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

Domestic Collaborators and Map of QUEST

TRIAM-1M

Kyushu U.

NIFS
Outline

• Purpose of QUEST project
• Plan for PWI research
• Plan for Current drive research
• Plan for Divertor research
• First experimental results
• QUEST is the main device for the research of steady state operation in this framework.
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 2 years) 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

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### Schedule and Research items

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Multi-Scale of Plasma-Wall Interaction

Scale

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 \( n_e \sim 10^{18} \text{ m}^{-3} \)

- Gas feed
- Wall pumping \( \sim 1.5 \times 10^{16} \text{ [H/m}^2\text{s]} \)
- Evacuation by pump-unit

High density \( n_e \sim 10^{19} \)

- Wall pumping \( \sim 4 \times 10^{17} \text{ [H/m}^2\text{s]} \)

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.

- 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°C)
First wall : W (300~500°C)
Divertor : W (400~500°C)
Limiter : SUS316L coated by W (300°C)
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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 $N_{\perp}$ and $N_{\parallel}$ 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 \textit{O-X-B conversion scenario}.

Current profile driven in the \textit{O-X-B conversion scenario}.

I_p/P=0.11 A/W is obtained in 100eV, 0.4x10^{19}\text{m}^{-3}.

Capability of EBCD on QUEST

EBCD in W-AS

\( n_e = 10.5 \times 10^{19} \text{m}^{-3} \), \( B_t = 2.15 \text{T} \), \( f = 70 \text{ GHz} \),
\( T_e = 0.8 \text{keV} \), \( I_{CD} = 2 \text{kA} \)
Dimensionless CD efficiency:
\[ \eta = 33 \, n_{20} \, I_A \, R_m / P(W) / T_e(\text{keV}) \approx 0.43 \]

EBCD in QUEST

O-X-B from LHS,
\( n_e = 0.2 \times 10^{18} \text{m}^{-3} \), \( B_t = 0.25 \text{T} \), \( f = 8.2 \text{ GHz} \),
\( T_e = 0.1 \text{keV} \)
Dimensionless CD efficiency:
\[ \eta = 33 \, n_{20} \, I_A \, R_m / P(W) / T_e(\text{keV}) \approx 0.46 \]
New Concept of Phased Array Antenna

16-WR137 inputs with intensity and phase controls

Orthomode Transducer (OMT)

8.2GHz

Polarization control for X/O-mode injection

Control of Incident Polarization and Mode
— Orthomode Transducer —

Control of Incident Angle and Beam Properties
— Phased Array Antenna —
Development of Phased Array Antenna

Experiment in Low Power Test Device

Distribution of E-field [dB]

Ex w/o steering

Ex With steering

QUEST, Advanced Fusion Research Center
## Schedule and Research items

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- **Construction**
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  - pellet

*We are here.*
Plan for divertor and 1\textsuperscript{st} wall

**1\textsuperscript{st} Step (2009-10) (300~500 °C)**

- Flat Open divertor (W)
- High temp. wall
  - Controllability of Magnetic flux
  - Heat and Particle flux
  - Diagnostics
  - Simulation (SOLDOR)

**2\textsuperscript{nd} Step (2011- )**

- Closed Divertor (W)
- High temp. wall
  - Controllability of particle flux
  - Heat and Particle flux
  - Diagnostics
  - Simulation (SOLDOR)

Vacuum Vessel (SUS316L) 150°C
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 handling**
  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**
## Schedule and Research items

<table>
<thead>
<tr>
<th>fiscal year</th>
<th>05</th>
<th>06</th>
<th>07</th>
<th>08</th>
<th>09</th>
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<tr>
<td>items</td>
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<tr>
<td>construction</td>
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<tr>
<td>High $\beta$</td>
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<td>&gt;10% (1sec)</td>
<td>20%</td>
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<tr>
<td>Plasma start-up</td>
<td>RF+OH</td>
<td>RF+OH+NBI</td>
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<tr>
<td>Current drive</td>
<td>RF</td>
<td>RF(8.2GHz)+NBI</td>
<td>16GHz</td>
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<tr>
<td>PWI</td>
<td>W</td>
<td>W, high Temp. wall</td>
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<td></td>
<td>Control of Recycling</td>
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<tr>
<td>Divertor</td>
<td>open</td>
<td>closed</td>
<td>advanced</td>
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<td>fueling</td>
<td>Gas puff</td>
<td>CT injection</td>
<td>pellet</td>
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</tbody>
</table>

We are here.
PF coils layout and connection

PF3-1
PF4-1
PF6
PF7
PF3-2
PF5-1
PF4-2
PF2
PF4-3
PF1
PF5-2
PF3-1
PF4-1
PF6
PF7
PF3-2
PF5-1
PF4-2
PF2
PF4-3
PF1
PF5-2

Series Connection
Cancel coil
First formation of Tokamak configuration
[QUEST] Formation of closed flux surface in OH + RF

#1450

-10  -5  0  5  10
Ip[kA]

0.48675sec  0.4923sec  0.49365sec  0.49875sec  0.50595sec

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

#1456

[QUEST]

- RF power [kW]
- Time [sec]
- CS [kA]

Graphs and images showing the evolution of Ip, Cs, and RF power over time. Times marked are 0.49 sec, 0.5025 sec, 0.50385 sec, 0.505275 sec, and 0.53 sec.
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

$\sim 1.5 \times 10^{16}$ 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

Parameters:
- $I_p = 0.3$ MA
- $B_T = 0.25$ T
- $P_{inj} = 3$ MW
- $n_{20} = 0.3$
- $\kappa = 2.55$
- $\delta = 0.68$
- $f_{rad} = 40\%$
- $f_{rad} = 50\%$
- $q_{95} = 4$
- $q_{95} = 3$

$\beta = 5\%$
$\beta = 10\%$
$A = 1.2$
$A = 1.4$

IP = 0.3 MA
BT = 0.25 T
Pinj = 3 MW
$\nu_{20} = 0.3$
$\kappa = 2.55$
$\delta = 0.68$
$frad = 40\%$
$frad = 50\%$
$q_{95} = 4$
$q_{95} = 3$
0.494secのときのnull点(0.41,-0.02)点
上下非対称性は渦電流の非対称性による。
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

![Diagram of plasma start-up scenario II](image-url)
Heating and Current drive

- Power and Required current drive efficiency
  
  Phase I  20-30kA at low density
  
  RF (0.45MW)
  
  Phase II (SS)  \(0.026 \times 10^{19} \text{ A/W/m}^2\)
  
  RF (1MW) \+[ NB (2MW) ]
  
  Phase II (1sec)  \(0.19 \times 10^{19} \text{ A/W/m}^2\)
  
  RF (1MW) + NB (2MW) with OH
Steady state chemical burning

CO₂, heat, light

Up stream

Chemical Reaction

Power deposition

Transport

Fueling

Reaction control and particle handing are important.
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
PF4-123CC (1 turn): 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

**#1456**
Sperical toksmaks (ST) have the possibility to realize cost-effective fusion power plants. High $\beta$ ($\sim 10\%$) 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 $\beta$
- Particle and heat handling
- Innovative concept

Mainly focus on the technological issue for SSO
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 handling

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

Density and Temperature distribution along outer divertor plate

Temperature distribution

Comparison with experimental data on the flat divertor
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
EBWCD

Experimental Observations

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

Simulation

- 30 kA at 15 GHz, 1 MW 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.
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。
• 40keV NB can be deposited at $3 \times 10^{19} \text{m}^{-3}$.
• 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.
Outline of divertor (under consideration of best position of poloidal field coils)

<table>
<thead>
<tr>
<th>位置</th>
<th>ポンプ</th>
<th>単体排気速度 m³/s(H₂)</th>
<th>台数</th>
<th>総排気速度 m³/s(H₂)</th>
</tr>
</thead>
<tbody>
<tr>
<td>下部</td>
<td>TMP</td>
<td>~2.3</td>
<td>6</td>
<td>13.8</td>
</tr>
<tr>
<td>下部</td>
<td>CRYO</td>
<td>10</td>
<td>4</td>
<td>40</td>
</tr>
<tr>
<td>上部</td>
<td>CRYO</td>
<td>10</td>
<td>4</td>
<td>40</td>
</tr>
</tbody>
</table>

（上部排気にに関しては設置予定）

Steady state operation
P=0.1 (Pa)
=> 9.4 (Pa m³/s)

Pulse operation
P=1 (Pa)
=> 94 (Pa m³/s)
Thermal desorption of D from W

Twall = 300°C

Twall = 600°C

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 x 10²⁰ and 2.0 x 10²¹ He⁺/m² at room temperature.

He – irradiation
D-Fluence

Iwakiri, Yoshida  JNM (2000) 1134