Concept of power and particle exhaust in DEMO using lithium technology

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Outline

1. Motivation. Why lithium?
2. Concept of power and particle exhaust using Li.
3. Simple hybrid modelling of Li in DEMO.
4. Radiation damage of PFCs by alphas.
5. Li dust injection in T-10 experiments.
6. Mock-up of PFC target.
7. Summary.
Motivation. Why lithium?

- The concept is aimed at solving two problems of DEMO operation:
  - Reduction of heat loading onto plasma-facing components below the technically acceptable level of 10 MW/m²
  - Protection of wall components from radiation damage by fast ions including thermonuclear alphas

- Lithium can help in solving both of them because:
  - Intensive recycling of Li at edge plasma may redistribute and reduce local heat loading through non-coronal radiation
  - Lithium in liquid state is insensitive radiation damage
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The Li concept essence

- The concept assumes a reactor operation with an essential concentration of lithium within the plasma edge region while a plasma core is maintained at $Z_{\text{eff}} \leq 2.0$ (less than lethal concentration).

- External injection rate of lithium into the plasma mantle and control of lithium recycling at the first wall and divertor by varying heat sink and pumping.

- The heat loads onto divertor plates may be noticeably reduced due to lithium radiation in the mantle and SOL.

- Deposition and erosion of lithium particles on PFCs during Li recycling determines a thickness of Li film on PFCs. The film protects PFCs from radiation damage by fast ions if it is thicker than alphas penetration depth.

- The film ablation may provide a mitigation from transients.
The concept realization

- External injections (1) of lithium
- Collecting system (2)
- To close the Li cycle the cleaning systems (3) together with the Li supply system (4) of lithium injectors are used
- The Li film with $\geq 50 \mu m$ thickness could be achieved by massive Li injection during few days
- Appropriate gap between separatrix and first wall reduces the Li effective recycling time and increases non-coronal Li radiation
- Local control of Li recycling by maintaining the surface temperature
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A simple steady –state hybrid model for core and edge tokamak plasmas was proposed in [1] and used for evaluations of Li in ITER and DEMO:

- 1D transport in core; four species: D, T, He, Li; δ-like sources and sinks
- $T_e = T_i$ (high density); $D = \chi/3$; $V(r) = (r/a)V(a)$; $A = aV(a)/D$ is varied
- SOL heat flux reduction (model [2]) due to Li non-coronal [3] radiation
- $\lambda_{SOL,MP} \approx 1$ cm was assumed [4]

This concept is also used in the design of the fusion neutron source based on the compact spherical tokamak FNS-ST [5].

Simple hybrid modelling of DEMO

Simulated densities and $Z_{\text{eff}}$ (a, b) and $T$ (c) profiles: (a) $A=0.5$. (b) $A=2.0$, $A=aV(a)/D$. 
Evaluations with $R_{Li} = 0.1$

### Input

<table>
<thead>
<tr>
<th>Parameter</th>
<th>DEMO $A=2.0$</th>
<th>DEMO $A=0.5$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R$ (m)</td>
<td>6.5</td>
<td>6.5</td>
</tr>
<tr>
<td>$a$ (m)</td>
<td>2.1</td>
<td>2.1</td>
</tr>
<tr>
<td>$q_{95}$</td>
<td>5.3</td>
<td>5.3</td>
</tr>
<tr>
<td>Elongation</td>
<td>1.7</td>
<td>1.7</td>
</tr>
<tr>
<td>$D$ puffing (10^{22} s^{-1})</td>
<td>3.11</td>
<td>4.64</td>
</tr>
<tr>
<td>$T$ pellets (10^{22} s^{-1})</td>
<td>1.47</td>
<td>2.04</td>
</tr>
<tr>
<td>$Li$ dust (10^{22} s^{-1})</td>
<td>7.33</td>
<td>11.31</td>
</tr>
<tr>
<td>$P_{NBI}$ (MW)</td>
<td>35.3</td>
<td>35.3</td>
</tr>
<tr>
<td>$P_{ECRH}$ (MW)</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>$D$ (m^2/s)</td>
<td>0.6</td>
<td>0.6</td>
</tr>
<tr>
<td>$\chi/D$</td>
<td>4.3</td>
<td>3.4</td>
</tr>
<tr>
<td>$\chi$ (m^2/s)</td>
<td>2.57</td>
<td>2.02</td>
</tr>
</tbody>
</table>

- $P_{div} \approx (0.55 \div 0.70)P_{in}$ by Li radiation for $n_{Li} \approx 0.1n_e \iff Z_{eff} \approx 1.7$

### Output

<table>
<thead>
<tr>
<th>Parameter</th>
<th>DEMO $A=2.0$</th>
<th>DEMO $A=0.5$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volume-averaged $Z_{eff}$</td>
<td>1.7</td>
<td>1.7</td>
</tr>
<tr>
<td>Volume-averaged $n_{e}/n_{G}$</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>$T_0$ (keV)</td>
<td>49.8</td>
<td>68</td>
</tr>
<tr>
<td>$T_s$ (eV)</td>
<td>342</td>
<td>332</td>
</tr>
<tr>
<td>$n_{e}(a)$ (10^{19} m^{-3})</td>
<td>3.99</td>
<td>5.98</td>
</tr>
<tr>
<td>$n_{Li}(a)$ (10^{19} m^{-3})</td>
<td>0.28</td>
<td>0.44</td>
</tr>
<tr>
<td>$\tau/ (ms)$</td>
<td>0.52</td>
<td>0.52</td>
</tr>
<tr>
<td>$n_{e}(a)\tau/ (10^{16} m^{-3}s)$</td>
<td>2.06</td>
<td>3.14</td>
</tr>
<tr>
<td>$P_{fus}$ (MW)</td>
<td>3000</td>
<td>3000</td>
</tr>
<tr>
<td>$P_{\alpha}$ (MW)</td>
<td>600</td>
<td>600</td>
</tr>
<tr>
<td>$Q = P_{fus}/P_{aux}$</td>
<td>54.2</td>
<td>54.2</td>
</tr>
<tr>
<td>$P_{in} = P_{aux} + P_{\alpha}$ (MW)</td>
<td>655.3</td>
<td>655.3</td>
</tr>
<tr>
<td>$I^{pr}$ (MW)</td>
<td>55.0</td>
<td>46.4</td>
</tr>
<tr>
<td>$I^{mtl} = I_{Li}^{mtl} + I_{He}^{mtl}$ (MW)</td>
<td>68</td>
<td>135.1</td>
</tr>
<tr>
<td>$P_{SOL} = P_{in} - I^{pr} - I^{mtl}$ (MW)</td>
<td>532.3</td>
<td>473.8</td>
</tr>
<tr>
<td>$F^{SOL}$ (MW)</td>
<td>100.6</td>
<td>120.0</td>
</tr>
<tr>
<td>$P_{div} = P_{SOL} - F^{SOL}$ (MW)</td>
<td>431.7</td>
<td>353.8</td>
</tr>
</tbody>
</table>
**Variation of Li recycling**

The enhanced radiation fraction (solid curves) and the lithium dust jet injection rate (dashed curves) versus the lithium recycling coefficient for fixed plasma density and $Z_{\text{eff}} \approx 1.7$ in DEMO, $A=0.5$ - thick curves, $A=2.0$ – thin curves, $A=aV(a))/D$.

- Noticeable part (up to 50%) of power can be radiated in the edge plasma while the average effective charge of 1.7 was maintained.
- External flux of Li dust decreases with an increase of lithium recycling coefficient (higher Li surface temperature).
- Further reduction of $P_{\text{div}} \leftarrow$ high Z (argon) gases for SOL.
Control of Li influx to plasma

- Total Li rate of $\sim 10^{23} /s$ was estimated for DEMO.
- Averaged over wall area, flux rate of $10^{20}$ Li atoms/m$^2$/s implies conditions on the surface ($T_{Li}$, particle flux to wall)?
- For that range $T_{Li} \sim 220-270^\circ$C may provide the flux rate and liquid lithium state.
- Locally (strike point) small areas with enhanced loss rate due to evaporation could be maintained at higher temperature $T_{Li} \sim 300-350^\circ$C.
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Radiation damage of PFCs by alphas

- Problem may appear because the radiation damage may cause structural changes and increase the surface erosion of material (2⁻³ times in C, W at 5 ÷ 10 dpa damaged by 4 MeV helium ions [V.S. Koidan et al., Proc. of 20th FEC, (2012), FT/P2-11]

![Fig. 9. Tungsten surface after plasma exposure to 2·10²² D⁺/cm²: a) area subjected only to plasma, b) the border between the irradiated (⁴He⁺² fluence of 5·10¹⁷, to the right) and non-irradiated zone, , c) damage (irradiated) zone (scale 100 microns).](image-url)
Radiation damage of PFCs by alphas

- It is rather valuable for FNS-ST because of very low confinement of alphas. Year alpha dose of $10^{25}$ particles/m² may produce 100 dpa within a couple of days.

- Averaged over 900 m² first wall area, year alpha dose of $10^{24}$ particles/m² estimated for DEMO may cause
  - $9 \times 10^2$ dpa in Be at $\sim 15 \, \mu m$ depth
  - $2 \times 10^3$ dpa in W at $\sim 5 \, \mu m$ depth
  - $3 \times 10^3$ dpa in Li at $\sim 50 \, \mu m$ depth

- Liquid state of lithium may help to solve this problem since it has no problems with dpa!
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Li dust injection in T-10 experiments

- The lithium dust injection of \((4\div5) \times 10^{20}\) at/s during 0.5 s of a plasma shot [V.Yu. Sergeev et al., FED 87 (2012) 1765] increased the plasma effective charge less than 20%. The injection caused gradual reduction of \(R_D\) from 0.9 to 0.85 during lithium injection.

- Only a weak cumulative effect of the lithium influence was observed due to the specific shut-down scenario of T-10 plasmas, which terminate with a major disruption. That may be a reason of the \(R_D\) behavior after the lithium gettering as well.

- Limit of Li influx of about \(10^{21}\) 1/s was comparable with the T-10 fueling rate.
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Sketch (a) and photo (b) of mock-up of the PFC element for FNS-ST [Mazul I. et al. 2012 Fusion Eng. Des. 87 437]: (1) heat carrier plate made of chromium–zirconium bronze, (2) sectioned beryllium coating, (3) copper layer, (4) stainless-steel base (vacuum vessel), (5) pipe for heat carrier (water) flow.
Mock-up: experiments on Tsefey-M

- Photo (a) and sketch (b) of test-bed experiments with the mock-up of the PFC element on the electron beam facility Tsefey-M [M.Rodig et al, FED 51–52 (2000) 715 ] at Efremov Institute.
- The mock-up has 2 sets of Beryllium tiles: 3x16x16 mm – 18 pieces and 3x7x16 mm – 6 pieces.
Mock-up: results of experiments

- Parameters of test-bed experiments
  - Cross section of water cooling: 204 mm²
  - Water velocity: 7 m/s
  - Water rate: 1.4 kg/s
  - Area of heat loads: 50 cm²
  - Water pressure at the entrance: 2 MPa ± 5%
  - Range of heat flux density: 5-10.5 MW/m² ± 5%

- 1 stage: Power load was lasting 30 sec and was incremented up to 5 MW/m² (1.0, 2.0, 3.0, 3.5, 4.0, 4.5, 5.0 MW/m²). Then, the cycle load (15 sec load, 15 sec pause) was done at 5.0 MW/m². The mock-up had successfully sustained during 1000 cycles. The surface temperature was about 260 °C.

- 2 stage: Power load was increased with a step of 0.5 MW/m² to reach the surface temperature of 600 °C. It is occurred at 10.5 MW/m². Then, the cycle load (15 sec load, 15 sec pause) was done at 10.5 MW/m². The mock-up had successfully sustained during 100 cycles.
Temperature fields of the mock-up

- Temperature (260 ÷ 600 °C) of tiles demonstrate the uniform radiation (IR)
- No tiles lost a thermal contact at both at 5 MW/m² (left – shot #120) and at 10.5 MW/m² (right – shot #95)
Summary

- Concept of tokamak reactor operation with lithium injection rate comparable with that of fueling is presented.
- Hybrid modelling of DEMO and ITER discharges shows reduction of divertor heat loading up to 50%. Non-coronal lithium radiation and recycling are provided by lithium flow of about $10^{23}$ l/s keeping the averaged $Z_{eff}$ value of about 1.7.
- Enhanced sputtering of PFC due to radiation damage by alphas may be significant in FNS-ST and DEMO (more moderate). Liquid Li film may solve this problem.
- Experiments on T-10 demonstrate that maximal Li injection rate of $10^{21}$ l/s is comparable with fueling rate.
- Mock-up of the water cooled first wall element of FNS-ST with Be tiles was successfully tested. No tiles lost a thermal contact at both 5 MW/m² (sustained 1000 cycles) and at 10.5 MW/m² (sustained 100 cycles) were observed.