Tritium management in a fusion reactor

- safety, handling and economical issues -

Tritium must be physically contained and safely confined

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Organizer
Grand in Aid for Scientific Research, MEXT, Priority area No.467
Tritium Science and Technology for Fusion
http://tritium.nifs.ac.jp/

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2nd International ITER Summer School, Kyushu Univ. July 22-25, 2008

Scientific Research in Priority Ar
Tritium for Fusion

A new research project for tritium for fusion has started in Japan

DT fusion reactor (Ignition and continuous burning)

$D + T = {}^{3}He\ (3.7MeV) + n\ (14MeV)$

To establish reliable and safe tritium fuel cycles and safe tritium confinement to build economic and safety fusion reactor

Encouraging yang scientist and students

Scientific Research in Priority Ar
Tritium for Fusion

Grant in Aid for Scientific Research

Tritium Science and Technology for Fusion Reactor

Organizer Professor Tetsuo Tanabe
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Research purpose

The main aim of this project is to establish tritium safety in a D-T fusion reactor. Since huge amount of radioactive tritium must be introduced into the reactor as a fuel, we are facing to lots of safety concerns newly appeared to be solved.

Main efforts will be to establish tritium safety in (1) a fueling system keeping continuous D-T burning, (2) tritium exhausting, recovering and refining processes, (3) a tritium breeding system with a breeding rate over 1.05, and (4) tritium monitoring and accounting systems.

In addition, easy isotopic exchange reactions of tritium with hydrogen in water and hydro-carbons result in the contamination of the systems, which require decontamination techniques. The project also aims to provide new insights into basic tritium science and technology.

Why we started new research projects for tritium in fusion

Limited resource requires safety T breeding system compatible with power production

Reactor

- **Recycling of fugue amount of T**
- **Safety confinement and possible contamination**
- **Difficulty of extrapolation of limited experience of T handling to fusion system**
- **Poor understanding of isotope effect**

Production of hazardous inorganic tritium

Contamination by permeation and leakage

Multi step contamination

Safety Confinement for regulation by Containment Physically & Chemically

ITER at France and a Test reactor in Japan require large numbers of tritium experts.

Already 50 years has passed after finding nuclear reactions give energy.

Fission reactors are already established as energy sources.

Why much longer time has been required for fusion than fission?

Significant amount of energy is required to overcome Coulomb potential.

The first priority has been plasma confinement to establish DT burning, and we will soon attain Q=10 in ITER.

But this is not enough for a fusion reactor to be an energy source!!.

Lots of engineering issues are remained to be solved.

Tritium safety is one of them.

Comparison of fission and fusion as energy sources

In a fission reactor, energy conversion, fuel breeding, waste-confinement in fuel pins of diameter

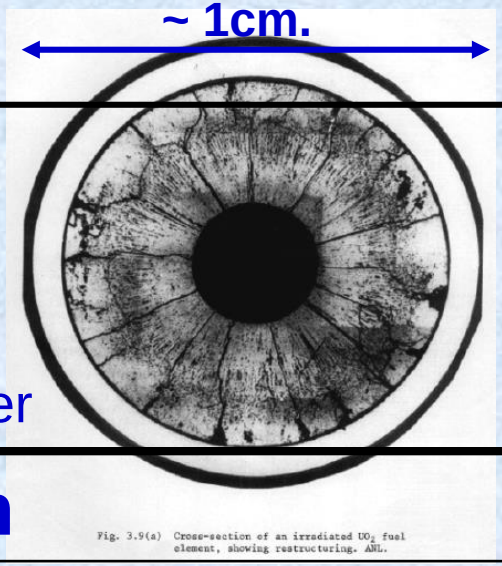
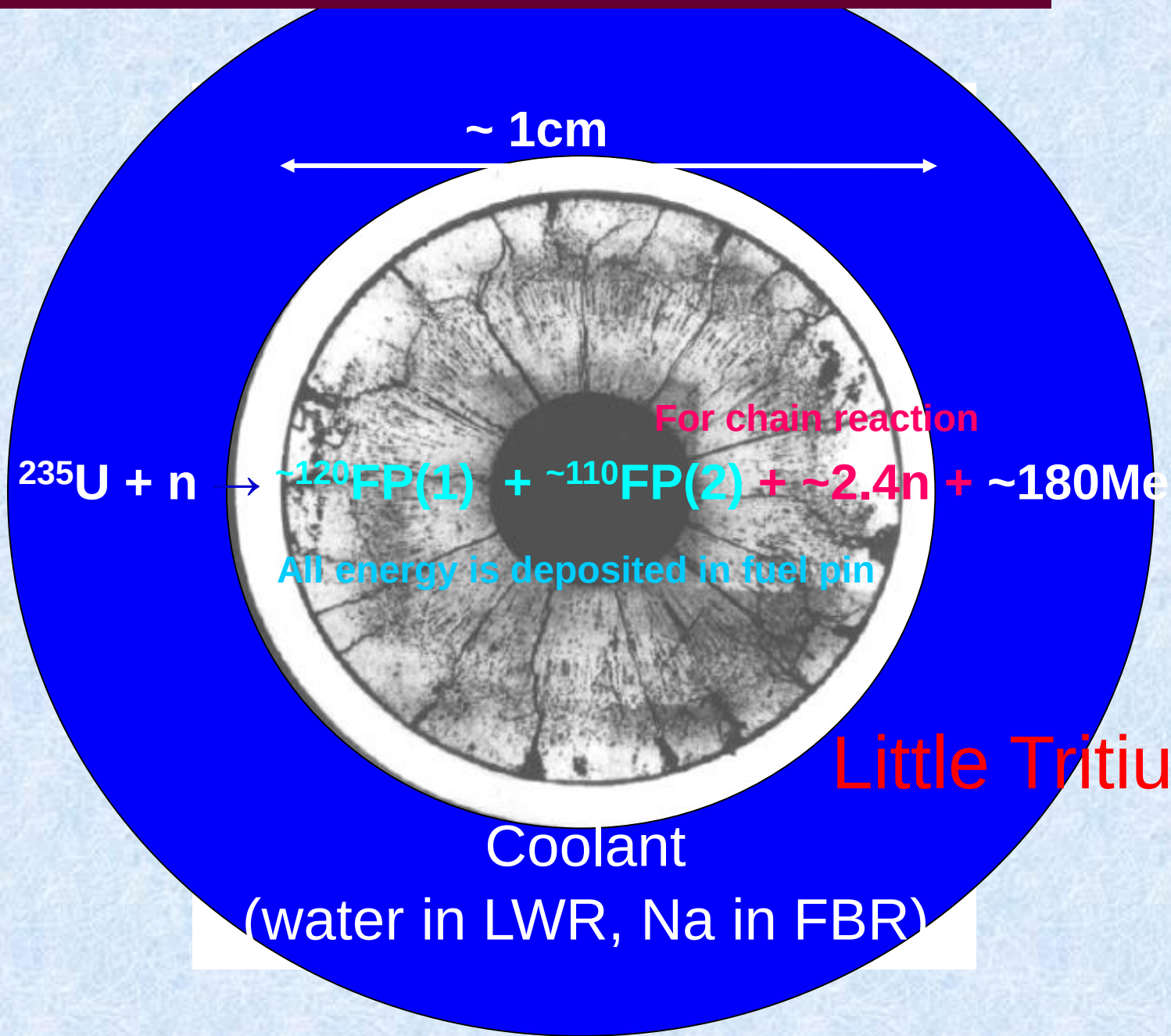


Fig. 3.9(a) Cross-section of an irradiated UO_2 fuel element, showing restructuring. ANL.

Fusion reactor is an open tritium handling system with a huge volume, which will be discussed today.

	Fission	Fusion
Energy Input	Nearly zero	Huge energy required Poor fueling efficiency
Energy conversion	Energy carried by fission products (FP, heavy ions) (~170MeV) is deposited in fuel pins.	Energy carried by neutron (14MeV) must be converted in large volume of blanket system
Fuel breeding and recovery	One fission produces more than 2 neutrons, easy to keep chain reactions and to breed fuels. Fuel pins retain both FP and new fissile and spent fuels are reprocessed to remove/recover them.	To keep breeding ratio more than 1, we need neutron multipliers (Be, Pb). Tritium breeding and energy conversion must be done simultaneously.
Nuclear Waste	Long life radioactive FPs must be handled with special care and will be reposed deeply under ground.	Waste is limited to activated structure materials, could be recycled.

Cross section of Fuel pin for FBR



Hydrogen related 5 fusion reactions

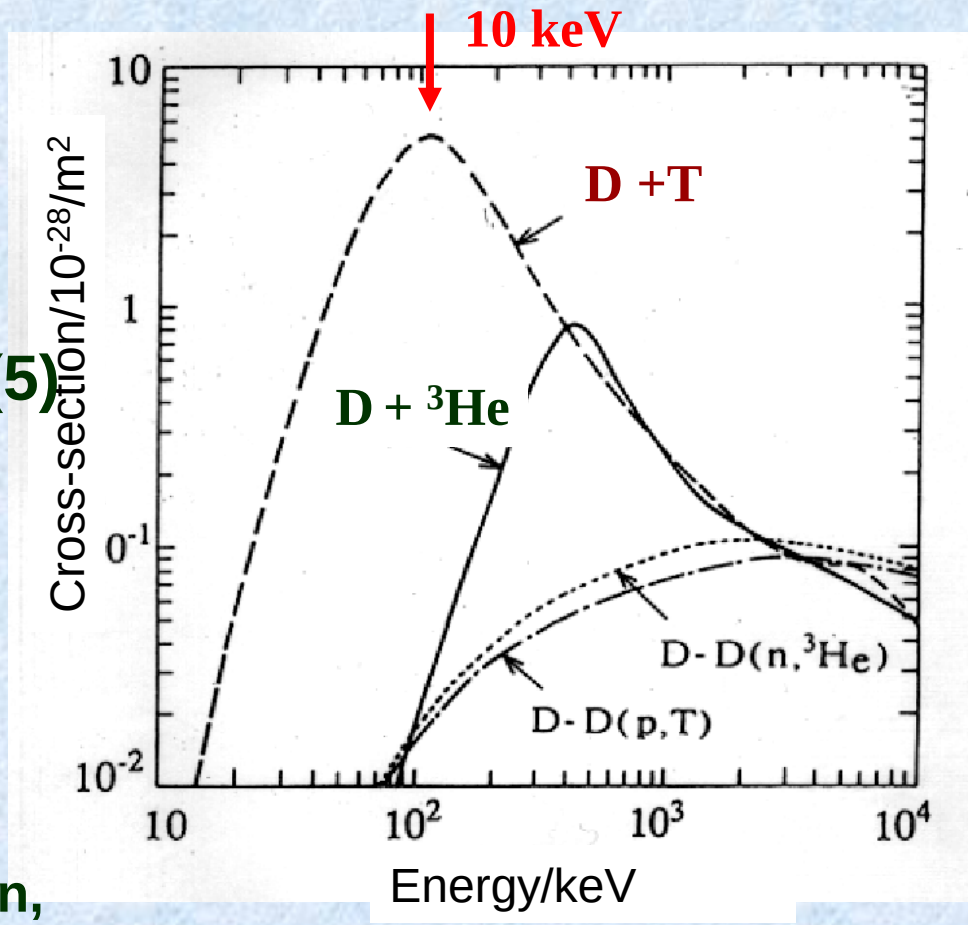
$D + T \rightarrow {}^4He + n + 17.6MeV$ (1)

$D + D \rightarrow T + H + 3.98M$ (2)

$D + D \rightarrow {}^3He + n + 3.25MeV$ (3)

$T + T \rightarrow {}^4He + 2n + 11.3MeV$ (4)

$D + {}^3He \rightarrow {}^4He + H + 18.3\ MeV$ (5)



Among above fusion reactions technically most suitable is the DT reaction (1)

The D ^{3}He reaction is very much attractive for no neutron production, though accompanying DD reactions do produce it.

We do not have enough T; need T breeding

$$D + T \rightarrow {}^{4}He\ (3.5MeV) + n(14.1MeV)$$

plasma heating Energy and T breeding

– Deuterium can be extracted from natural water (SMOW (standard mean ocean water) contains 0.016% D)

– Tritium must be imported (limited) or bred internally from lithium

- 56 kg tritium is required per GW year (thermal) of fusion power
- About 100 g tritium is produced per year in a standard CANDU fission unit
- 20 to 25 kg tritium (mainly in Canada) will be available for operation of ITER
- Tritium must be bred by reactions in blanket systems

$${}^{6}Li + n \rightarrow T + {}^{4}He + 4.8MeV$$

$${}^{7}Li + n \rightarrow T + {}^{4}He + n - 2.5\ MeV$$

$${}^{9}Be + n \rightarrow 2n + 2\ {}^{4}He - 2.5\ MeV$$

$${}^{A}Pb + n \rightarrow 2n + {}^{A-1}Pb - 7\ MeV$$

- Overall breeding ratio is expected to be above ~1.1 (must)

Very hard to attain

Fusion Safety Issues (General)

Mostly owing to Tritium and neutron activated materials

- **The Fusion Process Is Inherently Safe**
  - **No chain reaction**
  - **Reaction is thermally self-limiting**
  - **Limited to a few second burn without re-fueling**
  - **Power/energy densities in the reactor and plasma are low**
  - **Reaction products**
    - **Helium (totally inert)**
    - **Neutrons**
      - **Used to breed tritium**
      - **Absorbed in the surrounding material**

- **Most serious hazard involve the tritium fuel and activated dust from erosion of plasma facing components**

- **Hazard and Containment**
  - –Principle of defence-in-depth
    - Vacuum vessel
    - Cryostat
    - Building ventilation systems (sub-atmospheric condition)
  - –Passive safety features (natural physics) are used as extensively as possible
    - In case of active cooling system failure, decay heat from activated materials is low enough that all in-vessel components can be cooled by natural convection
    - Reactor “melt-down” is physically impossible
- **Environmental Impact**
  - –Currently, materials are not optimized for low-activation under neutron irradiation
    - Can be recycled for re-use after 50-100 years
  - –In the future, material optimized for low-activation can be readily recycled for use in fusion power-plant reactors.

- **Public Safety**

  (Emission of Tritium As Low As Reasonably Achievable (ALARA)

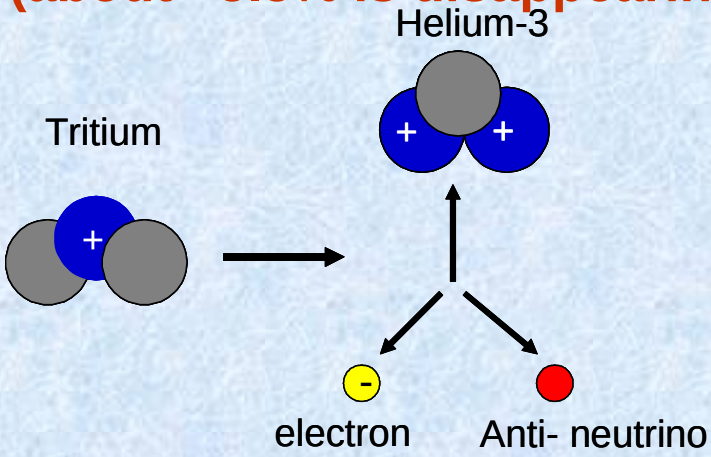
  - **Under normal operation:**
    - **Total releases will cause doses below 1% of that of natural background radiation: ~ 2 mSv/year, or 200 mrem/year.**

  - **Under the worst case, the most severe hypothetical event, the holy-Moses-oh-my-God-we-are-all-done-for scenario:**
    - **Fusion reactor site boundary dose will be less than 50 mSv (5000 mrem).**
    - **In comparison: 50 mSv/year is the US NRC dose limit for adults working with radioactive material.**
    - **In comparison: 100 mSv is considered "low-dose"; correlation with adverse biological effect (e.g. cancer) currently could not be established.**
    - **In comparison: Plant workers and fire fighters battling the fire at Chernobyl received 700~13400 mSv of radiation; 20% of them died from radiation effects.**

Concerns are coming from Tritium and activated materials

Tritium ($^3T \rightarrow {}^3He + \beta$ electron)

Half life $t_{1/2}$ = 12.323 ∓ 0.004 years
(about ~5.5% is disappearing in a year)



Maximum range of electron

Air 6mm

Metals <~1μm

Shielding of tritium radiation is not really a issue (Except direct exposure of organs)

- Electrons emitted to neighboring molecules would enhance some chemical reactions.
-Effect of self irradiation would appear only at very high conc.
-Decay heat : 324 mW/1g could enhances T release from solid

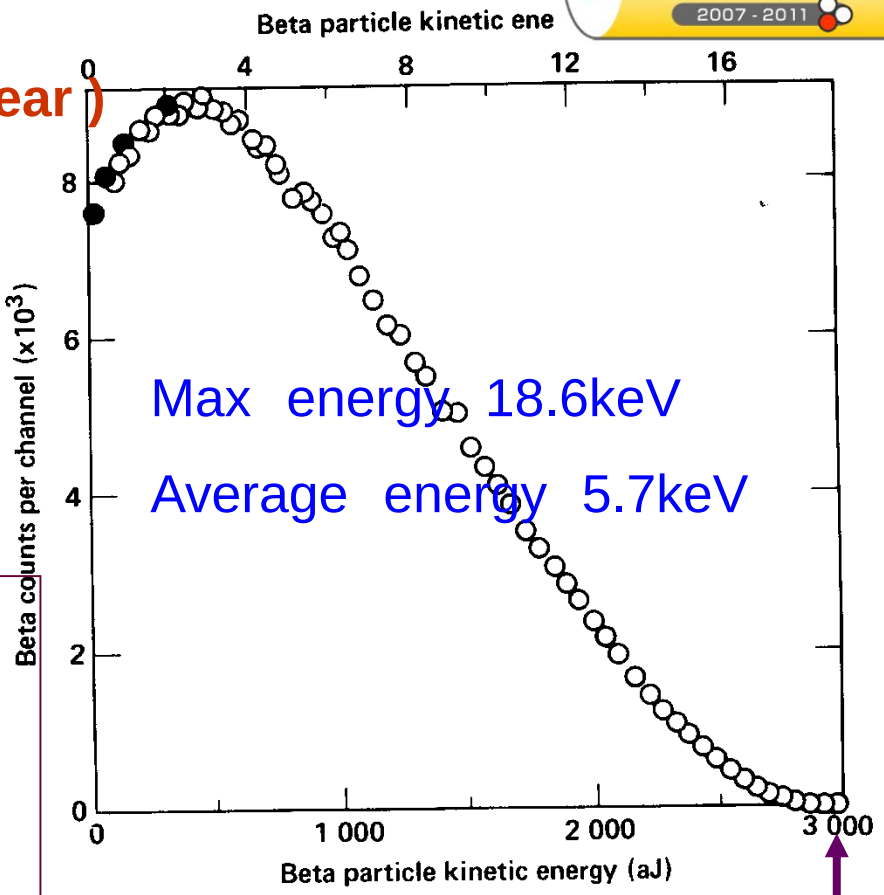
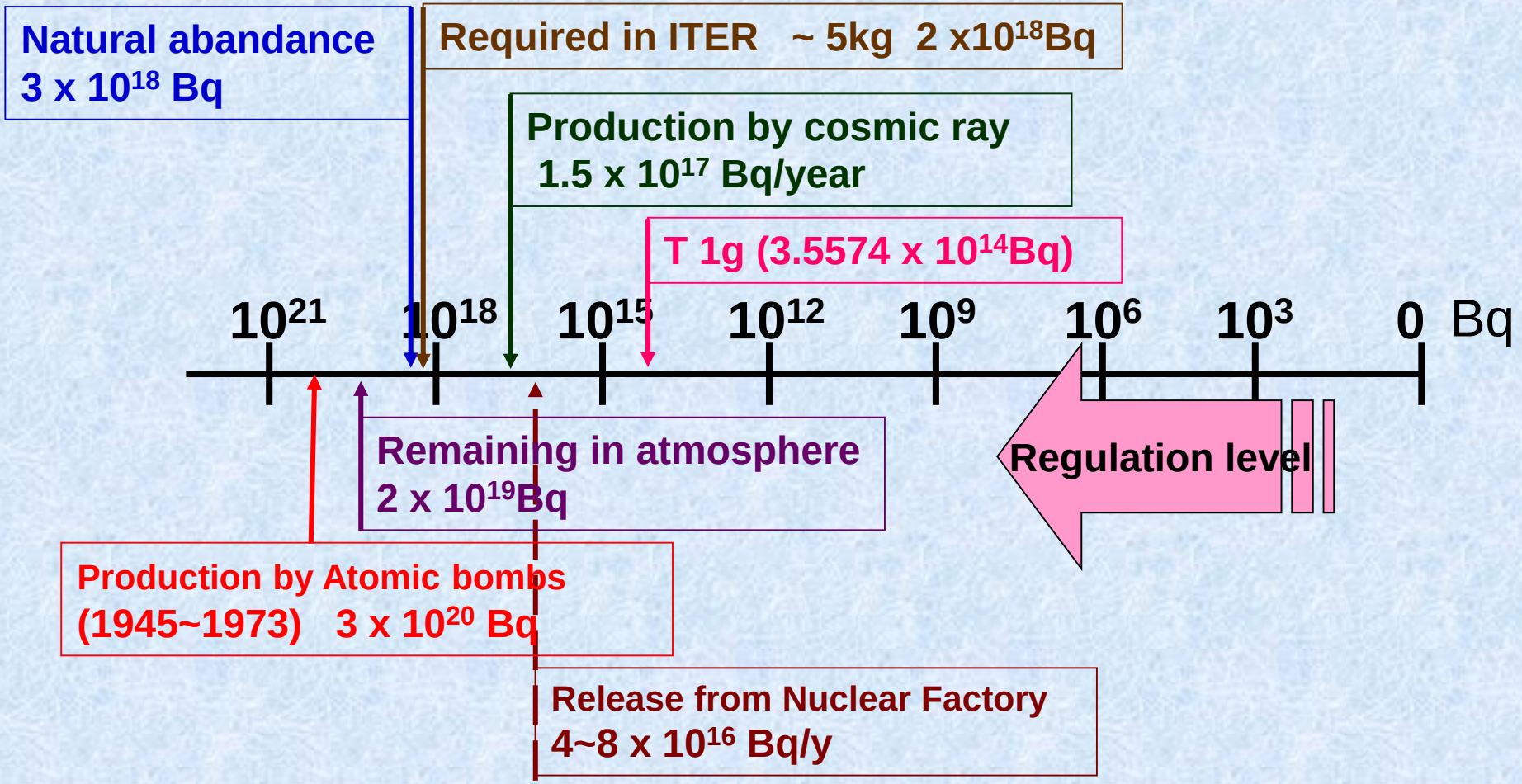


Fig. 16.2. A high-resolution spectrum of the tritium beta-particle kinetic energy (open circles). The closed circles are special low-energy points from another source. The spectrum was measured by J. J. Simpson, University of Guelph.

Precise measurements of edge energy would give neutrino mass

Tritium Abundance
(limited resources and regulation for safety)



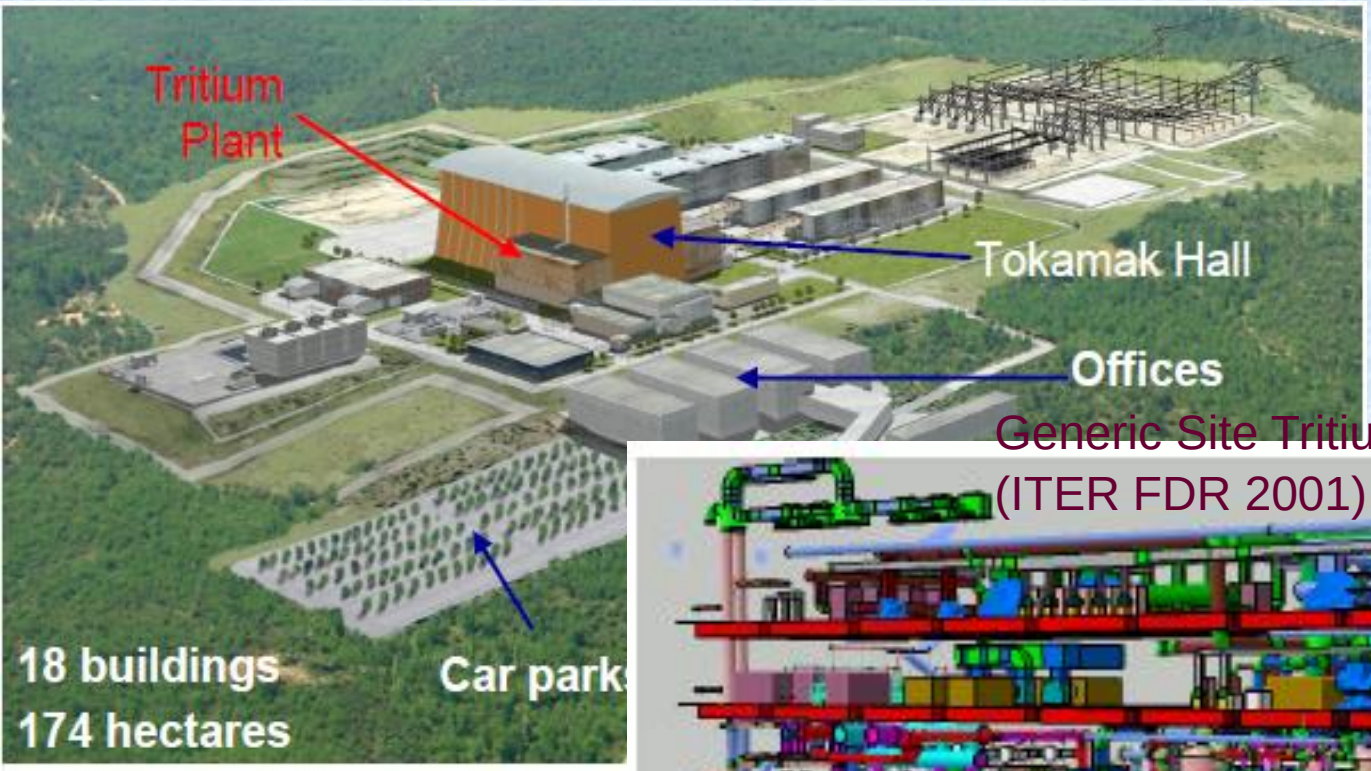
Quantitative analysis	Gravimetric Radiation heat Volumetric (PVT) Disintegration (dps)

No single method can cover whole range.
Poor resolution inhibits cross-cheek

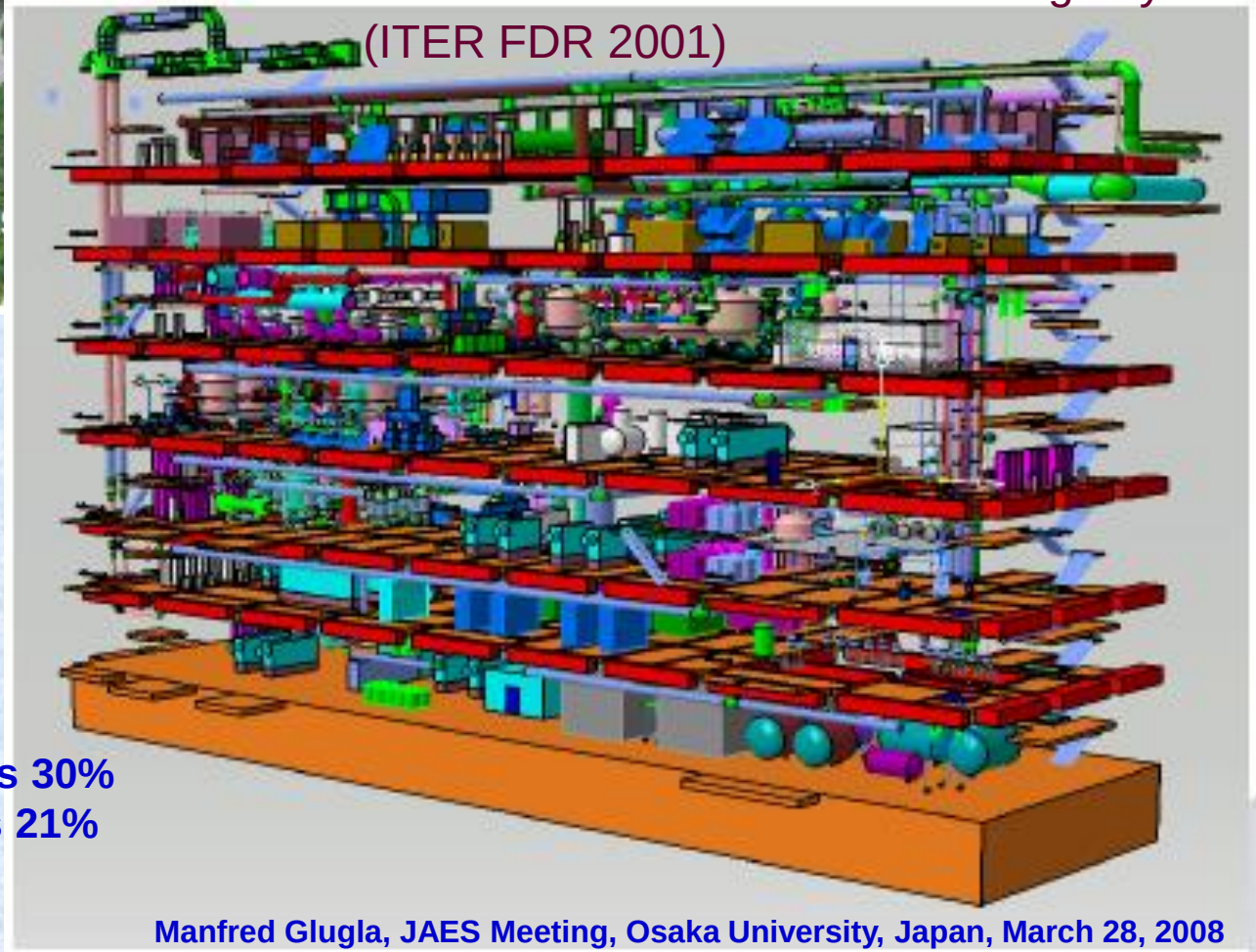
Tritium and ITER

- First fusion machine fully designed for equimolar DT operation
  - Tokamak vessel will be fuelled through gas puffing & Pellet Injection (PI)
  - Neutral Beam (NB) heating system will introduce deuterium
- Employing DT as fusion fuel has quite a number of consequences
  - It causes alpha heating of the plasma
  - The fusion reaction will eventually provide energy
  - Closed DT loop is required due to the small burn-up fraction
    - Primary tritium systems for processing of tritiated fluids
    - Auxiliary systems necessary for the safe handling of tritium
  - Multiple barriers vital for DT confinement
    - Atmosphere & Vent Detritiation are crucial elements in the concept

After all a rather complex chemical plant, i.e. the Tritium Plant of ITER is needed for deuterium-tritium fuel processing



Generic Site Tritium Plant Building Layout (ITER FDR 2001)



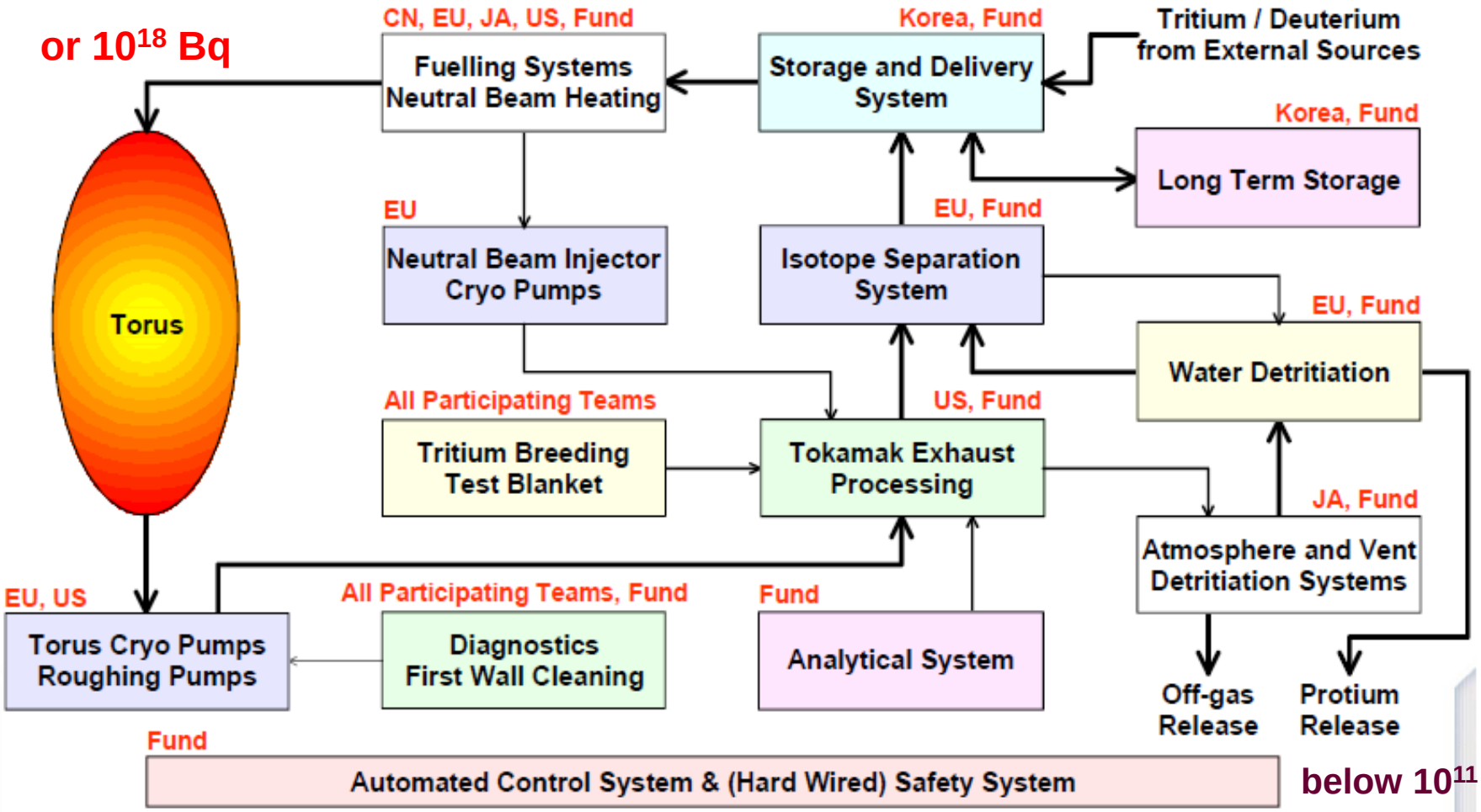
- **Dimensions**
  - Length: 79 m
    Width: 20 m
    Height: 34 m
- **Space occupation**
  - HVAC: 18%
  - Detritiation systems 16%
  - Tritium processing systems 30%
  - Non Tritium Plant systems 21%
  - Non process areas 15%

The ITER DT Fuel Cycle

~ a few kg of T

or 10^{18} Bq

20-25 kg of Tritium from Canada



below 10^{11} Bq/y

T concentration 10^{-12}

Note: No electricity generating systems

Problems related tritium safety in a DT fusion reactor

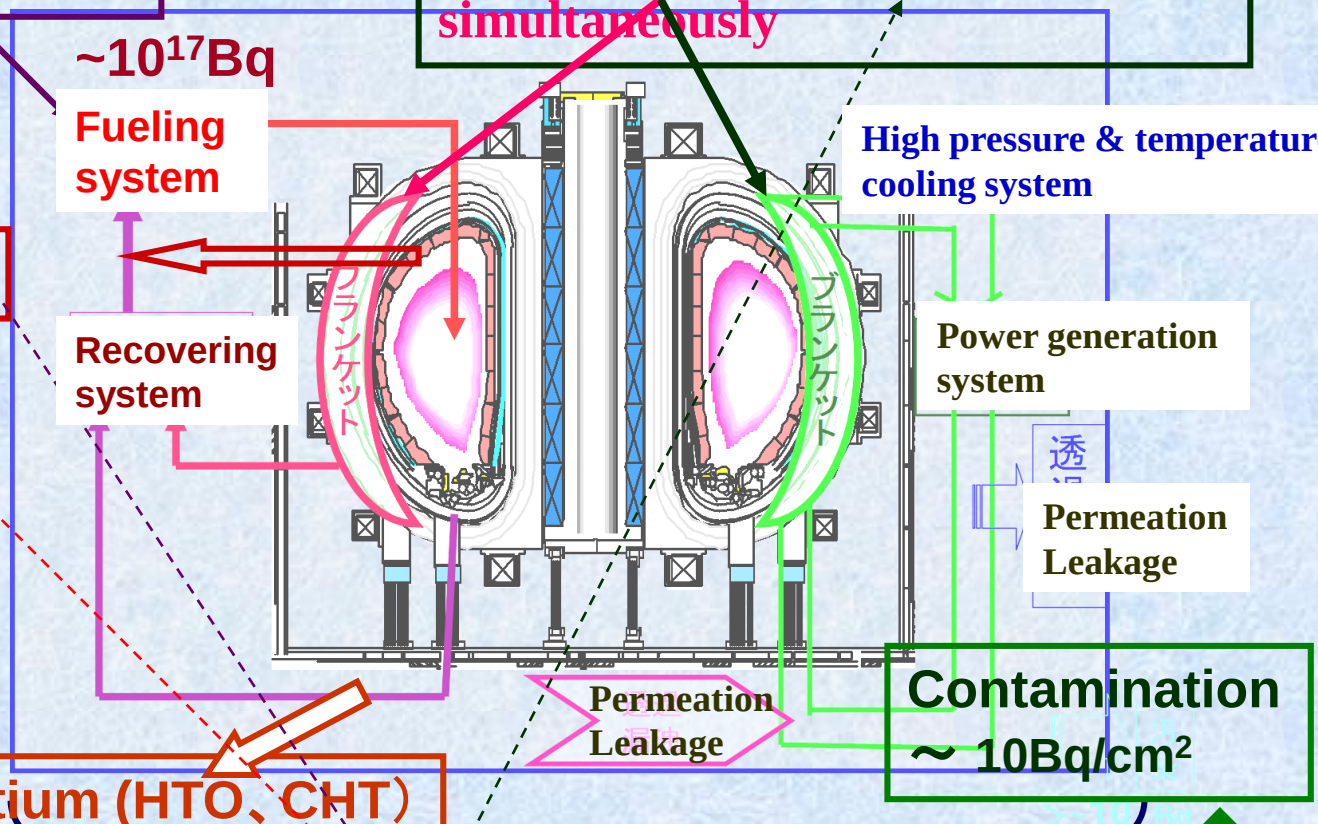
Fueling recycling system with controlling D/T ratio

Blanket system realizing power generation and tritium production simultaneously

Huge tritium inventory

Unbalance between tritium fueling and recovering

Exhaust of organic tritium (HTO、CHT)



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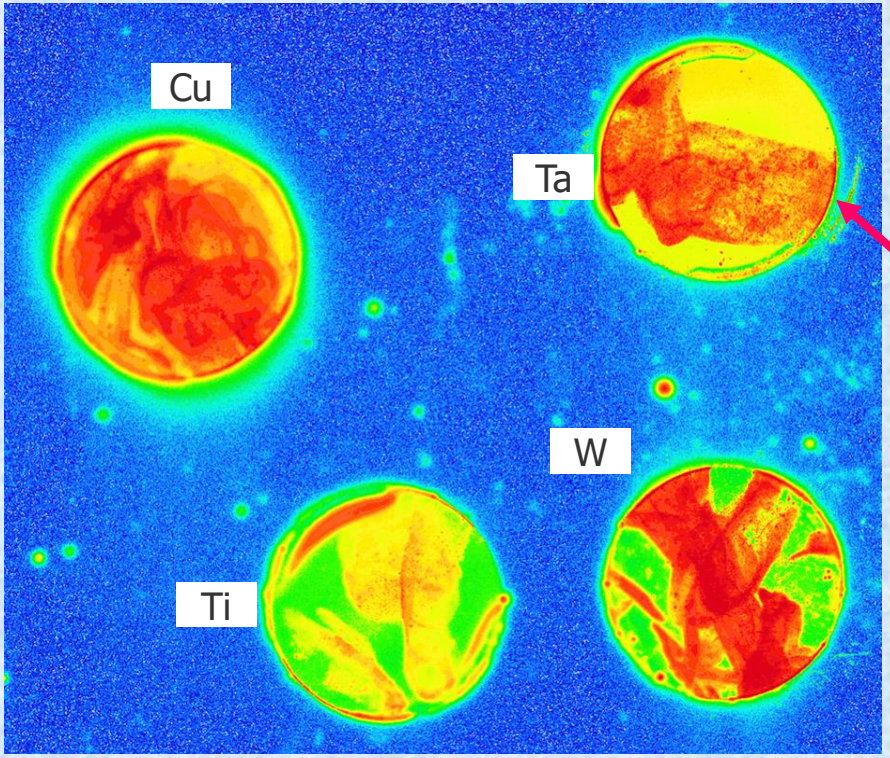
A DT fusion rector is a huge tritium handling facility with poor fuelling efficiency.

Multi-step Contamination ・・・・

Ex. Contamination by gloves in safety box

Metal plates exposed to D plasma in TPL

and handled in a T handling glove box



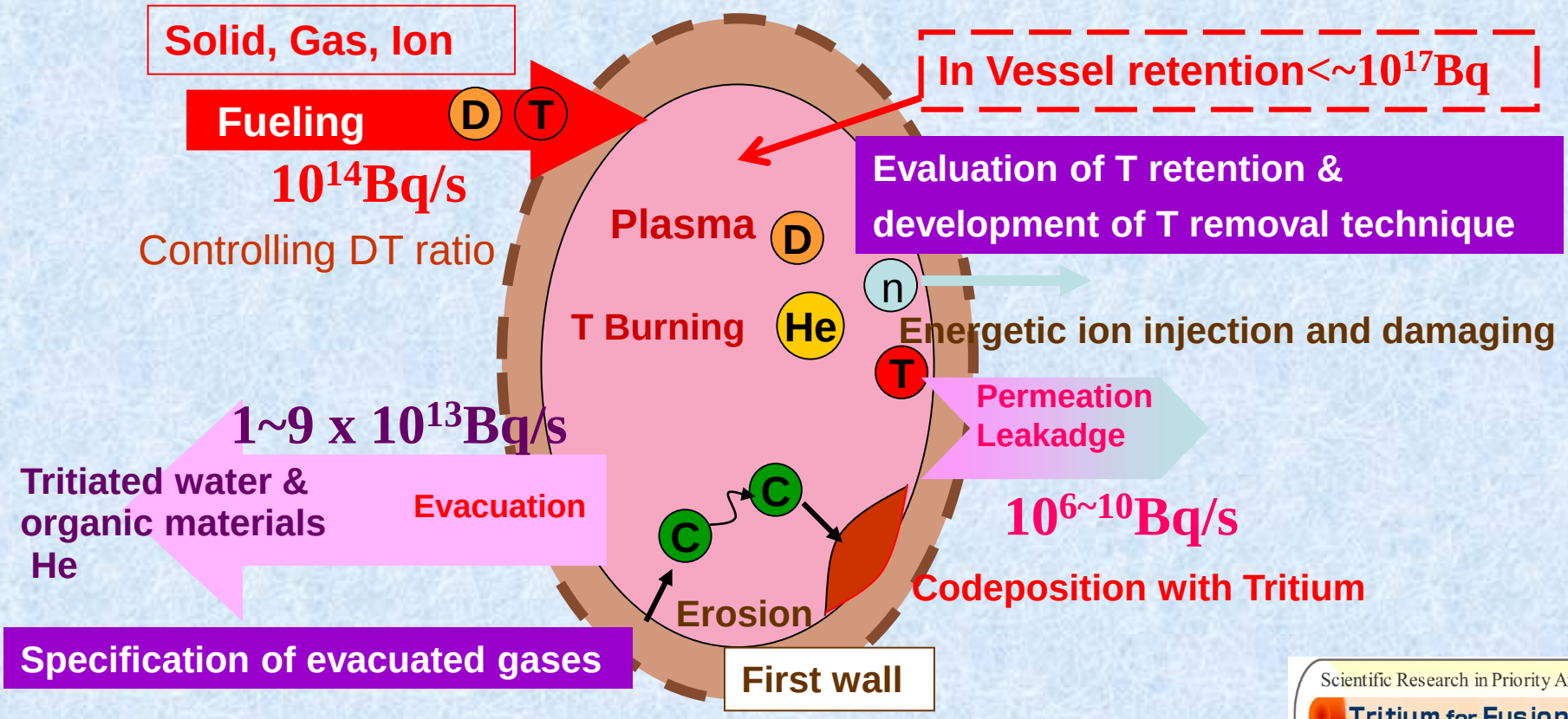
Traces of glove fingers

Possible contamination by permeation

Issues and problems to be solved relating tritium – I

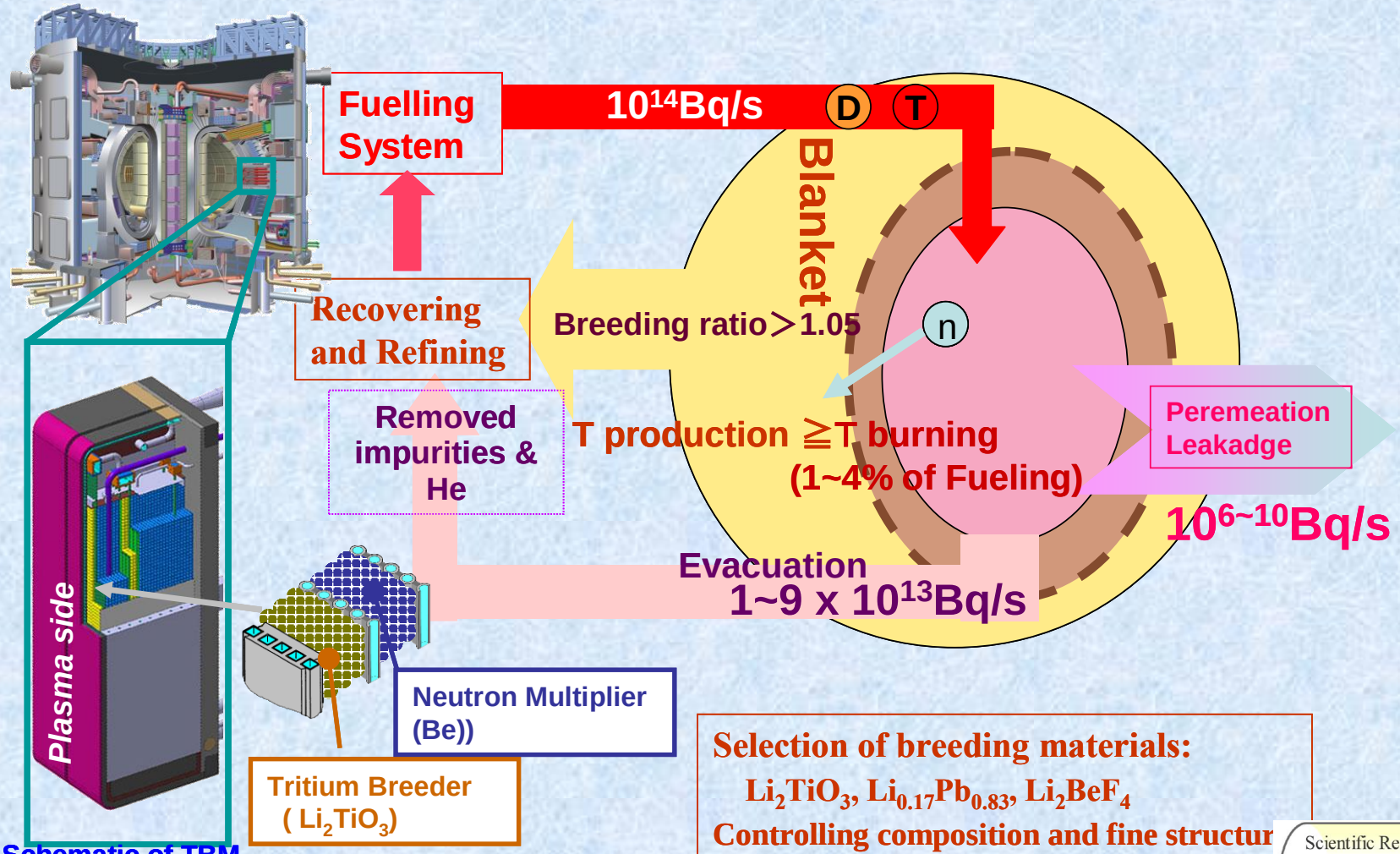
- **Controlled fueling to keep continuous DT burning**
- **Tritium removal from in vessel components**
- **Tritium accountancy in tokamak system**

Tritium behavior in vessel



Issues and problems to be solved relating tritium – Ⅱ

- Tritium breeding with enough margin and compatible with energy conversion
- Limited resource of Tritium (CANDU reactors are the main source)
- Tritium recovery in fuel cycles and breeding systems and its refinement



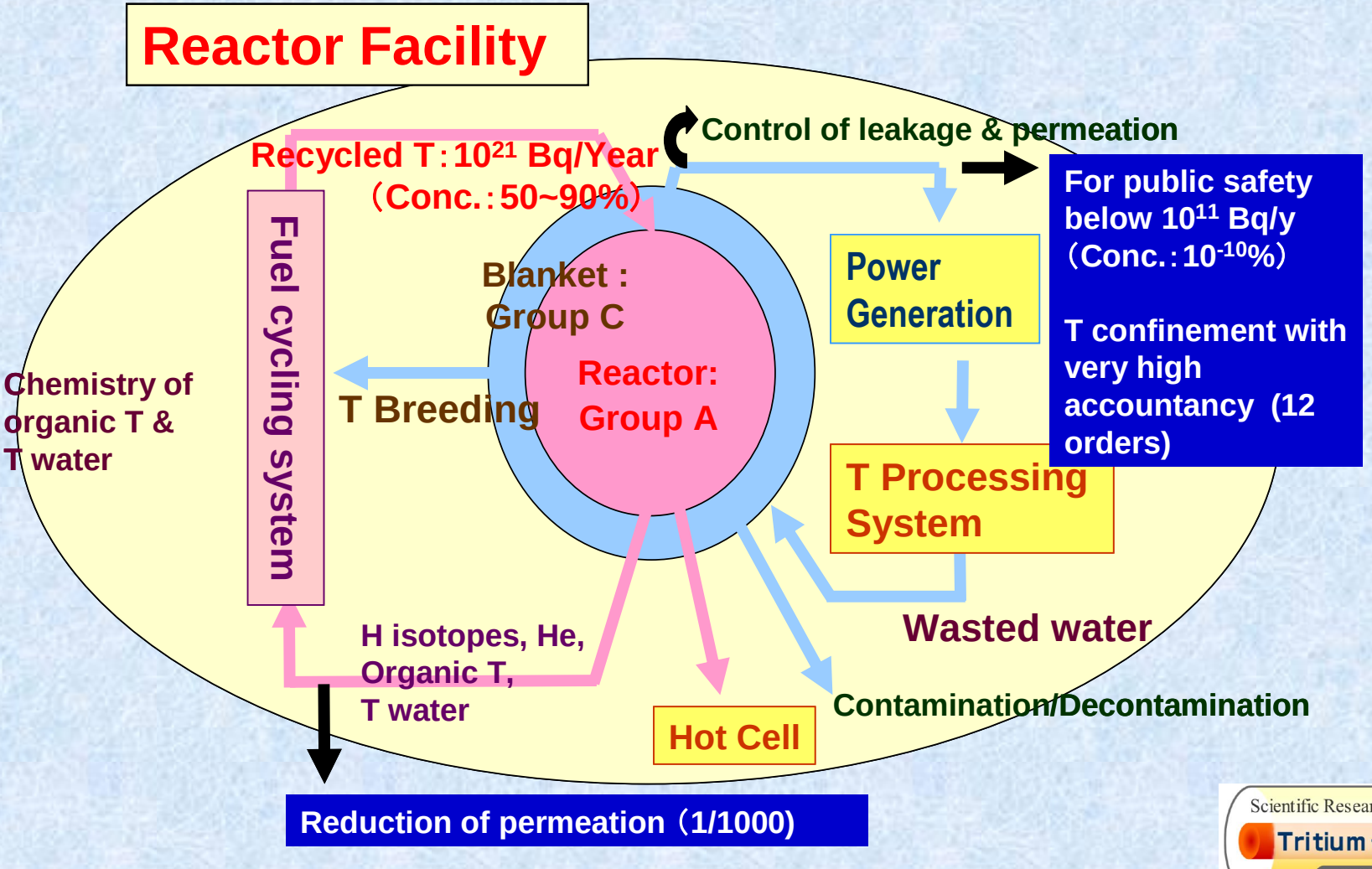
Selection of breeding materials:

Li_2TiO_3, $Li_{0.17}Pb_{0.83}$, Li_2BeF_4

Controlling composition and fine structur

Issues and problems to be solved relating tritium - Ⅲ

- **Physical confinement and Safety confinement**
- **Detritiation and/or decontamination**
- **Safety reposition**



What make difficult to resolve the problems?

- **Difficulty of detection and quantitative analysis measurement) with high accuracy.**
- **No way to measure tritium in bulk except combustion detection and calorimetry.**
- **T behavior in a DT reactor can not be simulated by that in DD plasma machine**
- **Large mass difference among all hydrogen isotopes**
- **Tritium breeding must be compatible with energy conversion (or economic)**
- **Tritium is chemically very active and react with most of impurities, in particular water and hydrocarbon molecules, in air to make more hazardous.**
- **Permeation and leakage are unavoidable**

Tritium in burning plasma

It seems very hard to control DT ratio constant

How to control DT ratio 1/1 (or keep burning efficiency the highest)

Feed back from neutron yield

Possible but quite depend on confinement time which could be significantly different for D and T, Influence of toroidal and poloidal inhomogeneity

D, T concentration

Quantitative evaluation of D and T in plasma center is not easy

Plasma opacity could disturb optical measurements like Thomson scattering

Fuelling

Fuelling efficiency (Penetration depth) of T and D are different.

D and T must be separately fuelled

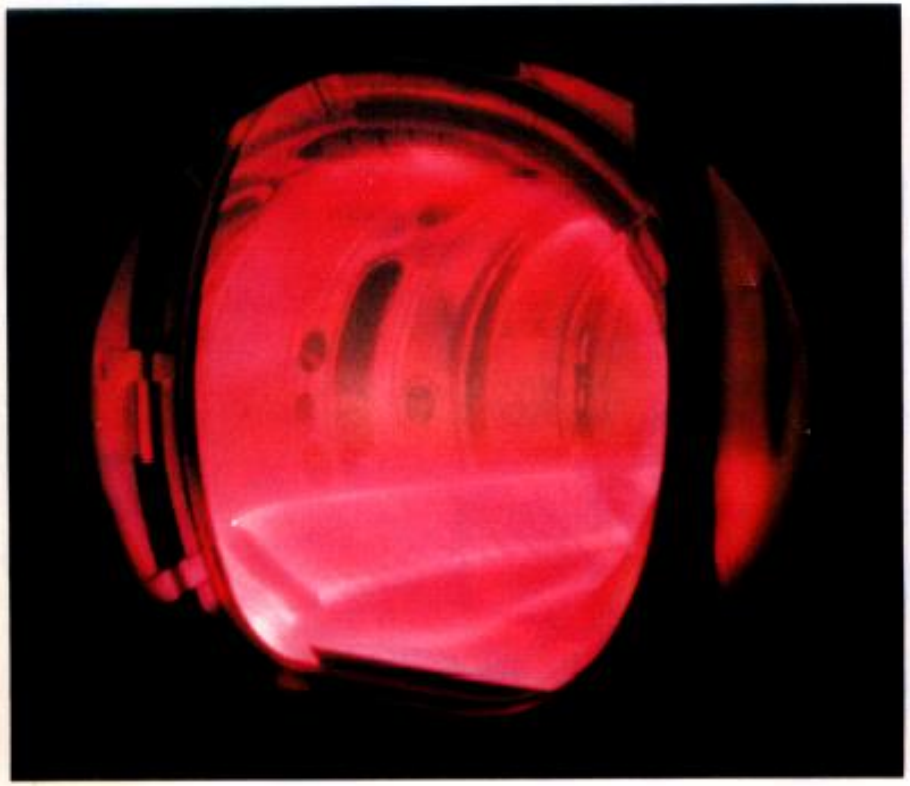
Recycling and retention

next view graph

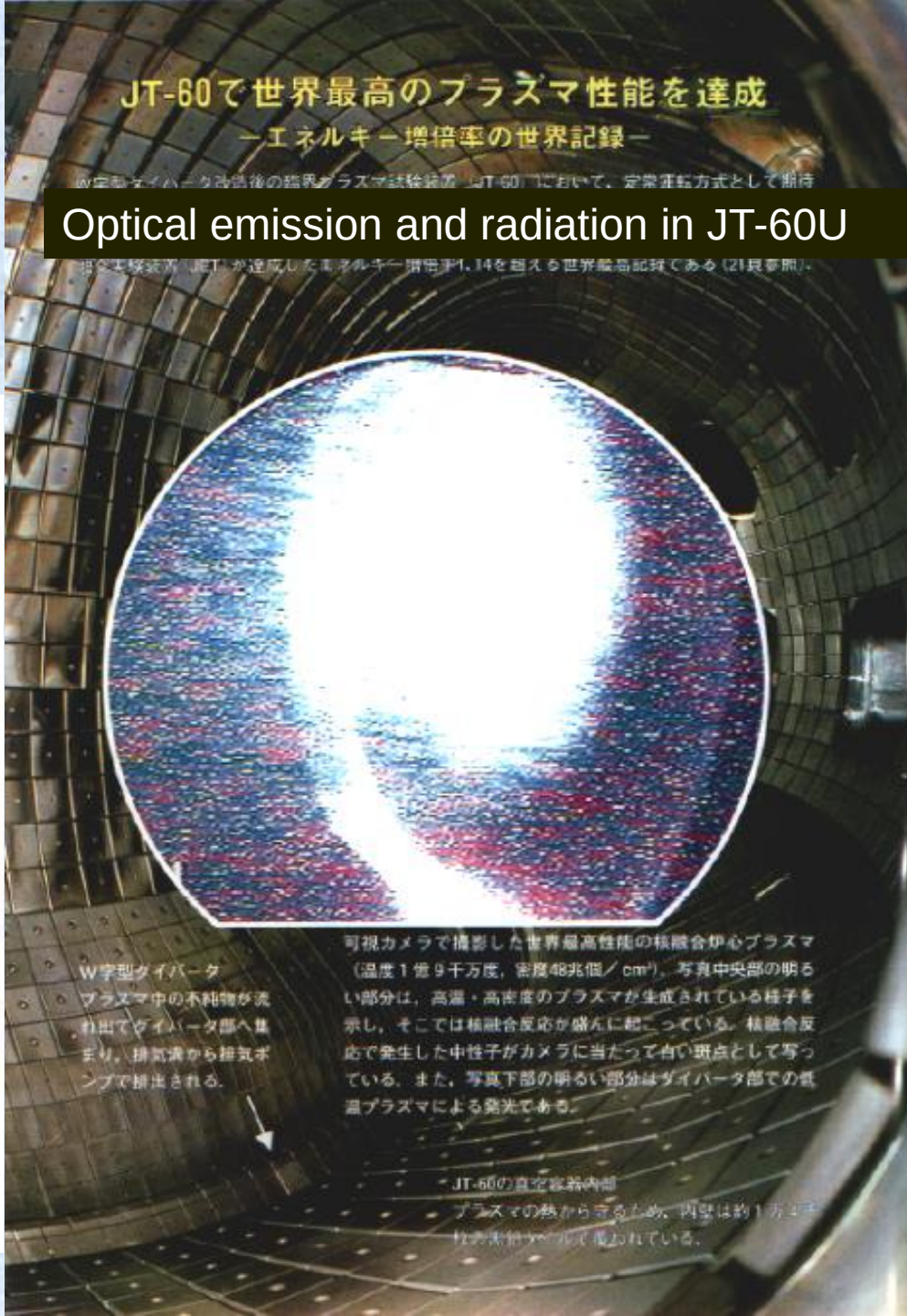
Plasma opacity

Optical emission (Blamer series at edge)

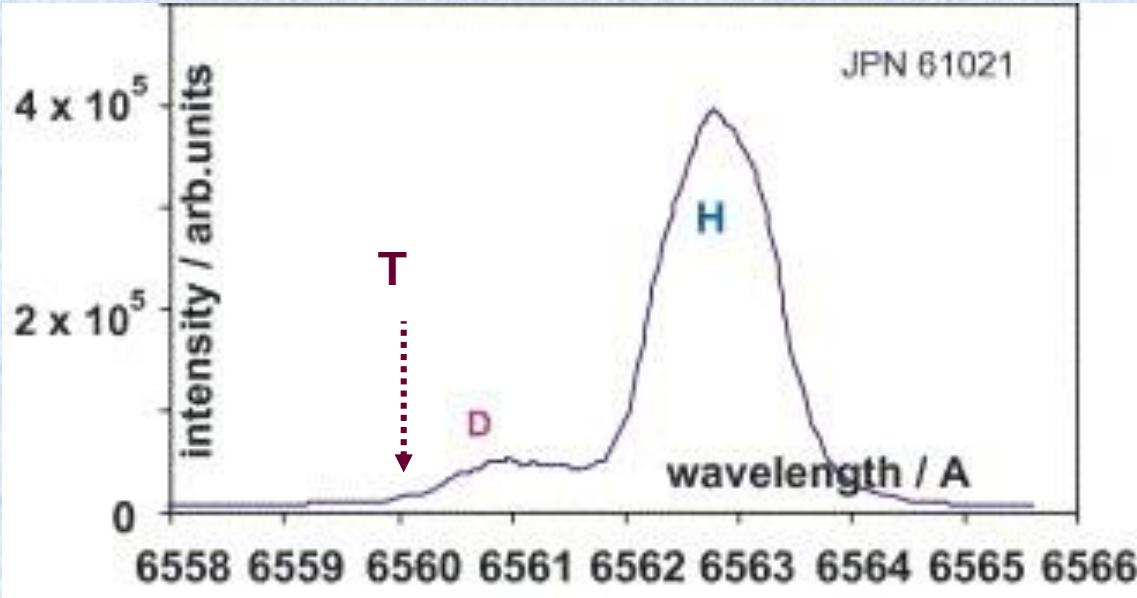
From TEXTOR plasma



TEXTORプラズマとALT-Ⅱトロイダル
ポンプリミター（接線方向の窓より撮影）
詳細はP１参照



Optical emission near edge plasma



Balmer lines	H (nm)	D (nm)	T (nm)	H−D (nm)	H−T (nm)
α	656.28529	656.10104	656.04166	0.18425	0.24363
β	486.1362	486.00028	485.9563	0.13592	0.1799
γ	434.04946	433.92829	433.88902	0.12117	0.16044
δ	410.1765	410.06191	410.02479	0.11459	0.15171
ε	397.0072	396.89992	396.86329	0.10728	0.14391
IP(cm-1)	109678.76	109708.608	109718.538	−29.844	−39.774
IP(eV)	13.598	13.602	13.603	3.7001meV	4.9313meV

Effect of different mass on velocity and flux among hydrogen isotopes gases

Simple molecular kinetics tells that velocity for D and T at the same energy different. So as rotational and vibrational state are.

Maxwell-Boltzman's law gives

$$\bar{v} = \sqrt{\frac{8RT}{\pi m}} \quad \text{, hence} \quad \overline{v_H} / \overline{v_D} = \sqrt{2} \qquad \overline{v_H} / \overline{v_T} = \sqrt{3}$$

Molecular kinetics gives incident flux to wall surface under pressure *P*

$$J = nv = \frac{P}{(2\pi mkT)^{1/2}} \qquad J_H / J_D = \sqrt{2} \qquad J_H / J_T = \sqrt{3}$$

Isotope effects

Mass ratio of H, D and T is 1:2:3

under the same pressure $v_H / v_D = \sqrt{2}$ and $v_D / v_T = \sqrt{3/2}$

$\phi_H / \phi_D = \sqrt{2}$ $\phi_D / \phi_T = \sqrt{3/2}$

to give the same flux $p_H / p_D = 1/\sqrt{2}$ and $p_D / p_T = \sqrt{2/3}$

Relating to

Different confinement	Outgoing flux ratio would be SQR(2/3)
Impinging energy to wall surface	?
Reflection coefficient	May be SQR(3/2) but no data for T
Recycling flux ratio	Unknown retention time
Pumping speed ratio	For mechanical pumping SQR(3/2) Unknown for cryo-pump

Tritium retention (solubility, diffusivity and permeability, trapping effect)
Surface residence time

Cryogenic Separation of Hydrogen Isotopomers

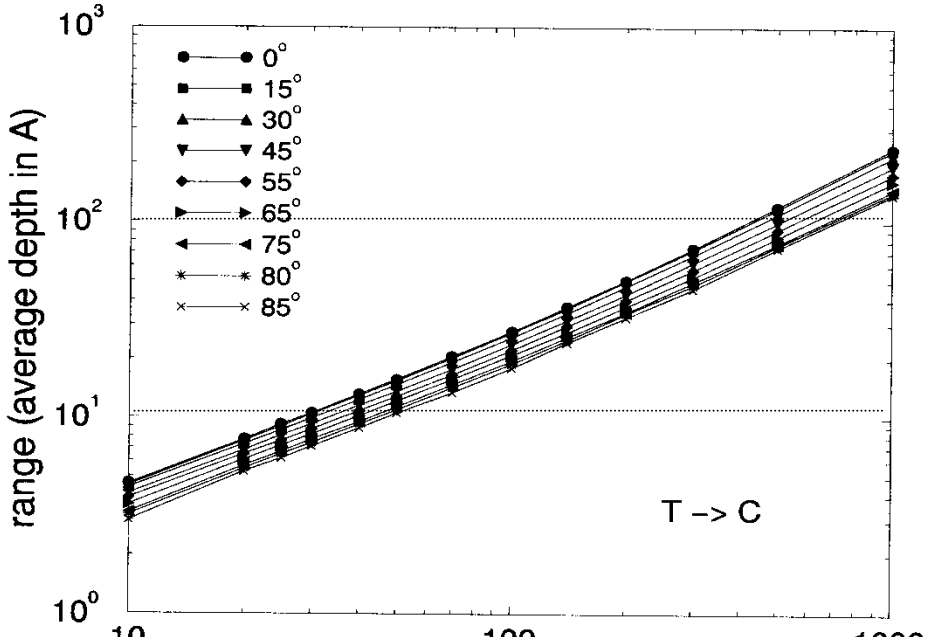
- Six molecular hydrogen isotopomers with different boiling points

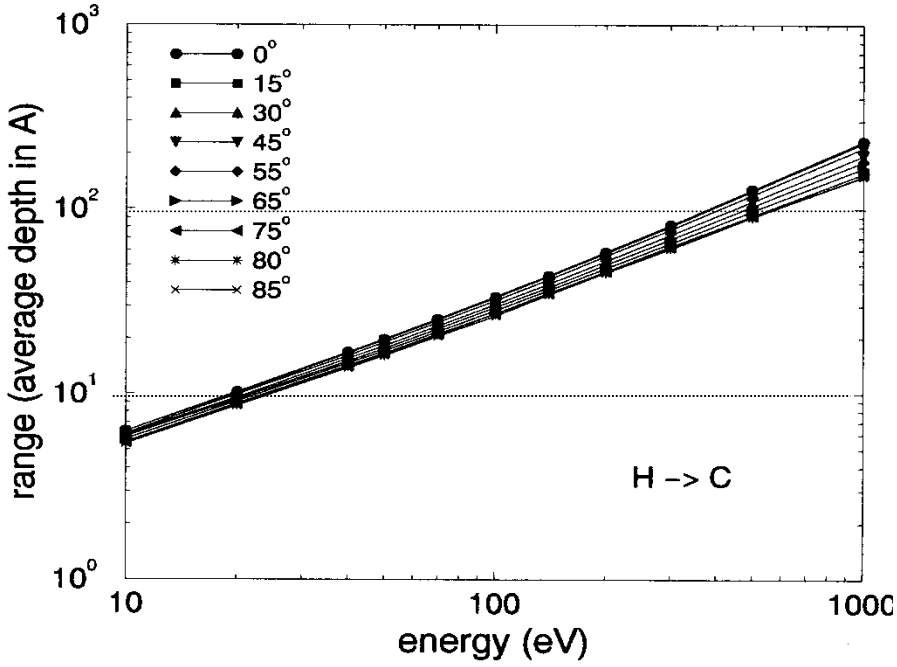
Isotopomer	H2	HD	HT	D2	DT	T2
Boiling Point [K]	20.7	22.1	23.5	23.8	25.0	25.5

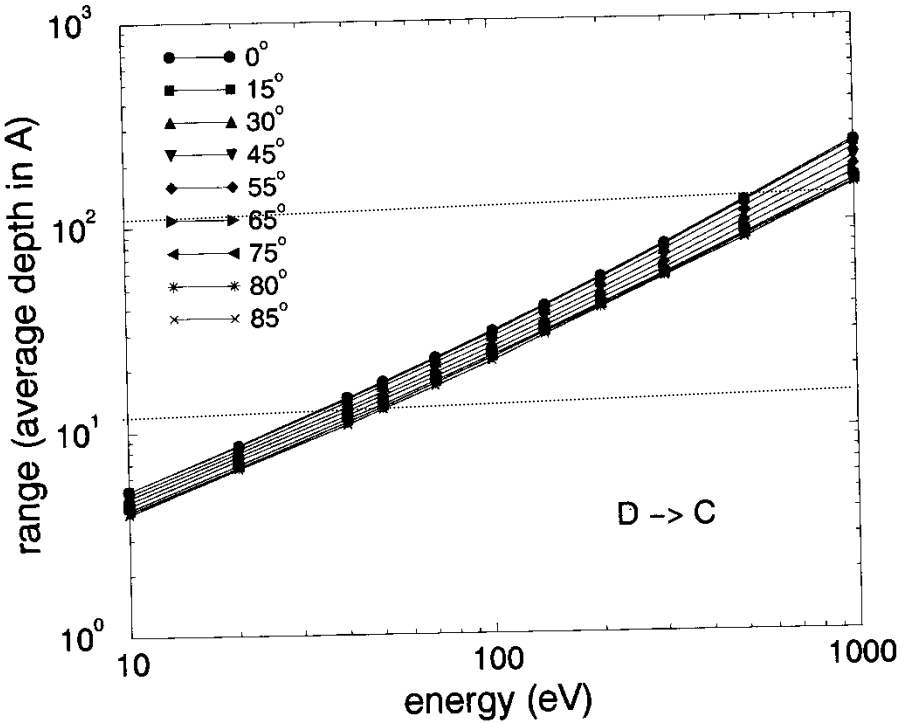
- H isotopomer separation requires cryogenic temperature distillation
- Separation between HT and D_2 is particularly difficult

Energetic hydrogen injection into carbon

While reflection coefficients quite depend on mass, larger for a lighter isotope, projected ranges for three isotopes are not so different as mass differences owing to large electron stopping.







Estimation of in-vessel tritium retention includes very large error and uncertainty

- Evaluation of **hydrogenic retention** in present tokamaks is of high priority to establish a **database** and **a reference for ITER** (400 s…usually 10-20 s today).

- T retention constitutes an **outstanding** problem for ITER operation particularly for the **choice of the materials** (carbon ?)

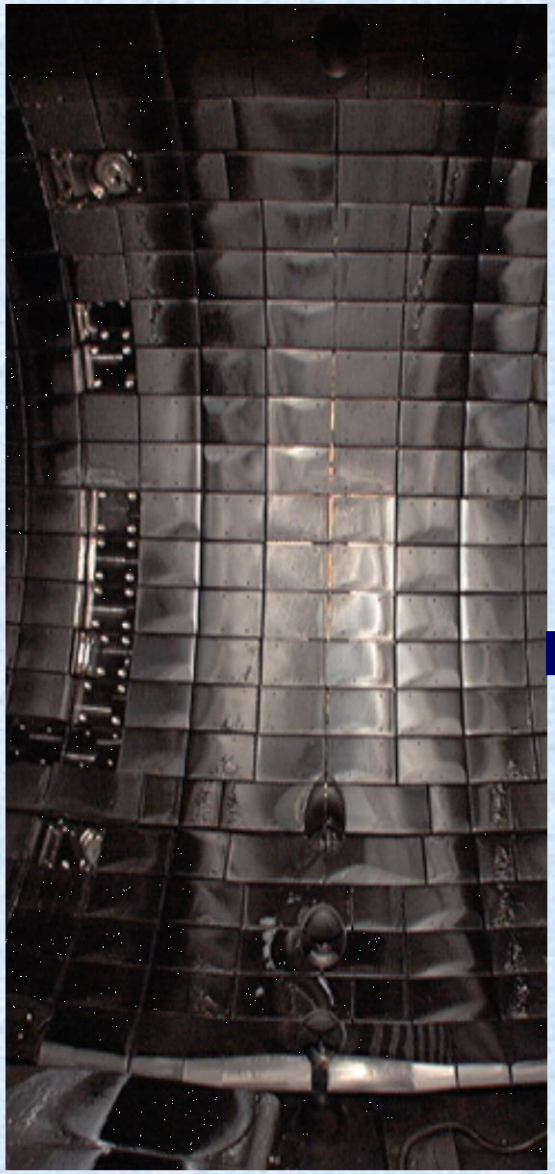
- A **retention rate of 10%** of the T injected in ITER would lead to the in-vessel T-limit (350/700g) in ~**35/70 pulses**. (every ~ **35/70** shots require removing of in vessel T?)

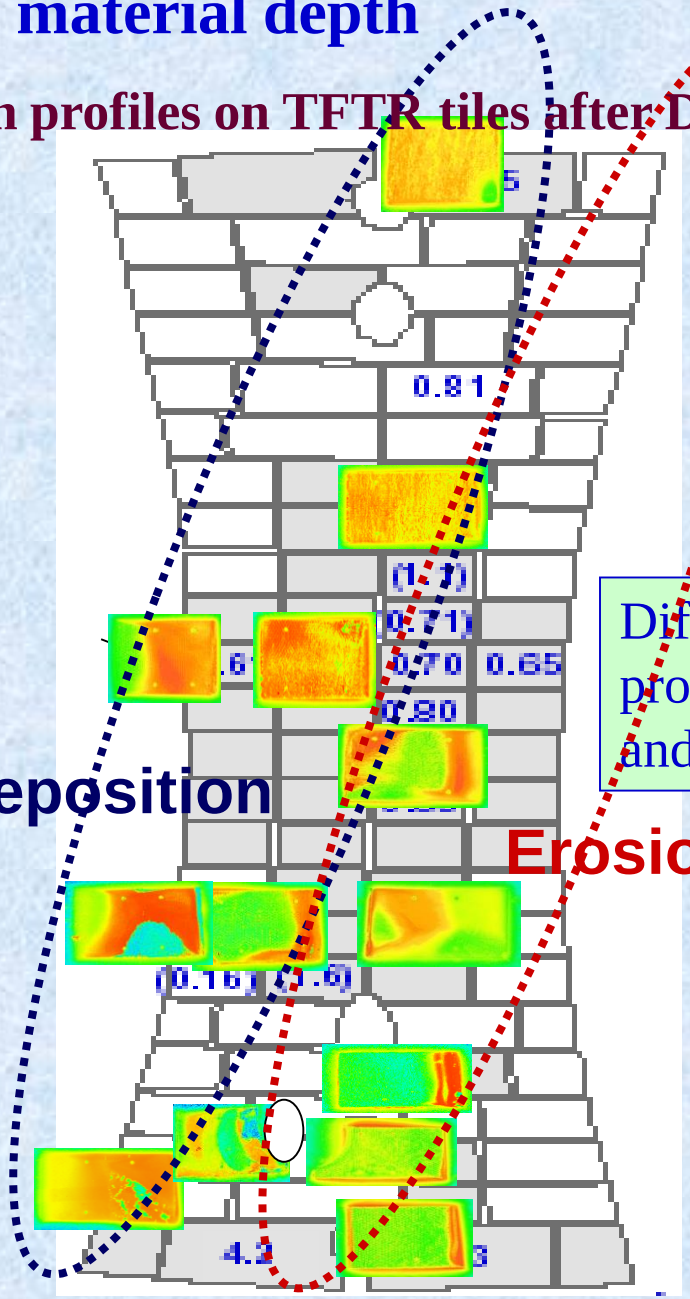
- Retention rates of this order **or higher** (~20%) are regularly found using **gas balance**.

- Retention rate **often lower** (3-4%) are obtained using **post mortem analysis**

T retention is quite non-uniform in toroidal and poloidal directions as well as in material depth

T retention profiles on TFTR tiles after DT experiments





Deposition

Erosion

Different deposition profiles between upper and lower area

Grey : CFC

White : Graphite

Complicated distribution of Tritium in Reatcor

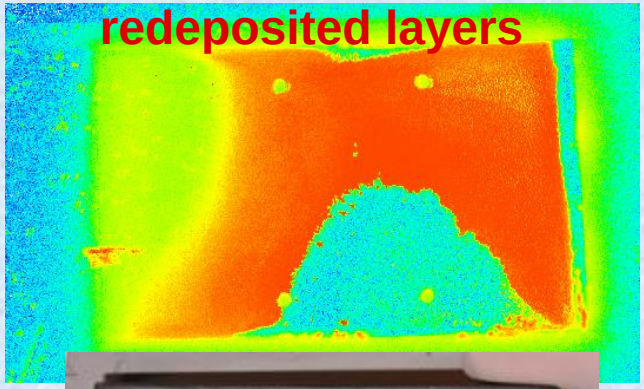
Large retention in redeposited layres

Inhomogeneous retention

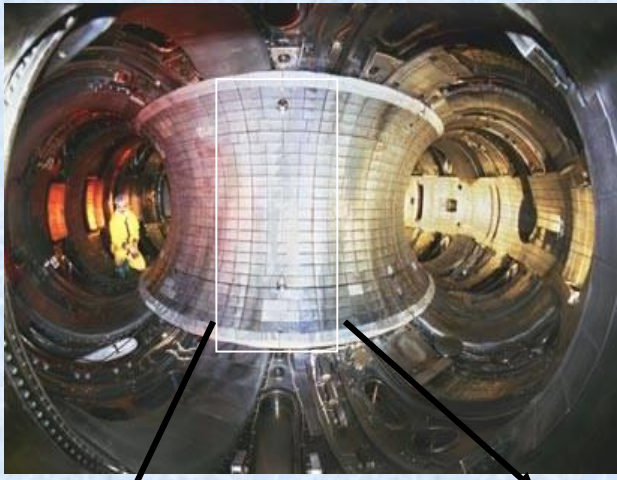
Machine dependent distribution

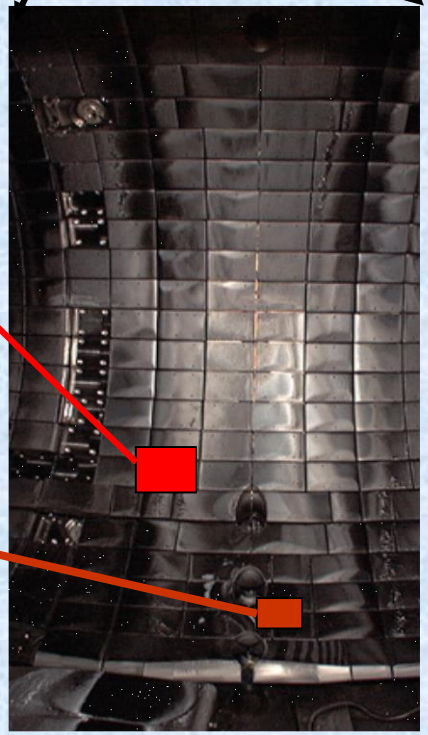
Correct evaluation of T inventory

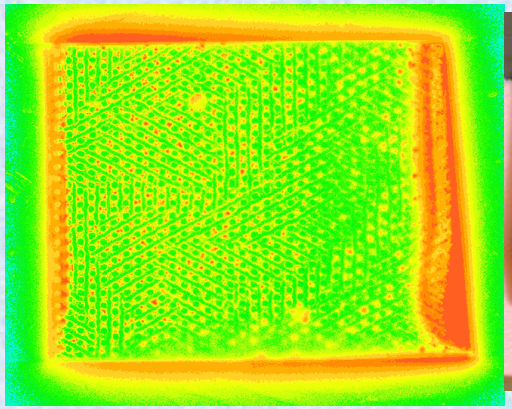
T retained in redeposited layers



TFTR(After DT discahrges)





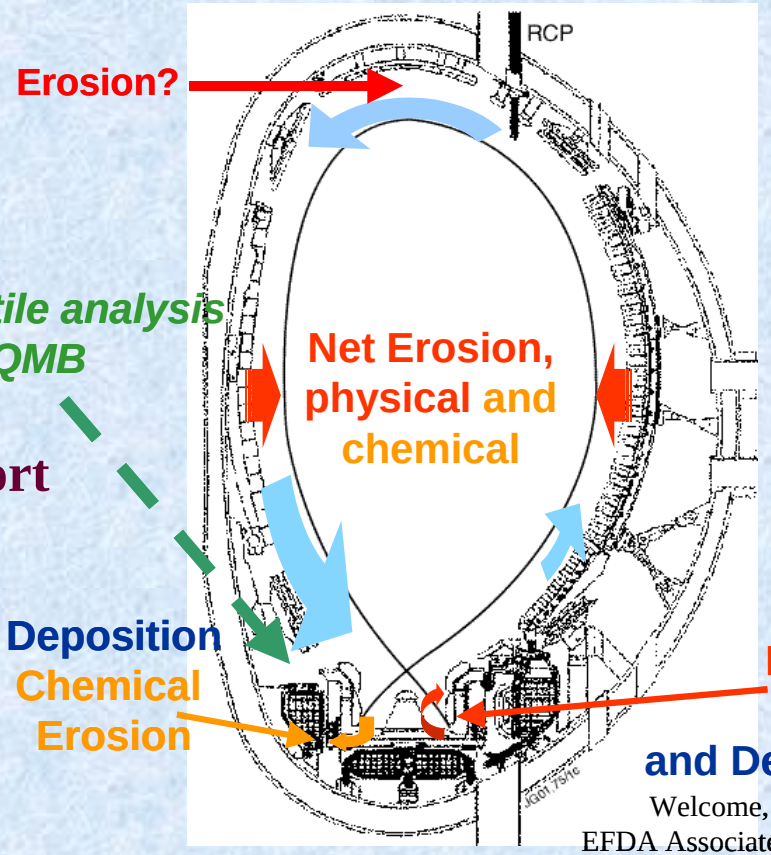


99E0014-04

Tritium retention in deposits at shadowed area and debris(dust)

Outer diveror **erosion**
First wall **erosion**
Inner wall **deposition**

Missing mass balance



Mechanism

Local transport & Long range transport

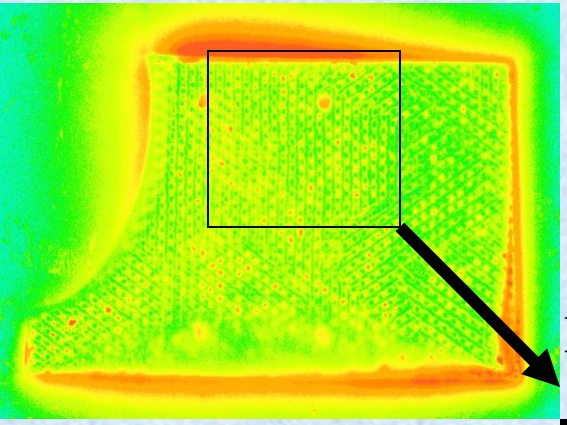
- **Deposition of HC radical or H & C codeposition**
- **Retention of tritium afterword?**

Welcome, J.Pamela,
EFDA Associate Leader for JET

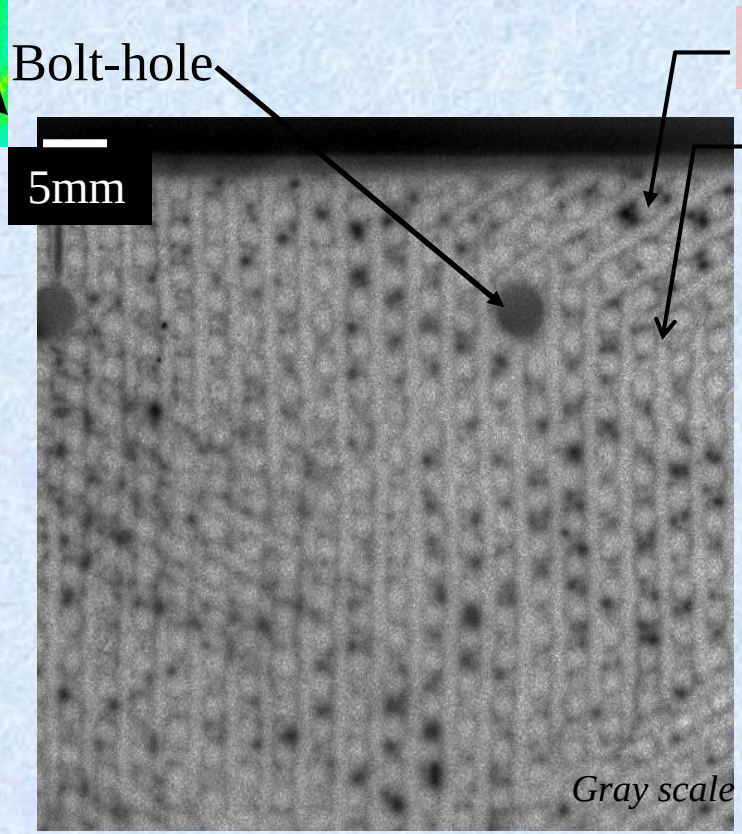
Materials properties also modify tritium retention characteristics

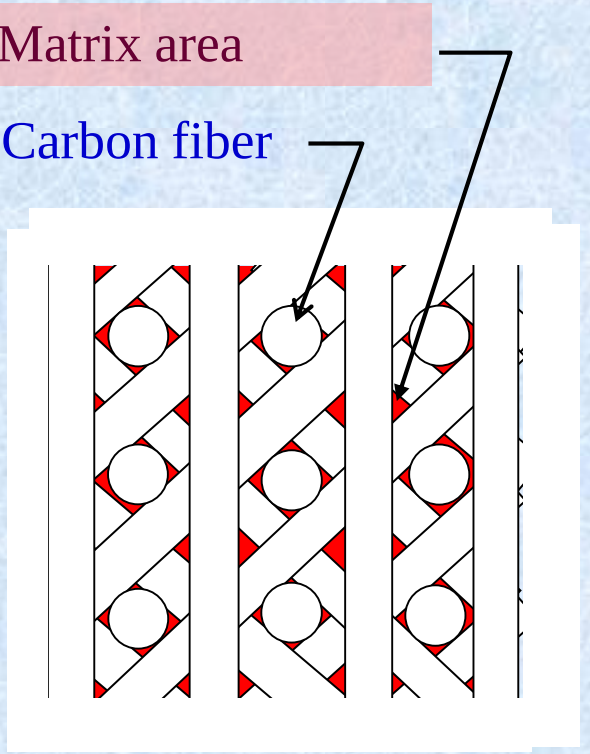
Matrix has higher retention than fivers

Different erosion yield between matrix and fibers produced non flat surface and codeposition with T on shadowed area



Tritium image
(KC3 CFC tile)



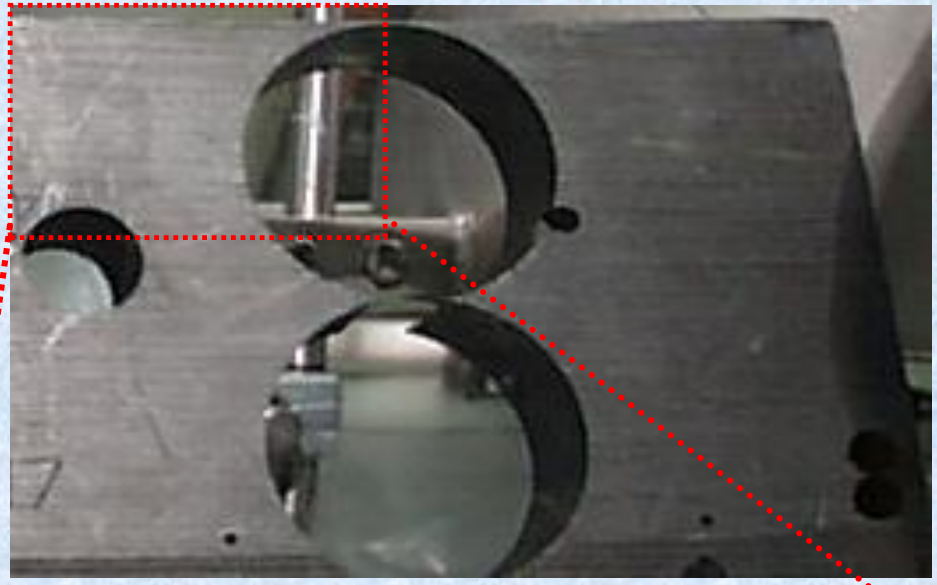


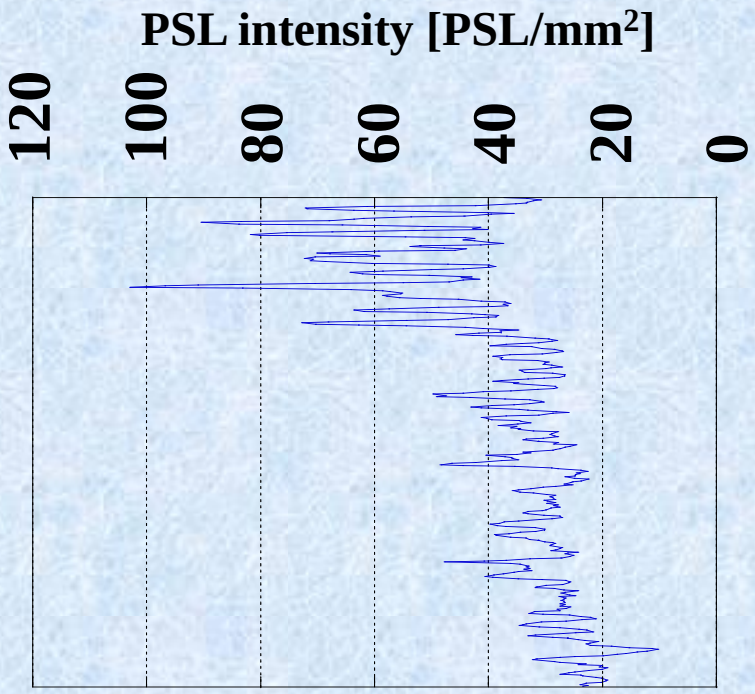
(4-D CFC)

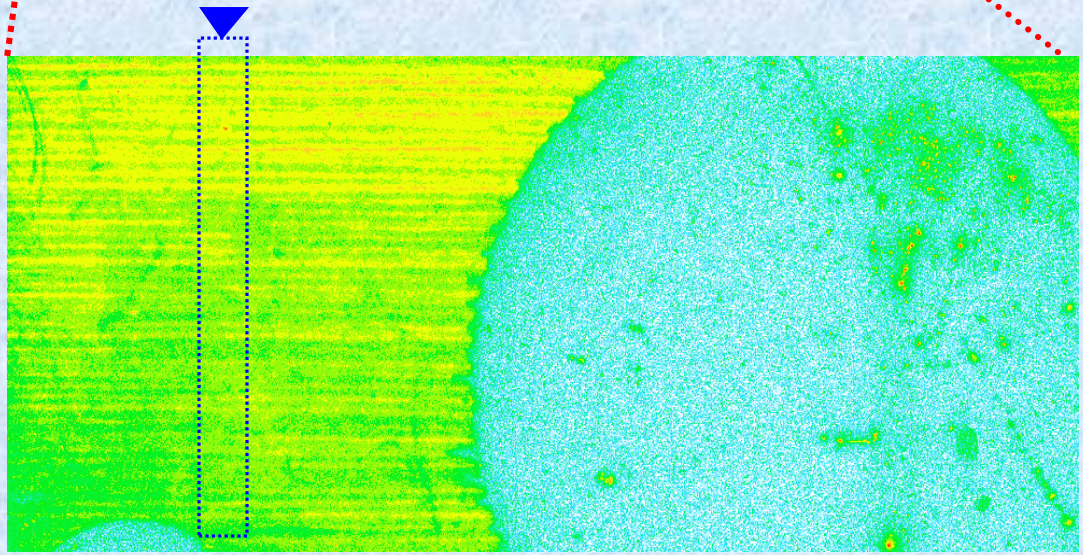
Tritium absorption at non-plasma facing surface in JET

Backs side of BN7

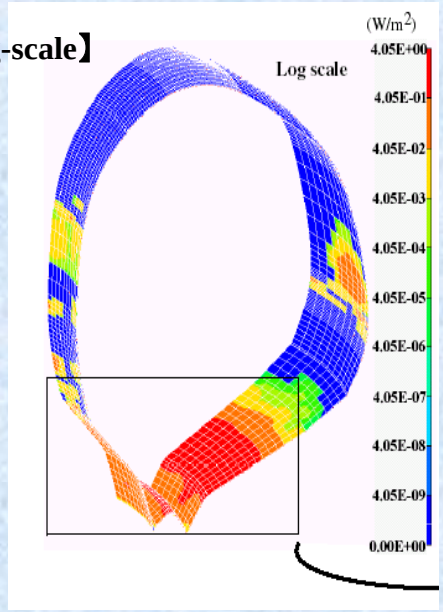
Stripes corresponding the woven structure of 2-D CFC



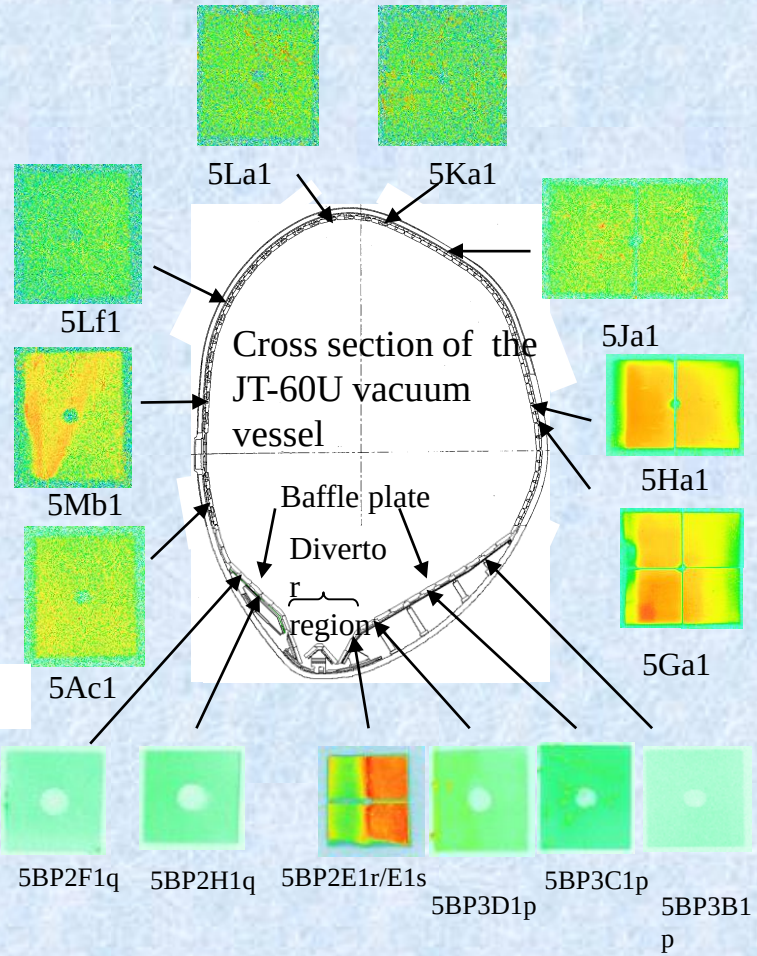




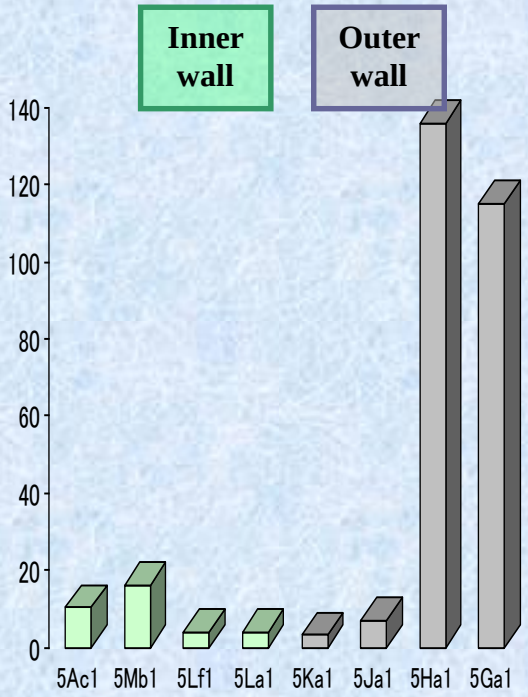
Tritium retention on the first wall



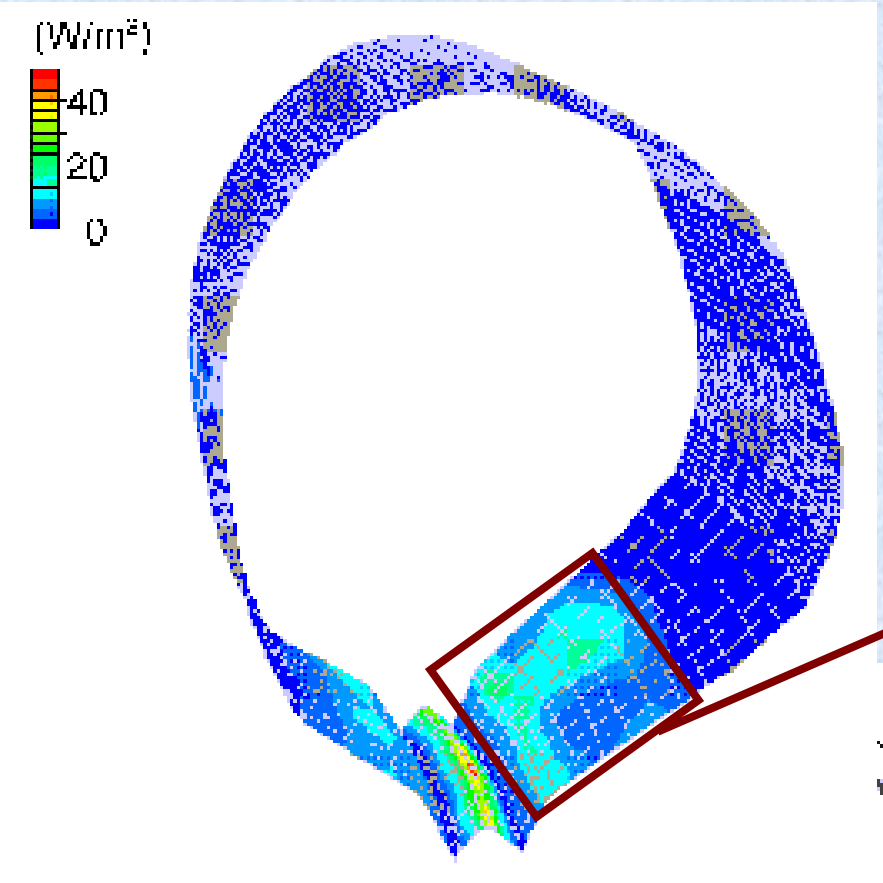
Particle flux by OFMC

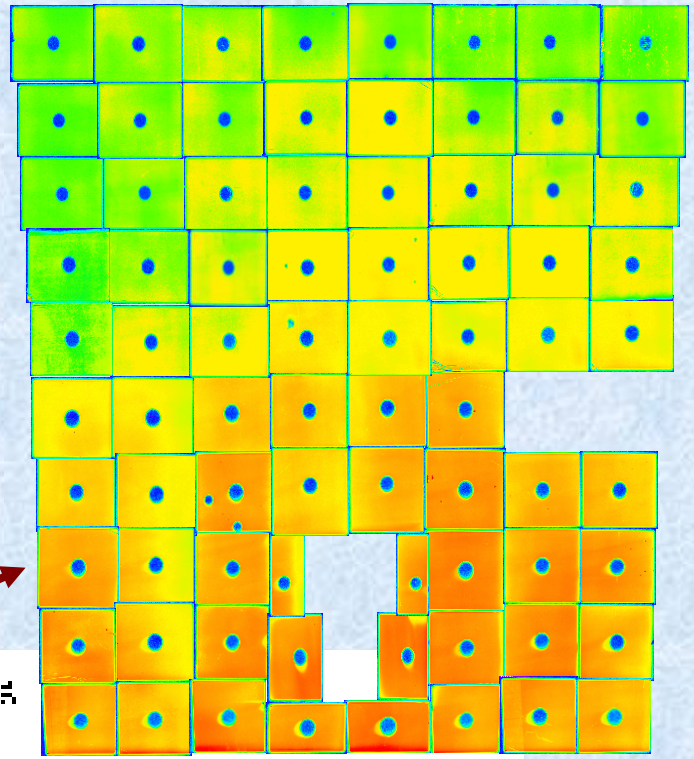


Tritium distribution by IP

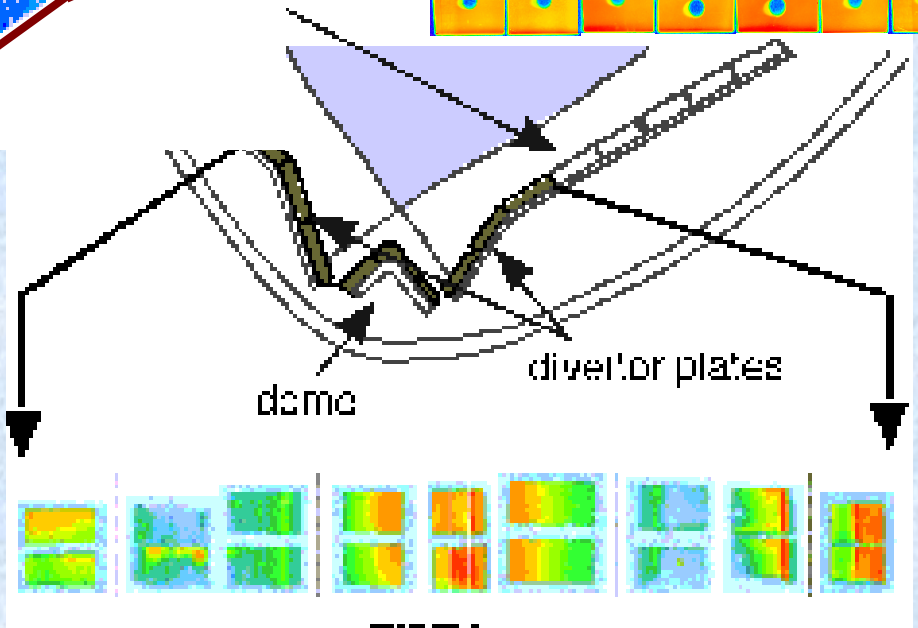


Tritium retention

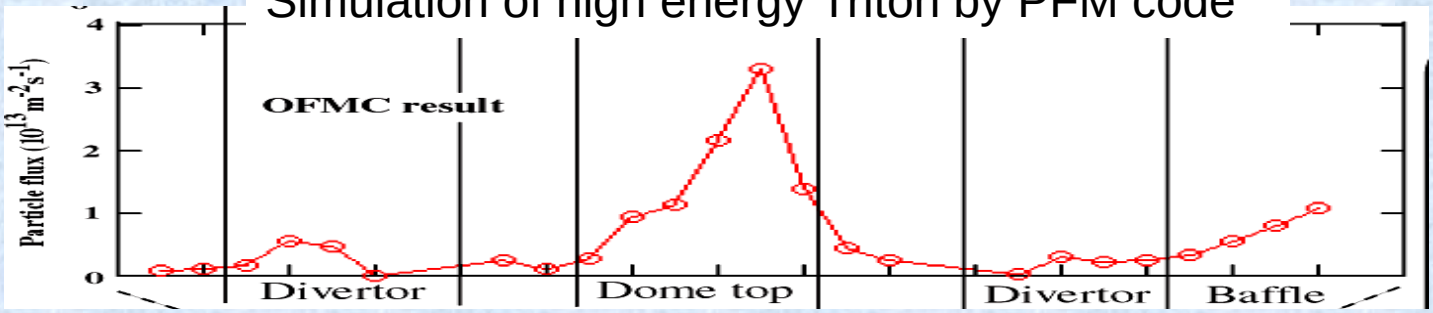


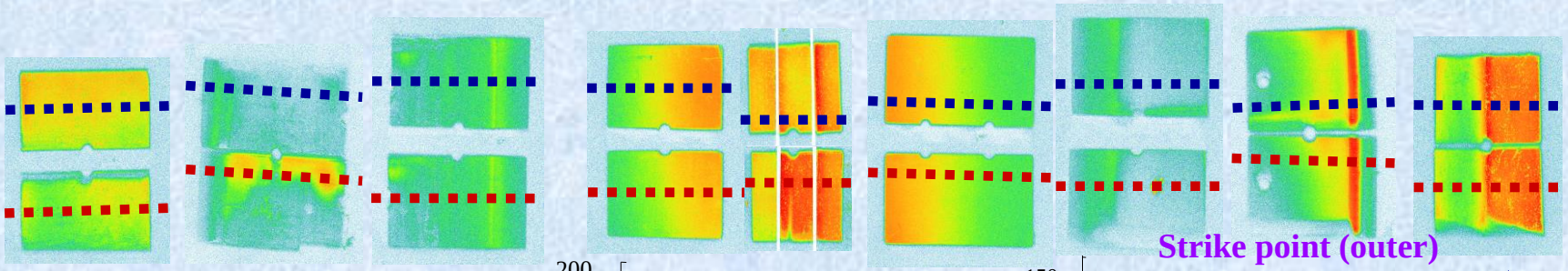


OFMC calculation

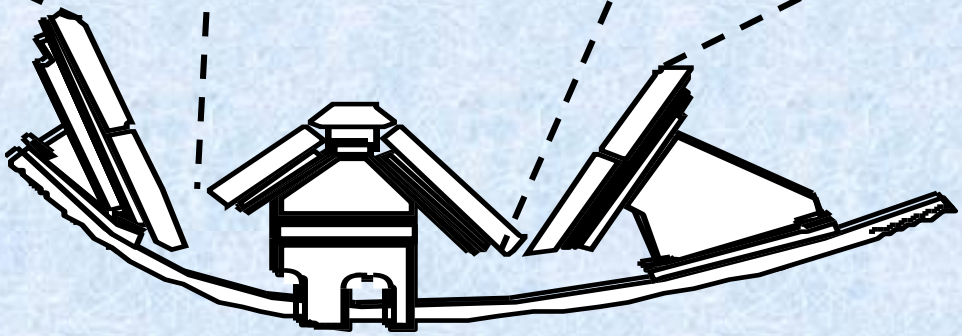


Simulation of high energy Triton by PFM code





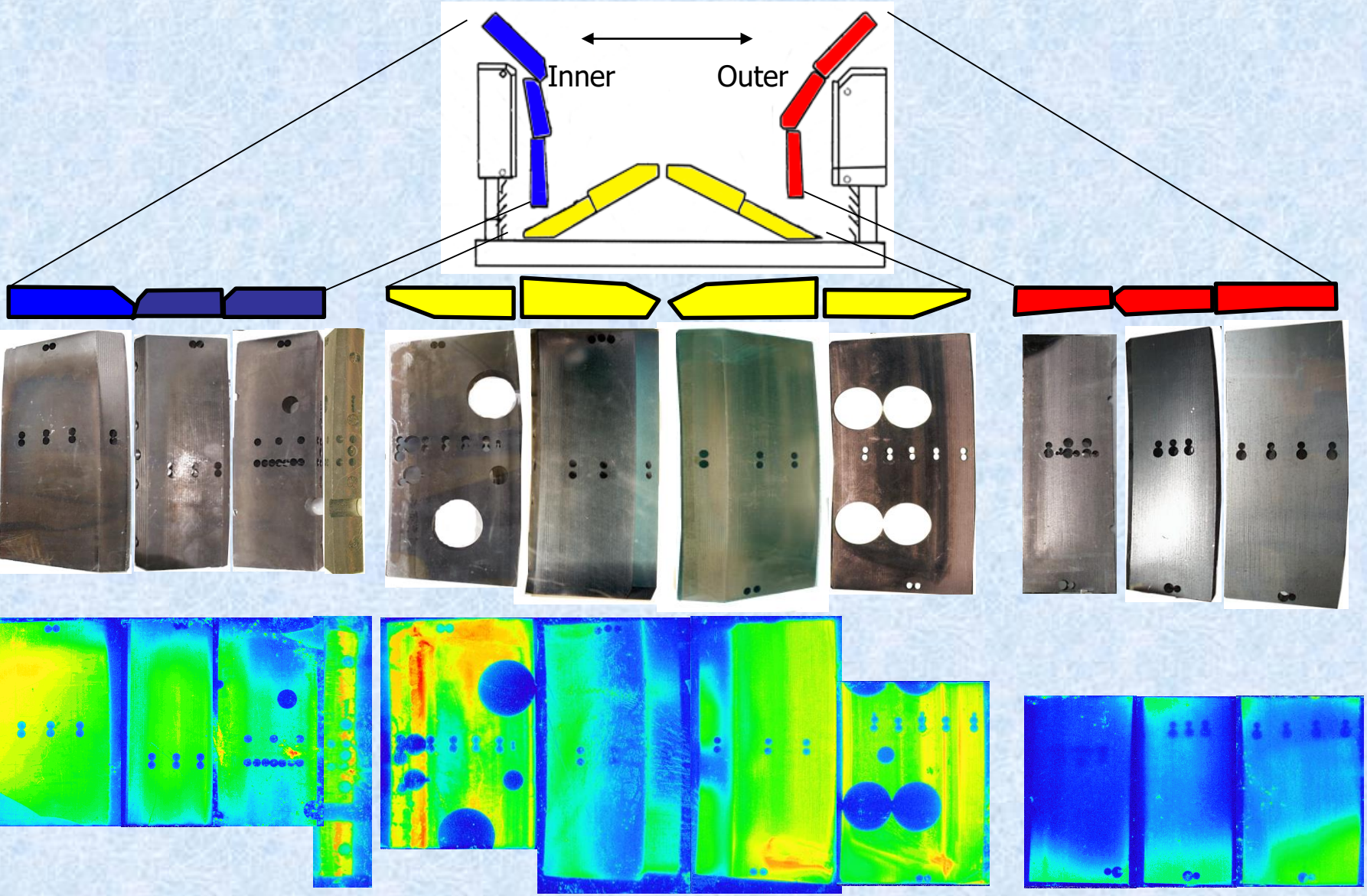
T distribution on W-shaped divertor tiles in JT-60U



JET MarkII-A divertor :

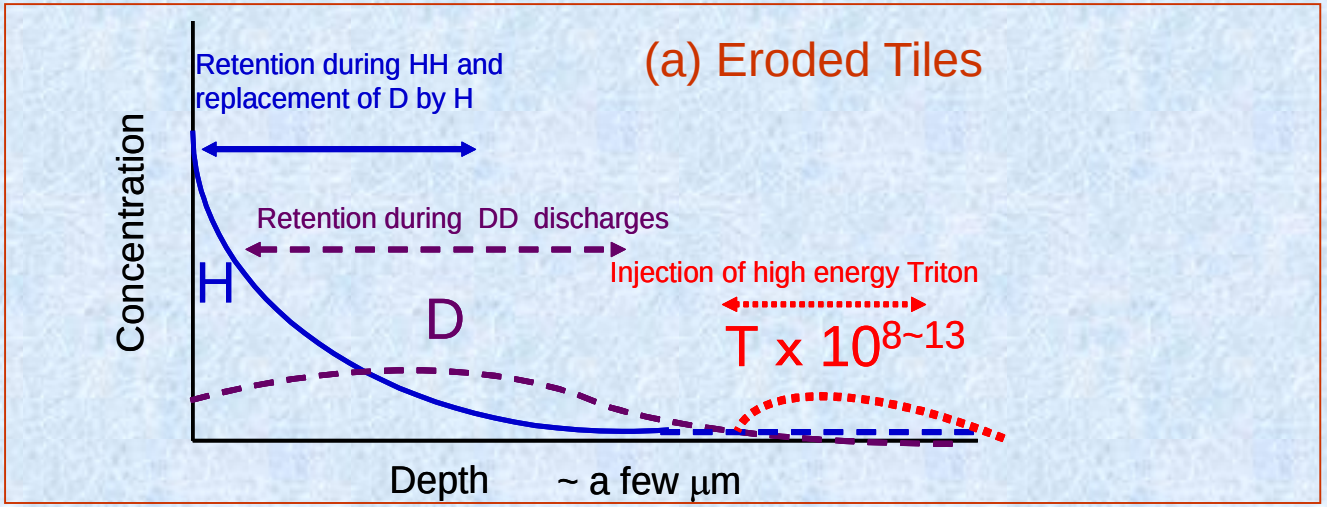
Significant codeposition of tritium and carbon on plasma shadowed area

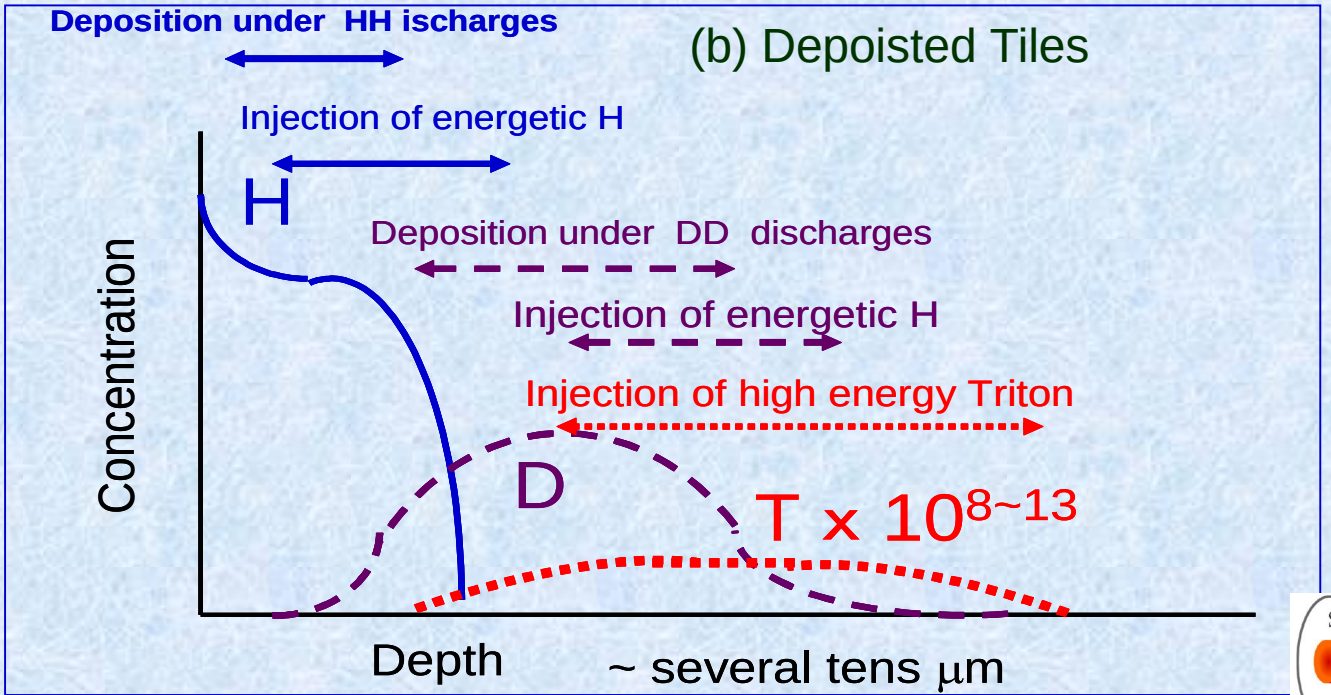
Deposition profiles were not uniform at all in both poloidal & toroidal directions



H,D,T profiles in plasma facing materials in current tokamaks are completely different. (There are reasons for that.)

At the moment there no data how different D and T behavior in DT mixed plasma.





Scientific Research in Priority Ar
Tritium for Fusion

Contamination and Decontamination

Tritium can easily radio chemically replace the ubiquitous lighter hydrogen isotopes, above all the protium (H) / deuterium in water and hydrocarbons in air

$$HT + H_2O = HTO + H_2 - \Delta G$$

$$HT + CH_4 = CH_3T + H_2 - \Delta G$$

In particular all solid surface absorbs water molecule and is easily oxidized

$$M + HTO = MOT + \frac{1}{2}H_2 - \Delta G$$

Exposure of skin is not so important owing to thin penetration of β-electron

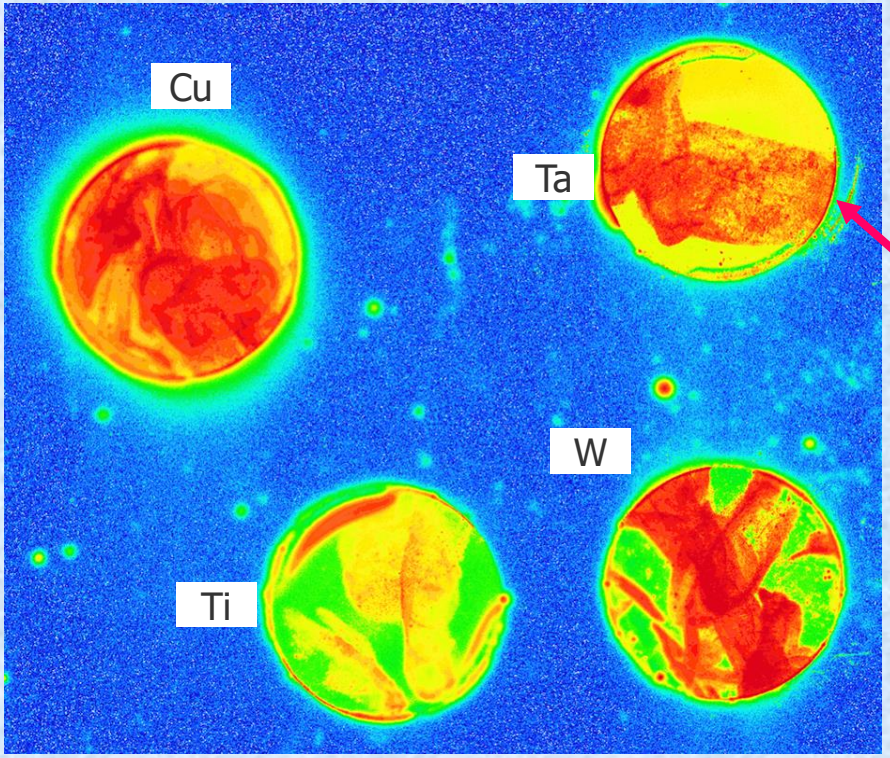
In case, T is going in your body, you should drink water to remove it.
For that purpose, Beer is very good!

Multi-step Contamination ・・・・

Ex. Contamination by gloves in safety box

Metal plates exposed to D plasma in TPL

and handled in a T handling glove box



Traces of glove fingers

Possible contamination by permeation

Summary I (Tritium in Fusion)

Amount to be handled 10^1 ~ 10^{17} Bq

monitoring 1kBq release

Temperature 10^1 ~ 10^9 K

Pellet(20K)、 Gas at RT(300K)、Plasma (10^5 ~ 10^9K)

Characteristics of Tritium

Chemistry of excited state and non-equilibrium thermodynamics

Effect of β electron emission and/or radiation heat

Defect formation by electron excitation and He production

Adsorption, solution, diffusion and permeation in materials

Difficulty in quantitative analysis (accountancy)

Counting of disintegration（ 1~10^6Bq　limited to T near surface）

Mass and pressure measurements

Radiation heat measurement（accompanying large error）

Summary II (Tritium in Fusion)

Tritium handling system, which uses mostly established techniques, can be build for ITER or even reactor.

However, handling of huge amount of tritium in ITER gives somewhat different problems. (Mostly relating tritium behavior in tokamak)

→ Huge inventory in tokamak and its accountancy

→ Controlled fuelling of DT

→ Possible permeation and leakage leading to cross-contamination

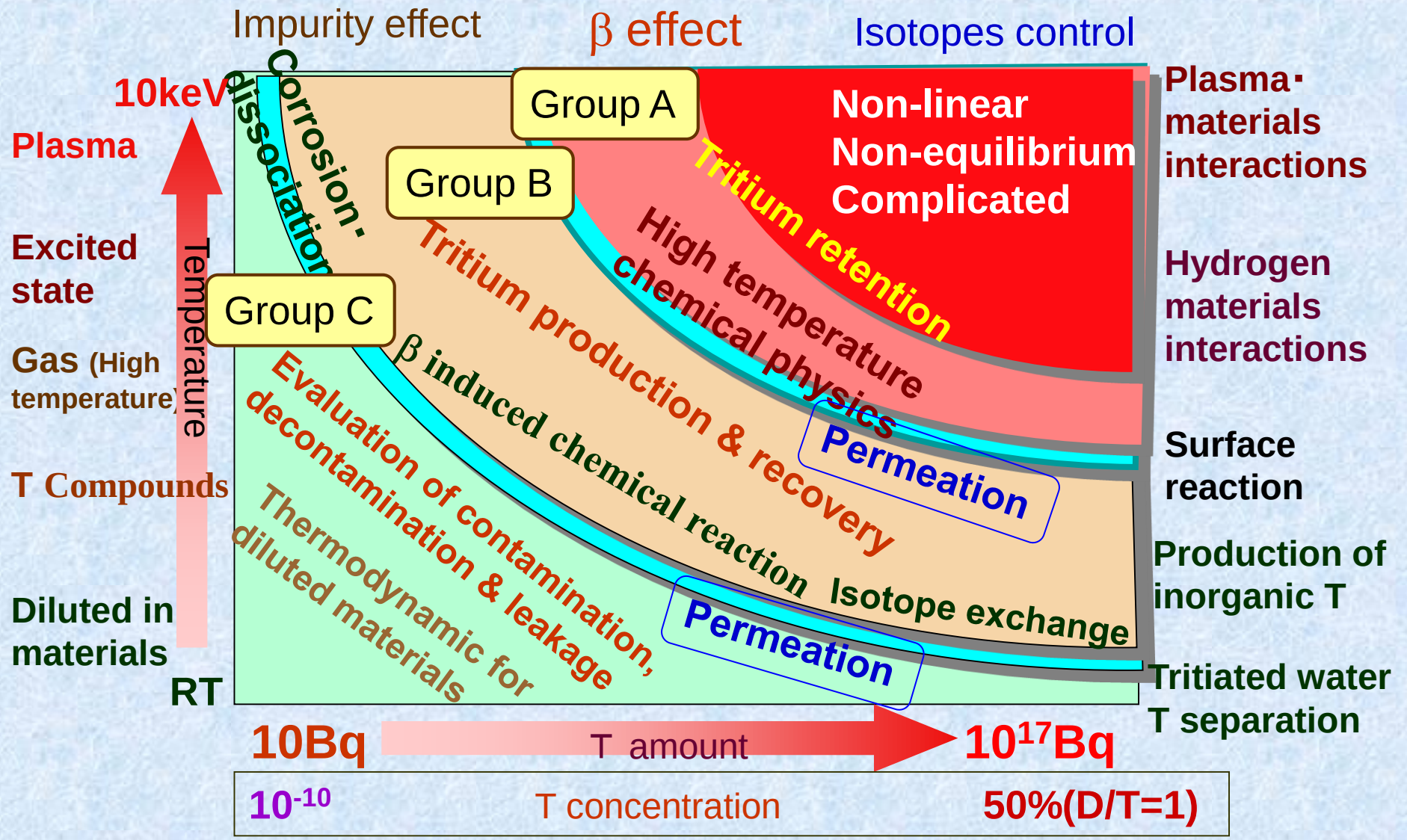
→ Contamination of remote handling system

Most of tritium problem is directly related to the safety of operators and/or professionals. But public safety does not seem to become significant problems.

Nevertheless, we are facing a world wide lack of experts in tritium science and technology.

Tritium Science & Technology for Fusion Reactor

Scientific Research in Priority Ar
Tritium for Fusion



Summary

Given by Manfred Glugla

- Tritium processing systems constitutes an essential support for ITER
  - Tritiated impurities and highly tritiated water need to be processed
- Tritium Plant inner fuel cycle design is well advanced
  - Interface definition and design integration progressing
  - Processes have been optimized in all stages of the design
    - Direct link between Isotope Separation System and Water Detritiation System
  - Design is based on world wide experience in tritium handling
- Substantial changes have been introduced into the Tritium Plant design following site specific aspects and evolution of requirements
  - Tritium Plant building was optimized, particularly in view of safety, installation, operation and maintenance
- There is a worldwide lack of experts in tritium science & technology
- Tritium Plant is not on a critical schedule path towards First Plasma

2001 ITER Tritium Plant Design Shortfalls

- Tritium Plant building layout
  - Life safety issues (airlocks & personnel egress / length of path to an exit)
    - Different confinement zones for tritium and tritiated water handling
      - Taking advantage from different Derived Air Concentration limits is unworkable
  - Installation and maintenance issues
    - Crane and crane shaft instead of an elevator with airlocks
    - No common pattern or free passage for equipment movement
      - Unequal floor levels for Tokamak building / Tritium Plant building
- Tritium confinement concept
  - HVAC with 90% recycle bears the risk for tritium cross contamination
  - Separate under pressure control system technically not feasible
  - Dedicated Atmosphere & Vent Detritiation Systems for different functions
    - Very complex and hence with by far too high failure rates
- Tritium processing requirements not completely defined

ITER Tritium Confinement Philosophy

- Confinement of tritium within its respective fuel cycle processing systems and components is in effect most important safety objective
  - Basic targets of confinement
    - Prevent spreading of radioactive material in normal operation
      - Maintain contamination level as low as reasonably achievable (ALARA principle)
    - Keep radiological consequences for operators, public and environment in off-normal conditions within acceptable levels
  - Confinement function is achieved by a coherent set of physical barriers and / or auxiliary techniques intended to confine radioactive substances
    - IAEA practice is to use the term "containment" for physical barriers
      - Term "confinement" is more general, refers to function of confining radioactive material within a certain volume and includes filtering and atmosphere processing
    - Primary confinement system is designed to prevent releases of radioactive materials into the accessible working areas
    - Secondary confinement system prevents releases of the contamination to the working areas accessible by non-authorized radiological workers, the general public and the environment

Tritium handling facilities in Japapn

Facility	Daly limit	One years limit	Using group
JAEA	9.25 PBq	740 PBq	A, B, C01
Toyama Univ.	8.0 TBq	560 TBq	C02
Kyushu Univ.	3.7 GBq	18.5 GBq	A,B
Nagoya Univ.	3.7 GBq	370 GBq	C01
Shizuoka Univ.	1 GBq	80 GBq	C02
Univ.Tokyo	50 GBq	50 GBq	B02
Osaka Univ.	30 TBq	1 PBq	

1 PBq = 1 x 10^{15}Bq **1 TBq = 1 x 10^{12}Bq** **1 GBq = 1 x 10^{9}Bq**

JAEA

Inner & Outer Fusion Reactor Fuel Cycles

- Among the potential fusion reactions technically most suitable is the reaction between deuterium and tritium

  $D + T \rightarrow {}^4He\ (3.5\ MeV) + n\ (14.1\ MeV)$

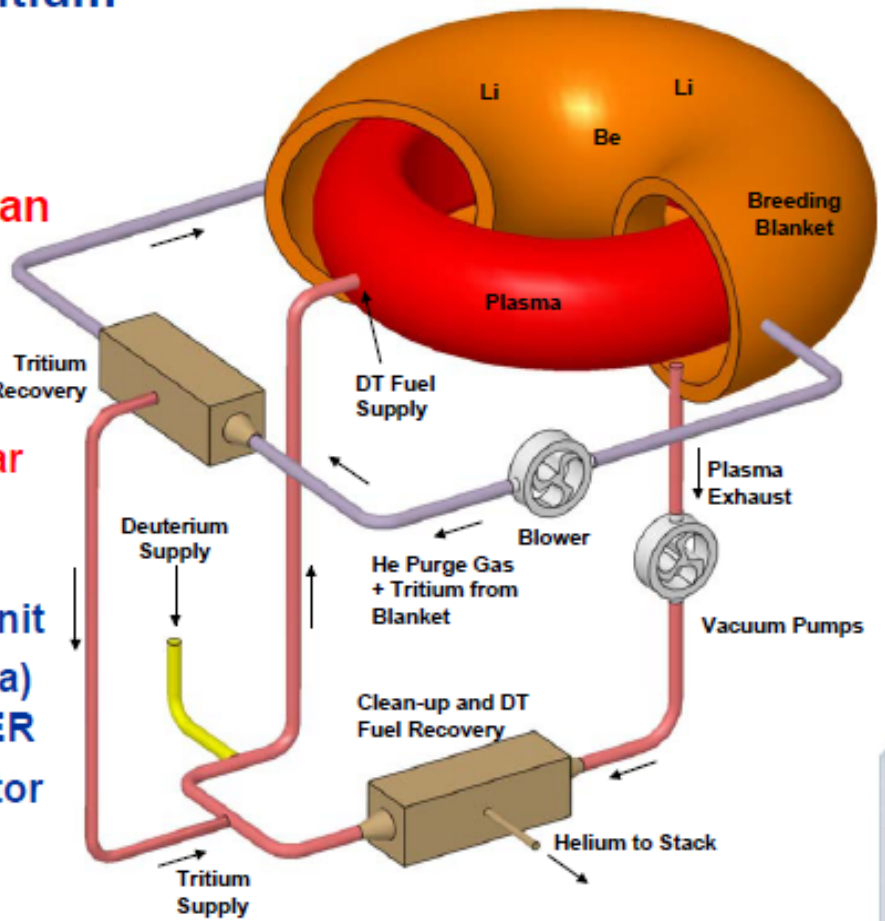
  – Deuterium can be extracted from natural water (SMOW (standard mean ocean water) contains 0.016% D)

  – Tritium must be imported (limited) or bred internally from lithium

  - 56 kg tritium is required per GW year (thermal) of fusion power
  - About 100 g tritium is produced per year in a standard CANDU fission unit
  - 20 to 25 kg tritium (mainly in Canada) will be available for operation of ITER
  - Breeding reactions in a fusion reactor

    $n + {}^6Li \rightarrow T + {}^4He$

    $n + {}^7Li \rightarrow T + {}^4He + n$

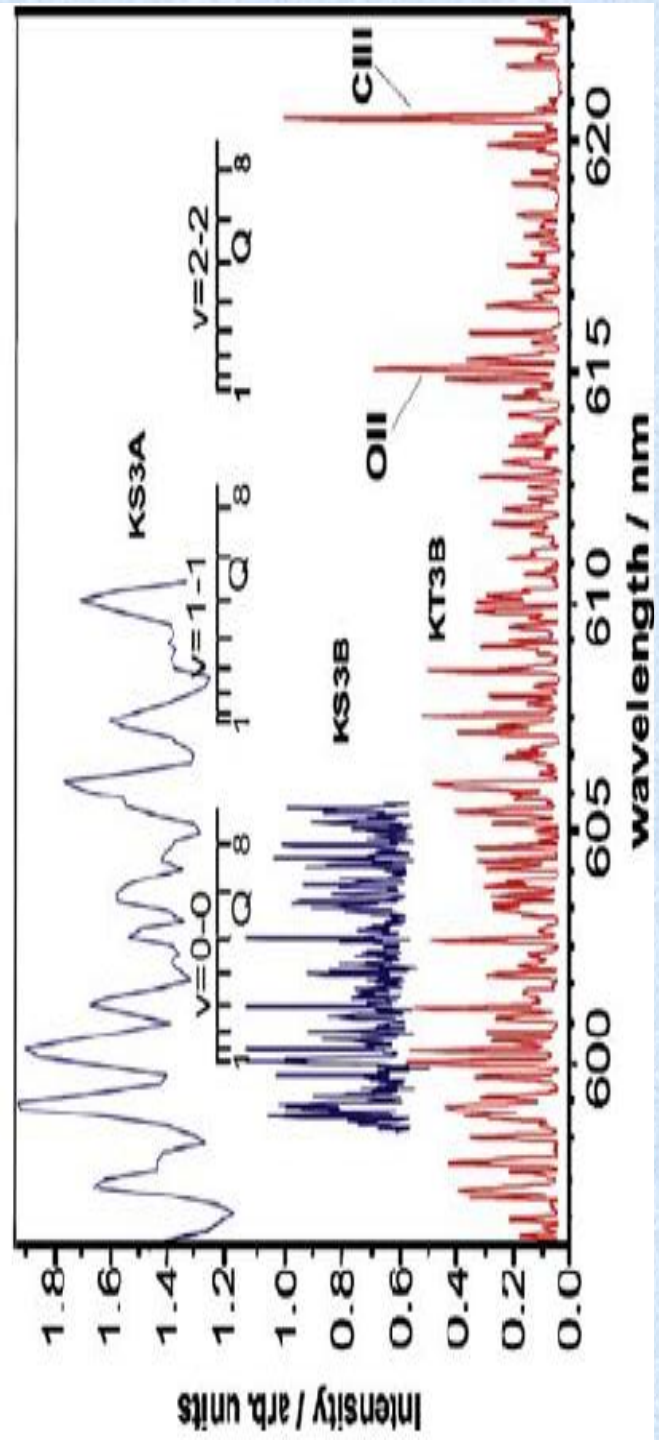


Main Functions of ITER Tritium Systems

- Handling of incoming and outgoing tritium shipments
- Storage / delivery of tritium & deuterium to / from fuel cycle
  - Inventories determination
- Torus vacuum pumping & gas transfer to tritium processing systems
  - High vacuum cryo-pumping and rough vacuum pumping
- Processing of tritium containing fluid streams
  - Tokamak exhaust / other tritiated off-gases for recycling of tritium and deuterium
  - Decontamination of gases prior to controlled release into the environment
  - Separation of hydrogen into specific isotopic species for refueling
  - Detritiation of water and recovery of the tritium
  - Extraction / recovery of tritium from Test breeding Blanket Modules

Molecular deuterium sources in the outer divertor of JET,

A. Pospieszczyk et al. J. Nucl. Mater. 337-339(2005)500



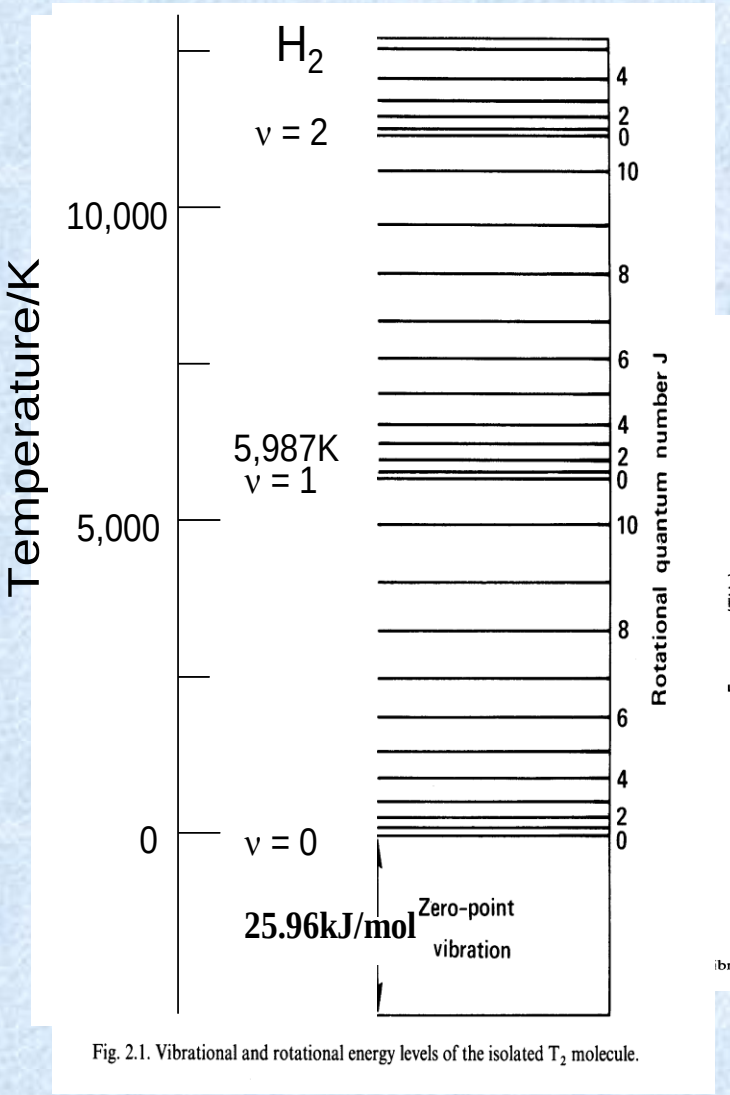
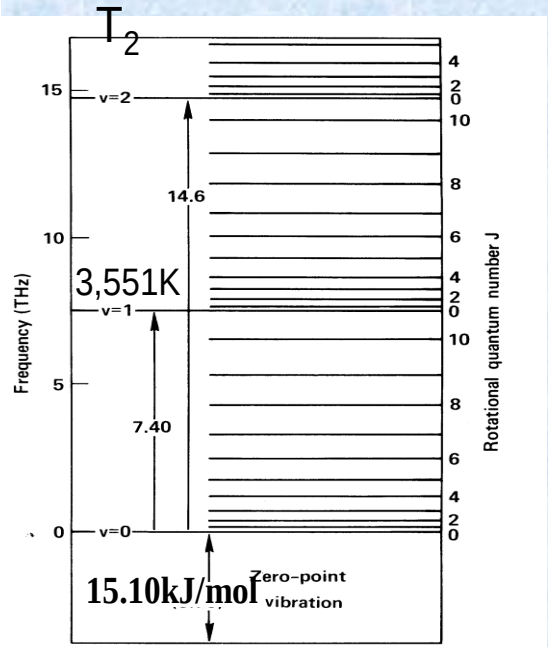


Fig. 2.1. Vibrational and rotational energy levels of the isolated T_2 molecule.



ibrational and rotational energy levels of the isolated T_2 molecule.

Fig. 3(b). D_2 before and T_2 spectra during a T2 puff into the H-mode phase of JPN 61830.

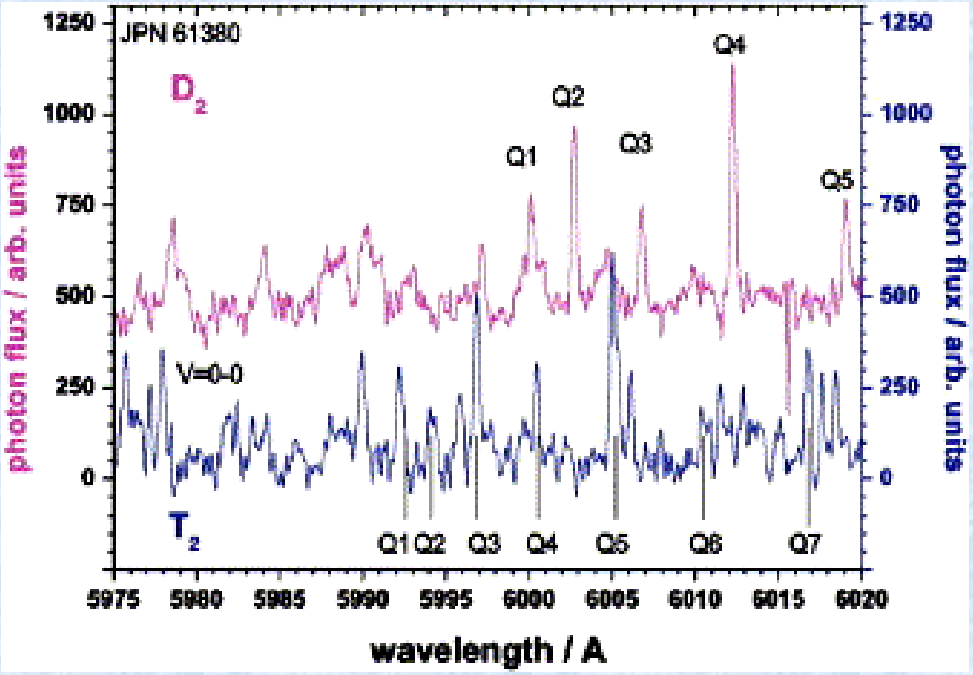
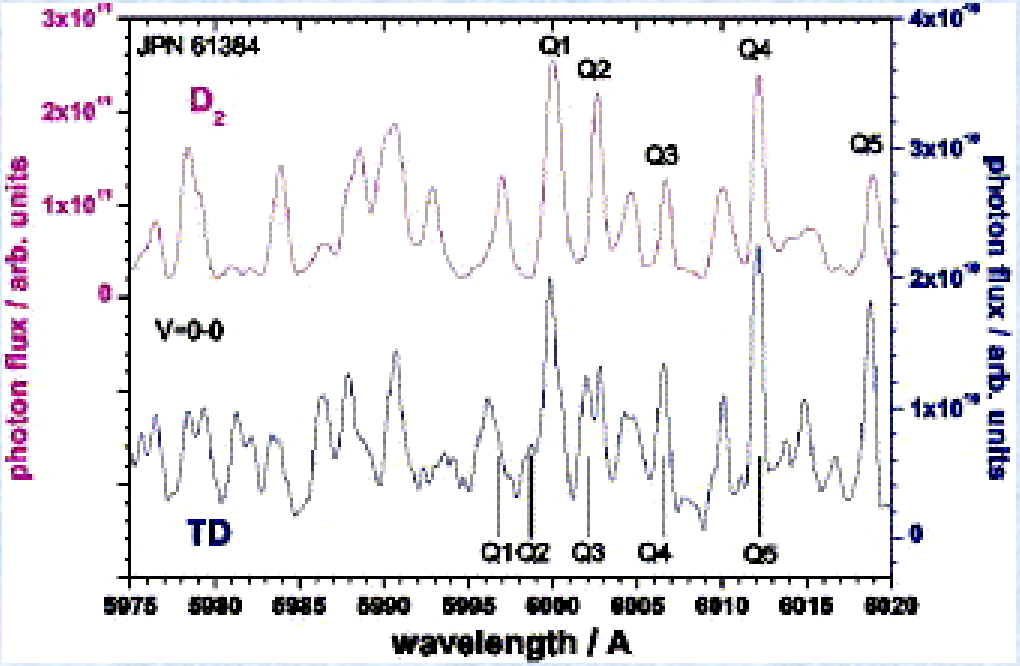


Fig. 3(e). D_2 spectra before and TD spectra from the 2. line of sight of KT3B during the T2 puff shown in (a).



Molecular (H/D/T) sources in JET, A. Pospieszczyk, ,et al. J. Nucl. Mater.363-365(2007)811

水素中には必ず、水分が含まれている

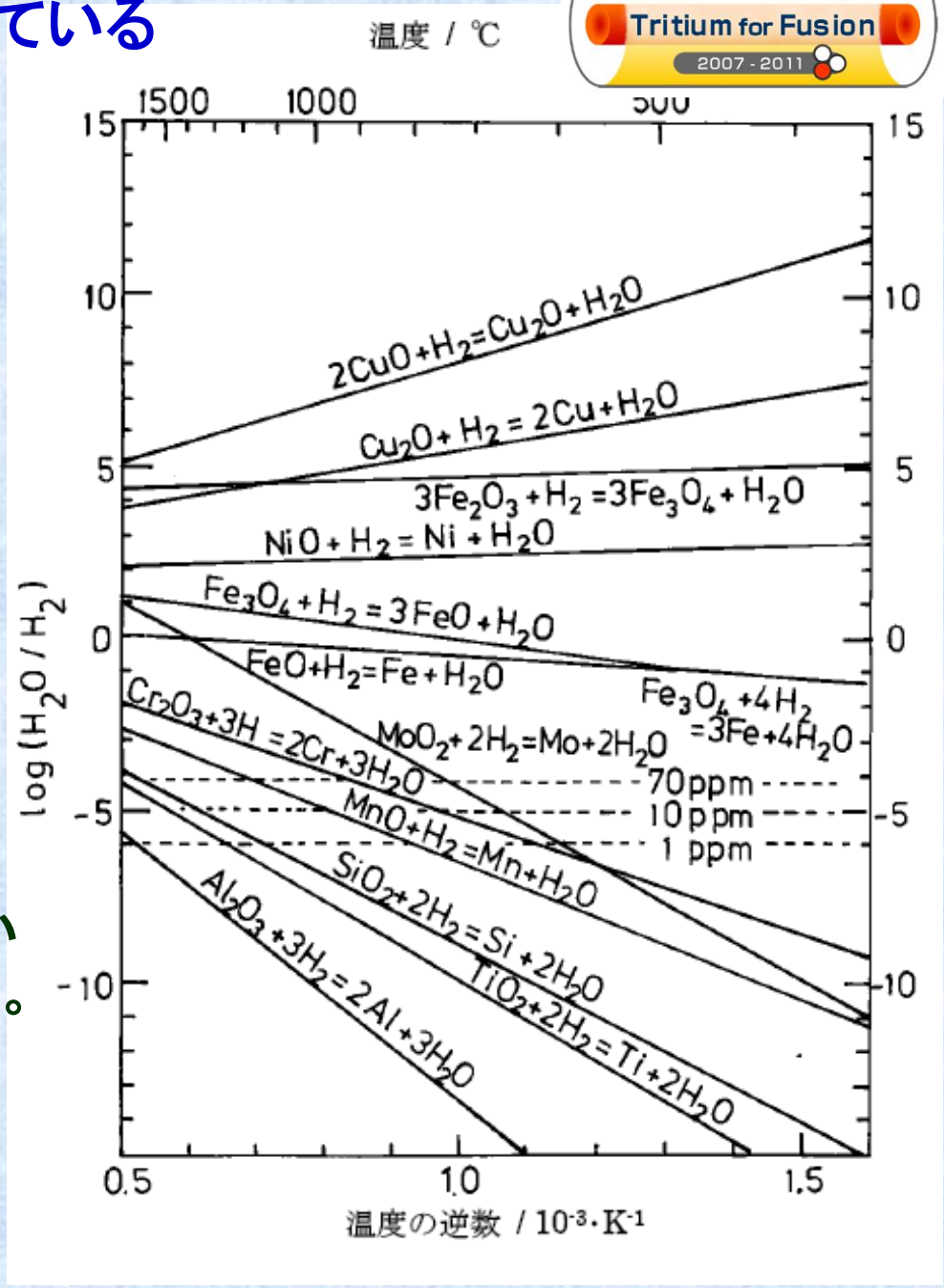
金属表面では酸化/還元が起こる。

$$M + H_2O = MO + H_2 - \Delta G$$

$$\Delta G = -RT \ln K$$

$$= -RT \ln \left[\frac{P(H_2O)}{P(H_2)} \frac{a(M)}{a(MO)} \right]$$

非常にCleanな水素といえども
水分を10ppm以下にすることは難しい
ので、鉄だと室温付近では酸化される。



溶解度と熱力学

$$M+\frac{1}{2}H_2 = M(H)-\Delta G(M(H))$$

$$\Delta G(M(H)) = -RT\ln K = -RT\ln\left[P(H_2)^{1/2}\,a(M)/a(M(H)\right]$$

$$\approx -RT\ln\left[P(H_2)^{1/2}/\mathrm{c}\right]$$

$$c \propto P(H_2)^{1/2}\exp(-\Delta G/RT)$$

Sievert's low (K_S Sivert's const.)では

$$x = K_S P(H_2)^{1/2}$$

$$K_S \approx \exp(-\Delta G) = \exp(-\Delta H + T\Delta S)$$

熱力学的には分配係数 S（Solubility）を導入して

$$\ln S = A - \frac{B}{T} + \frac{1}{2}\ln\left(\frac{P(H_2)}{P_0(T)}\right)$$

$$S = \left(\frac{P(H_2)}{P_0(T)}\right)^{1/2}\exp(A-\frac{B}{T})$$

$$P_0(T) = \left(\frac{\sqrt{4\pi MkT}}{h}\right)^3\left(\frac{2\pi\sqrt{I_r kT}}{h}\right)^2$$