Development of liquid lithium PFCs on EAST providing an alternative design for DEMO divertor

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Outline

- Liquid metal plasma facing components (PFCs)
- Development of flowing liquid Li limiter (FLiLi)
  - Introduction
  - Design of FLiLi in EAST
  - Experimental results of FLiLi in EAST
- Summary and Outlook
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- Summary and Outlook
DEMO divertor challenges

- High fusion power, Long plasma pulse
- High neutron dose,
  - Low activation materials
  - High erosion resistance: low sputtering
  - High power handling: 20-50 MW/m² in long plasma

**Table 1.** Overview of key parameters of the ITER ($Q = 10$) and DEMO1 reference designs (2013).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>ITER ($Q = 10$)</th>
<th>DEMO1</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R$ [m]</td>
<td>6.2</td>
<td>9.0</td>
</tr>
<tr>
<td>$A$</td>
<td>3.1</td>
<td>3.6</td>
</tr>
<tr>
<td>$\kappa_X$</td>
<td>1.85</td>
<td>1.75</td>
</tr>
<tr>
<td>$\delta_X$</td>
<td>0.48</td>
<td>0.50</td>
</tr>
<tr>
<td>$B_T$ [T]</td>
<td>5.3</td>
<td>6.5</td>
</tr>
<tr>
<td>$I_P$ [MA]</td>
<td>15.0</td>
<td>16.8</td>
</tr>
<tr>
<td>$P_{\text{heat,add}}$ [MW]</td>
<td>500</td>
<td>1790</td>
</tr>
<tr>
<td>$\langle n_e \rangle [10^{19} \text{ m}^{-3}]$</td>
<td>10.1</td>
<td>9.3</td>
</tr>
<tr>
<td>$n_{GW} [10^{19} \text{ m}^{-3}]$</td>
<td>11.9</td>
<td>8.6</td>
</tr>
<tr>
<td>$\beta_N$ [t]</td>
<td>1.8</td>
<td>2.5</td>
</tr>
<tr>
<td>Pulse length [h]</td>
<td>0.1</td>
<td>1.7</td>
</tr>
<tr>
<td>$q_{\text{neuton,wall}}$ [MW m$^{-2}$]</td>
<td>$\sim 0.5$</td>
<td>1.1</td>
</tr>
<tr>
<td>Total dpa</td>
<td>$\sim 3$</td>
<td>20 + 30</td>
</tr>
</tbody>
</table>
Can solid tungsten suitable for DEMO divertor?

- High melting temperature, high thermal conductivity, low sputtering yield, low recycling

- Low tritium inventory?
  - Bubbles formation due to ions implantation
  - Tritium may be co-deposited into cracks

- Compatible with hot fusion plasmas if heat flux from plasma is not well controlled?
  - High Z impurities and transport, power radiation, core impurity concentration
  - Needs helps, i.e. N₂ puffing

- Operation mostly within brittle regime?
  - Neutron induced displacement/embrittlement? DEMO high neutron dose @divertor: 2-5 dpa/fpy
  - ductile-brittle-transition temp. \( T_{DBT} \) (260-650° C)
  - recrystallization temp. \( T_{rec} \) (1300° C)

- Power handling is enough for DEMO?
  - Limit of power load of ~10 MW/m² in present design, such as ITER
  - Erosion and lifetime, melting and droplet, dust production
  - Thermal cycle cracking and H implantation cracking
Why study liquid metal PFCs in a tokamak environment?

- Self-healing/renewable preventing erosion
- Less sensitive/immune to the neutron damage
- A long lifetime plasma-facing component
- Better handling of the high heat flux
- Regenerative properties - ‘erosion’ not a problem
- Absorption & removal impurities by LM flow
- Vapor screening/radiation reducing PSI to LM
- Option for fuel recycling, breeding

Possible liquid metals and/or alloys:
- Li (Tm=186°C, Z=3, T-breeder)
- Sn (Tm=231°C, Z=50)
- Ga (Tm=29.8°C, Z=31)
- SnLi alloy

Solid metal:  \( q_{\text{plasma}} = q_{\text{cond}} \)
Liquid metal:  \( q_{\text{plasma}} = q_{\text{cond}} + q_{\text{evap}} + q_{\text{rad}} + q_{\text{mass}} \)

\[ \Gamma_{\text{evap}} << \Gamma_{\text{plasma}} \]
Why lithium PFCs for fusion energy development?

- Lithium is the lowest Z=3 metal – compatible with hot fusion, plasma concentration up to 15%
- Lithium melts at 180°C and boils at 1344°C – expected operating temperature of 200 – 400°C (low lithium vapor pressure) – compatible with fusion reactor environment
- Lithium reacts and captures D, T, O – Can provide strong divertor particle pumping – e.g., low-recycling, radiative divertor

Lithium PFC with mostly beneficial results on plasmas

Recycling suppression, Impurities reduction, Confinement improvement
MHD stability, Reduction L-H threshold, ELM mitigation
Effective vapor/particle shielding, Low Li core dilution

NSTX and LTX(PPPL, USA), FTU(NEA, Italy), TJ-II(CIEMAT, Spain)
T--11M(Trinity, RF), T--10 (Kurchatov Insitute, RF)
ISTTOK(IPFN, Portugal), KTM(NNCRK, Kazakhstan)
EAST(ASIPP, China), HT-7(ASIPP, China)
Flowing Liquid Lithium Limiter/Divertor in fusion devices

Thin film static LiLiD in NSTX without flow

Capillary Porous System, Small-Flow (FTU, JT-II, T11-M)

Liquid-Metal Infused Trenches, medium flow (UIUC, USA)

Flowing Liquid Lithium Limiter, slow-Flow (EAST, China)
Other possible material options for liquid metal PFCs?

• Sn, SnLi et al. (compared to Li)
• Higher power handling than solid PFCs
• Lower evaporation rate
• Absolute sputtering yield of liquid Sn have the temperature dependence
• Higher Z → Concentration for Sn 0.055% 
• FTU, TJ-II have first Sn, SnLi (20:80) experiments in fusion devices
  – heat load up to 18 MW/m², could be withstood by 1mm thick CPS actively cooled system.
  – Evaporation should not be a problem if the surface temperature is less than 1300 °C
• Need more investigation!

From Pilot-PSI / Magnum-PSI

M.D. Coventry et al. / Journal of Nuclear Materials 335 (2004) 115–120
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Li applications for EAST

- **Mission:** Steady-state, H-mode, high parameters operation
  - R=1.9m, a=0.45m
  - SN, DN divertor configuration
  - 2006 first plasma

**Li experiments:** i.e. recycling and impurity suppression, and ELM control, alternative PFC for future fusion reactor

- Three Li coating systems
- Two Li aerosol injectors
- One Li granule injector
- Flowing liquid Li limiter
Li coating helps long pulse H mode in EAST

With help of Li coating

- 2010 first H-mode
- 2012 >30s H-mode
- 2016 >60s H-mode
- 2017 >100s H-mode

70g Li coating (+~250g before) + active Li injection lead low recycling, low impurities, fully non-inductive, $V_{\text{loop}} \sim 0$. 

Ip=0.4MA, $<n_e> \sim 3.0 \times 10^{19}/m^3$, $P_{RF} \sim 3.0$MW, $H_{98y2} \sim 1.1$, USN, $Te(0) \sim 4.0$keV
ELM suppression using Li aerosol injection in EAST

Reproducible steady-state ELM-free H-mode up to 18s @ C divertor, P~2.1MW in 2012


- No accumulation of W impurities in core plasma
- Story energy and confinement is kept
- USN, W divertor P~3-5MW @ 2016-2017

J.S. Hu, 5th ISLA (2017)
R. Maingi, J.S. Hu et al., submitted to NF
ELM trig using Li granule injection in EAST

- **LSN, Carbon divertors**
- $P_{\text{heating}} = 2.5\text{MW, } H_{98(y,2)} \approx 0.85$
- Granule size: $0.7 \pm 0.1\text{mm}$,
- Trigger efficiency = 100%
- Heat flux 1/2 of nature ELM

D. Mansfield, NF 53 (2013)

- **USN, W divertors**
- $P_{\text{heating}} = 5\text{MW, } H_{98(y,2)} \approx 1.2$
- Granule size: $0.3, 0.5, 0.7, 0.9$
- stored energy drops by ~10%
- Depends on Li size and plasma

J.S. Hu, 5th ISLA (2017)
Development of liquid Li limiter in ASIPP

- 2008: Static liquid lithium limiter with free surface in HT-7
- 2009: Static liquid Li limiter with CPS in HT-7
- 2011: Static liquid Li limiter with re-filling system in HT-7 with full Mo walls
- 2012: Flowing limiter Exp. with different design in HT-7:
- 2014–2020: Flowing Li limiter Experiment on EAST
- Further plan: possible flowing LLD with full W walls in EAST

Provide an alternative choice of divertor design with self-recovery and replenish surface without neutron damage for future fusion reactor device
Experiences and Lessens from HT-7 experiments (1)

- Static limiter
- Surface \(\sim 377 \text{cm}^2\)
- Li thickness \(\sim 3\text{mm}\) (free surface), \(1\text{mm}\) above CPS
- Placed Li plate melt at \(230^\circ\text{C}\)

Evaporation, sputtering not serious than Li droplets injection

Serious Li droplet ejected due to JXB force if using Li thicker than \(1\text{mm}\).

droplet ejection \(\rightarrow\) plasma disruption \(\rightarrow\) more droplet ejection
Experiences and Lessens from HT-7 experiments (2)

Thin film Li with CPS (after top Li was ejected) would reduce Li droplet ejection

- Reduced the plasma induced current in Li
- Tension surface would against JXB force
- Stable plasma with good confinement could be obtained
- No observed damage of mesh even if Li is thin film

100 mesh CPS with wire diameter 0.1mm, aperture 0.15mm

\[ P = 2\sigma \cos \theta / R, \quad \sigma \approx 406 \text{ mNm}^{-1}, \]
\[ R = 0.075 \text{ mm}, \quad P \approx 1 \times 10^4 \text{ Pa} \]
Experiences and Lessens from HT-7 experiments (3)

- Filling Li from outside is difficult due to wetting is not good between Li and SS.
- Plasma heating could drive Li flowing with a small velocity
- Serious Li droplet ejection due to thick Li

During plasma discharge

Filling lithium

Li droplet ejection
Experiences and Lessens from HT-7 experiments (4)

- To get well wetting of lithium on substrate plate
  - High temperature of substrate
  - Lithium coating first
  - surface cleanings
  - Mo better than SS substrate
Liquid metal plasma facing components (PFCs)

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Summary and Outlook
FLiLi limiter with a slowly flowing thin Li film

- Thin film <0.1mm
  - Surface tension against JXB force to reduce droplet ejection

- Flowing rate ~2 cm$^3$ s$^{-1}$
  - (10%)Li + D = LiD
  - 2 cm$^3$ s$^{-1}$ × 0.5g/6 × 6.02 × 10$^{23}$ × 10% = 1 × 10$^{22}$Li/s
  - Particle flux control ~10$^{22}$D/s

- Heat flux control
  - Heat convection directly to Li → to thin guide wall → then heat sink
    → comparable with Solid PFCs
  - Enlarged heat area on dense Li vapor to reduce peak flux
  - Vapor shielding to reduce PSI intensity
  - Li evaporation/burst for temperature balance
  - Power radiation by Li ions
  - ELM mitigation for peak flux reduction
  - Ignorable heat removal directly by Li flowing
    - 16MW/m$^2$ require a Li flowing speed up to 8.6m/s
Design guidance for the FLiLi limiter

- Thickness of the active pumping layer
  \[ \delta \leq h \ll W, L \]

- \( T_{LiLi} > 450^\circ C \), similar as Li wall conditioning

- \( T_{LiLi} < 450^\circ C \), pumping particles, i.e. control recycling

If LiLi absorbing capacity as 10%

\[ \frac{dN}{dt} = \frac{10^{22}}{s}. \]

\[ \frac{dN_{LiLi}}{dt} = \frac{10^{23}}{s}, \quad \frac{dLiLi}{dt} \mid_{Liter/s} = 2 \cdot 10^{-3}. \]

If EAST FLiLi DIVERTOR:
\( R = 1.8 \text{ m}, \ W_{LiLi} = 11.3 \text{ m}, \ \delta = 0.1 \text{ mm} \)

Particle pump: \( V \) only need 0.2 cm/s

Leonid E. Zakharov, 2nd ISLA, Princeton
Basic engineering design of FLiLi limiter

- Distributor + Guide plate + Copper heat sink + collector + EM pump
- Heater, cooling system
- Li driven to distributor by liquid EM pump
- Li flow out from channels of distributor
- Li flowing down on guide plate to collector due to gravitation
- Li from collector to refresh the limiter (or to recovery system)
Preliminary work of FLiLi driven by Ar in HT-7(2012)

- Face to face Li coating on SS plate before Li filling for better wetting
- Successfully driven by Ar
- Uniformly flowing and optimized plasma control are beneficial for reduction Li ejection, and then reduce plasma disruption.
- Enlarge plasma wetting area, reduce peak heat flux
- Increase plasma confinement by 30%

With Ar @ 40,000 Pa, speed ~2.1 mm/min

Stability of plasma

No heat sink, no EM pump
Key components design FLiLi for EAST

**Inner EM pump:**
- Adjustable current: 0~100A
- Using EAST Toroidal B: 2T

100A ≈ 23.7 kPa, for Li flow ~3 cm³/s

**Temperature controlled Li valve**
- Small volume
- Response time: 2~4s

Both is suitable for the utilization inside of tokamak to save place

R. Jun et al., RSI (2015)
Design of first FLiLi Limiter for EAST in 2014

- Limiter surface $350\text{mm} \times 320\text{mm}$
- 2 heaters (220v, 2kW)
- Copper heat sink with heater and cooling
- 3.7L capacity of liquid Li
- Li flowing rate higher than 2cm$^3$/s

200 horizontal channels ($0.8 \times 0.8\text{mm}^2$)

Inner EM pump 0-100A
Upgraded FLiLi design for 2016 experiment

- A new designed distributor with homogeneous channels
- Two independent EM pumps
- Horizontal capillary structure (micro trenches) on the limiter SS layer surface

- HIP technology to join SS thin layer and Cu heat sink
- Using 0.5mm SS layer instead of 0.1mm

Examples:

- Distributor before Li operation in 2016
- Li wetting test

G.Z. Zuo et al., submitted to RSI (2017)
Li filling and movable system of FLiLi limiter in EAST

R. Jun et al., RSI (2015)
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Li was easily driven to flow at surface at $I_{EM}=20$A.

Interaction area changed and enlarged on dense Li vapor, following to flow.

NOTE: pictures are at the initiation of plasmas at 0.2s.
Evolutions of color during plasma start-up phase (shot #52692)

- The small zone of bright white light, with apparent discrete vertical flow channels, step by step expanded to fill the entire surface of the limiter at 2.756s.
- Meanwhile the intensity of the Li-II emission also increased.
- No obvious droplet was found!
- Most Li emission due to evaporation and sputtering.

@204ms, @981ms, @2396ms, @2756ms
Vapor shielding to reduce PSI intensity

Li emission similar as Li aerosol injection, stronger than that after Li coating,
• high energy neutral Li atoms just around the limiter
• Uniform shielding Li\(^+\) layer around plasma,
  – Li-I line emitted by neutral Li atoms at 670.8nm is red color
  – Li-II line emitted by Li\(^+\) ions at 548.4nm emits a green color
Li emission depends on position, EM current and heating

- **Position** → heat flux and particle flux → evaporation + sputtering
- **EM current** → more fresh Li supply
- **Plasma heating** → heat flux → Li temp. → evaporation

Higher heat flux and particle flux, more fresh Li, stronger Li emission
We speculate that

- Continued heat from plasma $\rightarrow$ increase Li temp. $\rightarrow$ increase PSI area $\rightarrow$ balloon burst to cool down Li $\rightarrow$ increase Li emission

- Beneficial for long plasma operation of the FLiLi
Li burst for reduce heat flux to diveror
→ similar as Li aerosol injection

- Strong Li emission reduce heat flux on divertor.
- Reduce impurities and recycling
- Increase radiation, most at edge
- Increase plasma stored energy
- Change edge profile
Further reduction of recycling and impurities  
→ similar as fresh Li coating

Before this experiment, 2.9 kg Li via evaporation for coating in 82 days
Effect of the FLiLi limiter on Ohmic plasma

\( \rightarrow \) similar as fresh Li coating

- Decrease Loop voltage
- Increase Stored energy
- Target plate recycling has a modest \(~16\%\) reduction
- The edge electron temperature decreased, and peaked slightly in the center.
ELM mitigation in H-mode for peak flux reduction ➔ similar as Li aerosol injection

- ELMs mitigated meanwhile baseline Li emission ~6×
- ELM-free H-modes with 25% increase of $W_{MHD}$ and $H_{98}$
- MHD suppressed and ion saturation current reduced
- Effect on either C or W divertor

2014: $B_t=2T$, $I_p=400kA$, $n_e=3\sim3.5 \times 10^{19}/m^3$, $P_{LHCD}=600kW$, $P_{NBI}\sim1.3MW$, LSN(C)

2016: $B_t=2T$, $I_p=400kA$, $n_e=2\sim3 \times 10^{19}/m^3$, $P=5MW$, USN(W)
Improvement of Li coverage uniformity and erosion resistance using upgraded system

<table>
<thead>
<tr>
<th>Year</th>
<th>Li flow from distributor channels (%)</th>
<th>Li coverage surface (%)</th>
<th>Descript of Li flow from top to bottom</th>
<th>Surface erosion</th>
</tr>
</thead>
<tbody>
<tr>
<td>2014</td>
<td>50%</td>
<td>~30</td>
<td>Become narrow</td>
<td>Obvious damage</td>
</tr>
<tr>
<td>2016</td>
<td>66%</td>
<td>&gt;80%</td>
<td>Become wide</td>
<td>No obvious damage</td>
</tr>
</tbody>
</table>

Li limiter surface in 2016

Li limiter surface in 2014
New upgrading is going on well

- Using Mo instead of SS as Li plate to increase uniformity of wetting and flowing
- Upgrading temperature control and heat removal capacity using optimized cooling and heating
- One is same as before: thin Li film flowing on smooth Mo plate driven by gravity
- Other one: Li flow in slots driven by both of thermoelectric magnetohydrodynamic (TEMHD) force and gravity

Will be tested in HIDRA in Illinois soon and then in EAST at the beginning of 2018
Liquid metal plasma facing components (PFCs)

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Summary and Outlook
Based on systemic experiments in HT-7, FLiLi limiter have been successfully developed and tested in EAST.

- Using concept of flowing thin Li film to avoid Li droplets ejection
- Liquid Li driven by built-in DC EM pumps to form a recirculating close loop system for fusion devices

Flowing Liquid Li PFCs has lots benefits to provide an alternative resolution for the divertor design of future DEMO device

- Partly ameliorate lifetime and power-exhaust issues
- Allowing for a self-healing, self-replenishing surface
- No susceptibility to neutron damage
- Beneficial for recycling control and impurities reduction, similar as an active Li wall conditioning, FLiLi limiter improve plasma performance
- Heat exhaust not only by heat convection as solid PFCs, but also control heat flux from plasma via vapor shielding, radiation, ELM mitigation, even burst evaporation
Outlook

Long way to design an FLiLi divertor for future DEMO device:

- FLiLi divertor should be investigated in tokamak machine!
- Wetting and flowing uniformity should be improved!
- Geometry of FLiLi divertor and heat sink design with well temperature control!
- Safety and T recovery should be concerned!

To concern radiation/detachment in FLiLi divertor increase its possibility

Welcome for any collaboration!
Thank you!
Hefei Superconducting Tokamak (HT-7)

- Middle size tokamak (R=1.2, a=0.27m)
- 1994--2012

**Before 2011**

- Doped graphite with SiC coating
- C Limiter (~2m²); SS liners (10m²)

**After 2011**

- Full metal walls: Mo limiters + SS liners

The last campaign was operated in Oct. 2012, specially testing flowing Li limiter!
Corrosion behaviors of 304SS exposed to static liquid Li

- Weight loss increase with corrosion time and show a $\frac{1}{2}$ power law trend
- Specimens show non-uniform corroded morphologies
- Corrosion behaviors are sensitive to temperature

X. Meng, JNM 480 (2016)
Experimental parameters

- \( I_p = 0.4 \text{ MA} \),
- \( B_T = 1.9 \text{ T} \),
- \( n_e(0) = 1.3 \times 10^{19} \text{ cm}^{-3} \),
- \( T_e(0) = 1.1 \text{ keV} \).
- Lower single-null configuration, \( \kappa = 1.6 \) and \( \delta = 0.54 \).
- LHW from 0.3 to 0.65 MW,
- NBI from 1.15 to 1.3 MW
- Before the experiment, 2.9 kg Li via evaporation for coating in 82 days

- Two CCD cameras at the D port to respectively monitor looking to the limiter and opposite direction.
- \( \text{D} \alpha, \text{LiI} / \text{LiII}, \text{CIII}, \text{MoI} \) and visible bremsstrahlung (VB)
- 64 absolute extreme ultraviolet (AXUV)
- An IR camera
- Divertor triple Langmuir probe arrays
Efflux from FLiLi during and between discharges comparable to Li aerosol injection in EAST and DIII-D

- Li limiter temperature: ~350°C;
- Li evaporation:
  - ~$3.8 \times 10^{18}$/s (0.0445 mg/s);
- Li sputtering:
  - ~$(3.6-7.2) \times 10^{20}$/s (4.1-8.2 mg/s, ~40-80 mg/shot (~10 s/shot));

Sputtering rate: 0.5-1

- $\Gamma_i = n_e C_s \sin \theta$
- $Ne = 6 \times 10^{18}$ m$^{-3}$
- $Te = 40$ eV
- $\theta \sim 3.5°$

Li efflux during discharge

- Interval duration between two shots is 600 s (10 mins)
- About 26.7 mg Li evaporates from FLiLi inter-shots;

- Li accumulates shot by shot
- Also comparable to pre-discharge Li coating in NSTX

Li efflux inter-shots
Well controlled Li flowing, i.e. uniform thin film flowing, would reduce Li droplet ejection or Li burst; otherwise, abundant Li injected to plasma would lead disruptions.

Controllable passive Li efflux from FLiLi due evaporation, sputtering would form a Li radiative mantle as Li aerosol real-time injection. —— not only reduce the PFCs erosion, but also improve plasma performance, mitigate ELMs.