# Agenda

- Discussion of EAST status and plans w.r.t. lithium research, and our recent phone/e-mail interactions with them.
- Discussion and agreement on key deliverables, milestones, and names of people.
- Brain-storm a bit on ways to optimize/enhance the linkages/synergy between the KSTAR and EAST parts of the proposal.
- 4. Discussion of page allocation for proposal text - one idea is to follow funding:
  - PPPL/PU - 6 pp, Purdue - 1.5 pp, UIUC - 1.5 pp, UCLA - 1 pp

# Status of EAST/Li part of "Long Pulse PMI Solutions" led by ORNL

J. Menard

May 17, 2012

# Table of preliminary estimate of funding request by major task and Institution

| | | |
|---|---|---|
| ORNL | 900 | KSTAR |
| LLNL | 400 | KSTAR |
| UCSD | 200 | KSTAR |
| GA | 100 | KSTAR |
| Tech-X | 75 | KSTAR |
| PPPL+PU | 800 | EAST |
| UIUC | 200 | EAST |
| Purdue | 200 | EAST |
| UCLA | 125 | EAST |
| | 3000 | |

- KSTAR
  - Participate in KSTAR experiments (ORNL, GA) to benchmark edge cross-field transport with SOLPS (ORNL) and UEDGE (LLNL, UCSD) with the existing divertor to predict new divertor
  - BOUT++ for changes to the edge turbulent transport with the proposed divertor changes (LLNL), evaluate the evolution of the wall recycling state with evolving wall temperature and surface concentration with the WALLPSI code (UCSD) + FACETS framework to couple WALLPSI with UEDGE and SOLPS (TXC).
- EAST
  - Described on next slide…

# EAST/Lithium specific goals and deliverables for the 3-year period

- Magnum-PSI for plasma response parameters from bare and Li-coated PFCs relevant to the EAST tokamak, diagnostic upgrades (QMB) for monitoring real-time erosion and deposition within the tokamak. Evaluate Li coating lifetime, and optimize Li usage (PPPL). Complement Magnum results with University-based tests (UIUC, Princeton, Purdue)
- Model erosion/redeposition and transport calculations (WBC-Redep and OEDGE/DIVIMP code) + mixed material effects would also be modeled. (Purdue, PPPL, Princeton)
- Develop the technology of liquid metal handling and PFCs to provide designs and guidance to the EAST team, for eventual testing in EAST: gaseous cooling systems for the lithium limiter and possible future divertor applications + infrastructure: liquid metal circulating loops, and actively-cooled capillary restrained systems, Lithium-Metal Infused Trenches (LiMIT) - (PPPL, UIUC)
- Model the transient effects on liquid Li behavior + free-surface MHD modeling of stationary and transient performance of free-surface liquid metal PFC concepts that are to be tested on the EAST lithium limiter (UCLA, Purdue)

# Proposed PPPL work scope and cost inputs: Staff FTEs - M&S and travel costs

| New | | |
|---|---|---|
| **PPPL** | **700** | |
| | **190** | **Magnum+EAST+travel** |
| | **100** | **Stotler** |
| | **200** | **Post-doc + student** |
| | **210** | **Lab R&D** |
| | | |
| PU | 100 | |
| | 100 | Koel + PPPL partial post-doc |
| | | |
| Illinois | 200 | |
| | 60 | Full Grad |
| | 80 | 0.5 Research eng. |
| | 10 | 0.5 month Ruzic |
| | 50 | M&S + undergrads + travel |
| | | |
| Purdue | 200 | |
| | 60 | JP Allain grad student |
| | 90 | Brooks WBC/Redep |
| | 50 | Hassanein/Sizyuk |
| | | |
| UCLA | 100 | |
| | 100 | Ying/Morley modeling? |
| | | |
| Lithium total | 1300 | |

| **PPPL cost breakdown** | **per year** | |
|---|---|---|
| | | |
| **Magnum+EAST+travel total** | 190 | |
| ~5 trips (travel) | 50 | |
| Magnum hardware+labor | 70 | Shifts to Lab R&D by 3rd year |
| Jaworski time (0.2) | 70 | |
| | | |
| **Stotler computation time** | 100 | |
| | | |
| **1 full post-doc to help w/ EAST** | 200 | |
| | 150 | post-doc |
| | 50 | grad student |
| | | |
| **Lab R&D total** | 210 | |
| Engineer | 50 | |
| Drafting | 30 | |
| Machining | 30 | |
| Welding | 20 | |
| Technician | 30 | |
| Hardware | 50 | |
| | | |
| | | |
| | | |
| | | |

# Status of interaction with host facilities and plans for obtaining support letters

- Conference call (including presentation materials from us) with lithium experts (Jiansheng Hu+) at EAST on May 9 regarding lithium limiter interest plans, interest, goals *(Jaworski, Menard, Ruzic, Andruczyk)*
- Follow-up Q&A via e-mail  May 11 with Jiansheng Hu
- Expect can get letter of support from JS Hu, H Guo, J. Li, B. Wan after we share draft proposal from them and get feedback

# Possible issues in meeting the PPPL schedule for budget input (due June 6) and draft text (due June 11)

- PSI meeting next week interferes with draft writing and budget prep. (Jaworski, likely several others)
- Trip to EAST week of June 11 to perform experiments (Menard, Jaworski) will both assist and interfere with finalization of proposal

PPPL PRINCETON PLASMA PHYSICS LABORATORY

# Lithium Material Transport and Liquid Metal Technologies for International Collaboration with ASIPP

MA Jaworski

May 9th, 2012

# Overview

- Lithium issues and the need for this research
- Proposal overview
- Activities ongoing at PPPL ready to contribute to this work
- Benefits of the research to EAST and US programs
- Overview of research plan

# Lithium has several outstanding issues to resolve if it is to have a future

- In-vessel inventory creates problems in steady-state
  - Continual increase of lithium if not removed
  - Tritium co-deposition detrimental to plant operation
- Technical implementation unproven on large-scale devices
- Power-cycle undeveloped which is integrated with lithium PFC temperatures

**These are common objections to the liquid lithium in the US program and must be addressed**

# PPPL and ORNL are proposing to work on EAST and KSTAR to address these issues

- ORNL+collaborators is focused on KSTAR
- PPPL+collaborators is focused on EAST material migration and lithium technology
  - PPPL collaboration with Magnum-PSI and U-Illinois IIAX facility provide basic Li-coating data (e.g. sputter yield)
  - Purdue+PU+PPPL contributing surface science experiments and modeling of material migration
- Liquid metal technology program is a parallel effort
  - PPPL and U-Illinois focused on liquid metal PFC and associated loop
  - UCLA contributing LM-MHD simulations

# PPPL is currently researching these topics due to NSTX Li usage

- NSTX has years of experience with Li evaporation, powder and, recently, Li on molybdenum liquid lithium divertor
- Several internally funded projects are underway which contribute to the technology aspects
- PPPL researchers have experience in laboratory and in confinement devices for understanding impact of Li on overall machine performance

# Reliable operation is the goal of the Liquid Lithium Test Stand

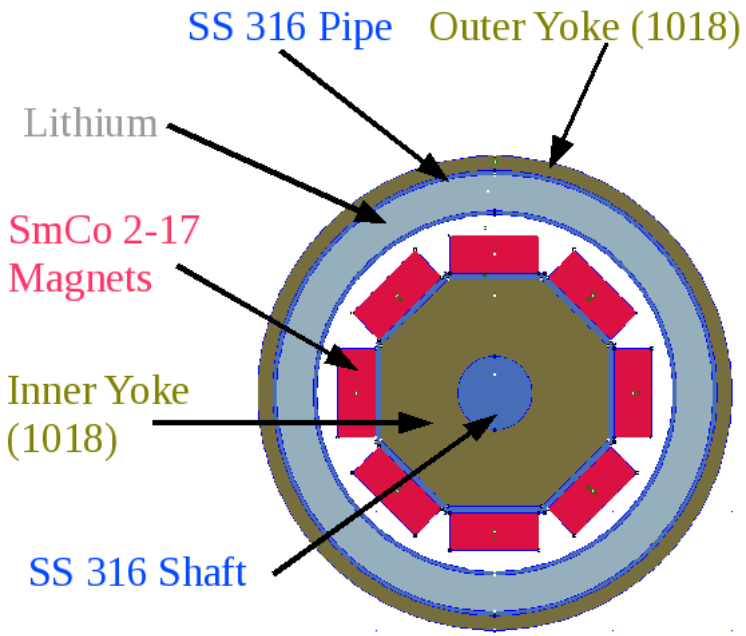
R037

- Project will demonstrate operation of a liquid lithium loop for tokamak campaign-relevant periods of time
  - E.g. 8 hours operation/day, 5 days a week, 15 run-weeks
  - Tokamak relevant vacuum (e.g. 1e-7 Torr base)
- Reliable startup, shut-down, and restart
- Reliable introduction and removal from vacuum system (free-surface flow in vacuum)

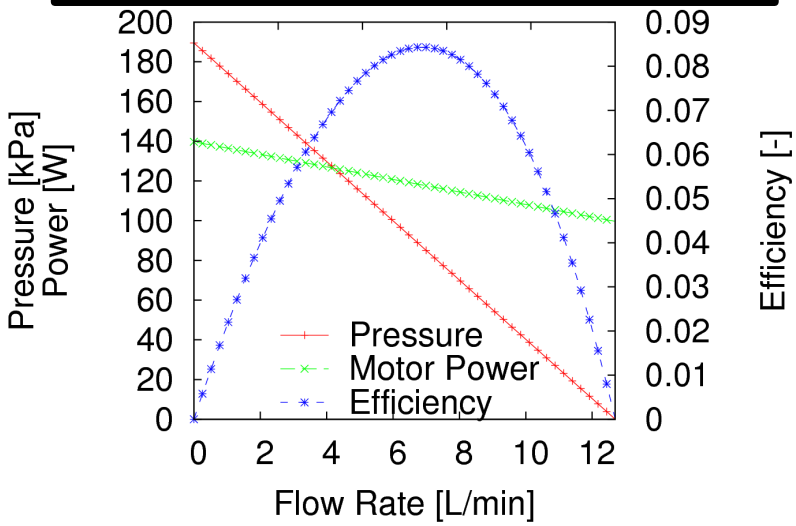
**We are targeting robust and reliable operation in challenging environments to support a user-facility**

# New liquid metal pump will provide precise control of flow

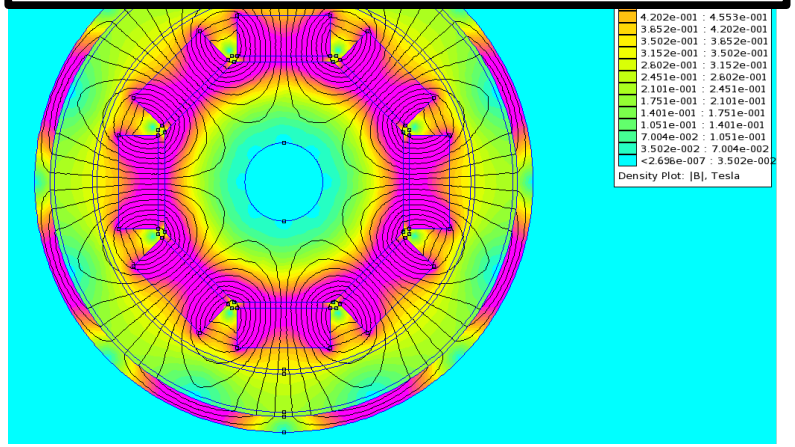
- Simple pump design developed for LDRD
- Fine control of system pressure through speed control of motor
- Avoids uncontrolled flow during Ar piston operation




**Predicted pump performance**



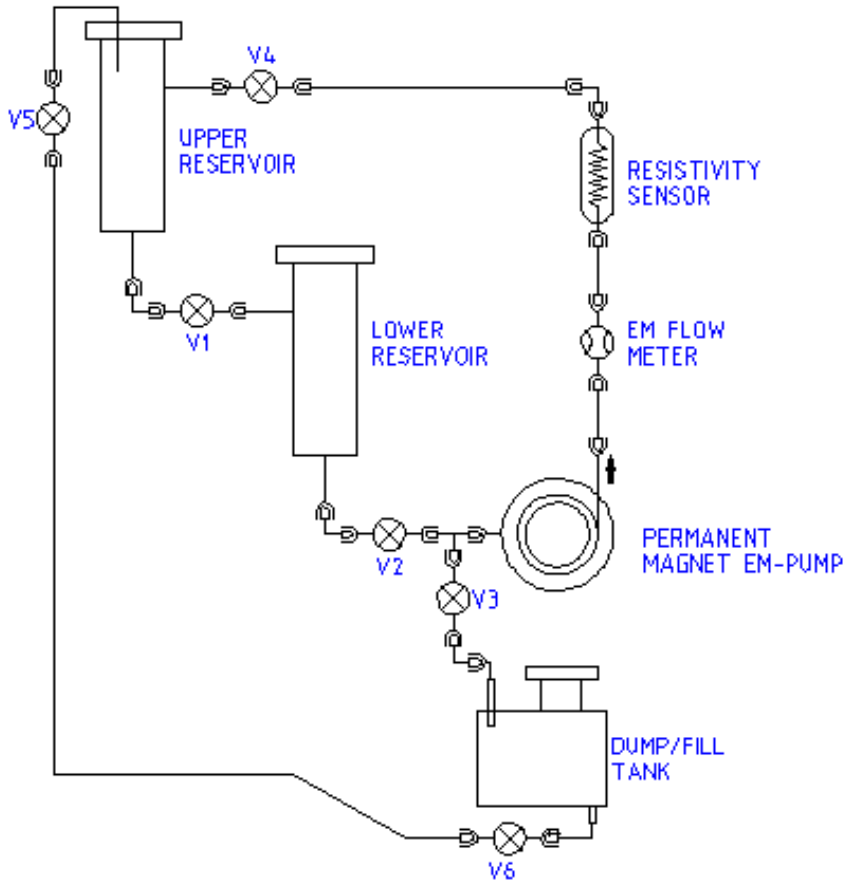

**Magnetic field simulation with actual material properties**



# Project is on track to begin closed-loop testing in late June, vacuum in August

- Fabrication and assembly will occur in May and June
- First experiments will demonstrate loop operation alone
- Vacuum system integration to proceed in August

**Liquid Lithium Test Stand Loop Diagram**



# Exploration of advanced cooling schemes is underway with "Next-step development..." R035

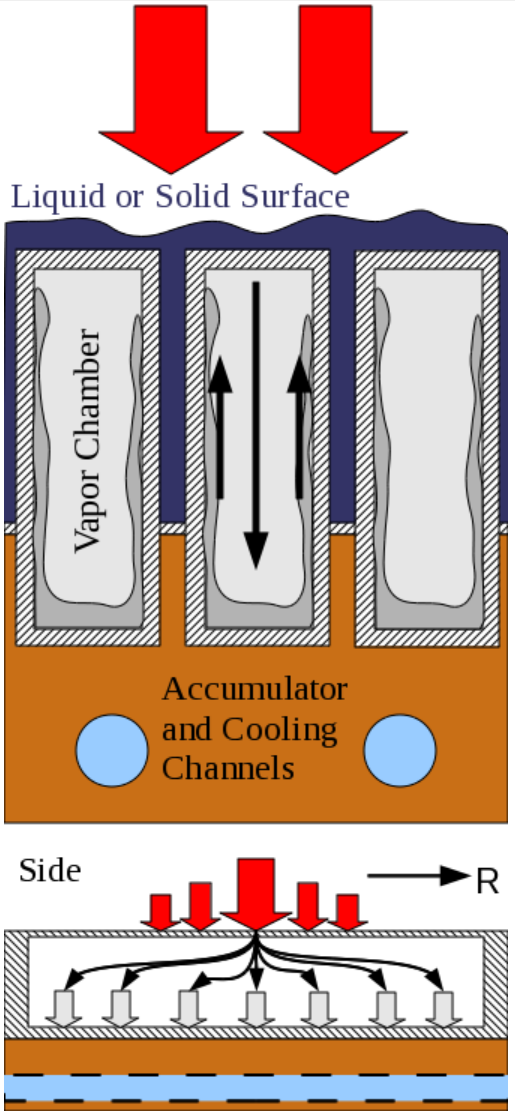
- Project carries forward engineering analysis of "soaker-hose" concept
  - A. Khodak performing thermal analysis
  - Optimization of gaseous cooling for liquid lithium PFCs
- Examining purification systems and other sub-systems for maintaining liquid metal system
- Scope and planning for on-site coolant plant to support experiments

**We are advancing liquid lithium PFCs and loop systems for testing and long-term, on-site operation**

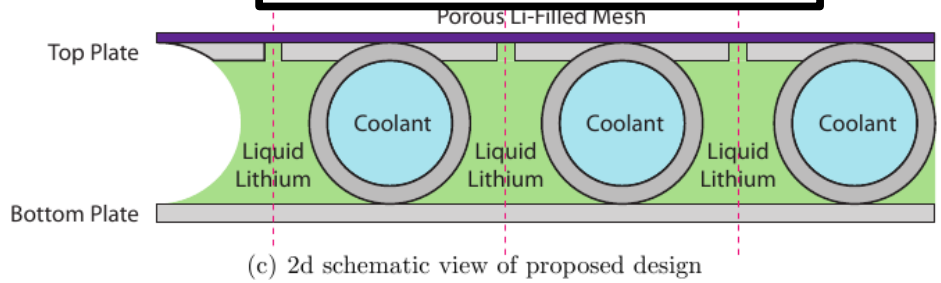
# Advanced power extraction schemes impact solid PFC concepts as well as liquids

- Most concepts rely on active cooling
  - Thin, slow-flow LM concepts
  - Solid PFCs
- Efficiently dealing with heat flux *peaking* is important for divertor concepts
  - Impinging-jet cooling in T-tube and EU "finger" concepts
  - Vapor box/heat pipe another possibility
- Coolant channels used as generic term here

**Vapor-box & accumulator concept for NSTX-U**




**Soaker-hose concept**



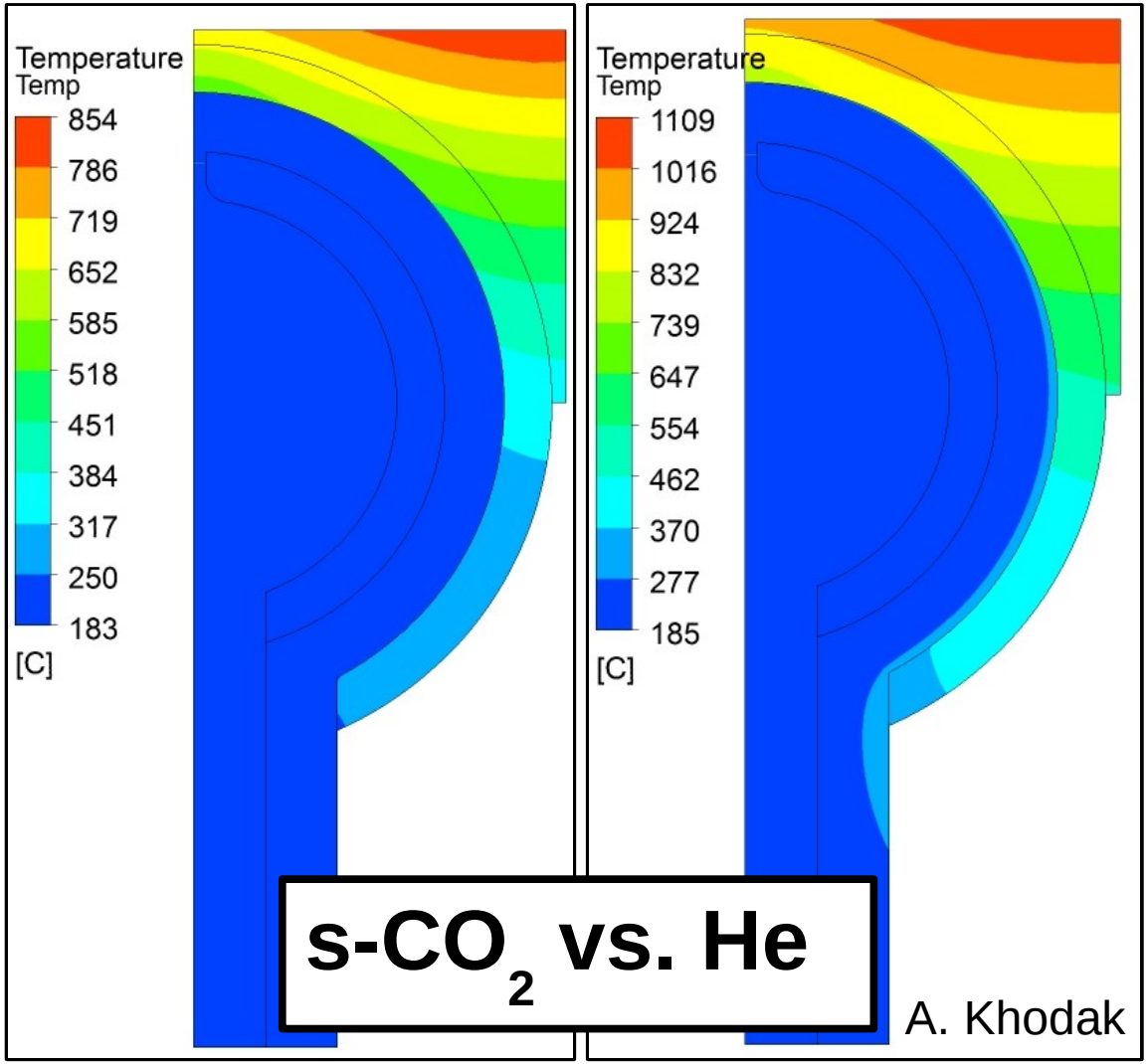

(c) 2d schematic view of proposed design

Goh, Goldston, and Jaworski

# Initial studies show supercritical $CO_2$ more effective coolant than helium

- ARIES-CS T-tube simulation provides ANSYS/CFX check
  - Good agreement found with ref. k-ε turbulence model
  - Allows parameter study locally at PPPL
- Identical volumetric flow-rates modeled
  - s-$CO_2$ density 10x that of helium, both at 10MPa
  - 255C lower temperature
- Larger pressure drop (~10x) with s-$CO_2$

**$T_{max}$ = 854C vs. 1109C**



# A self-consistent power cycle using s-$CO_2$ addresses a key criticism of Li PFCs

- Low temperature PFCs (e.g. Li) often criticized for "throwing away" fusion power
- s-$CO_2$ cycles are operating now and under continuing development for fission power plants
  - Dostal found comparable thermal efficiencies for s-$CO_2$ at 550C and a comparable He cycle at 850C
  - s-$CO_2$ out-performs He at equivalent temperatures
- This LDRD is developing a self-consistent s-$CO_2$ cycle to complement the PFC cooling work
  - s-$CO_2$ not limited to low-temperature PFCs; could be utilized for high temperature PFCs as well

# Completion of FY2012 objectives with current funding makes significant steps for LM-PFCs

- **R037** will demonstrate loop and flow in vacuum by August and conduct experiments on restart and handling
  - Design time and drafting has offset peak spending for procurements (project had March start date)
  - Technician/machinist/welding labor will utilize significant amount of budget in May-June
- **R035** will have 2D and 3D simulations, purification and coolant system design activities done by Sept.
  - Current simulation job originally estimated at 500hrs, can complete in FY2013
  - Other activities originally proposed for full year of FY2012 can be completed in FY2013 (e.g. free-surface diagnostic development)

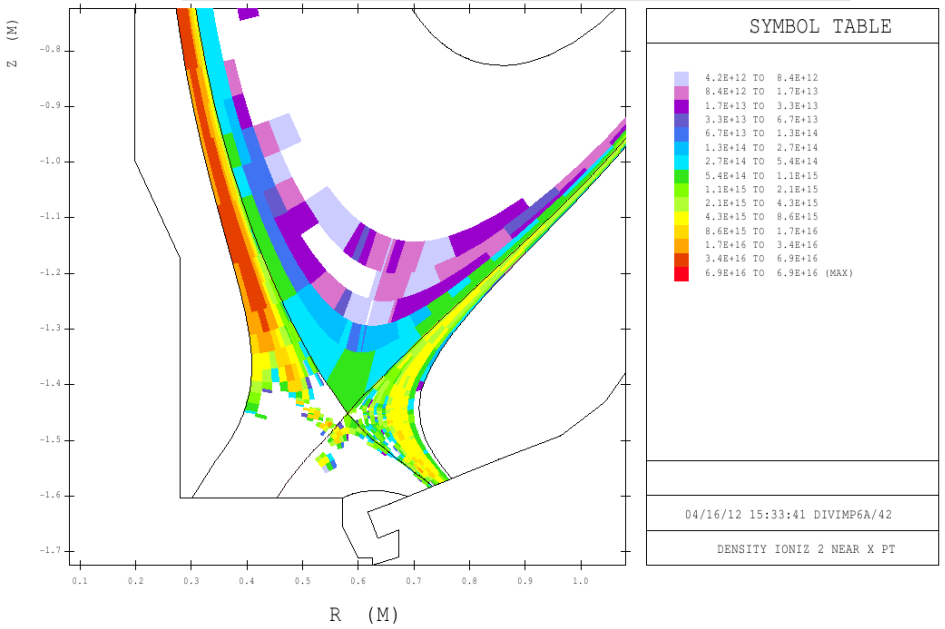
# Overcoming the technical challenges facing liquid metal PFCs

- These projects are developing practical experience operating liquid metal loops here at PPPL
- We are developing new gaseous cooling schemes to control the PFC temperatures
- Questions of robustness and reliability are central to this work

# Impurity transport codes already in use for interpreting NSTX data

- OEDGE code suite produces fluid background with EIRENE neutral hydrogen
- DIVIMP simulates impurity transport with Monte-Carlo methods
- DIVIMP can also run on SOLPS/UEDGE fluid backgrounds
- Local redeposition and transport can be modeled with WBC-Redep (Purdue)
- Simulations already being used for diagnostic development and radiation simulations

**DIVIMP impurity transport modeling of Li in NSTX**



# We expect the collaboration to be mutually beneficial

- Material transport in EAST could be used to optimize Li injection and the achievement of long-pulse discharges
- Robust and reliable technology development is a central focus in support of operation on confinement devices (i.e. reliability, ease of use)
- Work addresses the question of whether in-vessel lithium (co-deposited T) can be controlled (introduction and removal) or if other liquid metals should be pursued (e.g. Sn, Ga)
- Provides technical experience with LM PFCs and associated components so that confinement devices can determine if or when it should be implemented

# Proposed research plan

- Magnum-PSI and IIAX studies determine sputter yields on Li-coated PFC materials (years 1&2)
- Surface science studies ongoing to understand controlled physics and chemistry of Li surfaces (years 1-3)
- EAST studies to focus on material migration (years 1-3)
  - Accurate modeling of EAST edge plasma
  - Measurement of erosion/redeposition through existing and upgraded diagnostics (e.g. div. spectroscopy, marker tiles, isotope expts., QDMs)
  - Assessment of material migration from evaporated coatings, powder and granule injection, other means (e.g. ELI)
- Development of designs and testing of LM technologies so that EAST or others can implement in convenient timetable (years 1-3)
  - Multiple limiters possible (e.g. LIMIT, soaker-hose, FLiLi)
  - Basic loops, pumps, purification systems being developed at PPPL

# Discussion questions for ASIPP

- Any feedback you have on the existing plan and your own research priorities would help us strengthen our proposal.
- Is there a written or definite plan for lithium usage on EAST or anything to help us refine timetables?  Timetables of divertor/PFC upgrades?
- Would ASIPP/EAST commit to testing technology elements either within the first 3-year cycle or early in the second 3-year cycle?

# Thank you for your consideration

**Questions?**

**Notes from May 9th conference call with ASIPP.**
**Participants:**
**M.A. Jaworski, J. Menard (PPPL)**
**D. Andruczyk (U-Illinois)**
**Guizhong Zuo, Jiansheng Hu, Jiangang Li (ASIPP)**

**Comments from J. Menard:**

Comment from Jiansheng – proposal is very good.

Will test lithium limiter in fall 2012 in HT-7, then will be shut down. Only can test through that time.

If get good results then test in EAST.

EAST will do Liquid lithium limiter.

Of course choose one good design for the test.

If design has a problem, need to be able to remove…

If can test in USA, and manufacture and ship to China, then test in EAST… at least 2-3 years later.

EAST has 2 limiters now at midplane – can change 1 to test lithium. 1 for solid.

J. Li – need to test limiter before divertor.

Basic plan - careful testing in USA, then test in EAST. But can only test 1 lithium limiter at a time.

**Additional discussion comments:**

There was a question from ASIPP of what physical size the limiter might be.
PPPL+Illinois are first considering physical dimensions that would be compatible with existing vacuum ports and equipment (e.g. 500mm port with MAPES attached).

While a flowing divertor is the ultimate goal, we all agree that demonstration on a limiter is a good first demonstration before making large changes to the divertor.

Issues of control and overall flow-rate are a concern for ASIPP, particularly after initial tests in HT-7. The technology program planned will include system testing with liquid metal loops to ensure normal operation does not result in unwanted lithium motion. This is a central focus of current PPPL research on liquid metal loops and will be a part of the proposal.

Another possibility is to create self-enclosed limiters or pre-charged systems. These will limit the amount of lithium that can be injected into the machine. These will still require testing to ensure normal operation does not result in unwanted lithium motion.

There are some practical questions concerning the measurement of material migration in EAST. There seemed hesitancy to rely on schemes that require tile removal and post-run analysis. This would eliminate marker tiles and isotopic tracer experiments. We suggest a complementary method

which is to upgrade EAST diagnostic systems with a set of quartz microbalance (QMB) devices in strategic locations throughout the machine. These can provide real-time data and would be ideally suited to a long-pulse device like EAST. Several groups in the collaboration have experience with this type of diagnostic system including PPPL, U-Illinois and Purdue.

**Additional questions for discussion in this document or at meetings in Aachen and Hefei:**

1. Does ASIPP have a strong preference to continue using the EM-pump on-site?

At present, PPPL is targeting a smaller loop and lithium inventory than currently present at ASIPP. We would recommend that the tested components design of the integrated system be duplicated for tests on EAST. An alternative is to interface with the EM-pump system available and specify pumping pressure and flow-rate compatible with the test devices.

Comment: We don't persist to using EM-pump on site. But we think EM-pump for continually flowing lithium and would decrease man's power. If you think there are some other better methods, we can use it.

2. What time line might EAST have for implementing tests on a movable limiter?

I expect that rigorous testing of the fully integrated system (PFC, lithium loop, gaseous cooling) will require 2-3 years. Could EAST be ready to test a design at the start of the 4$^{th}$ year or possibly the end of the 3$^{rd}$? What competing upgrades should we be aware of that might delay or alter a liquid lithium limiter testing plan?

Comment: In ASIPP side, the test would be in next campaign after at least 1.5 years later, if everything is successfully tested before and we have enough time to design. I think it is no problem to test after 4 years.

3. Is EAST interested in additional applications of the gaseous cooling system being considered for liquid lithium PFCs?

PPPL will continue to work with supercritical-CO2 as the initial studies show promise in improving cooling efficacy and overall power-cycle efficiency. This technology is applicable to conventional, solid high-Z components as well as liquids. If EAST is interested in this application, we will include some words about it in the proposal targeting gaseous active cooling of divertor targets as well as liquid lithium limiter targets.

Comment: We only worry about the cooling efficiency. As we known, heat load of EAST plasma should be higher than HT-7. Please calculate the cooling efficiency if using gaseous cooling system. Otherwise, we need to design a robust structure for water cooling.

4. Does ASIPP wish to gain experience in fabrication of integrated system components or prefer to have system delivered by PPPL/U-Illinois collaborators?

For the first 3-year funding cycle, we expect resources enough to construct the testing system to prove out operation. Funding for a deliverable system may not be available until the 4$^{th}$ year of the grant (if renewed). Alternatively, designs generated by US collaborators could be shared and implemented by ASIPP when convenient to the EAST schedule (question 2). Does ASIPP have a strong preference for constructing their own equipment for inclusion on EAST?

Comment: For time save, it is better to fabrication in ASIPP. We have a factory with very strong fabrication capacity. in ASIPP. But it need budget support. Do you think USA could support it? And send one technician to ASIPP for a long duration during the fabrication? Otherwise, it is better fabrication in USA. At this moment, we have not a strong preference. Any design is welcome, To test it

in EAST only depends on the reliability and high value of the design.

5. To what degree will water-cooling remain in the EAST system and is there an expected upgrade to a gaseous cooling system in the near future?

Comment: At this moment, we have lots of water cooling systems for IC coils, PFCs and so on. I have no idea it could or should be changed. If some calculation show the gaseous cooling system could be used for different components, I will discuss it with the head of ASIPP.

These are some immediate questions that come to mind.

PPPL-PU outline for 3-year planning

Year 1:
PPPL personnel (Jaworski) will be participating in collaborative experiments on Magnum-PSI to obtain plasma response parameters from bare and Li-coated PFCs relevant to the EAST tokamak (including graphite, TZM and tungsten). These studies will provide validation data for comparison with fluid reconstructions and comparison with ADAS and other CRMs describing lithium radiation and transport in the Magnum simulator device.

PPPL personnel (Jaworski+post-doc) will also be developing an experimental and diagnostic upgrade plan for implementation on EAST including quartz deposition systems for monitoring *real-time* erosion and deposition within the tokamak. Other diagnostic or analysis upgrades and consultations with EAST will also occur during this period to perform scenario development for material migration studies. These studies will target the usage of available plasma diagnostics, upgraded diagnostics such as the QDMs, MAPES in conjunction with evaporator, Li dropper and granule injector operation. Scenarios for long-pulse will be developed based on evaluation of Li coating lifetime analysis and optimized usage of the injection schemes available. Initial plasma reconstructions will be disseminated to collaborators for initial modeling efforts and diagnostic optimization.

PPPL personnel will prepare a vacuum test chamber and develop a set of uniform mounting and interfacing hardware for usage at PPPL and EAST for limiter head testing (assumes PPPL LDRD completion of loop). Vacuum system will include active cooling loop for usage with experiments. Design for soaker-hose will be refined for fabrication.

(PPPL personnel (Ji group) will perform design and scoping studies for a fast-flow system.)

Year 2:
PPPL personnel will perform experiments to obtain information on long-pulse material migration within the EAST tokamak with and without injection schemes using upgraded diagnostics and developed scenarios from year 1. Experimental studies will form the basis of computational simulations and the development of a reference divertor plasma description from suitable plasma code (OEDGE/SOLPS/UEDGE). Reference plasma will be disseminated to collaborators.

PPPL personnel will perform tests on candidate limiter soaker-hose limiter head to determine quiescent operational parameters. Robustness and reliability tests will be performed. Limiter head from U-Illinois will also be tested if available.

(Candidate design for fast-flow system will be developed. Upgraded pumping system designed and implemented if necessary to testing.)

Year 3:
PPPL personnel will perform experiments examining heavy lithium usage in EAST targeting heat-flux mitigation properties and any associated changes in transport.

PPPL designs for liquid lithium limiter iterated and tested for final design candidates for EAST evaluation.

Items from Charles related to PPPL/PU.
Bruce and I propose to write a page or two on surface analysis at PPPL in support of the PMI-long-pulse proposal along the following lines:
Key deliverables:
1. Li wetting vs. substrate temperature for single xtal Mo, TZM, stainless..., using scanning Auger microscopy (SAM), and
2. D uptake vs. temperature using the new ion source and temperature programmed desorption (TPD) on Li coated single xtal Mo and TZM before and with exposure to H2O, O2 etc.

Years 1 and 2 in studies 1 and 2 above.

Suggest additional study of sticking coefficients for gases and self-sticking as functions of temperature and impurity coverage.

Dear colleagues,

Attached is the final pre-proposal submitted to OFES on our collaborative 'PMI long pulse' proposal. Thanks for all of your contributions.

Here are the final targeted budget numbers (3.0 M total):
KSTAR: ORNL - 0.9 M, LLNL - 0.4 M, UCSD - 0.2 M, GA - 0.1 M, Tech-X - 0.075 M
PPPL - 0.8 M, Purdue - 0.2 M, UIUC - 0.2 M, UCLA - 0.125 M

To develop the narrative based on the pre-application (after approval from DoE), I propose the following breakdown of writing assignments, and schedule. The listed names are responsible for facilitating input from all contributors, but drafts should be circulated periodically to entire email list. The lead name is ultimately responsible for the draft of that section.

A. Outline - 25 pages maximum for narrative
1. Introduction, including why EAST and KSTAR, etc. 3-4 pages (Maingi, Menard)
2. KSTAR - 10 pages (Maingi, Pankin, Petrie, Pigarov, Xu)
3. EAST - 10 pages (Jaworski, Brooks, Morley, Ruzic)

I will send out a more detailed outline of KSTAR part, and Jon/Mike will coordinate the EAST part.

B. Deadlines - working backwards from submission deadline

June 4 - first draft of narrative

June 14 - final draft of narrative, plus 1st complete draft at each institution incl. some budget information for management approval at each institution

June 21 - final PDF submitted separately from each institution, including separate budget pages from each institution, common narrative

C. Style
For consistency, the following style which would be used for each device has worked well in the past, and should be used as a template:

1) Background (20-33%) - why important in this facility; should avoid too much overlap with introduction to entire proposal
2) Recent results if appropriate (20-33%) - from the facility scientists, and/or from co-authors of this proposal on their own facilities or targeted facilities
3) Proposed experiments and analysis - this is the meat (33-60%)

Please email and comments, questions, and suggestions to this proposed process.

Best regards,
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Rajesh Maingi