Table of contents : Chapter indexing and suggested authors

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11. NSTX-U Collaborator Research Plans by Institution

a. Existing and potential NSTX-U collaborators, edited by **Menard**

1. Research Goals and Plans for Plasma Material Interactions and Plasma Facing Components

1.1. Overview of goals and plans

1.1.1. Establish predictive capability for the performance of FNSF and ITER

1.1.2. Physics thrusts and goals by topical area (Jaworski)

1.1.2.1. Extending performance improvements with lithium-based PFCs
1.1.2.2. Assessing material erosion and transport of low-Z coatings and high-Z PFCs
1.1.2.3. Establishing the scientific basis for new divertor regimes based on liquid lithium PFCs

1.1.3. Enabling technologies and tools (Jaworski, Skinner)

1.1.3.1. Surface science to establish atoms-to-PFCs understanding
1.1.3.2. Upgrade path to an all-metal NSTX-U
1.1.3.3. Laboratory R&D on liquid metal systems and PFCs

1.2. Research Plans **(Group needs to re-organize this)**

1.2.1. Lithium-based performance improvements and extension to long-pulse (Maingi, Skinner, Koel, Allain, Jaworski)

1.2.1.1. Motivation: FNSF needs high H-factor, lithium coatings have demonstrated ability to achieve in NSTX

1.2.1.2. Machine performance studies with lithium coatings
1.2.1.2.1. Upgrade studies on ATJ (w, w/o Li)
1.2.1.2.2. Upgrade studies on high-Z substrate (w, w/o Li)

1.2.1.3. Critical parameters affecting lithium-based PFC performance
1.2.1.3.1. Surface chemistry effects (e.g. gettering, desorption, as functions of temperature, contamination, etc).
1.2.1.3.2. Effects due to substrate choice (e.g. ATJ vs. TZM vs. ODS steel)
1.2.1.3.3. Connections between laboratory studies and in-situ material analysis
1.2.1.3.4. Beyond lithium: surface science of high-Z liquid metals Ga and Sn

1.2.1.4. Liquid metal PFC design to extend lithium supply to long-pulse

1.2.2. Material erosion and transport of low-Z coatings and high-Z substrates (Jaworski, Skinner, Koel, Soukhanovskii, Stotler)

1.2.2.1. Motivation: wall erosion estimated to result in tons of material circulating the machine and may not be sustainable for a solid PFC

1.2.2.2. Assessing divertor and wall erosion and migration
- 1.2.2.2.1. Optical spectroscopy for gross erosion
- 1.2.2.2.2. QMB methods for net erosion/deposition
- 1.2.2.2.3. Marker tiles, ion beam analysis methods
- 1.2.2.2.4. Isotope experiments in a lithiated machines

1.2.2.3. Assessing the disposition of eroded/redeposited material
- 1.2.2.3.1. Surface science techniques and lab R&D
- 1.2.2.3.2. Dust production and formation from eroded material
- 1.2.2.3.3. Codeposits low-Z and high-Z materials and their remediation

1.2.2.4. Integrated design of liquid metal PFCs for supply and collection of PFC material

1.2.3. Establish the science and operating scenarios of the strongly-emitting regime (Jaworski, Gray, Goldston, Soukhanovskii, Kaganovich, Chang, Stotler)

1.2.3.1. Motivation: fusion heat-fluxes on advanced PFCs expected to result in elevated temperatures and strong eroded fluxes from evaporation and sputtering, may no longer be in a minority-impurity plasma but a strongly-emitting PFC regime

1.2.3.2. Assessing lithium heat-flux reduction and radiation
- 1.2.3.2.1. Infrared thermography and other techniques for quantifying heat-flux
- 1.2.3.2.2. Vapor shielding of the PFC in steady-state and under transient loads
- 1.2.3.2.3. Fluid and kinetic descriptions of energy and particle transport for the strongly-emitting regime

1.2.3.3. Liquid metal PFC design for long-pulse removal of heat and supply of lithium

1.2.4. Enabling technologies and other supporting R&D

- 1.2.4.1. Surface-science laboratories and tools for establishing an understanding from atoms-to-PFCs (Skinner, Koel, Allain)

- 1.2.4.2. Liquid metal loop development in support of liquid metal PFCs (Jaworski)

- 1.2.4.3. Integrated liquid metal PFC and thermal-hydraulic design and testing (Jaworski)
  - 1.2.4.3.1. Lithium laboratory work and testing for technological readiness
  - 1.2.4.3.2. Technical demonstrations on linear test-stands (e.g. Magnum-PSI)

- 1.2.4.4. An all-metal NSTX-U (Jaworski, Kaita)
  - 1.2.4.4.1. Upgrade from ATJ to TZM in the divertor
  - 1.2.4.4.2. Qualification of TZM coatings on graphite tiles for wall-armor

- 1.2.4.5. Additional and alternative lithium delivery systems (Jaworski, Mansfield?, Skinner, Andruczyk)
  - 1.2.4.5.1. LITER
  - 1.2.4.5.2. LITER-Upward and LITER-FAST
  - 1.2.4.5.3. Diffusive evaporation
  - 1.2.4.5.4. Gravity-assisted dust injection
  - 1.2.4.5.5. Granule injection
  - 1.2.4.5.6. Electrostatic spray

1.2.5. Plan: Years 1 & 2

- 1.2.5.1. Assessing lithium performance enhancements in NSTX-U
  - 1.2.5.1.1. Li-coating studies with LITER and other introduction methods
  - 1.2.5.1.2. Extending the database of lithium-enhanced performance with NSTX-U capabilities
  - 1.2.5.1.3. Effects of expanded coverage using diffusive evap, LITER-U or other tools
  - 1.2.5.1.4. Effect of up-down asymmetry of lithium evaporation
- 1.2.5.2. Assessing erosion from low-Z coatings and high-Z substrates
  - 1.2.5.2.1. Coating life-time and efficacy studies on carbon and high-Z metal substrate
  - 1.2.5.2.2. Erosion/redeposition quantification with QMB and other diagnostics
  - 1.2.5.2.3.

- 1.2.5.1.1. Establish control over the in-vessel inventory of liquid metal
  - 1.2.5.1.1.1. Control evaporation and condensing surface locations and material collection
  - 1.2.5.1.1.2. Near-term strategy: Leverage existing active cooling technologies for thermal control while developing next-step schemes

- 1.2.5.1.2. Develop adequate means of maintaining the liquid metal
  - 1.2.5.1.2.1. Perform efficient purification and establish robust operation and maintenance
  - 1.2.5.1.2.2. Near-term strategy: Learn from IFMIF EVEDA and develop robust, maintainable systems from day 1

- 1.2.5.1.3. Understand plasma response and physics of LM-PFC
  - 1.2.5.1.3.1. Develop descriptive and prescriptive models for the SOL/PMI of LM-PFCs
  - 1.2.5.1.3.2. Near-term strategy: Validate fluid and kinetic codes and databases against available linear-machine data as well as tokamak database

Plan: Years 1-2:

- 1.2.5.2. Test Li evaporation for pumping longer pulse duration NSTX-U plasmas
- 1.2.5.3. Test Li evaporation to upper vessel by evaporator/injector, He diffusion, electrostatic sprayer
- 1.2.5.4. Assess impact of full wall Li coverage on pumping, confinement
- 1.2.5.5. Test ELM control by midplane Li granule injector
- 1.2.5.6. Test Li-PFC prototypes on Magnum PSI and possibly LTX or EAST
- 1.2.5.7. Down select to best flowing Li-PFC concepts
- 1.2.5.8. Test on Magnum PSI and LTX or EAST
  - 1.2.5.8.1. Li coating lifetime
  - 1.2.5.8.2. Hydrogenic recycling/retention as a function of exposure time & temperature
  - 1.2.5.8.3. Erosion, migration, impurity production with and without lithium
- 1.2.5.9. Surface analysis experiments using MAPP
- 1.2.5.10. Modeling support - Neoclassical Li-physics simulation with XGC0 + DEGAS2

- 1.2.5.10.1. Self-consistent “kinetic” plasma modeling capability (successor to fluid plasma codes B2-EIRENE, UEDGE-DEGAS2, etc)
- 1.2.5.10.2. Non-equilibrium Li radiation, non-Maxwellian electrons
- 1.2.5.10.3. Include effect of Mo impurities, compared to C
- 1.2.5.10.4. Effect of Li influx on pedestal and plasma behavior

Plan: Years 3-5:

1.2.5.11. Test flowing Li-PFC on at least one toroidal sector of NSTX-U,
possibly full toroidal coverage system, pending lab-based tests
and modeling

1.2.5.12. Modeling support - Neoclassical-turbulence Li simulation in XGC1 + DEGAS2

- 1.2.5.12.1. Add self-consistent turbulence to the above
- 1.2.5.12.2. Adapt the code geometry to Magnum-PSI for Li radiation simulation validation
- 1.2.5.12.3. Study Li issues under 3D RMPs

1.3. Summary timeline for tool development to achieve research goals

1.3.1. Theory and simulation capabilities

- 1.3.1.1. SOLPS
- 1.3.1.2. UEDGE
- 1.3.1.3. XGC0, XGC1
- 1.3.1.4. DEGAS
- 1.3.1.5. NCLASS, MIST, STRAHL
- 1.3.1.6. Atomistic MD modeling

1.3.2. Diagnostics

- 1.3.2.1. High priority improvements for initial NSTX-U operation:
  - 1.3.2.1.1. MAPP probe
    - 1.3.2.1.1.1. XPS, AES, TPD, SAM…

- 1.3.2.2. Longer term NSTX-U boundary diagnostics:
  - 1.3.2.2.1. Molybdenum core, edge, divertor spectroscopy (VUV, visible)

1.3.3. Other facility capabilities including plasma control

1.3.3.1. Wall condition/material, PMI control
    1.3.3.1.1. Transition to full metal coverage for FNSF-relevant PMI development

1.3.3.2. Lithium PFC supporting technology
    1.3.3.2.1. Possible upgrades of existing Lithium evaporator (LiTER)
    1.3.3.2.2. Midplane Li granule injector for ELM control, Li delivery
    1.3.3.2.3. Upward Li evaporator
    1.3.3.2.4. Mo upper and lower divertor tiles
    1.3.3.2.5. Lab-based R&D
        1.3.3.2.5.1. Laboratory studies of D uptake as a function of Li dose, C/Mo substrate, surface oxidation, wetting…
        1.3.3.2.5.2. Tests of prototype of scalable flowing liquid lithium system (FliLi) at PPPL and on HT7 and/or EAST
        1.3.3.2.5.3. Basic liquid lithium flow loop on textured surfaces
        1.3.3.2.5.4. Analysis and design of actively-cooled PFCs with Li flows due to capillary action and thermoelectric MHD
        1.3.3.2.5.5. Magnum-PSI tests and supporting hardware
    1.3.3.2.6.

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