12th Int. WS on ST (ISTW2006)
as a Satellite Meeting with IAEA FEC
2006.10.11-13 / Chengdu

Recent Studies on TRIAM-1M and the New Project of Long Term Sustained Spherical Tokamak "QUEST" in Kyushu University

Presented by Kohnosuke SATO (Satcho)

H. Zushi 1), K. Nakamura 1), K. Hanada 1), M. Sakamoto 1), H. Idei 1), M. Hasegawa 1), S. Kawasaki 1), H. Nakashima 1), A. Higashijima 1), F. Wang 2), K. Sasaki 2), H. Xu 2), B. Rajendraprasad 2), M. Ogawa 2), K. Takagi 2), K. Nakashima 2), S. Nishi 2), N. Kimura 2), Y. Inada 2), Y. Nozaki 2), Y. Wataya 2), H. Sakai 2), M. Matsubara 2), S. Watanabe 2), N. Yoshida 1), K. Tokunaga 1), T. Fujiwara 1), M. Miyamoto 2), M. Tokitani 2), K. Uehara 3), Y. Sadamoto 4), Y. Nakashima 5), Y. Higashizono 5), Y. Takase 6), A. Ejiri 6), S.Kado 6), T. Shikama 6), S.Iio 7) , T. Takeda 8), Y. Hirooka 9), T. Morisaki 9), Y. Nakamura 9), K. Toi 9), T. Shimozuma 9), S. Kubo 9), T. Fujimoto 10), A. Iwamae 10), T. Maekawa 10), M. Nagata 11), N. Nishino 12), O. Mitarai 13)
All Japan ST Research Group*, M. Peng** (Device Review Committee*, **)

1) Advanced Fusion Research Center, Research Institute for Applied Mechanics, Kyushu University, Fukuoka, Japan,
2) Interdisciplinary Graduate School of Engineering Sciences, Kyushu University, Fukuoka, Japan,
3) Japan Atomic Energy Agency, Ibaragi, Japan
4) Joetsu University of Education, Niigata, Japan
5) University of Tsukuba, Ibaragi, Japan
6) The University of Tokyo, Tokyo, Japan
7) Tokyo Institute of Technology, Tokyo, Japan
8) The University of Electro-Communications, Tokyo, Japan
9) National Institute for Fusion Science (NIFS), Gifu, Japan
10) Kyoto University, Kyoto, Japan
11) University of Hyogo, Hyogo, Japan
12) Hiroshima University, Hiroshima, Japan
13) Kyushu Tokai University, Kumamoto, Japan

Summary of the Project in Kyushu University

Advanced Fusion Research Center,
RIAM, Kyushu University

◆ TRIAM-1M Project : Has just finished its operation/mission on Dec. 2005.

(1) Systematic study on plasma-wall interaction in long duration discharges

(5 hours 16 min. discharge, Dynamic and static retention, Co-deposition, Hot-spot and dust problems, etc.)

(2) Study on physical mechanism of LHCD and ECCD, relevant to ITER

(3) Study on high performance plasmas

High Ion Tem. (HIT) mode / Enhanced Current Drive (ECD) mode in SSO

◆ Next Project "Plasma Boundary Dynamics Exp. Device" : Construction has just started

--- Study on steady state operation of a spherical tokamak ---

(1) Long duration and steady state operation of a low aspect-ratio tokamak

EBW, NBI, LHCD (low density), etc.

(2) PWI (Plasma-Wall Interaction) in steady state spherical tokamak plasmas

Active wall temperature control, divertor control, active particle control

(Phenomena analysis, understanding, and control in the region of typical PWI time scale, not in the region of current diffusion time.)

(3) Systematic understanding of the toroidal plasmas with the relationship to LHD (in steady state plasmas)

<< Talk Outline >>

∗Introduction

All Metal Device, Super Long Term Discharge : 5 hours 16 min.

∗Recent Studies on TRIAM-1M

PWI Studies in TRIAM-1M/Steady State Operation (SSO) :

Global particle balance, Importance of co-deposition,
Dynamic and static retentions, Hot spot and dust problem
Difficulty in particle control

⇒ Importance of PWI especially in SSO

⇒ Necessity of “Active Control of Wall” ⇒ Motivation of “QUEST”

∗New ST Project “QUEST” in Kyushu University

Background, Purpose and Features

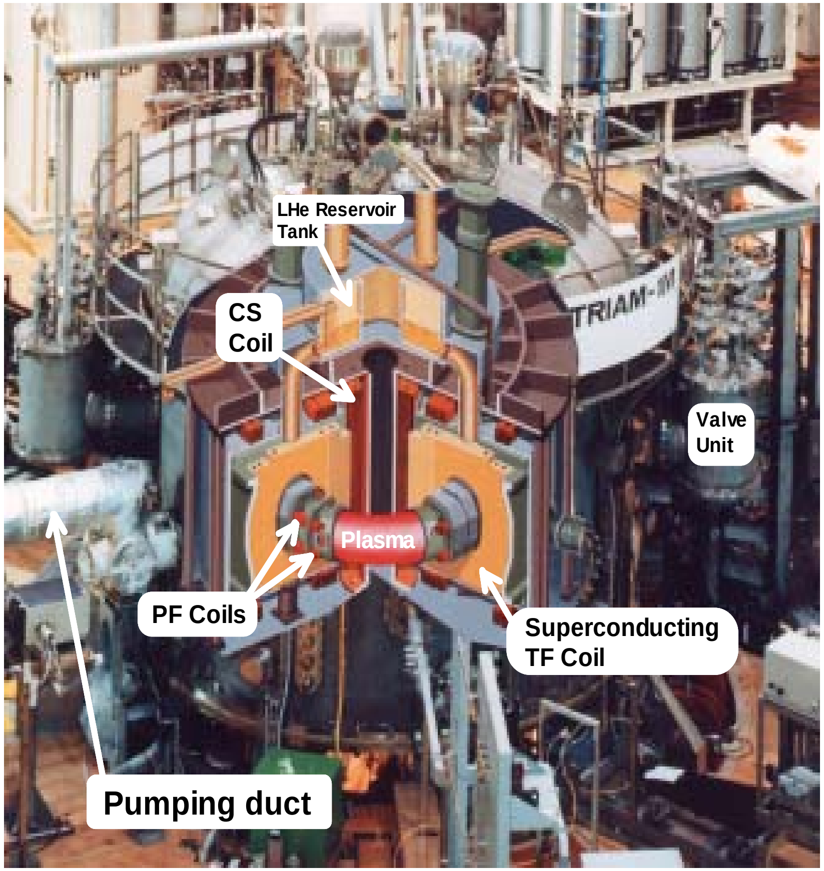
Device Size and Various Parameters

Importance of Current Drive in ST and PWI Studies

∗Summary

Bird's-Eye View and Device Features of TRIAM-1M

TRIAM, Advanced Fusion Research Center



Bird's-eye view of TRIAM-1M

Major Radius	0.80 m
Minor Radius	0.12 m x 0.18 m
Toroidal filed	8 T (Steady State)
Plasma Current (OH) (LHCD)	≦ 430 kA ≦ 70 kA
Additional Heating	450 kW (LHCD) 200 kW (ECH)

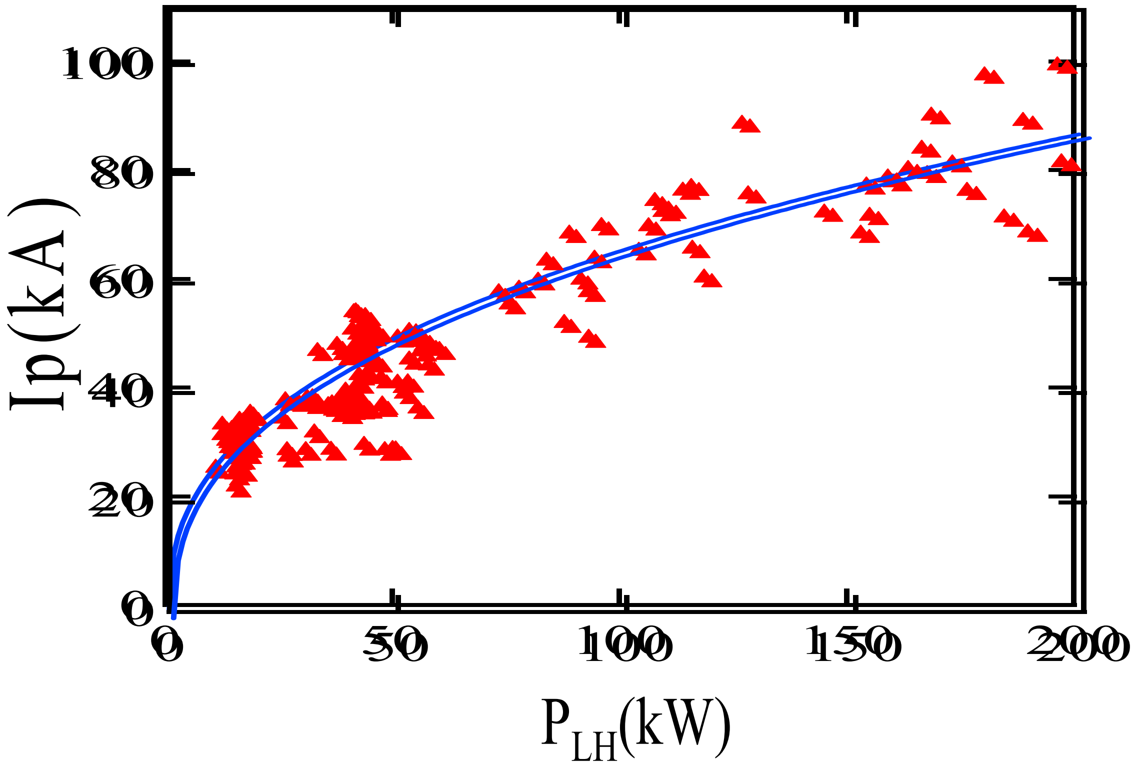
TF coils : Nb_3Sn (superconductor)

PF coils : Cu (normal conductor)

Plasma facing components: High Z
- Vacuum vessel : Stainless steel
- Limiter : Molybdenum
- Divertor : Molybdenum

◆ **W/O low Z material and coating**

Lower Hybrid Current Drive Characteristics in Long Term/Steady State Discharge

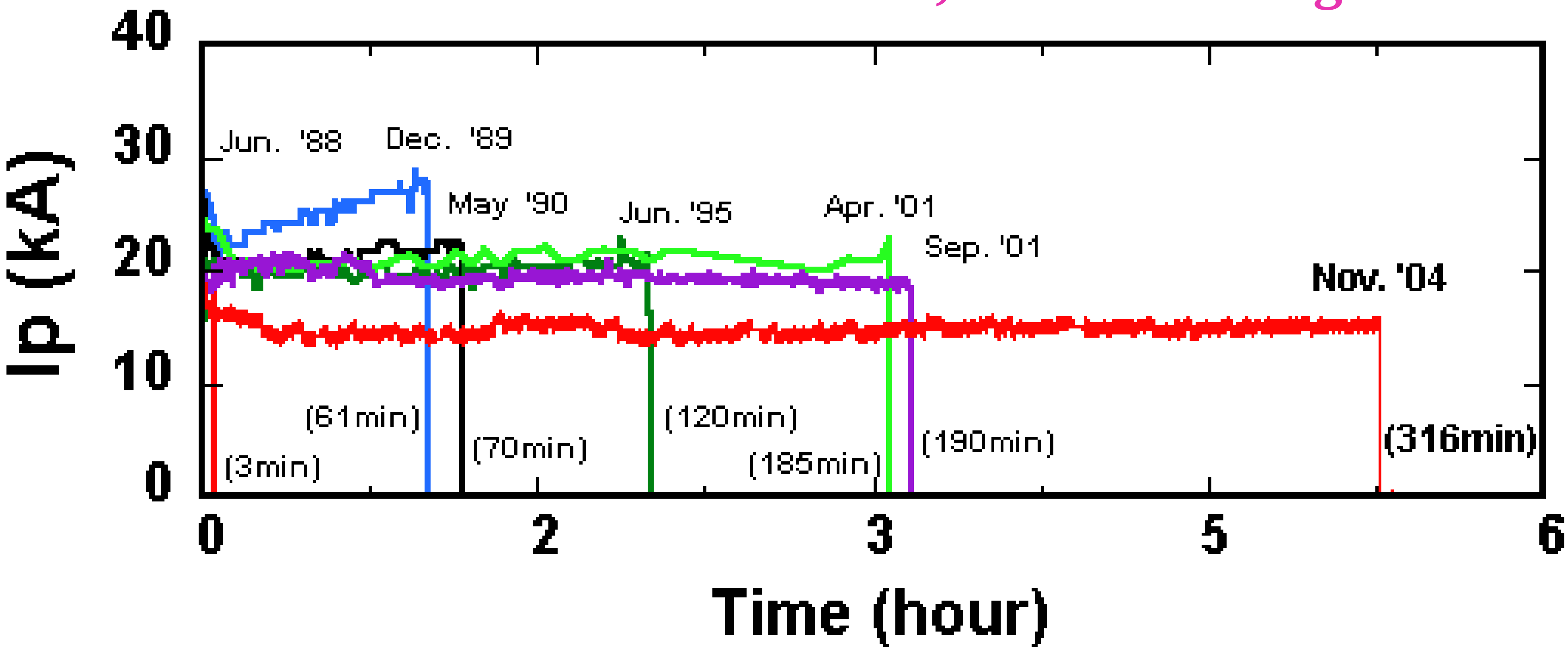


Recent experimental region of plasma current Ip vs LH-power P_{LH} in TRIAM-1M

Progress of Long Term Tokamak Operation with TRIAM-1M

TRIAM, Advanced Fusion Research Center

2.45 GHz LHCD, Limiter configuration



In TRIAM-1M, the study and development of the long pulse operation have actively been carried out.

Particle control is one of the key issues for long pulse operation.

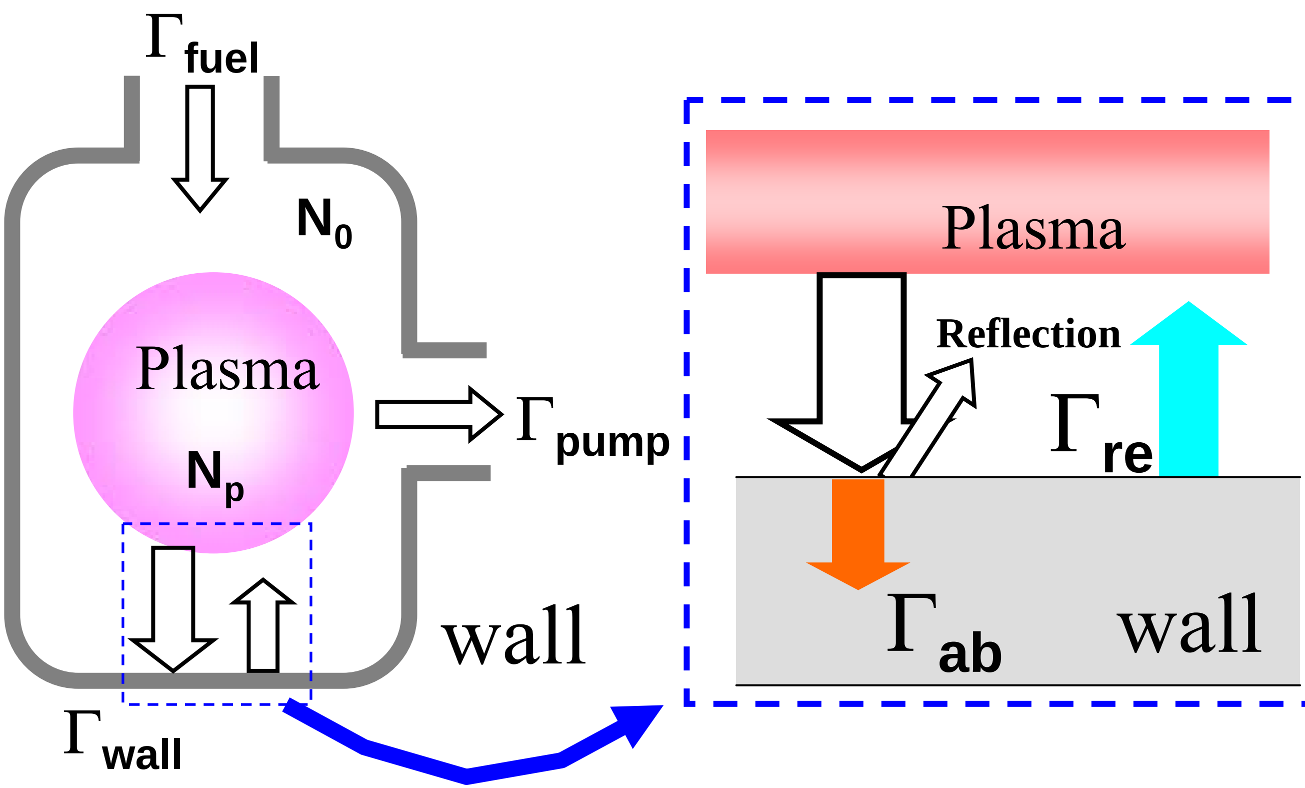
Global Particle Balance in the Main Chamber

TRIAM, Advanced Fusion Research Center

In the main chamber

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

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



$\Gamma_{wall} = \Gamma_{ab} - \Gamma_{re}$

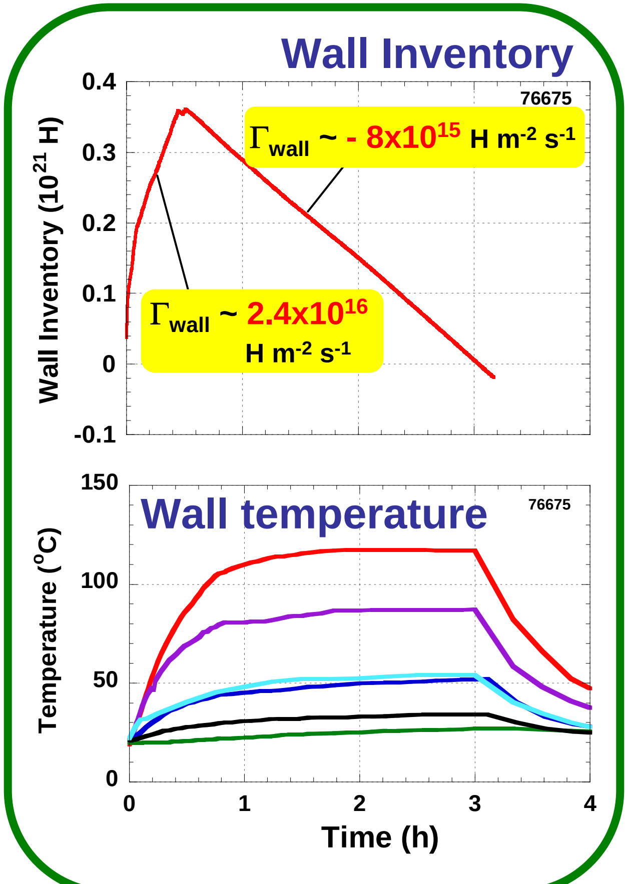
Positive : Sink
Negative : Source

Γ_{ab}: **hydrogen absorption**
Γ_{re}: **hydrogen re-emission**

Impact of Wall Temperature on Global Wall Pumping

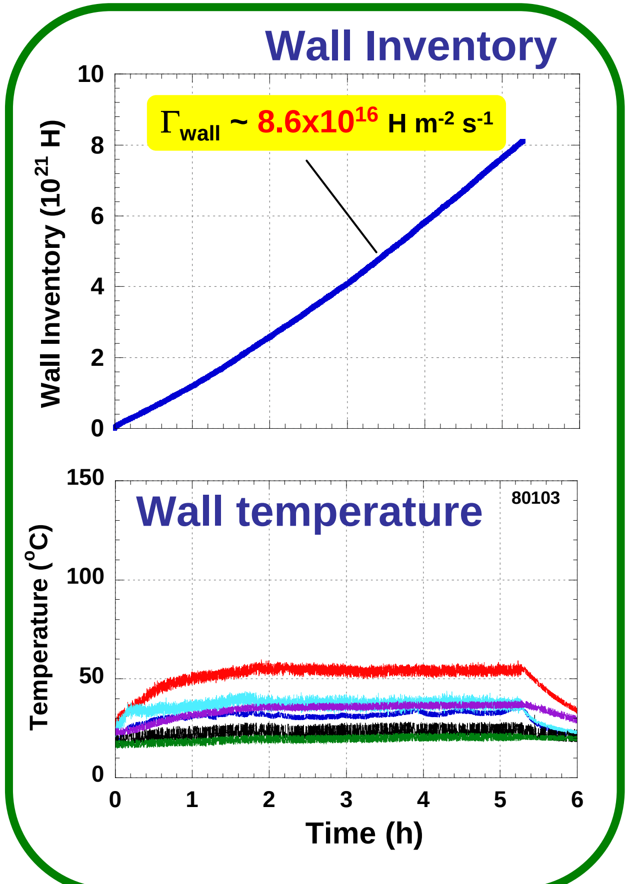
TRIAM, Advanced Fusion Research Center

T_{wall}^{max} ~120℃



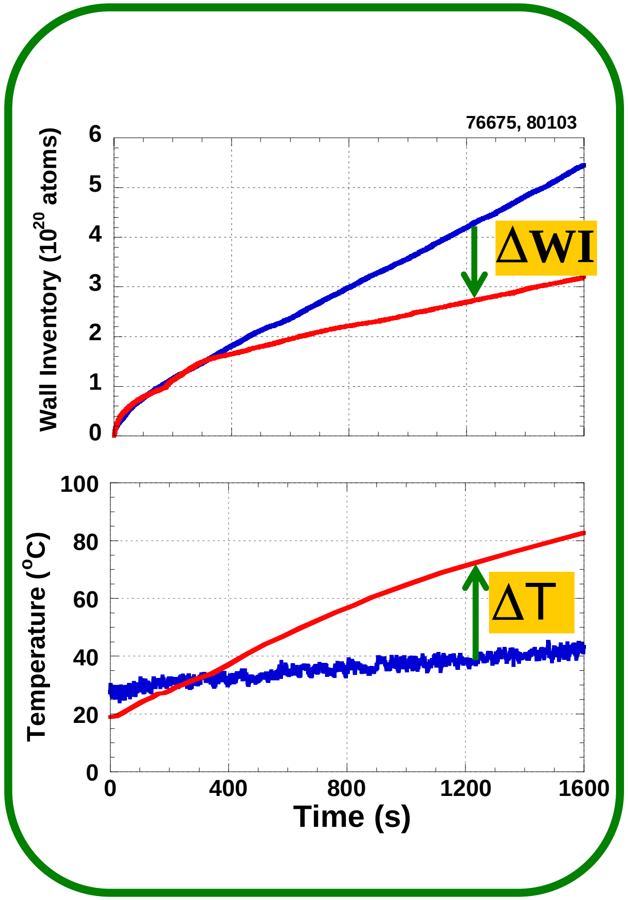
τ_D ~ 3 h 10 min

T_{wall}^{max} ~55℃



τ_D ~ 5 h 16 min

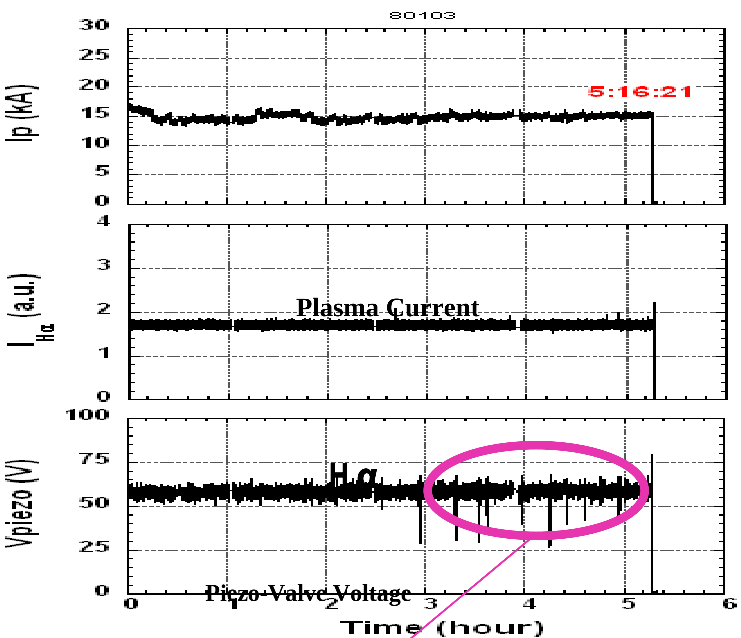
Comparison



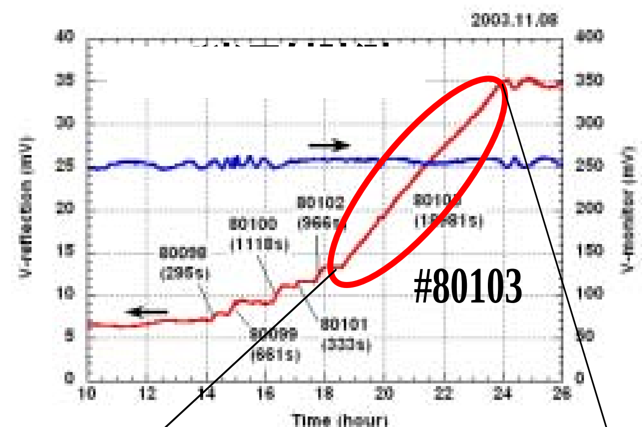
Accumulation of Exp. Results on Long Term Sustained Plasmas
--- Achievement and Understanding of Super Long Duration Discharge ---

TRIAM, Advanced Fusion Research Center

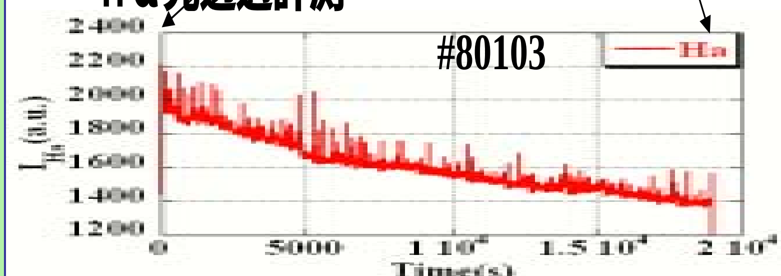
Recent Results



In-situ re-deposition measurement
(Laser reflection and Hα transmission)



・Hα光透過計測



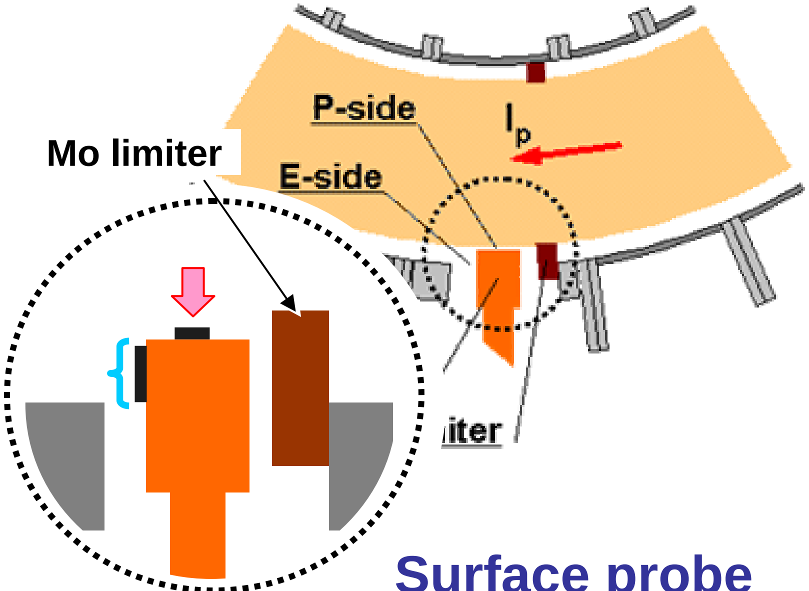
・Gas fueling is controlled (by piezo-valve) so as for Hα light to be constant.

・It occurs in the discharge period after 3 hours that the piezo-valve automatically close (no gas feeding) during several tens of seconds intermittently.

・This means the particle balance is kept constant only by the wall fueling in the latter half of super long term discharge.

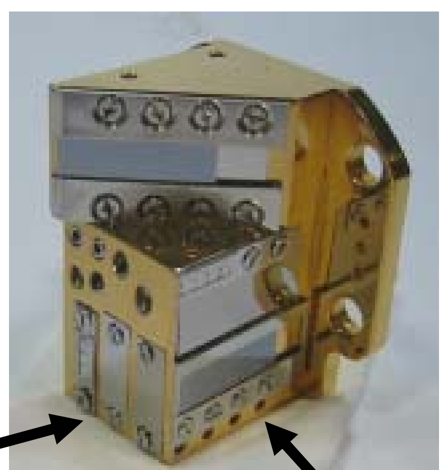
Mo Deposition in SOL

TRIAM, Advanced Fusion Research Center



Surface probe

Probe head

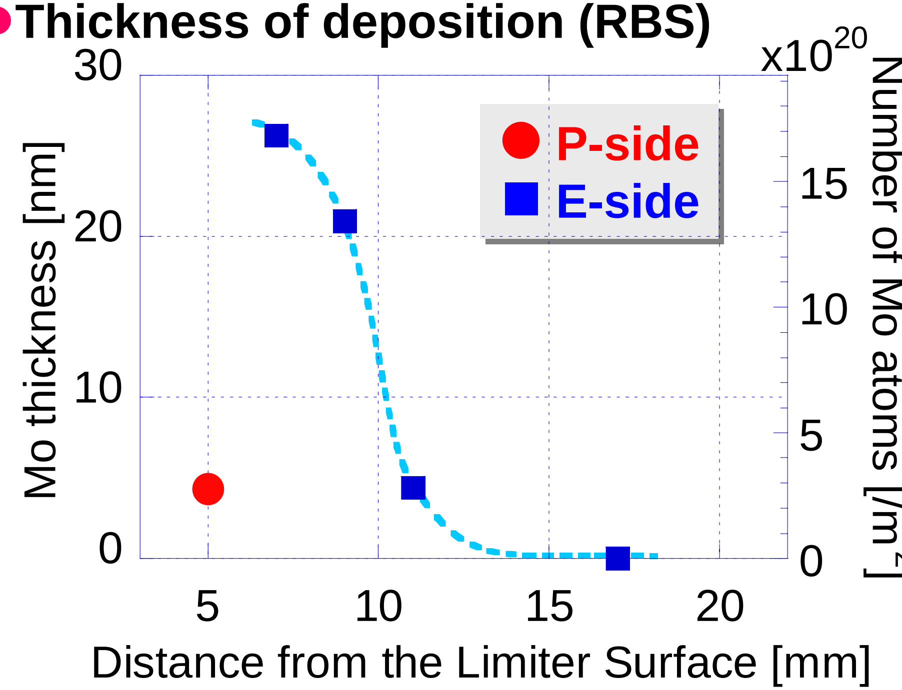


Plasma facing side

Electron drift side

2.45 LHCD (τ_D ~ 72min)

- **Thickness of deposition (RBS)**



Deposition rate

P-side	E-side
6.4×10^{16} (Mo/m^2s)	3.9×10^{17} (Mo/m^2s)

After M. Miyamoto, et al., J. Nucl. Mater. 337-339 (2005) 436.

Good Agreement of Wall Pumping Rate by Macroscopic and Microscopic Methods

Wall pumping rate
~2.4 x 10^{16} (H/m^2s)

↔

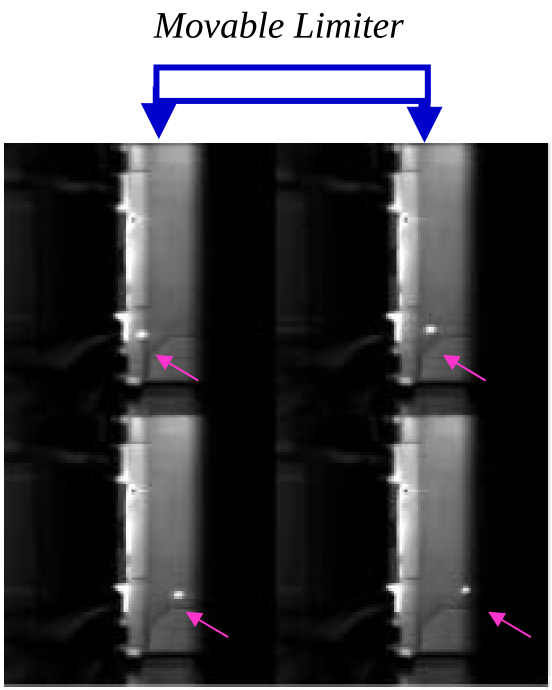
Retention rate
~1.3 x 10^{16} (H/m^2s)

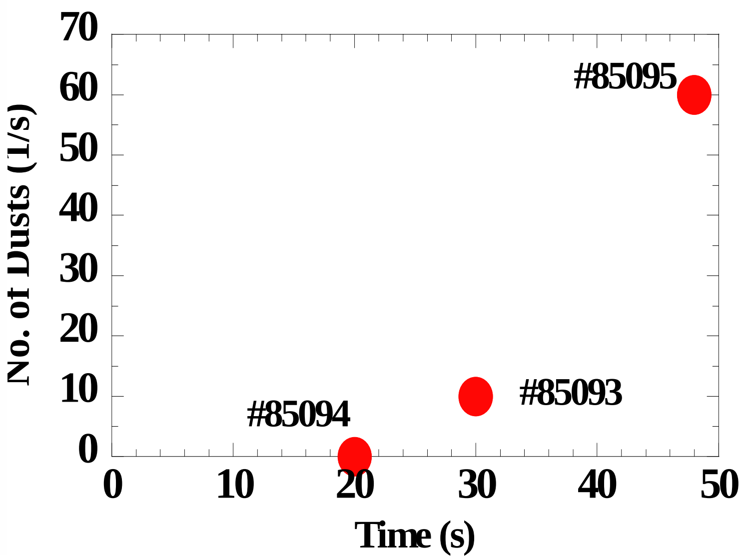
Macroscopic method
[Particle balance]
Dynamic retention

Microscopic methods
Surface probe
ERD: Elastic Recoil Detection
Static retention

Dust Measurement by Fast Camera and CCD

TRIAM, Advanced Fusion Research Center





An example of a dust particle behavior observed by the high speed framing camera system.

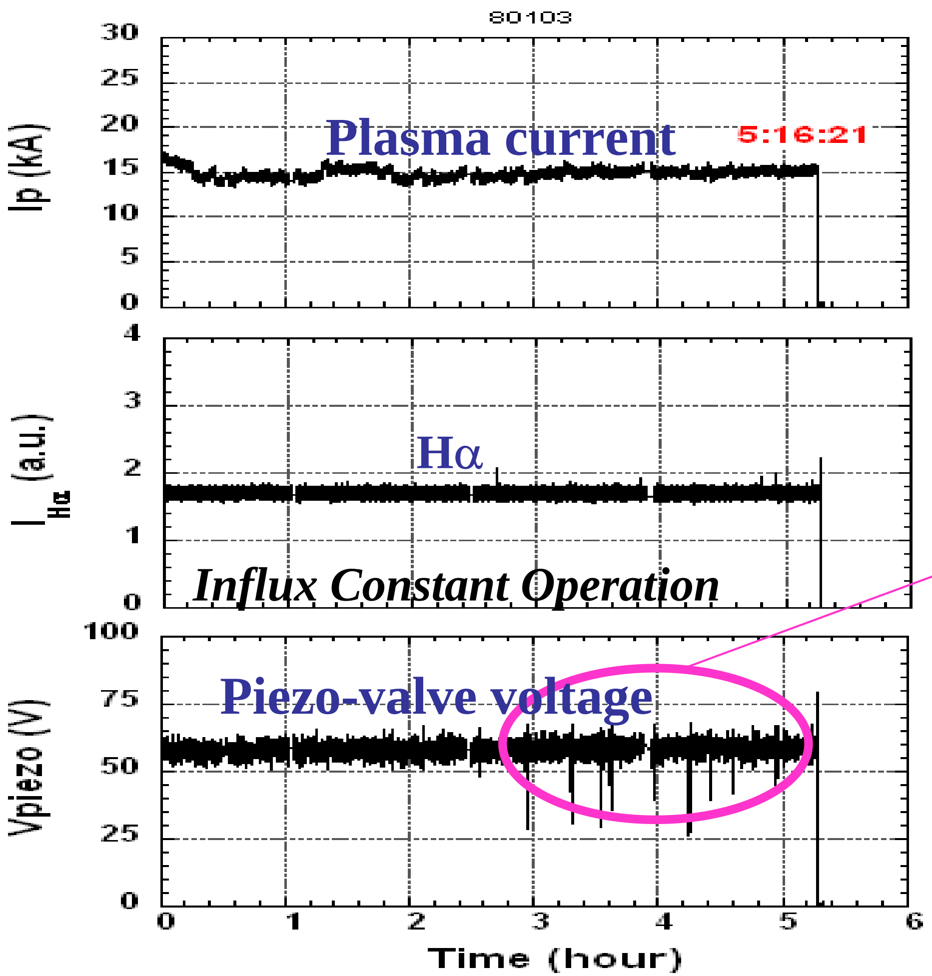
The number of dust particles as a function of discharge duration observed by the high speed framing camera system..

Accumulation of Exp. Results on Long Term Sustained Plasmas
--- Achievement and Understanding of Super Long Duration Discharge ---

TRIAM, Advanced Fusion Research Center

- Achievement of 5 hours 16 min. dis.

(B = 6T, Prf ~ 12kW, ne ~ 1 x 10^{12} cm^{-3})



Key issue for the achievement of super long term discharge is that high power could be injected keeping the wall temperature to be low by using a movable limiter with high heat removal capability.

- **Gas fueling is controlled (by piezo-valve) so as for Hα light to be constant.**
- **It occurs in the discharge period after 3 hours that the piezo-valve automatically close (no gas feeding) during several tens of seconds intermittently.**
- **This means the particle balance is kept constant only by the wall fueling in the latter half of super long term discharge.**

Proposed Steady State Particle Control in New ST Device

- A wall plays a significant role of particle sink and source
- Adsorption by "co-deposition" is infinite
- Control of wall pumping and emission of particles are quite difficult

⇓

- Necessity of "Active Control of Wall"
  ⇒ Recycling rate to be unity by "High Temperature Wall"

⇓

- One of the motivations for the study of "QUEST"
- Necessity of high heat load study

Based on the “Report” :

『FUTURE DIRECTION OF NATIONAL FUSION RESEARCH (Report)』

Working Group on Fusion Research, Special Committee on Basic Issues, Subdivision on Science, Council for Science and Technology (January 8, 2003)

We have decided (in 2003-04)

(1) To shut down TRIAM-1M activity,

(2) To start a new project of long term sustained spherical tokamak (ST) in Kyushu University.

It has been proposed and approved in 2005. The device construction has just been started last year as the first year of three years plan (2005-2007 FY).

Purposes and Particularities of the Project

∗Purposes

(1) Long Term / Steady-State Sustainment of Tight Aspect Ratio Tokamak (Spherical Tokamak)

EBW, NBI, LHCD (low density), CHI, etc.

(2) Investigation on Physics & Engineering of Long Term Sustained ST Plasma (Plasma-Wall Interaction)

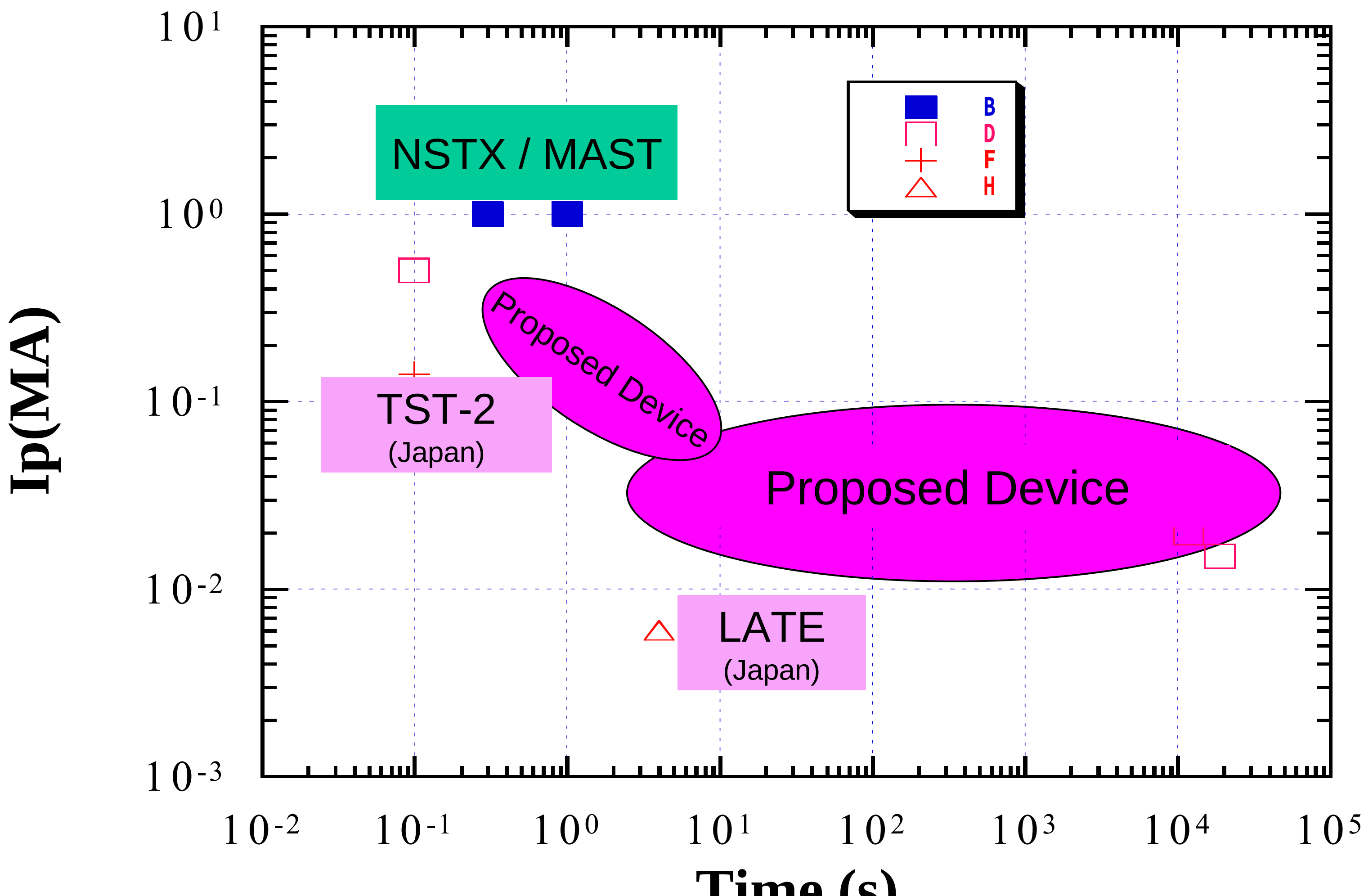
(not in the region of the order of L/R-time, but in the region of much more long duration)

(3) Comprehensive Understanding of Toroidal Plasmas with LHD (in Steady State Plasmas)

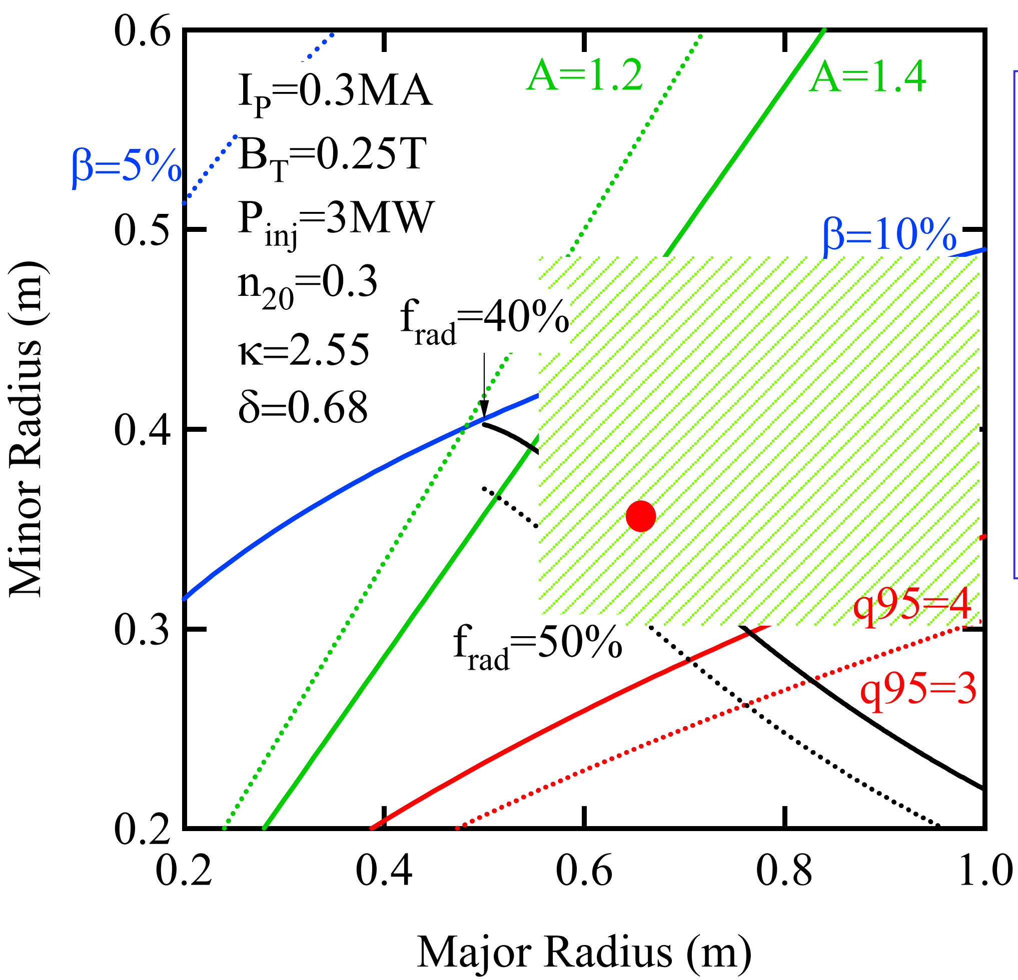
∗Particularities

(1) Large Plasma Volume
(2) High Accessibility / Flexibility ⇒ Active wall temp. control
(3) Low Cost
(4) Large Infrastructure for Exp.

Research Region of the Proposed Device



Choice of the Device Size



Purpose in the 2nd Period

- Plasma current **100 kA** CW
- β-value **10% 1** sec

(Choice of device size relevant to the 2nd period purpose)

Next Project： “QUEST”
Summary of the Device Parameters

∗Objectives

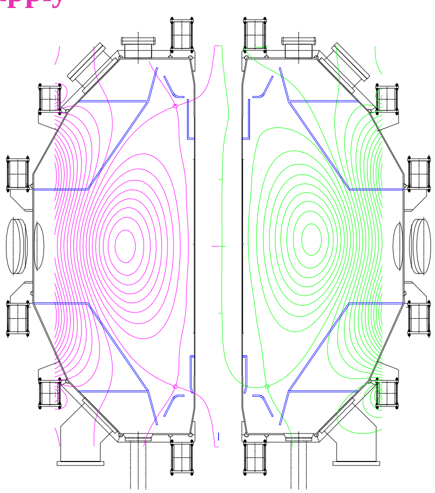
(1) Steady state operation of the low aspect tokamak
EBW, LHCD (low density), etc.

(2) Physics and engineering research on long duration and steady state plasma（PWI）
“Steady state” = Not in the region of O (L/R-time), but L/R-time << τ.

(3) Systematic understanding of the toroidal plasma
with LHD（in Steady State Plasmas）

∗Features

Large plasma volume, Good accessibility, Low cost, Existing RF system, Effective utilization of existing power supply



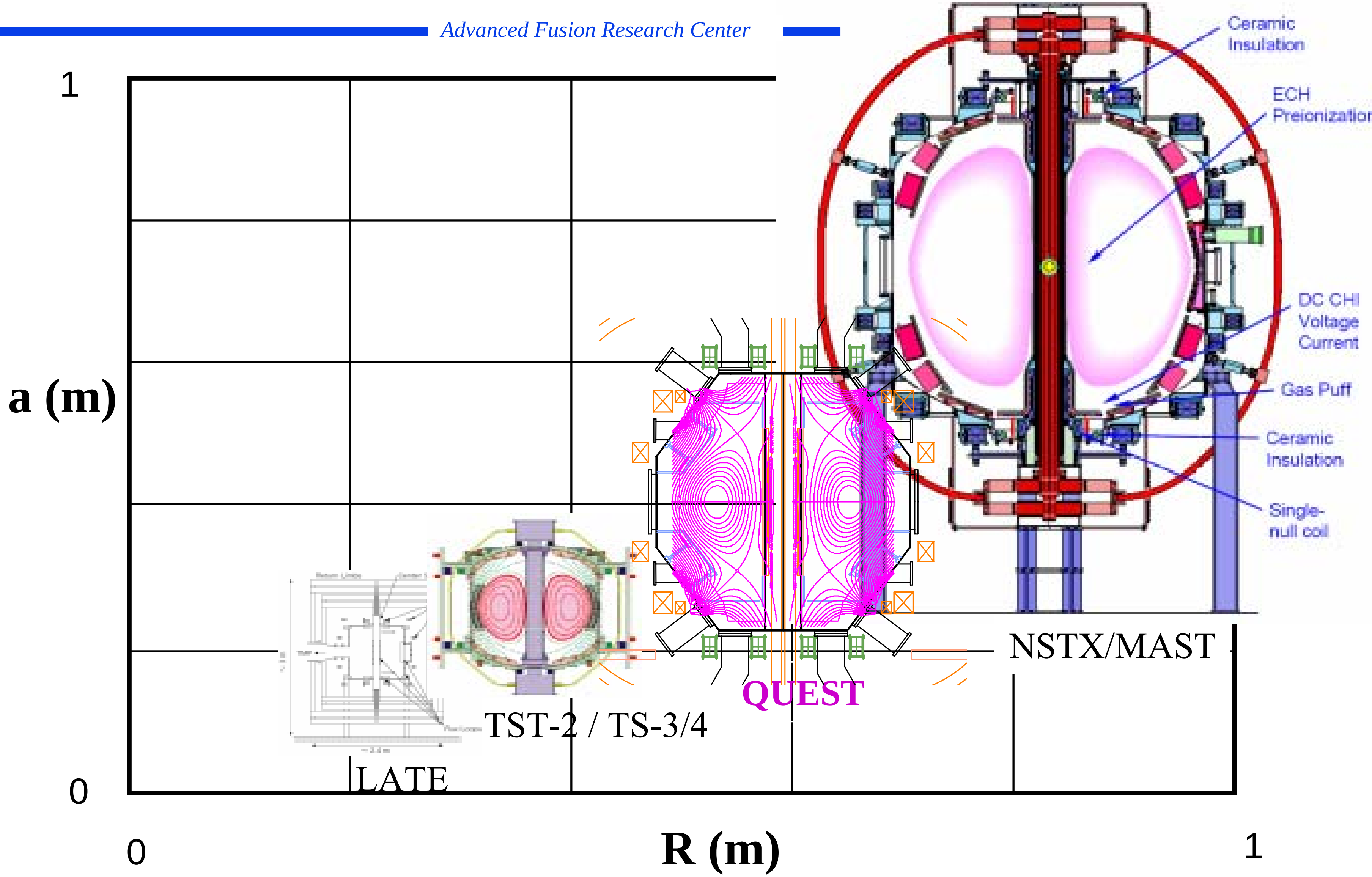
“QUEST” (Qushu Univ. Exp. on Steady-State Spherical Tokamak) proposed and designed. Typical examples of SN and DN configurations

Period	1st	2nd（CW）	2nd（Pulsed）	Final
Major R (m)	0.68			0.64
Minor a (m)	0.40			0.36
Aspect Ratio	1.70			1.78
Radius of V.V.(m)	1.4			
Height of V.V.(m)	2.8			
B_T(T)	0.25	0.25	0.5	0.25
I_p(MA)	～0.02	0.1	0.3	0.5
P_{in}(MW)	0.45	1	3	3
κ	1.6	1.6	1.6	2.5
δ	0.4	0.4	0.4	0.7
$<n_e^{20}>(m^{-3})$	-	0.04	0.3	0.3
$<T_e>$(keV)	-	0.27	0.33	0.54
$<T_i>$(keV)	-	0.27	0.33	0.54
τ_E(ms)	-	1.8	5.5	10.8
β(%)	-	1.4	13	21
β_N	-	1.4	4.2	3.8
β_P	-	0.36	0.35	0.17
q_{95}	-	11.1	3.7	5.0
Γ_H (MW/m2)	-	9.1	13.6	13.6
F_{rad}		20	40	40
Γ_P (Pa m^3/s)	-	20.3	51.0	31.1
f_{GW}	-	0.20	0.50	0.24
I_{BS}(MA)	-	0.008	0.022	0.021
η_{CD}^{19}(A/W/m^2)	-	0.027	0.20	0.32

Comparison of Device Size

QUEST : Q-shu University Experiment on Steady State Spherical Tokamak

Advanced Fusion Research Center



EBW Current Drive

Experimental Observations

- 100kA at 60 GHz 600kW on COMPASS-D
- 8.1kA at 2.45 GHz 35kW, and 15.3kA at 5 GHz 130kW 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

- EBW CD 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 experimental studies are carried out on LATE and TST-2.

Current Drive Methods Expected

Methods	Specification	Current [kA]	Comments
OH	250 mVs	300	Impossible for more than one second
LH	8.2 GHz、0.4 MW	60	Possible by 1 MW (~150 kA)
EBW	8.2 GHz, 0.4 MW Increase up to 1 MW	200	Scaling
NB	30 keV, 2 MW	180	Calculation
		140	Scaling
BS		36	β～20% in pulse case
		1	continuous case

Target Parameters in Each Period

- 1^{st} Period

  Plasma current: 20-30 kA, continuous

- 2^{nd} Period

  Plasma current: 100 kA, continuous

  β-value: ~10 %, 1 sec

- Final Target (Research is only on the elements for targets*)

  β-value: ~20 %, Scientific base for Steady State ST plasmas

*The research will be as scientific and element-research for "Final Target"

Steady State Plasma

Target : 100kA, $0.4\times10^{19}m^{-3}$

Issues 1) Current Drive (100 kA only by RF CD)
2) Density (Pumping ability and particle compression)
3) Heat Load (~1.5 MW/m^2, continuous)
4) Particle Load (~17.5 Pa m^3/s, continuous)

Pulsed Plasma

Target : 300kA, $3\times10^{19}m^{-3}$, β>10%, 1 sec

Issues 1) Current Ramp Up (300 kA only by OH)
2) Density (Required for NBI target)
3) Additional Heating (RF+NBI)
4) Heat Load (~3 MW/m^2)
5) Particle Load (~50 Pa・m^3/s); need wall pumping)

Planning of Divertor Characteristics in QUEST

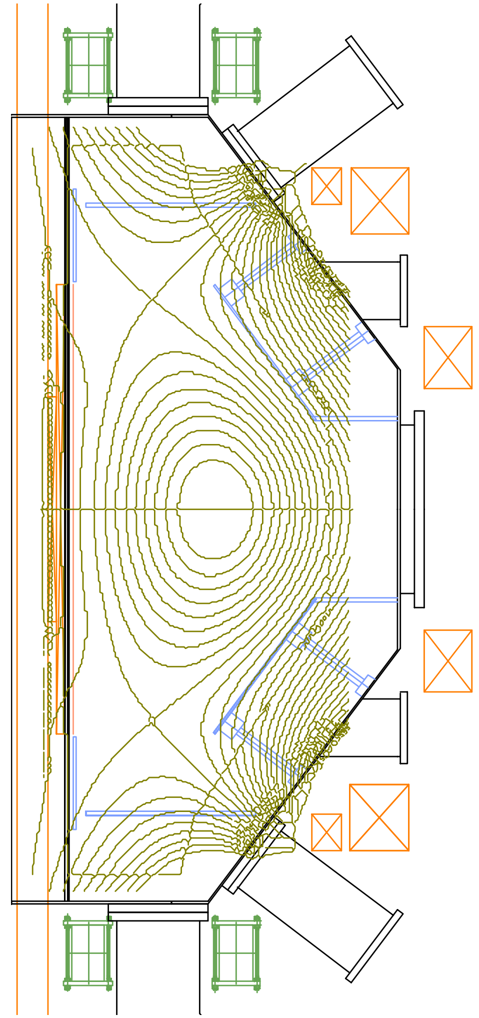
TRIAM, Advanced Fusion Research Center

Planned Parameters

		Unit	1 st Period	2nd (CW)	2nd (Pulsed)
Major R	Rp	m	0.68		
Minor a	a	m	0.4		
b	b	m	0.64		
Aspect Ratio		--	1.7		
V. V. Radius		m	1.4		
V. V. Height		m	2.8		
Plasma Current	Ip	MA	0.02-0.03	0.1	0.3
Elongation (Null point)	κ	--	1.6		
Triangularity (Null point)	δ	--	0.4		
Electron Density (av.)	<ne>	10^20/m3	-	0.04	0.3
Electron Temperature (av.)	<Te>	keV	-	0.27	0.33
Ion Temperature (av.)	<Ti>	keV	-	0.27	0.33
Heating Input	Pinj	MW	1	1	3
Max. Heat Load to Divertor		kW	-	800	-
Heat Flux to Divertor	Γ H	MW/m²	-	4.5	6.8
Max. Heat Load to Linar	Γ H	kW	-	400	-
Radiation Loss	F(rad)	%	-	20	40
Particle Flux to Divertor	Γ p	Pam3/s	-	20.3	51

1st Period：2005 - 2009
2nd Period：2010 - 2014

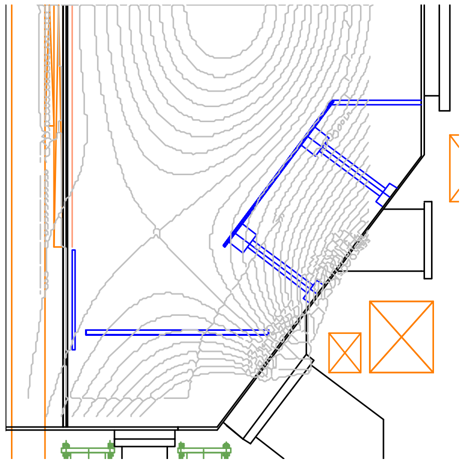
Standard Configuration of DN



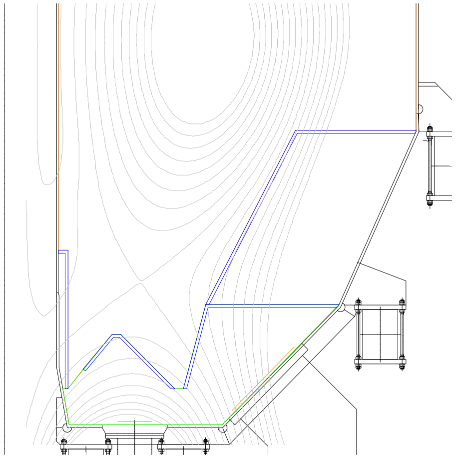
Divertor Planning in QUEST

TRIAM, Advanced Fusion Research Center

1st Period ︰2005 – 2009
Open Divertor (Planar shape)



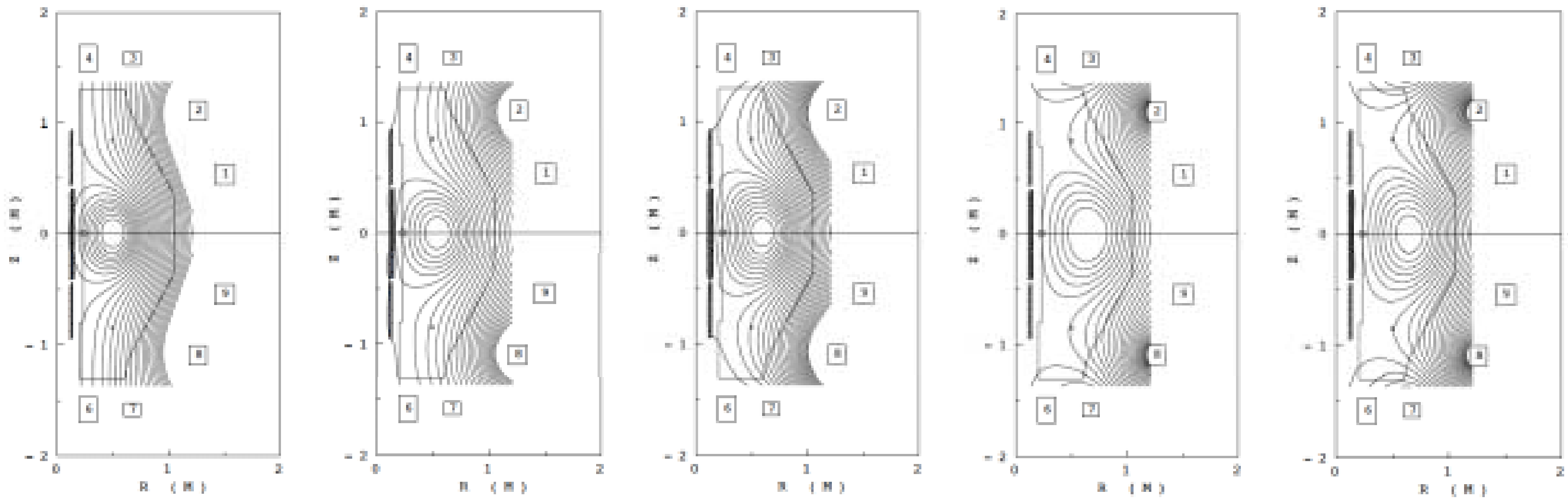
2nd Period︰2010 – 2014
Closed Divertor



Investigation Issue	1st Period					2nd Period
	H17	H18	H19	H20	H21	H22～H26
Conceptual Design of Closed Divertor by SOLDOR	■	■	■			
Diagnostics in Open Divertor				■	■	
Comparison of Open Divertor Results with SOLDOR				■	■	
Engineering Design of Closed Divertor					■	■ (fading)

1st Period ︰2005 – 2009 : Open Divertor (Planar shape)
2nd Period︰2010 – 2014 : Closed Divertor

Time Evolution of Plasma Equilibrium in Start-Up Phase -1



t = 1　　t = 2　　t = 3　　t = 4　　t = 5

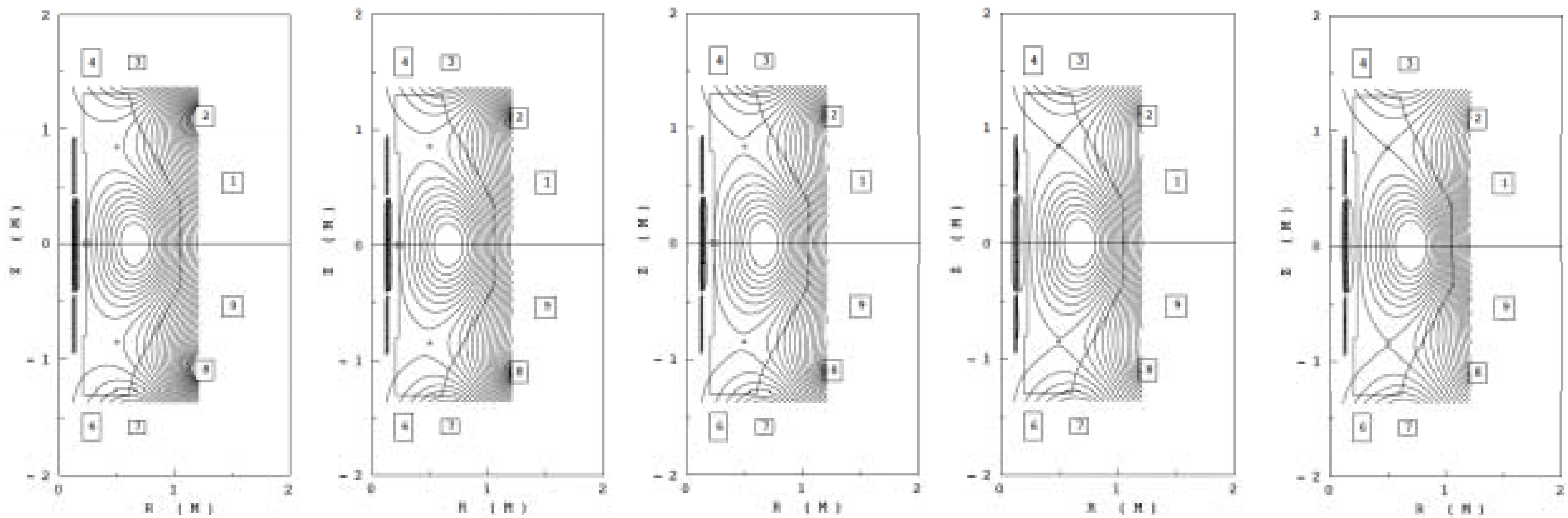
The start-up scenario is shown from κ∼1.3 limiter configuration to κ∼1.8 divertor configuration. The final configuration is with the plasma current of 100 kA, which is the planned value of steady state plasma. Other parameters are βp=0.5, li=0.8, and the DN divertor configuration.

The start-up conditions are as follows:

(1) Start-up with the inner limiter configuration of κ∼1.3, and proceed to divertor configuration.
(2) Gradually increase the elongation in the inner limiter configuration.
(3) Increase the minor radius at the beginning of start-up.
(4) Create an over-sized plasma with the limiter configuration, and proceed to the divertor configuration by decreasing the minor radius and increasing the major radius.
(5) Limiter location is R=23 cm. The coils of PF4-1, 4-2 and 4-3 are in series connection.

Figures show the time evolution of plasma equilibrium in each time step, where smooth transition from the limiter to divertor configuration (between t = 8 and t = 9) is observed.

Time Evolution of Plasma Equilibrium in Start-Up Phase -2

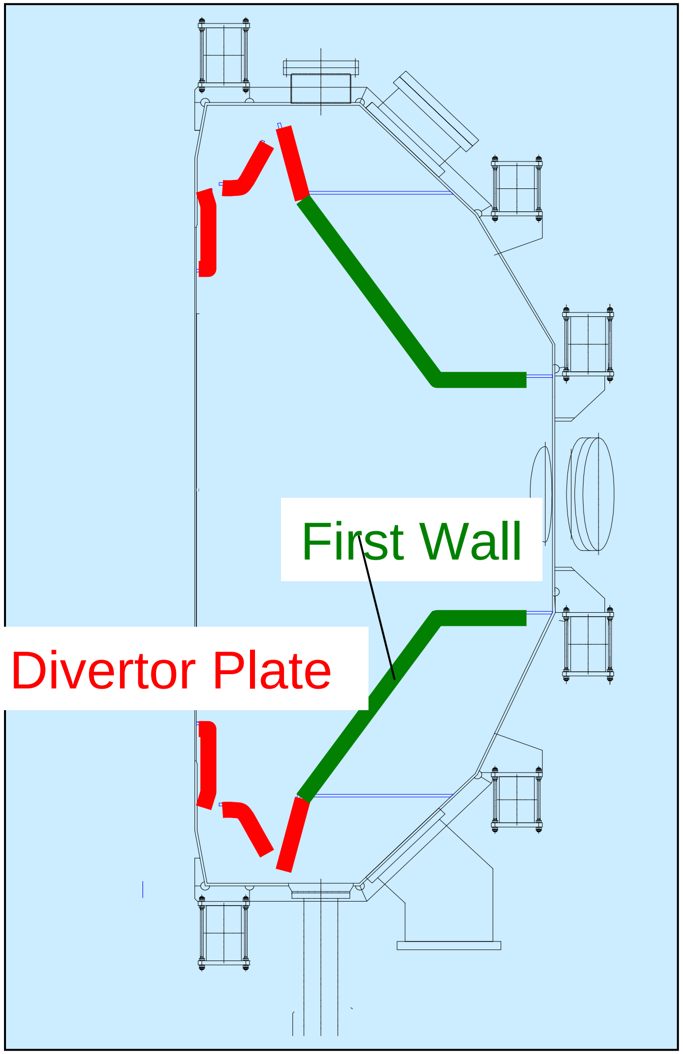


t = 6 t = 7 t = 8 t = 9 t = 10

⇒

limiter to divertor configuration

Actively Controlled High Temp. Wall and Divertor



Impossible by TRIAM-1M

First Candidate

Vacuum Vessel ： SUS304L
(< 100℃)

First Wall： W
(300~500℃)

Divertor Plate： W
(400~500℃)

"Steady State Research on ST (QUEST)"

Core Plasma

- **Current Drive**

  EBW, NBI, LHCD

PWI

- **Sustain a State of Recycling ~ 1**

  First wall → All metal (W wall)

  High temp. wall (～500℃)

  Equivqlent to 800 ℃ of coabon wall

  Divertor with Dome → compression of particles

  High pumping → Supply the amount as pumping

Summary-1 (TRIAM-1M)

◆ **TRIAM-1M Project : Has just finished its operation/mission on Dec. 2005.**

- **Systematic study on plasma-wall interaction in long duration discharges**
- **From the studies on "Super Long Term Discharge" (5 hours 16 min. and others) and PWI, quite important knowledges have been obtained:**

  * Global particle balance is one of the critical issues in the future fusion reactor.
  * Co-deposition effect plays a quite important role for wall pumping even in a metal wall device (though has been well recognized in carbon wall devices).
  * Good agreement of wall pumping rate estimated by macroscopic and microscopic methods : Dynamic Retention ⇔ Static Retention
  * Dust problem will be another critical issue for future devices.
  * There exists a significant difficulty in particle control without the active controlling of wall ⇒ Active wall control experiment in steady state ST

Summary-2 (New Project: "QUEST" - - - ST in Kyushu University)

TRIAM, Advanced Fusion Research Center

∗Purposes

(1) Long Term / Steady-State Sustainment of Spherical Tokamak
EBW, NBI, LHCD (low density), etc.
(2) Plasma-Wall Interaction in Spherical Tokamak
(Physics & Engineering of Long Term Sustained ST)
(3) Comprehensive Understanding of Toroidal Plasmas with LHD

∗Particularities

(1) Large Plasma Volume
(2) High Accessibility / Flexibility ⇒ Active wall temp. control
(3) Low Cost
(4) Large Infrastructure for Exp.

∗Design and Construction Started (2005-07)

∗ Collaboration Research Activity

(1) Domestic (Bilateral + Inter-Univ./ Institute) Collaboration
[NIFS] [RIAM, Kyushu Univ.]
(2) International Collaboration