Divertor simulation and PWI study using linear devices towards DEMO

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(alphabetical sequence)
Researches on plasma confinement devices such as tokamaks and stellarators are important to design and operate ITER and DEMO, since the topology of the magnetic field plays an important role and non-linear dependence between wall and plasma performance must be addressed.
Power & Particle Handling

- **Power handling** has a direct impact on machine protection.
  - Need to disperse the power

- **Particle handling** relates to plasma performance.
  - Need to concentrate the particles

Compatibility of power and particle handling is crucial for steady state operation.

*ITER*

100 MW

10 MW/m²
  (stationary)

20 MW/m²
  (non-stationary)

*DEMO*

500 MW

< 8 MW/m²
  (SlimCS*)

*Photo: © EFDA-JET*
There exists a large step towards DEMO

A large step from now to ITER and DEMO

<table>
<thead>
<tr>
<th></th>
<th>JET</th>
<th>ITER</th>
<th>DEMO*</th>
</tr>
</thead>
<tbody>
<tr>
<td>P/R (MW/m)</td>
<td>11</td>
<td>25</td>
<td>94-130</td>
</tr>
<tr>
<td>W_{th}/R (MJ / m)</td>
<td>3</td>
<td>60</td>
<td>125-395</td>
</tr>
<tr>
<td>operation time (s/ yr)</td>
<td>$4.0\cdot10^4$</td>
<td>$4.0\cdot10^5$</td>
<td>$2.4\cdot10^7$</td>
</tr>
<tr>
<td>Averaged neutron fluence (FW) (MW a / m²)</td>
<td>~0</td>
<td>~0.3</td>
<td>~10</td>
</tr>
<tr>
<td>T_{wall} (K)</td>
<td>500</td>
<td>500</td>
<td>1000</td>
</tr>
</tbody>
</table>

*Range given by different models within EFDA-PPCS (2005) [D. Maisonnier et al 2007 NF 47 1524]

- **New challenges for all issues related to** fluence, neutron damage and wall temperature (last two will indirectly affect all others via material issues)
Neutron compatibility will be required

Requirements for plasma facing materials:

- Plasma compatible (radiation/dilution)
- High heat exhaust capability
- Neutron compatibility
- High melting temperature
- Large thermal conductivity
- Low erosion (sputtering, evaporation)
- Low T retention
- Large operational temperature window
- High fracture toughness (ductility)
- Compatible with coolant and other PFCs
Road Map to DEMO

Integrated performance

ITER & DEMO

Plasma Confinement Devices

“Complementary studies”

Linear Plasma Devices

ITER 2021~

Construction

Design of DEMO

ITER

DEMO

ITER & DEMO Contribution

DEMO

Steady State Operation

What is necessary?

Extrapolation using simulation

Fundamental study

Innovation

New findings

ITER & DEMO

2nd IAEA DEMO Workshop, Dec. 2013
Linear plasma devices for divertor simulation and PWI in the world

DIFFER
MAGNUM-PSI
PILOT-PSI

FZ Juelich
PSI-2, JULE-PSI

ORNL
MPEX

UCSD
PISCES A
PISCES B

INL
TPE

MIT
DIONISOS

SCK-CEN
VISION I

NFRI, Molten salt
HEPRC, HEPTF

ANU
MAGPIE

Univ. Tsukuba, GAMMA10/PDX, APSEDAS
Nagoya Univ., NAGDISII, NAGDIS-PG
PS-DIBA

NIFS, Vehicle-1
Univ. Tokyo, MAP-II
Osaka Univ. HiFIT
Aichi Inst. Tech., AIT-PID
Tohoku Univ., DT-ALPHA
Tokai Univ., TPD-SheetV
Shinshu Univ., Kanazawa Univ

2nd IAEA DEMO Workshop, Dec. 2013
Excellent researches on divertor simulation and PWI have been done in linear plasma devices by utilizing characteristics (uniqueness and innovative ideas) of each device.

**Existing devices for example**
- PISCES-B: Beryllium
- MAGNUM-PSI, PILOT-PSI: High B field and transient heat load
- TPE: Tritium and radioactive material
- NAGDIS: W nanostructure, arcing etc.
- PS-DIBA: In situ measurement of dynamic & static retention
- GAMMA 10/PDX: High ion temperature

**New Project**
- JULE-PSI (FZ-Juelich)
- MPEX (ORNL)
- Japanese activity under NIFS bilateral collaboration (Nagoya Univ., Tohoku Univ., etc.)

Ref: N. Ohno, PMIF 2013
Tungsten nanostructure (fuzz) was firstly found in linear plasma devices

NAGDIS-II

Incident ion energy and W temperature are critical parameters for formation of nanostructure.


2nd IAEA DEMO Workshop, Dec. 2013
Formation conditions are well identified by experiments in linear plasma devices. Surface Temp: $1000 \text{ K} < T < 2000 \text{ K}$

Ion Incident Energy $>20 \text{ eV}$


Nanostructure thickness grows with $t^{1/2}$.

Formation conditions well identified by experiments in linear plasma devices

Surface Temp: $1000 \text{ K} < T < 2000 \text{ K}$
Ion Incident Energy $>20 \text{ eV}$


DEMO operational region
Effect of ELM-like transients

Continuous plasma with transient heat and particle

- Nanostructure was disappeared after only one plasma pulse for energy densities higher than 0.5 MJ/m².
- No material loss was observed.
- T~673 K before transient

G. De Temmerman et al., JNM 438 (2013) S78.

Magnetized coaxial plasma gun

- Single D plasma shot with 1.1 MJ/m².
- Mass loss was detected and it increased with the energy of the pulsed plasma.
- Melting and arc tracks were observed on the top surface.
- T~300 K before transient

Formation of W nanostructure leads to cooling of W target

- W surface temperature decreased as nanostructure was formed on the surface. Total emissivity increased from 0.18 (non-damage) to 0.45-0.55 (nanostructure).
- The cooling comes mainly from an increase in the total emissivity of blackened tungsten. In addition, a deepening of floating potential due to suppression of secondary electron emission also contributes to such a temperature reduction.

Plasma detachment was firstly demonstrated in a linear plasma device.

Radiation transport will play a significant role in DEMO

In the case of high density divertor plasma like DEMO (i.e. \( > 10^{21} \text{ m}^{-3} \)), the radiation transfer will play a significant role, since the plasma will be optically thick. The mean free path for L\( \alpha \) photons can be shorter than 0.2 mm.

Effective ionization rate coefficient will be increased and radiation cooling will be reduced. Small uncertainty of prediction of \( P_{\text{rad}} \) leads to large effect on target heat load.

Fundamental study using a linear plasma device is important for validation of the model and getting an accurate database, since the plasma is well defined.

2nd IAEA DEMO Workshop, Dec. 2013
Process of decreasing in electron and ion temperatures in SOL & divertor region and effect of transient plasma event like ELM are important to study the divertor detachment.
Features of GAMMA 10/PDX for PSI & Boundary Plasma Research

- There exists the plasma confinement region. (core-edge coupling)
- High Ion and electron temperatures (Te: ~50eV, Ti: 50~400eV)
- High magnetic field (0.15 ~ 1.5 T)
- Large plasma size (0.1~ 0.3 m)
- ELM simulation can be done by control of the thermal barrier.
Unique experimental capabilities

Magnum-PSI is operational and routinely produces ITER (and DEMO)-like plasmas

Asset: Magnum is unique to evaluate the impact of intense plasma flux, transient plasma events, long pulses and high temperature on the performance of materials and designs.
DEM0 related research

✧ 3 main lines of research related to power/particle exhaust for DEMO
✧ Behavior of solid materials under high flux/high fluence
  ✧ Surface evolution and influence on power exhaust under ion irradiation
  ✧ Diffusion/trapping of deuterium under high fluence, high temperature

✧ Assessment of power exhaust capabilities of liquid metals
  ✧ Use of realistic environment (high density divertor-like plasma)
  ✧ Understanding of power exhaust and material transport (erosion, re-deposition)

✧ Understanding of plasma detachment through advanced diagnosis
  ✧ Exploit similarities between Magnum plasma and DEMO divertor to understand the basic processes causing detachment
  ✧ Develop novel diagnostics (CTS) to provide fully diagnosed plasma for benchmarking of fluid codes (SOLPS, or other)

2nd IAEA DEMO Workshop, Dec. 2013
**PWI study of neutron-irradiated material**

Dedicated PMI studies are necessary for unprecedented operational conditions in DEMO. (e.g. neutron irradiation)

So far, TPE in INL has provided results of H isotope retention in neutron-irradiated W. (Japan-US TITAN project, subsequent project; PHENIX)

In PISCES-A, thermo-mechanical properties of damaged W surface and also high fluence erosion of EUROFER have been studied.

**IAEA CRP** on “Plasma-Wall Interaction with Irradiated Tungsten and Tungsten Alloys in Fusion Devices” has just started. ([https://wwwamdis.iaea.org/CRP/IrradiatedTungsten/](https://wwwamdis.iaea.org/CRP/IrradiatedTungsten/))

Some linear plasma devices join this CRP.
- TPE (Idaho National Laboratory)
- PSI-2 (FZ Juelich)
- LENTA (Kurchatov Institute)
- APSEDAS (Univ. of Tsukuba)

Depth profiles of D in non-irradiated and n-irradiated W specimens.
International Research Center for Nuclear Material Science (IRCNMS), Institute for Materials, Tohoku Univ. has a long history to conduct neutron irradiation tests using nuclear reactors overseas (BR2) as well as in Japan (JMTR, JOYO, JRR-3) → Many neutron-irradiated samples already exist in IRCNMS

A compact divertor simulator with a TDS device is constructing in Nagoya Univ (Prof. Ohno).
A new laboratory for plasma facing materials under extreme loads

Synergistic effects govern behaviour of PFM.

Hot Material Laboratory: controlled area, Hot Cells

Unique features at FZJ
Existing and planned facilities in the Hot Material Laboratory at FZJ

Plasma facility

- **Steady-state linear plasma generator** (B=0.2 T)
- Loading conditions (deuterium plasmas), with target biasing
  - \( q = 0.1 - 2 \text{ MW m}^{-2} \), simulation of transients by laser irradiation (40 J / 1ms)
  - \( n_e = 10^{17} - 10^{20} \text{ m}^{-3} \)
  - \( T_e \) up to 20 eV (\( T_i \sim 0.5 T_e \))
  - \( E_{\text{ion}} = 10\text{-}200 \text{ eV (biasing)} \)
  - \( \Gamma_{\text{ion}} = 10^{21} - 10^{23} \text{ m}^{-2}\text{s}^{-1} \)
  - \( F = 10^{27} \text{ m}^{-2} \) in 4 h
  - \( \Delta_{\text{flow channel}} \sim 6 \text{ cm} \)

*Pilot experiment PSI-2*

Linear plasma device JULE-PSI (inside Hot Cell) with integrated target analysis and exchange chamber (laser based surface diagnostics), end of 2015
Path to MPEX in phases

Source development:

• Individual high density production with Helicon source and electron heating (via Electron Bernstein Wave) experiments

• Phase I:
  – Combine helicon antenna and electron heating experiments
  – Proof of principle of MPEX source

• Phase II: Proto-MPEX
  – Integrated prototype high intensity plasma source test
  – Effect of recycling at target on open system and allow a transport region to be added between the source and target to examine creation of electron temperature and density gradients between source and target

Next step:

➢ Development of target chamber
Development of target station for the exposure of neutron irradiated samples

Material neutron irradiation in HFIR or SNS and subsequent plasma exposure in MPEX

Challenge:
- Minimize rad inventory in MPEX and cool down periods
Importance of advanced PWI study

**Novel compact and powerful dc plasma source** + **Ion beam analysis NRA, RBS, ERD**

**In-situ measurement of surface and hydrogen isotope retention during plasma exposure with ion beam analysis**

**Plasma Surface Dynamics with Ion Beam Analysis (PS-DIBA)**
Static and dynamic retention in W can successfully be evaluated as well as C.

Static retention decreases with surface temperature. More experiments are necessary.

There exists a large step from now through ITER to DEMO.

Predictive modeling and simulation must be developed to extrapolate to DEMO. Accurate database for simulation and accuracy validation of the modeling are necessary.

How to investigate divertor and PWI aspects for DEMO?

--- To use linear plasma devices and open systems

- Well controlled and well defined plasma parameters
- High reliability and reduced technical complexity
- Steady state operation
- Good access to plasma and PSI area with dedicated diagnostics
- New findings and innovative concept
- Cost effective