exhaust

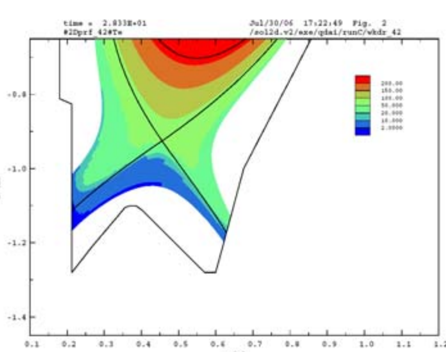
Comparison with experimental data on the flat divertor

An example of the calculation of plasma parameters in divertor

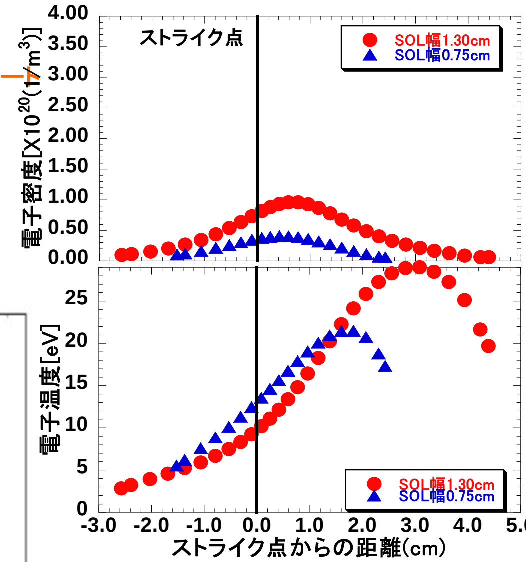
Mesh structure



Temperature distribution



Density and Temperature distribution along outer divertor plate



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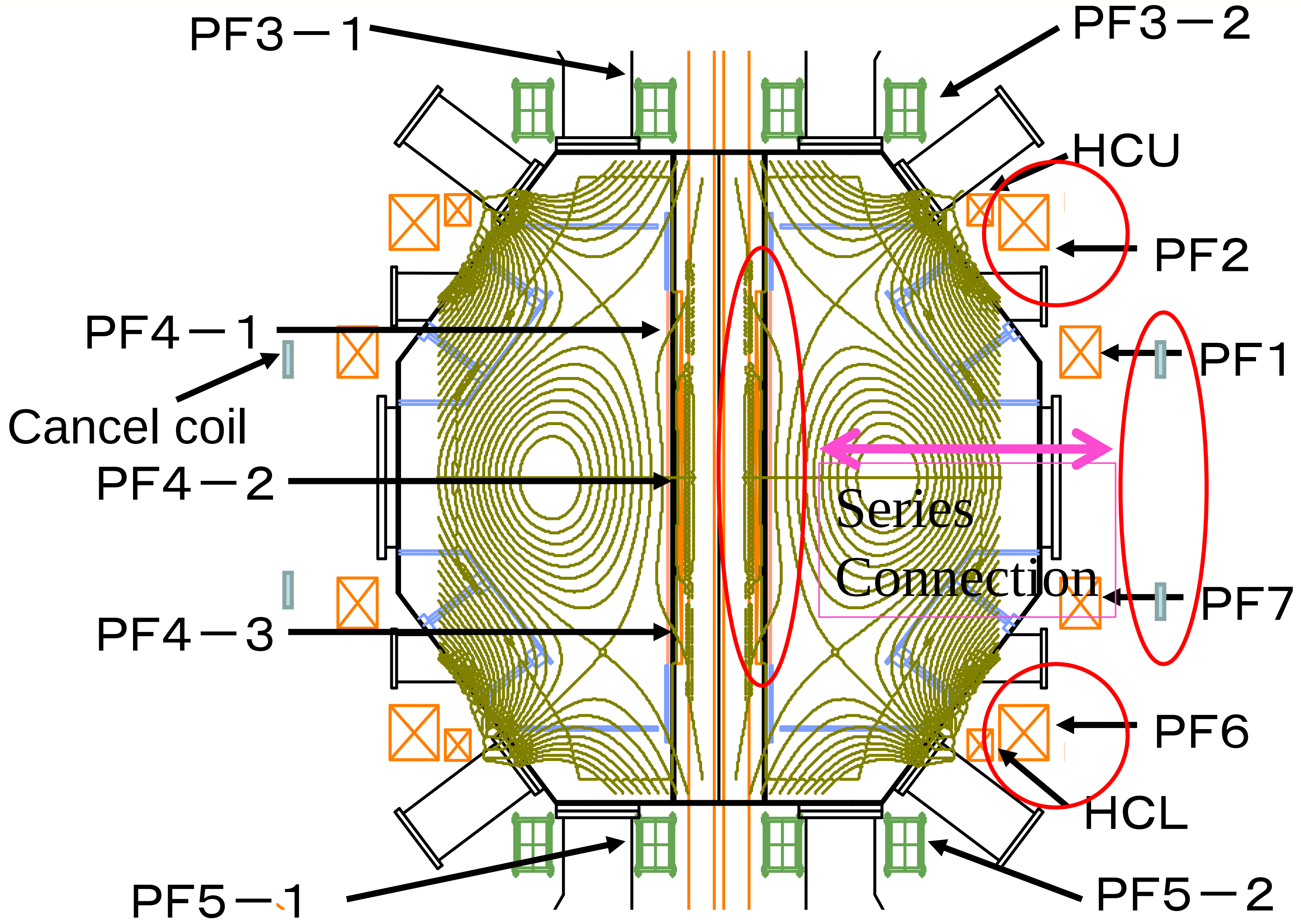
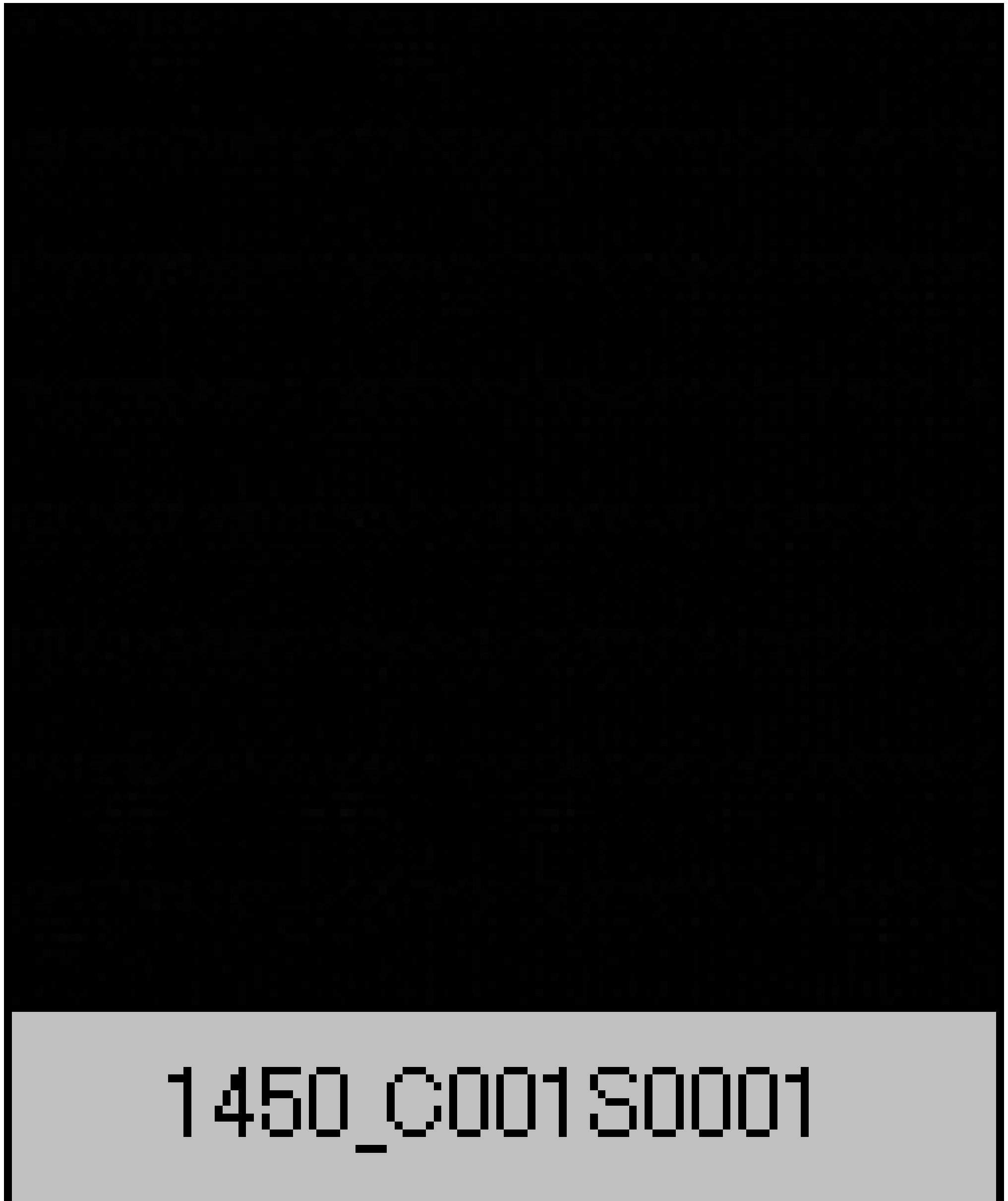
We are here.

PF coils layout and connection

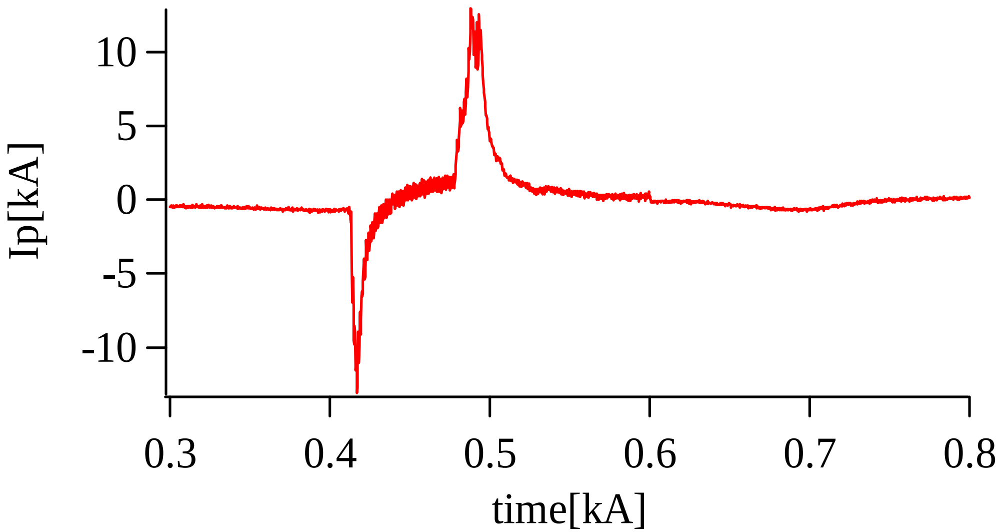


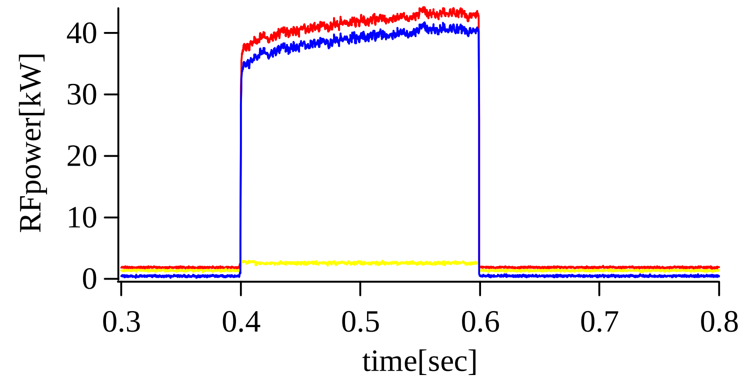
First formation of Tokamak configuration

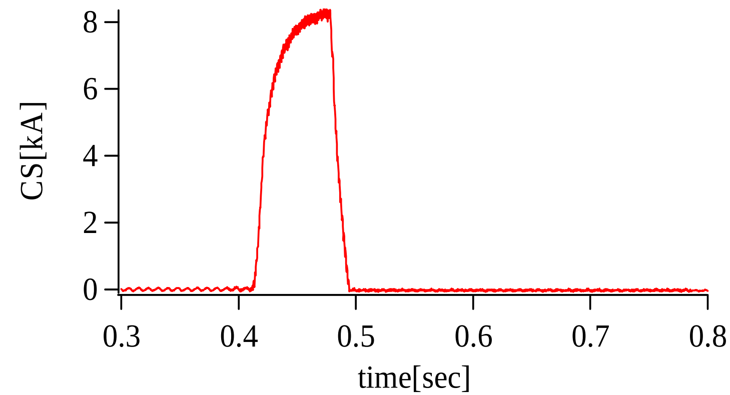


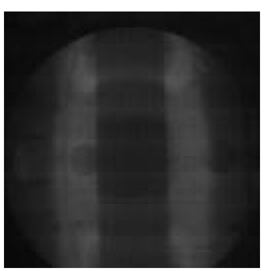
[QUEST] Formation of closed flux surface in OH +RF

#1450









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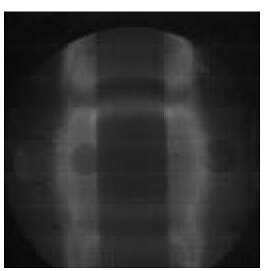

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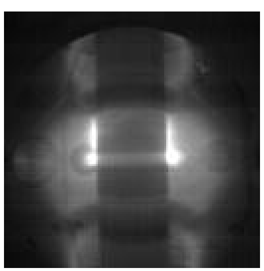

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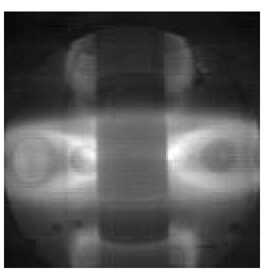

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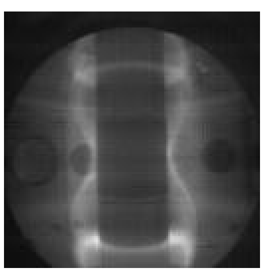

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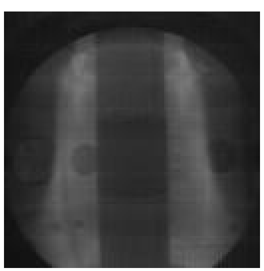

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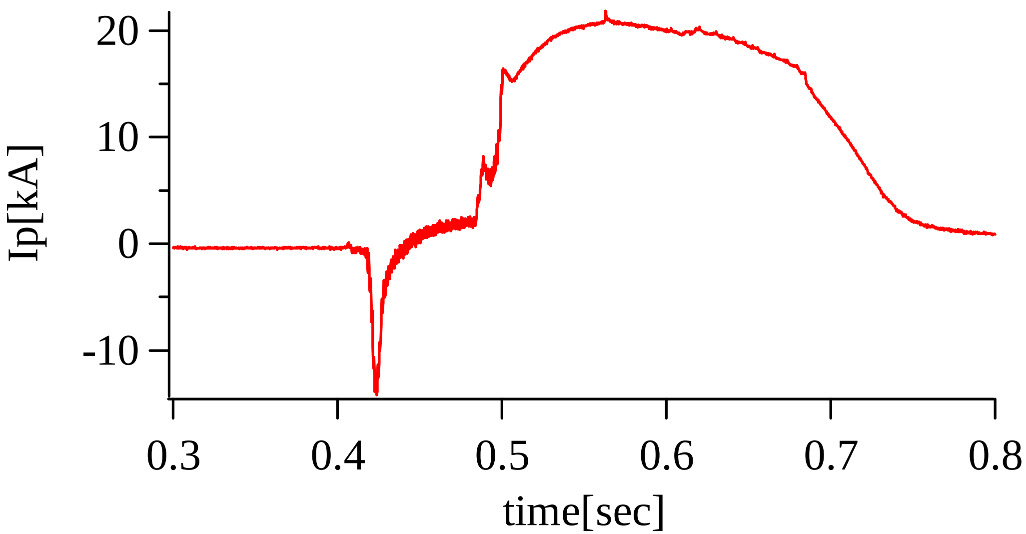
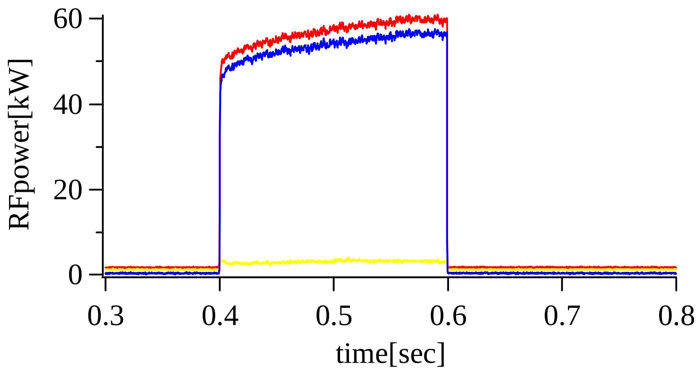
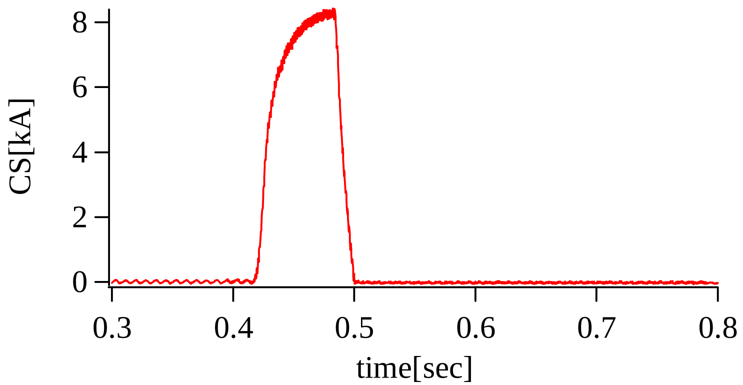
[QUEST]

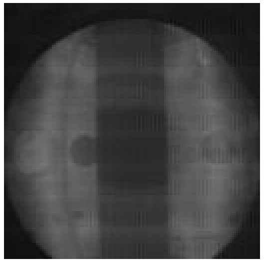
#1456

Formation of closed flux surface in OH +RF









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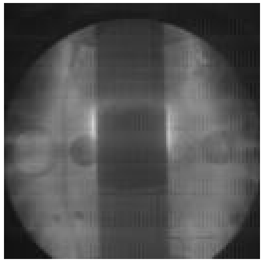

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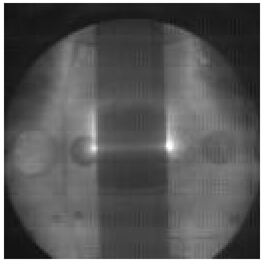

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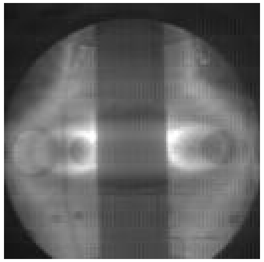

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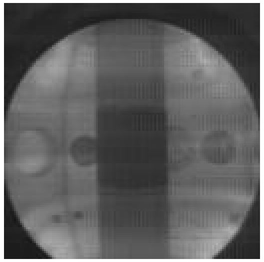
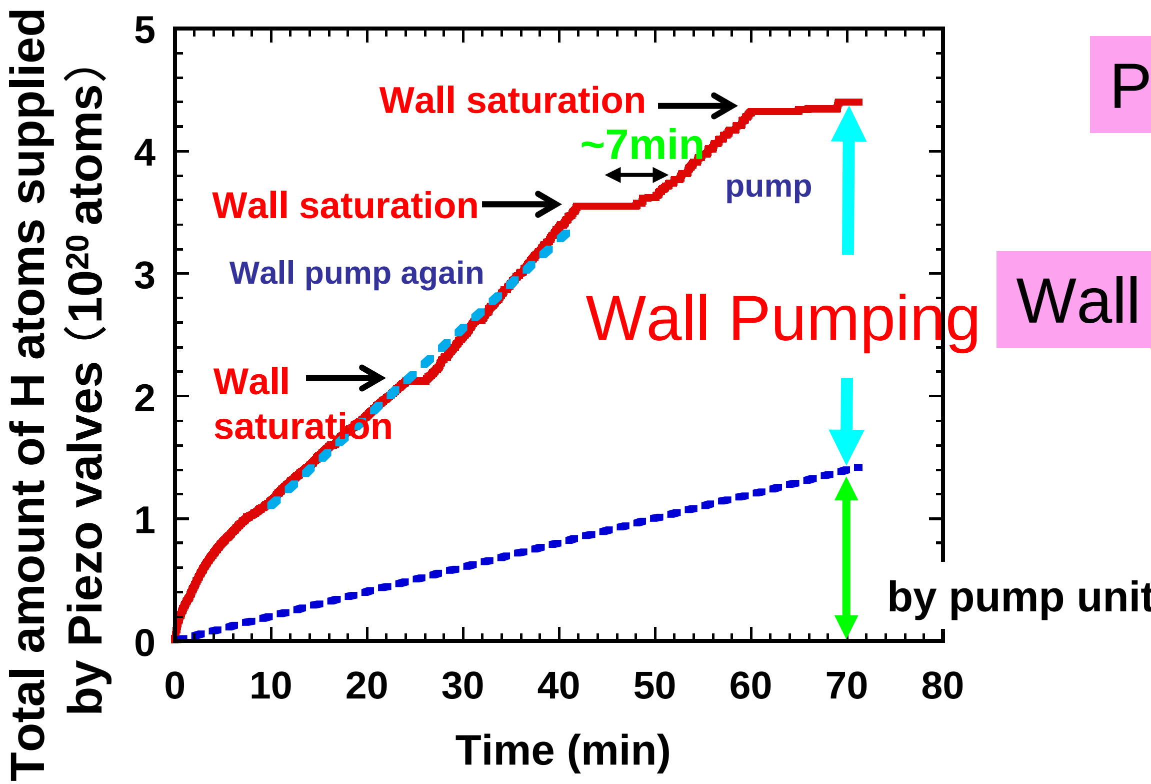


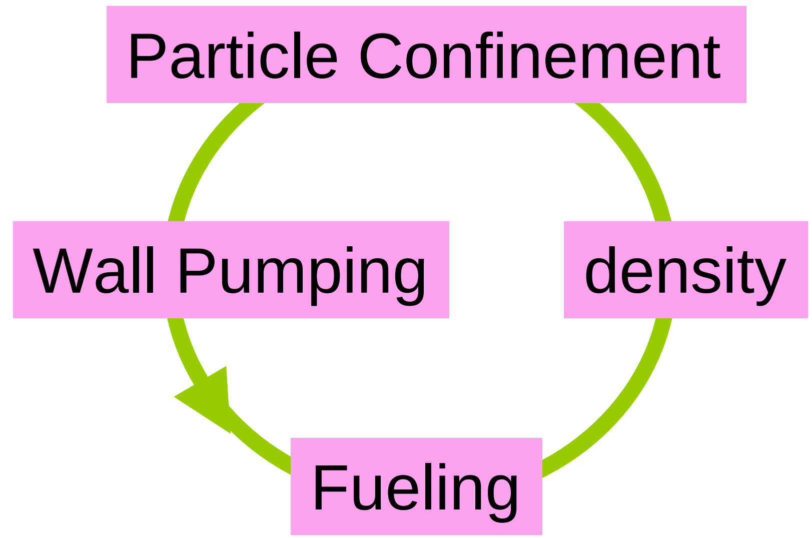
0.53sec

summary

- The QUEST program starts from 2005 to develop the scientific basis for achieving a steady state condition at sufficiently high beta (~20%), with high confinement and low collisionality, in a longer term program that contains three Phases of R&D.
- The first experimental data could be obtained. In next experimental campaign, we would like to obtain steady-state plasma.

Controllability of Wall Pumping

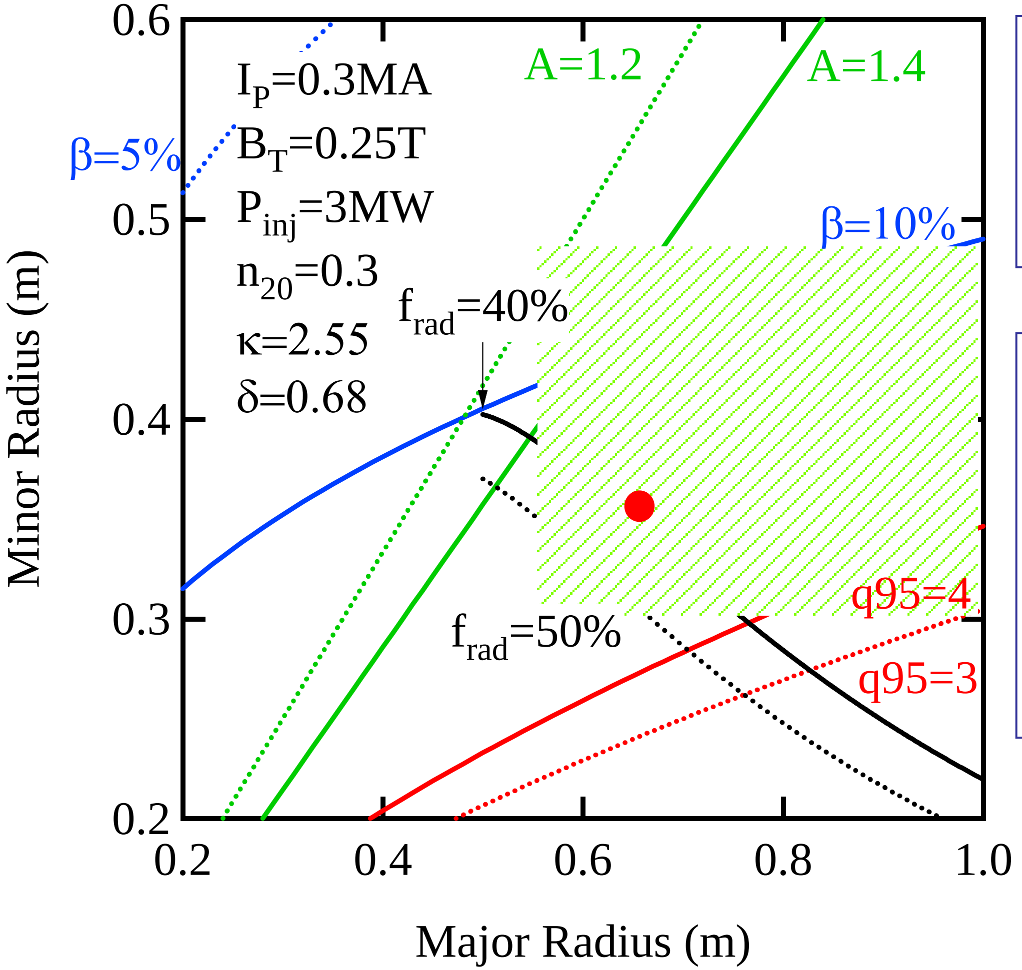




Wall pumping rate

~1.5 x 10^{16} atoms $m^{-2}sec^{-1}$

Feasibility of the Mission

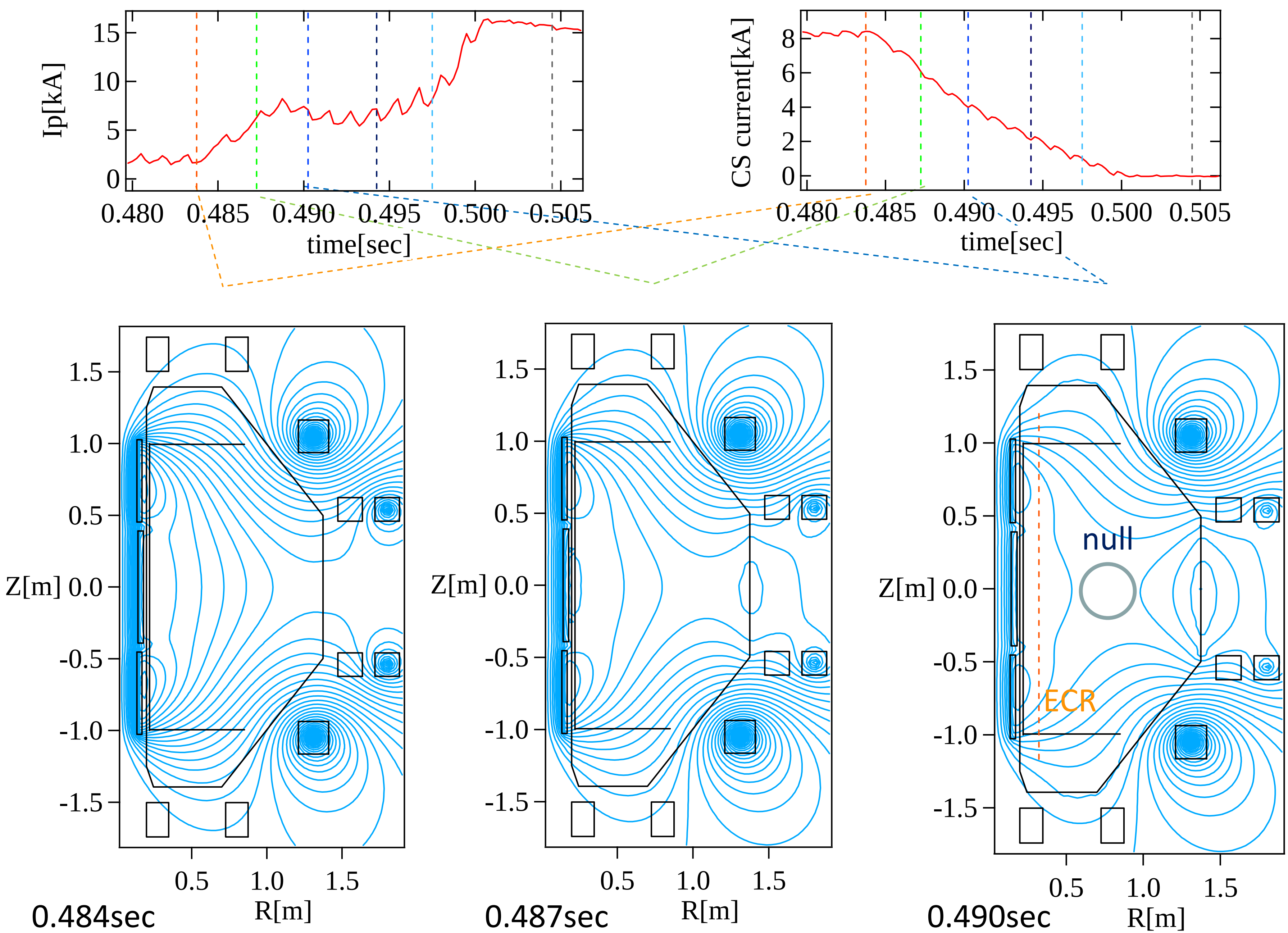


Mission in phase I

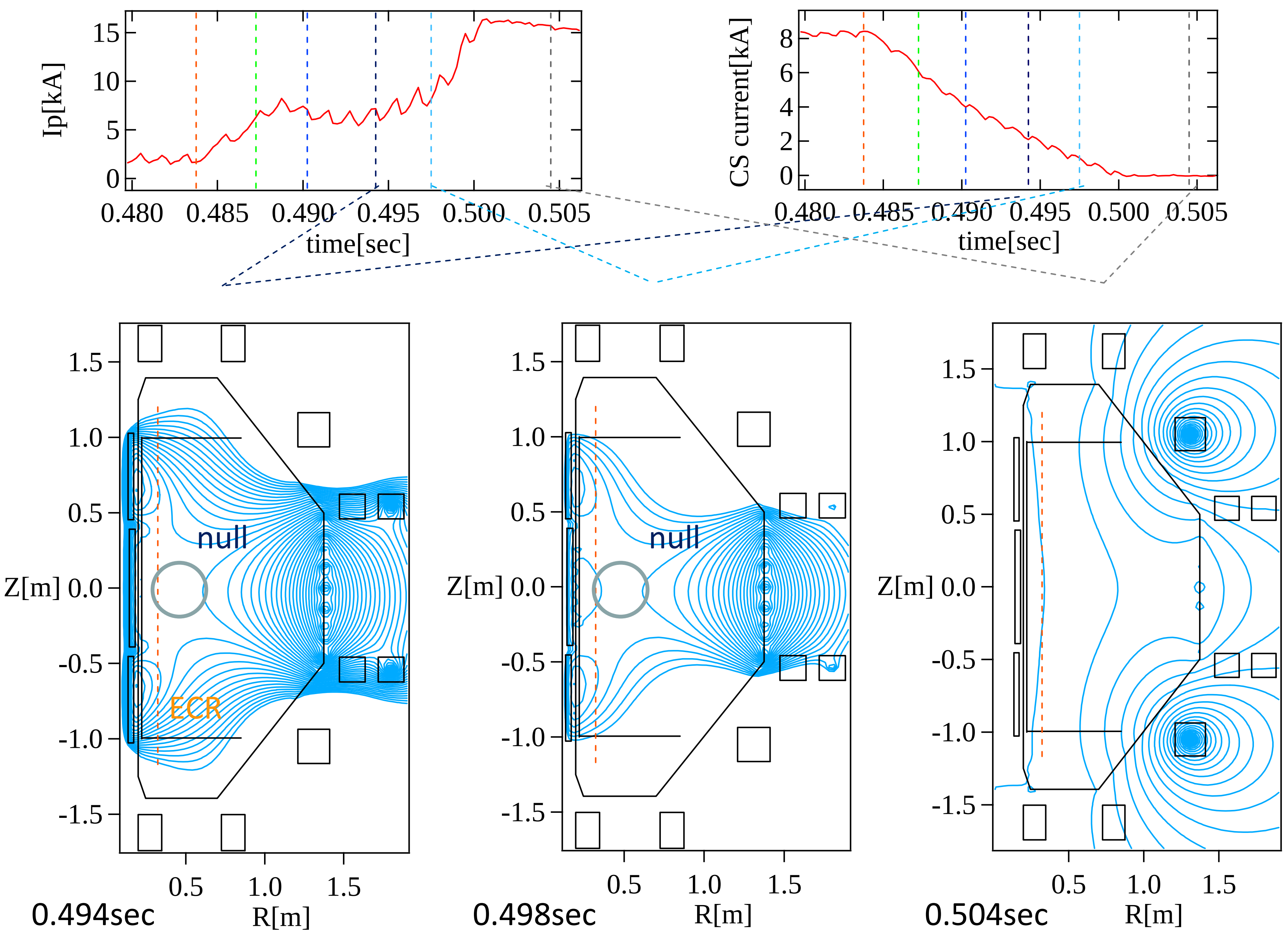
- plasma current 20kA in steady state

Mission in phase II

- plasma current 100kA in steady state
- plasma current 300kA at β>10% 1 sec

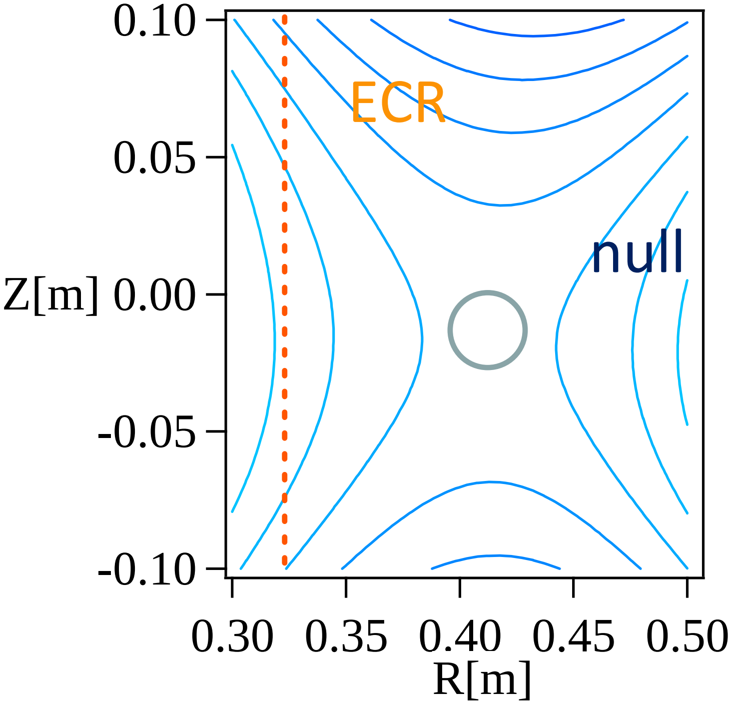


Ip[kA]
time[sec]
CS current[kA]
time[sec]
Z[m]
R[m]
0.484sec
0.487sec
null
ECR
0.490sec

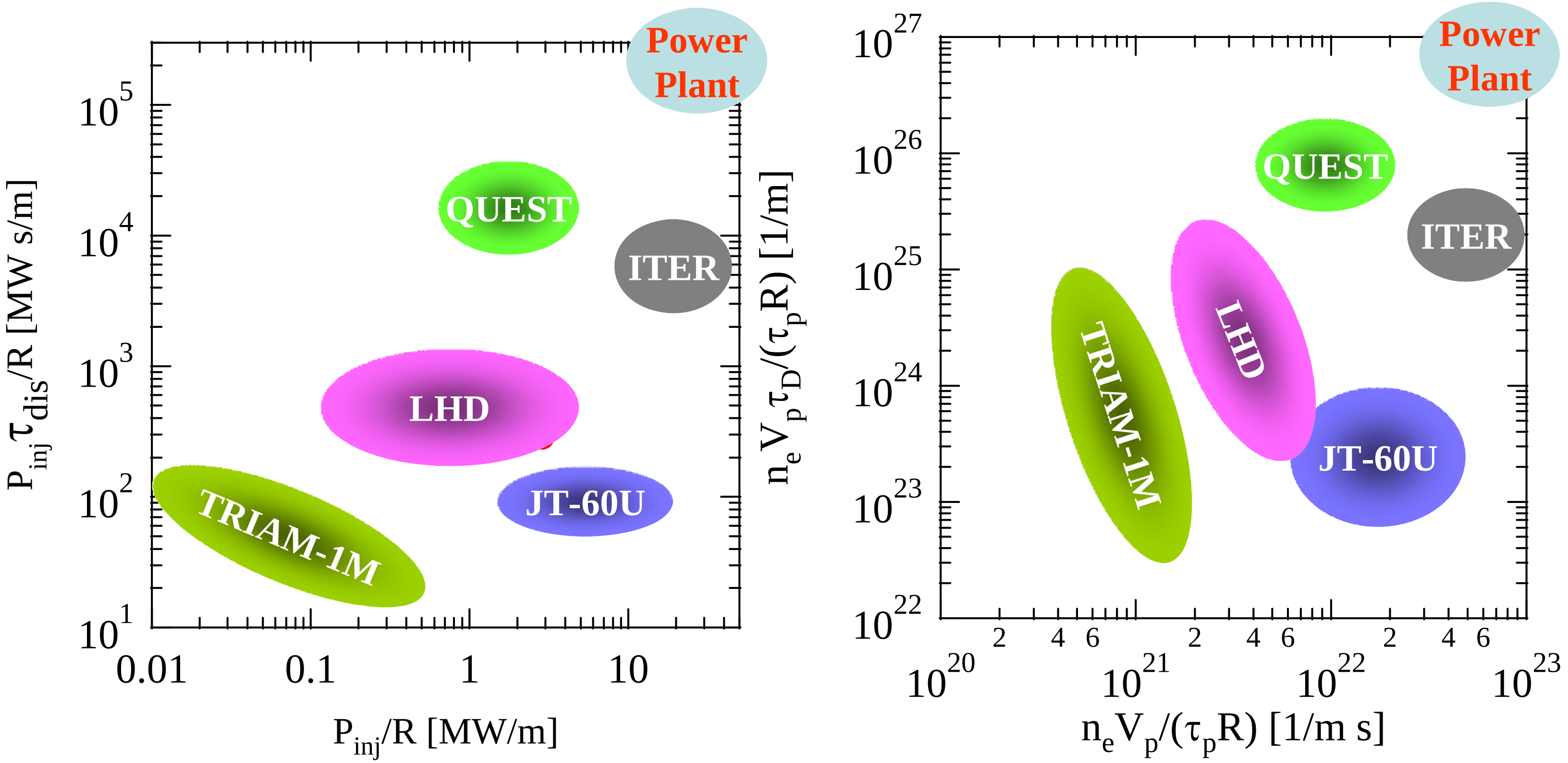


Ip[kA]
15
10
5
0
0.480
0.485
0.490
0.495
0.500
0.505
time[sec]
CS current[kA]
8
6
4
2
0
0.480
0.485
0.490
0.495
0.500
0.505
time[sec]
1.5
1.0
0.5
Z[m] 0.0
-0.5
-1.0
-1.5
null
ECR
0.5
1.0
1.5
R[m]
0.494sec
null
0.498sec
0.504sec

0.494secのときのnull点
(0.41,-0.02)
上下非対称性は渦電流の
非対称性による。

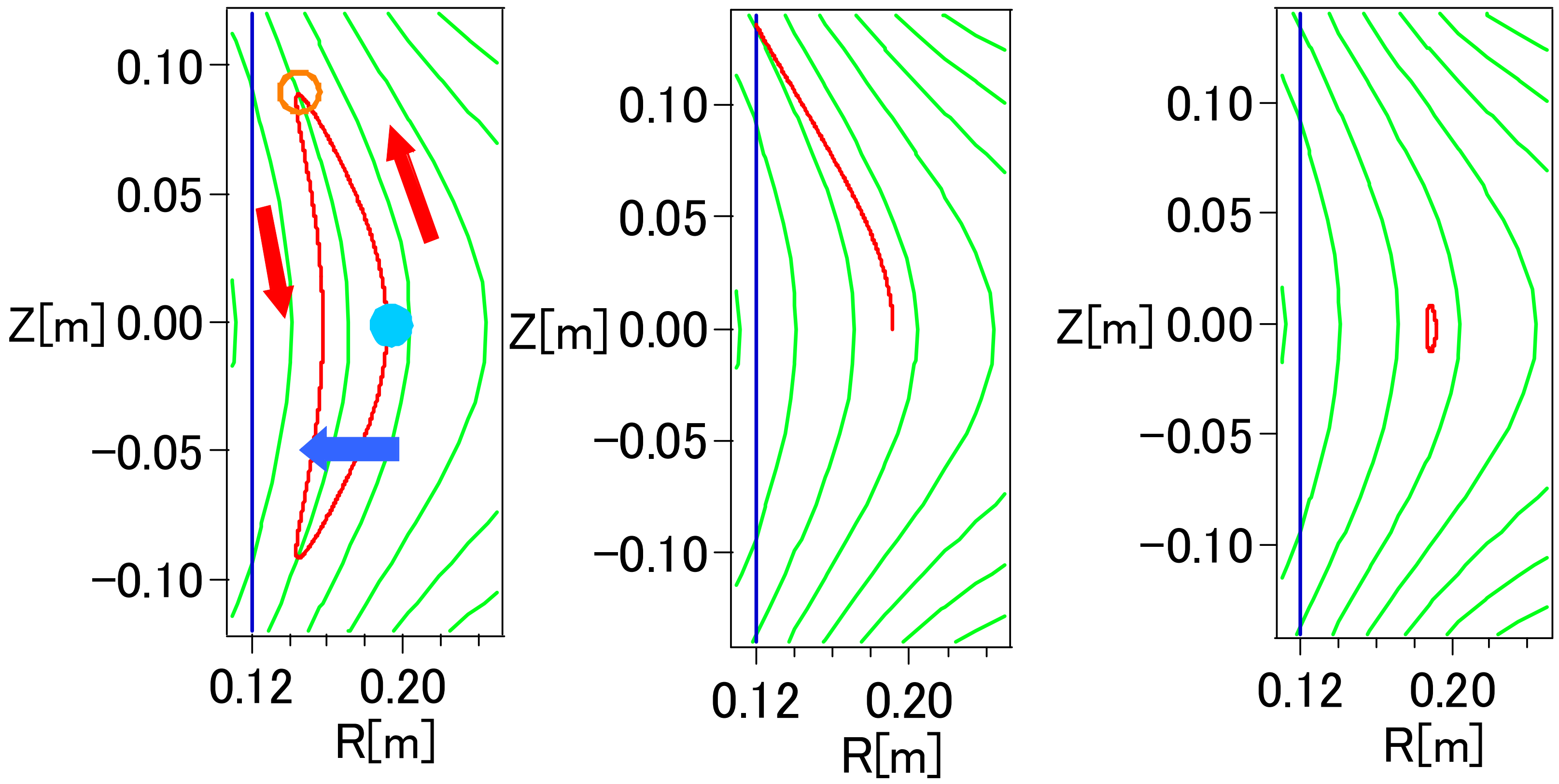


Heat and Particle load on QUEST



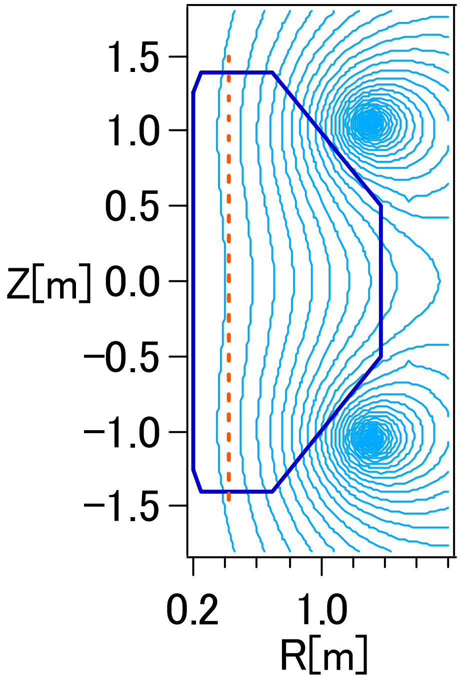
Operation region of QUEST on heat (left) and particle (right) handling. Left: The vertical axis is approximately proportional to heat load to divertor and the horizontal axis is approximately proportional to heat flux to the divertor. Right: The vertical axis is approximately proportional to fluence to the divertor and the horizontal axis is approximately proportional to particle flux, where we assume particle confinement time equals energy confinement time.

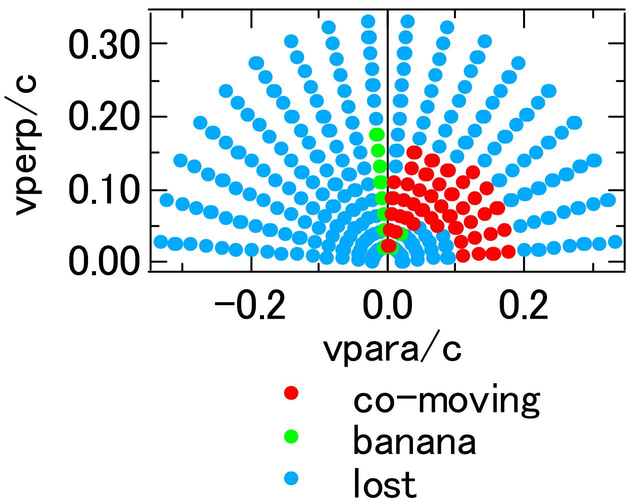
Plasma start-up scenario I

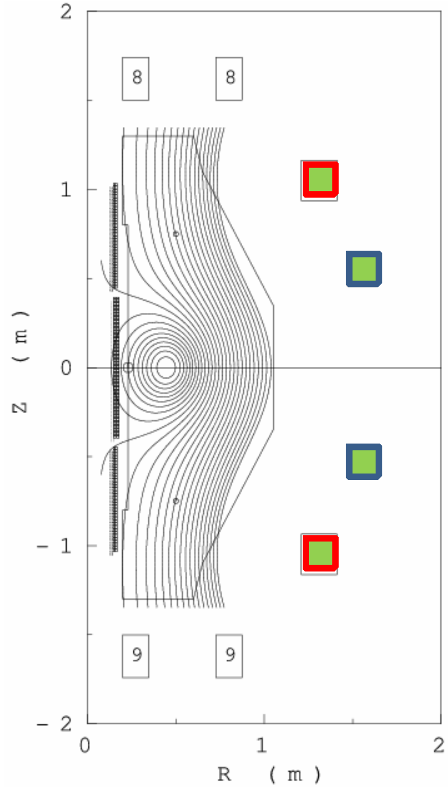


Typical orbit of energetic electron in open magnetic field

Plasma start-up scenario II







Heating and Current drive

- Power and Required current drive efficiency

  Phase I 20-30kA at low density

  RF (0.45MW)

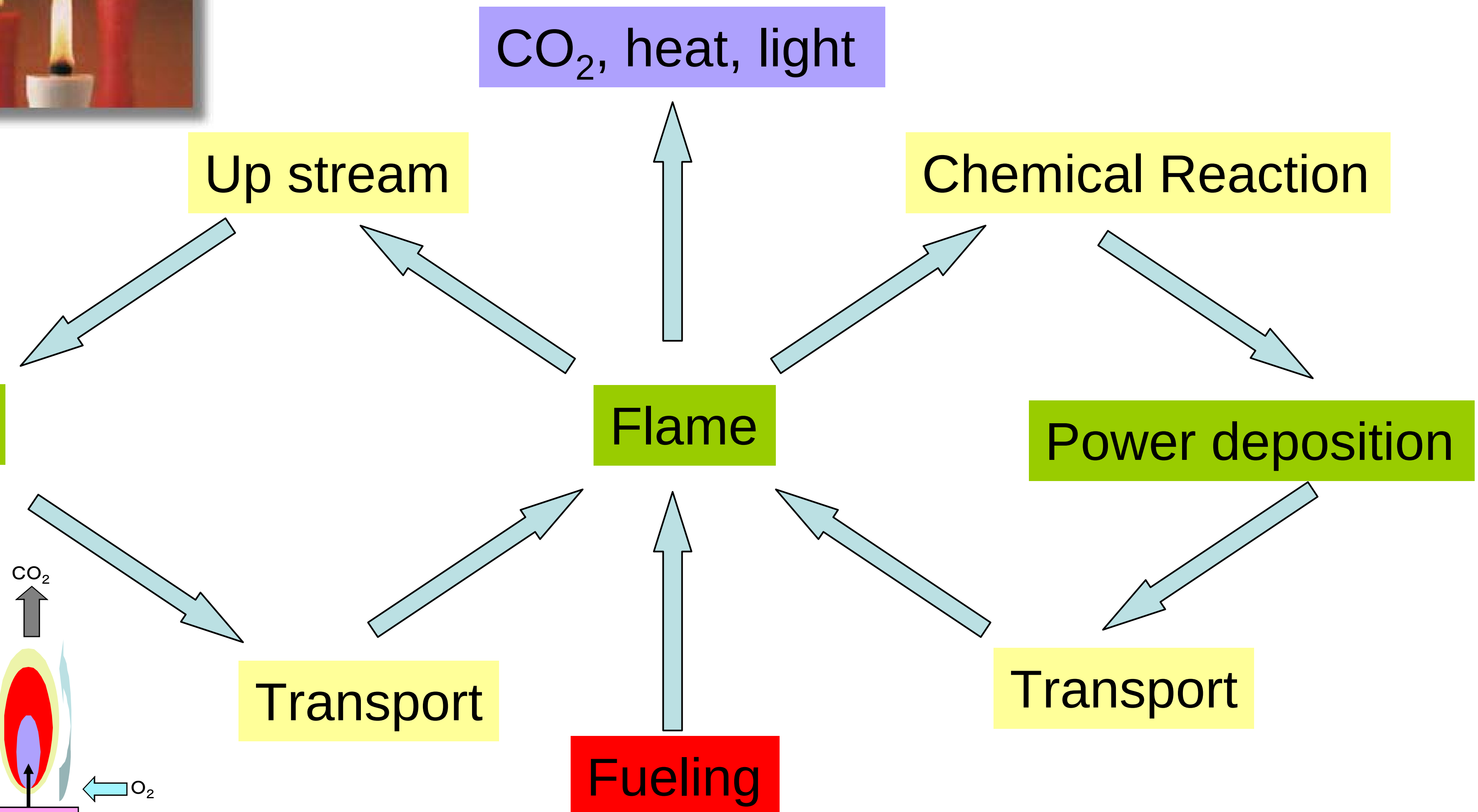
  Phase II (SS) 0.026×10^{19} A/W/m^2

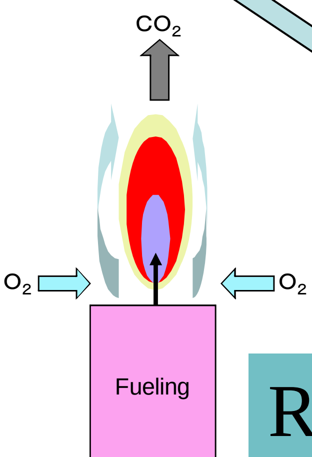
  RF (1MW) [+ NB (2MW)]

  Phase II (1sec) 0.19×10^{19} A/W/m^2

  RF (1MW) + NB (2MW) with OH

Steady state chemical burning



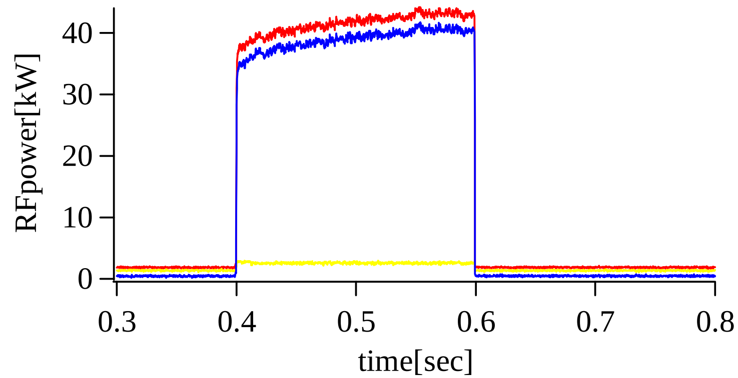


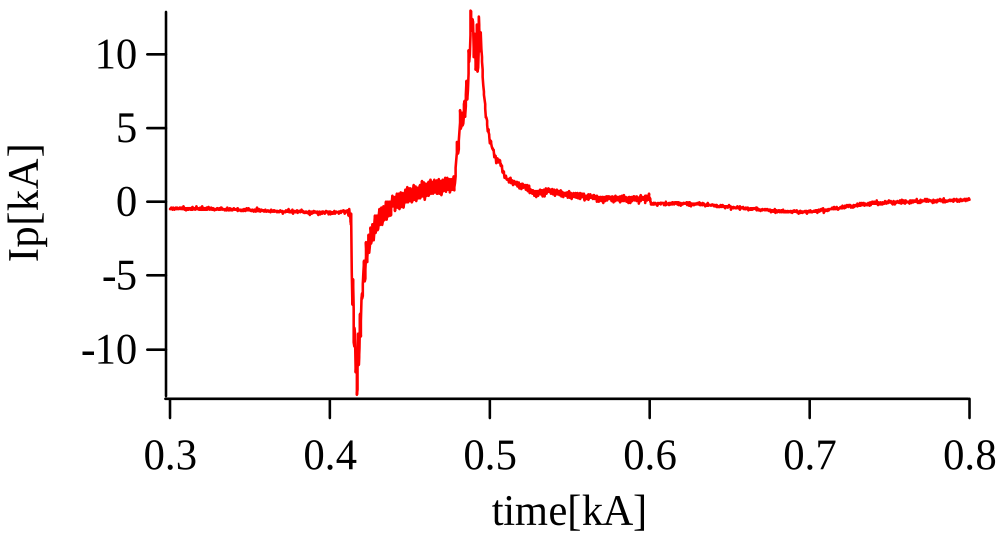
Reaction control and particle handing are important.

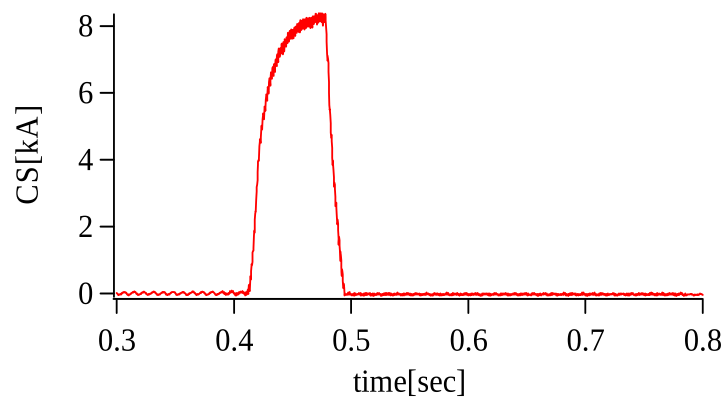
[QUEST]

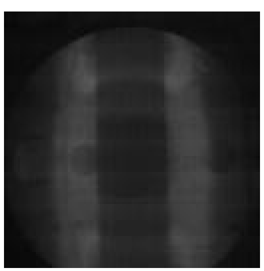
#1450

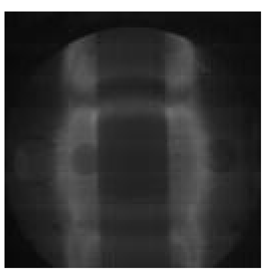
PF4-123CC(1turn):8.33kA「PGS」01.2605sec 「AT5」0.350sec
RF:3.3V(0.4-0.6sec) RF on
PF17: +000A
PF26: +000A==>+058A==>+175A==>+000A
(0.478s,0.438s,0.446s,1.000s)
TF: 27.5kA
gas 30ms@0.3ms power on

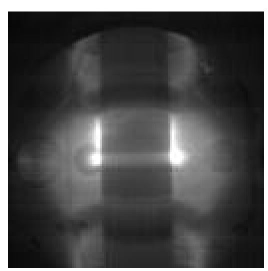







0.4545sec


0.486675sec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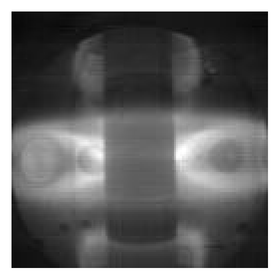
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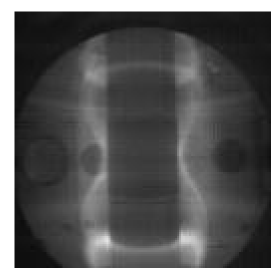
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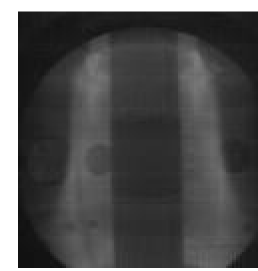
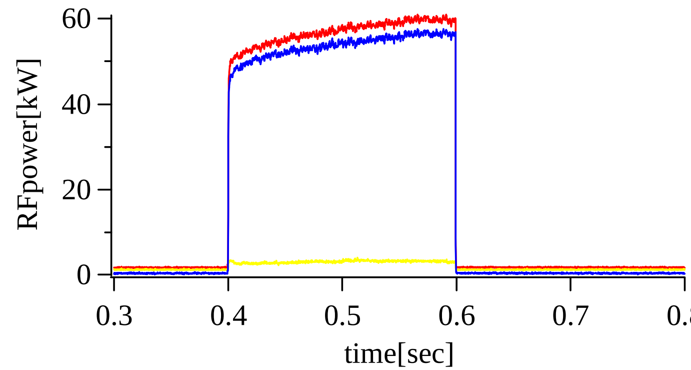
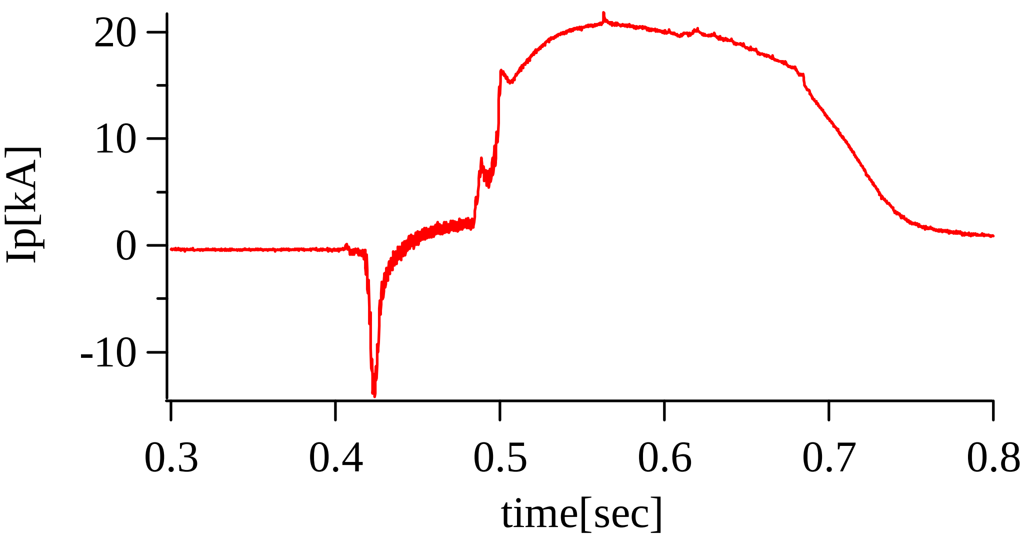

0.50595sec

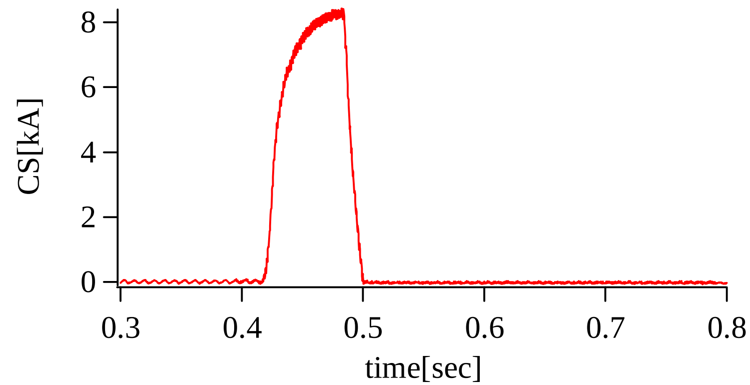
[QUEST]

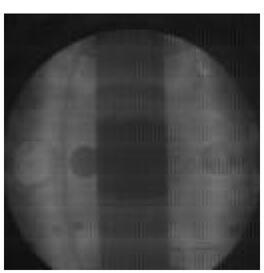
#1456

PF4-123CC(1turn):8.33kA「PGS」01.2605sec 「AT5」0.350sec
RF:4.3V(0.4-0.6sec) RF on
PF17: +000A
PF26: +000A==>+058A==>+475A==>+000A (0.438s,0.446s,1.000s)
TF: 30.0kA gas 30ms@0.3ms power on





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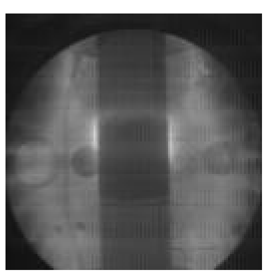
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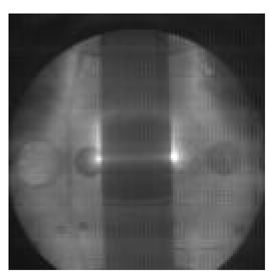
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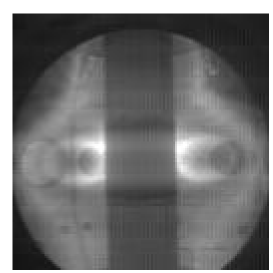
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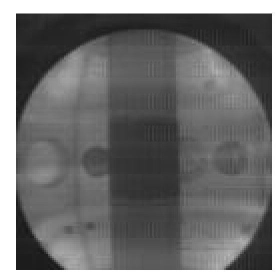
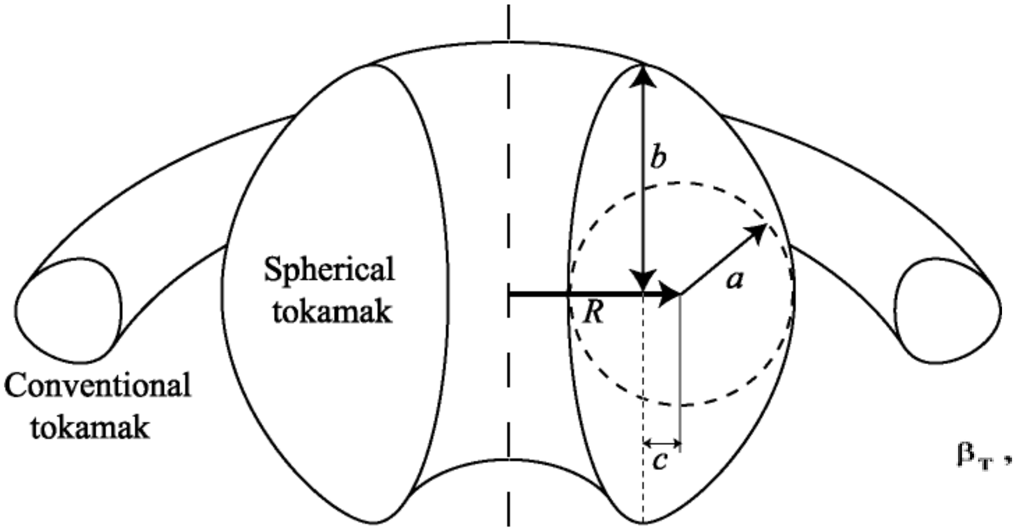
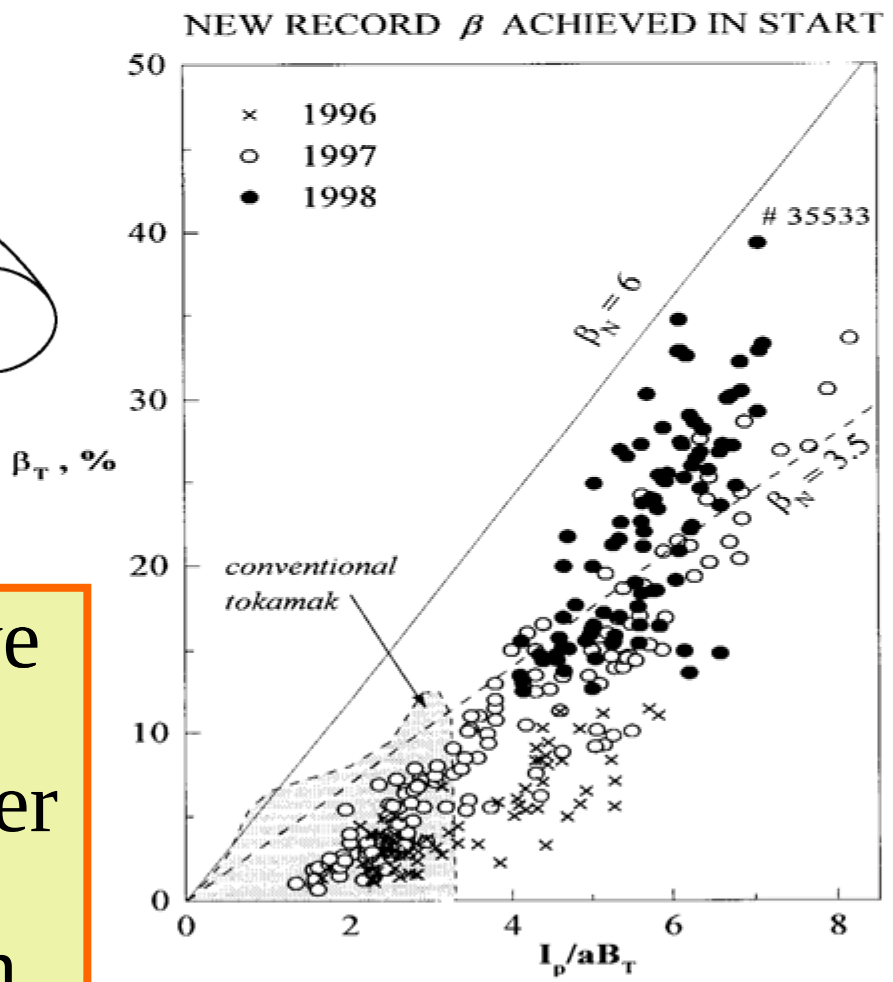

0.53sec

Sperical toksmaks (ST)





Sperical tokamaks (ST) have the possibility to realize cost-effective fusion power plants. High β (~10%) is the indispensable target in QUEST.

Required research items of QUEST

- Plasma start-up
- Non-inductive current drive
- Divertor Research
- Plasma wall interaction
- Achievement of medium or high β
- Particle and heat handling
- Innovative concept

Mainly focus on the technological issue for SSO

Simulation of design of divertor structure

Using SOLDOR/NEUT2D, Investigation of the divertor structure of QUEST has been executed.

Issues for divertor design

Heat handling

Heating of 1MW will be executed on QUEST in steady state and Heating of 3M is planned in pulsed discharge.

⇨ **Need to estimated heat flux on the divertor plate**

Particle handiling

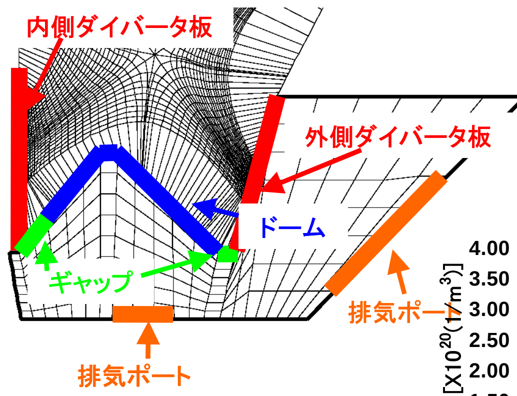
QUEST will be operated on the condition of R=1 due to high temperature wall and it is necessary to evacuate all of particle by pumping.

⇨ **Need to estimated required particle exhaust**

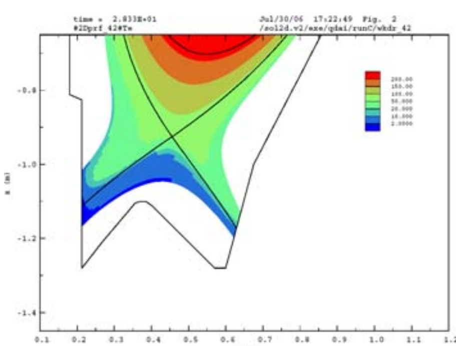
⇨ **Comparison with experimental data on the flat divertor**

An example of the calculation of plasma parameters in divertor

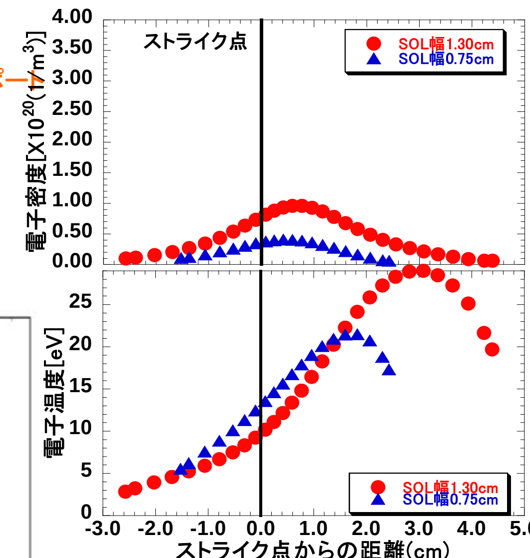
Mesh structure



Temperature distribution



Density and Temperature distribution along outer divertor plate



EBW アンテナ開発計画

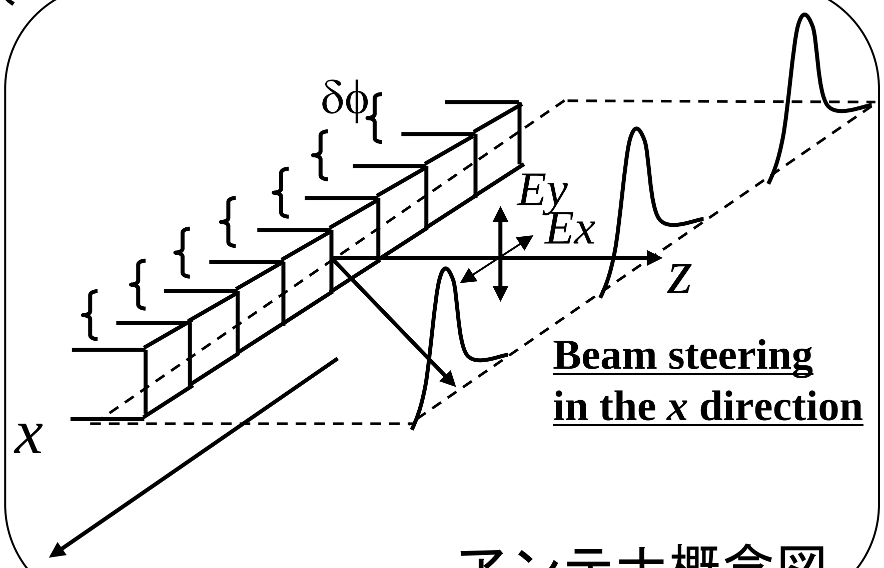
X-EBW（垂直入射）, O-X-EBW （斜め入射）、混合モードシナリオによる
加熱・電流駆動のために低周波数（~8GHz) 高周波コンポーネント開発が必要

1. X / O モード励起 ー Orthogonal Mode Transducer (OMT)の開発 ー

平成18年度：高電力仕様に向けた試作・開発、低電力試験
平成18年度：CPD／RF 伝送路での高電力試験

2. 入射角制御　ー Steering アンテナの開発 ー

平成18年度：概念設計、高周波設計
平成18年度：低電力仕様での試作、動作確認
平成19年度：新規 CPD アンテナ 製作
平成19年度：QUEST アンテナの詳細設計
（熱設計を含む）
平成19~20年度：QUEST アンテナの製作



アンテナ概念図

EBWCD

Experimental Observations

- 100kA at 60 GHz 600kW on COMPASS-D
- 15kA at 5 GHz 200kW on LATE
- 4 kA at 8.2GHz 170 kW on TST-2
- 1.2 kA at 140 GHz on W7-AS

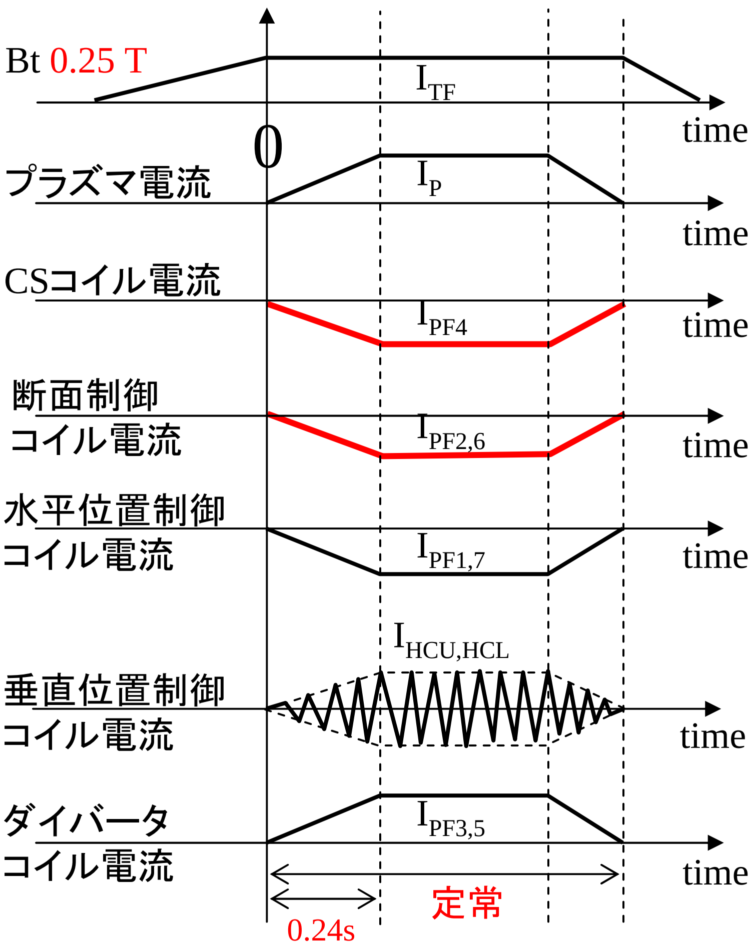
Simulation

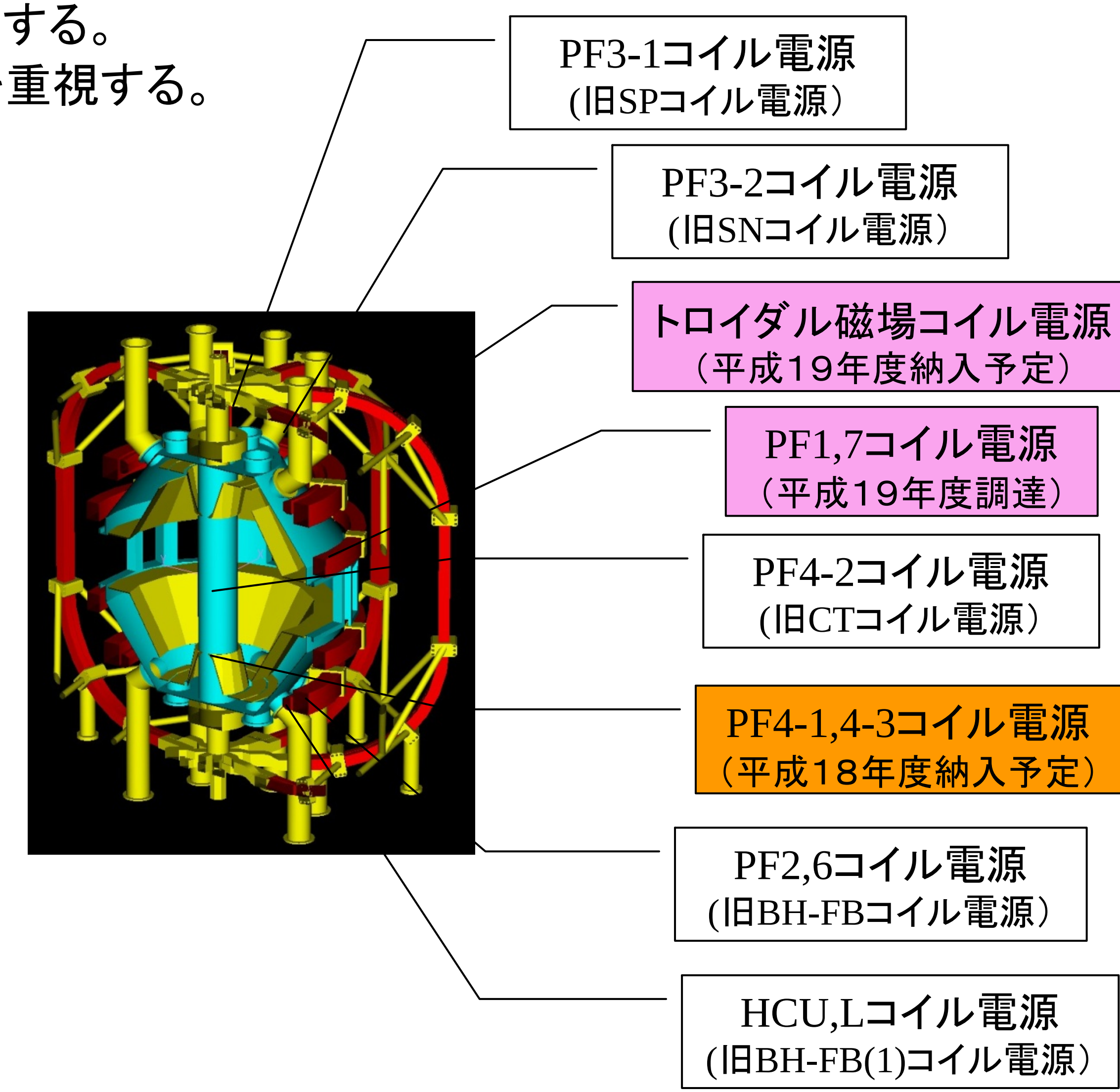
- 30kA at 15 GHz, 1MW on NSTX, but no optimization

- EBWCD in ST has the potential to attain the high current drive efficiency comparable to ECCD on conventional tokamaks.
- Even in ST, wave propagation of EBW has no limitations such as cut-off.
- The collaboration with LATE group will start in 2005.

磁場コイル電源の活用（定常運転時）

TRIAM-1Mの磁場コイル電源を活用する。
新設の磁場コイル電源は定常運転を重視する。

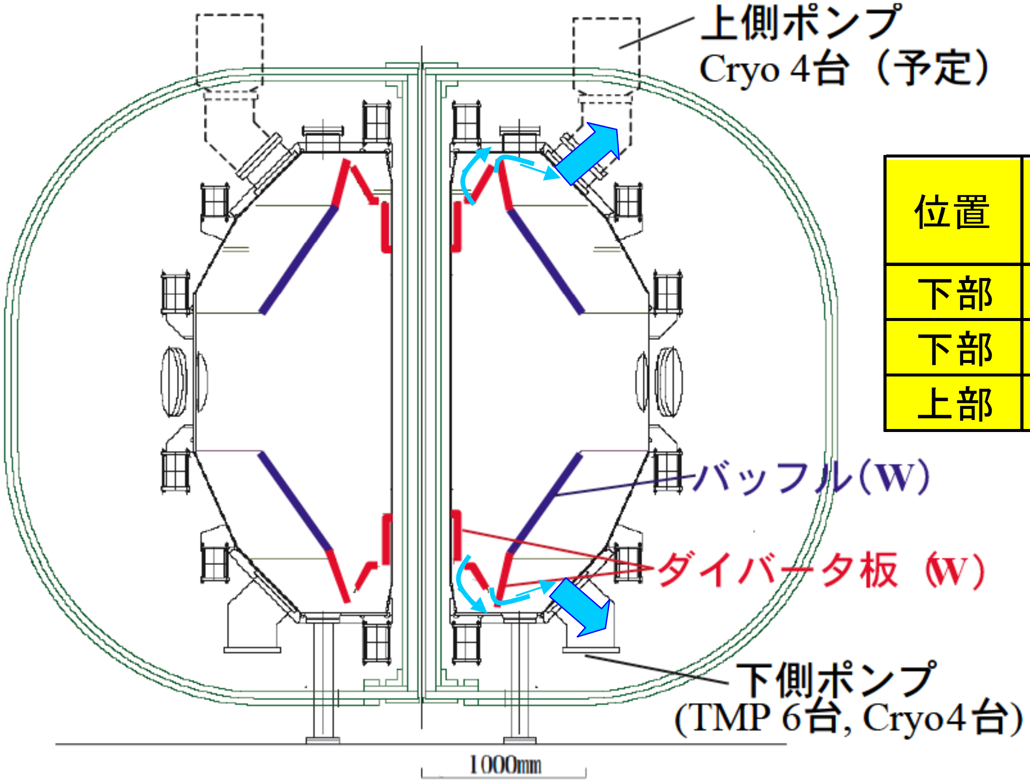




NBCD

- 40keV NB can be deposited at $3X10^{19}m^{-3}$.
- Plasma current of 100kA can be expected by 40keV 2MW NBI.
- There are no NBI in Kyushu University at present.
- Bootstrap current is not sufficient to maintain the plasma current in steady state.

Particle exhaust （divertor pumping）



位置	ポンプ	単体排気速度 $m^3/s(H_2)$	台数	総排気速度 $m^3/s(H_2)$
下部	TMP	**~2.3**	**6**	**13.8**
下部	CRYO	**10**	**4**	**40**
上部	CRYO	**10**	**4**	**40**

（上部排気に関しては設置予定）

Outline of divertor (under consideration of best position of poloidal field coils)

Steady state operation
P=0.1 (Pa)
==> 9.4 (Pa m^3/s)

Pulse operation
P=1 (Pa)
==> 94 (Pa m3/s)

Thermal desorption of D from W

Twall = 300C

Twall =600C

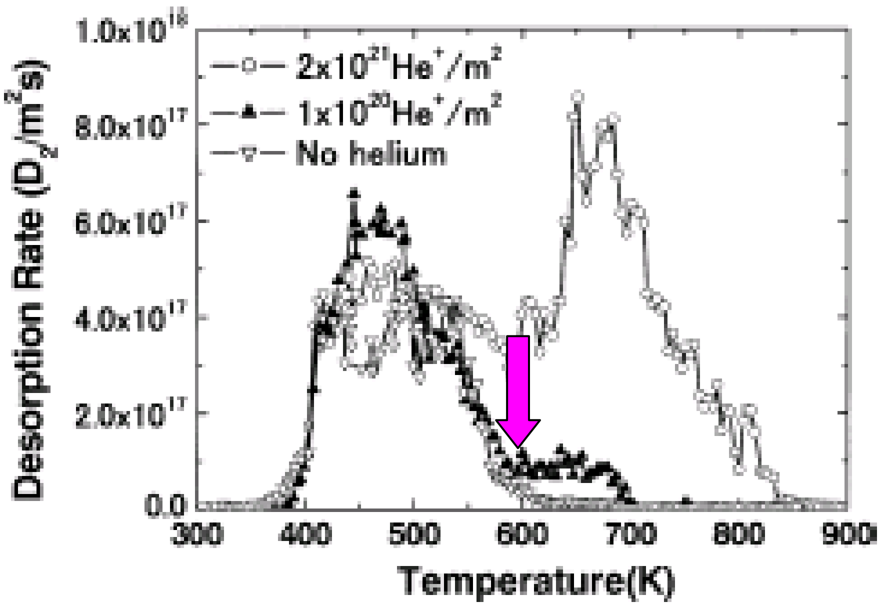
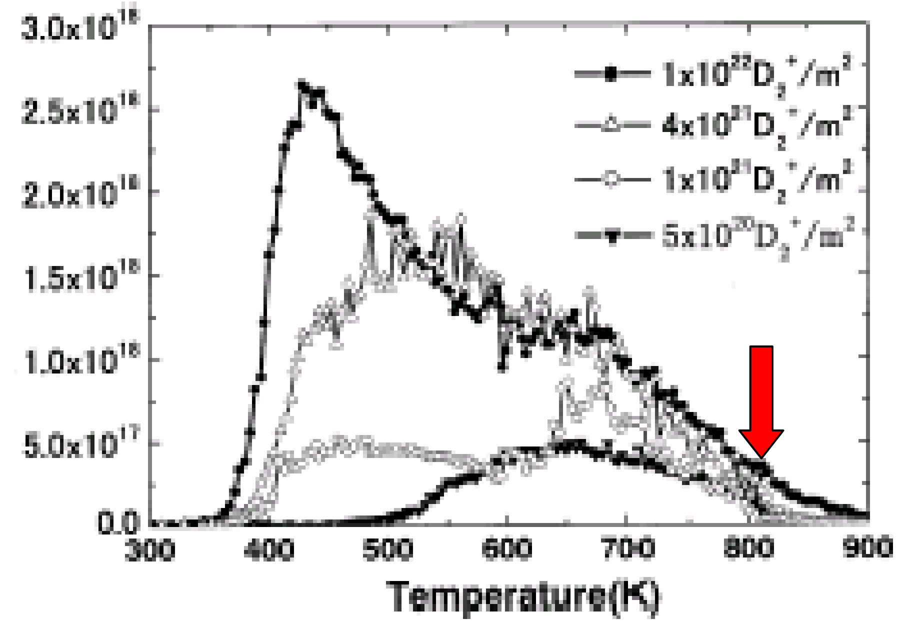


Fig. 1. Thermal desorption spectra of deuterium for samples without pre-irradiation and with pre-irradiation of 8 keV-He^+ to doses of 1.0×10^{20} and 2.0×10^{21} He^+/m^2 at room temperature.



. 2. Thermal desorption spectra of deuterium for tungsten irradiated with 8 keV-He^+ to 2×10^{21} He^+/m^2 at room perature for deuterium doses ranging from 5×10^{20} to 10^{22} D_2^+/m^2 introduced at room temperature.

He – irradiation

D-Fluence

Iwakiri, Yoshida JNM (2000) 1134