Lithium and Liquid Metal Studies at PPPL

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PPPL

Surface Analysis

High Power Devices

NSTX-U

IAEA TM on Divertor Concepts
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Test stands
Outline

- Motivation: high steady power exhaust and high confinement scenarios with liquid metal PFCs
- Options for liquid metal uses
- Excerpt of results from existing PPPL collaborations
- Summary
Development of liquid metal PFCs for fusion devices: transformative area, deserving of effort to assess viability

• Motivation 1: power exhaust challenge harder than thought
  – Heat flux footprint decreases with $I_p$; no increase with $R$
    ➢ Both steady and transient loads can exceed solid PFC limits; extrapolation risk beyond ITER

• Motivation 2: Confinement difficult with bare high-Z PFCs
  – Good confinement is challenging with ILW in JET; partial recovery with nitrogen seeding

• Evidence that liquid metal PFCs can exhaust higher power than solids, and lithium PFCs (liquid or solid) provide access to high confinement
Liquid metal PFCs are alternatives to solid PFCs, but have substantial R&D needs to assess viability

• Advantages
  – Erosion tolerable from PFC view: self-healing surface
  – Main chamber material and tritium transported to divertor could be removed via flow outside of tokamak
  – Liquid metal is neutron tolerant; protects substrate from PMI
  ✓ Liquid (and solid) lithium offer access to low recycling, high confinement regimes under proper conditions
  ✓ Very high steady, and transient heat exhaust in plasma gun tests

• Disadvantages and R&D needs
  ➢ Need stable surface & flows to maintain a fresh surface
  ➢ Liquid metal chemistry needs to be controlled
  ➢ Temperature windows need optimization

* Most of experience in fusion is with Li, but Sn and Sn-Li offer broader temperature windows; recent experience with Sn in FTU (ISLA 2015)
Lithium loaded targets withstood high steady and transient heat loads in plasma gun experiments

- Steady operation with heat loads from 1-11 MW/m² withstood for 3 hours
- Heat loads < 25 MW/m² withstood with Li targets (5-10 minutes, limited by Li inventory)
- Transient loads < 50 MW/m² withstood with Li targets without cooling (up to 15 s)
Lithium (solid and liquid) PFCs increase confinement

LTX (liquid and solid)

- 2-4x improvement over ITER98P(y,2) (H-mode scaling)

NSTX (coatings)

- H98y2 increased from 0.8 -> 1.4 (H-mode scaling)


Goal: cohesive program for liquid metals to be considered as PFC candidates for fusion devices

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Liquid metals can be used in several ways to address part or all of the particle and power exhaust challenge

- Provide particle exhaust, access to high H-factor
  - Slow flow; may have to use advanced divertors for power exhaust (example: flowing liquid lithium limiter in EAST, J.S. Hu, ISLA 2015)
  - Open issue on liquid metal substrate material

- Provide power exhaust: high PFC temperature solutions
  - Vapor-box configuration (Goldston, this conf.), compatible with W
  - Low recycling may be achievable in low flux areas; access to high confinement?

- Provide particle and power exhaust, access to high confinement: low PFC temperature solutions
  - Fast flowing liquid metal option (Majeski, this conf.)
  - Radiative liquid lithium divertor concept (M. Ono, NF 2013, ISLA 2015; see also Tabares, this conf.)
Compatibility with liquid lithium with a hot reactor first wall: Radiative Liquid Li Divetor configuration with $T < 500 \, ^{\circ}C$

High Temperature Solid First Wall:
- High electrical conversion
- Clean wall – for low T inventory and lithium contamination

Low RLLD Operating Temperature:
- Prevents excessive Li vaporization pressure
- Cooler divertor provides natural collection (pumping) surfaces for entire reactor chamber
- May permit use of iron based material for substrates and structural material
- Reduces Li corrosive issues
- Provides safer LL utilization

M. Ono et al., *Nucl. Fusion* **53** (2013) 113030
Lithium Provides Several Layers of Protection
Vaporization, Ionization, Radiation

M. Jaworski
Radial Transport

Li Vapor Shielding
M. Jaworski

LLD Tray

Power and particle flux

Divertor side wall

Divertor Entrance

Li Injection (ARLLD)
~ 100 MJ/mole

Li Radiative Cooling (RLLD)
~ 100 MJ/mole

Li Ionization
1st ionization – 0.5 MJ /mole
2nd ionization – 7.3 MJ /mole
3rd ionization – 11.8 MJ /mole

Li Vaporization (150 kJ mole)

*Two-point modeling also done for ITER-sized plasma

T.D. Rognlien et al., PoP 2002

M. Ono et al., Nucl. Fusion 53 (2013) 113030

M. Ono et al., Fusion Eng. Des. 89 (2014) 2838

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NSTX: Liquid lithium divertor operation exhausted high heat flux while compatible with reliable H-mode operation

- Liquid lithium divertor on NSTX: Cu heat sink, SS permeation barrier, Mo mesh, with overhead Li ovens to fill the LLD

- Up to ~ 1 MW power, ≤30% of input, exhausted stably on LLD
  \[- q_{\text{peak}}^{\text{OSP}} \leq 10 \text{ MW/m}^2 \]

- H-mode level energy confinement maintained on LLD

Jaworski et al., *Nucl. Fusion* 53 (2013) 083032
NSTX-U progressing toward liquid lithium PFCs with high-Z substrates

**Base:** 2014-18 5 year plan steps for implementation of cryo-pump + high-Z PFCs + LLD

- **2015-16:**
  - C
  - BN
  - Li
  - High-Z
  - Downward Li evaporator + Li granule injector

- **2017-18:**
  - Lower OBD high-Z row of tiles

- **2019-20:**
  - Cryo + full lower outboard high-Z divertor
  - Bakeable high-Z PFCs for liquid Li

- **2022:**
  - Cryo + high-Z FW and OBD + liquid Li divertor (LLD)

- **2023-24:**
  - All high-Z FW + divertors + flowing LLD module
  - Or
  - Flowing Li module
A three-step progression can achieve flowing, liquid metal PFCs

1. High-Z divertor tiles
   - Heat-flux handling
   - Substrate and structural (thermomechanical)

2. Pre-filled liquid-metal target
   - Builds from high-Z divertor tile design
   - Demonstrates liquid-metal wetting/reservoir

3. Flowing LM PFC
   - Integrates liquid lithium loop
   - Safety engineering updates
EAST: Liquid lithium limiter concept developed and fabricated at PPPL, and inserted via midplane port

- Designed and fabricated at PPPL
- Used a DC EM pump, with $B_T$ of EAST, for steady-state recirculation
- Implemented 10/14
- Eventual goal: LL divertor

EAST: Liquid lithium limiter compatible with EAST scenarios, including H-mode

- Lithium light increased when current driven in limiter system
- Performance improved in ohmic discharges
- $D_\alpha$ and impurities decreased in both divertors
- Damage to limiter observed; design upgrade started

J.S. Hu et al., *Nucl. Fusion* in preparation
Development of liquid metal PFCs is a transformative area, with substantial R&D needs to assess viability

- Evidence that liquid metal PFCs can exhaust higher power than solids, and provide access to high confinement

- Concepts for liquid lithium systems being developed at PPPL and elsewhere for present-day devices and reactors
  - Need to model with SOLPS/UEEDGE

- Range of PPPL in-house and collaborative activities aimed at evaluating liquid metal PFCs in high power, diverted tokamaks, in a progressive manner