「PWI-研究の進展」

ー図子秀樹先生ご退官を祝してー

平成27年3月11日
於：九大QUEST研究会

核融合研･総研大
廣岡慶彦

講演概要

1. PWI-研究とコア・プラズマ閉じ込め並列年表

1. 総論①核融合研究とPWI-研究の夜明け
2. 総論②過去50年のPWI-研究の進展

2. PWI-研究の進展と問題点

1. 各論①Ti-gettering
2. 各論②Carbonization
3. 各論③Boronization
4. 各論④Lithium conditioning

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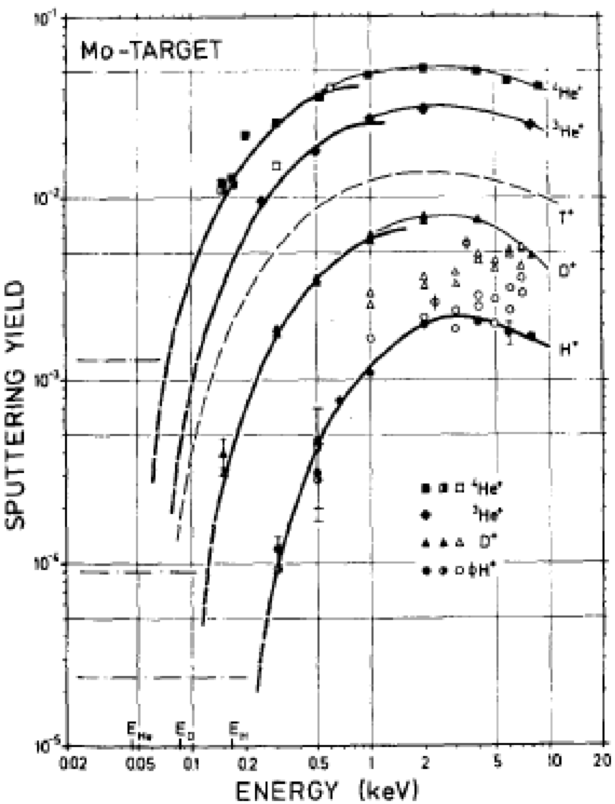
3. 今後の展望とまとめ

PWI-研究年表：総論①

表面物理・化学現象 ⇔ コアプラズマ性能

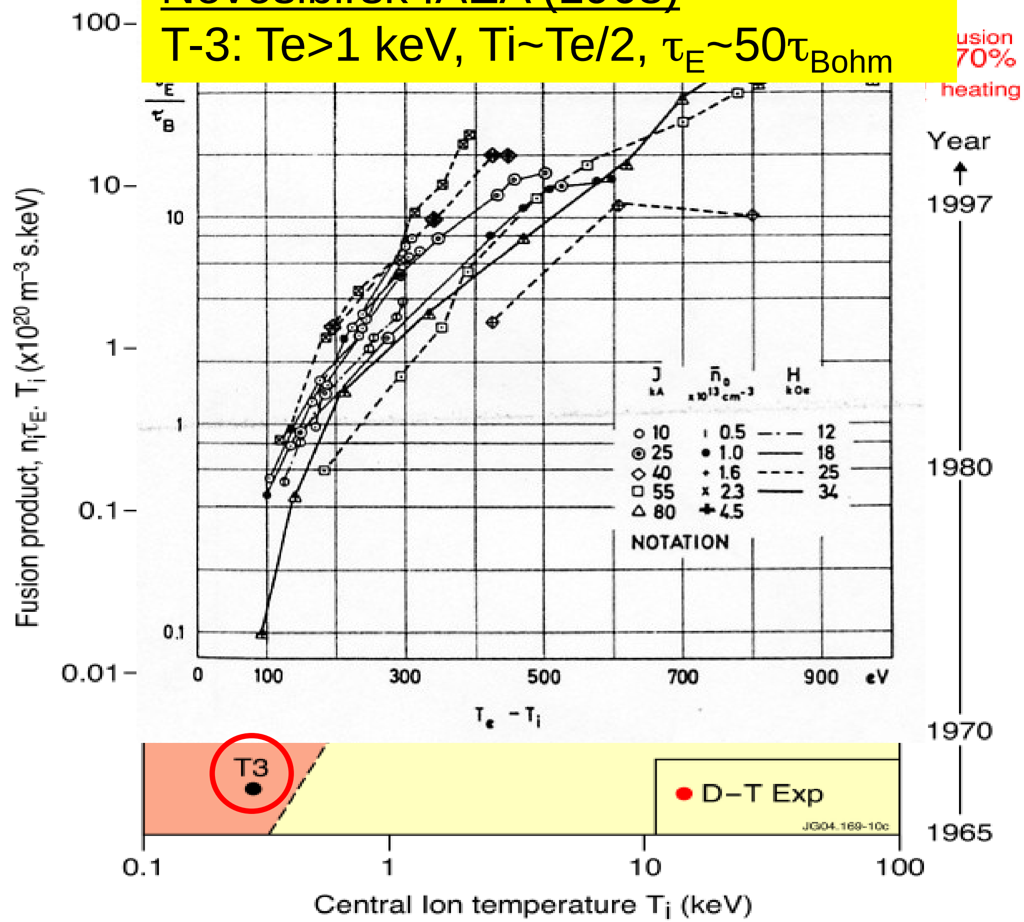
PWI-研究、1970年台に本格開始か?



Bay et al. J. Appl. Phys. 48(1977)4722.

Novosibirsk IAEA (1968)

T-3: Te>1 keV, Ti~Te/2, τ_E~50τ_{Bohm}



PWI-研究年表：総論②

表面物理・化学現象 ⇔ コアプラズマ性能

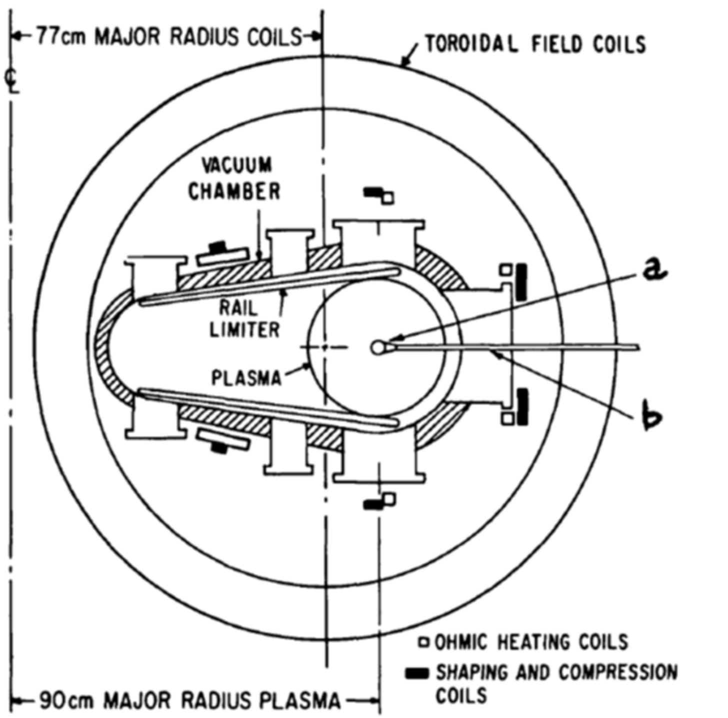
- 1972 Kulcinski: 1st wall in UWMAK.
- 1973 Kaminsky: He blistering in Nb.
- 1974 Kaminsky: Neutron-chunk(?) from Nb.
- 1975 Sttot: Ti-gettering in ATC.
- 1978 McCracken: Recycling in DITE.
- 1981 Wilson: Recycling from SUS304.
- 1983 Baskes: DIFFUSE-code.
- 1984 Viesack & Eckstein: TRIM-code.
- 1987 Winter: Carbonization in TEXTOR.
- 1987 Dylla: He/D wall conditioning in TFTR.
- 1987 Hirooka: Erosion-redeposition in PISCES.
- 1989 Winter: Boronization in TEXTOR.
- 1996 Mansfield: Lithium-coated divertor in TFTR.
- 2012 Kugel: Liquid lithium divertor in TFTR.

- 1958 ZETA DD-neutron(?) episode.
- 1968 Artsimovich: τ_E/τ_B~50 in T-3.
- 1969 Peacock: T_e~1keV in T-3.
- 1982 Wagner: H-mode in ASDEX.
- 1984 Wagner: ETB in ASDEX H-mode.
- 1987 Stracken: Supershots in TFTR.
- 1991 Jackson: VH-mode in DIII-D.
- 1991 JET-team: DT-shots in JET.
- 1994 Strachen: DT-shots in TFTR.
- 1997 JET-team: DT-shots in JET.
- 1999 JET-team: ELM-free DT-shots in JET.
- 2006 Ohyabu: Superdense mode in LHD.
- 2011 Kukushikin: Final ITER-divertor design

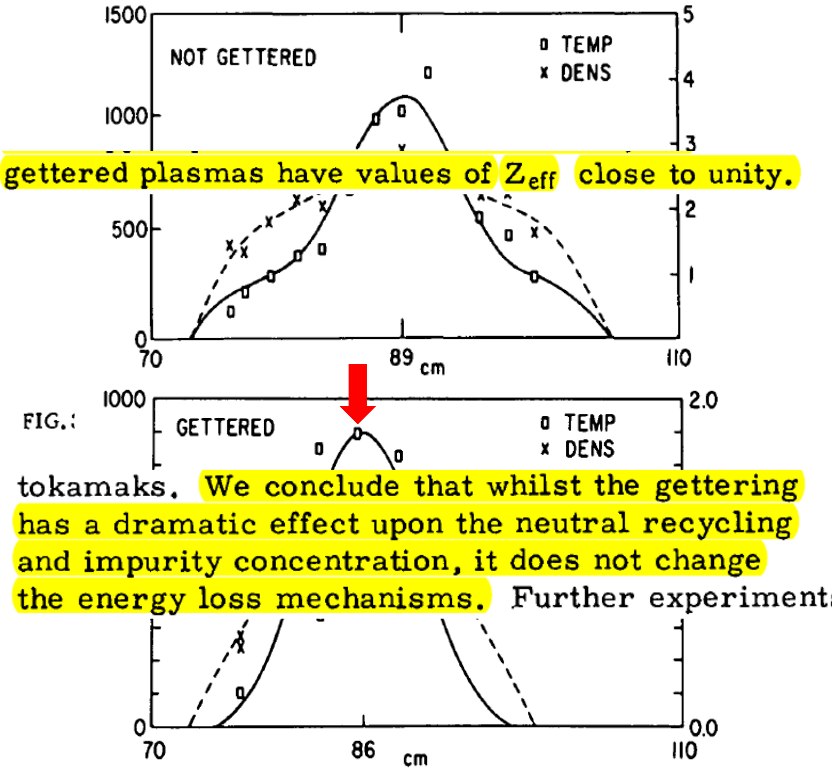
PWI-研究年表：各論①酸素不純物

表面物理・化学現象 ⇔ コアプラズマ性能

1975 Ti-gettering in ATC



Stott et al. Nucl. Fusion 15(1975)431.



gettered plasmas have values of Z_{eff} close to unity.

tokamaks. We conclude that whilst the gettering has a dramatic effect upon the neutral recycling and impurity concentration, it does not change the energy loss mechanisms. Further experiments

FIG.4b. Radial profiles of the electron temperature, T_e, and density, n_e.

PWI-研究年表②金属不純物

表面物理・化学現象 ⇔ コアプラズマ性能

In 1987 Carbonization in TEXTOR

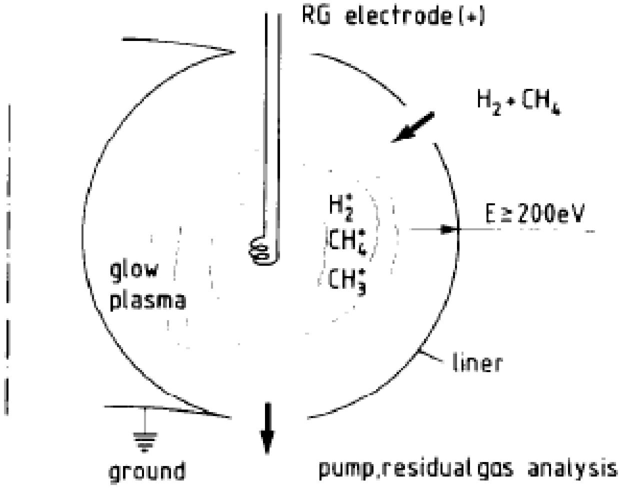


Fig. 1. Schematic sketch of the carbonization technique as developed at TEXTOR.

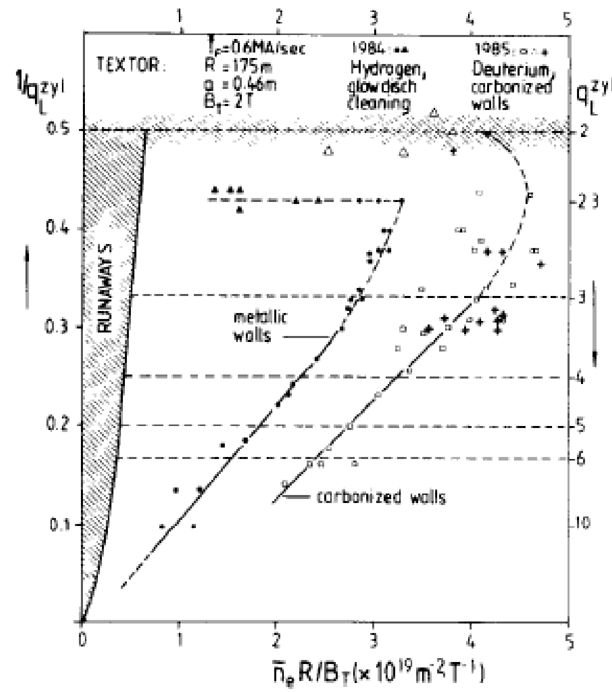


Fig. 8. Operational regime of TEXTOR with ohmic heating for conventionally RG-cleaned and for carbonized surface conditions [30].

Winter, J. Nucl. Mater.145-147(1987)131.

PWI-研究年表：各論③輻射損失

表面物理・化学現象 ⇔ コアプラズマ性能

In 1989, Boronization in TEXTOR

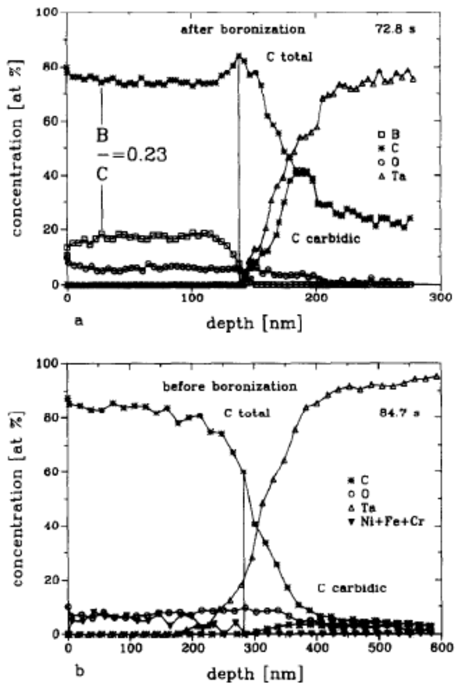


Fig. 2. AES depth profiles of redeposits collected at $r \sim 46.7$ cm on the electron drift side Ta-targets after boronization (a) and before (b) when TEXTOR was carbonized.

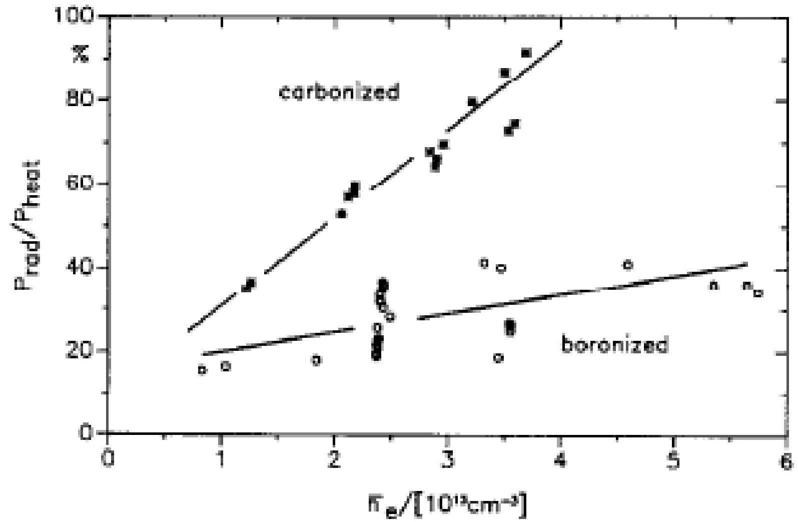


Fig. 7. Fraction of the radiated power P_{rad} relative to the ohmic input power P_{heat} for carbonized and boronized walls and limiters. Data for carbonized wall conditions have been taken from ref. [10].

Winter, J. Nucl. Mater. 162-164（1989）713.

PWI-研究年表：各論④閉じ込め改善へ

コアプラズマ性能 ⇔ 表面物理・化学現象

L-and H-modes in ASDEX

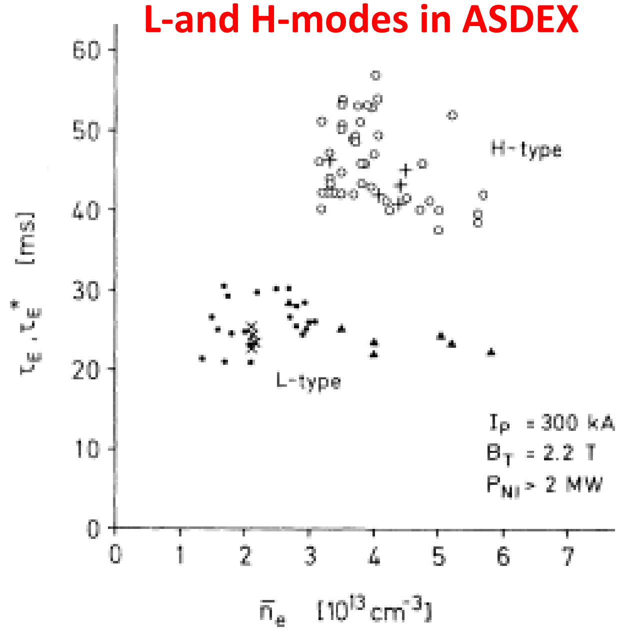


FIG. 2. Global energy confinement time vs average line density for toroidal limiter (triangles) and divertor discharges (other symbols). τ_E (plusses and crosses) is deduced from thermal profiles and τ_E^* (open circles, solid circles, and triangles) is determined from the diamagnetically measured $\beta_{p\perp}$.

Wagner PRL(1982).

Edge transport barrier in ASDEX

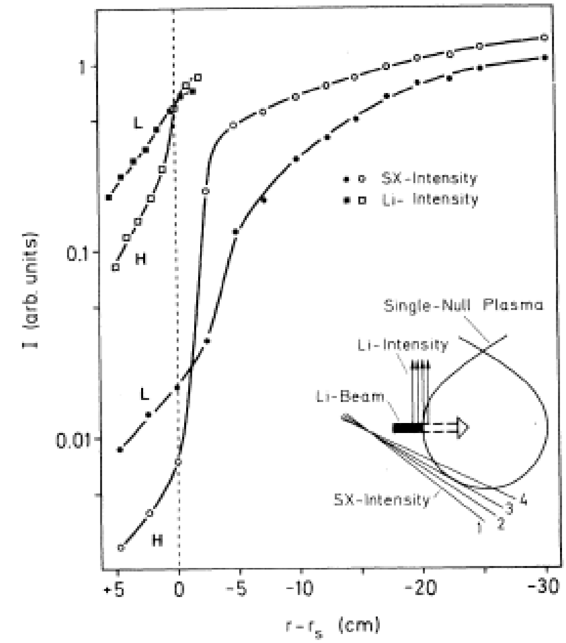


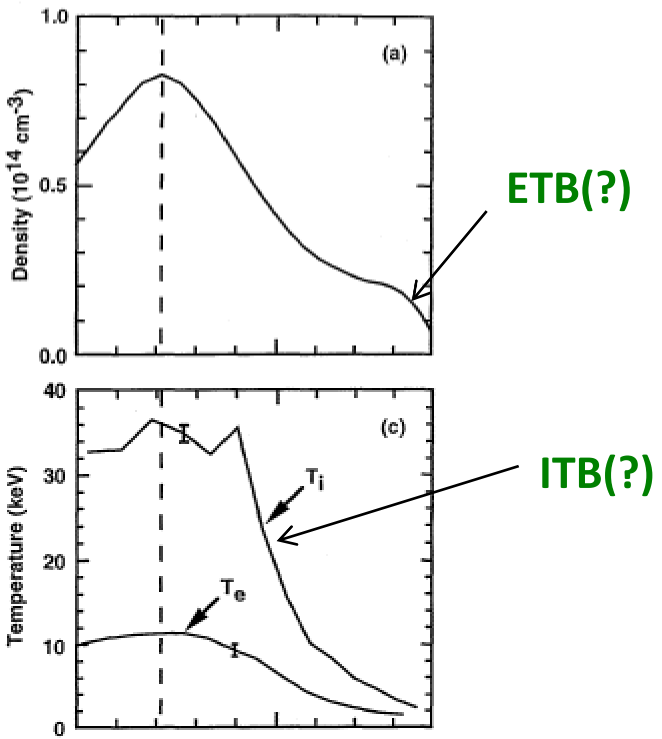
FIG. 2. Radial profiles of the SX (2-μm Be filter) and Li-beam intensities in the L phase prior to the H transition and shortly afterwards (SX, $\Delta t = 20$ ms; Li, $\Delta t = 55$ ms). $I_p = 375$ kA, $B_T = 2.2$ T, $\bar{n}_e = 3.3 \times 10^{13}$ cm^{-3}, $P_{NI} = 0.8$ MW. The inset depicts the observation geometry.

Wagner PRL(1984).

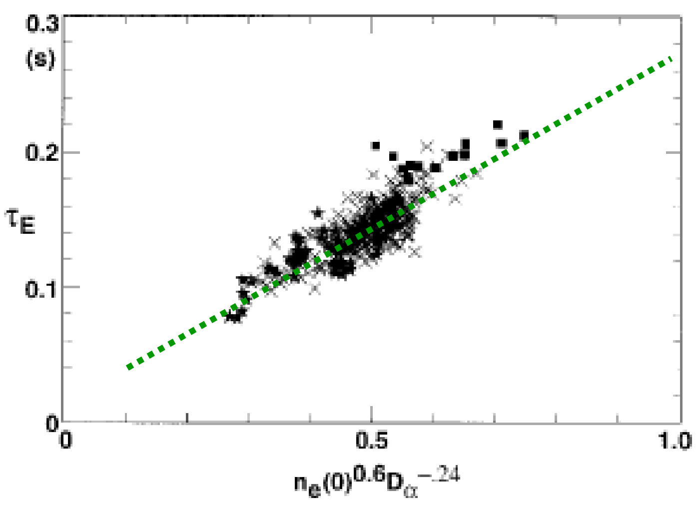
PWI-研究年表：各論⑤閉じ込め改善へ

表面物理・化学現象 ⇔ コアプラズマ性能

Supershot in TFTR



Mansfield et al. PPPL-Report#3097(1995).



Strachan, Nucl. Fusion 39(1999)1093.

PWI-研究年表：各論⑦閉じ込め改善へ

表面物理・化学現象 ⇔ コアプラズマ性能

Lithium effects on confinement

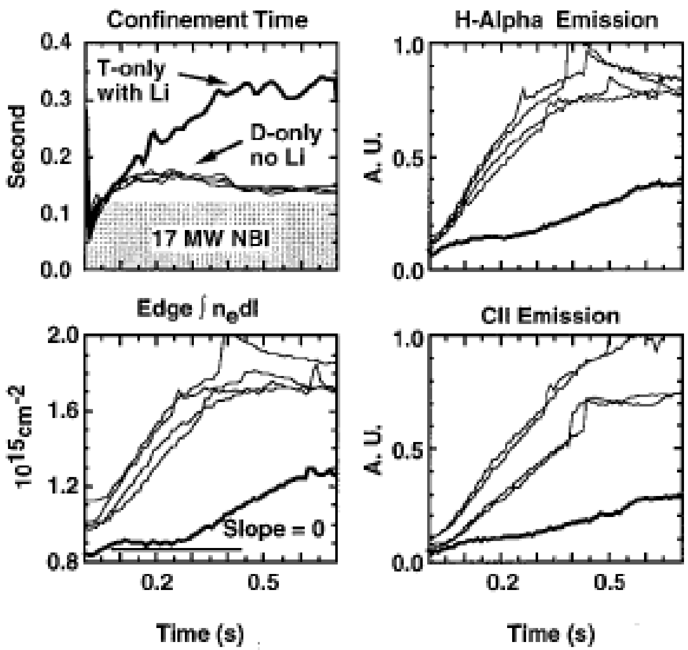


FIG. 6. Reduction in edge electron density and Dα and CII line emission and corresponding increase in energy confinement time for a T-only discharge (thick line) with good Li conditioning, and several D-only shots for comparison (thin lines).

Supershot confinement in TFTR

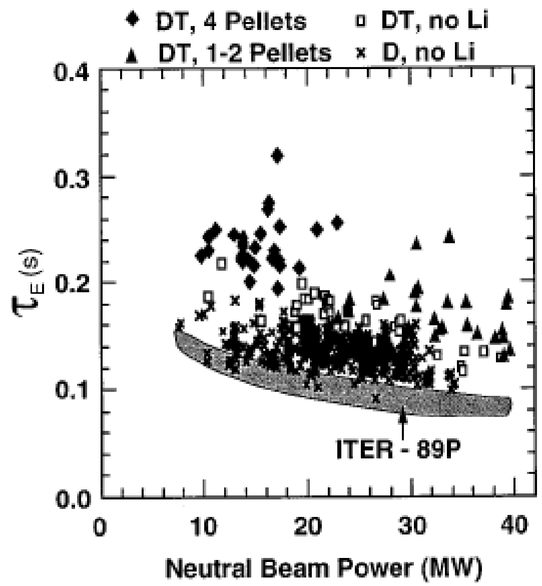


FIG. 2. Energy confinement time plotted as a function of neutral beam heating power for (×) D-only NBI with no Li conditioning, (□) D–T discharges without Li, and D–T discharges with Li conditioning (one to two pellets—triangles, four pellets—diamonds). The values for D–T discharges without Li are about 15% higher than the D-only values, illustrating the favorable isotope scaling discussed in Ref. 5. With tritium fueling plus Li conditioning, the values are two to three times the ITER-89P scaling (Ref. 3).

PWI-研究年表：各論⑥閉じ込め改善へ

表面物理・化学現象 ⇔ コアプラズマ性能

Superdense Core in LHD

IDB

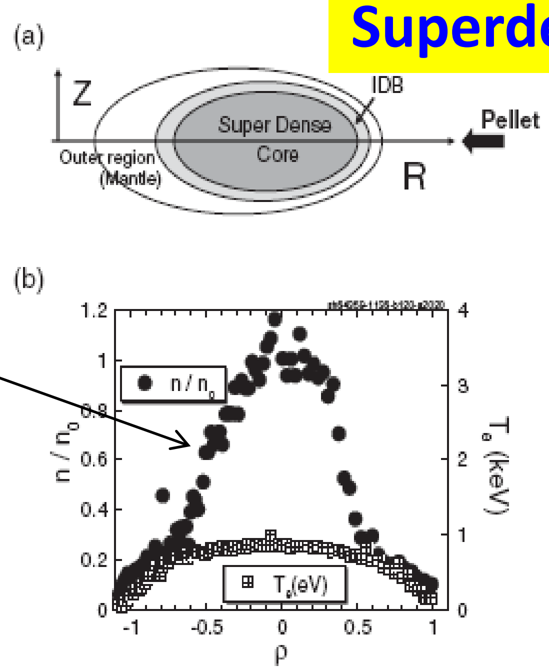
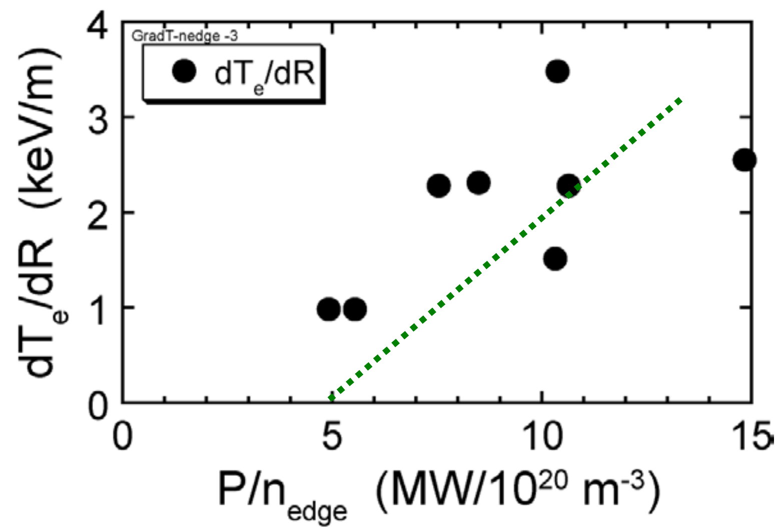


FIG. 1. (a) Illustration of a SDC plasma. (b) Density and temperature profiles of an SDC discharge with $R_{ax} = 3.75$ m are depicted. The density normalization factor $n_0 = 4.5 \times 10^{20}$ m^{-3}, $P = 10$ MW.

After N. Ohyabu et al., Phys. Rev. Lett.97(2006)055002.



After N. Ohyabu et al., PRL97(2006)055002.

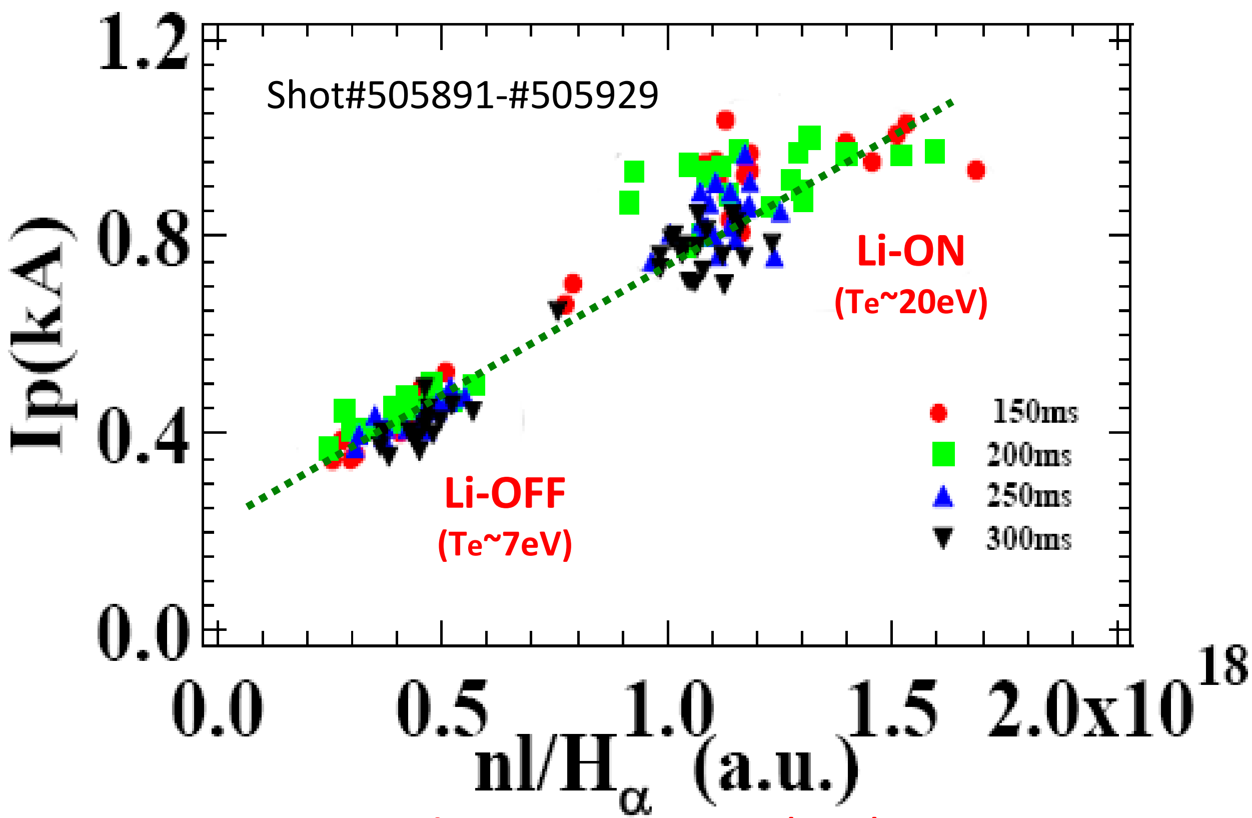
From the LHD superdense-core plasma exps.:

$$\chi = \frac{1}{2}(\chi_e + \chi_i) = -\frac{1}{2}\frac{q_e + q_i}{n_e(dT/dR)}$$

(*after G. Becker, Nucl. Fusion* 44(2004)*L*26)

PWI-研究年表：各論⑧閉じ込め改善へ

表面物理・化学現象 ⇔ コアプラズマ性能

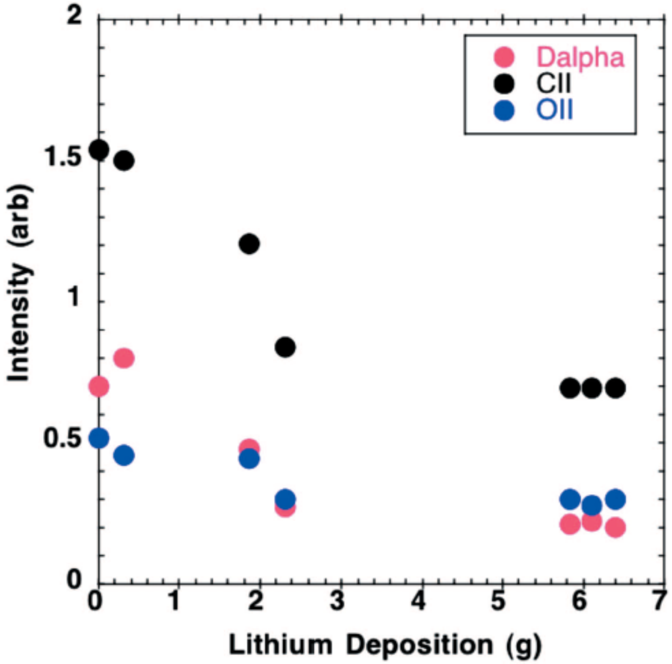


Hirooka, Fusion Eng. Des. 85(2010)818.

PWI-研究年表：各論⑧閉じ込め改善へ

表面物理・化学現象 ⟺ コアプラズマ性能

D-recycling and impurities in NSTX



Kugel et al., Phys. Plasmas 15(2008)056118

Stored energy in NSTX

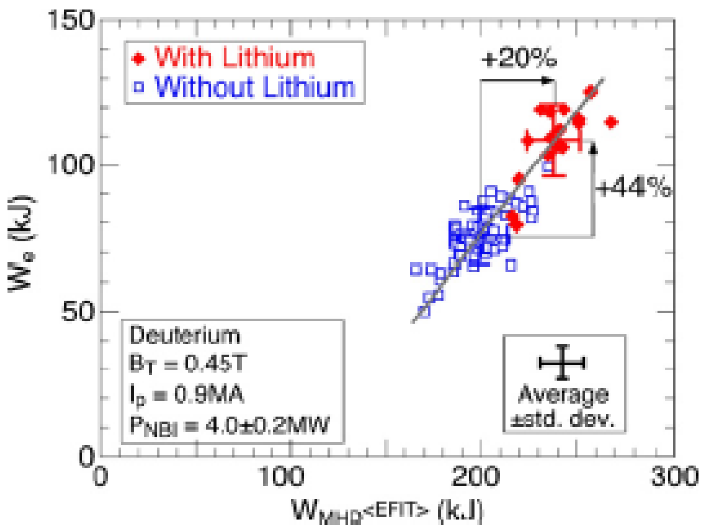


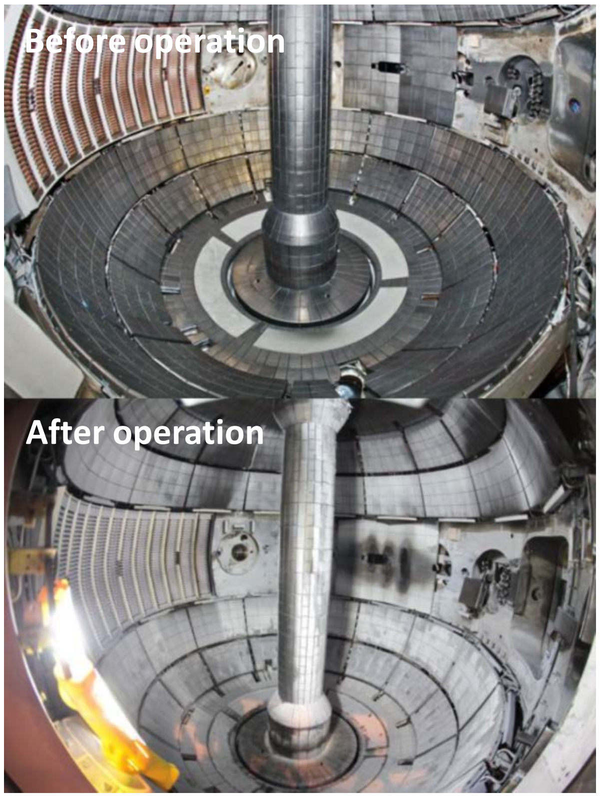
Fig. 3. Total stored energy from EFIT analysis and electron stored energy from volume integration of Thomson scattering measurements of n_e, T_e for similar H-mode discharges with and without lithium coating of the lower divertor.

Ono et al., Fusion Eng. Des. 85(2010)882.

PWI-研究年表：各論⑨閉じ込め改善へ

表面物理・化学現象 ⇔ コアプラズマ性能(?)

In 2012 Liquid lithium divertor in NSTX



Kugel et al. Fusion Eng. Des. 87(2012)1724

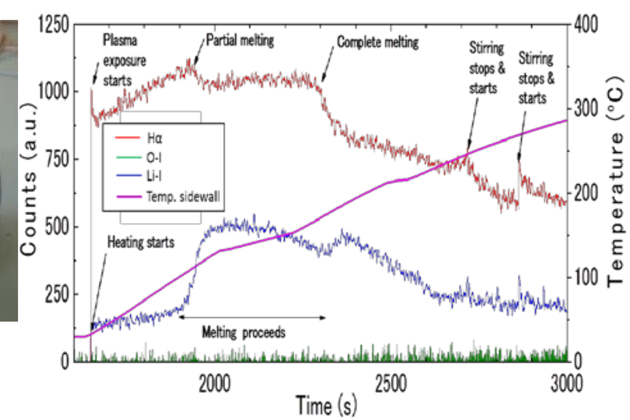
Buoying impurities: LiO_2, LiOH

$Li + O_2 \Rightarrow LiO_2$

$H_2 + 1/2O_2 \Rightarrow H_2O$

$Li + H_2O \Rightarrow Li(OH) + 1/2H_2$

Surface heating⇒No natural convection



HIrooka et al. Fusion Eng. Des. 89(2014)2833.

PWI-研究: 今後の展望①[超]高熱流除去

ITER-divertor design

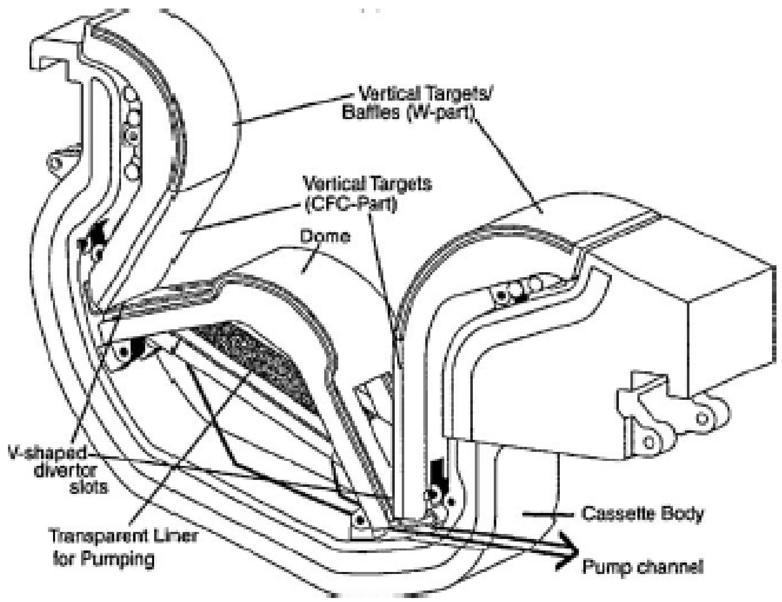


Fig. 5. ITER divertor design 2009 [3].

DEMO-divertor

- W-armor + F82H heat sink

  Max. heat flux : 5~8MW/m^2

  Plasma current~20-30MA

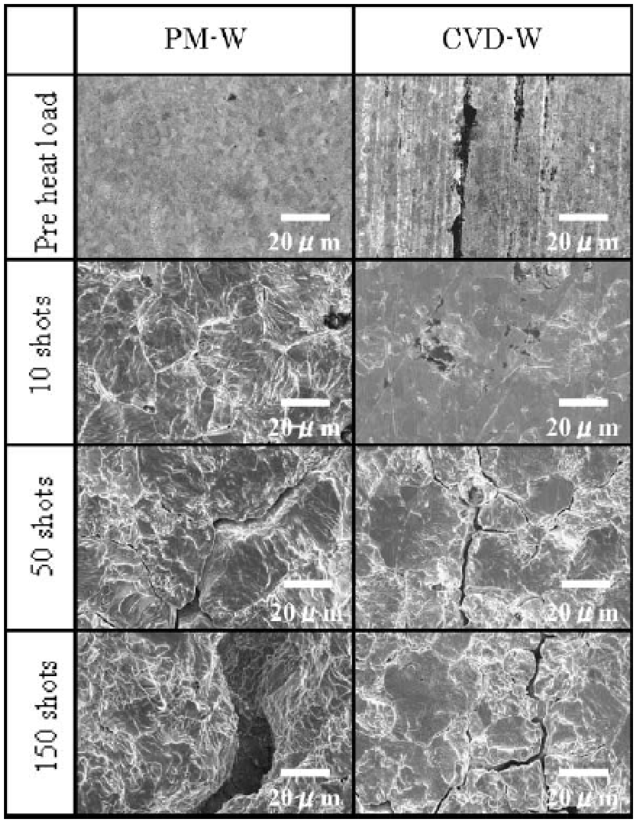
  Heating power~500MW

  PFC power width: λ_q= ~ 1㎜

- Need for an innovative PFC concept !

PWI-研究: 今後の展望②[超]高熱流除去

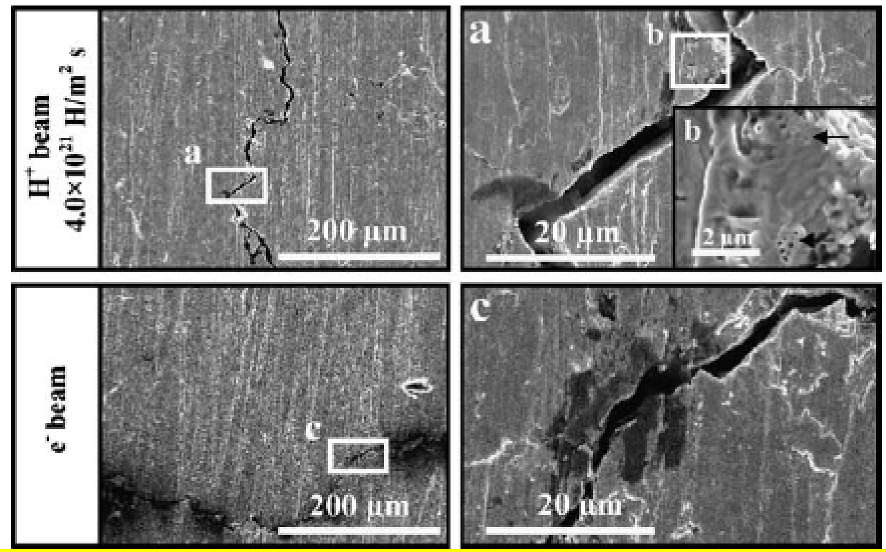
Thermal cycle cracking
(DBTT(~400℃) results in W-PFC cracking)



Max. Temp.~1300℃(50MW/m^2)

After S. Tamura et al. J. Nucl. Mater. 307-311(2002)735.

Hydrogen-implantation cracking



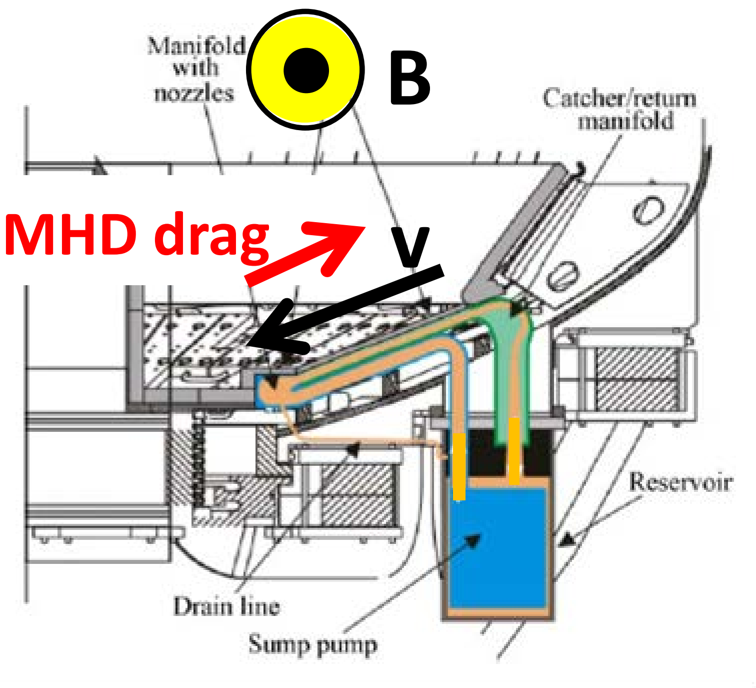
Tritium may be co-deposited into cracks.
Cracking can reach the bonding surface.

Possible metals and/or alloys:

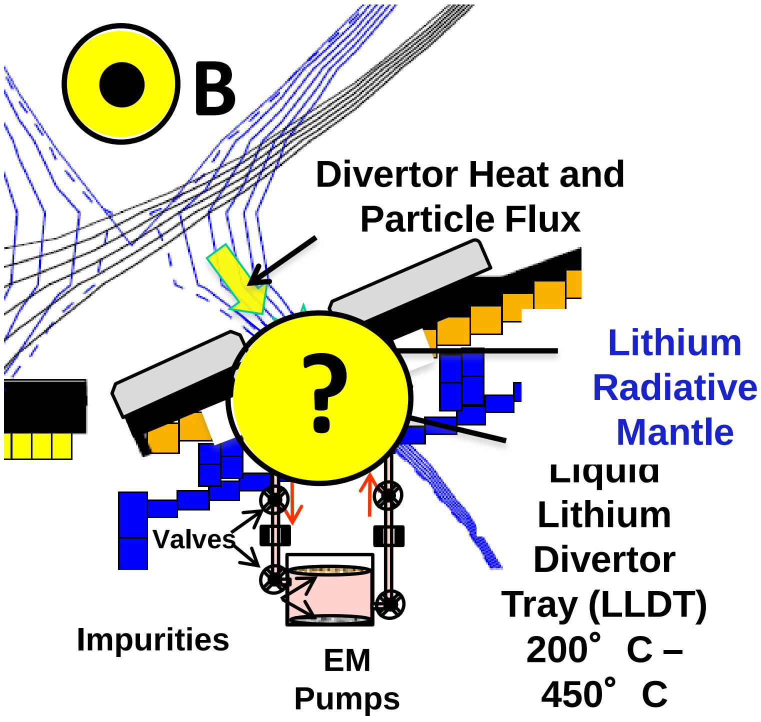
- Ga（T_m=29.8ºC, Z=31）
- Li(T_m=186 ºC, Z=3, T-breeder ）
- Sn（T_m=231ºC, Z=50）
- $Li_{17}Pb_{83}$（T_m=235ºC, Z=69*, T-breeder）

PWI-研究: 今後の展望③ダイバーター新概念

After A. Ying (UCLA)



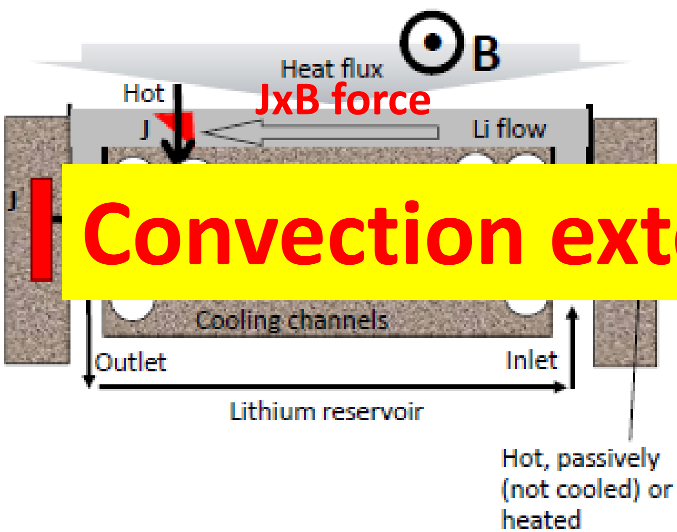
After M. Ono (PPPL NSTX-U)



PWI-研究: 今後の展望④ダイバーター新概念

TEMHD: JxB-force driven liquid metal PFC

After Jaworski (PPPL)



PoP experiments in HT-7(@AS-IPP)

Zuo et al. Fusion Eng. Des. (2014) in press

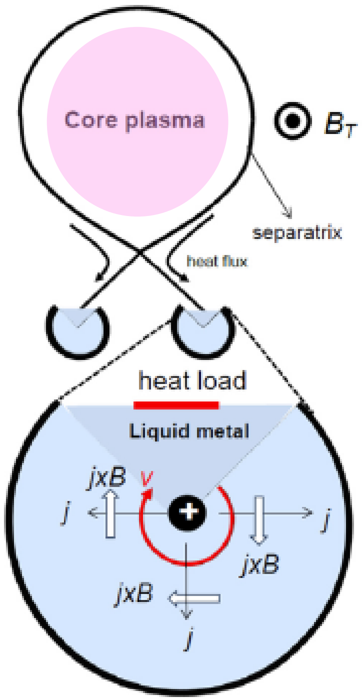
Convection externally <u>un</u>controllable!!

PWI-研究: 今後の展望⑤ダイバーター新概念

ACLMD: JxB-forced convection liquid metal PFC

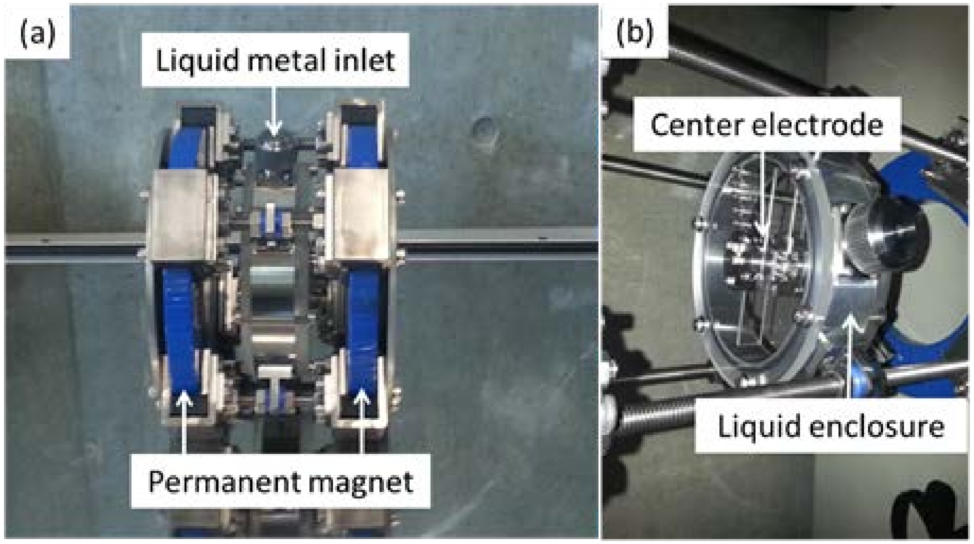
Acively Convected Liquid Metal Divertor

After Shimada and Hirooka



Shimada and Hirooka,
Nucl. Fusion 54 (2014) 122002

ACLMD-PoP experimental setup



Hirooka et al., TOFE-2014, Anaheim

PWI-研究: 今後の展望⑥ダイバーター新概念
ACLMD: JxB-forced convection liquid metal PFC

Table top setup in a globebox

Successful PoP experiment!!

Liquid temp. externa

Liquid metal: Ga_{67} $In_{20.5}$ $Sn_{12.5}$

まとめ（廣岡の個人的意見）

1. 1970年台から始まった磁気核融合エネルギー開発のためのPWI-研究は、イオンビームを用いた「素過程」研究を経て、2000年頃までに閉じ込め装置内の周辺プラズマと表面計測を基にした「現象論」へ進展した。現行ITER-PFCは、この段階までの知見を基に設計された。
2. 今後のDEMO-PFC開発には、超高熱流束除去能力だけでなく、コア閉じ込め性能改善を視野に、コア-周辺プラズマ-壁：物質異相境界領域に於ける熱・粒子流れの物理機構を理解し、『能動的に境界制御』する知見が益々重要になる。